EMPIRICAL MODELS OF EMISSIONS AND ENERGY EFFICIENCIES OF COAL-FIRED FLUIDIZED BED POWER PLANTS

J. Gruhl
J.D. Teare

Energy Laboratory
Report No. MIT-EL 78-015

September 1977

Empirical Models of Emissions and Energy Efficiencies of Coal-Fired Fluidized Bed Power Plants

J. Gruhl
J. D. Teare

September 1977
MIT Energy Lab
Cambridge MA 02139

NOTICE

This report was prepared at the M.I.T. Energy Laboratory, Cambridge, Massachusetts as an account of a portion of work performed on a subcontract to Exxon Research and Engineering Co., Linden, New Jersey, as part of a program sponsored by the U.S. Environmental Protection Agency. None of these organizations nor any person acting in behalf of these organizations (a) makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

EMPIRICAL MODELS OF EMISSIONS AND ENERGY EFFICIENCIES OF COAL-FIRED FLUIDIZED BED POWER PLANTS

Contents pages

ABSTRACT

Mass and energy balances of fluidized bed energy technologies are to a significant degree dependent upon the specific design being investigated. It is difficult to make any generally accurate comments about these balances. This study attempts to solve this difficulty by displaying a large amount of available data, especially on parametric experiments, for the specific designs. To the extent that generalizations about the efficiencies and emissions of these cycles are possible empirical correlation models have been developed, along with measures of the predictive quality of these models over existing data bases. These empirical correlations consist of probabilistic models that have been fit to published experimental data. In several instances, there have been comparison of these empirical models with available analytic models. In the cases of unavailable experimental data, such as for the potassium topping cycles, models have been fit to analytic data. Although the overall scale of this effort was very small compared to other fluidized bed reviews, such as those performed at Babcock and Wilcox, Burns and Roe, and Battelle-Columbus, the empirical models are new and in the narrow scope of this study some of the literature reviews are more comprehensive than others available at this time. Extensive bibliographic research and identification of on-going projects is also included in this report.

1. Summary

This report contains probabilistic models of the energy efficiencies and emissions of various fluidized bed coal (FBC) combustion configurations. There are several intended uses for these types of models, the primary ones being:

1. a means of generating information on FBC performance that can be useful in larger models that investigate national policy questions,
2. an input to an assessment of various energy cycles on a comparative basis,
3. a method for measuring the gap between analytical models and empirical models,
4. a method of directing the search for the most attractive values of design and operating parameters, and
5. a systematic method of identifying and quantifying the extent of need for key pieces of information that are now inadequately known.

There are still a number of conceptual uncertainties with respect to the "overall best" design, conceptual uncertainties that examinations with models can be helpful in resolving; some of these are shown in Table 1.1. In the final analysis, however, it will be a complex evaluation of tradeoffs that will determine the efficiency and emissions of the "optimum" system, and in this effort the modeling will be indispensible.

Table 1-1

Problem Areas [partially from (Wolfe, et al., 1976, p. 2-6)].

	Proposed Design	Primary Backup	Alternatives
Particulate Removal [1]	Cyclones and Aerodyne-type dust collectors	• Provision for third stage • Reduce gas velocity • Reduce fines content of solids feed • Alternative system: granular bed filter	• Cool gas and reheat prior to gas turbine • Modify turbine • Drop back on gas-turbine operating conditions
Hydrocarbon Control	Minimize during combustion	• Change combustion history	
Sulfur Dioxide Control	Dolomite, in bed; 1.2 to 2 Ca/S	• May have to increase use rate for some sorbents	• Select new stone, or different conditions
Nitrogen Oxide	Minimized during combustion (demonstrated)	• Promote reducing conditions in lower region of the bed	
Trace Metal Control	Minimize during combustion	• Larger coal particle sizes	• Change combustion temperature • Additional sorbents
Materials	Conventional boiler tube materials	• Use higher-grade materials (which are available)	
Coal Feed	Petrocarb feed system (lockhoppers)	• Increase number of feed points per bed • Reduce unit capacity: bed depth	• Alternative technology e.g., slurry feed, screw feeders
Alkali Metals [1]	Temperature maintained sufficiently low to avoid problem	• Lower temperature further to avoid problem	• Add sorbent to remove alkali metals
Combustion losses	Controlled by design and operation	• Modify combustion configuration	
Turndown and Load Follow	Vary bed temperature modular boilers	• Vary excess air • Vary bed depth or coal feed	• Additional modules • Recirculating bed
Spent Stone Disposal	Landfill	• Sulfur recovery, artificial regenerable sorbents • Commercial utilization	

---

[1] Control to achieve gas-turbine reliability and long life

2. Introduction

The objective of this study is to develop probabilistic models of the energy efficiencies and the emissions of the various fluidized bed coal combustion configurations. This is accomplished by fitting those models to the experimental data available in the literature. It is not a difficult task to fit models to data, once format and parameters have been decided; it is however a time consuming task. The amount of experimental data available on the atmospheric and the pressurized fluidized bed combustors now exceeds that which can be handled effectively by manual efforts. Revisions of these analytic models must be performed on a computerized data management system. EPRI has sponsored a data base on atmospheric experimental results that is now available (Strom, et al., 1976). No parallel data base is currently available for pressurized systems, although one is presently being undertaken at M.I.T. Energy Lab under DOE sponsorship.

This particular study has been kept tractable by focusing only on the endpoints of efficiencies and emissions; internal modeling efforts which do not aid in efficiency and emission characterizations, as interesting as they may be, are not included. An attempt has been made to mention analytic modeling efforts whenever these have been found, and to describe the gaps that exist between their predictions and the actual experimental results.

Clearly, the fact that experimental data have been used does not assure that these results are correct, or that they have been interpreted properly. Where conflicts in information have been found these are noted. An additional confounding difficulty is caused by the fact that much of the available data, particularly the earlier data, is far from the range of current interesting operating conditions and was often obtained on designs that are well below the current state-of-the-art. It is difficult or impossible, on sight, to determine the degree of validity of available results. Since there is continuing interest in improving the empirical models that are presented, it would be very helpful if experts in this field could forward critical responses. In addition, the sheer size of the bibliography is no guarantee that the important sources are included and additions would be appreciated.

3. Plant Design Configurations

Even within the categories of atmospheric, pressurized, and metal topping fluidized bed combustors there are considerable variations in the designs of the facilities. Variations occur, for example, in the placement of the tubes, shapes and size of combustion chamber, number of reheats, methods of returning fines, and so on. Some of the resulting differences in performance are not striking and the efficiency and emission information from these variations are comparable. Some variations are amenable to quantification such as cross-sectional area of combustion chambers. Unfortunately, however, some of the variations in configurations are not comparable or quantifiable and must essentially be accounted separately. After a description of FBC programs in progress, the design variations are enumerated.

3.1 Fluidized Bed Combustion Programs in Progress

The greatest advances and attention have revolved around the larger sized experimental facilities. The same organizations that have been involved in FBC research in the past have worked with these larger experimental rigs. New organizations have been introducing themselves to the field by way of paper studies.

In terms of analytic studies at the most general level, there are several programs that propose comprehensive across-the-board assessments of environmental aspects of energy technologies. These general assessments require results of analytic engineering evaluations such as those presented in this report and, in turn, these narrower scope studies must direct their search for information to be of most use to those broader programs. DOE sponsored overview programs include the National Coal Utilization Assessment being carried out by Argonne as part of their Regional Studies Program and the Environmental Control Technology Program also at Argonne [see (Gruhl, *et al*., 1976)].

Most of the more important of the other *overall assessments* have and are being developed with EPA sponsorship. One of the initial programs, conducted at EPA with help from Battelle-Columbus was completed in 1974 (Hall, Choi, and Kropp; 1974). This was one of the original projects to use modularization of fuel types, combustion types, and abatement types. The information from the module for high-pressure fluidized-bed combustion with combined cycle is shown in the following table and footnotes.

Table 3.1-1

Environmental Data for Module (Hall, Choi, Kropp, 1974).

Module - Fluid-Bed Combustion Plus Combined Cycle Unit - 10^6 Btu (input to combustion cycle).

Environmental Parameters	Fuel Input, Coal, East
Air	
NO_x, lb	0.14 (1)
SO_2, lb	0.7 (2)
CO, lb	0
Particulate, lb	0.02 (3)
Total organic material, lb	0
Heat, 10^6 Btu	0.62 (4)
Water	
Suspended solids, lb	0
Dissolved solids, lb	0
Total organic material, lb	0
Heat, 10^6 Btu	Negligible after cooling tower
Acid (H_2SO_4), lb	0
Solid	
Slag, lb	0
Ash, lb	17.3 (5)
Sludge, lb	0
Tailings, lb	0
Hazardous, lb	0
By-Products	1.9 (6)
Occupational Health	
Deaths	1.5×10^{-9} (7)
Total Injuries	3.6×10^{-8} (8)
Man Days Lost	1.4×10^{-5} (9)
Land Use, acre-hr/10^6 Btu	0.12 (10)
Approx. Module Efficiency	38% (11)

Footnotes for Table 3.1-1

(1) a. Average value of 0.07 and 0.22 lb/10^6 BTU reported in Westinghouse Report.

(2) a. SO_2 emission factor reported = 1 lb/10^6 BTU.
    b. Adjustment factor for sulfur content = 0.7 (i.e., 3.0/4.3).

(3) a. Particulate emission factor reported = 0.02 lb/10^6 BTU.

(4) a. Efficiency of the module (assumed) = 38%.

(5) a. Ash content of eastern coal (assumed) = 14.4%.
    b. Heating value of coal (assumed) = 24 x 10^6 BTU/ton.
    c. Limestone requirement per pound of sulfur = 1.75 lb.

(6) a. The sole by-product is elemental sulfur.
    b. Sulfur content of coal (assumed) = 3%.
    c. 90% of sulfur is collected by limestone (assumed).
    d. Sulfur loss from Claus unit = 0.35 lb/10^6 BTU.

(7) a. Injuries calculated from fluid-bed combustion plant and gas-fired power plant operations.
    b. 40 men operate a 500 ton coal/hr capacity combustion plant (assumed).
    c. Using chemical industry data for gasification plant, injuries per man hour = 8.1 injuries/10^6 man hours
    d. Death rate (assume) = 5% of injuries.
    e. Death attributed to a 100 MW gas-fired power plant = 0.01 deaths/year

(8) a. Injuries attributed to a 1000 MW gas-fired power plant = 0.6 injuries/year.

(9) a. Using chemical industry data for gasification plant, man-days lost per man hour = 528 days/10^6 man hours.
    b. Man days lost per death (assumed) = 6000 days/death.
    c. Man days lost attributed to a 1000 MW gas-fired power plant = 197 man-days/year.

(10)a. Land requirement for a 1000 MW coal-fired power plant (assumed) = 800 acres.
    b. Additional land requirement for fluid-bed combustion unit (assumed) = 150 acres.

(11)a. Efficiency = 38%.

Table 3.1-2 INTEGRATED TECHNOLOGY ASSESSMENT
(by Teknekron, Inc.)

Program: 1976-1979 to study 1975-2000

Initial Task Emphasis:

- Fossil fuel electricity generation
- Primary and secondary air pollutants
- Short-range and long-range dispersion of air
- Human populations exposed to air pollutants

Next Task Examines:

- Key assumptions
- Reliability of data
- Accuracy of models

Levels of confidence on economic and
environmental impacts

In terms of ongoing electric power assessment programs the Teknekron project is currently the most detailed under EPA sponsorship. Above is a brief description of the emphasis of that ITA program. A number of different assumptions will be used to create the inputs to many sensitivity studies planned for the ITA. The variables for these different scenarios are shown on the following page. The flow chart for the ITA mechanism is shown on the next following page in Figure 3.1-1. It is important to note that the ITA goes through the physically significant environmental modeling process and thus will require some kind of duration models for the emissions to make possible the exposure computations shown as an ITA module.

Table 3.1-2

Outline of Principal Elements in Scenario Specification

[from (Teknekron, Inc., 1976)].

ECONOMICS	TECHNOLOGY	POLICY
External to Industry	**Generation Technology**	**Pollution Control Policy**
. GNP - Incomes . Primary Energy Markets	. Coal / Nuclear . Continued Role of Oil and Natural Gas . Cost and Timing of Availability of New Technologies . Costs and Timing of Availability of Advances in Long Distance Transmission	. Limits on Performance Ambient Standards based on: Primary Pollutants Secondary Pollutants Hazardous Substances . Siting in Environmentally Acceptable Areas
Internal to Industry	**Pollution Control Technology**	**Demand Management Policy**
. Regulatory Policy (Prices) . Capital Markets . Commitment to Modernization . Tax Policies	. Availability, Cost and System Impacts of Controls for: Sulfur Oxides Nitrogen Oxides Primary Particulates Thermal Abatement Other Hazardous Substances	. Continued Emphasis on Conservation . Major Initiatives Toward Electrification

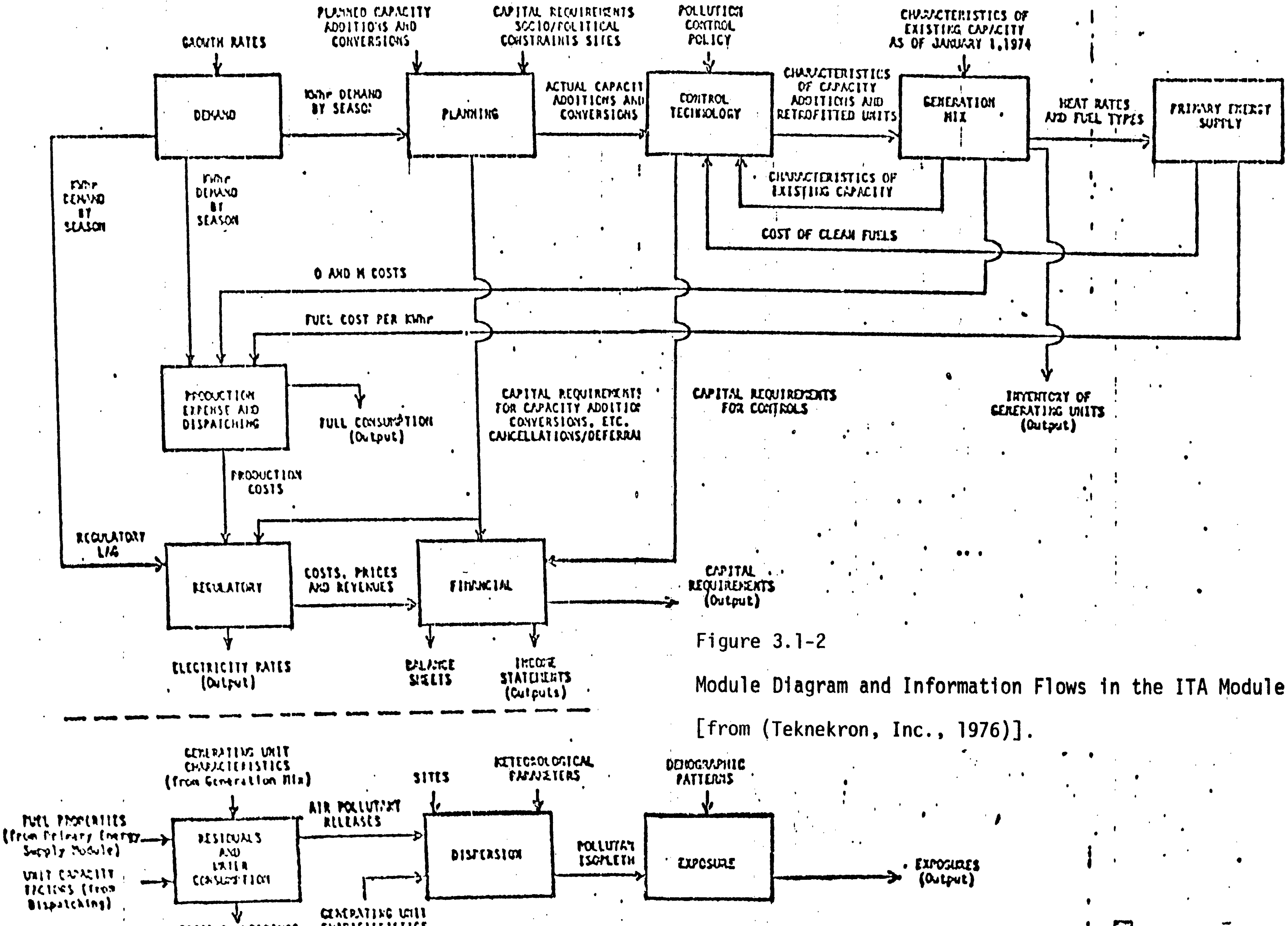


Figure 3.1-2

Module Diagram and Information Flows in the ITA Module

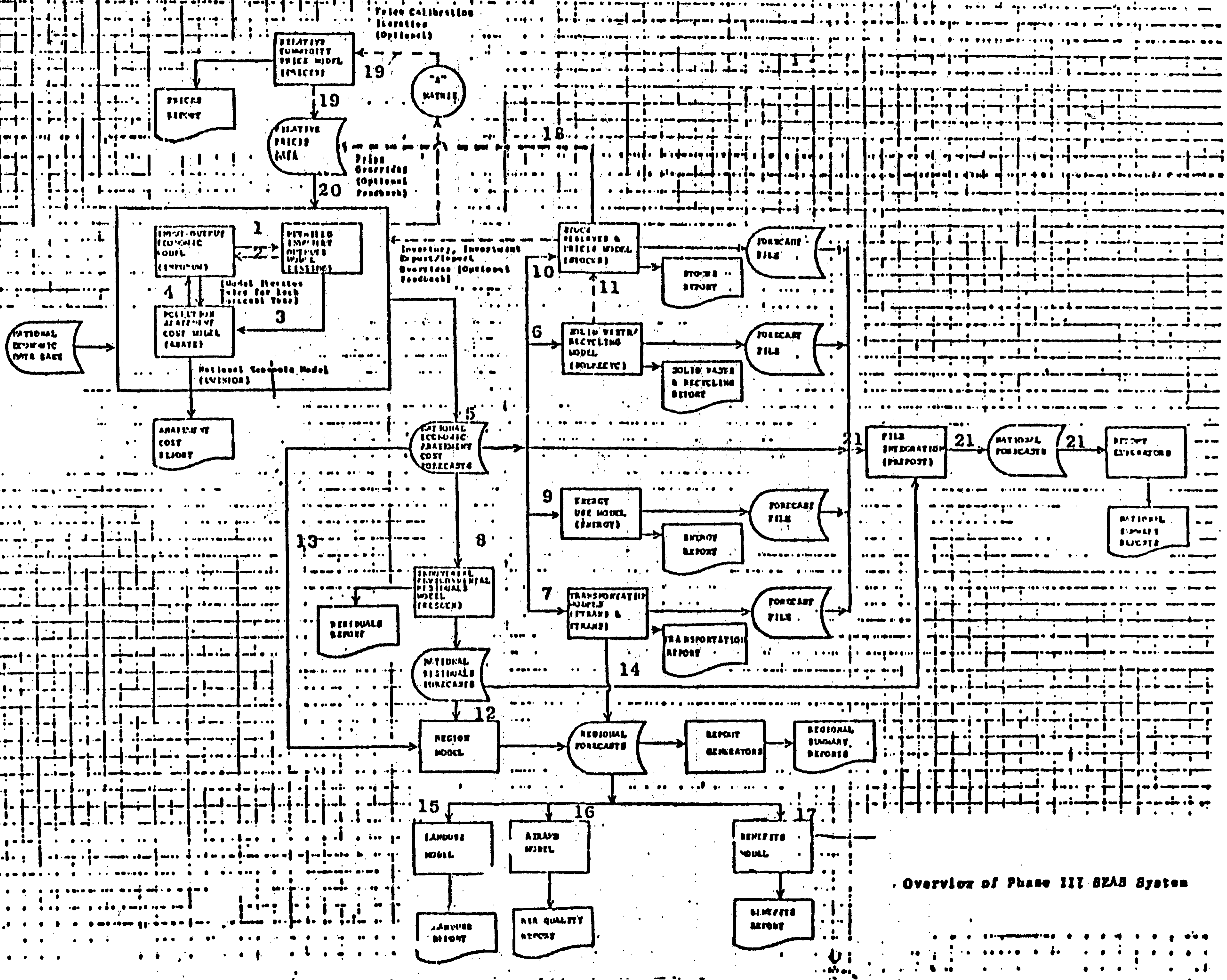
[from (Teknekron, Inc., 1976)].

Table 3.1-3 STRATEGIC ENVIRONMENTAL ASSESSMENT SYSTEM

Program:	in modules 1974-1976 combined 1977-1980 for period 1975-1985 (eventually 1990)
Purpose:	tool for assessing the potential impact of existing and proposed: - environmental regulations - environmental and energy policies based on alternative sets of assumptions for: - economic trends - demographic trends

The SEAS project, initiated at EPA and later receiving considerable revision from DOE, is briefly described in Table 3.1-3. It is a model of the interaction of energy and environmental problems with the entire national economy (modelled using a large input/output scheme). Thus, SEAS takes into consideration material and resource availability,capabilities of supportive industries, and so on. The list of atmospheric pollutants collected in SEAS is given on the following page, and the flow chart for SEAS on the next page after that. There may soon be revisions to the list and setup of SEAS pollutants, and anticipating these as near-future changes could be worthwhile. First, since respirability of particulates is strongly dependent upon particle size (around one to one-half micron being most deposited on lung surface) it would be useful to collect spectra of particle sizes. Hydrocarbons definitely should be split to inert, reactive, and different strengths of carcinogenic potential. These are areas where research on the emissions from FBC technologies is just now underway.

SEAS as shown in Figure 3.1-3 uses the shortcut of emission-to-ambient scaling rather than dispersion modeling, and uses emission-to-damage



Overview of Phase III SEAS System

Figure 3.1-3

of SEAS System (EPA, 1975)

scaling rather than dose-response modeling (the former using NEDS ratios of 1973 concentrations to emissions by industry and pollutant, and the later using 1971 damage estimates by regions).

If policy decisions about fluidized bed energy technologies are to be made using SEAS, then an updating of the FBC economics is necessary, as well as a quantification of constraints (resource, manpower, fabrication, and so on) to underscale FBC use. Retrofit potential of conventional boilers to the fluidized bed technology will also be needed.

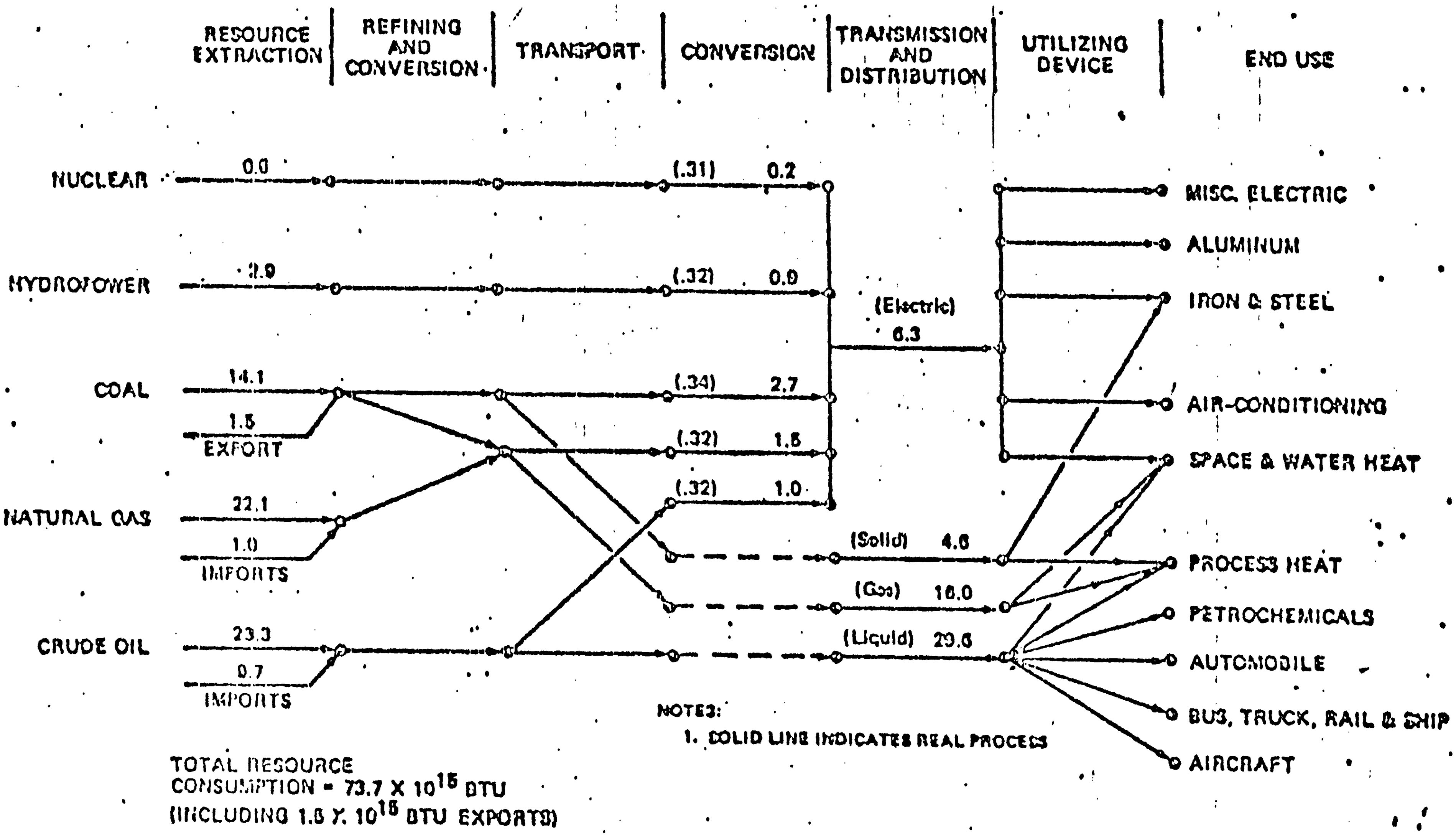
Table 3.1.4 AIR POLLUTANTS IN SEAS

- Particulates
- Sulfur Oxides
- Nitrogen Oxides
- Hydrocarbons
- Carbon Monoxide
- Photochemical Oxidants
- Other Gases and Mists
- Radionuclides to Air
- Antimony
- Arsenic
- Asbestos
- Beryllium
- Cadmium
- Chromium
- Lead
- Mercury
- Selenium
- Thallium
- Vanadium

Intermediate between ITA and SEAS in the hierarchy of assessments is the Energy Alternatives/EMDB/ MERES system. With initial sponsorship from CEQ this system now resides largely in DOE-funded national labs. As a resource to fluidized bed assessments, it is probably most useful as a data base on emissions from all of the various steps in a fuel cycle, that is, extraction, transportation, and so on. Figure 3.1-6 shows the fuel cycles that are modeled in the MERES system. Figure 3.1-7 shows more specifically how advanced cycles fit into the MERES schematic and the following page shows Table 3.1-5 with some comparative results, including fluidized bed cycle emissions. None of these overall energy assessment models have appropriate data about the fluidized bed technologies. Any research about the economics, performance, and environmental effects of FBC's should at some point make a conscious effort to get the appropriate information to these data bases and models that may play a central role in decisions about the research priorities and incentives accorded to the use of fluidized bed energy cycles.

Experimental Studies

Leaving these across-the-board assessments there are several projects that have been specifically designed to deal with fluidized-bed combustion. The experimental studies are treated with a sharp emphasis on recent research. The often seen table of current facilities is expanded in Table 3.1-6. The larger the facility the closer analogy it is to a commercial plant and in that light the Woodall-Duckham (formerly Babcock and Wilcox) 10 foot by 10 foot plant is of most interest. There is apparently no data yet from that plant. The DOE schedule for gradually scaling up from



NOTES:
1. SOLID LINE INDICATES REAL PROCESS

TOTAL RESOURCE
CONSUMPTION = 73.7×10^{15} BTU
(INCLUDING 1.5×10^{15} BTU EXPORTS)

Figure 3.1-6

The fuel cycles as they are represented in the Energy Alternatives/MERES system.

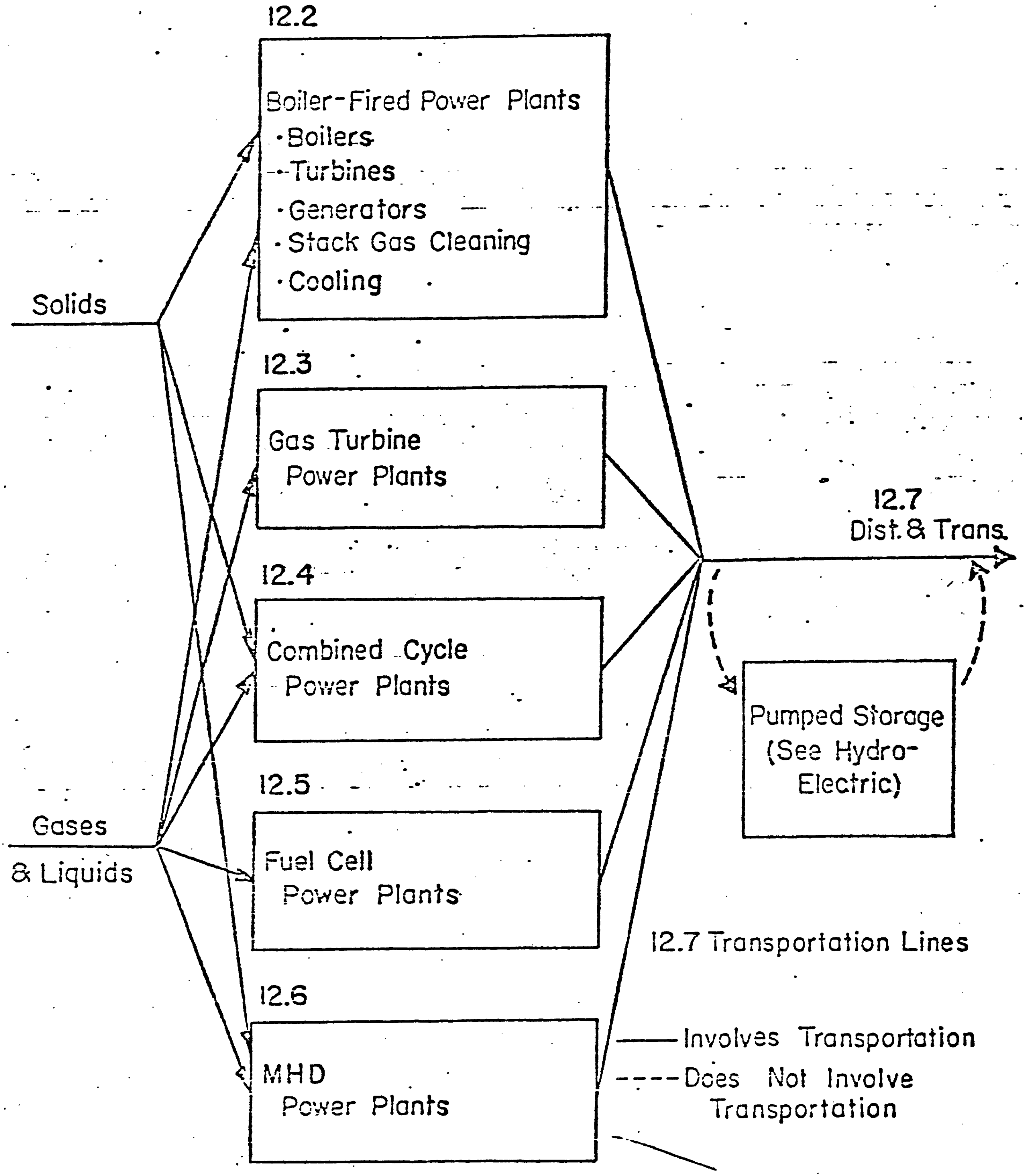


Figure 3.1-7

Electrical Generation System.

Table 3.1-5

Major Residuals for 10,000 Mwe Plants at 75 Percent Load Factor.

Plant Number	Description	Primary Efficiency	Nitrogen Oxides (10^3 tons)	Sulfur Oxides (10^3 tons)	Particulates (10^3 tons)	Thermal (10^{12} Btu's)	Solid (10^3 tons)
1[a]	Coal: Conventional steam No controls	38	21.8	119.2	48.5	31.1	298
2[a]	Oil: Conventional steam No controls	38	21.1	47.3	1.6	31.1	0
3[a]	Gas: Conventional steam No controls	38	11.2	.02	.43	31.1	0
4[b]	Eastern Coal: Conventional Boiler with wet limestone scrubbing	35	16.0	16.0	3.2	0	955
5[b]	Eastern Coal: Conventional Boiler with magnesium oxide scrubbing	35	19.2	16.0	3.2	0	410
6[b]	Western Coal: Conventional Boiler with wet limestone scrubbing	35	25.0	5.1	2.2	0	487
7[b]	Physically Cleaned Eastern Coal: Conventional Boiler with wet limestone scrubbing	35	17.6	6.4	1.4	0	417
8[a]	Coal: Steam plant with controls	38	23.2	19.1	2.6	0	1,009
9[a]	Northern Appalachian Coal: Atmospheric Fluidized Bed	36.8	4.3	10.2	.5	0	359
10[a]	Northwest Coal: Atmospheric Fluidized Bed	36.8	4.3	3.5	.3	0	243
11[a]	Northern Appalachian Coal: Combined-Cycle Pressurized Fluidized Bed	35.8	4.22	13.2	.8	0	362
12[a]	Low-Btu Gas (Northern Appalachian Coal): BuMines-Atmospheric Boiler plant with controls	38	0.391	28.8	6.78	0	0
13[a]	Low-Btu Gas (Northern Appalachian Coal): BuMines-Pressurized Combined-Cycle plant	40	0.577	2.66	.19	0	0

[a] (Wittman, 1974, 1975)

[b] (Battelle, 1973)

Table 3.1-5 (continued)

Residuals for Environmentally Controlled Combined-Cycle Electricity Generation

SYSTEM	Water Pollutants (Tons/10^{12} Btu's)										Air Pollutants (Tons/10^{12} Btu's)						Solids (Tons/10^{12} Btu's)	$^{F}/_{I}$[a]	Occupational Health 10^{12} Btu's		
	Acids	Bases	PO_4	NO_3	Total Dissolved Solids	Suspended Solids	Organics	BOD	COD	Thermal (Btu's/10^{12})	Particulates	NO_x	SO_x	Hydrocarbons	CO	Aldehydes		Land $\frac{\text{Acre-year}}{10^{12}\text{ Btu's}}$	Deaths	Injuries	Man-Days Lost
CENTRAL																					
1 BuMines-Pressurized Combined-cycle	0	0	U	U	3.4	0	.003	U	U	0	3.75	39.4	278.	0	0	0	0	.217/0 .217	.0002	.0188	2.08
2 Koppers-Totzek Combined-cycle	0	0	U	U	3.4	0	.003	U	U	0	.462	23.7	457.	0	0	0	0	.482/0 .482	.0002	.0188	2.08
NORTHERN APPALACHIA																					
3 BuMines-Pressurized Combined-cycle	0	0	U	U	3.4	0	.003	U	U	0	3.44	10.3	47.4	0	0	0	0	.205/6 .205	.0002	.0188	2.08
4 Koppers-Totzek Combined-cycle	0	0	U	U	3.4	0	.003	U	U	0	.503	19.6	91.2	0	0	0	0	.482/0 .482	.0002	.0188	2.08
NORTHWEST																					
5 BuMines-Pressurized Combined-cycle	0	0	U	U	3.4	0	.003	U	U	0	468.	32.4	165.	0	0	0	0	.181/0 .181	.0002	.0188	2.08
6 Lurgi Combined-cycle	0	0	U	U	3.4	0	.003	U	U	0	14.3	10.	28.6	0	0	0	0	.418/0 .418	.0002	.0188	2.08
7 Koppers-Totzek Combined-cycle	0	0	U	U	3.4	0	.003	U	U	0	.456	15.9	25.9	0	0	0	0	.418/0 .418	.0002	.0188	2.08
CENTRAL COAL																					
8 Combined-cycle Pressurized Fluidized Bed	0	0	U	U	18.2	0	.003	U	U	0	9.29	67.3	441.	0	0	0	6760.	1.62/.17 4.19	U	U	U
NORTHERN APPALACHIAN COAL																					
9 Combined-cycle Pressurized Fluidized Bed	0	0	U	U	18.2	0	.003	U	U	0	12.3	67.3	210.	0	0	0	5780.	1.62/.14 3.78	U	U	U
NORTHWEST COAL																					
10 Combined-cycle Pressurized Fluidized Bed	0	0	U	U	18.2	0	.003	U	U	0	9.70	67.3	71.8	0	0	0	3950.	1.62/.10 3.09	U	U	U

NA = not applicable, NC = not considered, U = unknown.

[a] Fixed Land Requirement $\left(\frac{\text{Acre - year}}{10^{12}\text{ Btu's}}\right)$ / Incremental Land Requirement $\left(\frac{\text{Acres}}{10^{12}\text{ Btu's}}\right)$.

Table 3.1-6

Fluidized-Bed Combustion Facilities

Location	Organization	Combustion and Regenerator Size	Pressure, atm	Gas Veloc. fps	Temp., F	Status/Purpose
France	Societe Anonyme Activit and Babcock-Atlantique	Ignafluid boiler	1		1800-2200	53/Modified conventional stoker
Czechoslovakia	Fuel Research Institute				1800	52/Combination of low grade fuel
United Kingdom	National Coal Board (NCB) and British Coal Utilization Research Association (BCURA)	6" diam. 12"x12"	1	2-3	1240-1680	62-77/Combustion
		36" x 18"	1	2-8	1420-1680	
		48" x 24" 36"x24"	5	2	1470-1745	
		27" diam.	1	6-14	1420-1680	
Virginia	Pope, Evans & Robbins (PER)	12" x 16" FBC	1	8-14	1450-2000	66-85/Combustion and regeneration, development plant
		20" x 6' FBM	1	12-15	1600-2050	
		20" x 20" CBC	1	12-15	1450-2000	
(West Virginia)		28' 8.2" x 12' (Rivesville)	1	9-12	1550	77/Modular design
(West Virginia)	U.S. Bureau of Mines	18" diam.	1	2-3	1450-1650	66-72/Combustion heat transfer
	Consolidation Coal	4" diam.	1.5	2-3	1700-1900	68-70/Combustion and regeneration
Australia	CSIRO	9" diam.	1	2-7	750-1850	67-68/Combustion
Illinois	Argonne National Lab.	6" diam.	1	3-7	1400-1700	68-75/Combustion, regeneration
		3" and 6" diam.	8	2-5	1450-1650	
New Jersey	EXXON R&D	3" diam.	1	2-4	1500-2000	68-77/Combustion, regeneration
		3" diam.	10	5	1500-2000	
		12.5" and 5" diam.	10	5-10	1700-2000	
New Jersey	Foster-Wheeler	18" diam.	1	--	---	Operating/Combustion cold flow model
		6' x 6'; 5" x 21"	1	4-12	70	
California	Combustion Power	20" diam.	1	4-10	1400-1800	73-77/Combustion (adiabatic)
		7" diam.	4	5-10	1400-1800	hot gas cleaning, additives
		6" diam.	5	5-10	1400-1800	74-75/Combustion
Germany	Bergbau-Forschung	16" x 31"	1	4-8	1470-1560	74-75/Combustion
Germany	Lurgi	5" diam.	1	>10	2000-2200	
		40" diam.	1	>10	2000-2200	62-70/Fast bed combustion of oil for Al_2O_3 production
		12' 5" diam.	1	>10	2000-2200	
Ohio,	Battelle-Columbus Laboratories	6" diam.	1	1-5	1400-2500	49/Bloating
		24" diam.	1	2-10	1400-1700	60-77/Combustion
		6" diam.	1	3-30	1400-1700	74-77/Combustion
		24" diam.	8	10	2100	75/Combustion (gasification)
		35" diam.	6	10	2100	"
United Kingdom	Woodall-Duckham	10' x 10'	1			75/Modified Conventional stoker
	Sheffield University	12" x 12"	1	2-4	1382-1632	75-16/Combustion

Table 3.1-6 - Fluidized-Bed Combustion Facilities (contin).

Location	Organization	Combustion and Regenerator Size	Pressure atm	Gas Veloc.	Temp., F	Status/Purpose
Conn.	Combustion	NA	1	NA	70	76-77/
	Engineering	NA	1	NA	NA	77-77/
Mass.	MIT has a facility	forthcoming end of 1977				
Minn.	Fluidyne Eng.	18 in.^{2}	1			76-77/
	Corp.	40"X64"	1			77-77/
N.J.	Foster-Wheeler	72"X72"	1	4-12	70	NA
New York	General Electric	1ft^2	1	NA	70	75-77/
N.Dakota	Grand Forks Energy Research Center	6"diam.	1	NA	NA	76-77/
W.Va.	Morgantown Energy Research	(2)18"diam.	1	NA	1600	76-77/
	Center	6ft^2	1	NA	70	77-77/
Oregon	Oregon State University	10ft^2	1	NA	70	75-77/
Penn.	Pittsburgh Energy Research	1.48"diam.	1	8-8.2	1750	75-77/
	Center	1.48"diam.	1	1.84-2	1620	75-77/
Virginia	University of Virginia	3.5-8.5	1	NA	70	76-77/

experimental units to pilot plants is shown in Table 3.1-7. On the international scene, Great Britian is pushing an advanced program. As of 1970, its projections are shown in Figure 3.1-8. Table 3.1-8 lists experimental studies that have recently concluded or are ongoing.

Table 3.1-7

Approximate Schedule for DOE Units (EPA, 1977).

Unit Size and/or Designation[a]	Contractor and/or Location	Approximate Starting Dates[b]		
		Design	Construction	Operation
0.5 MWe PDU AFBC	Pope, Evans, & Robbins Alexandria, VA	--	—	In operation
1.0 MWe PDU PFBC[c]	Combustion Power Co. Menlo Park, CA	--	—	In operation
3.0 MWe CTIU PFBC	Argonne National Lab. Argonne, IL	Mid '76	Mid '77	Late '78
30 MWe CTIU PFBC	Internatl. Energy Agcy. Grimesthorpe, U.K.	Late '76	Mid '77	Late '79
6.0 MWe CTIU AFBC	Morgantown Energy Res. Center Morgantown, WV	Late '76	Late '77	Late '79
13.0 MWe Pilot Plant, PFBC[d]	Curtis-Wright Woodridge, NJ	Late '76	Late '77	Late '79
30.0 MWe Pilot Plant, AFBC	Pope, Evans, & Robbins Rivesville, WV	—	In Progress	Sept., '76
MIUS PDU AFBC[e]	Oak Ridge National Lab. Oak Ridge, TN	In Progress	Late '76	Late '77
MIUS Pilot Plant AFBC[e]	Oak Ridge National Lab. Oak Ridge, TN	Mid '78	Late '80	Mid '81
Industrial and Institutional Applications[f]	Various[f]	Late '76[g]	Late '77[g]	Late '79[g]

(a) PDU is process development unit (1-10 tons coal/day), CTIU is component test and integration unit (10-100 tons coal/day), pilot plant is 100-1000 tons coal/day, AFBC is atmospheric pressure and PFBC is pressurized fluidized-bed combustor, MIUS is modular integrated utility system. All are boilers except where noted.

(b) Approximate schedule as of May, 1976.

(c) Flue gas drives turbine. No heat transfer surfaces.

(d) Flue gas mixed with air heated in tubes to drive turbine.

(e) Air heated in tubes to drive turbine and provide heat and cooling.

(f) Aerojet Energy/Ideal Basic Industries to produce combustion gas for cement kiln; Fluidyne Engineering/Owatonna Tool for hot process air heater; Battelle Memorial Institute/Fluidized Combustion, Combustion Engineering/Great Lakes Naval Training Center, Dow Chemical/Babcock & Wilcox, Zurn Industries/Burns & Roe, and Georgetown University/Fluidized Combustion for boilers; Exxon for crude oil still.

(g) Earliest starting date of any of the projects.

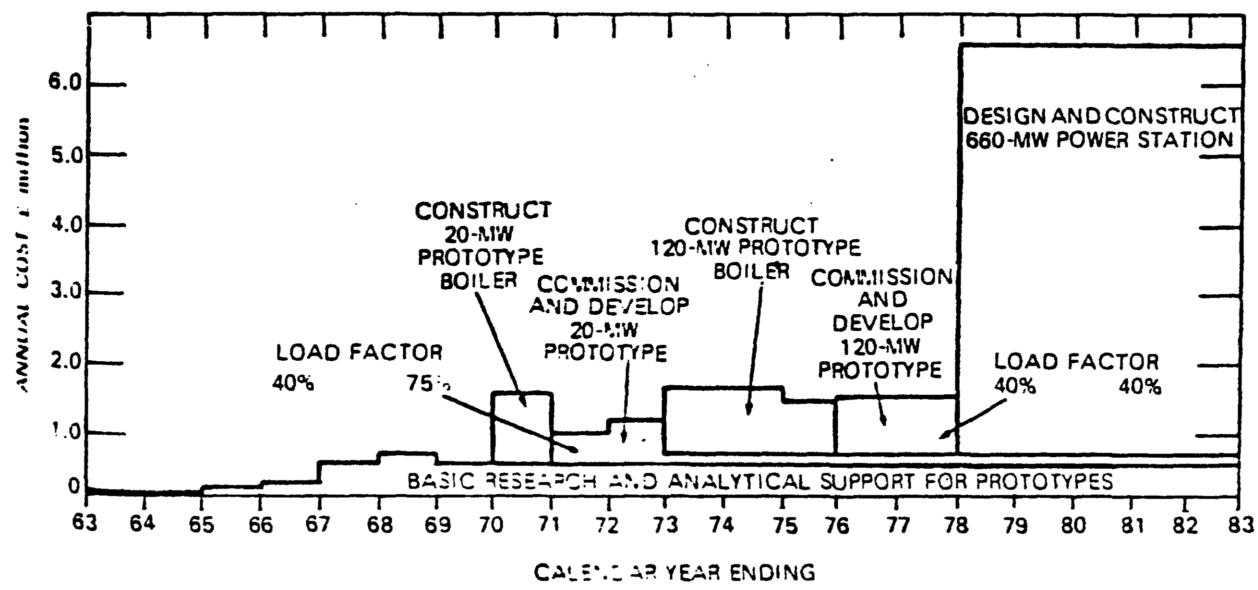


Figure 3.1-8

Cost and Time Scale of Developing Fluidised-Bed Combustion for Central Power Station Boilers (present day prices). (EPA, 1970).

Table 3.1-8 RECENT AND ONGOING EXPERIMENTAL FBC STUDIES

Aerotherm/Acurex:
- detailed emissions analysis of CPC filter (for EPA)

Agricultural Research Service:
- evaluation of FBC solid waste use (for DOE)

Argonne National Lab:
- testing of 6" pressurized combustor
- 4" pressurized sorbent regenerator (EPA/DOE)
- SO_x control
- sorbent regeneration (EPA/DOE)
- NO_x formation and control (EPA/DOE)
- particulate characterization and control (EPA/DOE)
- trace metal and hydrocarbon emissions (EPA/DOE)
- engineering support studies
- economic analysis
- combustion efficiency
- process control requirements (for DOE)

Babcock and Wilcox Co.:
- industrial application AFBC (DOE)
- effluent assessment
- demonstration plant (DOE/TVA), (EPRI)
- effect of sorbent particle size (EPRI)

Battelle Columbus Labs:
- multi-solid FBC plant (DOE)
- emissions analysis of atmospheric FBC (EPA)
- atm-24" agglomerating FBC to be built
- materials for corrosion/erosion conditions (EPRI)
- heat exchange materials (DOE)

Bergbau-Forschung:
- atmospheric FBC
- plans 8-atm FBC-15MW

Bharat Heavy Electricals:
- FBC development program

Bradford University:
- cold modeling of fluid mechanics of fines (EPRI)

British Coal Utilization Research Association:
- emissions analysis of 2'x3' pressurized unit
- atmospheric unit of utility size
- high temperature operations

Brookhaven National Laboratory:
- regeneration of $CaSO_4$ using SiO_2

Combustion Engineering Inc.:
- industrial FBC development (DOE)
- atmospheric FBC demonstration plant (TVA)

Combustion Power Company:
- turbine corrosion and erosion
- moving bed filter for hot gas cleanup (DOE)
- detailed emissions analysis (EPA)
- municipal waste combustion

Combustion Systems (formerly NCB, BP, & NRDC):
- FBC boiler construction (DOE/TVA)
- corrosion/erosion effects (EPRI)
- comprehensive analysis of emissions from pressurized FBC (EPA)

Commonwealth Scientific & Ind. Research Organization:
- heat transfer experiments
- burning Australian coals

Consolidation Coal Company:
- desulfurization with sorbents
- regeneration of dolomite

Construction Engineering Research Laboratory, Department of Army:
- fine particle precipitating in AFBC (DOE)

Curtis- Wright
- forthcoming pressurized unit in 1980 (DOE)

DOE
- commercialization potential at Rivesville and Morgantown units

EPA:
- limestone beds for SO_x control
- low temperatures
- sampling and analytic test rig, atmospheric pressure
- emissions analysis
- alternative add-on control devices (EPA)

Exxon Research & Engineering Company:
- emissions analysis of pressurized bench-scale (EPA)
- 8" pressurized sorbent regenerator
- emissions analysis of pressurized Miniplant - .65 MW (EPA)
- SO_x control
- sorbent regeneration (EPA)
- NO_x formation and control
- particulate characterization and control
- trace metal and hydrocarbon emissions
- deep bed combustion

Fluidyne Engineering Corp:
- industrial FBC (DOE)

Foster-Wheeler:
- demonstration plant AFBC (DOE/TVA)
- coal feeder development (DOE)
- cold test modeling of Rivesville plant

Fuel Research Institute:
- two-stage combustion of high ash coal
- solid and liquid fuel interchangeability
- retrofit of old boilers

General Electric:
- fluid dynamics and heat transfer using cold beds (EPRI)

Georgetown University:
- industrial FBC (DOE)

Grand Forks Energy Research Center:
- precipitation tests (DOE)
- alternative SO_2 control methods (DOE)

Ingersoll-Rand:
- dry coal screw development (DOE)

International Energy Agency:
- design, construction, and operation of FBC (DOE)

Jet Propulsion Laboratory:
- coal pump development (DOE)

Kennedy Van Saun:
- coal grinding and feed preparation (DOE)

Lehigh University
- centrifugal FBC (DOE)

Lockheed Missles and Space Company Inc.:
- candidates for coal feeders (DOE)
- corrosion chemistry (EPRI)

Lurgi Gesellschaft:
- FBC combustion of low grade fuels

Mechanical Technology Inc.:
- centrifuge gas cleaning (DOE)

Midwest Research Institute:
- sampling and characterization of AFBC and PFBC gaseous species (DOE)

John L. Minnick:
- field testing and theoretical evaluations of FBC waste uses (DOE)

MIT Energy Laboratory:
- heat transfer and corrosion (DOE)

Morgantown Energy Research Center:
- AFBC bench scale studies (DOE)
- AFBC fuel possibilities (DOE)
- fueling and slagging (DOE)

National Coal Board:
- utility sized atmospheric unit
- pressurized combined cycle unit

National Research Development Corporation:
- industrial and utility FBC applications

New York University:
- fluid dynamic and heat exchanger interrelationships (DOE)

Oak Ridge National Laboratory:
- evaluation of MIUS applications (DOE)

Ohio State University:
- corrosion chemistry (EPRI)

Oregon State University:
- cold modeling of heat exchangers (EPRI)

Pope, Evans and Robbins:
- modular cells with water walls
- carbon burnup cells
- once-through sulfur removal system
- limestone regeneration
- salt additions
- Rivesville Station - 30 MW (DOE)
- coal feeding systems
- distributor designs
- fly-ash sizes (DOE)

Rice University:
- heat transfer in counter-current FBC

Societe Anonyme Activit & Babcock-Atlantique:
- agglomeration of ash in 25-MW plant

Tennessee Valley Authority:
- characterization of solid and liquid wastes
- laboratory and field studies of solids leaching and solids degeneration (EPA)
- solid waste treatment
- laboratory studies on potential for marketable products from wastes

TRW Inc.:
- detailed emissions analysis of CPC filter (EPA)

U.S. Bureau of Mines:
- use of various American coals
- ash as bed material

University of Idaho:
- bubble behavior in scale-up of FBC (DOE)

University of Illinois:
- cold model of FBC (DOE)

University of Maryland:
- chemical additives effects on SO_2 removal (EPRI)

University of Virginia:
- gas solids interactions in FBC (DOE)

Virginia Agricult. Exper. Station:
- use of wastes in agricultural projects

Virginia Polytechnic Institute and State University:
- solid waste use for crops (DOE)

Washington State University:
- fate and behavior of fuel sulfur (DOE)

Western Michigan University:
- mechanisms of NO_x formation (DOE)

Westinghouse:
- laboratory scale studies
- SO_x control
- sorbent regeneration (EPRI)
- NO_x formation and control
- particulate characterization and control
- trace metals and hydrocarbons
- turbine blades for FBC

Woodall-Duckham:
- commercial operation of large-scale boiler
- retrofit of old boilers

Analytic Studies

The paper studies in progress include a wide range of modeling, evaluation, and fundamental research. The most comprehensive examples are being undertaken by Exxon and by Battelle. Other studies are listed in Table 3.1-9.

Table 3.1-9 RECENT AND ONGOING ANALYTIC FBC STUDIES

Babcock and Wilcox Ltd.:
- conceptual design studies
- literature survey and correlation of data AFBC (EPRI)

Battelle Columbus Labs:
- environmental assessment including emissions characterization, control, and impacts, state-of-art, R & D plan

Burns and Roe:
- conceptual design of AFBC (DOE)

Coal Research Establishment:
- atmospheric pressure combustors

Commonwealth Scientific & Indu. Research Organization:
- experimental programs

Consolidation Coal Company:
- experimental programs

Dow Chemical:
- scale up of unit sizes and effects on emissions (EPA)

EPA:
- comprehensive program on environmental characterization

EPRI:
- optimize heat transfer
- corrosion and erosion characteristics
- manufacturer's evaluation of data
- general program on technical development

Exxon Research and Engineering Company:
- energy, economic and environmental assessment of FBC industrial boilers (DOE/EPA)

Foster-Wheeler:
- conceptual designs - 800MW
- Rivesville design guidance

GCA/Technology Division:
- identification of new pollutants (EPA)
- control technology possibilities

General Electric:
- technical and economic assessment

Gilbert Associates:
- technical and economic study of FBC (DOE)

John Thompson Ltd.:
- conceptual design studies

Arthur G. McKee and Company:
- technical assistance on industrial FBC (DOE)

MIT:
- engineering support studies
- modeling and data base of FBC (DOE)

Mitre Corporation:
- manuals of FBC process variations indicating alternative sampling and analytic procedures (EPA)
- engineering support studies

NASA:
- technical and economic assessment, ECAS (DOE/NSF/NASA)

National Research Development Corp.:
- experimental programs

Oak Ridge National Lab:
- design studies and vendor surveys (DOE)

Preece, Cardew & Rider Ltd.:
- conceptual design studies

Ralph Stone & Company:
- solid and liquid waste disposal (EPA)

SATR:
- comprehensive FBC analysis (EPA)

Stone and Webster:
- conceptual design of AFBC (DOE)

Tennessee Valley Authority:
- characterization of solid and liquid wastes (EPA)
- marketing potential of wastes (DOE)
- designs and cost comparisons of AFBC, PFBC, and conventional plant with FGD (EPA)

U.S. Bureau of Mines:
- experimental programs

U.S. Department of Transportation:
- solid waste use in soil modification (DOE)

U.S. Office of Coal Research:
- experimental programs

Westinghouse Research Lab:
- Technical and economic assessment
- conceptual designs of atmospheric and pressurized boilers
- alternative FBC configurations
- environmental assessment of FBC solid waste (EPA)

3.2 Basis for Comparison

Fluidization is a conventional technique in the chemical process industries for compact and efficient heat and mass transfer. The newer concept of coal combustion in a fluidized bed makes possible rapid energy release from the fuel and efficient heat transfer to the working fluid. A fluidized bed combustor is a column of dense coal, lime, and ash particles that are suspended in an (usually) upward flowing air stream. The velocity of this upward combustion air, 2 to 15 ft/sec, sets the particles in a homogeneous turbulent motion, that resembles a boiling fluid, which enables

(1) high volumetric flow through rates for the air stream,
(2) very high heat transfer coefficients, partly due to reasonably uniform temperature distributions, and
(3) relatively low combustion temperatures.

Fluidized bed combustion can result in 25 times the (per unit volume per time) heat release rates. Heat transfer from the particles and combustion air to the heat transfer tubes placed inside the combustor can be 5 to 6 times that in conventional pulverized coal-fired boilers (per unit area per time) (Rao, 1975). The low combustion temperatures (1400 - 1900° F versus 3000° F for conventional power plants) have several advantages:

(1) They maximize the capture of SO_2 by the limestone or dolomite in the bed, thus forming solid calcium sulfate which is collected as spent bed material;

(2) They minimize the conversion of atmospheric nitrogen into NO_x, thus considerably reducing NO_x emissions; and

(3) They minimize klinker problems and may reduce trace metal emissions due to temperatures being below slagging and ash constituent volatilization points.

The principal configurations that can be used to categorize the different fluidized bed combustion designs include:

(1) atmospheric fluidized bed,
(2) pressurized fluidized bed, and
(3) liquid metal topping fluidized bed.

In atmospheric configurations the combustion chamber is at near-atmospheric pressure. Power is generated by a steam turbine. A pressurized system operates between 5 and 20 atmospheres, although 8 to 10 atmospheres seems optimum, and includes a gas turbine as well as the steam turbine. The gas turbine operates on the high pressure hot combustion gases and, in addition to creating extra electric power, drives the compressor to pressurize new combustion air. The primary motivation for using pressurized systems is the potential for smaller equipment size for the same heat output. In some "closed cycle" systems, pressurized air is used as a working fluid, thus there is no steam turbine. Liquid metal topping cycles, usually potassium, are also being considered in fluidized bed configurations. Although there are several other designs, one that is occasionally considered is the adiabatic combustor. In these combustors the fluidizing air throughout is greatly increased, so that all of the heat of combustion is carried by these gases. Thus, no bed submerged heat transfer tubes are used. The adiabatic combustor gases expand through a gas turbine and waste heat is recovered in a boiler which drives a steam turbine. Figure 3.2-1 shows a general comparison of sizes and components of comparable FBC technologies.

The next section lists some of the operating and design parameters that are useful variables for modeling cycle efficiencies and emissions. The following sections describe the more common FBC designs. Since this is in no way meant to be a text, these descriptions have been kept very brief.

3.2.1. Operating and Design Parameters

There is some merit in treating the results from each different experimental rig as incomparable with other results. The insight that can be gained by such a procedure is, however, then limited to the particular parametric investigations that have been performed at any one facility. If there is to be comparability, then a common set of operating and design parameters must be defined and collected for the various sets of experiments. An exhaustive list prepared at the M.I.T. Energy Lab for a DOE sponsored FBC data base is listed here in Table 3.2.1-1.

Table 3.2-1

General Data Per Module

Heat Input Systems - Furnaces and Heat Exchangers (General Electric, 1976).

	ATMOSPHERIC FLUIDIZED BED		PRESSURIZED FLUIDIZED BED		HEAT RECOVERY
CYCLE	ADVANCED STEAM	CLOSED HELIUM TURBINE	ADVANCED STEAM	POTASSUM TOPPING	OPEN CYCLE MHD
FURNACE ARRANGEMENT	VERTICAL TOWER (7 BED)	HORIZONTAL BOX TYPE (8 BED)	VERTICAL TOWER (7 BED)	HORIZONTAL BARRELS (7 BED)	RADIANT AND SECONDARY
PLAN	13' x 34'	14' x 167'	13' ϕ (8.5 x 8.5)	6-13 x 30 TL 1-13 x 14 TL	{100 x 115 {100 x 80
HEIGHT	178'	{26 {24	135'	13' DIAM	{150 {80
WEIGHT (TONS)	1457	1838	502	1361	8660
HEAT EXCHANGERS	—	AIR PREHEATERS HELIUM — RECUPERATORS — PRECOOLERS ORGANIC — BOILER — CONDENSER	FEEDWATER ECONOMIZERS	POTASSIUM CONDENSER — STEAM GENERATOR ECONOMIZER	FEEDWATER ECONOMIZER
APPROX. MW_e PER MODULE	~220	~129	~226	~217	~960
NO. MODULES REQUIRED	4	4	4	4	

Table 3.2.1-1 FBC Data Base Categories (J.F. Louis, S.E. Tung, 1977)

Source (reference or site)

Bed Design
- Geometry
- Rectangular
    - Length (meters)
    - width (meters)
  - Circular Diameter (meters)
  - Static Bed Height
  - Bed Height at Min. Fluidization (meters)
  - Bed Height at Oper. Cond. (meters)
    - Free Board Height (meters)

Inlet Gas Conditions
- Species Present
  - Composition (mol basis)
  - Molecular Weight
  - Temperature (Kelvin)
  - Pressure (Pascals)
  - Molar Flow Rate (KG-mole/sec)
  - Velocity (M/sec)
  - Density (KG-mole/meter^3)
  - Viscosity (Centipoise)

Sampling Point Conditions
- Height above Dist. (meter)
- Length or Radial Direction (meter)
- Width or Theta Direction (meter or deg)
- Gas or Solid Species Present
    - Composition
    - Temperature (Kelvin)
    - Pressure (Pascals)
    - Molecular Weight (Ks/Kg mole)

Fluidization Characteristics at Sampling Point
- Gas Velocity (Mag = dir)(meter/sec)
- Gas Viscosity (Centipoise)
- Gas Density (KG-mole/meter^3)
- Solid Density (Kg/meter^3)
- Mean Particle Diameter (meter)
- Particle Size Dist. (meters)
- Min. Fluidization Velocity (meters/sec)
- Voildage at Min. Fluidization
- Observed Voidage
- Fluidization Region (turbulent or bubbling)
- Mean Bubble Volume (meters)
- Bubble Height (meter)
- Bubble Width (meter)
- Bubble Frequency (sec^{-1})
- Bubble Voidage
- Emulsion Voidage

- Coal Feed
  - Coal Composition wt. Basis
    - C
    - H
    - O
    - N
    - S
    - ASH
    - H_2O
    - Vol. Frac.
  - Coal Type
    - Lower Heating Value (kcal/KG-mole)
    - Feed Rate (KG/sec)
    - Particle Size Distribution (meter)
  - Reacted Coal
    - Sampling Point
      - Heigh above Dist. (meter)
      - Length or Radial Coordinate (meter)
      - Width or Theta Coordinate (meter or deg)
    - Temperature Gas (Kelvin)
    - Pressure (Pascals)
    - Gas Composition Mole Basis
      - O^2
      - HC
      - CO_2
      - H_2O
      - H_2
      - N_2
      - SO_2
      - NO
      - NO_2
    - Temperature Solids (Kelvin)
    - Mean Coal Particle Size (meter)
    - Coal Particle Size Distribution (meter)
    - Mean Ash Particle Size (meter)
    - Ash Particle Size Distribution (meter)
    - Reacted Coal Composition Wt. Basis
      - C
      - H
      - O
      - N
      - S
      - ASH
      - H_2O
      - Vol. Frac.
    - Mean Residence Time (sec)
    - Residence Time Distribution

- Material of Const.
- Outside Diameter (meter)
- Inside Diameter (meter)
- Pitch
- Spacing
- Aligment
- No. of Tubes
- Age of Tube (Time of Use)(hr)
- Sampling Point
  - Height above Dist. (meter)
  - Length or Radial Direction (meter)
  - Width or Theta Direction (meter or deg)
- Tube Wall Mean Temp. (Kelvin)
- Tube Wall Temp. Dist. (Kelvin)
- Local Bed Temp. (Kelvin)
- Total Surface Area (meter^2)
- Heat Transfer Rate (Joule/sec)
- Heat Transfer Coefficient (Joule/sec·M)
- Working Fluid (steam, etc.)
- Mass Flow Rate (KG/sec)
- Inlet Cond. of Working Fluid
  - Temp. (Kelvin)
  - Pressure (Pascals)
  - Quality
- Outlet Cond. of Working Fluid
  - Temp. (Kelvin)
  - Pressure (Pascals)
  - Quality

Acceptor Feed

- Type of Acceptor
- Origin of Acceptor
- Acceptor Composition $CaO\cdot(CO_2)p\cdot(MgO(CO_2)q)R$
  - P
  - Q
  - R
- Mass Feed Rate (KG/sec)
- Mean Particle Size (meter)
- Particle Size Dist. (meter)
- Density Bulk (KG-mole/meter^3)
- Pore Size Distribution (meter)
- Mean Pore Size (meter)
- Pore Fraction
- Surface Area (meter^2)
- Percent Sulfated
- Number of Regenerations
- Regeneration Conditions
  - Temp. (Kelvin)
  - Pressure (Pascals)
  - Res. Time (sec)
- Overall Ca/S Ratio in Feed
- Temperature (Kelvin)

- Reacted Acceptor
  - Sampling Point
    - Height above Dist. (meter)
    - Length or Radial Direction (meter)
    - Width or Theta Direction (meter or theta)
  - Acceptor Specie
  - Molecular Weight
  - Temperature (Kelvin)
  - Velocity (mag + dir)(meter/sec)
  - Mean Particle Diameter
  - Particle Size Dist. (meter)
  - Min. Fluidization Velocity (meter/sec)
  - Density Bulk (KG-mole/meter^3)
  - Density True (KG-mole/meter^3)
  - Pore Size Distribution (meter)
  - Mean Pore Size (meter)
  - Pore Fraction
  - Surface Area (meter^2)
  - Percent Sulfated
  - Mean Res. Time (sec)
  - Res. Time Distribution (sec)

To collect and correlate this number of variables is well beyond this small, uncomputerized effort. The intent of this effort has been, therefore, to isolate the several dominant variables and make initial correlations between these and the performance measures of efficiency and emissions. The several dominant variables identified and used in the empirical models in this report are listed in Table 3.2.1-2.

Table 3.2.1-2. Fluidized Bed Operating and Design Variables

Bed Temperature
Static Bed Height
Superficial Velocity
Calcium to Sulfur Ratio in Bed
Combustible Losses
Fuel Source and Size
Fuel Constituents
Sorbent Source and Size
Pressure
Excess Air
Sulfur Absorbent Regeneration
Number and Temperature of Reheats
Addition of Salt
Secondary Air Injection
Steadiness of Coal Feed
Types of Particulate Controls

Although there are many possible performance measures, (see Table 3.2.1-3), the efficiencies and emissions are the only indicators of desirability modeled in this report.

Table 3.2.1-3. Fluidized Bed Combustor Indicators of Operating Effectiveness

Overall Energy Efficiency
Combustion Efficiency
Emissions
Heat Transfer
Corrosion and Erosion
Fouling
Combustion Stability
Waste Solids
Agglomeration
Reliability
Heat Release
Control and Turndown Ability
Startup Ability

3.2.2 Atmospheric FBC Designs

The general schematic of the atmospheric FBC configuration is shown in Figure 3.2.2-1. The water/steam cycle usually includes:

(1) a feedwater pump sending the water to
(2) an economizer and evaporator that heat the feedwater using the flue gas heat and combustion air heat,
(3) a first heating in the tubes immersed in the bed,
(4) the steam turbine,
(5) at least one reheat back in the bed,
(6) a second trip through the turbine, and
(7) the condensation

The air cycle includes coming in through:

(1) forced draft fans, then through the
(2) air preheater, then up through the
(3) fluidized bed,
(4) through the evaporator, then
(5) supplying heat to the air preheater
(6) through particulate removal devices,
(7) through the economizer,
(8) then through an induced draft fan, and
(9) up the stack.

Coal and sorbent enter into the bed at the feedpoints. Coal ash generally leaves the bed with the combustion air and is collected in the precipitators. The inburned carbon in this ash is either recycled to the bed or burnt in a separate carbon burning cell, as shown in Figure 3.2.2-2. The sorbent leaves the bed as spent material, and can either be regenerated and cycled back into the bed, or can be disposed either directly or after some treatment. Tables 3.2.2-1 and -2 show the different atmospheric FBC's used in the ECAS study comparing economics and efficiencies.

The operational configurations that are pushing the sizes of atmospheric FBC's up toward commercial sizes (about 220 MWe) are the Morgantown 6 MWe unit (see Figure 3.2.2-3), and the Rivesville 30 MWe unit (see Figure 3.2.2-4).

A relatively new configuration is the Battelle Multi-Solids FBC (see Figure 3.2.2-5). The MS-FBC process consists of two beds: a dense or conventional bed of high specific gravity and a superimposed or entrained bed. The entrained bed circulates through the dense bed picking up the heat of combustion. All of the heat exchange surfaces are contacted to the entrained bed. The perceived advantages include:

(1) much higher fluidizing velocities, 30-40 ft/sec,
(2) excellent limestone utilization, and
(3) much better response and control characteristics to changes in load.

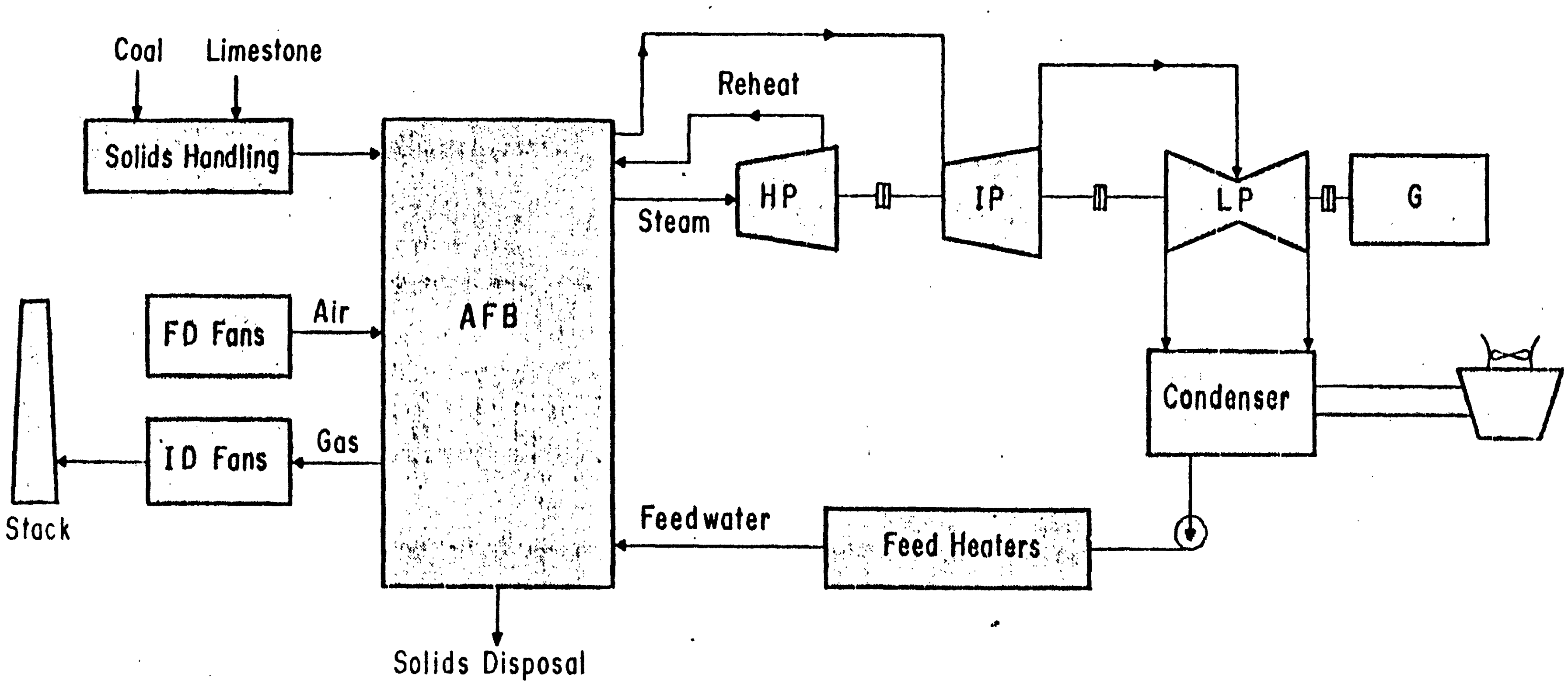


Figure 3.2.2-1

Advanced Steam Cycle-Atmospheric FBC (General Electric, 1976).

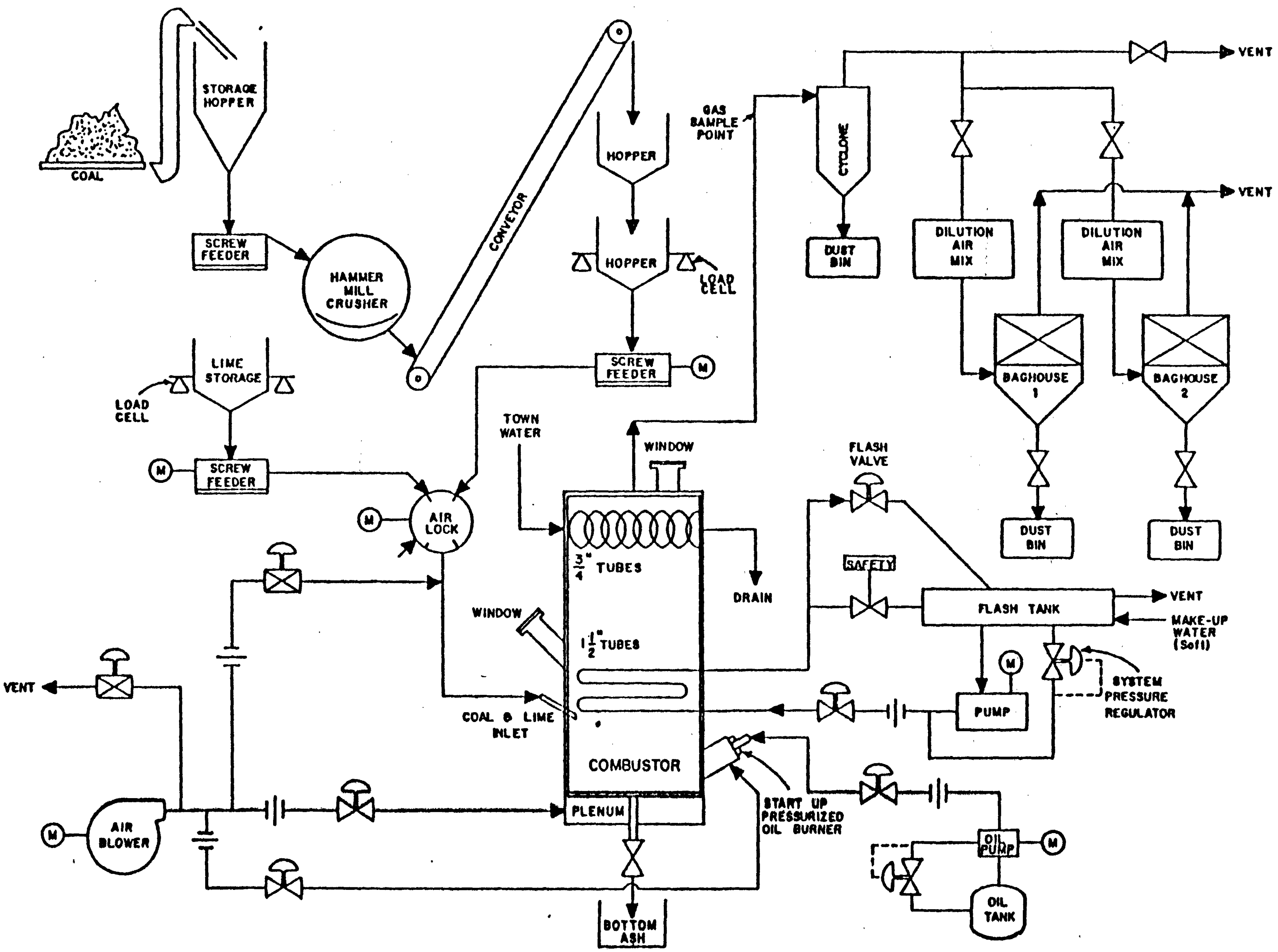


Figure 3.2.2-2

Flow Diagram of 20" x 20" Fluid Bed Pilot Plant (Gamble, 1977).

Table 3.2.2-1

Surfacing Data

Advanced Steam Cycle - Atmospheric Fluidized Bed (General Electric, 1976).

	MAIN BED CELLS	CARBON BURNUP CELLS
NUMBER	6	1
BED TEMP.	1550	2000
GAS EXIT TEMP. (°F)	730	730
% DUTY	90	10
EXCESS AIR	20%	3[illegible]%
DIMENSIONS:		
BED — PLAN	12 x 34	12 x 34
— HEIGHT (FEET)	4	4
SUPERFICIAL VELOCITY (FT/SEC)	10	9
HEAT TRANSFER COEFFICIENT		
— BED	40	40
— CONVECTION (Btu/HR FT² °F)	13	13

Table 3.2.2-2

Surfacing Data

Closed Gas Turbine Cycle - Atmospheric Fluidized Bed (General Electric, 1976).

	UPPER - 2ND STAGE MAIN BED CELLS	LOWER - 1ST STAGE HI-TEMPERATURE (AND CARBON BURNUP) BED CELLS
NUMBER	4	4
BED TEMP.	1550	2000
GAS EXIT TEMP. (°F)	1100	1550
% DUTY	54	46
EXCESS AIR	21%	22 +%
DIMENSIONS:		
BED — PLAN	11 x 40	9 x 40
— HEIGHT (FEET)	4	4-
SUPERFICIAL VELOCITY (FT/SEC)	8.1	4.4
O/A HEAT TRANSFER COEFFICIENT		
— BED	39	43
— CONVECTION (Btu/HR FT² °F)	10	7

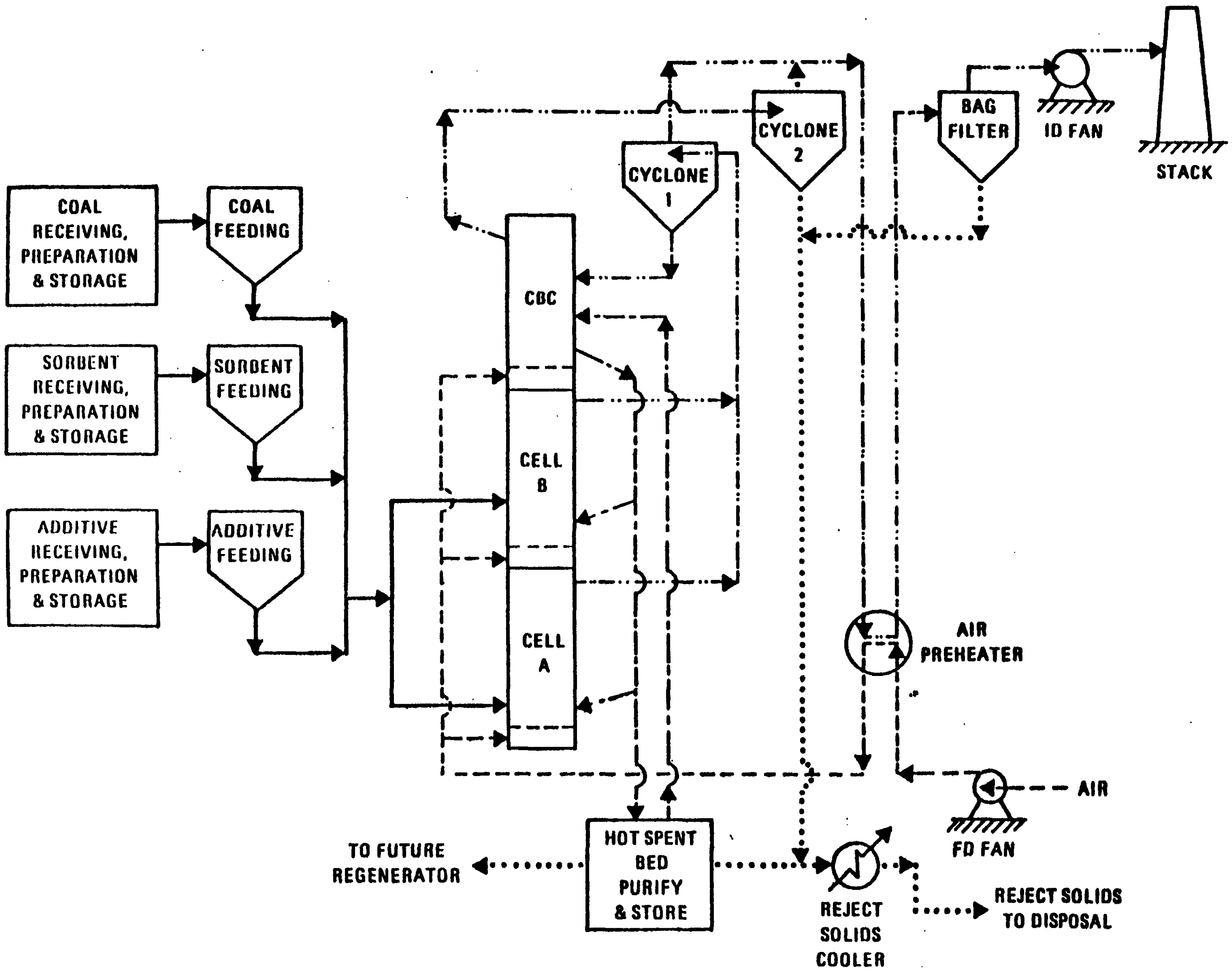


Figure 3.2.2-3

Atmospheric Fluidized Bed Component Test and Integration Unit (AFB/CTIU).

(Burns and Roe, 1977).

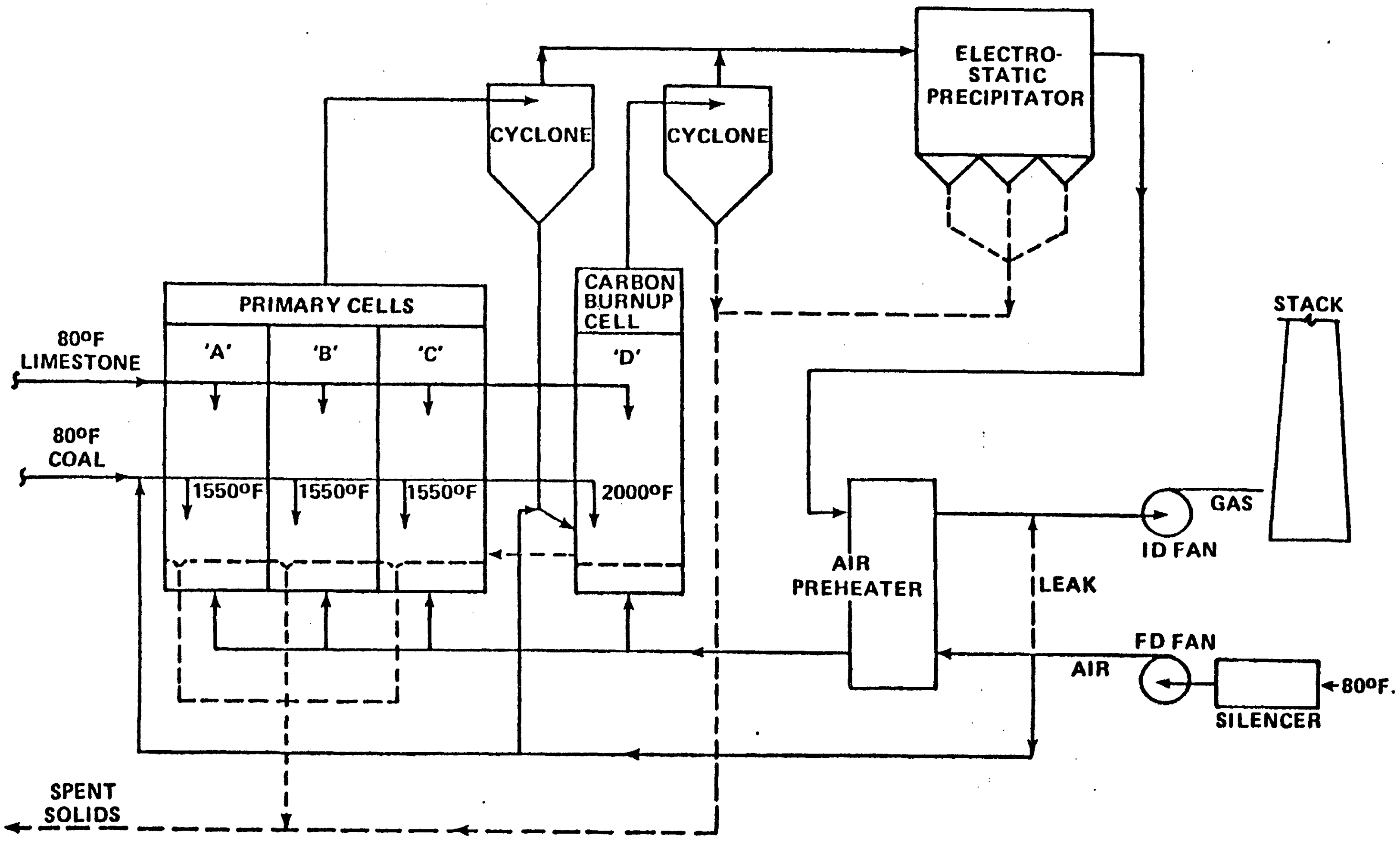


Figure 3.2.2-4

Fluidized Bed Boiler, 30-MWe (Burns and Roe, 1977).

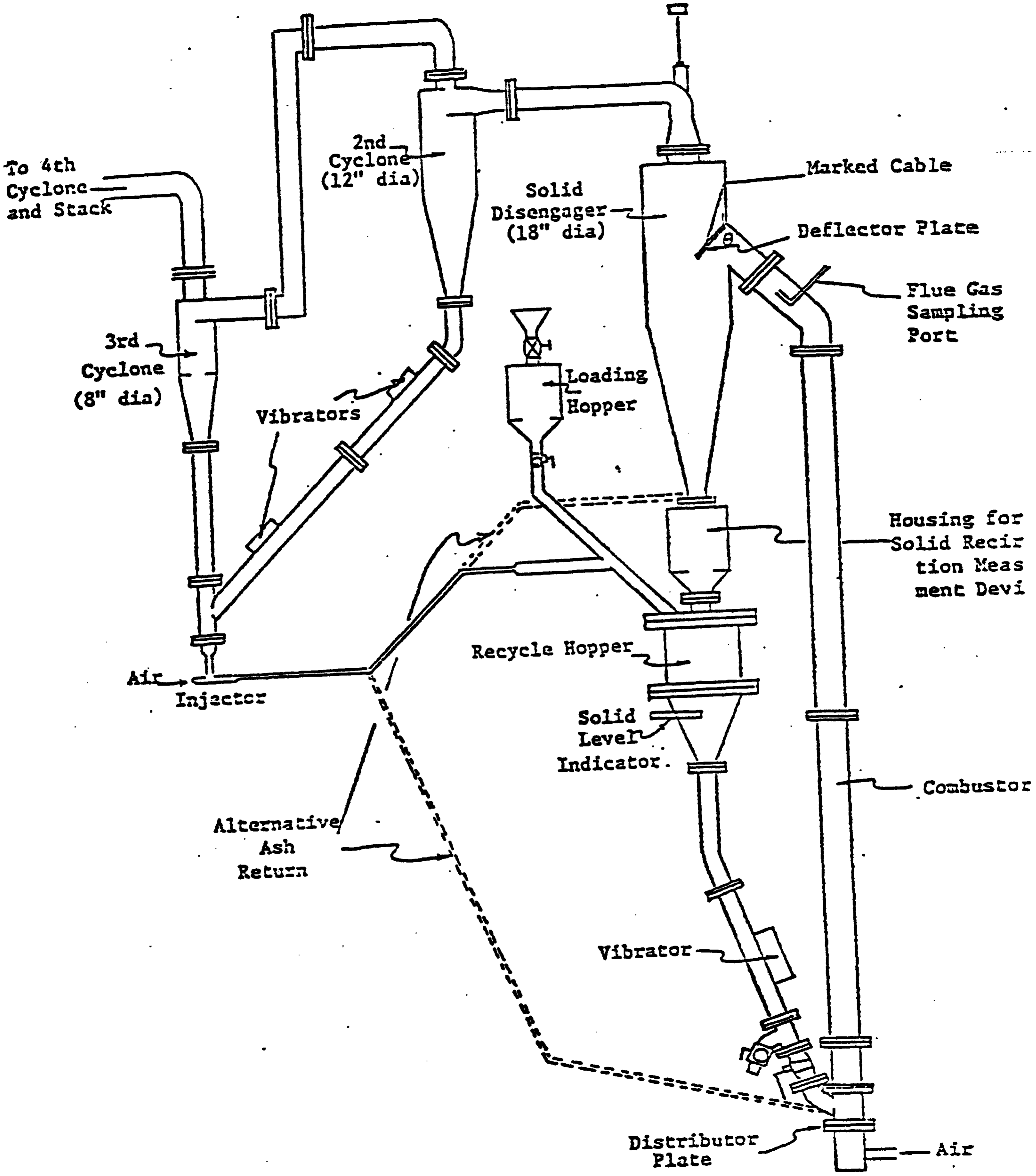


Figure 3.2.2-5

Schematic Diagram of the 6-inch MS-FBC Combustor (Vaughan, et al., 1977).

3.2.3 Pressurized FBC Designs

The general schematic for the combined gas turbine/steam cycle pressurized FBC configuration is shown in Figure 3.2.3-1. The water/steam usually travels through the same combination of components as it does in the atmospheric configuration. The combustion air cycle is different for the pressurized system:

(1) the air compressor operated in conjunction with the gas turbine pressurizes the air and sends it to,

(2) the fluidized bed, from which it must go to

(3) some combination of "hot side" particulate collectors to protect the blades in the

(4) gas turbine from which the gases go through

(5) an economizer, and then up the

(6) stack.

A schematic of a pressurized FBC test rig is shown in Figure 3.2.3-2.

There are a number of other configurations that can be built around the pressurized FBC central theme. In the pressurized adiabatic FBC, as previously described, heat transfer tubes are not used in the fluidized bed or the combustion gases above the bed (see Figure 3.2.3-3). Instead, the bed temperature is controlled by sending 200 to 500 percent excess air through the bed and into a gas turbine. This arrangement is that used by Combustion Power Co. in their CPU-400 facility.

In the pressurized air tube FBC the bed temperature is controlled by heat transfer tubes but the working medium is air instead of steam/water. A small test of this concept is being operated by Oak Ridge National Lab and is called the MIUS, Modular Integrated Utility System.

3.2.4. Potassium Topping FBC Designs

Although cesium has been considered, potassium is likely to be the liquid metal working fluid of the metal topping cycle FBC. A schematic of this system is shown in Figure 3.2.4-1. Except for the topping cycle, this configuration is very much like the gas turbine/steam cycle pressurized FBC. An alternative configuration makes use of the availability of heated process air and steam to operate a fluidized bed gasification subsystem (See Figures 3.2.4-2 and -3). By providing clean gaseous fuel to the combustion chamber, the need for "hot side" particulate removal is eliminated.

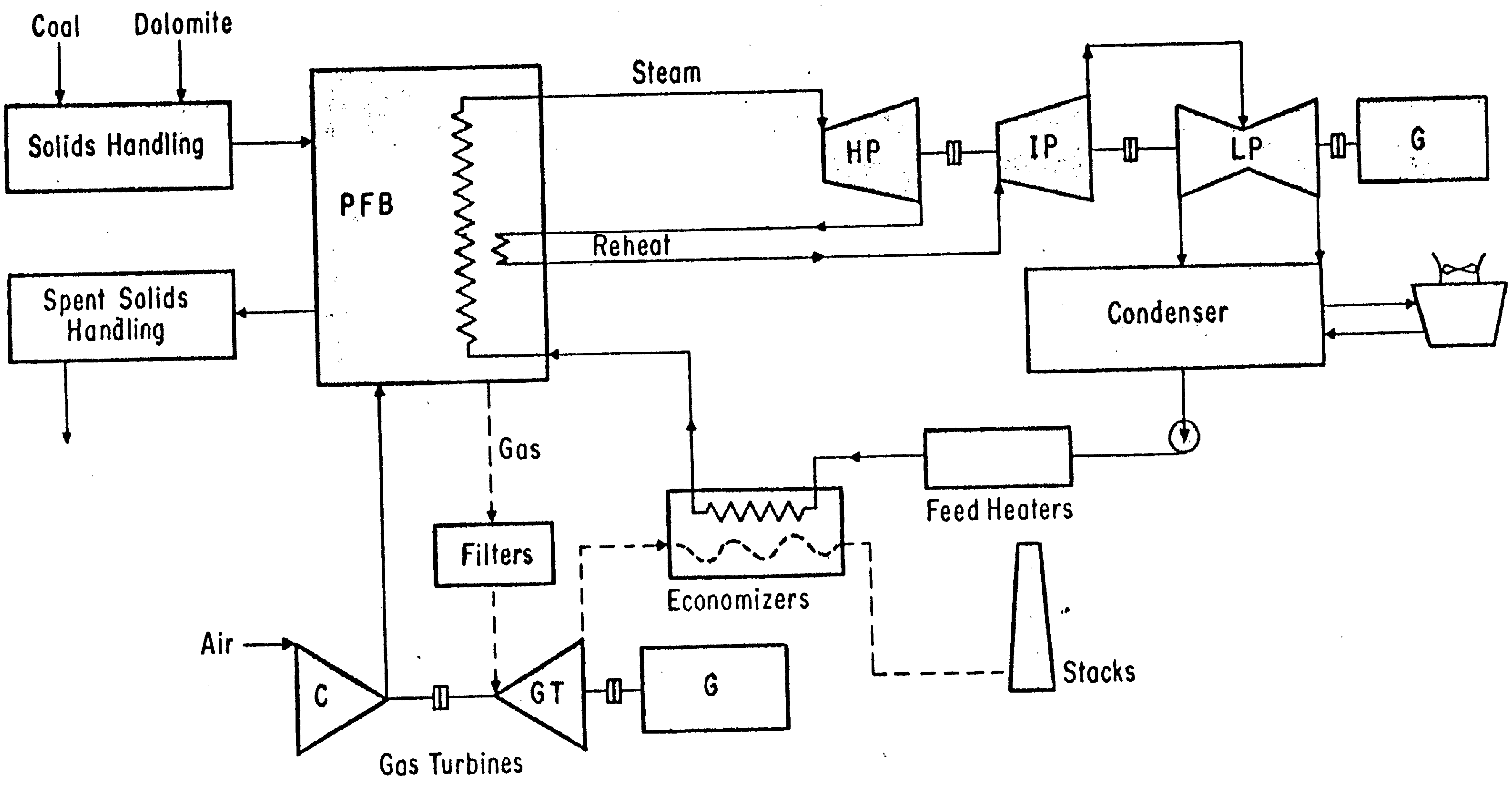


Figure 3.2.3-1

Advanced Steam Cycle - Pressurized FBC (General Electric, 1976).

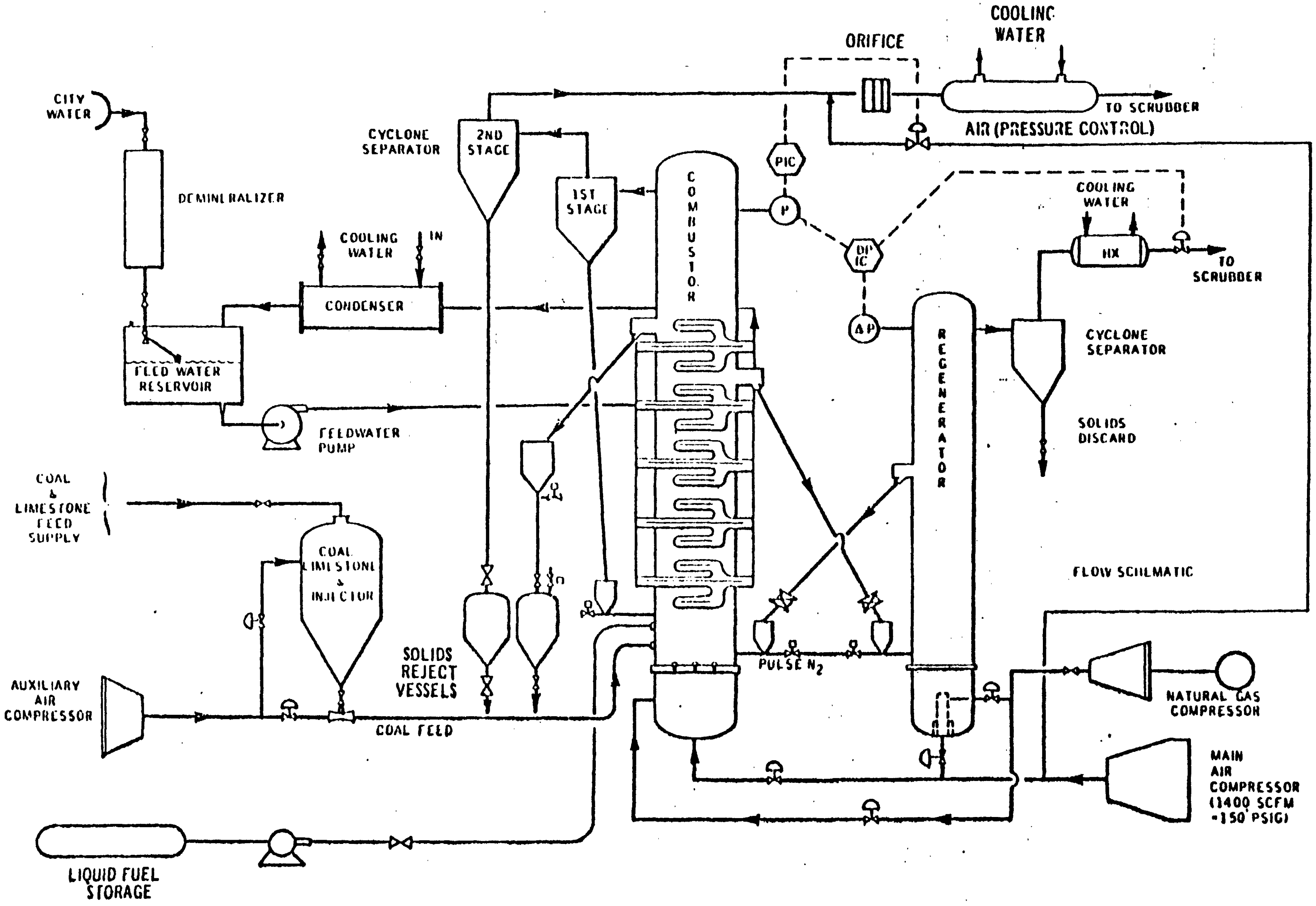


Figure 3.2.3-2

Exxon Fluidized Bed Combustion Miniplant (EPA, 1977).

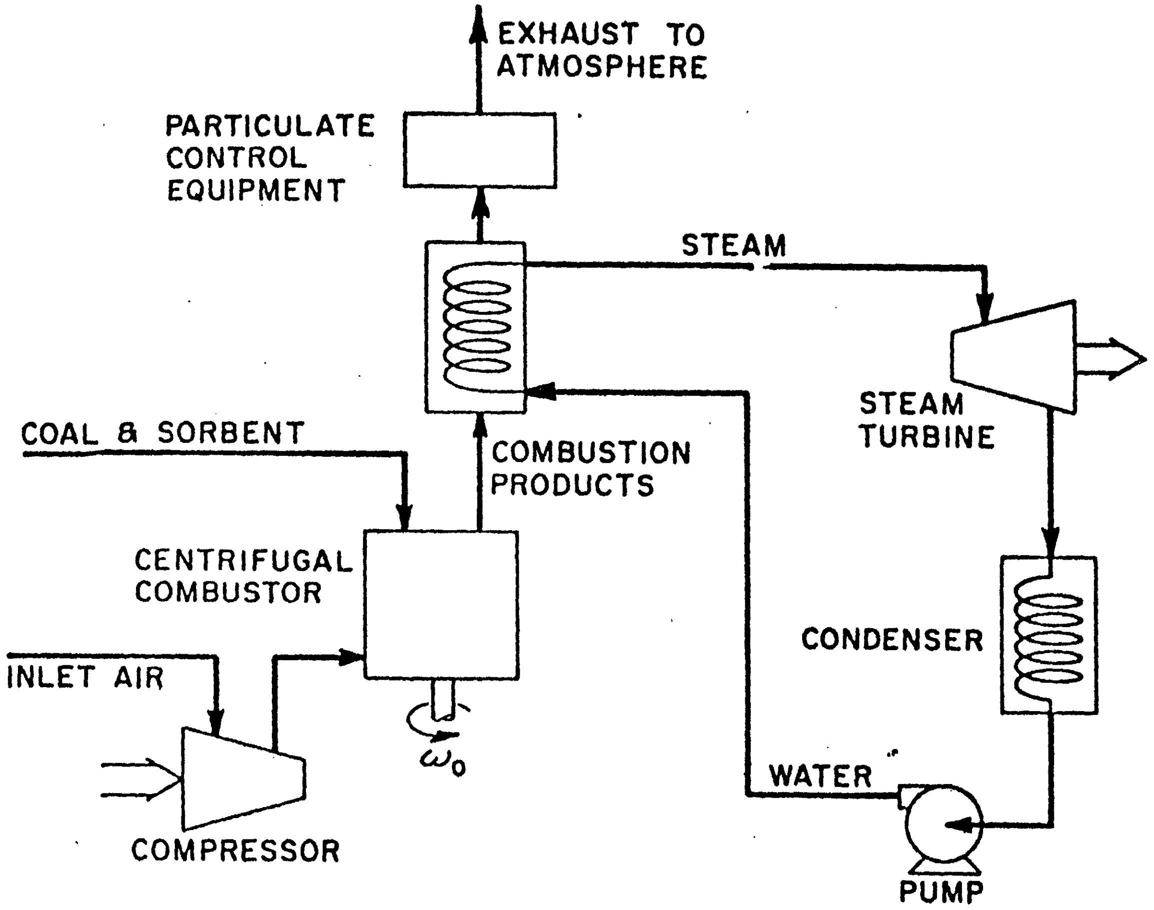


Figure 3.2.3-3

Adiabatic Combined Cycle (Levy, Chen, 1977).

