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February 1977

THE U.S. ENVIRONMENTAL PROTECTION AGENCY'S FLUIDIZED-BED COMBUSTION PROGRAM, FY 1976

Interagency
Energy-Environment
Research and Development
Program Report

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THE U.S. ENVIRONMENTAL PROTECTION AGENCY'S FLUIDIZED-BED COMBUSTION PROGRAM, FY 1976

by

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505 King Avenue
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SUMMARY

A vital element of the National Program on Fluidized-Bed Combustion (FBC) of coal for space-heating, steam-generation, and power-generation applications is the U.S. Environmental Protection Agency (EPA) program on the environmental characterization and control of this process. The goal of the EPA FBC program is to obtain all necessary environmental data over the full range of operating variables for all variations of the FBC process. It is EPA's responsibility to assure that all environmental problems are identified and adequately addressed. Conducting the environmental characterization in parallel with the process development program increases the likelihood of early detection and control, at a minimum cost, of any potential environmental problems that might result during commercial application of FBC.

Some of the important contributions that the EPA program will make to the National FBC program are:

- Establishment of environmental goals based on health and ecological effects of emitted pollutants,
- Comprehensive analyses of emissions from available operating units in order to identify emitted pollutants and their emission rates,
- Assessment of the feasibility and costs of existing and future control technology,
- Generating valuable technical information on control technology including: (1) pretreatment of input streams, (2) modification of process conditions for environmental control, (3) add-on control devices (including sorbent regeneration), (4) environmental impact of solid residue disposal, and (5) applications (paper) studies,
- Recommendations for environmental standards based on environmental goals, control technology capability, and costs,
- Development of manuals covering the best available technology for controlling emissions based on the assessment of available control technology.

The EPA's Environmental Assessment and Control Technology Development (EA/CTD) program is coordinated with the technology development program for FBC being conducted by the U.S. Energy Research and Development Administration (ERDA). A large portion of the EPA testing (e.g., comprehensive analysis and control technology) will be performed on ERDA units. Similarily, ERDA will use the EPA's pressurized FBC Miniplant for process development studies. EPA and ERDA are co-funding experimental work at Argonne National Laboratory and an industrial boiler applications study at Exxon Research and Engineering Company.

The EPA program consists of tasks on environmental assessment, comprehensive analysis of emissions, and control technology development. All of these tasks contribute to an overall technology assessment of the FBC process. The objectives of environmental assessment are: (1) to set emission goals based on health and ecological effects of emitted pollutants and (2) to identify and recommend research, development, and demonstration programs designed to develop the necessary information and control technology to implement these goals. Comprehensive analysis of emissions from operating units provide data on pollutants and their emission rates in order to identify the degree of control that may be required to meet emission goals. Control technology development efforts include engineering analysis, basic and applied research and development, and specific control process development. The contractors currently involved in this program are Battelle's Columbus Laboratories (BCL); GCA Corporation; the British Coal Utilization Research Association (BCURA) with Combustion Systems, Ltd. (CSL); Exxon Research and Engineering Company; the MITRE Corporation; Ralph Stone and Company; Tennessee Valley Authority (TVA); Westinghouse Research Laboratories; Argonne National Laboratory (ANL); Aerotherm-Acurex Corporation (AAC) and Dow Chemical Company (DCC).

The major accomplishments during the past fiscal year related to environmental assessment include a preliminary environmental assessment program completed by GCA and the initiation of a major contract with BCL for a broad environmental assessment. The preliminary assessment by GCA indicated that, except for major air pollutants which have been routinely monitored during operation of experimental FBC facilities, there were insufficient experimental data upon which to base firm conclusions concerning potential environmental problems for FBC. BCL has made several preliminary planning studies to define needed research areas for improving the data base. BCL has also initiated the development of a multimedia environmental goals (MEG) chart which is a concept for developing emission goals for specific pollutants based upon health/ecological effects data. Comprehensive analysis was initiated on a 6-inch (15.24 cm) diameter atmospheric-pressure FBC unit at BCL and was about to begin on a 2-foot by 3-foot (0.6 by 0.9 m) pressurized unit at BCURA; planning is underway for comprehensive analysis on other units in 1977, including the Exxon 0.63-MW pressurized Miniplant and the Rivesville 30-MW atmospheric boiler. A potential problem involving SO_3 production from FBC units at Exxon and BCL was also identified. A few measurements of 94 ppm or higher were obtained, although the average was only 5-6 ppm. These readings may be related to sampling techniques and must be further investigated to determine if a significant SO_3 problem exists in FBC combustors.

In the area of control technology development, the major accomplishments involved investigations on (1) pretreatment of input streams at Westinghouse, ANL, and Exxon; (2) effects of modification of process conditions at Exxon, ANL, and Westinghouse; (3) development of add-on devices at Exxon, ANL, and Westinghouse, (4) characterization, disposal, and utilization of solid residue at TVA, Westinghouse, and Ralph Stone; and (5) FBC applications at Exxon, TVA, and Dow. The aim of the pretreatment studies is to improve the efficiency of limestone and dolomite sorbents. Experimental studies conducted by Exxon, ANL, and Westinghouse have shown that precalcination improves sorption efficiency and the effect is more pronounced for pressurized systems. Pope, Evans and Robbins earlier found that common salt improves sorption efficiency and ANL is investigating the mechanism in order to promote practical application including use of less corrosive additives. Studies on the effects of modifcation of process conditions included a 240-hour demonstration run of the combustor of the Exxon Miniplant. Tests with the Miniplant and the ANL bench-scale combustor/regenerator system were used to identify the calcium to sulfur ratio necessary for meeting emission standards in pressurized FBC units. Tests on the effects of additives on limestone performance were also made. The effects of alternate sorbents were investigated by ANL and Westinghouse and Westinghouse also examined the effects of attrition on the regeneration capacity of calcium and alternate sorbents. Studies on the development of add-on controls include the initiation of shakedown runs on the regenerator and installation of a granular bed filter on the Exxon Miniplant. ANL has examined the factors involved in the one-step regeneration of sorbents and Westinghouse has designed a test facility to study particulate control at high temperature and elevated pressure. EPA has developed a mobile system to test atmospheric particulate control devices and this system will be tested on FBC units as soon as practical. The solid residue studies on utilization have been conducted by Ralph Stone who along with Westinghouse, has also been conducting studies on disposal, leaching, and low-temperature processing of the residue. Westinghouse, Ralph Stone, and TVA have been conducting studies on characterization of the solid. The Exxon applications study concluded that FBC is applicable to industrial boilers and can be more economical than conventional coal-fired boilers with flue gas scrubbing. The TVA study is comparing costs of FBC utility boilers with conventional units. The Dow study attempted to examine the effects of scale-up on pollutant emissions but could not reach any definite conclusions.

Major outputs anticipated during the next year under the category of environmental assessment are (1) progress in setting environmental goals based on health and ecological effects (including the first complete pass at producing the MEG chart); (2) comprehensive analysis on additional facilities including the 18-inch (45.7-cm) diameter unit at Morgantown Energy Research Center, the Miniplant combustor, the Rivesville unit, and the BCURA unit; and (3) initiation of the work to prepare preliminary recommendations of standards for atmospheric FBC units. Under the category of control technology development, some anticipated outputs are (1) further testing on the Miniplant including studies on pretreatment (precalcination of sorbent), modification of process conditions (different coal and sorbent combinations), and add-on devices (shakedown and operation of the Ducon granular bed filter plus completion of the shakedown and operation of the regenerator); (2) installation and initial testing on the Westinghouse high-temperature, high-pressure particulate control test passage; (3) testing of the EPA mobile particulate control devices on the Rivesville unit if the ERDA schedule permits; (4) further process studies and regeneration testing at ANL and Westinghouse; (5) further solid residue tests including establishment of field test cells using residue from various FBC units; (6) completion of the TVA study on cost comparisons of FBC versus flue gas desulfurization; (7) completion of the Exxon study on the assessment of industrial FBC applications; and (8) completion of the FBC sampling and analysis manual by MITRE.

THE U.S. ENVIRONMENTAL PROTECTION AGENCY FLUIDIZED-BED COMBUSTION PROGRAM

Annual Program Status Report for the Period July 1, 1975 to September 30, 1976

INTRODUCTION

Fluidized-Bed Combustion (FBC) of coal offers the potential for efficiently utilizing the country's large reserves of high-sulfur coal in a manner that controls the emissions of environmentally harmful pollutants associated with conventional combustion of coal.

The U.S. Environmental Protection Agency (EPA) recognized this potential and was a key sponsor of some of the early development work on this process. Current EPA activities are designed to complement those of the U.S. Energy Research and Development Administration (ERDA) which is presently conducting a substantial program to develop this technology toward space-heating, steam-generation, and power-generation applications and of the Electric Power Research Institute (EPRI) which is also conducting development programs aimed more specifically toward the needs of the power-generating industry. The EPA is closely monitoring additional development work outside the United States, especially in the United Kingdom.

The EPA program is aimed at the complete environmental characterization of FBC. It is EPA's responsibility to ensure that environmental concerns are identified and adequately addressed. Conducting the environmental characterization in parallel with the development programs increases the likelihood of early detection and control, at a minimum cost, of any potential environmental problems. The EPA program will make a number of important contributions to the overall U.S. program:

- Establishment of environmental goals based on health and ecological effects of emitted pollutants,
- Comprehensive analyses of emissions from available operating units in order to identify emitted pollutants and their emission rates,
- Assessment of existing and future control technology,
- Provide valuable technical information on control technology including: (1) pretreatment of input streams, (2) modification of process conditions for environmental control, (3) add-on control devices (including sorbent regeneration), (4) environmental impact of solid residue disposal, and (5) applications (paper) studies,

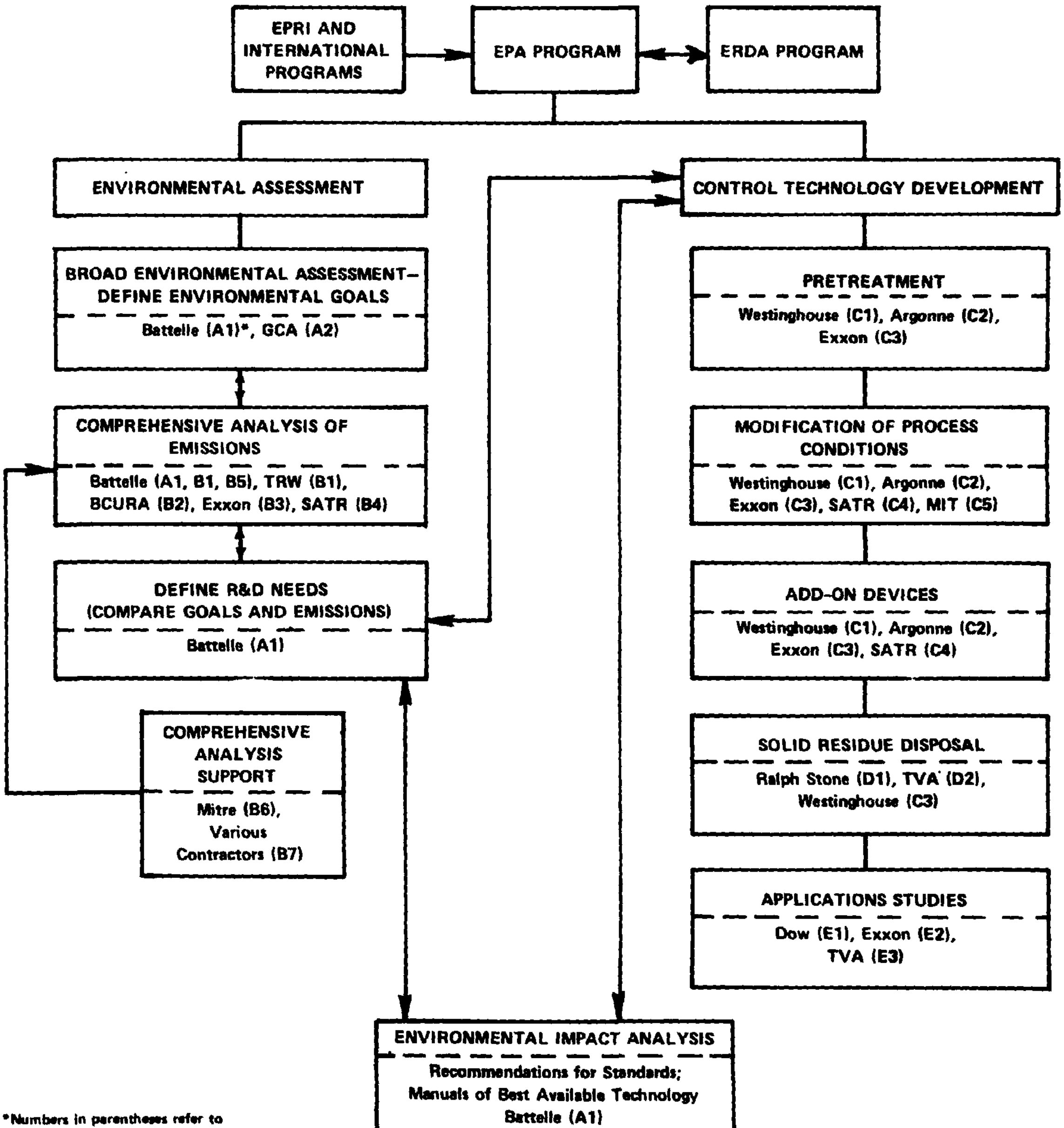
- Recommendations for environmental standards based on environmental goals, control technology capability, and costs,
- Develop manuals covering the best available technology for controlling emissions based on the assessment of available control technology.

The goal of the EPA FBC program is to obtain all necessary environmental data over the full range of operating variables for all variations of the FBC process. Plans are to obtain these data on a suitable experimental scale and on a time schedule compatible with the process development schedule envisioned in the national FBC development effort. It is anticipated that these data will be adequate to assess the total environmental impact of the process on all media (air, water, land) so that there will be assurance that the process will meet current and anticipated environmental standards. It will be necessary to have sufficient data available to serve as a basis for recommending additional standards, if future health effects studies or related work identify the need for such standards. Also, adequate data on suitable control technologies must be developed as a means to minimize the environmental impact.

