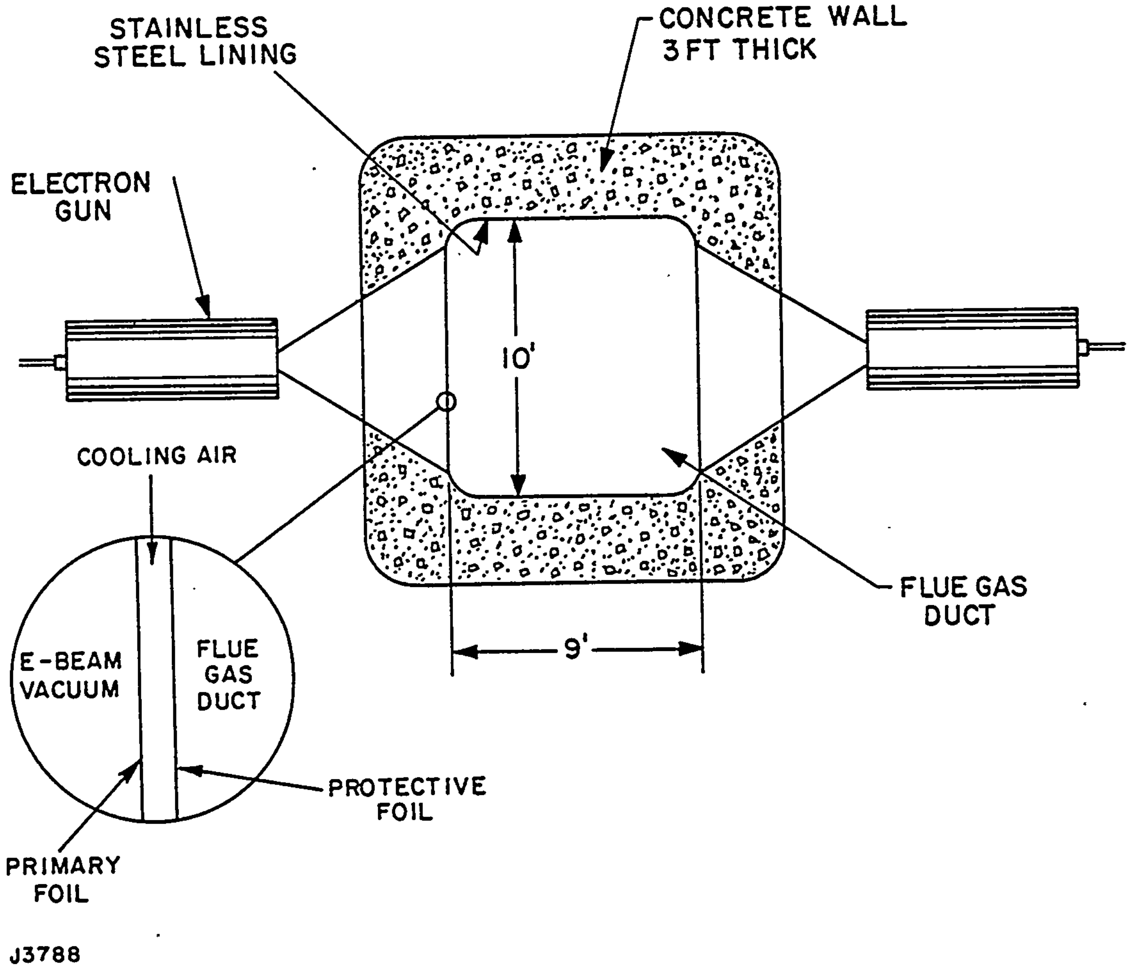
Slide AB-6.6

ELECTRON BEAM REACTOR CROSS-SECTION



Slide AB-6.7

TEST CONDITIONS

GAS SOURCE: LABORATORY SIMULATED
HEAVY-OIL BOILER FLUE GAS
IRON-ORE SIMTERING FLUE GAS
SPIKING

FLOW RATE: BATCH
FLOWS UP TO 10,000 NM^3/HR

GAS COMPOSITION:

SO_2	-	UP TO 2,000 PPM
NO_x	-	UP TO 1,000 PPM
H_2O	-	UP TO 20%
O_2	-	UP TO 20%
CO_2	-	UP TO 15%
PARTICULATES	-	UP TO 2 GR/FT^3

GAS TEMPERATURE: 60 TO 130°C

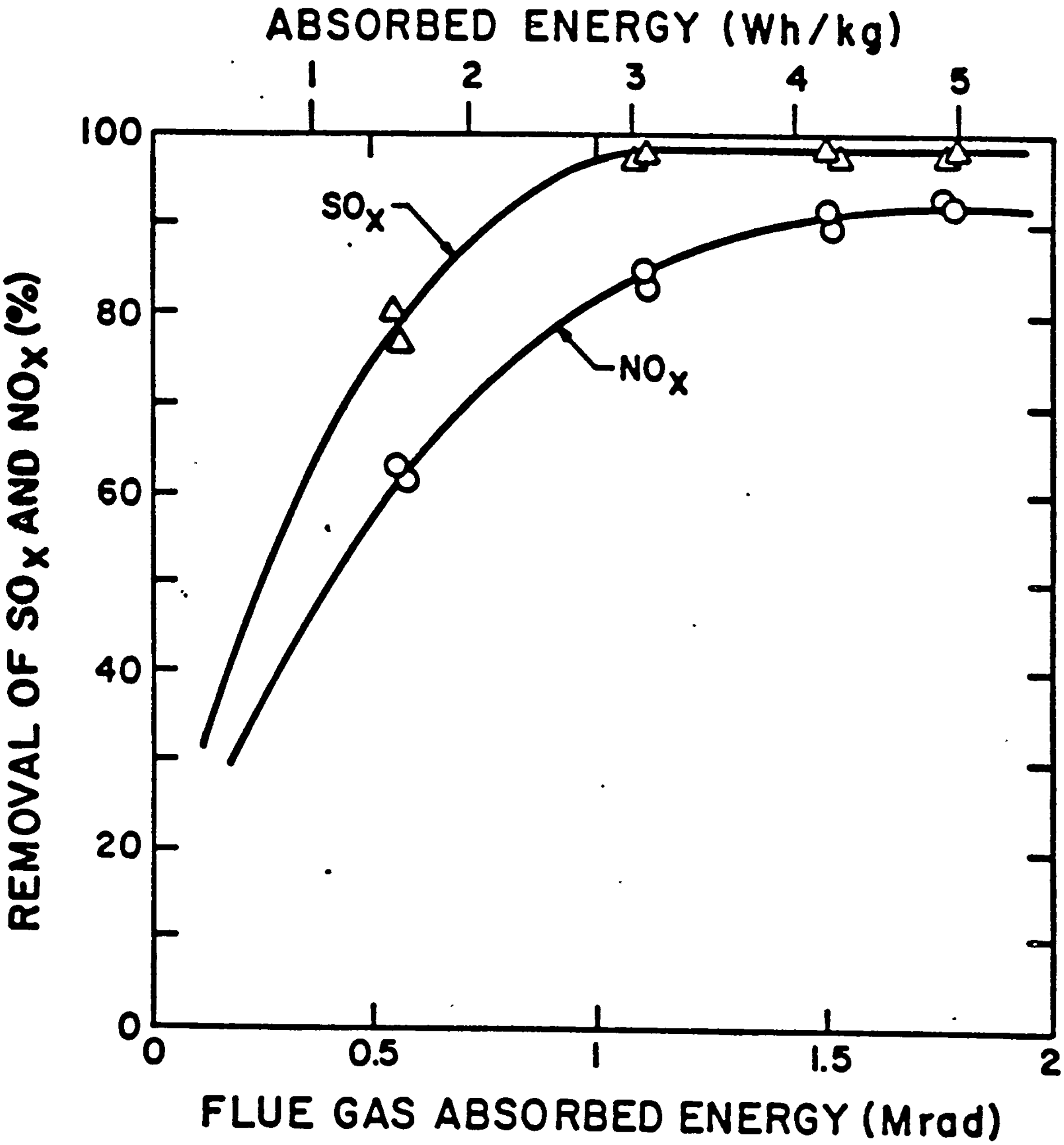
AMMONIA ADDED: 0 TO 2 TIMES STOICHIOMETRIC

ELECTRON DOSE: 0 TO 10 MRAD

RESIDENCE TIME: 0.05 TO 15 SEC.

DURATION OF TESTS: UP TO 3,000 HOURS

Slide AB-6.8



REMOVAL OF SO_x AND NO_x VS ABSORBED ENERGY

Operational problems include durability of the foil wall (1 to 1.5 mills) in the presence of flyash. Water is an essential component in the conversions. About 12 papers have been published by workers at the University of Tokyo on the chemical processes involved in E-beam scrubbing. Modeling is in progress. The device efficiency depends critically on the number of reactions that occur per ion pair produced. This number is said to be upward of 10.

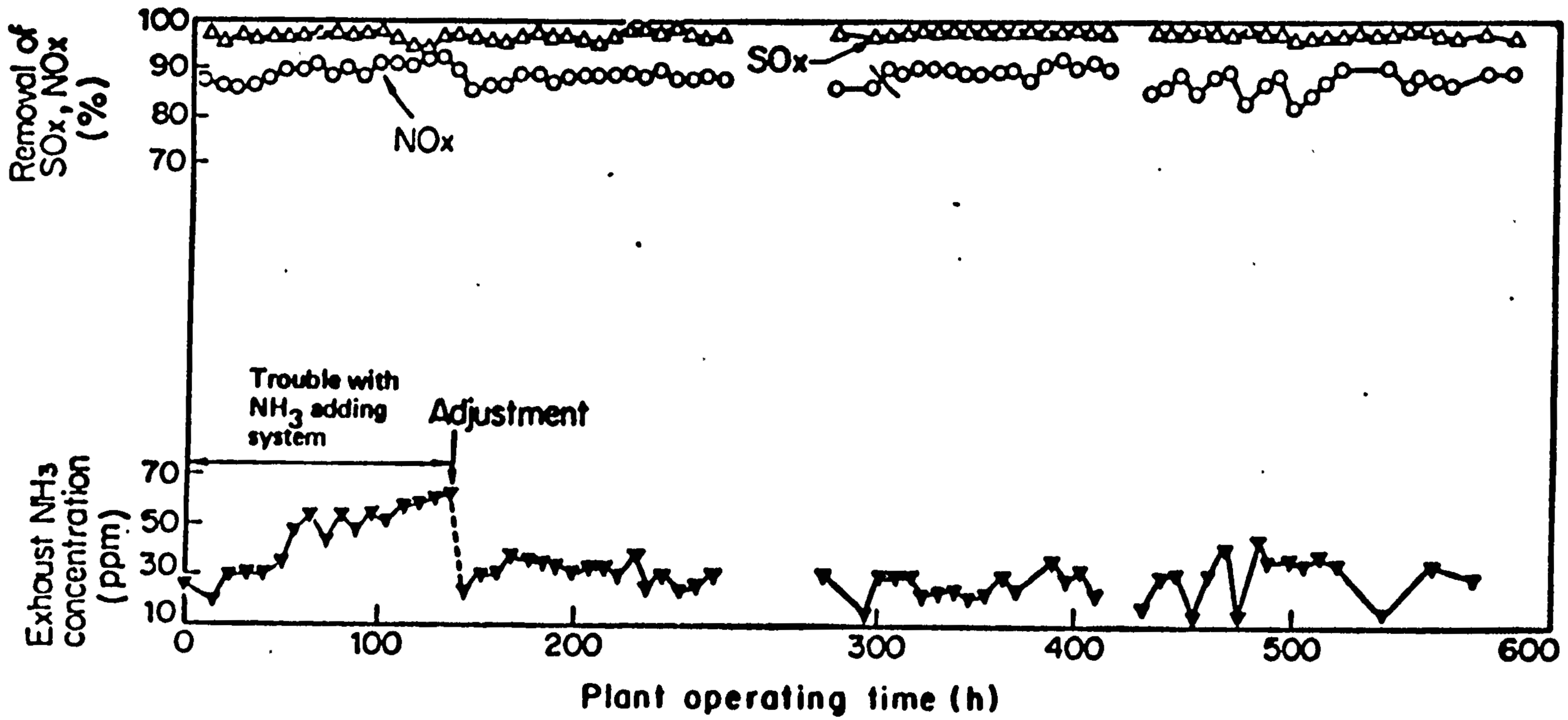
Slide AB-6.9 shows the excellent operational stability for SO_x and NO_x removals that has been achieved in long-term tests. The handling of fines is summarized in Slide AB-6.10. The E-beam induces particle condensation and an electrostatic precipitator (ESP) could then be used to reduce particulate levels to 5 mg/m^3 in a pilot plant. It has been shown experimentally that the presence of flyash does not interfere with gas scrubbing (see Slide AB-6.11). A schematic diagram of the incompletely understood reaction processes is shown in Slide AB-6.12. The market potential for the product fertilizers is substantial (Slide AB-6.13). Important areas for future research relate to trace metal concentrations and clean-up (Slides AB-6.14 to AB-6.16).

The PDU flow diagram for the DOE-sponsored study is shown in Slide AB-6.17, while the proposed operating conditions are indicated in Slide AB-6.18.

2. Slagging Combustors

Little, if any, experimental work has been done on retrofitting slagging combustors for utility applications. D. B. Stickler considered the following five principal topics, with information derived from Avco's MHD programs: coal-combustion behavior, transport and flow behavior of coal slag, MHD coal-fired combustors, high-throughput coal gasifiers, and issues relating to retrofits of slagging combustors.

Slide AB-6.9



CONTINUOUS OPERATION DATA FROM EBARA PILOT PLANT

Slide AB-6.10

AVCO/EBARA SCRUBBER HELPS REMOVAL OF FINE PARTICLES

- CONDENSATION MAKES FINE PARTICLES LARGER
- ESP ACHIEVED 5 mg/m^3 IN PILOT PLANT

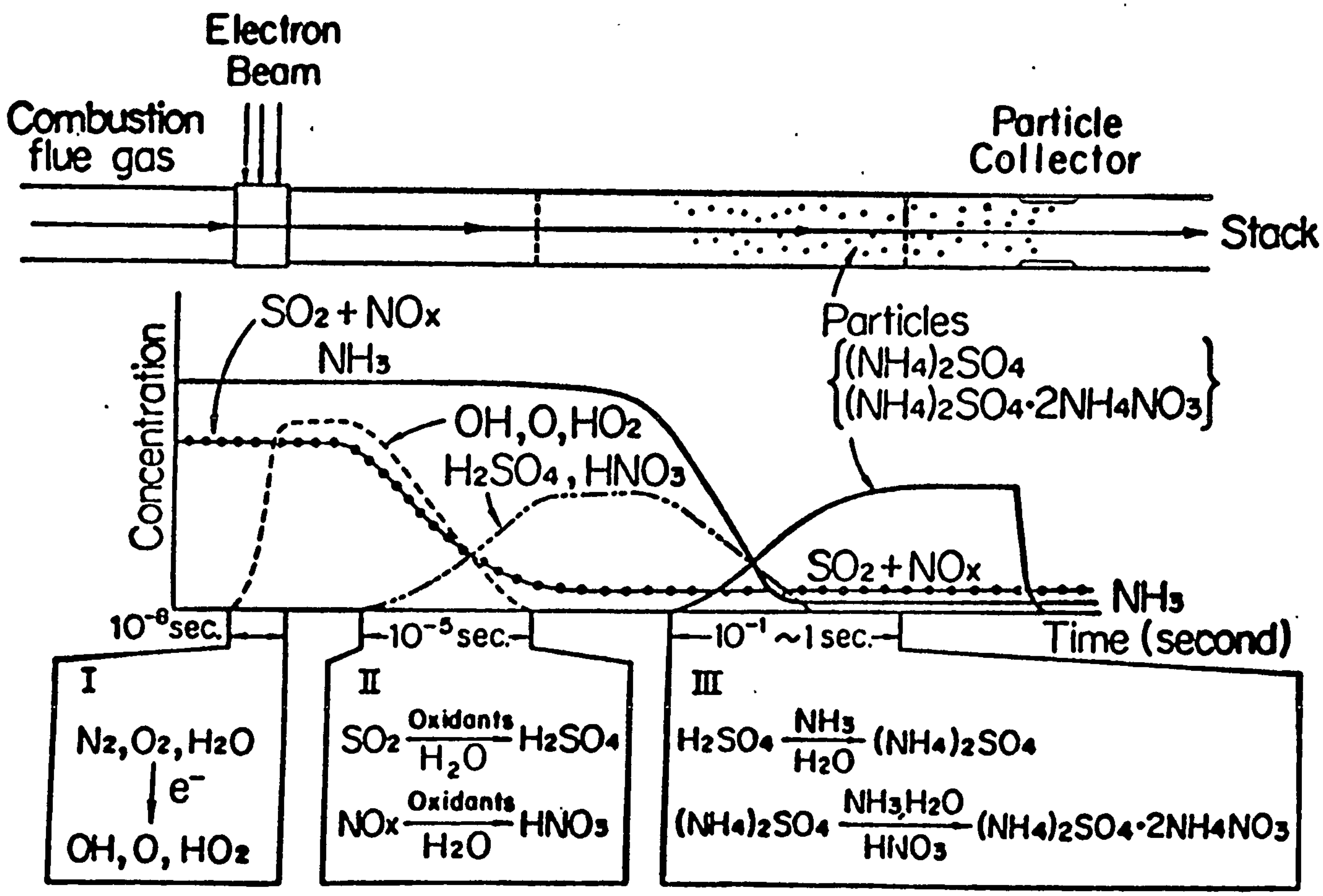
Slide AB-6.11

FLY ASH DOES NOT AFFECT REMOVAL EFFICIENCY

- ADDED FLY ASH FROM MONTANA AND NEW HAMPSHIRE POWER PLANTS
- MAXIMUM AMOUNT ADDED WAS 2 G/M^3
- CALCULATION SHOWS INSIGNIFICANT ENERGY ABSORPTION BY FLY ASH

Slide AB-6.12

MODEL OF REACTION MECHANISM FOR PRECIPITATION OF SO_x AND NO_x



Slide AB-6.13

MARKET POTENTIAL FOR BY-PRODUCT FERTILIZER

- 500 MW POWER PLANT BURNING 2.5% S COAL PRODUCES:

  147 KTONS/YR OF BY-PRODUCT (24%N ; 20%S)

- CURRENT DEMAND BASED ON AMMONIUM SULFATE / AMMONIUM NITRATE SALES:

  2,500 KTONS/YR 80% SULFATE: 20% NITRATE @ $65/TON

- S-DEFICIENCY REQUIREMENTS :

CROP – TYPE	
FIELD CROPS	1900 KTONS/YR
FORAGE CROPS	13,100
	15,000

GEOGRAPHIC	
ALTANTIC	1,100 KTONS/YR
CENTRAL	11,500
MOUNTAIN	2,000
PACIFIC	400
	15,000

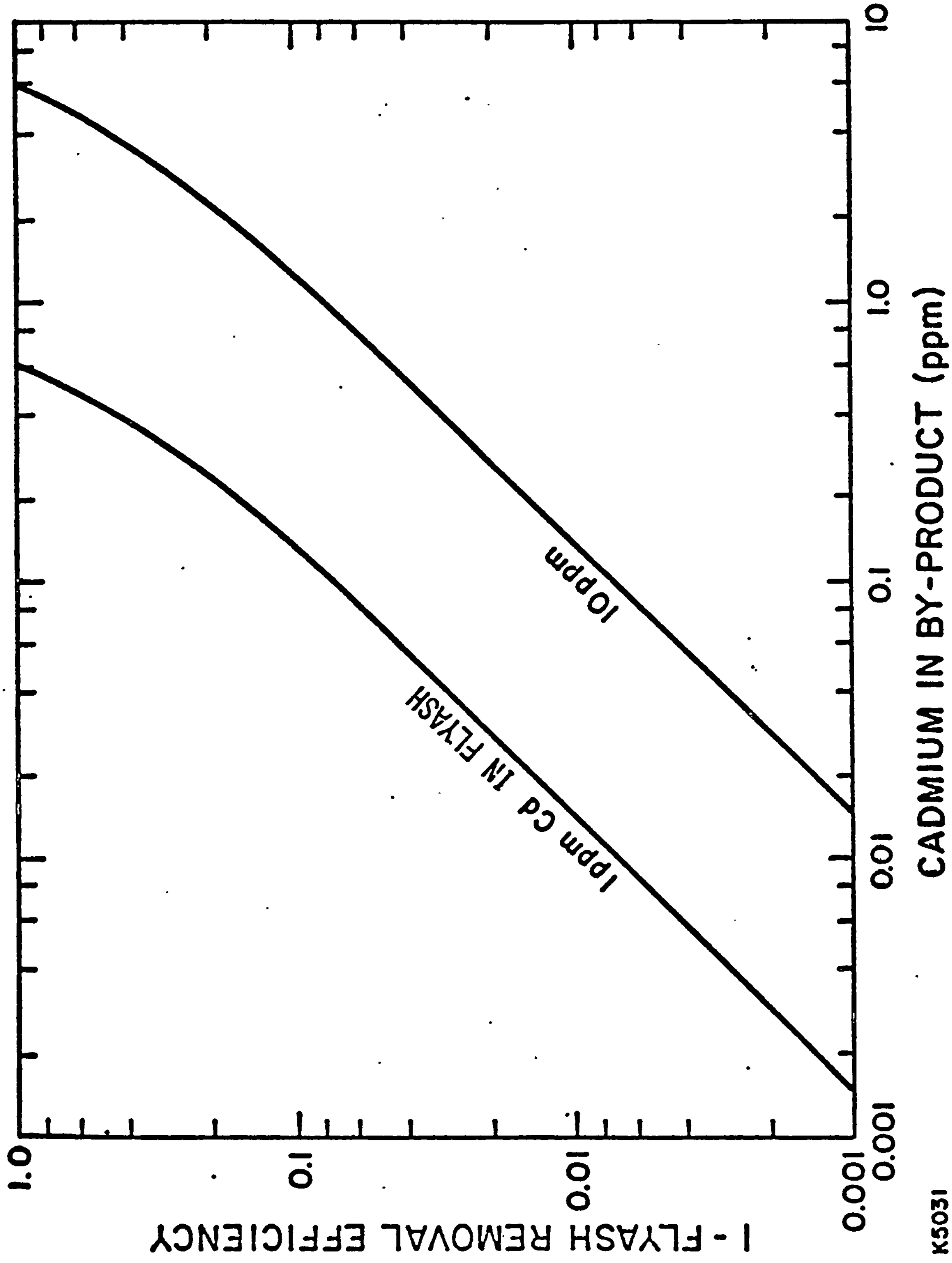
J73●7

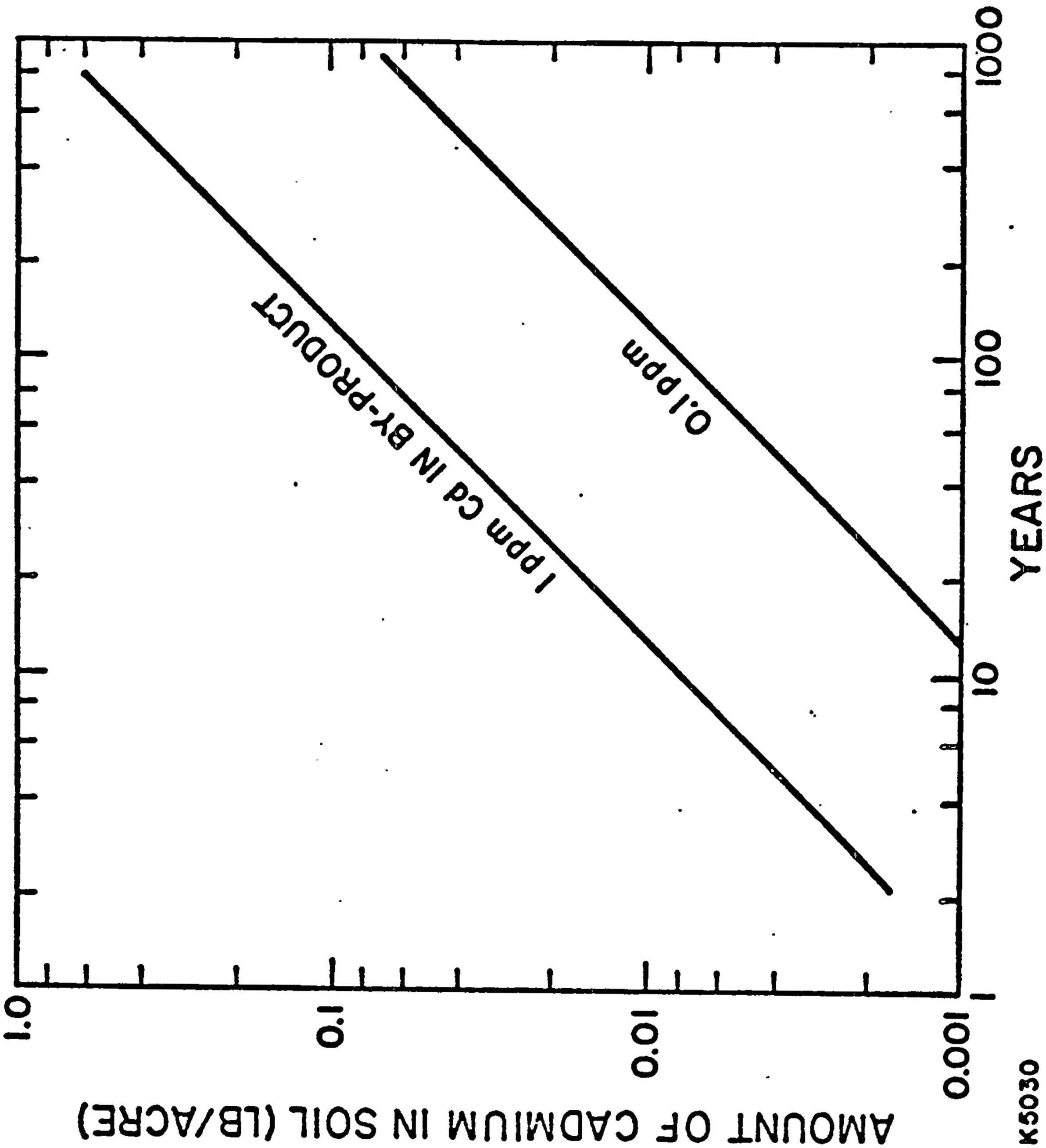
Slide AB-6.14

TABLE I. Range of Trace Metal Concentrations in Flyash Collected from Different Plants in the U.S.A.