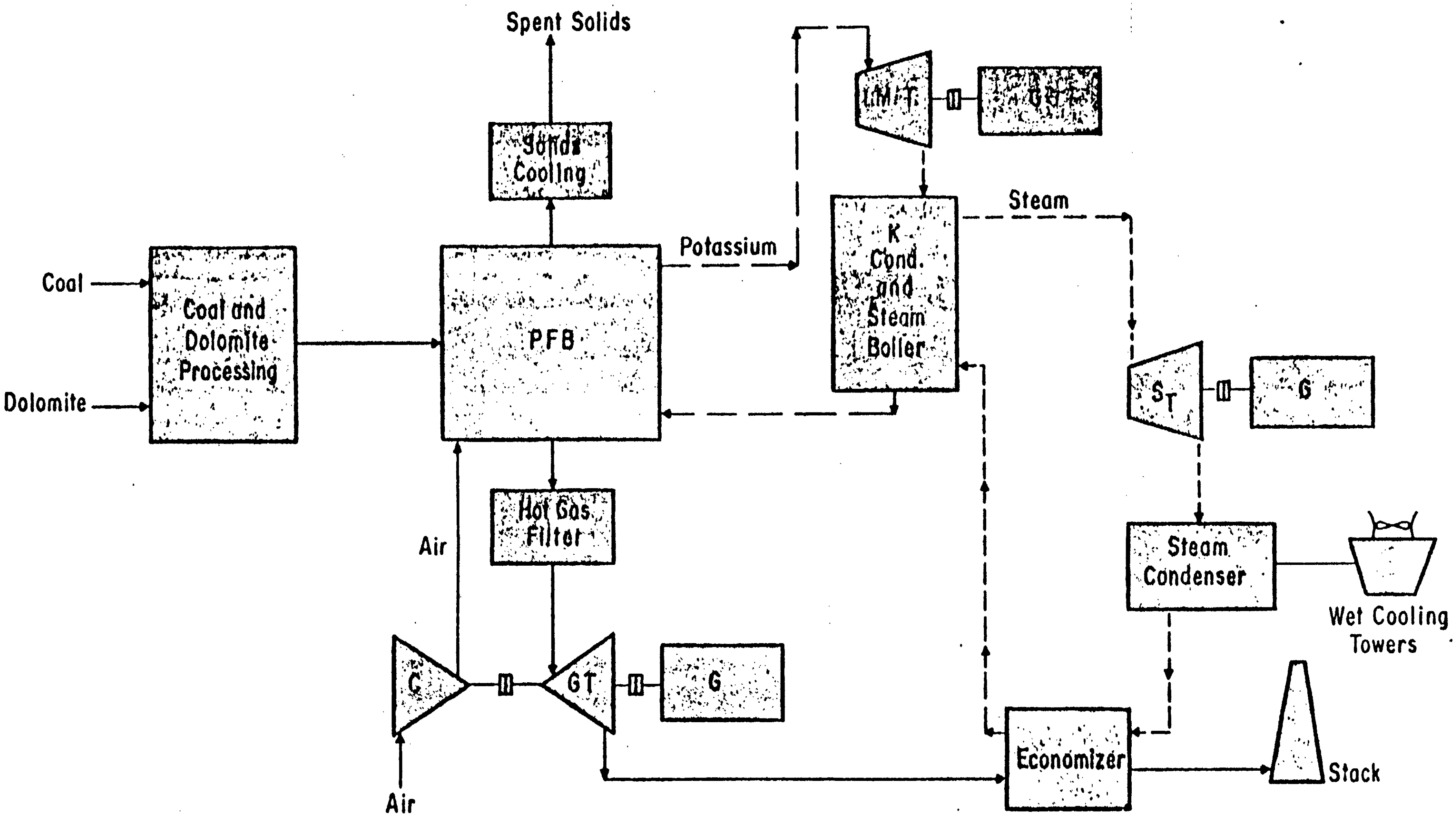


Figure 3.2.4-1

Potassium Topping Cycle Pressurized FBC (General Electric, 1976).

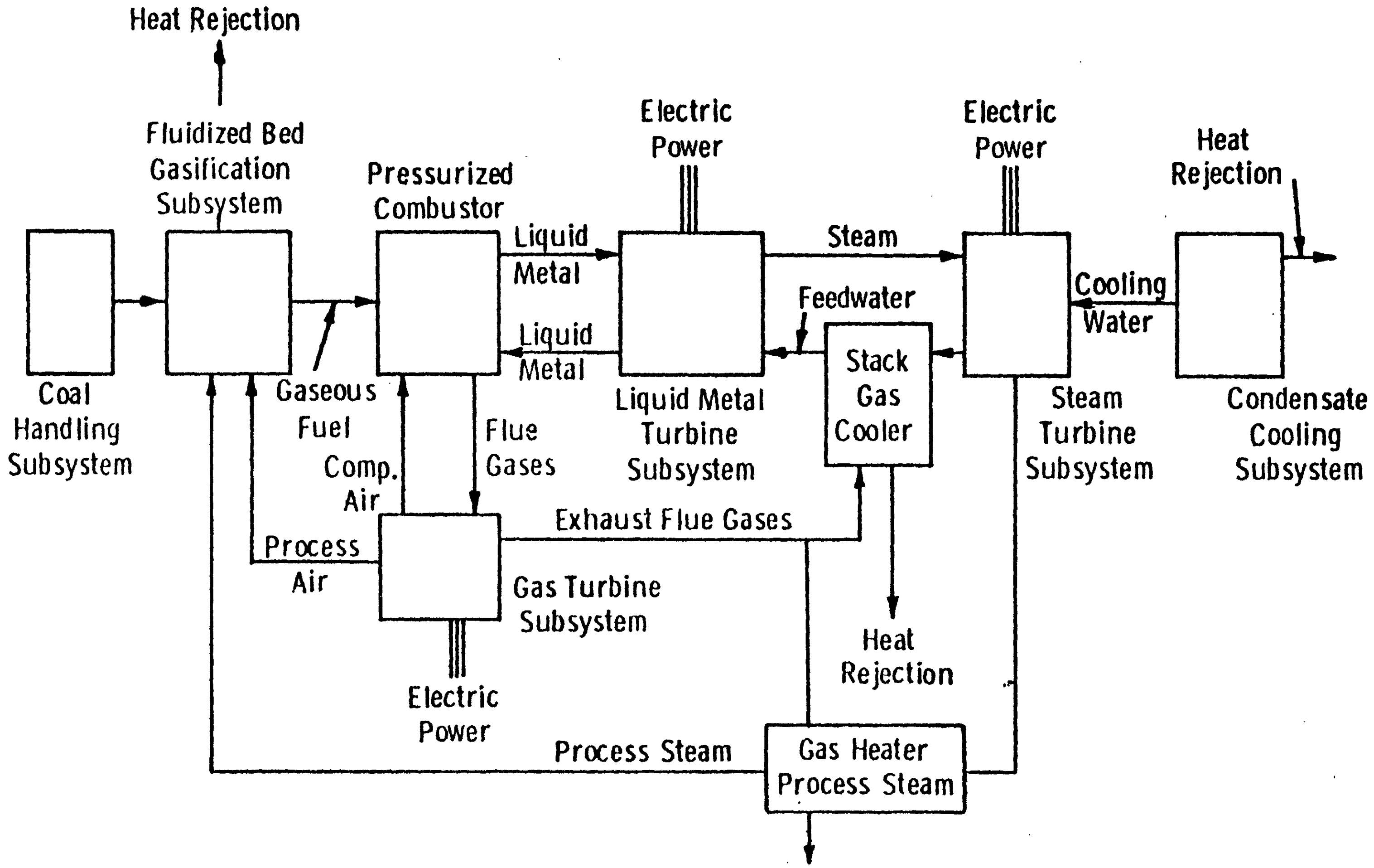


Figure 3.2.4-2

Flow Sheet for a Pressurized Furnace Plant Cycle (Deegan, et al., 1976).

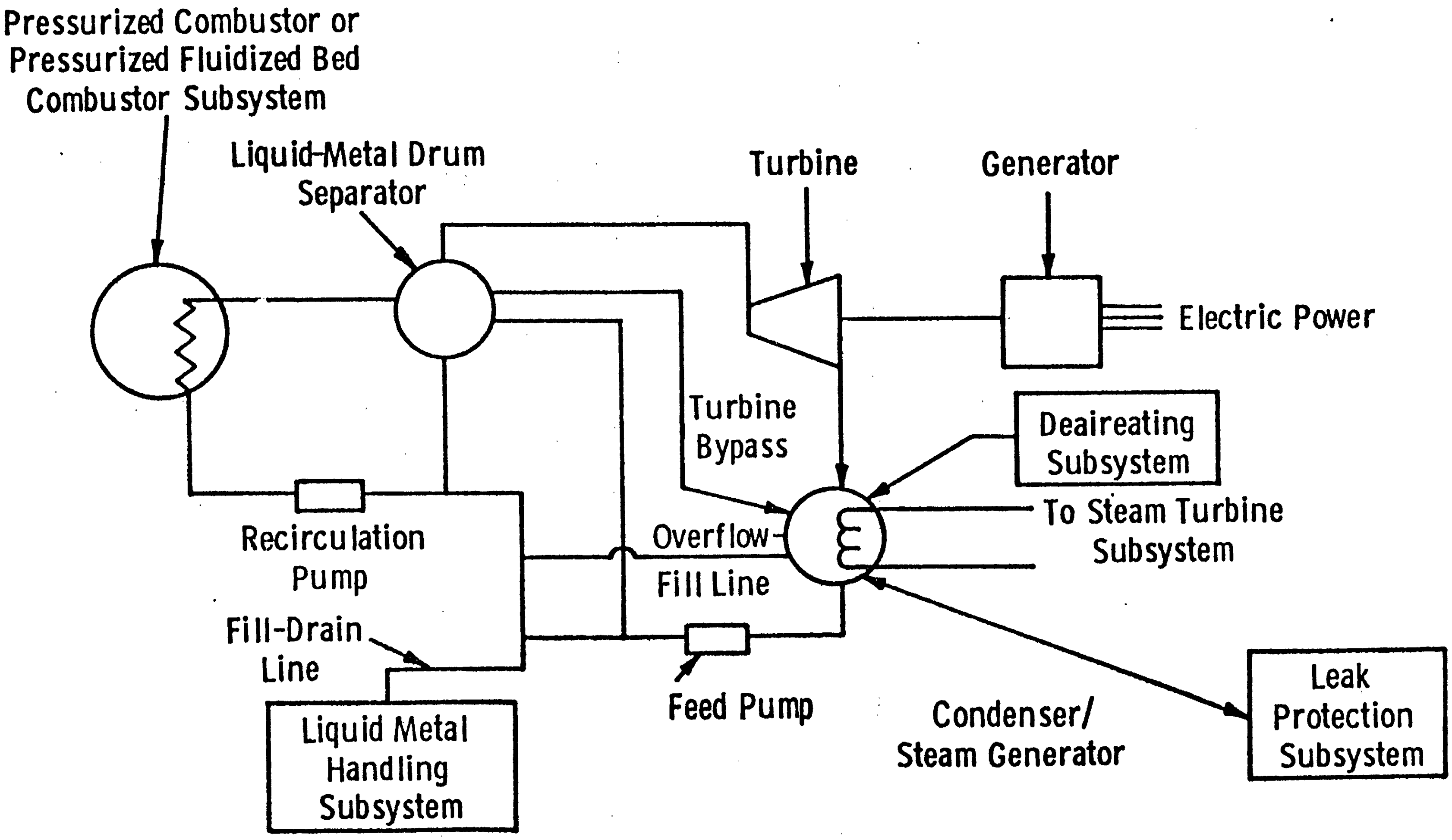


Figure 3.2.4-3

Flow Sheet for the Liquid Metal Turbine Subsystem (Deegan, *et al.*, 1976).

3.3 Energy Balance Evaluations

The only energy balances that have been developed for the various advanced cycles are analytic point-by-point accountings of the BTU inputs and outputs of each of the modules in the energy facilities. The two recent studies for which these were developed are (Wolfe et al., 1976) and (General Electric, 1976). The information from the latter study is available and an example is given in Figure 3.3.2-1. The Westinghouse research (Wolfe et al., 1976) involved an extensive parametric investigation of energy balances, and these results, unfortunately, have not been published. This data for the parametric studies from Westinghouse is of the format of the example in Table 3.3-1. Some of the assumptions used in computing these thermodynamic performances of the cycle configurations are shown in Table 3.3-2. The conversion of these assumptions into the performance data was accomplished at Westinghouse using their Generalized Performance and Heat Balance Program. Tables of the parametric studies of closed-cycle FBC performed as part of the ECAS project are listed in Tables 3.3-1 and -2.

In the absence of the Westinghouse data, the GE data are presented without comparison. It is, however, possible to investigate in a comparative manner the overall power plant efficiency, defined as the BTU output divided by BTU input, and the boiler efficiency as functions of several of the operating and design parameters. It must be emphasized that all such figures are projected values since there are not any large-scale fluidized bed combustors that are operational. It has not been possible to make probabilistic point-by-point energy or mass balance comparisons primarily due to the tremendous number of different FBC configurations and operating and design variations. Such probabilistic comparisons are beyond the scope of this report, but may be forthcoming from the DOE/MIT computerized FBC data base project.

3.3.1 Comparison of Fuels

The majority of evaluations of the constituent analysis of coals used in FBC experiments have been limited to the major characteristics and components of those coals. Some recent studies have also included analyses of coal ash components, particularly those of concern in corrosion/erosion of turbine blades (see Table 3.3.1-1). Although there have not generally been any more detailed analyses, the 20 or so different coals that have been used in FBC experiments are from coal seams that have been analyzed. Composition of coal will vary even within a seam, but these generally available analyses can be useful in finding components of coals that seem to be responsible for peculiar effects (such as the sulfur removal efficiencies on high chlorine coals). In addition, the general analyses can be useful in predicting trace metal emissions from future use of various U.S. coals (see Table 3.3.1-2). Trace metal analysis of the sorbents are unfortunately rarer, but nonetheless important, in predicting trace metal emissions (see Table 3.3.1-3 and Table 3.3.1-4).

Table 3.3-1

Parameters for Combined Closed-Cycle Gas Turbines (NASA, 1976).

Parameter	General Electric		
	Furnace		
	Atmospheric fluidized bed		
	Fuel		
	Coal		
	Bottoming-cycle fluid		
	R-22	FL-85	Steam
	Number of parametric points		
	7	1	5
Primary loop:			
Compressor discharge pressure, psia	1000	1000	1000
Helium turbine-inlet temperature, °F	1500	1500	1500
Compressor pressure ratio	2.5	2.5	2.5
Recuperator pressure drop, ΔP/P	0.03	0.03	0.03
Recuperator effectiveness	0.85, 0.9	0.6	0, 0.5, 0.85, 0.9
Compressor inlet temperature, °F	80	80	80
Helium heater pressure change, ΔP/P	0.015	0.015	0.015
Precooler	With	With	With
Vapor generator pressure drop, ΔP/P	0.01	0.01	0.01
Pressurizing loop:			
Turbine-inlet temperature, °F	----------------	---------	----------------
Pressure ratio	----------------	---------	----------------
Combustor pressure drop, ΔP/P	----------------	---------	----------------
Vapor generator pressure drop, ΔP/P	----------------	---------	----------------
Bottoming loop:			
Turbine-inlet pressure, psia	1500, 1600, 1700	650	125, 100, 400, 800
Turbine-inlet temperature, °F	390, 400, 410, 430	460	384, 413, 561, 900
Helium pinch-point ΔT	30, 50, 70	50	30
Turbine reheat pressure, psia	----------------	---------	----------------
Turbine reheat temperature, °F	----------------	---------	----------------
Desuperheating recuperator	None	None	None
Cooling tower type	Wet, dry	Wet	Wet, dry
Coal type	Illinois #6	Illinois #6	Illinois #6

[a] No recuperator.

Table 3.3-1 (continued)

Westinghouse						
Furnace						
Pressurized furnace						Pressurized fluidized bed
Fuel						
Distillate				HBTU gas	LBTU gas	Coal
Bottoming-cycle fluid						
R-12	Methylamine	SO_2	Steam			
Number of parametric points						
2	4	1	40	1	1	3
1000	1000	1000	500, 1000, 2000	1000	1000	1000
1500	1500	1500	1200, 1500, 1800	1500	1500	1500
2.5	2.5	2.5	1.5, 2, 2.5, 3, 4	2.5	2.5	2.5
(a)	(a)	(a)	(a)	(a)	(a)	(a)
(a)	(a)	(a)	(a)	(a)	(a)	(a)
200	200	200	96.5, 150, 200, 250, 300, 320	200	200	200
0.02	0.02	0.02	0.02, 0.04, 0.06	0.02	0.02	0.02
None	None	None	With, without	With	With	With
0.02	0.02	0.02	0.02, 0.04, 0.06	0.02	0.02	0.02
2200	1100, 2200	2200	1100, 1700, 2200	2200	2200	1700
10	10	10	5, 10, 15	10	10	10
0.06	0.06	0.06	0.03, 0.06, 0.09, 0.12	0.06	0.06	0.09
0.04	0.04	0.04	0, 0.02, 0.04, 0.06	0.04	0.04	0.04
2500	2000	1800	1250, 1600, 2000, 2500, 3500	3500	3500	3500
700	550	950	800, 850, 900, 1000	900	900	900
40	40	40	40, 60, 80	40	40	40
---------	---------	---------	250, 350, 500, None	500	500	500
---------	---------	---------	800, 850, 900, 1000, None	950	950	950
With, without	None	None	None	None	None	None
Wet	Wet, dry, direct condensing	Wet	Wet, dry, once through	Wet	Wet	Wet
Illinois #6	Illinois #6	Illinois #6	Illinois #6	Illinois #6	Illinois #6	Illinois #6 North Dakota Montana

Table 3.3-2

Contractors' Base-Case Parameters for Closed-Cycle Gas Turbines (NASA, 1976).

	General Electric case 1	Westinghouse		
		Case 25R	Case 48R	Case 5C
Furnace	AFB	PFB	Conventional atmospheric	Pressurized
Fuel	Illinois #6	Illinois #6	Distillate	Distillate
Compressor discharge pressure, psia	1000	1000	1000	1000
Helium loop:				
Turbine-inlet temperature, °F	1500	1500	1500	1500
Compressor pressure ratio	2.5	2.5	2.5	2.5
Recuperator effectiveness	0.85	0.9	0.9	-----
Recuperator pressure drop, ΔP/P	0.03	0.02	0.02	-----
Loop pressure drop,[a] ΔP/P	0.08733	0.059	0.059	0.040
Compressor inlet temperature, °F	80	96.5	96.5	200
Cooling tower type	Wet	Wet	Wet	Wet
Pressurizing loop:				
Turbine-inlet temperature, °F	--------	1700	-----	2200
Pressure ratio	--------	10	-----	10
Bottoming loop:				
Turbine-inlet pressure, psia	--------	----	-----	10
Turbine-inlet temperature, °F	--------	----	-----	3500
Working fluid	--------	----	-----	Steam

[a] Calculated as 1 - (Turbine pressure ratio)/(Compressor pressure ratio).

Table 3.3.1-1

Analyses of Coals Used in Various FBC Experiments (Babcock and Wilcox, 1977).

Sample No.	C-14237	C-14239
Sample Description	Coal Pittsburgh #8	Coal Pittsburgh #8
Date Received	10/22/76	11/5/76
Test No.'s	26-30	31-41
Total Moisture, %	5.0	5.0
Proximate Analysis (Dry), %		
Volatile Matter	40.0	40.3
Fixed Carbon	50.1	49.8
Ash	9.9	9.9
Btu per lb (Dry)	13260	13310
Btu per lb (M&A Free)	14720	14770
Sulfur (Dry), %	3.0	3.0
Ash Analysis (Spectrographic), %		
Silicon as SiO_2*	47.0	44.7
Aluminum as Al_2O_3	20.	20.
Iron as Fe_2O_3	24.	25.
Titanium as TiO_2	0.6	0.6
Calcium as CaO	1.0	1.6
Magnesium as MgO	0.6	0.5
Sodium as Na_2O**	1.2	1.1
Potassium as K_2O* *	1.7	1.7
Sulfur as SO_3*	1.0	1.8

---

*Gravimetric

**By Flame Photometer

Table 3.3.1-2

Probabilistic Display of the Constituents of 101 Representative U.S. Coals (Ruch, et al., 1974).

Constituent	Mean	Standard Deviation	Minimum	Maximum
As	14.02 ppm	17.70	0.50	93.00
B	102.21 ppm	54.65	5.00	224.00
Be	1.61 ppm	0.82	0.20	4.00
Br	15.42 ppm	5.92	4.00	52.00
Cd	2.52 ppm	7.60	0.10	65.00
Co	9.57 ppm	7.26	1.00	43.00
Cr	13.75 ppm	7.26	4.00	54.00
Cu	15.16 ppm	8.12	5.00	61.00
F	60.94 ppm	20.99	25.00	143.00
Ga	3.12 ppm	1.06	1.10	7.50
Ge	6.59 ppm	6.71	1.00	43.00
Hg	0.20 ppm	0.20	0.02	1.60
Mn	49.40 ppm	40.15	6.00	181.00
Mo	7.54 ppm	5.96	1.00	30.00
Ni	21.07 ppm	12.35	3.00	80.00
P	71.10 ppm	72.81	5.00	400.00
Pb	34.78 ppm	43.69	4.00	218.00
Sb	1.26 ppm	1.32	0.20	8.90
Se	2.08 ppm	1.10	0.45	7.70
Sn	4.79 ppm	6.15	1.00	51.00
V	32.71 ppm	12.03	11.00	78.00
Zn	272.29 ppm	694.23	6.00	5,350.00
Zr	72.46 ppm	57.78	8.00	133.00
Al	1.29 %	0.45	0.43	3.04
Ca	0.77 %	0.55	0.05	2.67
Cl	0.14 %	0.14	0.01	0.54
Fe	1.92 %	0.79	0.34	4.32
K	0.16 %	0.06	0.02	0.43
Mg	0.05 %	0.04	0.01	0.25
Na	0.05 %	0.04	0.00	0.20
Si	2.49 %	0.80	0.58	6.09
Ti	0.07 %	0.02	0.02	0.15
Org. S	1.41 %	0.65	0.31	3.09
Pyr. S	1.76 %	0.86	0.06	3.78
Sul. S	0.10 %	0.19	0.01	1.06
Tot. S	3.27 %	1.33	0.42	6.47
SXRF	2.91 %	1.24	0.54	5.40
ADL	7.70 %	3.47	1.40	16.70
Mois	9.05 %	5.05	0.01	20.70
Vol.	39.70 %	4.27	18.90	52.70
Fix C	48.82 %	4.55	34.60	65.40
Ash	11.44 %	2.89	2.20	25.80
Btu	12,748.91	464.50	11,562.00	14,362.00
C	70.28 %	3.87	55.23	80.14
H	4.95 %	0.31	4.03	5.79
N	1.30 %	0.22	0.78	1.84
O	8.63 %	2.44	4.15	16.03
HTA	11.41 %	2.95	3.28	25.85
LTA	15.28 %	4.01	3.82	31.70

Abbreviations other than standard chemical symbols: organic sulfur (Org. S), pyritic sulfur (Pyr. S), sulfate sulfur (Sul. S), total sulfur (Tot. S), sulfur by X-ray fluorescence (SXRF), air-dry loss (ADL), moisture (Mois), volatile matter (Vol.), fixed carbon (Fix. C), high-temperature ash (HTA), low-temperature ash (LTA).

Table 3.3.1-3

Coal Ash Contamination* of Benificated Lime/Anhydrite (Mesko, 1974).

	Raw Limestone #1359	Lime/Anhydrite
Ca	38.8%	39.0%
Mg	0.51%	0.43%
Fe	0.101%	0.42%
Al	0.15%	0.42%
Si	0.23%	1.14%
Na	0.027%	0.20%
K	0.08%	0.34%
Ti	0.012%	0.0380%
Zn	4 ppm	35 ppm
Cu	10 ppm	35 ppm
Ni	36 ppm	195 ppm
Co	28 ppm	90 ppm
Pb	43 ppm	180 ppm
As	70 ppm	—
P	1.6 ppm	1.6 ppm

*Sewickley coal ash 9.5 percent Al. On this basis the Lime/Anhydrite contains approximately 3% coal ash.

Table 3.3.1-4

Composite Analysis of Elements in Coal and Sorbents (μg/g) (Murthy, Nack, 1977).

Element	Coal	Limestone
Aluminum	12900.00	3998.49
Antimony	1.30	2.70
Arsenic	5.00	2.00
Barium	130.00	100.00
Beryllium	1.60	0.80
Bismuth	0.10	0.00
Boron	102.00	18.00
Bromine	15.00	5.00
Cadmium	2.50	1.00
Calcium	6780.00	374053.62
Carbon	730000.00	113711.95
Cerium	11.00	0.00
Cesium	1.00	0.00
Chlorine	1400.00	55.00
Chromium	20.00	11.00
Cobalt	9.60	100.00
Copper	15.00	47.00
Dysprosium	1.00	0.00
Europium	0.20	0.00
Fluorine	61.00	230.00
Gallium	3.10	0.00
Germanium	6.60	0.30
Hafnium	0.97	0.00
Indium	0.04	0.00
Iodine	2.78	0.00
Iron	21300.00	4295.92
Lanthanum	6.90	1.60
Lead	34.80	30.00
Lithium	25.00	0.00
Magnesium	500.00	3269.60
Manganese	25.00	500.00
Mercury	1.20	0.08
Molybdenum	7.50	37.00
Neodymium	6.40	0.00
Nickel	21.10	75.00
Nitrogen	13800.00	0.00
Phosphorus	71.10	187.00
Potassium	2300.00	1600.55
Praseodymium	76.00	0.00
Rhodium	290.00	0.00
Rubidium	14.00	0.00
Scandium	3.20	0.00
Selenium	2.10	0.32
Silicon	30300.00	12713.88
Silver	0.20	0.00
Sodium	1800.00	699.57
Strontium	200.00	490.00
Sulfur	43000.00	0.00
Tantalum	0.40	0.00
Tellurium	0.30	0.00
Terbium	0.23	0.00
Thorium	2.00	0.00
Tin	4.80	40.00
Titanium	700.00	399.27
Tungsten	1.90	0.00
Uranium	1.60	0.00
Vanadium	32.70	16.80
Ytterbium	0.55	0.00
Zinc	272.30	30.00
Zirconium	180.00	25.50

3.3.2 Atmospheric FBC Energy Balance

The two energy efficiency topics that are addressed in these various subsections include the overall power plant efficiencies and the combustion efficiencies. The results concerning overall plant efficiencies are correlations of various operating configurations and parameters to published analytic projections of what the efficiencies are likely to be. The last portion of this subsection contains an empirical correlation of a model to published combustion efficiencies.

In the temporary absence of a component-by-component program for energy balance calculations it is instructive to compare some of the bottom line results of different energy balance computations (see Table 3.3.2-1). These results do in fact bunch very closely. The range of values from 33.5% to 39.9% observed in the Westinghouse parametric studies is examined further in Table 3.3.2-2. The parametric points investigated in that research were obviously chosen to isolate, one at a time, some of the key design and operating parameters to point out the variations due to effects of each.

Figure 3.3.2-1 typifies the close relationship between the fluid bed and the conventional steam furnace systems. That close relationship shows the fluid bed system as consistently 0.2 to 0.3% lower in efficiency than the conventional furnace system. With this close correlation in mind and thus using all the atmospheric furnace parameterizations, Figures 3.3.2-2, -3, -4, -5, and -6 suggest overall efficiency variations as functions of bed temperature, condenser pressure, power plant total MWe output, coal type, and reheat temperatures, respectively. Correlations of those parameters to overall energy efficiency analytic projects are:

E_p = overall plant efficiency, %

E_t = thermodynamic efficiency, %

n = parameter for type of coal
    $n = .7955$ for bituminous
    $n = .8065$ for subbituminous
    $n = .7719$ for lignite

P_t = steam turbine throttle pressure, psia

T_t = throttle temperature, ^{o}F

T_1 = first reheat temperature, ^{o}F

T_2 = second reheat temperature, ^{o}F

T_3 = third reheat temperature, ^{o}F

C_p = condenser pressure, in.Hg abs.

Table 3.3.2-1 Atmospheric FBC Overall Efficiency Calculations

Description	Overall Plant Eff.	References
Loss Factor 11.4%	36%	(Keairns, et al., Sept. 1975)
Northern Application Coal	36.8%	(Hittman, 1974)
Northwest Coal	36.8%	(Hittman, 1974)
7.32% Aux. Power Loss, 87.92% AFB efficiency,	36%	(G.E. Co., 1976)
Various Operating points	33.5% to 39.9%	(Wolfe, et al., 1976)

Table 3.3.2-2

Parametric Studies of Atmospheric FBC Performed by Westinghouse (Wolfe, et al., 1976).

Parametric Point	6	9	12	24	27	31*	33	36	37	38	[illegible]	45	48
Power Output, MWe	465	466	467	466	467	466	466	465	465	466	465	466	466
Fuel													
Bituminous Coal	X	X	X	X	X	X	X	X			X	X	X
Subbituminous Coal									X				
Lignite Coal										X			
Furnace Type													
Atmospheric (Conventional)													
Fluid Bed	X	X	X	X	X	X	X	X	X	X	X	X	X
Steam Turbine													
Throttle Press, psia	5000	5000	5000	3500	3500	3500	3500	3500	3500	3500	2400	2400	2400
Throttle Temp, °F	1000	1200	1400	1200	1400	1200	1400	1000	1000	1000	1000	1200	1400
First Reheat Temp, °F	1000	1200	1400	1200	1400	1400		1000	1000	1000	1000	1200	
Second Reheat Temp, °F	1000	1200	1400										
Third Reheat Temp, °F	1000	1000	1000										
Condenser Press, in. Hg Abs	3.5	3.5	3.5	3.5	3.5	2	2	3.5	3.5	3.5	3.5	3.5	2
Thermodynamic Eff, % ①	44.5	47.5	50.1	46.1	48.3	48.5	47.5	43.4	43.4	43.4	42.6	45.1	46.5
Powerplant Eff, %	35.4	37.9	39.9	36.7	38.5	38.6	37.8	34.4	35.0	33.5	33.8	35.8	37.0
Overall Eff, %	35.4	37.9	39.9	36.7	38.5	38.6	37.8	34.4	35.0	33.5	33.8	35.8	37.0
Total Capital Cost × 10^{-6}, $	212.2	325.8	472.3	282.6	347.0	289.0	311.5	203.0	223.3	231.9	199.1	246.3	296.3
Capital Costs, $/kWe	456.1	598.4	1010.8	542.0	743.4	619.7	668.5	436.6	479.5	499.4	428.4	528.9	636.2
Cost of Elect. Mills/kWh													
Capital	14.417	27.079	31.955	17.134	23.501	19.680	21.131	13.803	5.159	5.787	13.543	16.719	26.112
Fuel ②	9.202	7.661	7.264	7.899	7.529	7.507	7.670	8.424	8.296	8.648	8.587	8.093	7.840
Oper. & Maint.	2.068	1.974	1.905	2.016	1.951	1.948	1.976	2.107	.894	.912	2.130	2.044	2.000
Total	24.69	31.71	41.12	27.05	32.98	29.05	30.78	24.33	24.35	25.35	24.26	26.86	29.95
Est. Time of Construction, yr	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Notes:

① Where Applicable

② Use Base Delivered Fuel Cost

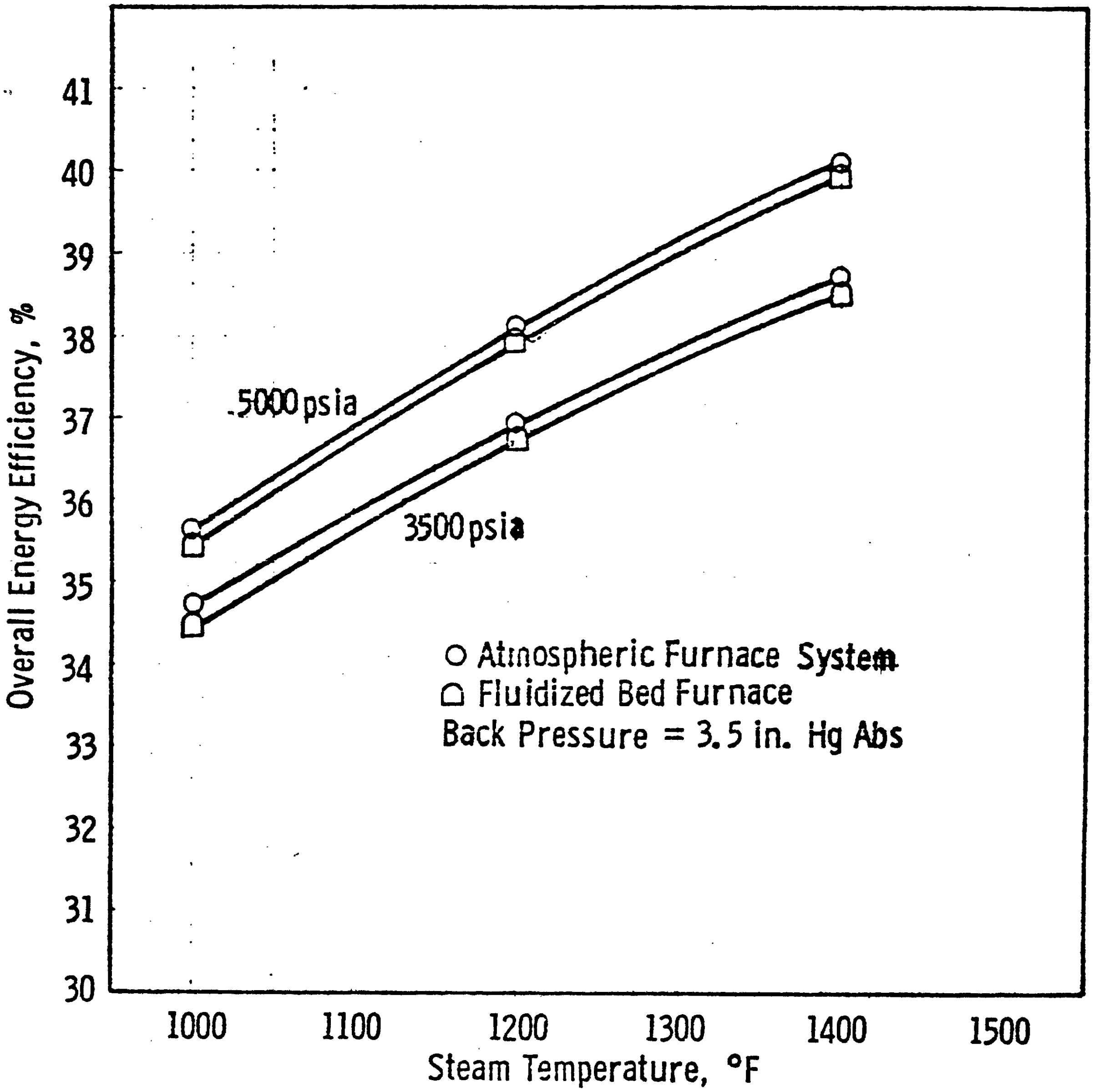


Figure 3.3.2-1

Effect of Temperature on Overall Efficiency for a 500 MWe Steam Plant with an Atmospheric Furnace (Wolfe, et al., 1976, p. 12-35).

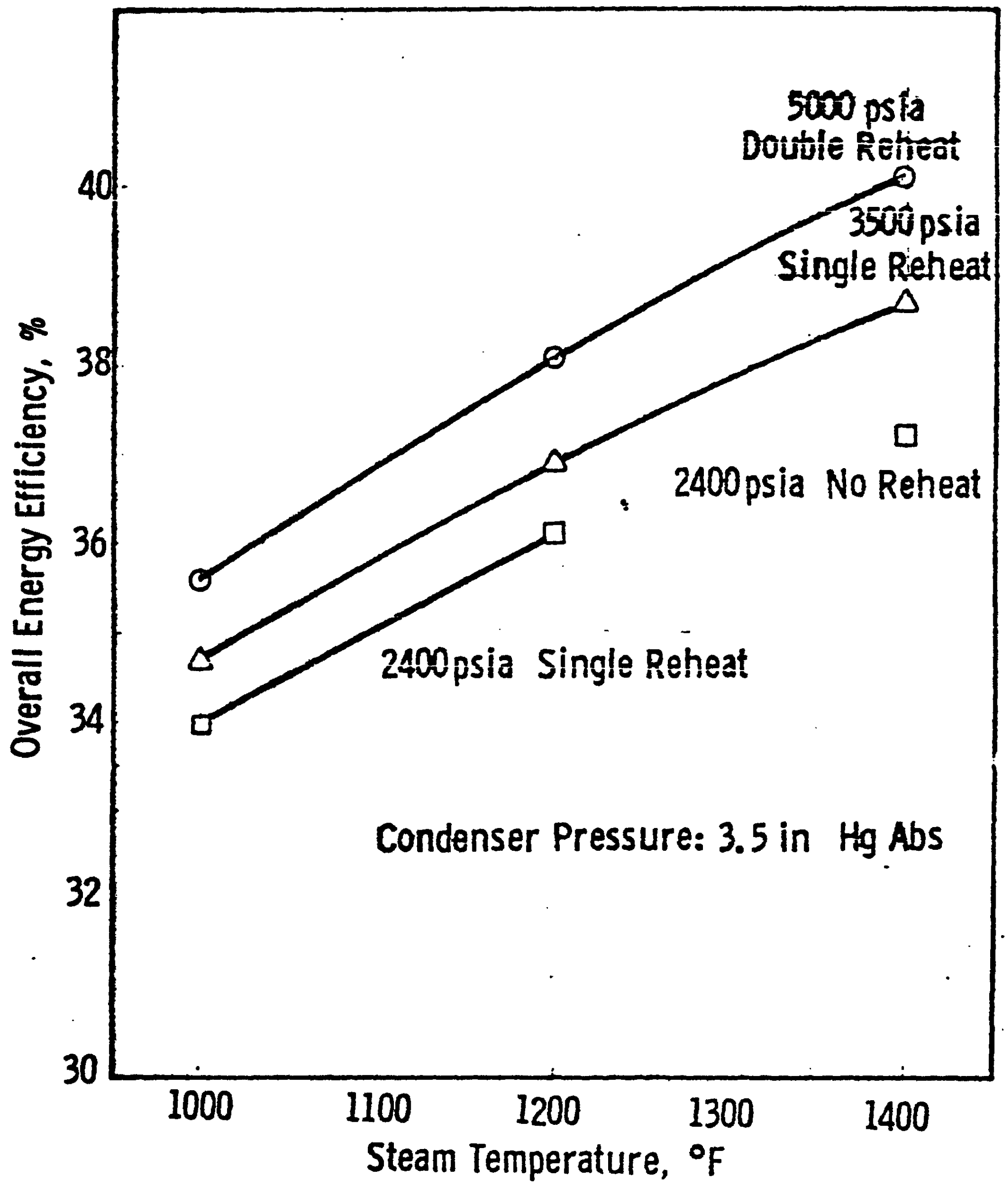


Figure 3.3.2-2

Effect of Steam Turbine Throttle Temperature on Overall Efficiency for a 500 MWe Steam Plant with an Atmospheric Furnace (Wolfe, et al., 1976, p. 12-34).

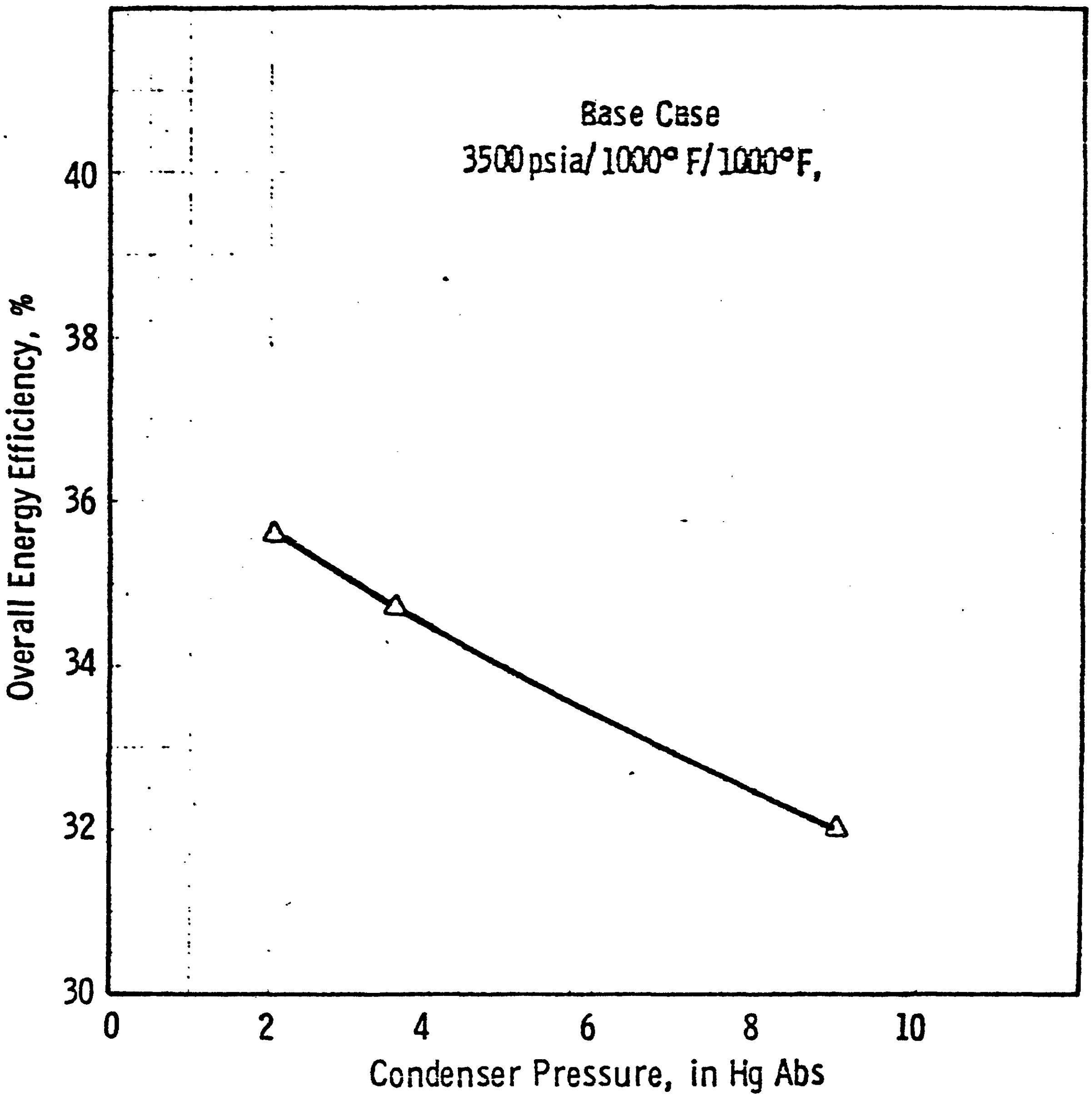


Figure 3.3.2-3

Effect of Condenser Pressure on Overall Efficiency for a 500 MWe Steam Plant with an Atmospheric Furnace (Wolfe, et al., 1976, p. 12-36).

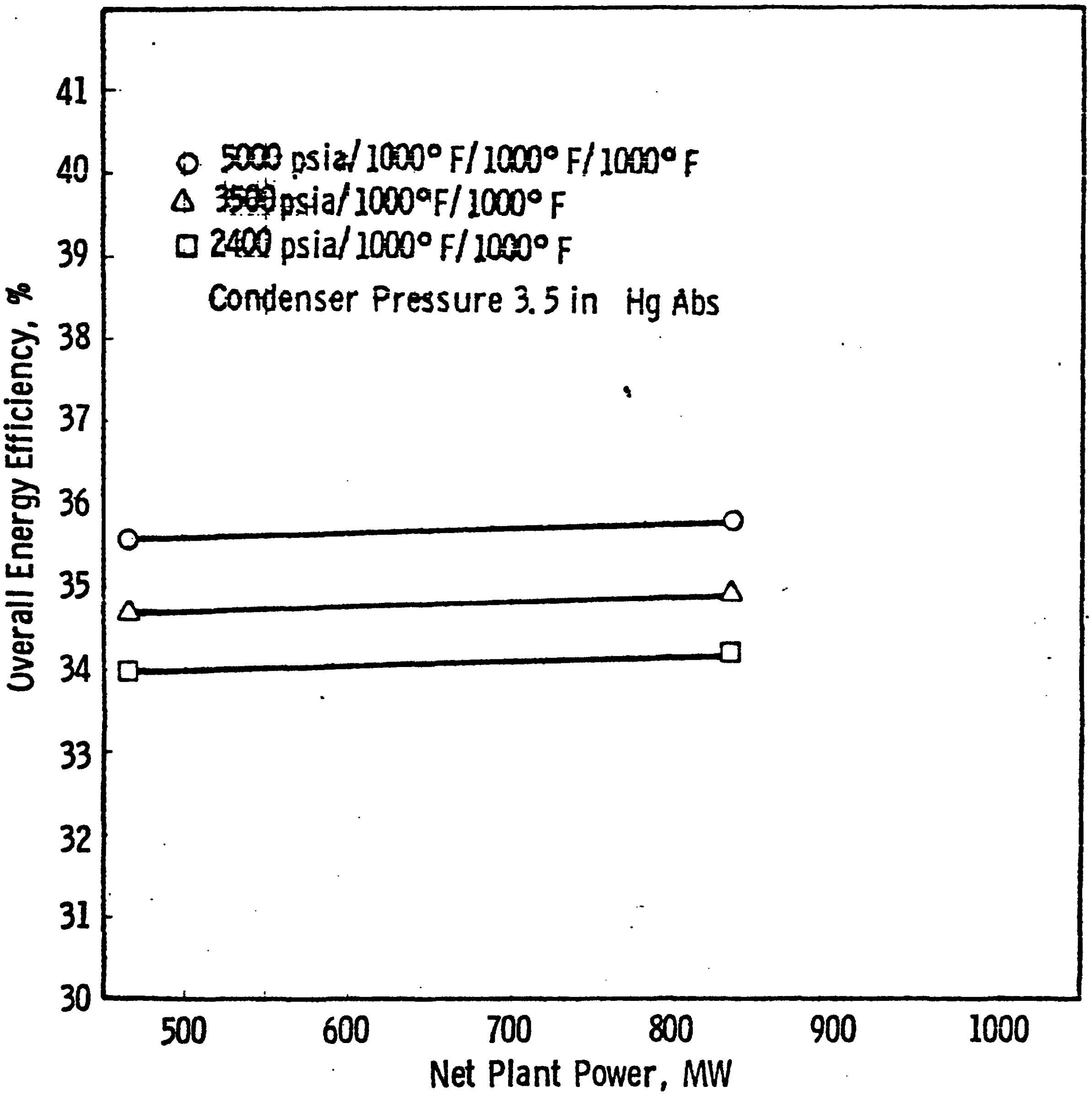


Figure 3.3.2-4

Effect of Plant Size on Overall Efficiency for a Steam Plant with an Atmospheric Furnace (Wolfe, <u>et al</u>., 1976, p. 12-38).

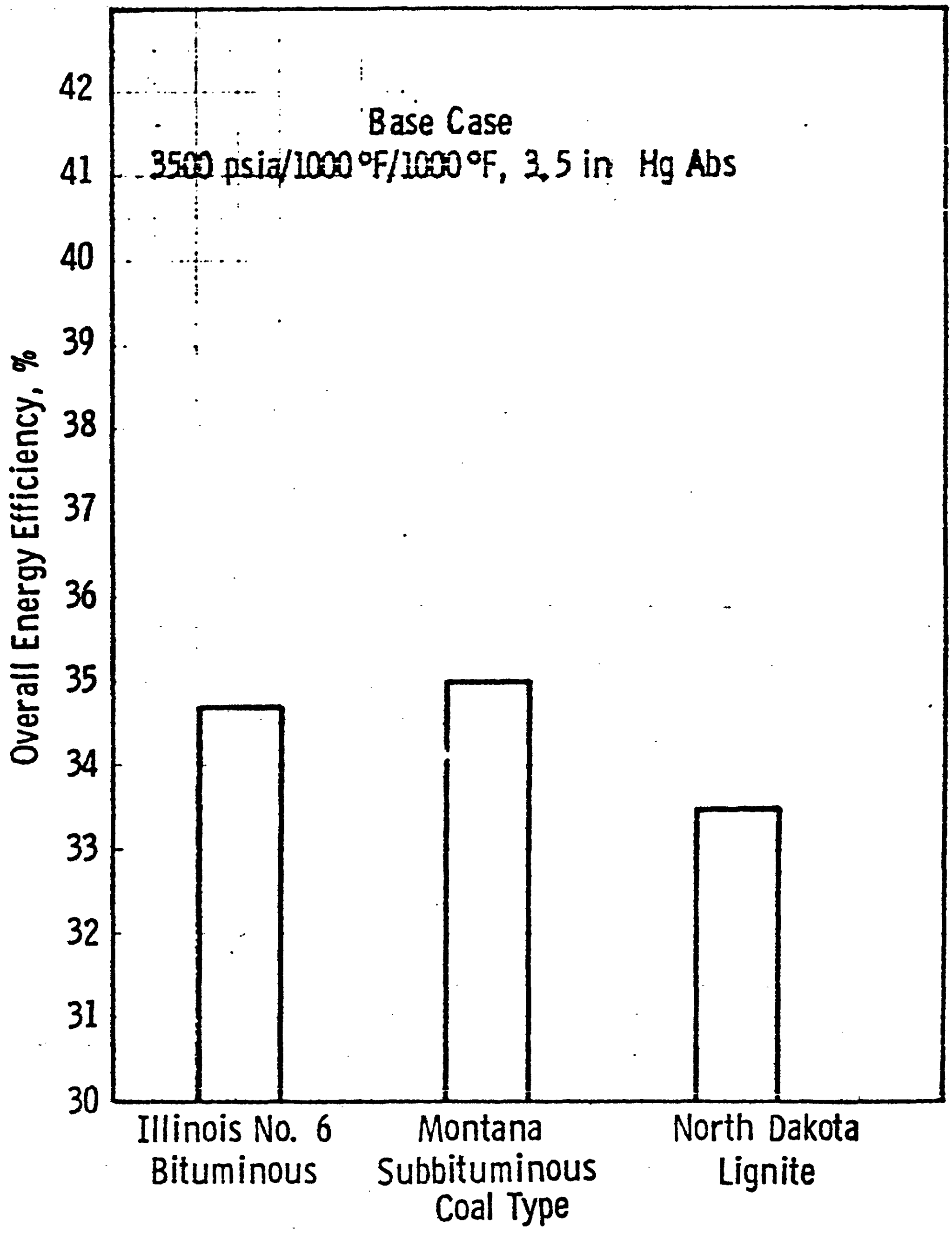


Figure 3.3.2-5

Effect of Coal Type on Overall Efficiency for a 500 MWe Steam Plant with an Atmospheric Furnace (Wolfe, et al., 1976, p. 12-39).

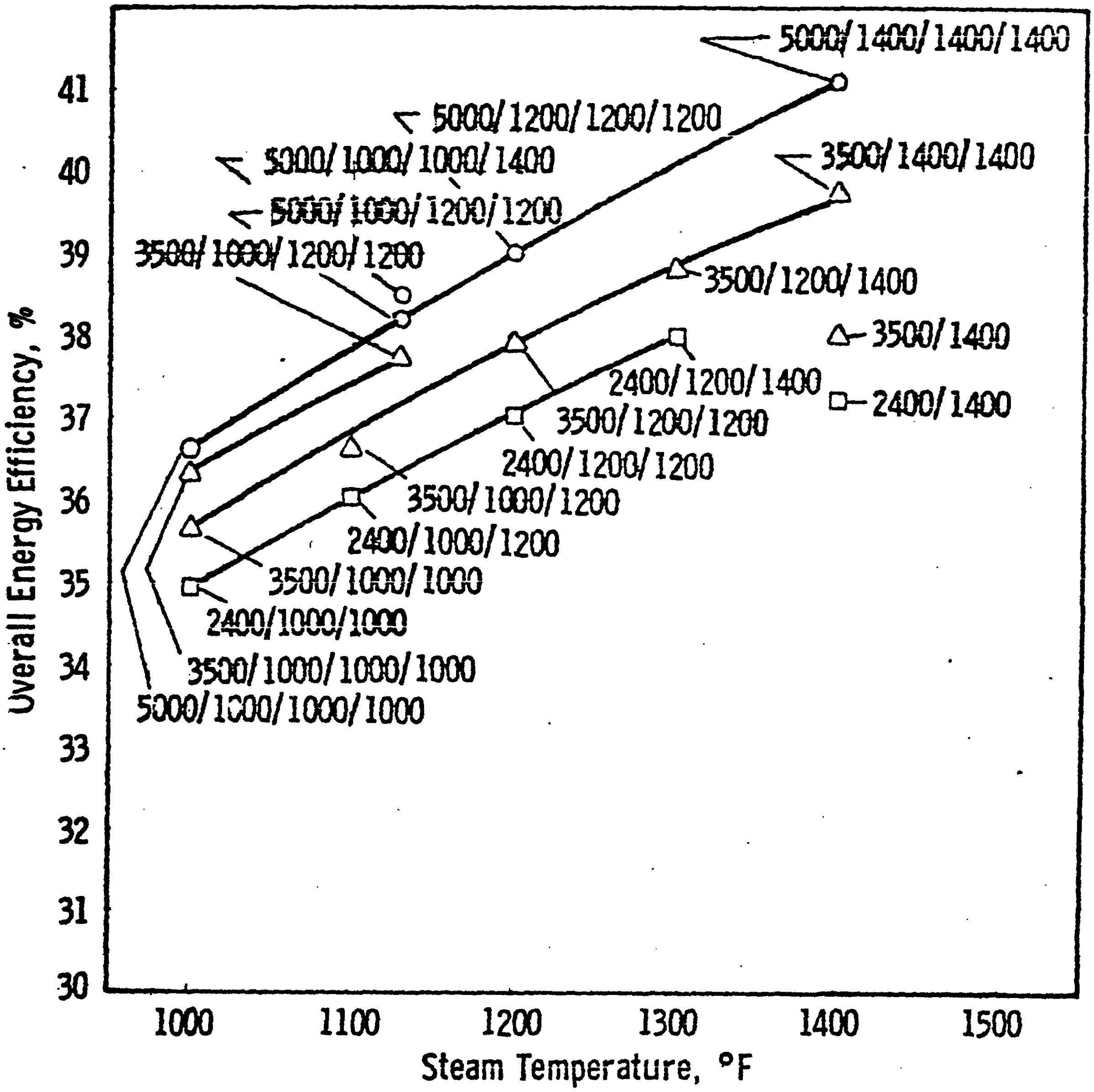


Figure 3.3.2-6

Effect of Steam Throttle Conditions on Overall Efficiency for a 500 MWe Steam Plant with an Atmospheric Furnace (Wolfe, et al., 1976, p. 12-40).

For no reheats:

and $C_p = 2$, $T_t = 1400$, $P_t = 2400$ to 3500

$$E_t = 46.5 + [P_t - 2400]\, 1100^{-1}$$

$$E_p = n\, E_t$$

For one reheat:

and $C_p = 2$, $P_t = 3500$, $T_t = 1200$, $T_1 = 1400$

$$E_t = 48.5\%$$

$$E_p = n\, E_t$$

for $C_p = 3.5$, $T_t = T_1 = 1000$ to 1400

$$E_t = 42.6 + .0125\, [T_t - 1000] + 0.9\, [P_t - 2400]\, 1100^{-1}$$

$$E_p = n\, E_t \quad [\text{gsd} = 1.004]$$

For three reheats:

and $Cp = 3.5, T_3=1000, P_t=5000, T_t=T_1=T_2=1000$ to 1400

$$E_t = 50.2 - 5.6[1400 - T_t]400^{-1}$$

$$E_p = n\, E_t\ [\text{gsd} = 1.007]$$

Detailed mass and energy balances of the various Westinghouse ECAS atmospheric FBC designs have not been published; the General Electric evaluation is shown in Figure 3.3.2-7. Of the total energy input to that facility, in the form of coal (to the combustor and the spent solids cooler), the approximate breakdown of energy outputs is given in Table 3.3.2-3. The auxiliary components that have been assumed are shown in Table 3.3.2-4. The overall material balance for the FBC with the carbon burnup cell is shown in Figure 3.3.2-8. Similarly, the material and energy balance for the Multi-Solids FBC is displayed in Figure 3.3.2-9.

Table 3.3.2-3

Energy Expenditures in GE Atmospheric FBC

Sensible heat loss to water	49.7%	
Electric generation	38.8%	
Auxiliaries		2.8%
Net Plant		36.0%
Sensible heat loss to air	11.3%	
Sensible heat loss to solids	0.2%	

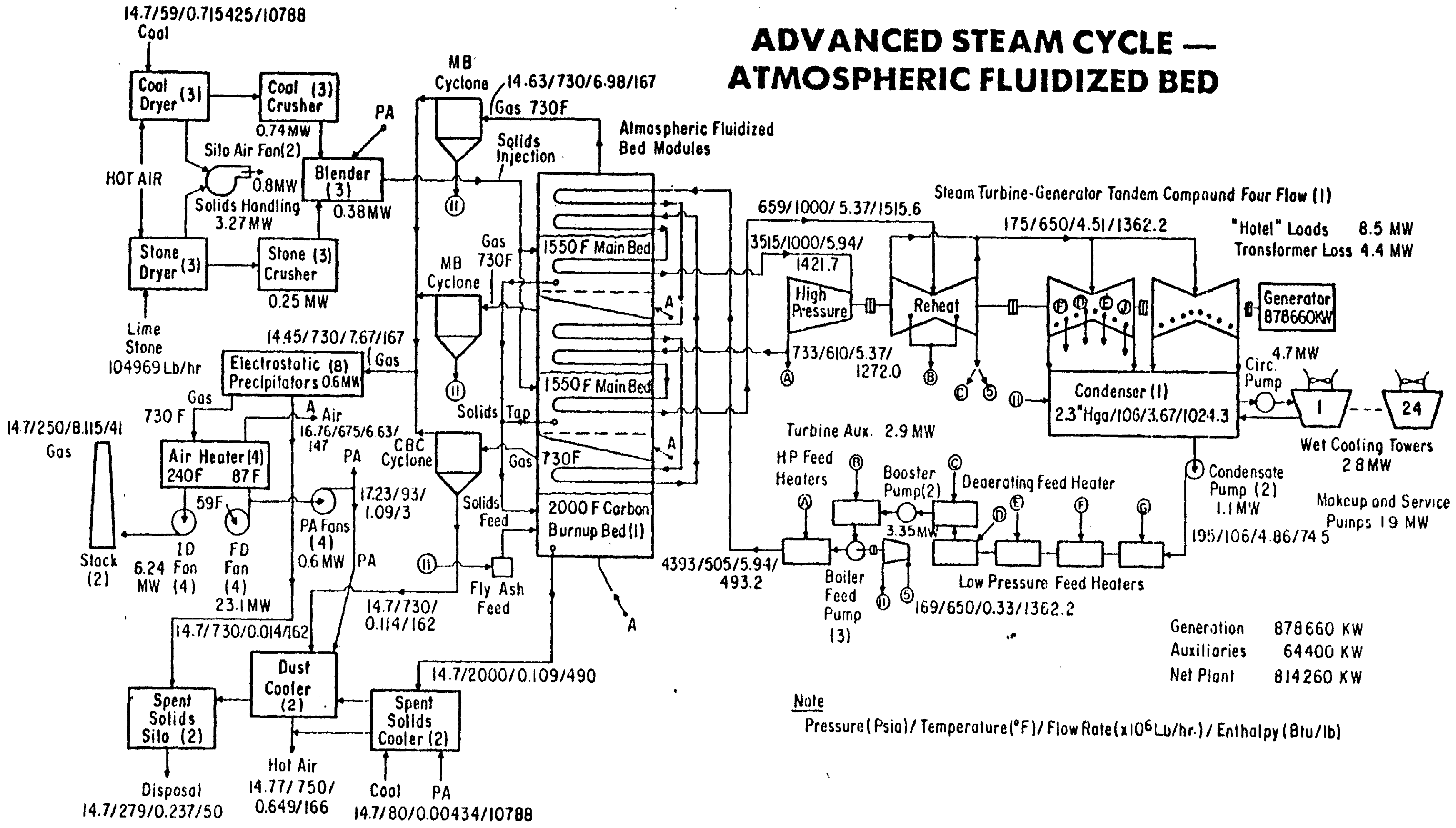


Figure 3.3.2-7

Heat Balance of General Electric Evaluation of the Atmospheric FBC (General Electric, 1976).

Table 3.3.2-4

Auxiliary LOSS Breakdown

Advanced Steam Cycle - Atmospheric Fluidized Bed (General Electric, 1976).

ITEM	ASSUMPTIONS	NO. OF UNITS	MW_e EACH	TOTAL MW_e	
FURNACE					
SA FANS	24" ΔP, 0.82 EFF	4	0.2	0.8	
FD FANS (4)	65" ΔP, 0.82 EFF	4	5.78	23.12	
PA FANS (4)	16" ΔP, 0.82 EFF	4	0.16	0.62	
ID FANS (4)	16" ΔP, 0.78 EFF	4	1.56	6.24	
ESP (8)		8	0.08	0.62	
SOLIDS HANDLING		4	0.34	1.37	32.8
TURBINE	0.33% OF GROSS kW	1	2.9		2.9
AUXILIARIES					
MAJOR PUMPS					
SERVICE	A/E ESTIMATE	2	0.45	0.9	
BOOSTER	600 PSI, 5.44 MILLION #, 75% x 90%	2	1.70	3.4	
CONDENSATE	185 PSI, 4.86 MILLION #, 70% x 90%	2	0.55	1.1	
CIRC. WATER	PROPORTION TO COOLING HEAT DUTY	3	1.57	4.7	10.1
WATER INTAKE	A/E ESTIMATE	2	0.50		1.0
SOLIDS HANDLING	BASED ON RATES AND LIFTS	1	1.90		1.9
"HOTEL" LOADS	A/E ESTIMATE 1% OF GENERATION	1	8.50		8.5
COOLING TOWER FANS	PROPORTIONAL TO HEAT DUTY	24	0.12		2.8
TRANSFORMERS	0.5% OF GROSS GENERATION	4	1.10		4.4
	TOTAL AUXILIARY POWER =				**64.4**

Table 3.3.2-4 (continued)

Heat Exchanger Characteristics

Advanced Steam Cycle - Atmospheric Fluidized Bed (General Electric, 1976).

HEAT EXCHANGER	NO. OF UNITS	VESSEL SIZE OR TYPE	OUTPUT OR DUTY PER UNIT MM Btu	EFFICIENCY	UNIT SURFACE AREA FT^2	UNIT WEIGHT (FOB) LB X 10^{-6}	UNIT COST (FOB) MM$	HEAT FLUX AVERAGE Btu HR^{-1} FT^{-2}
AFB MODULE	4	76'x33'x178'	1707	87.92%	160726	3.54	5.1*	10620

* HEAT EXCHANGE SURFACES AND PRESSURE PARTS ONLY

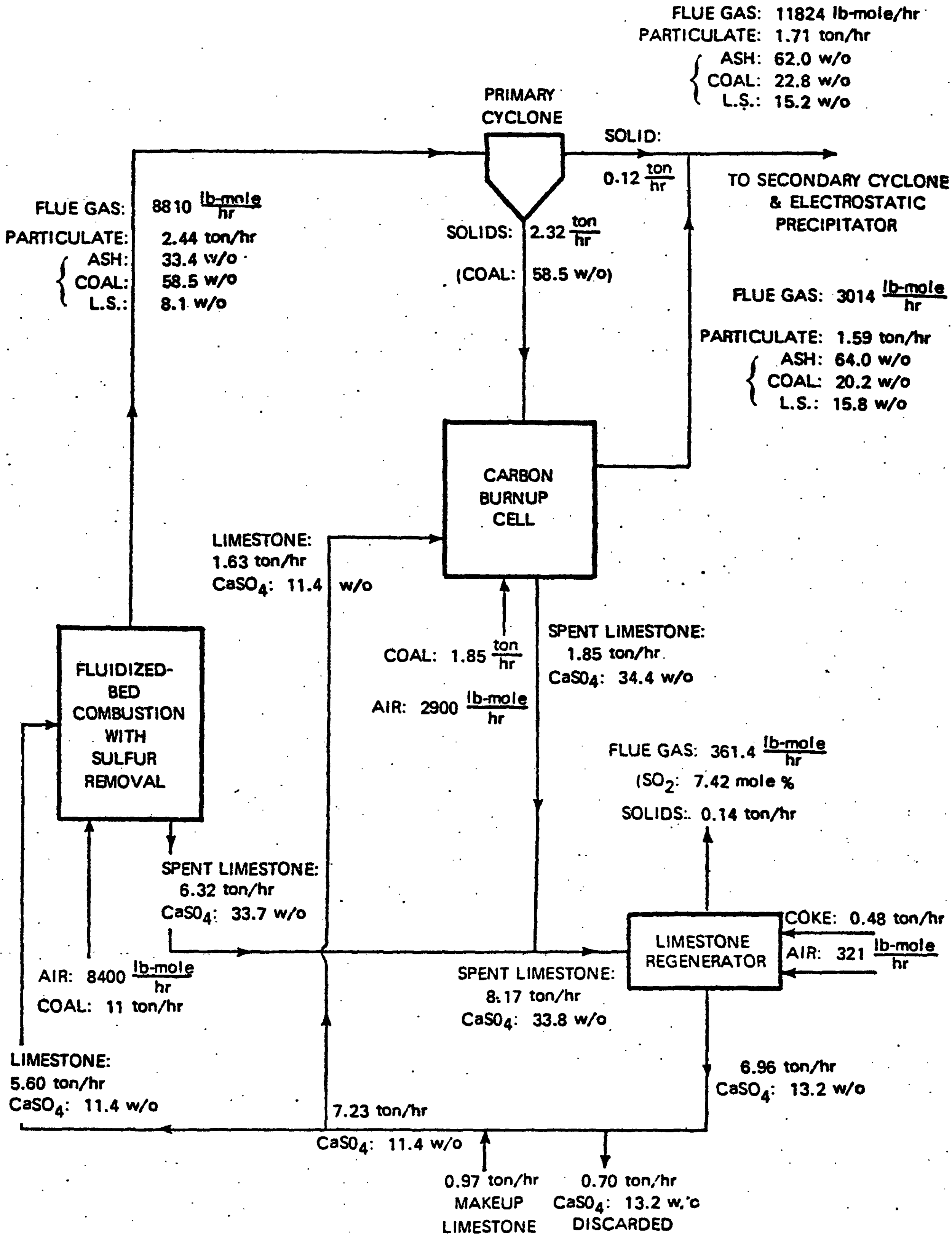


Figure 3.3.2-8

Overall Material Balance (Archer, Keairns, Yang, 1970).

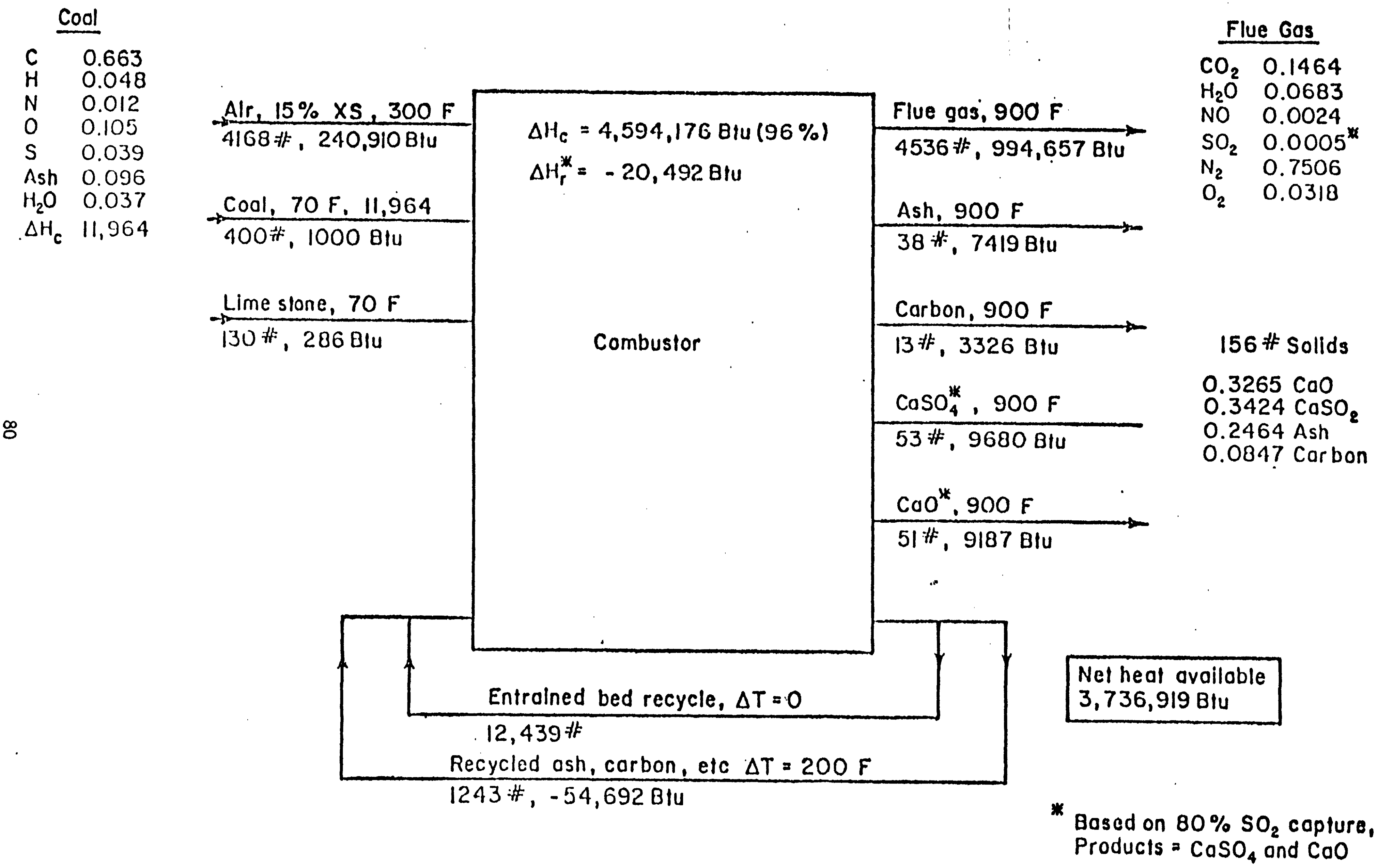


Figure 3.3.2-9

Example Heat and Material Balance for the SSEUS

Sub-Scale Experimental Unit Multi-Solids FBC (Weller, Nack, 1976).

Combustion efficiency, consisting of losses due to elutriated solid carbon and unburned combustibles, such as CO and hydrocarbons, has been the topic of a great deal of research. These analytic and experimental studies have been motivated by attempts to optimize the conceptual designs of FBC modules. The combustion efficiency information from the General Electric design was shown in Table 3.3.2-4 and a review of atmospheric FBC combustion efficiency experiments is shown in Table 3.3.2-5. These investigations have resulted in several general conclusions; one is that the unburned hydrocarbons do not represent a significant portion of the combustion losses, and are particularly insignificant when the oxygen in the flue gas is greater than 2% (see Figure 4.1.2.3-1). A second general conclusion is that bed design is critical in determining combustion efficiency. In (Archer et al., Nov. 1971, Vol. II), measurements indicate that much of the CO in the gas leaving the bed is formed from the reduction of CO_2 by carbon fines in the region 5 to 8 inches above the bed, where the temperatures are 200°C higher than bed averages.

In (Bloom et al., 1977) it is shown that, with proper design, combustion efficiencies can easily exceed 95 percent. This conclusion, however, requires the further combustion of the carbon fines, as the combustion efficiency of a "once-through" system is generally less than 92 percent. The two existing methods for the use of the fines are (1) the carbon burnup cell (Pope, Evans, and Robbins, June 1974, PB 236 254) in which the fines are fed to a separate bed running at higher temperature and with higher excess air, and (2) recycling the fines back to the original bed, (McLaren and Williams, August 1969) and (Rice and Coats, 1971). These references show an improvement in combustion efficiency from 85 up to 99 percent for the carbon burnup cell and from 93.3 up to 99.5 percent for fines return.

In (Bloom et al., 1977) it is speculated that the most suitable method for use of fines in systems with velocities greater than 10 fps is the carbon burnup cell and below 10 fps is the fines return. In addition to changing the strategy for use of fines, gas velocity has a more direct effect on combustion efficiency in that for increased gas velocities the time for the combustion is decreased and elutriation is increased. This effect has been shown experimentally (see Figures 3.3.2-10 and 11), and substantiated by other tests (McLaren and Williams, 1969). Tests on the effects of excess air, again similar to (McLaren and Williams, 1969) results, show a clear decreasing marginal return in efficiency for excess air greater than 15 percent, see Figures 3.3.2-12 and -13.

Increases in temperature, of course, also promote combustion efficiency, as shown in Figures 3.3.2.-14 and 15. Although efficiency would certainly increase at bed temperatures greater than 1800°F other problems such as ash agglomeration, volatilization of alkalis, and rapid drops in efficiencies of sulfur sorbents currently outweigh the combustion efficiency advantages at these higher temperatures. Effects of sorbent particle size on efficiency are shown in Figure 3.3.2-16.

On the basis of these parameteric studies and the EPRI data base (Strom, et al., 1976) an empirical model has been fit to the atmospheric combustion efficiency data (Gruhl, Tung, Schweppe, 1978).

This model is shown in Table 3.3.2-6 with scatterplot in Figure 3.3.2-17.

Table 3.3.2-5

Summary of the Results of Combustion Losses from Experiments Conducted by OAP Contractors and NCB Laboratories at Atmospheric Pressure (Archer, Staly, Nov. 1971, Vol. 2).

ORGANIZATION	REACTOR SIZE	BED MATERIAL	PARTICLE SIZE	BED TEMPERATURE (°F)	EXCESS AIR (%)	FLUIDIZING VELOCITY (FT/SEC)	FINES RECYCLE	TUBE IN BED	CARBON LOSS (%)	CO LOSS	HYDROCARBON LOSS	REFERENCE
PER	12" x 16"	Limestone BCR 1359	Bed:-10+28 mesh Coal:-1/4 x 0	1510-1620	5, 15 & 25	8-12	No	No	10-14	0.4-0.5% at 5% excess air; negligible at excess air >10%	<0.1%	[77] (b)
PER-Carbon Burn-up Cell Tests (Burn up Cell by itself)	12" x 15"	Coal Ash	600 - 1400	1750-2000	10-65	10-15	No	No	Combustion efficiency ranges from 65% to 90%			[27]
PER-Integrated FBM/CBC Tests	FBM 20" x 6' CBC 20" x 20"	Coal Ash	Bed:-8+16 mesh Coal: -1/4 x 0	FBM: 1590-1700 CBC: 1300-2050	5-27 overall	—	Recycle to CBC	No	1.6-6.4	—	FBM: 0-370 ppm CBC: 0-600 ppm	[76]
USBM	18" diameter	refractory	Bed:-16+48 mesh Coal: 1/8" x 0	1450-1650	8.6-37.0	2.4-3.4	Recycle to original bed	Yes	<1.3	Carbon burn-up efficiency ranges from 86% to 99.8%		[15]
ESSO	3" diameter	Limestone BCR 1359	Bed: 450μ, 930μ Coal: 200μ	1500-1800	5-30	2.6	No	No	3-13	450-750 ppm	—	[22]
Argonne	5" diameter	alumina	Bed: 30 mesh Coal: -14 mesh	1600	10-20	3	No	No	3-7	—	—	[3]
BCURA	12" diameter	refractory	Bed:-1/8" x 30 mesh; Coal: -1/4"+1/16"; 1/8" -0	1380-1800	0-90	7.2-10.6	No	Water cooling jackets	~20	—	—	[34]
BCURA	27" diameter	refractory or ash	Bed:-1/4"+ 30 mesh; Coal:-1/4" x 0; -1/8" x 0	1300-1330	0-90	7-14	Partial recycle to original bed	Yes	4-14	0.4% at 6% excess air 0.1% at 90% excess air	—	[42,35]
NCB-CRE	6" diameter	ash	Bed:-10 mesh Coal: -10 mesh	1300-1470	0-55	1-3	With & without recycle back to original bed	cooling coil	≤7% without recycle ≤1% with recycle	0.2-0.9% at 1300° F <0.3% at 1470° F	—	[7,1,23]
NCB-CRE	12" diameter	ash	Coal:-1/16"	1560	4-6	3	Partial recycle	Yes	6-7%	0.07-0.09 in flue gas	—	[71]
NCB-CRE	3 ft square	ash	Coal:-10 mesh	1300-1560	+30 to -30	2-4	No	No	10-25	<0.2	—	[70,101]
NCB-BCURA[a]	48" x 24"	ash	Bed: -1/16" Coal: -1/16"	1470	10-35	2	Recycle to original bed	Yes	1.3	<0.03%	—	[69]

NOTE: PER - Pope, Evans, and Robbins, Consulting Engineers, Alexandria, Virginia
USBM - U.S. Bureau of Mines at Morgantown, West Virginia
ESSO - ESSO Research and Engineering Company, Linden, New Jersey
Argonne = Argonne National Laboratory
BCURA - British Coal Utilization Research Association, England
NCB-CRE = National Coal Board Research Establishment, England

(a) Operating pressure at 1.5 atm.

(b) (Archer, et al., Nov. 1971, Vol. 2).

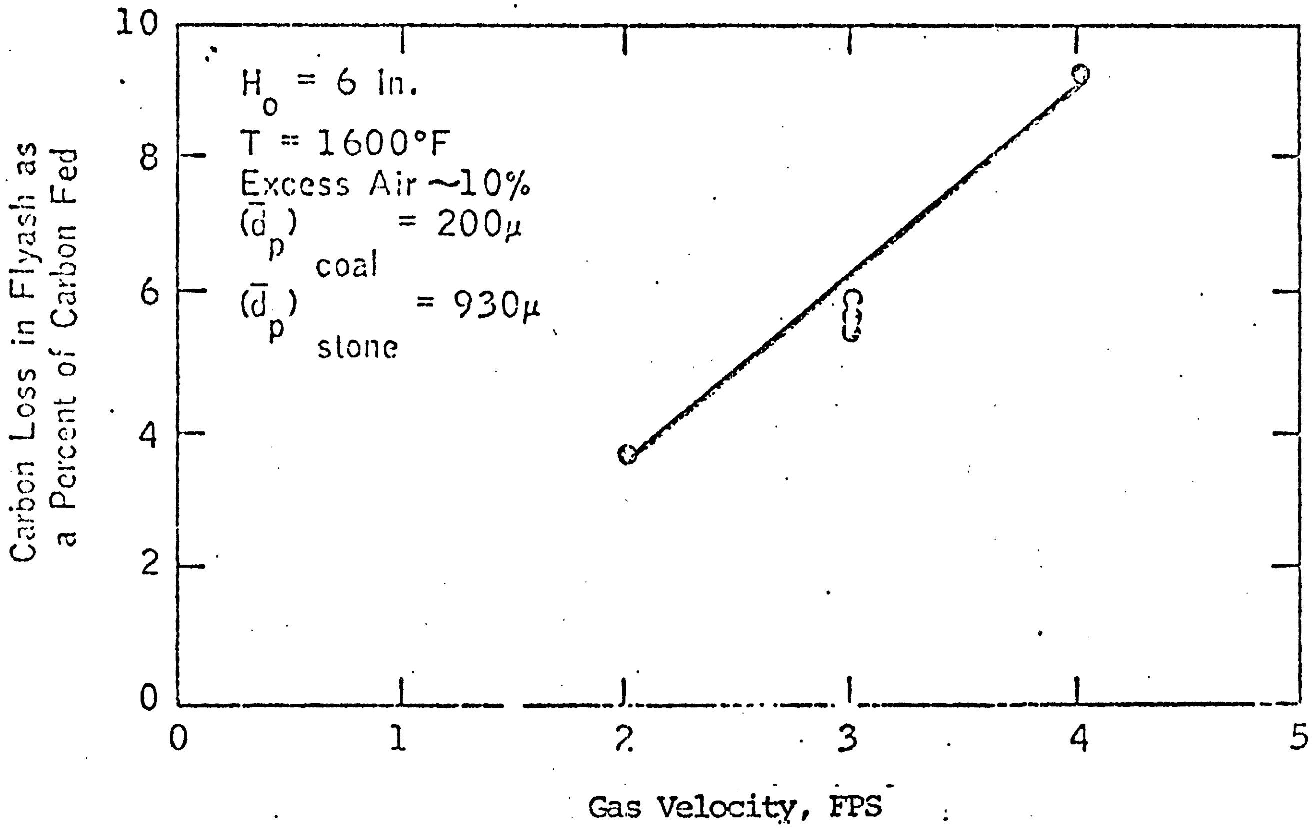


Figure 3.3.2-10

Effect of Superficial Gas Velocity on Combustion Efficiency (Hammons and Skopp, 1972).

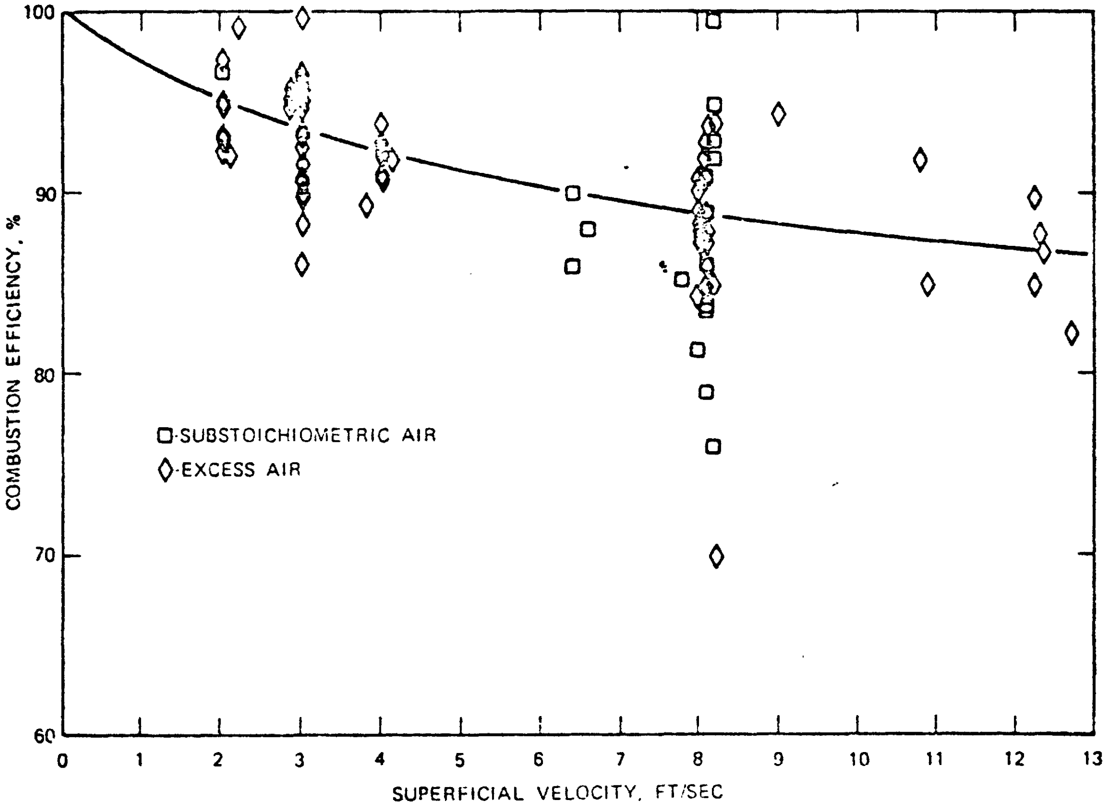


Figure 3.3.2-11

Combustion Efficiency **Versus** Superficial Velocity (Strom, et al., 1976).

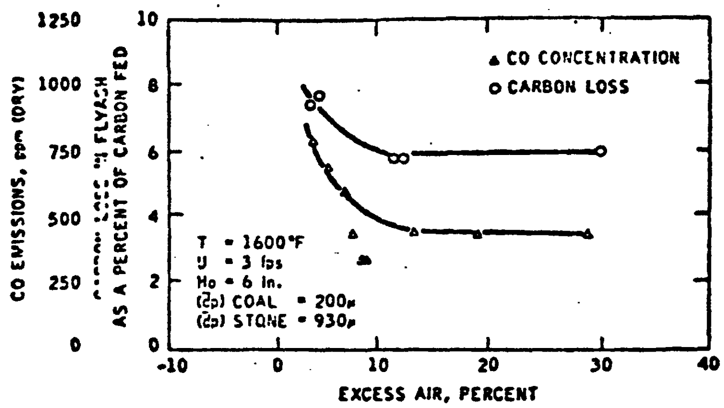


Figure 3.3.2-12

Combustion Efficiency not Affected by Excess Air in 10 to 30 Percent Range (Rice and Coats, 1971).

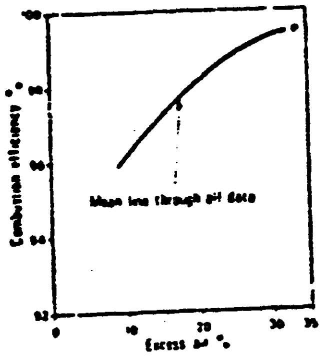


Figure 3.3.2-13

Combustion Efficiency Versus Excess Air in Fluidized Combustion (Locke, Lunn, Hoy, Roberts, 1975).

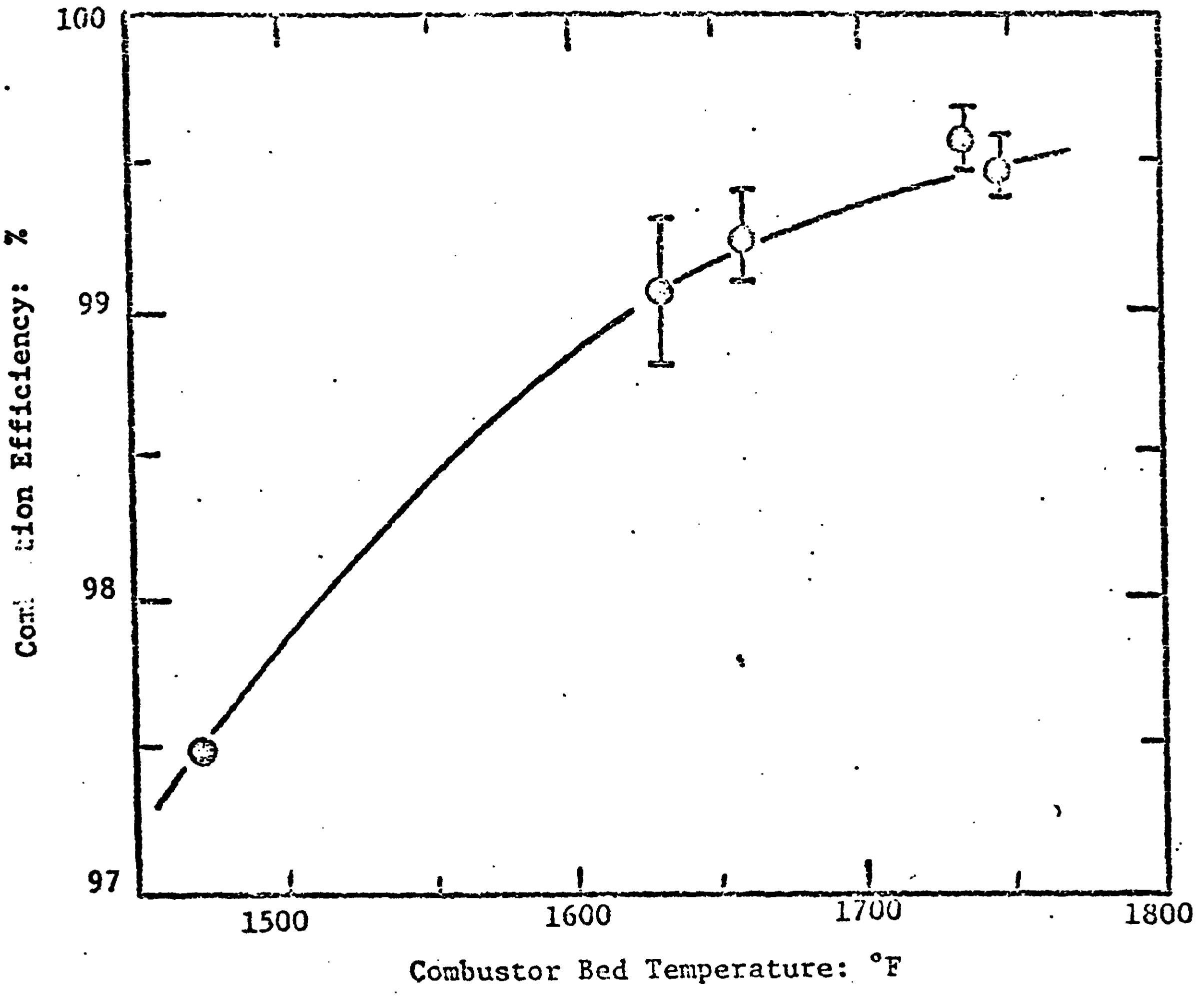


Figure 3.3.2-14

Effect of Temperature on Combustion Efficiency in the BCURA Pressurized Combustor (U.K. Nat. Res. Dev. Corp., 1973).

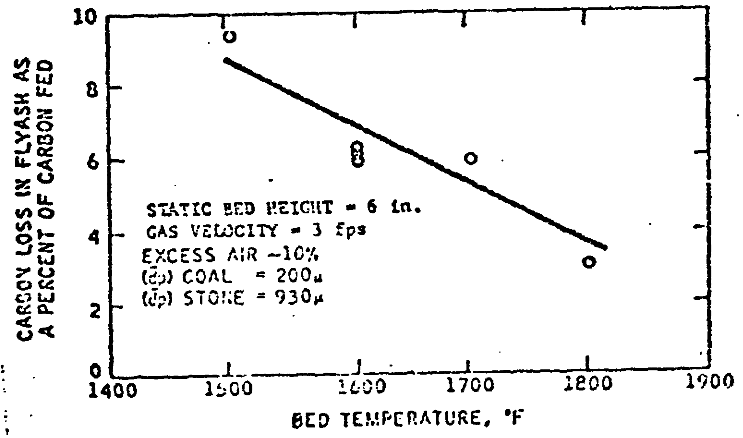


Figure 3.3.2-15

Effect of Temperature on Carbon Losses Data of Esso Research & Engineering Co. (Hammons and Skopp, 1972).

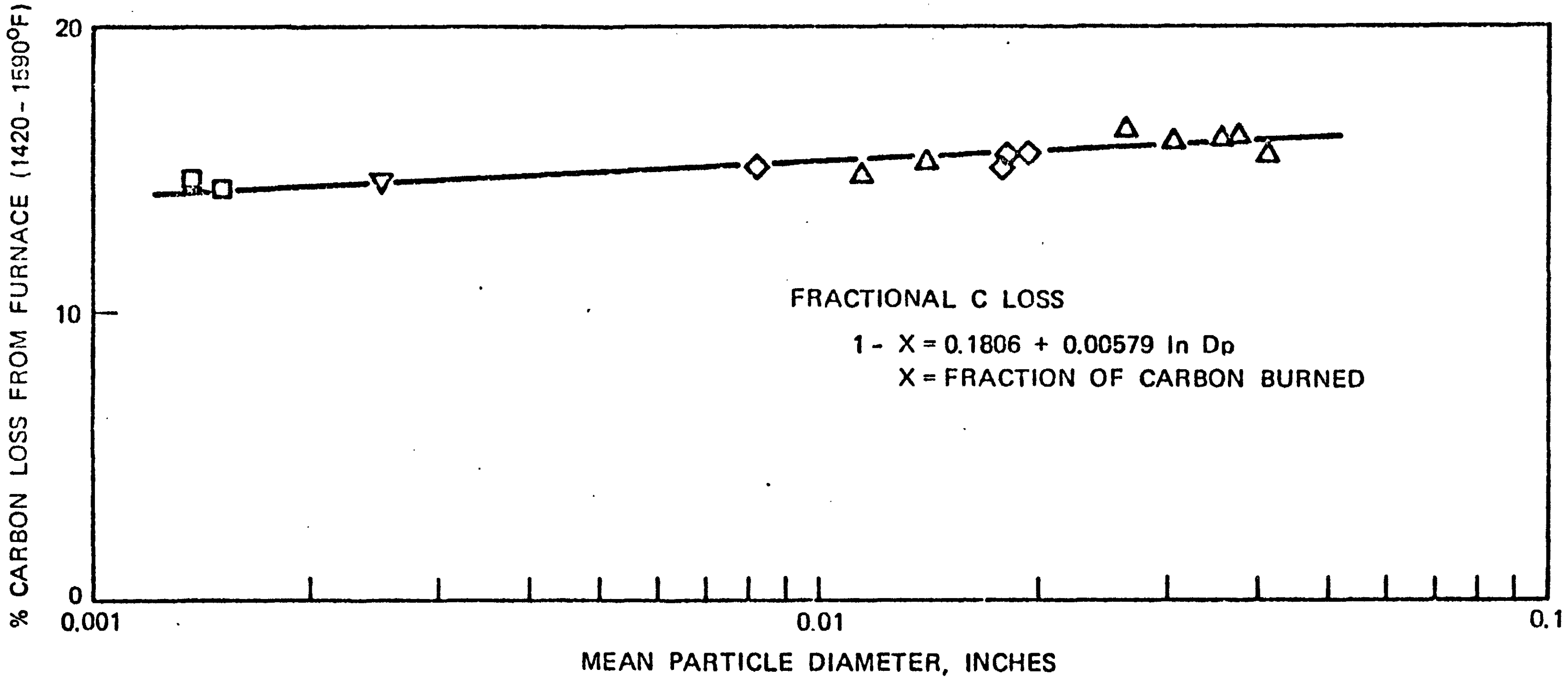


Figure 3.3.2-16

Percent Carbon Loss from the Furnace Versus Sorbent Feed Size

(Babcock and Wilcox, 1977).

Table 3.3.2-6 Empirical models of combustion efficiencies for which values of all modeling parameters were available(Gruhl, et al.,1978)

Symbols:

E = combustion efficiency, in percent
V = superficial velocity, in m/sec
D = static bed depth, in cm
X = excess air, in percent
A = bed area, in square meters
C = calcium to sulfur mole ratio
F = 1 or 0 indicator of fines recycled or not
M = calcium particle mean size, in microns

Model based upon parametric experiments and examination of trends:

$$E=96.[1.-.036V][1.+.011\mathrm{max}(-4.,[4.-.787D])](.972+.0035D)*$$

$$(.97+.008\mathrm{abs}[\mathrm{min}(7.,X)]\ )$$

Model based on data base for all experiments and least squares, rather than main trend, modeling:

$$E = 77.79 + 14.11(1.- .1434V)(1.+.02433\mathrm{max}[-4.,(4.-.787D)])(1.+.0746*$$

$$\mathrm{abs}[\mathrm{min}(7.,X)])(1.-.215A)(1.-.038C)(1.+.231F)(1.-.00016M)$$

[fit=arithmetic stand dev 2.95%]
on 144 experiments

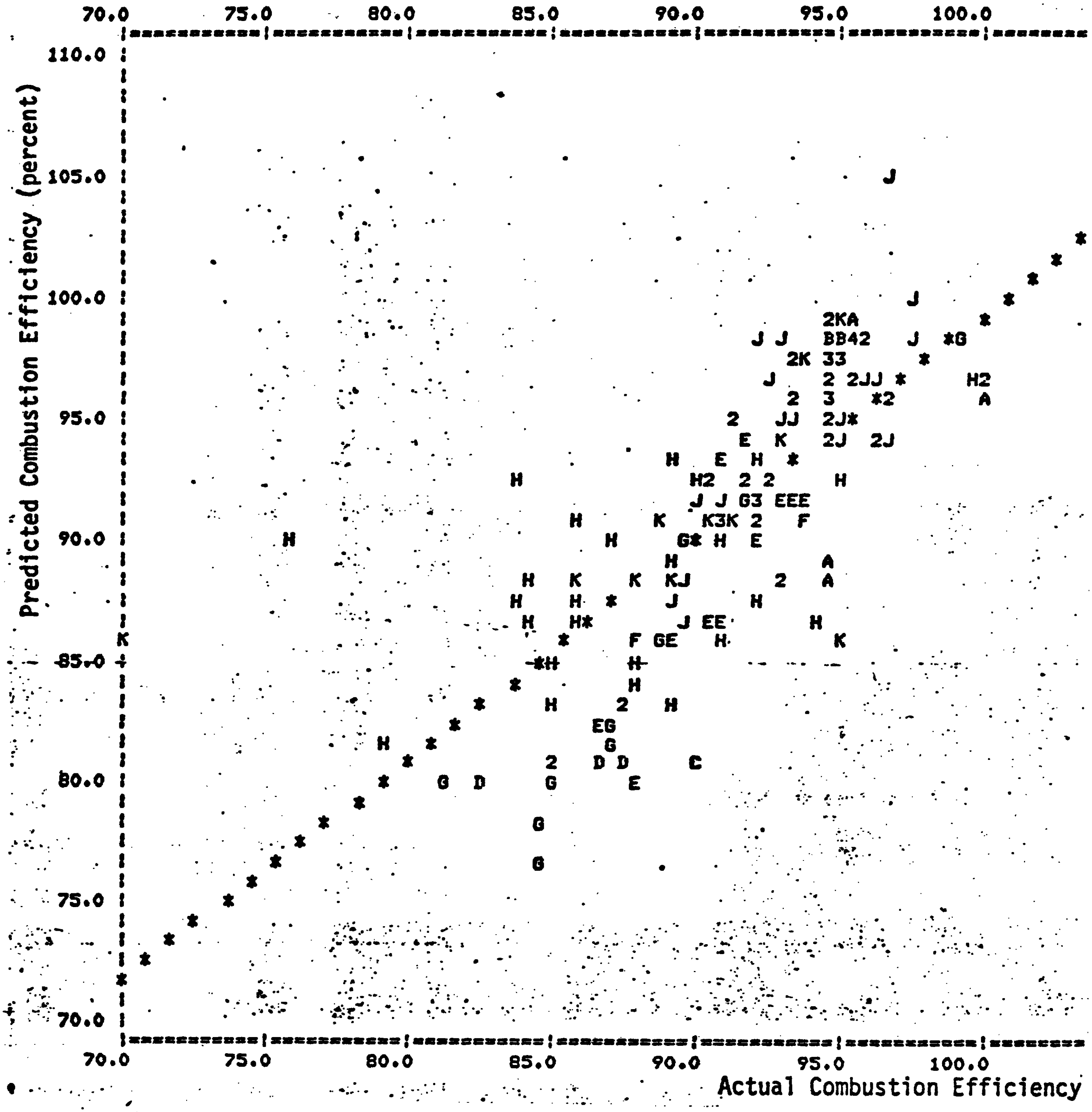


Figure 3.3.2-17 Scatterplot of combustion efficiency as observed versus predictions based on a data based developed model, the least squares fit criterion concentrates on reducing outlyers, robust estimation techniques could be used to cluster the mass of points while ignoring outlyers (Gruhl, Tung, Schweppe, 1978).

An empirical regression model was fitted by Pope, Evans, and Robbins to data from an FBC fitted with a carbon burnup cell (Ehrlich, 1970, PB 231 977). Although this fitting was done to data outside of the range of current combustion efficiencies, that is, the data is in the range from 65 to 90 percent, this is the only published data from the carbon burnup cell configuration. The formula developed was

$$L_c = 112.12 - .0935T - .367A - 1.028D + 6.93\,C + 1.51I - .170C\,I$$

(gsd = 1.12 = geometric standard deviation of the fit to the experimental data)

where

L = combustion losses

T = bed temperature, °F;

A = air rate, hr/lb;

D = static bed depth, in.;

C = carbon rate, hr/lb; and

I = inert rate, hr/lb.

This formula fits the data in (Ehrlich, 1970, PB 231 977) with 0% arithmetic mean for the difference between predicted and actual data and 2.21% arithmetic standard deviation. A later version of this model, based on studies of various numbers of feedpoints, does not show the accuracy of this earlier model (see Figure 3.3.2-18). There are, however, quite a few more points and the different design changes which both have an effect on the fit of correlation models.

Recycling of fines can have an order of magnitude effect on combustion efficiency and is likely to depend on the coal type used. Some preliminary research on industrial application of FBC's shows some results for different coal (see Figure 3.3.2-19).

3.3.3 Pressurized FBC Energy Balance

Here again the analytic predictions of overall plant efficiency are presented first with the experimental data on combustion efficiency presented later.

The results of the Westinghouse ECAS parametric investigations are shown in Figures 3.3.3-1 through -11. The model that fits these results is:

E_p = overall plant efficiency %

n = parameter for type of coal

n = 1.000 for bituminous

n = 1.040 for subbituminous

n = 1.015 for lignite

I_t = gas turbine inlet temperature, °F 1600 to 1800

P_r = gas turbine pressure ratio, 5 to 15

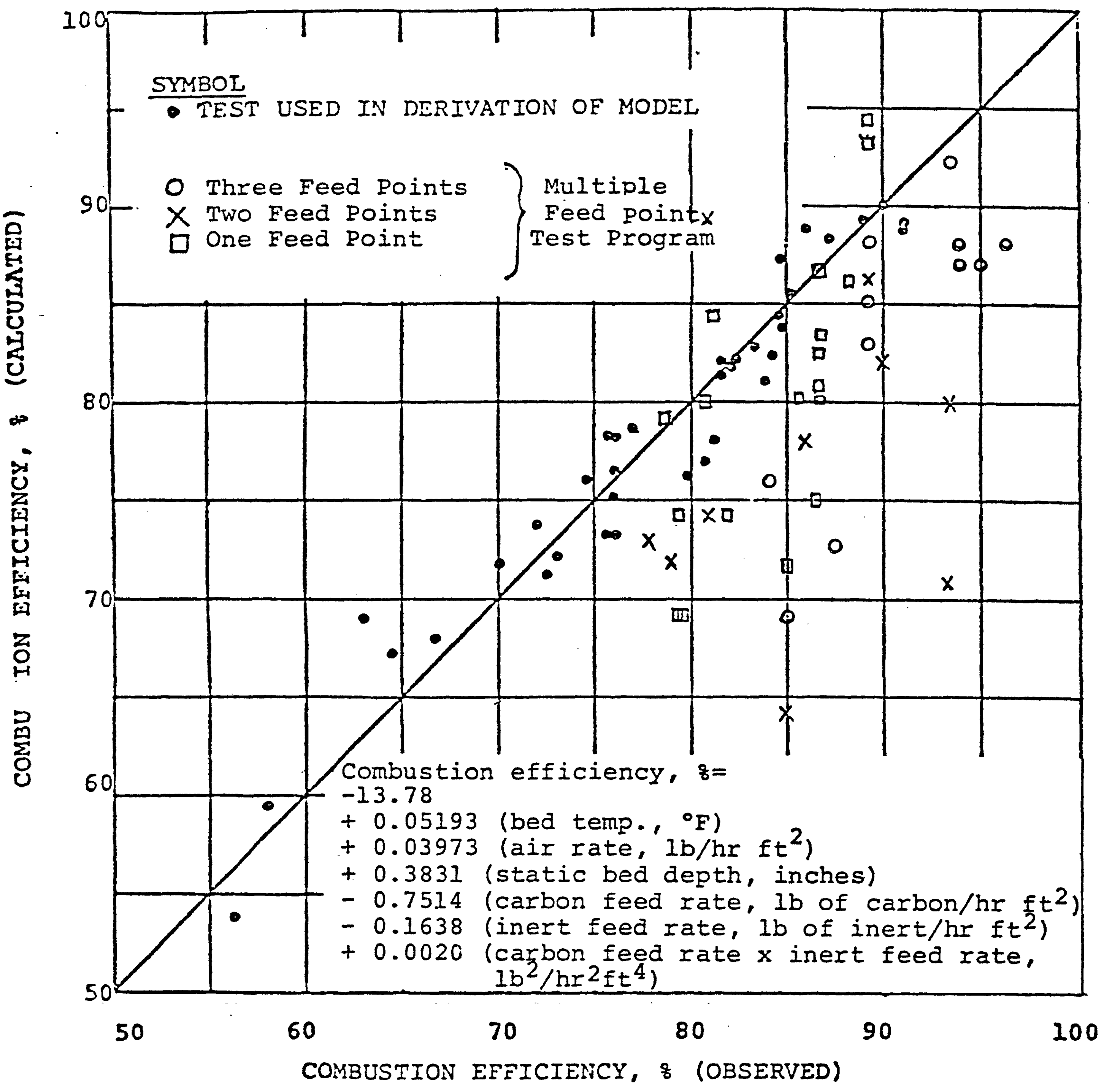


Figure 3.3.2-12

Comparison of Observed and Calculated Combustion Efficiency Using Equation from Previous One Feeder Tests (Reed, 1977).