THE SCOPE OF THE EPA FLUIDIZED-BED COMBUSTION PROGRAM

The EPA FBC program currently consists of 19 projects with a variety of contractors. It is supported by a general program for developing sampling and analytical techniques. For contractual purposes these projects have been arranged into five categories as shown in Table A-1 and Figure A-1 of the Appendix. Table A-1 and Figure A-1 also provide a brief schedule and status report on these projects. Figure 1 shows the functional structure and interrelationship of these projects. The relationship of the EPA program to the other FBC development programs is covered in a separate section.

The aim of environmental assessment is to set emission goals based on health and ecological effects of the emitted pollutants and to design research, development, and demonstration programs to compile the necessary information and control technology to implement these goals. Comprehensive analyses of emissions from operating units provide data on pollutants and their emission rates in order to identify the degree of control that may be required in order to meet the goals. The control technology development effort includes tasks on pretreatment, modification of process conditions, add-on devices, and solid residue disposal. The application studies examine control technology based on fluidized-bed combustion in terms of applicability to industrial boilers, costs in comparison to conventional boilers, and scale-up considerations. All of these projects contribute to an overall assessment of the FBC technology.



*Numbers in parentheses refer to project identification in Table A-1 and Figure A-1 on pages A-1 through A-3.

FIGURE 1. FUNCTIONAL STRUCTURE OF THE EPA FLUIDIZED-BED COMBUSTION PROGRAM

A. Environmental Assessment

The main objectives of the FBC environmental assessment (EA) effort are to (1) identify and quantify all pollutants which could be emitted by the process as it gains commercial acceptance, (2) recommend emission goals based on health and ecological effects of pollutants, including an approach utilizing a Multimedia Environmental Goals (MEG) chart, (3) conduct comprehensive analysis of emissions from FBC units (discussed in the following section), and (4) define a research and development program to obtain any necessary information and to develop necessary control technology.

In a preliminary study by the GCA Corporation, it was concluded that, except for major air pollutants, which have been routinely monitored during operation of experimental FBC facilities, there are insufficient data to base firm conclusions concerning potential environmental problems for FBC. Approximate theoretical assessments did not indicate any special environmental problems but experimental verification of this conclusion is necessary and should receive high priority.

The primary EA program was initiated with Battelle's Columbus Laboratories in January, 1976, and some of the specific products will be (1) manuals of best available control technology (MBACT) and (2) recommendations for emission standards for FBC. Thus far, Battelle has (1) completed the assessment of the current process/environmental background and has concluded that there exists a serious lack of experimental data on emission trace elements and compounds, and organic compounds; (2) begun to assist EPA to develop an overall plan of concerted experimental efforts at collection of needed environmental data; (3) defined an approach to a MEG chart as a tool for goal setting; (4) drawn up plans for comprehensive analysis of emissions at various ERDA- and EPA-operated FBC experimental facilities; and (5) initiated several technical program planning studies to define research areas and directions which should be addressed immediately to accelerate the FBC development and EA effort. These include alternative sorbents, regeneration, NO_x formation and control, trace elements, solid/liquid wastes, and particulate control.

Battelle has also obtained first-hand information on the status of worldwide FBC research and has concluded that efforts in the United States toward the development and environmental impact assessment of FBC are comprehensive in the depth and breadth of planned studies. Further, the ongoing EA work in the United States stands out as unique and unparalleled, in that no other country has embarked, even on a reduced scale, on developing environmental impact data concurrent with the development of the process.

A draft MBACT for the atmospheric FBC process is scheduled for issue in December, 1978. Preliminary recommendations to set standards for atmospheric FBC are scheduled to be prepared by December, 1977, with updated recommendations in December, 1978. A draft MBACT, and recommendations for standards for pressurized FBC will be prepared later. The manuals and recommendations will initially be based on data from the largest facilities existing at the time (Rivesville, the Exxon miniplant, the BCURA unit), and it will be updated as further data become available from additional units.

The Multimedia Environmental Goals (MEG) chart is a concept developed by the Industrial Environmental Research Laboratory (IERL) of EPA which, when carried through to a successful completion, will provide the emerging energy technologies with a unified presentation of environmental goals in all media. A sample MEG chart is shown in Figure 2. The format of the chart presents emission goals for specific pollutants from a specific process in all media (air, water, and land) in terms of best technology (Columns IA and IB), and in terms of desired ambient levels from the health/ecological effect standpoint (Column IC). Those emission goals based on health/ecological effects are derived from desired ambient levels determined by: current/proposed standards (Column II); toxicity-based permissible concentrations, such as concentrations based on threshold limit values (Column III); and mutagenic/carcinogenic/teratogenic-permissible concentrations (Column IV).

By comparing emissions from FBC units measured during the comprehensive analysis program, or the emissions expected using developing control technology (Columns IA and IB) with the health/ecological effects goals in Column IC, EPA can make decisions regarding how the control technology development program should be directed. A preliminary version of the MEG chart is under development. An updated MEG chart for FBC is scheduled for completion by December, 1978.

B. Comprehensive Analysis of Emissions

An indispensible component of the FBC environmental assessment process is the actual measurement of emissions. The measurement must be comprehensive, in that all streams of materials leaving the process must be identified whether they be continuous or intermittent, steady or variable, and whether they are gaseous, liquid, solid, or any combinations thereof. Streams of any size must be considered, and sound technical judgment, based on a thorough familiarity with the processes involved, must be applied to ensure that every possible effluent stream that might contribute an undesirable substance to the environment is considered. The comprehensive characteristic of the analysis also demands that these streams be analyzed for all possible pollutants. Comprehensive analyses of this magnitude applied to a complex process like fluidized-bed combustion systems is very extensive and time consuming, and thereby expensive. To meet the complex demands of the comprehensive analysis of emissions in the most cost-effective manner, a phased approach of sampling and analysis of emissions has been developed. This involves three levels of activity:

MULTIMEDIA ENVIRONMENTAL GOALS FOR ....
(Pollutant)

	Emission-Level Goals				Ambient-Level Goals				
	I				II		III		IV
	Best Technology		Based on Ambient Factors		Current or Proposed Ambient Standards or Criteria		Toxicity-Based Est. of Permissible Concentration (EPC)		Threshold Limit-Based EPC (for Carcinogen, etc)*
	A	B	C	D	A	B	A	B	A
MEDIA	Existing Tech, NSPS, BPT**	Developing Tech, BAT** Revised NSPS	Derived from Ambient-Level Goals (Cols II,III,IV)	Elimination of Discharge (EOD) Natural Background	Based on Health Effects	Based on Ecological Effects	Based on Health Effects	Based on Ecological Effects	Based on Health Effects
AIR, $\mu g/m^3$ (ppm vol)									
WATER, mg/l (ppm wt)									
Public Drinking Water									
Freshwater Ecological									
Marine Ecological									
LAND, $\mu g/g$ (ppm wt)									

* Acceptable death rate should be defined and natural background levels should be considered; whereas TLV data usually consider physiological or behavioral effects, threshold limit in this case refers to genetic (carcinogenic, teratogenic, mutagenic, etc.) effects.

** BPT = Best Practical Control Technology; NSPS = New Source Performance Standards; BAT = Best Available Control Technology.

FIGURE 2. SAMPLE MULTIMEDIA ENVIRONMENTAL GOALS (MEG) CHART

Level 1: The identification and measurement of all possible pollutants or classes of pollutants in all effluent streams, with the degree of accuracy considered to be of secondary importance.

Level 2: The more accurate measurement of specific pollutants in specific streams whereever Level 1 measurements indicated that unacceptable emissions might be occurring, considering the accuracy limitations obtained in Level 1 measurements.

Level 3: The measurement of significant pollutants (as identified in Levels 1 and 2) over extended periods of time. This program of measurements must be planned to demonstrate correlations of these pollutant emissions with time, operating conditions, feed stream composition, emission control techniques, and other operational parameters that might affect emissions.

In the case of comprehensive analysis of emissions from fluidized-bed combustion units, there is some existing knowledge concerning likely emissions of some pollutants (such as SO_2, NO_x, particulates, etc.). This prior knowledge justifies the inclusion of some Level 2 measurements in a comprehensive analysis experimental program which would otherwise include sampling and analyses only at the Level 1 depth and accuracy. Using this background knowledge of FBC emissions, a sampling and analysis plan has been developed by Battelle for application to laboratory and developmental combustors. The plan is readily expandable to larger demonstration units and to specialized units such as pressurized FBC units and those including sorbent regeneration.

Table 1 shows a simplified matrix of representative effluent streams and the pollutant species identified for analysis in each stream. Examples of the Level 2 analyses are the identification and measurement of specific POM compounds by gas chromatography-mass spectrometry in the effluent stack gas stream (gaseous and particulate) and the more accurate measurement by AA of a few trace elements known to be especially toxic. These two specific pollutant classes are of concern because the combustion conditions attained in the FBC process (1) preclude fixing of trace ash constituents in a fixed glassy matrix customarily obtained in conventional coal burning and (2) possibly permit release of coal fragments (polycyclics) into the effluent flue gas. As this program of sampling and analysis is applied to specific units, details of the matrix of measurements must be expanded to include the specific effluent streams appropriate to that FBC unit.

As part of the comprehensive analysis effort, the MITRE Corporation is preparing a Level 1/Level 2 sampling and analysis procedures manual for each of the fluidized-bed combustion process variations. The manual indicates alternative sampling and analytical procedures that can be

TABLE 1. SAMPLING AND ANALYSIS MATRIX FOR COMPREHENSIVE ANALYSIS OF FBC STREAMS

Species, Pollutants	Sample Collection Techniques[a]	Analysis Method[b]	System Stream or Material: Stack Particulates Mid >3µ	Stack Particulates Fine <3µ	Stack Gas	Waste from cyclone and bed	Coal Feed	Sorbent Feed	Leachate from Solid Waste (cyclone and bed)
On-Line Continuous Gas Measurements									
CO_2	Cw	NDIR			X				
SO_2	Cw	IR or UV			X				
NO	Cw	NDIR or CL			X				
NO_2	Cw	NDIR or CL			X				
CO	Cw	NDIR			X				
O_2	Cw	PM or PE			X				
Total Gaseous Hydrocarbon	Cw	FID			X				
Integrated Gas Phase Measurements									
H_2S	Ig	GC			X				
COS	Ig	GC			X				
Disulfides	Ig	GC			X				
SO_3/H_2SO_4	St	GR/IC			X				
NH_3	St	KJ			X				
Cyanides	St	CO			X				
HCl	St	TI			X				
Fluoride, volatile	St	SIE			X				
Integrated Specimens for Subsequent Group Analysis									
Trace metals	SASS/Gs	SSMS	X	X		X	X	X	X
Major Elements (Fe, Al, Si, K, Ca)	SASS/Gs	OES	X	X		X	X	X	
Organic, by class	SASS/Gs	EX/LC/IR	X	X	X	X	X		
Organic-reduced, sulfur compounds	SASS/Gs	GC	X	X	X	X	X		
POM	SASS/Gs	GC/MS	X	X	X	X	X		
Proximate	Gs	ASTM D3172-73					X		
Radionuclides	SASS/Gs	Gross α and β assay	X	X		X	X	X	
Ultimate	SASS/Gs	ASTM D3176-74	X	X			X		
Sulfur forms	Gs	ASTM D2492-68					X		
Biological	SASS/Gs	In vitro	X	X	X	X	X	X	
Integrated Specimens for Subsequent Specific Analysis									
Toxic Elements (Be, Cd, Hg, As, Pb, Se, Sb, Te)	SASS/Gs	AA	X	X	X	X	X	X	X
Cl^-	SASS/Gs	CO	X	X					X
F^-	SASS/Gs	DI/CO	X	X		X			X
Na	Gs	AA					X		
Ca	Gs	AA/TI					X	X	
Mg	Gs	AA						X	
$CO_3^=$	SASS/Gs	GE	X	X		X	X	X	
$SO_4^=$	SASS/Gs	TI/IC	X	X		X	X	X	X
$SO_3^=$	SASS/Gs	SO_2 GE/CO	X	X		X	X	X	X
$S^=$	SASS/Gs	GE/TI	X	X		X	X	X	
NO_2^-	SASS/Gs	CO/IC	X	X		X	X	X	X
NO_3^-	SASS/Gs	CO/IC	X	X		X	X	X	X
C "Non Carbonate"	Gs	C				X	X	X	
Heating value	Gs	ASTM D2015-66					X		
Particle morphology	Gs/Ci	SEM				X	X	X	
Particle size	Gs/Ci	Sieve - ASTM 410-38				X	X	X	
Particle mass	M5	Weight	X[c]	X					

(a) Cw - Continuous withdrawal through non-reactive line with mechanical filtration.
Ig - Integrated grab sample of gas in glass bulb.
St - Separate wet chemical train to collect gas (such as Method 6).
SAAS - Source Assessment Sampling System (train used for suspended particulates, organics, and volatile trace elements).
Gs - Grab multiple samples riffled to reduce to 100 g representative sample.
Ci - Cascade impactor in flowing stream.
M5 - EPA Method 5.

(b) NDIR - Non-dispersive infrared.
IR - Infrared.
UV - Ultraviolet.
CL - Chemiluminescence.
PM - Paramagnetic.
PE - Platinum Electrode.
FID - Flame Ionization Detector.
GC - Gas Chromatography.
GR - Goksoyr-Ross.
IC - Ion chromatography.
KJ - Kjeldahl.
CO - Colorimetric.
TI - Titration.
SIE - Selective-Ion Electrode.
SSMS - Spark Source Mass Spectroscopy.
OES - Optical Emission Spectroscopy.
EX - Extraction.
LC - Liquid Chromatography.
GC/FPD - Gas Chromatography with flame photometric detector.
GC/MS - Gas Chromatography with mass spectrography.
AA - Atomic absorption.
DI - Distillation.
GE - Gas Evolution.
C - Combustion.
ASTM - American Society for Testing Materials Standard Method.
SEM - Scanning Electron Microscope.