ELEMENT	RANGE OF CONCENTRATION (ppm)
Arsenic	9.7 - 161
Beryllium	5.1 - 17.4
Cadmium	<0.5 - 8
Mercury	0.04 - 0.31
Nickel	19.3 - 207
Selenium	6.75 - 27
Lead	43 - 80
Thallium	1.1 - 4.1
Uranium	9.4 - 30.1
Vanadium	133 - 440

Slide AB-6.15


1 - FLYASH REMOVAL EFFICIENCY
1.0
0.1
0.01
0.001
CADMIUM IN BY-PRODUCT (ppm)
0.001
0.01
0.1
1.0
10
10ppm
1ppm Cd IN FLYASH
K5031

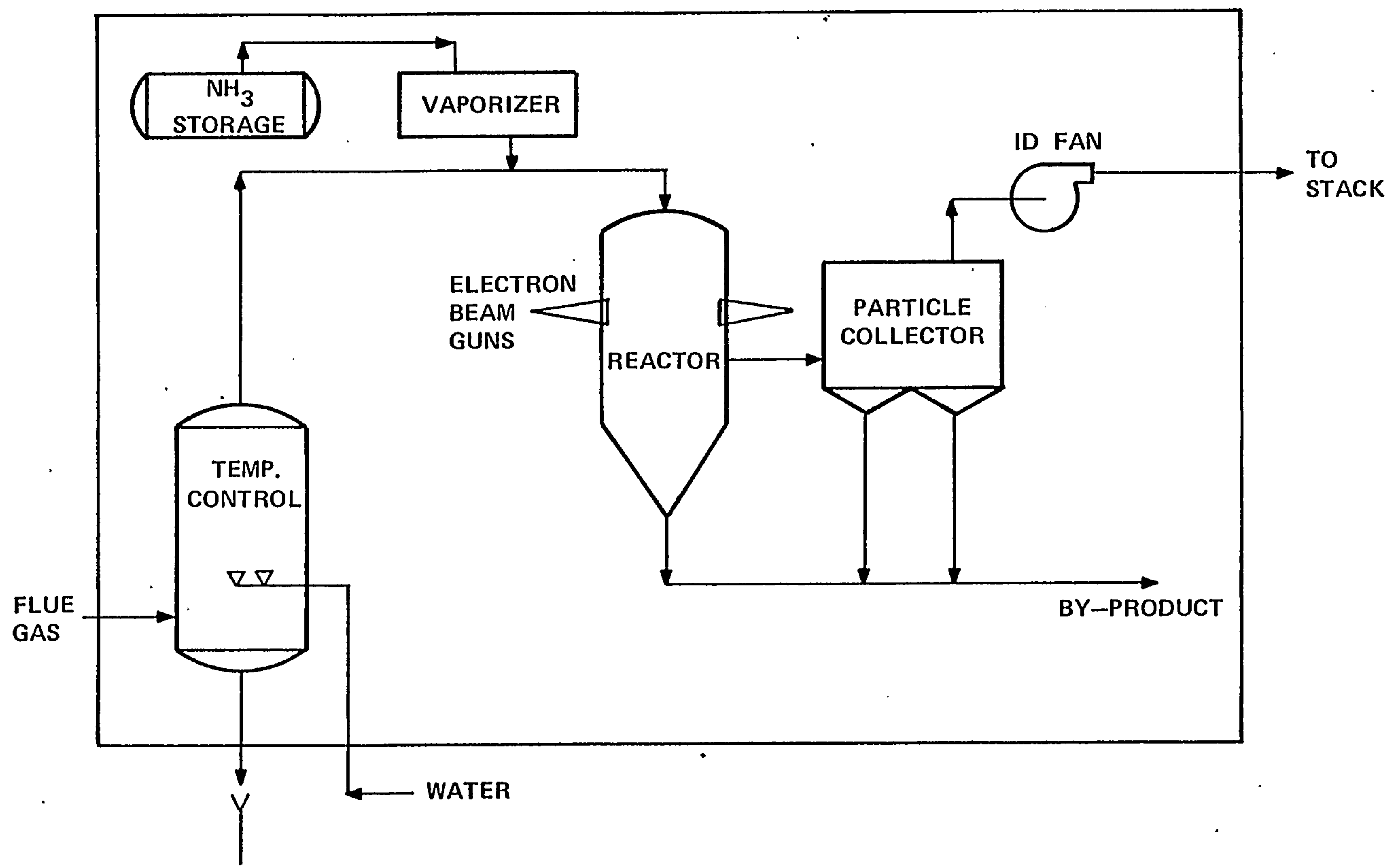

AMOUNT OF CADMIUM IN SOIL (LB/ACRE)
1.0
0.1
0.01
0.001
YEARS
1
10
100
1000
1 ppm Cd IN BY-PRODUCT
0.1 ppm
K5030

Slide AB-6.16

Slide AB-6.17

PRELIMINARY PDU PROCESS FLOW DIAGRAM

AERL



Slide AB-6.18

FLUE GAS SLIP–STREAM

- COAL–FIRED FLUE GAS
- FLOW RATE: ABOUT 20,000 CFM
- INITIAL CONCENTRATIONS:

  SO_x = UP TO 4000 PPM

  NO_x = UP TO 1000 PPM
- REMOVAL EFFICIENCIES: MEET OR EXCEED EPA REQUIREMENTS

In MHD applications, the pulverized coal is exposed to air at about 2000°F, which leads to hypergolic ignition. A combustion model has been developed for these operating conditions and involves a two-step pyrolysis reaction that is followed by oxygen attack on char. Successful predictions have been achieved of flame stability and flame extinction. The combustor developed for MHD applications produced slag layers. The development and time histories of these slag layers could be approximated by utilizing analytical procedures analogous to those employed for reentry heat shields.

A conceptual design for a slagging industrial combustor was discussed and will be further considered at the next CCAWG meeting. In response to the DOE proposal requests, a joint program was developed in collaboration with Riley-Stoker of Worcester, Massachusetts.

AB-7

COMMENTS ON PRESSURIZED (PFBC) AND ATMOSPHERIC (AFBC) FLUIDIZED-BED COMBUSTORS*
(August 1982)

1. New York University, Antonio Ferri Laboratories, Merrick and Stewart Avenues, Westbury, N.Y. 11590

Victor Zakkay and his colleagues have successfully run a PFBC since 1975. A new facility was constructed at a cost of ~\$700,000 and has been operational since early July 1982. It consists of a 30-inch i.d. burner operating at 1 to 10 atm, 1300-1400°F, with coal throughputs of 0.5 to 1.5 TPH. Shake-down tests have been run with bituminous coals (supplied as ground coals at -1/8" in barrels by Curtiss-Wright at a cost of ~\$500/T), although the primary studies will be concerned with North Dakota lignites. Combustion efficiencies generally exceed 99% and less than 100 ppm of NO_x are emitted. The primary emphasis has been on combustor design and control and on effluent clean-up.

Current activities deal especially with a response to an RFP from METC, which is being developed jointly with Burns and Roe. The basic design involves a three-stage fluidized bed reactor with the first stage carrying relatively large coal particles confined by grids in a circulating combustor, heat exchangers are located in the second stage, and an elutriator for particulate removal serves as the third stage. The design appears to be especially well suited for studies of the elementary sequential processes that occur in all fluidized bed combustors.

An interesting feature of the current DOE-sponsored program at NYU is a full-day visit once per week by a DOE representative from Gilbert and Associates.

*Prepared by S. S. Penner.

2. Curtiss-Wright Corporation, One Passaic St., Woodridge, N.J. 07075

Following extensive (i.e., over 10,000 hrs of operation with one-third of allowable NO_x and SO_2 production, as well as excellent durability for the in-bed heat exchanger and turbine-blade materials) experience with a small-scale model, a pilot plant is currently under construction and is expected to be operational by the fall of 1983. The equivalent electric power output of the plant should be somewhat more than 13 MW_e. The plant will have an industrial gas turbine with an air-flow capacity of 120 lb/sec and a 7:1 compressor pressure ratio. The power turbine will be gas-coupled to a gas generator and will be mechanically coupled to a gearbox and generator producing 7 MW_e. The gas will leave the power turbine through a bifurcated duct and enter a waste-recovery boiler producing a steam-flow rate of 58,000 lb/hr. This pilot plant is viewed as about a one-sixth scale version of a commercial module to be used in a 500 MW_e combined cycle plant.

The emphasis in this work is on the production of electric power and steam using high-sulfur coal under environmentally acceptable conditions. Observation of the construction phase of the pilot plant is an especially informative experience. A good description of these developments has been given by S. Moskowitz (Curtiss-Wright) and J. F. Geffken (DOE) in AIAA-81-0392, "Pressurized Fluidized Bed - A Technology for Coal-Fired Combined Cycle Power Generation," Aerospace Sciences Meeting, January 12-15, 1981, St. Louis, MO.

Like Victor Zakkay, Sy Moskowitz is currently heavily occupied responding to the RFP from METC on advanced concepts for PFBC.

3. AFBC at Georgetown University in Washington, D.C.

On Wednesday mornings at 10:00 a.m., a public tour is generally held of the AFBC commercial steam generator designed by Foster-Wheeler and others and operational on the Georgetown campus for about 3 years. The unit costs $\$12 \times 10^6$ and generates 100,000 lbs of steam per hour using a once-through fluidized bed combustor burning stoker coal.

Although this AFBC is supposed to operate as a commercial device without undue down-time, persistent operational problems have been caused by erosion of steam tubes as the result of particle-laden flows. Extensive modifications have been made in the baghouse to improve particulate removal efficiencies. The levels of SO_x are controlled by limestone absorption while NO_x control is achieved through controls of air-flow rates.

4. Conclusions

There is important work of diverse character in progress on AFBC and PFBC. The question of commercial acceptability for these units merits discussion by CCAWG, as do novel design concepts and potential problem areas in large-scale operations. Clearly identified problems deal with heat-exchanger tube erosion in particle-laden flows, with improved designs for coal feed, and with environmental clean-up.

Tentative plans have been made for a detailed review by CCAWG of PFBC during February of 1983. It may be useful to discuss both funded and unfunded concepts by talking especially to the large number of people who are currently responding to the RFP from METC.

CCAWG MEETING AT THE BABOCK AND WILCOX RESEARCH CENTER, 1562 BEESON STREET, ALLIANCE, OHIO 44601 (October 18, 1982)

CCAWG members C. R. Bozzuto, A. K. Oppenheim, S. S. Penner, L. D. Smoot, C. L. Wagoner, I. Wender, W. Wolowodiuk, and J. Birkeland (DOE) attended the meeting. Also present were G. Jordy (DOE), D. Stickler (AVCO-Everett), D. Anson (Battelle), D. Smith (General Electric), and E. Michaud (Babcock and Wilcox).

The topics discussed and the agenda are summarized in Table AB-8-1.

1. Summary of Discussions

J. Birkeland's review of the DOE Design Study of Advanced Fossil-Fuel Systems (DAFFS) was of particular interest to CCAWG members. There was considerable discussion of the preliminary report, especially of the February 1980 cost estimates for 3 PC, 2 PFBC, and 3 IGCC plants. It was noted that atmospheric fluidized bed combustors had not been included and might well have been shown to be the most favorable and lowest cost electricity-generation plants. While sensitivity analyses had been included in DAFF, several CCAWG members noted the importance of showing cost estimates as functions of allowable NO_x and SO_2 production levels well below those that are deemed to be acceptable today. Dr. Birkeland emphasized the possible importance of plant size in making comparisons of results obtained in the 500-MW_e DAFF studies with the 1000-MW_e ECAS (= energy conversion alternative systems) data released a few years ago. Several CCAWG members concurred with Dr. Birkeland's remarks that he was dealing with a highly sensitive subject that could not be summarized without extensive qualifications.

D. Stickler presented a good overview of potential developments of slagging combustors utilizing information and knowledge derived from extensive investigations of MHD combustors. Most of this work has been summarized previously in AB-6.

D. Anson presented an overview of coal-combustion studies at Battelle. His lecture presentation is outlined in Appendix AB-8-1.

D. Smith reviewed studies performed at the General Electric Company on the utilization of low-grade fuels in gas turbines. This work has been referred to previously in AB-5. Most of the turbine tests were conducted with synthetic fuels, including resids with ash contents up to 1000 ppm. The concentrations of sodium and potassium are of critical importance in defining the levels of hot corrosion. At a weight ratio of 3:1, Mg (usually added as an aqueous solution of epsom salts) is a useful inhibitor in reducing corrosion by V. Nut sheels have been used to remove some of the deposits. However, complete removal of solid deposits requires a water wash and soaking. Without cleanup, allowable peak turbine temperatures may be quickly derated by about 100^{o}F. Quantitative studies of blockage in stationary, first-stage blading were described in which a nozzle-area inlet number was employed as measure in an equation for the reduced rate of nozzle plugging (e.g., in % per 100 hrs of operation). Turbine studies with fuels containing the high ash levels that are characteristic of coals (i.e., at least 10 times higher concentrations than have been tested) remain to be performed. Ways should be sought to modify ash contents in order to eliminate sticking of the solid phase. The relations between beneficiation procedures and possible IGCC systems require quantification.

Coal-related studies at B&W were summarized by C. Wagoner and E. Michaud (see Appendix AB-8-2 for details). Also of interest are the development of a second generation laboratory furnace for ashing studies (Appendix AB-8-3) and observations on fireside deposition of ion-exchangeable calcium in coal (Appendix AB-8-4).

Table AB-8-1. Agenda for CCAWG Meeting

Babcock & Wilcox Research Center
1562 Beeson Street
Alliance, Ohio 44601
(216) 821-9110

Conference Room A
Monday, October 18, 1982

8:00 am	Introduction	C. Wagoner (B&W) S. Penner (CCAWG)
8:15 am	Review of the DOE Design Study of Advanced Fossil Fuel Systems, DAFFS	J. Birkeland (DOE)
9:25 am	Slagging, High-Intensity Combustors	D. Stickler (AVCO-Everett)
10:05 am	Coal-Related Studies at Battelle, Columbus	D. Anson (Battelle)
11:15 am	Discussion of Future Meetings and Agendas	S. Penner (CCAWG)
11:35 am	Lunch: Cold Buffet in Conference Room B	
12:15 pm	Utilization of High-Ash Fuels in Turbines	D. Smith (General Electric)
1:00 pm	Coal-Related Studies at Babcock & Wilcox	C. Wagoner (B&W) E. Michaud (B&W)
2:45 pm	Tour of B&W Facilities	E. Michaud (B&W)
4:00 pm	Adjourn	

APPENDIX AB-8-1

COAL COMBUSTION AT BATTELLE

Introduction and Background

The Battelle Memorial Institute dates from 1929, and work in coal combustion was one of its first activities. Soon afterwards, Ralph Sherman, using a cylindrical combustor some 2 ft. in diameter and 8 ft. long, carried out experiments on the combustion of pulverized coal that yielded classical data on radiant heat transfer from p.c. flames. In 1932 Bituminous Coal Research, Inc., was established by the coal producers, with Battelle staff and facilities. This was a very early example of a group funded industrial program, and served the interests of both industrial and domestic coal users, although it was not heavily involved in utility related work.

Highlights in coal combustion work during the 1940's and 1950's included the development of an efficient inverted (or downdraft) underfeed domestic coal stoker that overcame the smoke emission problems of conventional systems; the development of stable and efficient pulverized coal combustors for a gas turbine intended for locomotive applications; and the collection of data on slagging and corrosion by fuel ash which are assembled in W. T. Reid's authoritative book on the subject, which was produced in 1971.

In the early 1970's Battelle had extensive in-house funds, of which a substantial portion was invested in the Battelle Energy Program, aimed at providing solutions to the emerging energy crisis. The most important product of this program was a novel circulating fluidized bed combustion process, the Battelle Multi Solids Fluidized Bed (MSFB). The early development of this system was supported by federal funding, and it is now licensed for commercial use.

In the mid 1970's a large part of the combustion at Battelle related to the control of emissions to the atmosphere, with direct relevance to the use of coal in large utility boilers. Much of this work was, and still is, supported by coal burning utilities and by the Electric Power Research Institute (EPRI). Research related to coal combustion broadened in the late 1970's to include a substantial effort aimed at improving the reliability and performance of coal fired utility plant, which had been found to be deteriorating as mine mechanization increased. The electric utilities are anxious to reduce the impact of coal quality on plant availability, and to this end research is continuing into the relative overall economics of coal cleaning, use of chemical additives, and increased plant investment levels.

As fuel prices increase other industrial fuel users are finding that their production costs are significantly affected by fuel costs, and are turning, amongst other things, to wider use of coal and improvements in coal use efficiency.

Battelle's combustion related work has always reflected a substantial proportion of industrially supported effort, and this facilitates the transfer of the results of government supported basic work to the private sector. Currently, more than half of our work relevant to coal combustion is industry funded, compared with about 40 percent of Battelle research in all departments.

Recent and Current Work

Work recently completed and in progress at Battelle reflects the general picture given in the introduction. Most of the industrial sponsorship comes from the utility industry, directly or through EPRI. However, coal producers, additive vendors, and equipment manufacturers are responding to the users' requirements for more definitive data on their products, and are sponsoring independent research to provide those data. Listed below are some of the more important topics in the category of recent and current work for industry.

Recent and Current Projects for Industrial Sponsors

- Effect of coal properties on boiler deposits and plant performance (3 projects)
- Developments in fluidized bed combustion (conventional and MSFBC)
- Use of fuel additives to modify the properties of fly ash and coal ash deposits (3 projects)
- Design of a pilot scale pulverized coal combustion facility for fuels evaluation
- Combustion assessments of coal/oil and coal/water slurries (including ash deposition behavior).

Government sponsored work, as would be expected, is generally more concerned with advanced, high risk, or basic concepts. The following list is a sample of the more important recent and current projects.

Recent and Current Projects for Government Sponsors

- The potential for use of Peat Blends with Coal for Electric Power Generation DOE/GFETC/0231
- Calcium Oxide Interaction in the Staged Combustion of Coal - DOE DE-AC22-80PC-30301
- Utilization of Battelle Treated Coal in Gasification and Combustion Processes to Control Sulfur Emissions- DOE Contract W-7405-Eng-92-111
- Advanced Development of a Coal/Limestone Fuel Pellet for Industrial Boilers - EPA 68-02-3189
- Advanced Atmospheric Fluidized Bed Combustion Design - Spouted Bed - DOE Contract DE-AC21-82MS-19328
- Advanced Atmospheric Fluidized Bed Combustion Design - Ultra High Velocity Multisolid Fluidized Bed - DOE Contract DE-AC21-82M19331

- The Spouted Bed Combustor - A Novel Approach to burn low calorific value fuels in an environmentally acceptable manner - EPA Grant 8095840
- Coal Fired Closed Cycle Gas Turbine Research and Development (Subcontract to Rocketdyne) DOE Contract DE-AC01-80-ET15020

Several of these projects are referred to in more detail in the section on Current Research Interests, in which their importance in the context of ongoing work is made apparent.

Coal Burning Facilities

Battelle employs 3000 people at Columbus, and some 5000 elsewhere. Facilities that are available in-house cover all aspects of coal use from exploration to the toxicology of wastes and emissions. Facilities that are used for direct coal combustion research cover a range of types and scales. They are generally of rather simple basic design, and are capable of rapid low cost adaptation to specific sponsor requirements. The largest, having a thermal capability of 5 million Btu/hr, is presently nearing completion, and can handle a variety of fuels, although it is designed primarily for pulverized coal. This unit incorporates the main features of a pulverized coal fired boiler system - a vertical spindle 5 ball pulverizer, air preheat, dry ash removal, and variable swirl burner - and includes test sections simulating furnace wall and superheater tube conditions. At the other end of the scale is a flat flame methane burner into which pulverized coal can be fed in order to study reaction kinetics using classical optical and sampling techniques.

Fluidized bed combustion facilities include both a conventional bubbling bed with immersed heat transfer surface and pilot scale combustors using the MSFB technology. The range of coal burning facilities is summarized in the list which follows.

Coal Burning Experimental Facilities

- 5 Million Btu/hr Pulverized Coal Combustion Facility for research into combustion processes, deposits formation and characterization, emissions control, and other aspects of the evaluation of fuels and combustion systems
- 0.5 Million Btu/hr Multifuel Research Facility, used for fuels and additive evaluations and as a screening unit for larger scale work
- 25,000 Btu/hr Combustor, this unit fires vertically downwards into an externally heated reactor tube. This allows use of a simple aerodynamic flow field, and simplifies collection of time based data related to kinetics of single- and multi-staged combustion processes.
- Flat Flame Combustor, basically a "flat" methane flame with facilities for introducing pulverized coal particles into a controlled temperature and composition environment. Used for studies of in-flame chemical reactions in combustion and sulfur capture processes.
- 1 Million Btu/hr MSFB combustion pilot plant. This has been the most important vehicle for development of this process, to improve combustion and sulfur capture, and to provide a basis for commercial units.
- 0.4 Million Btu/hr MSFB combustion development unit. This was used for much of the early development work and has been especially useful in characterizing the combustion behavior of different fuels.
- 2 Milltion Btu/hr Fluidized Bed Combustor. This is a "conventional" bubbling bed with considerable flexibility as to base design and heat removal rates. It has been used as a vehicle for the development of in-bed diagnostics and for studies of the materiasl problems associated with high temperature heat transfer surfaces.

