United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/7-79-019
January 1979

EPA

Alternatives for High-temperature/ High-pressure Particulate Control

Interagency Energy/Environment R&D Program Report

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EPA-600/7-79-019

January 1979

Alternatives for High-temperature/ High-pressure Particulate Control

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Contract No. 68-02-2190
Program Element No. 1NE624

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Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ABSTRACT

High temperature and pressure (HTP) particulate control offers efficiency and potential economic advantages over cold gas cleanup in pressurized fluidized bed combustion (PFBC) and low-BTU coal gasification (LBCG) combined-cycle power generation systems. However, considerably more development will be necessary in order to demonstrate the technical and economic feasibility of HTP gas cleanup on a commercial scale.

This report presents the status of the most promising HTP particulate control devices currently being developed. Available data are presented and anticipated performance and development problems are discussed.

The alternative of recuperative heat exchange coupled with low temperature, high pressure particulate control is reviewed with regard to power system efficiencies for PFBC and LBCG combined-cycle processes. Successful hot gas cleanup has clear thermal efficiency advantages (1% to 7%) over cold gas cleanup. The economics of hot gas cleanup, however, are very speculative at the current state of development.

The relative cost of HTP, pre-turbine particulate control using cyclones, multiclones, and granular bed filters is compared with low temperature and pressure (LTP) post-turbine control using conventional electrostatic precipitators. HTP control equipment costs are estimated to be significantly higher than LTP equipment costs. However, LTP costs are significant and should not be neglected when considering the feasibility of hot gas cleanup for turbine protection followed by post-turbine fine particulate control to meet emissions regulations.

TABLE OF CONTENTS

FIGURES

FIGURES, continued

TABLES

TABLES, continued

ACKNOWLEDGEMENT

A.P.T., Inc. wishes to express its appreciation to Dr. Dennis Drehmel, EPA Project Officer, for excellent technical coordination and assistance in support of all our efforts under this contract.

SUMMARY AND CONCLUSIONS

INTRODUCTION

High temperature and pressure (HTP) particulate control offers system efficiency and potential economic advantages over cold gas cleanup in pressurized fluidized bed combustion (PFBC) and low-BTU coal gasification (LBCG) combined-cycle power generation systems. However, considerably more development will be necessary in order to demonstrate the technical and economic feasibility of HTP gas cleanup on a commercial scale.

Although HTP particulate control has been a recognized technical problem for over thirty years, no satisfactory solutions have been demonstrated. Renewed efforts have been directed at this problem during the past few years with the hope of developing new concepts and equipment for HTP particulate control. This report presents the status of the most promising devices currently being developed. Available data are reported and anticipated performance and problems are discussed.

Alternative approaches using recuperative heat exchangers coupled with cold gas cleanup are reviewed with regard to their effect on power system efficiencies for PFBC and LBCG combined-cycle processes. The relative costs of HTP gas cleanup for turbine protection are compared with the cost of post-turbine cleanup for emissions control.

PRIMARY AND SECONDARY COLLECTION

Most proposed HTP particulate control systems use one or two stages of cyclones for primary and secondary particulate removal. The primary cyclone recycles unreacted carbon to the combustor or gasifier. The secondary cyclone reduces the mass loading and size of particulates which pass through to the final collection stage.

Secondary cyclones may be multiclones, rotary flow cyclones, or other high efficiency cyclone designs. Cyclones may be subject to plugging if condensed tars are present. Primary and secondary cyclones are designed to collect particles with diameters larger than 10 to 20 μm. They generally are not effective for particles smaller than about 5 μm.

Primary and secondary particle collection equipment are commercially available although HTP applications are scarce and there is room for improved materials, designs, and engineering models.

TERTIARY COLLECTION

The third stage (tertiary) collection device must be capable of reducing the particle size and mass loading to a level which is compatible with gas turbine specifications and environmental emissions regulations. This most likely will require 90 to 99% collection efficiency on a particle size distribution with a mass median diameter of about 4 μm and a geometric standard deviation of 3 (based on data from the Exxon PFBC miniplant).

Cyclones

Conventional cyclones have been tested at high temperature and pressure and generally have been found to be inadequate for tertiary cleanup requirements.

High efficiency rotary flow cyclones have been proposed for the tertiary collection stage. To date, experimental data have not demonstrated that adequate collection efficiencies can be maintained with rotary flow cyclones. More high temperature and pressure tests are being planned.

The "cyclocentrifuge" is a device under preliminary development which uses a high reaction turbine to drive a centrifuge which serves as the exit tube in a cyclone. High collection efficiencies for fine particles have been predicted but experimental data are not available yet to validate the predictions. Operation of the centrifuge bearings at high temperature and pressure in a dirty environment is likely to present the most difficult development problem with this device.

Granular Bed Filters

Granular bed filters (GBFs) are often proposed as tertiary cleanup devices. A granular bed filter is defined as any filtration system comprised of a stationary or slowly moving bed of discrete, relatively closely packed granules as the filtration medium.

Some laboratory data are available which show that very high collection efficiencies (99+%) can be achieved if a filter cake is allowed to form on the surface of the granular bed. Large scale pilot plant and industrial GBF's have not been able to establish or maintain a filter cake and much lower efficiencies have resulted.

Extensive HTP tests on a fixed bed, pilot plant GBF were conducted at the Exxon PFBC miniplant. Efficiencies as high as 97% were achieved but could not be maintained for more than a couple of hours operation. In all runs in which more than one outlet concentration was measured, the efficiency was found to decrease with time. Further HTP tests are planned on a smaller scale GBF. If this GBF can be modified to meet emissions requirements over a prolonged run additional full scale tests will be conducted.

High temperature tests on a moving bed GBF (Combustion Power Company) are being conducted. Cold tests demonstrated that fine, submicron particles could be collected with greater than 90% efficiency using the proper velocities, dust loadings, and granule flow rates. No high temperature data are available.

The intermittently moving panel bed filter being developed at CCNY (Squires design) has obtained high collection efficiency (99+%) by establishing a filter cake. The major problem with this design is the requirement for low gas capacity and thus relatively large capital costs for a HTP installation. There are not many HTP data available for this device. Establishment of a good cake and high collection efficiency may be more difficult at high temperatures.

At this time, GBF's must be considered to be in a highly developmental stage. Design improvements and more data at HTP operating conditions are required before their feasibility as tertiary collectors can be adequately evaluated.

Scrubbers

Conventional wet scrubbers are not generally suitable for high temperature gas cleaning because they necessarily cool the gas. However, dry scrubbers and molten salt scrubbers are being developed as alternatives for HTP particulate control.

The A.P.T. dry scrubber (PxP) system uses large collector particles as collection centers for the fine dust particles. In the configuration presently being developed, the solid collectors are fed into a high velocity throat and contacted with the dust particles. The collectors are removed from the gas in an inertial separation device.

Low temperature and pressure data have been obtained which show that the primary collection efficiency (>90% at 1.0 μmA) is as would be expected from theoretical predictions for a venturi scrubber. A high temperature pilot demonstration of the PxP system is currently underway. The feasibility of electrostatic augmentation for improving the collection efficiency, lowering the pressure drop, and increasing particle-collector adhesion is being investigated.