(c) Coarse (>10µ) and Filter (<1µ) fractions included.

employed for the various potential pollutants for each variation, recommends preferred procedures, and identifies sampling and analytical technique research and development requirements. The manual is to be published in 1977.

In addition to these comprehensive analysis efforts, an extensive continuing effort is underway by EPA with a variety of contractors to develop new and improved sampling and analytical techniques. This effort is not part of the FBC program per se, but is in support of all of EPA's activities. As an example of the type of support provided by this effort, a Source Assessment Sampling System (SASS) has been developed by Aerotherm/Acurex which will be utilized in the Comprehensive Analysis Program. Figure 3 shows this system, which measures particulate mass and size distribution, organics, and trace elements. Another part of this effort is the development of a procedures manual for biological testing of the environmental effects of effluents from a wide variety of industrial processes. This is being done by EPA with assistance from Battelle. The Process Measurements Branch of IERL is also preparing a general guidelines document, procedures manuals, and technical manuals for sampling and analysis.

Two extensions of the comprehensive analysis of emissions are considered appropriate for FBC units. One overall objective of the analyses is to provide data to aid in the development and evaluation of control devices. Therefore in some situations within-system streams must be sampled and analyzed to a limited degree to provide this information. For example, particulate concentrations and characterization in the inlet to particulate control devices should be included, even though the stream at this location does not constitute an emission from the FBC unit. The second extension is the development and consideration of a simplified characterization of leachate from solids discarded from the FBC system. Because the solids from the bed and particulate collection devices destined to be discarded will probably be subject to some natural water leaching, some simple screening analysis of this leachate as a secondary emission should be considered. Follow-on evaluations of leachate properties will ultimately be required in site-specific experiments for each production and large demonstration FBC unit. A more detailed study of solid waste and leachates is described later.

During the next year, specific plans are being made to conduct comprehensive analysis of emissions from five FBC units as follows:

Type	Laboratory	Pilot	Pilot	Pilot	Demonstration
Operator	BCL	BCURA	MERC	EXXON	PER
Location	Columbus, Ohio	Leatherhead, England	Morgantown, W. Va.	Linden, N.J.	Rivesville, W. Va.
Size	6" diam.	2' x 3'	18" diam.	12" diam.	38' x 12'
Pressure	atmos	pressurized	atmos	pressurized	atmos
Current Status	operational	operational	being modified	being modified	construction
Sampling Schedule	completed 4/76	scheduled 4Q/76	sampled 9/76	planned 4Q/76	planned mid-1977
Fuel	coal	coal	culm	coal	coal
Sorbent	limestone	limestone	none	dolomite	limestone.

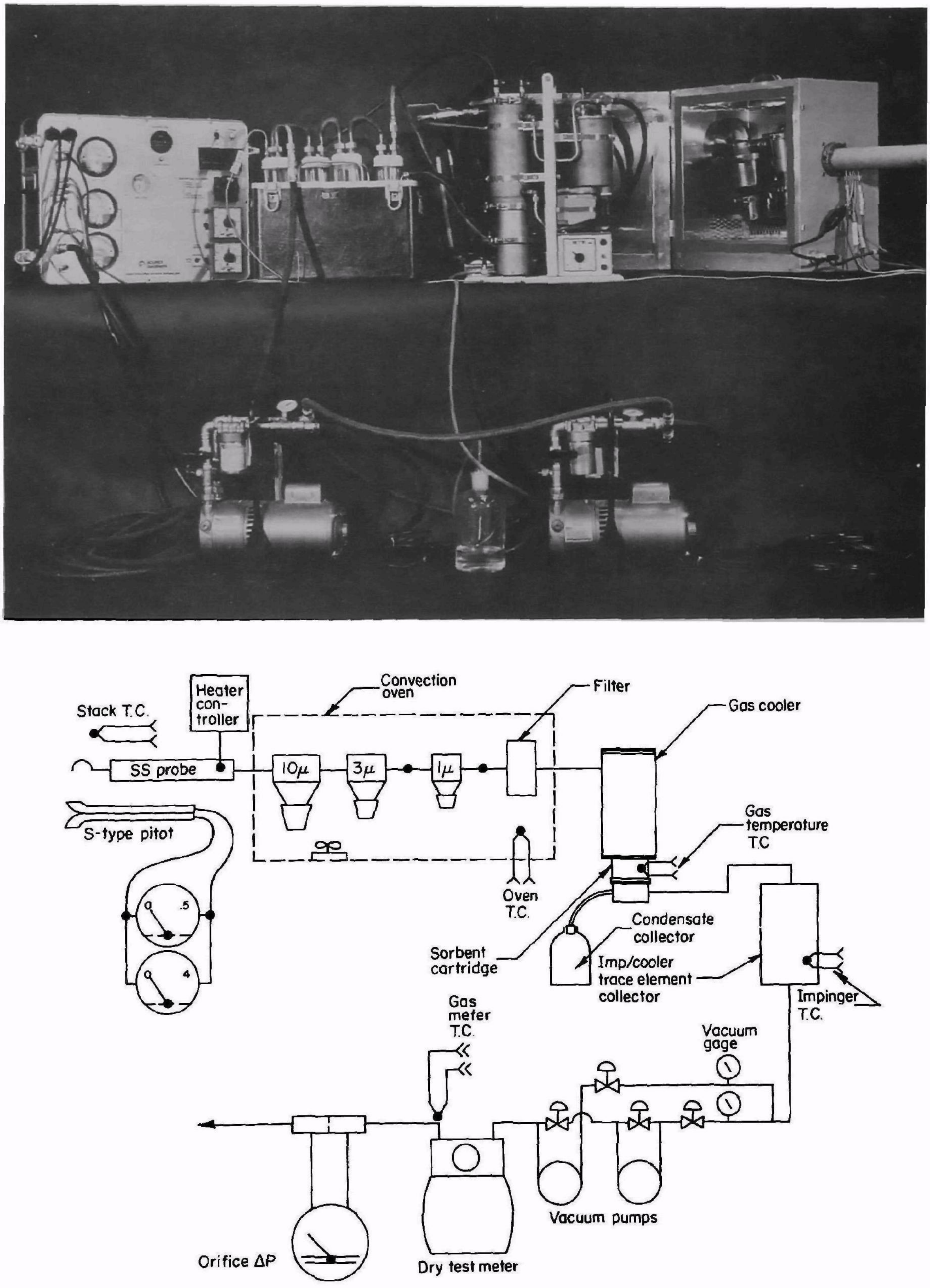


FIGURE 3. SOURCE ASSESSMENT SAMPLING SYSTEM (SAAS)

Additional comprehensive analyses will be considered when additional FBC units become operational, especially the larger units being planned in conjunction with ERDA programs and by industrial concerns.

The comprehensive analysis of emissions on Battelle's experimental FBC unit have been completed. This unit is of laboratory scale and used normally for process development. The combustion chamber is circular in cross section with metal walls and has no submerged cooling coils. A sketch of the unit is shown in Figure 4. During the comprehensive analysis of emissions, the operating conditions were within the following ranges:

Coal feed rate	4.1-7.7kg/hr (9-17 lb/hr)
Limestone feed rate	2.0-8.2kg/hr (4.3-18 lb/hr)
Air rate	39.5-68.5kg/hr (87-151 lb/hr)
Bed height	122cm (48 in)
Bed temperature	830-900 C (1525-1655 F)
Superficial gas velocity	183-287cm/sec (6.0-9.4ft/sec)
Ca/S ratio	2.9-7.7 to 1

Samples were obtained from the following streams: (1) coal feed, (2) limestone feed, (3) bed materials, (4) no. 1 cyclone catch, (5) sludge from stack scrubber, (6) stack filtered gas, (7) stack particulates > 2.3 micron, (8) stack particulates < 2.3 micron, (9) stack hydrocarbons adsorption column, and (10) stack volatile metals, impingers. Some preliminary results of this program are presented in Table 2. These data were intended to be used only for the purpose of evaluating the sampling and analysis techniques and were not for statistical evaluation or direct comparison with other fluidized-bed data.

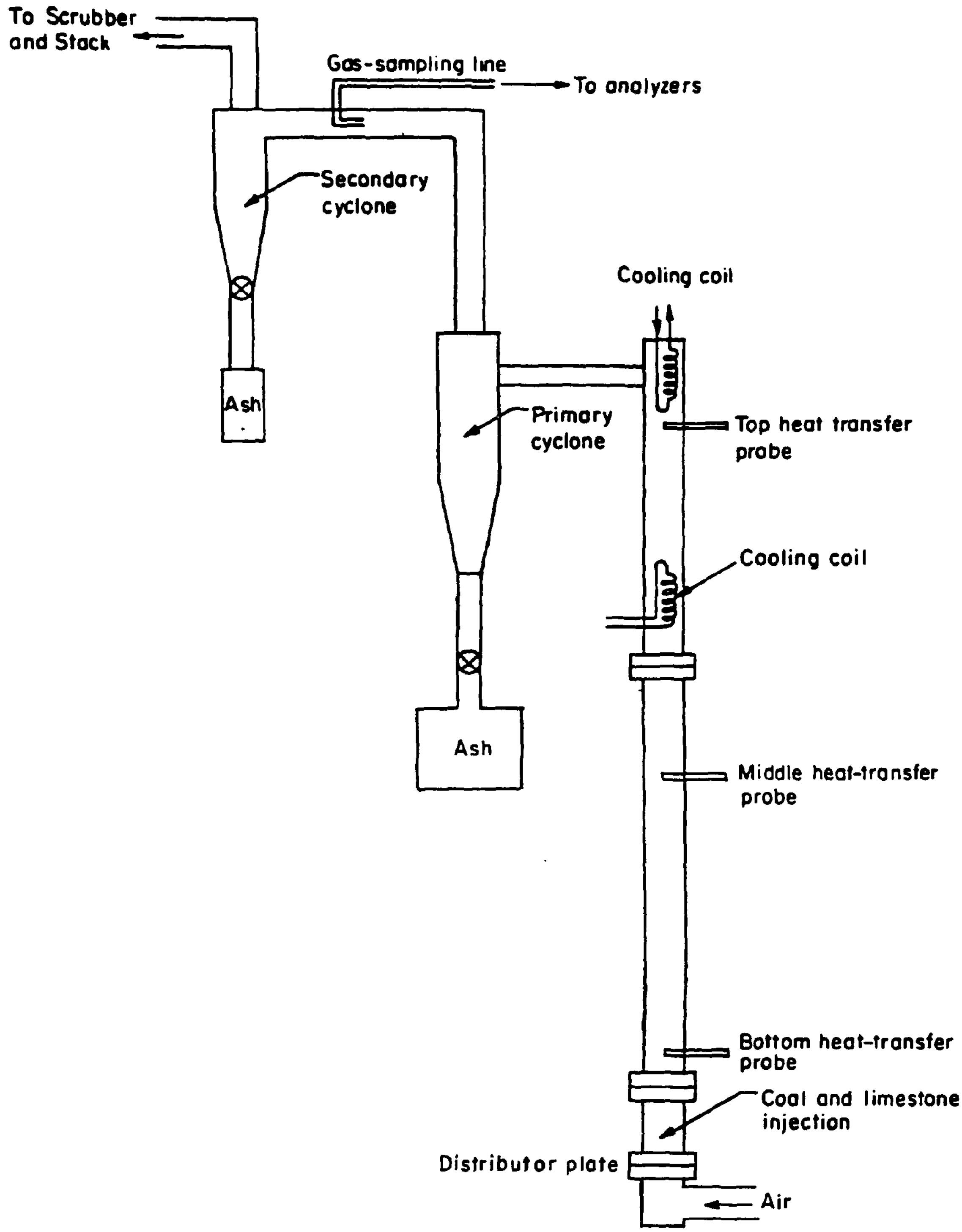


FIGURE 4. SCHEMATIC DIAGRAM OF BATTELLE'S FLUIDIZED-BED COMBUSTOR (15cm-6" in Diameter)

TABLE 2. RANGE OF PRELIMINARY RESULTS OF COMPREHENSIVE ANALYSIS - EMISSIONS FROM BCL 15-cm (6") FBC Unit

Component	ppm (Except Where Indicated) Range of Values
O_2 (%)	3.6 - 6.5
CO_2 (%)	14. - 17.
CO	790 - 2090
SO_2	700 - 730
NO_x	350 - 415
HC (ppm C)	85 - 360
HCl	37 - 44
HF	0.08 - 0.7
HCN	0.07 - 0.2
NH_3	1.8 - 7.1
SO_3	0.14 - 19
Particulate	
Loading (mg/m^3)	1500 - 1640
POM (mg/m^3)	5 - 72

C. Pretreatment of Input Streams

Presently, naturally occurring limestone and dolomite are widely used as SO_2 sorbents, and they have been shown effective. However, any improvement on sorbent utilization will produce significantly favorable impacts on FBC economics and environmental factors such as quantity of solid residue. Pretreatment of the input streams is a part of the EPA FBC program directly related to Control Technology Development and some preliminary investigations are presently underway at Westinghouse, Argonne and Exxon as part of their overall support studies programs.

Several experimental programs aiming at improving the sorption efficiency of limestone and dolomite are being conducted by EPA contractors. While optimization of the process conditions is being investigated, as discussed later, extensive fundamental studies concerning both physical and chemical aspects of the sorption phenomenon--such as chemical, physical and structural characterization of the sorbents, attrition behavior and kinetic studies--are also emphasized.

Pretreatment methods to maximize sorption of the limestone and dolomite are being investigated and it has been suggested that calcined limestone and dolomite possess greater sulfur oxide sorption capacity; the effect is more pronounced for the pressurized systems. Experimental studies conducted by Exxon, ANL and Westinghouse have confirmed the advantages of calcined sorbents.