Current Research Interests

Because Battelle's work is almost entirely dependent on sponsor's needs at any one time, there are many diverse projects in progress. This presentation therefore concentrates on topics in which Battelle workers have a strong interest and in which we see a reasonable continuity through both government and industrial contracts. These topics fall under the broad headings given below. All are discussed in the context of combustion only, although there are associated programs in materials technology, coal treatment, and fuels conversion technology such as gasification.

- Coal quality
- Mineral impurities in coal
- Modification of impurity content
- Slurry fuels
- Advanced combustion technology
- Diagnostics
- Chemistry.

Coal Quality. Coal purchases frequently are made on the basis of heating value, sulfur content, and proximate analysis. More discriminating buyers may also specify ultimate analysis, ash fusion temperatures, ash analysis, grindability, and swelling index. For power generation boilers operating at the upper end of the steam temperature range (1000 F or more), the really critical factor is very often the behavior of the ash in regard to deposit formation and slagging. None of the listed parameters gives an adequate guide to this behavior, although there is broad acceptance that ash behavior is sensitive to sulfur, iron, and alkali contents and that the ASTM ash fusion test provides a guide to slagging propensity.

Past work on coal slags provides consistent methods of correlating the behavior of fully molten and homogenized slag with ash composition. Boiler deposits are far from homogeneous, so that empirical relationships, based purely on elemental analyses, do not present the full picture. A typical example of such an empirical relationship is that published by Babcock & Wilcox which combines the amount of sodium in the ash with the base/acid ratio of the ash constituents.

In the past few years Battelle has had projects which have attempted to correlate coal quality records with utility plant performance and reliability. The success of the effort has been constrained by the limited extent of the records, both in regard to coal data and the causes of plant outages or load reductions. To complicate matters, coal sulfur and ash content, and obviously plant age itself, changed systematically over the time period studied. We are presently engaged in a very comprehensive collection and analysis of data from which better results should emerge. The willingness of utilities in the U.S. and abroad to complete and return exhaustive questionnaires on this subject attests to the importance attached to understanding why coals behave as they do, and ultimately knowing how to select them. With this broad support the exercise should at least lead to better empirically based guidelines.

At this time pilot scale combustion testing provides the best guide to coal selection but very small scale combustion tests still leave open many questions of similarity and considerable judgement is needed to apply test results to full scale plant behavior. An alternative approach, in which we have a keen interest, is in developing laboratory procedures based on parameters that relate more directly to the complex combination of chemical and physical factors affecting coal deposit behavior in a boiler environment.

Mineral Impurities in Coal. Closely related to the behavior of coal ash deposits is the nature of minerals in coal and the transformations which they undergo during coal combustion. The range of clay minerals, silicates, carbonates, sulfides, phosphates, and other rocks that are found with coal are greatly modified by thermal treatment and the changing chemical environment, and even after combustion they do not correspond to a laboratory ash. Now that analytical methods are available that greatly widen the scope of coal minerals indentification and characterization, it seems reasonable to build up a better understanding of the ways in which specific minerals contribute to deposit and emissions behavior. Battelle has a strong ceramics group and we have recently involved some of their people in examination of coal, fly ash, and ash deposits. This is a very promising and interesting area for future work.

Modification of Impurity Content. Modification of the impurity content of coal can be affected by selective cleaning or by addition. All practical cleaning processes are selective, usually in terms of specific gravity, but the basis of selection relates only indirectly to coal ash properties. Discussion of coal cleaning is not relevant here, but the effects of coal cleaning on combustion are. Density separation removes heavy rocks such as pyrite, calcite, and quartz minerals, but is ineffective on some of the alkali metal compounds. The questions facing a potential user are, to what extent will density separation improve a fuel? And what is the economically optimum treatment for a given coal and application? Several coal beneficiation processes are available, and Battelle has patented procedures that can reduce ash contents to less than 1 percent and remove 90 percent of the sulfur in coal, if such a level of cleaning can be justified. We feel that the utilization (combustion) aspects of coal cleaning have been severely underestimated and advocate more attention to coal combustion behavior, particularly as it affects impurities, in the specification and evaluation of cleaning procedures.

Once the total impurity level in a coal has been reduced, it becomes more feasible to modify the residual ash by making additions to the coal. Unlike cleaning procedures, additives are quite specific and may be chosen to retain sulfur, inhibit formation of bonded deposits, or induce self shedding properties in the deposits. The cost of using an additive would have to be less than that of further cleaning or use of a better grade of coal in order to achieve the same result.

Battelle has carried out work in the area of additives for both EPRI and a number of industrial sponsors and this work is expected to continue. A particular technique, which was developed by Battelle and which will be referred to later, involves hydrothermal impregnation of coal with calcium. Work has also been carried out on the effects of small additions of materials such as limestone, quartz, and dolomite on the strength of sinters made from fly ash. The experimental techniques were adapted from earlier work by Barnhart and Williams at Alliance. This work has, quite incidentally, provided data on the transport of certain elements between particles within deposits, and may have implications on both minerals behavior and the use of vapor phase additives.

Two additives that are dispersed as vapors and have been reported to change the properties of coal ash deposits are copper oxychloride and manganese (incorporated in an organic liquid). Both have been said to weaken deposits even when used at parts per million rates. Their actions are not understood but it is presumed that they modify the surfaces of fly ash particles (possibly selectively) so as to reduce interparticle bonding. Of the two, there is more experience with copper oxychloride, and it has been suggested that it affects deposit properties by promoting crystallization from glassy phases, and by influencing the development of voids in slags. We hope to receive support for investigation of additives of this kind - that is surface acting substances - for the purpose of inhibiting boiler fouling.

Slurry fuels. Coal/water slurries are among the more interesting fuels now being produced and tested. Battelle has carried out a number of industry sponsored combustion/deposit evaluations on slurries and we see considerable potential for their use. The ability to use them as oil replacements in existing plants depends on being able to achieve comparably rapid combustion, and (for boilers) comparably low ash deposition rates.

Combustion of slurries involves first the dryout of slurry droplets, then ignition and combustion of the solid residue. There is no doubt that these steps can be achieved without extensive modification to techniques used for oil firing, but there are few data on the burnout rate or methods of enhancing it to match that of oil.

The amount, nature, and behavior of ash forming impurities in slurries is of special interest and fits into Battelle's related activities in coal cleaning and additives. Deep cleaning of coal, and incorporation of additives by such methods as hydrothermal treatment, require size reduction to liberate impurities and expose surface. When applied to slurries, the elimination of the need for separation and drying significantly simplifies the beneficiation process. On this basis we see scope for the development of a range of "advanced" coal slurries having inherently low sulfur, low ash, and low deposition potential. While the cleaning processes are already developed, treatment of the slurries to produce the desired emission and deposition free properties requires further experimentation, particularly in the form of combustion testing.

Advanced Combustion Technology. Battelle has a number of projects involving the evaluation and/or development of advanced coal combustion technologies. Most of these have received or are receiving government financial support. They are described very briefly here, but all involve quite extensive efforts.

Battelle Multi Solids Fluidized Bed

Although the MSFB has entered the commercialization phase, development and research continue, with emphasis in further improvements in combustion sulfur capture, and NO_x control. Proposals have been made for pressurization of this type of unit. Pressurization would lead to a very compact unit, but would also be expected to change the fluidization behavior, two phase mixing in the entrained region, and spatial concentration of the carbon phase. This represents a significant extension of FBC technology, supported by math modeling to provide a sound basis for extrapolation to larger scales and higher pressures.

Flue Gas Dilution of Pulverized Coal Combustion. As part of a major experimental program on coal fired closed cycle gas turbines we have been studying air heater designs which incorporate both novel geometric layouts and extensive flue gas recirculation in a pulverized coal fired system. The objectives were to produce more uniform heating and less aggressive deposits than would be expected in a normal boiler combustion situation. This work has involved cold flow modeling, reduced scale combustion testing, and materials testing in p.c. fired environments.

Staged Combustion

Much of the staged combustion work at Battelle has been related to fluidized bed technology, using both the MSFB principle and conventional FBC. The MSFB is particularly amenable to staging. There has also been considerable bench scale and small lab scale work related to staged combustion of pulverized coal, some of which is described in a later section.

Spouted Bed Combustion

Spouted bed combustion is distinguished from fluidized bed combustion by the existence of vertically upward spouts in which air and reacting fuel penetrate the bed surface, the solids raining back onto the bed surface to be recycled. The recycled solids form an effective heat carrier, and in a gas fired system the recycled heat permits stable combustion of very dilute mixtures. Battelle currently has two projects in which the spouted bed principle is being examined in the context of coal firing, as well as for firing other gaseous, liquid, and solid fuels. The spouted bed may also be regarded as an extreme example of a directionally fluidized bed with controlled bed movement, and we consider that other alternatives of this sort warrant serious study.

Diagnostics

Diagnostics form an essential part of Battelle's coal combustion research effort, and in particular we have developed a strong capability in in-bed diagnostics for FBC systems. Fluidized beds constitute a very severe environment in which to make scientific measurements. We have been especially pleased with the results of in-bed measurements of oxygen partial pressure which have given valuable data on both temporal and spatial variations of oxygen partial pressure. These data relate to the corrosion of heat exchanger tubes immersed in a coal fired bed and are potentially important in relation to combustion and pollutant control. Other diagnostics techniques that have been developed deal with particle size distribution, temperature and velocity measurement. Extensive use has been made of laser and fiber optics technology.

The use of advanced diagnostics in investigation of physical and chemical conditions in fluidized bed combustors is very much needed. Present understanding of these conditions is very deficient, and for this reason considerable uncertainty remains as to the durability of advanced large scale fluidized bed combustor devices, and the potential for further improvement of in-bed reactions.

Chemistry

In the area of coal combustion chemistry, Battelle has been active for some time in work related to the formation and control of gaseous pollutants. The precursors of current programs were initiated to explain the production of corrosive salts (the alkali iron trisulfates) in boiler furnace deposits. In a series of small scale experiments the oxidation of H_2S to SO_2 and SO_3 in the absence of catalysts was demonstrated. Catalysts present in fly ash are judged important, however, in accelerating the production of SO_3 to form complex sulfates at or near tube surface temperatures. In more recent work related to staged combustion enhanced production of SO_3 has been demonstrated in the secondary combustion stage and has been attributed to the production of atomic oxygen as a by product of the $CO \longrightarrow CO_2$ reaction.

In work aimed at controlling SO_2 emission levels we have studied, in a small scale one dimensional flame system, the effects of limestone additions to powdered coal, with particular reference to coal treated by hydrothermal impregnation with CaO slurries solutions. Lime added in this way is far more effective than lime physically mixed with the coal, virtually complete SO_2 capture being observed at Ca/S = 2.5. Current work is concerned with the interaction between CaO and iron pyrite, FeS_2, in flames. In the absence of oxygen, SO_2 and S_2O are produced as well as CaS, according to the reaction scheme

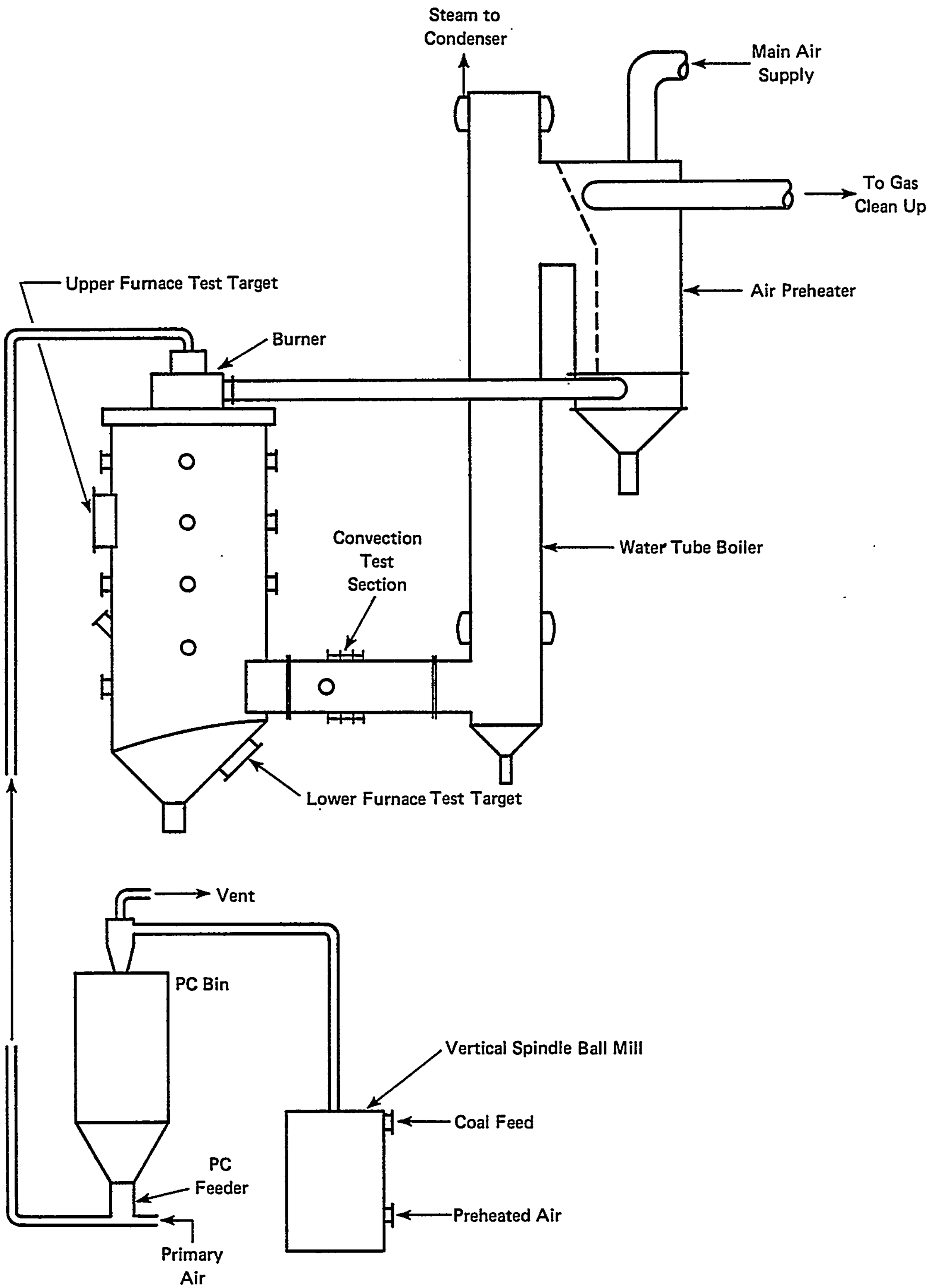
$$6FeS_2 + 3CaO \longrightarrow SO_2 + S_2O + 6FeS + 3CaS.$$

The capture of sulfur as CaS is an important issue in relation to several combustion techniques. Where sulfur is intimately associated with the coal, it reacts in a low oxygen environment, and hence will tend to form sulfides rather than sulfates. CaS, if formed, is more stable than $CaSO_4$ and hence affords the possibility of sulfur capture at temperature higher than 1600 F. This is applicable to stoker fired units and gasifiers as well as in staged combustion and FBC systems.

Future Work

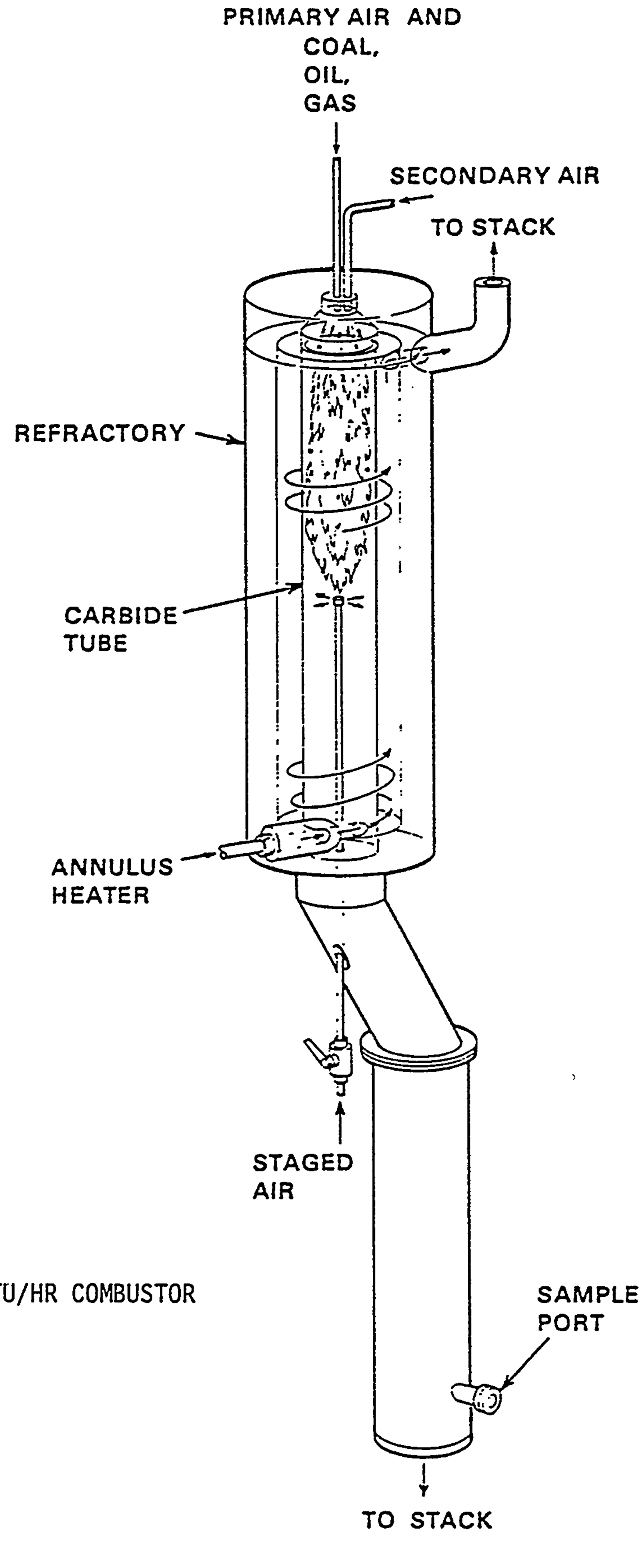
The topics in which we see a need for more work in the immediate future are:

- Mechanism of coal ash deposit formation and bonding
- Beneficiated coals and optimization of beneficiation treatments
- High purity coal slurry fuels
- FBC in-bed physical and chemical mechanisms
- Chemistry of emission control in coal combustion processes
- Advanced combustion processes.