Molten salt scrubbing is being investigated for simultaneous particulate and H_2S control. Pilot plant data indicate that the mass loading of particles leaving the molten salt venturi scrubber may be close to the anticipated environmental emissions standards. Tests will be conducted on a full-scale demonstration plant. No data are available yet.

Electrostatic Precipitation

The operation of an electrostatic precipitator at high pressures and temperatures has been demonstrated. Stable corona can be maintained at higher electric field strengths than in conventional precipitators. There are few studies providing data on fine particle collection at high temperature and pressure. Future development problems will involve electrode rapping and alignment, reentrainment, and materials problems associated with HTP designs.

Practical HTP electrostatic precipitation will be limited by thermal ionization at temperatures above 1,100 to 1,300°C. Also a positive barrier-type backup device may be required to prevent catastrophic turbine damage during possible electrical outages.

Fiber Filtration

High temperature filtration using metal or ceramic fiber filters is being investigated. In practice it is expected that the effect of temperature and pressure on filtration mechanisms will not be a limiting factor in the overall collection efficiency. The main problems will be the physical and chemical effects of a high temperature environment on the filter materials. These effects may appear as reduced mechanical strength and resilience or loss of adhesion, leading to mechanical leakage and decrease in efficiency.

Recent studies with ceramic fabric bags have shown that some have good properties for high temperature and pressure applications. More data are required to adequately establish the useful bag life and other important design parameters. Blanket or felted ceramic materials look most promising because they combine good filtration properties with relatively high strength. However, superficial gas velocities (air-to-cloth ratios) are low in comparison with granular bed filters and the large volume required for fabric filtration may present some economic limitations.

Membrane Filtration

Laboratory tests on ceramic membrane and honeycomb filtration materials have been conducted. The honeycomb materials were able to obtain high collection efficiencies (averaging 96+%) on fine limestone particles at temperatures up to 815°C.

More work is needed to determine optimum configurations for filtration and for cleaning. Also the durability and erosivity limitations need to be determined. The major advantage of these filtration media is that they have very high surface to volume ratios. Superfical velocities are similar to those for fabric filters.

HOT VERSUS COLD GAS CLEANUP

Pressurized Fluidized Bed Combustion

The relative advantages of hot versus cold gas cleanup are different for the three PFBC processes currently under development. These are: the water-cooled PFBC boiler, the air-cooled PFBC process, and the adiabatic PFBC process.

The efficiency loss between hot and cold gas cleanup is greatest for the adiabatic combustor configuration because all the working fluid passes through the bed and must be cleaned.

The air-cooled and water-cooled combustors appear to be capable of using cold gas cleanup techniques with fairly small (about 1 to 2% system efficiency) performance penalties. The Phase II ECAS studies showed the PFBC boiler process with hot gas cleanup to have a 7% advantage over conventional coal-fired boilers using flue gas scrubbing for SO_x control.

In order to fully assess the cold cleanup alternatives, recuperative heat exchangers must be studied more closely, especially regarding their effectiveness, availability, and cost for high temperature and pressure applications.

Post-Turbine Particulate Control

If gas turbines which have relatively high tolerance for fine particles can be developed, then it may be feasible to use currently available hot gas cleanup devices (cyclones, multiclones) to protect the gas turbine. In such cases the emissions regulations would have to be met by applying conventional particulate control equipment downstream from the gas turbine.

The cost of post-turbine particulate control equipment is noticeably less (about 10 to 30%) than the cost of hot gas cleanup as estimated in the ECAS Phase II design studies. However the post-turbine equipment costs are significant and must be considered in the overall capital cost for gas cleaning equipment when considering the feasibility of pre-turbine/post-turbine control systems.

Low-BTU Coal Gasification

Gas cleanup in LBCG processes must consider acid gas removal (principally H_2S and COS), tar removal, removal of alkali metal vapors and compounds, and fine particle removal. There is little incentive for hot particulate removal if the gas must be cooled and scrubbed to remove H_2S.

The presence of tars in LBCG processes presents serious problems. They will contaminate or plug subsequent H_2S and particulate removal systems unless they can be kept in the vapor phase. They may be removed in a quench scrubber before H_2S and particulate removal, however, this wastes approximately 20% of the available energy through sensible heat loss, and as much as 20% of the available chemical energy in the fuel gas. Hot H_2S and particulate control would save these energy losses and enable the tars to be burnt in the gas turbine combustor.

For all LBCG gasifiers where tar removal is not a problem, thermal efficiency advantages associated with hot gas cleanup (H_2S and fine particulate matter) appear to be marginal (1 to 2%). The Phase II ECAS studies showed LBCG combined-cycle processes with cold gas cleanup to have a 7% advantage over a conventional coal-fired boiler using flue gas scrubbing for SO_x control.

INTRODUCTION

The economic attraction of many advanced energy processes depends on the development of technology for cleaning gases at high temperatures and pressures. Two processes requiring high temperature and pressure gas cleanup are: 1) pressurized fluidized bed coal combustion, and 2) the combined open-cycle gas turbine-steam turbine system integrated with a low-BTU coal gasifier. These processes are among those recommended for further development by the Energy Conversion Alternatives Study (Lewis Research Center, 1976 and 1977).

Both of these processes require expension of the gas through a gas turbine at high temperature and pressure. The gas must be cleaned to remove corrosive gases, condensible vapors and particulate matter which could potentially damage the gas turbine. Any temperature and pressure losses during gas cleanup will reduce the overall thermodynamic efficiency of the process. Therefore it is desirable to clean the gas at system temperature and pressure.

Equipment for removing particulate matter from high temperature (HTP) gas streams has been under development to various degrees for over thirty years. Recently there has been renewed interest in this problem and a number of new concepts and improved materials are now being investigated.

In this report we review the present state-of-the art for HTP particulate collection and discuss the process requirements and possible alternative approaches to hot gas cleanup. In many situations, the requirement for hot particulate removal is coupled with a need for removing acid gas, and/or alkali metal vapor at high temperature and pressure. Therefore, systems which potentially can remove particulates, gases, tars and condensible vapors will be especially attractive.

It has been assumed that readers are basically familiar with conventional particulate control technology. Details on conventional control equipment are presented by Calvert, et al. (1972), Billings and Wilder (1970) and Stern (1977).

PARTICULATE REMOVAL REQUIREMENTS

The degree to which particles must be removed from low-BTU coal gasification (LBCG) and pressurized fluidized bed combustion (PFBC) processes depends on the gas turbine tolerances for particulate matter, the size distribution and mass loading of particulate matter, the gas composition, turbine blade material, gas temperature, other process parameters and environmental regulations.

There are no current New Source Performance Standards (NSPS) for advanced fossil-fuel conversion processes. In order to allow for industry growth while maintaining regional air quality standards, it would be necessary to control particulate emissions from new sources more stringently than current standards. The NSPS for particulate emissions from advanced fossil fuel conversion processes will most likely be as stringent as the anticipated new standards for boilers. That is, <0.05 lb/10^6 BTU (21.5 mg/MJ), or at least be based on BACT (best available control technology).