An earlier study by PER showed that the addition of common salt to the limestone bed had favorable effects on improving the SO_2 sorption capacity of the limestone. ANL is currently conducting a detailed investigation of the mechanism for the action of salt in order to promote its practical application, particularly toward finding a less corrosive additive. Use of such an additive could substantially reduce the amount of solid waste from the process.

D. Modification of Process Conditions

A number of experimental process studies in support of the Control Technology Development Objective of the EPA FBC program are underway, and much valuable information has been generated by Exxon and ANL. Major experimental equipment is located at Exxon and ANL, however, laboratory-scale equipment is in use at Westinghouse and MIT. A Sampling and Analytical Test Rig (SATR) is also planned to interact on these process studies.

Exxon is conducting a program in their 10-cm (4-inch) diameter pressurized bench-scale fluidized-bed combustor and in the Miniplant facilities. The Miniplant includes a 31.75-cm (12.5-inch) diameter pressurized combustor and a 20.32-cm (8-inch) diameter pressurized regenerator. Successful operation of a 100-hour shakedown run and a 240-hour continuous demonstration run for the combustor were completed during the first half of FY 1976. A major portion of a combustor process variables study has been completed. The coupling of the combustor and the regenerator in the Miniplant is in progress, and the total integrated operation, with continuous circulation of solids between the combustor and regenerator, is planned for 1977. A schematic diagram and a photograph of the Miniplant are shown in Figures 5 and 6. ANL, in a project co-funded with ERDA, is conducting laboratory and bench-scale work, which includes testing on their 15.24-cm (6-inch) diameter pressurized combustor and 11.43-cm (4-1/2-inch) diameter pressurized regenerator.

SO_2 Emission and Sorbent Requirement

Effective SO_2 control has been recognized as one of the most important advantages of the FBC process. It is well known that the SO_2 emission from FBC depends on many process conditions such as sorbent/coal feed ratio, sorbent type, temperature, pressure, gas velocity, bed height, and sorbent particle size. Therefore, EPA's emphasis has been on the effects of the process variables as they relate to SO_2 control; sorbent utilization efficiency and optimum operating conditions.

Following shakedown of the Miniplant, Exxon conducted a systematic process variable study to investigate the effect of sorbent-type Ca/S ratio and temperature on SO_2 removal in pressurized FBC systems. Testing was also completed on the bench-scale combustor. The data from this study is shown in Figure 7. It was observed that the SO_2 removal ability of dolomite was unaffected by temperature, while higher temperature operation (e.g., 930 C) greatly improved the SO_2 removal ability of limestone. The improved limestone utilization efficiency is attributed to the calcination of limestone at higher temperature.

Based on the results obtained, sorbent requirements for a once-through pressurized FBC system are predicted as shown in Table 3. Although a significantly higher Ca/S molar ratio is required for limestone than for dolomite, the sorbent requirements are roughly the same on a weight basis.

NO_x Emissions

Past studies have shown that the NO_x emission from FBC is generally lower than that from a conventional coal-fired boiler system. Also, an increase in operating pressure significantly reduces the NO_x emission for FBC. Significant NO_x data were obtained from Exxon's Miniplant, BCL's 15-cm (6-inch) atmospheric unit and ANL's 15-cm (6-inch)

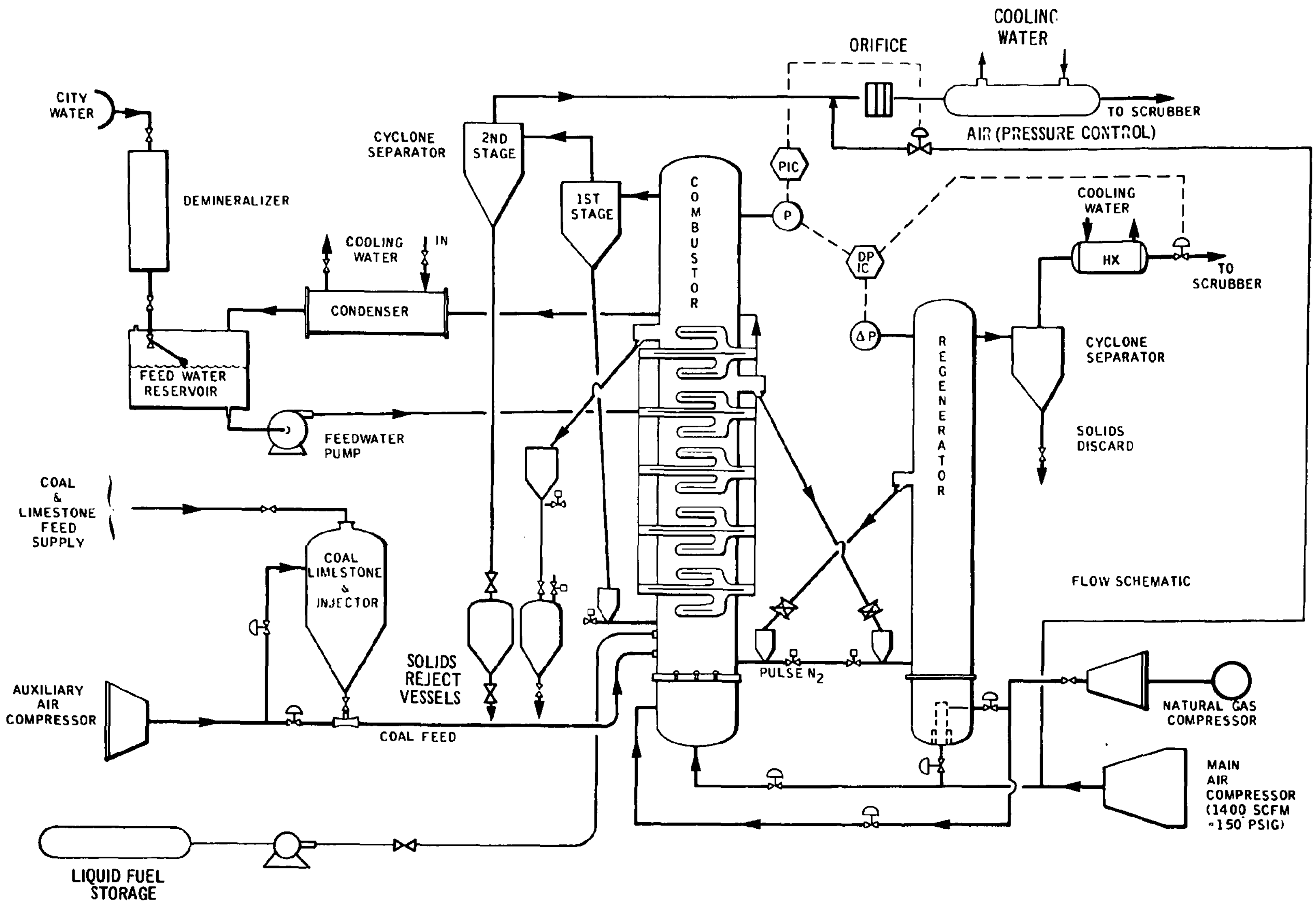


FIGURE 5. EXXON FLUIDIZED BED COMBUSTION MINIPLANT

FIGURE 6. EXXON FLUIDIZED BED COMBUSTION MINIPLANT

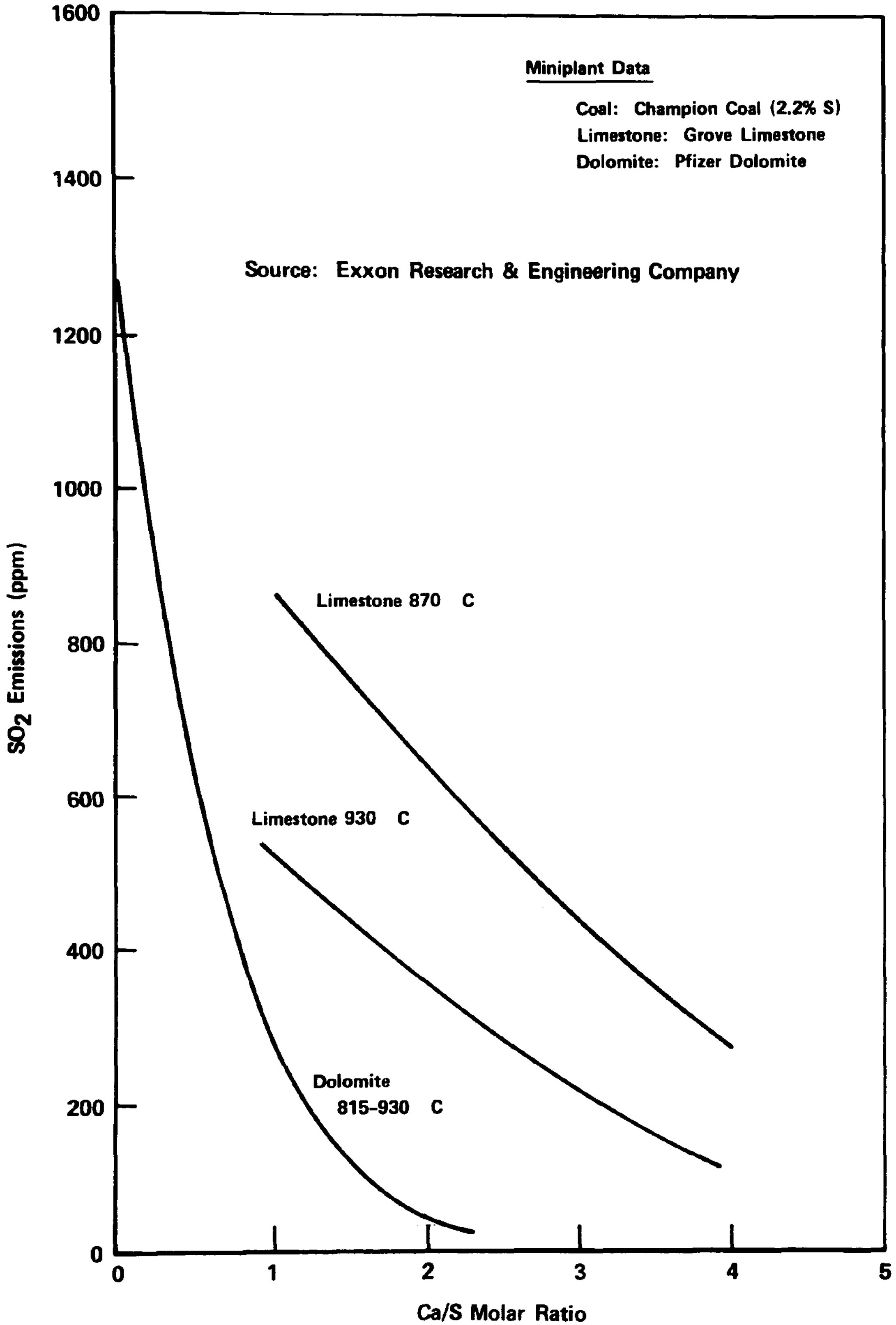


FIGURE 7. COMPARISON OF THE CORRELATIONS OBTAINED FOR DOLOMITE AND LIMESTONE

TABLE 3. SORBENT REQUIREMENT FOR PRESSURIZED FBC (ONCE-THROUGH)

Coal Sulfur (%)	Retention Level Required (%)[1]	Ca/S (mole/mole)		Sorbent/Coal Wt. Ratio	
		Limestone	Dolomite	Limestone	Dolomite
2.0	59	1.3	0.8	0.082	0.102
3.0	73	2.1	1.05	0.198	0.195
4.0	79	2.75	1.18	0.344	0.292
5.0	84	3.25	1.3	0.51	0.4

(1) Based on current EPA emission standard: .51 μg/J (1.2 lbs SO_2/million Btu).

Source: Exxon Research and Engineering

pressurized unit during 1976. Shown in Figure 8 is the correlation of NO_x emission and excess air from Exxon's study. The data indicate that NO_x emissions will increase with increasing excess air but not exceed the current EPA standards. Under a normal operating condition of 15 percent excess air and 10 atmospheres, the NO_x emissions are equivalent to 0.09 μg/J (0.2 lbs NO_x/million Btu). This emission rate is significantly less than the current EPA standard of 0.3 μg/J (0.7 lbs NO_x/million Btu).

ANL's results of 0.07-0.09 μg/J (.15-.2 lbs/10^6 Btu) agreed closely with Exxon's data and preliminary results from the comprehensive analysis of BCL's 15-cm (6-inch) unit are also in good agreement (0.14 μg/J or 0.3 lb/10^6 Btu) at approximately 20 percent excess air.

A fundamental study on NO_x formation and control is being conducted at MIT under EPA sponsorship. The objectives of this study are: (1) to develop a model to predict NO_x emissions from FBC at atmospheric and elevated pressure, (2) to provide physical-chemical input parameters for the model, (3) to provide information for the development of new control technology and (4) to test the model over a wide range of significant operating variables by comparing predicted data with experimental data.

Particulate Emissions

Particulate emissions from FBC of coal have been a major concern from both environmental and engineering standpoints. Past studies have confirmed that the particulate emissions are affected by many factors, such as the characteristics of feed coal and sorbent, FBC geometry, heat transfer surfaces, operating conditions, and the design of cyclones, etc. Several projects on particulate emissions and controls have been conducted by Exxon, Westinghouse and ANL. It is recognized that further development of particulate control technology is imperative (e.g., high efficiency cyclones, electrostatic precipitators, and granular bed filters). Supporting this finding are recent measurements from Exxon Miniplant operation which indicate that the particulate loading in the flue gas leaving the final cyclone was no less than 0.3 grams per standard cubic meter (0.13 grains scf). In some cases the particulate loading was as high as 2.8 grams per standard cubic meter (1.26 grains/scf). These particulate emissions are unsatisfactory when compared to the current EPA emission standards of 0.09 grams per standard cubic meter (0.04 grains/scf). These emissions are also excessive for a stream being fed to a turbine as is contemplated for pressurized FBC.