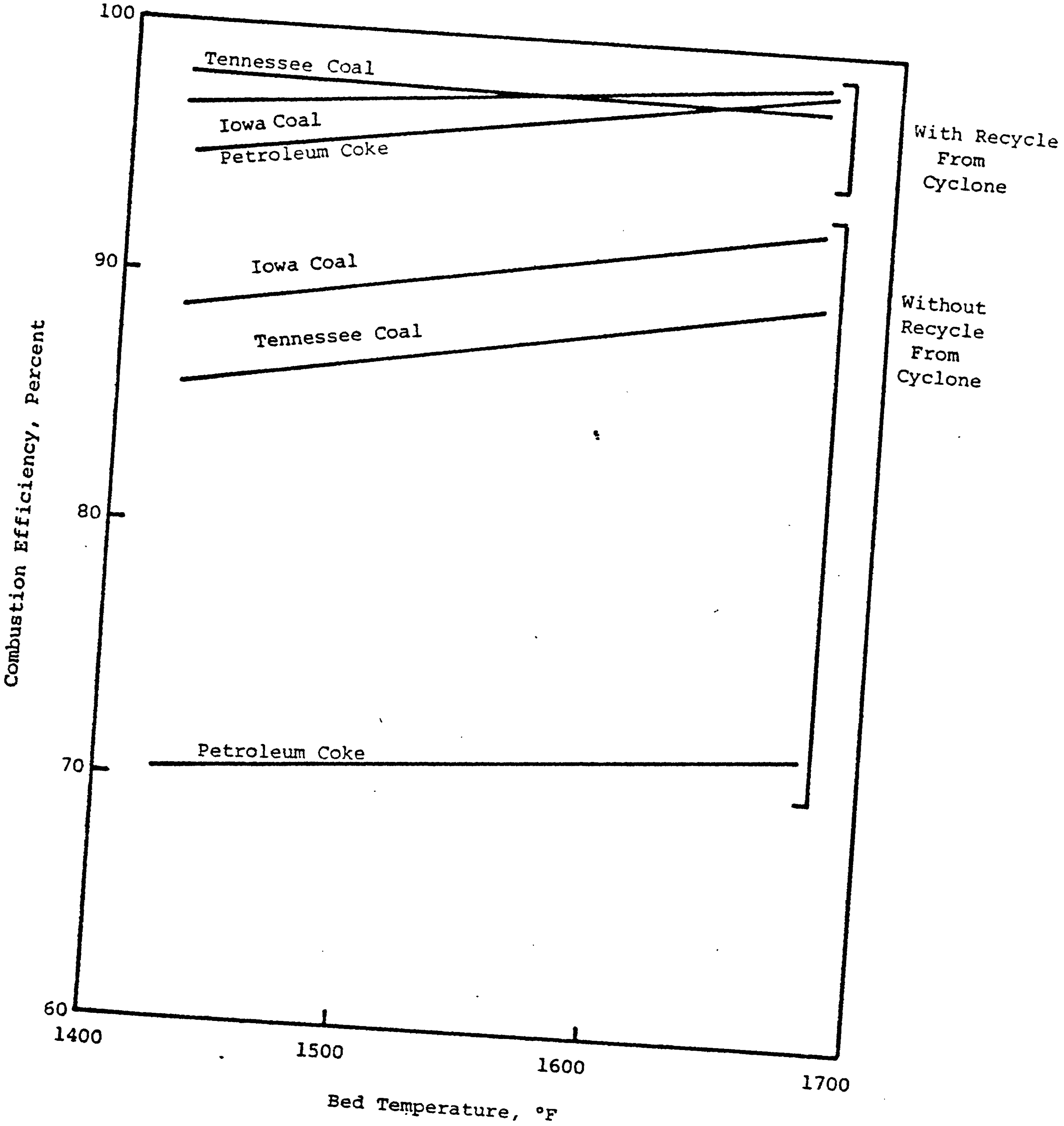


Figure 3.3.2-19

Combustion Efficiency Vs. Bed Temperature Measured in 18" FBC Test Program (Hanson, DeCoursin, 1977).

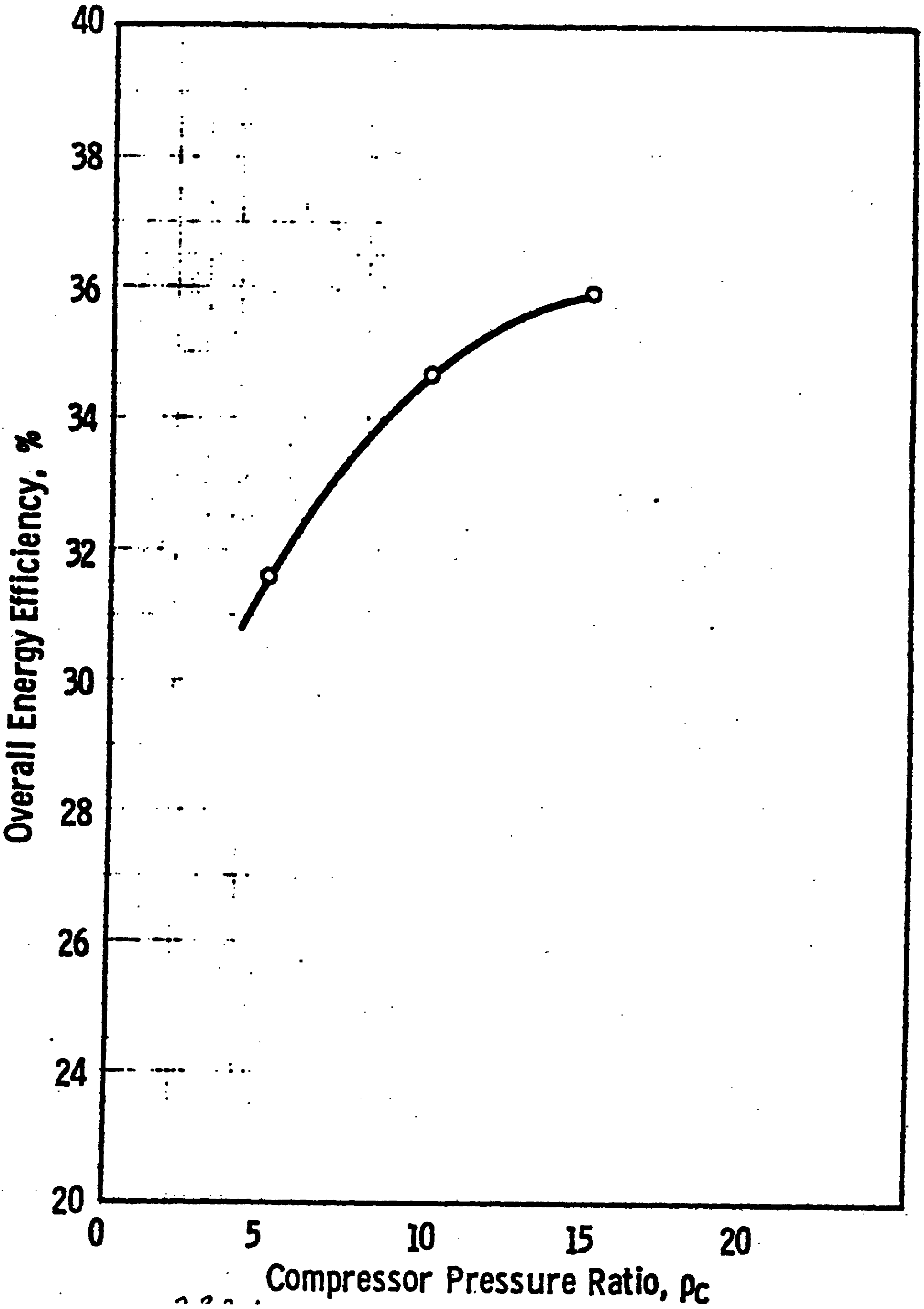


Figure 3.3.3-1

Effect Compressor Pressure Ratio on Overall Energy Efficiency for a Pressurized Fluidized Bed Boiler Plant (Wolfe, et al., 1976).

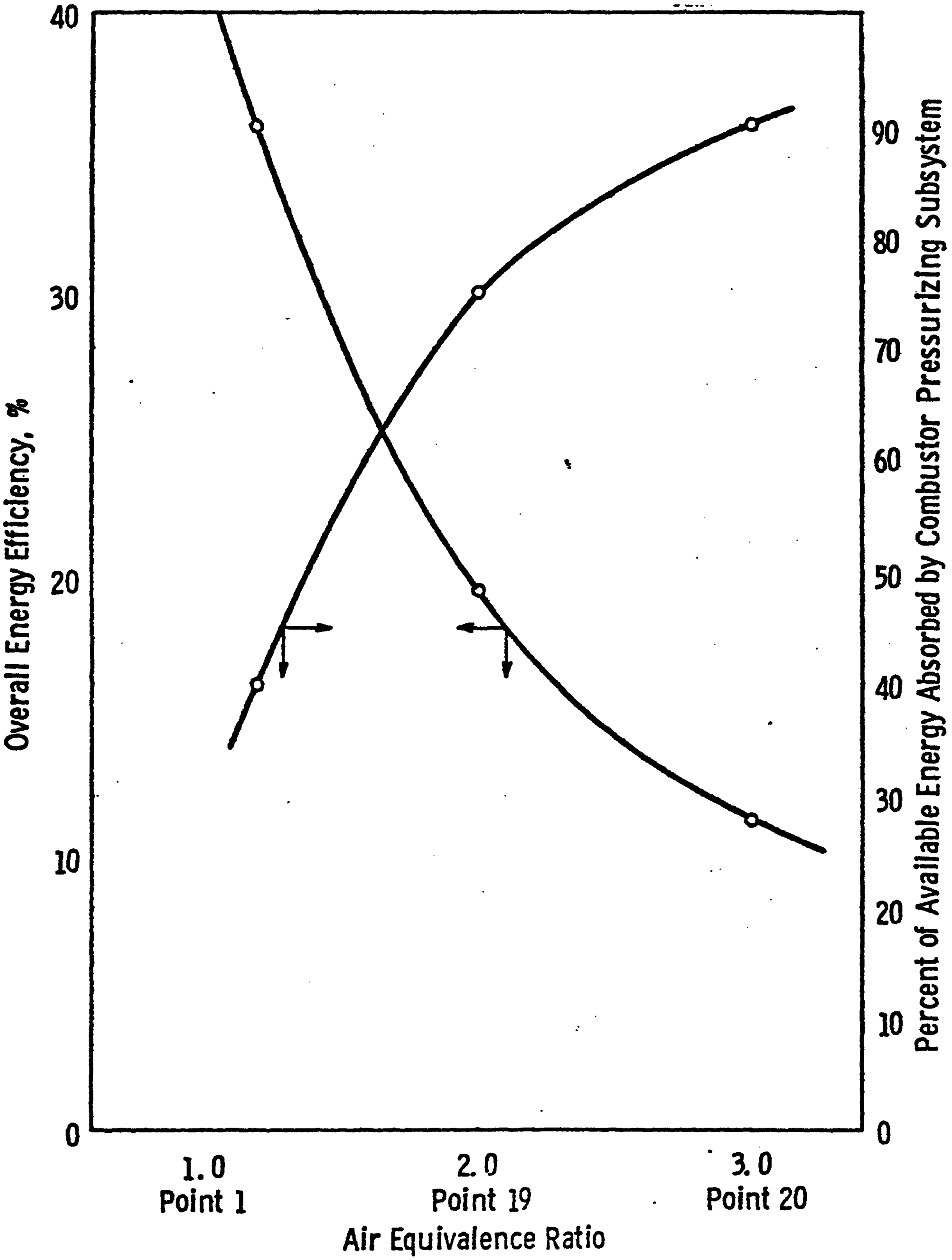


Figure 3.3.3-2

Effect of Air Equivalence Ratio Variation on Overall Energy Efficiency for a Pressurized Fluidized Bed Boiler Plant (Wolfe, et al., 1976).

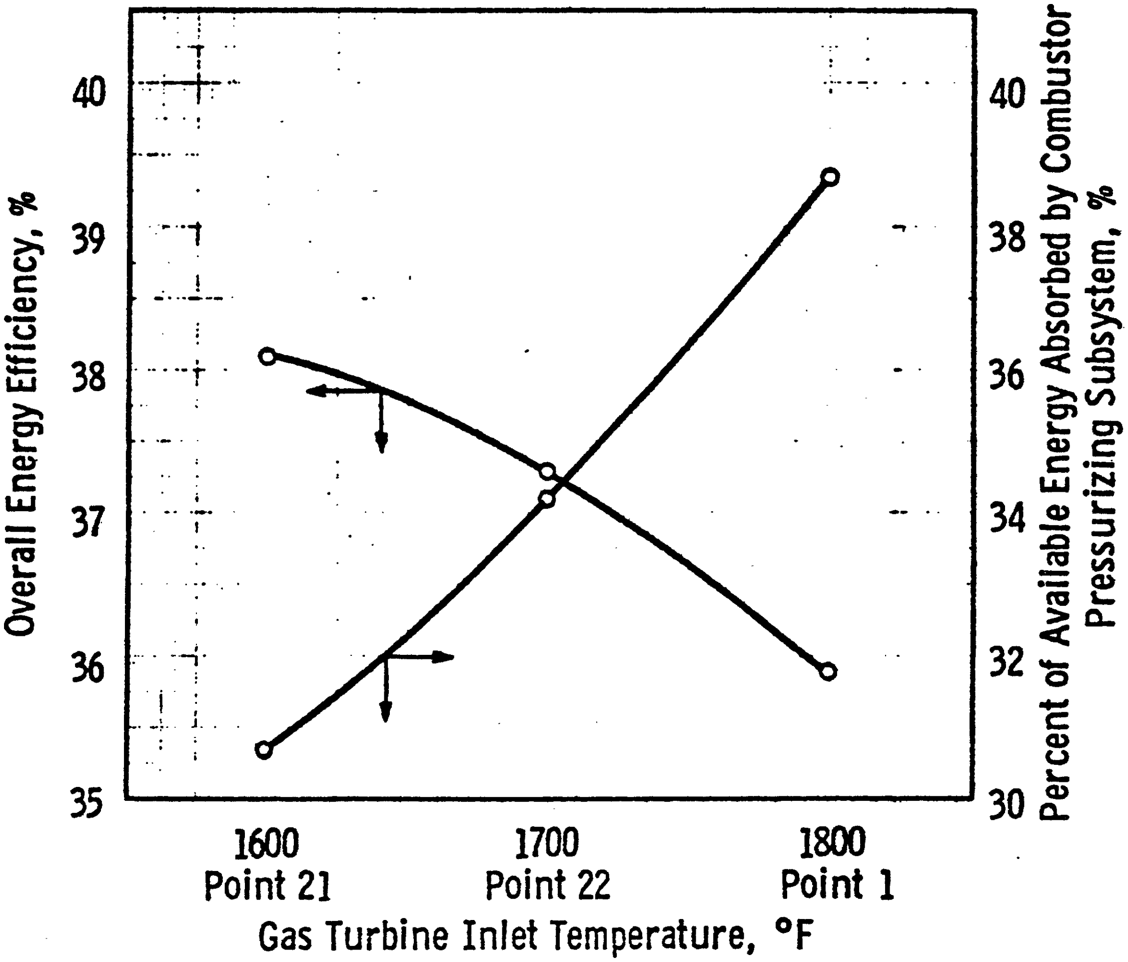


Figure 3.3.3-3

Effect of Gas Turbine Inlet Temperature on Overall Energy Efficiency for a Pressurized Fluidized Bed Boiler Plant (Wolfe, et al., 1976).

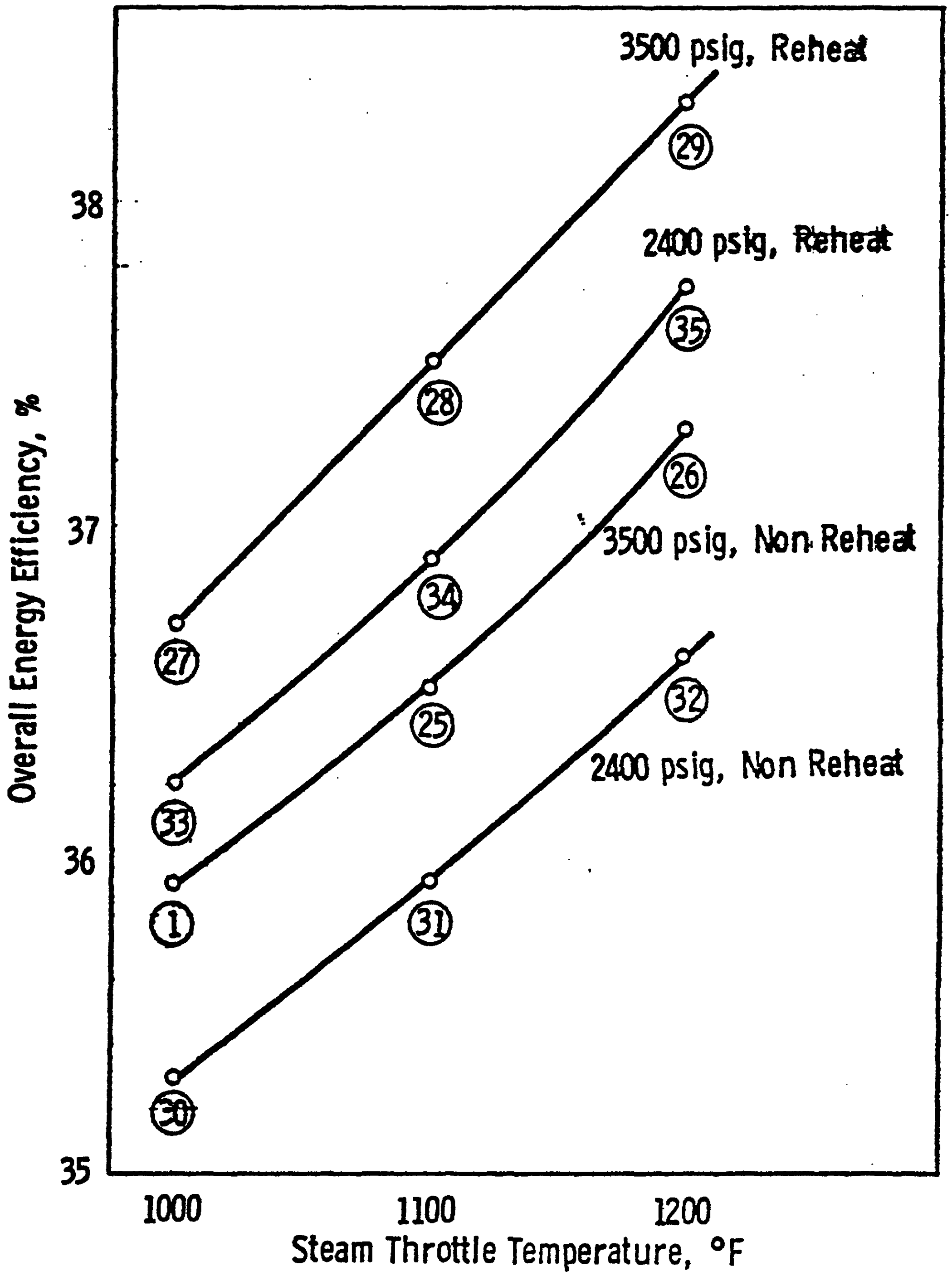


Figure 3.3.3-4

Effect Steam Throttle Temperature on Overall Energy Efficiency for a Pressurized Fluidized Boiler Plant (Wolfe, et al., 1976).

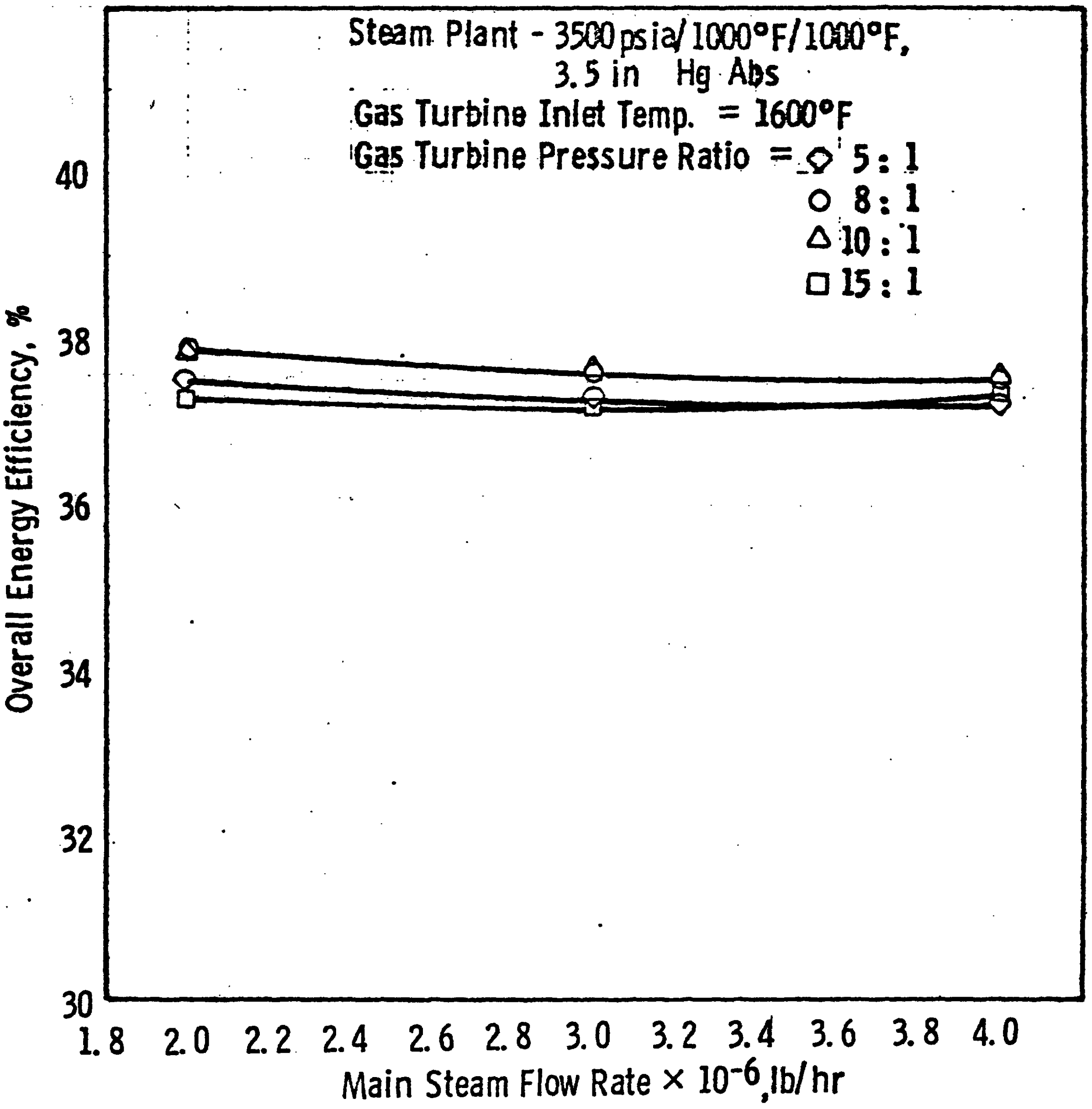


Figure 3.3.3-5

Effect of Steam Flow Rate and Pressurizing Gas Turbine Pressure Ratio on Overall Efficiency for a Nominal 600 MWe Steam Plant with a Pressurized Fluidized Bed Boiler (Wolfe, et al., 1976).

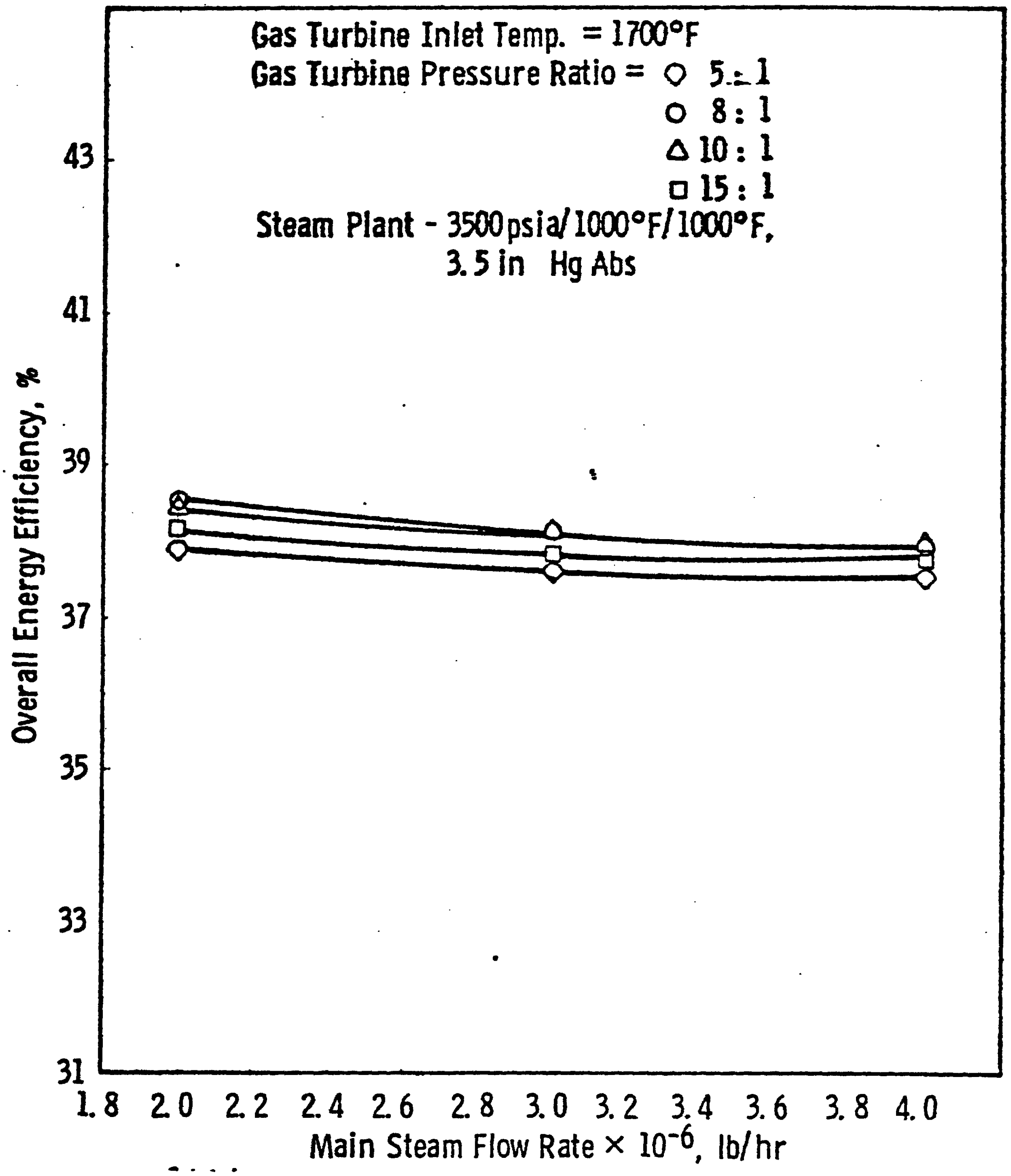


Figure 3.3.3-6

Effect of Steam Flow Rate and Pressurizing Gas Turbine Pressure Ratio on Overall Efficiency for a Nominal 600 MWe Steam Plant with a Pressurized Bed Boiler (Wolfe, et al., 1976).

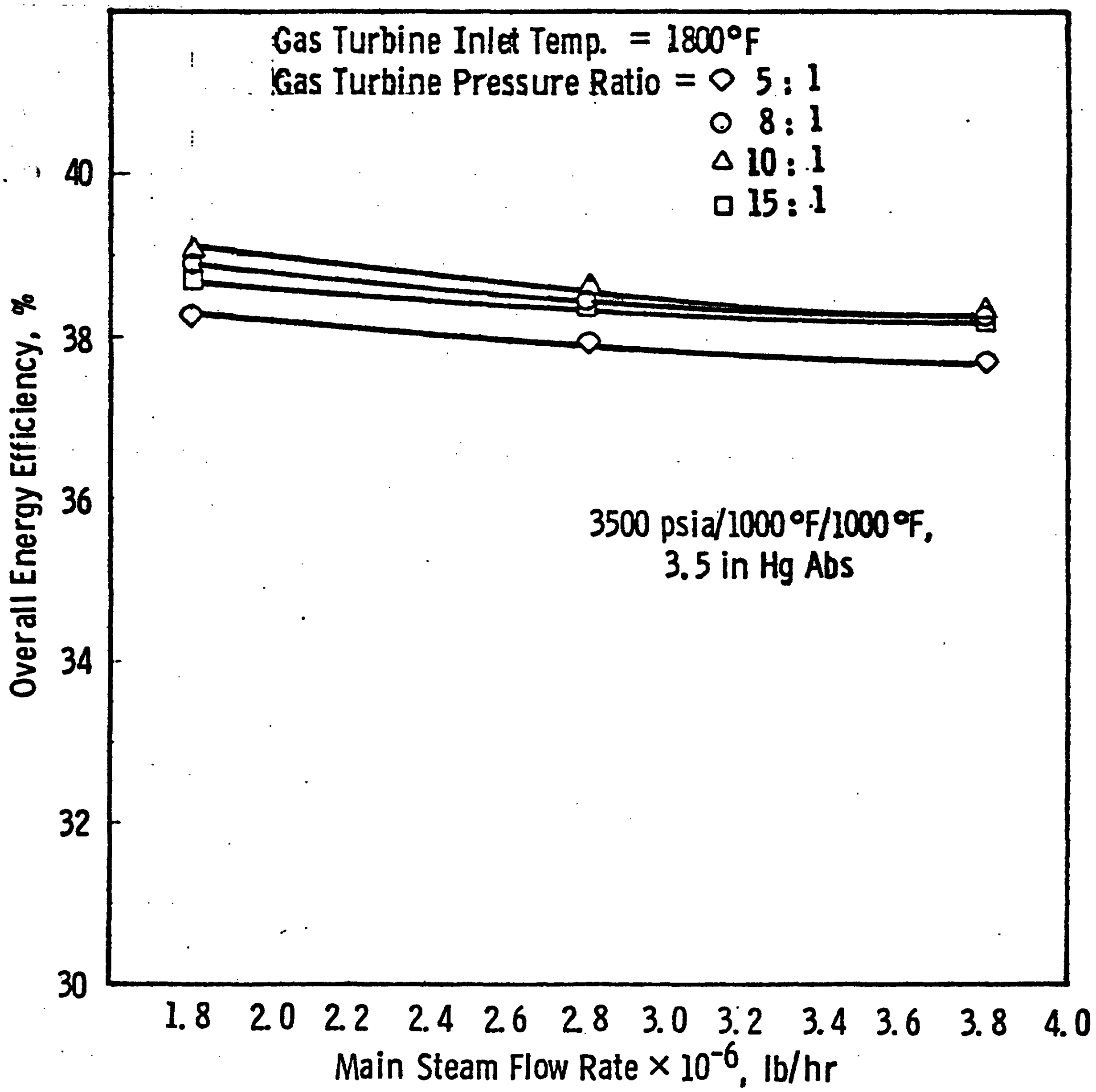


Figure 3.3.3-7

Effect of Steam Flow Rate and Pressurizing Gas Turbine Pressure Ratio on Overall Efficiency for a Nominal 600 MWe Steam Plant with a Pressurized Fluidized Bed Boiler (Wolfe, et al., 1976).

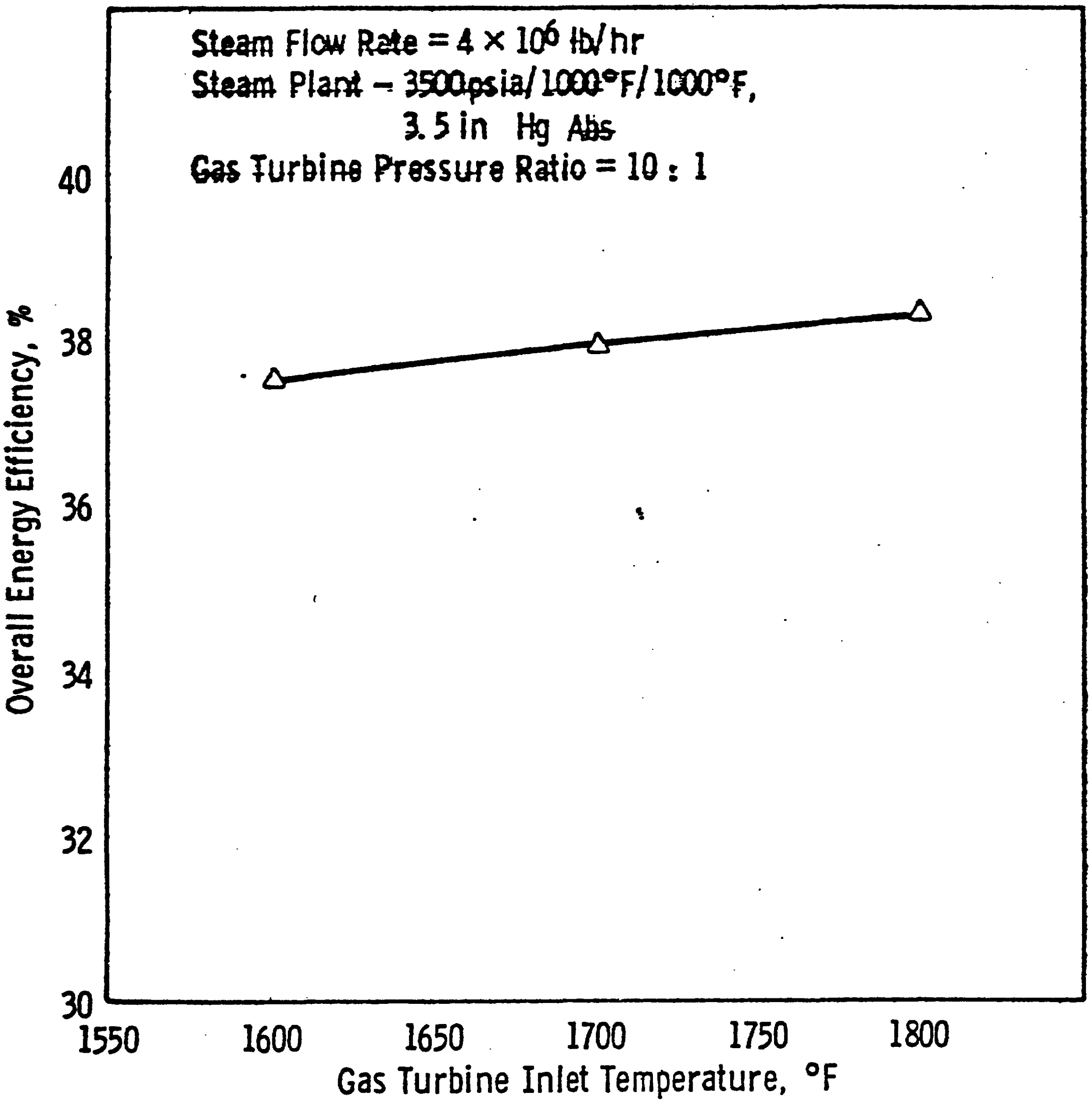


Figure 3.3.3-8

Effect of Pressurizing Gas Turbine Inlet Temperature on Overall Efficiency for a Nominal 600 MWe Steam Plant with a Pressurized Fluidized Bed Boiler (Wolfe, et al., 1976)

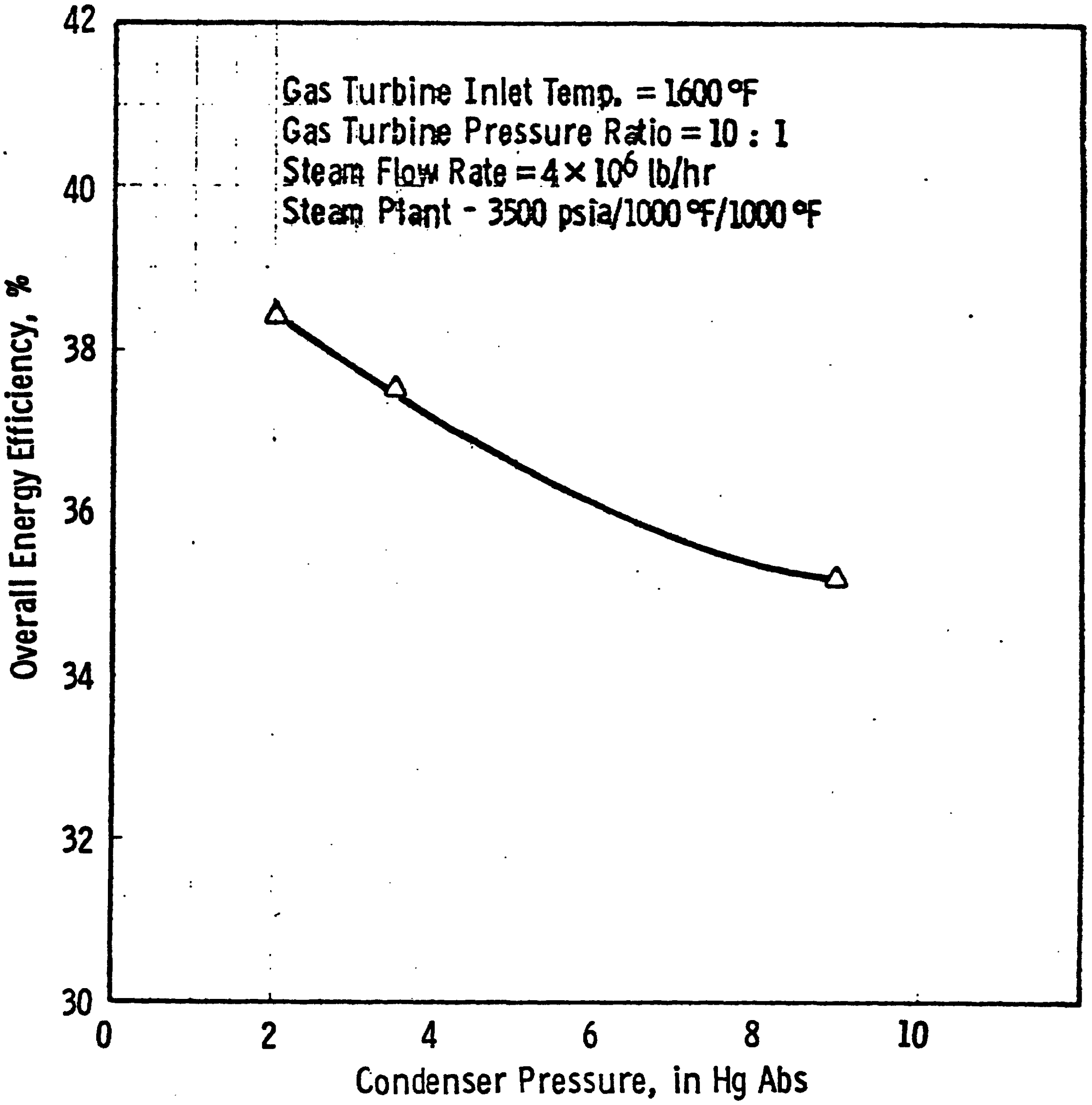


Figure 3.3.3-9

Effect of Condenser Pressure on Overall Efficiency for a Nominal 600 MWe Steam Plant with a Pressurized Fluidized Bed Boiler (Wolfe, et al., 1976).

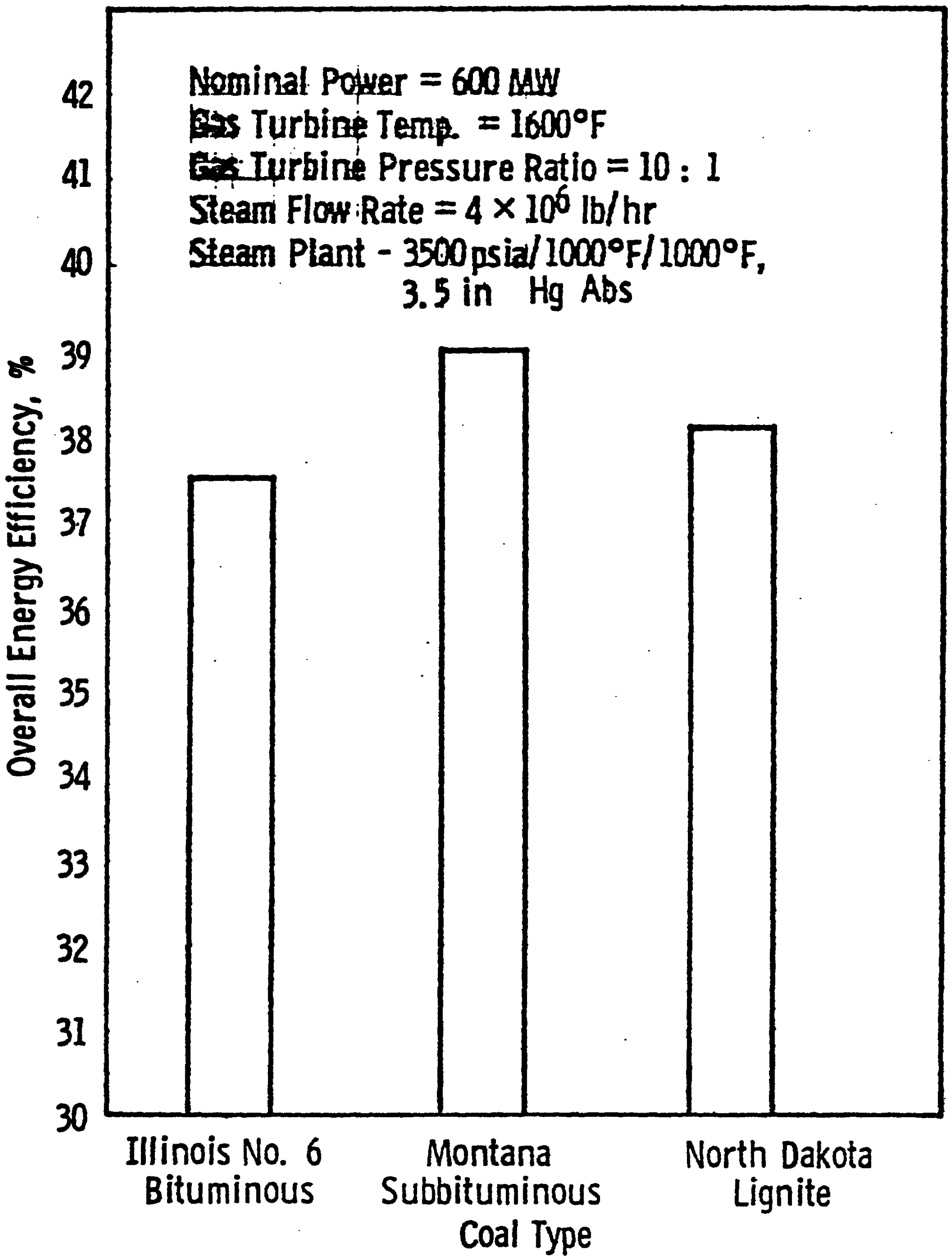


Figure 3.3.3-10

Effect of Coal Type on Overall Efficiency for a Nominal 600 MWe Steam Plant with a Pressurized Fluidized Bed Boiler (Wolfe, et al., 1976).

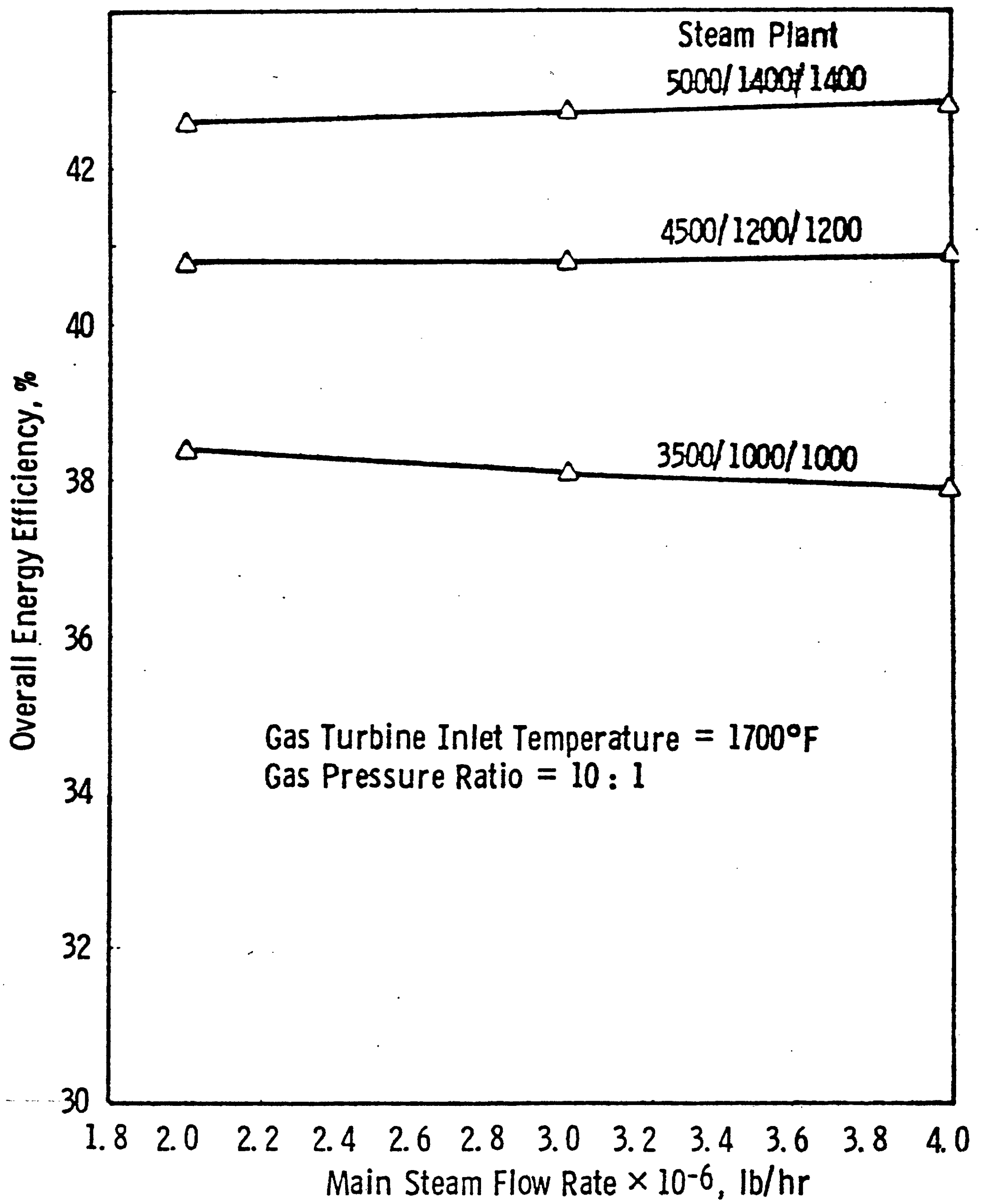


Figure 3.3.3-11

Effect of Steam Flow Rate and Steam Turbine Throttle Conditions on Overall Efficiency for a Nominal 600 MWe Steam Plant with a Pressurized Fluidized Bed Boiler (Wolfe, et al., 1976).

A_e = gas turbine air equivalence ratio, nominal 1.1 to 1.8

T_p = steam turbine throttle pressure, 3500 to 5000 psia

T_t = steam turbine throttle temperature, 1000 to 1400°F

R_t = steam turbine reheat temperature 1000 to 1400°F

C_p = condenser pressure, in.Hg abs, 2.0 to 9.0

one reheat

for $R_t = T_t$

$$E_p = n \quad \{37.55 + .018[T_p-3500] + .005\ [R_t - 1000] + 0.5\ [A_e -1.1] + 0.45[3.5-C_p] + 0.41[I_t-1600]\ 100^{-1} -0.8 \text{ abs val } |1.0-P_r{}^{-1}|\}$$

Parametric analytic studies of the energy efficiency of adiabatic combustors is shown in Figure 3.3.3-12.

Mass and energy balances for the pressurized FBC are given in Figure 3.3.3-12 for the General Electric ECAS results and in Figure 3.3.3-13 and Tables 3.3.3-1 and -2 for the Westinghouse ECAS results.

Combustion efficiency should be better for pressurized FBC's than for atmospheric FBC's. Figures 3.3.3-14 and -15, however, show very poor combustion efficiencies even for very high excess air percentages. On the other hand, Figure 3.3.3-16 displays much better combustion efficiencies for excess air at 15%. These results do not agree with the (Nack, <u>et al</u>., 1975) 1470°F, 2 ft/sec, 3.5 atm at 97%, 1470°F, 2 ft/sec, 5 atm at 99%, 1650°F, 2 ft/sec, 4.8 atm at 99%, and 1750°F, 2 ft/sec, 4.8 atm at 99.5%. An empirical model has been developed using Figure 3.3.3-16 for temperature, gas velocity, and a fixed point for excess air, and the previous figures are used for effect of excess air changes. This results in the empirical equation:

$$L_c = 10(.01T_b - 13.5)^{-1} + (.003T_b - 4.75)\ (Vg -2)^2 \times \text{ANTILOG}\ [(\log 2)x(0.6 - .04Ae)]$$

[No gsd was calculated because the data set was so small that the fit was unreasonably good. Within a year ther should be available at MIT Energy Laboratory a data base for pressurized FBC. Until this equation has been fine-tunned on such a data base it should be considered useful for determining functional forms, but presently without useful coefficients].

where

L_c = combustion losses, %

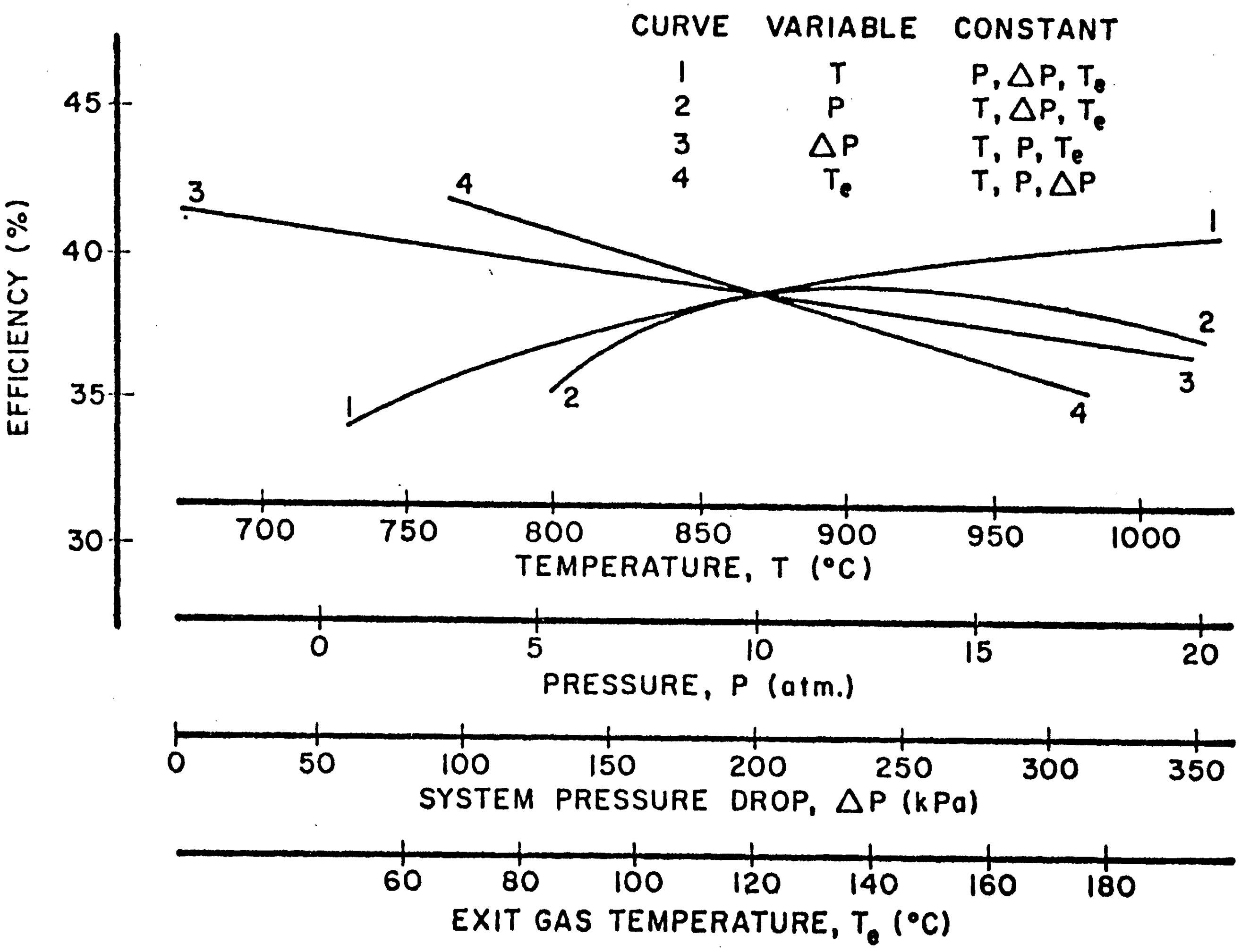


Figure 3.3.3-12

Efficiency of Adiabatic Combined Cycle (Levy, Chen, 1977).

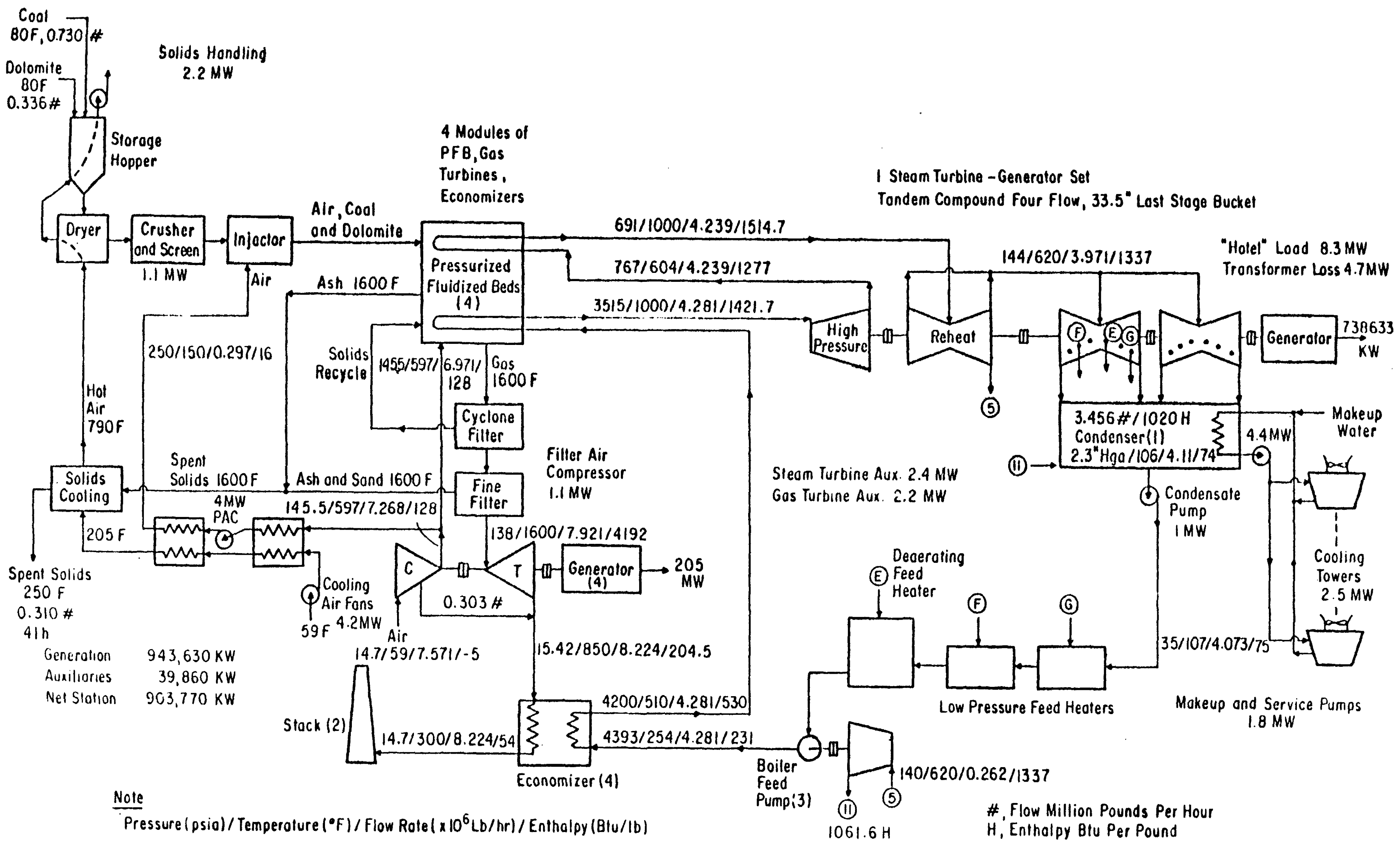


Figure 3.3.3-12 (continued)

Advanced Steam Cycle - Pressurized FBC (General Electric, 1976).

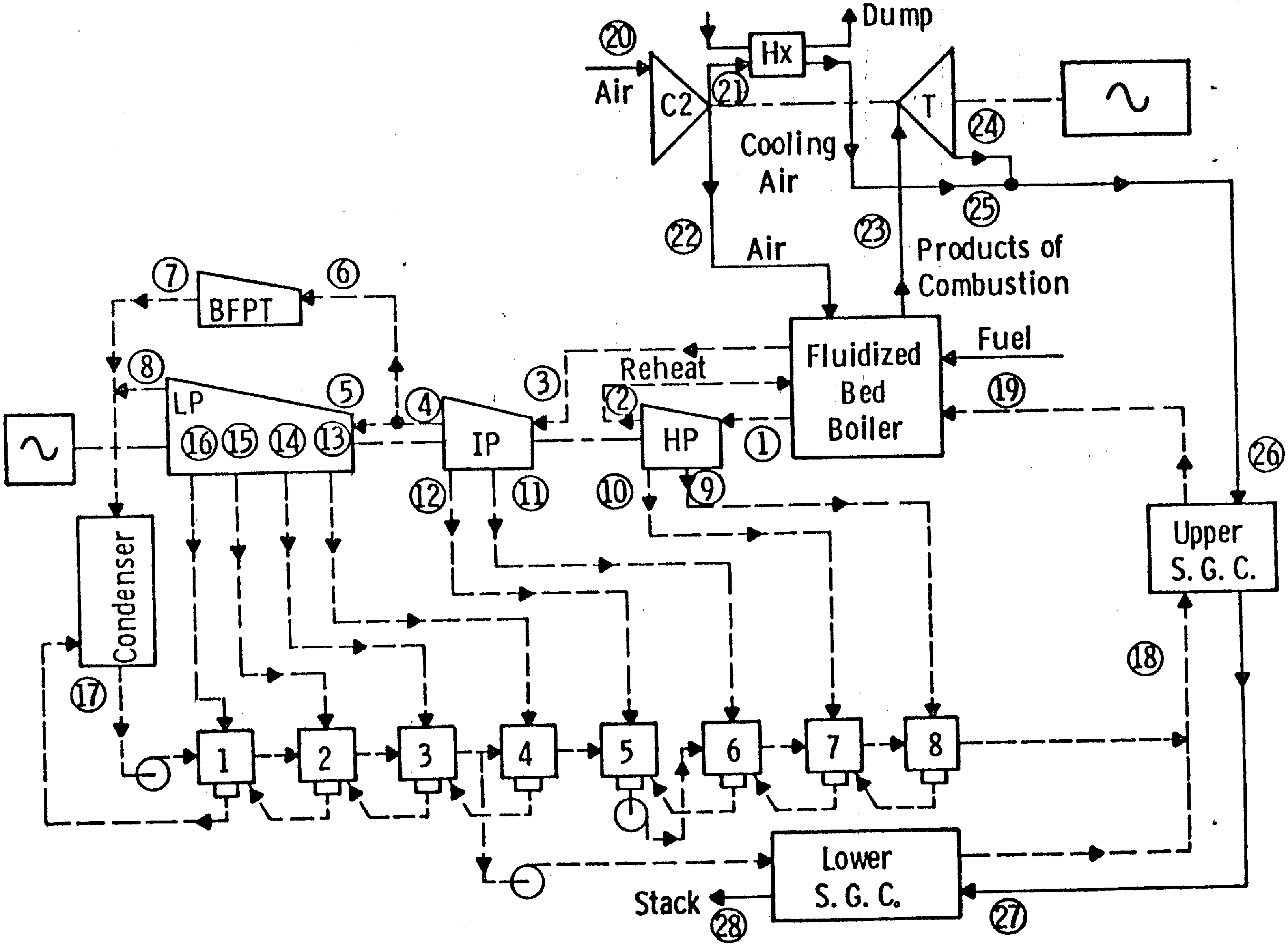


Figure 3.3.3-13

Schematic of Pressurized Fluidized Bed Boiler Power Plant (Wolfe, et al., 1976).

Table 3.3.3-1

Advanced Steam Pressurized Fluidized Bed Boiler Base Case (Parametric Point 7) (Wolfe, et al., 1976).

Location	Flow Rate of Steam X 10^{-3}, lb/hr	T, °F or (1-x)*	P, psia	Flow Rate Gas, lb/s
1	4000.0	1000	3500	—
2	3639.8	557	608	—
3	3639.8	1000	534	—
4	3386.0	617	121	—
5	3166.1	617	121	—
6	219.9	617	121	—
7	2.919	4.9%	1.7	—
8	2742.7	7.5%	1.7	—
9	177.8	650	925	—
10	182.4	557	608	—
11	135.9	843	304	—
12	117.9	617	121	—
13	81.6	434	47.9	—
14	64.4	341	28.1	—
15	153.8	240	15.0	—
16	123.6	3.4%	5.2	—
17	2962.6	117	1.7	—
18	4000.0	530	≈ 4000	—
19	4000.0	608	≈ 4000	—
20	—	59	14.7	1520
21	—	595.8	145.9	92.7
22	—	595.8	145.9	1427.3
23	—	1600	134.2	1563.2
24	—	866.6	15.3	1563.2
25	—	470	145.9	92.7
26	—	844.4	15.3	1655.9
27	—	584	15.0	1655.9
28	—	275	14.7	1655.9

* 1-x = % moisture
x = quality

Table 3.3.3-2

Advanced Steam Pressurized Fluidized Bed Boiler - Preferred Case (Parametric Point 31) (Wolfe, et al., 1976).

Location	Flow Rate of Steam X 10^{-3}, lb/hr	T, °F or (1-x)*	P, psia	Flow Rate Gas, lb/s
1	4000.0	1000	3500	—
2	3640.4	557	608	—
3	3640.4	1000	534	—
4	3387.0	617	121	—
5	3167.1	617	121	—
6	219.9	617	121	—
7	219.9	4.9%	1.7	—
8	2743.5	7.5%	1.7	—
9	177.5	650	925	—
10	182.1	557	608	--
11	135.7	843	304	--
12	117.7	617	121	—
13	81.5	434	49.9	--
14	64.5	341	28.1	--
15	153.9	240	15.0	--
16	123.7	3.4%	5.2	--
17	2963.4	117	1.7	—
18	4000.0	530	≈ 4000	--
19	4000.0	642	≈ 4000	--
20	--	59	14.7	1520
21	--	595.8	145.9	120.1
22	--	595.8	145.9	1399.9
23	--	1800	134.2	1538.3
24	—	1008.9	15.3	1538.3
25	--	470	145.9	120.1
26	--	970.4	15.3	1658.4
27	--	584	15.0	1658.4
28	--	275	14.7	1658.4

* 1-x = % moisture
x = quality

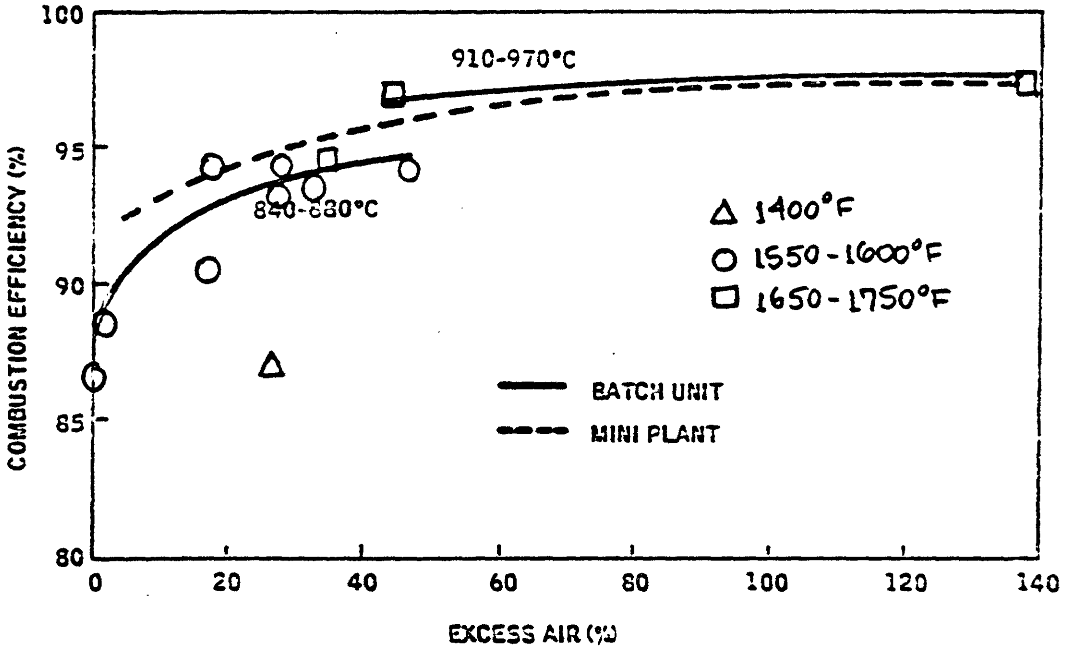


Figure 3.3.3-14

Comparison of Combustion Efficiencies (Hoke, et al., 1976).

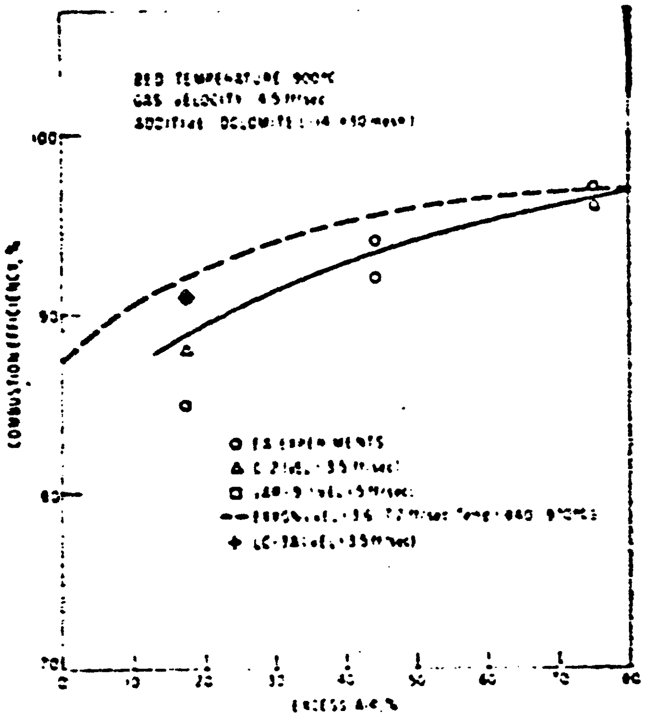


Figure 3.3.3-15

Effect of Excess Air on Combustion Efficiency (Vogel, Swift, Montagna, Lenc, and Jonke, 1975).

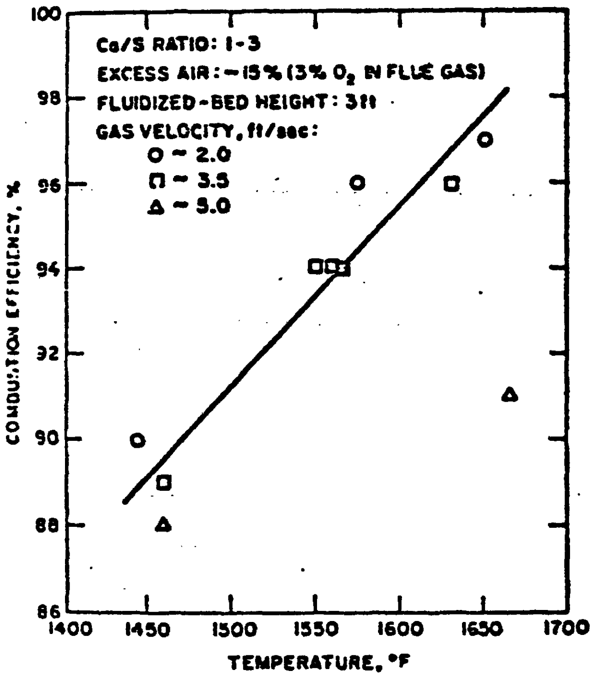


Figure 3.3.3-16

Combustion Efficiency as a Function of Bed Temperature (Vogel, Swift, Montagna, Lenc, and Jonke, 1975).

T_b = bed temperature, $^{\circ}$F, valid (450 to 1650°F)

V_g = fluidizing velocity, ft/sec, valid 2.0 to 5.0

A_e = excess air, in %, valid 0 to 140%

It should be pointed out that, even if they are exactly correct, specific terms in these empirical relations cannot be exploited without affecting a number of other FBC performance measures. For example, decreasing the fluidizing velocity causes a sharp increase in combustion efficiency. Figure 3.3.3-17 shows the lower limit on fluidizing velocity imposed by particle sizes. Figure 3.3.3-18, however, shows another advantage to decreasing velocity. In addition, each of the emissions will be affected in one way or another by velocity changes, and it can quickly be seen that many of the FBC parameters must be chosen with careful consideration to all effects.

3.3.4 Potassium Topping FBC Energy Balances

Tables 3.3.4-1 through -4 show the best design, parametric points from the Westinghouse ECAS study. When all of the liquid metal topping cycle designs are considered, the following model fits their efficiencies:

E_p = net overall plant efficiency, %

n = parameter for effect of different fuels
n = 1.000 bituminous
n = 0.986 subbituminous
n = 0.962 lignite

R_e = recuperator effectiveness range 0.0 to 0.8

C_r = liquid metal circulation, ratio 1:1 to 2.5:1

G_f = gas feedwater heater, 1 if yes, 0 if no

G_e = gas economizer, 1 if yes, 0 if no

S_r = stages of steam reheat, 0 or 1

P_r = compressor pressure ratio, 5 to 15

A_r = air equivalence ratio, 1.2 to 3.0

T_I = gas turbine inlet temperature °F, 1600 to 1800

T_L = liquid metal inlet temperature, °F, 1400 to 1600

T_c = liquid metal condenser temperature, °F, 1100 to 1300

T_t = steam turbine throttle temperature, °F, 1000 to 1200

P_t = steam turbine throttle pressure, psia, 2400 to 3500

P_B = steam turbine back pressure, in.Hg abs, 2 to 9

M_s = cycle power in MWe, 400 to 1600

θ = parameter for effect of liquid metal
1.000 for potassium
1.014 for cesium

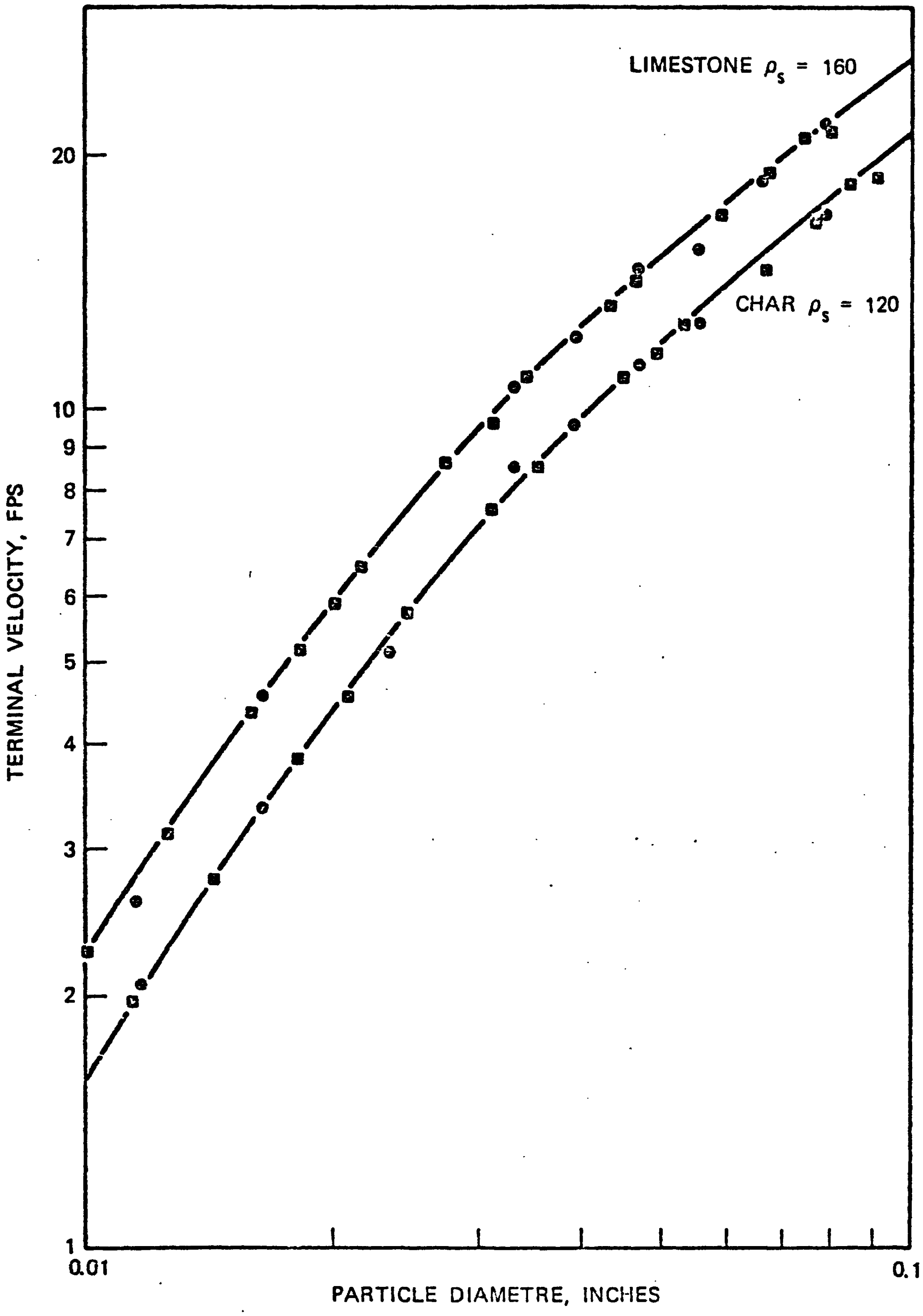


Figure 3.3.3-17

Terminal Velocity of Limestone and Coal Char (Babcock and Wilcox, 1977).

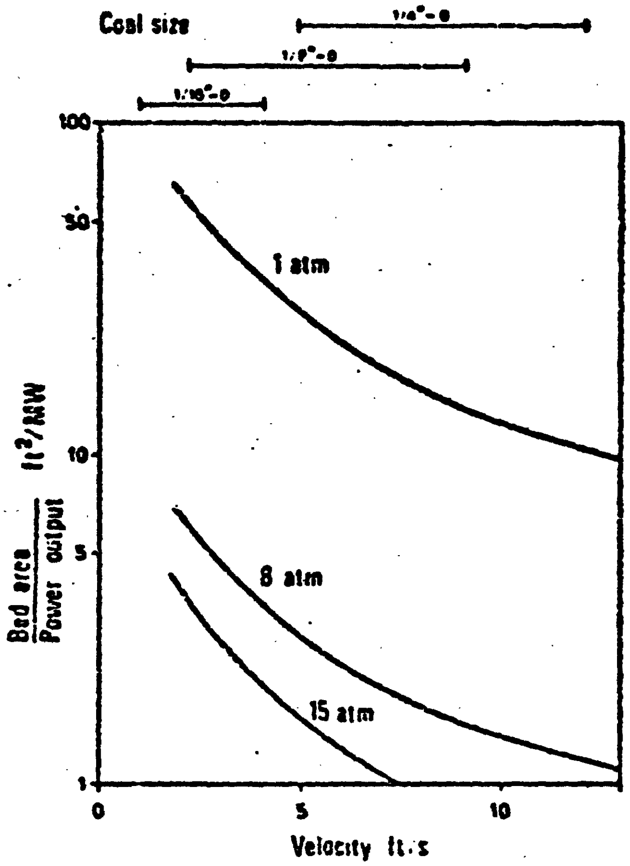


Figure 3.3.5-18

Area of Bed/Power Output Versus Fluidizing Velocity in Fluidized Combustion (Locke, Lunn, Hoy, Roberts, 1975).

Table 3.3.4-1

Summary Sheet Liquid-Metal Rankine Topping Cycle Base Case No. 1, Point 1

(Deegan, *et al.*, 1976).

Parameter Values	
Net Power (MWe)	1133.6
Combustor Pressurizing Subsystem	
Combustor type	PFB
Fuel	Illinois No. 6
Gas turbine inlet temp., °F	1800
Compressor pressure ratio	15
Air equivalence ratio	1.2
Liquid-Metal Subsystem	
Fluid	K
Turbine inlet temperature, °F	1400
Condensing temperature, °F	1100
Circulation ratio	2.5:1
Steam Turbine Subsystem	
Turbine inlet temperature, °F	1000
Turbine inlet pressure, psig	3500
Reheat temperature, °F	NA
Condensing pressure, in Hg abs	3.5
Heat Rejection	Wet towers

(a)

Performance and Cost	
Power Plant Efficiency, %	35.9
Overall Energy Efficiency, %	35.9
Capital Cost, 10^6 $	776.1
Capital Cost, $/kWe	684.6
Cost of Electricity, mills/kWh	31.58

(b)

Natural Resources	
Coal, lb/kWh	0.881
Sorbent, lb/kWh	0.466
Total Water, gal/kWh	0.767
Cooling water	0.611
Gasifier process	0.000
Condensate makeup	0.006
Waste-handling slurry	0.096
Scrubber waste	0.053
NO_x suppression	0.000
Total Land, acres/100 MWe	114.6
Main plant	16.5
Disposal land	77.2
Access railroad	20.8

(c)

Major Components						
Component	Size, ft (W x L (or D) x H)	Weight, 10^3 lb	Cost Mfg., 10^3 $	FOB Plant, $/kWe	Units Required	Total Cost, 10^3 $
PFB	13.6 x 121	700	5,820	4.98	16	93,160
L-M Turbine			3,000	2.56	8	24,000
Condenser-Steam Generator	27.2	155	2,300	1.97	4	9,200
Cooling Tower	43 x 40 x 70		230	0.20	13	2,990

(d)

Environmental Intrusion		
	lb/10^6 Btu	lb/kWh
SO_2	0.723	0.0068
NO_x	0	0
HC	0	0
CO	0	0
Particulates	0.0365	3.45×10^{-4}
	Btu/kWh	
Heat to Water	2904	
Heat, Total Rejected	5239	
	lb/kWh	lb/day
Wastes		
Ash	0.084	2.36×10^6
Spent sorbent	0.464	13.03×10^6

(e)

Table 3.3.4-2

Summary Sheet Liquid-Metal Rankine Topping Cycle Base Case No. 2, Point 4 (Deegan, et al., 1976).

Parameter Values	
Net Power (MWe)	1144.4
Combustor Pressurizing Subsystem	
Combustor type	PFB
Fuel	Illinois No. 6
Gas turbine inlet temp., °F	1800
Compressor pressure ratio	15
Air equivalence ratio	1.2
Liquid-Metal Subsystem	
Fluid	K
Turbine inlet temperature, °F	1400
Condensing temperature, °F	1100
Circulation ratio	2.5:1
Steam Turbine Subsystem	
Turbine inlet temperature, °F	1000
Turbine inlet pressure, psig	3500
Reheat temperature, °F	NA
Condensing pressure, in Hg abs	3.5
Heat Rejection	Wet towers

(a)

Performance and Cost	
Power Plant Efficiency, %	34.8
Overall Energy Efficiency, %	35.0
Capital Cost, 10^6 $	926.1
Capital Cost, $/kWe	809.2
Cost of Electricity, mills/kWh	35.88

(b)

Natural Resources	
Coal, lb/kWh	0.904
Sorbent, lb/kWh	0.478
Total Water, gal/kWh	0.813
Cooling water	0.601
Gasifier process	0.052
Condensate makeup	0.006
Waste-handling slurry	0.099
Scrubber waste	0.054
NO_x suppression	0.000
Total Land, acres/100 MWe	113.9
Main plant	17.3
Disposal land	75.98
Access railroad	20.65

(c)

Major Components

Component	Size, ft (W x L (or D) x H)	Weight, 10^3 lb	Cost Mfg., 10^3 $	FOB Plant, $/kWe	Units Required	Total Cost, 10^3 $
PFB	14.5 x 25	220	2,200	1.95	8	17,600
L-M Turbine			3,000	2.66	8	24,000
Condenser-Steam Generator	27.2 (sphere)	155	2,300	2.04	4	9,200
Cooling Tower	43 x 40 x 70		230	0.20	13	2,990

(d)

Environmental Intrusion

	$lb/10^6$ Btu	lb/kWh
SO_2	0.723	0.0074
NO_x	0	0
HC	0	0
CO	0	0
Particulates		
	Btu/kWh	
Heat to Water	2990	
Heat, Total Rejected	5730	
	lb/kWh	lb/day
Wastes		
Ash	0.090	2.44×10^6
Spent sorbent	0.498	13.4×10^6

(e)

Table 3.3.4-3

Summary Sheet Liquid-Metal Rankine Topping Cycle, Point 49 (Deegan, et al., 1976).

Parameter Values	
Net Power (MWe)	1140.0
Combustor Pressurizing Subsystem	
Combustor type	PFB
Fuel	Illinois No. 6
Gas turbine inlet temp., °F	1600
Compressor pressure ratio	15
Air equivalence ratio	1.2
Liquid-Metal Subsystem	
Fluid	K
Turbine inlet temperature, °F	1400
Condensing temperature, °F	1100
Circulation ratio	2.5:1
Steam Turbine Subsystem	
Turbine inlet temperature, °F	1000
Turbine inlet pressure, psig	3500
Reheat temperature, °F	1000
Condensing pressure, in Hg abs	3.5
Heat Rejection	Wet towers

(a)

Performance and Cost	
Power Plant Efficiency, %	42.4
Overall Energy Efficiency, %	42.4
Capital Cost, 10^6 $	760.3
Capital Cost, $/kWe	666.9
Cost of Electricity, mills/kWh	29.60

(b)

Natural Resources	
Coal, lb/kWh	0.746
Sorbent, lb/kWh	0.395
Total Water, gal/kWh	0.737
Cooling water	0.603
Gasifier process	0.000
Condensate makeup	0.007
Waste-handling slurry	0.082
Scrubber waste	0.045
NO_x suppression	0.000
Total Land, acres/100 MWe	102.6
Main plant	16.4
Disposal land	65.4
Access railroad	20.7

(c)

Major Components						
Component	Size, ft (W x L (or D) x H)	Weight, 10^3 lb	Cost Mfg., 10^3 $	FOB Plant, $/kWe	Units Required	Total Cost, 10^3 $
PFB	16.6 x 100	840	5,910	5.05	16	94,612
L-M Turbine			3,000	2.56	8	24,000
Condenser-Steam Generator	26.7 (sphere)	196	2,300	1.96	4	9,200
Cooling Tower	43 x 40 x 70		230	0.20	13	2,990

(d)

Environmental Intrusion		
	lb/10^6 Btu	lb/kWh
SO_2	0.723	0.0058
NO_x	0	0
HC	0	0
CO	0	0
Particulates	0.043	3.46×10^{-4}
	Btu/kWh	
Heat to Water	3156	
Heat, Total Rejected	3934	
	lb/kWh	lb/day
Wastes		
Ash	0.072	2.01×10^{6}
Spent sorbent	0.395	11.1×10^{6}

(e)

Table 3.3.4-4

Summary Sheet Liquid-Metal Rankine Topping Cycle, Point 46 (Deegan, et al., 1976).

Parameter Values	
Net Power (MWe)	1139.9
Combustor Pressurizing Subsystem	
Combustor type	PFB
Fuel	Illinois No. 6
Gas turbine inlet temp., °F	1600
Compressor pressure ratio	15
Air equivalence ratio	1.2
Liquid-Metal Subsystem	
Fluid	Cs
Turbine inlet temperature, °F	1400
Condensing temperature, °F	1100
Circulation ratio	2.5:1
Steam Turbine Subsystem	
Turbine inlet temperature, °F	1000
Turbine inlet pressure, psig	3500
Reheat temperature, °F	1000
Condensing pressure, in Hg abs	3.5
Heat Rejection	Wet towers

(a)

Performance and Cost	
Power Plant Efficiency, %	42.9
Overall Energy Efficiency, %	42.9
Capital Cost, 10^6 $	823.2
Capital Cost, $/kWe	722.2
Cost of Electricity, mills/kWh	31.25

(b)

Natural Resources	
Coal, lb/kWh	0.737
Sorbent, lb/kWh	0.390
Total Water, gal/kWh	0.780
Cooling water	0.649
Gasifier process	0.000
Condensate makeup	0.007
Waste-handling slurry	0.081
Scrubber waste	0.044
NO_x suppression	0.000
Total Land, acres/100 MWe	103.31
Main plant	16.4
Disposal land	64.6
Access railroad	22.33

(c)

Major Components						
Component	Size, ft (W x L (or D) x H)	Weight, 10^3 lb	Cost Mfg., 10^3 $	FOB Plant, $/kWe	Units Required	Total Cost, 10^3 $
PFB	16 x 100	770	5,590	4.78	16	89,430
L-M Turbine			2,000	1.71	8	16,000
Condenser-Steam Generator	26.7 (sphere)	196	2,300	1.96	4	9,200
Cooling Tower	43 x 40 x 70		230	0.20	14	3,220

(d)

Environmental Intrusion		
	lb/10^6 Btu	lb/kWh
SO_2	0.723	0.0054
NO_x	0	0
HC	0	0
CO	0	0
Particulates	0.0418	3.10×10^{-4}
	Btu/kWh	
Heat to Water	3214	
Heat, Total Rejected	3929	
	lb/kWh	lb/day
Wastes		
Ash	0.066	2.36×10^6
Spent sorbent	0.364	10.219×10^6

(e)

$$
\begin{aligned}
E_p = \eta\theta \{ .370 &+ 0.0073\ R_e + 0.00 M_s + 0.00\ C_r \\
&+ 0.075\ G_F + 0.038\ G_e - 0.00043\ (15-P_r)^2 \\
&+ (.493\ A_r^{-1} -.4108) + .00482\ (P_t - 3500) \\
&-10^{-6}\ G_F\ (T_I - 1800)^2 \\
&+ \text{Sign}\ (3.5 - P_B) \times .006\ (\text{abs val}\ |\ 3.5-P_B\ |\ )^{.5} \\
&+ .0085\ S_r + .01\ (.006 + .001\ S_r)\ (T_t - 1000) \\
&+ 5.0 \times 10^{-6}\ (T_L + T_C - 2500) + [.022-5.5\text{x}10^{-7} \\
&\quad (T_I - 1600)^2]\}
\end{aligned}
$$

Figures 3.3.4-1, -2, and -3 with Table 3.3.4-5 show the mass and energy balances of the potassium topping cycle FBC. There are at this time no experimental data to which empirical combustion efficiency models can be fit. The results would be very much like the pressurized FBC case, except the combustion chamber operating points would be quite different, probably set to optimize other portions of the system than the very flexible topping cycle.

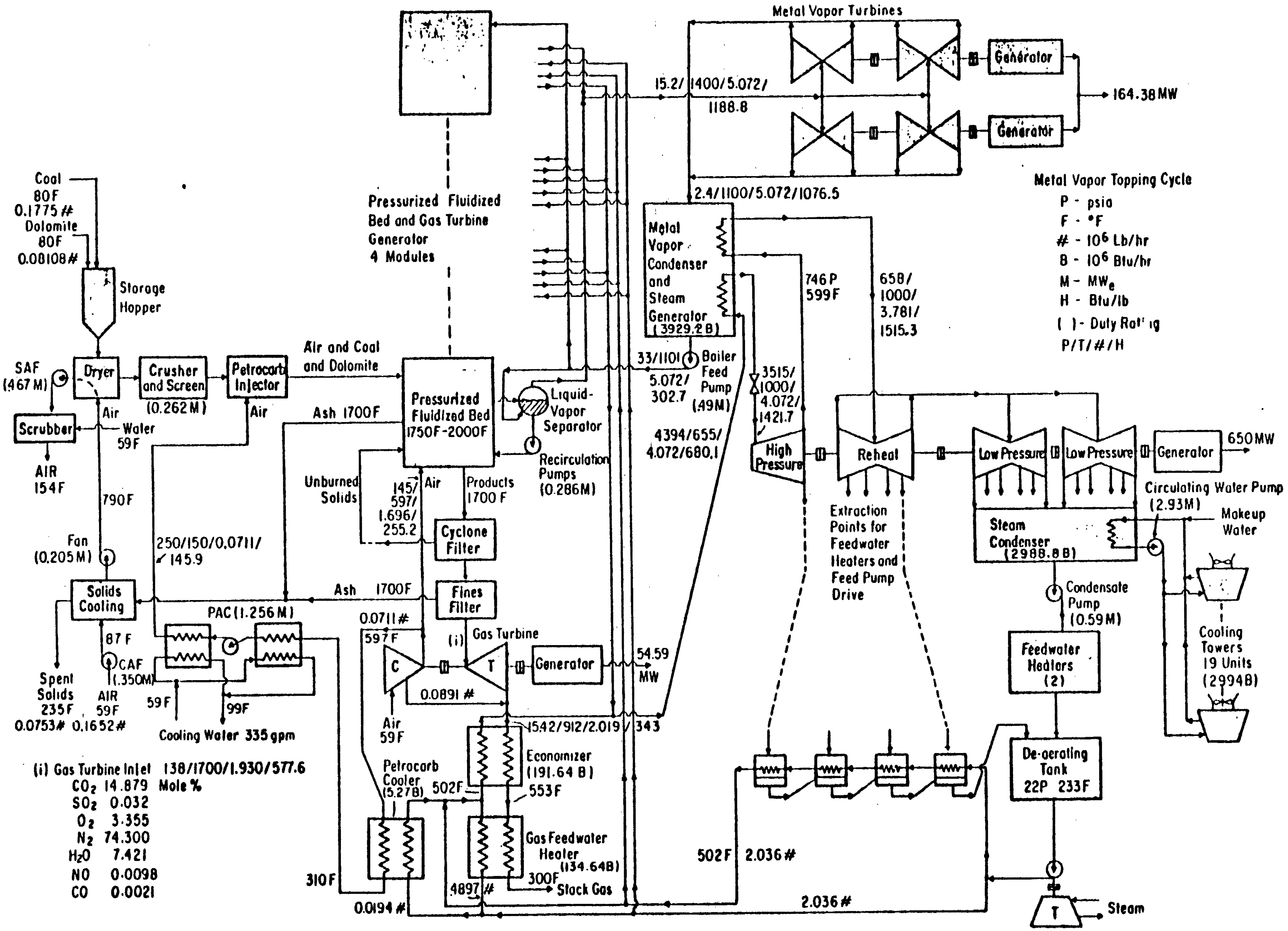


Figure 3.3.4-1

Potassium Topping Cycle (General Electric, 1976).

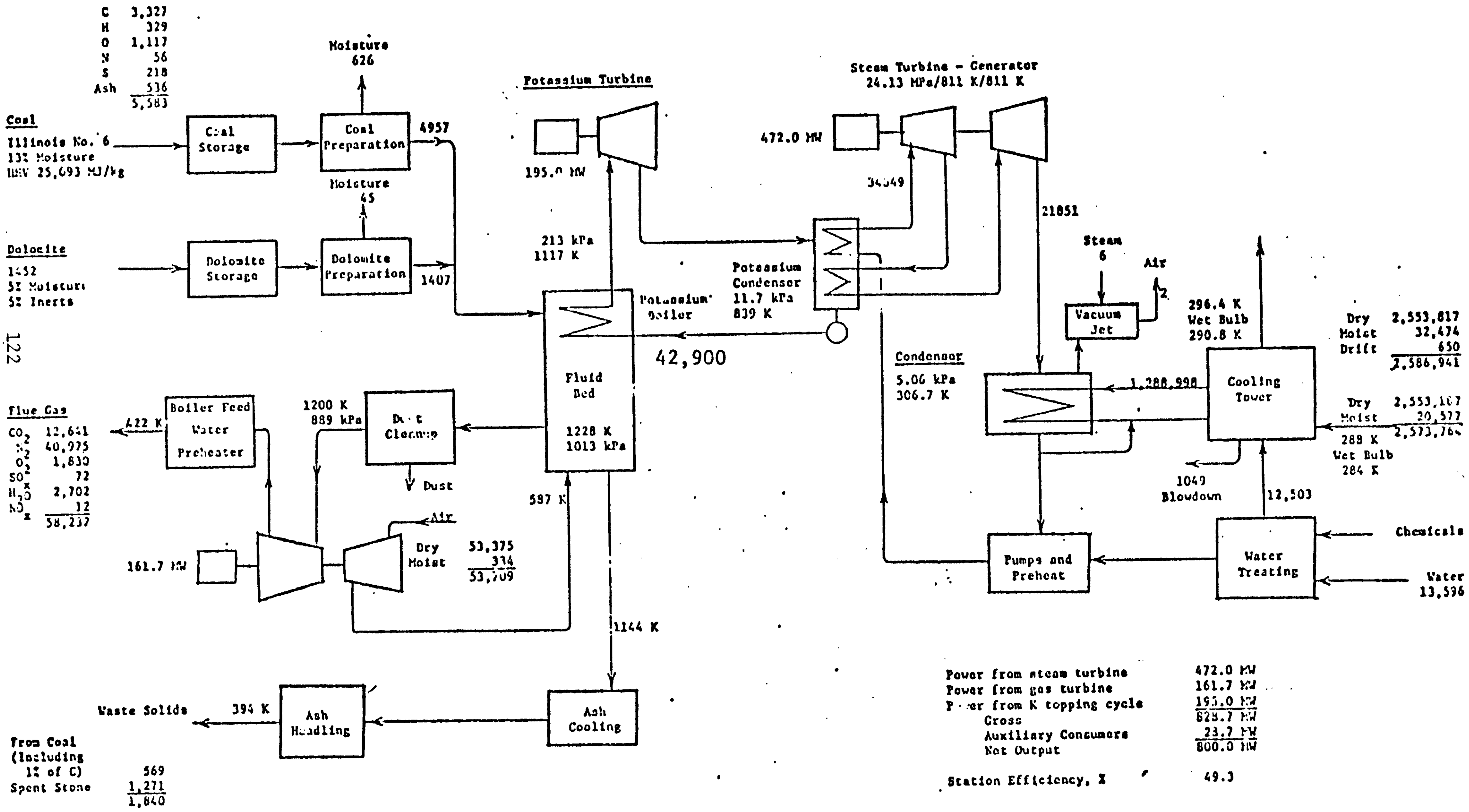


Figure 3.3.4-2

Potassium Topping Cycle on PFB Combustion (Jahnig and Shaw, 1977).

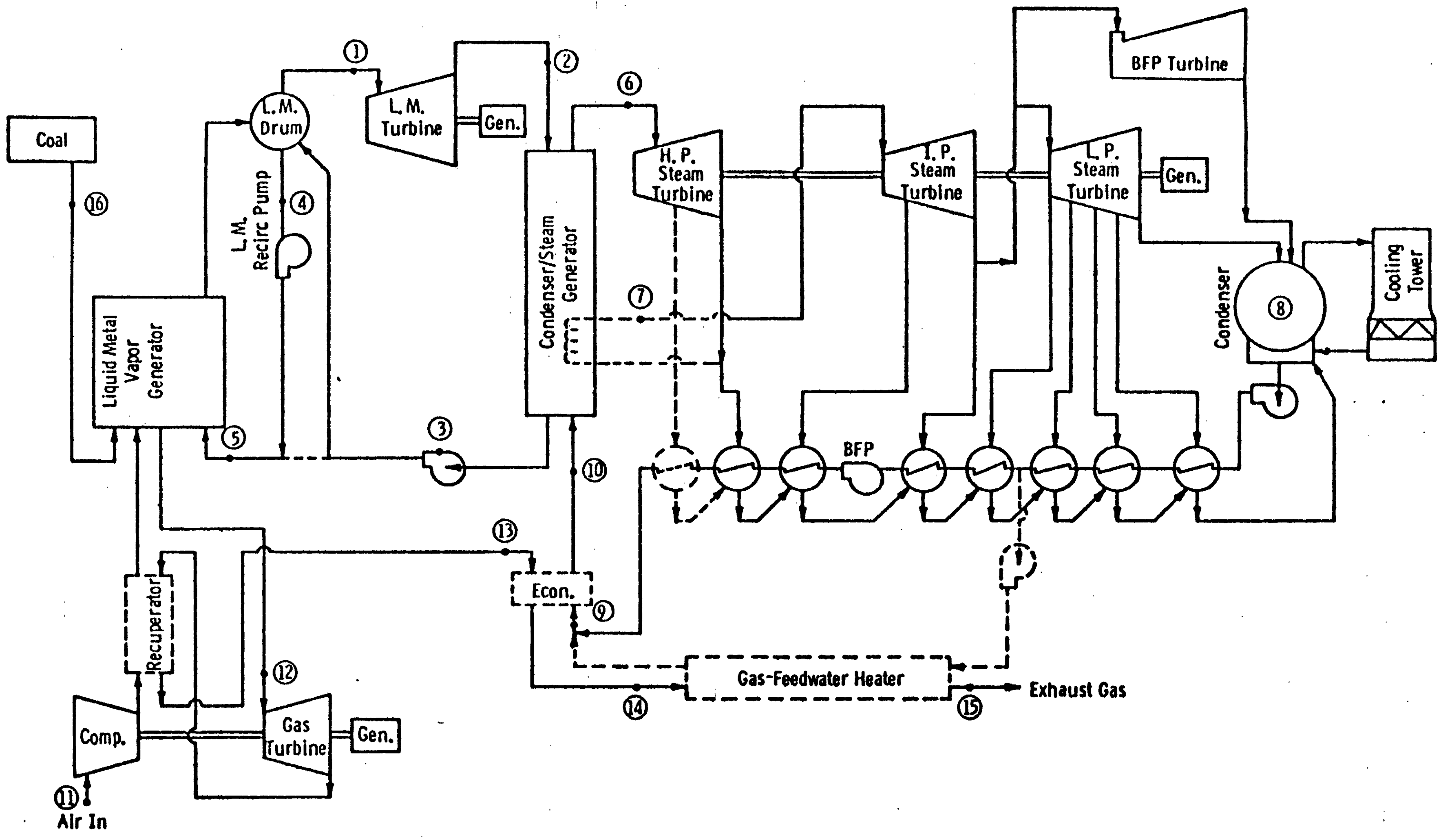


Figure 3.3.4-3

Schematic Liquid Metal Rankine Topping Cycle Pressurized Fluidized Bed (Deegan, et al., 1976).

Table 3.3.4-5

Liquid-Metal Rankine Topping Cycle Components and Operating Parameters for Base Case 1 (Deegan, et al., 1976).

```
                                                                              * * * * * * * EFFICIENCIES * * * * *
POWER OUTPUT(MWE)              1200     GAS TURBINE INLET
FURNACE                 PR.FLD.BED        TEMPERATURE (DEG-F)   1800.0    L.M.SYSTEM                          .097
COAL                            BIT     GAS ECONOMIZER              NO    PRESSURIZING SUBSYSTEM              .267
WORKING FLUID                     K     GAS FEEDWATER HEATER        NO    STEAM CYCLE                         .420
RECUPERATOR EFFECTIVENESS       0.0     L.M.CIRCULATION RATIO    2.5 1    GROSS PLANT                         .380
COMPRESSOR PRESSURE RATIO        15     L.M.FEEDHEATER              NO    NET PLANT                           .370
AIR EQUIVALENCE RATIO           1.2     STAGES OF STEAM REHEAT       0    NET POWER OUTPUT(MWE)           1169.57


                                 TOTAL FLOW       TEMPERATURE      PRESSURE        THERMAL LOAD    POWER OUTPUT
**** STATE POINTS ****           10E06 LBM/HR       DEG-F            PSIA          10E09 BTU/HR        MWE

 1 L.M.TURBINE INLET               7.382           1400.000         15.200                            188.000

 2 L.M.CONDENSER                                   1100.000          2.400            5.856

 3 L.M.FEED PUMP              5277.000 GPM         1100.000         33.900                               .363

 4 L.M.RECIRC PUMP           13574.000 GPM         1280.000         20.610                               .173

 5 L.M.BOILER INLET                                1280.000                           6.600

 6 STEAM TURBINE THROTTLE          6.774           1000.000       3515.000                            720.600

 7 STEAM REHEAT                                       0.000          0.000

 8 ST.COND.BACK PRESS.                                               3.500IN.HG       3.396

 9 FINAL FEEDWATER                                  560 .000

10 COND/SG WATER INLET                              560.000

11 COMPRESSOR INLET               10.320             59.000         14.690

12 GAS TURBINE INLET              11.216           1800.000                                           291.500

13 GAS ECON.GAS INLET,                                0.000                            0.000

14 GAS FWH GAS INLET                                  0.000                            0.000

15 STACK GAS EXHAUST                                844.000

16 AS RECEIVED COAL             499.400T/HR                                           10.775
```

4. Environmental Assessment

The primary impetus for developing fluidized bed technologies for combustion of coal is the economic potential. Part of the economic gain results from the lack of need for scrubbers. It does seem that there are other enviromental gains that are possible through the use of fluidized bed combustion of coal, but environmental data is lacking on many key points. In FBC there are at least 602 inorganic potential pollutants and 491 organic potential pollutants (ERDA, 1977).

4.1 Air Emissions of Atmospheric FBC

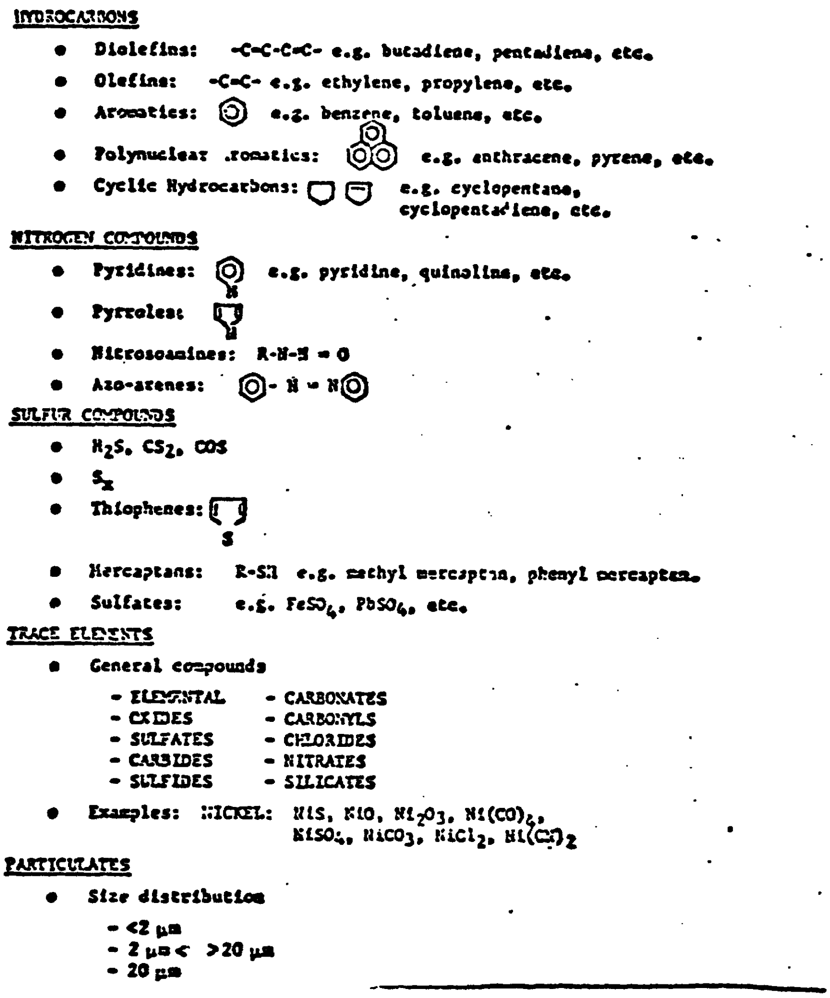
Those air emissions that have been measured on experimental rigs and the analytic projections show that the potential hazards of these emissions are about the same as those for conventional coal-fired units with scrubbers. There is, however, serious lack of experimental data on the emissions of trace elements and compounds, and organic compounds (Battelle-Columbus, 1977). A list of these potentially troublesome air emissions is shown in Figure 4.1-1.