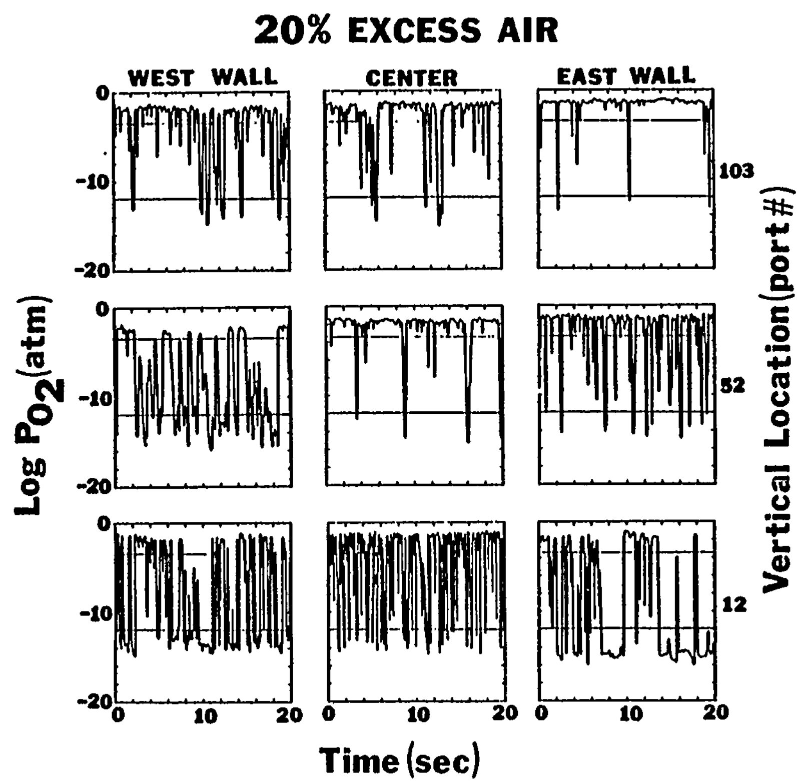


5M Btu/hr PC COMBUSTION RESEARCH FACILITY

BENCH SCALE
COMBUSTOR

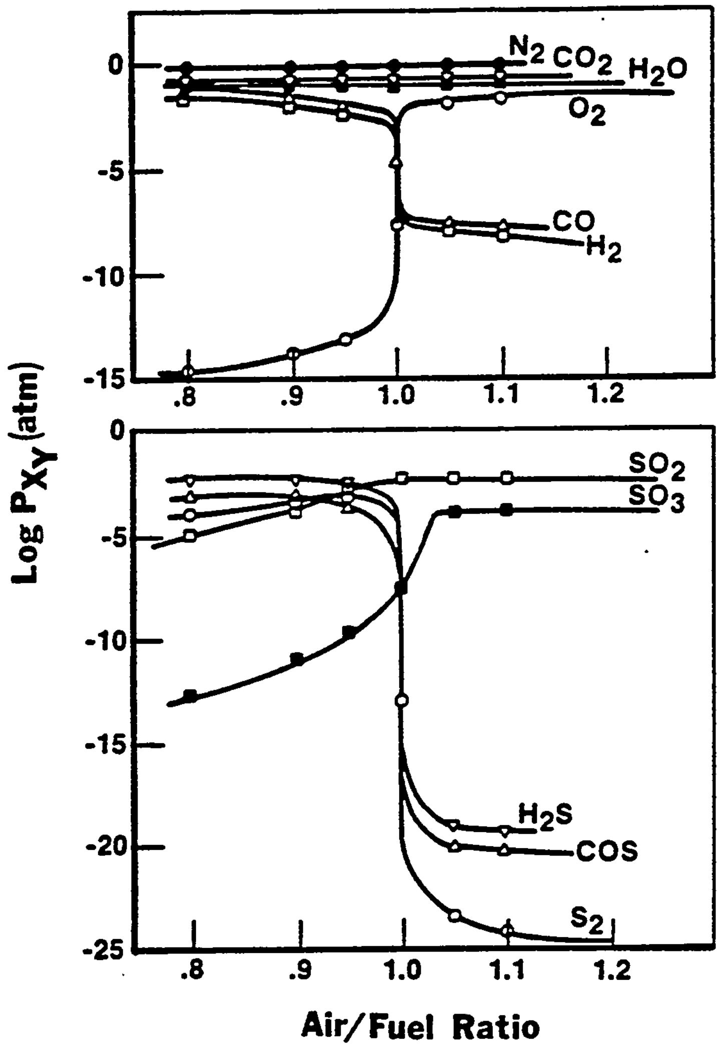


25,000 BTU/HR COMBUSTOR

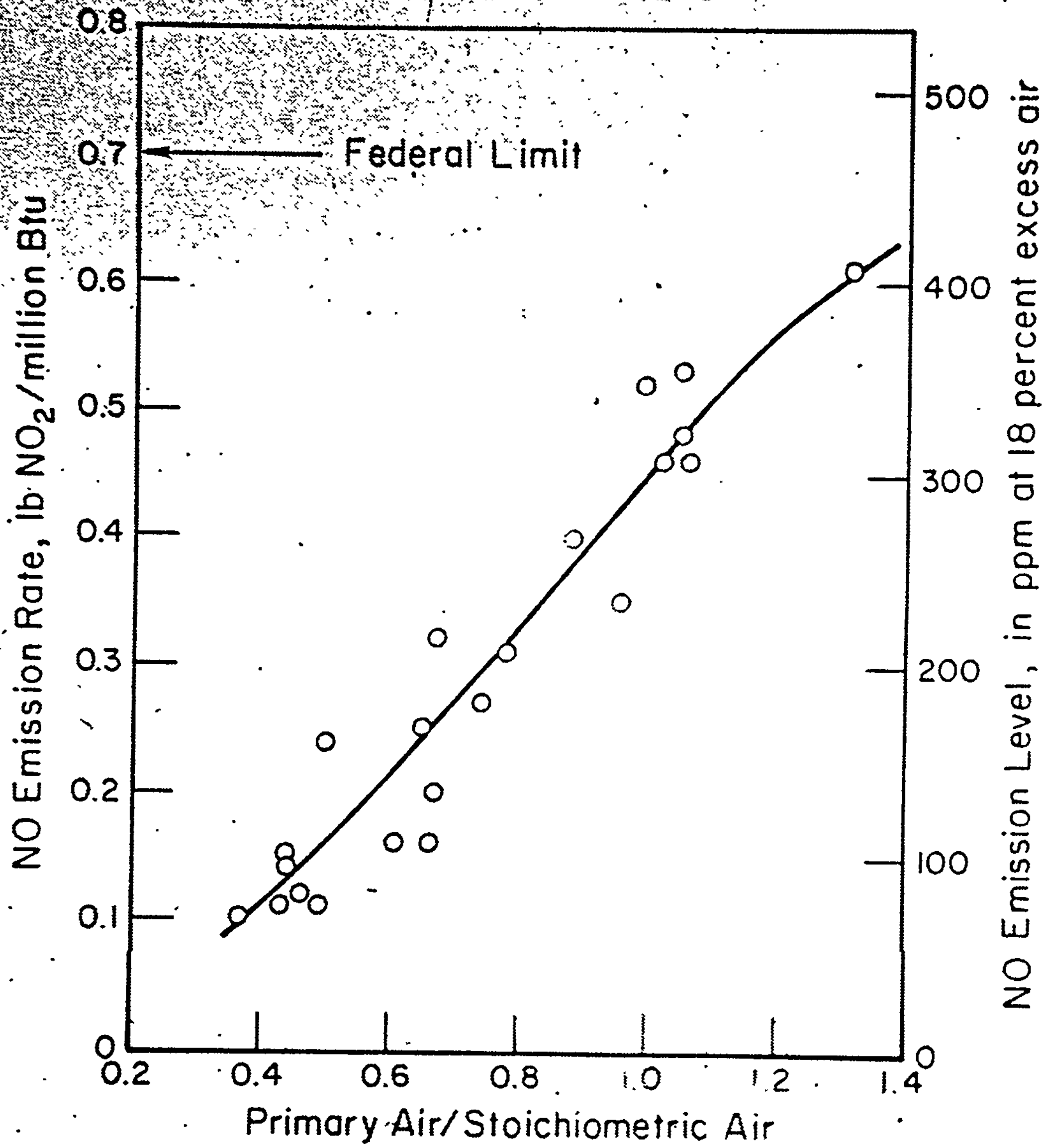


PARTIAL PRESSURE OF OXYGEN WITHIN
A BUBBLING FLUIDIZED BED

Level 12 - Below tube bank
52 - Lower tube bank
103 - Upper tube bank



EQUILIBRIUM COMPOSITION FOR
COMBUSTION PRODUCTS AT 1150K



EFFECT OF PRIMARY AIR ON NITROGEN OXIDES EMISSIONS (COAL)
(MULTI SOLID FLUIDIZED BED)

APPENDIX AB-8-2

COAL-RELATED STUDIES AT B&W

CHUCK WAGONER

GENE MICHAUD

QUANTITATIVE MEASUREMENT OF SLAGGING AND FOULING EFFECTS

EXPERIMENTAL TECHNIQUES

- TRADITIONAL

  DEPOSITION

  ASTM ANALYSES

- ENGINEERING ORIENTED

  DEPOSIT REMOVAL

  HEAT TRANSFER BETWEEN CLEANING CYCLES

CORRELATIONS AND CREDIBILITY

FUEL / ASH CHARACTERISTICS

- LAB, FREQUENTLY ASTM ASH
- SMALL PILOT-SCALE
- LARGER PILOT-SCALE
- FULL SCALE

STEAM GENERATOR PERFORMANCE

- AVAILABILITY
- CAPACITY
- HEAT RELEASE RATES
- EFFICIENCY
- DEPOSITION

TRADITIONAL CORRELATION SEQUENCE

- LABORATORY CHARACTERIZATION OF FUEL, ASTM ASH, AND SIMULATED FLY ASH
- CALCULATION OF INDICES (HARDWARE DESIGN EXPERIENCE, EMPIRICISM)
- STEAM GENERATOR DESIGN DETAILS

EASTERN COAL

TABLE 10-1. DESIGN VALUES OF PLAN AREA HEAT RELEASE RATES

HAZARD EPRI CS-1418

Boiler Manufacturer	References	Period	Fuel Type	10^6 Btu/ft.^{2} Hr Plan Area
Combustion Engineering	Lyons[1]	1977	Eastern bituminous	2.07
			Midwest bituminous	1.79
			Texas lignite	1.65
			North plains lignite	1.47
CE	Harris[2]	1972	Eastern bituminous	1.8 - 2.5
			Midwest bituminous	1.7 - 2.0
			Subbituminous	1.7 - 2.0
			Oil	2.3 - 2.7
CE	Tuppeny[6]		All - 60's vs 70's	
Babcock & Wilcox	Gray[3] or	1970's	All coals	1.45 - 1.90
	Heil[4]	1960's	All coals	1.90 - 2.15
Foster Wheeler	Frederick[5]	1970's	All coals	1.70 - 2.00

Plan Area Heat Release Rates for Test Boilers

	Boiler	Fuel Type	Design	Actual	
2	Labadie	Midwest bituminous	2.06	1.84	89 %
1	Mill Creek	Midwest bituminous	1.90	1.59	84
5	Cliffside	Eastern bituminous	2.06	1.89*	92
3	Morgantown	Eastern bituminous	2.57	2.28*	89
4	Montour	Eastern bituminous	2.15	2.28	106

* Not slagging-limited.

GENERATION LOSS UP TO 16%

References:

1. Lyons, D. E. and Blackburn, S. S., "Design for availability - An Update", Proc. American Power Conf., Vol. 39, 1977, pp 349-368.

2. Harris, D. A., "Effect of Various Fuels on Furnace Design", presented at REA Generating Conference, Owensboro, Kentucky, June, 1972.

3. Gray, R. J., Brauer, W. C., and Leland, S. C., "Design and Initial Operation of the Wyokak Plant", Proc. 1979 American Power Conference.

4. Heil, T. C., Durrant, O. W., "Designing Boilers for Western Coal", presented at Joint Power Generation Conference, Dallas Texas, Sept. 1978.

5. Fredrick, J. L and Pai, R. H., "A Primer of Design Considerations for Western Coal", Heat Engineering, Sept. 1977, Foster Wheeler Energy Corp.

6. Tuppeny, W. H., Jr. "Effects of Changing Coal Supply on Steam Generator Design", Proc American Power Conference, Vol 40, 1978, pp 367-380

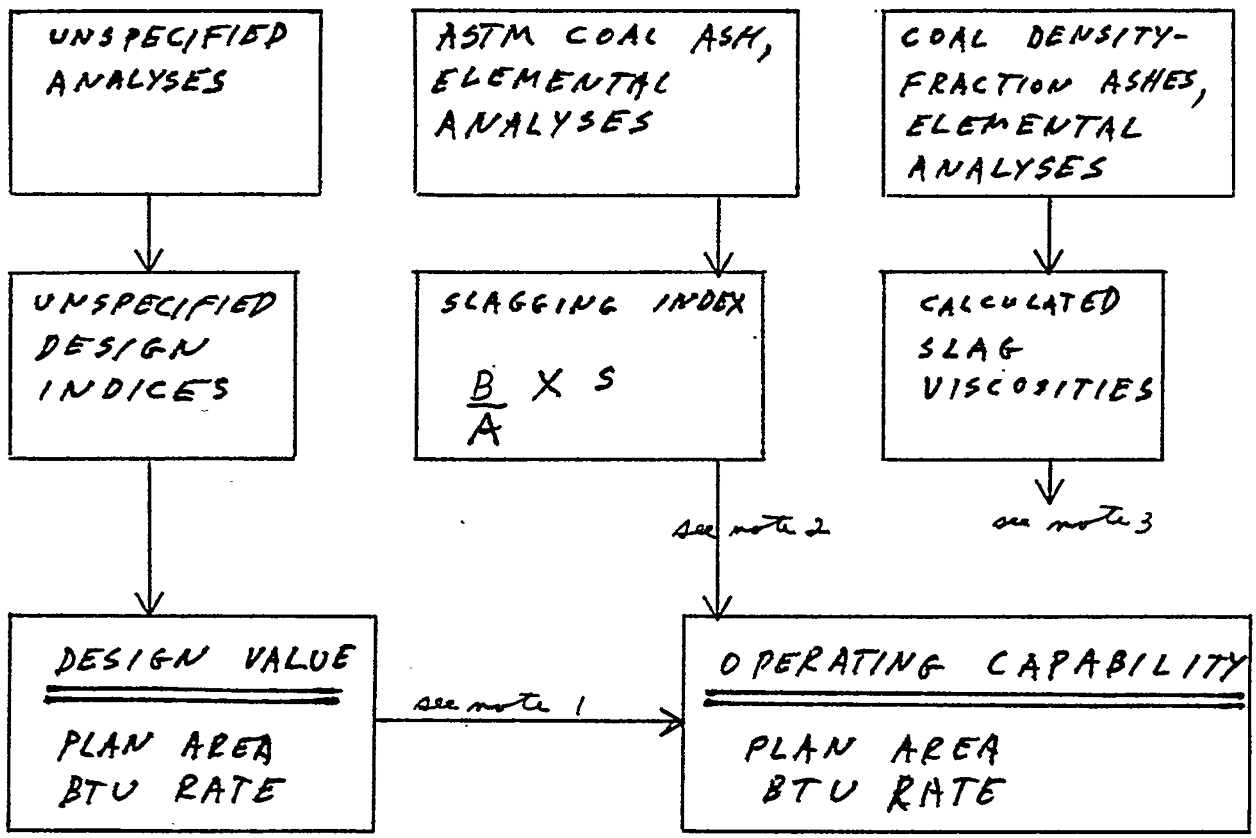
"BETTER PREDICTIVE TOOLS ARE REQUIRED"

[illegible], DIMMER

EASTERN COAL

40-MONTH EXPLORATORY STUDY, RESULTS

EPRI CS-1418



notes:

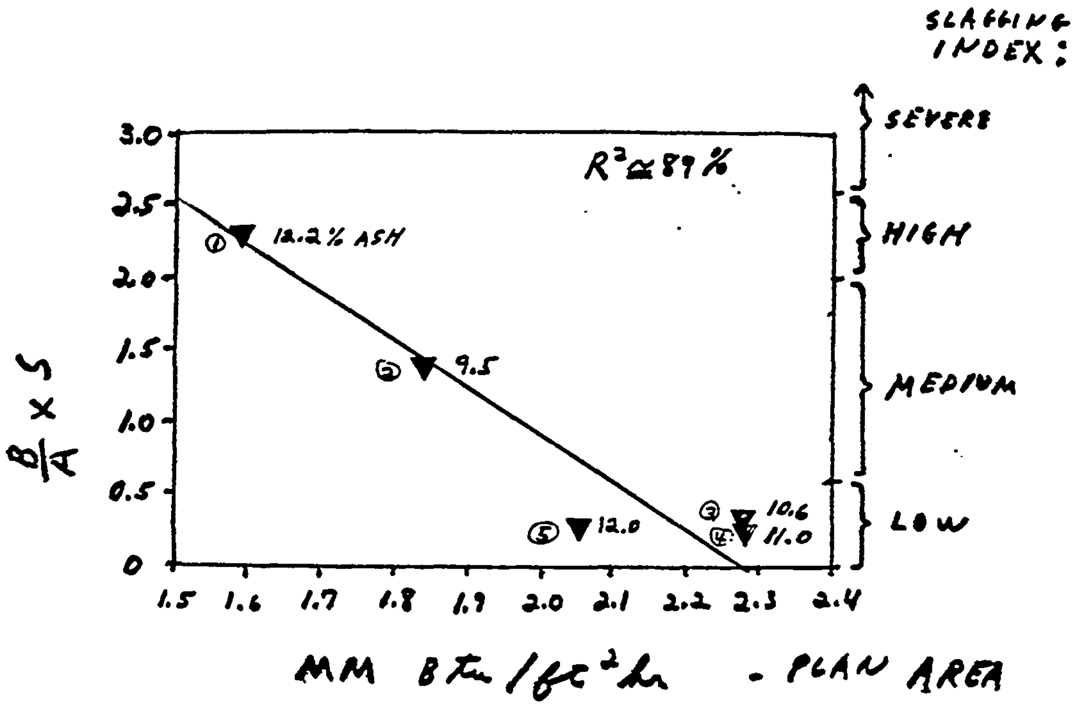
1. generation loss up to 16 %

2. "a realistic design basis for the coals fired" p 10-3

3. "the relation of furnace ash characteristics to iron and calcium segregation in coal density fractions appears to be a fruitful subject for research" p 10-14

EASTERN COAL:

DEMONSTRATED OPERATING CAPABILITY CORRELATION



FROM DATA BY
HAZARD
EPRI CS-1418

FACTORS AFFECTING ASH DEPOSITION

FUEL CHARACTERISTICS

1. PROPERTIES OF COAL SUBSTANCE

(a) Physical—density, hardness, specific heat, thermal expansion, thermal conductivity, etc.
(b) Chemical—behaviour during heating, i.e. carbonization, gasification and combustion.

Technological Properties

1. Proximate analysis
2. Ultimate analysis
3. Free-swelling index
4. DTA/TGA analysis
5. Grindability
6. Calorific value
7. Sieve analysis
8. Ignitability

2. PROPERTIES OF COAL ASH

Determined by the concentration and type of minerals in the coal containing the following elements:

(a) Sodium–potassium
(b) Sulphur
(c) Chlorine
(d) Phosphorus
(e) Calcium–magnesium
(f) Iron
(g) Silicon

Technological Properties

1. Fusion temperatures
2. Viscosity of slag
3. Surface tension of slag
4. Volatility of constituents in slag
5. Sintering temperature and strength of ash

BOILER DESIGN AND OPERATION

1. FIRING METHOD

(a) Slag tap, P.C. and cyclone
(b) Dry ash, P.C.
(c) Fuel bed, chain grate, and spreader stoker

2. FURNACE DESIGN

(a) Rating
(b) Wall construction
(c) Type, number and arrangement of burners
(d) Furnace geometry

3. TUBE BANK DESIGN

(a) Horizontal or vertical tubes
(b) Spacing, side and back
(c) Depth of bank
(d) Alignment
(e) Freedom of tube movement

4. COMBUSTION CONDITIONS

(a) Excess air
(b) Air temperature
(c) Load cycles
(d) Residence time

5. PROPERTIES OF FLUE GASES

(a) Temperature
(b) Flow patterns
(c) Composition—volatiles, SO_3, etc.

6. PROPERTIES OF ENTRAINED ASH

(a) Dust loading
(b) Size consist.
(c) Composition—alkalis, carbon, etc.
(d) Microstructure

SOOT-BLOWER DESIGN AND OPERATION

1. BLOWING MEDIUM

(a) Air or steam
(b) Pressure
(c) Temperature

2. TYPE OF SOOT BLOWER

(a) Short retractable (IR)
(b) Long retractable (IK)
(c) Fixed position rotating (G9B and A2E)
(d) Travelling frame

3. LOCATION AND SPACING OF SOOT BLOWERS

4. SOOT-BLOWER NOZZLES

(a) Type
(b) Size
(c) Number
(d) Angle of attack

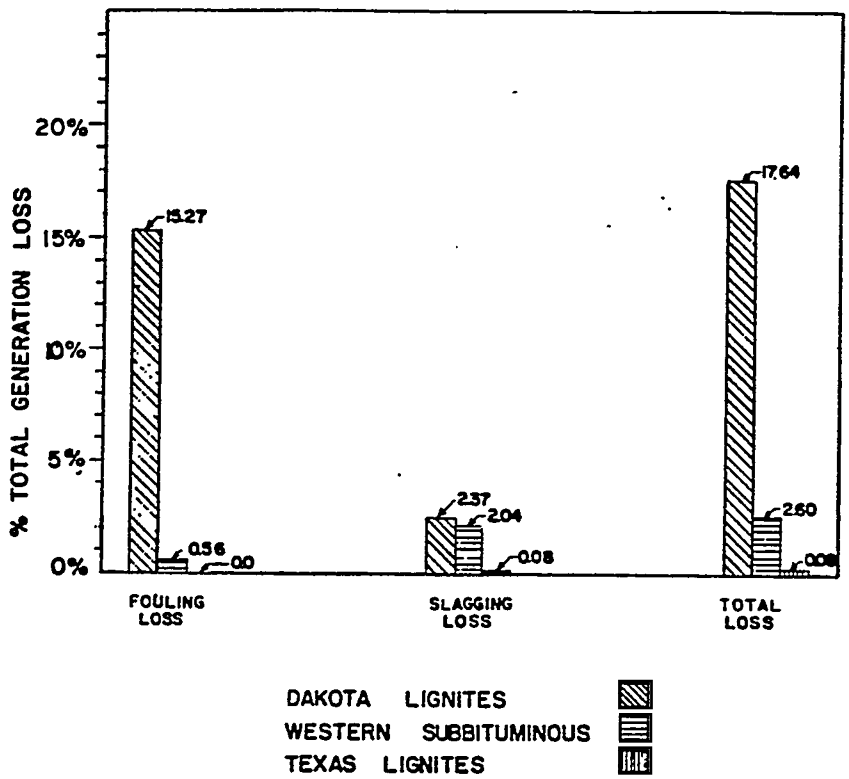
5. LANCE TUBE SPEED

(a) Rotational
(b) Axial

6. FREQUENCY OF BLOWER OPERATION

ATTIG, BARNHART
MARCHWOOD CONFERENCE
MAY 1963

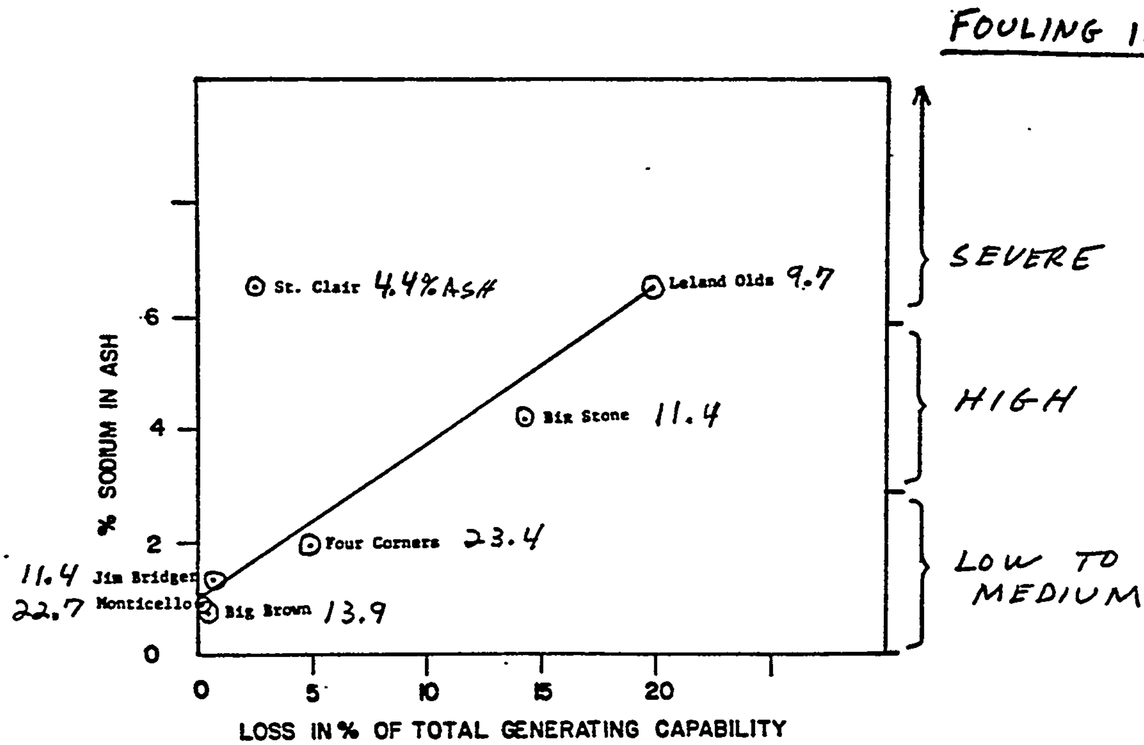
WESTERN COAL



Percentage of Potential Generation Lost Due to Slagging and Fouling

BURKHARDT
DOE/GFETC/0059-1

WESTERN COAL



% Sodium vs. Loss of Generating Capacity

FROM DATA BY BURKHARDT
DOE/GFETC/0059-1

WESTERN COAL ASH DEPOSITION, COSTS AND RECOMMENDATIONS

BURKHARDT DOE/GFETC/00 59-1
DECEMBER 1980

- $1,794,600 F+S COSTS PER STEAM-GENERATOR YEAR (415 MW AVG. SIZE FOR 23 UNITS STUDIED)

- "TESTING SHOULD BE PERFORMED WHICH EVALUATES SOOT BLOWER EFFECTIVENESS" (#1)

- "UTMOST IMPORTANCE SHOULD BE PLACED ON CONTROLLING FURNACE GAS EXIT TEMPERATURES" (#2)

CREDIBILITY OF TRADITIONAL CORRELATIONS

EXPERIENCE FACTOR -

WORST WHEN MOST NEEDED!

COAL SOURCE

- EXISTING MINE
- CORE DRILLING
- CLEANING PLANT (WASHED, SRC)

COAL FORM

- PULVERIZED
- BLENDED PC
- MICRONIZED
- COM, CWM

ENGINEERING ORIENTED MEASUREMENTS

QUANTITATIVE BOILER DIAGNOSTICS

- IN LARGE STEAM GENERATORS
- IN SMALL PILOT-SCALE

DIRECT DATA COMPARISON GOALS

- MINIMIZE SCALING CORRECTIONS AND INDEX / CORRELATION COSTS
- OBTAIN QUANTITATIVE DATA WITH SAME TECHNIQUE
  - AT DIFFERENT POWER PLANTS
  - WITH SMALL AND LARGE SCALE
- IMPROVE ABILITY TO EVALUATE NEW OR MODIFIED FUELS

ENGINEERING ORIENTED MEASUREMENTS

ADDITIONAL GOALS

- ESTABLISH A STANDARD BOILER DIAGNOSTIC PROCEDURE

- IMPROVE COMMUNICATIONS AMONG
  - UTILITIES
  - BOILER MANUFACTURERS
  - ENGINEERING SOCIETIES
  - TECHNICAL STANDARDS SOCIETIES
  - COMPUTER MODELERS
  - SPONSORING ORGANIZATIONS

APPENDIX AB-8-3

THE SECOND-GENERATION LABORATORY ASHING FURNACE

by

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Prepared for

The Engineering Foundation Publication:

Experimental Research Into Fouling and Slagging Resulting From
Impurities in Combustion Gases

Proceedings of the July 1981 Conference

Session 3 — Pilot Plant Experience in North America

THE SECOND-GENERATION LABORATORY ASHING FURNACE

ABSTRACT

In 1963, Attig and Barnhart described a Babcock & Wilcox laboratory ashing furnace at an international conference in Marchwood, England [1]. The small, pulverized fuel-fired furnace was designed to produce fly ash with properties similar to ash from a utility steam generator.