As FBC processes develop, particulate emission is one area which must be carefully monitored to ensure that proper control techniques are applied as necessary to eliminate significant environmental impact.

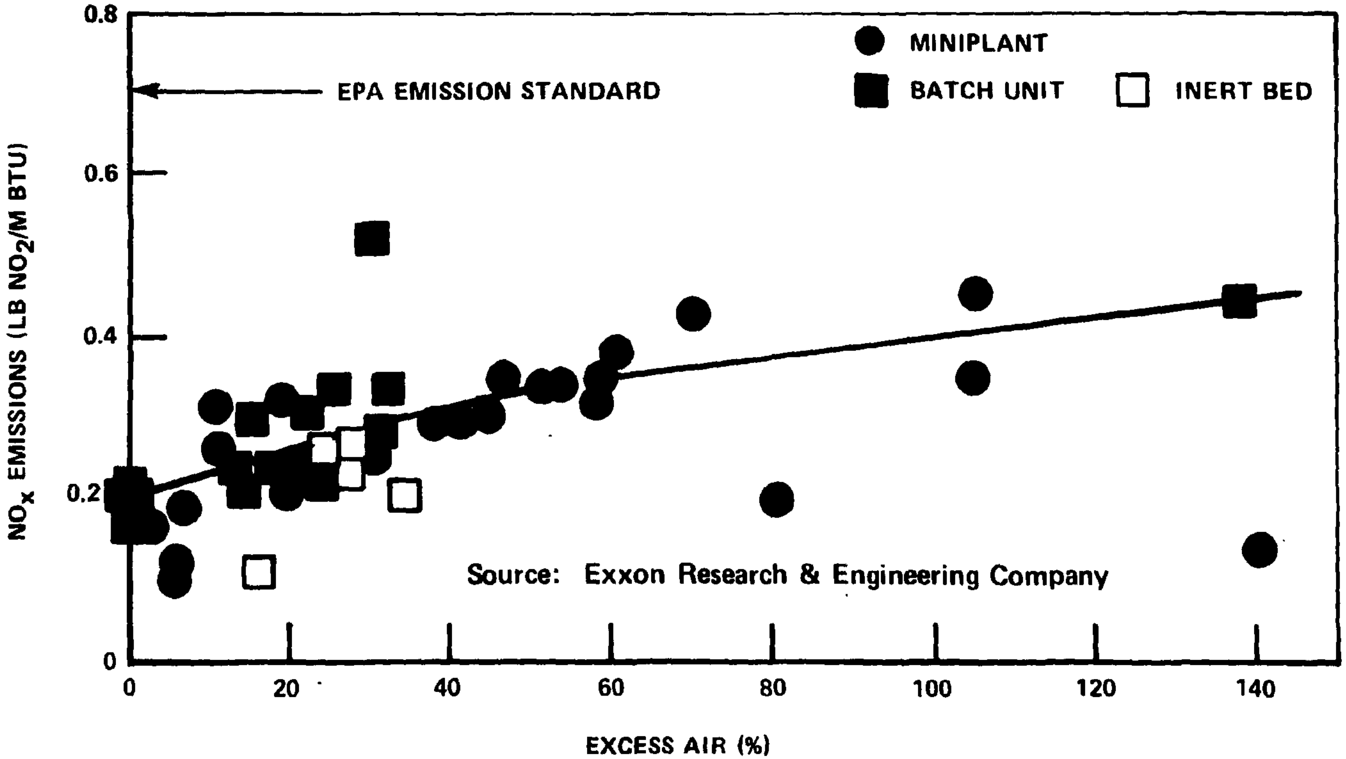


FIGURE 8. NO_x EMISSIONS

Alternative Sorbents

Although naturally occurring limestone and dolomite have been shown to be effective sulfur dioxide sorbents, a few problems--such as high sorbent requirement, loss of reactivity upon regeneration and cyclic use, and unsatisfactory physical integrity--are associated with their use. While methods of improving the limestone and dolomite utilization efficiency are actively being studied, feasibility studies employing alternative sorbents which can eliminate or reduce the above-mentioned problems are being conducted by several EPA contractors.

ANL is currently conducting a laboratory-scale study on synthetic sorbents. The synthetic sorbents are prepared by impregnation of a porous support material (e.g., alumina) with an active metallic oxide (e.g., CaO, SrO, BaO, Na_2O, and K_2O, etc.). Preliminary studies have concluded that the synthetic sorbents possess significantly superior desulfurization and regeneration reactivities than limestone and dolomite. It appears that CaO impregnated in alumina is currently the best choice among those sorbents being studied. Further studies on improving the physical integrity (attrition resistance) and the cyclic-use capability of the sorbents are in progress.

In addition, Westinghouse Research Laboratory has completed an initial evaluation of many possible alternative SO_2 sorbents based on considerations of thermodynamic feasibility, physical properties, heat balance, material balance, cost and availability. A preliminary study has identified 14 sorbents potentially acceptable for atmospheric FBC and 11 sorbents for pressurized FBC. An experimental study to verify the applicability of these candidate sorbents is currently in progress.

Trace Element Emissions

Inorganic trace elements such as mercury, lead, and beryllium, emitted from fossil-fueled power plants, incinerators, and industrial sources are receiving increased attention as potentially dangerous air pollutants. The process of coal combustion releases trace elements to the environment as vapors and/or in association with particulate emissions. Although a substantial fraction of the trace elements present in the coal during combustion is retained with the flyash removed by emission control devices, significant quantities of trace elements (such as mercury) may still be emitted as vapors or in association with submicron size particles that are not efficiently removed by present-day devices. A brief summary of work on trace elements emissions follows:

- At ANL, solids from the experiments conducted with the 15-cm (6-inch) diameter pressurized combustor were analyzed for trace elements employing primarily neutron activation and to a lesser degree, atomic absorption, fluorimetry and specific ion electrode methods. The gases were analyzed for mercury and fluorine. Selected results of these analyses, presented in Table 4, show that most elements are volatilized to a lesser degree in FBC than in conventional combustors. This is expected because the bed temperature in FBC is lower (1600 F) compared with 2800 F in conventional combustors. However, mercury, being low boiling, appears to volatilize about the same in both systems.

- Exxon studied trace element retention in a 10-cm (4-inch) diameter PFBC bed, and their results agreed generally with the ANL data (Table 4). Exxon employed the neutron activation method of analysis.

- Spark source mass spectrometric (SSMS) analysis of the solid samples from the Battelle 6-inch FBC unit indicated emission levels for Hg, Br, Pb, Sc, and K compared to those from other FBC units (see Table 4). On the other hand, the F and As levels were comparable to those for conventional fired units. The remaining elements were found to be generally at higher levels than those observed in the other combustion units. The data on these elements are suspect due to the low accuracy of the SSMS method and the experiment was not designed to obtain an accurate mass balance.

- Westinghouse provided thermodynamic projections of trace element emissions which indicated that Hg should volatilize and not condense. This was confirmed by experimental data at Exxon and ANL. Thermodynamics also predicted that several volatilized elements, such as Be, F, and Pb, can condense as sulfates and chlorides if these anions are present in sufficient amounts.

Other Pollutants

There are other compounds which will receive attention in the EPA FBC program, as indicated in the previous discussion of "Comprehensive Analysis". These other compounds include: gaseous and solid organic compounds; and a variety of inorganic gaseous compounds, such as SO_3, gaseous sulfides and disulfides, NH_3, cyanides, and gaseous chlorides and

TABLE 4. PROJECTED STACK EMISSION OF SELECTED TRACE ELEMENTS FROM CONVENTIONAL AND FLUIDIZED-BED COMBUSTORS EXPRESSED AS A PERCENTAGE OF THE ELEMENT ENTERING THE SYSTEM

Element	Conventional Combustion[(a)]	Fluidized-Bed Combustion ANL[(a)]	Fluidized-Bed Combustion Exxon[(b)]	BCL[(c)]
Mercury	90	80	No Data	75
Fluorine	90-100 (estimated)	40	No Data	98
Bromine	100 (estimated)	65-82	79	90
Arsenic	50-60	15	14	59
Lead	0-60	0-20	No Data	21
Beryllium	No Data	20-40	No Data	98
Scandium	10	0-3	15	0
Chromium	0	25	0	(d)
Cobalt	10-20	0-20	No Data	(d)
Sodium	20	4-5	12	(d)
Potassium	30	0-10	25	25-54[(d)]
Iron	0	0	20	(d)
Manganese	0	0	4	(d)

(a) Source: Argonne National Laboratories.

(b) Source: Exxon Research and Engineering.

(c) Source: Battelle-Columbus Laboratories
Spark Source Mass Spectometer Data (SSMS)

(d) Data Suspect Dut to Accuracy Limitations of SSMS fluorides. In their preliminary environmental assessment, GCA estimated the possible emissions of such pollutants from FBC systems, based upon available data, thermodynamic considerations and chemical experience (see Table 5). Battelle is continuing this investigation as part of its FBC environmental assessment effort. In general, it is concluded that further data are necessary before definitive conclusions can be drawn concerning the emissions of these pollutants from FBC.

During the 240-hour run of the Miniplant combustor, Exxon measured SO_3 levels in the flue gas ranging from 0 to 94 ppm, with values generally averaging about 5.5 ppm. The few high measurements of SO_3 are considerably greater than the levels from conventional combustors (about 20 ppm). The preliminary results of comprehensive analysis on the Battelle 6-inch I.D. atmospheric unit show an SO_3 level of about 20 ppm in one run. These results are not conclusive; there is some concern that the few high level data points may be the result of sampling error or conditions, and this possibility is being investigated. The temperature of FBC is about the same as commercial sulfuric acid processes in which SO_2 is oxidized to SO_3 and this may explain the higher levels. Further evaluation of these results and more comprehensive investigations are required to establish whether SO_3 emissions from FBC is a problem.

E. Add-On Controls

The development and testing of add-on controls is an important part of control technology development. Control technology will be an important factor in the ultimate commercialization, acceptance, and environmental aspects of FBC.

Several programs are currently underway which demonstrate laboratory and practical applications of control technology. The principal thrust of these studies at this time is on particulate control, since particulate control is an identified need for both atmospheric and pressurized FBC systems. Neither type of FBC system can meet the current EPA New Source Performance Standard for large coal-fired boilers (0.04 $\mu g/J$ or 0.1 $lb/10^6$ Btu) without some control device in addition to conventional cyclones. Control technology for other pollutants will be developed as the need is identified.

Mobile Control Devices

EPA has developed mobile test control devices including a fabric filter, a scrubber and an electrostatic precipitator. These units are mounted on 12-meter (40 ft) vans and will be tested on appropriate available atmospheric-pressure FBC units as soon as practical. They will also be tested on conventional combustors and other industrial emission sources in order to define recommended control devices.

The mobile devices have been designed for a wide range of operating conditions. The capacity of each device is given in Table 6. For

TABLE 5. ESTIMATED* GAS PHASE (STACK) EMISSIONS OF POTENTIAL POLLUTANT SUBSTANCES FROM FBC

Substances	Estimated Stack Gas Concentration
HF, HCl, CH_4, C_2H_4, C_2H_6, HCN, NH_3, $(CN)_2$, H_2S, COS, H_2SO_4, H_2SO_3, HNO_3, Be, F, Cl, Na.	1 ppm
Diolefins, aromatic hydrocarbons, polynuclear aromatic hydrocarbons, phenols, azoarenes, As, Pb, Hg, Br, Cr.	1 ppb
Carboxylic acids, sulfonic acids, polychlorinated biphenyls, alkynes, cyclic hydrocarbons, amines, pyridines, pyrroles furans, ethers, esters, epoxides, alcohols, ozone, aldehydes, ketones, thiophenes, mercaptans	0.1 ppb

* Estimates are based on thermodynamic considerations and chemical experience. These estimates should be good to within an order of magnitude.

Source: GCA Corporation

TABLE 6. CAPACITIES OF EPA MOBILE CONTROL DEVICES

	Electrostatic Precipitator	Bag Filter	Wet Scrubber
Actual volume handled, m^3/min (cfm)	84.95 (3000)	0.74-8.50 (26-300)	8.50-14.16 (300-500)
Maximum design temperature, C (F)	482.2 (900)	132.2 (270)*	371.1 (700)
Negative pressure than can be accommodated by on trailer blower, kPa (in H_2O)	-4.9 (-20)	-7.3 (-30)	-7.3 (-30)
Available ducting length, m (ft)	30.5 (100)	--	--

* 143.3 C (290 F) is probably acceptable, higher temperatures must be reduced by dilution with fresh filtered air.

operation, a slip stream from the stack gas is ducted to each of the three devices which are mounted on the vans. The operating parameters for each device can be varied to determine the optimum performance obtainable by that collection process and the design parameters that will provide this optimum.

Sampling and Analytical Test Rig

An FBC Sampling and Analytical Test Rig (SATR) is being designed and built for EPA by the Acurex Company, Aerotherm Division. The SATR will be located at RTP, N.C. and be used for a variety of studies including add-on control devices. Some of the programs currently anticipated are (1) evaluation of conventional electrostatic precipitators and bag filters, (2) evaluation of high-temperature particulate control devices, (3) NO_x emission studies, (4) NO_x control by staged combustion, and (5) NO_x control by ammonia injection. The anticipated operating ranges are (1) coal feed rate of 10 to 50 kg/hr (22 to 110 lb/hr), (2) sorbent feed rate of 0 to 25 kg/hr), (3) excess air of 10 to 300 percent, (4) bed temperature of 750 to 1100 C (1380 to 2010 F), and (5) fluidizing velocity of 1 to 5 m/sec (3 to 16 ft/sec).

Particulate Control Test Facility

A test facility has been designed by Westinghouse to study particulate control at high temperature (800-900 C, 1472-1652 F) and elevated pressure (1500 kPa, 216 psi). The facility will produce a simulated flue gas flow of up to 14.2 m^3/min (500 ft^3/min) at high temperature and pressure to test selected control devices. The system is designed to generate dust loadings up to 57.5 gm/m^3 (30 gr/scf) and to measure efficiencies up to 99.99 percent. Specifications and design drawings have been completed and installation will be started in 1977.