4.1.1 Air Balance

No experimental data has been found on air balances around fluidized bed combustion systems. The analytic data that is available is that which was developed for the ECAS study and is shown in section 3.3.2.

4.1.2 Flue Gas Emissions

Air emissions that have received the most experimental study are those represented in the new source performance standards, see Table 4.1.2-1.



HYDROCARBONS

- Diolefins: -C=C-C=C- e.g. butadiene, pentadiene, etc.
- Olefins: -C=C- e.g. ethylene, propylene, etc.
- Aromatics: e.g. benzene, toluene, etc.
- Polynuclear aromatics: e.g. anthracene, pyrene, etc.
- Cyclic Hydrocarbons: e.g. cyclopentane, cyclopentadiene, etc.

NITROGEN COMPOUNDS

- Pyridines: e.g. pyridine, quinoline, etc.
- Pyrroles:
- Nitrosoamines: R-N-N = O
- Azo-arenes: - N = N

SULFUR COMPOUNDS

- H_2S, CS_2, COS
- S_x
- Thiophenes:
- Mercaptans: R-SH e.g. methyl mercaptan, phenyl mercaptan.
- Sulfates: e.g. $FeSO_4$, $PbSO_4$, etc.

TRACE ELEMENTS

- General compounds
  - ELEMENTAL
  - OXIDES
  - SULFATES
  - CARBIDES
  - SULFIDES
  - CARBONATES
  - CARBONYLS
  - CHLORIDES
  - NITRATES
  - SILICATES
- Examples: NICKEL: NiS, NiO, Ni_2O_3, $Ni(CO)_4$, $NiSO_4$, $NiCO_3$, $NiCl_2$, $Ni(CN)_2$

PARTICULATES

- Size distribution
  - <2 μm
  - 2 μm < >20 μm
  - 20 μm

Figure 4.1-1

Selected Examples of Conceivable Pollutants Which Could Form in Coal Fired Fluidized-Bed Combustion (Fennelly, Durochee, Klemm, Hall, 1975).

Table 4.1.2-1 Primary New Source Performance Standards (NSPS) for Solid-Fueled Air Pollution Sources

Source:	Pollutant:	Threshold:
STEAM GENERATORS		
Fossil-fuel fired = 250×10^6 Btu/hr input	Particulate Matter	0.1 lb/10^6 Btu input 20% opacity
	Sulfur Dioxide	1.2 lb/10^6 Btu
	Nitrogen Oxides (as NO_2)	0.7 lb/10^6 Btu

For the other air pollutants the models developed here have relied in varying degrees on implications of other fluidized bed types and existing data on conventional boilers.

4.1.2.1 Sulfur Oxides

Principles of in-situ removal of sulfur dioxide in an atmospheric FBC are not totally understood but the parameters of importance are known (see Table 4.1.2.1-1), and experimental data on the apparent effects of changes in these parameters is available.

Table 4.1.2.1-1
Parameters Affecting In-Bed Sorption of Sulfur Oxides

Major Parameters:
- Ca/S ratio
- Bed temperature
- Superficial gas velocity

Minor Parameters:
- Stone type and source
- Gas-solid mixing factors
- Regenerated stone activity factors
- Sorbent size and feed location
- Bed depth and internals
- Coal type and constituents
- Coal feed location and means
- Excess air
- Addition of salt and other additives
- Oxidized reducing conditions in bed
- Recycling of fine particles

Effect of Calcium to Sulfur Ratio

To a great extent there are large nonlinear effects from the variations of two or more of the parameters affecting sulfur oxide sorption. In general, however, the Ca/S ratio is the dominant variable with sulfur retention increasing sharply for increasing Ca/S ratios; typical results are shown in Figure 4.1.2.1-1 to -12. The reaction that takes place at atmospheric pressure is the endothermic calcination:

$$CaCO_3 = CaO + CO_2$$

from which the calcium oxide is then sulfated:

$$CaO + SO_2 + 1/2\ O_2 = Ca\ SO_4$$

In the development of empirical models for SO_2 capture in the bed the most important initial modeling task is the effect of Ca/S ratio.

Effect of Bed Temperature

Particularly in an FBC at atmospheric pressure, the bed temperature can be an important operating parameter. In the coarse limestone (490-630 μm) studies (Jonke et al., 1972), Illinois coal peaked for 1500 to 1550°F and Pittsburgh coal showed optimum SO_2 retention at 1450 to 1470°F (see Figure 4.1.2.1-13). In (Ehrlich et al., 1972, p. 231), these types of observations are supported. Recent experimental data at CPC (Nack et al., 1975, p. 360) shows that these optimum temperature effects, while present for Ca/S ratios of 1.5, were "little" for Ca/S ratios of 3 to 5, contrary to the Pittsburgh data in Figure 4.1.2.1-13.

It should also be noted, from Figure 4.1.2.1-14, that the optimum temperature for retention is dependent upon the Ca/S mole ratio. Figures 4.1.2.1-15 through -17 show additional temperature effects. The reason for the downturn in sulfur capture has not been explained by available thermodynamic or kinetic data. Such analytic models show SO_2 levels decreasing up to and beyond 2000°F, thus there exists here a gap between the empirical and analytic models. The possible explanation that slag buildup, fouling, or some irreversible factor was responsible for reduced sulfur capture efficiencies at higher temperatures has been dismissed by experiments which have approached the optimum temperature from both the higher and the lower temperatures.

Effect of Superficial Gas Velocity

There is good agreement in the available data on the effects of superficial gas velocity on sulfur retention. There is little effect for high Ca/S ratios (3-5) and lower gas velocities (<10 fps). Low Ca/S ratios (1.5) show significant sulfur retention with increased gas velocity (see Figure 4.1.2.1-18). The factors responsible for decreased sulfur capture with increasing fluidizing velocities are :

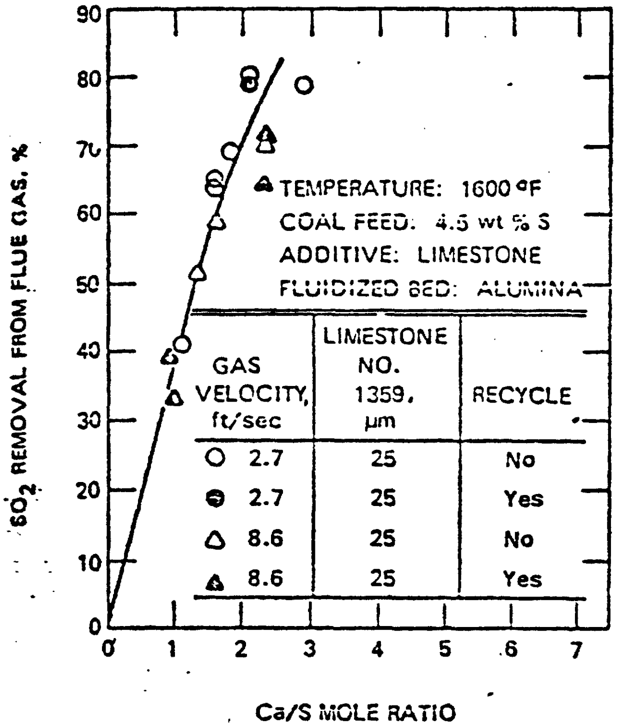


Figure 4.1.2.1-1

Effect of Calcium/Sulfur Mole Ratio on SO_2 Removal with Fine Limestone Additive (Anastasia, et al., 1970).

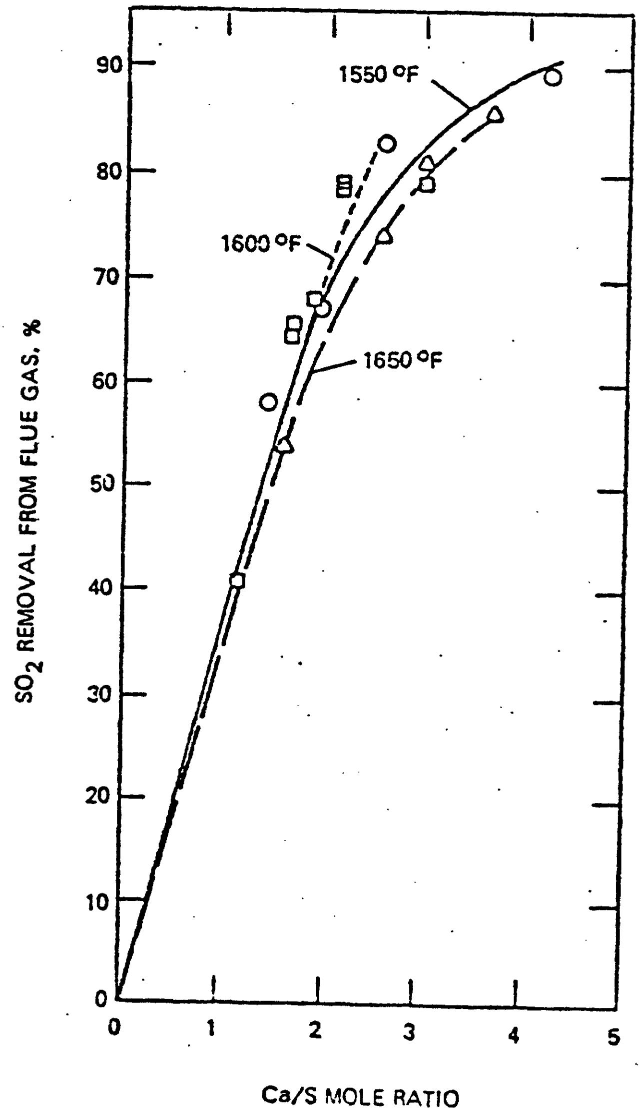


Figure 4.1.2.1-2

Effect of Combustion Temperature on SO_2 Removal with Fine Limestone Additive (Anastasia, et al., 1970).

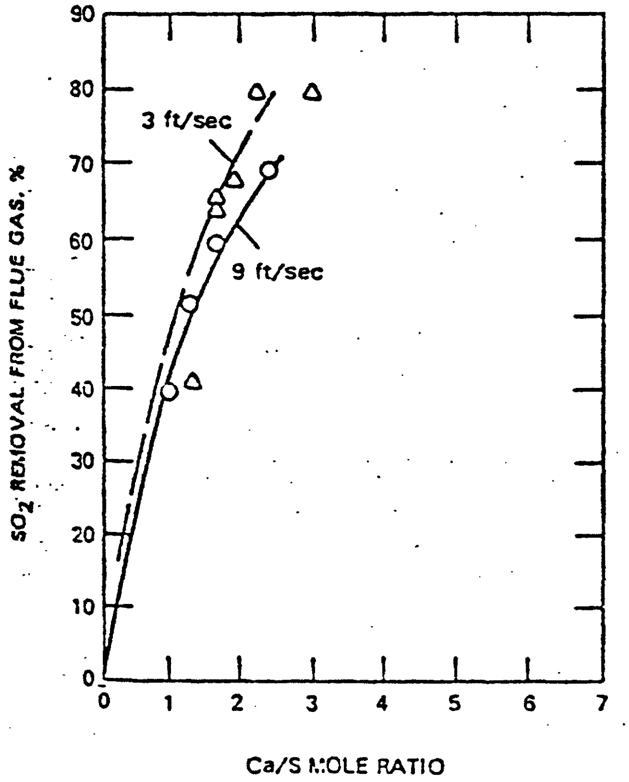


Figure 4.1.2.1-3

Effect of Gas Velocity on SO_2 Removal with Fine Limestone Additive (Anastasia, et al., 1970).

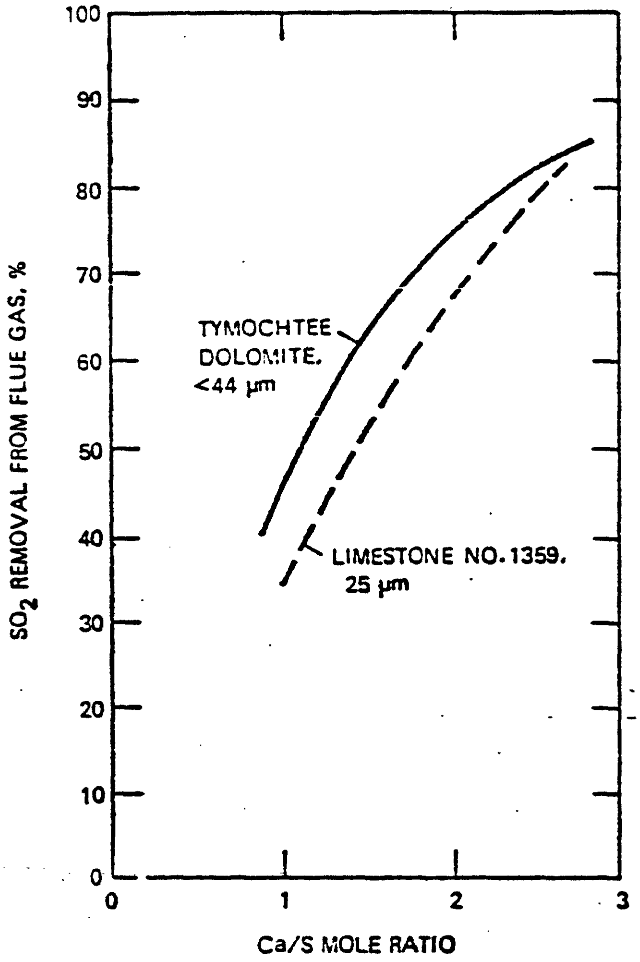


Figure 4.1.2.1-4

Control of SO$_2$ Emission with Tymochtee Dolomite No. 1359 Limestone (Anastasia, et al., 1970).

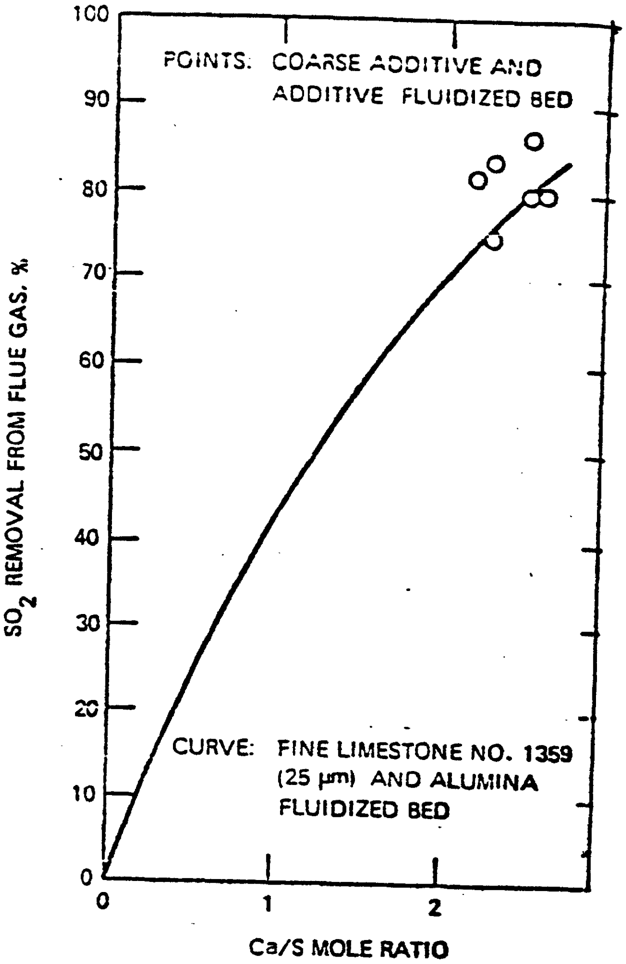


Figure 4.1.2.1-5

SO$_2$ Removal with Coarse Additive and Inert Fluidized Beds and with Fine Additive and Additive Fluidized Beds (Anastasia, et al., 1970).

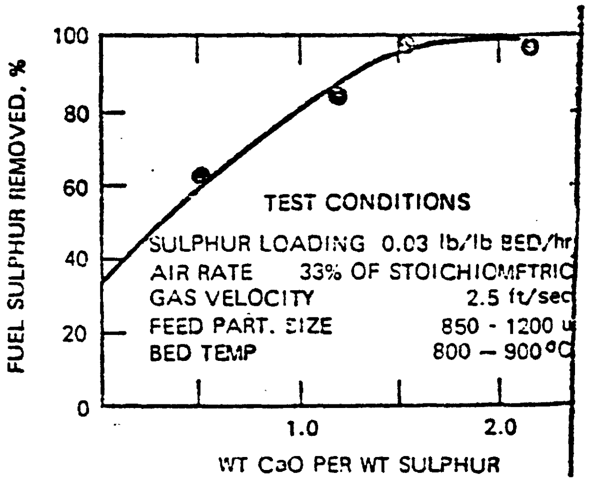


Figure 4.1.2.1-6

Effect of Makeup Rate on Desulphurising Efficiency (Moss, 1970).

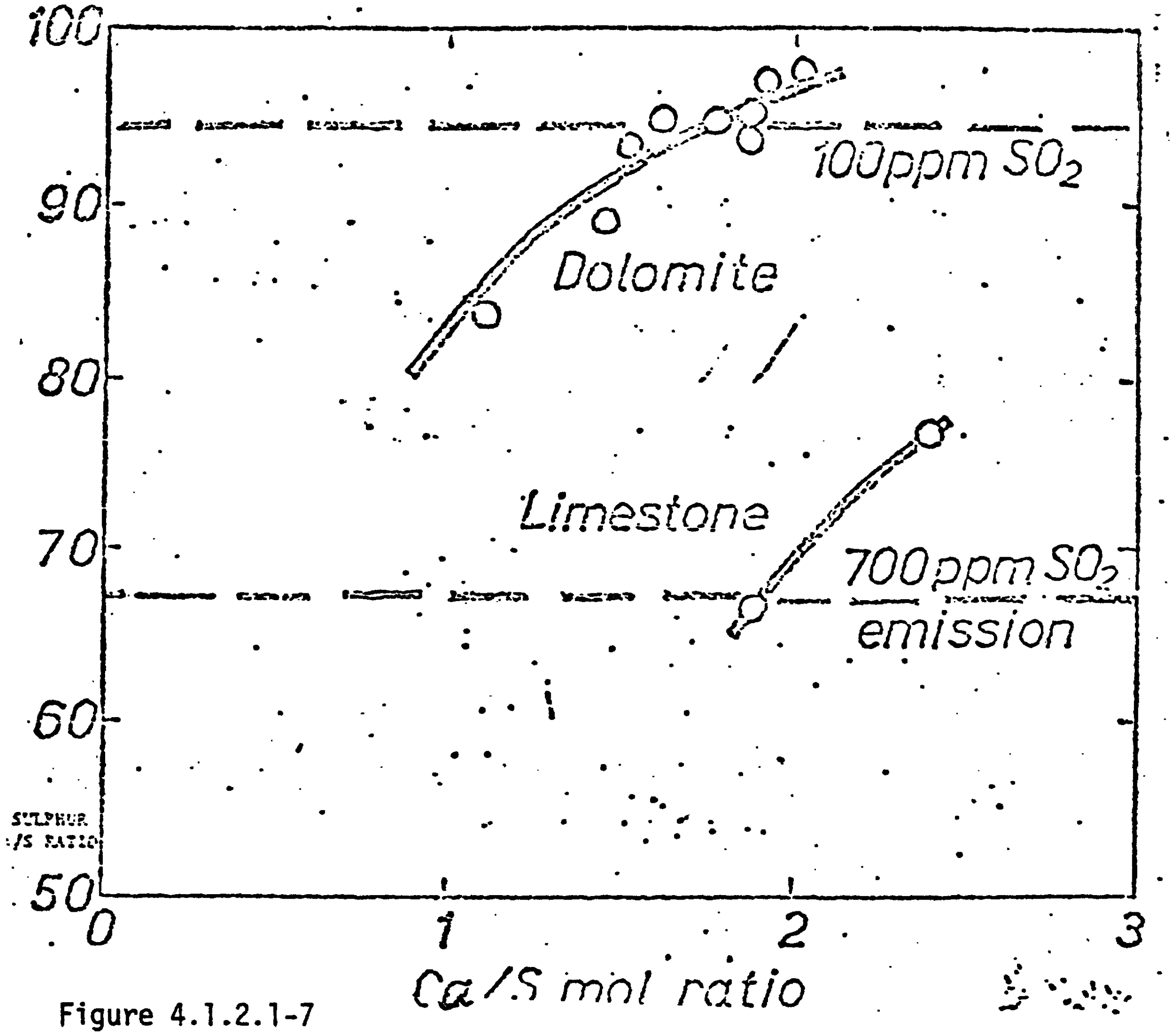


Figure 4.1.2.1-7

Reduction in Sulphur Emission Due to Ca/S Ratio (Hoy, Roberts, 1973).

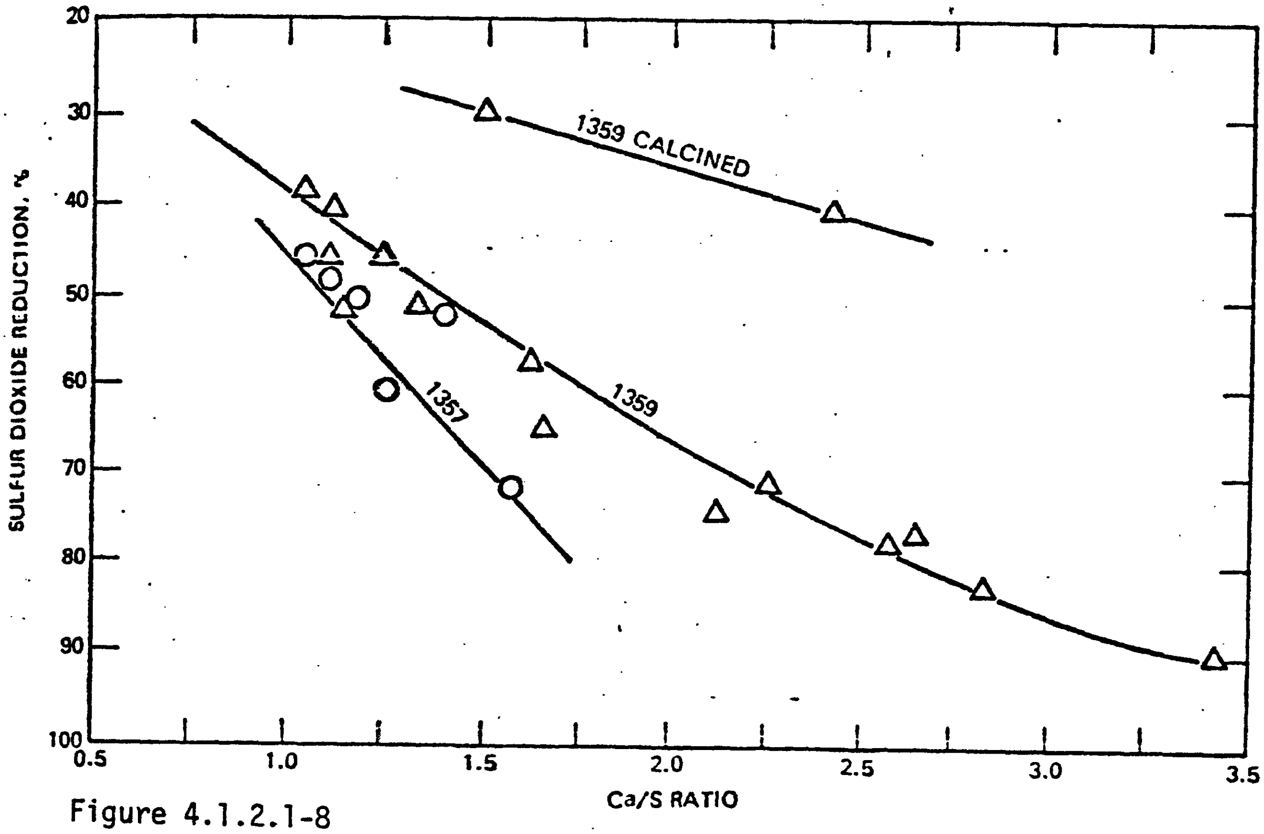


Figure 4.1.2.1-8

SO_2 Reduction -- Effect of Limestone-to-Sulfur Ratio (Glenn, Robison, 1970).

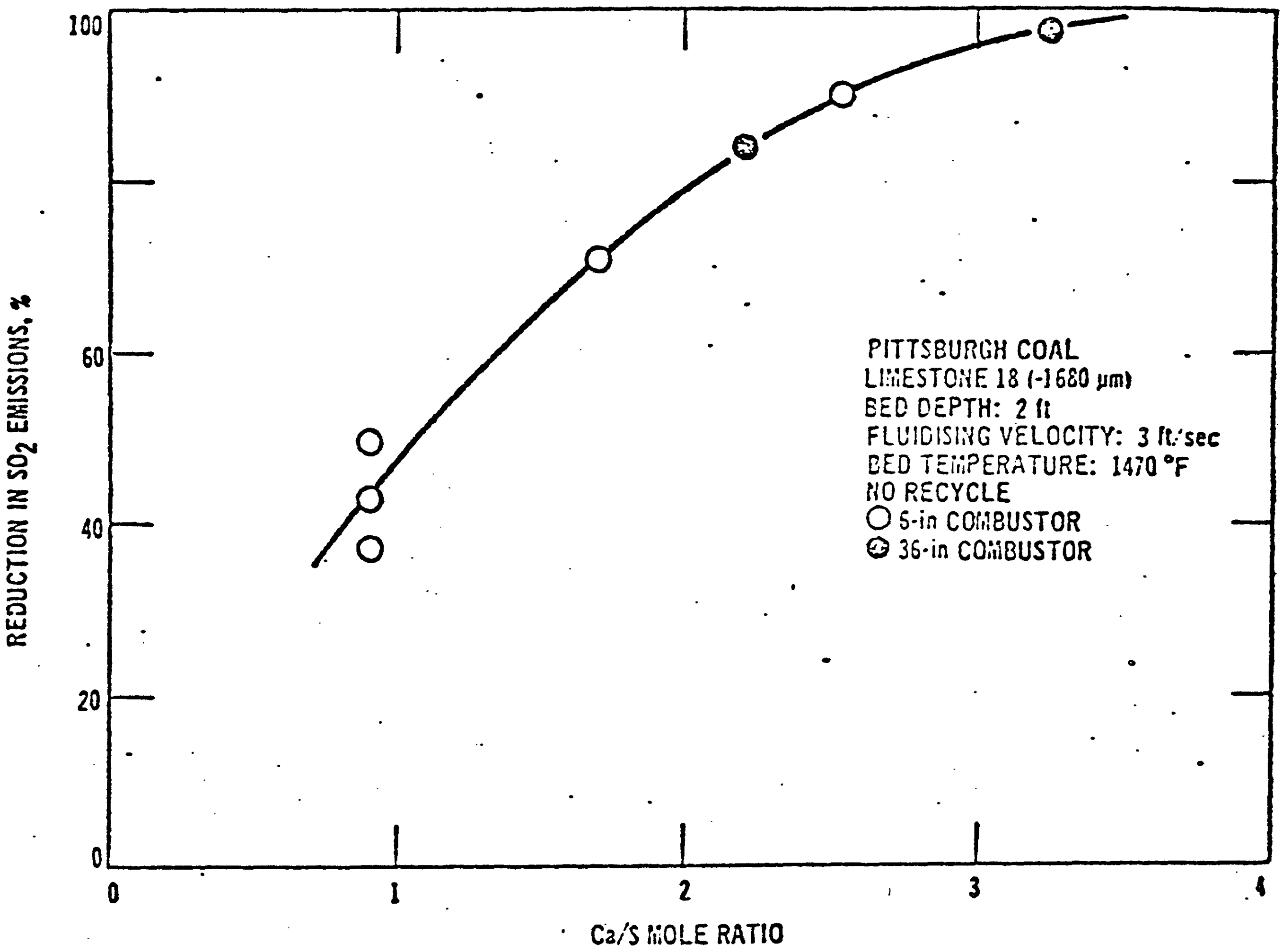


Figure 4.1.2.1-9

Sulfur Reduction Vs. Ca/S Mole Ratio (Wright, 1973).

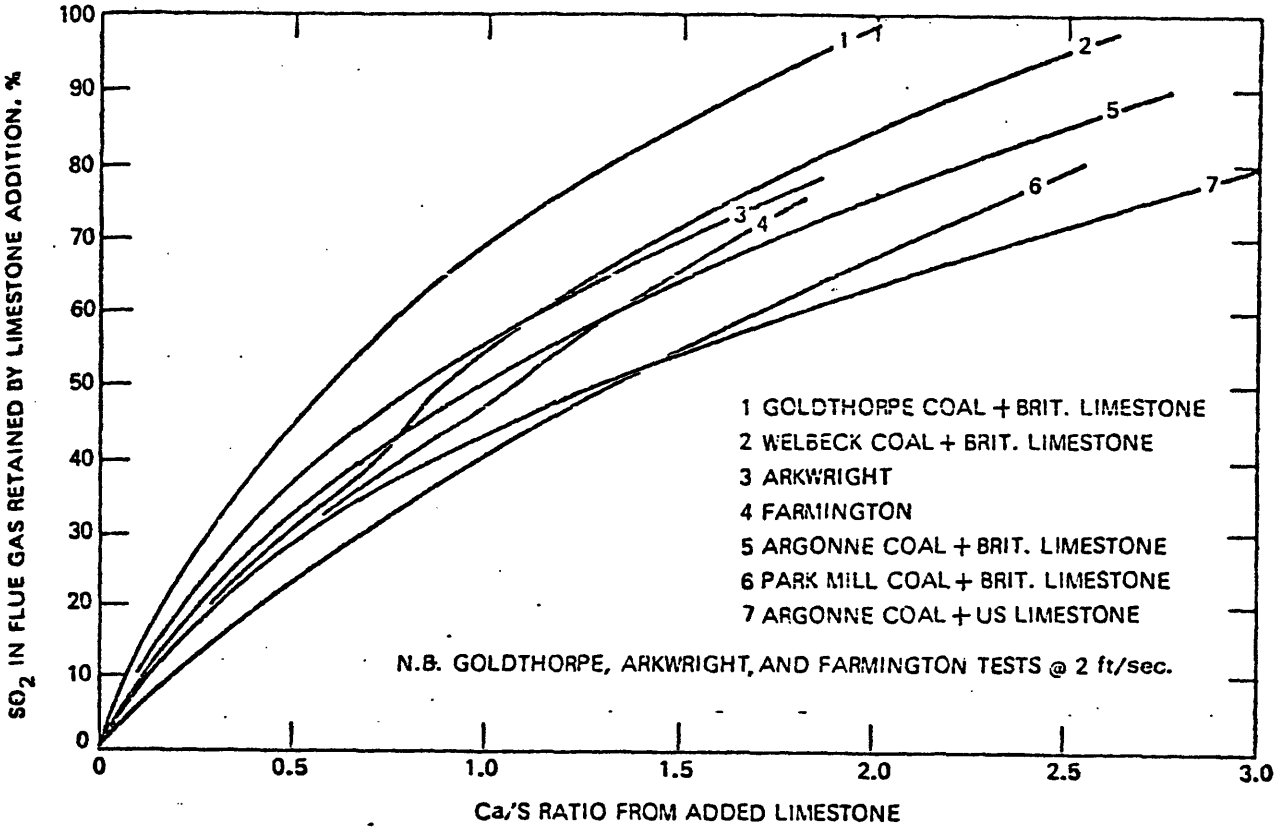


Figure 4.1.2.1-10

Effect of Limestone Addition on Retention of SO$_2$ (Davidson, Small, 1970).

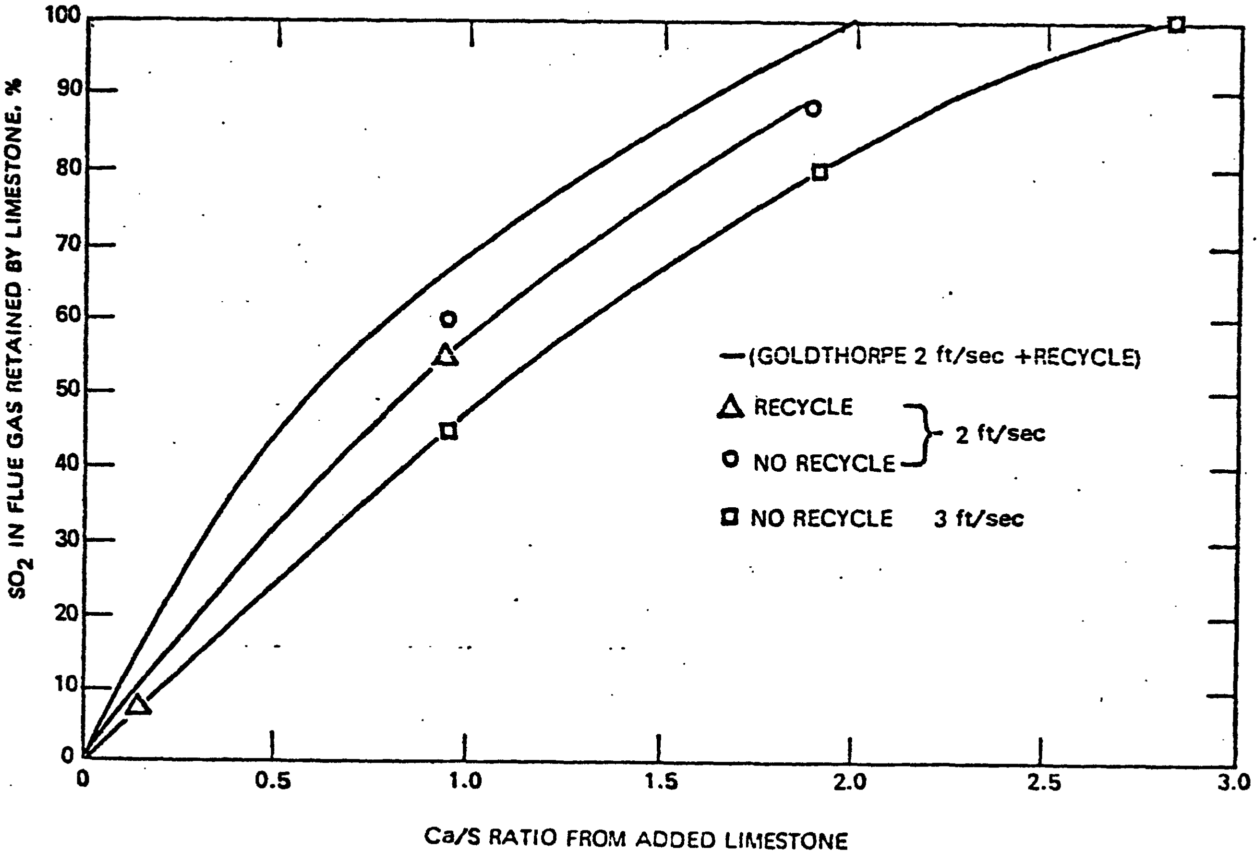


Figure 4.1.2.1-11

Retention of Sulphur by Limestone Addition to the Feed (Welbeck Coal) (Davidson, Small, 1970).

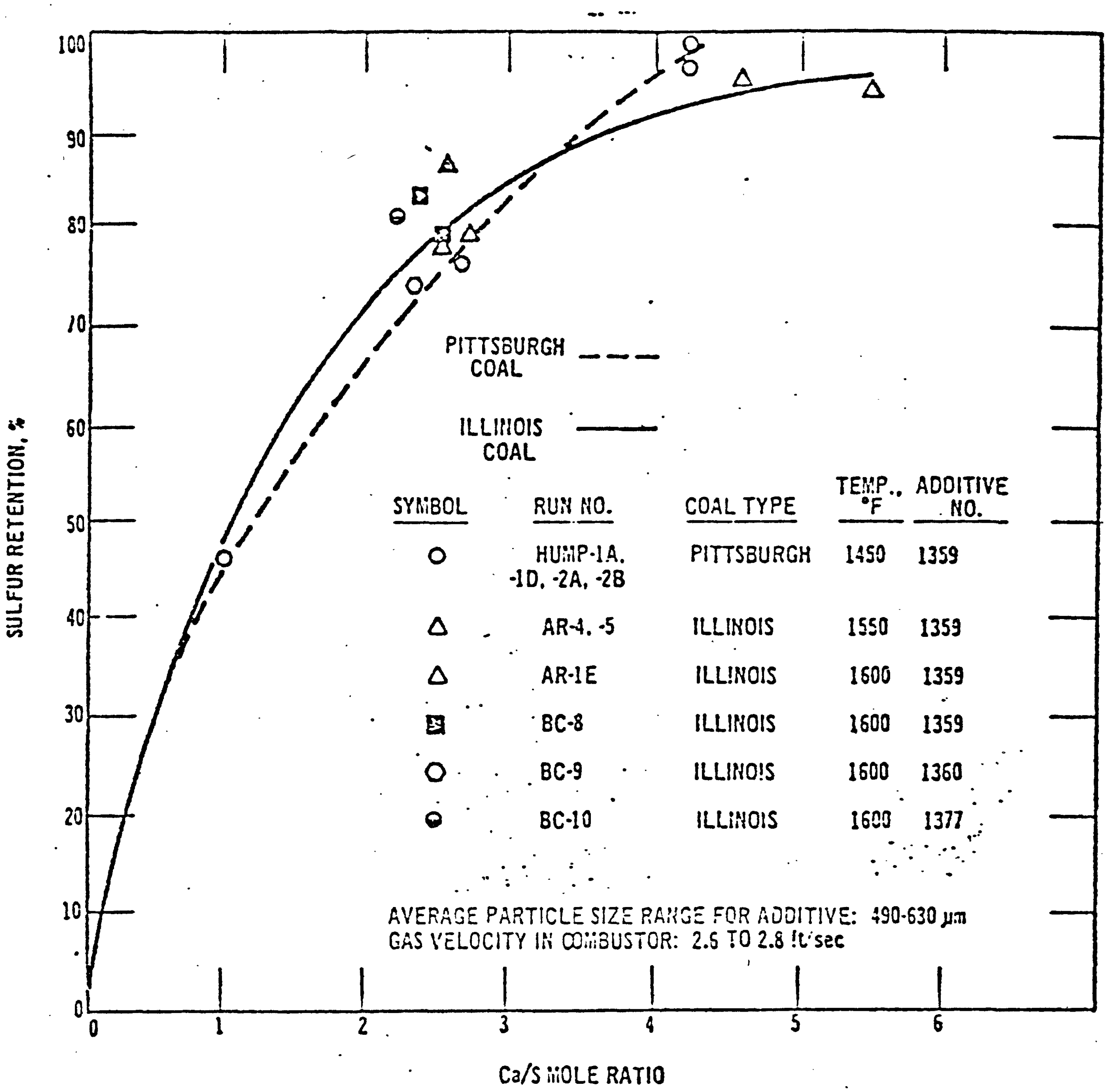


Figure 4.1.2.1-12

Sulfur Retention Vs. Ca/S Mole Ratio (Vogel, et al., 1973).

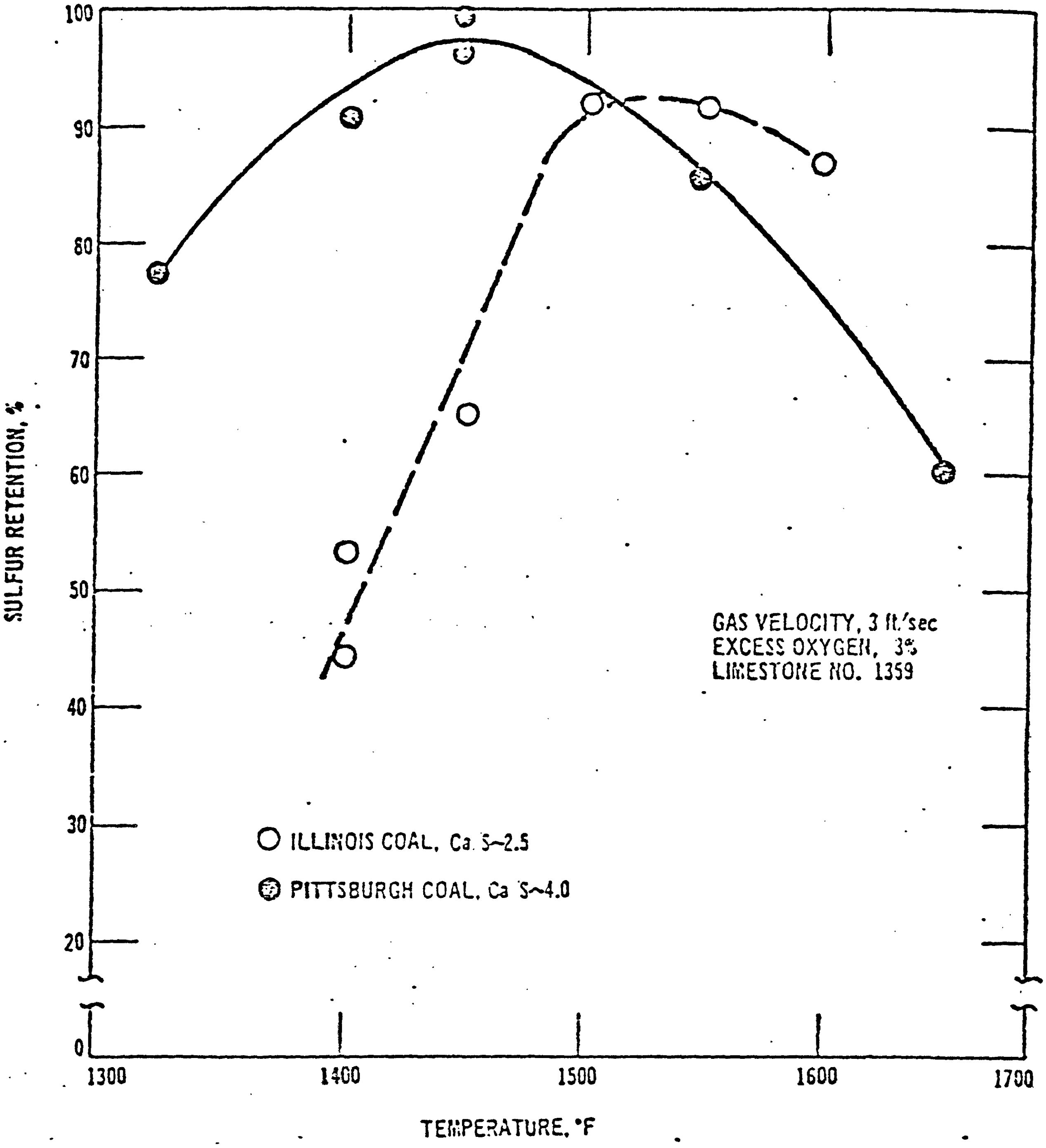


Figure 4.1.2.1-13

Sulfur Retention Vs. Bed Temperature (Jonke, et al., 1972).

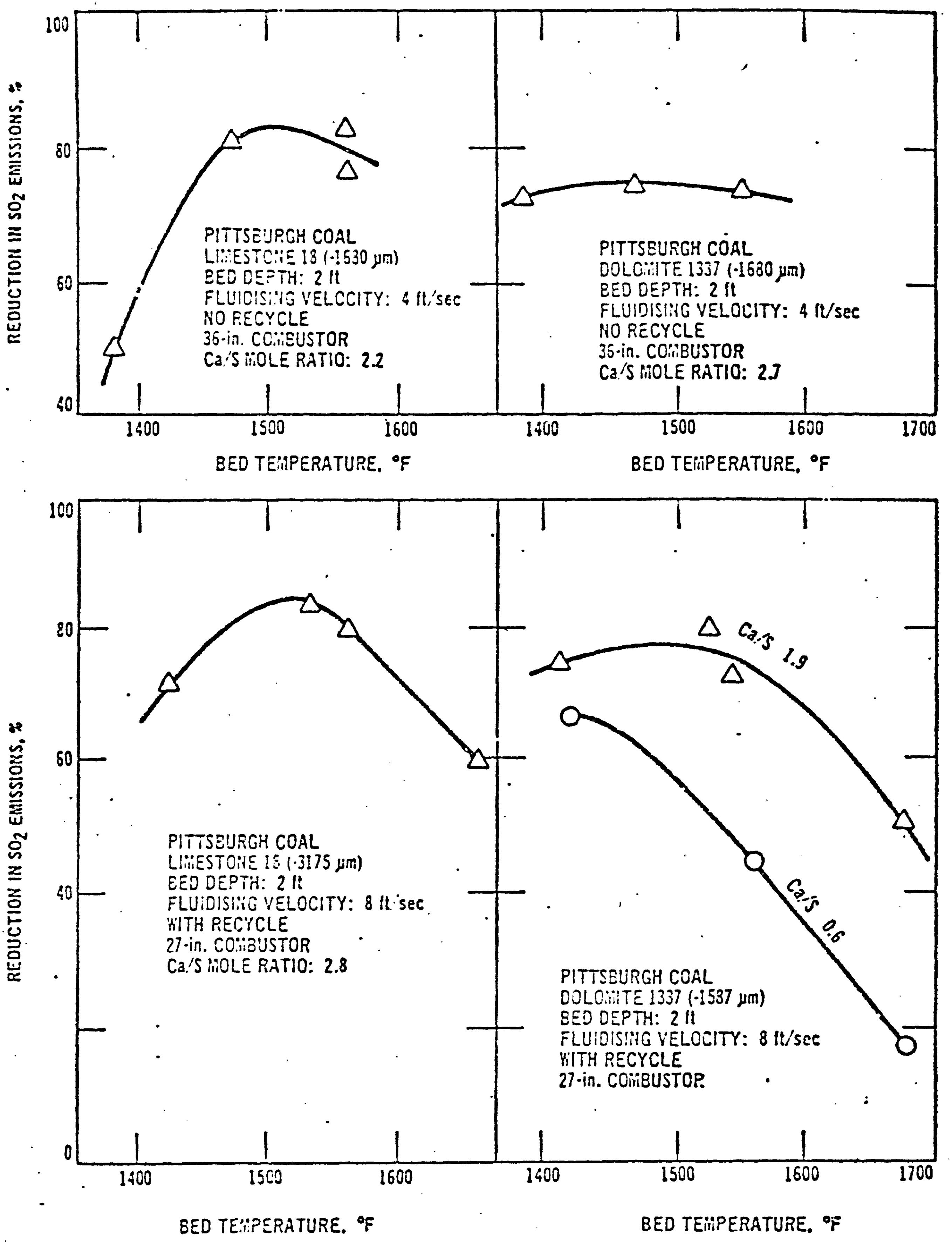


Figure 4.1.2.1-14

Sulfur Reduction Vs. Bed Temperature (Wright, 1973).

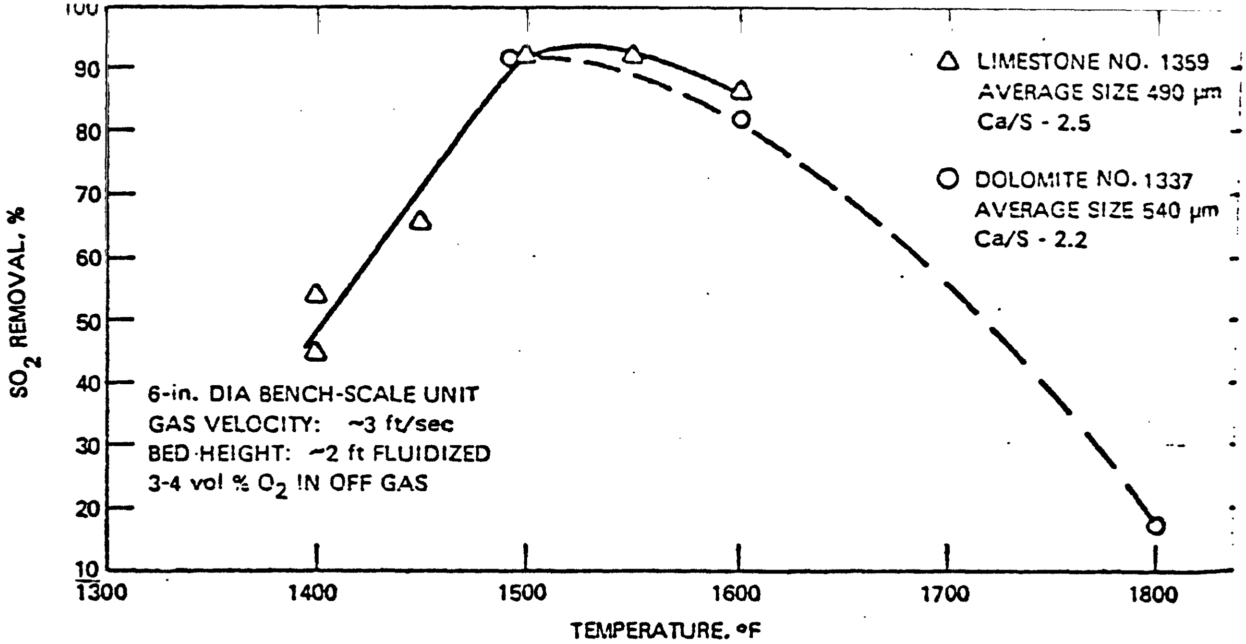


Figure 4.1.2.1-15

Effect of Fluidized-Bed Combustion Temperature on SO_2 Removal (Anastasia, et al., 1970).

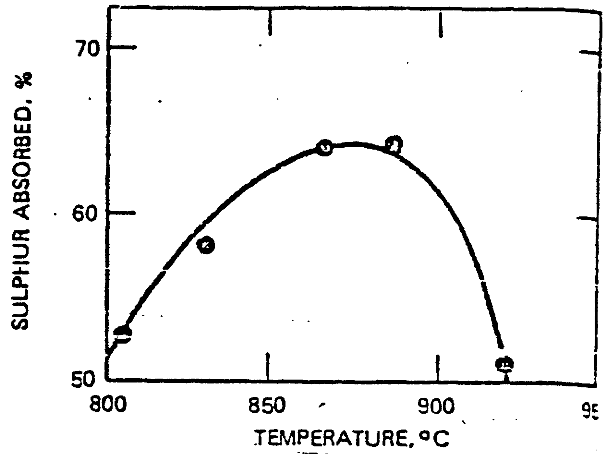


Figure 4.1.2.1-16 Optimum temperature for sulfur oxide absorption bt lime (31% of bed reacted)(Moss, 1970)

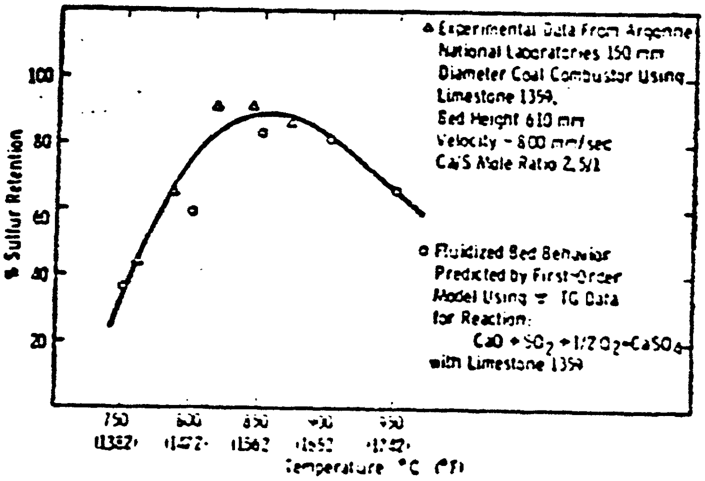


Figure 4.1.2.1-17

The Effect of Temperature on Sulfur Retention in a Fluidized Bed of Limestone 1359 (Keairns, et al., 1975).

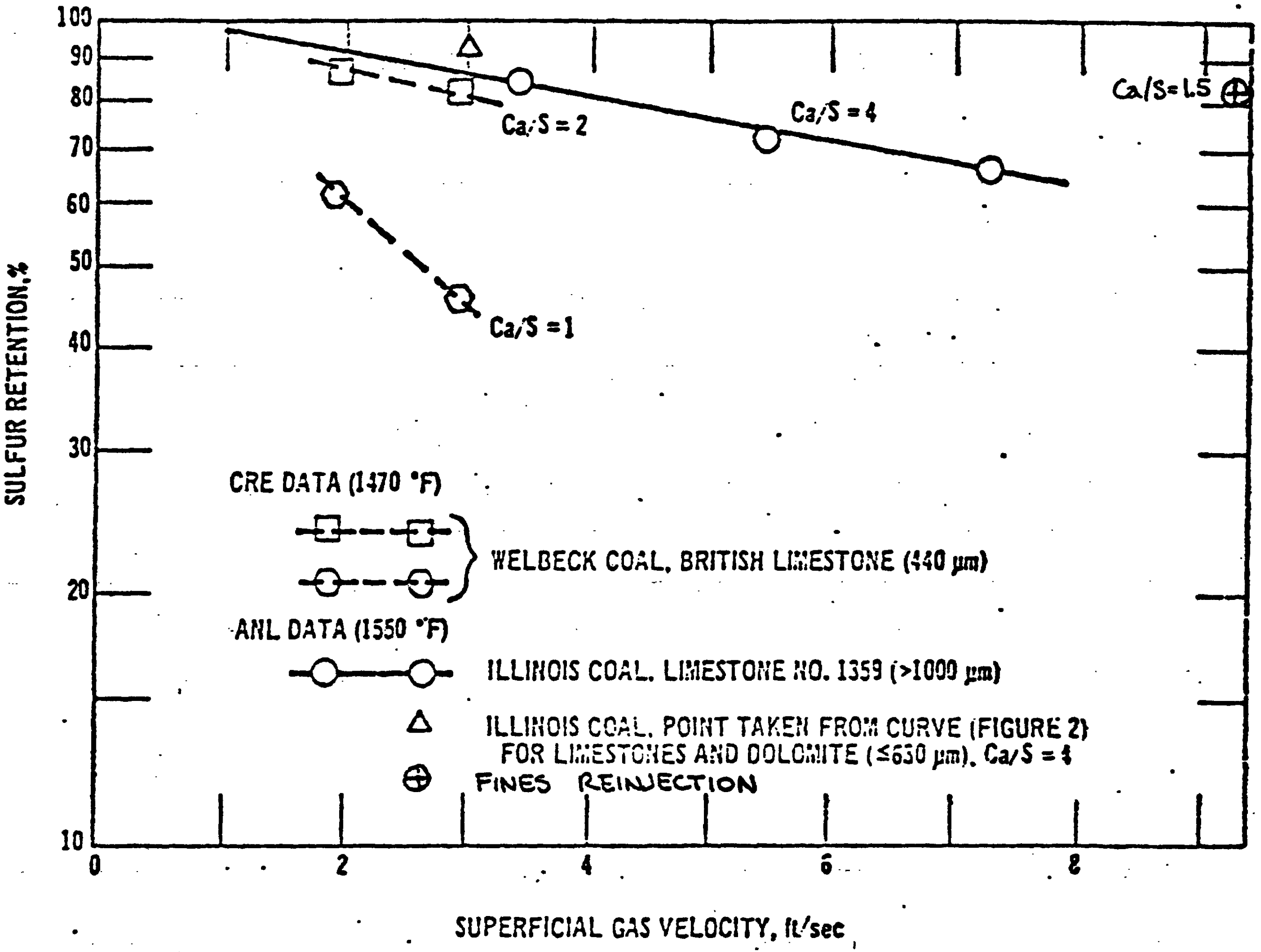


Figure 4.1.2.1-18

Sulfur Retention Vs. Superficial Gas Velocity

(Jonke, et al., 1972) and (Nack, et al., 1975, p. 360).

(1) reductions in gas and solids residence time.

(2) decrease in bed density.

(3) increase in production of large bubbles causing SO_2 bypassing, and

(4) increase in elutriation of under-utilized sorbent material.

Effects of Minor Parameters

The interaction of three parameters is shown in Figure 4.1.2.1-19 as performed at the Pope, Evans and Robbins facility. Limestone particle size has an insignificant effect in the range above 200 u. However, sulfur retention is sharply increased with sizes decreasing below 200 u. A sharp trade-off between elutriation and sulfur retention is evident in particle sizes at and below the 44 u size. If both coal and sorbents are ground to these fine sizes then low fluidizing velocities are necessitated, producing low system throughput, with undersirable economics. Babcock and Wilcox have performed extensive studies on the size of sorbents and its effect on sulfur retention. Figures 4.1.2.1-20 and -21 clearly show the size distributions associated with different meshes. Figures 4.1.2.1-22 and -23 display the parametric sulfur reductions as a function of sorbent size.

Figure 4.1.2.1-19 shows the expected increase in capture rate with deeper beds, due to greater interaction times (for constant gas velocities). This effect is corroborated in (Jonke et al., 1972, p. 231) but not to the extent shown in Figure 4.1.2.1-19. The reverse effect has been reported (Hammons and Skopp, 1972), but discounted due to small bed diameter (3 inch) causing the prevalance of slugging.

Bed depth effects may not be exploitable, since bed depth is proportional to bed pressure drop, which may be limited by available fans.

Compositional variations among different limestone sources are shown in Table 4.1.2.1-2. Recent experiments (Nack et al., 1975, p. 360) show however that dolomite, and not limestone, is likely to be the better sorbent in atmospheric beds. Most dolomites investigated have had nearly equal molar amounts of $CaCO_3$ and $MgCO_3$. The $MgCO_3$ calcinating to MgO appears to account for better utilization of CaO, as shown in data from (Skopp, Sears and Bertrand, 1969) in Figure 4.1.2.1-24. The postulated mechanism of MgO maintaining porosity of dolomite to facilitate sorption has been supported experimentally, (Jonke et al., June 1970) and (National Coal Board, February 1971). Original porosity of the different stone sources can be of paramount importance in sulfur retainability (Potter, 1969). No method has been found to predict the reactivity of different limestones and dolomites.

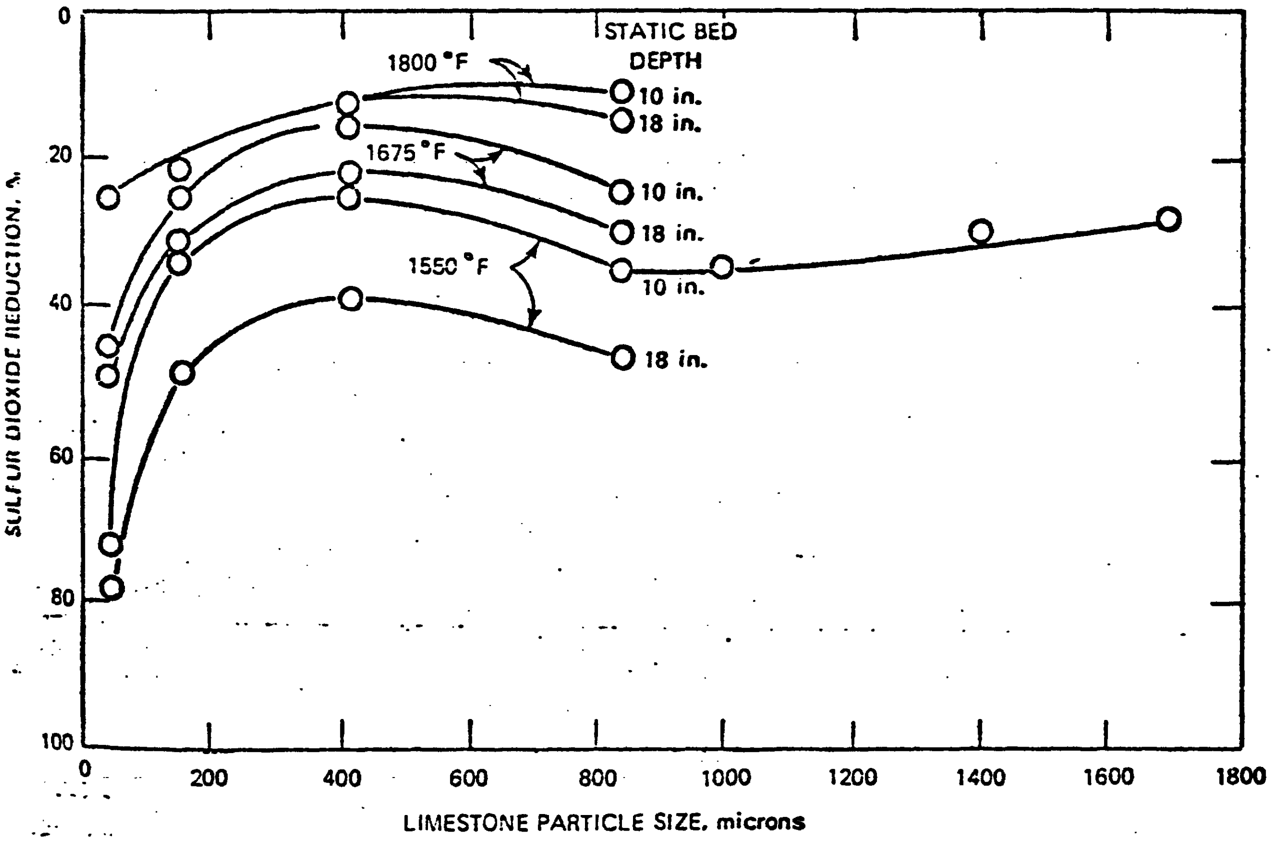


Figure 4.1.2.1-19

SO_2 Reduction -- Effect of Limestone Particle Size, Bed Depth, and Temperature (Ehrlich, <u>et al</u>., 1972, p. 231).

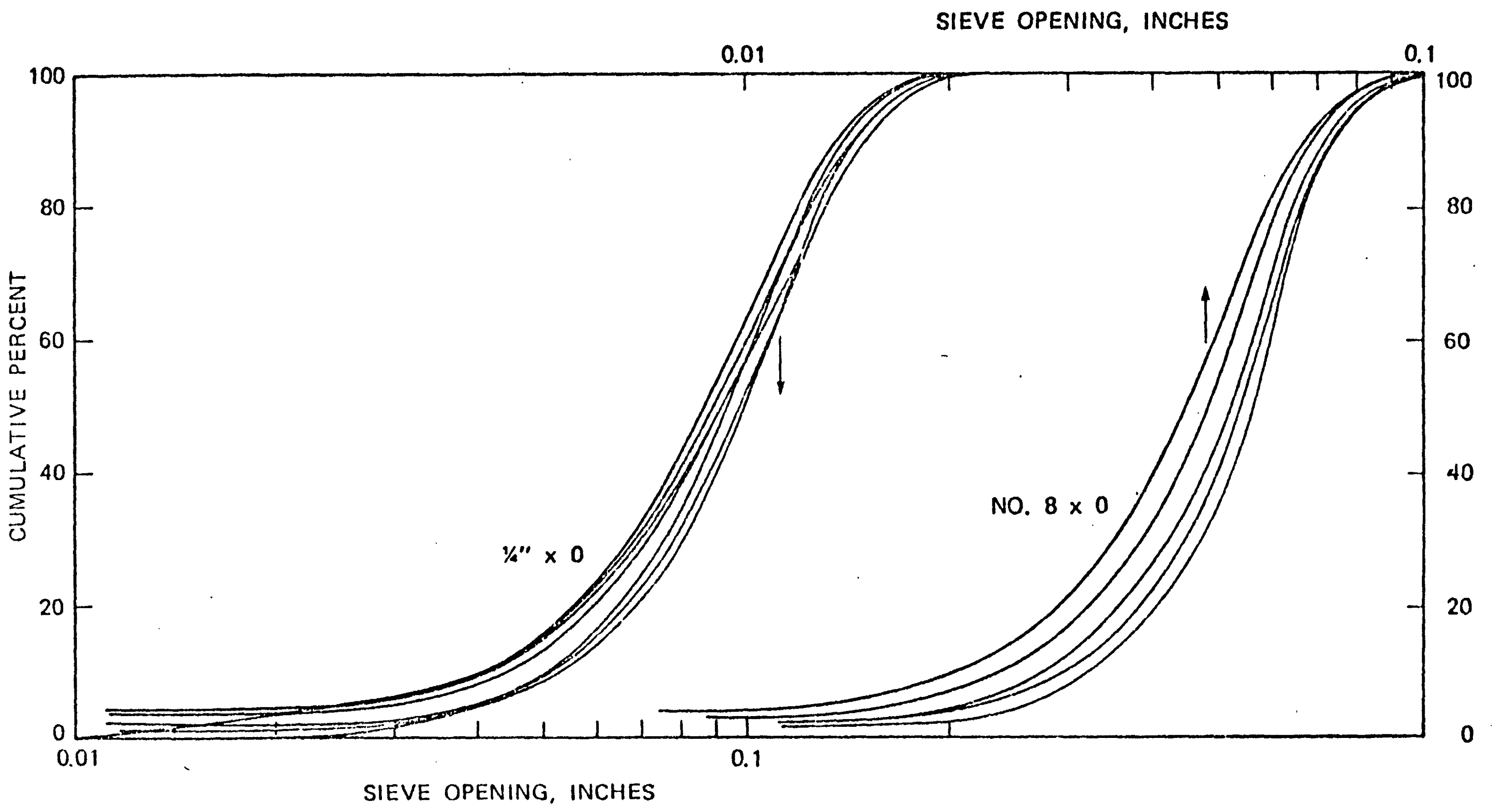


Figure 4.1.2.1-20

Limestone Size Distribution (Babcock and Wilcox, 1977).

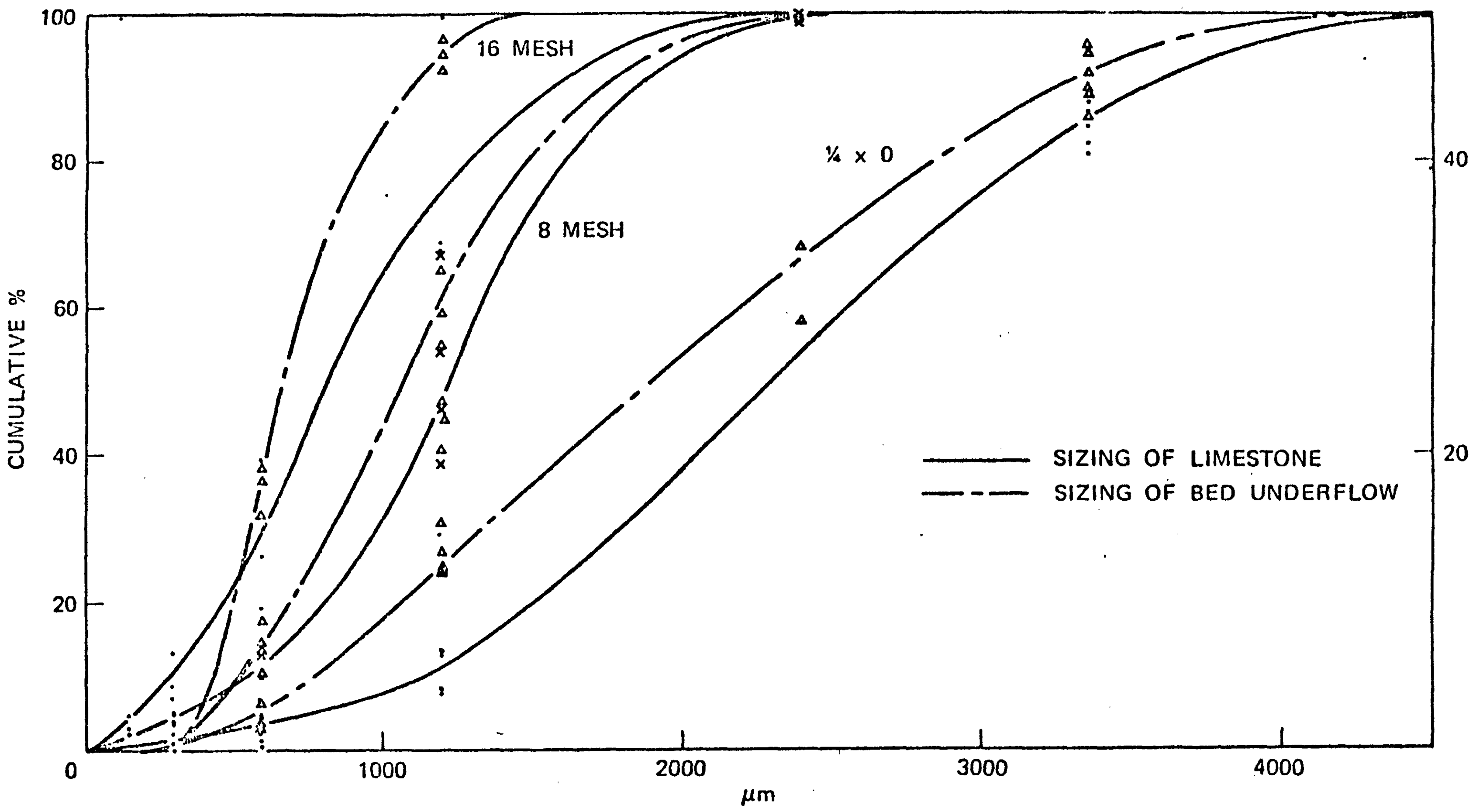


Figure 4.1.2.1-21

Size Distribution, Limestone Feed and Bed Underflow (Babcock and Wilcox, 1977).

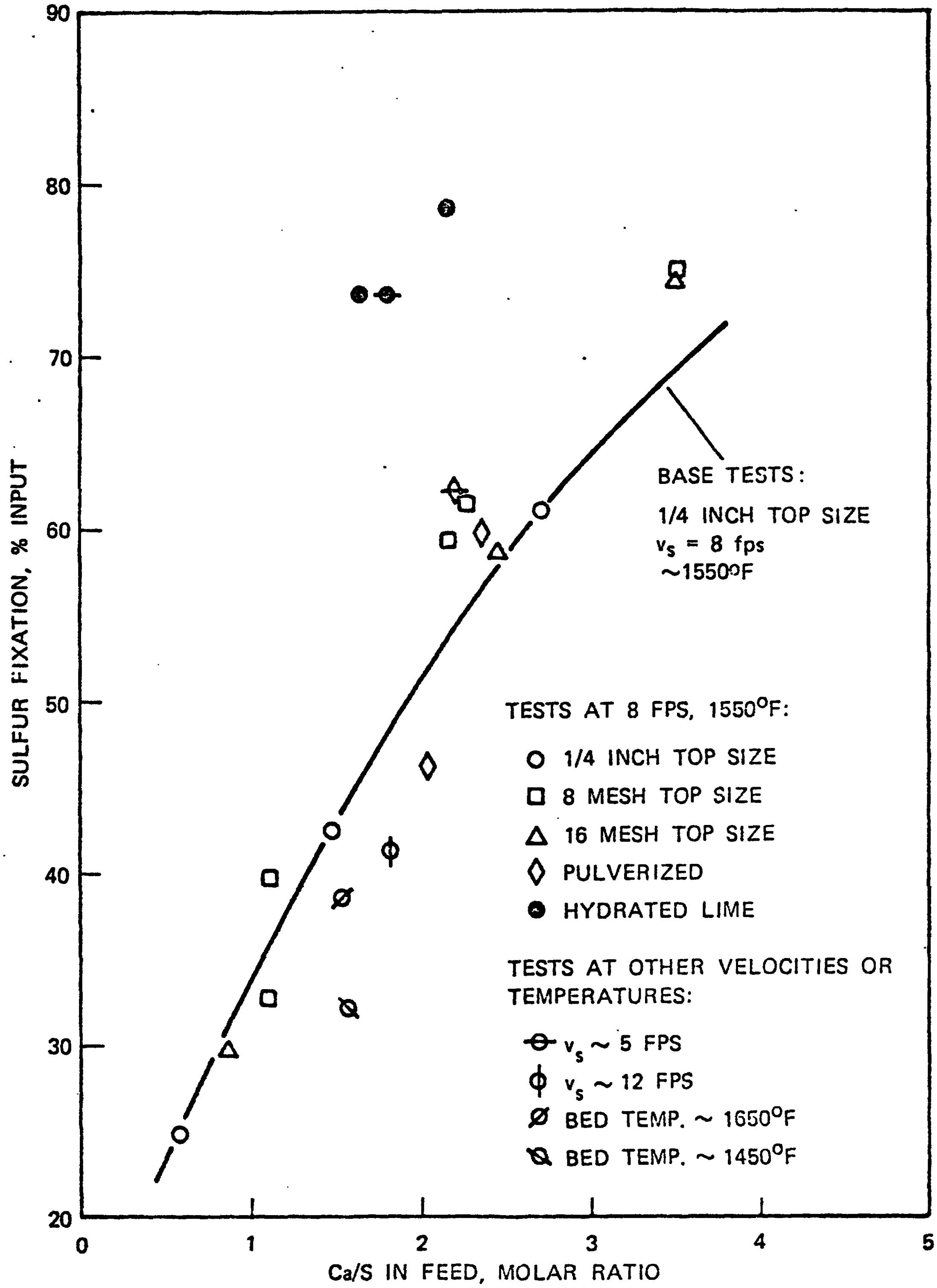


Figure 4.1.2.1-22

Sulfur Fixation Versus Ca/S for Lowellville Limestone and Hydrated Lime (Strom, et al., 1976).

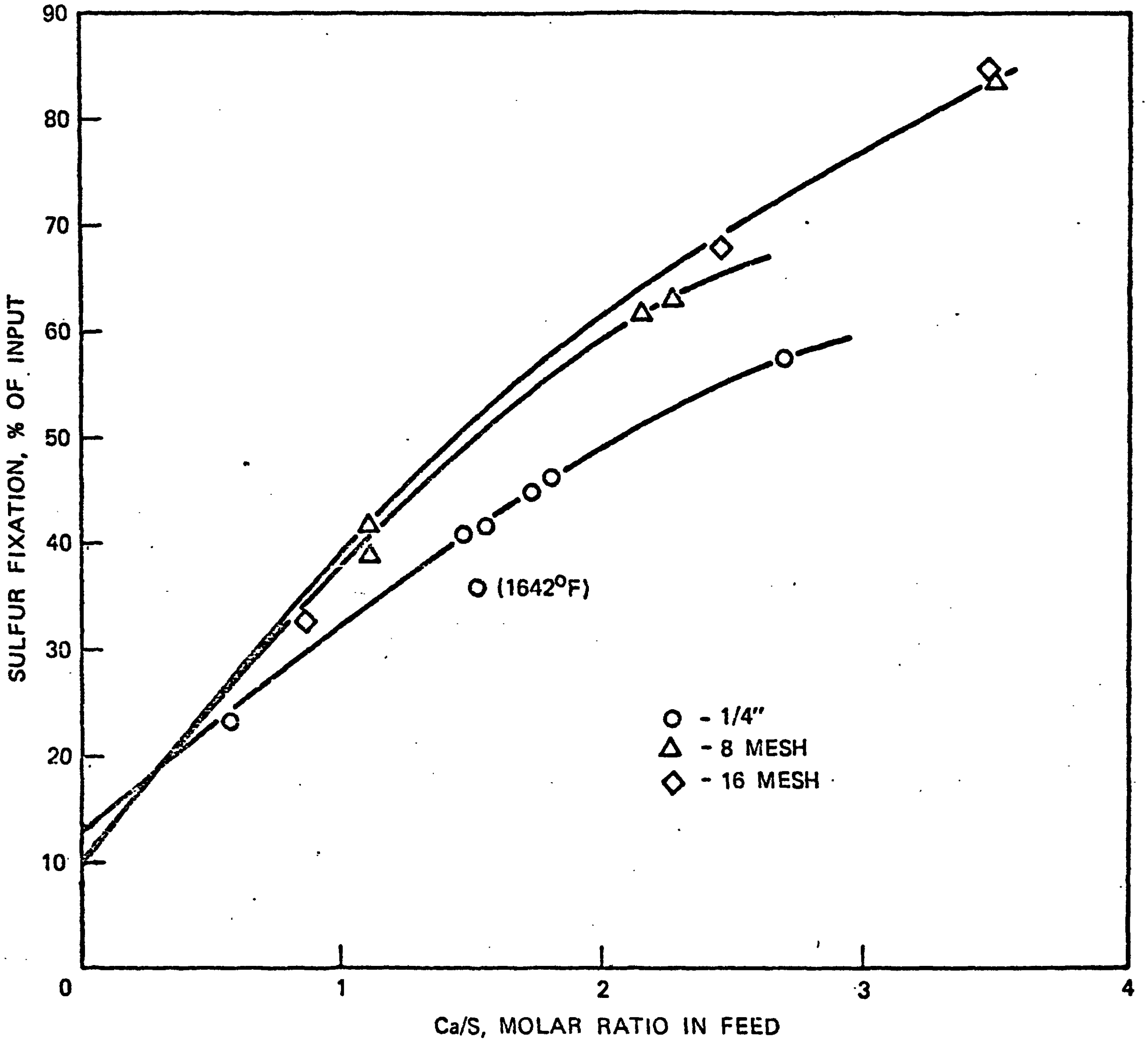


Figure 4.1.2.1-23

Percent Sulfur Fixation Vs. Ca/S Ratio (Strom, et al., 1976).

Table 4.1.2.1-2

Composition of Limestones Used in Kinetic and in Pilot-Plant Studies[a] (Horio and Wen, 1975).

Author	Borgwardt			Coates and Rice Davidson and Smale Jonke et.al. Robinson et.al.	Davidson and Smale
System	Kinetic Study			Fluidized-Bed Combustor	
Type of Limestone	Type 3[c]	Type 4[d]	BCR 1343	BCR 1359	British Limestone
$CaCO_3$	95.3	97.8	96.0	97.8	> 97.0
$MgCO_3$	3.89	0.00	0.96	1.3	[b]
Fe_2O_3	0.20	0.31	0.38	0.12	[b]
Al_2O_3	ND	0.01	[b]	0.16	[b]
SiO_2	ND	1.53	1.70	0.60	[b]
Ignition loss	43.67	43.15	42.8	43.6	[b]

[a] Only the data related to this paper are presented.

[b] Not reported.

[c] Type 3: calcite limestone with few scattered fine-grained dolomite rhombos.

[d] Type 4: calcitic limestone, very fine, equant granular, and dense.

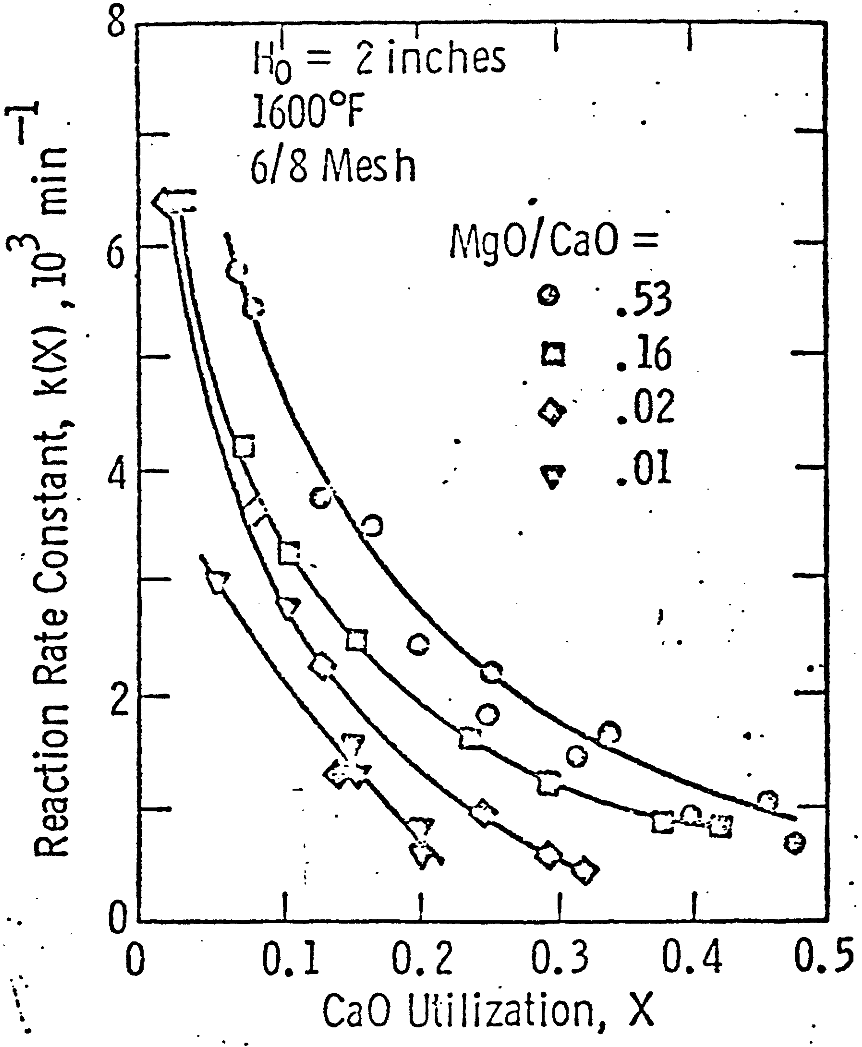


Figure 4.1.2.1-24

Effect of MgO/CaO Ratio on Stone Reactivity (Skopp, Sears, and Bertrand, 1969).

The use of regenerated sorbent decreases the collection of sulfur. There are several more or less well studied reasons for this effect. It may be possible to simply scale down the reactivity of the sorbent depending upon the amount of recycled material in the bed.

Figures 4.1.2.1-25 through -28 show some of this decreased reactivity.

Excess air can be used to increase sulfur retention in the bed, see Figures 4.1.2.1-29 through -32. A much more important factor in setting excess air levels is, however, the maximization of combustion efficiencies which occur in the excess air range of 5% to 15%.

Bed size may be important for small test units, with wall effects and slugging from bubble sizes approaching bed areas. Larger units should be free of these effects.

Effects of coal and sorbent feeds on sulfur retention could be substantial. The position of sulfur released in the bed and extent of oxidizing and reducing zones are the important factors.

Although the naturally occurring limestone and dolomites have been shown to be effective sorbents, and are attractive from a cost per unit basis, the search for alternative sorbents has been extensive. Problems that have arisen with the natural sorbents include rapid declines in reactivity upon regeneration (due to sintering, pore plugging, and poisoning by ashes of various coals as described in section 4.5) or very large quantities to be paid for and disposed of in the non-regenerated configurations. Alternative sorbents have been studied at Radian Corporation (Lowell and Parson, 1975), Argonne (Snyder _et al._, 1975), and Catalytrica Association (Cusumano and Levy, 1975). Table 4.1.2.1-3 shows the list of potential sorbents that is being considered.

Table 4.1.2.1-3
Alternative Sorbents

CaO
SrO
$LiAlO_3$
$LiFeO_2$
$LiTiO_3$
$NaAlO_2$
$NaFeO_2$
$CaAl_2O_4$
$SrAl_2O_4$
$SrTiO_3$
$BaAl_2O_4$
$BaTiO_3$

With the exception of CaO and $CaAl_2O_4$ there is no experimental data on effectiveness of these materials. Models are available for representation of the SO_2 removal efficiency of the $CaAl_2O_4$ sorbent in (Snyder _et al._, 1975).

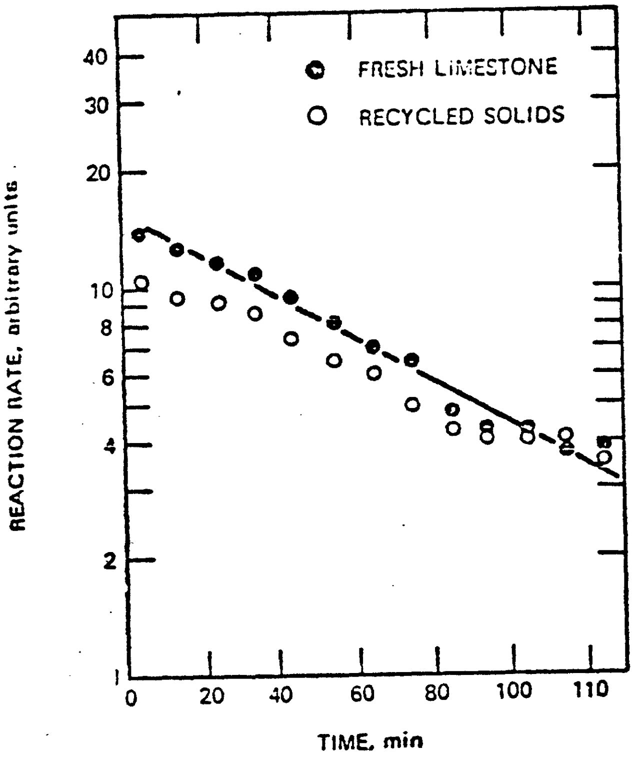


Figure 4.1.2.1-25

Reaction Rates at an SO_2 Partial Pressure of 3.2 mm Hg for Fresh Limestone and Recycled Solids (Anastasia, et al., 1970).

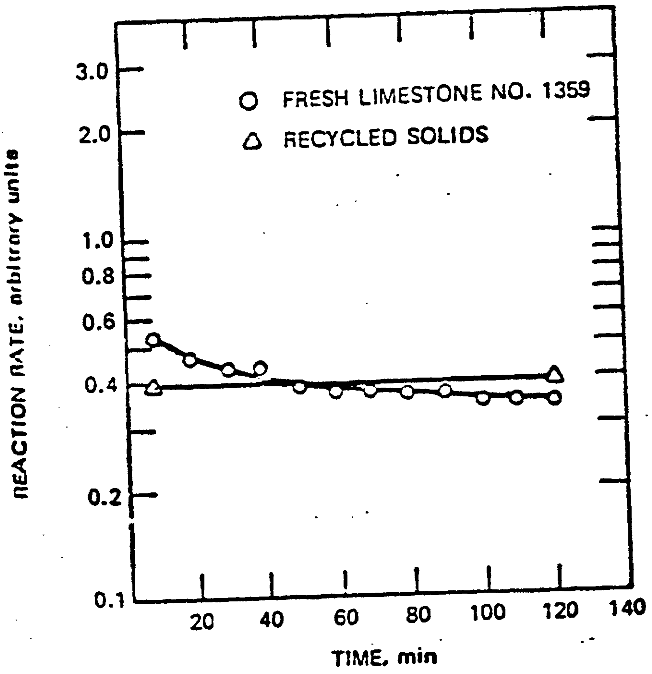


Figure 4.1.2.1-27

Reaction Rates at an SO_2 Partial Pressure of 0.4 mm Hg for Fresh Limestone and Recycled Solids (Anastasia, et al., 1970).

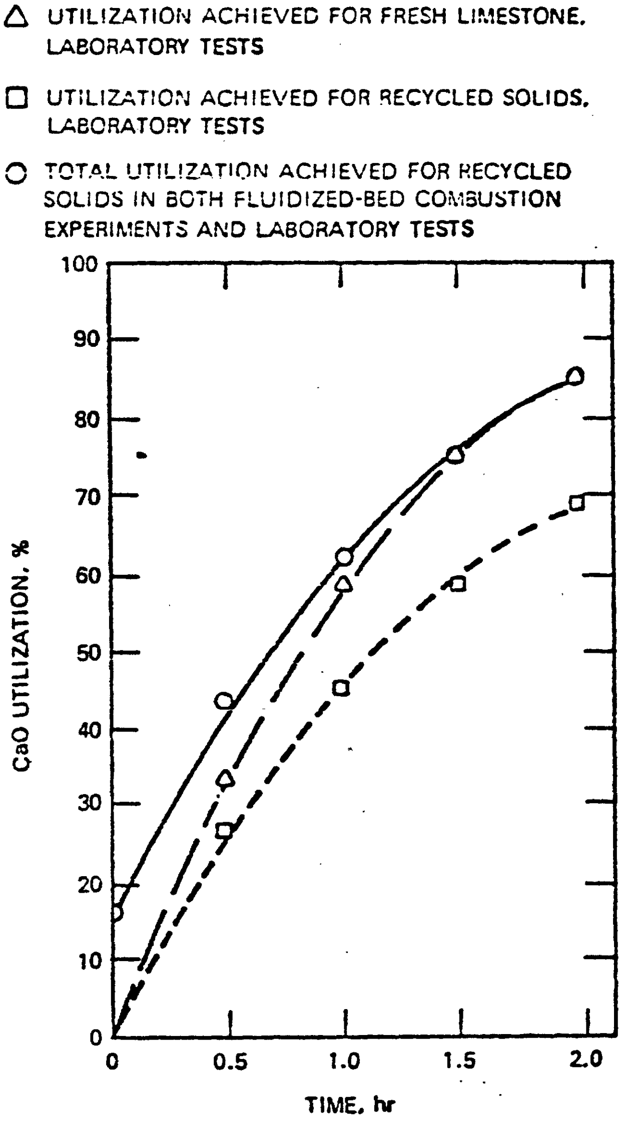


Figure 4.1.2.1-26

CaO Utilization for Fresh Limestone No. 135 and for Recycled Solids (Anastasia, et al., 1970).

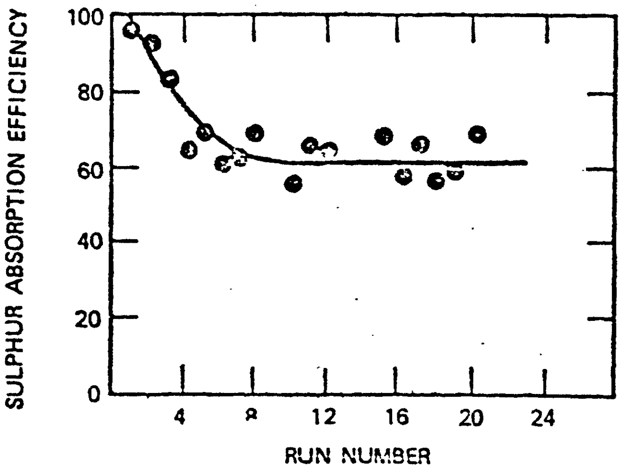


Figure 4.1.2.1-28

Bed Ageing Effect Replacement Rate o.5 wt CaO/wt S (Moss, 1970).

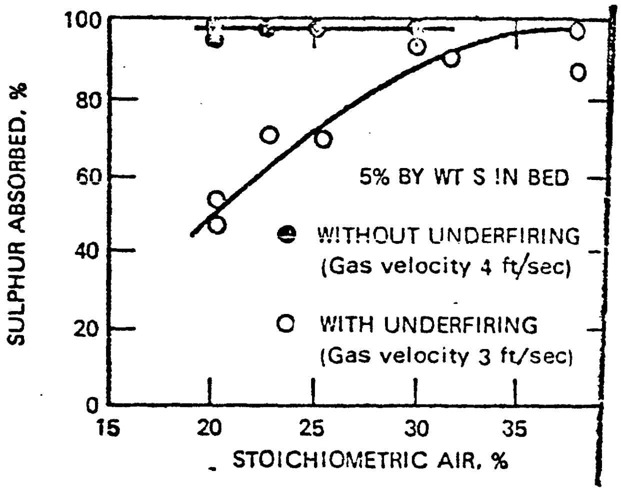


Figure 4.1.2.1-29

Stoichiometric Air Rate with and without Underfiring (Moss, 1970).

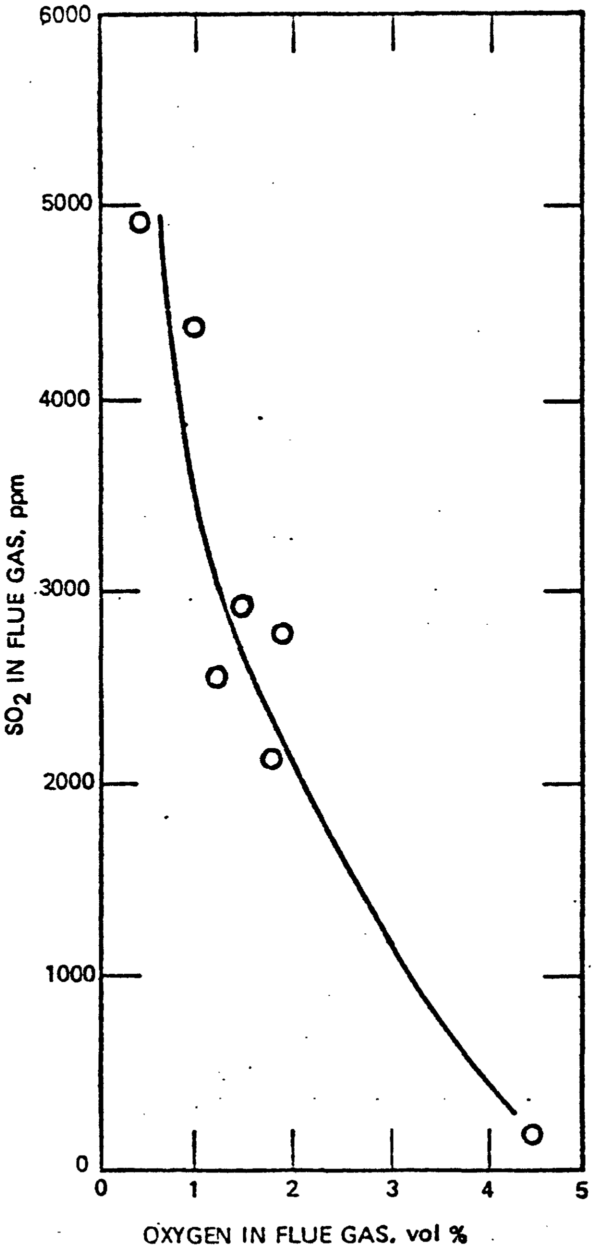


Figure 4.1.2.1-30

Desorption of SO_2 During Natural Gas Combustion as a Function of Oxygen Concentration at 1820-1850 °F (Jarry, et al., 1970).

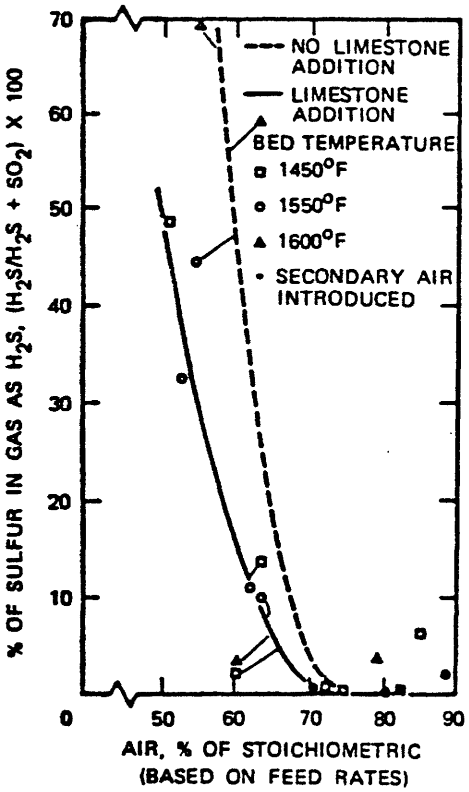


Figure 4.1.2.1-31

Sulfur Appearing as H_2S as a Function of Stoichiometric Air (Vogel, 1973).

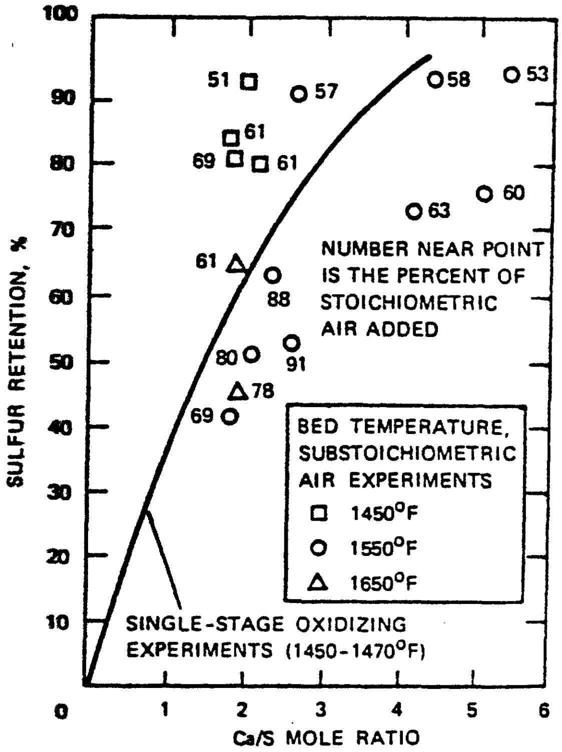


Figure 4.1.2.1-32

Sulfur Retention as a Function of Stoichiometric Air (Vogel, 1973).

The effect of coal type on sulfur retention is not well understood. Figure 4.1.2.1-10,-12, and -13 show some results; Figure 4.1.2.1-33 displays additional findings. Of course, the sulfur content of the coal is the primary factor effecting SO_2 emissions. Other factors have not been identified but could include:

(1) ash content;
(2) volatile content;
(3) ash composition;
(4) swelling index, and;
(5) ratio of organic to inorganic sulfur.

Decrease in coal particle size should increase sulfur retention due to contact and reaction rates. Such effects have not been experimentally verified.

The addition of salt (NaCl) to the bed has at times almost doubled the effective Ca/S ratio in the control of SO_2 emission (U.S. Office of Coal Research, 1974). The data on chlorine as the potential chemical attriter in this process is shown in Table 4.1.2.1-4.

Table 4.1.2.1-4
Effect of Chlorine on Effective Ca/S Ratio

Low Cl Coal	Raised to Cl Level	Increase in Effective Ca/S Ratio	Reference
0.08%	0.2%	75%	Henschel, 1970
0%	2%	60%	USOCR, 1974
0%	0.7 - 1%	60%	Nack *et al.*, 1975

Although there can be raised some severe questions of desirability of intentionally adding salt to an environ already hampered by corrosion problems, the chlorine content model is the only available mechanism for describing variability in SO_2 removal that is due only to variations in coal source [sulfur content has been dismissed as a potential important parameter (Archer *et al.*, 1971)]. In (Pope, Evans, and Robbins, 1975) effects of salt addition were observed to be:

(1) decrease in carbon content of bed, flyash, and dust;

(2) increase in chlorine content of flyash with negligible change in chlorine content of bed;

(3) increase in sulfur content of flyash and dust with little bed affect; and

(4) decrease in flyash collection rate.

The results of their studies with and without salt are shown in Figure 4.1.2.1-34.

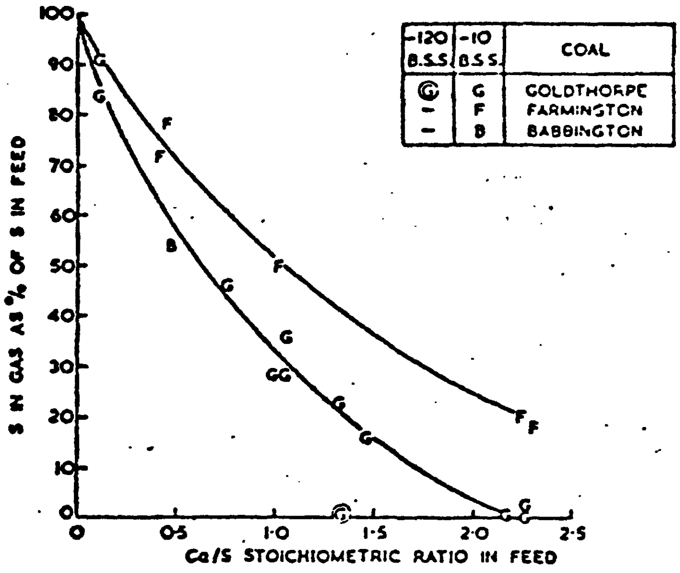


Figure 4.1.2.1-33

Effect of Coal Type on Sulfur Retention (McLaren and Williams, August 1969).

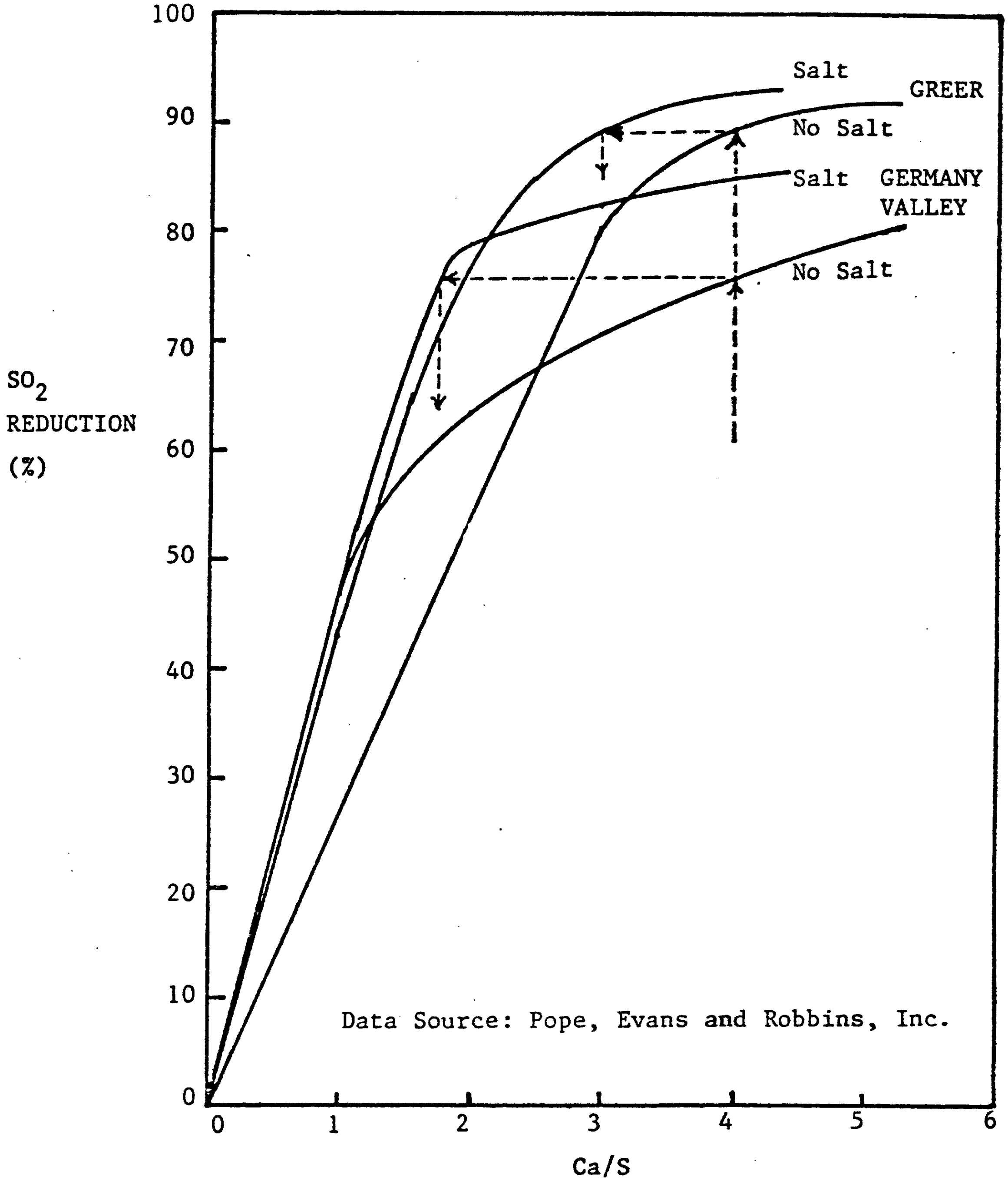


Figure 4.1.2.1-34

Effect of Salt on Sulfur Capture (Gasner, 1977).