A second-generation furnace was completed early in 1981. This new unit has one added capability -- the combustion of solid-liquid mixtures. It is designed to provide improved understanding of formation and characteristics of deposits formed on sootblown heat-transfer surfaces.

INTRODUCTION

Accurate prediction of the effectiveness of sootblowing and the quality of heat transfer in a steam generator is a necessity for the boiler designer. The required accuracy is difficult to obtain for a fuel that has not been burned previously in a boiler and is available only in a small quantity. Further complications arise because of wide potential variations in ash quality and quantity.

The design objective of the second-generation laboratory ashing furnace (LAF II) is to obtain useful engineering information directly from combustion tests using a limited amount of fuel. This permits using core drillings or material from restricted small-scale production runs.

Improvements include a new coal feeder and combustion chamber/guard heater design. A complete system was added for storing, pumping and burning coal-oil mixtures (COMs), or other solid-liquid mixtures. Also, we are developing a deposition test section as part of a current Department of Energy (DOE) contract.

LABORATORY ASHING FURNACE (LAF II)

Description of Pulverized Fuel Unit

An isometric drawing of the pulverized fuel-fired unit is shown in Figure 1. The LAF II is comprised of five major components:

1. A system for feeding pulverized fuel
2. A laminar flow coal burner to minimize impingement of ash on the furnace wall
3. A refractory combustion chamber with a three-zone, electrically-powered guard heater to control outward heat flux through the furnace walls
4. A water-cooled pressurized boiler to cool the hot flue gas
5. A system for collecting fly ash

Pulverized fuel is prepared using a small impact mill to achieve a product with about 70 to 75 weight percent passing a No. 200 sieve (75μ). Any material not passing a No. 60 sieve (250μ) is removed by sieving. The sample of pulverized fuel is air-dried at 105°F and loaded into the hopper of a twin-screw feeder. Higher levels of moisture are simulated by adding steam to the combustion air.

The coal feeder is mounted on load cells and weighed continuously. Additional fuel can be added at any time because the feeder is not pressurized.

Fuel passes from the feeder into an eductor where it is mixed with primary air and transported to the burner. Typically, primary air is 20 percent of total combustion air. Secondary air passes through an electrically-powered preheater, is heated to about 400°F, and then is delivered to the burner.

The burner is comprised of three concentric tubes. Preheated secondary air flows through the inner and outer tubes; primary air/pulverized fuel flows through the middle tube. No swirl is imparted by the burner. This keeps furnace wall slagging at a minimum.

Typical firing rates for pulverized fuel are in the range of 50,000 to 150,000 Btu/hr.

The furnace wall is a silicon carbide tube that is four feet long with a one foot inside diameter. The wall is enclosed by a three-zone guard heater with Globar elements. This heater is used to control the rate of cooling of the flame. Typical wall temperature is between 2500° and 2600°F. Furnace residence times are on the order of one to two seconds. The furnace wall can be cooled to permit extinction measurements as described in a recent publication by Winegartner and Lin [2].

An uncooled refractory slagging probe can be inserted above the furnace outlet to simulate flame impingement on the high temperature surface of a thick wall slag. The furnace exit gas temperature at this convergent location usually is near 2450°F.

A deposition test section (Figure 2) will be designed and constructed as part of a current contract sponsored by DOE [3]. This will adapt the existing LAF II for fundamental deposition studies. The refractory-walled section will be located below the exit of the combustion chamber. Ports will be included for insertion of deposition tubes and sootblower nozzles, and will permit application of optical diagnostic instruments. The air-cooled tubes will be designed to have the capability for slowly rotating the deposition surface in a harmonic oscillation to provide a uniform thickness of deposit. The deposition section/tube combination will be designed to simultaneously simulate furnace wall slagging and superheater fouling conditions, including metal and gas temperature combinations, tube alloys, and sootblowing.

Deposition tube metal temperatures will be determined from thermocouples embedded in the tube. Deposit surface temperature will be measured using two-color pyrometry. Deposit thickness will be determined from analysis of time-lapse photography. Heat flux from the hot gas through the deposit and tube wall will be determined from calorimetric measurements of the cooling fluid. These measurements will allow calculation of the thermal conductivity of the deposit. Spectral emissivity of the deposit, from visible to mid-infrared wavelengths, will be determined from measurements of spectral irradiance in spectral regions where the combustion product gases are essentially transparent. In wavelength regions where the combustion gases are absorbing, the emissivity will be estimated by interpolation.

The deposition section will be two feet long with an inside diameter of five inches. Flue gas velocity will be nearly 10 feet per second at the superheater tube. The deposition tubes will have one inch outside diameters.

A pressurized water heat exchanger cools the flue gas before fly ash is collected in a cyclone separator followed by a bag filter. The sample of fly ash is used for a variety of laboratory analyses, including measured sintering strength [4,5].

Description of Coal-Oil Mixture (COM) System

The system for handling solid-liquid mixtures is shown in Figure 3. The main components include a heated, 55-gallon storage tank with an air-powered mixer, a Moyno pump with a variable speed drive, heated connecting lines, and a burner with either an internal or external mixing sprayer plate that can use either air or steam for atomization.

The slurry burner is installed in place of the pulverized fuel burner.

The storage tank is mounted on load cells and weighed continuously.

RESULTS AND DISCUSSION

Six coal-oil mixtures, one No. 6 oil, and three parent pulverized coals have been tested using LAF II this year under contract to the U. S. Maritime Administration (MARAD)[6]. As a result, we have measured relative values and ranked the fuels using the following parameters:

- Atomizer Wear
- Flame Quality and Length
- Slagging Potential from Deposition on Refractory Probe
- Fly Ash Sintering Potential from Measured Sintering Strength
- Carbon Conversion Efficiency

Although details cannot be released at this time, significant differences were found among the fuels.

CONCLUSIONS

The choice of COM fuel for a shipboard demonstration on the Great Lakes for MARAD was greatly aided by testing using LAF II. The results complemented other laboratory analyses and greatly improved our ability to predict engineering properties from fuel analyses.

The LAF II is expected to continue to produce useful engineering information in future studies.

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[2] E. C. Winegartner and C. J. Lin, "Laboratory Combustibility Testing of Solid Fuels," Presented at ASME Winter Annual Meeting; December 1979.

[3] C. L. Wagoner, "Measurement of Fundamental Properties Characterizing Coal Minerals and Fireside Deposits," Presented at the Department of Energy AR & TD Contractor's Review Meeting, Pittsburgh, Pennsylvania; March 4, 1981.

[4] D. H. Barnhart and P. C. Williams, "The Sintering Test: An Index to Ash-Fouling Tendency," Trans. of the ASME - Vol. 78, pp. 1229-1236, August 1956.

[5] S. J. Vecci, C. L. Wagoner and G. B. Olson, "Fuel and Ash Characterization and Its Effect on the Design of Industrial Boilers," Presented to the American Power Conference, B&W Paper No. BR-1117; April 1978.

[6] "At-Sea Test and Demonstration of a Coal-Oil Mixture as a Marine Boiler Fuel," U. S. Maritime Administration Contract MA-80-SAC-01037.

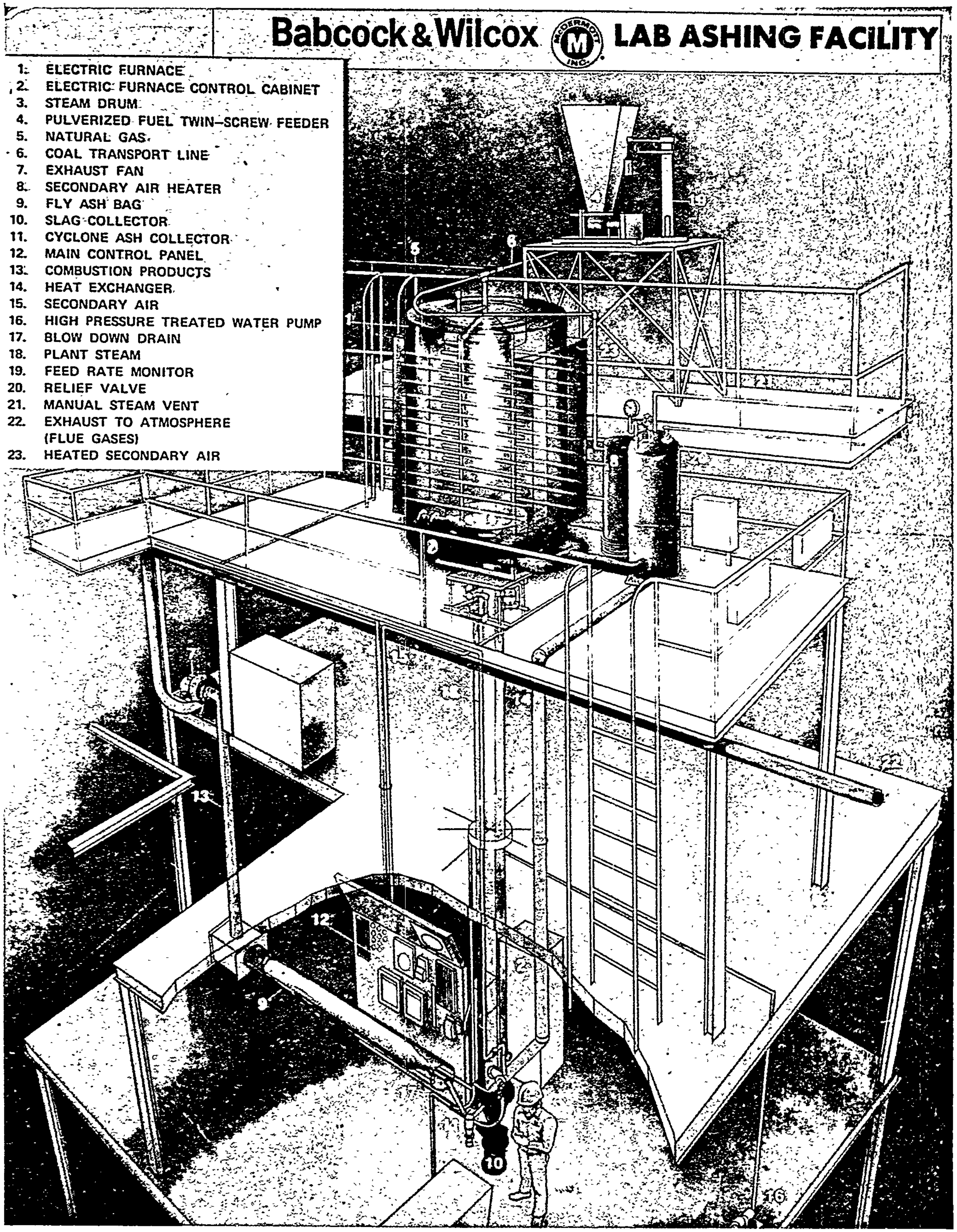
Babcock & Wilcox LAB ASHING FACILITY
1. ELECTRIC FURNACE
2. ELECTRIC FURNACE CONTROL CABINET
3. STEAM DRUM
4. PULVERIZED FUEL TWIN–SCREW FEEDER
5. NATURAL GAS
6. COAL TRANSPORT LINE
7. EXHAUST FAN
8. SECONDARY AIR HEATER
9. FLY ASH BAG
10. SLAG COLLECTOR
11. CYCLONE ASH COLLECTOR
12. MAIN CONTROL PANEL
13. COMBUSTION PRODUCTS
14. HEAT EXCHANGER
15. SECONDARY AIR
16. HIGH PRESSURE TREATED WATER PUMP
17. BLOW DOWN DRAIN
18. PLANT STEAM
19. FEED RATE MONITOR
20. RELIEF VALVE
21. MANUAL STEAM VENT
22. EXHAUST TO ATMOSPHERE (FLUE GASES)
23. HEATED SECONDARY AIR

FIGURE 1

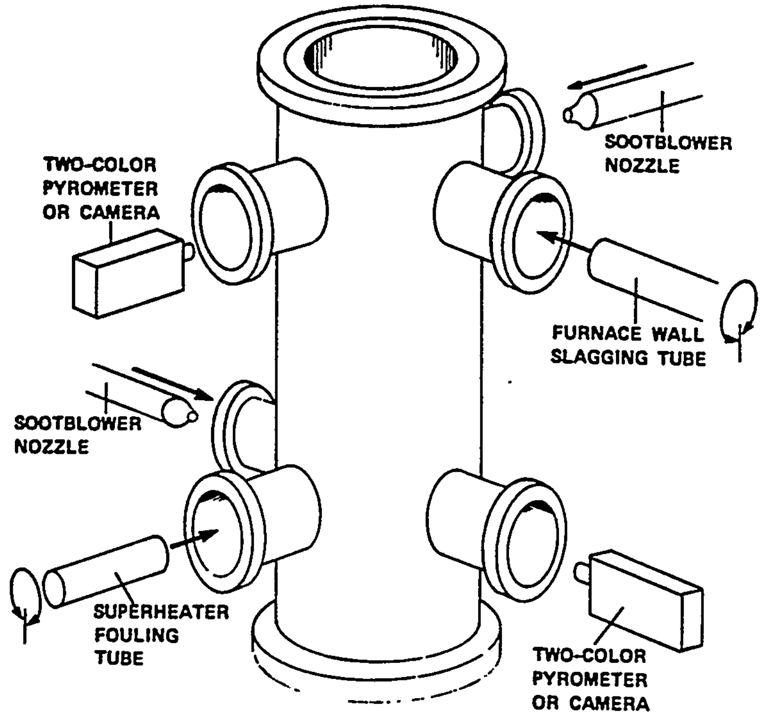

FIGURE 2 CONCEPTUAL DRAWING OF DEPOSITON TEST SECTION

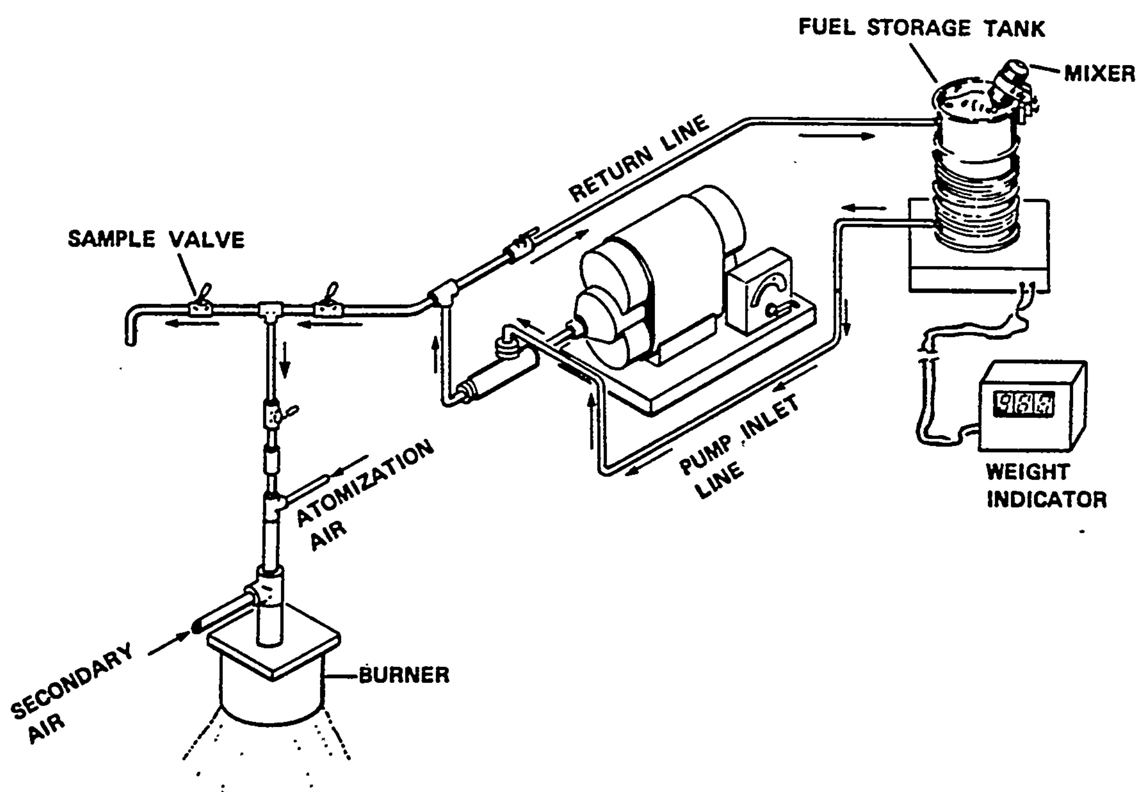

FIGURE 3 SYSTEM FOR SOLID-LIQUID MIXTURES

APPENDIX AB-8-4

Preliminary Observations of the Influence on Fireside Deposition of Ion-Exchangeable Calcium in Coal*

by

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Prepared for

The Engineering Foundation

International Conference on Fouling of Heat Exchange Surface

Session on Chemical Reaction Fouling
White Haven, Pennsylvania

October 31 - November 5, 1982

*This Document is an Extended Abstract Prepared for Inclusion in Conference Preprints

ABSTRACT

Recent work indicates the role of ion-exchangeable calcium in low-rank coal can be more important than previously thought. A sample of subbituminous coal was modified by removing about one-half of the ion-exchangeable calcium. Contrary to most published correlations, ash fouling and slagging characteristics associated with combustion of pulverized fuel were changed significantly. Heat transfer rates and sootblower cleaning capabilities were reduced when the calcium was lowered. This investigation was sponsored by the U.S. Department of Energy (DOE), Pittsburgh Energy Technology Center under its program for Advanced Research and Technology Development.

INTRODUCTION

A project is underway with the goal of measuring the fundamental properties characterizing coal minerals and fireside deposits.

In an early phase of the activity at Pennsylvania State University, samples of a Montana subbituminous coal (Decker coal) were prepared in which a significant amount of the ion-exchangeable sodium or calcium was replaced with hydrogen ion. These samples are being burned as pulverized fuels in small-scale tests by Babcock & Wilcox (B&W); the resulting deposits are analyzed and compared with those of the unmodified parent coal.

To date, combustion tests have been concluded for the parent coal and a low-calcium sample. Although analyses are not yet complete, preliminary observations indicate that when burning low-rank coals, the role of ion-exchangeable calcium in fireside deposition may be more important than previously reported by many investigators. This conclusion is based on measurement of significant differences for deposition rates, heat transfer properties, and ease of removal by sootblowing.

LABORATORY ASHING FURNACE

The second-generation laboratory ashing furnace (LAF II) was described in detail[1] at a recent conference sponsored by the Engineering Foundation.

Figure 1 is a drawing of the pulverized-fuel-fired unit. Firing rates of approximately 100,000 Btu/hr are being used during the current investigation for DOE.

The concept of the deposition test section is shown in Figure 2. This design permits direct measurement of deposition rate, deposit thermal conductivity and emissivity, heat flux, and sootblowing effectiveness during a 40-hour test period. Simultaneous data are obtained for separate radiant and convective heat exchange surfaces.

RESULTS AND DISCUSSION

Figure 3 shows the influence of time and sootblowing on heat flux (heat absorption rate) for a typical sootblowing cycle during a test with unmodified (parent) Decker coal. Heat flux decreased with time for the furnace wall tube, and sootblowing did not restore the flux to earlier levels. Thin layers (up to about 0.040 inch) of dry, granular and reflective ash mainly were responsible for the changes in heat flux. Visually, both the furnace wall and superheater tubes appeared relatively clean, and the sootblowing seemed effective.

Figure 4 illustrates the appearance of the superheater tube about 20 hours after sootblowing. The parent Decker coal produced this deposit. Sootblowing appeared to remove virtually all of the deposit. In contrast, Figure 5 shows a much greater amount of deposition produced under similar test conditions with a modified Decker coal sample. The modification reduced the amount of ion-exchangeable calcium by about 50 percent. Sootblowing was relatively ineffective in removing this deposit, as seen in Figure 6, which is a photograph taken immediately after sootblowing.

This behavior was not predicted using well established correlations, including those developed in the United States by the Grand Forks Energy Technology Center(GFETC)[2] or Babcock & Wilcox[3], or in Australia by L. J. Garner[4].

Recent investigations by C. J. Lin and E. C. Winegartner[5] involved limestone additions to coals from North Dakota and Montana. The addition of calcium in an inorganic form ($CaCO_3$) reduced fouling rates for the North Dakota lignite. However with the Montana coal (Decker), limestone added at 25 lb/ton coal caused the fouling rate to double. This could indicate that the role of inorganic calcium may be vastly different than that of ion-exchangeable calcium.

Haller and Moore[6] identified mixtures of Na_2SO_4-$CaSO_4$ with low melting points ranging between 1623 - 1700 F as the glue that bonds flyash particles together to form superheater deposits when low-rank Western U. S. coals are burned. In Figure 7, data are shown as triangles that were reported in Table 1[6] for the amount of immiscible Na_2SO_4-$CaSO_4$ phase that formed in slag-viscometer samples produced by melting ash from four lignitic coals, each containing different levels of Na_2O; calcium concentrations in the lignitic ashes were reported between 19 - 24% as CaO. Fouling classifications as proposed by Gray and Moore[7] for lignites as a function of Na_2O in ash also are shown in Figure 7.

Haller and Moore[6] emphasized the dominant role of sodium in fouling. They also pointed out that increased calcium concentration can lead to increased melting temperatures for the Na_2SO_4-$CaSO_4$ system. Although the results obtained with the low-calcium-modified Decker coal (no change in sodium level compared with parent Decker) cannot be explained on the basis of a variation in sodium content via Figure 7, a closer look at the Na_2SO_4-$CaSO_4$ system is warranted.

A phase diagram for the Na_2SO_4 - $CaSO_4$ system[8] was examined to determine what relationships would result if calculations were made using specific values for the elemental composition of ASTM ash prepared from parent and low-calcium-modified Decker coals, normalized to a system containing only sodium and calcium sulfates. The liquidus temperature calculated for the low-calcium-modified coal is about 2030 F, a value 100 degrees lower than calculated for parent Decker. The amount of low melting material that would be present as the mixture initially melts was calculated to be 1.4 times greater for the low-calcium coal. Although these data predict increasing potential for deposition with lower calcium, they appear to underestimate the magnitude of increase observed in Figure 5.

Work at the Grand Forks Energy Technology Center[2] with Beulah and Velva lignites shows increased depositon rates with lower total calcium contents when sodium levels are high. This seems to be in general agreement with the B&W results, except the magnitude of change was less for the GFETC results.

CONCLUSION

Initial results show that ion-exchangeable calcium can have a significant influence on fireside deposition. As knowledge of the role of calcium in depositon improves, it may be possible to increase boiler efficiency and availability when burning low-rank coals.

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[1] C. L. Wagoner, "The Second-Generation Laboratory Ashing Furnace," Presented at the Engineering Foundation Conference on Experimental Research Into Fouling and Slagging Resulting from Impurities in Combustion Gases, Henniker, New Hampshire; July 14, 1981.

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[3] S. J. Vecci, C. L. Wagoner and G. B. Olson, "Fuel and Ash Characterization and Its Effect on the Design of Industrial Boilers," Presented to the American Power Conference, B&W Paper No. BR-1117; April 1978.

[4] L. J. Garner, "Formation of Boiler Deposits from Combustion of Victorian Brown Coals," J. Inst. Fuel, Vol. 40 No. 314, March 1967, pp. 107-116.

[5] C. J. Lin and E. C. Winegartner, "Coal Ash Fouling Test in a Laboratory Furnace," Presented at Joint ASME/IEEE Power Generation Conference; October 1981.

[6] K. H. Haller and G. F. Moore, "Burning North Dakota Lignite in a Modern Utility Boiler; Big Stone Test," Presented at ASME Winter Annual Meeting; December 1979.