The gas turbine specifications also impose a gas cleanup requirement. The useful life of a gas turbine depends on the extent of erosion and corrosion damage to the internal components of the turbine. The extent of damage depends upon the concentration and size of particulate matter entrained in the gas, upon the chemical composition of the gas and particles, and upon the gas temperature, turbine design and other operating parameters.

Erosion damage results from the inertial bombardment of particles onto the stator and rotor blades of the gas turbine. The erosion damage is proportional to the kinetic energy of the particulate matter striking the turbine blades. Therefore the damage is more severe when larger more massive particles are present in the gas stream. Large concentrations of very small particles may be even less harmful than their total mass would imply because their trajectories would tend to follow the gas streamlines and thus would be less likely to strike the turbine blades.

Corrosion damage depends on the amount of particulate matter that adheres to the turbine surfaces as well as the chemical composition of the gas and particles. In general, the most corrosive compounds are those containing sodium and potassium. Liquid deposits of such compounds can form inside the turbine at temperatures between about 500°C and 1,000°C. These molten films attack the protective oxide scale on the blade material, and thus initiate accelerated oxidation of the turbine components.

The buildup of particulate deposits on the turbine blades also can significantly impair the aerodynamic performance of the blades. Furthermore, large agglomerates can break off from such deposits and cause additional erosion damage.

There is much debate regarding the definition of acceptable particle concentrations for gas turbines. There is general agreement that large particles must be removed from the gas. Robson (1976) recommends a maximum allowable concentration of 2.7 mg/Nm³ (0.0012 gr/SCF) for particles larger than 2 μm* in diameter.

There is less agreement on the allowable turbine tolerance for fine particles. A Westinghouse study (Westinghouse, 1974) proposed that a concentration of 340 mg/Nm³ (0.15 gr/SCF) of particles smaller than 2 μm could be tolerated. Sverdrup and Archer (1977) recommended that the concentration be maintained below 4.6 mg/Nm³ (0.002 gr/SCF) for all particle sizes with no particles larger than 6 μm.

The variation in turbine tolerance estimates is not surprising considering the scarcity of direct experience with large coal-fired industrial gas turbines, the difficulty of extrapolating data from small turbines, the variations in existing and proposed turbine materials and blade temperatures, and variations and uncertainties in the chemical and physical properties of the particles and gases.

These uncertainties pose a major problem to engineers

*Throughout this report we have used the convention of "μm" for physical diameter and "μmA" for aerodynamic diameter. Particle densities are given whenever they are known.

involved in the development and evaluation of advanced energy processes. Developers of hot gas cleanup devices do not know how efficient their equipment must be at removing fine particles. At the same time, estimates of the cost of electricity and capital investment for advanced energy processes are strongly dependent on assumptions concerning the cost (and indirectly the efficiency) of gas cleanup equipment.

This predicament results in part from the necessity for parallel development of advanced industrial scale gas turbines and high temperature and pressure gas cleanup technology. The cost of HTP gas cleanup will vary inversely with the allowable particle concentration entering the gas turbine. However, the process emissions must satisfy all environmental regulations.

Gas turbines which can tolerate relatively large concentrations of fine particles may necessitate particulate control equipment downstream from the gas turbine. The cost of this control equipment must be considered in the overall economic evaluation of the process. If expensive control equipment is required to protect the turbine, economics may require that this equipment satisfy the emissions regulations as well.

BACKGROUND

Pressurized Fluidized Bed Coal Combustion

The combustion of coal in a fluidized bed of limestone or dolomite offers many advantages over conventional coal-fired boilers. The primary advantage is the ability to burn high sulfur coals without requiring flue gas desulfurization equipment. Also PFBC processes have the potential for lower introgen oxide emissions, higher thermodynamic efficiencies, more efficient fuel utilization, lower cost of electricity and lower capital costs compared with conventional coal-fired power plants using stack gas scrubbers for SO_x control.

There are three approaches currently being considered for PFBC processes. The first is the PFBC boiler illustrated in Figure 1. Combustion takes place at a pressure of 10 atm and a temperature around 900°C. The combustion temperature is

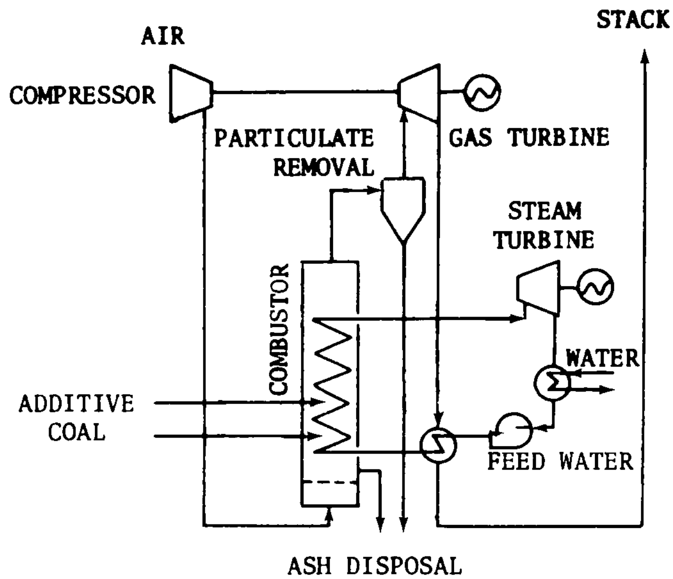


Figure 1. Water-cooled combustor.

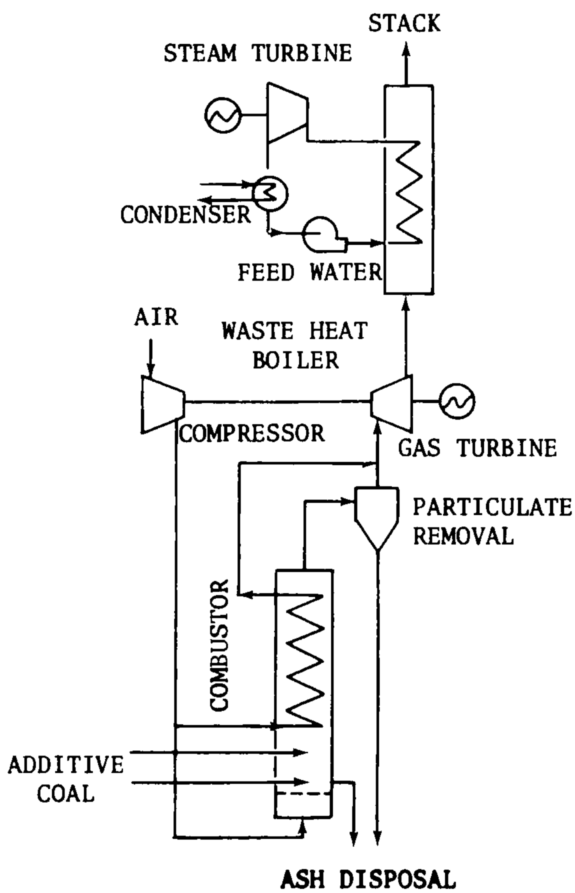


Figure 2. Air-cooled combustor.