In recent experiments, the Multi Solid FBC has performed slightly better than the conventional design FBC's (see Figure 4.1.2.1-35).

Beginning with a model of the sulfur reduction as a function of Ca/S ratio, the Ca/S ratio effect can be eliminated from parametric studies on temperature. In this way a temperature model can be developed, and both temperature and Ca/S ratio effects can be removed from bed depth effects. This solution of the sets of parametric experiments eventually results in a model of SO_2 emission from the atmospheric FBC. Models built up directly from theoretical grounds, based on population balance equations and considering residence time distributions of particles in the bed, have shown accuracy +6.5% of SO_2 removal percentage (Horio and Wen, 1975); see Figure 4.1.2.1-36 for example. These calculations are for coarse limestone, steady state and other assumptions and require the use of an iterative procedure of formulas and lookup graphs. It does represent one of the complex analytic models that can be compared to the following empirical models. These models were developed on the EPRI data base (Strom, et al., 1976) and are discussed further in (Gruhl, Tung, Schweppe, 1978). Table 4.1.2.1-5 shows the original model with Figure 4.1.2.1-37 the scatterplot of the fit. Table 4.1.2.1-6 and Figures 4.1.2.1-38 show a refined model. Table 4.1.2.1-7 and Figures 4.1.2.1-39 and -40 show the best model over the mass of data.

4.1.2.2 Nitrogen Oxide Emissions

NO_x emissions in atmospheric FBCs with inert beds range from 450 to 800 ppm (Pereira, Beer, Gibbs, and Hedley, 1974). With the addition of limestone these levels drop to 250 to 600 ppm (Nack et al., 1975). There is a potential for a problem here as the USEPA's new source performance standards for coal-fired utility boilers limits NO_x emissions to 0.7 lb of NO_2 per 10^6 BTU of heat input, or roughly 525 ppm in emissions (Strom et al., 1976). An average of 353ppm was found in the massive data collection effort of (Strom, et al., 1976), see Figure 4.1.2.2-1.

Experiments in which argon was substituted for atmospheric nitrogen showed little change in these NO_x concentrations (Jonke et al., 1969), (Shaw and Thomas, 1968); using nitrogen-free fuel substantially eliminated NO_x formation (Jonke et al., June 1970), thus placing the source clearly as the nitrogen bound in the coal. The amounts of nitrogen bound in coal are clearly capable of producing these levels of NO_x concentrations, with 1.0-1.5% nitrogen coal capable of yielding 2025-2850 ppm NO_x emissions. Two reactions have been proposed as actors in the freeing of the 80-90% of the bound nitrogen that does not become NO_x. One reaction is

$$2NO + 2CO = N_2 + 2CO_2 ,$$

and the contention that this takes place is substantiated by experiments in pressurized FBCs where increasing excess air reduces the availability of CO (see Figures 4.1.2.2-2 through -6). The effects of excess air is not as apparent, however, when all of the data is plotted on a single display, as shown in Figure 4.1.2.2-7. Additional experiments where stage combustion was used, secondary air injection into the freeboard, apparently also shows that with better mixing there is improved use of the CO and subsequent reductions in NO emissions, see Figure 4.1.2.2-8.

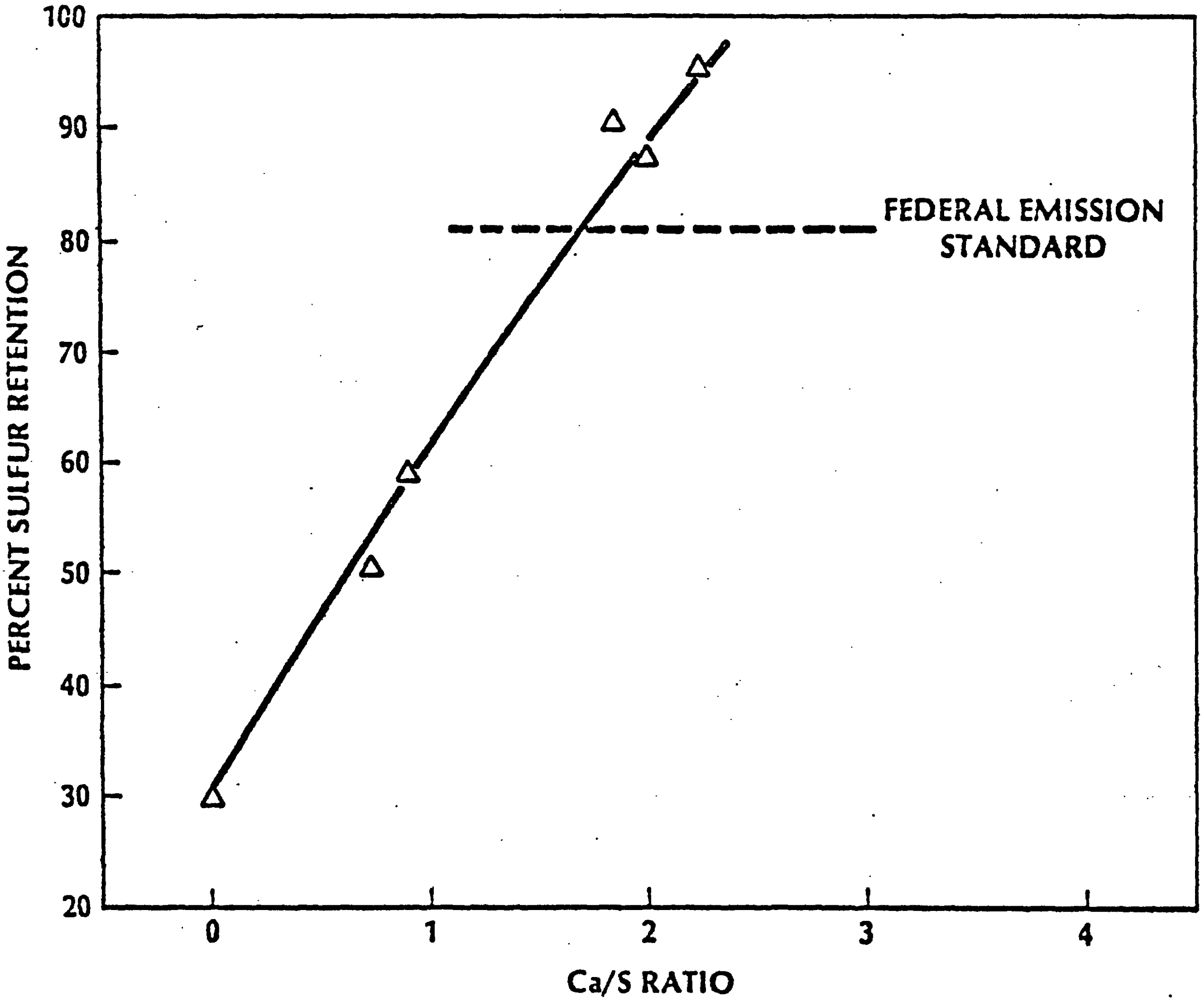


Figure 4.1.2.1-35

Effect of Ca/S Ratio on Sulfur Retention in Multisolid Fluidized-Bed Combustion (Nack, Weller, Liu, 1977).

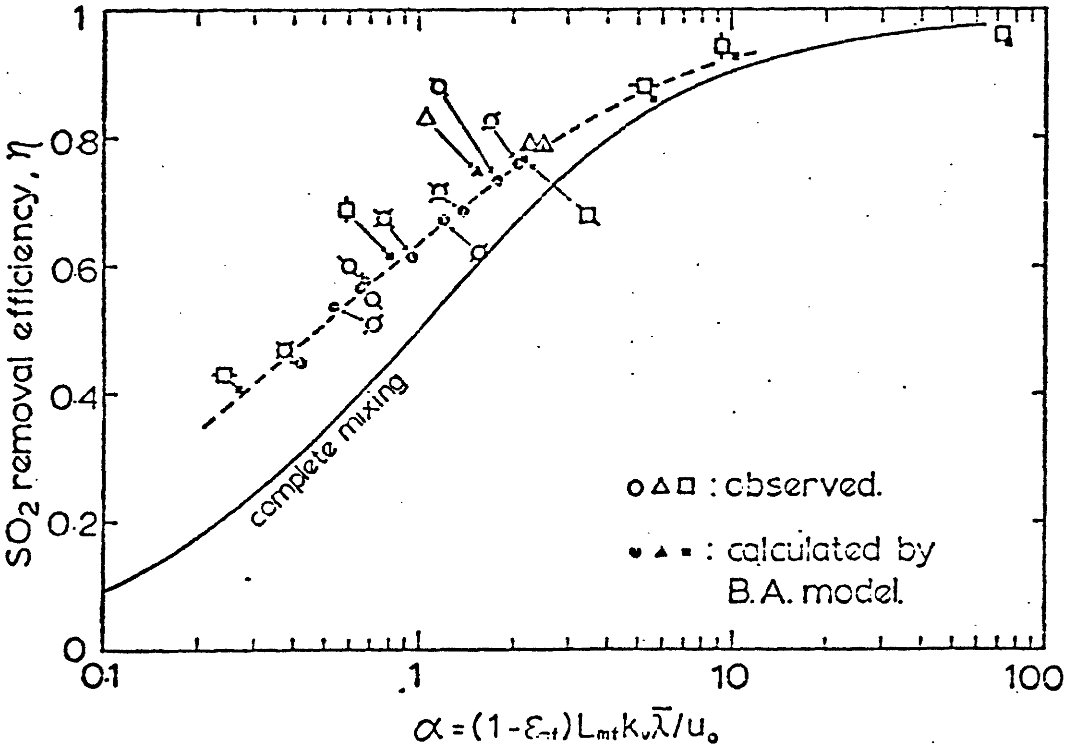


Figure 4.1.2.1-36 Comparison of observed SO_2 removal efficiency as a function of a Bubble Assemblage Model (Horio and Wen, 1975)

Table 4.12.1-5 Empirical models of sulfur removal for observations where removal equalled or exceeded 80%

Symbols:

S = sulfur removed, as percent
C = calcium to sulfur mole ratio
V = fluidizing velocity, in m/sec
T = bed temperature in degrees centigrade
D = static bed depth, in cm
A = bed area, in square meters
M = calcium mean size, in microns
P = parameter for effect of coal source
Q = parameter for effect of calcium source
R = number of times sorbent reused, 1+number of recycles

Model from a limited number of parametric experiments:

$$S = 100.-(30.6/C)[(V/.3048)^{.25}-.30][1.+.429(\frac{1.8T-1492+45.5abs(2.35-C)}{127.3})^{2}] * [2.24(\frac{D}{2.54})^{-.25}](R^{-.5})P$$

[fit=arithmetic standard dev. 5.43%]

Model on data base where all experiments with these parameters and S over 80%:

$$S = (100.-\frac{41.4}{C+.414})(.923+.0762V^{-1})(.997+.0247A)[1.23-.00015(1.8T+32)] * (1.0058-.000013M)(.99337\ P\ Q)$$

[fit=arithmetic standard dev. 3.46%]
on 41 experiments

Tables of parameters:

coal source	P_{param}	$P_{data\ base}$	calcium source	$Q_{data\ base}$
Pitt seam 8 washed	0.48	1.05	BCR1337 dolom	0.98
Pitt seam 8 unwashed	0.83	1.00	BCR1360 limes	1.00
Peabody Coal Co.	0.80	1.01	BCR1359 limes	0.99
Pitt seam unspecified	0.92	1.00	BCR1359H hyd lm	1.01
Commonw. Edison supplied	0.97	0.98	Tymochtee dolom	1.04
Park Hill coal	1.04	1.00	US limestone 18	1.02
Illinois coal unspec.	1.13	1.00	UK limestone	1.02
Welbeck coal unspec.	1.28	0.975	Stow-on-Kent	0.92

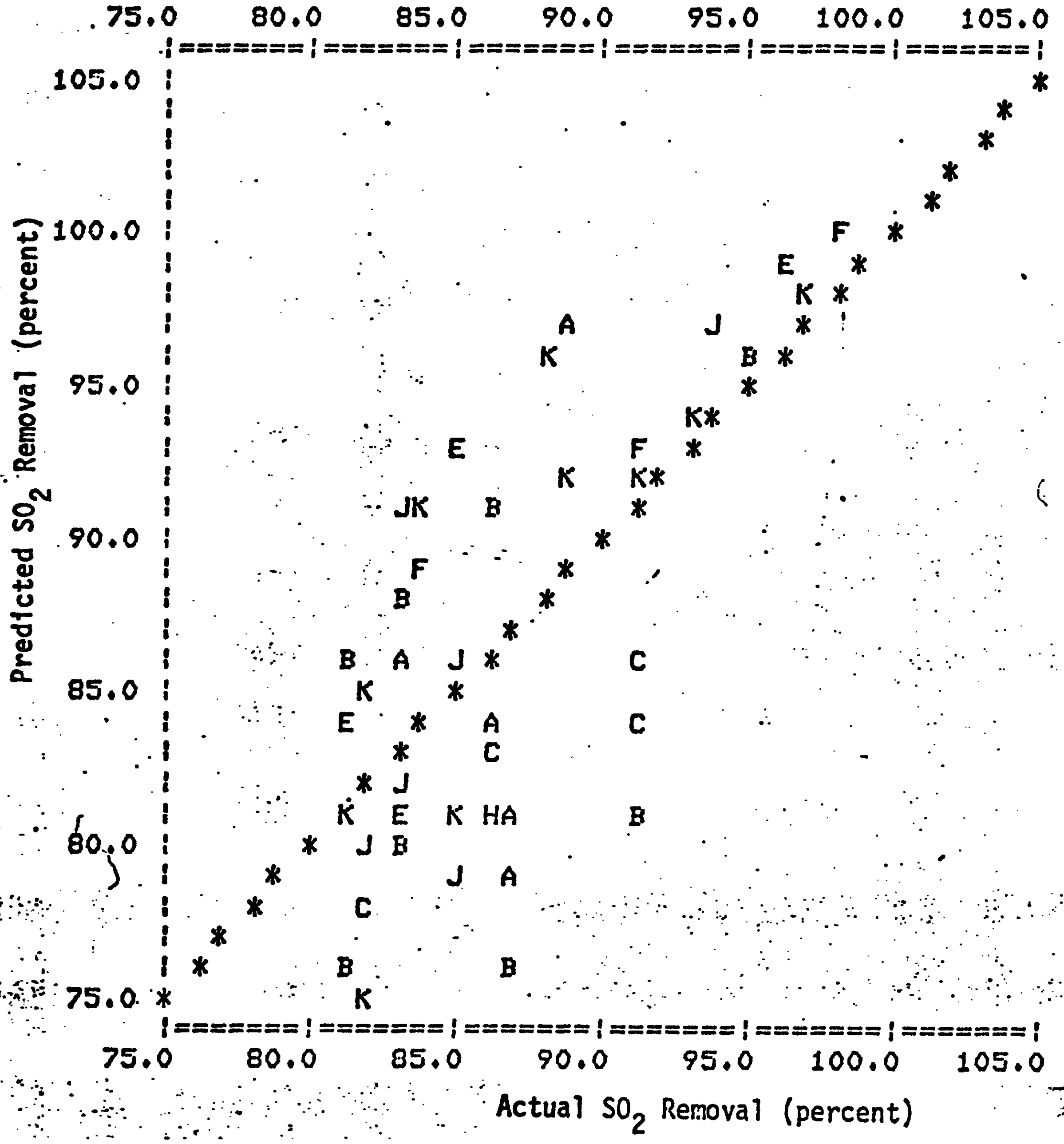


Figure 4.1.2.1-37 Scatterplot of SO_2 removal as observed versus predictions based on a data base developed model, the least squares fit approach concentrates on containing outlyers and has relative indifference to values within general band around the identity line (symbols refer to positions in data base)

Table 4.12.1-6 Empirical model of sulfur removal for observations exceeding 80% removal, eliminating calcium mean as a variable to increase the number of applicable experiments where all variables were reported

Symbols:

S = sulfur removed, as percent
C = calcium to sulfur mole ratio
V = fluidizing velocity, in m/sec
T = bed temperature, in degrees centigrade
A = bed area, in square meters
F = 1 or 0 for fines recycled or not
G = MgO/CaO in sorbent
P = parameter for effect of coal sources
Q = parameter for effect of calcium sources

Model on data base where all experiments with these variables reported and with S over 80%:

$$S = (101.- \frac{30.97}{C+.3097})(1.208+\frac{.40}{V+.762}+.0151V^2)(1.+.0095A)[1.-.00022(1.8T+32.)]$$

$$*(1.-.0012F)(1.-.00476G)[1.-.00000246(1.8T+1500.)^2]\ 1.002\ P\ Q$$

[fit=arithmetic stand dev 3.976%]
on 62 experiments

Table of parameters:

coal source	$P_{\text{data base}}$	calcium source	$Q_{\text{data base}}$
Pitt seam 8 washed	0.993	BCR1337 dolom	0.995
Pitt seam 8 unwashed	1.000	BCR1360 limes	0.991
Peabody Coal Co.	1.015	BCR1359 limes	0.992
Pitt seam unspecified	1.002	BCR1359H hyd lm	1.023
Commonw. Edison supplied	0.998	Tymochtee dolom	1.031
Park Hill coal	0.974	US limestone 18	1.007
Illinois coal unspec.	0.991	UK limestone	1.014
Welbeck coal unspec.	0.959	Stow-on-Kent	0.925

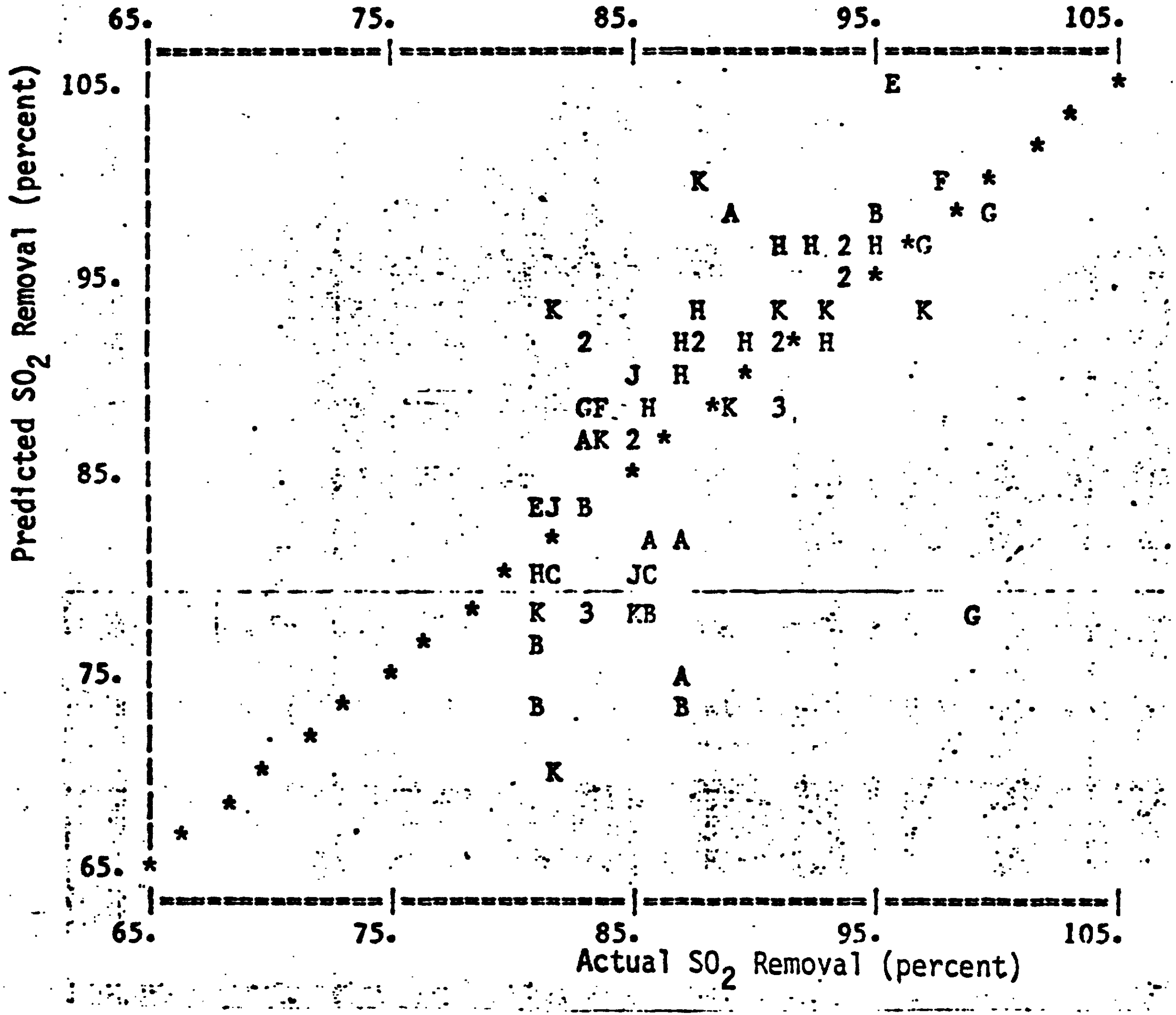


Figure 4.1.2.1-38 Scatterplot of SO_2 removal as observed versus predicted based on data base developed model, not using calcium mean as a variable only because it is not often measured and thus reduces the number of experiments that can be applied

Table 4.1.21-7 Empirical model of sulfur removal for all observations for which values of all parameters were available

Symbols:

S = sulfur removed, as percent
C = calcium to sulfur mole ratio
V = fluidizing velocity, in m/sec
A = bed area, in square meters
M = calcium particle mean size, in microns
L = sulfur content of coal, in percent
X = excess air, in percent
P = parameter for effect of coal source
Q = parameter for effect of sorbent source

Model on data base for all experiments:

$$S = \left(100. - \frac{209.58}{C+20.96}\right)(1.-.0912V)(1.+.0108A)(1.-.00011M)*$$
$$(1.-.0000117L)(1.-.000516X)\ P\ Q$$

[fit=arithmetic stand dev 13.2%]
on 296 experiments

Tables of parameters:

coal source	$P_{\text{data base}}$	calcium source	$Q_{\text{data base}}$
Pitt seam 8 washed	1.789	BCR1337 dolom	1.033
Pitt seam 8 unwashed	1.688	BCR1360 limes	1.160
Peabody Coal Co.	1.615	BCR1359 limes	0.971
Pitt seam unspecified	1.721	BCR1359H hyd lm	1.228
Commonwealth Edison	1.404	Tymochtee dolom	1.230
Park Hill coal	1.712	US limestone 18	1.065
Illinois coal unspec.	1.535	UK limestone	1.000
Welbeck coal unspec.	1.693	Stow-on-Kent	1.000

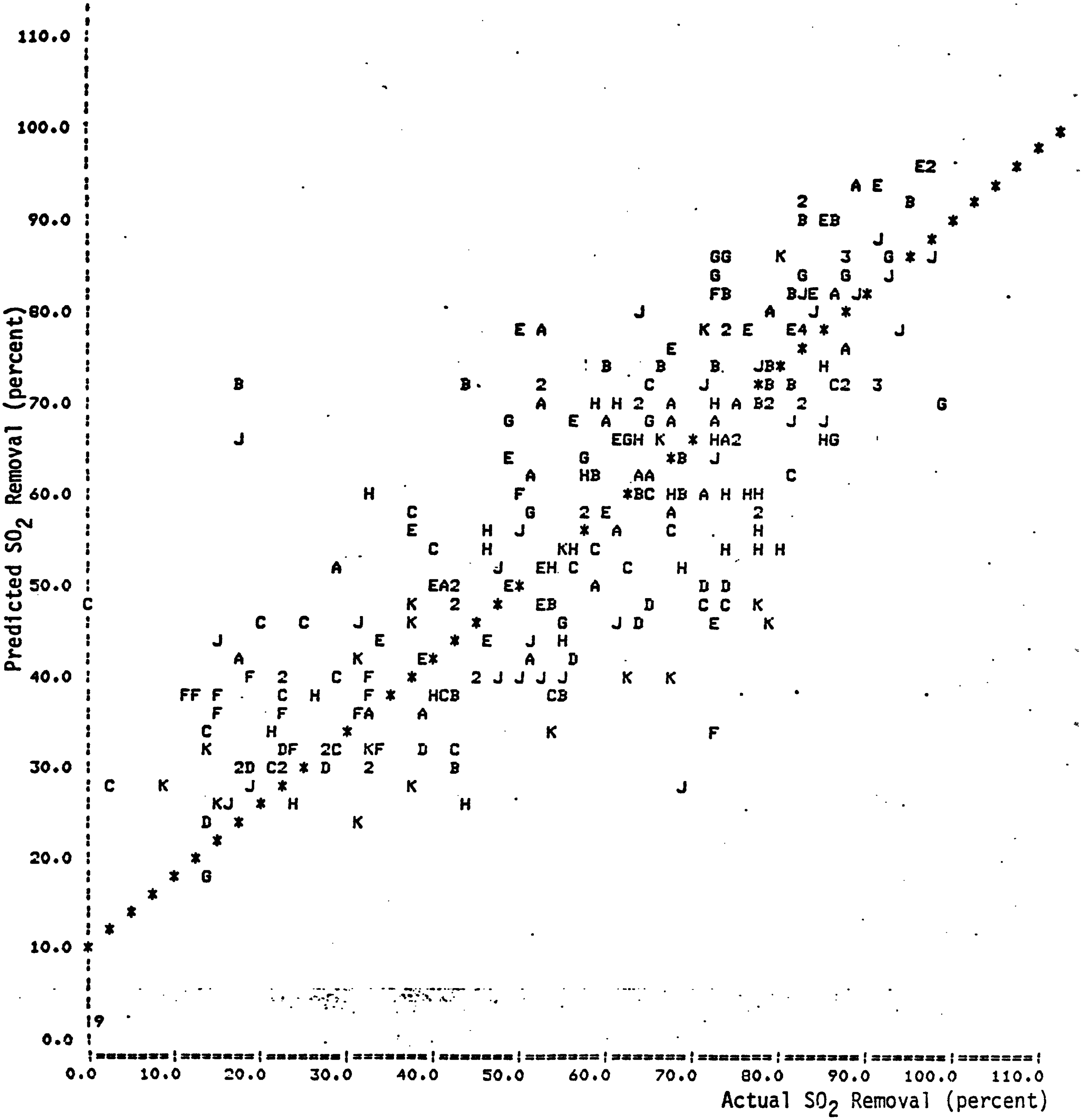


Figure 4.1.2.1-39 Scatterplot of SO_2 removal as observed versus predictions based on all experiments, numbers refer to multiple occurrences with the 9 in the lower left representing about 40 experiments

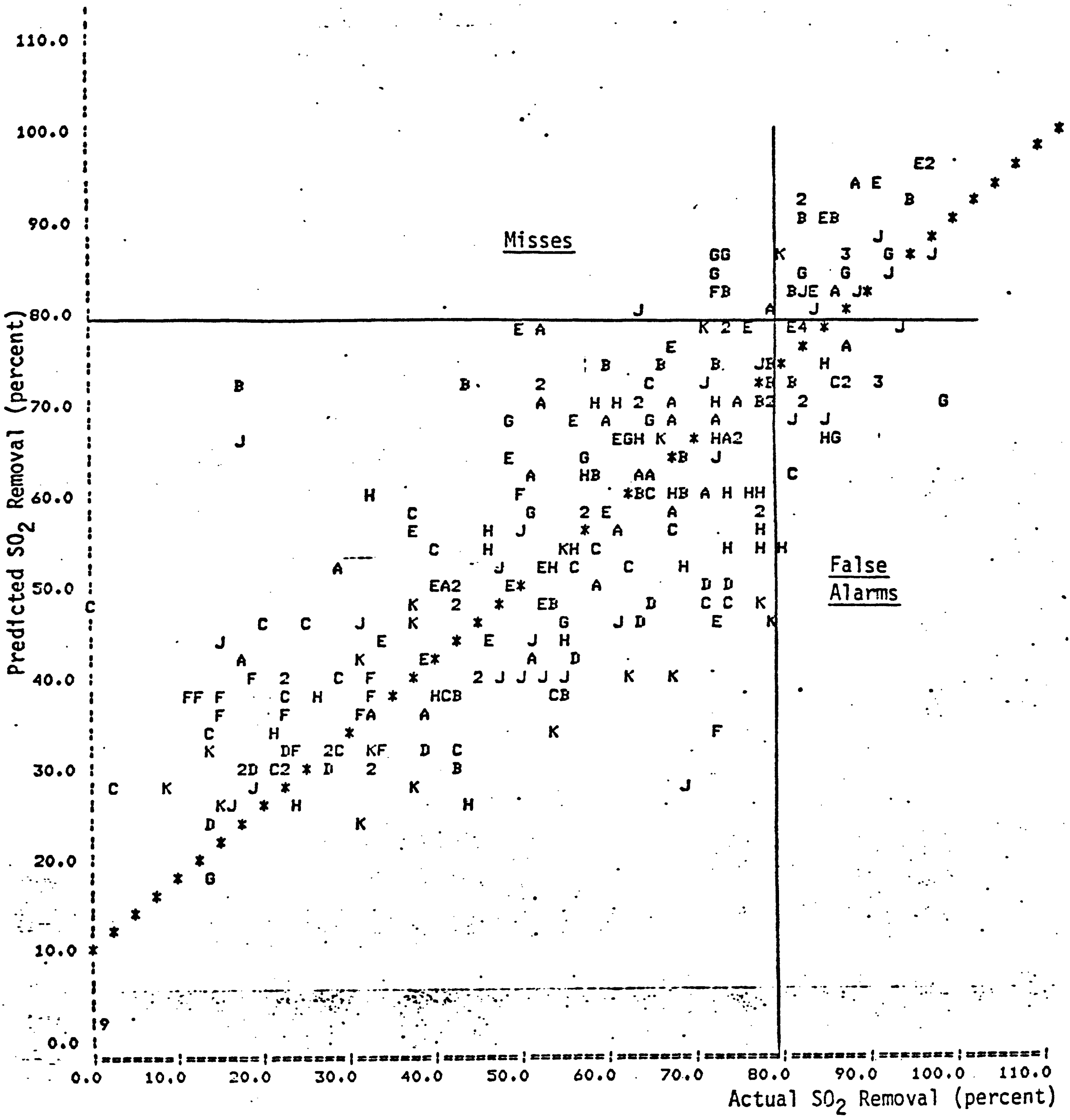


Figure 4.1.2.1-40 Using this model to design a combustor to meet the SO$_2$ standard by removing 80% or more of the SO$_2$ would result in more than 1/5 of the designs being improper (misses) and would exclude more appropriate designs (false alarms) than it would include, one might conclude that there is currently too much uncertainty to make it appropriate to design an environmentally acceptable combustor.

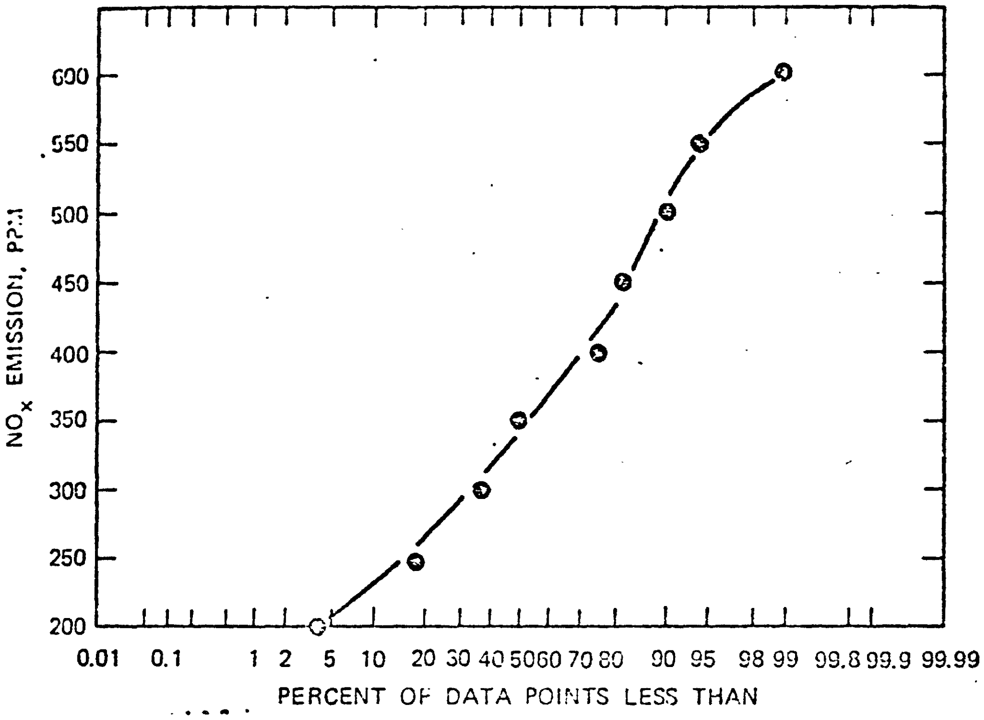


Figure 4.1.2.2-1

NO$_x$ Emission Versus Percent of Data Points Less Than...

(Stromm, et al., 1976).

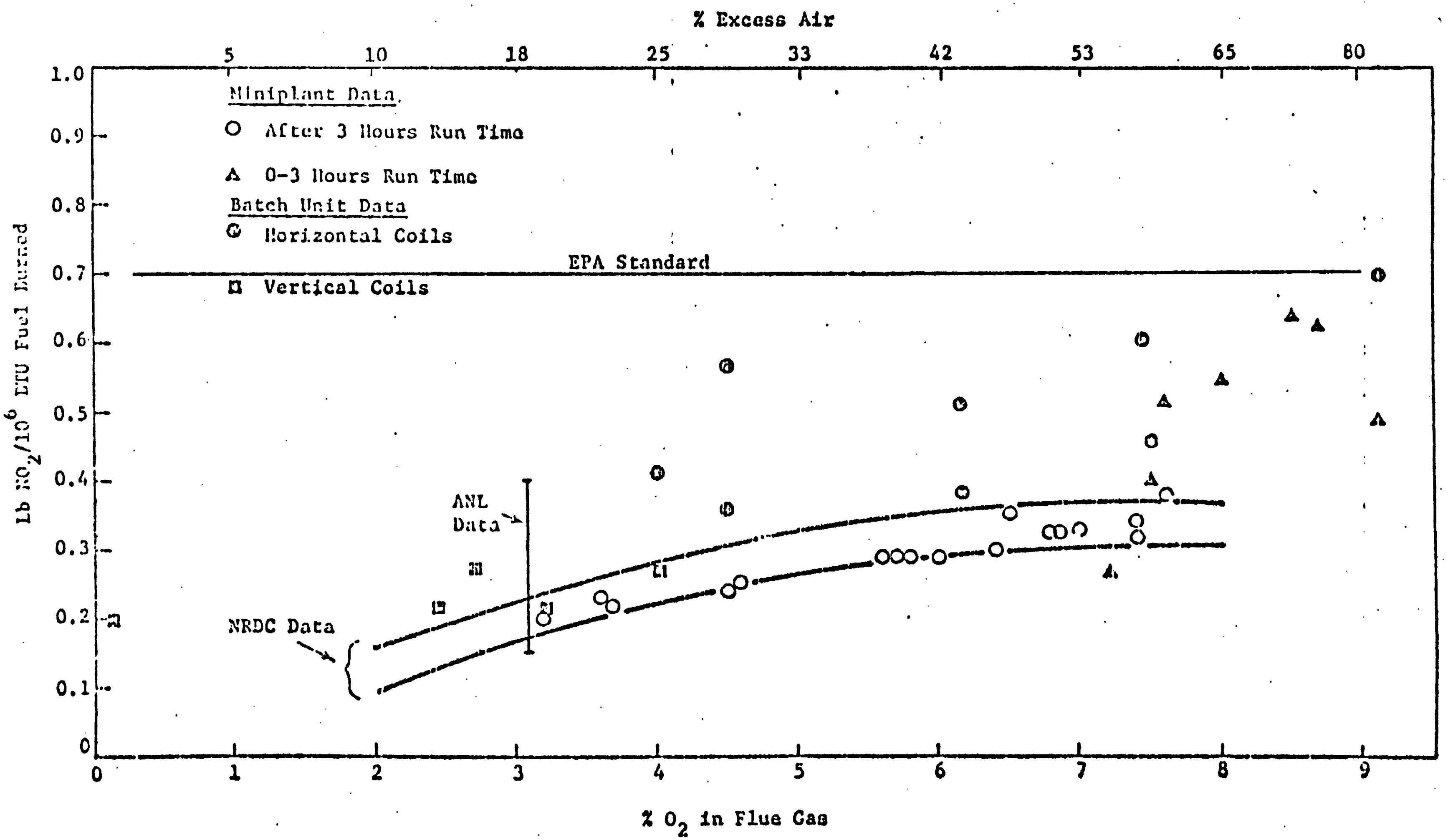


Figure 4.1.2.2-2

Miniplant NO_x Emission Data (run 12.1)

(Nack, et al., 1975).

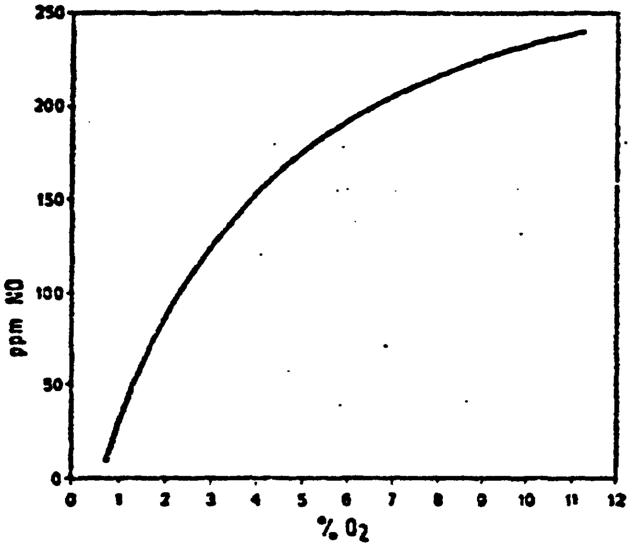


Figure 4.1.2.2-3

Correlation of O_2 and NO Concentrations in the Exhaust Gas from Fluidized Combustion (Locke, Lunn, Hoy, Roberts, 1975).

CURVE NO.	BED SIZE	BED TEMPERATURE (°F)	BED MATERIAL	BED HEIGHT (INCHES)	FLUIDIZING VELOCITY (FT/SEC)	AVERAGE COAL SIZE
1	FBC 12" X 16"	1750	SINTERED ASH	8	14	-1/4", OHIO NO. 8, UNWASHED
2	FBM 20" X 72"	1770-1840	SINTERED ASH	13	12-14	-1/4", OHIO NO. 8, WASHED

REFERENCE: (2)

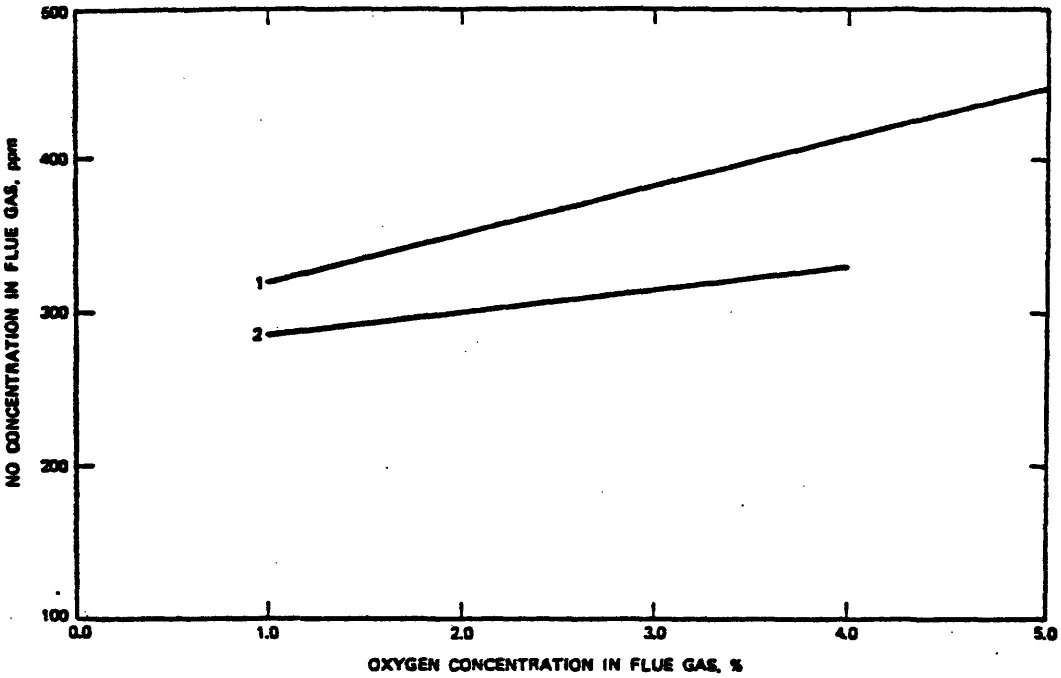


Figure 4.1.2.2-4

Effect of Oxygen Concentration on NO Generation (Archer, et al., 1971).

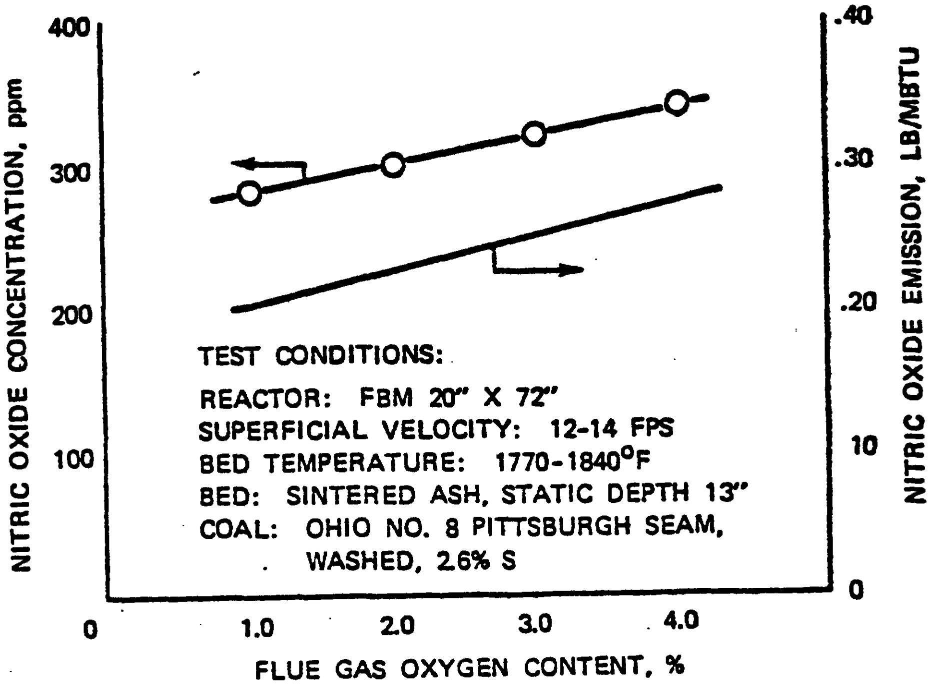


Figure 4.1.2.2-5

Variation of NO Concentration with Flue Gas Oxygen Content (Robison, et al., 1970).

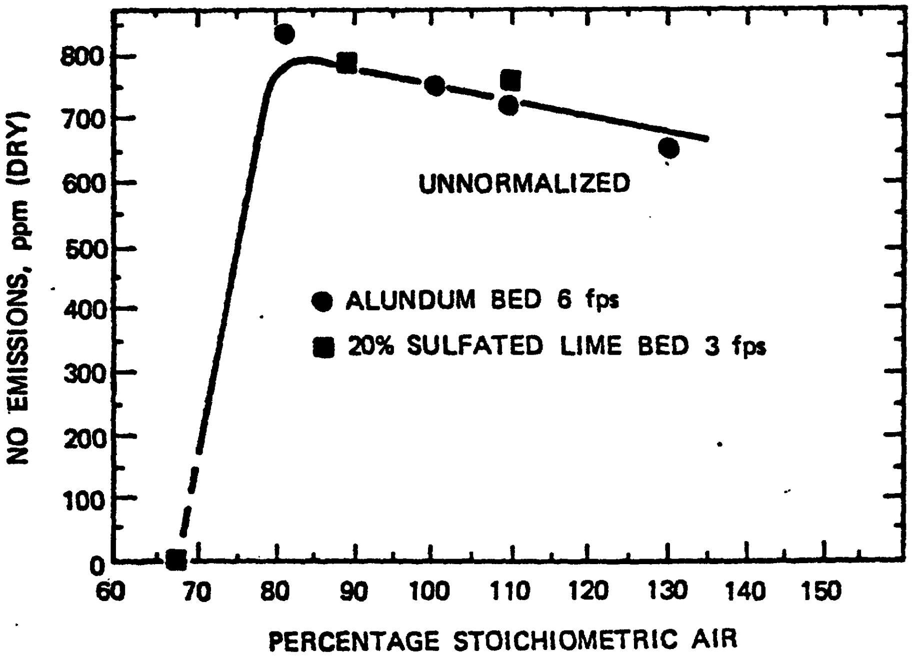


Figure 4.1.2.2-6

NO Emissions as a Function of Percentage Stoichiometric Air (Skopp, et al., 1971).

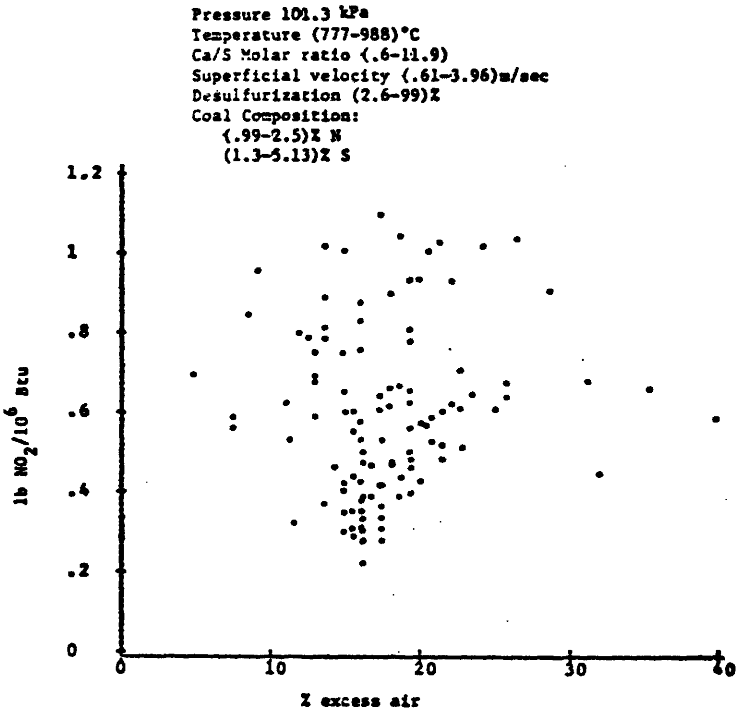


Figure 4.1.2.2-7

Composite Plot of Atmospheric Fluid-Bed Combustion Data of Argonne, Exxon, NCB, and PER (Keairns, et al., 1977).

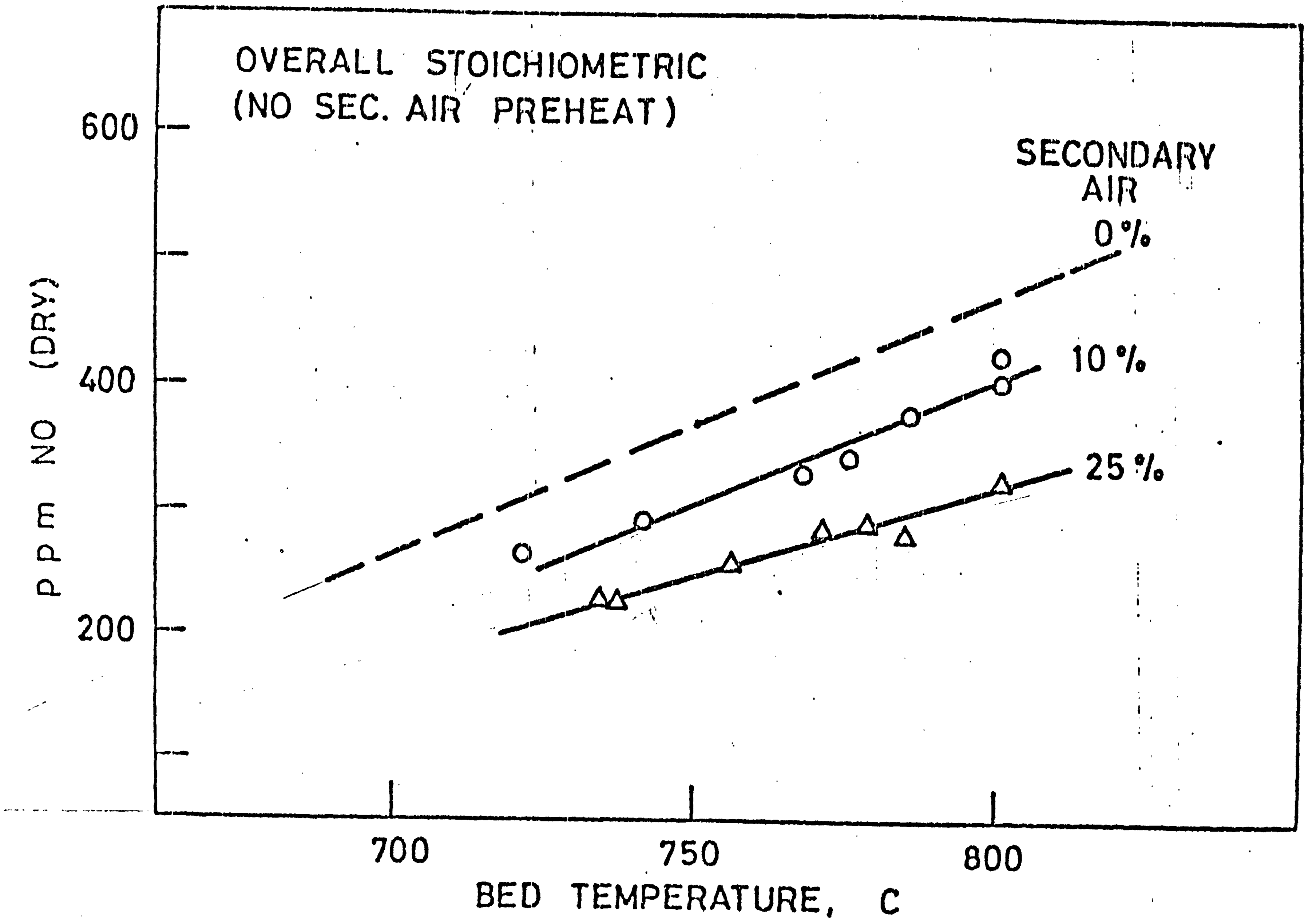


Figure 4.1.2.2-8

The Effect of Secondary Air Injection into the Freeboard on NO Emission (Gibbs, Pereira, and Beér, 1976).

The other reaction (Skopp et al., 1971) has

$$4NO + 2SO_2 + 2CaO = 2N_2 + 2CaSO_4 + O_2$$

which has been supported by low NO_x emissions (70-100 ppm) in two-stage combustion experiments (Nack et al., 1975, p. 362). Effects of availability of CaO and SO_2 on NO_x are shown in Figures 4.1.2.2-9 and -10, respectively. The two sets of reactions may in fact be coupled, based on work of (Hammons and Skopp, 1971), (Robison, et al., 1970) and (Jonke, et al., 1969), although their results are somewhat conflicting. It appears that the $CaSO_4$ from the second reaction is a selective catalyst for the first reaction, from the reference (Hammons and Skopp, 1971). $CaSO_4$ as bed material produced the lowest NO levels, and CaO beds eventually reached that lowest NO level after $CaSO_4$ formation had built up that substance in the bed. The higher Ca/S ratios of Figure 4.1.2.2-9 substantiate this result in that $CaSO_4$ is in lower concentrations with higher Ca/S ratios. The addition of limestone reduces NO emissions by 30-40%, (Jonke, et al., 1969).

Differences in NO emissions due to char particle sizes are shown in Figure 4.1.2.2-11, with the effect being due apparently to differences in diffusion and surface area (Beer and Martin, 1976).

The effect of gas velocity and Ca/S ratio on NO formation is shown in Figure 4.1.2.2-12. The effect of fluidizing velocity on NO emissions is two-fold (Beer and Martin, 1976); the initial rise of concentrations with velocity, see Figure 4.1.2.2-13, is apparently due to increased oxygen supply and shortened residence time in the reducing environment of the char, then the decrease in NO emissions at higher velocities is due to backwashing. The observation that NO reduction is directly proportional to the gas residence time supports the hypothesis, that a large part of the fuels' nitrogen is converted to NO then reduced by reaction with CO or SO_2 or both.

Catalytic decomposition of NO with nickel powders added to the bed have been observed, and although nickel would be too expensive the possibility of other catalysts exits.

The influence of bed temperature upon NO emissions is apparently not as pronounced as it was once thought to be. There seems to be little disagreement on the fact that there is oxidation of atmospheric nitrogen that begins in the fluidized bed temperature range. A possible cause for this fixation at such low temperatures is that the coal surface temperatures may reach 2000°F which could cause the atmospheric nitrogen fixation (Strom, et al., 1976). In (Strom, et al., 1975) it is claimed that when bed temperatures increase above 1650°F there is a significant increase in NO_x formation (see Figure 4.1.2.2-14), due both to increased fixation of atmospheric N_2 at higher temperatures and reduced availability of CO. In (Pereira, et al., 1974) this so-called thermal NO formation is noted to add 0% to total NO at about 1300°F with a linear rise to account for almost 20% of the total NO at about 1800°F. However, in the (Pereira, et al., 1974) experiments it was determined that the fuel bound nitrogen was producing decreased NO emissions in this range with essentially a leveling-off of total NO emissions, see Figure 4.1.2.2-15, -16, and -17.

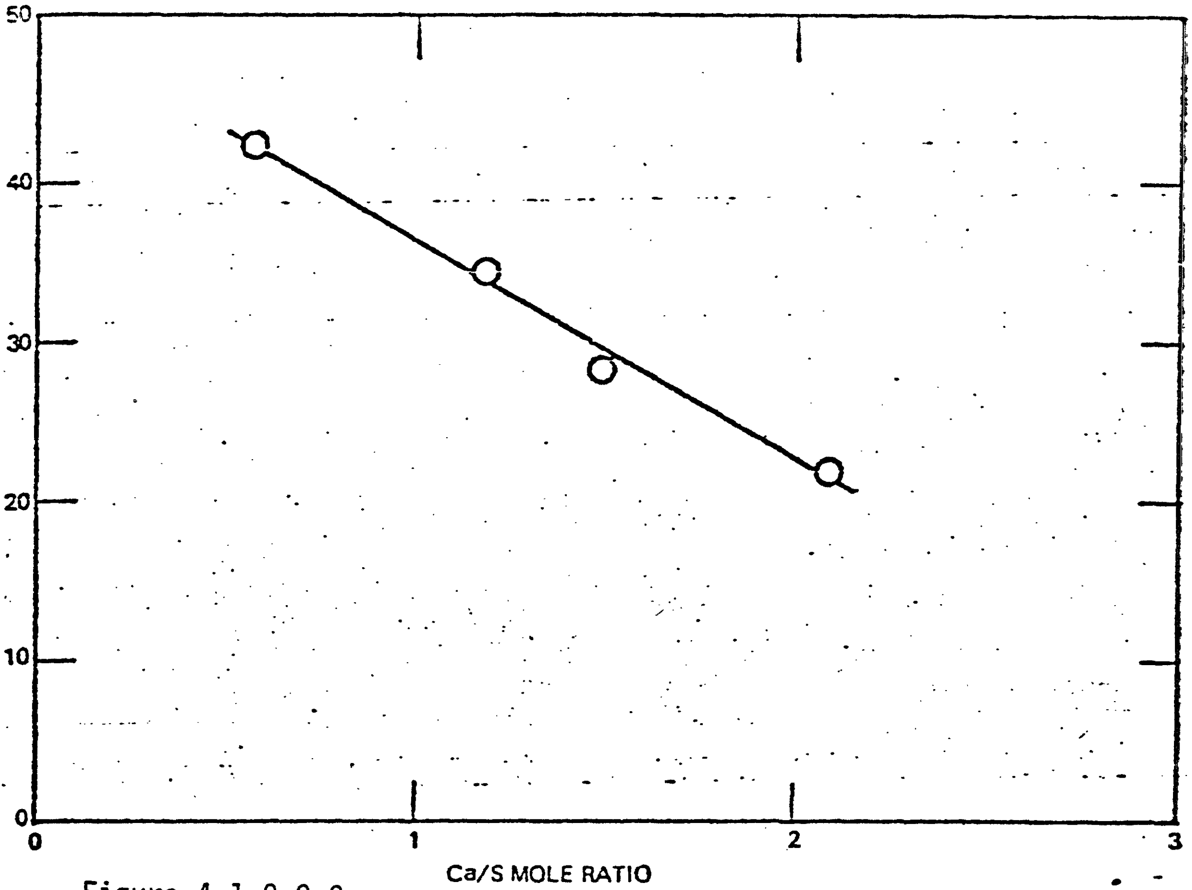


Figure 4.1.2.2-9

Nitric Oxide Reduction with -325 Mesh (<44 μm) Tymochtee Dolomite (Jarry, et al., 1970).

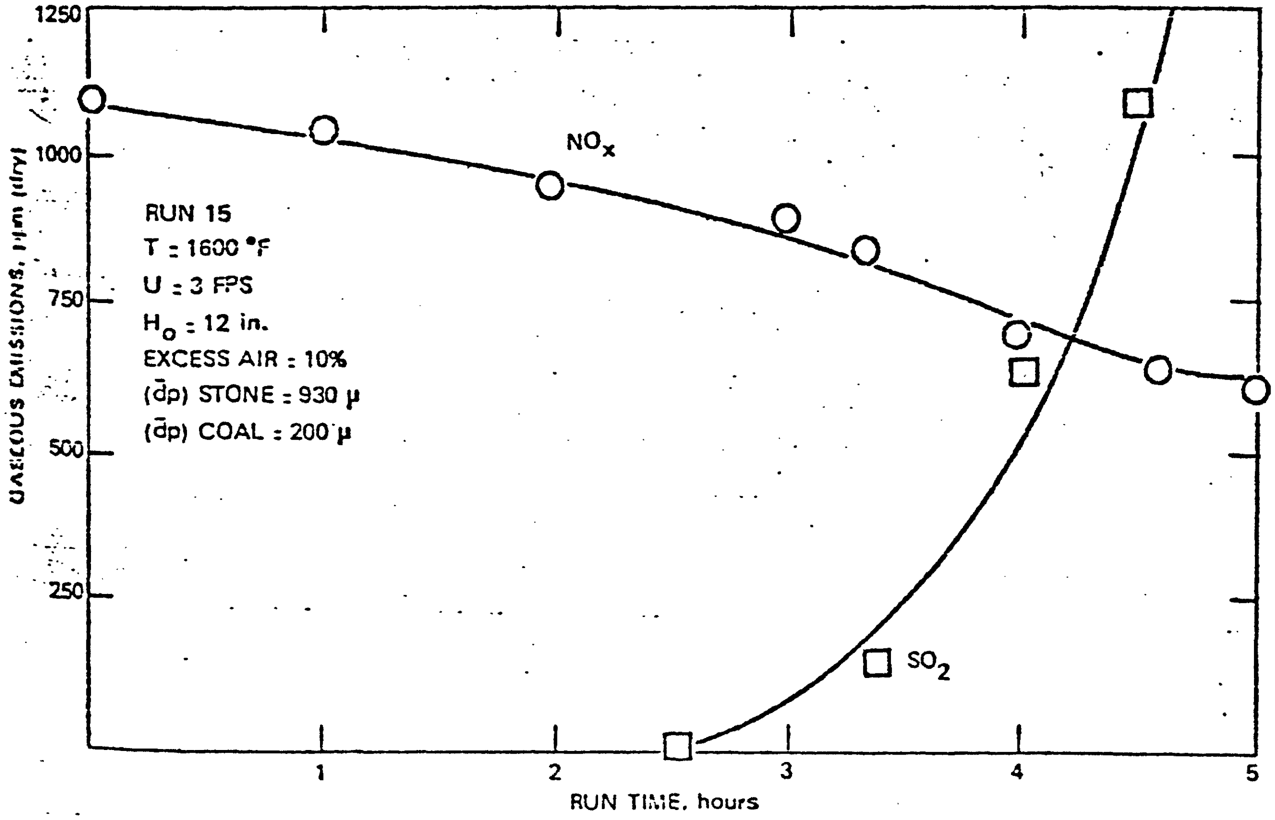


Figure 4.1.2.2-10

Typical NO_x Emissions with Limestone Bed (Hammons and Skopp, 1970).

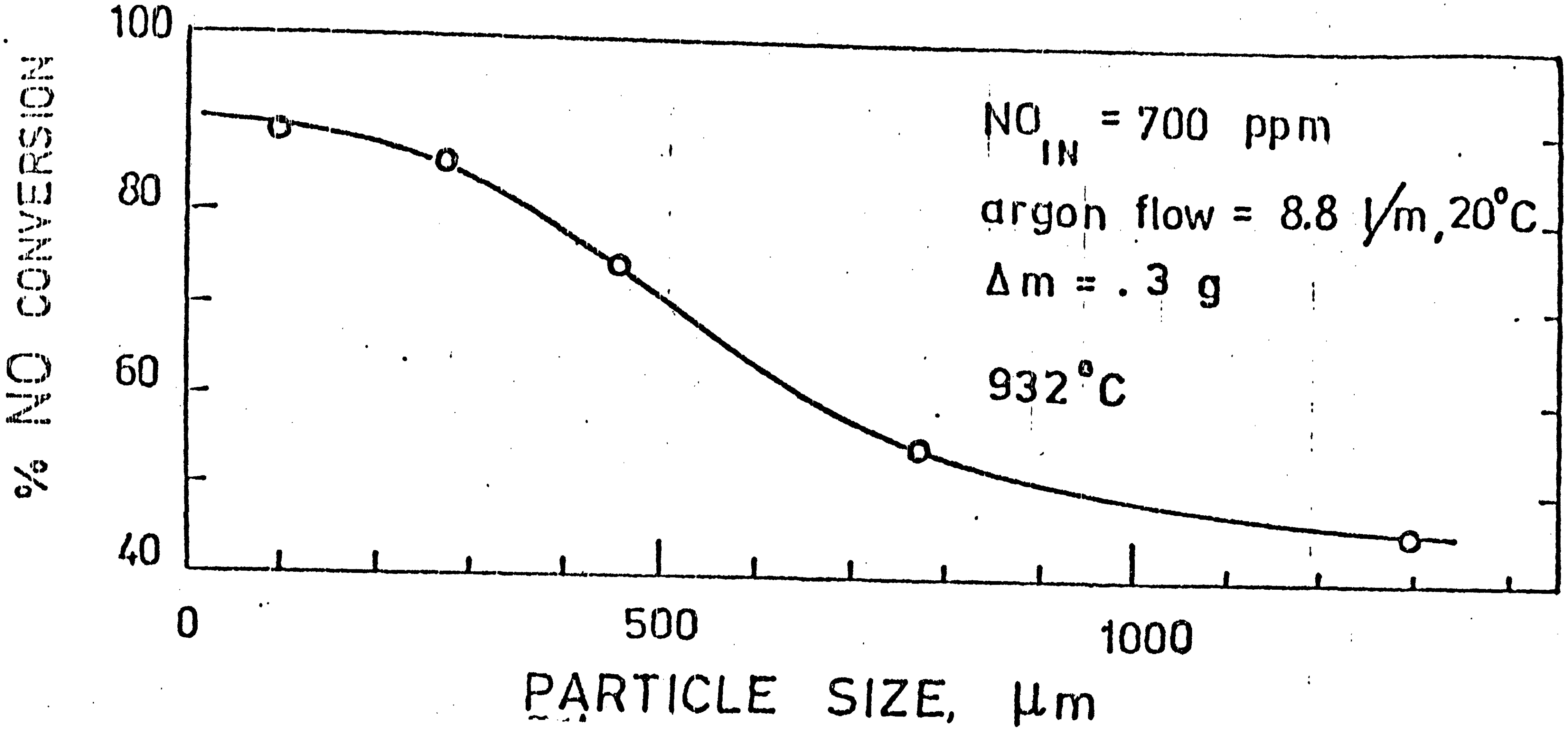


Figure 4.1.2.2-11

The Effect of Char Particle Size on the Conversion of NO (Gibbs, Periera, and Beér, 1976).

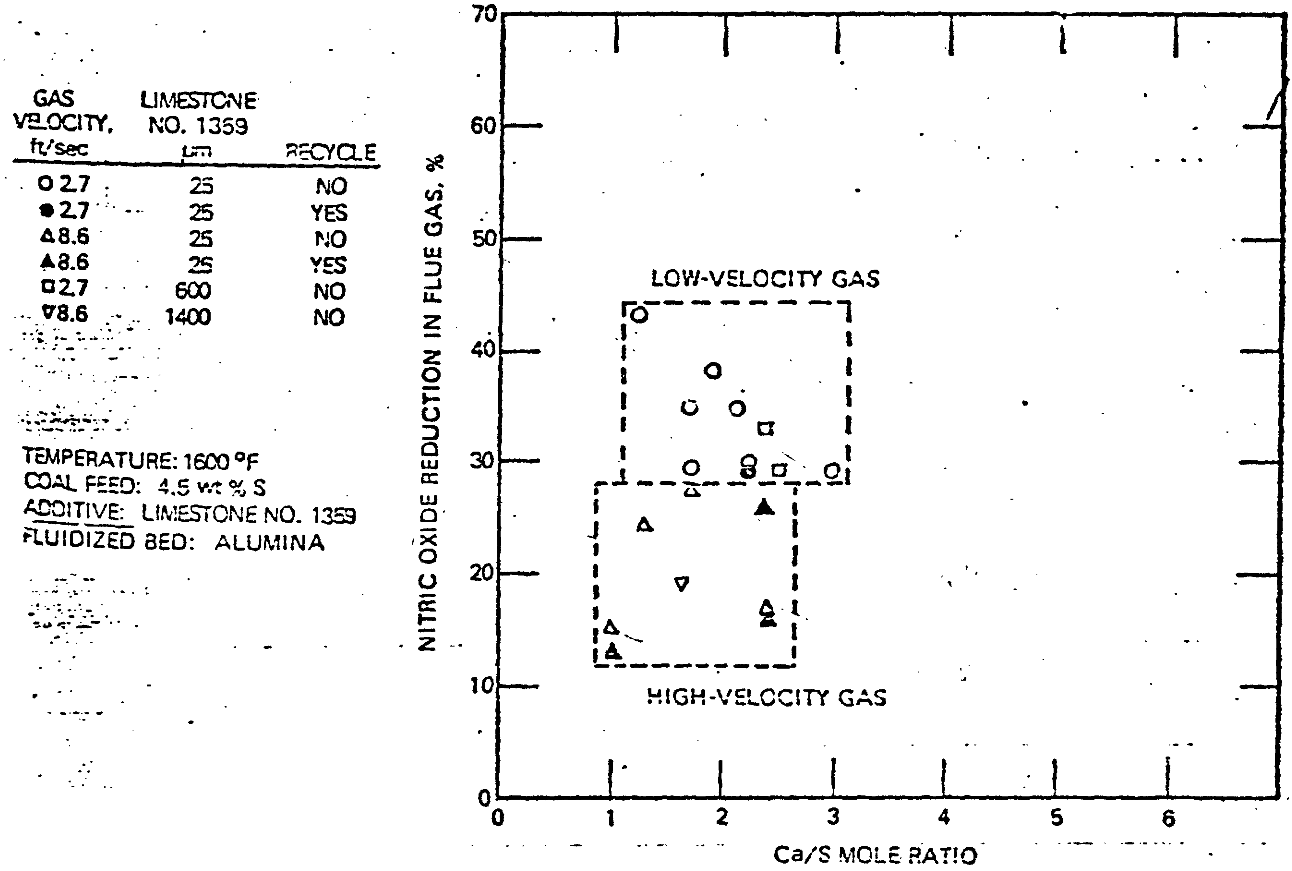


Figure 4.1.2.2-12

Effect of Gas Velocity on Nitric Oxide Reduction in Flue Gas (Jarry, et al., 1970).

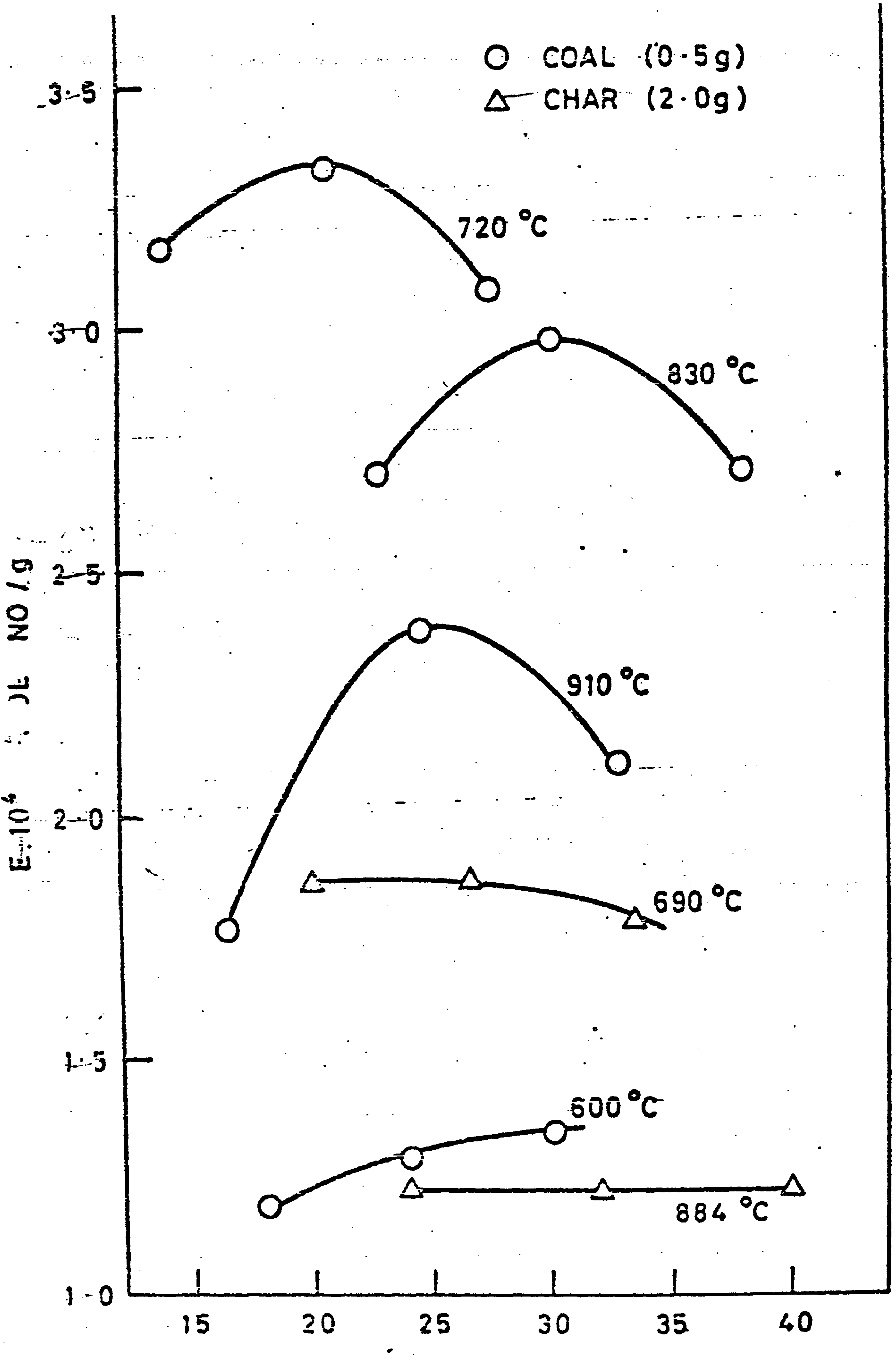


Figure 4.1.2.2-13

Effect of Fluidizing Velocity on NO Emissions Gas: 21% O_2 in Argon, Coal and Char, 1300 µm.

(Periera and Beér, 1975).

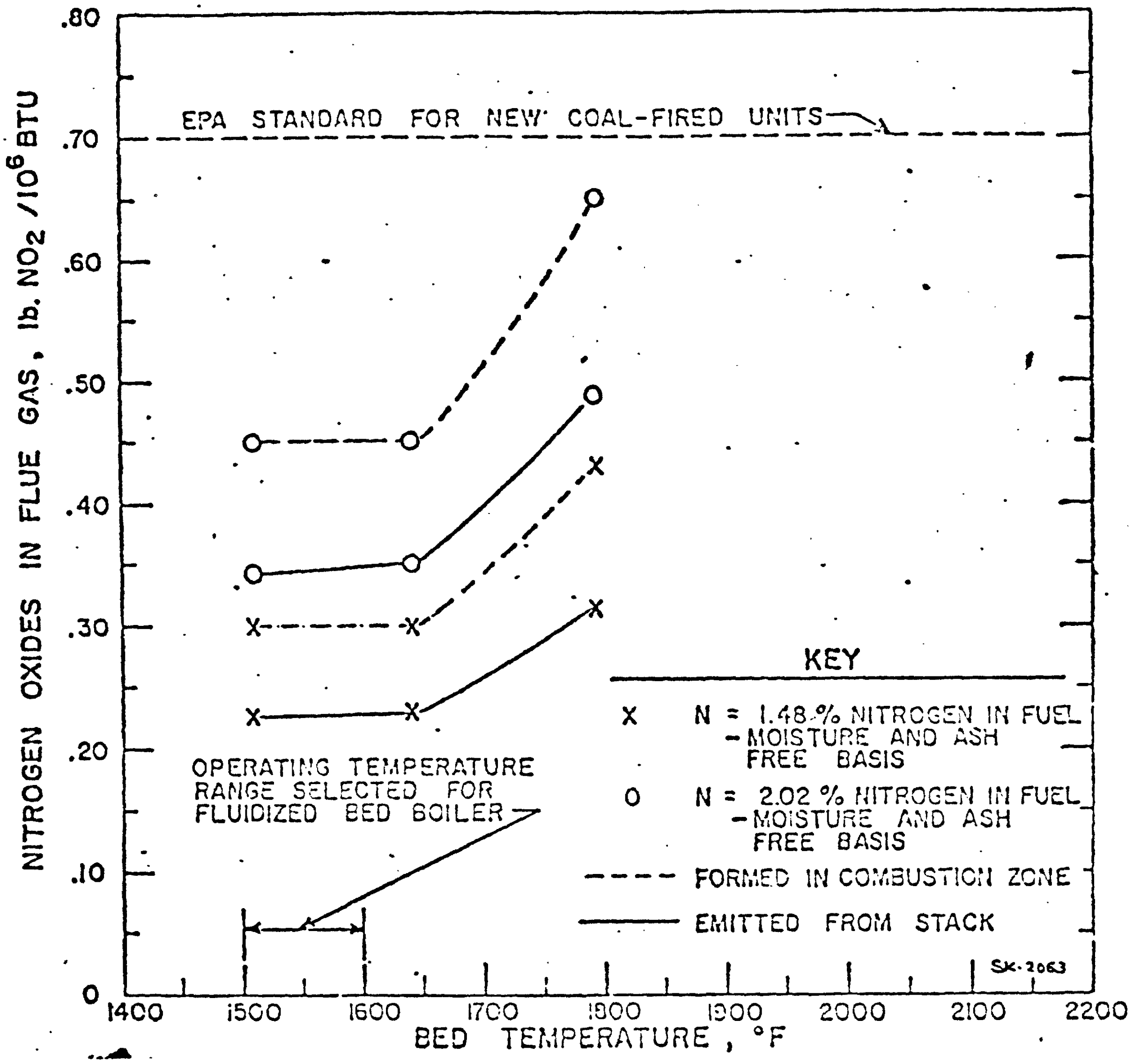


Figure 4.12.2.-14

NO_x Versus Temperature from Sources Claiming an Upturn in Emissions (EPA, Feb. 1977).

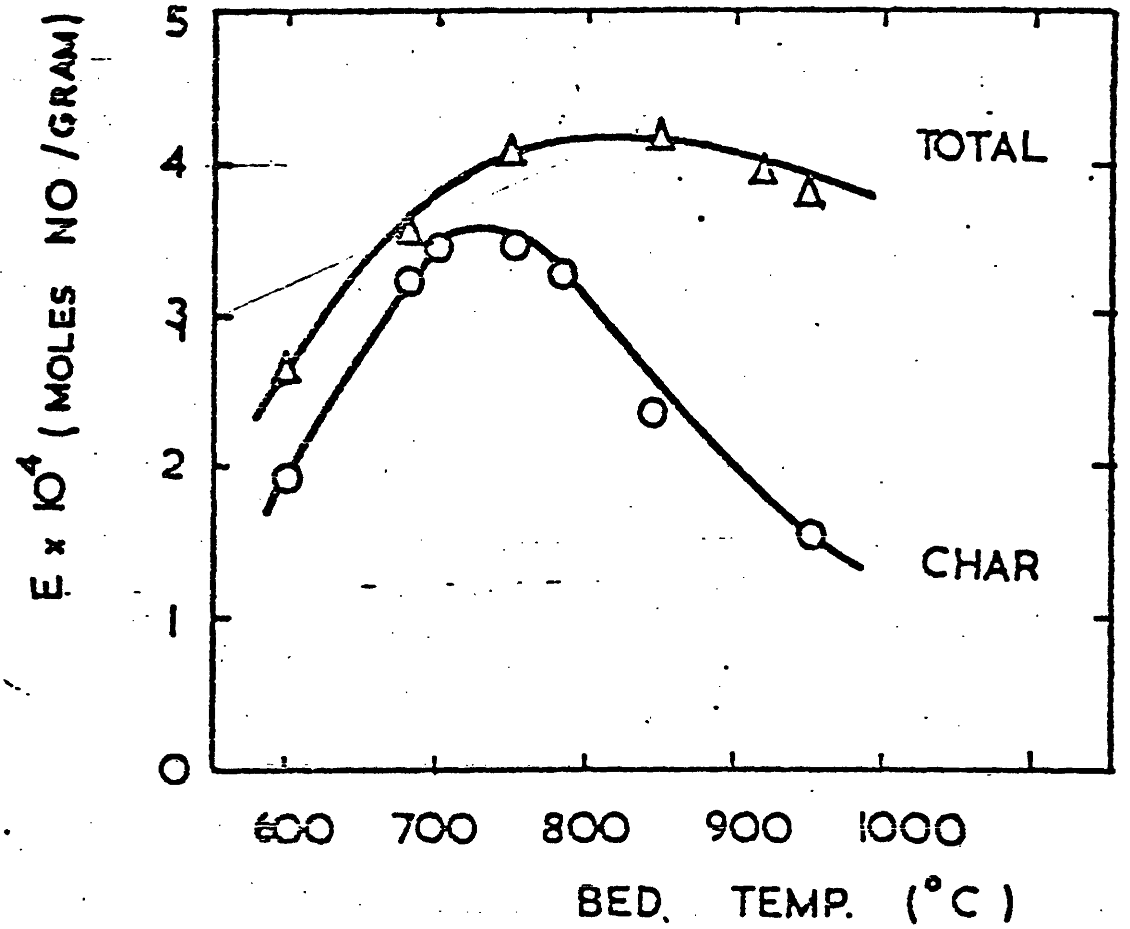
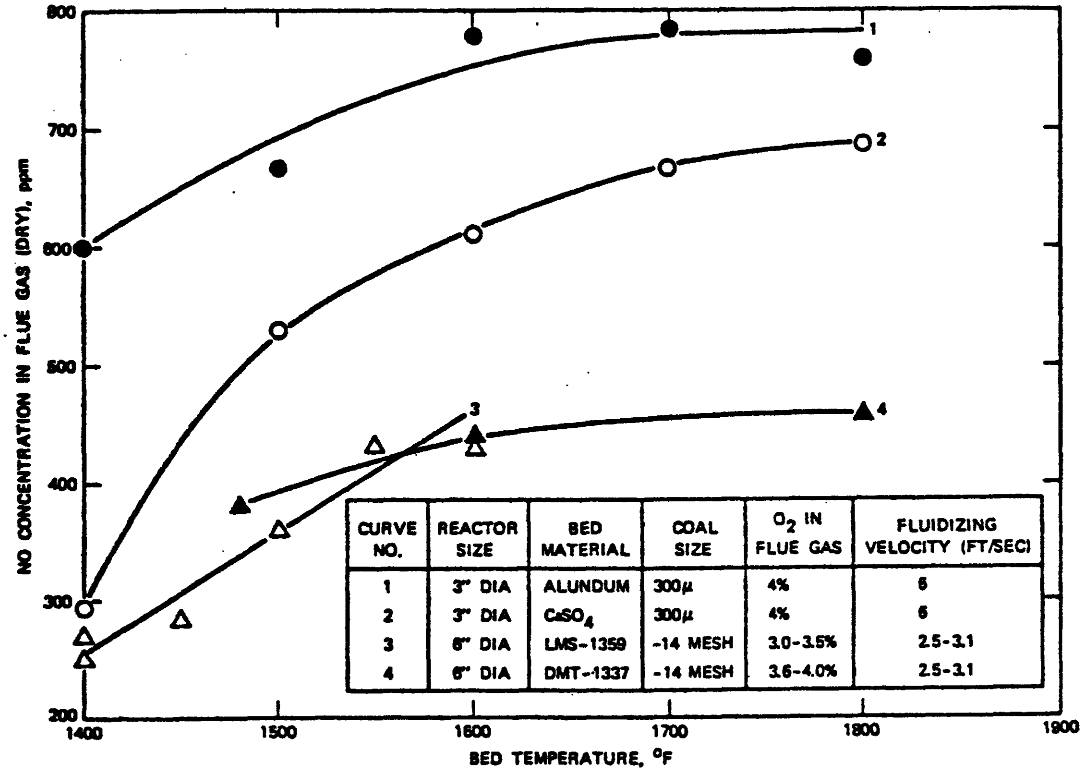


Figure 4.1.2.2-15

Total and Char Emission Indexes as a Function of Bed Temperature (Pereira, et al., 1974).



CURVE NO.	REACTOR SIZE	BED MATERIAL	COAL SIZE	O_2 IN FLUE GAS	FLUIDIZING VELOCITY (FT/SEC)
1	3" DIA	ALUNDUM	300μ	4%	6
2	3" DIA	$CaSO_4$	300μ	4%	6
3	6" DIA	LMS-1359	-14 MESH	3.0-3.5%	2.5-3.1
4	6" DIA	DMT-1337	-14 MESH	3.6-4.0%	2.5-3.1

Figure 4.1.2.2-16

Effect of Bed Temperature on NO Concentration (Archer, et al., 1971).

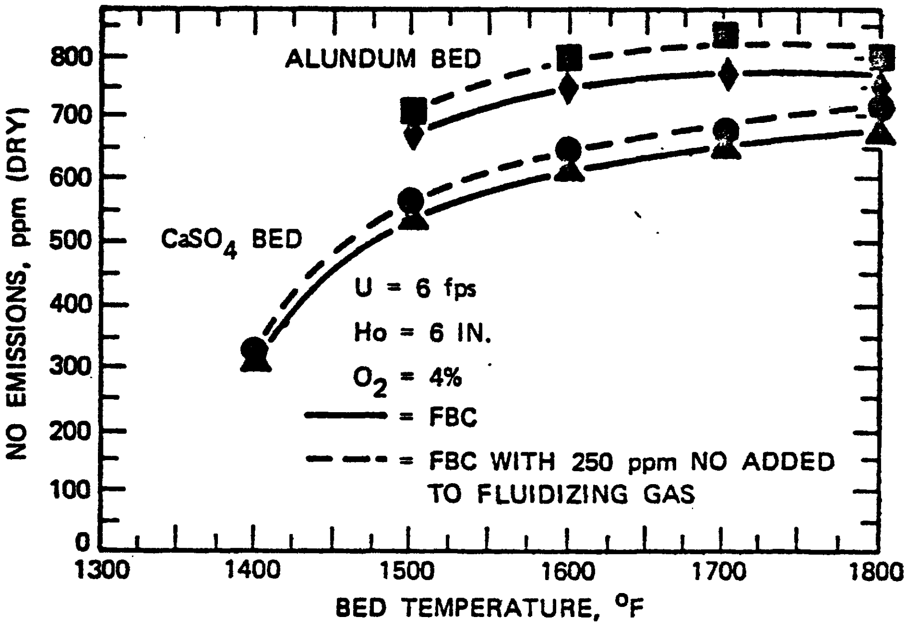


Figure 4.1.2.2-17

NO Emission as a Function of Bed Temperature (Skopp, et al., 1971).

It has been suggested (Pereira, et al., 1974) that some of the discrepancies in measurements may be due to differences in the location of the reported emissions. In the collection of all available data (Strom, et al., 1976) Strom did not attempt to sort out the appropriate and misleading data. That report does display the Pope, Evans and Robbins model that matches the data displayed in Figure 4.1.2.2-14:

$$NO_x = 0.28 \times 10^6 (1 + 1.7N)K$$

where NO_x = volume ppm

K = equilibrium constant

N = nitrogen content of fuel, wt%

where $K = 8.67 \times 10^{-5}$ at 1340°F, 2.33×10^{-4} at 1520°F,

5.31×10^{-4} at 1700°F, 1.07×10^{-3} at 1880°F,

1.94×10^{-3} at 2060°F.

Under assumptions of baseloaded operation, a preliminary model has been developed on the basis of correlations to experimental data. This empirical model is also based upon data for systems that had no secondary reheat and is matched to the data that is reported in the EPRI data base (Strom, et al., 1976). Table 4.1.2.2-1 and Figure 4.1.2.2-18 show this NO_x model, for details see (Gruhl, Tung, Schweppe, 1978).

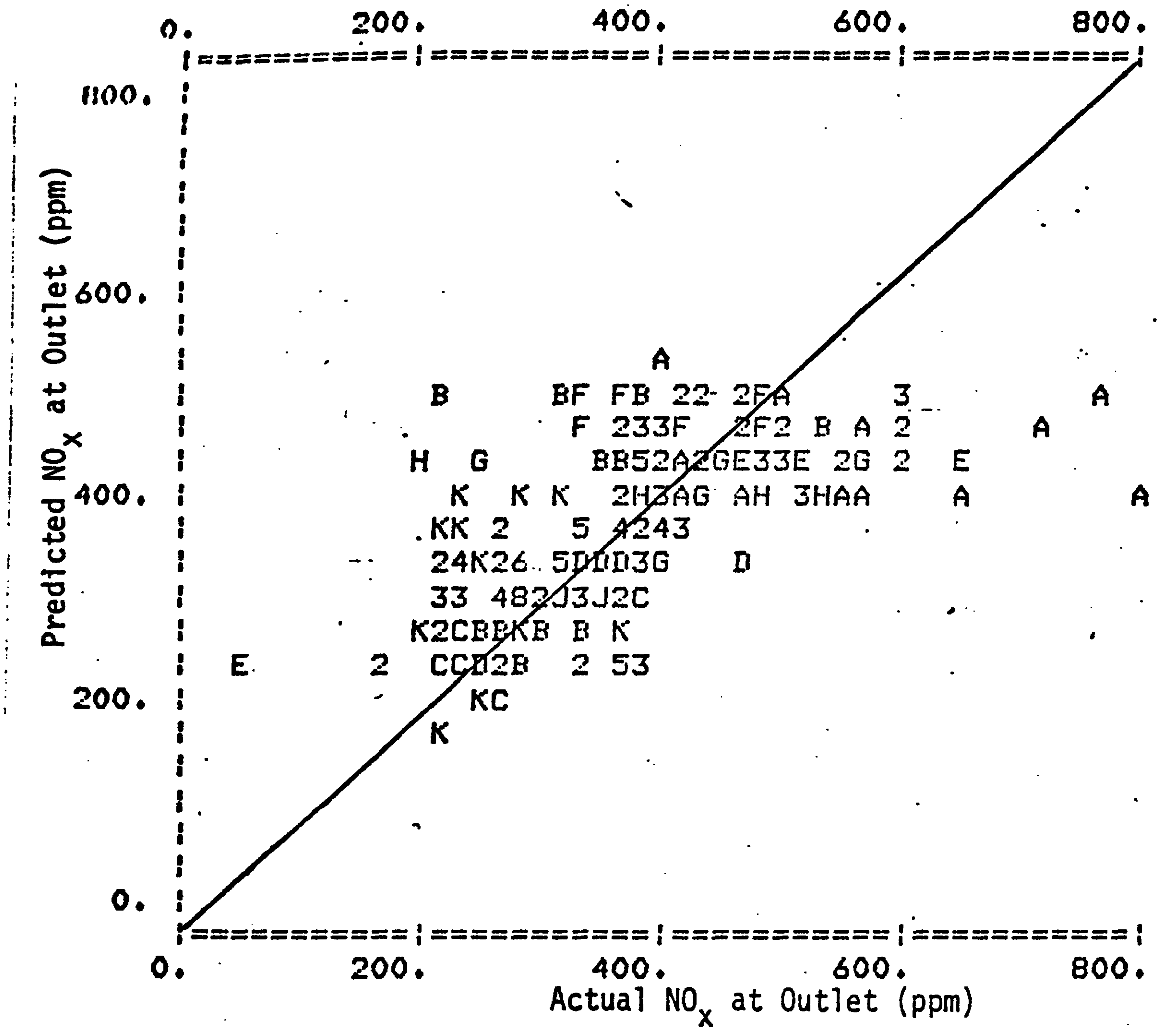


Figure 4.1.2.2-18 Scatterplot of NOx predictions versus observations, showing general lack of good fit to data due possibly to unmeasured variables or differences in position or techniques of measurement

Table 4.1.2.2-1 Empirical model of NO_x at outlet based on data base experiments

Symbols:

N = NO_2 equivalent of NO_x at outlet, in ppm
C = calcium to sulfur mole ratio
V = fluidizing velocity, in m/sec
T = bed temperature, in degrees centigrade
X = excess air, in percent
Q = parameter for effect of sorbent source

Model on all data base experiments for which the above variables were available:

$$N=(-5818+82.41C+6.43CV+362.V+6.9(1.8T+32.)-.267V(1.8T+32.)$$
$$-.065C(1.8T+32.)-.00182(1.8T+32.)^2)(1.106-.0074X)\,1.053\,Q$$

[fit=arithmetic stand dev 91ppm]
on 198 experiments

Table of parameters:

calcium source	$Q_{\text{data base}}$
BCR1337 dolom	0.90
BCR1360 limes	0.85
BCR1359 limes	1.00
BCR1359H hyd lm	0.70
Tymochtee dolom	0.85
US limestone 18	1.00
UK limestone	1.00
Stow-on-Kent	0.85

An alternative model has been fit to the group of data which is initially level with bed temperature and then rises sharply:

Alternative NO_x Emission Correlation for Atmospheric FBC

N_o = NO_x emissions in ppm [NO,dry]
N_c = nitrogen in coal in %, valid 1.4 to 2.0%
T_b = temperature in bed, in °F, valid in range 1500° to 1800°F

$$N_o = .22[N_c - .48][1 + .01 \frac{T_b - 1510]}{130}[1 + .0027 (\max[1640, T_b] - 1640)]$$

Two stage combustion drastically reduces the NO_x emissions. Given that there are no parametric studies, probably due to the extremely low levels being out of interest (70 to 100ppm at Argonne, 110 to 280 at Esso England, and 200 to 620 ppm at Esso R & D, see Figure 4.1.2.2-19), and assuming the same types of mechanisms are effecting emission the one-stage combustion NO_x emissions are simply scaled:

NO_x = NO_x emissions in ppm dry basis

NO_x (two stage) = NO_x (one stage) [2.17 - .0035 Min (620, NO_x (one stage))

(gsd = 1.26)

Carbon burnup cell experiments at Pope, Evans, and Robbins show that NO_x emissions from that cell range from 350 to 800ppm (see Figure 4.1.2.2-20). This could be a factor in overall emissions, as shown in (Strom, <u>et al</u>., 1976) if 15% of the total air is used in the carbon burnup cell with 800ppm of NO_x then the primary combustor emission must be less than 476ppm to meet the overall 525 ppm stack emission standard. An empirical model for the emissions from the carbon burnup cell has been developed by Pope, Evans, and Robbins:

$$NO_x = -464.3 + 0.4257\,T + 0.329\,R_{air} + 4.468\,H - 2.337\,R_c$$
$$- 0.7829\,R_I + 0.005372\,R_c\,R_I$$

where NO_x = ppm
T = bed temperature, °F
R_{air} = air rate, $lb/hr\text{-}ft^2$
H = bed height, in.
R_c = carbon rate, $lb/hr\text{-}ft^2$
R_I = inert rate, $lb/hr\text{-}ft^2$

A comparison between observed and calculated values is shown in Figure 4.1.2.2-21.

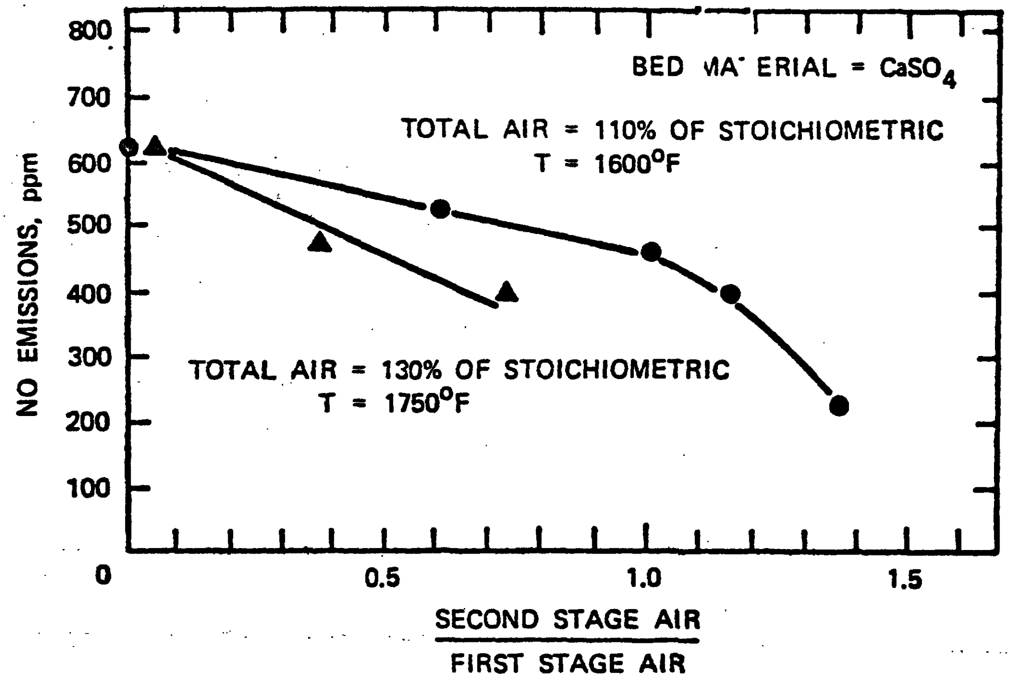


Figure 4.1.2.2-19

NO Emissions in Staged Combustion Tests (Skopp, et al., 1971).

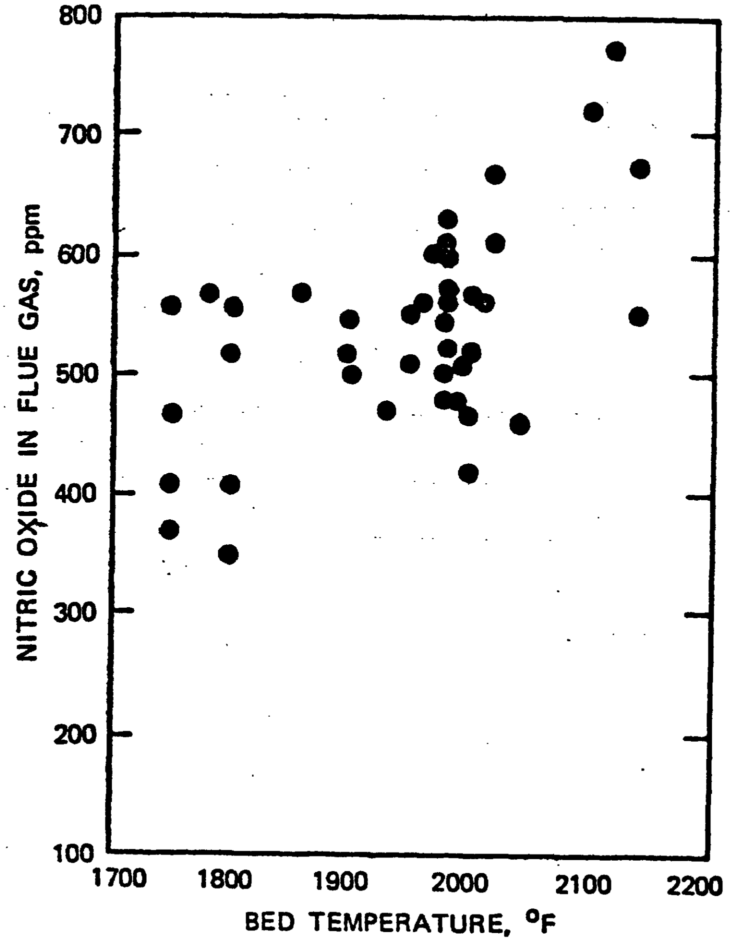


Figure 4.12.2.-20

NO Emissions during Carbon Burnup Cell Tests (Strom, et al., 1976).

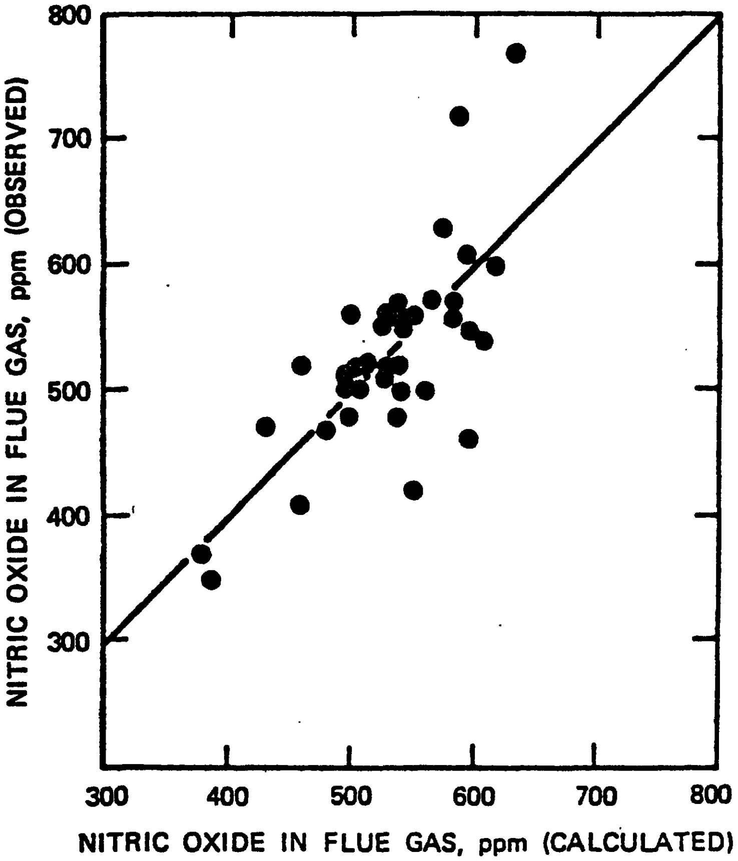


Figure 4.1.2.2-21

Comparison of Observed and Calcinated Nitric Oxide Emission from CBC Tests (Robison, 1972).

4.1.2.3 Hydrocarbon Emissions

Data concerning the extent of hydrocarbon emission in FBCs is limited to the observation, of the gaseous hydrocarbon emission (see Figure 4.1.2.3-1). These gaseous hydrocarbons are inert compared to the carcinogenic hydrocarbons represented by the polycyclic compounds (see Table 4.1.2.3-1). While there is general knowledge that the formation of these larger compounds, such as benzapyrene, is in fact favored by combustion temperatures in the 1500 to 1700°F range (ANL-EC/1, 1976, section 6.3.5) little data on their concentrations exist. In fact, little is known about quantities of these compounds found in conventional coal-fired power plants, with some qualitative information available (see Table 4.1.2.3-2).

Based on data in (Strom, et al., 1976) the model for CH_4 is shown in Table 4.1.2.3-3 and Figure 4.1.2.3-2.

If oxygen is modelled instead of excess air, it appears (Nack, et al., 1975) that the relationship between oxygen and excess air is appproximately:

E_A = excess air in percent, valid for 0 to 85% E_A or 0 to 9.5% O_F

$$E_A = .5O_F^2 + 5O_F - 1$$

It has been speculated that increases in the bed temperature have an inverse effect on the hydrocarbon levels. This was not observed over the data base. The magnitude of this supposed effect has not been recorded, the 10% drop for 100°F increase from 1500°F is sometimes assumed. The fundamental reason for this decrease arises from a decrease with temperature in the

(1) number of hydrocarbons that will survive after cleavage of structural hydrocarbon networks of the coal;

(2) hydrocarbon decomposition products that will condense (Fennelly, Durochee, Kemm, Hall, 1975).

Using the ratio of 10^{-5} for beno (x) pyrene to CH_4 in coal combustion (Hangebruck, von Lehmden, Meeker, 1964) and the fact that substituted polynuclear aromatic hydrocarbon will be in smaller concentrations (especially for chlorine substitute as HCe in the predominant Ce form at FBC temperatures):

BAP_e = Benz (a) pyrene in emissions in ppb

PCB_e = polychlorinated biphenyls

H = hydrocarbons from Table 4.1.2.3-3

$BAP_e = .01\ H$

$PCB_e < BAP_e$

There is a sharp conflict between this estimate and the uncontrolled polycyclic organic material levels of 5 to 72 mg/m^3 from 6" Battelle unit

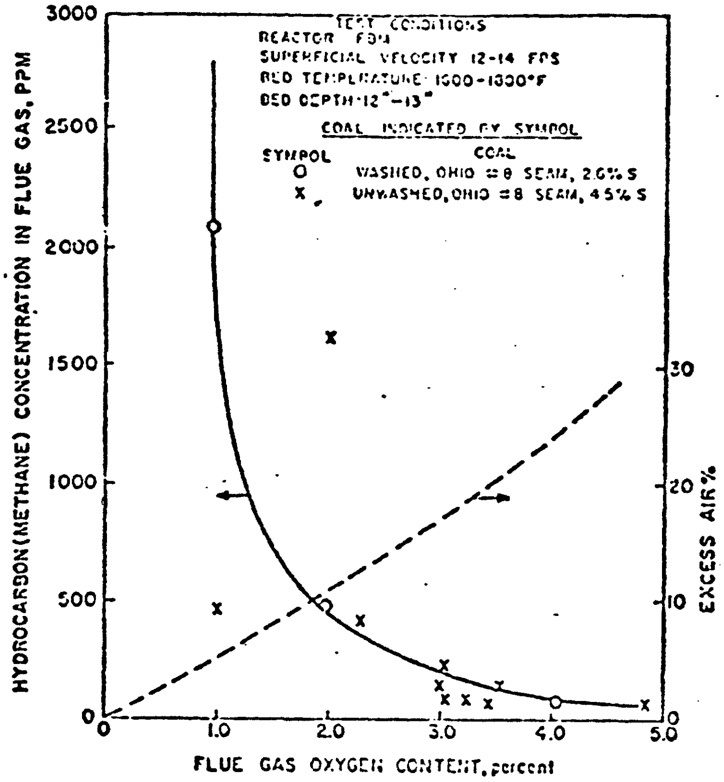


Figure 4.1.2.3-1

Variation in Hydrocarbons Concentration with Flue Gas Oxygen Content in FBM[10] [from (Glenn, Robison, 1973)].