Miniplant Ducon Filter

A granular-bed utilizing Ducon filters has been designed by Exxon for particulate control at their Miniplant. Additional particulate cleaning is required because the two stages of cyclones on the Miniplant have reduced particulates to no less than 0.3 g/std m^3 (0.13 gr/scf) which is above the New Source Performance Standard.

The device consists of a steel shell, 2.44 m (8 ft) in diameter, and 3.66 m (12 ft) tall, rated at 1138 kPa (165 Psi) at 760 C (1400 F). It will be lined with 12.70 cm (5 in.) of insulating refractory. Four parallel filter tubes with about 10 elements in each tube will be installed. Three tubes will be of the Ducon design and one an Exxon design. The Ducon design backflushes the filter with a short high pressure (2068 kPa, 300 Psi) pulse without disconnecting the filter from the system. The Exxon filter disconnects a tube out from the system and fluidizes the granular bed with a reverse gas flow. About 276 kPa (40 Psi) over system pressure is needed. Figure 9 shows the basic features of the operation of the device.

Fabrication and installation of the filter unit is well underway and shakedown operation and initiation of a test program to define the performance of the device will take place in 1977.

Regeneration of Sorbent

Experimental studies on regeneration of limestone and dolomite were conducted mainly at Argonne and Exxon. Currently, the one-step reductive regeneration process is being actively investigated by both organizations. This process regenerates the spent, sulfated SO_2 sorbent by the reaction:

$$CaSO_4 + \begin{matrix} CO \\ H_2 \end{matrix} = CaO + \begin{matrix} CO_2 \\ H_2O \end{matrix} + SO_2$$

The Argonne program investigated regeneration at essentially atmospheric pressures, and involved treatment in the bench scale regenerator vessel of batches of sulfated sorbent prepared previously in the bench combustor. The Exxon program will be directed towards regeneration at elevated pressure; the Miniplant has the capability to continuously circulate solids between the combustor and the regenerator.

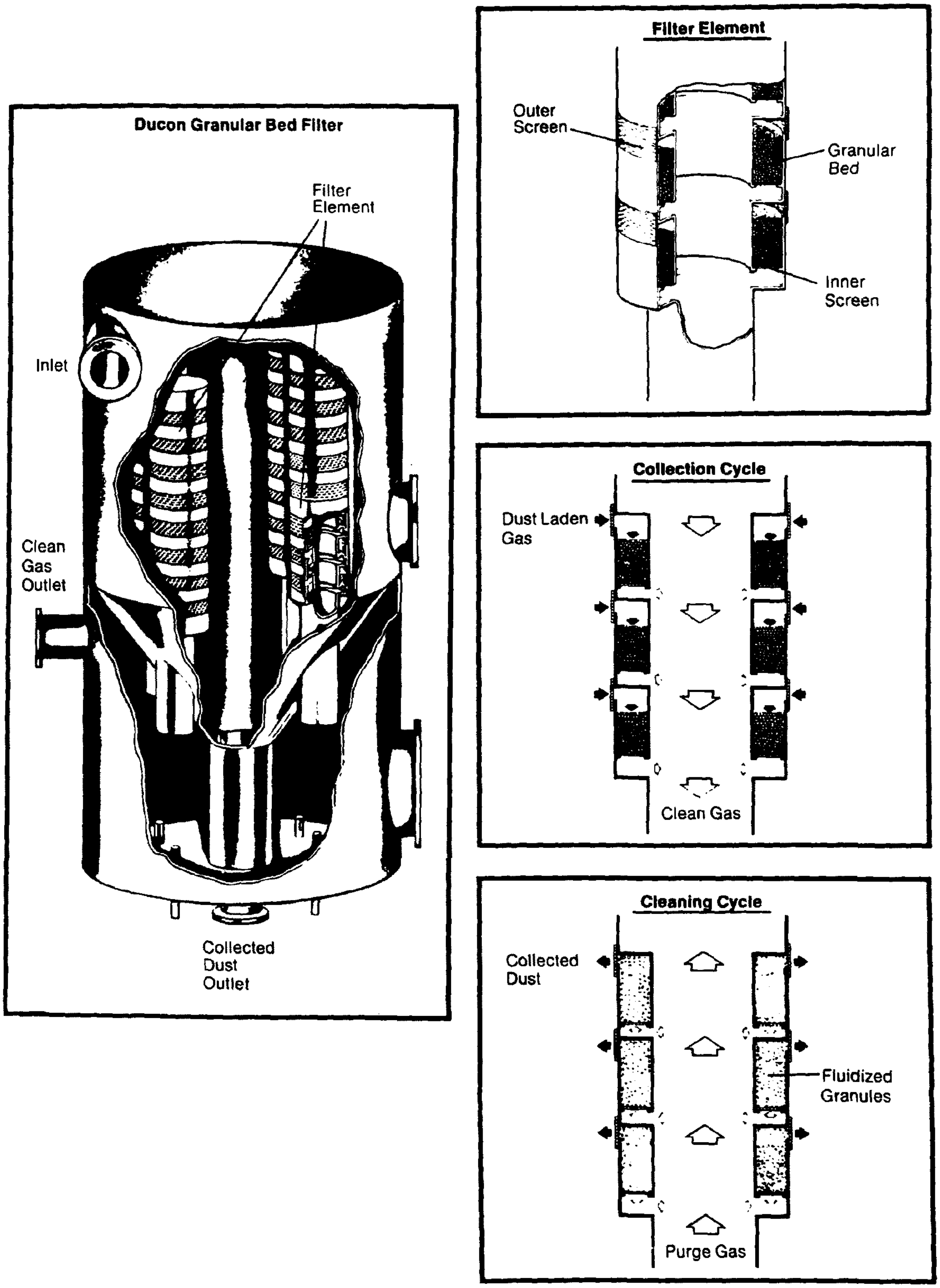


FIGURE 9. DUCON GRANULAR BED FILTER

Some of the typical operating conditions are:

	ANL	Exxon Miniplant
Regenerator Size	4-1/2" diameter	8-1/2" diameter
Reductant	Coal	Natural Gas
Temperature (C)	1100 (2012 F)	1100 (2012 F)
Pressure (kPa)	153 (22 psi)	1000 (145 psi)
SO_2 Concentration in Off-gas (% wt basis)	8.5	3

ANL's work has demonstrated that partial combustion of coal can be used as the source of reducing agent. Sulfated Tymochtee dolomite and Greer limestone have been successfully regenerated. Parametric studies revealed that the extent of regeneration decreased with decreasing solid residence time at all temperatures and increased with increasing regeneration temperatures. The SO_2 concentration in the off-gas increased with increasing regeneration temperatures and with decreasing pressures. As high as 9 percent SO_2 in the off-gas has been obtained and this concentration is high enough for recovering the sulfur as sulfuric acid.

The technical feasibility of cyclic use of sorbents was demonstrated by ANL in a 10-cycle, batch combustion/regeneration experiment. Encouraging results were obtained. In each combustion step, Arkwright coal was combusted in a bed of Tymochtee dolomite at a pressure of 810 kPa (117 psi) and a bed temperature of 900 C (1652 F). The regenerator was operated at 153 kPa (22 psi) and 1100 C (2012 F). The reactivity of the Tymochtee dolomite decreased linearly in each cycle. It was calculated, based on this data, that, in a continuous combustion/regeneration system, fresh sorbent would have to be added at a calcium to sulfur mole ratio of 0.35 to meet the EPA New Source Performance Standard of 1.2 lb $SO_2/10^6$ Btu with the 2.8 percent sulfur Arkwright coal.

A major effort at Exxon has been concentrated on the operation of the Miniplant regenerator. Several shake-down tests with the regenerator operated in batch mode (uncoupled with the combustor) have shown satisfactory performance of the regenerator. Coupling of the combustor and the regenerator in the Miniplant is currently underway.

Other Work

In addition to the particulate control work being conducted as a direct part of the FBC program, EPA is conducting a broad program aimed at developing, and at understanding the mechanisms of, particulate control technology.

F. Solid Waste Disposal

Extensive investigations on the FBC solid waste have been started only recently. The solid residue from FBC is an area of major environmental concern. The residue studies are in support of the control technology development objective of the EPA program.

Spent sorbent and coal ash are constantly withdrawn from the fluidized bed and can be immediately discarded (once-through), or the sorbent may be separated from the ash and reused after a regeneration process. Even with regeneration, the sorbent material eventually becomes less reactive and a portion must be discarded. The solid waste residue must be discarded in an environmentally acceptable manner to avoid problems from leaching, dusting, runoff, air pollution, and water pollution.

The EPA FBC solid residue program consists of projects with Ralph Stone and Company, Westinghouse Research Laboratories and the Tennessee Valley Authority (TVA). In addition, ERDA is sponsoring, or has sponsored, programs in the area of residue utilization with the Department of Agriculture, IU Conversions Systems, British Coal Utilization Research Association (BCURA), Virginia Polytechnic Institute (VPI), and Pope, Evans, and Robbins (PER). The early efforts have been valuable in pointing out the direction for detailed laboratory and field investigations.

Liquid wastes from FBC have not been identified as a significant environmental problem except as leachate water from solid waste disposal beds. If other problems related to liquid wastes are identified as a result of the Environmental Assessment Program, provisions will be made for detailed investigation.

Scope of Current EPA Solid Waste Programs

The scope of current programs in FBC solid waste includes: (1) characterization of solid waste materials resulting from variations of the FBC process and input materials; (2) laboratory and field studies to identify solid leaching properties and the effects of long-term exposure of solid waste and solid waste by-products to the environment, (e.g., lysimeter tests, shake tests and field study planning); (3) laboratory studies of physical and chemical treatment of solid wastes to reduce the environmental impact upon disposal; (4) laboratory and marketing studies of the potential for utilization or for manufacturing marketable products from solid waste material; and (5) environmental impact from disposal by methods other than conventional landfill (e.g., ocean disposal, land-spreading, acid-mine treatment, and flue-gas desulfurization sorbent).

Characterization of Spent-Bed Materials

The detailed characterization of the spent-bed (waste) materials is important to the overall FBC program in two major ways. First, as a means of understanding the basic mechanisms of sulfur removal in the combustor and reactions taking place in regeneration processes and, second, to determine the elements, compounds, properties and physical structures of materials which could have potential adverse environmental impact. Westinghouse, Argonne, Ralph Stone and Company and TVA have planned characterization efforts aimed at determining the physical and chemical properties of FBC waste material.

Many analytical techniques are being used in the characterization study including: classical wet chemistry, x-ray diffraction, electron microscopy, scanning electron microscopy, electron microprobe, differential and gravemetric thermal analysis, atomic absorption and mass spectrometry. For example, Argonne has analyzed regenerated and sulfated dolomite particles by electron microprobe and has determined that a radial variation exists in the sulfur content which depends on the sulfation or regeneration time. In the sulfation experiments, a shell of sulfate is formed on the outer surface of the particle which moves toward the center of the particle as the sulfation time is increased.

In regeneration processes, it appears that a two-step reaction takes place; an early stage where the primary regeneration-reaction zone moves radially into the sulfated particle, leaving some residual sulfur behind the advancing zone, and a second (slower) stage which will remove most of the residual sulfur. In a commercial FBC regeneration process, in which the solids residence time would be short (high solids throughput rate), probably only the first (rapid) stage of regeneration would occur. Hence, most but not all of the sulfur could be removed.

The spent-bed (solid waste) material from the FBC of coal will consist primarily of varying ratios of calcium sulfate, calcium oxide, coal ash and smaller amounts of other compounds and trace elements depending on the initial compositions of the coal and sorbent and the operating conditions of the FBC unit. Magnesium oxide will be present if dolomite is used as the sorbent and the composition of the spent-bed material will also vary if regeneration processes are used. Withdrawal point, mixing of cyclone ash with the spent bed, and the Ca/S ratio will also be factors affecting the ultimate composition.

Table 7 lists some typical examples of sorbent and coal input and output compositions which might be expected for FBC combustors. It must be remembered that compositions of naturally occuring materials such as coal, limestone and dolomite will vary considerably from point to point in a deposit and values must be averaged. The values in Table 7 are preliminary and detailed characterization will depend on future work involving waste material which is typical of commercial FBC units.

TABLE 7. EXAMPLES OF TYPICAL COAL AND SORBENT INPUT AND OUTPUT COMPOSITIONS (MAJOR CONSTITUENTS) FOR FBC COMBUSTORS (WEIGHT PERCENT)

Compound	Coal, Pittsburgh #8(1)	Limestone, #1359-Grove(2)	Dolomite, #1337-Pfizer(1)	Coal Ash(1)	Atmospheric FBC Waste(3) Limestone, #1359	Atmospheric FBC Waste(3) Dolomite, #1337	Pressurized FBC Waste(3) Limestone, #1359	Pressurized FBC Waste(3) 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) $H_2O + CO_2$

Environmental Impact of Disposal

One of the primary aims in the EPA solid waste disposal program is to determine the degree of environmental impact from the disposal of large quantities of FBC waste material. Work in progress includes analysis of leachate from residues generated by currently operating experimental units (e.g., Exxon Miniplant, PER, ANL, etc.). Much of the preliminary information has been obtained from simple shake tests and a comparison with leachates from flue gas desulfurization (FGD) waste. FGD waste has many similar characteristics to that obtained from FBC, except it is usually disposed of as a sludge, whereas fluidized-bed residue is a dry solid. Table 8 lists some preliminary comparisons of trace elements from FBC ash and spent stone leachates with ash ponds and FGD sludge liquors/ supernatants. There are indications that there may be some problems associated with trace elements in leachates, however this must be confirmed when the results from large-scale lysimeter tests and further shake tests are available early in 1977.