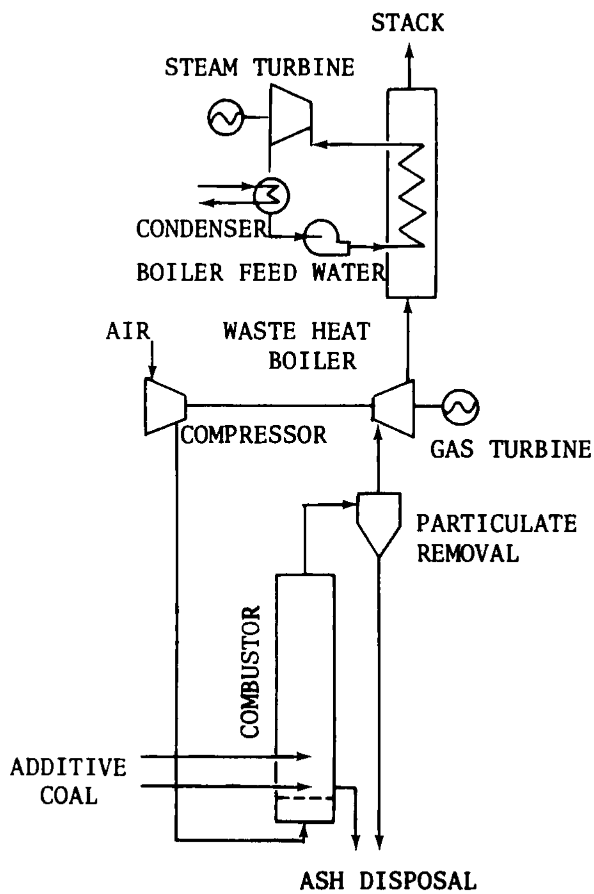


Figure 3. Adiabatic combustor.

maintained using water-cooled heat exchanger tubes. The steam generated is used to drive a steam turbine. The products of combustion leave the combustor at high temperature and pressure, and pass through the HTP gas cleanup system before being expanded through the gas turbine.

Beecher, et al. (1976) reported the conceptual design of an advanced steam plant using a PFBC boiler. The plant generates a net electric power of 679 MW. Four PFBC boiler modules are used to fire two gas turbine generators. The turbine inlet temperature is 959°C. Each turbine handles a gas flow of 345 kg/s (760 lb/s). Each boiler has two stages of cyclones for dust removal. The first stage removes large particles and conveys them to the carbon burnup cell. The second stage is a multiclone device which removes coarse and fine particles and thereby reduces the loading to the tertiary (third stage) cleanup devices. Four granular bed filters (43 kg/s or 95 lb/s each) are proposed for tertiary cleanup for each boiler.

The overall cost of electricity will be affected by the capital cost and operating cost of the particulate control equipment. The capital cost is a function of the size and number of units required, which depend primarily on the total volumetric gas flow to be treated at high temperature and pressure. The operating cost depends on the power requirement of the control equipment and the temperature and pressure losses which occur. In the PFBC boiler system, approximately 80% of the total electricity is generated in the steam turbine cycle. Only 20% is generated downstream of the hot gas cleanup system in the gas turbine cycle.

An air-cooled PFBC process is being developed by Curtiss-Wright Corporation under D.O.E. sponsorship. A schematic diagram of this process is shown in Figure 2. The FBC unit is cooled by passing approximately two-thirds of the compressed air through heat exchanger tubing in the combustor. The other third of the compressed air is used for combustion.

The effluent gas from the combustor is cleaned before it is mixed with the hot gas from the heat exchanger tubes. The mixed gas is then expanded through the gas turbine and passed through a waste heat boiler.

The principal advantage of this process is that it dilutes the gases leaving the cleanup equipment thereby reducing the mass loading entering the gas turbine. The total flow to the gas turbine is increased threefold. For equivalent size plants, the combustion gas flow will be approximately the same as that required with the PFBC boiler. Depending on the heat loss during cleanup and the efficiency of heat transfer, the mixed gas may attain a higher or lower temperature than the effluent gas temperature from the PFBC boiler. All electricity is generated downstream from the control equipment.

The third type of PFBC process currently being developed uses the adiabatic fluidized bed combustor. This process has been developed by the Combustion Power Company for refuse combustion and also is being investigated for its potential in burning coal.

The adiabatic system is illustrated in Figure 3. The bed temperature is maintained suitably low by using large volumes of excess air (300%). Thus the gas flow rate is approximately the same as the total flow used in the air-cooled PFBC process.

In the adiabatic combustor system, all the gas passes directly through the combustor and must be cleaned. Therefore the size (and capital cost) of the cleanup equipment will be significantly more than in the other designs. Furthermore, all the power generation occurs downstream from the cleanup equipment and therefore the cost of electricity will be especially sensitive to temperature and pressure losses during cleanup.

The particulate emissions and high temperature and pressure cleanup requirements for fluidized bed combustion processes has been reviewed by Parker and Calvert (1977). Particulate emissions data from their survey are presented in Table 1.

TABLE 1. SUMMARY OF FBC PARTICULATE EMISSION CHARACTERISTICS

	Exxon Miniplant*	Argonne Natl. Labs	Combustion Power Co**	National Coal Board (G.B.)	Pope, Evans & Robbins**
Temperature, °C	820-950	790-900	760-980	750-950	300-400
Pressure, atm	5-10	to 8	3-7	1-5	1
Mass loading, g/Nm^3	1.8-2.8	0.5-4.8	0.09	3.0	0.2-1.7
Mass loading, gr/SCF	0.8-1.8	0.2-2.1	0.04	1.4	0.5-4
Mass median diameter, μm	4-8	---	1.2	---	4.6
Geometric standard deviation	2.7	---	1.9	---	2

* Particle density estimated to be 1.5 g/cm^3

** Waste-fired combustor

The particulate removal requirements for pressurized fluidized bed combustion processes will depend on the turbine tolerances for fine particles and the emissions regulations for coal-fired boilers.

An emission of 0.05 lb/10^6 BTU corresponds to a particulate loading of approximately 57 mg/DNm^3 (0.025 gr/SCF) based on the heat input of the coal and emissions data from the Exxon PFBC miniplant (Hoke, et al., 1978). The emissions regulations will be approximately the same for all three PFBC designs.

Particulate control to protect the gas turbine is coupled with the problem of alkali metal vapor removal. HTP control equipment for PFBC processes may need to remove alkali metal vapors as well as fine particles.

Recent data taken at the Exxon miniplant (Bertrand, et al. 1978) indicated that 2 ppm sodium vapor, 0.05 ppm potassium vapor were present in the effluent gas. Gas analyses for the same run showed very low H_2S and hydrocarbon concentrations and 285 ppm SO_2. These data are listed in Table 2.