Table 4.1.2.3-1

Classes of Known or Suspected Carcinogenic or Cocarcinogenic Compounds Associated with Processing and Utilization of Coal

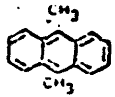
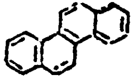
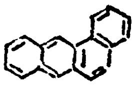
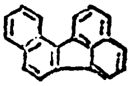
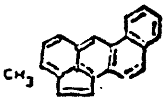
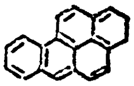
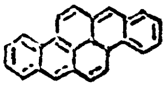
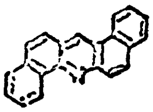
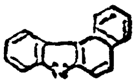
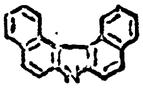
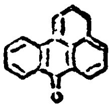
Compound Class	Representative Compound	Structure
Polynuclear Aromatic Hydrocarbons		
Anthracenes	9,10-dimethylanthracene	
Chrysenes	chrysene	
Benzathracenes	benzo(a)anthracene	
Fluoranthenes	benzo(j)fluoranthene	
Cholanthrenes	20-methylcholanthrene	
Benzopyrenes	benzo(a)pyrene	
Dibenzpyrenes	dibenzo(a,h)pyrene	
Nitrogen-, Sulfur-, and Oxygen-Containing Polycyclic Compounds		
mono-and dibenzacridines	dibenz(a,h)acridine	
benzocarbazoles	7H-benzo(c)carbazole	
dibenzocarbazoles	7H-benz(c,g)carbazole	
benzathrones	7H-benz(d,e)anthracen-7-one	

Table 4.1.2.3-1 (continued)

Carcinogenic Polycyclic Organic Materials

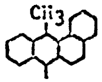
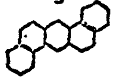
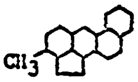
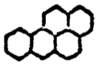
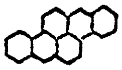
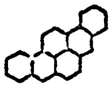
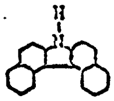
	Compound	Structure	Carcinogenicity
1.	7,12 Dimethylbenz[a]-anthracene		+ 4
2.	Dibenz[a,h]anthracene		+ 3
3.	Benzo[c]phenanthrene		+ 3
4.	3 Methylcholanthrene		+ 4
5.	Benzo[a]pyrene		+ 3
6.	Dibenzo[a,h]pyrene		+ 3
7.	Dibenzo[a,i]pyrene		+ 3
8.	Dibenzo[c,g]carbazole		+ 3

Table 4.1.2.3-2

Polycyclic Organic Material (POM) in Conventional Coal-Fired Power Plant Emissions

		Location Where Found		
	Test No.	Coal	Ashes	Stack Gas
POM-1 *7-12 dimethylbenz [a]anthracene	166	○ ○ ○	○ ● ●	○ ● ○
	169	○ ○ ○	○ ○ ○ ○ ○ ○	○ ○ ○
POM-2 *benzo[a] pyrene	166	● ● ●	● ● ●	○ ○ ○
	169	○ ○ ○	● ● ○ ● ○ ●	● ● ○
POM-3 3 methyl-cholanthrene	166	○ ○ ○	○ ○ ○	○ ○ ○
	169	● ● ●	○ ● ● ● ● ●	● ● M
POM-4 *dibenz[a,h] anthracene	166	● ● ●	○ ○ ○	○ ○ ○
	169	● ○ ●	○ ○ ○ ○ ● ○	○ ○ M

○ : Analysis found no POM

● : Analysis found some POM

M : Data missing

*Instruments calibrated for isomer shown. The presence of these isomers relative to other isomers was not verified.

Table 4.1.2.3-3 Empirical model of CH_4 equivalent of the hydrocarbon at the outlet

Symbols:

H = CH_4 equivalent of hydrocarbon concentrations at outlet, in ppm
A = bed area, in square meter
N = number of the reference from which the data was collected
C = calcium to sulfur ratio in bed, molar ratio
Z = coal top particle diameter in microns
X = excess air, in percent

Model based on all data in base:

$$H = 146.(1.+10.65A)(0 \text{ if } N \text{ greater than } 4.5 \text{ else } 1.)(1.-.2249C)*$$

$$(1.-.000125Z)(1. \text{ if } X \text{ less than } 0. \text{ else } 11.98/(X+.15))$$

[fit=arithmetic stand dev 11.1]
over 196 experiments

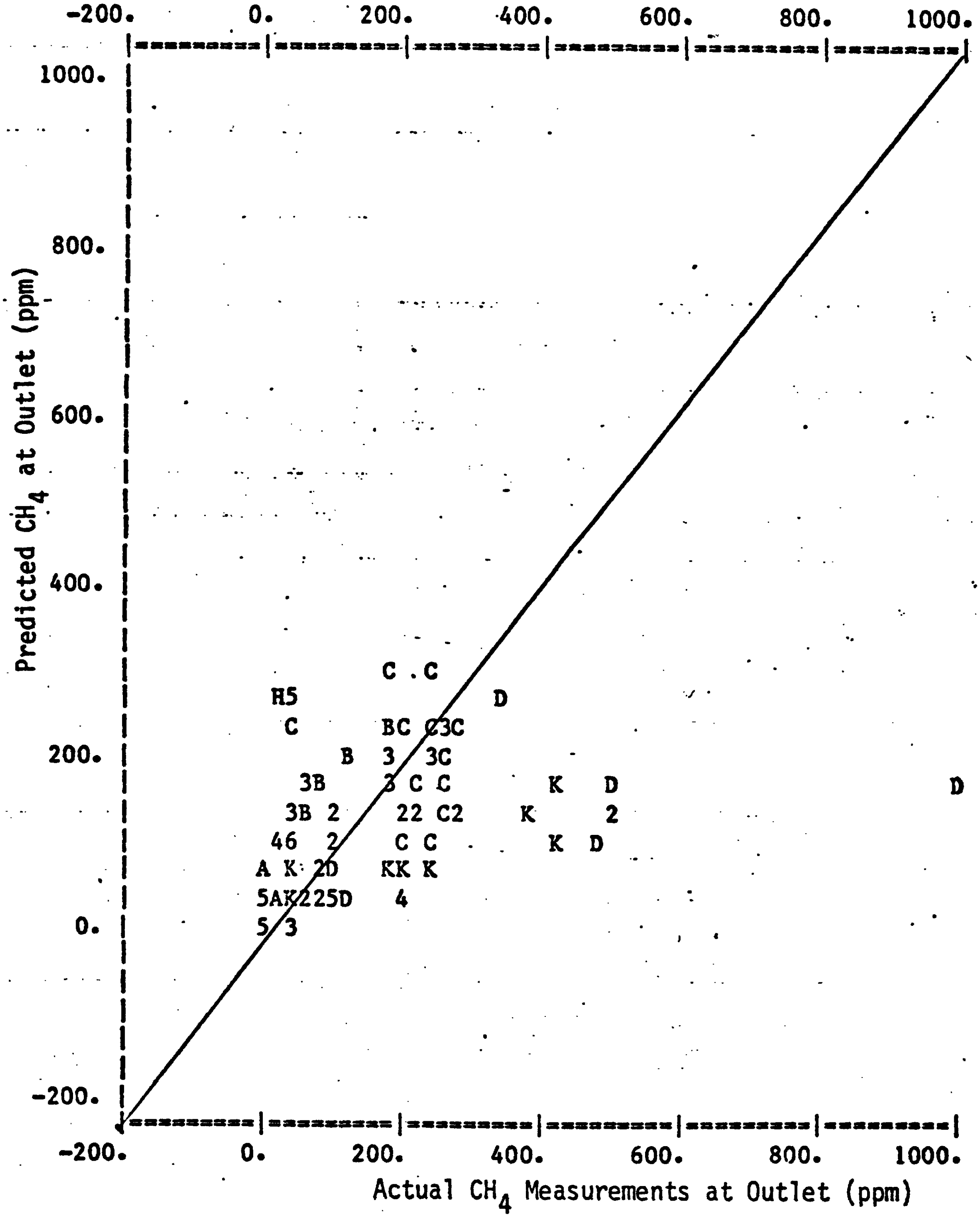


Figure 4.1.23-3 Scatterplot of predicted versus observed CH_4 concentrations at outlet

(Battelle, Feb. 1977). To account for this wide disagreement the formula is changed by a factor of 100 and a large geometic standard deviation is assumed:

$$BAP_e = H$$

(gsd = 15.0)

Other hydrocarbon material is expected to be emitted (Fennelly, Durochee, Klemm, Hall, 1975) in the following concentrations:

E(X) = emission of X in ppm

$E(C_2H_4, C_2H_6) = 10.$

E(Diolefims, aromatic hydrocarbons, phenols, azoarenes) = .001

E(Carboxylic acids, sulfonic acids, polychlormated bephenyls, alkynes, cyclic hydrocarbons, amines, pyridines, pyroles, furans, ethers, esters, epoxides, alcohols, aldehydes, ketones, thiophenes, mercaptans) = .0001

(gsd = 3.16 for these order of magnitude estimates)

4.1.2.4 Trace Metals

In sources as recent as February 1977 (Bloom *et al.*, 1977) trace emissions are dismissed in 2 or 3 sentences as needing study, and indeed no work on atmospheric FBC trace emissions is published. Experiments that have been conducted on pressurized FBCs do show significant improvement in trace element retention over conventional steam-fired power plants. The mechanisms responsible for this performance are listed in Table 4.1.2.4-1 and many are likewise at work in atmospheric FBCs.

Table 4.1.2.4-1
Mechanisms that Reduce Trace Element Emissions in FBCs

1. Combustion temperatures below volatility of some elements.
2. Sorbent reaction with elements.
3. Larger coal particle sizes.
4. Agglomeration and precipitation.

In experimental data (Ruth, 1975) obtained by neutron activation of materials collected in cyclone diplegs and filters, and even disregarding solids lost in handling, the recovery of many trace elements was high [see Table 4.1.2.4-2; also in (Hoke, Nutkis and Ruth, 1974)].

The data from Argonne (NTIS report CONF-750616-4, Vogel *et al.*, 1975), and other sources, shown in Table 4.1.2.4-3, was developed using pressurized FBC's. It is necessary to go to this data despite its limited applicability to atmospheric FBCs due to the lack of atmospheric bed trace element data. Tables 4.1.2.4-4 and -5 suggest the beginnings of modeling information necessary for simulating trace metal changes due to bed temperature variations and different sorbents. Such models have been developed for this report but only on those trace elements that are currently suspected of being carcinogenic health hazards (see Table 4.1.2.4-6).

Table 4.1.2.4-2

Concentrations and Recoveries of Trace Elements (Ruth, 1975).

	CONCENTRATIONS (PPM)				
Element	W. Virginia Coal	Tymochtee Dolomite	Bed	Overhead(1)	Recovery(%)(2)
Al	27000	10900	27000	71300	65.3
Sb	0.253	0.0527	0.501	0.606	78.2
As	3.7	0.566	8.02	9.4	85.9
Cs	0.349	0.439	0.403	2.04	100.0
Cl	1050	447	787	627	21.2
Fe	13800	3240	19600	39900	80.5
Mn	20	42	102	105	95.5
K	599	2180	1280	4040	74.8
Rb	3.74	12.2	9.17	31.1	97.2
Na	784	303	364	3200	88.1
Sr	205	130	278	690	77.6
U	0.652	2.23	3.13	4.41	93.9

(1) Overhead consists of flyash + entrained dolomite.
(2) Recovery = percentage of element present in coal and dolomite that can be accounted for in solids removed from combustor (bed + overhead).

TABLE 4.1.2.4-3 PROJECTED STACK EMISSION OF SELECTED TRACE ELEMENTS FROM CONVENTIONAL AND FLUIDIZED-BED COMBUSTORS WITH TWO CYCLONES AND ONE FILTER EXPRESSED AS A PERCENTAGE OF THE ELEMENT ENTERING THE SYSTEM (Battelle-Columbus, 1977)

Element	Conventional Combustion (a)	Fluidized-Bed Combustion			
		ANL(e) (dolomite)	Exxon (b)	BCL(c)	ANL(e) (alumina)
Mercury	90-100	80	-	75	20-70
Fluorine	90-100 (estimated)	40	-	98	85-97
Chlorine	100	-	-	-	-
Bromine	100 (estimated)	65-82	79	90	100
Molybdenum	25	-	-	-	-
Arsenic	25-60	15-17	14	59	15
Boron	25	-	-	-	-
Lead	0-60	5-20	-	21	0
Beryllium	25 (estimated)	13-29	-	98	37-44
Scandium	10	12-17	15	0	0
Lanthanium	-	11	-	-	0
Chromium	0	0-25	0	(d)	36-73
Selenium	70	-	-	-	-
Cobalt	10-20	4-20	-	(d)	0-21
Vanadium	30	-	-	-	-
Sodium	20	0-15	12	(d)	0-16
Aluminum	10	-	35	-	-
Potassium	30	23-26	25	25-54(d)	0
Cadmium	35	-	-	-	-
Iron	0	5-8	20	(d)	0-6
Antimony	25	-	22	-	-
Manganese	0	0	4	(d)	0
Uranium	-	-	6	-	-
Zinc	13-28	-	-	-	-

(a) Source: Argonne National Laboratories (Klein, et al., 1975)(Kaakinen, et al., 1975)(Jahnig,Shaw, 1976)
(b) Source: Exxon Research and Engineering (Ruth, 1975)
(c) Source: Battelle-Columbus Laboratories, Spark Source Mass Spectometer Data (SSMS)
(d) Data Suspect Due to Accuracy Limitations of SSMS
(e) Source: Argonne National Laboratories (Swift, Vogel,Panek, Jonke, 1975)
- = NO DATA

Table 4.1.2.4-4

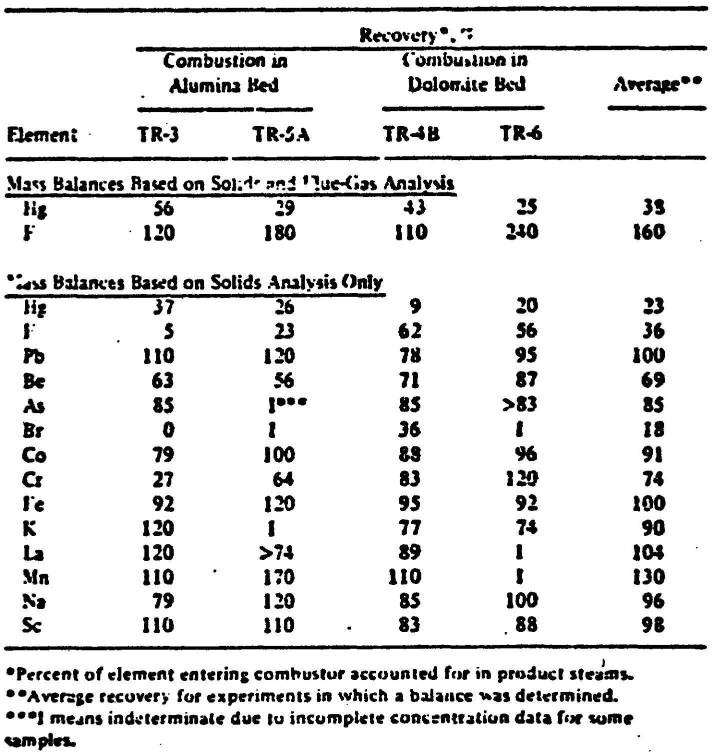
Elemental Concentration[a] of High-Temperature Ash Corrected for Weight Losses at the Stated Temperatures. Ash Prepared at 542 to 990°C by Heating for 24 hr. in Air Flow of 0.6 scfh. (ANL-ES-CEN1016)

		Heating Temperature (°C)						
		340	542	640	740	840	940	990
ppm	Be	6.5 ±0.6	6.3 ±0.6	6.2 ±0.6	6.2 ±0.6	6.8 ±0.7	7.2 ±0.7	6.3 ±0.6
	Pb	15±2	26±3	29±3	29±3	54±5	10±1	21±2
	V	210±50	200±50	230±60	150±40	130±30	150±40	130±30
	Cr	90±9	91±9	87±8	100±10	94±9	93±9	170±20
	Co	17.0 ±0.8	16.9 ±0.8	17.1 ±0.9	15.4 ±0.8	14.0 ±0.7	14.4 ±0.7	13.9 ±0.7
	Ni	52±5	52±5	53±5	62±6	60±6	66±7	100±10
	Cu	130±10	110±10	110±10	120±10	120±10	126±10	130±30
	Zn	540±30	510±30	520±30	460±20	480±20	560±30	560±30
	Mn	500±20	550±30	540±30	680±30	650±30	660±30	670±30
	Hg	0.01						
	Li	59±3	64±3	62±3	63±3	63±3	63±3	66±3
	Cl	90±10	91±10	22±10	17±10	17±10	13±10	21±10
%	Al	4.6 ±0.2	5.7 ±0.3	5.4 ±0.3	8.1 ±0.4	7.7 ±0.4	8.1 ±0.4	8.0 ±0.4
	Fe	10.5 ±0.5	10.7 ±0.6	11.1 ±0.6	11.2 ±0.6	11.3 ±0.6	11.5 ±0.6	11.5 ±0.6
	Na	0.74±0.04	0.75±0.04	0.87±0.04	0.79±0.04	0.80±0.04	0.81±0.04	0.76±0.04
	Mg	0.28±0.01	0.29±0.01	0.33±0.02	0.54±0.03	0.42±0.02	0.40±0.02	0.40±0.02
	K	1.08±0.05	1.26±0.06	1.21±0.06	1.24±0.06	1.25±0.06	1.29±0.06	1.28±0.06
	Ca	4.9 ±0.2	4.3 ±0.2	4.2 ±0.2	6.4 ±0.3	6.0 ±0.3	5.6 ±0.3	6.2 ±0.3
	Ti	0.6 ±0.1	0.6 ±0.1	0.5 ±0.1	0.4 ±0.1	0.4 ±0.1	0.4 ±0.1	0.5 ±0.1

[a] By atomic absorption. Each precision is based on an estimate of the precision of measurement obtainable with standard solution.

Table 4.1.2.4-5

Mass Balances for Trace And Minor Elements Around ANL's 6.0 in. Diameter. Pressurized Fluidized-Bed Combustor (Swift, Vogel, Panek, Jonke, 1975).



	Recovery*, %				
	Combustion in Alumina Bed		Combustion in Dolomite Bed		Average**
Element	TR-3	TR-5A	TR-4B	TR-6	
Mass Balances Based on Solids and Flue-Gas Analysis					
Hg	56	29	43	25	38
F	120	180	110	240	160
Mass Balances Based on Solids Analysis Only					
Hg	37	26	9	20	23
F	5	23	62	56	36
Pb	110	120	78	95	100
Be	63	56	71	87	69
As	85	I***	85	>83	85
Br	0	I	36	I	18
Co	79	100	88	96	91
Cr	27	64	83	120	74
Fe	92	120	95	92	100
K	120	I	77	74	90
La	120	>74	89	I	104
Mn	110	170	110	I	130
Na	79	120	85	100	96
Sc	110	110	83	88	98

*Percent of element entering combustor accounted for in product steams.

**Average recovery for experiments in which a balance was determined.

***I means indeterminate due to incomplete concentration data for some samples.

Table 4.1.2.4-6

Classes of Known or Suspected Carcinogenic or Cocarcinogenic Compounds Associated with Processing and Utilization of Coal (continued).

Inorganic Substances		
As	tricalcium arsenate	$Ca_3(AsO_4)_2$
Se	selenide salt	$[M^{+2}]Se$
Co	cobalt sulfide	CoS
Ni	nickel carbonyl	$Ni(CO)_4$
Be	Beryllium oxide	BeO
Cr	chromate salts	$[M^{+2}]CrO_4$
Pb	lead chromate	$PbCrO_4$
Zn	zinc chromate	$ZnCrO_4$
Hg	elemental mercury	Hg
Cd	cadmium sulfide	CdS

Figure 4.1.2.4-1 shows the levels of some of the carcinogenic trace metals as they have been recorded as varying with temperature. The deviations for this figure represents two standard deviations or approximately the 5% and 95% confidence range. This tentative model of emissions is for pressurized FBC as no atmospheric data is available.

It would be useless to attempt at this time to draw out any other parameters for the trace metal models due to the lack of a wide range of operating or design parameters in the available experiments (see Table 4.1.2.4-7).

The forms of the trace element emissions are as follows (Fennelly, Durochee, Klemm, Hall, 1975)

Gas Phase	(<2μm material)
≈ 1 ppm	F, Na
≈ 1 ppb	As,Pb,Hg,Br,Cr,Ni,Se,Cd,V,Be

Solids	(>2μm material)
≈ 1 ppm	Al,Ca,Fe,K,Mg,Si,Ti,Cu,Zn,Ni,U,V
≈ 1 ppb	Ba,Co,Mn,Rb,Sc,Sr,Cd,Sb,Se,Ca,
≈ 0.1 ppb	Eu,La,Sn,Ta,Th

Based upon a worst case analysis in that study, where all input of the trace element is emitted, the following elements show cause for concern from the health effects perspective:

In emitted phase: Be,As,U,Pb,Cr,V,Cl
Possible enrichment on <2μm particles: Pb, Cr, Se, Br, Hg

The compounds formed by the trace elements are extremely important in determining health impacts, for example, $Ca_3(AsO_4)_2$, $N_i(CO_4)$, $CO(CO)_6$, $ZnCrO_4$ and others in Table 4.1.2.4-6 are potentially potent pollutants. Analysis of emissions as minute as these, however, is not available and may well be beyond present analytic capabilities.

The possibility of additives or sorbents being used in the bed to reduce trace element and alkali metal emissions has been an area of some investigation. The focus of these studies has been to reduce the corrosive potential of the combustion gas stream before it reaches the turbine blades. Numbers useful for trace element modeling are not yet available.

A potentially useful control measure that can be used on trace metals is physical coal cleaning. Although no specific results are available, it is known that arsenic, beryllium, copper, and antimony are closely correlated with the pyritic material in coals.

Another important control device for trace metals may be the use, especially in atmospheric FBC, of unnecessary additional particulate collection devices. Table 4.1.2.4-8 distinctly shows the preferential collections at further downstream collectors, due to the smaller sizes predominant in the downstream catches (see Figure 4.1.2.4-2).

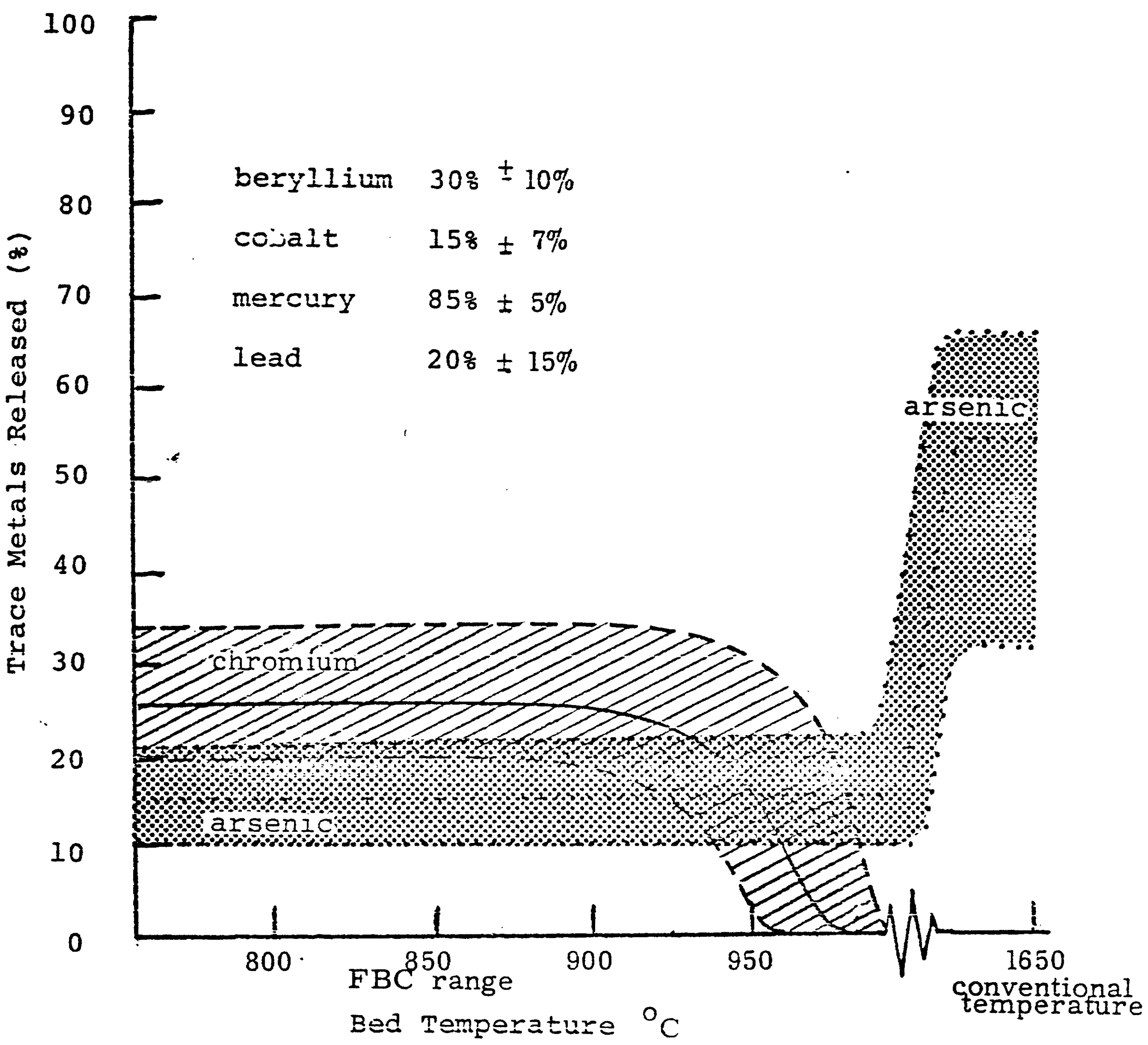


Figure 4.1.2.4-1

Trace Metals Released from Pressurized Fluidized Bed Combustors.

Table 4.1.2.4-7

Summary of Average Operating and Flue-gas Compositions for Trace-Element Experiments (W.M. Swift, G.J. Vogel, A.F. Panek and A.A. Jonke, 1975).

				Feed Rates					Flue-Gas Analysis Dry Basis				
Expt.	Run Time, hr	Bed Temp, °F	System Pressure atm	Coal, lb/hr	Dolomite, lb/hr	Air, scfm	Ca/S Ratio	Gas Velocity, ft/sec	O_2, %	CO_2, %	SO_2, ppm	NO, ppm	CO, ppm
Experiments in a Fluidized Bed of Alumina													
TR-5A	6.0	1670	8	29.4	0.0	67.1	0.0	3.3	3.0	16.0	2180	110	70
TR-3	4.0	1560	10	24.9	0.0	63.0	0.0	2.4	3.9	16.1	1660**	180	120
Experiments in a Fluidized Bed of Tymochtee Dolomite													
TR-6	7.5	1660	8	29.7	6.1	67.9	1.2	3.4	2.9	16.5	440	150	39
TR-4B	4.75	1550	10	28.2	14.2	75.5	2.9	3.0	3.8	19.0	140	200	35

*All experiments made with as-received Arkwright coal.

**Low value due to malfunction of SO_2 IR analyzer.

Table 4.1.2.4-8

Concentrations of Trace, Minor, and Major Elements in Particulate Matter Recovered at Various Stages of Removal from Flue Gas (Vogel, Sept. 1974).

Source of Solids	Concentration					Carbon Free	
	Pb, ppm	Be, ppm	C, wt, %	S wt %	Ca, wt, %	Pb, ppm	Be, ppm
(Experiment TRACE-3)							
Primary Cyclone	95	2.65	51.3	0.86	1.29	195	5.44
Secondary Cyclone	260	5.95	29.2	1.80	1.80	367	8.40
(Experiment TRACE-4B)							
Primary Cyclone	70	1.55	2.3	4.5	15.4	72	1.59
Secondary Cyclone	180	5.20	13.1	2.6	5.58	207	5.98
Filter	300	6.77	8.4	3.1	6.65	328	7.39
(Experiment TRACE-5A)							
Primary Cyclone	15	2.29	34.1	1.8	2.11	22.8	3.47
Secondary Cyclone	13	6.62	16.8	2.5	2.02	15.6	7.96
Primary Filter	22	6.75	6.6	4.9	2.89	23.6	7.23
Secondary Filter	46	8.05	—	—	—	—	
(Experiment TRACE-6)							
Primary Cyclone	16	2.24	19.6	4.8	8.11	19.9	2.79
Secondary Cyclone	27	5.63	11.3	3.1	4.89	30.4	6.35
Primary Filter	96	7.70	5.2	4.3	5.44	101.3	8.12

Trace Emissions

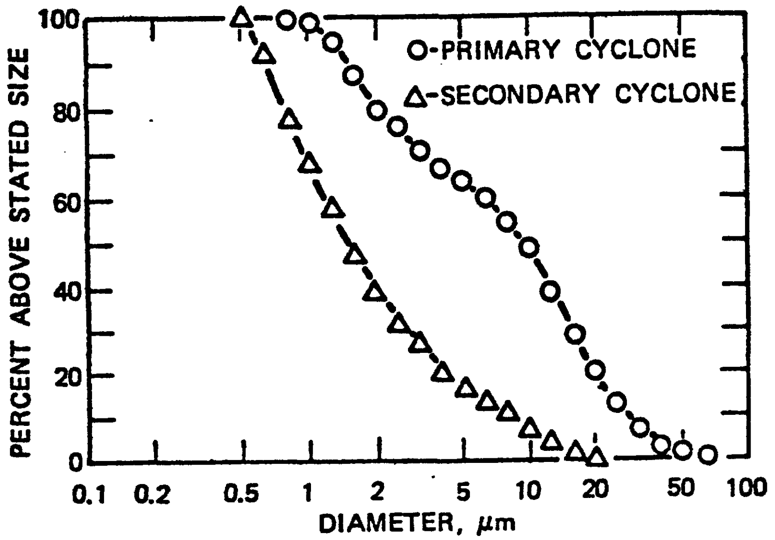


Figure 4.1.2.4-2

Particle Size Distributions of Primary and Secondary Cyclone Catch (Strom, et al., 1976).

4.1.2.5 Particulates

The problems that have been recognized in the area of particulate loadings in the fluidized combustor flue gas have been "significantly, but not hopelessly difficult" (ANL, 1976). Thus, the experimental investigations of fluidized bed particulate emissions have been aimed not at the parametric studies, as for the preceding emissions, but at alternative technologies for bringing particulate levels down to reasonable levels. Some add-on technologies that have been studied are the "hot side" electrostatic precipitators, cyclones (centrifugal collectors), wet scrubbers, and stone, ceramic, porous metal, granular bed, and various other types of gravity and momentum collectors and filters.

The reasons for the high particulate levels in the offgases include:

(1) presence in combustor of numerous additive and sorbent incombustible particles,

(2) the entraining and elutriating capabilities of the upward flow of fluidizing air, and

(3) combustion temperatures below slagging point of coal ash.

There are a number of predictions from design studies that particulate loadings can be controlled down to the 0.1 lb/10^6 Btu (.00095 lb/kWh electric, .01 g/kWh thermal) EPA New Source Performance Standard (Farmer, Magee, Spooner, 1977), (Shaw 1977) (GE, 1976). The actual experimental data are for uncleaned emissions and pressurized (8 atm) combustors, and show ranges of 7 to 39 lb/10^6 Btu heat input depending upon original size and degradation of sorbent (Jonke, July 1976), Ca/S mole rates (see Figure 4.1.2.5-1), fluidizing velocity (Vogel, Swift, Montagna, Lenc, and Jonke, 1975) (see Figures 4.1.2.5-2 to -6), design (bed internals, freeboard), bed depth (Keairns, et al., Sept. 1975) and apparently depending on combustor size (Dow Chemical, July 1975).

The constituents of the particulate material include (Keairns, et al., Sept. 1975):

(1) fly ash,
(2) soot
(3) unburned or partially-burned coal, and
(4) calcined or sulfated SO_2 sorbent.

The mean size and size distributions of uncleaned particulate matter have been characterized as shown in Table 4.1.2.5-1.

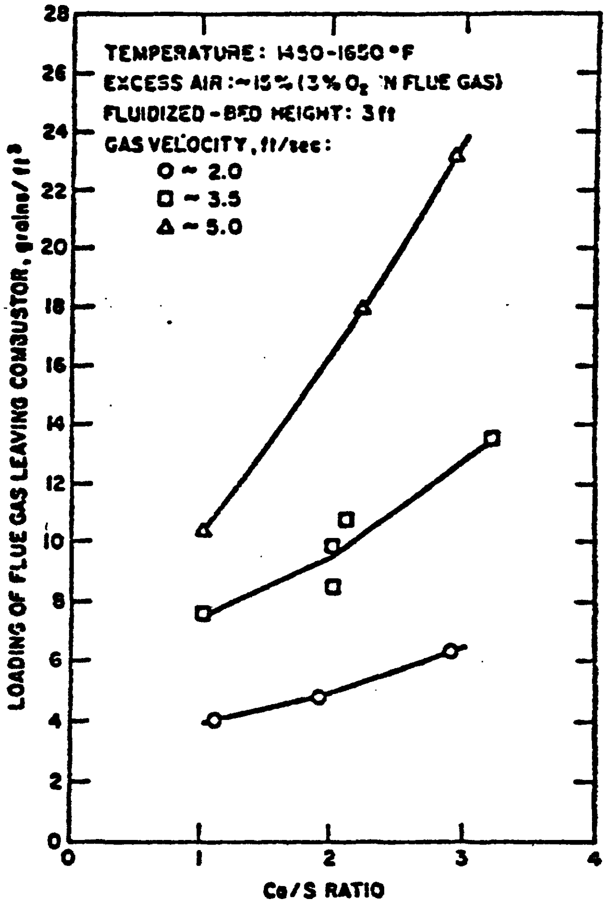


Figure 4.1.2.5-1

Solids Loading of Flue Gas Leaving Combustor

(G.J. Vogel, W.M. Swift, J.C. Montagna, J.F. Lenc and A.A. Jonke, 1975).

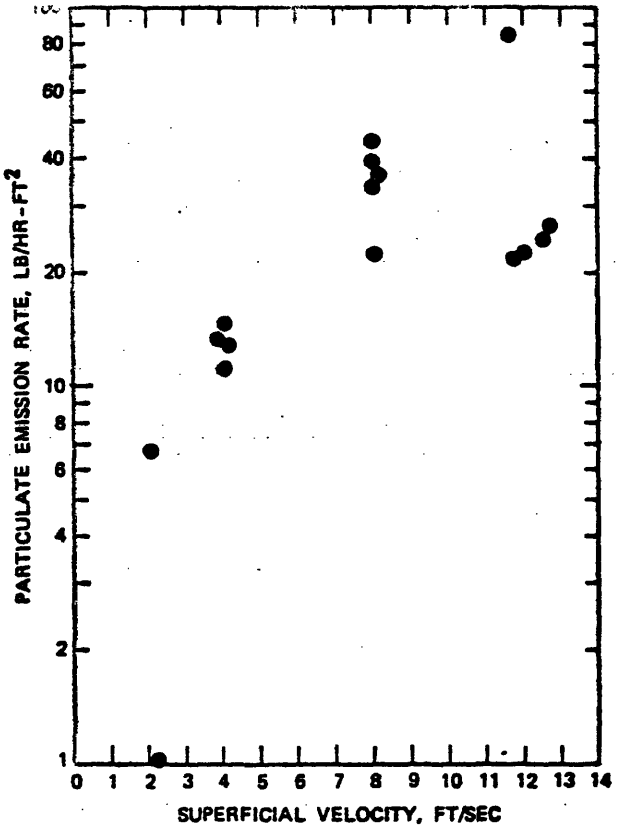


Figure 4.1.2.5-2

Particulate Emission Rate Versus Superficial Velocity - Stone 1 (Strom, et al., 1976).

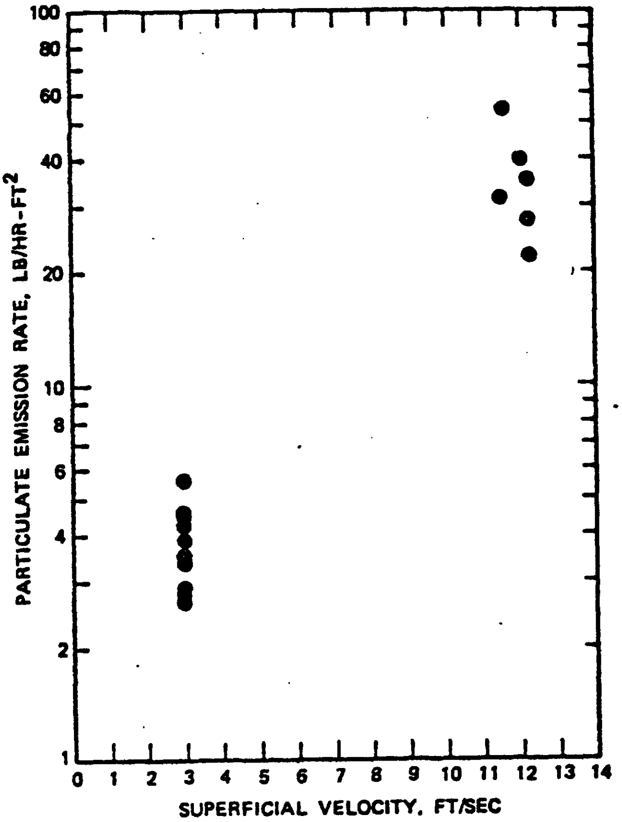


Figure 4.1.2.5-3

Particulate Emission Rate Versus Superficial Velocity - Stone 3 (Strom, et al., 1976).

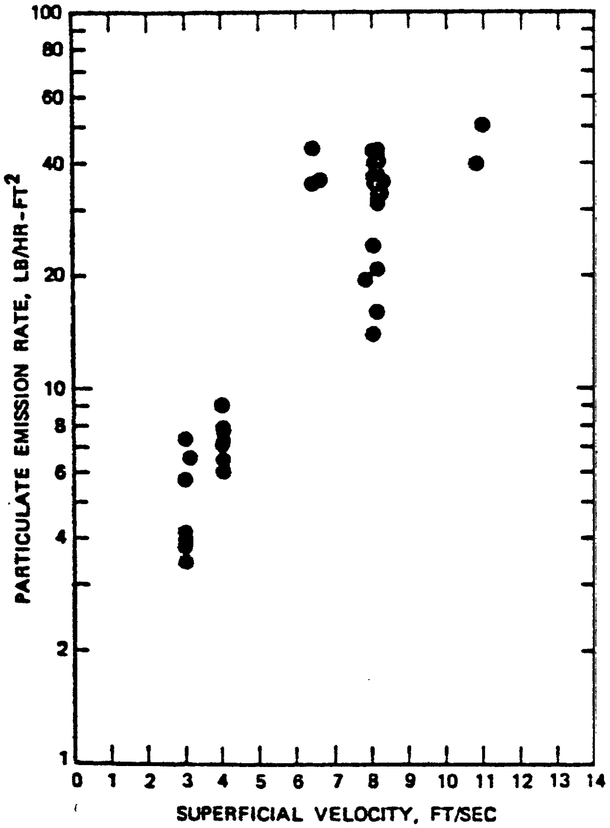


Figure 4.1.2.5-4

Particulate Emission Rate Versus Superficial Velocity - Stone 7 (Strom, et al., 1976).

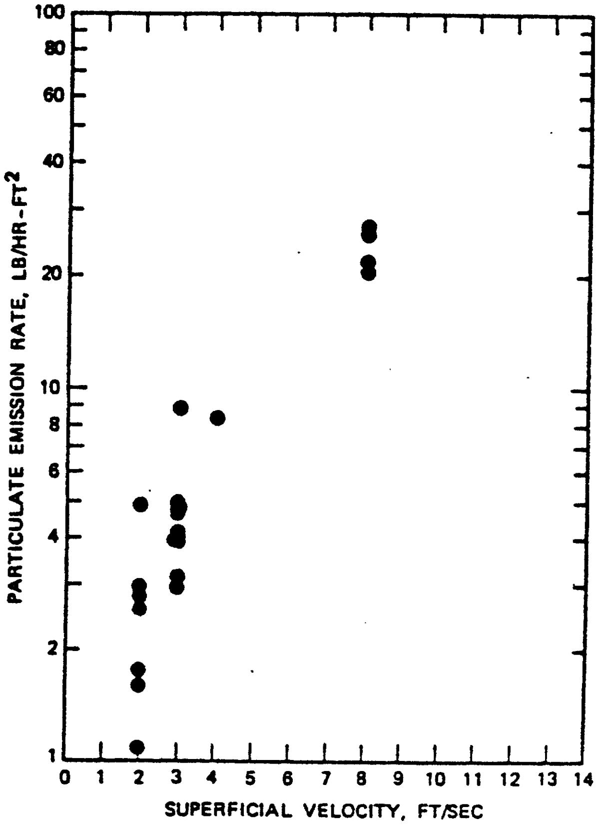


Figure 4.1.2.5-5

Particulate Emission Rate Versus Superficial Velocity - Stone 8 (Strom, et al., 1976).

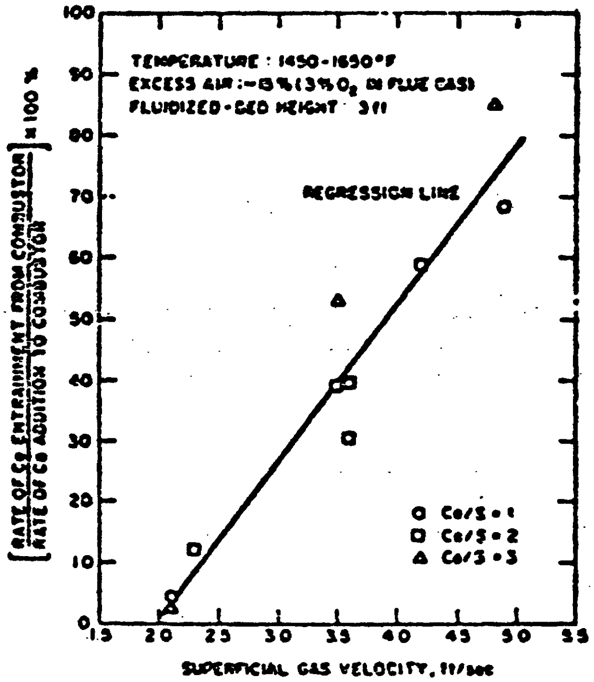


Figure 4.1.2.5-6

Entrainment as a Function of Superficial Gas Velocity

(G.J. Vogel, W.M. Swift, J.C. Montagna, J.F. Lenc and A.A. Jonke, 1975).

Table 4.1.2.5-1 Characterization of Particulates

Mass Media Particle Size	Reference
20 µm	conventional combustor
100 µm	(Jonke, Swift, Vogel, 1975)
"shifted to larger size", >20µm	(Osborne, Bulger, 1976)
"looks favorably coarser", >20µm	(Iammartimo, 1976)
design studies 35µm to 150µm	(Keairns, et al., Sept. 1975)
~7µm	(Fennelly, Durocher, Klemm, Hall 1975)
95% less than 10µm, 85% less than 5µm	(Nack, et al., 1977)
Properties	
not soft or friable	(Shange and Chronowski, 1975)
highly resistive	(Strom, et al., Feb. 1976)

The empirical model developed for uncleaned particulate emissions is shown in Table 4.1.2.5-2 and Figure 4.1.2.5-7, see (Gruhl, Tung, Schweppe, 1978) for details.

The size characterization of mass median diameter of uncontrolled particulates, using only the experimental studies (with >20 modeled as 40µm) and heavily weighting (3 times) to the smaller measurement due to the expert sentiment (ANL,1976) that it is far more accurate in the smaller particle range:

P_s = uncontrolled particulate size (by weight) distribution

geometric means:
P_s = 9.1µm
(gsd = 4.3)
geometric standard deviation of size = 2.25

Table 4.1.2.5-2 Empirical model of outlet dust loading for all observations for which values of all variables were published

Symbols:

U = outlet dust loading, in tonnes/day
V = fluidizing velocity, in m /sec
A = bed area, in square meters
X = excess air, in percent
C = calcium to sulfur mole ratio
Z = coal top particle diameter, in microns
F = 1 or 0 indicator of fines recycled or not
G = MgO to CaO ratio in sorbent
T = bed temperature in degrees centigrade
P = parameter for effect of coal source
Q = parameter for effect of calcium source

Model based on data base for all experiments:

$$U = .1576(1.+\min[0.,\{-16.774+24.56V-3.54V^{2}])(1.+3.53A)(1.-.0055X)*$$

$$(1.+.2124C+.00627C^{2})(1.+.000097Z)(1.+.2165F)(1.-.014G)*$$

$$(1.+.0000122[1.8T-1555.]^{2})\ P\ Q$$

[fit=arithmetic stand dev 2.94]
on 118 experiments

Tables of parameters:

coal source	$P_{\text{data base}}$	calcium source	$Q_{\text{data base}}$
Pitt seam 8 washed	0.783	BCR1337 dolom	3.090
Pitt seam 8 unwashed	0.927	BCR1360 limes	1.720
Peabody Coal Co.	0.067	BCR1359 limes	3.713
Pitt seam unspecified	1.000	BCR1359H hyd lm	2.674
Commonwealth Edison	0.117	Tymochtee dolom	3.707
Park Hill coal	0.328	US limestone 18	0.143
Illinois coal unspec.	0.063	UK limestone	2.785
Welbeck coal unspec.	2.794	Stow-on-Kent	1.000

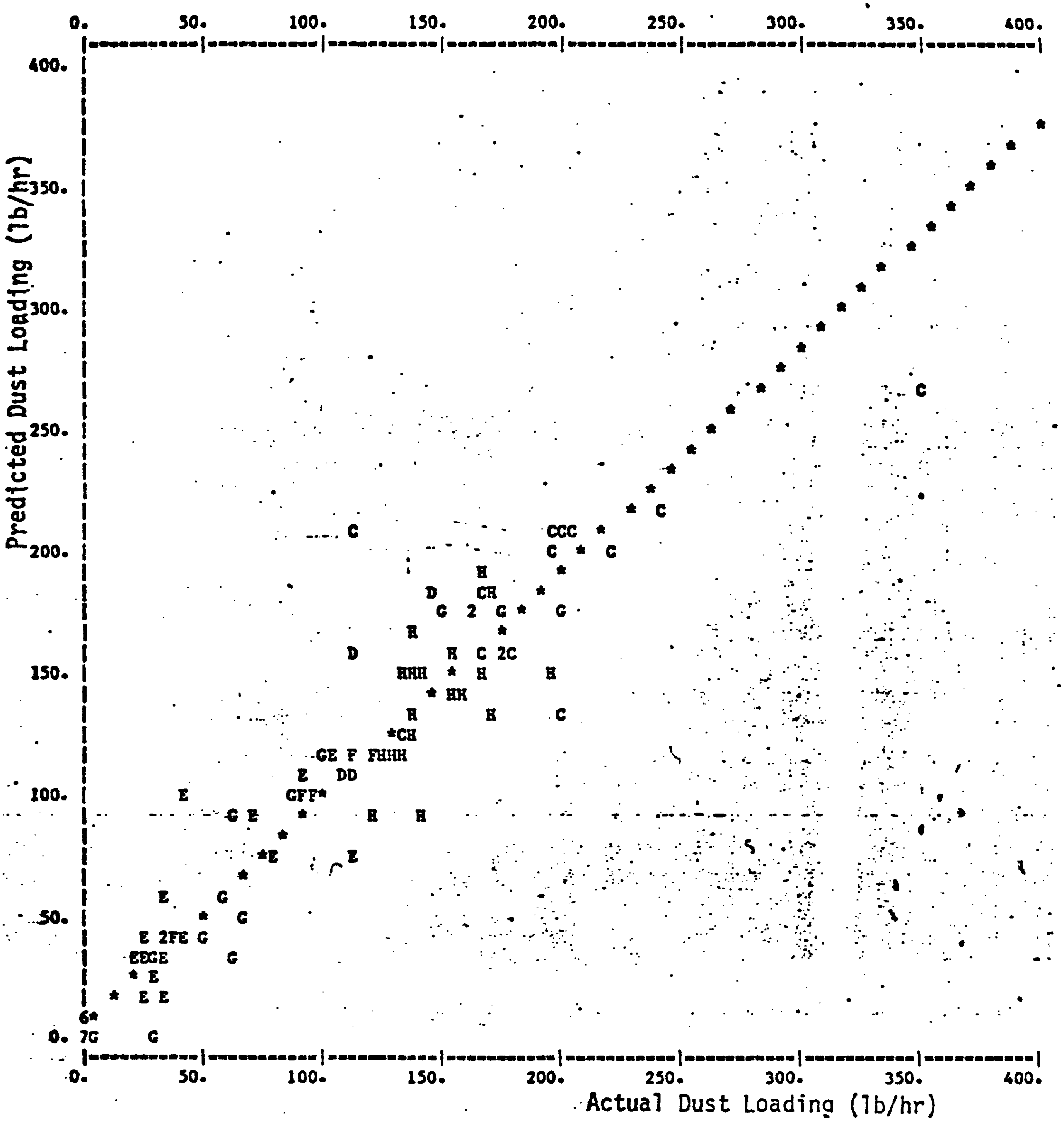


Figure 4.1.2.5-7 Scatterplot of outlet dust loading in lb/hr for observations versus predictions, the 118 points are fit with an arithmetic standard deviation of 6.48, lb/hr*.4536=tonne/day

Figure 4.1.2.5-8 shows a counter distribution, while 4.1.2.5-9 and -10 show mass distributions including those after a cyclone dust collector.

P_s = particle size (by weight) distribution after cyclone dust collector, microns

geometric mean P_s = 5.6 microns
(gsd = 1.3)

geometric standard deviation of size = 2.38
(gsd = 1.09)

From Figure 4.1.2.5-11 it can be seen that some idea of streams 1 and portions of 3 have been modeled. Figure 4.1.2.5-12 shows the emissions from the carbon burnup cell tests, so if one is used this emission can be modeled. Regression models have been fit to the carbon burnup cell emissions by Pope, Evans and Robbins:

E(part) = particulate emissions $lbs/hr/ft^2$

B_d = bed depth (static), inches

T = temperature, ^oF

A = air feed rate, $lb/hr/ft^2$

C = carbon feed rate, $lb/hr/ft^2$

I = inert feed rate, $lb/hr/ft^2$

$$\begin{aligned} E(part) = {} & 15.57 - 0.00664T - 0.00134A + 0.0236B_d \\ & -0.03034C + 0.00461\,I \\ & +0.0034\,CI \end{aligned}$$

(geometric mean error = .956)
(gsd = 1.51)

To complete this picture it is necessary to have mass and size collection efficiencies for all of the control technologies for FBC emissions. This is not available. For atmospheric FBC, where turbine blade corrosion is not a problem, "it seems probable" that available control technologies can bring particulate levels down to the standard. Low temperature electrostatic precipitators probably won't work well due to high electrical resistivity, and hot precipitators may not perform well due to low combustion temperatures, that will leave the important alkalis unvaporized (Strom, et al., 1976). It is believed, however, that a combination of "two cyclones in succession to collect the coarser particles followed by a low-pressure-drop bag house for finer particulates would be suitable (ANL, 1976). Figure 4.1.2.5-13 shows typical abatement performances for conventional combustors, which is of limited applicability.

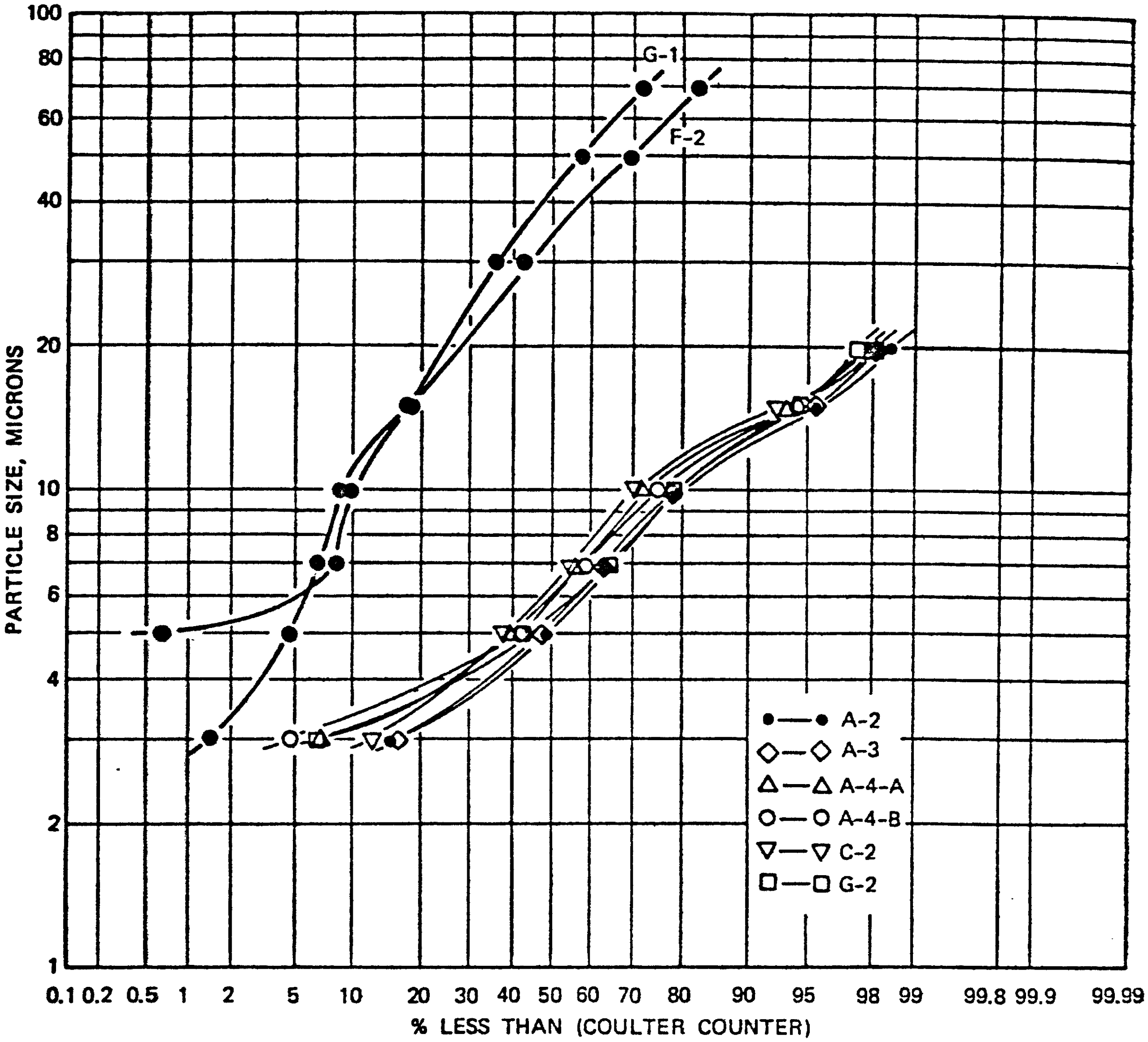
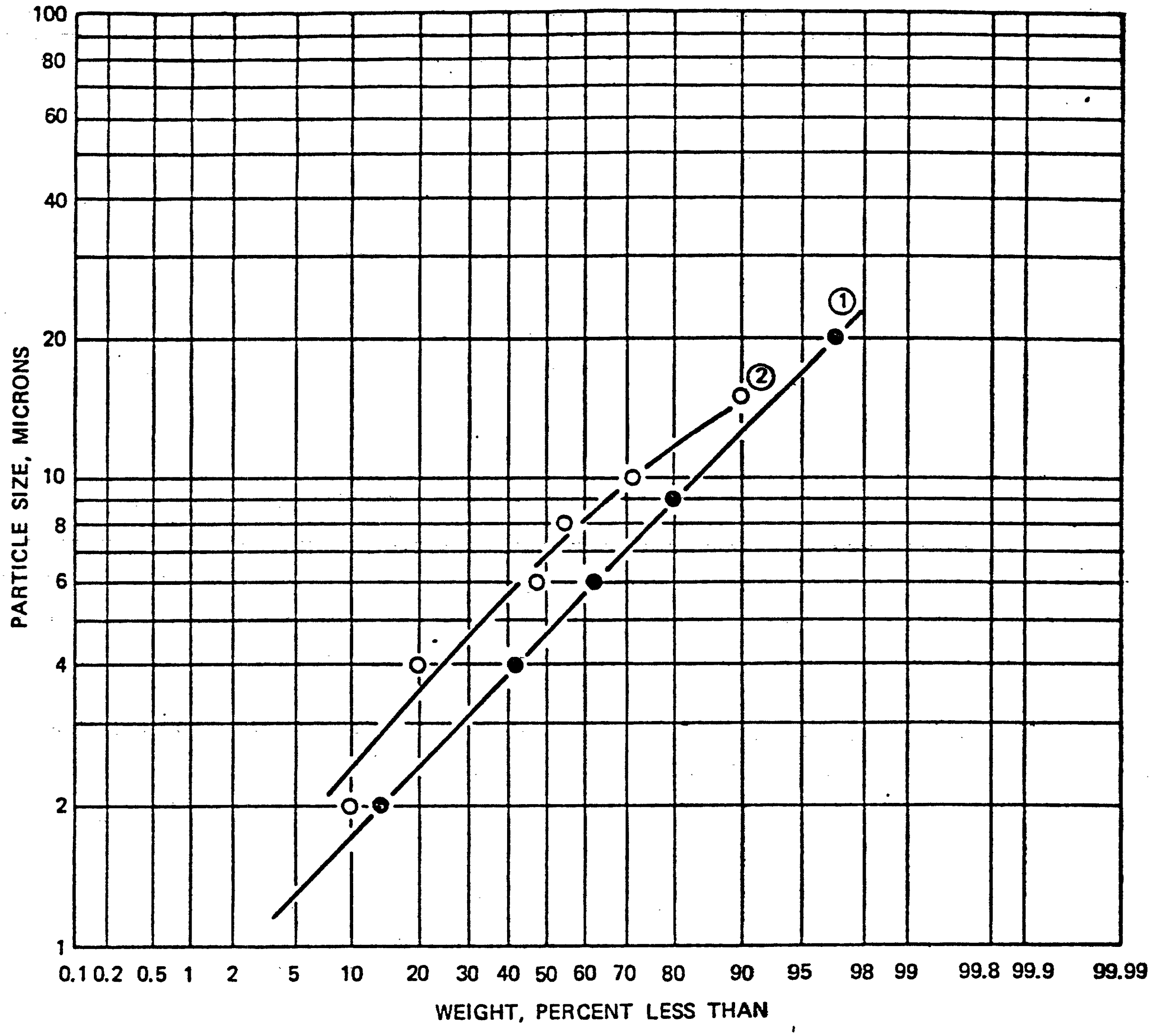


Figure 4.1.2.5-7

Particle Size Distribution of Elutriated Ash in Inert Bed Tests (Strom, et al., 1976).



1 Coulter counter assuming equal density spheres

2 Exhaust stack after cyclone dust collector

Figure 4.1.2.5-9

Particle Size Distributions from Pose, Evans and Robbins Test (Strom, et al., 1976).

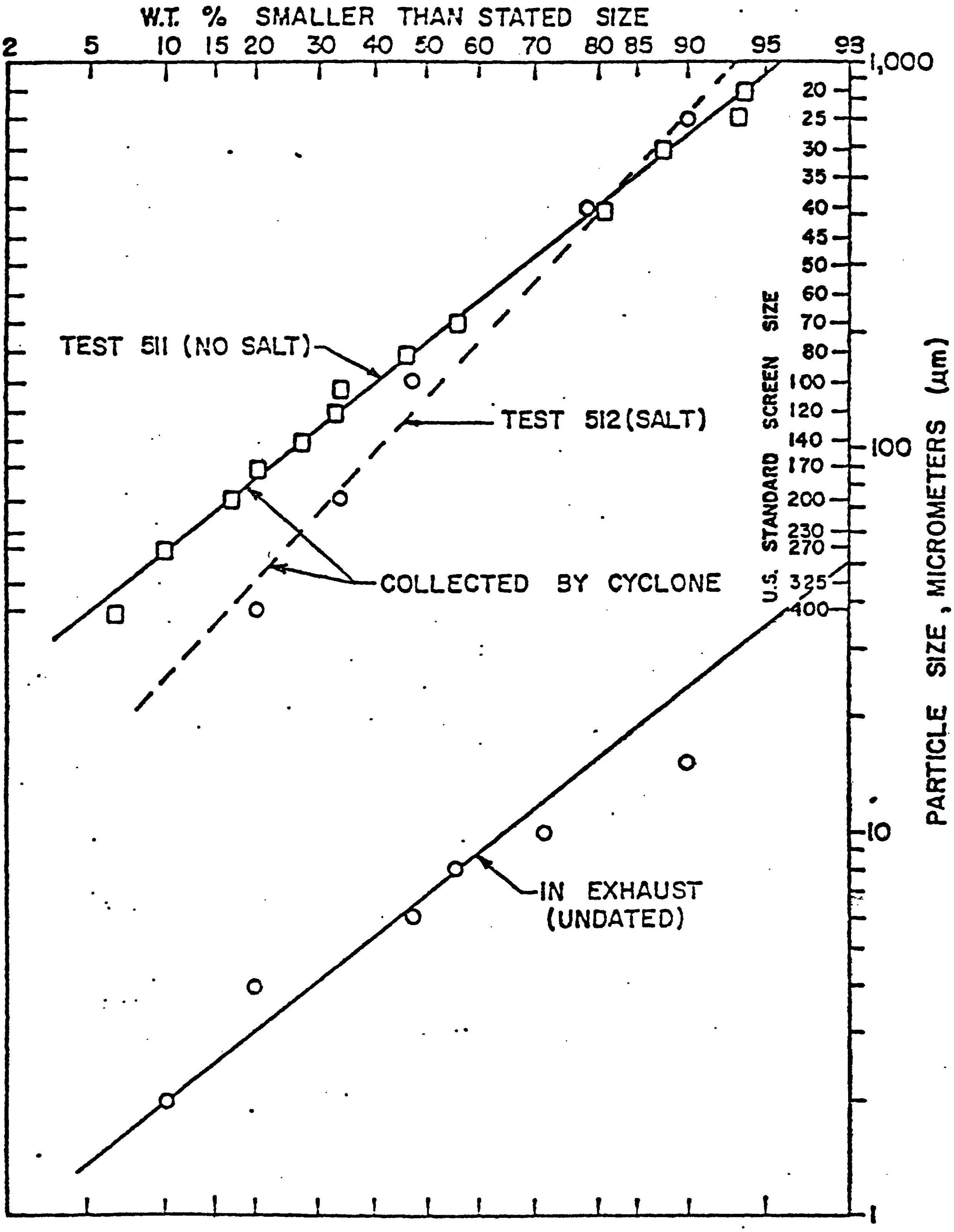


Figure 4.1.2.5-10

Flyash Size Distribution (Pope, Evans, and Robbins, 1974).

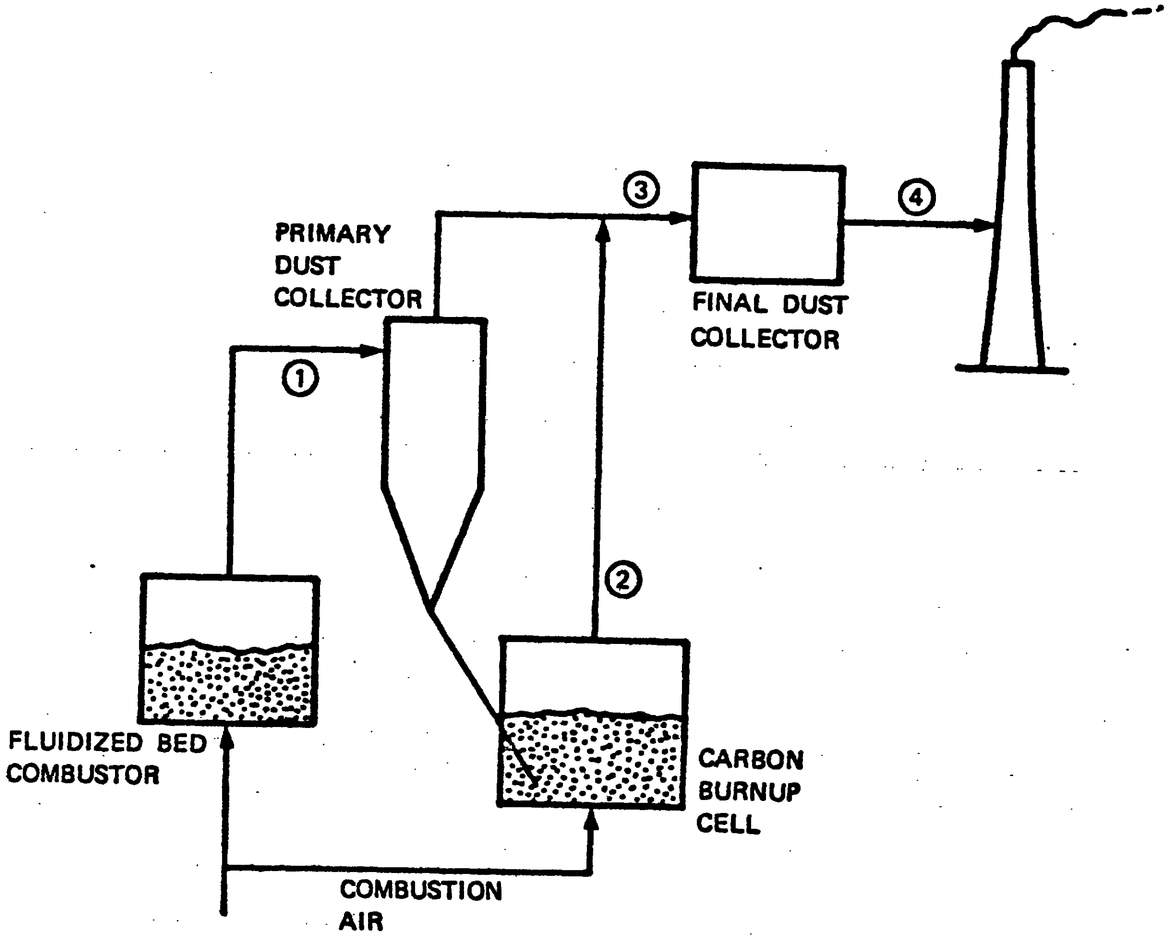


Figure 4.1.2.5-11

Fluidized Bed Combustion System Flow Sheet (Strom, et al., 1976).

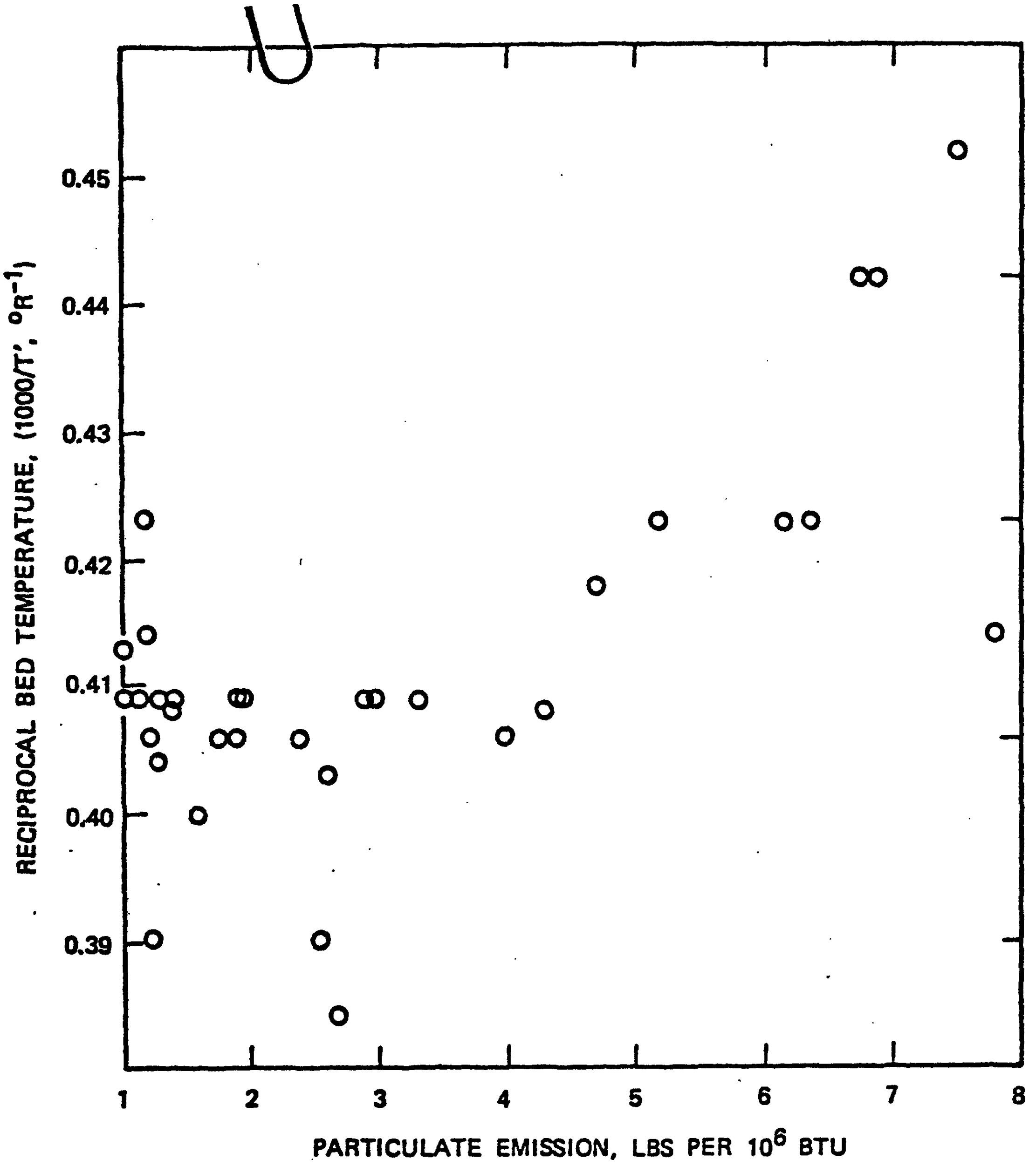


Figure 4.1.2.5-12

Particulate Emissions from Carbon Burnup Cell Tests (Strom, et al., 1976).

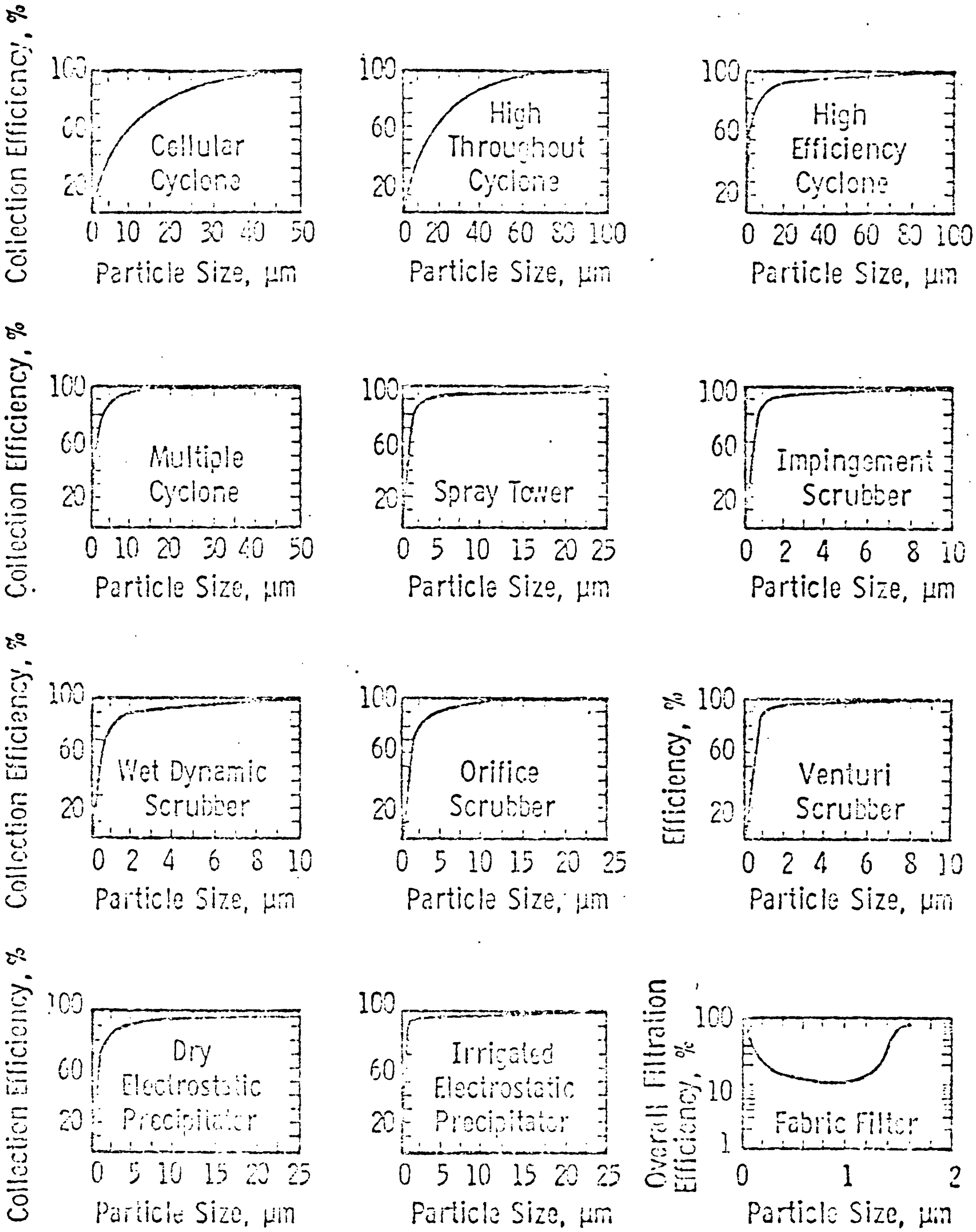


Figure 4.1.2.5-13

Survey of Particle Collection Systems (Stairmand, 1956).

The speculation about a 0.02 lb/10^6 BTU standard for fine particulates (Balzhiser, 1976) apparently would also not cause a problem for the atmospheric FBC. Meeting this standard may well bring down the overall particulate level to below 0.05 lb/10^6 BTU.

4.1.2.6 Carbon Monoxide

Emission levels of CO from the fluidized bed are not of concern technologies. There are several reactions that influence the CO levels, but it is generally believed (Beer, 1977) that CO concentrations are proportional to both the level of feed of coal volatiles and the level of fines in the feed (see Figure 4.1.2.6-1). CO is possibly produced in the dense phase of the bed (Louis, Tung, 1977) and by carbon fines carried to the freeboard. Concentrations between 0.04 (General Electric, 1976) and 1.2 lb/10^6 BTU (Shaw and Cain, 1977) and 2000ppm (ANL, 1976) have been projected for atmospheric FBC. There does not appear to be any manner of correlating the experimental levels with measured parameters. An inverse relationship with excess air is somewhat (Coates and Rice, 1973) indicated, but is not elsewhere borne out.

Table 4.1.2.6-1 shows a series of CO measurements for experiments that all have excess air greater than 10%, thus 461ppm is the prediction from the above model. The results of that Table show an arithmetic average of 2042ppm and an arithmetic standard deviation of 3761ppm, and the EPA analysis at Battelle (Battelle-Columbus, 1977) shows a range of 790-2090ppm. Obviously the CO concentrations are very much dependent upon variations in designs. The model developed on the EPRI data base (Strom, *et al.*, 1976) is shown in Table 4.1.2.6-2 and Figure 4.1.2.6-2.

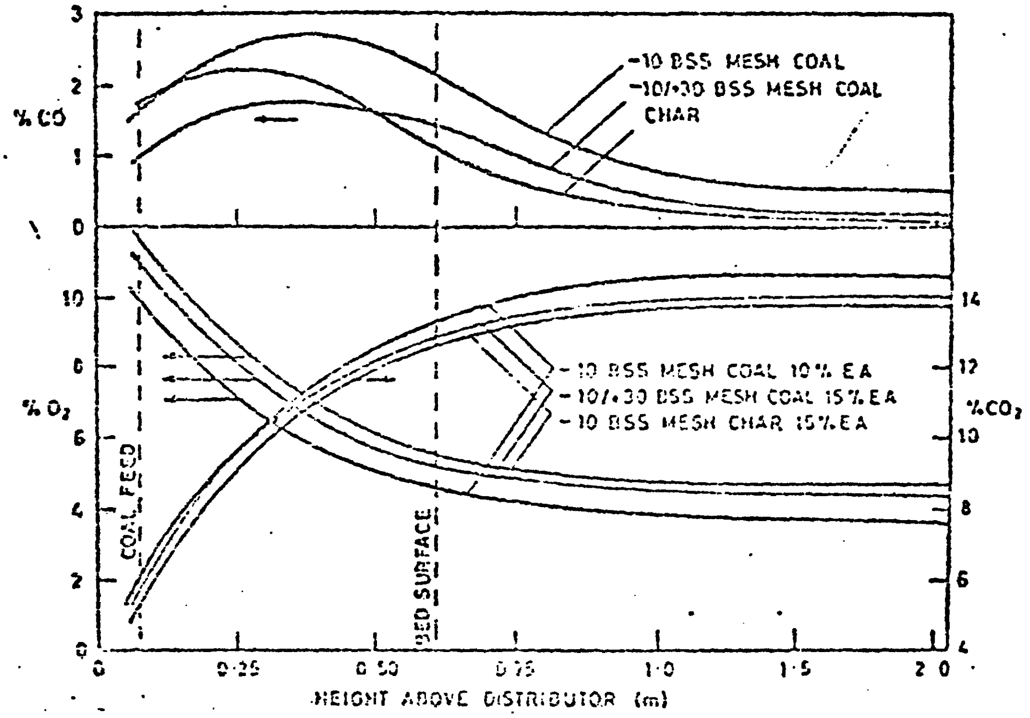


Figure 4.1.2.6-1

The Effect of Coal Feed Size and Volatile Content on the CO_2, CO and O_2 Concentrations in the Bed and the Freeboard (Beér, 1977).

Table 4.1.2.6-1

Flue Gas Compositions (Strom, *et al.*, 1976).

TEST NO.	FREEBOARD					WET-SCRUBBER INLET					
	VOL.%,D.B.		PPM, D.B.		DUST LOAD GRN/SCF	VOL.%,D.B.		PPM, D.B.			DUST LOAD GRN/SCF
	O2	CO2	SO2	CO		O2	CO2	SO2	CO	NOX	
19	5.3	12.6	683.	8100.	12.9	2.7	14.1	839.	2700.	285.	3.3
20	4.2	12.5	1943.	10800.	12.3	2.5	13.3	1475.	5400.	212.	3.7
21	4.0	13.2	1717.	6750.	11.8	3.0	14.1	1126.	3240.	334.	3.3
22	4.5	12.8	1648.	6210.	13.0	3.0	14.3	1107.	270.	215.	3.5
23	4.3	13.4	1477.	5400.	13.2	3.1	14.8	1673.	1890.	300.	3.9
24	3.7	12.3	1342.	12960.	14.2	2.9	13.8	1403.	270.	213.	3.4
25	5.6	12.4	790.	3240.	12.0	3.0	14.6	1265.	0.	56.	2.7
26	3.9	13.9	850.	5940.	12.1	2.9	14.6	879.	1350.	213.	3.9
27	4.0	14.2	1012.	5400.	12.0	3.4	14.6	849.	1080.	285.	3.9
28	3.6	14.5	384.	5670.	13.6	3.0	15.2	589.	810.	322.	4.3
29	3.4	13.9	1316.	5400.	11.1	3.3	14.5	1143.	0.	233.	3.4
30	4.2	13.7	1140.	1890.	10.0	3.2	14.5	1502.	0.	303.	3.2
31	3.8	14.0	961.	9450.	13.8	3.0	14.8	1035.	0.	238.	4.0
32	3.6	14.6	623.	7020.	15.9	2.7	15.1	676.	0.	0.	4.4
33	4.3	13.3	1540.	7020.	11.4	3.5	14.4	1546.	0.	269.	3.5
35	3.8	13.9	1062.	5670.	18.8	2.7	14.6	992.	0.	246.	6.4
36	3.2	14.1	696.	18630.	27.1	3.1	14.4	930.	16200.	296.	7.2
37	3.0	14.5	983.	14040.	22.0	2.9	14.1	895.	8910.	190.	7.3
38	4.1	13.4	282.	11340.	19.3	3.0	14.3	387.	2700.	199.	9.2
40	3.6	14.1	318.	3375.	17.4	3.1	14.8	524.	0.	313.	8.6
41	4.1	13.4	581.	7290.	19.1	3.0	14.6	484.	0.	265.	8.1

NOTE: CO MEASUREMENTS REPORTED IN THIS TABLE ARE TOTAL COMBUSTIBLES REPORTED AS HEAT-EQUIVALENT CO.

D.B. = Dry Basis

Table 4.1.2.6-2 Empirical model of CO concentrations at outlet

Symbols:

O = CO concentration at outlet, in ppm
A = bed area, in square meters
Z = coal top particle diameter, in microns
X = excess air, in percent
F = 1 or 0 variable if fines recycled or not
L = sulfur content of coal, in percent
V = fluidizing velocity, in m/sec

Model based on least squares best fit to <u>all</u> available data:

$$O = \max\left[50.,\ (-303+149.A^{-1}-2.6A^{-2})(1.-.00008Z)(-22.276+1.199[X+15] +98.12[X+15]^{-1})(1.+1.087F)(1.-.04116L)(1.-.0377V) \right]$$

[fit=arithmetic stand dev 1010 ppm]
on 124 experiments

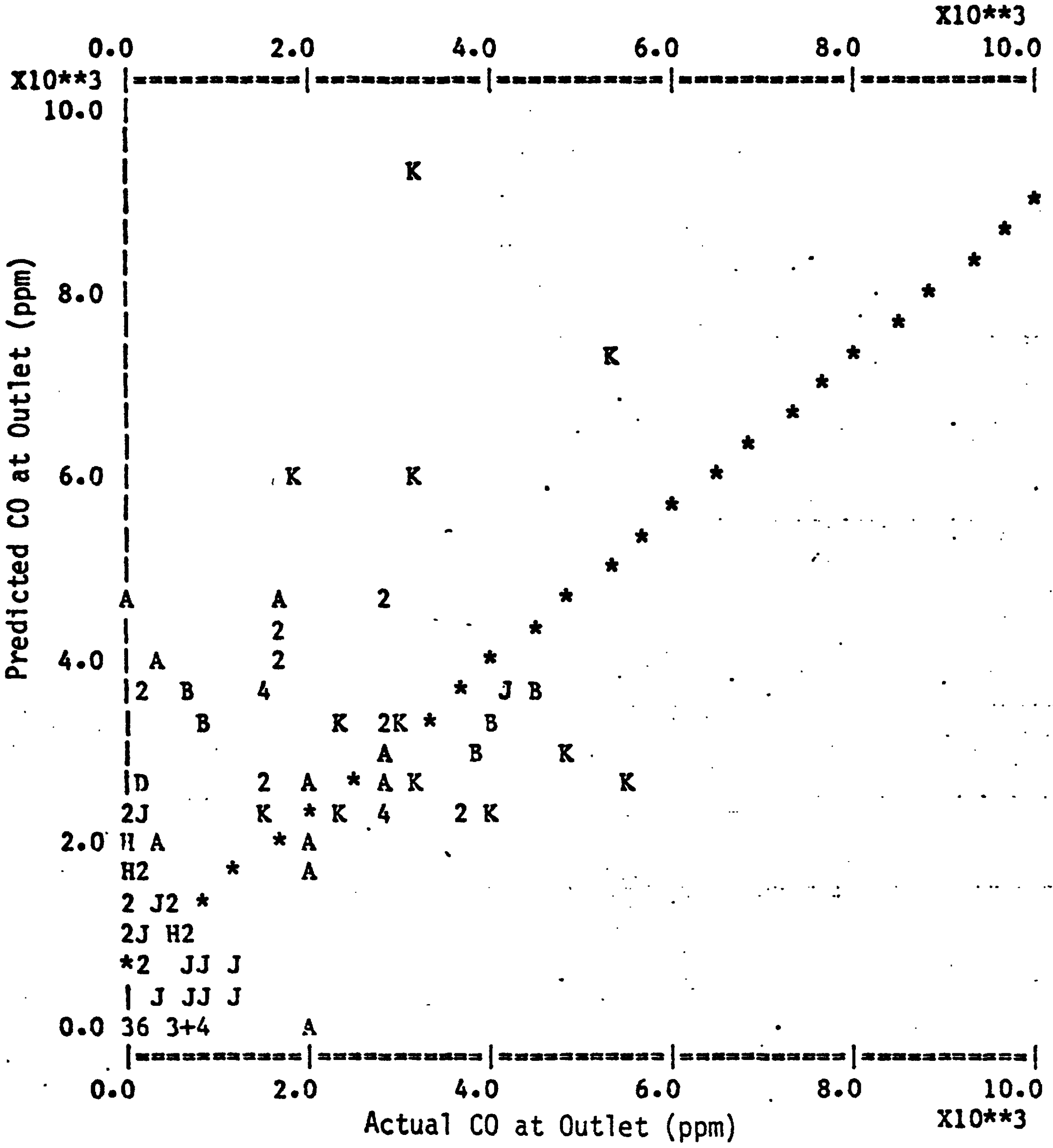


Figure 4.1.2.6-2 Scatterplot showing the relatively poor fit to the wildly varying CO data, this is for all the data together and is very similar to the superposition of scatterplots from the separate cluster modeling efforts

4.1.2.7 Other Flue Gas Emissions

Based on rough estimates using equilibrium calculations based on free energy minimization (Fennelly, Durochee, Klemm, Hall, 1975) the following concentrations are likely (ranges are assumed to be spreads of one geometric standard deviation)

E(X) = emissions of X

$E(CO_2)$ = 15.4%
(gsd = 1.10)
E(HF) = .24ppm
(gsd = 2.96)
E(HCN) = .118ppm
(gsd = 1.69)
$E(NH_3)$ = 3.6ppm
(gsd = 1.99)
E(HCl) = 40.0 ppm
(gsd = 1.09)
$E(SO_3)$ = 5.5ppm
(gsd = 17.)
$E(C_2N_2, COS, H_2S, H_3SO_4, HNO_3)$ = 1.0 ppm
(gsd = 3.16)
$E(O_3)$ = .0001ppm
(gsd = 3.16)

4.1.3 Other Than Flue Gas Air Emissions

Aside from the flue gas emissions the major air pollution concerns at fluidized bed power plants will involve the process of handling coal and sorbent. A list of these potential problems (Jahnig and Shaw, 1976) includes:

- Wind action on coal storage and handling
- Wind action on sorbent and wastes
- Water vapor from grinding
- Air and rust from cooling tower
- Possible fugitive dust from area
- Transients due to upsets, cleaning, and so on

There is no reason to believe that the same control measures developed for conventional coal-fired power plants with scrubbers and cooling towers would not be sufficient to control these emissions.

4.2 Air Emissions of Pressurized FBC

In most cases the emissions from pressurized FBC can be described in terms of the atmospheric FBC emission projections. There have been a couple of experiments that use pressure as a parameter, and from these pressure could be an additional term in the previous empirical equations. There are several reasons why this is not advantageous:

(1) the relationships would be based on very few data points,

(2) the empirical equations for pressurized FBC seem to be quite different from the atmospheric equations, and

(3) only pressures in the 8 to 10 atmospheric range are of interest.

These new empirical equations are fit to the pressurized data.

4.2.1 Air Balance

The air balance in the pressurized combined cycle design of (General Electric, 1976) is shown in Figure 3.3.3-12. Tables 3.3.3-1 and -2 show the gas and steam flow rates for two of the parametric cases investigated by Westinghouse for ECAS (Wolfe, et al., 1976).

4.2.2 Flue Gas Emissions

In general, the emissions situation for the pressurized FBC is much like the atmospheric FBC except for sightly smaller magnitudes. These smaller magnitudes are not solely due to the decreased used of coal for given power levels, but also includes more favorable kinetic reaction rates for key reactions.

Sulfur Oxides

Experimental data on pressurized FBC emissions is not as abundant due to the substantially fewer number of parametric studies conducted on pressurized vessels. In addition, there are apparently no systematic collections of pressurized data as there is for the atmopheric FBC emissions (Strom, et al., 1976). Parametric studies of the effect of Ca/S ratio on sulfur retention are shown in Figures 4.2.2-1 through -10. In terms of ppm emissions these results can be seen in 4.2.2-11. Temperature has very little effect at the high pressures (see Figure 4.2.2-12) and thus it is readily apparent that the addition of a new pressure parameter to the atmospheric FBC SO_2 emission model is not going to be adequate.

Fluidizing velocity is the other parameter of concern in this empirical model. BCURA has also conducted pressurized studies (Nack, et al., 1975). The net results of all these studies can be shown in the empirical equation:

N_{so} = sulfur NOT removed in percent

C_a = Ca/S ratio valid in range 0.4 to 2.5

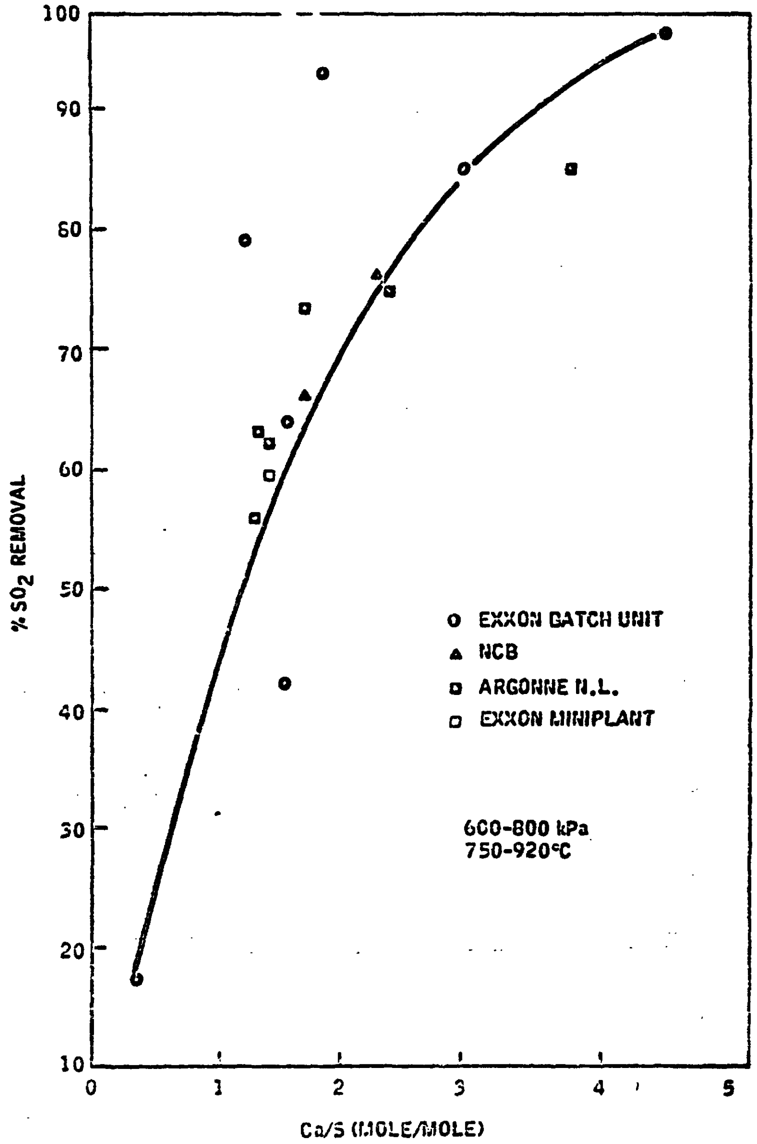


Figure 4.2.2-1

Comparison of SO_2 Removal Results - Limestone Sorbent (Hoke, et al., 1976).

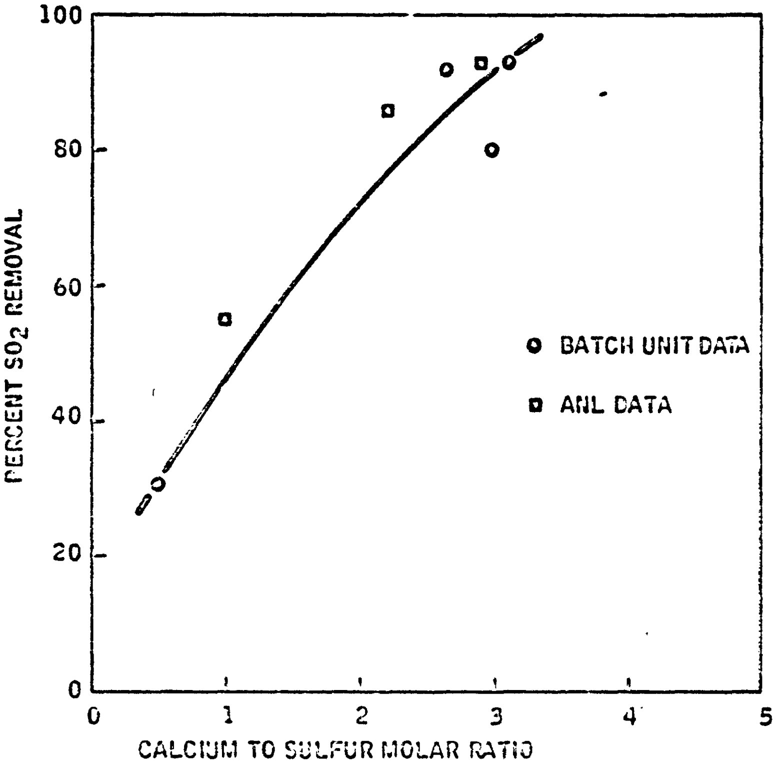


Figure 4.2.2-2

Comparison of SO_2 Emissions from Batch Unit and Argonne N.L. Study Dolomite Sorbent (Hoke, et al., 1976).

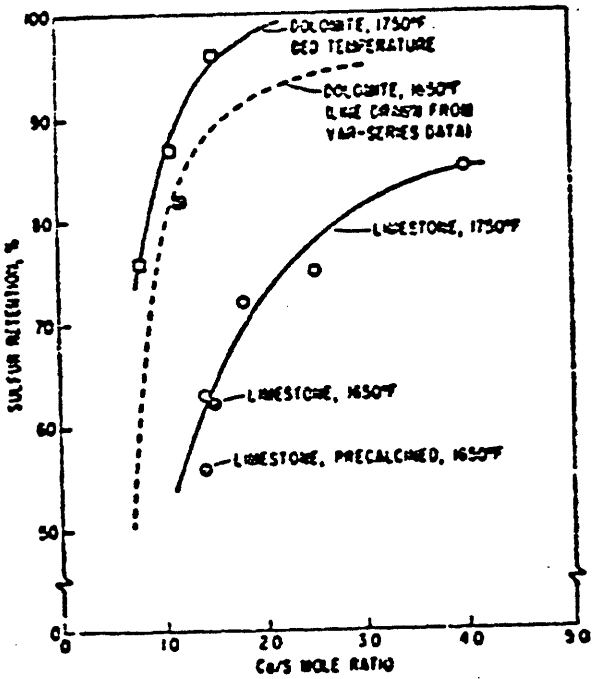


Figure 4.2.2-3

Sulfur Retention Capabilities of Additives Compared Molar Basis

(G.J. Vogel, W.M. Swift, J.C. Montagna, J.F. Lenc and A.A. Jonke, 1975).

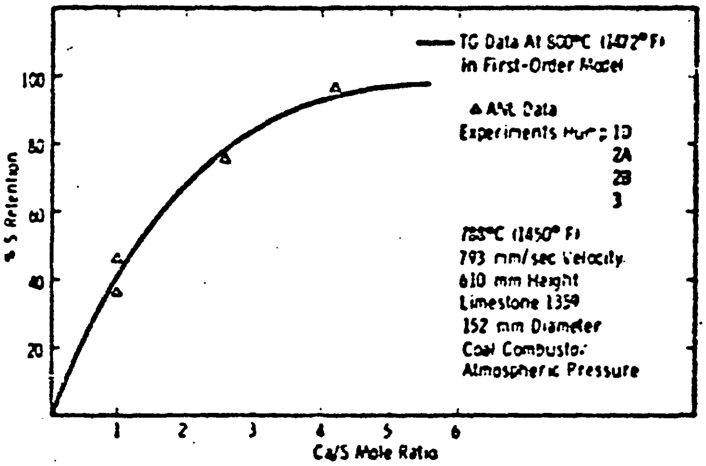


Figure 4.2.2-4

The Effect of Ca/S Mole Ratio on Sulfur Retention.

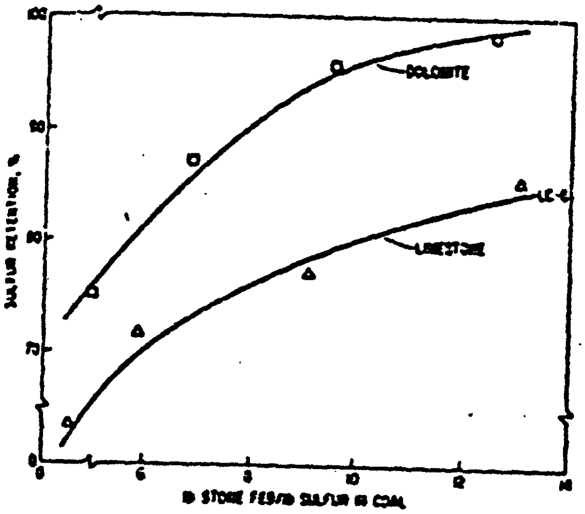


Figure 4.2.2-5

Sulfur Retention Capabilities of Additives Compared Mass Basis.

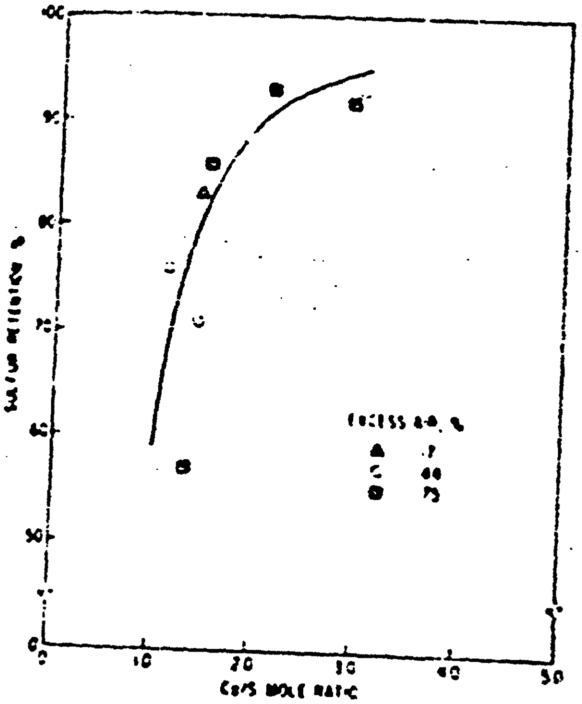


Figure 4.2.2-6

Effect of Excess Combustion Air on Sulfur Retention.

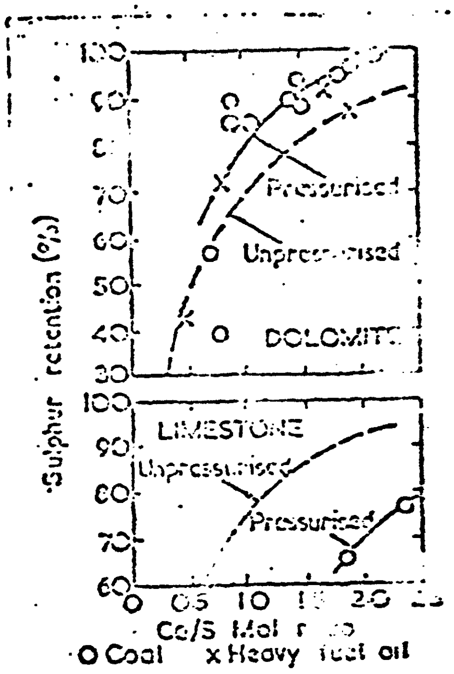


Figure 4.2.2-7

Effect of Ca/S Net Ratio on Sulfur Retention.

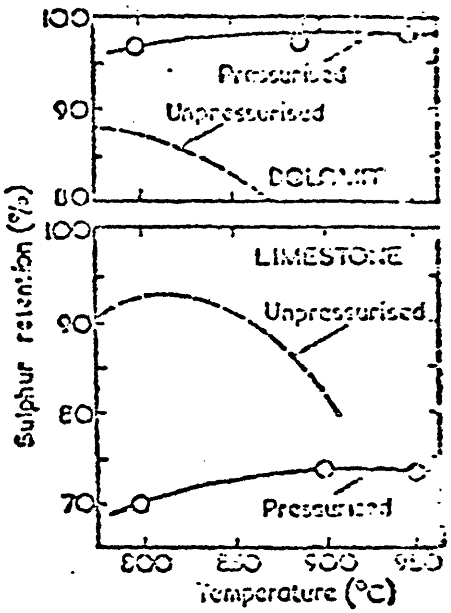


Figure 4.2.2-12

Effect of Temperature on Sulfur Retention.