Ralph Stone and Company is currently investigating residue leachate by the use of column lysimeters simulating eight environments thought to be representative of typical disposal sites. These are: limestone quarry, dolomite quarry, coal mine, ocean (shore landfill), sanitary landfill and three standard soil environments. Stone is also planning field investigations when sufficient quantities of residue become available for large scale testing.

One of the problems receiving considerable attention is the defining of standardized shake, lysimeter and leaching tests. Standardized tests are essential to allow comparison of data between laboratories and to provide quick, inexpensive methods to evaluate the effects of process variations on the properties of the waste materials. Westinghouse, Ralph Stone and TVA are providing input to the solving of this problem and it is expected that standard methods will be available and used in 1977.

Westinghouse has prepared a preliminary estimate of the environmental impact from land disposal of spent sorbent and ash as projected from current experimental data (Table 8). Indications are that landfill disposal of spent stone will not cause problems which cannot be solved using current control technology. This must be confirmed as more data becomes available on leachates from residue representative of that obtained from large-scale FBC. Emphasis during the early stages of the FBC solid waste program will be on once-through, throw-away processes, since these will be the first to reach commercial utilization. Regeneration processes, as a method of reducing the solid waste burden, will receive greater emphasis later.

TABLE 8. TRACE METALS IN ASH, FGD SLUDGE POND, LIQUORS/SUPERNATANTS, AND FBC ASH AND SPENT STONE (EXCEPT pH, CONCENTRATIONS IN PPM)

	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 9. ENVIRONMENTAL IMPACT OF SPENT SORBENT FROM FLUIDIZED BED COAL COMBUSTION PROCESS

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

Westinghouse also is currently investigating low temperature processing of waste material, prior to disposal, which has the potential of reducing leachate problems significantly.

Table 10 is an example of preliminary FBC leachate concentration estimates compared to estimates from landfill leachate, gypsum leachate, and FGD supernatant concentrations and proposed EPA and World Health Organization water supply intake criteria. Data such as presented in Tables 8, 9 and 10 will be important for interpreting leaching results and, initially, drinking water standards will be used as a guide to environmental impacts. Ultimately, the MEG chart will be used to interpret the data obtained from leachate testing and relate the results to health and ecological effects.

Utilization and Marketing

There are several possible uses for spent bed material which are currently being investigated. These include: landspreading, fertilizer, ceramics, concrete, brick, plaster, acid mine treatment, road deicers, FGD treatment, and land reclamation. Current indications are that there is a definite potential for utilization which must be confirmed by market and economic analyses.

Future Studies

In 1977, it is expected that detailed characterization of typical residues from FBC will be completed. Westinghouse, Ralph Stone and TVA will be involved in these studies which should ultimately define the limits and variability of FBC waste materials and provide the information necessary to determine potential environmental impact. Trace element determinations will receive a high priority to insure that no potential harmful components will be overlooked. Shake, column and laboratory leaching tests will be standardized and used to screen residue for detailed analysis as necessary. Ralph Stone and Company will plan for small-scale and large-scale field tests of residue to be implemented as soon as sufficient quantities of material become available. Sufficient information will have been obtained to allow recommendations to be made for disposal sites or alternate disposal methods. Utilization studies and market projections for potential products from FBC waste will be essentially complete. Evaluation of Westinghouse's low temperature processing of residue to reduce leachate and environmental impact will also be completed.

The EPA FBC solid waste program is also directly related to the environmental assessment program and to the ERDA program. Therefore, changes and developments in the FBC process must be carefully evaluated with regard to their effects on the environmental impact of FBC solid waste. Close coordination with the ERDA development program is essential to identify and minimize environmental impacts before commercialization of the FBC process.

TABLE 10. COMPARISON OF FBC WASTE LEACHATE WITH SANITARY LANDFILL, GYPSUM, AND FGD LEACHATE

	Proposed EPA and WHO Water Supply Intake Criteria	FBC Waste Leachate	Sanitary Landfill Leachate	FGD Supernatant/ Leachate	Iowa No. 114 Gypsum
pH	5-9	7-12 + [(a)]	4-6	8-12 +	∿7.4
TDS	500[(b)]	2000-9000	10,000-14,000	8000-10,000	
SO_4^{-2}	250	1000-6500	400-650	3,000	∿1500
Ca	75	300-6000++	900-1700	800	∿600

(a) + indicates some data points of higher value were obtained but are not regarded as representative.

(b) Values (except pH) in ppm.

Source: Compiled by Battelle from information supplied by: Westinghouse Research Laboratories, Argonne National Laboratories, Pope Evans and Robbins, National Research Development Corporation (BCURA), R. Stone and Company, Aerospace Corporation, Battelle, and open literature.

Additional problems associated with solid waste, not presently known, will be identified as larger quantities of waste material become available for detailed investigation.

G. Application Studies

Since FBC has the potential of being a less polluting and a more efficient method of coal combustion, and because efforts to assess its environmental impact should also be related to the factors which affect its market penetration, EPA has participated in studies on FBC applicability to industrial boilers. EPA also initiated (1) a study to compare costs of alternate processes for coal combustion with reduced pollution and (2) an assessment of the effect of experimental scale on emissions from FBC units.

Application of FBC to Industrial Boilers

This program is jointly funded by FEA, ERDA and EPA with Exxon as the contractor. The study has several objectives.

1. Determine the maximum, minimum and most likely demand for industrial coal-fired FBC technology considering cost, availability of fuel, and other relevant factors.

2. Determine the anticipated reduction in national/regional oil and gas consumption by the use of coal-fired industrial FBC technology, both for new units and retrofit of existing units.

3. Assess the economic impact of widespread industrial application of the pertinent FBC technology to all affected segments of the economy.

4. Determine and define the specific technical requirements for representative applications of the pertinent FBC technology.

5. Assess the potential environmental impacts of the above.

The significant interim conclusions of the Exxon industrial FBC study are: (1) a good potential exists for use of FBC technology in the chemicals, paper, petroleum refining/petrochemicals, primary metals and food industries (possibly 3×10^{15} Btu/year by the year 2000); (2) fluidized bed industrial boiler systems can be more economical than conventional coal-fired systems with flue gas scrubbing; (3) larger boilers (up to 250,000 lbs/hr, 113,400 kg/hr steam production) favor FBC since they are likely to be more compact than conventional boilers and (4) to realize the above potentials, there is an urgent need to demonstrate the reliability of

FBC technology on a reasonable plant scale. The study also confirmed that emissions of SO_2 and NO_x from industrial fluidized bed boilers can be reduced to levels below those specified in current Federal emission standards. Particulate can also be reduced to these levels by the use of control technology. The study is continuing and final conclusions are yet to be determined.

Cost Comparison Studies

Under EPA sponsorship, TVA is conducting a study to compare the projected capital and operating costs of commercial atmospheric- and pressurized-FBC power plants with a conventional coal-fired power plant employing FGD. The costs being used for atmospheric and pressurized FBC systems were those developed by General Electric, Foster Wheeler and Bechtel under the Energy Conversion Alternatives Study (ECAS) which is jointly funded by NASA, ERDA, and NSF. Under the EPA-TVA study, GE is extending their previous cost estimates to include a conventional boiler with a non-regenerative lime scrubber. The initial estimates (for a roughly 800-MW system) show atmospheric and pressurized FBC to have somewhat lower costs of electricity than a conventional boiler with scrubber. TVA is conducting parametric cost studies using the GE input. A final report is scheduled for 1977.

Studies on Effect of Scale-Up

Dow studied the effect of experimental scale on the emissions from FBC systems. Emissions data from 12 experimental FBC units of different sizes were examined, and the available data were plotted in an effort to determine the effect of scale-up. This technique did not lead to any definite conclusions.

RELATIONSHIP OF THE EPA PROGRAM TO THE DEVELOPMENT PROGRAMS

The major program in the United States for development of FBC technology is presently being conducted by ERDA. The ERDA program addresses the potential applications of coal-fired FBC in the electric utility and the industrial sectors, and in commercial/residential community usage. The Electric Power Research Institute (EPRI) is conducting a coordinated program in FBC technology research and development, keyed to the needs of electric utilities.

Development work is also being done outside the United States, especially in the United Kingdom. Significant funding for the British work is provided by ERDA and EPRI.

ERDA Development Program

The ERDA program strategy is to continue work on research and component development while proceeding to large-scale prototype development. The development sequence of the ERDA program is based on a manageable scale-up program for both atmospheric and pressurized combustors.

This sequence consists of laboratory-scale testing and bench-scale units (less than 1 ton coal/day) at ANL; process development units (PDU, 1 to 10 tons coal/day) at PER for atmospheric and at Combustion Power Company (CPC) for pressurized units; component test and integration units (CTIU, 10 to 100 tons coal/day) planned at Morgantown Energy Research Center (MERC) for atmospheric and at ANL and the International Energy Agency (IEA) for pressurized units; pilot plants (100 to 1000 tons coal/day) at Rivesville (30-MWe) for atmospheric and Curtiss-Wright (13-MWe) for pressurized units; and demonstration plants (over 1000 tons coal/day) which have not yet been designated. In addition to these units, which are aimed primarily at utility applications, ERDA is cofunding a project with the Department of Housing and Urban Development to design and construct a modular integrated utility system (MIUS) using an atmospheric fluidized-bed combustor to provide the total electricity, heat, air conditioning, and hot and cold potable water requirements for housing complexes. ERDA has also recently initiated eight projects for the design, development, and construction of demonstration units for industrial and institutional applications such as process steam, process heat, and space heating. Table 11 gives an approximate schedule for these units.

Other fluidized-bed combustion activities include system studies and system definition to provide a continually updated program objective and to aid in projecting potential acceptability to industry; environmental risk studies; technical risk studies; safety impact studies; and an energy conversion alternatives study (ECAS). The ECAS is examining economic and energy efficiency considerations of alternative schemes for generating power including several schemes based on fluidized-bed combustors.

EPRI Development Program

The emphasis of the EPRI program is on aspects of FBC which are of specific interest to utilities and encouraging boiler manufacturers to participate in the development of fluidized-bed boilers. Since the EPRI program is being conducted in a close relationship to the ERDA program, there has been no need for EPRI to sponsor the construction of large-scale test facilities. However, EPRI has sponsored studies on relatively large units owned by others. For example, EPRI has sponsored process development studies

TABLE 11. APPROXIMATE SCHEDULE FOR ERDA UNITS

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.

on a 3 x 3 ft (91 x 91 cm) atmospheric unit owned by Babcock and Wilcox and will sponsor more such studies plus component tests on a 6 x 6 ft (183 x 183 cm) Babcock and Wilcox unit which is under construction (to be operable in Fall, 1977). Most of the EPRI program is oriented toward atmospheric boilers.

Specific studies sponsored by EPRI include investigations of fluidization and heat transfer characteristics in cold model configurations most likely to be used for utility boilers; engineering design, evaluation, and economic studies on the application and retrofit of fluidized-bed combustors and their components to utility boilers; studies related to the selection and utilization of SO_2 sorbents; investigation of corrosion/erosion problems and their elimination; studies on combustion characteristics and carbon utilization; and investigation of hot gas cleanup. EPRI is also conducting studies on transportation, health effects, and environmental effects which are applicable to all types of power plants and are not specific to FBC systems.

International Development Programs

The EPA is monitoring closely international FBC activities which are at various stages of development and are aimed at implementation of processes that address specific and sometimes unique applications.

Pollution control is often a secondary reason for interest in FBC in most countries. In the United Kingdom, organizations such as the National Coal Board, National Research Development Corporation, Combustion Systems, Ltd., Babcock and Wilcox, Ltd. (U.K), and Woodall Duckham (subsidiary of Babcock and Wildox, Ltd.) have been and are developing processes for both industrial and utility applications. British coal is primarily low sulfur and inert material or ash is generally used as the bed material. Lower fluidizing velocities (2-8 fps or 60-240 cm/sec) and, hence, smaller particles are used by the British, so their units have physical and operating characteristics different from the U.S. units. Swedish organizations have expressed interest in commercial systems for applications such as district heating. The Japanese are investigating applications to nonreactive fuel utilization, i.e., coke breeze burning for steam and power generation. Additional research is being conducted by West Germany (Bergbau-Forschung) and India (Bharat Heavy Electricals).

Some existing units which have received attention are the Renfrew boiler (Scotland), the Ignifluid boiler (France), and the Duklafluid boiler (Czechosolvakia). The Renfrew unit, built by Babcock and Wilcox (U.K.), is the largest existing fluidized-bed boiler that is amenable to sulfur control and was converted from a conventional boiler to a fluidized-bed unit with a published capacity of 45,000 pounds of steam per hour. It has operated at 20,000 pounds per hour and is currently being upgraded. The Ignifluid and Duklafluid boilers are similar to each other and are not typical fluidized-bed combustors as compared to most of those of interest in the U.S. development effort. The fluidized zone acts as a reducing (fuel) gas generator and there are no tubes in this zone. The fuel gas generated in this zone plus unburned carbon is combusted in a regular boiler with secondary air supply.

Significant units in the planning stage include a 30 MW, 10 atm. steam generation-gas turbine demonstration project sponsored by the International Energy Agency (IEA) of which the United States (ERDA) is a member (other members are the United Kingdom and West Germany); a proposed project on gas generation/hot gas cleanup/gas turbine pilot plant to be built by Bergbau-Forschung of Essen, Germany; and a 25 MW district heating unit to be built in Enkoping, Sweden. The IEA and German units should provide significant inputs to the development and commercialization of pressurized systems while the Swedish unit is quite versitile in being designed for completely automated operation with a capability for fuel switching.

EPA Contributions to the Development Programs

The EPA program complements the ERDA technology development program as well as the EPRI and International programs by,

- Providing information on pollutant emissions,
- Establishing environmental goals for the process,
- Recommending best available control technology,
- Recommending environmental standards,
- Developing control technology,
- Contributing to the ERDA process development studies,
- Contributing to studies on economics and acceptability of the process.