Low-BTU Coal Gasification

Low-BTU coal gasification processes are under development as a possible means of obtaining electrical energy from coal while satisfying all environmental regulations. Preliminary economic analyses (Lewis Research Center, 1976 and 1977) indicate that a combined cycle gas turbine-steam power generation cycle fired by gas from an integrated low-BTU coal gasifier offers significant economic advantages over conventional coal-fired boilers in terms of more efficient coal usage and lower cost of electricity. A typical process flow diagram is shown in Figure 4.

The basic gasification process converts solid coal into a combustible gaseous fuel by reacting it with air and steam. The product gas contains hydrogen, carbon monoxide, carbon dioxide, nitrogen, methane and hydrogen sulfide. The product gas leaves the gasifier at high temperature (500 to 1,500°C)

TABLE 2. GAS ANALYSIS FROM EXXON MINIPLANT PFBC UNIT

COMPONENT	CONCENTRATION
CO_2	13.5 %
O_2	4.5 %
SO_2 (std.dev.)	285 ppm (110 ppm)
NO_x	50 ppm
CO	600-750 ppm
H_2S	1 ppm
COS	not detectable
CS_2	not detectable
CH_4	18 ppm
C_2H_6	14 ppm
C_3 to C_6	not detectable
Na	2 ppm
K	0.5 ppm

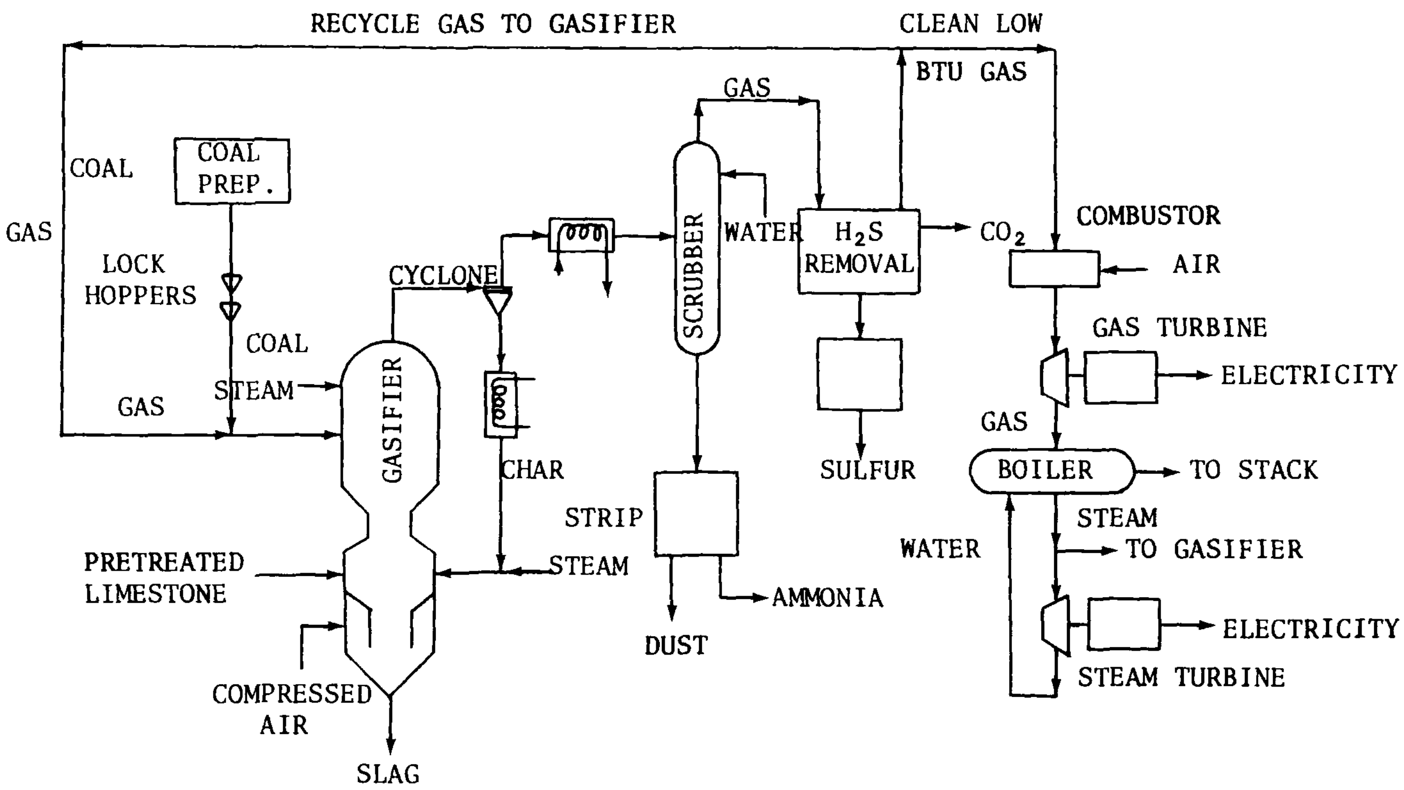


Figure 4. LBCG combined-cycle system.

and often at high pressure (10 to 20 atm). The gas usually will contain large concentrations of entrained particulate matter (ash, carbon, and possibly tars). Alkali metal vapors and other contaminants also may be present.

There are many different processes for gasifying coal, and the gaseous and particulate emissions can vary widely from one process to another. The most popular classification of gasification processes is classification according to the flow of the gas relative to the coal. The four basic gasifier types classified in this manner are:

1. Fixed or slowly moving beds of solids
2. Entrained solids
3. Fluidized beds
4. Molten baths

Gasifiers also may be classified with regard to the ash removal method. At temperatures below approximately 1,000°C the mineral matter in the ash remains dry. At temperatures somewhat higher the ash becomes tacky and tends to agglomerate. At even higher temperatures the ash melts. Molten ash usually becomes free-flowing at temperatures of about 1,500°C to 1,600°C. Therefore coal gasifiers can be classified as dry bottom, ash agglomerating, or slagging gasifiers with regard to ash removal. Gasifiers also can be classified as to pressure level, number of reaction stages, and the source of oxygen (either air blown or oxygen blown).

In general, particulate emissions are expected to be greater for entrained bed and fluidized bed dry bottom gasifiers. Particulate emissions should be less for ash agglomerating and molten bath gasifiers. Parker and Calvert (1977) reviewed the available data on particulate emissions from coal gasification processes and their results are summarized in Table 3.