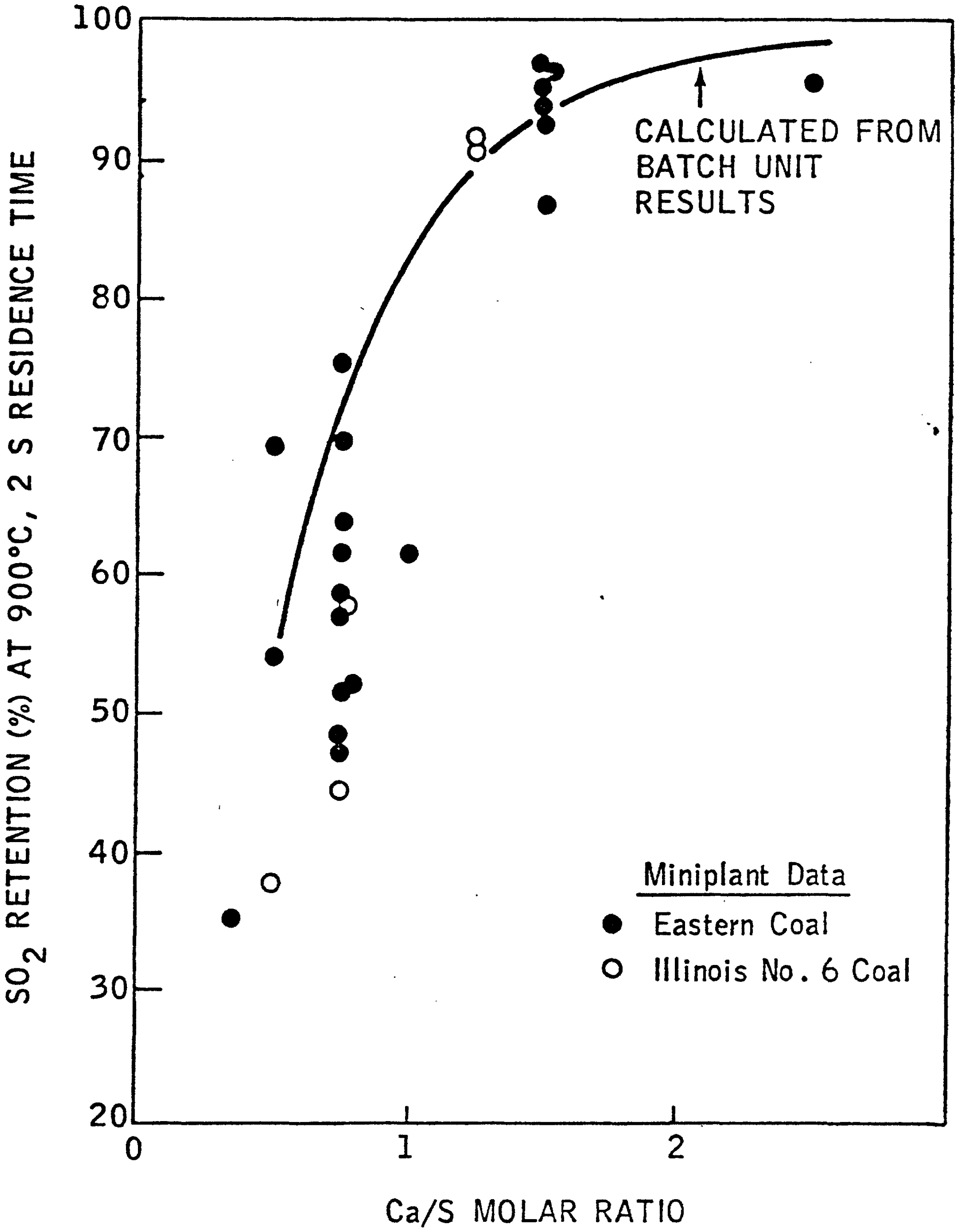


Figure 4.2.2-8

Comparison of Desulfurization Results, Batch and Miniplant Units (Hoke, Nutkis, Kinzler, 1977).

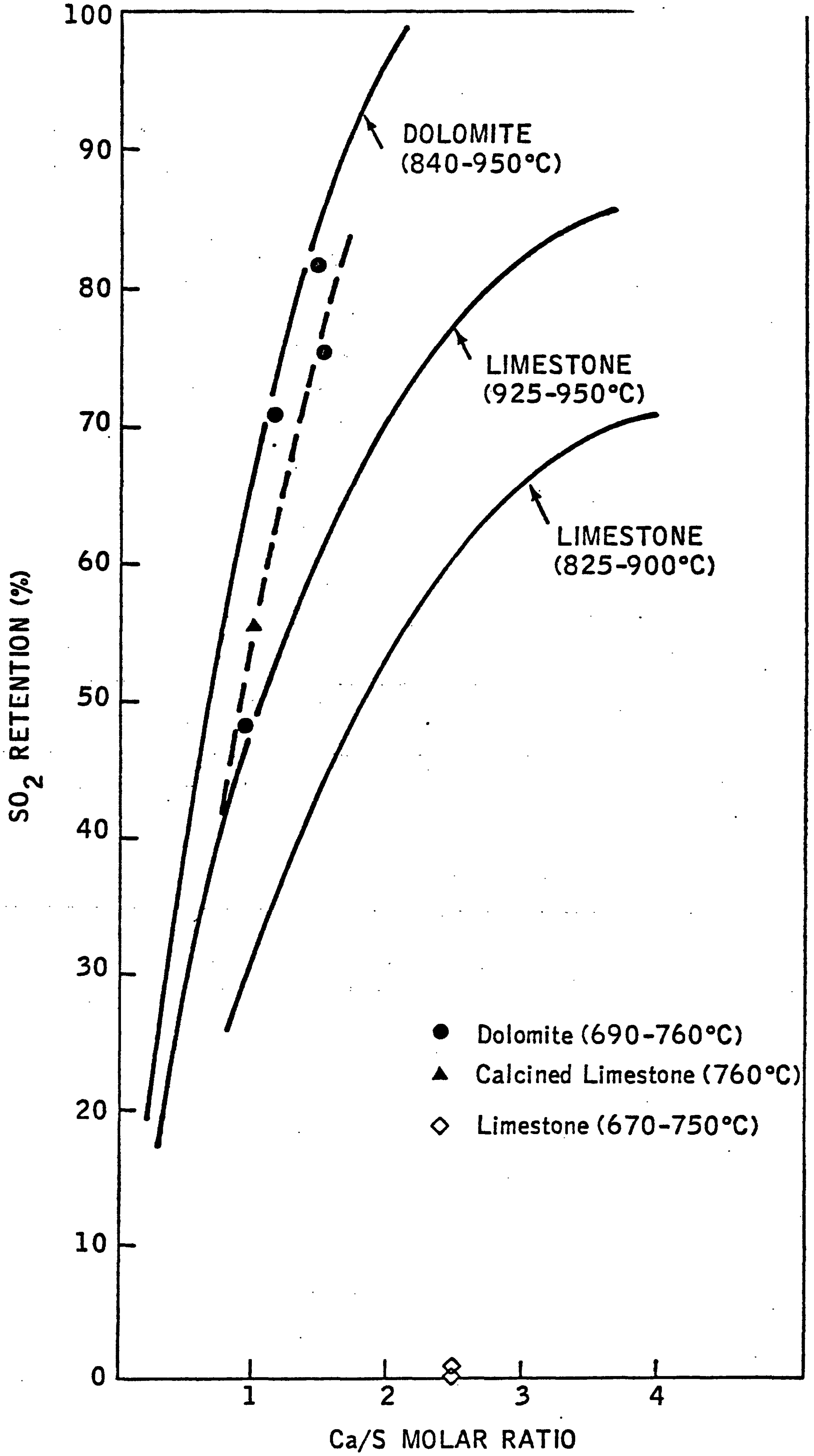


Figure 4.2.2-9

Effect of Low Temperature Operation on SO$_2$ Retention (Hoke, Nutkis, Kinzler, 1977).

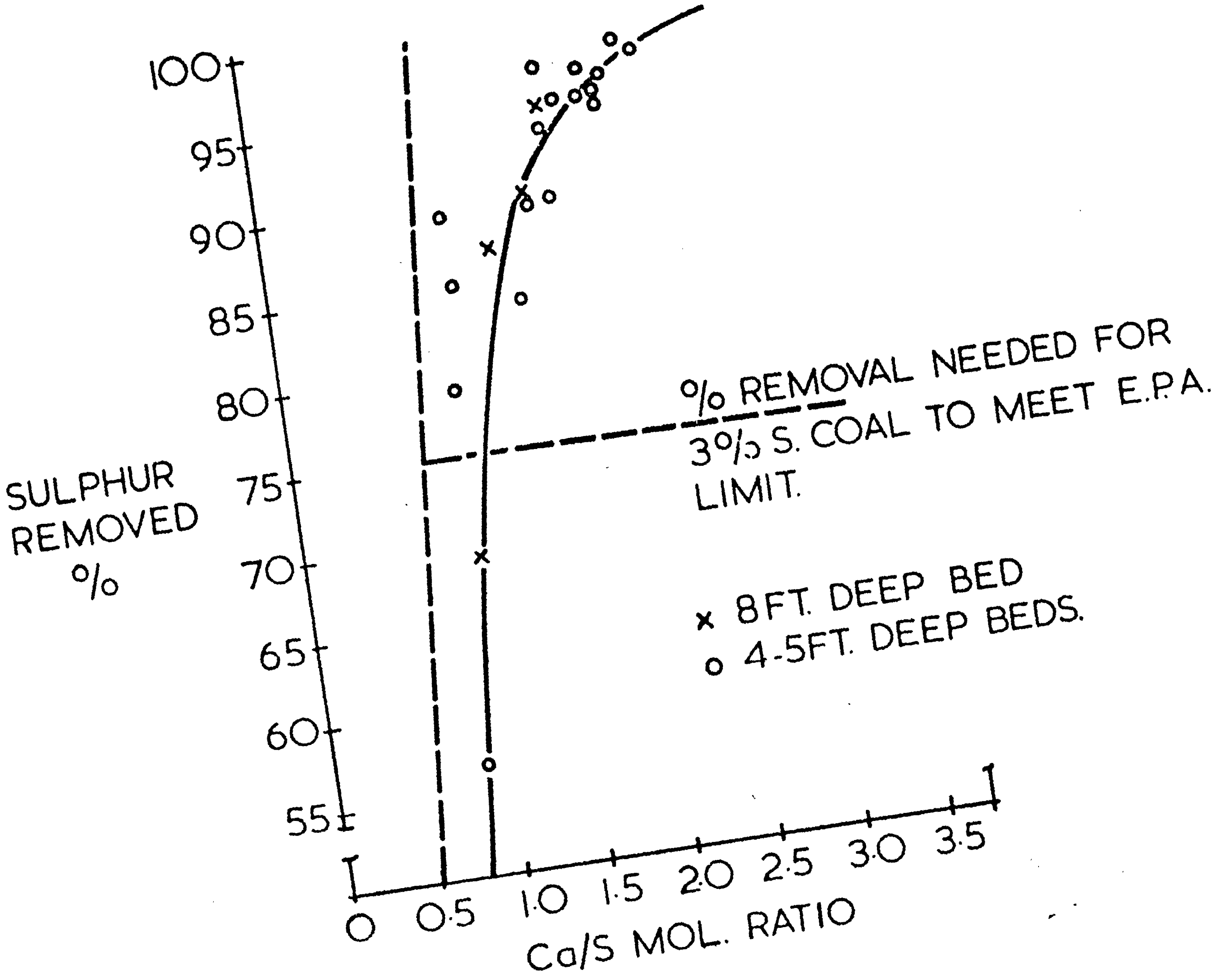


Figure 4.2.2-10

Sulfur Removal V Ca/S Ratio (Hoy, Roberts, 1977).

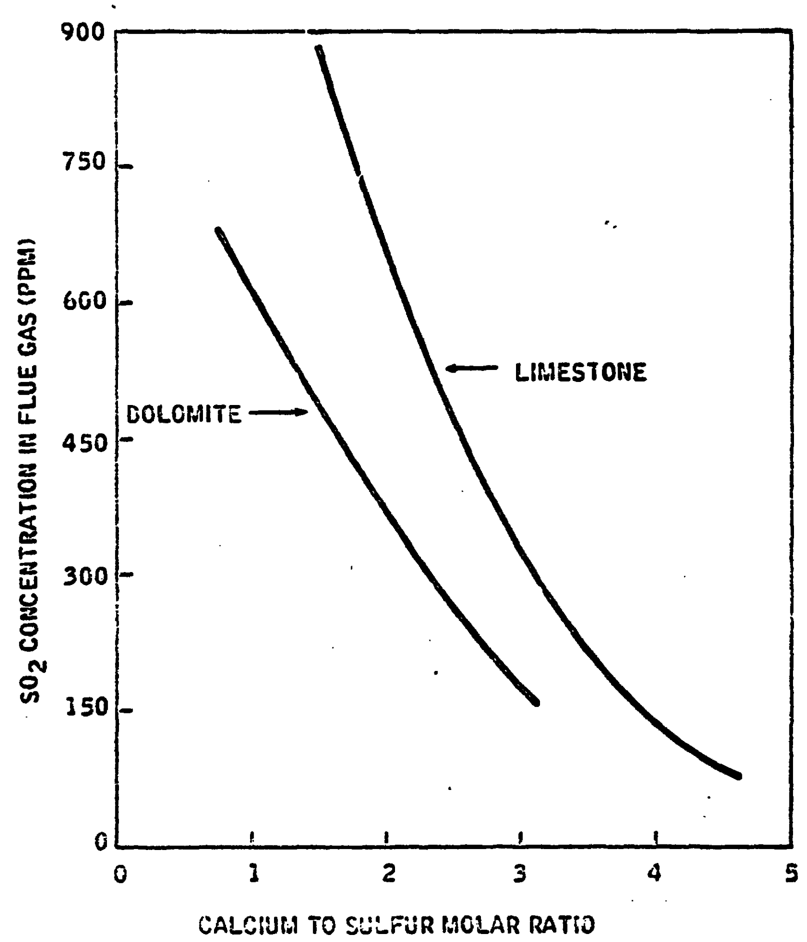


Figure 4.2.2-11

Comparison of SO_2 Emissions from Limestone and Dolomite Sorbents. Batch Unit Data (Hoke, et al., 1976).

Tb = bed temperature in °C, valid in range from 800° to 950°C

V_f = fluidizing velocity in ft/sec, valid in range from 2.0 to 5.0

S_p = parameter for effectiveness of dolomite used, by source

$$N_{so} = S_p \frac{.098}{C_a} [0.04 - \frac{T_b - 800}{7500}][0.95 + \frac{2Vf^4}{[C_a]}]$$

[gsd = 1.10]

This formula has not been fit to a data base, as none currently is available, so although the functional forms may be considered useful, the coefficients are highly speculative.

A smoothed parametric SO_2 model developed at Argonne National Labs is shown in Figure 4.2.2-13. The mathematical fit to this model is:

$$N_{so} = [5 + 43\ C_a^{-3}][2.86 - 0.00128\ T_f]$$
$$x\ [.238\ V_f - .19]$$

where T_f = bed temperature in °F. This model does not, however, fit as well as that previously derived.

Nitrogen Oxides

Nitrogen oxides levels from pressurized FBC's are much lower than those from atmospheric combustors. The reason is apparently that elevated pressure offers an overall more effective NO reduction environment. The limited data available on adiabatic pressurized FBC (that is the type without heat transfer surfaces in the bed and with temperature controlled by large amounts of excess air) show levels higher than the more common design (Keairns, et al., 1975).

Argonne National Laboratory experiments (Nack, et al., 1975) show a sharp drop in NO_x emissions as the pressure moves from 1 to 4 atmospheres, at which point there is a leveling off (see Figure 4.2.2-14). Concentrations ranged from 120 to 270 ppm and correlated with Ca/S ratios, (see Figure 4.2.2-15). Experiments at ESSO have verified the occurrence of an NO and SO_2 reaction. BCURA showed ranges of 70 to 250 ppm. Experiments at Exxon (Hoke, et al., 1976) indicated increasing NO_x levels with increasing excess air, although some of these points have been contradicted by similar tests at CPC (Nack, et al., 1975), (see Figures 4.2.2-16 through -18.

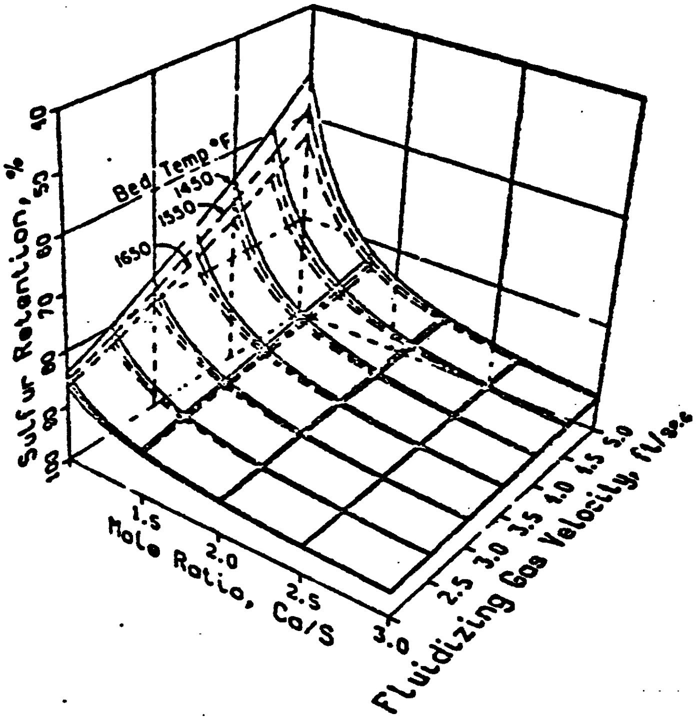


Figure 4.2.2-13

Effect of Bed Temperature, Fluidizing Gas Velocity and Ca/S Mole Ratio on Sulfur Retention in the Bed During Combustion

(G.J. Vogel, W.M. Swift, J.C. Montagna, J.F. Lenc and A.A. Jonke, 1975).

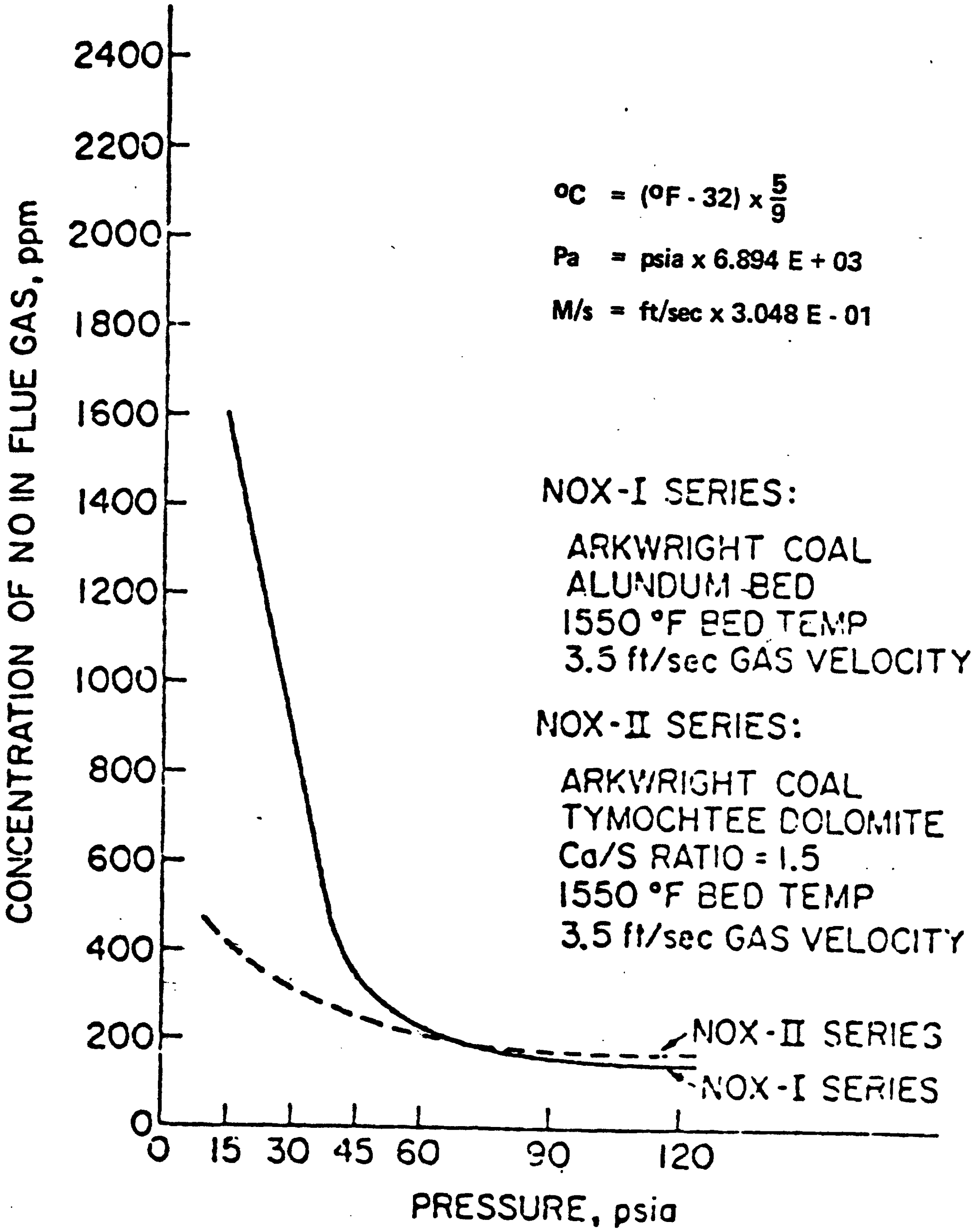


Figure 4.2.2-14

Effect of Pressure on NO with Inert and Dolomitic Bed Materials (Vogel, Swift, Montagna, Lenc, Jonke, 1975).

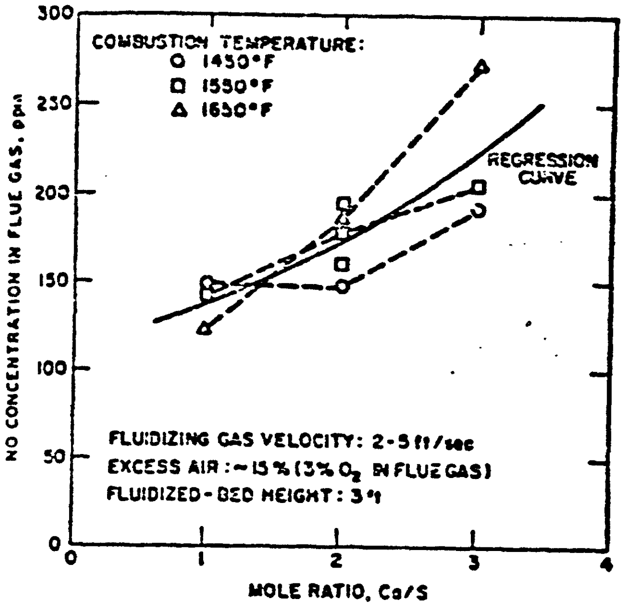
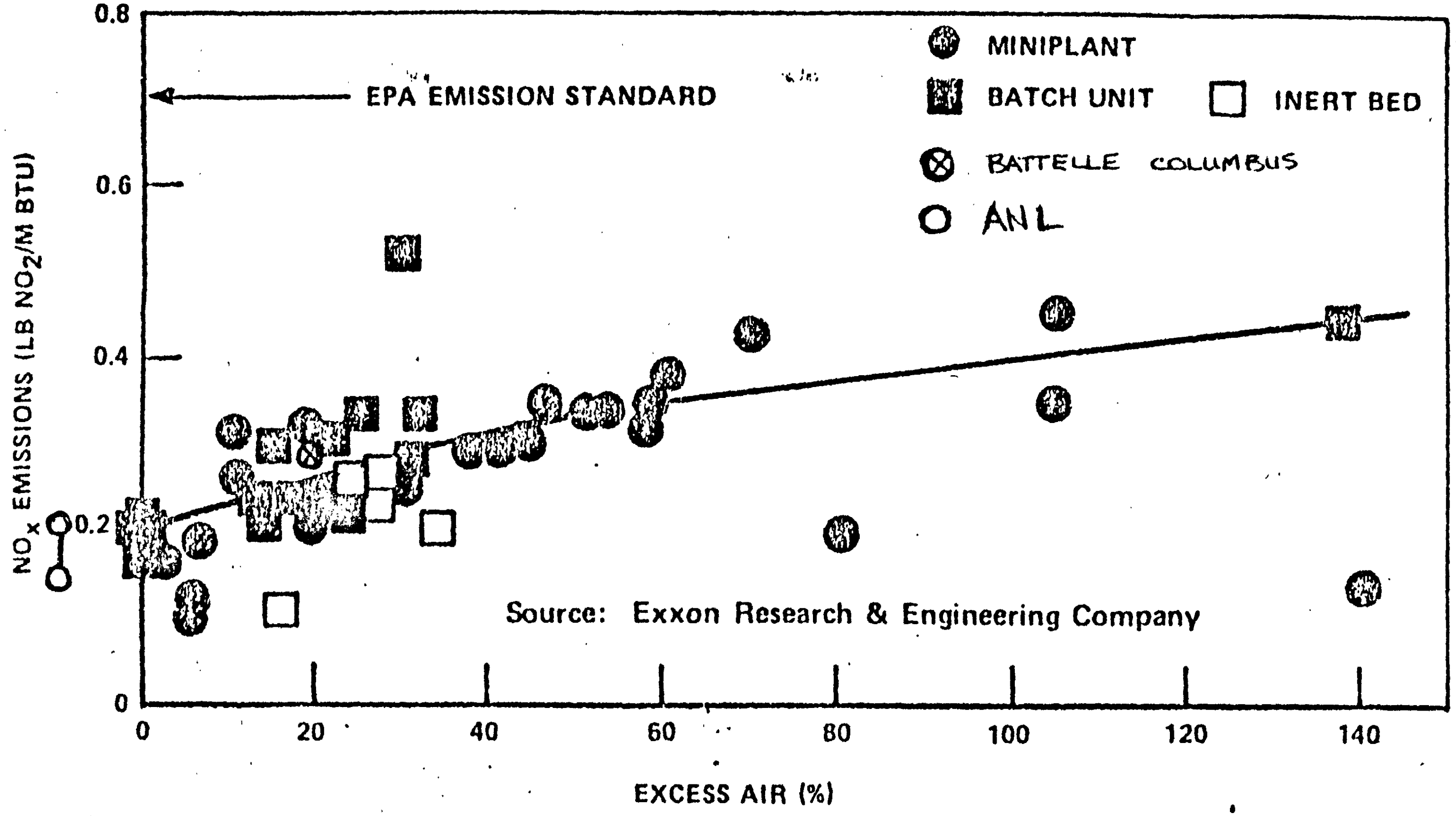


Figure 4.2.2-15

NO Concentration in Flue Gas as a Function of Ca/S Mole Ratio.



Source: Exxon Research & Engineering Company

Figure 4.2.2-16

NO$_x$ Emissions (Battelle-Columbus, 1977).

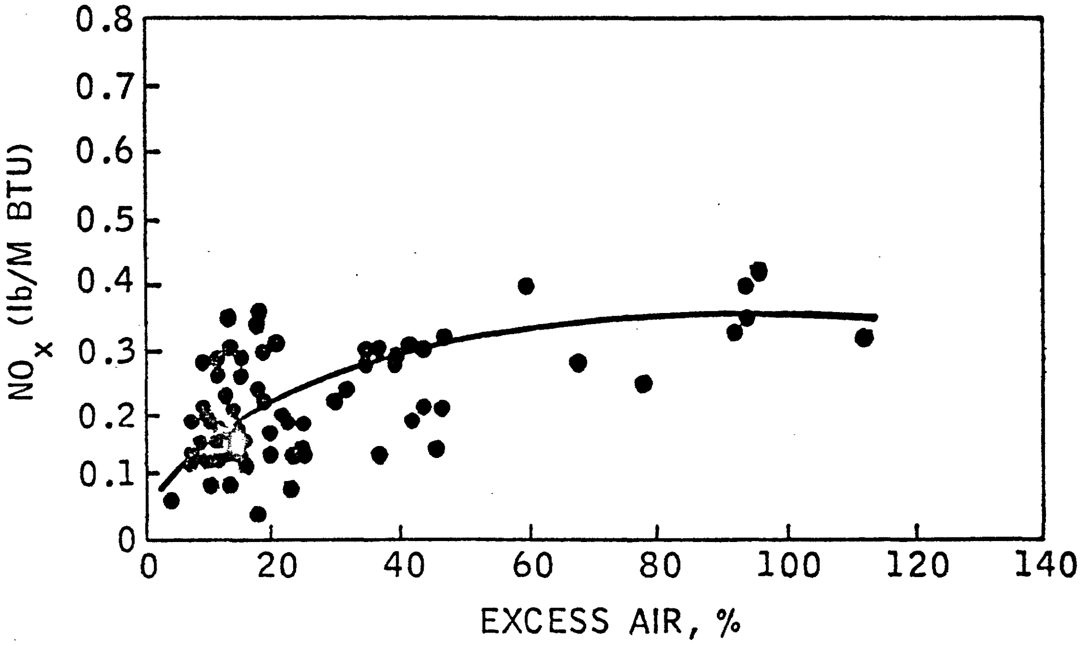


Figure 4.2.2-17

NO_x Emissions (Hoke, Nutkis, Kinzler, 1977).

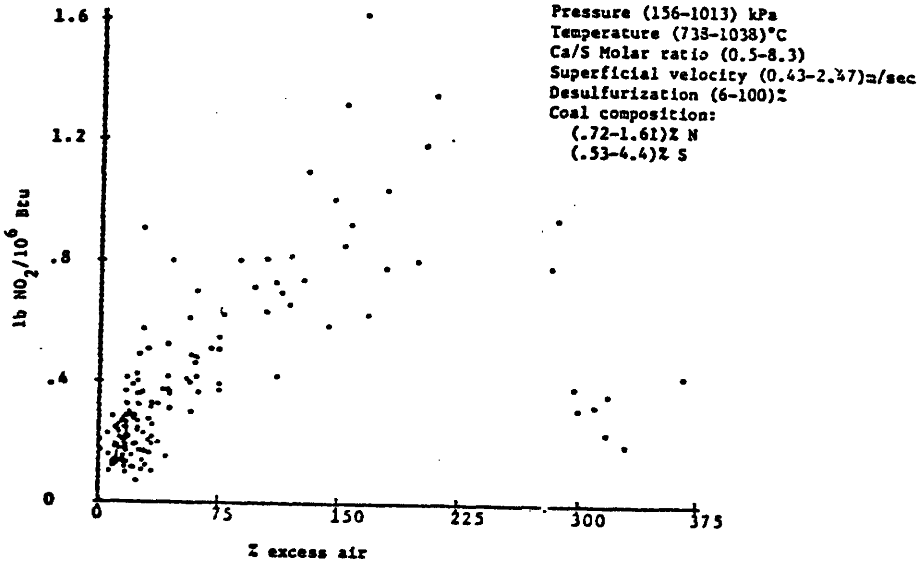


Figure 4.2.2-18

Composite Plot of Pressurized Fluid-Bed Combustion Data of Argonne, Combustion Power, Consolidation Coal, Exxon and NCB (Keairns, et al., 1977).

The correlations of NOx emissions pressurized FBC is:

N_o = NOx emissions in ppm [NO,dry]

N_c = nitrogen in coal in %; valid in range 0.8% to 1.7%

A_e = excess air in %; valid in range 10% to 70%

P = pressure in psia; valid in range 15 to 120psia

T = bed temperature in ^oC; valid in range 625^o to 1000^oC

Ca = calcium to sulfur mole ratio, valid in range 1.0 to 3.0

$$N_o = N_c\,[205 + 9.2A_e][1 - .66 \log_{10} \frac{P}{15})]$$
$$[1.1 -.1(\frac{T - 875}{125})^2] + 40\,[Ca-2.0]$$

[1.31 = gsd]

This equation has not been fit to a data base, so although the functional forms may be useful, the coefficients should not be considered accurate. The addition of fluidizing velocity and other parameters would reduce the uncertainty in this prediction, but parametric experiments indicating the effect of other parameters are not available.

The adiabatic FBC would have NO_x emissions of about 330 ppm (NO,dry) or about 0.4 lb $NO_2/10^6$ BTU input (Keairns, et al., Sept. 1975). This is based upon CPC data and is verified by extrapolations of Exxon and NRDC data. Figure 4.2.2-19 shows excess air requirements of adiabatic combustors, and Figure 4.2.2-18 showed the experimental levels at these levels.

N_o = NO_x emissions in ppm [NO,dry]

N_o = 330

<u>Hydrocarbons and Trace Metals</u>

The only available hydrocarbon data is displayed and fitted with a model in section 4.1.2.3, although this is for the atmospheric pressurized system. The trace metal emissions have been experimentally studied and these models, for the pressurized FBC, are displayed in section 4.1.2.4.

<u>Particulates</u>

As we displayed in section 4.1.2.5 the particulate levels and sizes for a pressurized FBC can be modeled by the empirically derived formula given in that section. For combined cycle configurations it is estimated (Keairns, et al., Sept. 1975) that the constraining factor in particulate levels may well be the permissable erosion and loading of the turbine blades, not the EPA standard. Thus, levels below .1 lb/10^6 BTU are likely if pressurized FBC are to be feasible.

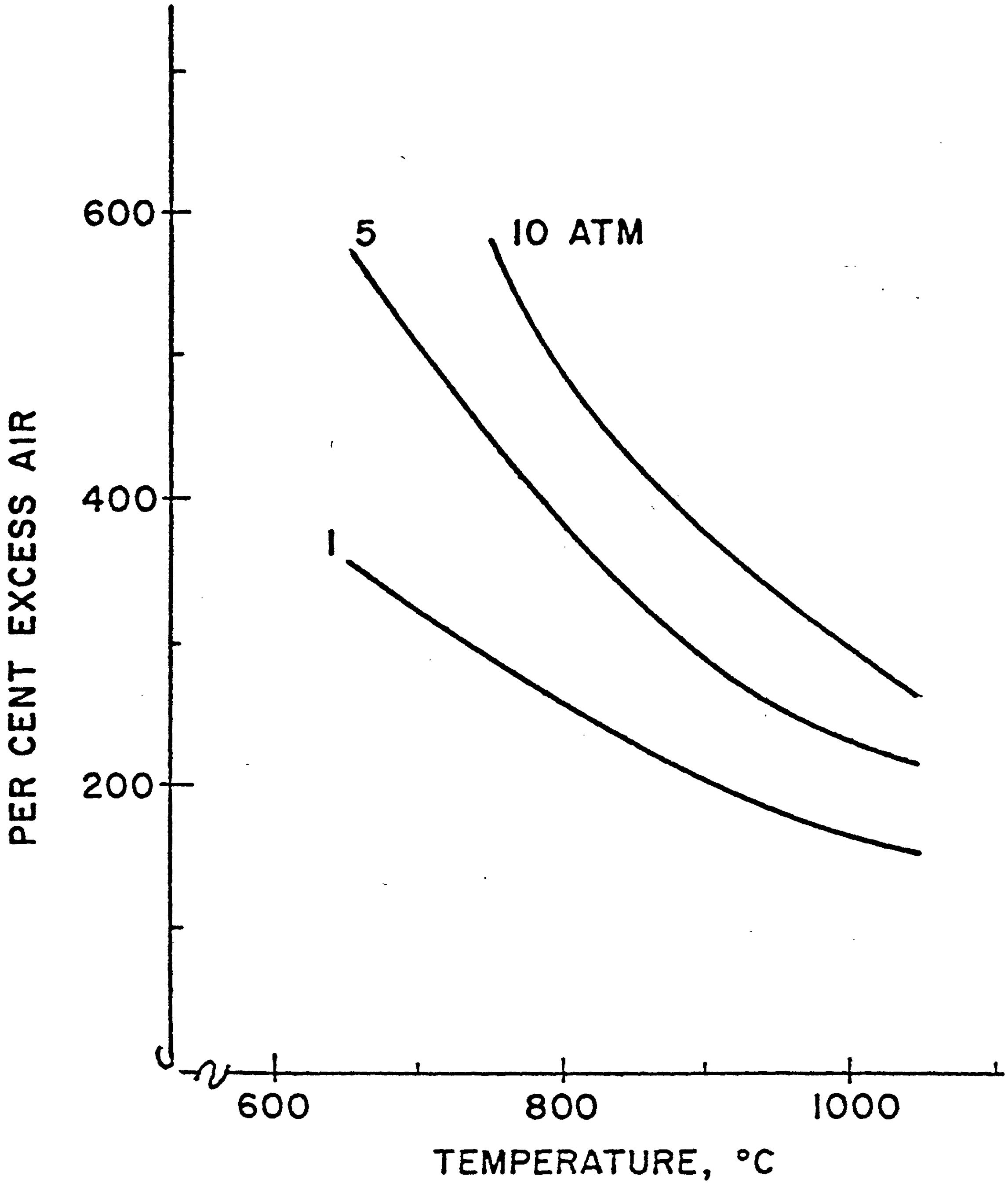


Figure 4.2.2-19

Excess Air Requirements for Adiabatic Combustor (Levy, Chen, 1977).

The only proven "hot-side" control for particulates is a form of cyclone (Strom, et al., Feb. 1976). The best results to date (see Table 4.2.2-1) have come from two cyclones in series after a 6 inch combustor, reducing the loading by .91 to .93 (Vogel, Swift, Montagna, Lenc, Jonke, 1975):

P_c = controlled particulate emissions in lb/10^6 BTU input

P_o = uncontrolled particulate emissions

n_p = efficiency of a particular control configuration

n_p = .91 to .93 for two cyclones in series

n_p = .988 to .996 for two cyclones and a single granular bed filter

n_p = .9999 for two cyclones and two granular filters (Nack, et al., 1977)

$$P_c = (1-n_p)P_o$$

Additional efficiencies are shown in Figure 4.1.2.5-1. It would appear that the problem is easily solved, the two cyclones and one filter translates to .085 to .148 lb/10^6 BTU, with two filters this yields .0017 lb/10^6 BTU. It is, in fact, true that the emission standard is apparently easily met, compared to the requirements of the turbine blades. Westinghouse research as shown in Table 4.2.2-1 displays the severe requirements of the blades on particulate loadings in certain size ranges. If the FBC emissions were in proportion to the acceptable loads at the various sizes, then .11 to .16 lb/10^6 BTU would be the acceptable range (a little above the standard). With the FBC, particulate size distribution as it apparently is, the overall particulate emission may well have to be as low as 0.010 lb/10^6 BTU to meet the turbine requirements (ANL, 1976) [0.0017 from (Nack, et al., 1975) seems to be a one digit misprint]. This would, of course, automatically satisfy the speculated 0.03 lb/10^6 BTU emission standard for 3μm or smaller particulates.

Stating the turbine blade requirements in terms of size versus loadings carries and implicit assumption about the corrosive potential of the particulates. Alkali constituencies of coal ashes vary to such an extent that the size versus loading requirements will have to be made with specific coals in mind (Strom, et al., 1976) (Burns & Rec, 1977). The major portion of this corrosion/erosion research, as outlined in section 3.1, is yet to be completed.

Carbon Monoxide

As in the atmospheric FBC the pressurized FBC shows a very large, but still insignificant, range of CO concentrations; levels between ≈0. in (Nutkis, 1975), 0.02 lb/10^6 BTU in (General Electric, 1976) and 0.93 lb/10^6 BTU (Shaw and Cain, 1977) or 170 ppm (ANL, 1976), 150 to 650 ppm averaging 400 ppm for the Exxon batch unit, 50 to 150 ppm in the Exxon Miniplant, (Hoke, 1975). These figures range from 1/2 to 1/12 of the atmospheric FBC

Table 4.2.2-1

Particulate Emissions Projected from Particulate Control System Options (Keairns, et al., 1977).

	1 Two Cyclones in Series	2 Three Cyclones in Series	3 Two Cyclones with Granular Bed
	gr/scf	gr/scf	gr/scf
Particle Size (Micron)			
0-2	0.24	0.16	0.007
2-4	0.52	0.019	0.0009
4-6	0.10	0.0016	0.00003
6-10	0.004	0.0004	----
10+	0.0022	0.0002	----
TOTAL	0.3082	0.1812	0.0078

ASSUMPTIONS:

1. Dust loading from boiler – 10gr/scf - particle size analysis as shown in reference (1)
2. Cyclones are high efficiency multiple cyclone units--efficiency taken from Jackson (1963) (14)
3. Granular bed efficiency based on Westinghouse Laboratory Data.

Table 4.2.2-2

Proposed Dust Loading Distribution Acceptable for Gas Turbine Feed (Archer, et al., 1971).

Ave. particle dia. μm	Wt. % in Size range	Concentrations gr/SCF
< 1	76.8	.08-.12
1-2	16.6	.02-.03
2-3	4.7	.005-.008
3-4	1.6	.002-.003
4-5	.2	.0002-.0003
5-6	.1	.0001-.0002
6-7	0	0

levels. The reason for the decline with pressure is not definitely decided, but the equation (Strom, et al., 1976)

$$2NO + 2CO = 2CO_2 + N_2$$

provides a reasonable explanation. Experimental data show a nearly constant value of $CO + CO_2$ concentrations. Although, this reaction is by itself very slow, it is catalyzed by CaO or dolomite, and inhibited by CO_2 levels higher than 17%.

Experiments at Exxon have shown a considerable variation, a factor of four, due to unsteadiness of coal feed (Hoke, 1975). This source also claims a temperature dependent term, but without published backup information. In the absence of other information the same type of model as was used in the atmospheric CO prediction is used here, scaled to reflect the lower values:

E_{co} = emissions of CO from pressurized FBC in ppm [dry]

C_f = nondimensional parameter for regularity of coal feed

$C_f = 1.0$ for unsteady batch feed

$C_f = 0.25$ for very smooth constant flow

P = pressure, in atm

$$E_{co} = C_f\,[1.10 - .099P]\ E_{co}\ (\text{atmospheric})$$

[gsd = 2.43]

4.2.3 Other Air Emissions

The kinds and amounts of these emissions would be nearly identical to those listed in section 4.1.3. There would be some scaling necessary due to slightly different distributions of waste heat and different energy efficiencies. Experimental data is limited to the conventional coal-fired power plant experiences.

4.3 Air Emissions from Potassium Topping FBC

Although no experimental data are available for this advanced energy cycle, it is useful to relate the analytic speculations of the manner in which emissions would be scaled in comparison with the other FBC technologies. These scalings are primarily due to differences in efficiencies and changed output configurations.

4.3.1 Air Balance

Published analytic models of the materials balances are limited to those displayed in section 3.3.4. These can be useful for determining new values of gaseous, liquid, and solid emissions.

4.3.2 Flue Gas Emissions

Emissions from a potassium topping cycle using a pressurized FBC heat source are essentially the same as the pressurized FBC emissions--at least for HC and particulates there has been little change predicted from analytic studies.

Table 4.3.2-1 Summary of Analytic Projections for Potassium Topping FBC Emissions

Emission	$lb/10^6$ Btu	10^{-4} lb/kwhr
SO_2	0.692[c], 0.723[a], 1.188[b]	53.3[c], 54.-74.[a], 83.3[b]
NO_x	0.0[a], 0.164[c], 0.193[b]	0.0[a], 12.5[c], 13.2[b]
HC	0.0[a,c]	0.0[a,c]
CO	0.0[a], 0.020[c], 0.096-0.379[b]	0.0[a], 1.5[c], 6.6-26.3[b]
Particulates	<0.006[b], 0.037-0.042[a], 0.100[c]	0.07[b], 3.1-3.5[a], 7.7[c]

a: (Deegan, 1976)

b: (Shaw and Cain, 1977)

c: (General Electric, 1976)

It should be noted that there are no experimental data in this area, so these results are speculative. Minor differences have been perceived for SO_x and NO_x emissions as described in the following text.

Sulfur Oxides

Design studies have shown a 0.6% increase in sulfur oxide emissions from the pressurized FBC case (General Electric, 1976), (Shaw and Cain, 1977). The same formula is, therefore, used with this slight scaling. The per Btu input effects are changed by:

N_{so} [pot top] = 1.006 N_{so} [press FBC]

The mechanism supposely responsible for this effect is not explained. Considering the (speculated) substantial increase in efficiency of the potassium cycle with about 18% (Jahnig and Shaw, 1977) less sulfur entering the system about 18% less would be emitted in the flue gases.

Trace Metals

In the absence of speculation to the contrary, it perhaps could be assumed that trace metals would experience a similarly reduced level of emission, that is, in proportion to the ratio of cycle efficiencies.

Nitrogen Oxides

Based on design studies the potassium topping cycle shows 8% higher NO_x emissions than pressurized FBC's in (General Electric, 1976) and 25% lower emissions in (Shaw and Cain, 1977).

Any increase would be counterintuitive, considering the 11% decrease in use of fuel. The scaled down formula as for pressurized FBC is thus assumed:

N_o = NO_x emissions in ppm [NO, dry]

N_c = nitrogen in coal in %; valid in range 0.8% to 1.7%

A_e = excess in air in %; valid in range 10% to 70%

P = pressure in psia; valid in range 15 to 120 psia

T = bed temperature in °C; valid in range 625° to 1000°C assuming vertical coils

Ca = calcium to sulfur rates, valid in range from 1.0 to 3.0

$$N_o = 0.75\ N_c\ [205 + 9.2A_e]\ [1-.66 \log_{10} \frac{P}{15}]\ x$$

$$[1.1 - .1\ (\frac{T-875}{125})^2] + 40\ [Ca - 2.0]$$

It would be possible on the basis of (Beer, 1977) to separate the fuel and atmospheric sources of nitrogen to get a more exact formula. In the absence of any experimental data, this effort does not seem to be warranted.

Carbon Monoxide

The analytic study (General Electric, 1976) projects no difference between potassium topping pressurized FBC, while (Shaw and Cain, 1977) projects a 20% reduction in the topping cycle's emissions. In light of these comparative results, a slightly reduced (perhaps 10%) version of the pressurized FBC may be useful if a preliminary analytic model is desired. The geometric standard deviation would have to be adjusted upward accordingly.

4.3.3 Other Air Emissions

Aside from the same concerns outlined in section 4.1.3 the liquid metal topping cycle has an additional concern. Any failure in the liquid metal cycle would probably result in the emission of hazardous metal hydroxides through the flue. Special control and containment procedures would probably be required to limit these emissions.

4.4 Emissions to Water

It is generally believed that heat and other aquatic emissions "at power plants equipped with fluidized-bed coal combustors can be accomplished by standard industrial practices such as are now in use in conventional coal-fired utility plants" (Argonne Nat. Lab, ANL-ECT-1, 1976). Since there are no published experimental data for fluidized bed combustor facility water emissions, the information on conventional coal-fired facilities is presented in Table 4.4-1.

Table 4.4-1 Water Emissions of Conventional Power Plants (Teknekron, 1977)

	Central Region Controlled	Central Region Uncontrolled	National Controlled	National Uncontrolled
Acids	0	21.9	0	19.9
Bases	Unknown	Unknown	Unknown	Unknown
Other Dissolved Solids	0	41.1	0	37.2
Suspended Solids	37.8	98.1	5.14	53.0
Chemical Oxygen Demand	0	0	0	0

All values in tons/10^6 BTU input.

In (CEQ, 1975) is the result that pressurized FBC have 18.2 tons/10^{12} BTU total dissolved solids and .003 tons/10^{12} Btu organics. Other than this the best that can be done to make the Table 4.4-1 values applicable to the various fluidized bed cycles is to scale these numbers by plant efficiencies.

Other water emissions data, created by various analytic studies is presented in Table 4.4-2. The potential additional concern of water contamination by the liquid metal cycle accidental releases is nowhere addressed quantitatively. In addition, there is considerable potential (Strom, *et al.*, 1976) for highly acidic water emissions due to leaching of the landfilled ash and sorbent (see Table 4.4-3). Quantities of CaO, on the order of 60% of the spent additive, would be the prime concern (see Table 4.4-4), although CaS forming H_2S would also occur. Leaching of trace metals from fluidized bed residues is another potential concern (see Table 4.4-5). The thixotropic nature of scrubber sludge, if caused by Ca SO_3, would not be a concern in fluidized bed residues.

4.5 Solid Effluents

Solid waste from FBC cycles is composed of several types of materials (see Tables 4.5-1 and -2). Identification of levels of wastes is a fairly straight forward analytic procedure, depending to a certain extent upon design and operating parameters (see Table 4.5-3).

TABLE 4.4-2 Water Use in FBC Cycles (given by references, since there are obviously discrepancies in designs and definitions).

Total Water[c,d]	Conventional Furnance	Atmospheric FBC	Pressurized FBC	Potass Top FBC
gals/Kw-hr	-	1.208-.905	.973-.837	.839-.653
-cooling water[c,d]	-	1.035-.757	.822-.694	.662-.530
-condensate makeup[c,d]	-	.01033-.01027	.00851-.00693	.00697-.00494
-waste handling slurry[c,d]	-	.1063-.0899	.0985-.0887	.1097-.0797
-scrubber waste water[c,d]	-	.05619-.04753	.05275-.04751	.06012-.04369
Total Water[b], gals/kwhr	-	0.611	0.548	0.414
Cooling Evaporation[b] gals/kw hr	-	0.453	0.405	0.306
Cooling Blowdown[b], gals/kw hr	-	0.140	0.127	0.096
Plant General Use[b], gals/kw hr	-	0.018	0.016	0.012
Condensate Makeup[b], gals/kw hr	-	0.0	0.0	0.0
Water Discharge[b], lb/kw hr	-	1.32	1.19	0.90
Makeup Water[a] tons/day/MWe	32.7	31.1	23.8	17.0
Cooling Water[a] tons/day/MWe	2864	-	2260	1611

Note: Extreme cases in (c) and (d) were omitted
conversion factors of 96 x gal/kwhr = tons/day/MWe
and 12 x lb/kwhr = tons/day/MWe do not reconcile the differences in numbers.

a: (Jahnig and Shaw, 1977)
b: (General Electric, 1976)
c: (Wolfe, 1976)
d: (Deegan, 1976)

Table 4.4-3

Environmental Impact of Spent Sorbent from Fluidized Bed Coal Combustion Process (EPA, 1977).

Sample	Process	Sorbent	Environmental Parameters						
			Heat Release	Trace Metal	Total Dissolved Solids	Sulfide	pH	Sulfate	Calcium
Spent Sorbent (bed material)	Pressurized System once - through	Limestone	ND <0. 2°C		▩		▩ pH = 12.5	▨	▩
"	Pressurized System once - through	Dolomite	ND <0. 2°C		▨		▩ pH = 11.9	▨	▨
"	Atmospheric System once - through	Limestone	ND <0. 2°C		▩		▩ pH = 12.3	▨	▩
Flyash (fines of sorbent/ash)	Pressurized System once - through	Limestone	ND <0. 2°C		▨		▩ pH 8 to 11	▨	▨
Mixture of Spent Bed Sorbent and Flyash	Pressurized System once - through	Limestone	ND <0. 2°C		▨		▩ pH 8 to 10	▨	▨
Gypsum	Natural	–	ND <0. 2°C		▨		pH = 7.4	▨	▨

▩ Do Not Meet Either The Drinking Water or Gypsum Leachate Criteria

▨ Pass Gypsum Leachate Criteria But Not Drinking Water Standards

☐ Pass Both Drinking Water and Gypsum Leachate Criteria

* ND <0.2 C indicates not detected with 0.2 C being the minimum detection limit.

Source: Westinghouse Research Laboratory

Table 4.4-4

Leaching of Bed Material from the Pressurized Combustor (NRDC, no date).

Sample	A	B	C	D
Analysis of Samples				
CaO wt %	31.3	30.2	30.0	43.4
MgO wt %	21.6	20.9	22.1	1.76
S wt %	9.0	8.3	11.80	9.60
CO_2 wt %	10.0	11.0	0.33	0.07
Analysis of Solutions				
pH	10.5	10.8	11.1	11.6
Ca mg/l	107	101	163	224
Mg mg/l	2.0	1.9	0.2	0.2
SO_3 mg/l	237	219	217	201
Proportion Dissolved				
Ca %	47	46	76	72
Mg %	2	2	0.2	0.2
SO_3 %	100	100	73	83

Sample A	Taken during NCB/APCO Test 2.5 Coal: Pittsburgh; Additive: U.S. Dolomite 1337 Temperature 1465°F; Pressure 3.5 atm
Sample B	Taken during NCB/APCO Test 3.2 Coal: Pittsubrgh; Additive: U.S. Dolomite 1337 Temperature 1480°F; Pressure 5.0 atm
Sample C	Taken after Test 3 (Present work) Coal: Illinois; Additive: U.S. Dolomite 1337 Temperature 1655°F; Pressure 5.6 atm
Sample D	Taken after Test 4 (Present work) Coal: Illinois; Additive: U.K. Limestone Temperature 1740°F; Pressure 5.9 atm

Table 4.4-5

Trace Metals in Ash, FGD Sludge Pond, Liquors/Supernatants, and FBC Ash and Spent Stone (Except pH, Concentrations in PPM) (EPA, 1977).

	Ash Pond		FGD Sludge Pond		FGD Sludge Liquors		FBC Ash Leachates		FBC Spent Stone Leachates		EPA Proposed Standards Public Water Supply Intake
	Mean	High	Mean	High	Mean	High	Mean	High	Mean	High	
pH	10.9[(a)]	12.5	8.9	9.7	7.4	9	11.4	12.2	12.16	12.5	5 to 9
Antimony	0.017	0.33	0.021	0.035	-	-	-	-	<0.3	<0.3	-
Arsenic	<0.036	0.084	<0.011	0.03	<0.068	0.20	0.68	2.5	5.0	5.0	0.1
Barium	<8.24	40.	<0.866	2.0	-	-	-	-	-	-	-
Beryllium	0.0011	0.003	0.002	0.002	<0.041	0.18	-	-	<0.01	<0.01	-
Boron	3.66	16.9	3.286	6.3	-	-	0.39	0.61	0.37	0.83	1.0
Cadmium	<0.0031	<0.01	<0.0012	0.002	0.038	0.10	0.0025	0.01	<0.1	<0.2	0.01
Chromium	<0.267	1.0	<0.0043	0.011	<0.087	0.21	ND	<0.1	<0.1	<0.1	0.05
Copper	<0.031	0.092	<0.027	0.045	<0.070	0.20	-	-	<0.1	<0.1	1.0
Fluorine	4.88	17.3	15.93	31.5	-	-	-	-	-	-	-
Germanium	<0.01	0.01	<0.013	0.02	-	-	-	-	-	-	-
Mercury	0.0033	0.015	0.008	0.001	<0.045	0.12	3.8	6.2	8.8	13.2	0.002
Lead	0.0088	0.024	0.005	0.0061	0.072	0.18	1.3	2.5	<0.92	2.4	0.05
Manganese	<0.002	<0.002	<0.002	<0.002	-	-	-	-	<0.05	<0.05	-
Molybdenum	0.169	0.69	0.066	0.075	-	-	9.7	17	<5.8	12	-
Nickel	<0.037	<0.05	<0.05	<0.05	-	-	-	-	<0.1	<0.1	-
Selenium	<0.10	0.47	0.023	0.045	<0.75	2.5	-	-	-	-	0.01
Vanadium	<0.12	<0.2	<0.1000	<0.1	-	-	-	-	<0.05	<0.05	-
Zinc	<0.055	<0.19	<0.0270	<0.052	0.14	0.30	0.028	0.08	<0.4	<0.4	5.0
Samples	5		5		5		4		4		

(a) Underline indicates value higher than EPA and WHO standards.

Sources: Data compiled by Battelle from information supplied by Aerospace Corporation, R. Stone and Company, Westinghouse Research Laboratory, and EPA.

Table 4.5-1 Composition of Solid Waste Material (General Electric, 1976)

	Atmospheric FBC	Pressurized FBC	Potassium Top. FBC
Ash	31%	42%	42%
Calcium Sulfate	42%	26%	26%
Unreacted Lime	24%	13%	13%
Magnesium Oxide	0%	16%	16%
Carbon	3%	4%	4%

Table 4.5-2

Examples of Typical Coal and Sorbent Input and Output Compositions

(Major Constituents) for FBC Combustors (Weight Percent) (EPA, 1977).

Compound	Coal, Pittsburgh #8(1)	Limestone, #1359-Grove(2)	Dolomite, #1337-Pfizer(1)	Coal Ash(1)	Atmospheric FBC Waste(3)		Pressurized FBC Waste(3)	
					Limestone, #1359	Dolomite, #1337	Limestone, #1359	Dolomite, #1337
$CaSO_4$	--	--	--	--	43.7	31.5	60.6	64.1
CaO	--	3.8	28.9	1.9	54.0	30.2	37.4	6.6
$CaCO_3$	--	92.3	--	--	--	--	--	--
MgO	--	0.3	22.9	0.6	(a)	36.7	(a)	22.9
Fe_2O_3	--	0.1	0.2	27.3	(a)	(a)	(a)	(a)
SiO_2	--	0.5	0.5	45.3	(a)	(a)	(a)	(a)
Al_2O_3	--	--	--	21.2	(a)	(a)	(a)	(a)
C	71.2	--	--	--	--	--	--	--
S	4.3	--	--	--	(b)	(b)	(b)	(b)
H_2	5.1	--	--	--	--	--	--	--
O_2	6.3	--	--	--	--	--	--	--
N_2	1.3	--	--	--	--	--	--	--
H_2O	3.3	--	47.4(c)	--	--	--	--	--
Ash	8.5	--	--	--	--	--	--	--
Other Trace Elements & Compounds	--	--	--	--	2.3	1.6	2.0	1.2

Sources:
- (1) Battelle's Columbus Laboratories, open literature.
- (2) Exxon Research and Engineering.
- (3) Westinghouse Research Laboratories.

(a) Included in other.
(b) Included in $CaSO_4$ value.
(c) $H_2O + CO_2$

TABLE 4.5-3 Solid Wastes and Materials Use in FBC Cycles

	Conventional Furnance	Atmospheric FBC	Pressurized FBC	Potass. Top FBC
Coal[c,d], lb/kwhr	-	.936-.792	.899-.740	1.421-.728
Sorbent[c,d], lb/kwhr	-	.495-.419	.476-.392	.530-.385
Coal[a], lb/kwhr	.776	.778	.715	.582
Sorbent[a], lb/kwhr	.186-.207	.264	.186	.152
Total Waste Solids[a], lb/kwhr	.294	.353	.236-.259	.192
Coal[b], lb/kwhr	-	.884	.808	.714
Sorbent[b], lb/kwhr	-	.227	.372	.326
Spent Solids Conglomerate[b] lb/kwhr	-	.292	.342	.302

Note: Extreme cases in (c) and (d) were omitted conversion factors of 12 x lb/kwhr = tons/MWe-day

a: (Jahnig and Shaw, 1977)
b: (General Electric, 1976)
c: (Wolfe, 1976)
d: (Deegan, 1976)

The most difficult effect to model is the regeneration process. Regenerated sorbent is less reactive than fresh sorbent, thus the calcium to sulfur ratio must be higher for a given desired level of sulfur reduction, in fact $R = 0.77\ N^{-0.5}$ where R is the utilization efficiency and N is the number of cycles was the best fit in an experimental study of this phenomenon (Zielke, _et al._, 1970). This effect will somewhat offset the effect of the average number of reuses of sorbent before it is disposed. This number will be determined by the particular regeneration scheme (see Figure 4.5-1), as well as the operating parameters chosen for that scheme. The following analytic models are for solid wastes from any of the FBC cycles:

A_s = ash output, tons/hour

S_o = spent sorbent output, tons/hour

S_c = sulfur content of coal, %

C_a = calcium to sulfur mole ratio used in bed

I_p = percent inerts in additive

A_c = ash content of coal %

B_c = btu content of coal btu/lb

M_s = megawatt size of facility

E_f = efficiency of facility %

R_n = average number of uses of sorbent, 1.0 for no regeneration; up to 7.0 for regeneration

$$A_s = 1.706 \times 10^3\ A_c\ M_s\ B_c^{-1}\ E_f^{-1}$$

$$S_o = 4.73 \times 10^3\ S_c\ Ca\ Ms\ B_c^{-1}\ E_f^{-1}(1-.01I_p)^{-1}\ R_n^{-1}$$

The range of values of ash output for the ECAS liquid metal topping cycles (Deegan, 1976) was .033 to .045 tons/MWhr. Spent sorbent outputs ranged from 0.182 to 0.188 tons/MWhr.

Although some specific mass balances are presented in sections 3.3.2, 3.3.3, and 3.3.4, some general balance computations are possible using Figures 4.5-2 and -3, and the following definitions:

X = fraction excess air

Y = amount of elutriated char expressed as a fraction by weight of the coal fed to the combustion zone

Z = fraction of sulfur in coal appearing in stack gas

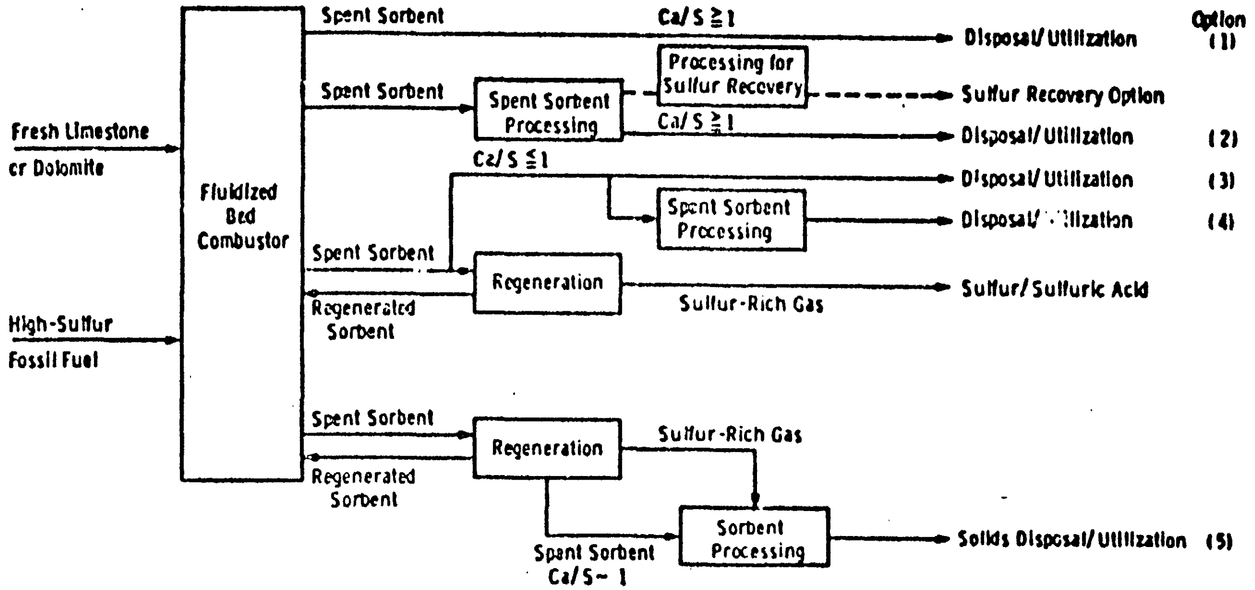


Figure 4.5-1

Sulfur Removal System Process Alternatives (Keairns, et al., 1975).

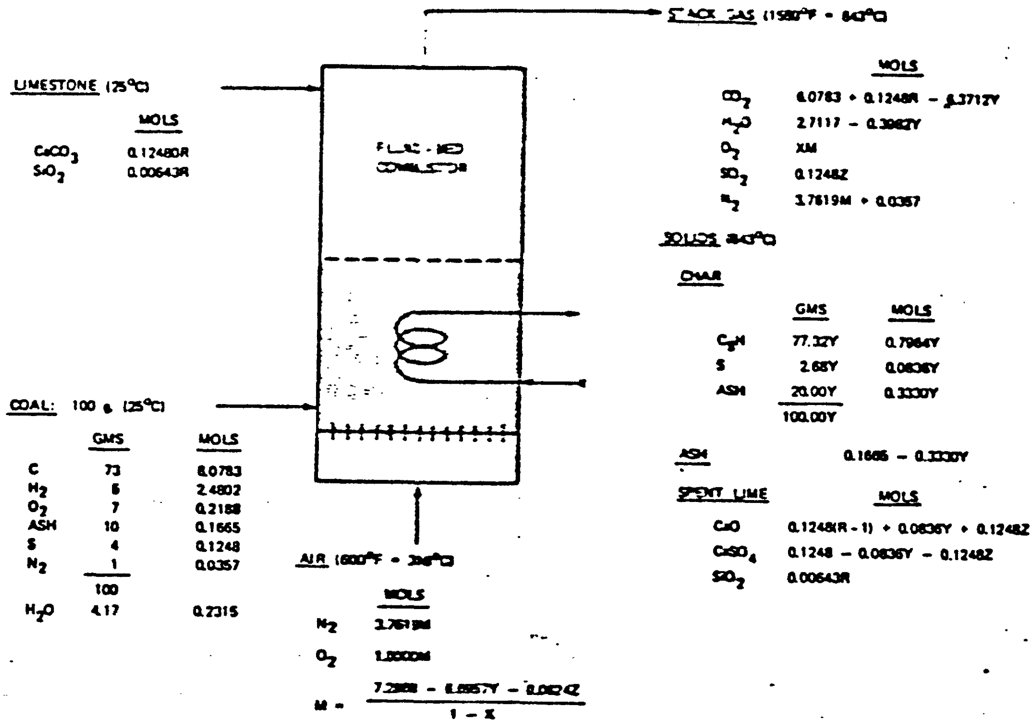


Figure 4.5-2

General Mass Balance for Fluidized Bed Combustor (Strom, <u>et al</u>., 1976).

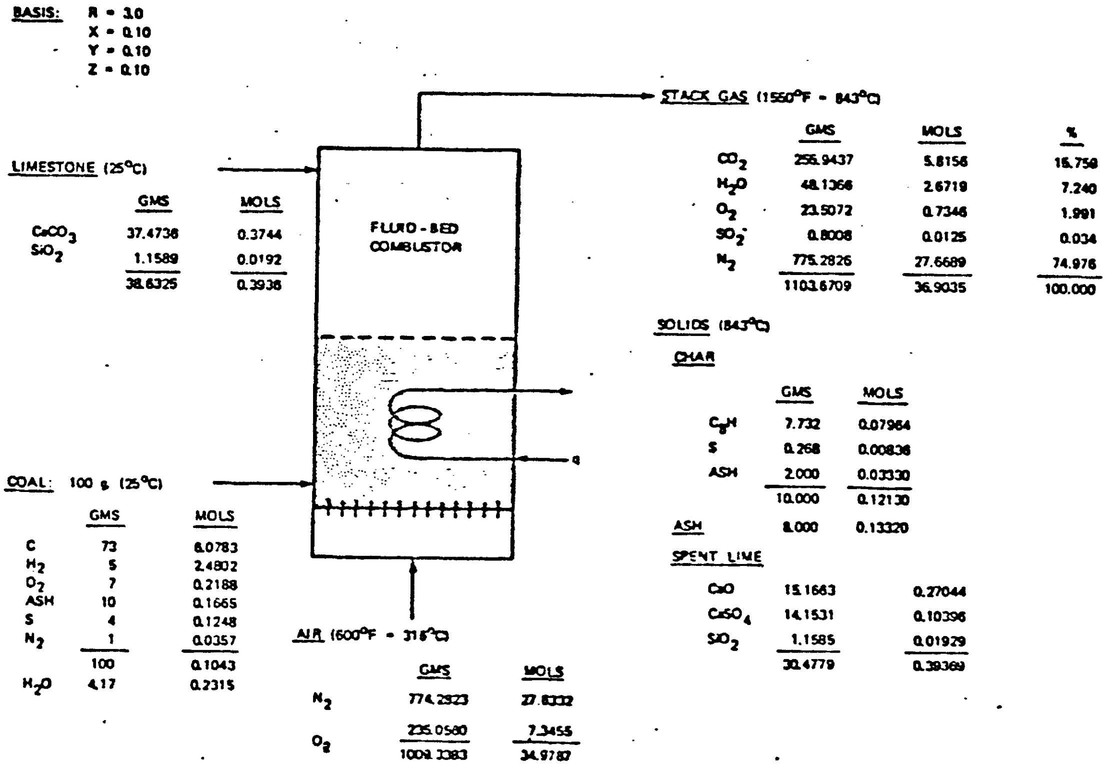


Figure 4.5-3

Specific Mass Balance for Fluidized Bed Combustor (Strom, <u>et al</u>., 1976).

R = mole ratio of Ca in limestone to S in coal

A_o = area of bed cross section, ft^2

V_o = superficial gas velocity, ft/sec

W_s = coal feed rate, tons/hr

Q_1 = heat transferred to cooling surface, Btu/hr

Q_2 = heat release from combustion of coal, Btu/hr

θ = approximate nominal retention time of solids in bed, hrs.

then from (Strom, et al., 1976)

$$A_o = 294.7\ W_s\ V_o^{-1}$$

$$Q_1 = 1.67 \times 10^7\ W_s$$

$$Q_2 = 2.38 \times 10^7\ W_s$$

$$Q_1/A_o = 5.66 \times 10^4\ V_o$$

$$Q_2/A_o = 8.08 \times 10^4 V_o$$

$$\theta = 83.0\ H(1-e)\ V_o^{-1}$$

where e appears to be the basis of the natural log system [although a sample computation shows e = .70 in (Strom, et al., 1976)].

4.6 Noise, Odor, and Aesthetics

Effects of noise pollution on the general public can generally be effectively dealt with by proper siting of the facility. Occupational hazards in the form of measurable hearing impairment have been observed in most power plant employees. Potential solutions to these problems are the same as those outlined for conventional power plants (Jannig and Shaw, 1976).

The primary odors from FBC are likely to come from SO_2 collections during stagnant atmospheric episodes. These and the other emission and ash pond smells will be very similar to conventional power plant odors. There is, however, the potential for much larger quantities of H_2S from the FBC cycles, and this could pose a distinct odor problem.

Aesthetics has been a problem for conventional power plants and is likely to receive about the same magnitude of concern for the FBC cycles. The fact that the pressurized units will be smaller in size is one potential advantage, otherwise the conventional types of aesthetic solutions are likely to be considered: various types of shielding, clustering, enclosing and squaring off structures, imaginative painting of larger structures, and simulation of high-rise apartments.

4.7 Other Fuel Cycle Effects

There are undesirable environmental impacts that result from all of the various processes within the total fuel cycle of fluidized bed coal combustors: mining, transportation, handling, storage, and preparation of coal and sorbent stone. To the extent that these effects have been examined, (Argonne National Lab, ANL-ECT-1, 1976) and (CEQ, 1975) for example, these problems are presumed to be of the same type and the same magnitude as those currently controlled by "standard industrial practices such as now in use at conventional coal-fired utility plants" (Argonne National Lab, ANL-ECT-1, section 6.3.6, 1976). Of course, with the FBC cycles requiring significantly less coal per MWe, they will thus have proportionately less impact than the conventional systems. The best data base for computing these fuel cycle effects is the EMDB at Brookhaven National Labs. This data base contains information about the common pollutants but is deficient concerning the various trace elements and different kinds of hydrocarbons. Another deficiency, not only of this data base, but of the available knowledge, is the lack of quantified occupational hazards. Table 4.7-1 is a list of the types of hazards that are likely to be of concern for FBC's.

Table 4.7-1 Combustion hazards in FBC systems and preventive steps, from (Rao, 1975, pp. 352-7)

COMPONENT	SAFETY HAZARD	CAUSE	EFFECT	PREVENTIVE STEPS	
				IN DESIGN	IN OPERATION
COAL PREPARATION Coal crusher	Fire Explosion	Ignition due to mechanical friction, and mechanical impact.	Propagation of fire and explosion through ducts to other components.	Provide pressure relief valves, allow proper separation from other components and subsystems, design to operate with flow velocity greater than flame speed. Consider installing a rupture disc.	Use less reactive carrier gas, maintain coal/air ratio beyond combustion limits, maintain proper flow velocity to prevent flame propagation upstream. Monitor O_2 concentration, temperature and pressure.
Coal dryer	Fire Explosion	Ignition of coal fines and volatile gases evolving from coal due to heating.	Propagation of fire through ducts and development of detonation.	Provide pressure relief valves, allow proper separation from other components.	Same as above.
COAL STORAGE Silos Bunkers Bins	Fire Explosion	Ignition of coal dust due to accumulation of combustible gases and coal fines, due to local temperature buildup.	Damage will be extensive, affecting the total plant and surroundings.	Provide ventilation and air circulation, fire detection and fire fighting equipment, sounding alarm, and relief valves, allow proper separation from the plant. Provide safeguards to protect from natural calamities (for example, lightning arrester).	Minimize coal dust accumulation by periodic removal of coal fines. Monitor temperature at "critical" locations to detect smouldering fires and flames at an early stage.
COAL TRANSPORT Conveyors (Mechanical)	Fire	Ignition	Propagation of fire to other components and subsystems.	Allow proper physical separation, provide fire detection and fire fighting equipment, and sounding alarm.	Monitor temperature at critical locations, minimize accumulation of coal fines, establish operating conditions and procedures and operate according to the set procedures.
Conveyors (Pneumatic	Fire Explosion	Ignition due to mechanical friction and heating, and due to electrostatic charge buildup and flame propagation.	Propagation of fire and development of detonation. Propagation of hazard to other subsystems and components.	Provide physical barriers and ample separation, design to keep a minimum flow velocity, greater than flame velocity, provide good grounding, and safety valves.	Monitor temperature at critical locations, use less reactive carrier gas, maintain coal/air ratio beyond combustion limits, minimize leaking to the surrounding atmosphere.
	Rupture	Explosion or mechanical failure due to erosion.	Leakage of coal fines into the surrounding air can result in secondary fires and explosions.	Design with adequate factor of safety.	Periodic check for mechanical integrity.
Ducts	Rupture	Same as above.	Same as above.	Same as above.	Same as above.
	Fire Explosion	Ignition due to mechanical friction, heating, electrostatic charge buildup and flame propagation.	Propagation of flame and development of detonation. Hazard propagation to other subsystems.	Provide physical barriers and ample separation, good grounding and safety valves.	Use less reactive carrier gas, minimize leaking to the surrounding atmosphere.

Table 4.7-1 (continued)

COMPONENT	SAFETY HAZARD	CAUSE	EFFECT	PREVENTIVE STEPS	
				IN DESIGN	IN OPERATION
COAL FEEDERS					
Pneumatic feeders (for coal, coal fines and carbon-containing fly ash)	Fire Explosion	Ignition due to heat feedback, electrostatic charge buildup, and flash back of flame. Coal/salt feeder plugging due to hygroscopic salt and caking coal can induce flame propagation upstream.	Flame propagation and explosion can spread to other subsystems and components.	Provide means to unplug, design to maintain a minimum flow rate exceeding flame speed. Provide vents and safety valves, rupture disc.	Monitor temperature and pressure at critical locations, maintain the designed minimum flow rate, use less reactive carrier gas.
Mechanical feeders (gravity feeders, screw feeders)	Fire Explosion	Ignition due to heat feedback, mechanical friction, heating and pressurization due to plugging.	Same as above.	Provide means to unplug, provide safety valves and adequate controls.	Monitor temperature at critical locations.
AIR SUPPLY					
Air compressor Air blower	Failure	Mechanical or electrical.	Incomplete combustion of coal yields explosive mixture of combustible gas.	Provide adequate controls, and stand-by source for air supply	Monitor gas composition at critical locations.
	Explosion	Accumulation of lubricating oil.	Initiation of secondary fire and explosion hazards.	Same as above.	Prevent accumulation of oil.
WATER SUPPLY					
Water pumps	Failure	Mechanical or electrical.	Heat exchange tubes and water walls get over heated and rupture pressurizing combustor.	Provide stand-by water supply source, adequate controls, including pressure relief valves.	Monitor heat exchanger wall temperature at critical locations.
FB COMBUSTOR					
Combustor vessel	Rupture Explosion	Excessive stresses due to thermal and dynamic stresses, pressure induced stress, thermal shock, fatigue, and accumulation of combustible gases in some modes of operation; run away combustion.	Destruction of boiler, fire and explosion propagation to other parts of the plant.	Provide adequate pressure relief and controls, sounding alarm and fire fighting equipment, and physical barrier between the boiler and operating personnel.	Monitor operating conditions, maintain near normal design conditions; coal, air and limestone feed rates need adequate control.
Air distributor	Failure	Thermal stresses, fatigue, buckling.	Changes in fluidization characteristics may result in bed temperature excursion in some regions.	Allow for thermal expansion.	Monitor temperature of bed material at different locations. Periodic check.
Start-up burner	Fire Explosion	Flame propagation upstream due to heat feedback, and development of detonation.	Flame propagation upstream to other subsystems and components, explosion of boiler components.	Provide flame arrester, and pressure, relief, and adequate controls.	Establish safe operating procedures, follow the operating procedures, monitor critical variables of operation, and quality of fluidization.

Table 4.7-1 (continued)

COMPONENT	SAFETY HAZARD	CAUSE	EFFECT	PREVENTIVE STEPS	
				IN DESIGN	IN OPERATION
HEAT EXCHANGERS					
Immersed tubes and tube bundles	Failure	Erosion, chemical and stress corrosion, thermal and dynamic stresses, vibration induced stress, abnormal temperature, thermal shock, fatigue, and operation in reducing atmosphere.	Pressurization of combustor by steam, production of combustible gas and/or quenching of fire in the combustor.	Provide adequate controls for fuel and air throughputs, pressure relief valves, adequate design should include consideration of tube failures as a possibility, provide vibration dampers.	Monitor combustion gas temperature and composition, identify range for safe operation, establish and follow safe operating procedures.
BED MATERIAL TRANSPORT					
Withdrawal	Failure Rupture	Runaway temperature due to excess unburned carbon, erosion and corrosion, plugging.	Hot bed material leaking from transport tube can cause secondary fires and explosions.	Provide fire fighting equipment, adequate controls for fuel and bed material throughputs, provide means to unplug.	Monitor carbon content of bed material. Periodic check of structural soundness.
PARTICLE SEPARATORS					
Cyclones, inertial separators	Fire Explosion	Accumulation of carbon containing fly ash, combustible gas, and plugging.	Fire and explosion propagation and failure of ducting.	Provide adequate controls.	Establish safe operative procedures, monitor critical variables and check periodically.
Granular filters	Failure	Static and dynamic stresses, thermal stress, fatigue, erosion, runaway temperature	Hot granular material cause secondary fires.	Provide adequate controls, design should consider static and dynamic stress, thermal expansion, fatigue, erosion.	Monitor critical variables, check periodically, operate according to established safe operation procedure.
	Fire Explosion	Accumulation of carbon containing fly ash, and combustible gas.	Same as above.	Provide adequate controls, pressure relief valves.	Same as above.
Bag filters	Fire Explosion	Accumulation of carbon containing fly ash and combustible gas. Ignition due to electrostatic charge buildup.	Hazard propagation by secondary fires and explosions.	Choose adequate materials for bag filters, provide adequate controls.	Monitor critical variables, and prevent accumulation of combustible gases and carbon content by periodic removal.
Electrostatic precipitators	Fire Explosion	Accumulation of carbon containing fly ash and combustible gas.	Hazard propagation by secondary fires and explosions.	Provide adequate controls.	Monitor critical variables, prevent accumulation of combustible gases and carbon content by periodic removal.
AIR PRE-HEATERS					
Air pre-heaters (Ljungstrom type)	Fire Explosion	Carbon containing fly ash, CO, UHC in hot combustion gas mixes with air resulting in a high potential for fire and explosion.	Hazard propagation by secondary fires and explosions.	Avoid using these types of pre-heaters, provide flame arresters	Minimize leaking of air into combustion gases with better seals.

5. Conclusions

This study of mass and energy balances has been aimed at the development of empirical correlation models of the energy efficiencies and environmental emissions of various fluidized bed combustion technologies. These empirical correlations consist of probabilistic models that have been fit to published experimental data. In several instances, there have been comparisons of these empirical models with available analytic models. Extensive bibliographic research and identification of on-going projects was also completed as a portion of this task.

From the standpoint of recommending future work in this area it would be desirable to have an updated data base of fluidized bed emissions and efficiency information. An on-going project at MIT is concerned with putting together just such a data base. There are several advantages to having such data bases available for all of the advanced energy technologies:

(1) they can be used as design tools to search for attractive configurations and operating parameters, particularly those unexpected synergistic effects that could be identified and exploited;

(2) they can be a ready source of latest information on the performance of that energy cycle;

(3) analytic models can be systematically tested against such a data base to evaluate the gap between theoretical and experimental information; and finally,

(4) they can be used to systematically identify and quantify the need for key pieces of information that are now inadequately known.

This final objective is perhaps the most important in that it could be a mechanism for developing R & D strategies. The process involved in developing the R & D priorities begins with the use of probabilistic empirical models to define probabilistic data on economic, efficiency, and emission performance. This type of data can be compared for alternative energy cycles to develop ratings of the relative attractiveness of those alternatives. It may be that the data is too uncertain to allow for necessary decisions between alternatives in which case R & D efforts can be aimed directly at the key pieces of information needed to reduce the uncertainties. In addition, the risk of potential problems in the economic, efficiency, and emission areas can be quantified. The relative attractiveness of the various energy cycles can also be used to set priorities on R & D projects that would increase the chance for technological feasibility of those energy cycles. In the fluidized bed technologies, some of the areas which are highlighted (because they contribute the greatest uncertainties in the probabilistic models) include, in order of importance as perceived during the work of this project:

(1) particulate removal to achieve gas-turbine reliability and long life (in pressurized units);

(2) up-to-date economic data and projections of the FBC retrofit potential of conventional boilers;

(3) combustion efficiencies;

(4) coal and sorbent feed continuity;

(5) boiler tube material and heat transfer information;

(6) turndown, load following, combustion transients and instabilities;

(7) trace metal control;

(8) reductions in solid waste amounts and data effectiveness of disposal schemes;

(9) hydrocarbon control; and

(10) sulfur oxide control predictions due to sorbent and coal characteristics and design configuration variations.

All of these areas of uncertainty must be investigated with due regard to the consequences of scale-up to commercial sizes.

6. References and Bibliography

Most of this bibliography is from the source (Strom, et al., 1976) with a number of additions. A very large, but untyped, bibliography is available for a reproduction charge, hard copy or microfiche: Gruhl, J. and N. Gruhl, 1977, "Fluidized Bed Combustors - An Informal Bibliography", MIT Energy Laboratory, Cambridge, MA 02139, September 1977.

This list of references is primarily from those listed in (Strom, et al., 1976). Additional references have been selected and spliced into that bibliography with the principal criteria for selection being (1) relevance to this reports' topics and (2) most recent citations. These selections of additional references were made from an extensive (1000 source) list generated in the course of this report and from three computerized literature searches complied at Exxon Research Engineering Company in Linden, N.J. by Karen Landsberg.

T. A. Afaneseva and others, Kinetics of the Aggregation of Particles of a Fluidized Bed, Izbk. Dokl. Nauch.-Tekh. Konf. Invanof. Khim-Tekhncl. Inst., 1973, pp. 40-42.

V. G. Ainshtein, Heat Transfer Between a Fluidized Bed and a Surface, Int. Chem. Engr., January 1966, Vol. 6, No. 1.

E. K. Akopov, Reversible Adiagonal System of Sodium and Potassium Chlorides and Sulphates, Zhur Obshchei Khim, Vol. 24.

C. W. Albright, Coal Carbonization Process, U. S. Patent 3,337,417, August 22, 1967.

P. G. Alfredson, Behaviour of Pulsed Fluidised Beds - Part I: Bed Expansion, Trans. Instn. Chem. Engrs., 1973, Vol. 51.

P. G. Alfredson, Behaviour of Pulsed Fluidised Beds - Part II: Bed Contraction, Trans. Instn. Chem. Engrs., 1973, Vol. 51.

American Institute of Chemical Engineering, Third Internationa Heat Transfer Conference, August 7-12, 1966, Papers 113-151 - Volume IV.

L. J. Anastasia, Pollution Control Capabilities of Fluidized-Bed Combustion, Proceedings of Second International Conference on Fluidized-Bed Combustion, October 4-7, 1970 (U.S. Environmental Protection Agency).

Anastasia, L.J., et al., International Conference on Fluidized Bed Combustion, 2nd Proc., U.S. Environmental Protection Agency, 1970.

Anon., Better Theory for Fluid Bed Design, New Scientist, July 14, 1966, Vol. 31, No. 85.

Anon., A Big Leap Forward for Ecology, Industrial Gas, February 1971.

Anon., Breakthrough in Coal Combustion, Heat. Vent. Engr., June 1969, Vol. 42, No. 503, pp. 626-628.

Anon., British Coal Research - Significant Breakthrough for Coal with Fluid-Bed Combustion, Colliery Guardian, March 1969, Vol. 217, pp. 151-152.

Anon., Coal-Burning Fluidized-Bed Combustion System, Coal Res. CSIRO, April 1968, No. 34, pp. 2-5.

Anon., A Coal-Burning Fluidized-Bed Combustion System, Journal of Fuel and Heat Technology, September 1968.

Anon., Commercial Breakthrough Likely in Fluidised Bed Boiler, Electrical Review, March 15, 1974, Vol. 194, No. 4, pp. 233-234.

Anon., Cost Assessment for Large Fluid Bed Boilers, Electrical Review, Lond., January 29, 1971, Vol. 188, No. 5, p. 163.

Anon., The Design of Fluid Bed Boilers - I, Steam and Heat. Engr., March 1971, pp. 6-12.

Anon., The Design of Fluid Bed Boilers - II, Steam and Heat. Engr., April 1971, pp. 28-34.

Anon., Fluid Bed Combustion, Works Engineering, January 1969.

Anon., Fluid Bed Boilers, Chemistry Ind., February 6, 1971, No. 6, p. 171.

Anon., The Development of Fluid Bed Combustion, Steam and Heat. Engr., April 1969.

Anon., The Development of Fluid Bed Combustion - 2, Steam and Heat. Engr., May 1969, Vol. 38, No. 450, pp. 50-54.

Anon., Fluid Bed Combustion, Works Engineering, November 1970, Vol. 13.

Anon., Fluid Bed Combustion and Coal Sales, Steam and Heat. Engr., May 1969, Vol. 38, pp. 4-5.

Anon., Fluid Bed Gasifier Reduces Sulphur Oxides Emission, Steam and Heat. Engr., September 1970, Vol. 39, No. 466, pp. 32-34.

Anon., Fluidised Bed Combustion, Journal of Fuel and Heat Technology, March 1969, Vol. 16, No. 2, pp. 2-5.

Anon., Fluidized-Bed Combustion, C&EN, August 27, 1973, Vol. 51, No. 35.

Anon, "Fluidized Bed Combustion - - Full Steam." Environ Sci Technol. v 10 n 2 Feb 1976 p 120-121.

Anon., Fluidised-Bed Combustion - The Present State of the Art, Works Engineering, July 1972, pp. 19-21.

Anon., Fluidised-Bed Combustor Research by NCB, Electl. Times, May 1969, Vol. 155, No. 18, pp. 106-107.

Anon., Fluidised Bed Starts Growing Up...with Coalplox Close Behind, New Scientist, March 1973.

Anon., Fluidized-Bed Advance Made, Oil & Gas Journal, January 1973.

Anon., Fluidized-Bed Hydrogenation, Oil & Gas Journal, May 29, 1972.

Anon., Fluidized Bed Steam Generators for Utilities, Environmental Science & Technology, November 1974, Vol. 8, No. 12.

Anon, "Fluidized Combustion", Volume 1, Institute of Fuel, London, England, Symposium Series, 1975.

Anon., Last Hope for Coal, Nature, Lond., March 1, 1969.

Anon., NCB Develop Fluidised Combustion System as Core for Their Coal-Based Energy Complex, Chem. Age Internal., December 1972, Vol. 6.

Anon., NCB Pins Hope in Fluidised Combustion System, Electrical Review, Lond., May 2, 1969, Vol. 184, No. 18, p. 634.

Anon., New Coal Combustion System, Energy International, December 1968, Vol. 5, p. 30.

Anon., New Method of Combustion, Nature, Lond., May 3, 1969.

Anon, "Optimization of Limestone Utilization and Sulfur Capture in a Single Combustion Zone Fluidized - - Bed Boiler." US Off of Coal Res. Res and Dev Rep n 88 Final Prep by Pope, Evans and Robbins, Inc. New York, N.Y. for US Dep of the Inter. Off of Coal Res (Rep PER 545-72). Washington, D.C., Mar 1974. 43 p.

Anon., Pressurized Fluid Bed Coal Combustion, Combustion, October 1972.

Anon., Smokeless Fluid Bed, Chem. Age Internal., February 9, 1973, Vol. 106, (2795), No. 12.

Anon., Sulphur Removed by Fluid Bed, BR Chem. Engr., October 1970, Vol. 15, No. 10.

Anon., Utilisation of the Fluid Bed Combustion Technique for Power Generation and Industrial Steam Raising, Steam and Heat. Engr., June 1969, Vol. 38, No. 451, pp. 12-13.

D. H. Archer, Coal Gasification for Clean Power Production, Coal Symposium Paper, 1973.

D. H. Archer, Coal Gasification for Clean Power Generation, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

D. H. Archer, Evaluation of the Fluidized Bed Combustion Process Volume I - Summary Report, Office of Air Programs (EPA), Contract No. CPA 70-9, November 15, 1969 - November 15, 1971.

D. H. Archer, Evaluation of the Fluidized Bed Combustion Process Volume II - Technical Evaluation, Office of Air Programs (EPA), Contract No. CPA 70-9, November 15, 1969 - November 15, 1971.

D. H. Archer, Marketable Designs for Fluidized-Combustion Boilers, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

D. H. Archer, A Pressurized Fluidized-Bed Boiler Development Plan, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

Archer, D.H., D.L. Keairns, J.R. Homm, "Evaluation of the Fluidized Bed Combustion Process", Vol. II, Technical Evaluation. Westinghouse Research Labs., Pittsburgh, Pa. Nov. 1971.

Archer, et al., 1970. "Evaluation of the Fluidized Bed Combustion Process", Westinghouse Research Labs, Pittsburgh, PA.

Argonne National Laboratory, 1976, "Environmental Control Implications of Generating Electric Power from Coal", ANL-ECT-1, Argonne, Illinois, December.

D. T. Argyriou, Bubble Growth by Coalescence in Gas Fluidized Beds, 60th Annual AIChE Meeting, November 26-30, 1967.

H. R. F. Arnstein, Big Economics from Pressurized Fluid-Bed Combustion, The Engineer, July 24, 1969.

J. B. Arots, Studies on Fluidized Bed Incineration and Pyrolysis of Shipboard Wastes, Aerospace Division of the American Society of Mechanical Engineers, 74-ENAs-19, July 29-August 1, 1974.

Z. Asaki, Thermal Decomposition of Limestone in a Fluidized Bed, Metallurgical Transactions, February 1974, Vol. 5.

R. C. Attig, Additive Injection for Sulfur Dioxide Control: A Pilot Plant Study, Babcock & Wilcox Company, Research Center Report 5460, March 27, 1970.

M. M. Avedesian, Combustion of Carbon Particles in a Fluidised Bed, Trans. Instn. Chem. Engrs., 1973, Vol. 51.

H. S. Avery, Hot Hardness of Hard Facing Alloys, J. Welding, 1950, Vol. 29, No. 7.

H. S. Avery, Surfacing by Welding for Wear Resistance, Composite Engineering Laminates, Ed. by A. G. H. Deity, The MIT Press, Cambridge, Massachusetts, 1969.

Babcock and Wilcox, 1977. "Effect of Sorbent Particle Size on Sulfur Fixation in Fluidized Bed Combustors," for EPA February.

Babcock & Wilcox, Steam, Babcock & Wilcox Company, 1960, 37th Ed.

Badin, E.J., 1976, "Utilization of By-Product Ash from Fluidized Bed Combustion of Coal," MITRE Corp./METREK Division, MTR-7339, September.

A. Baerg, Heat Transfer in a Fluidized Solids Bed, Canadian Journal of Research, August 1950, Vol. 28, Section F, No. 8.

J. Baeyens, An Investigation into Slugging Fluidized Beds, Chemical Engineering, 1974, Vol. 29, pp. 255-265.

A. H. Bagnulo and others, Development of Coal Fired Fluidized-Bed Boilers, Office of Coal Research, Res. Develop. Rept. 36, 1971, Vol. I, (PB 234 343).

R. C. Bailie and M. Ishida, Gasification of Solid Waste Materials in Fluidized Beds, AIChE Symposium Series, 1972, Vol. 68, No. 122, pp. 73-80.

R. C. Bailie, Solid Waste Incineration in Fluidized Beds, Industrial Water Engineering, November 1970, pp. 22-25.

M. H. I. Baird, Spontaneous Oscillation of a Gas-Fluidized Bed, Chem. Engr. Science, 1973, Vol. 28.

F. J. Ball, Dry Fluidized Activated Carbon Processes for Stack SO_2 Recovery as Sulfur, Journal of the Air Pollution Control Assoc., January 1972, Vol. 22, No. 1, pp. 20-26.

Balzhiser, R.E., NOx Control Technology, Report of Work in the Fossil Fuel and Advanced Systems Division, EPRI Journal, No. 1, 30-32, Feb. 1976.

T. E. Ban, Conversion of Solid Fuels to Low Btu Gas, Am. Chem. Soc., Div. of Fuel Chem. Prepr., 1974, Vol. 19, pp. 79-98.

J. J. Barker, Heat Transfer in Packed Beds, Part 1, I&E Chem., April 1965.

J. J. Barker, Heat Transfer in Fluidized Beds, Part 2, I&E Chem., May 1965.

M. H. Barker and S. J. Wright, Heating Apparatus, U. S. Patent 3,589,342, June 29, 1971.

M. H. Barker, Fluid-Bed Boilers, Inst. Mech. Engrs. Convention on Steam Plants for the 1970's, London, April 1969.

W. J. Bartel, Heat Transfer from a Horizontal Bundle of Bare and Finned Tubes in an Air Fluidized Bed, AIChE Symposium Series, Vol. 69.

Battelle, 1973. "Environmental Considerations in Future Energy Growth", Columbus and Pacific Northwest Labs, for EPA.

Battelle-Columbus Labs, 1977. "The U.S. Environmental Protection Agency's Fluidized Bed Combustion Program 1977", Battelle, Columbus Ohio, February.

R. N. Bartholomew, Heat Transfer from the Wall of a Tube to a Fluidized Bed, AIChE Symposium Series, No. 4.

W. Bartok, Laboratory Studies and Mathematical Modeling of NO$_X$ Formation in Combustion Processes, December 1971, (PB 211 480).

A. P. Baskakov, Investigation of the Thermal Conductivity of a Bed Fluidized in the Presence of Banks of Horizontal Tubes, Int. Chem. Engr., January 1973.

A. P. Baskakov, Nondecarburizing Heating of Steel Parts in Fluidized Bed, Trans. from Metallovedenie i Termicheskaya Obrabotka Metallov, January 1973, UDC 621.785:66.096.5.

A. P. Baskakov and others, Heat Transfer to Objects Immersed in Fluidized Beds, Power Technology, i, 1973, pp. 273-282.

W. G. Bauer, Fluidization - Its Implications for Lime and Nonmetallic Industries, Pit and Quarry, May 1962.

W. G. Bauer, Fluidization - Multipurpose Process Tool, Pit and Quarry, Part 1: Minerals Processing Potential, June 1965, Part 2: System Components, July 1965.

B. J. Baxter, Fluidized-Bed Combustors Used in HTGR Fuel Reprocessing Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

Becker, H.A., J.M. Beer, B.M. Gibbs, "Model for Fluidized Bed Combustion of Coal." Fluid Combust. Conf. Proc. Imp. Coll. of Sci and Technol. London Engl., Sep 16-17 1975, Pap A1, 10 p. Publ. by Inst. of Fuel (Symp. Ser. n 1. v 1), London, Engl. 1975.

Beér, J.M., 1977. "The Fluidized Combustion of Coal", MIT Dept. of Chemical Engineering, Cambridge, MA, June.

Beer, J.M. and G.B. Martin, 1976. "Application of Advanced Technology for NO$_x$ Control: ALternate Fuels and Fluidized Bed Coal Combustion," AIChE 69th Annual Meeting, Chicago, Ill., November, 28.

J. L. Beeson and others, Coal Char Gasification in a Continuous Electrofluid Reactor, Ind. Eng. Chem. Process Des. Develop., 1970, Vol. 9, No. 3, pp. 460-465.

C. Bennett, Heat Treating in the Fluid-Bed Furnace, Metal Progress, April 1961, pp. 82-87.

Beranek, Jaroslav, 1977, "Contribution of Fluidized-Bed Technology to Protection of Air Cleanliness", USTAV Teor. Zakl. Chem. Tech., Csav Prague OChr. Ovzdusi 8 12 77-83.

R. R. Bertrand and others, Combustion of Coal in a Bed of Fluidized Lime, Am. Chem. Soc., Div. Fuel Chem. Prepr., August 1973, Vol. 18, No. 4, pp. 25-29.

F. V. Bethell, Mathematical Modelling of the Limestone-Sulphur Dioxide Reaction in a Fluidized-Bed Combustor, Fuel, April 1973, Vol. 52.

G. N. Bhat, Studies on the Gaseous Fluidization of Solids, British Chem. Eng., Part 1: Wall Effect on Fluidization Characteristic, December 1963; Part 2: Correlating Head Loss during Flow through Fixed and Fluidized Solids Beds by Means of Dimensionless Groups, March 1964; Part 3: Incipient Bubbling in Fluid Beds, May 1964; Part 4: Effect of Temperature on Fluidized Beds, July 1965; Part 5: Wall-to-Bed Heat Transfer Characteristics, September 1965.

D. Bhattacharyya, Radial and Axial Velocity Distributions within Packed Beds Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

C. E. Billings, Mercury Balance on a Large Pulverized Coal-Fired Furnace, Journal of the Air Pollution Control Assoc., September 1973, Vol. 23, No. 9, p. 773.

T. J. Birch, Hydrogasification of Brown Coal to Produce Methane Natural Gas, Aust. Chem. Process. Eng., October 1971, Vol. 24, No. 10, pp. 29-36.

T. J. Birch, Hydrogasification of Brown Coal Char in a 20-ft Continuous Fluidized Bed Reactor, Journal of the Institute of Fuel, January 1969.

J. W. Bishop and others, Development of Coal Fired Fluidized-Bed Boilers Pope, Evan & Robbins Final Report, Prepared for OCR, Vol. I, June 1965 - February 1970.

J. W. Bishop, Development of Coal Fired Fluidized-Bed Boilers, Vol. II, September 1972, (PB 234 344).

J. W. Bishop, Fluidized-Bed Boiler Cuts Pollutants, Electrical World, January 15, 1973.

J. W. Bishop, Method for Regulating Heat Output from an Oxidizing Fluidized Bed, U. S. Patent 3,565,022, February 23, 1971.

J. W. Bishop, The Modular Fluidized-Bed Boiler Concept, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

J. W. Bishop, Status of the Direct Contact Heat Transferring Fluidized Bed Boiler, ASME Winter Annual Meeting and Energy Systems Expo., December 1-5, 1968.

R. J. Bishop, Formation of Alkali-Rich Deposits by a High Chlorine Coal, Journal of the Institute of Fuel, February 1968.

J. G. A. Bitter, A Study of Erosion Phenomena - Part I, Wear, 1963, Vol. 6.

J. G. A. Bitter, A Study of Erosion Phenomena - Part II, Wear, 1963, Vol. 6.

C. H. Black, Effectiveness of a Fluidized Bed in Removing Submicron Particulate from an Air Stream, I&EC Des. and Dev., October 1969, Vol. 8, No. 4.

Bloom, S. G. et al., 1977. "State of Technology on Fluidized Bed Combustion," Battelle Columbus Lab, Columbus, Ohio, February.

R. H. Boll, The Role of Chemical Thermodynamics in Analyzing Gas-Side Problems in Boilers, ASME Paper 60-WA-182.

R. H. Borgwardt, Kinetics of the Reaction of SO_2 with Calcined Limestone, Environmental Science & Technology, January 1970, Vol. 4, No. 1.

R. H. Borgwardt, Properties of Carbonate Rocks Related to SO_2 Reactivity, Environmental Science & Technology, April 1972, Vol. 6, No. 4, p. 350.

D. C. Boteler, Partial Devolatilization of Coal in Two Entrained-Bed Carbonizers, Bureau of Mines Report of Investigation 7843, 1973.

J. S. M. Botterill, The Achievement of High Rates of Heat Transfer, 60th Annual AIChE Meeting, November 26-30, 1967.

J. S. M. Botterill, Achieving High Heat Transfer Rates in Fluidized Beds, British Chemical Engineering, July 1968.

J. S. M. Botterill, Comeback for Coal in the Fluidized Burner, New Scientist, February 1969, Vol. 41, No. 638, pp. 445-447.

J. S. M. Botterill, Progress in Fluidization, British Chemical Engineering, January 1965, Vol. 10, No. 1.

J. S. M. Botterill, Progress in Fluidization, British Chemical Engineering, August 1968, Vol. 13, No. 8, pp. 1121-1126.

Botterill, J.S.M., D.E. Elliott, 1977, "The Contribution of Fluid-Bed Technology to Environmental Protection and Energy Saving", Energy Environ., (Proc.) Sect. 2 Man His Environ., Symp. 295-305.

K. McGregor Bowling, Filter Aids from Coal, Commonwealth of Australia - 291,778, June 17, 1969.

K. McGregor Bowling, Fluidized-Bed Coal Processing, Coal Res. CSIRO, December 1971, Vol. 45, pp. 39-46.

K. McGregor Bowling, Fuel Processing in Fluidized Beds, British Chemical Engineering, August 1968, Vol. 13, No. 8, pp. 1127-1133.

K. McGregor Bowling and P. L. Waters, Some Theoretical and Experimental Studies on Fluidized Gasification of Solid Fuels, Mech. Chem. Eng. Trans., 1968, Vol. 4, No. 2, pp. 234-240.

H. Brauer and others, Gas Residence Time Distribution in Multistage Fluidised Beds, Warme- und Stoffubertragung 3, 1973, pp. 153-156.

D. H. Broadbent, Development of Fluidized-Bed Combustion for Firing Utility Steam Boilers, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

J. E. Browning, Fluidized-Bed Combustion Broadens Its Horizons, Chem. Eng., 1971, Vol. 78, No. 15.

R. W. Bryers, Design Features of Pressurized Fluidized-Bed Boilers, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

Bryers, Richard W., Wayne E. Kramer, "Status of Technology of Fluidized Beds for The Combustion of Solid Fuels", TAPPI Eng Conf. Pap. Houston, Tex. Oct 4-7 1976 Publ by TAPPI, Atlanta, Ga., 1976 Book 1 p 27-54.

D. B. Bukur, Analysis of a Model for a Nonisothermal Continuous Fluidized Bed Catalytic Reactor, Chemical Engineering Science, 1974, Vol. 29.

Burns and Roe, Inc., 1977, "Conceptual Design of an Atmospheric Fluidized Bed Combustion (AFBC) Electric Power Generating Plant, AFBC State-Of-The-Art Report," Edward J. Cosgrove, Burns and Roe, Inc., June.

I. A. Burovoi, The Determination of Mixing Coefficients in Fluidized Bed Reactors, International Chemical Engineering, October 1965, Vol. 5, No. 4.

R. S. Burton III and R. C. Bailie, Fluid Bed Pyrolysis of Solid Waste Materials, Combustion, February 1974, Vol. 45, No. 8, pp. 13-19.

R. S. Burton, Municipal Solid Waste Pyrolysis, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

F. R. Campbell, Transport Properties of Porous Lime and Their Influence on the Decomposition of Porous Compacts of Calcium Carbonate, Chemical Engineering Science, 1970, Vol. 25, pp. 929-942.

Campbell, E.K., J.F. Davidson, 1977, "Combustion of Coal in Fluidized Beds", Fluid. Technol., Proc. Int. Fluid. Conf. 2. 285-8.

E. L. Carls, Review of British Program on Fluidized-Bed Combustion: Report of U. S. Team Visit to England, ANL ES-CEN-1000, August 1969.

N. S. Carslaw and J. C. Jaeger, Conduction of Newtonian Solids, Oxford University Press, Oxford, England, 1959.

S. Chalchal, Coal Combustion and Desulfurization in a Rotating Fluidized Bed Reactor, October 1974, (BNL-19308).

A. V. Chechetkin and A. I. Dementev, Aerodynamic Processes in a Unit of Variable Cross-Section for Heating and Calcining Coal in a Fluidized Bed, Coke Chem., USSR, 1965, Vol. 10, pp. 15-19.

P. Cheremisinoff and B. Rao, Fluid Bed Free Board Design, Process Technology, March 1973, Vol. 18, No. 3, pp. 121-124.

L. Cheung, Minimum Fluidisation Velocity of a Binary Mixture of Different Sized Particles, Chemical Engineering Science, 1974, Vol. 29, pp. 1301-1303.