[7] R. J. Gray and G. F. Moore, "Burning the Subbituminous Coals of Montana and Wyoming in Large Utility Boilers," Presented at ASME Winter Annual Meeting; November 1974.

[8] E. M. Levin, C. R. Robbins and H. F. McMurdie, Phase Diagrams for Ceramists, Columbus, Ohio: The American Ceramic Society, 1964, p. 345.

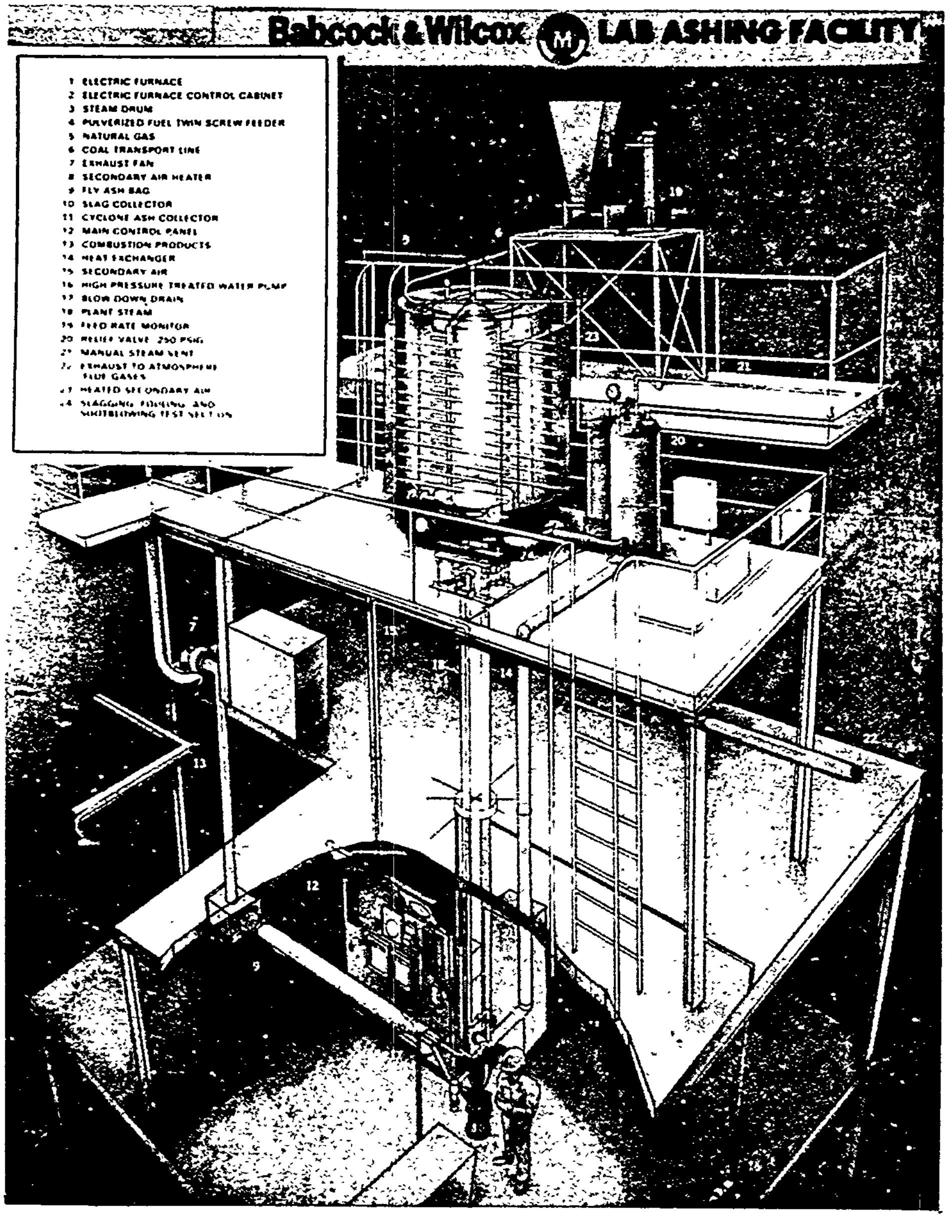


FIGURE 1 Laboratory ashing furnace

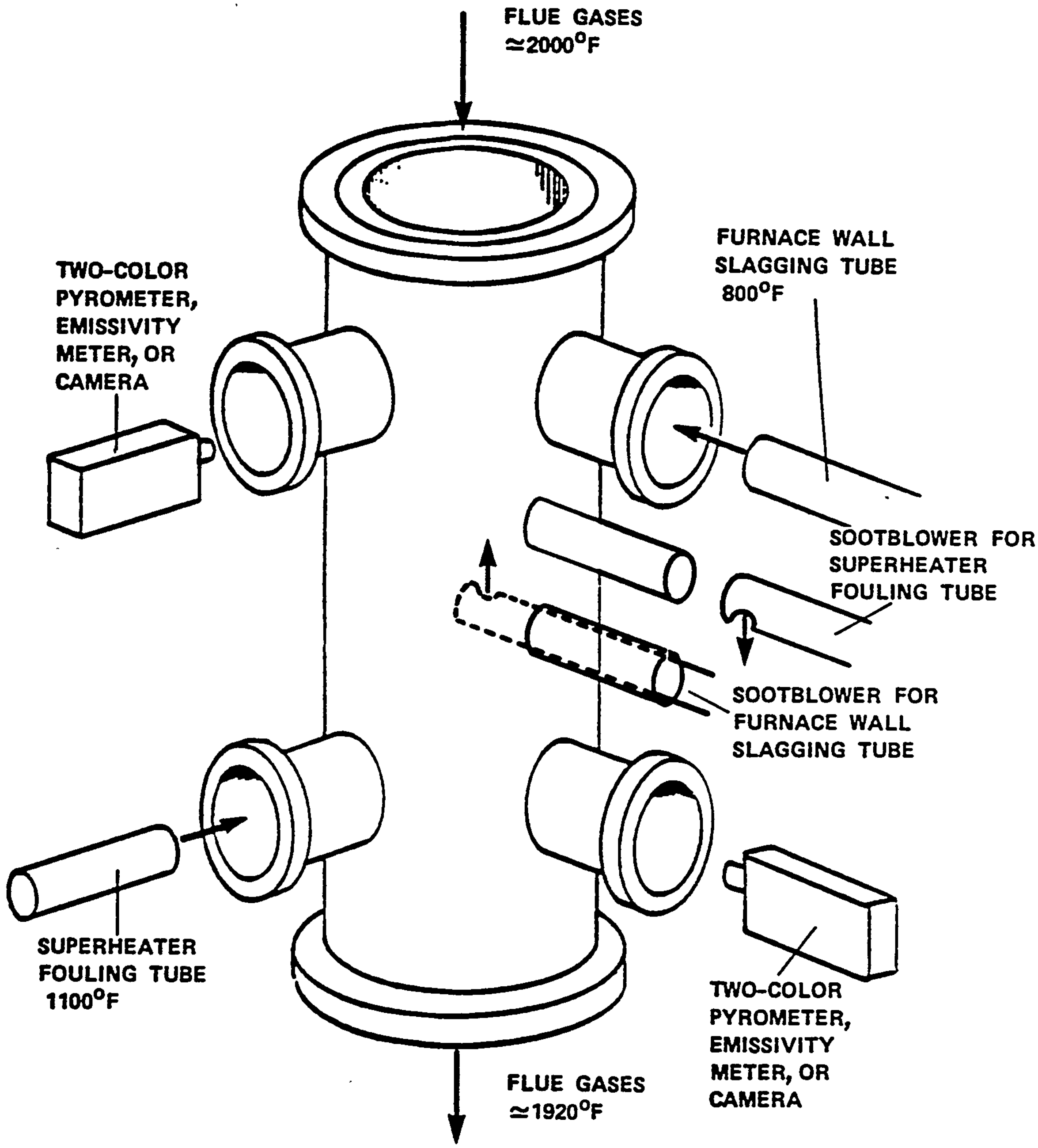


FIGURE 2 Schematic diagram of slagging, fouling and sootblowing test section

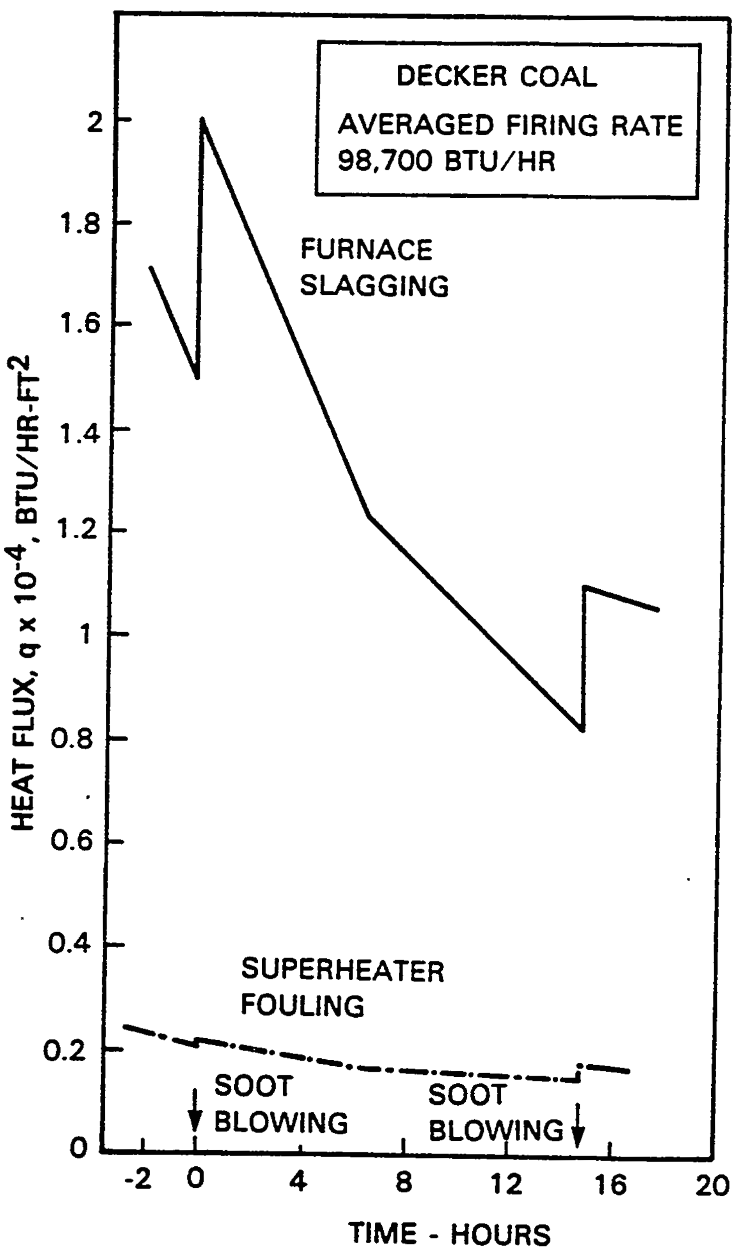


FIGURE 3 **Effect of time and sootblowing on heat flux for a typical sootblowing cycle during test with parent Decker coal**

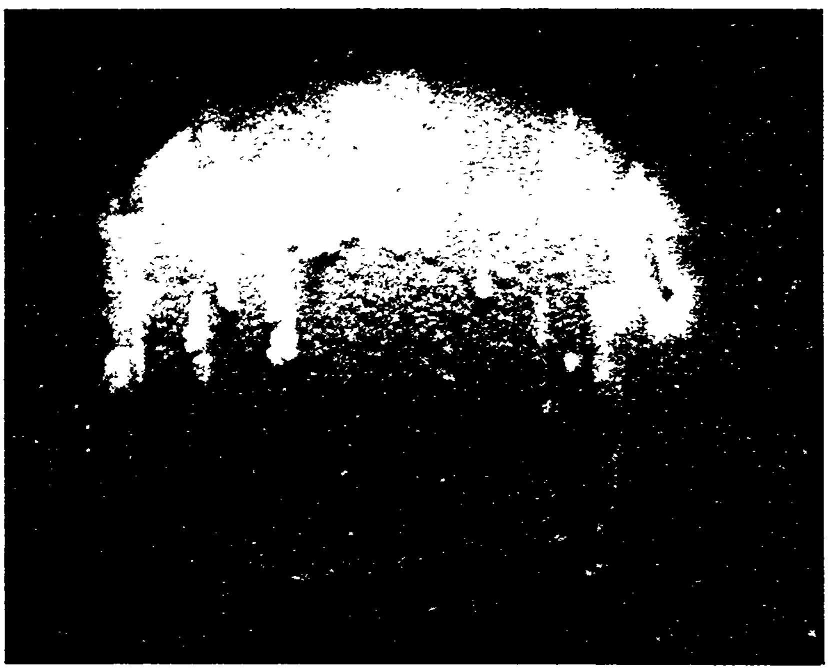


FIGURE 4 Superheater tube deposit about 20 hours after sootblowing during test with parent Decker coal

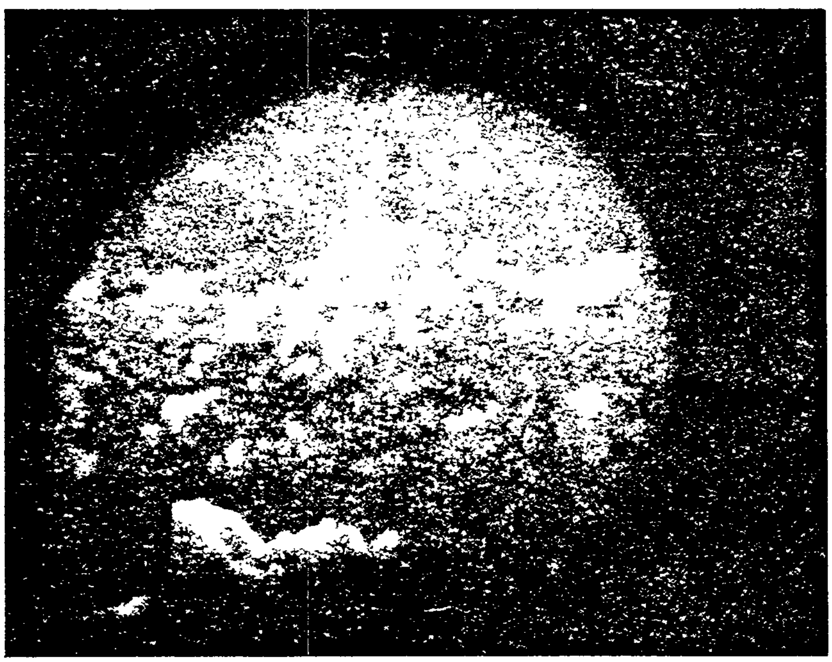


FIGURE 5 Superheater tube deposit about 20 hours after sootblowing during test with modified Decker coal for lower ion-exchangeable calcium

FIGURE 6 Effect of sootblowing on superheater tube deposit from modified Decker coal for lower ion-exchangeable calcium

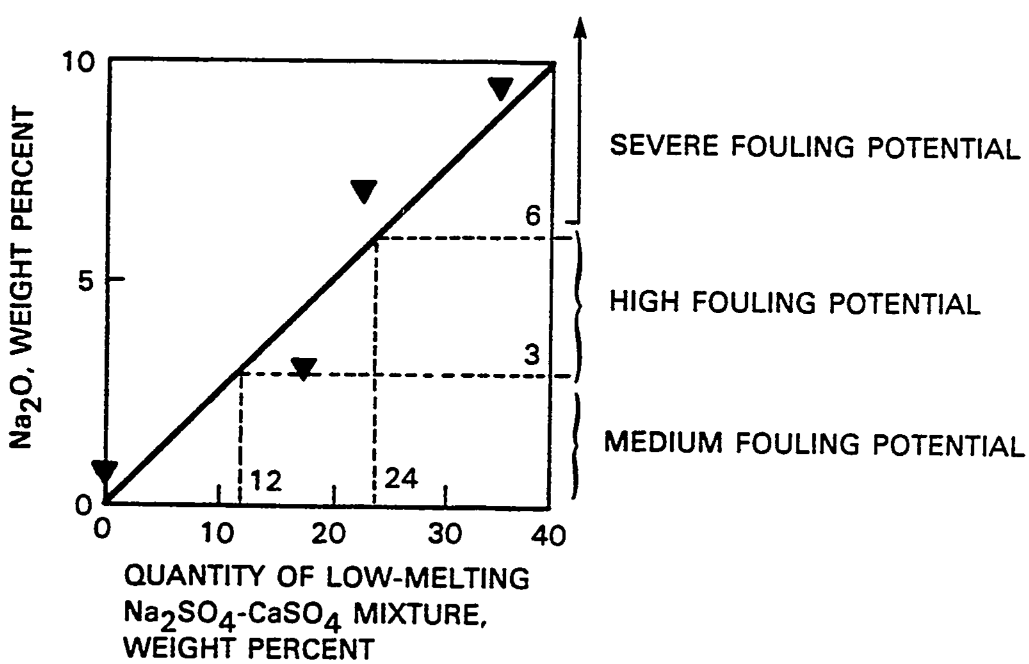


FIGURE 7 **Relationships among total Na_2O in lignitic coal ash (ASTM analysis), quantity of low-melting immiscible liquid phase formed when lignitic ash is melted (slag viscometer melt), and superheater fouling classification (B&W index)**

CCAWG MEETING AT FOSTER WHEELER CORPORATION, JOHN BLIZARD RESEARCH CENTER, 12 PEACH TREE HILL ROAD, LIVINGSTON, NEW JERSEY 07039*
(December 9, 1982)

CCAWG members J. M. Beér, C. R. Bozzuto, I. Glassman, A. K. Oppenheim, S. S. Penner, R. E. Sommerlad, C. L. Wagoner, I. Wender, W. Wolowodiuk, J. Birkeland (DOE), and G. Jordy (DOE) attended this meeting. Also present were D. Bienstock (PETC), H. Fruh (FWDC), C. Harrison (EPRI), S. Moskowitz (Curtiss-Wright), I. Lutes (FWDC), H. Nack (Battelle-Columbus), A. Robertson (FWDC), F. Rourke (FWDC), S. P. N. Singh (Oak Ridge National Lab.), and V. Zakkay (NYU).

The topics discussed and the agenda are summarized in Table AB-9-1.

1. Summary of Discussions

A. Robertson (FWDC) presented an excellent overview of the development of pressurized fluidized bed combustors. His view graphs are self-explanatory and are enclosed in Appendix AB-9-1. These view graphs cover the following topics: advantages of PFB operations over conventional PC combustors, PFB combined cycles (air-cooled PFB and water/steam cooled PFB), overall plant efficiency vs. compressor pressure ratio for various turbine-inlet temperatures, the CURL/Leatherhead PFB and 1972-73 test results, the Exxon PFB miniplant cooling coil after 1200 hours of operation, SO_2 retention vs. Ca/S mole ratio in miniplant dolomite tests for contact times between 0.5 and 3.0 sec, NO_x emission (in g/Mj or lb/MMBTU) vs.% of excess air, combustion efficiency vs. average temperature in Exxon tests, CFCC tube bundle configuration at NCB-CURL for 16.8% packing density, heat-transfer coefficients vs. height above the distributor for immersed tubes in a 9-ft bed at 1420 and 1620-1640^{o}F, freeboard heat-transfer coefficients vs. height above the bed surface, factors

*Prepared by S. S. Penner.

affecting turbine expander life, Sta-Laval and GE cascades used in turbine tests, cyclone configurations and test data for particulate removal in PFBC at Exxon and CURL, viewgraph of a 170 MW PFB demonstration plant, catcracker and PFB comparisons, low-risk PFB cycles, schematic diagrams of a contained 250 MW PFB steam generator and a superheater reheater, PFB barge shipments of shop-assembled 125 MW units, test results obtained with the Grimethorpe PFB and at CURL/ Leatherhead, notes on hot-gas cleanup.

S. Moskowitz presented a comprehensive overview of the Curtiss-Wright pilot plant development (see Appendix AB-9-2 and also AB-7-2) status and program. The PFB coal combustion program at NYU was ably summarized by V. Zakkay (Appendix AB-9-3).

These presentations were followed by discussions of critical areas in PFB development that require further R&D. The technical uncertainties listed by V. Zakkay (see Appendix AB-9-3, p. 7) were generally accepted, except that S. Moskowitz considered turbine deposition to be of relatively low priority. Furthermore, all participants concurred that further work needed to be done to improve our understanding of the fluid mechanics and combustion properties of PFB, including fuel dispersion from feed points, combustion chemistry, calcination and sulfur retention, and freeboard processes.

The Battelle-Columbus multisolid FB (MSFB) combustor was next reviewed by H. Nack (see Appendix AB-9-4). The operational concept of this idea is well illustrated in the second and third viewgraphs (see Appendix AB-9-4). A 0.4×10^6 Btu/hr pilot and performance data are shown in Appendix AB-9-4, as are the following data: solids residence times tests, sulfur capture, NO_x emission, influence of fuel reactivity, a summary of technical features, and selected applications. There was general agreement that the MSFB combustor presented a potentially useful concept but that a good deal of fundamental and development work needed to be done in order to gain needed understanding for optimal designs and practical exploitation of this configuration.

Operational experiences with commercially available (from FW) AFBs were next described by I. Lutes, H. Fruh, and F. Rourke of FWDC. The Shell, Netherlands, program is summarized in Appendix AB-9-6. While operational difficulties were encountered, equip-ent modifications to assure successful operations have been implemented without undue difficulties.

S. P. N. Singh (ORNL) provided a comprehensive overview of coal-beneficiation techniques, including both commercially practiced and developing procedures (see Appendix AB-9-6). A cost summary is included in Table 3 of Appendix AB-9-6. Discussions ensued on the commercial viability of these techniques (with C. R. Bozzuto noting that the economic value of removing the necessity for post-combustion SO_x removal was about $6/ton and increased reliability in utility operation was equivalent to savings of about $1/ton), which was viewed by several participants as unconvincing in view of required cleaning costs. There was, however, general agreement that research on improved beneficiation techniques was needed and that coal beneficiation represented an integral component of programs leading to possible commercialization of coal-water slurries.

The discussions were concluded with a summary of completed work on coal-methanol slurries by D. Bienstock of PETC (see Appendix AB-9-7 for details). Dr. Bienstock made a convincing case for the following statement: When slurry preparation, pipelining, and combustion are considered in an integrated system, an optimal mixture may well consist of coal in water containing small amounts of methanol. Additional research in this field is clearly justified.