The contributions of the EPA program can be arranged according to key outputs which fall under environmental assessment or the control technology development categories and which are given in Table 12 along with their expected completion dates. Many of the EPA outputs will be available in time to influence the design and construction of the ERDA units and data from the subsequent operation of the ERDA units will be used to update the EPA outputs.

The EPA program is being conducted in coordination with the FBC technology development program being conducted by ERDA. Much of the EPA testing (comprehensive analysis, control technology) will be performed on ERDA units. ERDA will use EPA's pressurized FBC Miniplant for process development studies. EPA and ERDA are co-funding the experimental work at ANL and the industrial boiler applications study at Exxon.

Thus, the EPA program is an integral part of the development program for fluidized-bed combustion in the U.S. By conducting the EPA program in parallel with the technology development programs, any significant environmental problems should become apparent during the early stages of development. These problems can then be addressed at a time when choices can still be made among alternative process variations in order to choose the more environmentally acceptable ones. Such choices at the early stages of development will avoid the expense and inconvenience of redesigning and retrofitting large units after construction.

TABLE 12. ANTICIPATED SCHEDULE FOR OUTPUTS OF THE EPA PROGRAM

Output	Date
Environmental Assessment	
Comprehensive analysis plan for existing units	7/76
Complete first version of Multimedia Environmental Goals Chart	3/77
Reports on environmental problems identified through comprehensive analysis and biological screening tests	6/77 6/79 6/81
Design of phased test program for Rivesville unit	3/77
Preliminary recommendation to set standards for atmospheric units based upon initial comprehensive analyses on Rivesville unit	12/77
Updated recommendations to set standards for atmospheric units based upon further comprehensive analyses and control device characterization on Rivesville and other existing facilities	12/78
Manual of best available control technology for atmospheric units based upon Rivesville and other existing facilities	12/78
Update of Multimedia Environmental Goals Chart	12/78
Updated recommendations of standards and updated technology manual for atmospheric units based upon further comprehensive analysis and control device characterization on Rivesville and MERC, CTIU, and upon testing of second-generation control devices	12/80
Initial recommendation to set standards for pressurized units based upon initial comprehensive analysis and control device characterization on Curtiss-Wright pilot plant and Argonne CTIU	9/81
Manual of best available technology for pressurized units based upon control device characterization on Curtiss-Wright and Argonne units, and upon high temperature/pressure device testing	9/81
Control Technology Development	
Preliminary recommendations for testing particulate control devices	1/77

TABLE 12. (Continued)

Output	Date
Control Technology Development (Continued)	
Complete initial sorbent precalcination tests on Exxon Miniplant	11/76
Initial schedule for control technology testing on PDU, CTIU, and pilot-scale facilities	6/77
Initiate testing of Ducon filter on Miniplant	1/77
Initiate particulates control device testing on Westinghouse test stand	6/77
Report on testing of solid waste disposal and utilization methods	12/77
Complete environmental testing of Miniplant combustor in once-through sorbent operation	12/77
Initial report on control technology testing on atmospheric PDU and pilot facilities	12/78
Complete first phase of particulates control device testing on the EPA Sampling and Analytical Test Rig in support of other control device testing projects	7/79
Updated report on control technology testing on atmospheric PDU, CTIU, and pilot facilities	12/80
Complete environmental testing of Miniplant combustor/regenerator system	6/81
Complete testing on control technology for atmospheric industrial boiler	6/81
Initial report on control technology testing on pressurized PDU, CTIU, and pilot facilities	9/81
Complete testing of control technology for atmospheric utility boiler	6/83
Update report on control technology testing on pressurized PDU, CTIU, and pilot facilities	9/83
Complete testing of control technology for pressurized utility boiler	1/86

While the results of preliminary EPA investigations indicate that FBC will not cause serious environmental pollution problems, the emissions and effects of numerous potential pollutants have yet to be studied and further analytical and experimental work is necessary to ensure that adequate consideration has been given to all likely environmental hazards.

The EPA is playing a significant role in ensuring that the FBC systems that are developed to the commercialization stage are environmentally acceptable with respect to both solid wastes and atmospheric emissions. The rate of commercialization of the FBC process will be affected by various engineering and economic factors including costs, efficiency, application to specific needs, and system and components availability. Close coordination of the EPA program with the technology development effort will assure efficient integration of environmental considerations and will increase the acceptance by potential FBC users.

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APPENDIX A

CURRENT PROJECTS IN THE EPA FLUIDIZED-BED COMBUSTION PROGRAM

TABLE A-1. OVERVIEW OF THE EPA FLUIDIZED-BED COMBUSTION PROGRAM

A. Broad Environmental Assessment

1. Environmental Assessment/Systems Analysis and Program Support of Fluidized-Bed Combustion: Battelle-Columbus Laboratories began February, 1976.

2. Preliminary Environmental Assessment of the Fluidized-Bed Combustion Process: GCA Corporation, completed except for issuing final report.

B. Comprehensive Analysis of Emissions

1. Comprehensive Analysis of Emissions from an Atmospheric-Pressure Fluidized-Bed Combustion Unit (6 in. or 15 cm diameter): Battelle-Columbus; with support from TRW, Inc.

2. Comprehensive Analysis of Emissions from the BCURA Pressurized Fluidized-Bed Combustion Unit (36 in. x 24 in. or 91 x 61 cm): Combustion Systems, Ltd./BCURA; sampling planned for early September, 1976.

3. Comprehensive Analysis of Emissions from the Fluidized-Bed Combustion Miniplant (12.5 in. or 32 cm diameter pressurized combustor and 8.0 in. or 20 cm diameter pressurized regenerator) and Bench-Scale Equipment (4 in. or 10 cm pressurized batch combustor and 3.25 in. or 8 cm pressurized batch regenerator): Exxon Research and Engineering Co., sampling planned to start 1976.

4. Comprehensive Analysis and Sampling/Analytical Technique Development on Sampling and Analytical Test Rig (SATR).

5. Comprehensive Analysis on Other Units: Battelle-Columbus is preparing a plan for comprehensive analysis on other existing and planned units.

6. Preparation of a Sampling and Analytical Manual for Fluidized-Bed Combustion Applications: The MITRE Corporation; Revising draft of manual.

7. Development of Improved Sampling and Analytical Techniques: Various Contractors.

C. Studies of Pretreatment, Modification of Process Conditions, and Add-On Devices

1. Experimental and Engineering Support of the Fluidized-Bed Combustion Program (theoretical and experimental studies using a variety of laboratory equipment): Westinghouse Research Laboratories, began December, 1975, but extends previous work.

2. Support Studies of Pollutant and Waste Control in Fluidized-Bed Combustion/Regeneration Systems (theoretical and experimental studies using a 6 in. or 15 cm diameter pressurized combustor, a 4.25 in. or 11 cm diameter pressurized regenerator and a variety of laboratory equipment): Argonne National Laboratory--co--funded with ERDA; continuing study.

TABLE A-1. (Continued)

3. Miniplant and Bench-Scale Studies in Support of the Fluidized-Bed Combustion Program (theoretical and experimental studies using the 12.5 in. or 32 cm diameter pressurized combustor and 8.0 in. or 20 cm pressurized regenerator miniplant plus the 4 in. or 10 cm diameter pressurized combustor and 3.25 in. or 8 cm pressurized regenerator bench-scale units): Exxon Research and Engineering Company; continuing study.

4. Design, Construction and Operation of a Fluidized-Bed Coal Combustion Sampling and Analytical Test Rig: Contractor to be selected/EPA; Contract for construction to be awarded August, 1976; rig to be operable December, 1977.

5. Basic NO_x studies - MIT.

D. Solid Waste Disposal

1. Environmental Assessment of Disposal of Solid Wastes from Fluidized-Bed Combustion Units: Ralph Stone and Co.; began December, 1975.

2. Study of Disposal of Fluidized-Bed Combustion Waste Products: Tennessee Valley Authority; began June, 1975.

E. Application Studies

1. The Effect of Experimental Scale on Emissions from Fluidized-Bed Combustion Units: Dow Chemical Company; Completed.

2. Application of Fluidized-Bed Technology to Industrial Boilers; An Economic, Environmental and Energy Analysis: Exxon Research and Engineering Company--co-funded with FEA and ERDA; Completed except for issuing final report.

3. Cost Comparison of Commercial Atmospheric and Pressurized Fluidized-Bed Power Plants to Conventional Coal-Fired Power Plant with Flue Gas Desulfurization: Tennessee Valley Authority; Completed except for issuing final report.

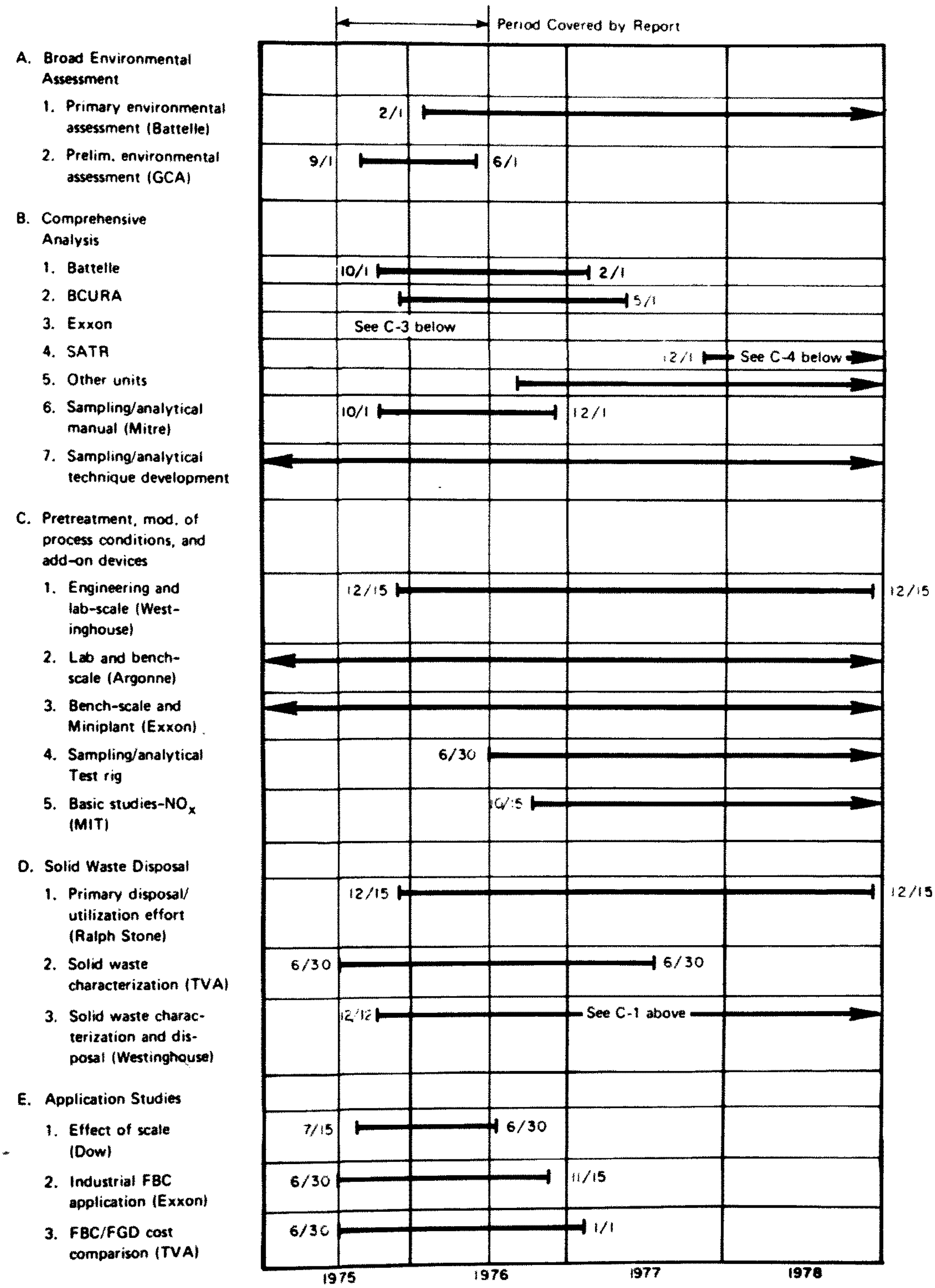

FIGURE A-1. THE EPA FLUIDIZED BED COMBUSTION PROGRAM

Project starts
Project finishes
Project continues

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-77-012	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE The U.S. Environmental Protection Agency's Fluidized-Bed Combustion Program, FY 1976		5. REPORT DATE February 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) (Individuals not identified)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle-Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201		10. PROGRAM ELEMENT NO. EHE623A
		11. CONTRACT/GRANT NO. 68-02-2138
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		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES There was no previous annual program status report published. IERL-RTP project officer for this report was D. B. Henschel, Mail Drop 61, 919/549-8411 Ext 2851.

16. ABSTRACT The report describes the objectives, content, and fiscal year 1976 progress of the research and development program being conducted by the EPA for environmental characterization of the fluidized-bed combustion (FBC) process. EPA's FBC program is a contract program, utilizing a variety of contractors, aimed at ensuring that all potential environmental problems associated with this developing energy technology are identified and adequately addressed. EPA's program is being conducted in coordination with the FBC technology development program being conducted by the U.S. Energy Research and Development Administration (ERDA). Some important contributions of EPA's FBC program to the National effort will include: establishment of environmental goals based on health and ecological effects of emitted pollutants; comprehensive analyses of emissions from operating FBC units; assessment and development of any necessary environmental control technology; recommendations for environmental standards for the process; and development of manuals of best available technology.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Dolomite (Rock)	Air Pollution Control	13B
Fluidized-Bed Processors	Calcium Oxides	Stationary Sources	07B
Desulfurization	Nitrogen Oxides	Fluid-Bed Combustion	07A
Flue Gases	Waste Disposal	Environmental Assessment	07D
Limestone	Combustion	Sorbent Regeneration	21B
	Residues	Particulate Control	08G

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