Chronowski, R.A., Benjamin Molayem, 1975, "Nitrogen Oxides (NOx) Emissions from Atmospheric Fluidized-Bed Boilers", Am. Soc. Mech. Eng., (Pap.) 75-PWR-4. 7 pp.

S. F. Chung, Longitudinal Dispersion of Liquid Flowing Through Fixed and Fluidized Beds, 60th Annual AIChE Meeting, November 26-30, 1967.

B. T. F. Chung, A Model of Heat Transfer in Fluidized Beds, Journal of Heat Transfer, February 1972.

A. R. Ciuffreda, Petroleum Industry Material Selection as Related to Coal Conversion Processes.

Claypoole, George T., Herbert Finfer, William H. Hayes, "Conceptual Design of a Utility, Multicell, Coal Fired, Fluidized Bed Steam Generator Combustion Control System", Adv Instrum v 31 1976, Proc of 31st Annu ISA Conf. adn Exhib. Houston, Tex. Oct 10-14 1976 pt 1 Pap 560, 5 p.

N. H. Coates and others, Combustion of Coal in Fluidized Beds, AIME Transactions, September 1970, Vol. 247, pp. 208-210.

N. H. Coates, Fluid-Bed Combustion of Various U. S. Coals, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

N. H. Coates, Sulfur Dioxide Reduction by Combustion of Coals in Fluidized Beds of Limestone, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

Coates, N.H. and R.L. Rice, "Sulfur Dioxide Reduction by Combustion of Coals in Fluidized Beds of Limestone", Bureau of Mines, Morgantown, W. Va., May 1943

W. E. Cole, Fluid Bed Combustion of Natural Gas, Proc. Conf. Nat. Gas Res. Tech., 1972.

W. E. Cole, Studies on the Combustion of Natural Gas in a Fluid Bed, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

Combustion Power, Energy Conversion from Coal Utilizing CPU-400 Technology, OCR 94 International, November 1974, Period July 1973 - June 1974, (PB 237 028).

Combustion Power, Energy Conversion from Coal Utilizing CPU-400 Technology, Monthly Progress Reports No. 1 (July-August 1973) through 12 (July 1974).

Control Techniques for Sulfur Oxide Air Pollutants, National Air Pollution Control Administration, January 1969, Publication No. AP-52, (PB 235 817).

Control Systems Division (CSD), Pressurized Fluidized-Bed Combustion of Coal (EPA), March 1, 1972.

Converting Solid Wastes to Electricity, Environmental Science & Technology, August 1970, Vol. 4, No. 8, pp. 631-633.

E. D. Cooper, Pilot- and Plant-Scale Fluidized Bed Calciners, Chem. Eng. Prog., July 1965, Vol. 61, No. 7, pp. 87-96.

COPAC-4, Abatement of Nitrogen Oxides Emissions from Stationary Sources, National Academy of Engineering, National Research Council.

G. G. Copeland, Design and Operation of Fluidized Bed Incinerators, Ind. Wastes, 1970, R-245-R-249.

G. G. Copeland, Disposal of Solid Wastes by Fluidized-Bed Combustion, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

Copeland, G.G., "12 Year Review of Fluidized Bed Technology." Tappi Alkaline Pulping Conf Prepr 1975, for Meet. Williamsburg, Va, Oct 27-29 1975 p 53-65.

C. E. Copes, The Pseudo Particulate Expansion of Screen-Packed Gas-Fluidized Beds, 60th Annual AIChE Meeting, November 26-30, 1967.

Coughlin, R.W., et al., 1972, "Air Pollution and its Control," AIChE Symposium Series No. 126, Vol. 68.

Council on Environmental Quality, 1975. "Energy Alternatives", CEQ, Washington, D.C.

R. W. Coutant, Investigation of the Reactivity of Limestone and Dolomite for Capturing SO_2 from Flue Gas, August 1968, (PB 180 834).

R. W. Coutant, Investigation of the Reactivity of Limestone and Dolomite for Capturing SO_2 from Flue Gas, June 1969, (PB 184 945).

R. W. Coutant, Investigation of the Reactivity of Limestone and Dolomite for Capturing SO_2 from Flue Gas, November 20, 1970, (PB 196 749).

R. W. Coutant, Investigation of the Reactivity of Limestone and Dolomite for Capturing SO_2 from Flue Gas, October 1971, (PB 204 385).

J. W. T. Craig, Chemically Active Fluid-Bed Process for Sulphur Removal during Gasification of Heavy Fuel Oil - Second Phase, November 1974, (PB 240 632).

J. W. T. Craig, Study of Chemically Active Fluid-Bed Gasifier for Reduction of Sulfur Oxide Emissions, Esso England Interim Report, APCO Contract CPA 70-46, June 22, 1970 - February 22, 1971.

J. W. T. Craig, Study of Chemically Active Fluid Bed Gasifier for Reduction of Sulfur Oxide Emissions, Final Report, June 22, 1970 - March 1972, June 1972.

J. W. T. Craig, Sulphur Retention in Fluidized-Beds of Lime under Reducing Conditions, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

R. R. Cranfield, Large Particle Fluidisation, Chemical Engineering Science, 1974, Vol. 29, pp. 935-947.

D. E. Creasy, Gas Fluidization at Pressures and Temperatures above Ambient, British Chemical Engineering, July 1971, Vol. 16, No. 7, pp. 605-610.

M. S. Crowley, Influence of Particle Size on Erosion Resistance of Refractory Concretes, Ceramic Bulletin, 1969, Vol. 48, No. 7.

CSIRO, Gasification of Coal in Fluidized Beds, Coal Research in CSIRO, May 1969, No. 37.

G. P. Curran, Coal-Based Sulfur Recovery Cycle in Fluidized-Lime-Bed Combustion, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

G. P. Curran, The CO_2 Acceptor Gasification Process - A Status Report - Application to Bituminous Coal, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

G. P. Curran, The CO_2 Acceptor Process, Coal Processing Technology, CEP Tech. Manual, 1975, Vol. 2.

G. P. Curran, Low-Sulfur Producer Gas via an Improved Fluid-Bed Gasification Process, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

G. P. Curran, Low-Sulfur Producer Gas via a High Temperature Sulfur Removal Process, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

G. P. Curran, Production of Low-Sulfur Boiler Fuel by Two-Stage Combustion - Application of CO_2 Acceptor Process, Proceedings of Second International Conference on Fluidized-Bed Combustion (EPA), October 4-7, 1970.

G. P. Curran, Studies on Mechanics of Fluo-Solids Systems, Office of Coal Research, R&D Report No. 16, Interim No. 3, Book 1, Contract No. 14-01-0001-415, July 1964 to June 1968, (PB 184 718).

G. P. Curran, Phase II. Bench-Scale Research on CSG Process, Laboratory Physico-Chemical Studies, R&D Report No. 16, Interim No. 3, Book 2, (PB 184 719).

G. P. Curran, Phase II. Bench-Scale Research on CSG Process, Operation of the Bench-Scale Continuous Gasification Unit, R&D Report No. 16, Interim No. 3, Book 3, (PB 184 720).

Cusumano, J.A. and R.B. Levy, "Evaluation of Reactive Solids for SO_2 Removal During Fluidized Bed Coal Combustion", Catalytica Associates Inc. for EPRI, October 1975.

A. J. B. Cutler, ASME, Journal Engr. for Power, July 1971.

A. D. Dainton, Seventh World Power Conference, Moscow, 1968.

C. N. Das and S. Sarkar, Heat Transfer in Dilute-Phase Fluidized Bed, Indian J. Technology, September 1967, Vol. 5, No. 9, pp. 276-279.

D. C. Davidson, The Retention of Sulphur by Limestone in a Pilot-Scale Fluid-Bed Combustor, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

J. F. Davidson, Bubble Formation at an Orifice in an Inviscid Liquid, Trans. Instn. Chem. Engrs., 1960, Vol. 38.

Davidson, D.C. and A.W. Small, 1970. 2nd International Conference on Fluidized Bed Combustion, Hueston Woods, Ohio, October 4-7.

J. F. Davidson, Differences between Large and Small Fluidized Beds, AIChE Symposium Series, Vol. 69, No. 128.

W. L. Davis, Jr., Large-Scale Fluidized-Bed Drying of Iron-Ore Concentrate, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

L. Davies, Gas Interchange between Bubbles and Continuous Phase in a Fluidized Bed, British Chemical Engineering, August 1967, Vol. 12, No. 8, pp. 1223-1226.

Deegan, et al., 1976. "ECAS Studies", Westinghouse Research Labs, Pittsburgh, PA.

R. H. Demmy, Ignifluid Boilers for an Electric Utility, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

R. H. Demmy, Ignifluid Boilers for an Electric Utility, 69th National Meeting of AIChE, May 16-19, 1971.

R. J. Demski, Bureau of Mines Test of Fluidized Bed Combustor of Pope, Evans, and Robbins, Alexandria, Va., Bureau of Mines Report, March 1973.

C. A. Depew, Heat Transfer to Horizontal Gas-Solid Suspension Flows, ASME-AIChE Heat Transfer Conference, August 3-6, 1969.

The Development of Fluid Bed Combustion - 2, Steam and Heat. Engr., May 1969.

Desulfurization of Coal in a Fluidized Carbonizer, United Engineers & Constructors, Inc., September 1956.

B. R. Dickey, Application to Combined Cycle Power Production of Fluid-Bed Technology Used in Nuclear Fuel Reprocessing, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

B. R. Dickey, Waste Heat Disposal Using Fluid-Bed Wet-Dry Towers, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, Vol. 70, 1974.

E. K. Diehl, Desulfurized Fuel from Coal by Inplant Gasification, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

I. Di Federico, Plane Cross-Flow Heat Exchangers with Heat Generation within a Fluid Stream, *Nuclear Engineering and Design*, 1971, pp. 41-53.

Deleted

S. Dobner, Production of Low Btu Gas from Coal with High and Low Temperature Sulfur Removal Schemes, AIChE Workshop, 1975, Vol. 6, Presented at Mtg., Chicago, Ill., October 17, 1973.

DOE, 1977. "Proceedings of the Fluidized Bed Combustion Technology Exchange Workshop," Vols I and II, cosponsored by EPRI, NTIS: CONF-770447-P-1,-2, April.

DOE, 1976, "Program Plan for Fossil Demonstration Plants," DOE Fossil Energy, Division of Fossil Demonstration Plants, Nov. (FE-2213-22-02.

M. A. Doheim, Fluidisation in the Ferrous Industry, *Iron and Steel International*, October 1974.

K. Doichev, Energetic Aspects of the Transition between Aggregative and Particulate Fluidization, Chemical Engineering Science, 1974, Vol. 29, pp. 1205-1210.

W. M. Dow, Heat Transfer between a Vertical Tube and a Fluidized Air-Solid Mixture, *Chem. Eng. Prog.*, December 1951, Vol. 47, No. 12.

Dow Chemical, "The Effect of Experimental Scale on the Emissions from Fluidized Bed Combustion Units", Dow Chemical U.S.A. for USEPA, July 1975. EPA Contract No. 68-02-1329.

A. N. Dravid, Power Generation Using the Shell Gasification Process, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

D. D. Dunlop, Fluidized Bed Report Surrounded by a Fluidized Sand Heat Exchanger, U. S. Patent 3,562,115, February 9, 1971.

J. Eden and L. Grainger, Fluidised Bed Boilers at the Crossroads, *Electrical Review*, Lond., October 30, 1970, Vol. 187, No. 10, p. 620.

S. Ehrlich, Air Pollution Control through New Combustion Processes, *Environmental Science & Technology*, May 1970, Vol. 4, No. 5, pp. 396-400.

S. Ehrlich, Combustion of Carbon-Bearing Sly Ash in a Carbon-Burnup Cell, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

S. Ehrlich, Development of a Fluidized-Bed Boiler, AIChE Symposium Series, Vol. 68, No. 126.

S. Ehrlich, Part II - The Fluid Bed Boiler and Its Applicability to Pollution Control, AIChE 69th National Meeting, May 18, 1971.

Ehrlich, S., 1971. "Combustion of Carbon-Bearing Fly Ash in a Carbon-Burnup Cell," NTIS #PB 231977.

Ehrlich, Shelton, "Coal Fired Fluidized Bed Boiler." Fluid. Combust. Conf. Proc. Imp Coll of Sci and Technol. London, Engl. Sep 16-17 1975 Pap C4, 10 p. Publ by Inst. of Fuel (Symp Ser n 1 v 1.) London, Engl. 1974.

S. Ehrlich, NO_x Emissions from Fluidized-Bed Boilers, *Fuel*, October 1974, Vol. 53, p. 284.

S. Ehrlich, Particle Emissions from a High Temperature Fluidized-Bed Fly Carbon Burner (Abstract), Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

Ehrlich, S., *et al.*, 1971. "Development of a Fluidized Bed Boiler", AIChE Symposium Series, 68(126) pp. 231-240.

D. E. Elliott, Exploiting Shallow Fluidized Bed Technology, Unknown Source.

D. E. Elliott, Fluid Bed Boilers Challenge to Nuclear, *Electrical Review*, Lond., November 28, 1969, Vol. 185, No. 22, p. 786.

D. E. Elliott, Fluidised Beds for Combined Cycle Plant, *Electrical Review*, Lond., March 6, 1970, Vol. 186, pp. 360-361.

D. E. Elliott, Has Coal a Future?, *The Chartered Mechanical Engineer*, July 1970, Vol. 17, No. 7, pp. 299-303.

D. E. Elliott, Possible Use of Fluid-Bed Combustion and Heat Transfer, Paper 22, Institute of Fuel, Total Energy Conference, December 1971, Proc. Vol. 1, pp. 361-372.

D. E. Elliott, Small-Scale Applications of Fluidized-Bed Combustion and Heat Transfer (The Development of Small, Compact Fluidized-Bed Boilers), Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

Elliott, D.E., "Fluidized Bed Boilers." Energy Eng. Conv. of Lines of Dev. In Energy Eng. Prepr. Duesseldorf, Germany, May 5-7 1975, p. 95-104. Publ. by VDI-Verlag. Duesseldorf, Germany, 1975.

D. E. Elliott, Some Economic Aspects of High-Temperature Steam Cycles, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

Endrenyi, S., B. Palancz, "Mathematical Model for Combustion Coal in Fluid Bed" Int Semin on Future Energy Prod - - Heat and Mass Trnsfer Probl. Dubrovnik, Yugosi, Auf 25-30 1975 Publ by Hemisphere Publ Corp. Washington, D.C. 1976 v 2 p 579-587.

Environmental Protection Agency, Atmsopheric Fluidized Bed Vapor Generator, Pat. Appl. 324,041, January 16, 1973, (PB 221 703).

Environmental Protection Agency, Document on Fluidized-Bed Combustion for Sulfur Dioxide Control, June 14, 1971.

Environmental Protection Agency, Proceedings of International Conference on Fluidized Bed Combustion (2nd), Research Triangle Park, N.C., 1970.

EPA, 1975. "Strategic Environmental Assessment Systems", EPA, Washington, D.C.

EPA, 1977, "The U.S. Environmental Protection Agency's Fluidized Bed Combustion Program, FY 1976," Interagency Energy-Environmental Research and Development Program Report, Battelle Columbus Laboratories, February (EPA-600/7-77-012).

EPRI, 1976, "Digest of Current Research in the Electric Utility Industry, Electric Power Research Institute, May, EPRI RD-2.

J. W. Evans, Application of a Porous Pellet Model to Fixed, Moving, and Fluidized Bed Gas-Solid Reactors, Ind. Eng. Chem. Process Des. Develop., 1974, Vol. 13, No. 2.

Farmer, M.H., E.M. Magee, F.M. Spooner, 1977. "Application of Fluidized Bed Technology to Industrial Boilers", Exxon Research and Engineering Co., Linden, N.J., p 220, January.

W. Fehndich, Wear Studies on Boiler Pipes, Mitteilungen der VGB, 49(1):58-70, February 1969.

H. L. Feldkirchner, Coal Desulfurization Aspects of the HYGAS Process, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

H. F. Feldmann, Fluidization Properties of Coal Char, Potential Paper Prepared by Bureau of Mines.

Fennelly, Paul F., Hans Klemm, R. Robert, Donald F. Durocher, "Coal Burns Cleaner in a Fluid Bed", Environ Sci Technol v 11 n 3 Mar 1977 p 244-248.

Fennelly, Paul F., Donald F. Durocher, Hans Klemm, Robert R. Hall, "Preliminary Environmental Assessment of Coal Fired Fluidized Bed Combustion", Proc of the Int Conf on Fluid-Bed Combust. 4th McLean, Va, Dec 9-11 1975 Publ by MITRE Corp (M76-36), McLean, Va. 1976 p 475-491.

J. R. Ferron, Studies of Gas-Solid Heat Transfer in Fluidized Beds, 54th Annual AIChE Meeting, December 2-7, 1961.

A. A. Field, Combustion: Two Steps for the Future, Heat, Piping Air Cond., February 1972, Vol. 44, No. 2, pp. 87-89.

M. A. Field, Combustion of Pulverized Coal, Cheney & Sons Ltd., Banbury, England, 1967.

N. F. Fillippovskii, Investigation of the Temperature Field in a Fluidized Bed Close to a Heated Plate and of Heat Transfer between Them, International Chemical Engineering, January 1973, Vol. 13, No. 1.

D. H. Fine, Nitrogen in Coal as a Source of Nitrogen Oxide Emission from Furnaces, Fuel, April 1974, Vol. 53, p. 120.

I. Finnie, Erosion by Solid Particles in a Fluidized Stream, Symposium on Erosion and Cavitation, ASTM Special Tech. Pub., 1962, No. 307.

I. Finnie, Erosion of Metals by Solid Particles, Journal of Materials, September 1967, Vol. 2, No. 3.

I. Finnie, Some Observations on the Erosion of Ductile Metals, Wear, January 1972, Vol. 19, No. 1.

W. H. Fischer, Proceedings of a Workshop on Regeneration of Sulfated Limestone/Dolomite for Fluidized Bed Combustion, ERDA Fossil Energy, Washington, D. C., March 3-4, 1975.

L. R. Fleisher, Investigation of Corrosion-Deposition Phenomena on Gas Turbine Blades, Westinghouse Research Labs, 1973, (PB 221 095).

Fluid Bed Combustion - 1, Steam and Heat. Engr., April 1969.

Fluid Bed Gasifier Reduces Sulfur Oxides Emission, Steam and Heat. Engr., September 1970.

Fluidization Fundamentals and Application, AIChE Symposium Series, 1970, Vol. 66.

Fluidized Bed Combustion Company, 200/800 Megawatt Fluidized Bed Steam Generator Proposal, June 18-24, 1974.

Fluidized-Bed Combustion Should Reduce Air Pollution, Power, July 1970, p. 46.

Fluidized Beds Take on New Life, C&EN, December 14, 1970, pp. 46-48.

Fluidized Combustion Company, "Program Preparative: 200-MW Atmospheric Fluidized Bed Steam Generating System, Prepared for Consumer's Power Company, March 1976.

A. J. Forney, Decaking of Coals in a Fluid Bed, Bureau of Mines Report of Investigations 6797, 1966.

A. J. Forney, Steam-Oxygen Gasification of Various U.S. Coals, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

Foster Wheeler, Multicell Fluidized Bed Steam Generator Development, Interim Report, July 1974, Report No. 1432-0001-1237-FWC-1.

A. P. Fraas, A Fluidized Bed Combustion System, Chemical Engineering Progress, March 1973, Vol. 69, No. 3.

A. P. Fraas, Fluidized Bed Coal Combustion System Coupled to a Potassium Vapor Cycle, AIChE Symposium Series, Vol. 70, No. 137, Conf. 721106-2.

Fraas, A.P., 1977, "Application of the Fluidized Bed Coal Combustion System to the Production of Electric Power and Process Heat", Report Conf-760402-4, 23 pp.

Fraas, A.P., G. Samuels, M.E. Lackey, "New Approach to a Fluidized Bed Steam Boiler" ASME Pap n 76-WA/Pwr-8 for Meet Dec 5 1976 12 p.

J. A. Francisovich, Method of Subsurface Burning of Quantities of Refuse Material, U. S. Patent 3,518,952, July 7, 1970.

D. A. Furlong, Combustion of Municipal Solid Wastes in a Fluidized Bed, Prepared for 69th AIChE Meeting, May 16-19, 1971.

J. D. Gabor, Wall-to-Bed Heat Transfer in Fluidized Beds, AIChE Journal, January 1972.

Gamble, R.L., 1977. "Development of Fluidized Bed Combustion Systems," in (DOE, 1977).

Gamble, R.L., "Design of the Rivesville Multicell Fluidized-Bed Steam Generator", Proceedings of the Fourth International Conference on Fluidized-Bed Combustion, The MITRE Corp., McLean, Virginia, 1976, pp. 133-151.

B. W. Gamson, Heat and Mass Transfer Fluid Solid Systems, Chemical Engineering Progress, January 1951, Vol. 47, No. 1.

Gasner, L.L., 1977. "Enhancement of Sorbent Utilization by the use of Additives," in (DOE, 1977).

D. Geldart, Gas-Solid Reactions in Industrial Fluidized Beds, Chemistry and Industry, January 13, 1968, pp. 41-47.

D. Geldart, A Strategy for the Design of Fluidized Bed Chemical Reactors, The Chemical Engineer, June 1970, pp. 147-155.

D. Geldart, Types of Gas Fluidization, Powder Technology, May 1973, Vol. 7, pp. 285-292.

N. I. Gel'Perin, Heat Exchange between Finned Tubes and a Fluidized Bed of Granular Particles, Khim i Technologiya Tupiiv i Masel, September 1972.

N. I. Gel'Perin, Heat Transfer between a Fluidized Bed and Staggered Bundles of Horizontal Tubes, International Chemical Engineering, January 1969, Vol. 9, No. 1, pp. 137-142.

N. I. Gel'Perin, The Heat Transfer Coefficient between a Surface and a Fluid Bed, British Chemical Engineering & Process Technology, October 1971.

N. I. Gel'Perin, Heat Transfer Measurements from a Fluidized Bed to a Surface in the Presence of Longitudinal and Traverse Gas Flow, Khimicheskaya Promyshlennost, 1958, No. 6.

General Electric Co., 1976. "Study of Advanced Energy Conversion Techniques for Utility Applications Using Coal or Coal Derived Fuels," Corporate Research and Development, Schenectady, New York, February.

W. E. Genetti, Heat Transfer in a Fluidized Bed Tubular Heat Exchange, A Thesis Submitted to Oregon State University, June 1968.

F. J. Gerchow, Specifying Pneumatic Conveying System, Chemical Engineering, February 17, 1975.

R. W. Gerstle, Air Pollutant Emissions from Coal-Fired Power Plants, Report No. 2, Journal of the Air Pollution Control Association, February 1965, Vol. 15, No. 2, p. 59.

R. N. Ghar, Calculate Degree and Time of Mixing in Fluid Beds by Quick Method, Process Engineering, March 1973.

Gibbs, B.M., J.M. Beer, "Pilot Plant Study of Fluidized Bed Coal Combustion." High Temp. Chem. Reaft. Eng. Symp. Proc. Harrogate. Engl. June 16-18 1975, Pap 23. 11 p. Publ. by Inst. of Chem. Eng. (Symp. Ser. n 43). London, Engl. 1975.

Gibbs, B.M., F.J. Pereira, and J.M. Beer, 1976. "The Effect of Air Staging on the NO Emission from Fluidized Combustion of Coal," 16th International Symposium on Combustion, MIT, August.

L. G. Gibilaro, A Model for a Segregating Gas Fluidised Bed, Chemical Engineering Science, 1974, Vol. 19, pp. 1403-1412.

Gibson, J., "Fluidized Bed Combustion." Coal Energy Q n 7 Winter 1975 p 9-17.

R. D. Glenn, Characterization of Emissions from Fluidized-Bed Combustion of Coal and Control of Sulfur Emission with Limestone, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

Glenn, R.D. and E.B. Robison, 1970. "Characterization of Emissions from Fluidized Bed Combustion of Coal and Control of Sulfur Emission with Limestone", 2nd International Conference on Fluidized Bed Combustion, EPA, PB-214-750.

Glenn, R.D. and E.B. Robison, "Characterization of Emissions from Fluidized Bed Combustion of Coal and Control of Sulfur Emission with Limestone, U.S. EPA, Research Triangle Park, N.C., October 1970. PB-214-750/2.

B. J. Gliddon, C.E.G.B. Research Report.

A. A. Godel, Manufacture of Activated Carbon by Gasification in a Fluidized Bed, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

A. A. Godel, The Scale-Up of a Fluidized-Bed Combustion System to Utility Boilers, AIChE Symposium Series, 1971, Vol. 67.

A. A. Godel, Selective Extraction of Clinker at the Bottom of a Deep Self-Agglomerating Fluidized Bed, Proceedings of Third Internation Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, December 1973.

A. A. Godel, Ten Years of the Application of the Fluidised Bed Combustion Technique, Rev. Gen. Therm., April 1966, Vol. 5, pp. 349-359.

W. M. Goldberger, Collection of Fly Ash in a Self-Agglomerating Fluidized-Bed Coal Burner, The American Society of Mechanical Engineers, November 12-17, 1967, 67-WA/FU-3.

W. M. Goldberger, Fly Ash Emission and Erosion by Fly Ash from a Self-Agglomerating Fluidized-Bed Coal Burner, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

J. S. Gordon, Study of the Characterization and Control of Air Pollutants from a Fluidized-Bed Boiler - The SO_2 Acceptor Process, July 1972, (PB 229 242).

J. R. Grace, Design of Fluidised Beds with Internal Baffles, Chemical and Process Engineering, June 1970.

J. R. Grace, Fluidization and Its Application to Coal Treatment and Allied Processes, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

J. R. Grace, On the Two-Phase Theory of Fluidization, Chemical Engineering Science, 1974, Vol. 29, pp. 327-334.

L. Grainger, Future Trends in Utilisation of Coal Energy Conversion, Energy Digest, January/February 1974.

Gruhl, J., 1976a. "Health/Environmental Consequences of Energy Conversion Alternatives - A Bibliography," MIT-EL-76-020 WP, 30 pp., August.

Gruhl, J., 1976b. "Components for Modeling the Public Health Impacts of Energy Facilities - A Bibliography," MIT-EL-76-024 WP, 34 pp., October.

Gruhl, J., S.E. Tung and F.C. Schweppe, 1978. "Robust Techniques for Developing Empirical Models of Fluidized Bed Combustors," MIT Energy Lab, Cambridge MA, February.

Gruhl, J., et al., 1976. "Systematic Methodology for the Comparison of Environmental Control Technologies for Coal-Fired Electronic Generation," MIT-EL 76-012, 216 pp, November.

P. Guigon, Particle Interchange between Stages in a Baffled Fluidized Bed, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

S. N. Gupta, Fluid-Particle Heat Transfer in Fixed and Fluidized Beds, Chemical Engineering Science, 1974, Vol. 29.

J. F. Haggerty, Modelling Coal Char Gasification in a Fluidized Bed, Fuel, October 1972, Vol. 51.

Haldipur, G.B., T.D. Wheelock, "Desulfurization of Coal in a Fluidized Bed Reactor", Am Chem Soc Div Fuel Chem Prepr v 22 n 2 Desulfurization of Coal and Coal Char. New Orleans, La. Mar 21-25 1977 p 50-61

Hall, E., P. Choi and E. Kropp, 1976. "Assessment of the Potential of Clean Fuels and Energy Technology," EPA-600/2-74-001, 185 pp, February.

Hall, E., P. Choi, E. Kropp, "Assessment of the Potential of Clean Fuels and Energy Technology", Battelle Columbus Labs, Ohio, Feb. 1974.

J. S. Halow, Fluidized-Bed Applications, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

Hammon, G. and A. Skopp, 1971. "NO_x Formation and Control in Fluidized Bed Coal Combustion Processes", presented ASME Winter Annual Meeting, Washington, D.C.

Hammons, G.A. and A. Skopp, "NO_x Formation and Control in Fluidized Bed Coal Combustion Processes", Esso Research and Engineering Co., Linden, N.J., December 1971.

Hammons, G.A. and A. Skopp, "A Regenerative Limestone Process for Fluidized Bed Coal Combustion and Desulfurization", Esso Research and Engineering Co., Linden, N.J. 1972.

G. A. Hammons, NO_x Formation and Control in Fluidized Bed Coal Combustion Processes, ASME Winter Annual Meeting, November 28 - December 2, 1971.

G. A. Hammons, A Regenerative Limestone Process for Fluidized Bed Coal Combustion and Desulfurization, Esso R&E Final Report, Contract No. CPA 70-19 for APCO, February 28, 1971, (PB 198 822).

G. A. Hammons, A Regenerative Limestone Process for Fluidized Bed Coal Combustion and Desulfurization, AIChE Symposium Series, Vol. 68, No. 14.

G. A. Hammons, A Regenerative Limestone Process for Fluidized Bed Coal Combustion and Desulfurization, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

G. A. Hammons, Studies of NO_X and SO_X Control Techniques in a Regenerative Limestone Fluidized Bed Coal Combustion Process, Esso R&E Interim Report, Prepared under Contract CPA 70-19, January 1 - June 1, 1971.

Hanson, M.A. and D.G. DeCoursin, 1977. "Industrial Applications Fluidized Bed Combustion Process," in (DOE, 1977).

Y. Hara, The Analysis for the Rate of the Thermal Decomposition of Limestone, Transactions ISIJ, 1968, Vol. 8, pp. 97-100.

H. Harboe, Fluidized-Bed Air Heaters for Open and Open/Closed Gas Turbine Cycles, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

Harboe, H., C.W. Maude, "Pressurized Fluidized Bed Combustion with Special Reference to Open Gas Turbines." Inst of Eng. Aust: Annu Eng Conf. Townsville, May 10-14 1976 Publ by Inst of Eng. Aust. Sydney, 1976 Pap 621/2 p 350-354.

R. P. Hangebrauck, Fluid Bed Combustion, Its Potential and Its R&D Requirements, NAPCA.

W. F. Harris, Environmental Assessment of SO_2 and Trace Emissions from Coal Utilization, Presented at Coal and the Environmental Technical Conference, Louisville, Kentucky, October 22-24, 1974.

D. Harrison, The Rate of Rise of Bubbles in Fluidised Beds, Trans. Instn. Chem. Engrs., 1962, Vol. 40.

J. A. Harrison, Part 2 Instrumentation and Control, Process Engineering, June 1969.

P. R. Harrison, Time Variations of Lead, Copper and Cadmium Concentrations in Aerosols in Ann Arbor, Michigan Atmos. Environ., 1971, Vol. 5, p. 613.

M. Hartman, Reaction of Sulfur Dioxide with Limestone and the Influence of Pore Structure, Ind. Eng. Chem., Process Des. Develop., 1974, Vol. 13, No. 3, p. 248.

M. Hartman, Reactivity of Limestones with SO_2 in Flue Gas, Int. Second Congress on Chem. Eng., 3rd, Proc., Copenhagen, Denmark, January 28-30, 1974, Vol. A, p. 31.

J. D. Hatfield, Investigation of the Reactivities of Limestone to Remove Sulfur Dioxide from Flue Gas, June 1970, (PB 202 407).

W. B. Hatfield, Development and Analysis of a Model for an Idealized Continuous Fluidized Bed Chemical Reaction, PhD Thesis, University of Minnesota, August 1970.

E. M. Healey, Fluidised Bed Combustion - Part 1 Heat Transfer Advantages, Process Engineering, June 1969.

Deleted

Heat Transfer - Research Studies for 1954, AIChE.

T. K. Heath, Process for the Thermal Oxidation of Spent Liquor, U. S. Patent 3,635,790, January 18, 1972.

C. Van Heerden, Mechanism of Heat Transfer in Fluidized Beds, IEC, June 1953, Vol. 45, No. 6.

P. M. Heertjes, The Partial Coefficient of Heat Transfer in a Drying Fluidized Bed, Chemical Engineering Science, 1956, Vol. 5.

D. B. Henschel, Minutes of Panel Discussion and Summary Session, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

B. C. Herod, New England Lime Company Obtains Efficient Results with Fluidizing Calcium, Pit and Quarry, May 1956.

V. W. Heschel and E. Klose, Designing Thermal Fluid Bed Reactors, Forsch'heft (508), 1972, pp. 121-163.

J. Highley, The Effect of the Spacing between Solid Feed Points on the Performance of a Large Fluidized-Bed Reactor, AIChE Symposium Series, Fluidization, pp. 219-227.

J. Highley, Reduction in Sulfur Dioxide Emission by Fluidized-Bed Combustion, Salford University Symposium, April 1973.

Hill, B.J., "Fluidized Combustion." Energy Dig v 5 n 4 Aug 1976 p 25-30.

A. W. D. Hills, The Mechanism of the Thermal Decomposition of Calcium Carbonate, Chemical Engineering Science, 1968, Vol. 23, pp. 297-320.

Hittman Associates, Baseline Data: "Environmental Assessment of a Large Coal Conversion Complex", Columbia, Md. 1974.

Hittman, 1974, 1975. "Environmental Impacts, Efficiency, and Cost of Energy Supply and End Use", Hittman Associates Inc., Columbia, MD.

Hoke, R.C., M.S. Nutkis, D.D. Kingler, 1977. "Pressurized FBC Studies," in (DOE, 1977).

Hoke, Ronald C., "Emissions from Pressurized Fluidized-Bed Coal Combustion", Proc of the Int Conf on Fluid-Bed Combust. 4th, McLean, Va. Dec 9-11 1975 Publ by MITRE Corp (M76-36), McLean, Va. 1976 p 559-576.

Hoke, R.C., R.R. Bertrand, "Pressurized Fluidized Bed Combustion of Coal." Fluid Combust Conf. Proc. Imp Coll of Sci and Technol. London, Engl. Sep 16-17 1975 Pap D5, 11 p. Publ by Inst of Fuel (Symp Ser n 1. v 1), London, Engl. 1974.

Hoke, R.C., 1975. "Emissions from Pressurized Fluidized Bed Coal Combustion", Exxon Research and Engineering Co., Linden, N.J.

Hoke, R.C., M.S. Natkis, L.A. Ruth, "A Regenerative Limestone Process for Fluidized Bed Coal Combustion and Desulfurization", Exxon Monthly Report No. 53 for USEPA, July 1974.

Hoke, R.C., et al., 1975. "Combustion and Desulfurization of Coal in a Fluidized Bed of Limestone", Combustion, January.

Hoke, R.C., et al., 1976. "Studies of the Pressurized Fluidized Coal Combustion Process", EPA 600/7-76-011, September.

R. C. Hoke, Combustion and Desulfurization of Coal in a Fluidized Bed of Limestone, IEEE-ASME Joint Power Generation Conference, Miami Beach, September 15-19, 1974, 74-PWR 6.

R. C. Hoke, Combustion and Desulfurization of Coal in a Fluidized Bed of Limestone, Combustion, January 1975, pp. 6-12.

R. C. Hoke, A Regenerative Limestone Process for Fluidized-Bed Coal Combustion and Desulfurization, Proceedings of Third International Conference on Fluidized-Bed Combustion (EPA), December 1973.

R. C. Hoke, A Regenerative Limestone Process for Fluidized-Bed Coal Combustion and Desulfurization, National Environmental Research Center, January 1974, EPA-650/2-74-001.

Horio, M. and C.Y. Wen, 1975. "Analysis of Fluidized Bed Combustion of Coal with Limestone Injection", in Fluidization Technology (D.L. Keairns ed.), McGraw-Hill.

A. G. Horsler, High-Pressure Fluidized Beds, Chemical Engineering Progress, 1969, Vol. 65, No. 10.

S. Hovmand and others, Chemical Reaction in a Pilot-Scale Fluidized Bed, Trans. Instn. Chem. Engrs., July 1971, Vol. 49, pp. 149-162.

W. B. Howard, Gas Mixing Patterns in a Fluidized Bed, 60th Annual AIChE Meeting, November 26-30, 1967.

Hoy, H.R. and A.G. Roberts, 1972. "Fluidized Combustion of Coal at High Pressures", AIChE Symposium Series, 68, pp. 225-230.

Hoy, H.R., A.G. Roberts, 1977. "Further Experiments on the Pilot-scale Pressurized Combustor at Leatherhead, Scotland," in (DOE, 1977)

H. R. Hoy, Fluidized Combustion of Coal at High Pressures, AIChE Symposium Series, Vol. 68, No. 126.

H. R. Hoy, Fluidized Combustion under Pressure, BCURA Industrial Laboratories, Leatherhead, England.

H. R. Hoy, Pilot-Plant Experiments at BCURA, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

H. R. Hoy and A. G. Roberts, Power Generation via Combined Gas/Steam Cycles and Fluid-Bed Combustion of Coal, Gas Oil Pwr., July-August 1969, Vol. 65, pp. 173-176.

H. R. Hoy and J. E. Stantan, Fluidised Combustion under Pressure, ACS Div. Fuel Chem., May 1970, Vol. 14, No. 2, pp. 59-77.

L. D. Hulett, Trace Element Measurements at the Coal-Fired Allen Steam Plant - Particle Characterization, Presented at the Coal and the Environment Technical Conference, Louisville, Kentucky, October 22-24, 1974.

T. R. Ingraham, Mechanism of the Absorption of SO_2 by Limestone, Chemical Engineering Progress, June 1971, Vol. 21, No. 6, p. 347.

Institute of Gas Technology, Preparation of a Coal Conversion Systems Technical Data Book, OCR Contract No. 14-32-0001-1730, January 1975, Report No. 3.

Institute of Gas Technology, Preparation of a Coal Conversion Systems Technical Data Book, ERDA Contract No. E(49-18)-1730, April 1975, Report No. 6.

Institute of Gas Technology, Preparation of a Coal Conversion Systems Technical Data Book, ERDA Contract No. E(49-18)-1730, May 1975, Report No. 7.

E. Ishigaki, A Burning Apparatus, U. S. Patent 3,625,165, December 7, 1971.

T. Ishii, Effect of Packing on the Catalytic Isomerization of Cyclopropane in Fixed and Fluidized Beds, 55th National AIChE Meeting, February 7-11, 1965.

S. S. Iskhakov, Carburizing in a Fluidized Bed, Metallovedenie i Termicheskaya Obrabotka Metallov, November 1969, UDC 621.785.51.062.5:621.785:66.096.5.

M. Jackson, Fluidized Beds for Submicron Particle Collection, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, 1974, Vol. 70.

P. J. Jackson, The Psyco-Chemical Behavior of Alkali Metal Compounds in Fireside Boiler Deposits, CEGB Conf. Mechanisms of Corrosion by Fuel Impurities, Butterworth, 1963.

R. Jackson, The Mechanics of Fluidised Beds, Part I: The Stability of the State of Uniform Fluidisation, Trans. Instn. Chem. Engrs. 1963, Vol. 41.

R. Jackson, The Mechanics of Fluidised Beds, Part II: The Motion of Fully Developed Bubbles, Trans. Instn. Chem. Engrs., 1963, Vol. 41.

A. Jacob, Effect of Gas Thermal Conductivity on Local Heat Transfer in a Fluidized Bed, Canadian Journal of Chemical Engineering, June 1957.

C. E. Jahnig, Generalized Correlation for Free Fall and Multiparticle Systems, Annual AIChE Meeting, December 8-11, 1957.

Jahnig, C. E. and H. Shaw, 1976. "Environmental Assessment of an 800 MWe Conventional Steam Power Plant," Exxon/GRU. 1 DJAD. 76, Exxon R&E Co., Linden, N.J., 54 pp, September.

S. C. Jain, Heat Transfer in a Screen-Packed Fluidized Bed, 69th National Meeting of AIChE, May 16-19, 1971.

J. C. Janka, Estimation of Coal and Gas Properties for Gasification Design Calculations, R&D Report No. 22, January 1971, OCR, Contract No. 14-01-0001-381.

R. L. Jarry, Comparative Emissions of Pollutants during Combustion of Natural Gas and Coal in Fluidized Beds, Proceedings of Second International Conference on Fluidized-Bed Combustion, U. S. Environmental Protection Agency, October 4-7, 1970.

K. M. John, Design of Fluidized Bed Combustors, Chemical Engineering, 1972, Vol. 23, No. 1, pp. 33-37.

T. E. Johnson, Evaluation of the Regenerative Pressurized Fluidized-Bed Combustion Process, February 1974, (PB 232 012).

R. D. Jolly, An Examination of the Net Pressure Drop in Fluidized Beds, Chemical Engineering Science, March 1973.

D. C. R. Jones, Fluidisation in the Coal Industry, Fluidisation Papers Joint Symposium, London, 1963.

J. F. Jones, Char Oil Energy Development, Office of Coal Research, December 1971.

J. F. Jones, Fluidized Bed Pyrolysis of Coal, Chemical Engineering Progress, June 1964, Vol. 60, No. 6.

J. F. Jones, Multistage Pyrolysis of Coal, Chemical Engineering Progress, February 1966, Vol. 62, No. 2.

J. F. Jones, Pyrolysis of Agglomerating Coals in Multiple Fluidized-Bed Reactors, Chemical Processes to International Convetion on Fluidization, Eindhoven, Holland.

J. A. H. de Jong, Homogeneous Gas - Solid Fluidization, Powder Technology, February/March 1974, Vol. 9, pp. 91-97.

A. A. Jonke, Fluidized Bed Combustion: A Status Report, Coal Processing Technology, CEP Tech. Manual, 1975, Vol. 2.

A. A. Jonke, Fluidized-Bed Combustion Related to Air Pollution.

A. A. Jonke, Pollution Control Capabilities of Fluidized-Bed Combustion, AIChE Symposium Series, Vol. 68, No. 126.

A. A. Jonke, Reducing Pollution from Fossil Fuel Combustion Instr. and Control Systems, July 1971.

A. A. Jonke, Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion, Annual Report, July 1968 - June 1969, (ANL/ES-CEN-1001).

A. A. Jonke, Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion, Annual Report, July 1969 - June 1970 (ANL/ES-CEN-1002).

A. A. Jonke, Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion, Argonne National Laboratory, Annual Report, July 1970 - June 1971.

A. A. Jonke, Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion, Monthly Progress Reports Nos. 62 (December 1973) through 68 (June 1974), October 1974.

A. A. Jonke, Work Plan for Continuation of the Project: Reduction of of Atmospheric Pollution by the Application of Fluidized-Bed Combustion, April 1971, p. 38, (ANL/ES-CEN-1003).

Jonke, A.A., J.C. Montagna, J.F. Lenc, G.J. Vogel, "The Regeneration of Sulfated Dolomite from a Coal-Fired FBC ((Fluidized Bed Combustion)) Process by Reductive Decomposition of Calcium Sulfate in a Fluidized Bed", Ind Eng Chem Process Des Dev V16 N.2 230-36 (Apr 1977) in English.

Jonke, A.A., W.M. Swift, G.J. Vogel, "Fluidized Bed Combustion: Development Status." Argonne National Laboratory, Ill., Trans. Soc. Min. Eng. AIME, v 258 n 2 June 1975, p 159-167.

Jonke, A.A. et al., "Reduction of Atmospheric Pollution by the Application of Fluidized Bed Combustion", (Annual Report), Argonne National Lab, Argonne, Ill., 1969.

Jonke, A.A. et al., "Reduction of Atmospheric Pollution by the Application of Fluidized Bed Combustion", Argonne National Lab. Argonne, Ill. 1970.

Jonke, A.A. et al, "Pollution Control Capabilities of Fluidized Bed Combustion", AIChE Symposium Series No. 126, Vol. 68,1972 pp. 241-251.

J. W. Kaakinen, Trace Element Behavior in Coal-Fired Power Plant, Environmental Science & Technology, Vol. 9, No. 9, p. 862, September 1975.

J. Kaspar and M. Rosch, A New Development in the Field of Fluidized Bed Granulation, Chem. Eng. Tech., 45 (10A), pp. 736-739, 1973.

D. L. Katz, Evaluation of Coal Conversion Processes to Provide Clean Fuels, Part I, EPRI 206 001, February 1974, (PB 234 202).

D. L. Katz, Evaluation of Coal Conversion Processes to Provide Clean Fuels, Part II, EPRI 206 002, February 1974, (PB 234 203).

V. J. Kavlick, High-Pressure Electrothermal Fluid-Bed Gasification of Coal Char, Fluidization Fundamentals and Application, CEP Symposium Series, Vol. 66, No. 105.

Keairns, D.L. et al., "Fluidized Bed Combustion Process Evaluation. Phase II. Pressurized Fluidized Bed Coal Combustion Development", Westinghouse Research Labs., Pittsburgh, Pa., National Environmental Research Center, Research Triangle Park, N.C., Sept. 1975.

D. L. Keairns, Design of a Pressurized Fluidized-Bed Boiler Power Plant, AIChE Symposium Series, Vol. 68, No. 126.

D. L. Keairns, Evaluation of the Fluidized-Bed Combustion Process, Volume I, Pressurized Fluidized-Bed Combustion Process Development and Evaluation, EPA-650/2-73-048a, U.S. Environmental Protection Agency, December 1973.

D. L. Keairns, Evaluation of the Fluidized-Bed Combustion Process, Volume II, Fluidized-Bed Boiler Combined-Cycle Power Plant Development, Volume I Appendices, EPA-650/2-73-048b, U.S. Environmental Protection Agency, December 1973.

D. L. Keairns, Evaluation of the Fluidized-Bed Combustion Process, Volume III, Pressurized Fluidized-Bed Boiler Development Plant Design, EPA-650/2-73-048c, U.S. Environmental Protection Agency, December 1973.

D. L. Keairns, Evaluation of the Fluidized-Bed Combustion Process, Vol. III Appendices, Contract CPA 70-9, Westinghouse Research Lab, November 15, 1969 - November 15, 1971.

D. L. Keairns, Fluidized-Bed Boilers - Concepts and Comparisons, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

D. L. Keairns, Fluidized-Bed Combustion Utility Power Plants - Effect of Operating and Design Parameters on Performance and Economics, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

Keairns, D.L., (ed.), 1976, Fluidization Technology, Volumes I and II, McGraw-Hill.

Keairns, D.L., D.H. Archer, J.R. Hamm, B.W. Lancaster, E.P. O'Neill, R.A. Newby, C.H. Peterson, C.C. Sun, E.F. Sverdrup, E.J. Vidt, W.C. Yang, "Systems Implications of Desulfurization by Limestone in Pressurized Fluidized Bed Combustion", Proc of the Int Con on Fluid Bed Combust. 4th, McLean, Va. Dec 9-11 1975 Publ by MITRE Corp (m76-36), McLean, Va. 1976 p 493-523.

Keairns, D.L., et al., 1977. "Experimental and Engineering Investigations for the Development of Fluidized Bed Combustion Processes," in (DOE, 1977).

D. L. Keairns, Fluidized-Bed Oil Gasification/Desulfurization, Vol. IV, EPA-650/2-73-048d, Westinghouse Research Lab, December 1973.

J. Keenan and S. Kaye, Gas Tables, John Wiley & Sons, N.Y., N.Y., 1948.

E. Kellett, Boiler Systems, U.S. Patent 3,633,521, January 11, 1972.

K. N. Kettenring, Heat and Mass Transfer in Fluidized Systems, Chemical Engineering Progress, March 1950.

N. V. Kharchenko, The Rate of Heat Transfer Between a Fluidized Bed and an Immersed Body at High Temperatures, International Chemical Engineering, October 1964.

Kiang, K.D., H. Nack, J.H. Oxley, W.T. Reid, "Fluidized Bed Combustion of Coals" Technol and Use of Lignite, Proc of a Synp. Grand Forks, ND, May 14-15 1975, Publ by DOE, Off of Public Aff. Tech Inf Cent. (GFERC/IC-75/2), Oak Ridge, Tenn. 1975 p 36-64.

K. J. Kim, Heat and Mass Transfer in Fixed and Fluidized Bed Reactors, International Chemical Engineering, Vol. 7, No. 1, January 1967.

C. N. Kimberlin, Jr. and others, Production of Coke, U.S. Patent 3,459,655, August 5, 1969.

Klein, D.H., et al., 1975 "Pathways of 37 Trace Elements Through Coal-Fired Power Plant", Environmental Science and Technology, 9, p 973, October.

C. W. J. van Koppen, Fluidbed-Vuurhaarden, DeIngenieur, Vol. 77, No. 13, pp. 37-43, March 1965.

V. N. Korolev, Heat Transfer from a Surface to a Fluidized Bed, Heat Transfer, Soviet Research, Vol. 3, No. 4, July-August 1971.

V. N. Korolev, The Fluid Mechanics and Structure of the Fluidized Bed in the Vicinity of a Plate Submerged in It, Heat Transfer, Soviet Research, Vol. 6, No. 4, July-August 1974.

O. Kubaschewski, Oxidation of Metals and Alloys, Academic Press, Inc., p. 211, 1953.

J. Kubie, A Model of Heat Transfer in Gas Fluidized Beds, Int. J. Heat Mass Transfer, Vol. 18, 1975.

D. Kunii, Bubbling Bed Model (Model for the Flow of Gas Through a Fluidized Bed), I&EC Fundamentals, Vol. 7, August 1968.

D. Kunii, Fluidization Engineering, John Wiley & Sons, Inc., 1969.

V. P. Kurbatov, Heating in an Electrically Conducting Layer of Carbon-Containing Particles, Metallouedenie i Teamcheskaya, UDC 621.785:66.096.5, June 1971.

J. Lambiris, Total Incineration Process, U.S. Patent 3,601,070, August 24, 1971.

W. C. Lapple, Generalized Mechanics of Fluid Flow Through Particulate Material, M.S. thesis, Kansas University, 1957.

L'Ashkov, V.I., Yu. A. Streltsov, V.V. Streltsov, A.I. Derevyakina, "Design Calculation of a Fluidized-Bed Fixed Packing Reactor Under Countercurrent Conditions. III.", IZV Vyssh Uchebn Zaved Khim Khim Tekhnol 1975 v18 N.4 678 Chem Abstr V83-208032 in Russian.

B. S. Lee, E. J. Pyrcioch, and F. C. Schora, Jr., Hydrogasification of Coal in High-Pressure Fluidized Bed, Chem. Eng. Progr. Symp. Ser., Vol. 66, No. 105, p. 152, 1970.

B. S. Lee, Kinetics of Particle Growth in a Fluidizer Calciner, 54th Annual AIChE Meeting, December 2-7, 1961.

R. E. Lee, National Air Surveillance Cascade Impactor Network II, Size Distribution Measurements of Trace Metal Components, Environmental Science & Technology, Vol. 6, No. 12, p. 1025, November 1972.

R. E. Lee, Trace Metal Pollution in the Environment, Journal of the Air Pollution Control Association, Vol. 23, No. 10, p. 853, October 1973.

M. B. Leland, Heat Exchange System, U.S. Patent 2,926,143, February 23, 1960.

S. Lemezis, Coal Gasification for Electric Power Generation, Combustion, Vol. 45, No. 5, November 1973.

R. Lemlich, Heat Transfer to a Liquid Fluidized Bed, AIChE Journal, Vol. 4, No. 3, September 1959.

M. Leva, Chemical Engineering Progress, 43, pp. 549-554, 1947.

M. Leva and Grummer, Chemical Engineering Progress, 43, p. 633, 1947.

M. Leva, Fluidization, McGraw Hill, N.Y., N.Y., 1959.

O. Levenspiel, Bed Wall Heat Transfer in Fluidized Systems Heat Transfer, Symposium Series, Vol. 50, No. 9.

Levy, E.K., and J.C. Chen, 1977. "Centrifugal Fluidized Combustion of Coal," in (DOE, 1977).

Levy, E.K., C. Dodge, J. Chen, "Parametric Analysis of a Centrifugal Fluidized Bed Coal Combustor." ASME Pap n 76-HT-68 for Meet Aug 9-11 1976. 9 p.

W. K. Lewis, Entrainment from Fluidized Beds, 54th Annual AIChE Meeting, December 2-7, 1961.

W. K. Lewis, IEC, 41, p. 1104, 1949.

S. U. Li and others, Upflow Three-Phase Fluidized Bed Coal Liquefaction Reactor System, U.S. Patent 3,644,192, February 22, 1972.

P. B. Liao, Fluidized-Bed Sludge Incinerator Design, Incinerator Design, Vol. 46, No. 8, August 1974.

C. J. Lim, Residence Time Distribution of Gas in Spouted Beds, The Canadian Journal of Chemical Engineering, Vol. 52, April 1974.

J. M. Limerick, Copeland System for Burning Bark, Debris, and Sludge Starts Up at Great Lakes, Pulp and Paper Magazine of Canada, Vol. 73, No. 1, January 1972.

T. Linden, Inst. Mech. Engrs., 160, p. 235, 1949.

H. Littman and A. P. Stone, Gas-Particle Heat Transfer Coefficients in Fluidized Beds by Frequency Response Techniques, Chem. Eng. Progr. Symp. Ser., Vol. 62, No. 62, pp. 47-55, 1966.

B. Locke, Fluidized Combustion for Advanced Power Generation with Minimal Atmospheric Pollution, J. Inst. Fuel, 47 (392), pp. 117-147, 1974.

H. B. Locke, Combustion of Residual Fuel Oils in Fluidized Beds, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

Locke, Brian, Howard Lunn, 1977, "Advances in Pollution-Free Heat and Power Generation Made Possible by Developments in Fluidized Combustion Technology", Combust. Syst. LTD., London.

Locke, H.B., H.G. Lunn, 1977, "Fluidized Combustion Power Cycles with Environmentally Acceptable Stack Gases", Int. Congr. Chem. Eng., Chem. Equip. Des. Autom., (Proc.), 5th S-J, SJ4.20. 7 pp.

Locke, Brian, Howard Lunn, "Advances in Pollution-Free Heat and Power Generation Made Possible by Developments in Fluidized Combustion Technology", D. chema Momogr v 80 n 1616-1638 1976 p 77-104.

Locke, H.B., H.G. Lunn, H.R. Hoy, A.G. Roberts, "Fluidized Combustion in Great Britain - - Environmentally Clean Steam and Power Generation from Coal, Heavy Oil and Dirty Fuels", Proc of the Int Conf on Fluid-Bed Combust. 4th, McLean, VA, Dec 9-11 1975 Publ by MITRE Corp (M76-36), McLean, VA, 1976 p 69-91.

Louis, J.F. and S.E. Tung, 1977. "Modeling of Fluidized Bed Combustion of Coal," MIT Energy *Laboratory*, DOE, May.

Lowell, P.S. and T.B. Parsons, 1975. "Identification of Regenerable Metal Oxide SO_2 Sorbents for Fluidized Bed Coal Combustion", EPA/650/2-75/065, Washington, D.C.

R. C. Mallatt and others, Tertiary Treatment and Fluidized Bed Incineration at American Oil Company, Procl. Div. Refining, Amer. Petrol. Inst., 50, pp. 651-669, 1970.

R. S. Mann, Gas-Solid Heat Transfer in Fluidized Beds, *I&EC Process Design & Development*, Vol. 7, No. 3, July 1968.

I. G. Martyushin, Fluidized Bed Apparatus Divided into Sections by Grid Trays, 1974, (N75-14779).

K. B. Mathur, Developments in Spouted Bed Technology, *The Canadian Journal of Chemical Engineering*, Vol. 52, April 1971.

C. W. Matthews, A Design Basis for Utility Gas from Coal, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

C. W. Maude, Practical Approaches to Power Generation from Low Grade Fuels, *The Chemical Engineer*, May 1975.

C. R. McCann, NO_x Emissions from Two-Stage Combustion of Pulverized Coal, 65th Annual Meeting of Air Pollution Control Association, June 18-22, 1972.

E. A. McCracken, Mathematical Solutions to Fluid Bed Models, 60th Annual AIChE Meeting, November 26-30, 1967.

W. A. McCurdy, Pressurized Bluidized Bed Combustion, National Research Development Corp., London, England, October 1974, (PB 236 498).

L. McLain, Can Shallow Fluidized Beds Offer Savings in Waste Heat Recovery and Drying? *Process Engineering*, Heat Transfer Survey, pp. 30-32, 1973.

J. McLaren, Combustion Efficiency, Sulphur Retention, and Heat Transfer in Pilot Plant Fluidized-Bed Combustors, *Combustion*, Vol. 41, No. 11, May 1970.

J. McLaren and D. F. Williams, Combustion Efficiency, Sulphur Retention and Heat Transfer in Pilot-Plant Fluidized-Bed Combustors, *J. Inst. Fuel*, Vol. 42, No. 343, pp. 303-308, August 1969.

J. McLaren, Fluidized Bed Combustion, *Energy Int.*, 5 (3), pp. 12-13, March 1968.

J. McLaren and D. F. Williams, Process and Apparatus for the Combustion of Carbonaceous Material, U.S. Patent 3,540,387, November 17, 1970.

J. McLaren and W. Harris, Solid Fuel Combustion Apparatus, U.S. Patent 3,636,896, May 12, 1970.

J. F. McMahon, Fluidized Bed Hydrogenation Process for SNG, Chemical Engineering Progress, December 1972.

J. Medlin, Fluid Mechanical Description of Fluidized Beds, Convective Instabilities in Bounded Beds, Ind. Eng. Chem., Fundam., Vol. 13, No. 3, 1974.

D. Merrick, Particle Size Reduction and Elutriation in a Fluidized-Bed Process, AIChE Symposium, Control of Particulate Emissions from Gaseous Fluidized Beds, November 1972.

D. Merrick, Particle Size Reduction and Elutriation in a Fluidized-Bed Process, Fluidization and Fluid-Particle Systems, Vol. 70, 1974, AIChE Symposium Series.

J. E. Mesko, Atmospheric Fluidized Bed Steam Generators for Electric Power Generation, 36th Meeting American Power Conference, 1974.

J. E. Mesko, Multicell Fluidized-Bed Boiler Design, Construction, and Test Program, OCR 90 INTI, August 1974, (PB 236 254).

Mesko, J.E., "Fluidized Combustion Energy Conversion Techniques for High Sulfur-Low Grade Fuels", Presented at the American Chemical Society 172nd National Meeting, San Francisco, August 29-September 3, 1976.

Mesko, J.E., "Atmospheric Fluidized Bed Steam Generators for Electric Power Generation", American Power Conference, 1974.

Metals Handbook, Vol. 1, Properties and Selection of Metals, 8th Ed., Am. Soc. Metals, Metals Park, Ohio.

H. S. Mickley, Heat Transfer Characteristics of Fluidized Beds, IEC, Vol. 41, No. 6, June 1949.

H. S. Mickley, Mechanism of Heat Transfer to Fluidized Beds, AIChE Journal, Vol. 1, No. 3, September 1953.

T. Mii and others, Temperature Effects on the Characteristics of Fluidized Beds, Journal of Chemical Engineering of Japan, 6 (1), pp. 100-102, February 1973.

C. O. Miller, Fluidization Studies of Solid Particles, IEC, Vol. 43, No. 5, May 1951.

Minutes of Second Information Exchange Meeting, NCB/NAPCA, Hobart House, London, April 20, 1970.

S. N. Mironov, Experimental Investigation of the Combustion of Pulverized Anthracite, Teploenergetika, January 1965.

MIT Energy Laboratory, 1977, "Fluidized Bed Combustor Model and Computer System Development," Documentary Notebook, MIT, Cambridge, MA.

MITRE Corp., 1977, "Background Information on the RD &D Programs for the Development of Fluidized Bed Combustion Systems," M77-31, Prepared by MITRE, METREK Division.

MITRE Corp., 1976, "Proceedings of the Workshop on Utility Industrial Implementation of Fluidized Bed Combustion Systems," Sponsored by DOE, Coordinated by MITRE/METREK Division, Conf. 760490, M76-62, October.

The Proceedings of the Fourth International Conference on Fluidized-Bed Combustion, sponsored by the U.S. Energy Research and Development Administration, the MITRE Corporation, McLean, Virginia, May 1976.

MITRE Corp., 1975, "The Proceedings of the Fourth International Conference on Fluidized Bed Combustion," DOE/MITRE, December 9-11.

Mitre Corporation, National Fluidized Bed Combustion Program, Vol III, State-of-the-Art Report, prepared for OCR-ERDA, March 1975.

Mitre Corporation, National Fluidized Bed Combustion Program, Vol. V, Bibliography, prepared for OCR-ERDA, March 1975.

S. Mori, Heat Transfer Coefficient Between Solid Particles and Gas in Fluidized Bed, Heat Transfer - Jap. Res., July-September 1973.

S. Mori, Heat Transfer During Bubble Formation in Gaseous Fluidized Beds, Heat Transfer - Jap. Res., Vol. 2, October-December 1973.

S. Mori, High Pressure Fluidization and the Momentum Relations, PhD, Chemical Engineering, University of Utah, 1973.

J. B. Morris, Combustion Behavior of Small Particles, Ind. & Eng. Chem., May 1966.

G. Moss, The Design, Construction, and Operation of the Abingdon Fluidized-Bed Gasifier, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

G. Moss, The Fluidized-Bed Desulfurizing Gasifier, AIChE Symposium Series, Vol. 68, No. 126.

G. Moss, The Fluidized-Bed Desulfurizing Gasifier, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

G. Moss, Sulphur Removal During Fluidized Bed Combustion, Chemical Engineering, 23 (1), pp. 24-29, Spring 1972.

D. R. Muirhead and others, Incinerators, U.S. Patent 3,577,938, May 11, 1971.

D. R. Muirhead, Incinerators, U.S. Patent 3,577,939, May 11, 1971.

J. D. Murray, Mathematical Aspects of Bubble Motion in Fluidized Beds, 55th National AIChE Meeting, February 7-11, 1965.

J. D. Murray, On the Mathematics of Fluidization, Part 1, Fundamental Equations and Wave Propogation, Journal of Fluid Mech., Vol. 21, 1965.

J. D. Murray, On the Mathematics of Fluidization, Part 2, Steady Motion of Fully Developed Bubbles, Journal of Fluid Mech., Vol. 22, 1966.

K. S. Murthi, Reaction of Sulfur Dioxide with Calcined Limestones and Dolomites, Environmental Science and Technology, Vol. 5, No. 9, pp. 776-781, September 1971.

Murthy, K.S. and H. Nack, 1977. "Progress in EPA's Fluidized Bed Combustion Environmental Assessment and Control Technology Development Program," in (DOE, 1977).

H. Nack, Fluidized Bed Combustion Review, International Conference on Fluidization, Asilomar, California, June 1975.

Nack, H., A.E. Weller, K.T. Liu, 1977. "Battelles' Multisolid Fluidized Bed Combustion (MS-FBC) Process," in (DOE, 1977).

Nack, H. et al., 1975, "Fluidized Bed Combustion Review," Battelle Columbus Laboratories, June.

National Aeronautics and Space Administration
Comparative Evaluation of Phase I from the Energy Conversion Alternatives Study (ECAS) Funding Org.- DOE and NSF, February, 1976, Report No. - NASA TM X-71855.

National Coal Board, 1971. "Reduction of Atmospheric Pollution", Vols. I,II,III to EPA-OAP.

National Research Development Corporation, Pressurized Fluidized Bed Combustion, R&D Report No. 85, Interim No. 1, OCR - Contract No. 14-32-0001-1511.

National Research Development Corp., 1973. "Final Report to OCR", US D.I, Contract 14-32-0001-1511, November.

D. F. S. Natusch, Toxic Trace Elements: Preferential Concentration in Respirable Particles, Science, Vol. 183, p. 202, January 1974.

A. Nazemi, Dilute Phase Hold-up in a Large Gas Fluidized Bed, Fluidization and Fluid-Particle Systems, AIChE Symposium Series, Vol. 70, 1974.

J. Nelson, Mineral Constituents in Coal, C.E.G.B. Conf. Mechanism of Corrosion by Fuel Impurities, Butterworth, 1963.

P. A. Nelson, Particle to Fluid Heat and Man Transfer in Dense Systems of Fine Particles, Chem. Engr. Sci., Vol. 30, 1975.

W. Nelson, J. Engr. for Power, 82, p. 194, 1960.

New Boilers May Keep Coal Competitive, C&EN, January 11, 1971.

R. A. Newby and others, Assessment of Fluidized Bed Oil Gasification for Power Generation, Journal of the Air Pollution Control Association. 23 (1), pp. 23-29, January 1973.

R. A. Newby, Fluidized-Bed Oil Gasification for Clean Power Generation - Atmospheric and Pressurized Operation, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

W. J. Nicholson, Solids Blending in a Fluidized Bed, 55th Annual AIChE Meeting, February 7-11, 1965.

Nielson, K.L., R.J. Robertus, C.T. Crowe, D.T. Pratt, "An Attempt ot Reduce NOx Emissions from Pulverized Coal Furnances", Environ Sci Technol V9 N.9 859-62 (Sept 1975).

P. Novotny, Fluid-Bed Combustion of High-Ash Coals, Tech. Dig. (Prague), 1968.

P. Novotny, Fluid-Bed Combustion of High-Ash Fuels, Sntl. Tech. Digest, 2 (12), pp. 12-15, 1968.

M. S. Nutkis, Design of Fluidized-Bed Miniplant, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

Nutkis, Melvyn S., 1977, "Pressurized Fluidized Bed Coal Combustion", Fluid. Technol., Proc. Int. Fluid. Conf. 2, 329-37.

Nutkis, Melvyn S., "Operation and Performance of the Pressurized FBC Miniplant", Proc of the Int Conf on Fluid-Bed Combust. 4th, McLean, Va. Dec 9-11 1975 Publ by MITRE Corp (M76-36), McLean, Va. 1976 p 221-238.

E. P. O'Neill, Kinetic Studies Related to the Use of Limestone and Dolomite as Sulfur Removal Agents in Fuel Processing, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

A. A. Orning and C. R. McCann, A Study of Fluidized Bed Combustion of Coal, Society of Mining Engineers of AIME, February 1968.

Osborne, J.M., and L. Bulger, Overview Assessment of Pressurized Fluidized-Bed Technology, Report SL-3268, prepared by Sargent & Lundy for Argonne National Lab., June 1976.

D. F. Othmer, Fluidization, Reinhold Publishing Co., N.Y., N.Y., 1956.

J. I. Paige, Sorption of SO_2 and Regeneration of Alkalized Alumina in Fluidized-Bed Reactors, Bureau of Mines Report of Investigations 7414, August 1970.

Parks, Donald J., Edward A. Fletcher, "Formation and Emission of Nitric Oxide in Fluidized Bed Combustion." Environmental Sci. Technol. V 9 n 8, Aug. 1975, p 749-756.

D. J. Parks, Formation of Nitric Oxide in Fluidized Bed Combustion, PhD, Mechanical Engineering, University of Minnesota, 1973.

T. Parsons, Applicability of Metal Oxides to the Development of New Processes for Removing SO_2 from Flue Gases, Vol. I, July 1969, (PB 185 562).

T. Parsons, Applicability of Metal Oxides to the Development of New Processes for Removing SO_2 from Flue Gases, Vol. II, July 1969 (PB 185 563).

B. A. Partridge, Chemical Reaction in a Bubbling Gas-Fluidized Bed, Trans. Instr. Chem. Engrs., Vol. 44, pp. T335-358, 1966.

G. K. Patterson, Drag Reduction Correlations, AIChE Journal, Vol. 16, No. 3, May 1970.

R. J. A. Paul, Stability of Coupled Fluid Beds, Brit. Chem. Engr., Vol. 13, No. 5, May 1968.

N. J. Peet, The Rapid Carbonization of High Organic Sulphur, Fuel, Vol. 48 1969.

M. Pell, Desulfurization of Fuels with Calcined Dolomite - II, Reaction of CaO with H_2S, Sulfur and SO_2 Developments, a CEP Technical Manual, pp. 151-157.

M. Pell, Reaction of Hydrogen Sulfide with Fully Calcined Dolomite, PhD thesis, City University of New York, 1971.

Pereira, F.J. and J.M. Beer, 1975. "NO Formation from Coal Combustion in a Small Experimental Fluidized Bed," 2nd European Symposium on Combustion, Orleans, France, August.

Pereira, F.J., J.M. Beer, B. Gibbs, and A.B. Hedley, 1974. "NO_x Emissions From Fluidized Bed Coal Combustors," 15th International Symposium on Combustion, The Combustion Institute, Pittsburgh, PA, pp 1149-1156.

J. C. Petrie, Heat Transfer from Horizontal Tube Bundles to Air-Fluidized Beds, 60th Annual AIChE Meeting, November 26-30, 1967.

J. C. Petrie, In-Bed Heat Exchangers, Chemical Engineering Progress, July 1968.

L. J. Petrovic, Effectiveness Factors for Heat Transfer in Fluidized Beds, The Canadian Journal of Chemical Engineering, Volume 46, April 1968,

J. R. Pfafflin, Heat and Mass Transfer in Fluidized Beds, Fluidization and Fluid-Particle Systems, Vol. 70, AIChE Symposium Series, 1974.

J. R. Pfafflin and others, Unsteady State Thermal Responses of Fluidized Beds, Journal of the Institute of Fuel, September 1973.

J. P. Piney, Fluidized Bed Fly Ash Filter, Journal of the Air Pollution Control Association, Vol. 18, No. 10, pp. 684-685, October 1968.

A. L. Plumley, Removal of SO_2 and Dust from Stack Gases, presented at the American Power Conference, Chicago, Illinois, April 25, 1967.

E. M. Poole, Fluid Bed Boilers, Literature Search 72-47.

E. M. Poole, Sand Wear Rates, Literature Search 75-12, March 24, 1975.

Pope, M., "Pilot and Research Plants: A Progress Report", Proceedings of the Fourth International Conference on Fluidized-Bed Combustion, The MITRE Corp., McLean, Virginia, 1976, pp. 123-132.

Pope, Evans, and Robbins, Development of Coal Fired Fluidized-Bed Boilers, Monthly Progress Reports Nos. 1 (April 1965) through 15 (June 1966), October 1974, (PB 236 544).

Pope, Evans, and Robbins, Development of Coal Fired Fluidized-Bed Boilers, Monthly Progress Reports Nos. 16 (July 1966) through 31 (September 1967), October 1974 (PB 236 542).

Pope, Evans, and Robbins, Development of Coal Fired Fluidized-Bed Boilers, Monthly Progress Reports Nos. 32 (October 1967) through 44 (October 1968), October 1974, (PB 235 898).

Pope, Evans, and Robbins, Development of Coal Fired Fluidized-Bed Boilers, Monthly Progress Reports Nos. 45 (November 1968) through 54 (August 1969), October 1974, (PB 235 899).

Pope, Evans, and Robbins, Development of Coal Fired Fluidized-Bed Boilers, Monthly Progress Reports Nos. 55 (May 1971) through 64 (February 1972), October 1974, (PB 236 541).

Pope, Evans, and Robbins, "Multicell Fluidized Bed Boiler Design, Construction and Test Program", OCR R and D Report No. 10, Interim Report No. 1 for Oct. 1972 - June 1974, PB 236-245.

Pope, Evans, Robbins, 1975. "Muticell Fluidized Bed Boiler, Design, Construction and Test Program, PER Report.

Pope, Evans, and Robbins, Interim Report No. 1 on Multicell Fluidized-Bed Boiler Design, Construction, and Testing Program, OCR Contract No. 14-32-0001-1237, August 1974.

Pope, Evans, and Robbins, Multicell Fluidized-Bed Boiler, Monthly Progress Reports Nos. 1 (October 1972) through 9 (June 1973), (PB 235 844).

Pope, Evans, and Robbins, Multicell Fluidized-Bed Boiler, Monthly Progress Reports Nos. 10 (July 1973) through 14 (November 1973), (PB 235 845).

Pope, Evans, and Robbins, Multicell Fluidized-Bed Boiler, Monthly Progress Reports Nos. 15 (December 1973) through 18 (March 1974), (PB 235 846).

Pope, Evans, and Robbins, Multicell Fluidized-Bed Boiler, Monthly Progress Reports Nos. 19 (April 1974) through 21 (June 1974), October 1974, (PB 235 847).

Pope, Evans, and Robbins, Optimization of Limestone Utilization and Sulfur Capture in a Single Combustion Zone Fluidized-Bed Boiler, OCR R&D Report No. 88, Final, March 20, 1974.

Pope, Evans, and Robbins, Package of Information Providing Synopsis per Fluidized-Bed Boiler Development, June 1971.

M. Pope, Progress in Fluidized-Bed Boilers, Power Engineering, May 1970.

A. E. Potter, Sulfur Oxide Capacity of Limestones, Ceramic Bulletin, Vol. 48, No. 9, p. 855, 1969.

Pressurized Fluidized Bed Combustion, NRDC R&D Report No. 85 (Interim No. 1), prepared for OCR.

Preston, E., et al., 1977, "Environmental Assessment of a 30-MWe Multi-Cell Fluidized Bed (MFB) Boiler," at the Monongahela Power Plant in Rivesville, West Virginia, the MITRE Corp/METREK Division, (E(49-18)-1779).

R. J. Priestley, Where Fluidized Solids Stand Today, Chemical Engineering, July 9, 1962.

Proceedings of Second International Conference on Fluidized-Bed Combustion, sponsored by U.S. Environmental Protection Agency, October 4-7, 1970.

T. A. Pumpyanskaya, Tempering of Carburized Steel in a Fluidized Bed, Translated from Metallovedenie i Termicheskaya Obrabotka Metallov, UDC 66.096.5:669-155.2, January 1973.

E. Raask, Tube Erosion by Ash Impaction, Wear, Vol. 13, No. 4/5, April/May 1969.

M. I. Rabinovich, Heat Transfer from a Horizontal Tube to a Spouting Bed in a Tapered Cylindrical Vessel, Heat Transfer - Soviet Research, Vol. 5, No. 5. September-October 1973.

J. Raghuraman, A Stochastic Model for Residence Time and Contact, Time Distributions of the Gas in Multistage Fluidized Beds, Chemical Engineering Science, Vol. 29, pp. 697-703, 1974.

J. Raghuraman, An Experimental Investigation of the Residence Time Distribution of Solids in Multistage Fluidization, Chemical Engineering Science, Vol. 30, pp. 145-150, 1975.

J. Raghuraman, Residence Time Distribution of Solids in Multistage Fluidized Beds, Chemical Engineering Science, Vol. 28, No. 1, January 1973.

K. A. Rahn, Diurnal Variations of Aerosol Trace Element Concentrations as Determined by Non-Destructive Neutron Activation Analysis, Atmos. Environ., Vol. 5, p. 413, 1971.

D. W. Rahoi, Controlling Fuel-Ash Corrosion with Nickel Alloys, Metals Engineering Quarterly, February 1974.

K. S. Raju and others, Heat Transfer in Externally Heated and Internally Cooled Fluidized Beds, Indian J. Technology, Vol. 5, No. 8, pp. 237-240, August 1967.

K. S. Rao, Fluidized Bed Low-Temperature Carbonization of Coal, Ind. Eng. Chem. Prod. Res. Develop., Vol. 11, No. 2, 1972.

Rao, C.S.R., 1975. "Safety Aspects of Fluidized Bed Combustion Systems", Proceedings of the 4th International Conference on Fluidized Bed Combustion, MITRE Corp.

V. R. Rao and V. F. Stepanchuk, Combustion of Gaseous Fuels in Fluidized Beds, Indian J. Technology, Vol. 5, No. 8, pp. 245-248, August 1967.

R. Rasch, Lecture at the 4th International Congress of the IAM in Barel, abstracted from "Solid Waste Management of Plastics," DeBell and Richardson.

Reaction Kinetics and Transfer Processes, AIChe Symposium Series, Vol. 48, 1952.

Recent Soviet Research on Fluidization - Part 1, British Chemical Engineering, Vol. 9, No. 7, pp. 461-463, July 1964.

Reduction of Atmospheric Pollution, National Coal Board Report, Vol. I - Main Report, September 1971.

Reduction of Atmospheric Pollution, National Coal Board Report, Appendices: Vol. 2 of 3, September 1971.

Reduction of Atmospheric Pollution, National Coal Board Report, Appendices: Vol. 3 of 3, September 1971.

Reed, R.R., 1977. "Mutiple Feed Pint CBC Test Program," in (DOE, 1977).

Reh. L., "Possibilities of Employing Fluidized Bed Combustion in Power Plant Operation." VGB Kraftwerkstech v 56 n 8 AUg 1976 p 509-518.

L. Reh, Combustion of Oil or Gas in Fluidized Beds, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

L. Reh, Fluidized Bed Processing, Chemical Engineering Progress, Vol. 67, No. 21, February 1971.

W. T. Reid, Basic Factors in the Capture of Sulfur Dioxide by Limestone and Dolomite, Journal of Engineering for Power, January 1970.

Removal of Fly Ash by Fluidized Bed Techniques, Final Report, North Star Research Institute, Contract 14-69-0070-375, March 8, 1968.

H. Reuter, On the Nature of Bubbles in Gas and Liquid Fluidized Beds, 55th National AIChE Meeting, February 7-11, 1965.

R. L. Rice, Combustion of Coals in Fluidized Beds of Limestone, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

R. L. Rice, Fluid Bed Combustion: Suitability of Coals and Bed Materials, Power Engineering, December 1971.

Rice, R.L. and N.H. Coates, "Fluid Bed Combustion: Suitability of Coals and Bed Materials", Power Engineering, Vol. 75, No.12, December 1971, pp. 36-38

J. F. Richardson, Heat Transfer Between Particles and a Gas in a Fluidized Bed, Trans. Instn. Chem. Engrs., Vol. 37, 1959.

J. F. Richardson, Sedimentation and Fluidization, Part II - Heat Transfer from a Tube Wall to a Liquid-Fluidized System, Trans. Instn. Chem. Engrs., Vol. 36, 1958.

H. Ritzmann, The Influence of the Scale Up on the Local Rheological Properties of Gas Fluidized Beds, Chemical Engineering Science, Vol. 29, February 1974.

A. G. Roberts, Fluidized Combustion of Fossil Fuels, Coal Processing Tech., CEP Tech. Manual, Vol. 2, 1975.

A. G. Roberts, The Combustion of Coal in Fluidized Beds Under Pressure, BCUEA Gaz., No. 65, pp. 17-19, 1968.

Roberts, A.G., et al., "Fluidized Combustion Power Cycles with Environmentally Acceptable Stack Gases", presented in a panel discussion on Clean Energy from Coal, Part IV Clean Burning of Coal, AIChE 67th Annual Meeting, Washington, D.C., December 1-5, 1974.

Robison, E.B., et al., 1970, "Characterization and Control of Gaseous Emissions from Coal-fired Fluidized Bed Boilers," Pope, Evans and Robbins, October (PB 198 413).

Robinson, E.B., et al., "Characterization and Control of Gaseous Emissions from Coal-Fired Fluidized Bed Boilers", Pope, Evans and Robbins, Alexandria, Va., Oct. 1970.

E. B. Robison, Characterization and Control of Gaseous Emissions from Coal-Fired Fluidized-Bed Boilers, October 1970, (PB 198 413).

E. B. Robison, Study of Characterization and Control of Air Pollutants from a Fluidized-Bed Combustion Unit, The Carbon-Burnup Cell, February 1972, (PB 210 828).

F. L. Robson, Fuel Gasification and Advanced Power Cycles - A Route to Clean Power, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

Roger, L.L., "Reaction Products of Coal-Ash and Limestone from Fluidized Bed Combustors" J Inst Fuel v 50 n 402 Mar 1977 p 14-18.

T. K. Ross, Distribution of Sulfur in Corrosion Products Formed by Sulfur Dioxide on Mild Steel, Corrosion Science, Vol. 5, 1965.

J. Rossoff, Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Initial Report, May 1974, (PB 237 114).

G. F. Round, Thermal Separation of Coal-Oil Suspensions in a Fluidized Bed, The Canadian Journal of Chemical Engineering, February 1966.

P. N. Rowe, The Mechanisms of Solids Mixing in Fluidized Beds, Trans. Instn. Chem. Engrs., Vol. 43, 1965.

P. N. Rowe, Variation in Shape with Size of Bubbles in Fluidized Beds, Chemical Engineering Science, March 1973.

Ruch, R.R., J.J. Gluskoter, and N.F. Shimp, 1974, "Distribution of Trace Elements in Coal," EPA-650/2-74-118, pp 49-54, May.

L. A. Ruth, Desulfurization of Fuels with Half-Calcined Dolomite: First Kinetic Data, Environmental Science & Technology, Vol. 6, No. 12, p. 1009, November 1972.

L. A. Ruth, Reaction of Hydrogen Sulfide with Half-Calcined Dolomite, PhD thesis, City University of New York, 1972.

Ruth, L.A., "Regeneration of CaSO$_4$ in FBC, Fourth International Conf. on Fluidized Bed Combustion", McLean, Va., Dec. 1975, pp. 425-438.

Ryabchikov, S. Ya., B.K. Amerik, "Investigation of Dust Collection Systems in Fluid Bed Vessels." Chem. Technol. Fuels Oils v 11 n 1-2, Jan-Feb 1975, pp 118-121.

R. K. Saksena and C. R. Mitra, Minimum Fluidizing Velocity for Homogeneous Systems and Mixtures, Indian Chemical Engineering, 14 (3), pp. 35-37, July-September 1972.

M. R. Schmid and others, The Fluidized-Bed Pyrolysis of Western Bituminous Coals, Chem. Eng. Progr. Symp. Ser., Vol. 64, No. 85, pp. 26-30, 1968.

H. W. Schmidt, Combustion in a Circulating Fluid Bed, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

K. A. Schowalter and E. F. Petras, Clean-Char Process, Am. Chem. Soc. Div. Fuel Chem. Prepr., Vol. 19, No. 2, pp. 1-17, April 1974.

F. G. Schultz, Hot Sulfur Removal from Producer Gas, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

K. Schwitzgebei, Thermodynamic Basis for Existing Experimental Data in Mg-SO$_2$-O$_2$ and Ca-SO$_2$-O$_2$ Systems, Environmental Science & Technology, Vol. 7, No. 13, p. 1147, December 1973.

R. V. Seibel, Design of Atmospheric Fluidized-Bed Combustion Steam Generator, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

G. D. Sergeant, Relative Roles of Chemical and Mass Transfer Rate Control in Fluidized-Bed Combustion of Coal Chars, Fuel, Vol. 52, 1973.

R. G. Seth, Water Heater Having Fluidized Bed Combustion and Heat Exchange Region, U.S. Patent 3,645,237, June 10, 1970.

N. A. Shakhova, The Problem of Interphase Heat Transfer in a Fluidized Bed, International Chemical Engineering, July 1974.

Shang, J.Y. and R.A. Chronowski, 1975. "Comparison of AFBC and PFBC", Proc. of 4th International Conference on Fluidized Bed Combustion, Mitre Corp., McLean, VA., December.

Shaw, H., 1977 see (Shaw, Cain, 1977).

Shaw, H. and W.C. Cain, 1977. "Environmental Considerations in Advanced Energy Conversion Technology Assessments", Proceedings 12th IECEC, Washington, D.C., August.

I. D. Shaw, T. W. Hoffman, and P. M. Reilly, Experimental Evaluation of Two-Phase Models Describing Catalytic Fluidized-Bed Reactors, Fluidization and Fluid-Particle Systems, Vol. 70, AIChE Symposium Series, 1974.

Shaw, J.T., 1977, "Reduction of Air Pollution by the Application of Fluidized-Bed Combustion Under Pressure with Special Reference to Emissions of Nitric Oxides (NOx)", Control Gaseous Sulphur Nitrogen Compd. Emiss., Pap. Int. Conf., 2nd 2. V. 30 pp. 76.

Shaw, J.T. and A.C. Thomas, "Oxides of Nitrogen in Relation to the Combustion of Coal", The Seventh International Conference on Coal Science, Prague, June 1968.

R. Shinnar, Complex Mixing Models for Chemical Reaction Systems, City College Research Foundation, N.Y., December 1971, (AD 734 762).

L. L. Shrier, Corrosion, Vol. 1, Section 9, Wiley & Sons, N.Y., N.Y., 1963.

F. G. Shultz, Removal of Hydrogen Sulfide from Simulated Producer Gas at Elevated Temperatures and Pressures, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

W. L. Silence, Sliding Wear in Coal Gasification, Workshop on Material Problems: Research Opportunities in Coal Conversion, Ohio State University, April 16-18, 1974.

L. O. Sillen, Solid Gas Equilibria of Importance in Burning Concentrated Calcium or Magnesium Sulfite Waste Liquor, Svenskpapperstidning Engr., 55, September 4, 1952.

R. B. Sims, Fluidization Technology for Improved Handling, Transport and Treatment of Coal, World Power Conference, Tokyo Sectional Meeting, October 16-20, 1966.

W. Sisson, Calculate Heat Energy Absorbed by Boiler Fluid, *Power Engineering*, p. 33, February 1971.

M. Sittig, Fluidized Solids, *Chemical Engineering*, pp. 219-231, May 1953.

E. Skinner, Materials of Construction, *Chemical Engineering*, p. 137, December 15, 1958.

A. Skopp, Fluid Bed Studies of the Limestone Based Flue Gas Desulfurization Process, August 27, 1969, (PB 189 495).

A. Skopp, Studies of the Fluidized Lime-Bed Coal Combustion Desulfurization System, Esso R&E Final Report, Prepared under Contract CPA 70-19 for EPA-CSD, January 1 - December 31, 1971, (PB 210 246).

Skopp, A., J.T. Sears and R.R. Bertrand, "Fluid Bed Studies of the Limestone Based Flue Gas Desulfurization Process", Esso Research and Engineering Co., PB 189 495, 1969.

Skopp, A., *et al.*, "Studies of the Fluidized Lime Bed Coal Combustion Desulfurization System . Part 1 Design of the High Pressure Fluidized Bed Combustion Lime Regeneration Pilot Unit - The FBCR Miniplant. Part 2 Factors Affecting NO_x Formation and Control in Fluidized Bed Combustion", Esso Research and Engineering Co., Linden, N.J. December 1971.

C. E. Smeltzer, Mechanisms of Metal Removal by Impacting Dust Particles, *J. Basic Engineering, Trans., ASME*, September 1970.

J. R. Smith and others, Pressure Fluid Bed Boiler Power Plant Operation and Control, *The American Society of Mechanical Engineers*, September 15-19, 1974.

R. S. Smith and others, Fluid Bed Reactor Material Combustion Apparatus, U.S. patent 3,596,614, August 3, 1971.

T. W. Smoot, Monolithic Refractories for Process Equipment, *Chemical Engineering*, August 16, 1965.

Snyder, R.B. *et al.*, W.I. Wilson, G.J. Vogel, A.A. Jonke, "Synthetic Additives for SO//2 Removal from Combustion Gas in a Fluidized Bed Coal Combustor." Energy and Environ. 3rd Natl Conf. Proc. Hueston Woods State Park Ohio, Sep 29-Oct 1 1975 p 262-266. Publ by AIChE. Dayton and Ohio Valley Sect. New York, NY, 1975.

M. L. Spector, Combustion of High-Sulfur Coal in a Fluidized Bed Reactor, U.S. patent 3,625,164, December 7, 1971.

M. L. Spector, Combustion of High-Sulfur Coal with Minimal Ecological Trauma, U.S. patent 3,599,610, August 17, 1971.

T. S. Sprague, Heat Transfer Apparatus, U.S. patent 2,973,251, February 28, 1961.

A. M. Squires, City College Studies of the Coalplex, May 1973, (PB 229 101).

A. M. Squires, Clean Power from Coal, Science, Vol. 169, No. 1948, August 28, 1970.

A. M. Squires, Clean Power Systems Using Fluidized-Bed Combustion, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

A. M. Squires, Coal: A Past and Future King, Ambio, Vol. 3, No. 1, pp. 1-14, 1974.

A. M. Squires, Desulfurization of Fuels with Calcined Dolomite - I, Introduction and First Kinetic Results, CEP Symposium Series, Vol. 67, No. 115, pp. 23-34, 1971.

A. M. Squires, Panel Bed Filters for Simultaneous Removal of Fly Ash and Sulfur Dioxide - III, Reaction of Sulfur Dioxide with Half-Calcined Dolomite, Journal of the Air Pollution Control Association, Vol. 21, No. 5, p. 272, May 1971.

A. M. Squires, Process for Gasifying Granulated Carbonaceous Fuel, U.S. patent 3,840,353, October 8, 1974.

A. M. Squires, Pulverized-Fuel Combustion in Trouble, Am. Chem. Soc. Div. Fuel Chem., Vol. 14, No. 2, pp. 1-12, May 1970.

A. M. Squires, Role of Solid Mixing in Fluidized-Bed Reaction Kinetics, AIChE Symposium Series, Vol. 65, No. 128.

Stairmand, C.J., 1956. "Design and Performance of Modern Gas Cleaning Equipment," Journal of the Institute of Fuel, February.

F. M. Stephens, Improvements in and Relating to Combustion of Carbonaceous Solids and Liquids in Particulate Form in Fluidized Beds, British patent 1,066,340, April 26, 1967.

J. T. Stewart, Fluidized-Bed Coal Gasification - Process and Equipment Development, Proceedings of Third Internation Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

D. C. Strimbeck, Process Environment Effects on Heat Pipes for Fluid-Bed Gasification of Coal, 1974, (LA-UR-74-984).

Strom, S.S., et al., 1976. "Preliminary Evaluation of Atmospheric Pressure Fluidized Bed Combustion Applied to Electric Utility Large Steam Generators," EPRI pp 412-1, February.

Strom, S.S., et al., 1976, "Summary Evaluation of Atmospheric Pressure Fluidized Bed Combustion Applied to Electric Utility Large Steam Generators," Babcock & Wilcox Company, EPRI FP-308, Project 412-1, Vols. I and II, October 1976.

R. T. Struck, Small Continuous Unit for Fluidized Coal Carbonization, Ind. and Eng. Chem., Vol. 6, No. 1, January 1967.

R. D. Sudduth, Process and Apparatus for the Fluidized Calcining of Coke, U.S. patent 3,607,062, September 21, 1971.

P. D. Sunavala, Some Recent Trends in Combustion Research, Indian Chemical Journal, Vol. 6, No. 1, pp. IX-XVI, July 1971.

E. F. Sverdrup, Gas Turbines for Fluid-Bed Boiler Combined Cycle Power Plant, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

J. J. Svoboda, Ignifluid Contribution to Air Pollution Control, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

W. M. Swift, Decomposition of Calcium Sulfate in a Two-Zone Reactor.

W. M. Swift, Potential of Fluidized-Bed Combustion for Reducing Trace-Element Emissions, Paper 75-46.3 at the 68th Annual Meeting of the APCA, Boston, June 15-20, 1975.

Swift, W.M., G.J. Vogel, A.F. Panek, A.A. Jonke, "Trace-Element Mass Balances around a Bench-Scale Combustor", Proc of the Int Conf on Fluid Bed Combust. 4th McLean, Va. Dec 9-11 1975 Publ by MITRE Corp (M76-36), McLean, Va. 1976 p 525-543.

N. I. Syromyatnikov, The Theory of External Heat Transfer in a Fluidized Bed, International Chemical Engineering, July 1974.

A. Talwalker, Preparation of a Coal Conversion System Technical Data Book, IGT, ERDA Contract E(49-18)-1730, April 1975.

A. B. Tayler, A Simple Model for Fluidized Combustion of Coal, ASME, 1973.

Teknekron, Inc., 1976. "An Integrated Technology Assessment (ITA) of Electric Utility Energy Systems", Berkeley, CA.

Tennessee Valley Authority, Sulfur Oxide Removal from Power Plant Stack Gas: Conceptual Design and Cost Study, Sorption by Limestone or Lime: Dry Process, 1968, (PB 178 972).

G. G. Thurlow, Coal as a Fuel for Boiler Furnaces, Journal for the Institute of Fuel, August-September, 1972.

G. P. Tilly, Sand Erosion of Metals and Plastics: A Brief Review, Wear, Vol. 14, No. 4, 1969.

Thurlow, G.G. Fluidized Combustion - the present position - 1. Heat-Air Condit. Journ. 44 (520) 16-19 (March 1975).

R. D. Toomey, Heat Transfer Between Beds of Fluidized Solids and the Walls of the Container, Heat Transfer - Symposium Series, No. 5.

Y. S. Touloukian, Thermophysical Properties of Matter, Specific Heat Nonmetallic Solids, Vol. 5, N.Y., 1970.

W. E. Trauffer, Florida's New 200 TPD Lime Plant, Pit and Quarry, May 1962.

K. L. Tseitlin, Wear of Metals in Fluidized Beds, Zashchita Metallov, Vol. 4, No. 5, September-October 1968.

U.K. National Research Development Corp., 1973. "Final Report to O.C.R.", US Department of Interior, Contract No. 14-32-0001-1511, Nov. 1973.

United Engineers and Construction Inc., 1976, "Advanced Steam Cycles Using Fluidized Bed Steam Generation and Heating Task 1," Electric Power Research Institute, United Engineers and Constructors, Inc. and Westinghouse Electric Corporation, EPRI FP-317, Project 582-1, December.

U.S. Environmental Protection Agency, 1970, "Proceedings of Second International Conference on FLuidized Bed Combustion," Office of Air Programs (PB214 750/2).

U.S. Office of Coal Research, 1974. "Coal Technology: Key to Clean Energy", USDOI Annual Report, Washington, D.C.

Utilization of the Fluid-Bed Combustion Technique for Power Generation and Industrial Steam Raising, The Steam and Heating Engineer, 45, pp. 12-13, June 1969.

J. Valchar, Theoretical Analysis of Agitation in a Multi-Stage Fluid Bed Reactor, British Chemical Engineering, Vol. 10, No. 8, August 1965.

R. H. Vander Molen, Energy from Municipal Refuse Through Fluidized Combustion - The CPU 400 Pilot Plant, AIChE 66th Annual Meeting, Philadelphia, November 11, 1973.

N. N. Varygin, Use of a Fluidized Bed for the Thermal and Chemicothermal Treatment of Metals, Metallovedenie i Termicheskaya Obrabotka Metallov, UDC 621.785:66.096.5, June 1971.

Vaughan, D.A., et al., 1977, "FBC-Ind. Appl. Demo Proj., Special Technical Report on Battelle's Multi-Solids Fluidized Bed Combustion Process," Battelle, February 7, (FE2472-8).

V. N. Vedamurthy, An Analysis of the Conductive and Radiative Heat Transfer to the Walls of Fluidized Bed Combustors, Int. J. Heat Mass Transfer, Vol. 17, 1974.

J. Verloop, On the Origin of Bubbles in Gas-Fluidized Beds, Chemical Engineering Science, Vol. 29, pp. 1101-1107, 1974.

J. Verloop, Periodic Pressure Fluctuations in Fluidized Beds, Chemical Engineering Science, Vol. 29, 1974.

V. A. Vinokurov, Heat Treatment in a Fluidized Bed Furnace, Metallovedenie i Termicheskaya Obrabotka Metallov, UDC 621.785:66.096.5, June 1971.

C. G. Vogel, Personal Communication, August 1975.

G. J. Vogel, A Development Program on Pressurized Fluidized-Bed Combustion, OCR 93 Int. 1, (ANL/ES CEN 1007).

G. J. Vogel, Bench-Scale Development of Combustion and Additive Regeneration in Fluidized Beds, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

G. J. Vogel, Development Program on Pressurized Fluidized-Bed Combustion, Quarterly Report, January 1 - April 1, 1975, (ANL/ES CEN 1010).

G. J. Vogel, Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion, U.S. Environmental Protection Agency, Office of R&D, NERC-RTP, Control Systems Lab, June 1974, (PB 237 366).

Vogel, G., W. Swift, A. Jonke, 1977, "Control of Atmospheric Pollution by Fluidized-Bed Combustion", Proc., Natl. Conf. Health. Environ. Eff.. Control Technol. Energy Use 212-19.

Vogel, G.J., W.M. Swift, J.C., Montagna, J.F. Lenc., A.A. Jonke, "Application of Pressurized, Fluidized Bed Combustion to Reduction of Atmospheric Pollution." Fluid. Combust. Conf. Proc. Imp. Coll. of Sci. and Technol. London, Engl. Sept. 16-17 1975, Pap D3. 11 p. Publ. by Inst. of Fuel (Symp. Serv.n 1. v 1). London Engl. 1974.

Vogel, G.J., and others. Application of Pressurized Fluidized-Bed Combustion to Reduction of Atmospheric Pollution. Pap. D3 to Fluidized Combustion Conf. Imperial College, London. Institute of Fuel, Symp. Ser. No. 1, Proc. Vol. 1 (1975).

Vogel, G.J., et al., 1973, "Reduction of Atmospheric Pollution by the Application of Fluidized Bed Combustion and Regeneration of Sulfur-Containing Additives," Argonne National Laboratory, June, (PB 227 058), (EPA-R2-73-253).

G. J. Vogel, Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion and Regeneration of Sulfur-Containing Additives, National Environmental Research Center, Office of Coal Research, September 1974.

G. J. Vogel, Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion and Regeneration of Sulfur-Containing Additives, Annual Report, July 1971 - June 1972, ANL/ES CEN 1005, June 1973.

H. A. Vreedenberg, Heat Transfer Between a Fluidized Bed and a Horizontal Tube, *Chemical Engineering Science*, Vol. 9, 1958.

H. A. Vreedenberg, Heat Transfer Between a Fluidized Bed and a Vertical Tube, *Chemical Engineering Science*, Vol. II, 1960.

H. A. Vreedenberg, Heat Transfer Between Fluidized Beds and Vertically Inserted Tubes, *J. Appl. Chem.*, 2, Supplementary Issue No. 1, 1952.

G. L. Wade, Fluidized-Bed Combustion of Municipal Solid Waste in the CPU-400 Pilot Plant, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

J. S. Walton, Gas-Solid Film Coefficients of Heat Transfer in Fluidized Coal Beds, *Industrial and Engineering Chemistry*, June 1952.

J. Warshawsky and L. H. Pipe, Method and Apparatus for Incinerating Combustible Wastes, U.S. patent 3,605,655, September 20, 1971.

G. B. Watson, Critical Heat Flux in Reclined and Vertical Smooth and Ribbed Tubes, 5th International Heat Transfer Conference, Tokyo, September 3, 1974.

B. Weber and K. Rose, Mathematische Modellierung von Wirbelschichten, *Chem. Tech.*, Vol. 22, No. 10, pp. 594-596, October 1970.

F. J. Weinberg, Combustion Temperatures: The Future? *Nature*, Vol. 233, September 24, 1971.

Weller, A.E. and H. Nack, 1976. "Fluidized Bed Combustion - Industrial Applications Demonstration Projects," Quarterly Progress Report, Battelle Columbus, February 8.

Weller, A., et al., 1976, "Fluidized Bed Combustion Industrial Application Demonstration Projects," Quarterly Technical Progress Report October 1-December 31 Battelle (FE 2472-7) and June 30-September 30, (FE 2472-10).

C. Y. Wen, Calculate Fluidized Heat Transfer by Nomegraph, *Chemical Engineering*, July 1957.

C. Y. Wen, Fluidized Bed Heat Transfer: A Generalized Dense Phase Correlation, *AIChE Journal*, December 1956.

C. Y. Wen, Gasification of Solid Particles Containing Carbon, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

C. Y. Wen and T. M. Change, Investigation of Heat Transfer Problems in Fluidized Coal Gasification, Coal Research Bureau Report No. 22, June 1966.

C. Y. Wen, Reaction Rate of Sulfur Dioxide with Particles Containing Calcium Oxide, *Environmental Science and Technology*, Vol. 7, No. 8, p. 703, August 1973.

L. Wender, Heat Transfer Between Fluidized-Solids Beds and Boundary Surfaces - Correlation of Data, AIChE Journal, March 1958.

K. G. Werner, Fluidized Bed Combustion, A Bibliography with Abstracts, NTIS/PS-75/256.

J. Werther, Influence of Bed Diameter on the Hydrodynamics of Gas Fluidized Beds, Fluidization and Fluid-Particle Systems, Vol. 70, AIChE Symposium Series, 1974.

Westinghouse, Advanced Coal Gasification System for Electric Power Generation, OCR/R&D 81/Int. 1, May 1974, (PB 236 971).

T. D. Wheelock, Sulfuric Acid from Calcium Sulfate Sulfur and SO_2 Developments, CEP Technical Manual, 1971.

R. K. Wilhelm, Chemical Engineering Progress, 44, p. 201, 1948.

D. F. Williams, Pilot Plant Experiments at the Coal Research Establishment (CRE), Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

Wolfe, R. W. et al., 1976. "Energy Conversion Alternatives Study (ECAS), Westinghouse Phase I Final Report, Volume XI, Advanced Steam Systems," NASA CR-134941, Westinghouse Electric Corp. Research Labs, Pittsburgh, February.

R. H. Wolk and others, Coal Hydrogenation, U.S. patent 3,617,465, November 2, 1971.

E. T. Woodburn, Thermal Decomposition and Hydrogenation of Coal Dust in a Shock Tube, Fuel, Vol. 52, January 1974.

S. J. Wright, Fluidized-Bed Combustion and the Design of Boilers, Proceedings of Second International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, October 4-7, 1970.

S. J. Wright, Heat Transfer in Fluidized Beds of Wide Size Spectrum at Elevated Temperatures, British Chemical Engineering, Vol. 15, No. 12, December 1970.

S. J. Wright, The Combustion of Coal in Fluidized Beds, 36th International Conference, Chem. Ind., 1967.

S. J. Wright, The Combustion of Coal in Fluidized Beds for Firing Shell Boilers, Journal of the Institute of Fuel, pp. 235-240, June 1969.

S. J. Wright, The Design of Fluidized Combustion Systems Burning Solid Fuel, International Chemical Engineering Symposium Series, No. 27, Instn. Chem. Engrs., London, 1968.

S. J. Wright, The Reduction of Emissions of Sulphur Oxides and Nitrogen Oxides by Additions of Limestone or Dolomite During the Combustion of Coal in Fluidized Beds, Proceedings of Third International Conference on Fluidized-Bed Combustion, U.S. Environmental Protection Agency, December 1973.

W. C. Yang and D. L. Keairns, Recirculating Fluidized-Bed Reactor Data Utilizing a Two-Dimensional Cold Model, Fluidization and Fluid-Particle Systems, Vol. 70, AIChE Symposium Series, 1974.

K. Yoshida, Mechanism of Bed Wall Heat Transfer in a Fluidized Bed at High Temperatures, Chemical Engineering Science, Vol. 29, 1974.

Y. H. Yu, Power-Law Fluids Flow Through Multiparticle System, 60th Annual AIChE Meeting, November 26-30, 1967.

S. S. Zabrodsky, Compound Heat Exchange Between a High Temperature Gas-Fluidized Bed and a Solid Surface, Int. J. Heat Mass Transfer, 16, February 1973.

S. S. Zabrodsky, Hydrodynamics and Heat Transfer in Fluidized Beds, The MIT Press, Cambridge, Mass.

E. Zahavi, Heat Transfer in Liquid-Fluidized Beds, Int. J. Heat Mass Transfer, Vol. 14, 1971.

F. Zenz, Bubble Formation and Grid Design, International Chemical Engineering Symposium Series, No. 30, 1968.

F. A. Zenz, Fluid Catalyst Design Data, Petroleum Refiner, April-November, 1957.

F. Zenz, Incipient Fluidization, unpublished paper.

E. N. Ziegler, Effects of Solid Thermal Properties on Heat Transfer to Gas Fluidized Beds, I&EC Fundamentals, Vol. 3, No. 4, pp. 325-328, November 1964.

E. N. Ziegler, Mechanism of Heat Transfer in a Fluidized Bed, I&EC Fundamentals, Vol. 3, No. 2, pp. 94-98, May 1964.

E. N. Ziegler, The Interstitial Fluid-Bed Reactor, Chem. Tech., November 1972.

C. W. Zielke, Sulfur Removal During Combustion of Solid Fuels in a Fluidized Bed of Dolomite, Journal of the Air Pollution Control Association, Vol. 20, No. 3, pp. 164-169, March 1970.

Zielke, C.W., et al., 1970. "Sulfur Removal During Combustion of Solid Fuels in a Fluidized Bed of Dolomite", J. Am Poll. Control Assoc., 20,3.