Particulate control for coal gasification processes is closely coupled with acid gas removal (principally H_2S, COS, and C_2), tar removal, and alkali vapor removal. In some processes there may be a need for NH_3 removal also. There is little

TABLE 3. SUMMARY OF PARTICULATE EMISSION DATA FOR COAL GASIFICATION PROCESSES

Process	Gasifier Exit Temperature °C	Gas Cleanup Temperature °C	Pressure atm	Mass Loading		Control Devices Used or Anticipated	Remarks
				g/Nm^3	gr/SCF		
I Fixed Beds							
Lurgi	400-600	200	20-30	24	10	scrubbers	tars present
USBM Stirred Bed	500-650	---	7	24	10	scrubbers	tars present
II Dry Fluidized Beds							
Winkler	800-1,000	150-200	1	--	--	cyclones, scrubbers, electrostatic precipitators	
USMB Synthane	400-750	250	10	--	--	scrubber	tars & heavy hydrocarbons present
CO_2 Acceptor - Gasifier	800-850	200	10	20	8.8	venturi scrubber	
CO_2 Acceptor - Regenerator	1,000	1,000	10	18	7.8	cyclones, sand bed filters	
BCR Fluidized Bed	1,000-1,150	650	20	--	--	--	
III Ash Agglomerating Fluidized Bed							
Battelle - Union Carbide	1,100	--	7	--	--	cyclones	
IGT U-Gas	1,000	400	20	--	--	proprietary process	
Westinghouse	750-900	--	10-15	--	--	rotary flow cyclones, granular bed filters	

TABLE 3. Continued

Process	Gasifier Exit Temperature °C	Gas Cleanup Temperature °C	Pressure atm	Mass Loading g/Nm³	gr/SCF	Control Devices Used or Anticipated	Remarks
IV Slagging-Entrained Flow							
Koppers-Totzek	1,200-1,300	200	1	40	17.5	two disintegrator or venturi scrubber in series	MMD 1,000μm $\sigma_g \sim 15$
Combustion Engineering	900	150	10	--	--	scrubber	
Foster Wheeler	1,000	100	30	--	--	scrubber	
BYU	650-1,300	--	1	--	--	--	bench scale development
Texaco	1,400	300	15	--	--	--	
V Molten Bath							
ATC Molten Iron	1,100	--	1	--	--	--	
Atomics Internat'l	950	--	5	--	--	--	alkali metal fumes present
VI In-Situ							
LERC	--	250-350	2-7	--	--	scrubbers	tars present

advantage to hot particulate control unless acid gases and metal vapors also can be controlled at high temperature.

Gas cleanup at low temperature (system pressure) is being proposed for most coal gasification processes. There are three basic reasons for this:

1. The energy content of the gas is predominantly chemical energy rather than sensible heat. Sensible heat accounts for approximately 10 to 20% of the total energy content of the gas.
2. High pressure/low temperature gas cleanup equipment is available commercially although it has not necessarily been optimized for coal gasification applications. No hot gas cleanup systems have been demonstrated to be satisfactory and they must be considered as not commercially available.
3. Coal gases which contain tars must be cooled in the tar removal quencher to prevent tars from depositing in downstream system components.

If the gas can be kept hot enough it is conceivable that tar condensation can be prevented and tars can be built in the gas turbine combustor. In this case hot gas cleanup would save the sensible heat in the gas and the chemical energy in the tars. Tars can contain as high as 20% of the chemical energy in the gas leaving the gasifier (MERC, 1978). However, most LBCG processes which emit tars propose a quench to remove the tars. Although relying on existing technology, this severely limits the thermal efficiency of the process. Tar removal is a problem with fixed bed and slowly moving bed gasifier designs where the gasifier temperature is too low to crack tars.

If the process temperature is high enough to prevent the formation of tars (as in many entrained bed and fluidized bed gasifier designs), it usually is proposed that the gas be cooled in a heat exchanger to provide process steam for the gasifier or superheat steam for the steam turbine cycle of the process.

Hot gas cleanup has some advantages over cold gas cleanup for coal gasification processes in terms of the overall thermodynamic efficiency. However, the availability and cost of hot gas cleanup systems (particulate removal and acid gas removal) may hinder realization of the higher thermodynamic efficiency in practice.

In the next section of this report we review the current developmental status and anticipated problems or limitations of high temperature and pressure particulate control devices. In the final section we review the advantages and disadvantages of hot versus cold gas cleanup for pressurized fluidized bed combustion and low-BTU coal gasification combined-cycle processes.

PARTICULATE CONTROL DEVICES

PRIMARY AND SECONDARY COLLECTION

Most proposed high temperature and pressure particulate control systems use three particle collection stages as illustrated in Figure 5. The first stage usually is a large cyclone which removes coarse particles and recycles them to the combustor or gasifier. The particles removed in the primary cyclone are predominantly unreacted carbon.

In the PFBC system these large particles can ignite and cause fires in the primary cyclone. Fires may cause excessive temperatures and corrosion in the cyclone. Very sticky particles may also be present and can eventually cause the cyclone to become plugged. This problem has been encountered in the fluidized bed combustion of refuse although it has not been a serious problem with coal combustion. The PFBC systems use limestone or dolomite as bed sorbent material to react with sulfur from the coal. The primary cyclone also will collect and recycle large sorbent particles.

In gasification processes where tar removal is required, plugging of the primary cyclone may be a problem. In such situations the primary collection stage is usually a quench tower which cools the gas, and condenses and removes tars and other coarse particles.

In processes where tars are not a problem or where hot gas cleanup is viable, primary cyclones may be used. Because of the reducing atmosphere and the presence of hydrogen sulfide, materials requirements will be different than for combustion processes.

The purpose of the secondary collection stage is to remove particles larger than approximately 20 μm in diameter. This

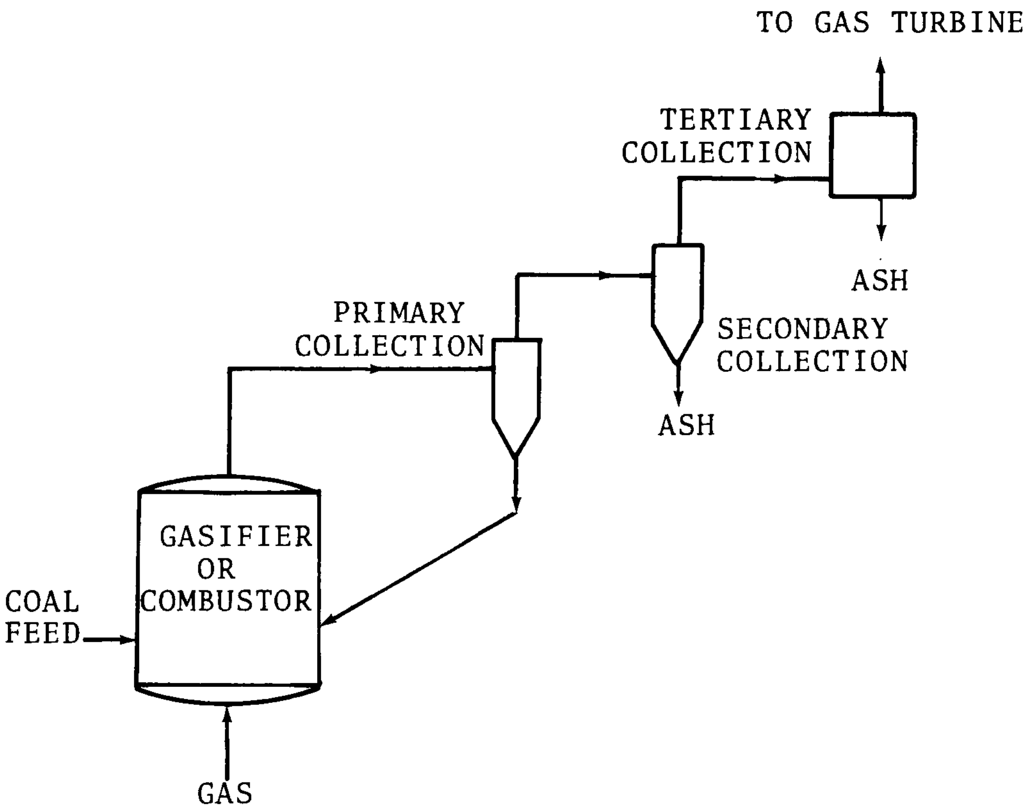


Figure 5. Three stage hot gas cleanup.