TABLE AB-9-1

CCAWG AGENDA FOR THE MEETING ON DECEMBER 9, 1982

8:30-8:45	INTRODUCTION	R. E. Sommerlad (FWDC) S. S. Penner (UCSD)
8:45-9:40	OVERVIEW OF PFB DEVELOPMENTS	A. Robertson (FWDC)
9:40-10:30	CURTISS-WRIGHT'S ACTIVITIES IN PFB	S. Moskowitz (C-W)
10:30-11:30	PFB ACTIVITIES AT NYU	V. Zakkay (NYU)
11:30-12:15	MULTISOLID FB	H. Nack (Battelle)
12:15-12:30	BREAK	
12:30-1:15	OPERATION OF GEORGETOWN & SHELL AFB	I. Lutes (FWDC), H. Fruh (FWDC), and F. Rourke (FWDC)
1:15-2:00	PHYSICAL CLEANING OF COAL	S. P. N. Singh (ORNL)
2:00-2:30	COAL/METHANOL SLURRIES	D. Bienstock (PETC)
2:30-3:00	DISCUSSION OF FUTURE MEETINGS	S. S. Penner (UCSD)
3:00-4:00	TOUR OF FWDC R&D FACILITIES	W. Wolowodiuk (FWDC)
4:00	ADJOURN	

APPENDIX AB-9-1

OVERVIEW OF PFB DEVELOPMENTS

A. ROBERTSON
FWDC
DECEMBER 9, 1982

PFB COMBUSTION CYCLES

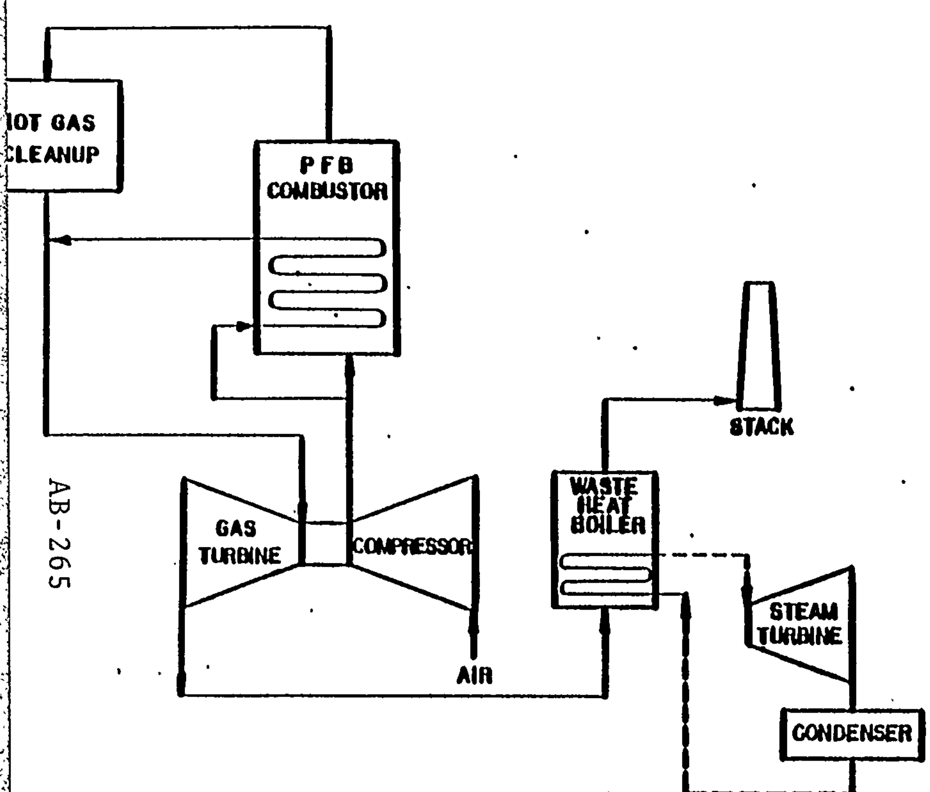
OPERATE AT ≈1650°F AND 5 TO 15 ATM WITH FLUIDIZED DOLOMITE BEDS.

COMBUSTS HIGH SULFUR COAL EFFICIENTLY - ENVIRONMENTALLY ACCEPTABLE EMISSIONS.

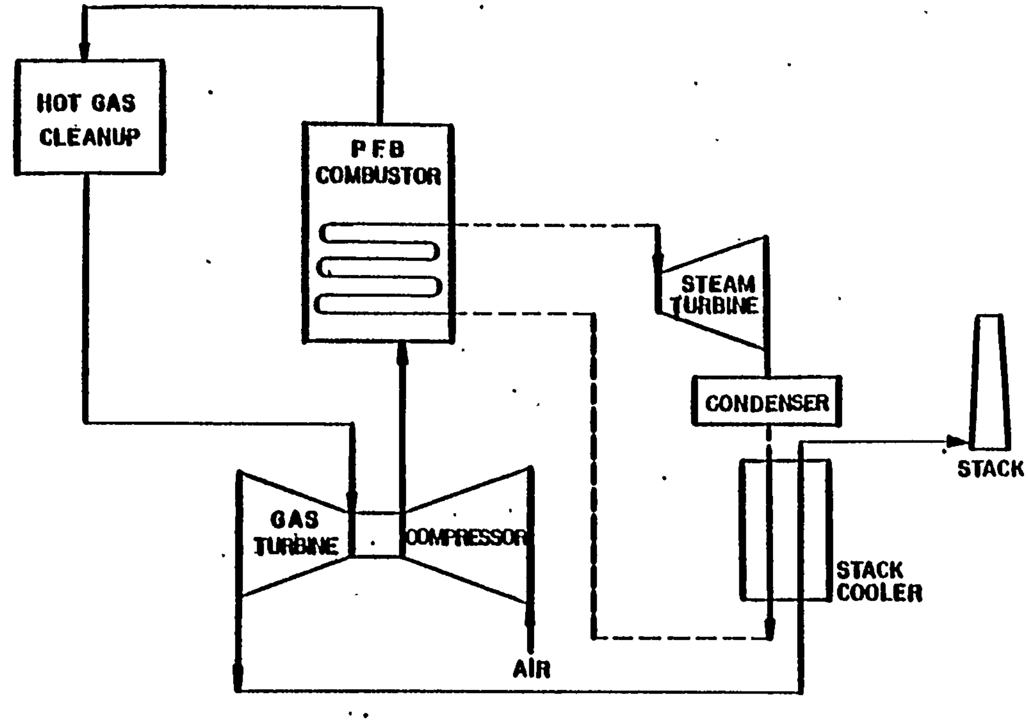
BEDS CONTAIN AIR OR WATER COOLED TUBES.

GAS TURBINES/EXPANDERS PROVIDED FOR POWER RECOVERY.

PROVIDES HIGH EFFICIENCY (≈40%) COMBINED STEAM TURBINE GAS TURBINE CYCLES.



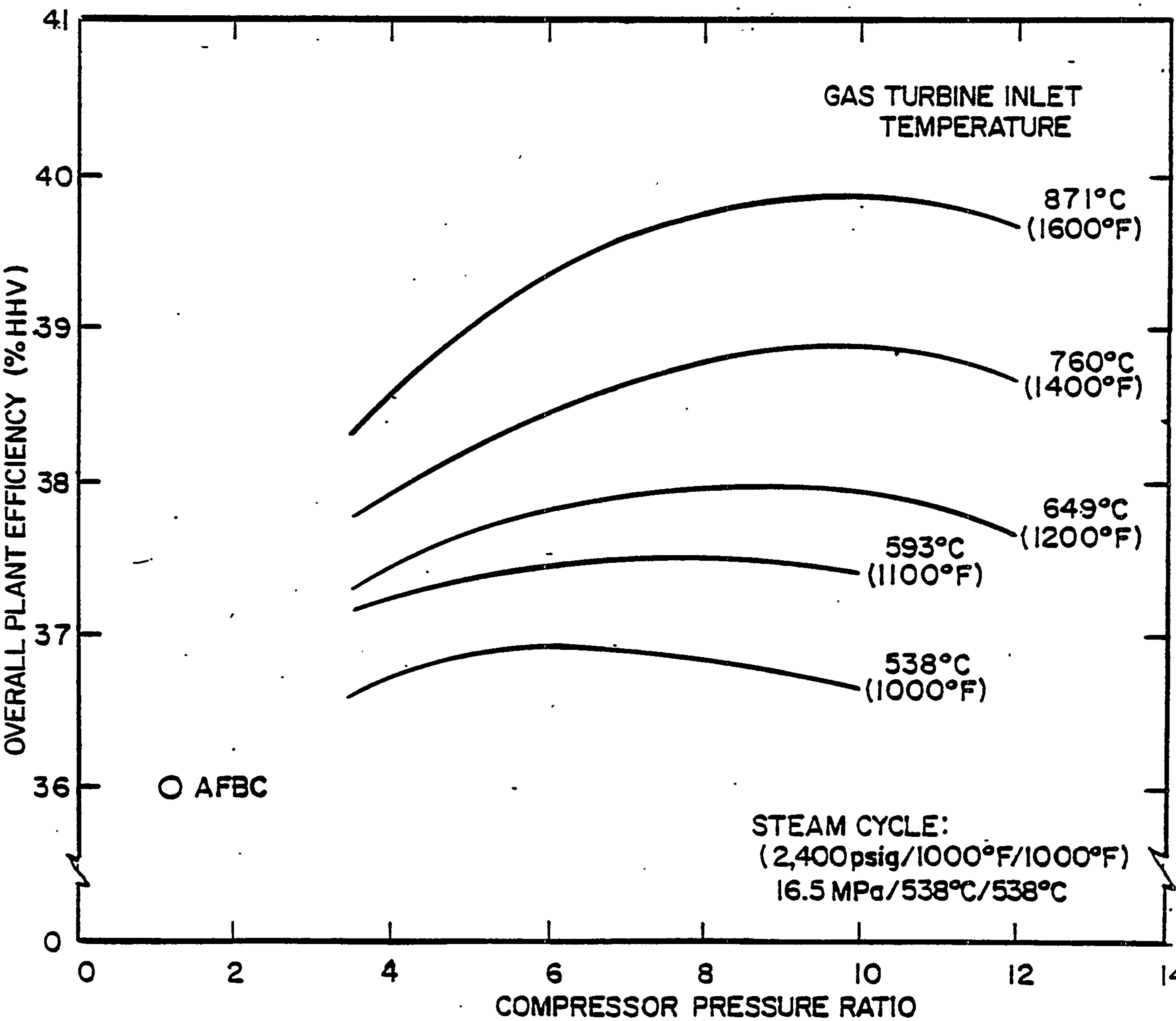
AIR COOLED PFB



WATER/STEAM COOLED PFB

ALTERNATE PFB COMBINED CYCLES

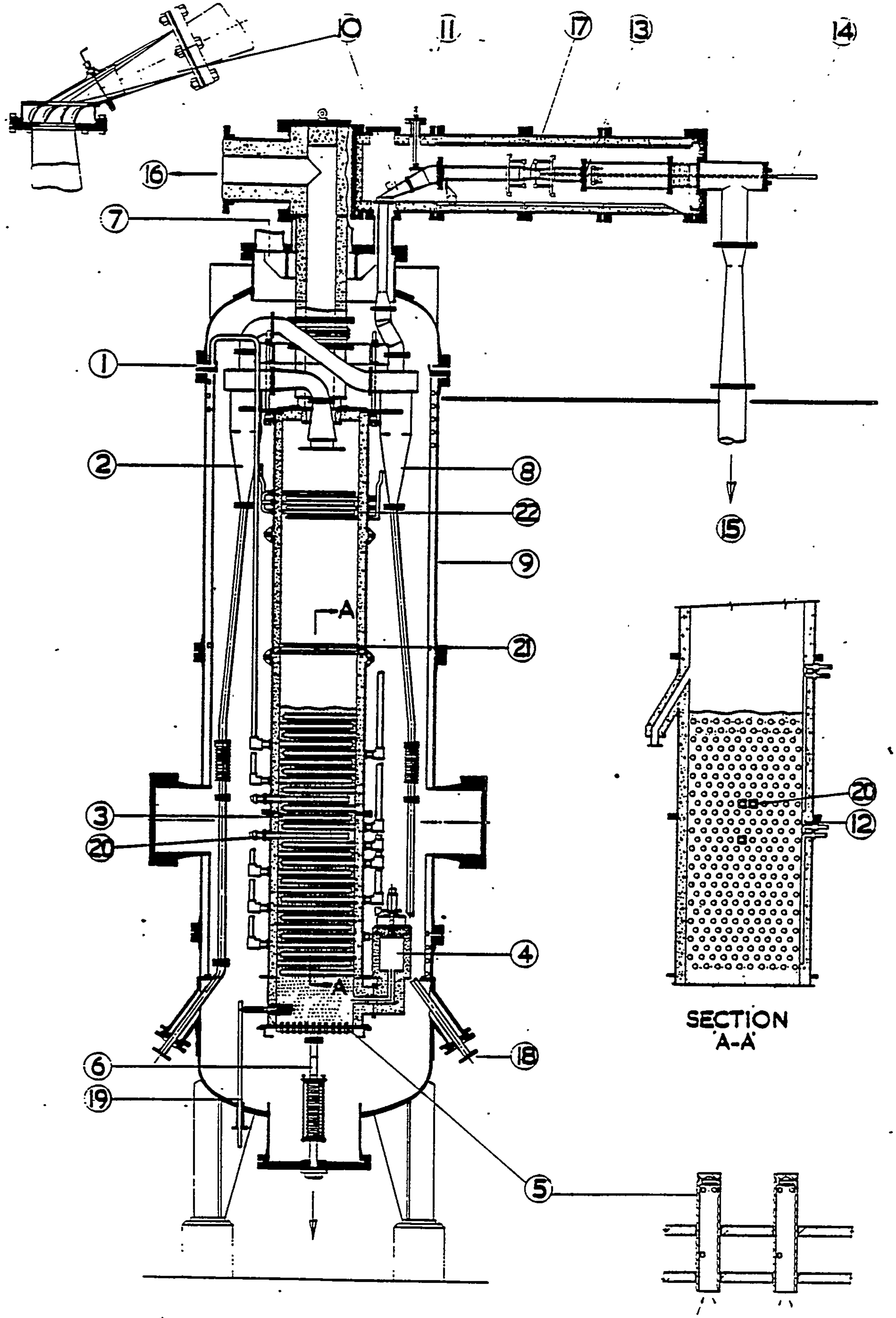
EFFECTS OF TURBINE INLET TEMPERATURE AND PRESSURE RATIO ON PFBC OVERALL EFFICIENCY



REF: 80-GT-102,
R Graves, ORNL

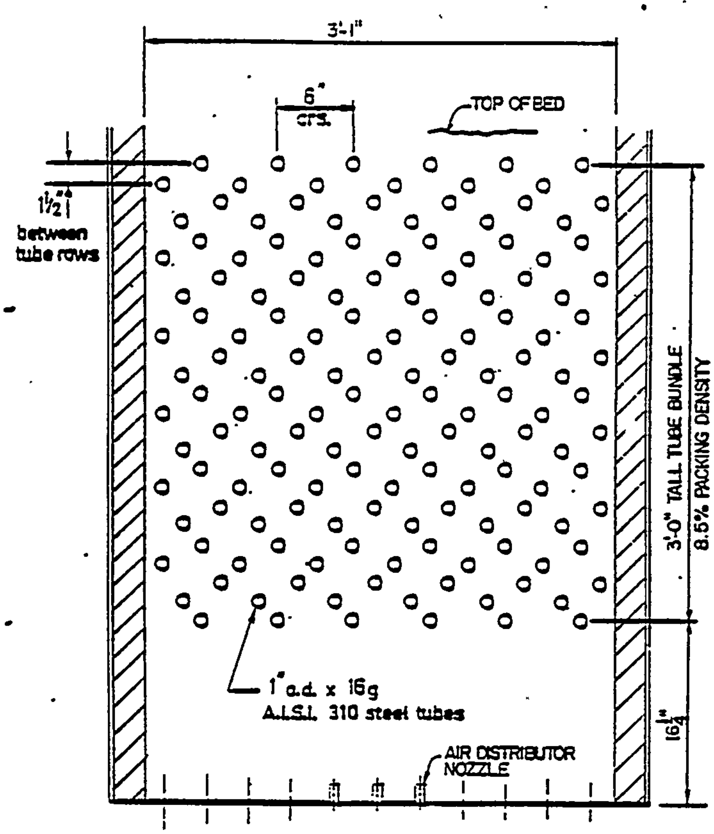
EXTENSIVE TESTS HAVE BEEN CONDUCTED AT SEVERAL PFB FACILITIES TO IDENTIFY:

- SULFUR CAPTURE EFFICIENCIES
- NO_x EMISSIONS
- COMBUSTION EFFICIENCIES
- HEAT TRANSFER COEFFICIENTS
- BED ELUTRIATION RATES
- HOT GAS CLEANUP EQUIPMENT
- TURBINE MATERIAL EROSION & HOT CORROSION



ARRANGEMENT OF CURL/LEATHERHEAD PFB

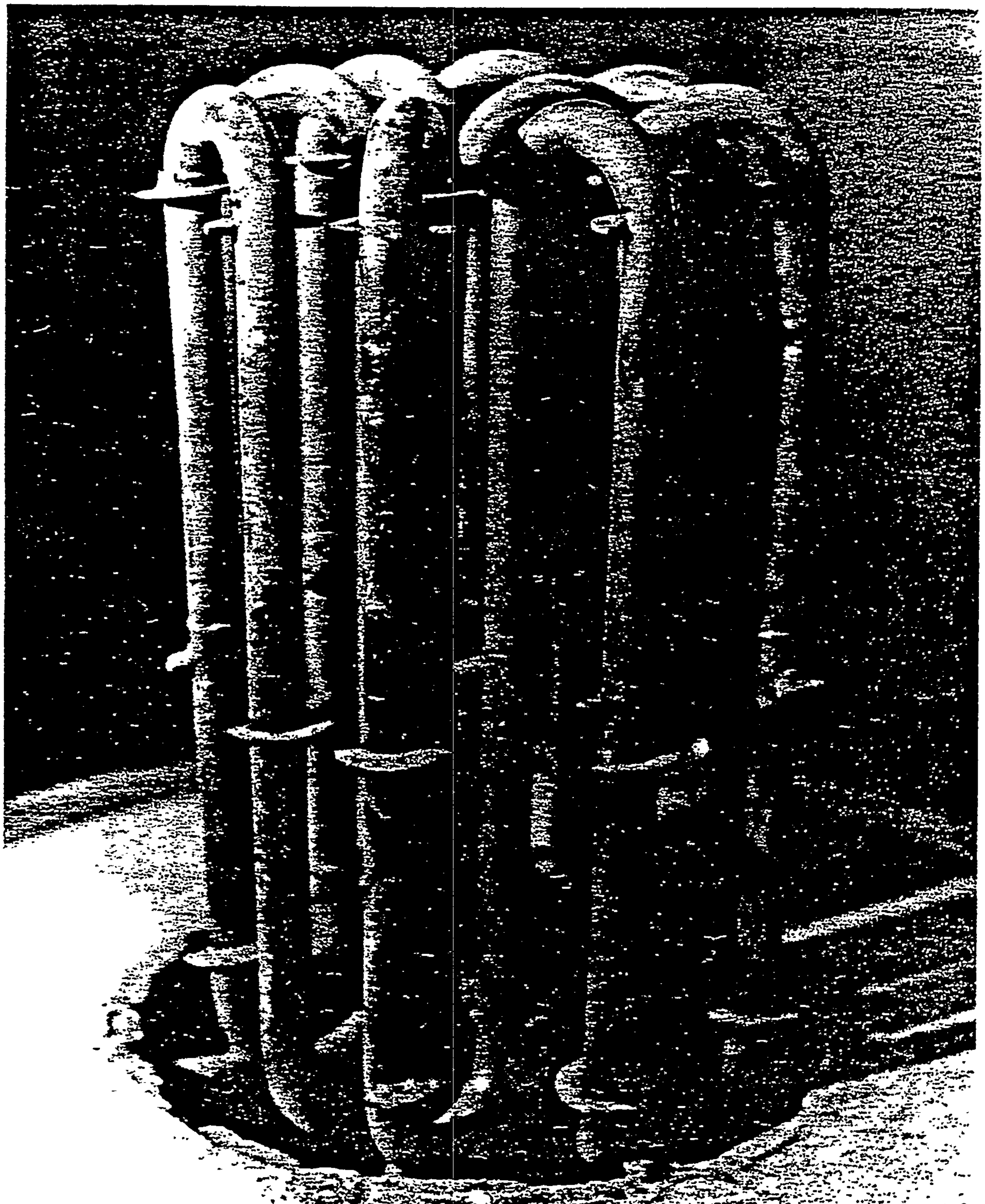
LEATHERHEAD 1972-73 TESTS



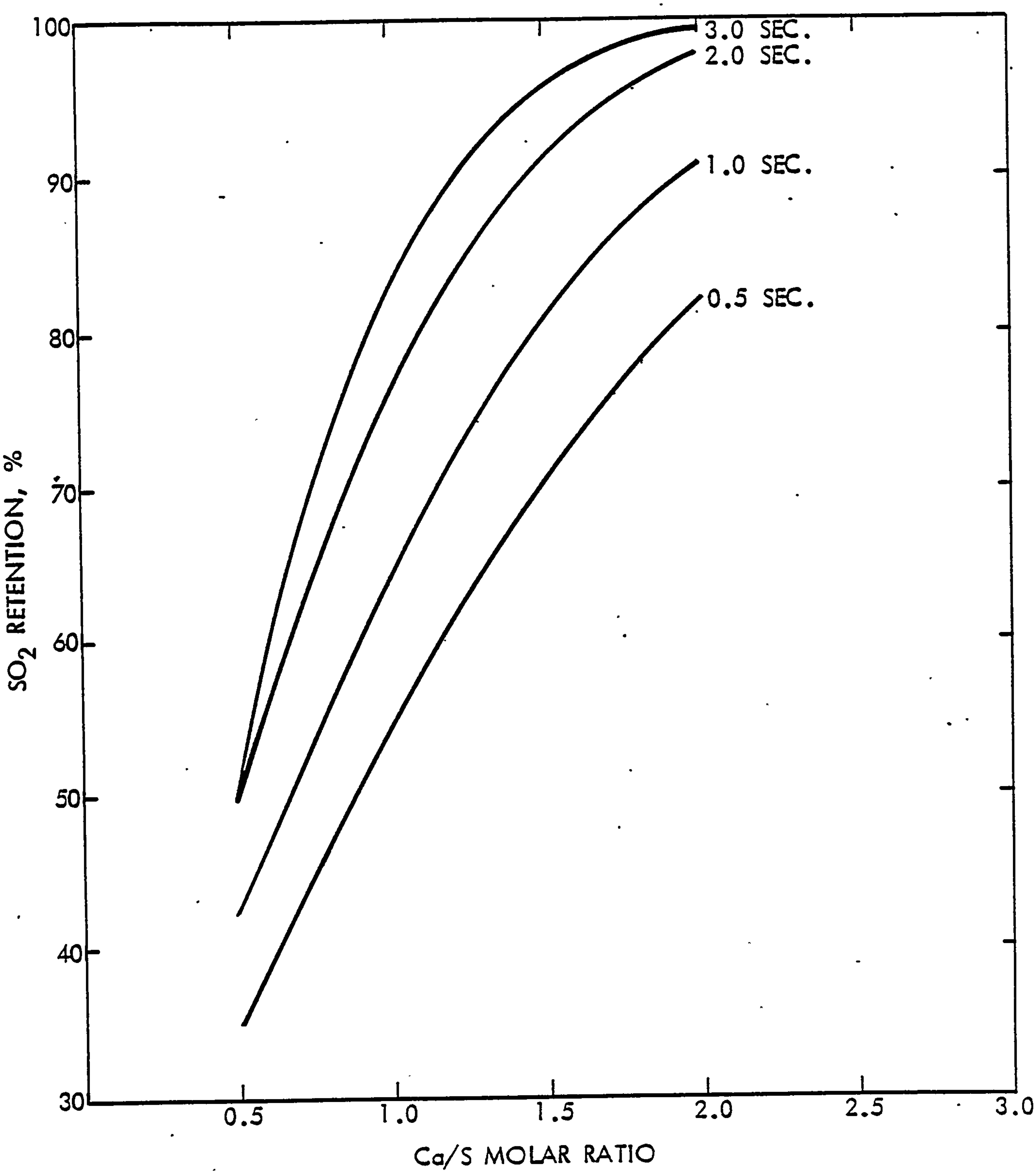
Test No.		1	2	3.1	3.2	4.1	4.2
Fluidising velocity	ft/s	2.3	2.5	2.3	2.3	2.2	2.3
Bed depth	ft	4.4	4.6	4.4	4.7	4.0	4.1
Combustor pressure	psig	66	72	71	68	73	72
Excess air	%	14	19	16	20	16	16
Bed temperature	°F	1630	1745	1670	1655	1645	1740
Cascade inlet temperature	°F	1600	1675	1620	1590	1575	1565
Coal		Pittsburgh		Illinois			
Combustion efficiency	%	99	99½	n.d.	99	n.d.	99½
SO_2 Acceptor		U.S. Dolomite 1337				U.K.Limestone	
Ca/S mole ratio		2.0	2.2	1.4	1.7	2.1	2.0
Sulphur retention	%	97	99	85	98	75	74
SO_2 emission	$lb/10^6$ Btu	0.11	0.05	0.54	0.10	1.3	1.4
NO_x emission	$lb/10^6$ Btu	0.36	0.22	0.21	0.21	0.11	0.13