reduces the particle size and mass loading to the third stage or tertiary collector. Proposed designs for secondary collectors use various high efficiency cyclones or multiclones. In some cases it may be desirable to eliminate the secondary collector in order to increase the size and loading of particles to the tertiary collector. An example of this might be a ceramic fiber baghouse in which large particles and high dust loadings are required in the formation of a dust cake which is necessary to maintain high collection efficiency.

Experimental measurements of the fractional collection efficiency for the conventional secondary cyclone at the Exxon PFBC miniplant have been reported by Hoke, et al., (1978). Their data are plotted in Figure 6.

Beecher, et al. (1976) described the design of a 680 MWe power plant. Four pressurized fluidized bed boilers supplied gas to two gas turbines. Each turbine handled 345 kg/s (760 lb/s) of gas. Each boiler had four primary cyclones, one secondary collector, and four tertiary collectors associated with it. Each cylone handled about 43 kg/s of gas or approximately 850 m^3/min (30,000 ft /min) at 966°C (1,770°F) and 10 atm. A flow diagram of the cleanup system is shown in Figure 7.

The first stage of particulate removal is a group of four cyclone collectors housed in a pressure vessel. The solids collected by these cyclones consist of dolomite fines, coal ash, and unburnt char. To maximize the combustion efficiency of the system, these solids are fed to a carbon burn-up cell operating at approximately 1,000°C. The combustion products from the burn-up cell mixed with the gases leaving the primary cyclone and pass on to the secondary collector.

The primary cyclones are made from Haynes Alloy 188 which is a cobalt-based high temperature, corrosion-resistant superalloy. The inner surfaces are lined with a hard refractory. Maintenance of these surfaces is anticipated at approximately 2 year intervals.

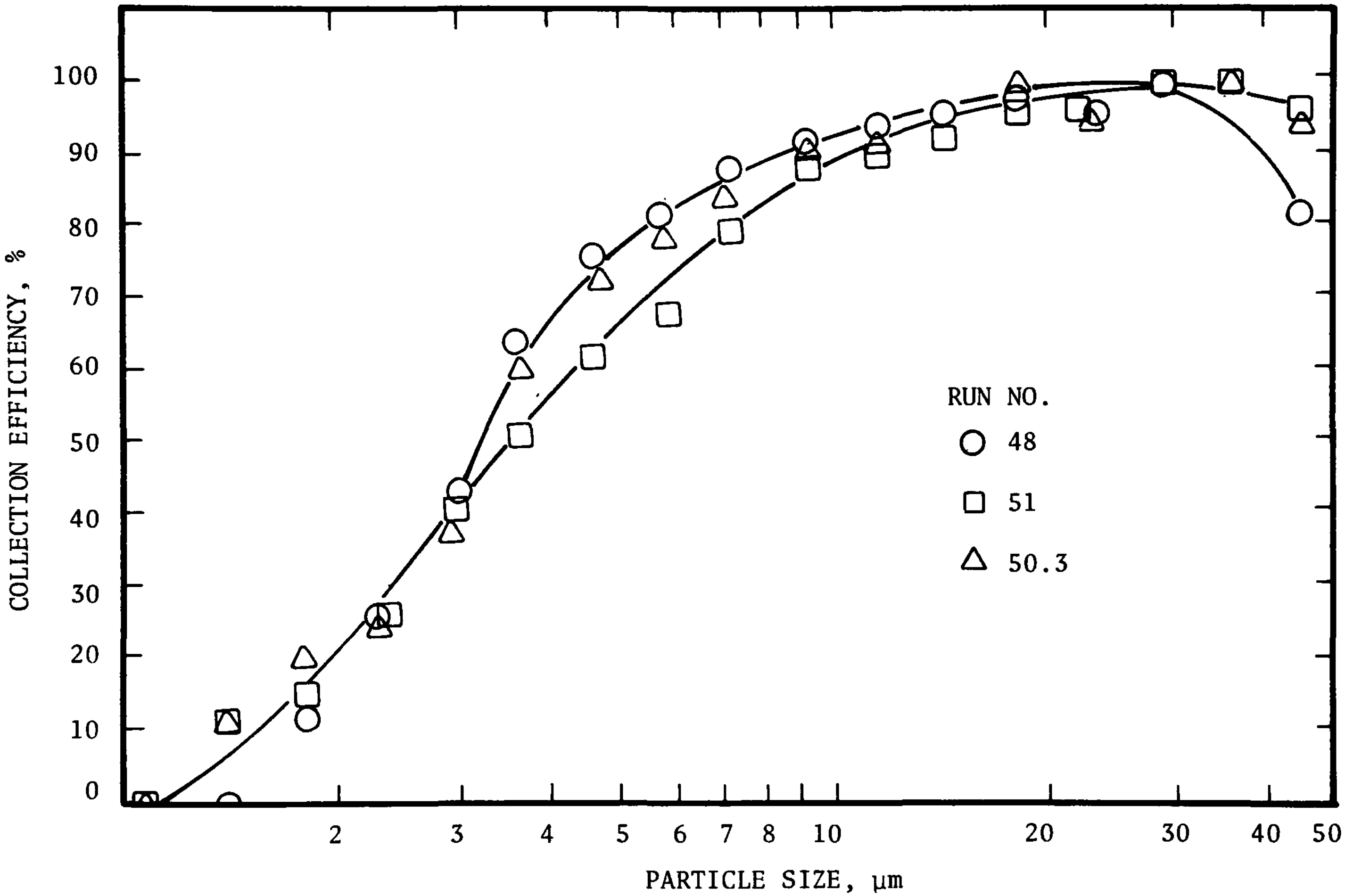


Figure 6. Fractional efficiency for secondary cyclone (from Hoke, et al., 1978).