n.d. = Not determined

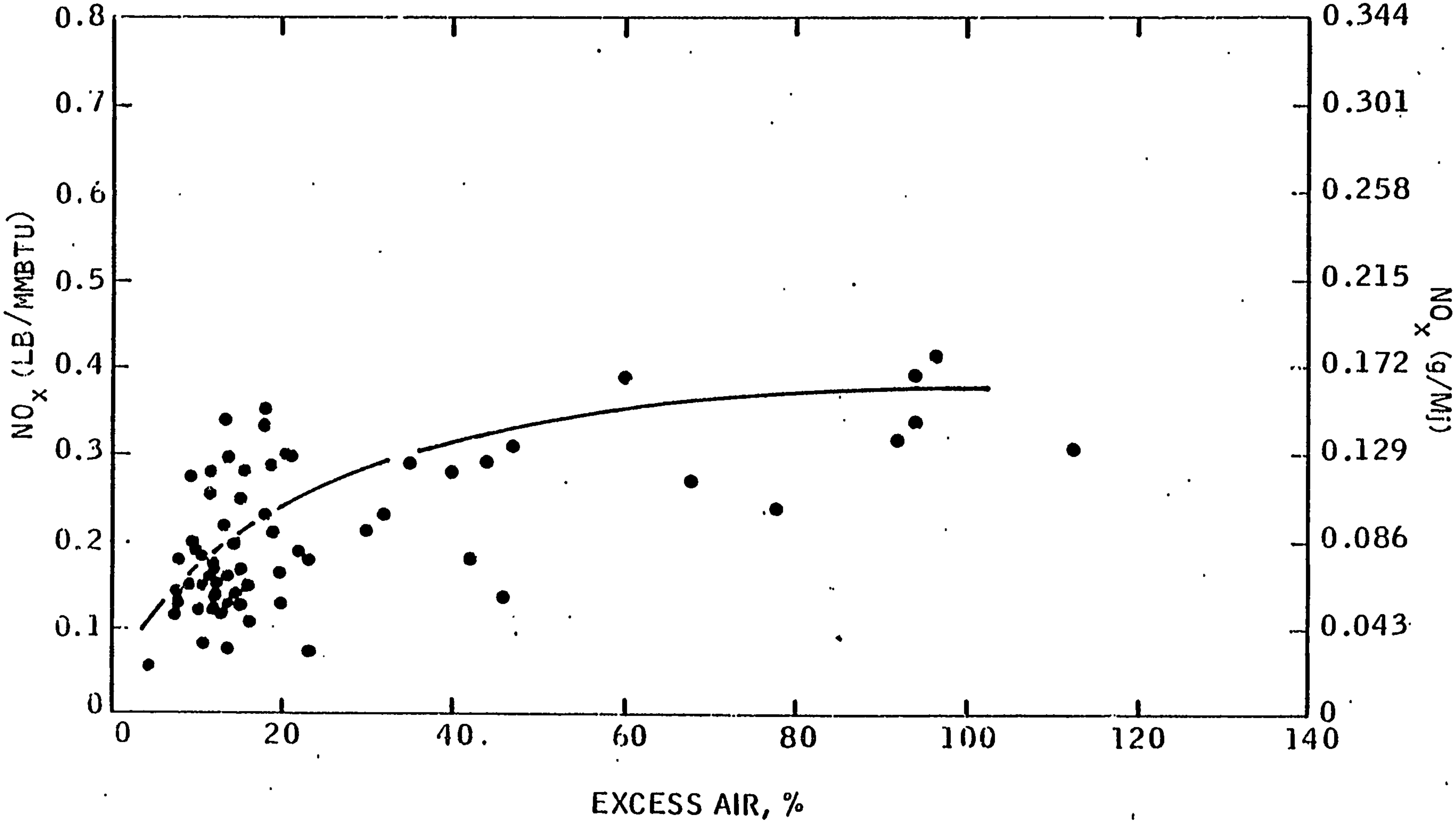
EXXON
MINIPLANT COMBUSTOR COOLING COIL 1A AFTER
1200 HOURS OPERATION

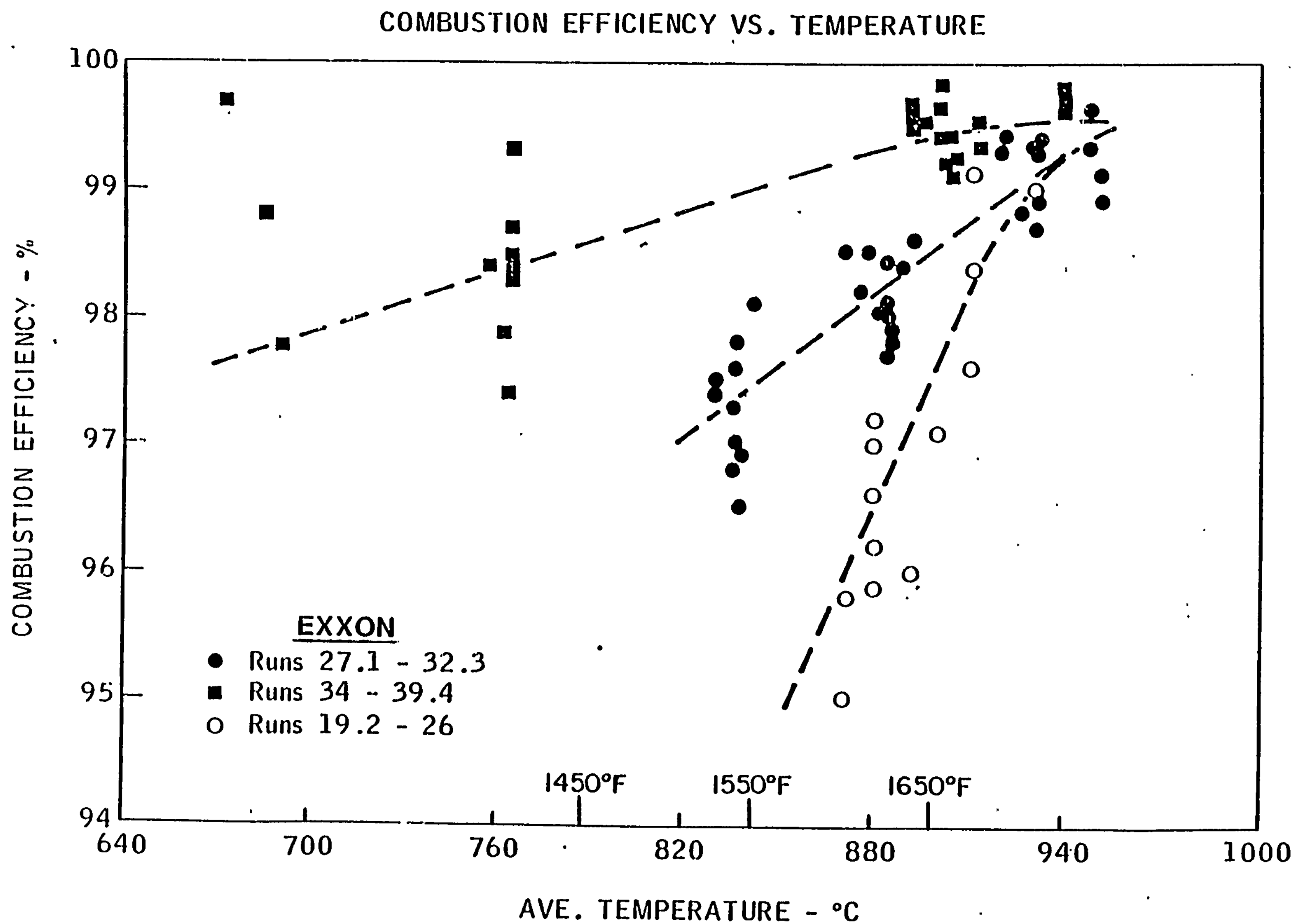


CALCULATED SO_2 RETENTION VS. Ca/S
MINIPLANT DOLOMITE RUNS

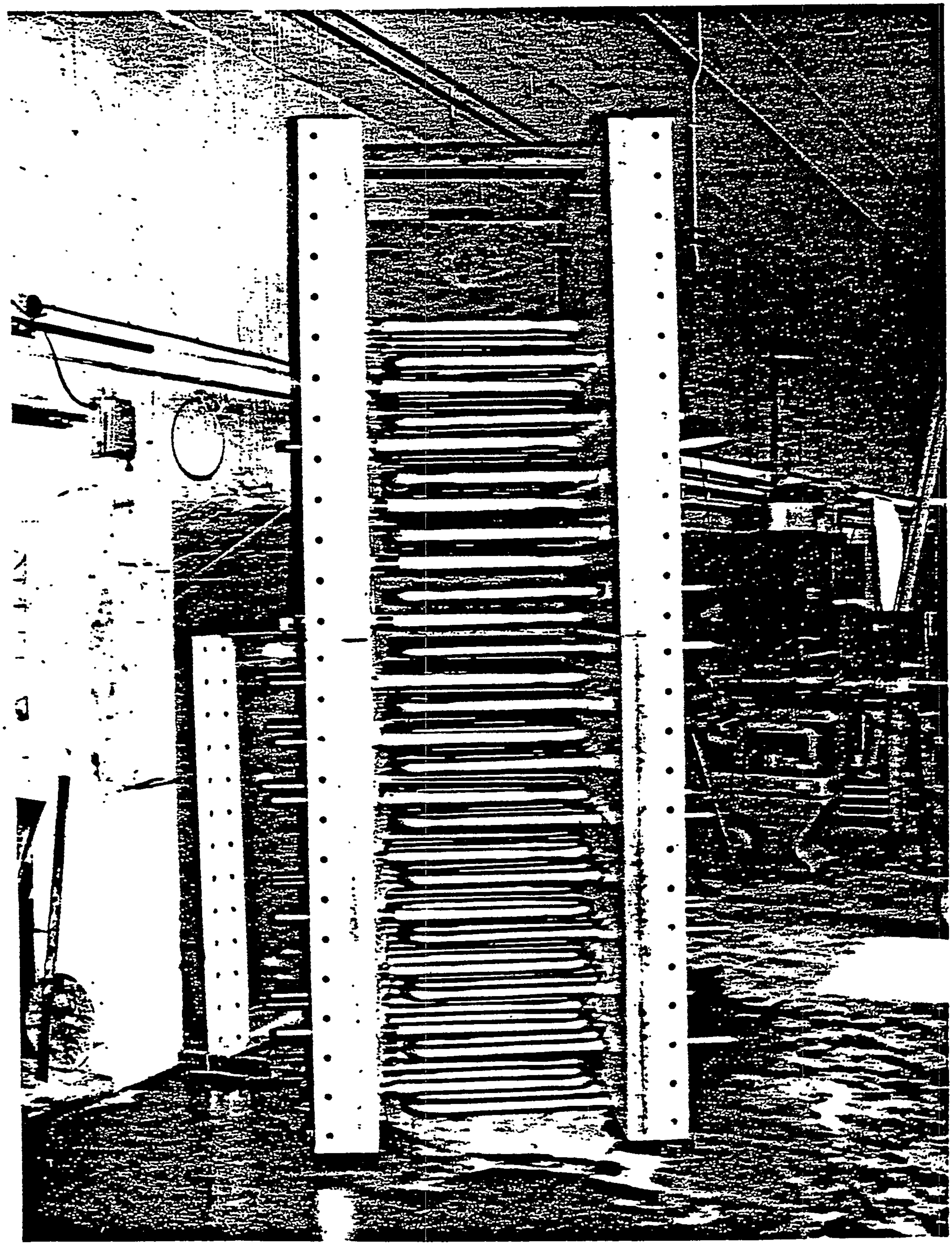


NO_x EMISSIONS VS. EXCESS AIR



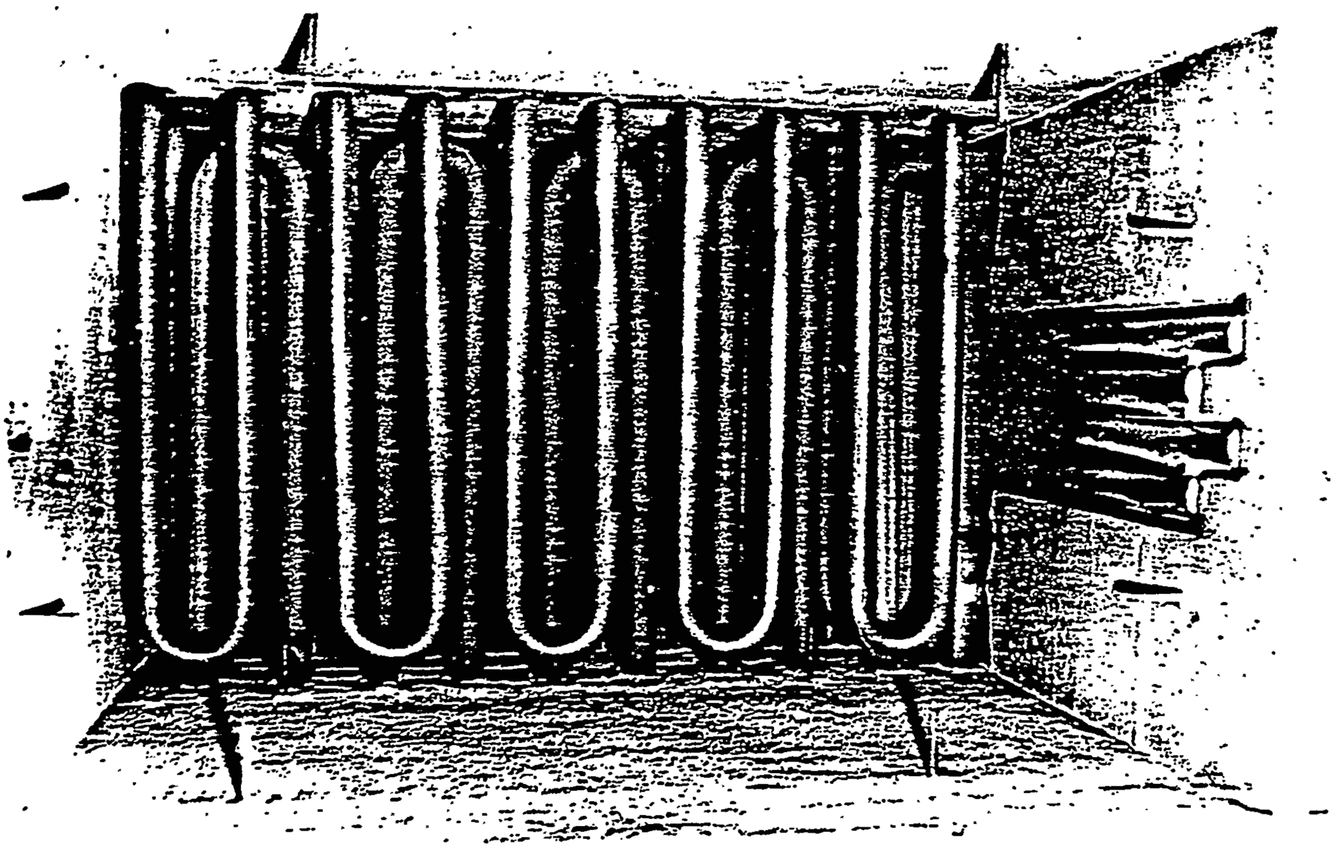


COMBUSTION EFFICIENCY VS. TEMPERATURE
COMBUSTION EFFICIENCY - %
100
99
98
97
96
95
94
EXXON
Runs 27.1 - 32.3
Runs 34 - 39.4
Runs 19.2 - 26
1450°F
1550°F
1650°F
640
700
760
820
880
940
1000
AVE. TEMPERATURE - °C



CFCC Prototype Tube Bundle Configuration as Tested at NCB-CURL.

TUBE BUNDLE PACKING DENSITY 16.8%



Plan View of CFCC Prototype Tube Bundle Configuration as Tested at NCB-CURL.

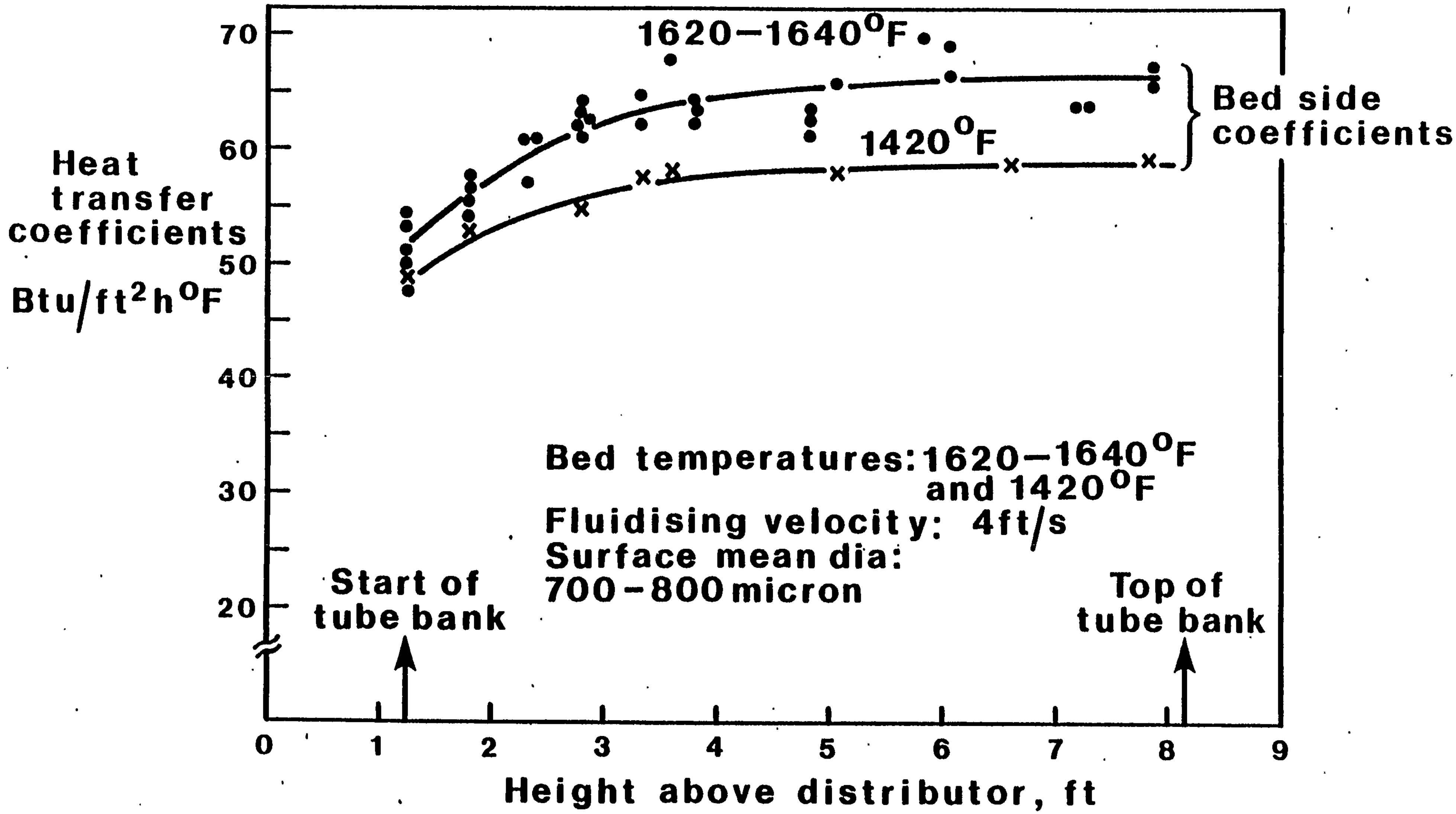


Fig.40 Heat transfer to immersed tubes: Bed depth 9ft.

D657

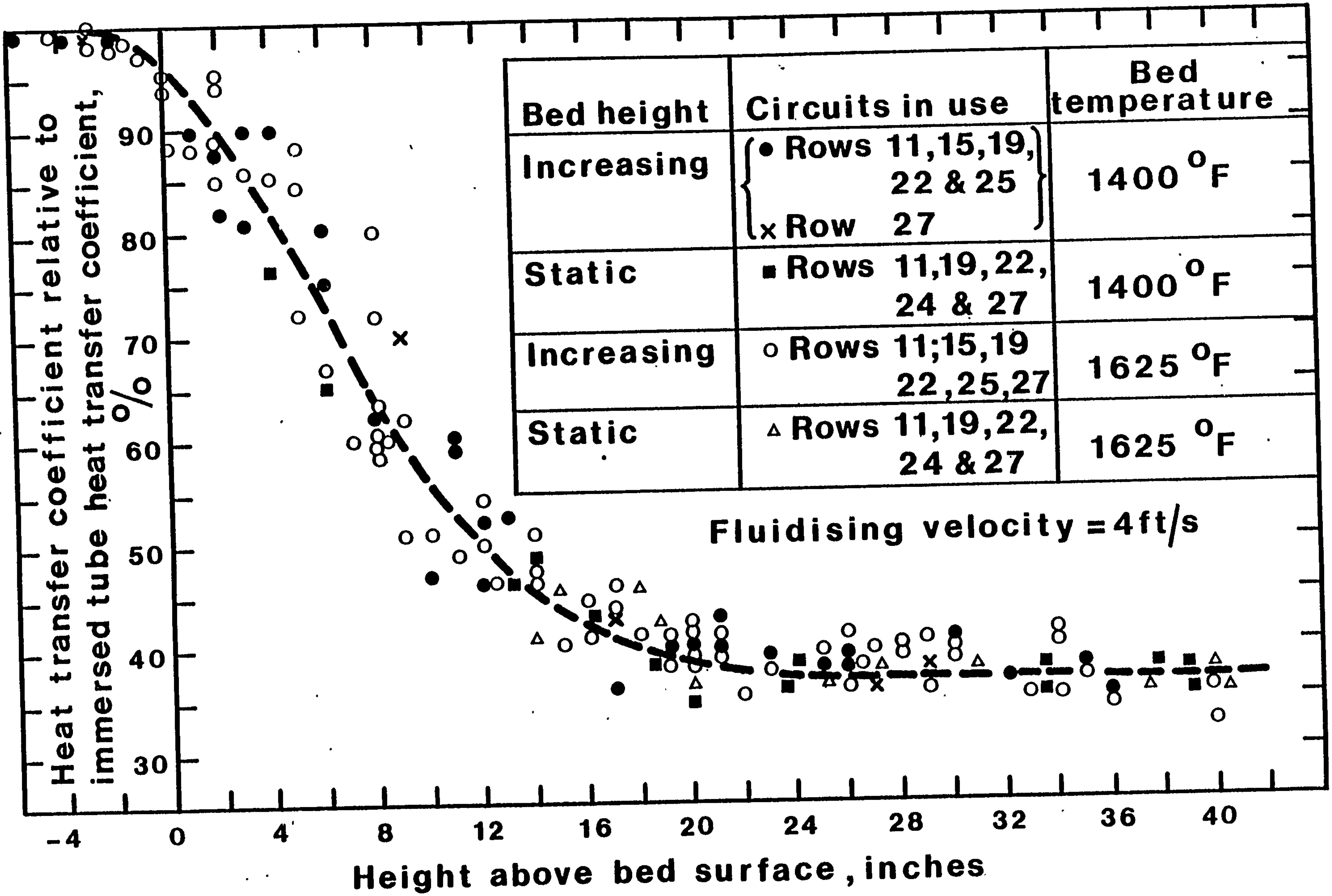


Fig.43 Freeboard heat transfer coefficients

D590