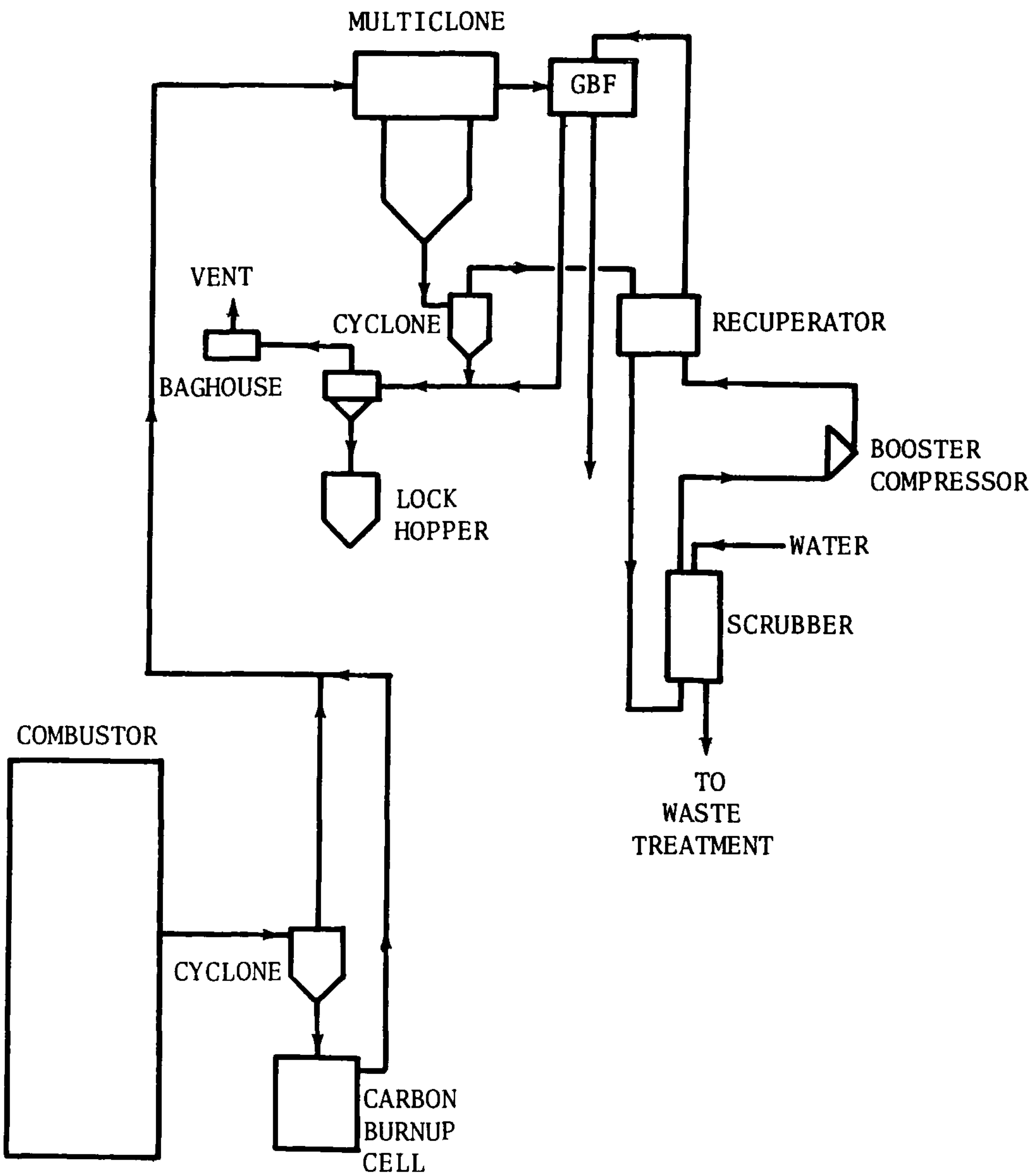


Figure 7. HTP particulate control system for Westinghouse PFBC design.

The second stage collector is a multiclone (multiple cyclone). Approximately 1% of the gas flow is bled off and used to transport the collected solids. The solids are removed from the bleed stream by a separate cyclone, then are depressurized, and deposited in an ash lock-hopper. The bleed gas is cooled in a recuperator, scrubbed, compressed, reheated and used as the reverse cleaning gas for the tertiary collectors (granular bed filters).

The particulate mass loadings and overall efficiencies for each cleanup stage are listed in Table 4. The estimated temperature and pressure losses are shown in Table 5. The estimated gas cleanup costs per gas turbine are listed in Table 6.

Primary and secondary collection equipment are commercially available although high temperature and pressure applications are scarce and there is room for substantial improvements in materials, designs, and engineering models. Also, high temperature and pressure conditions necessitate the use of expensive materials and fabrication techniques.

In the design reported by Beecher, et al. (1976), eight primary cyclones served each gas turbine at an average major component cost of $117,250 per cyclone (1975 dollars). Each cyclone handled 850 m^3/min (30,000 ACFM) of gas.

For comparison we have used the curves presented by Neveril, et al. (1978) to estimate the cost of a conventional cyclone of similar capacity. A 10 gage stainless steel cyclone handling 850 m^3/min would cost approximately $23,000 (1975 dollars). If the materials were 10 gage carbon steel the cost would be approximately $11,000. It should be noted that the HTP cyclone handles approximately 2.2 times the mass flow of gas handled by the conventional cyclone in this comparison.

TERTIARY COLLECTION

The final collection stage must reduce the mass loading of particles to a level compatible with gas-turbine operating specifications and environmental standards. This most likely will require 90 to 99% collection efficiency on a particle

TABLE 4. ESTIMATED GAS CLEANING EQUIPMENT PERFORMANCE (BEECHER ET AL., 1976)

Stage	Inlet Loading, g/g gas	Outlet Loading, g/g gas	Efficiency %
Primary Cyclone	0.0245	0.0005	97.9
Multiclone	0.01521	0.00075	95.1
Granular Bed Filter	0.00075	0.000014*	98.1

* Equivalent to 16.9 mg/Nm^3 (0.0074 gr/SCF) entering the gas turbine

TABLE 5. ESTIMATED TEMPERATURE AND PRESSURE LOSSES FOR GAS CLEANUP SYSTEM (BEECHER, ET AL. 1976)

Description	Temperature Drop, °C	Pressure Drop*, %
Primary Cyclone	2.2	0.6
Multiclone	3.1	2.0
Granular Bed Filters	11.8	0.6

* % of gas turbine discharge pressure

TABLE 6. ESTIMATED GAS CLEANUP EQUIPMENT COSTS PER GAS TURBINE (FROM BEECHER ET AL., 1976)*

	Major Comp. Material	Installation	Total
1. First Stage Cyclone Separators	$ 938,000	$ 462,000	$1,400,000
2. Multiclones	1,594,064	785,136	2,379,200
3. Multiclone Bleed Cyclone	34,550	8,650	43,200
4. Multiclone Bleed Cooler	27,900	4,500	32,400
5. Multiclone Bleed Scrubbers	24,900	7,500	32,400
6. Multiclone Bleed Scrubber Water Cooler	21,600	1,000	22,600
7. Multiclone Bleed Recuperator	24,200	1,000	25,200
8. Multiclone Bleed Compressor	180,000	23,500	203,500
9. Multiclone Bleed Motor	36,800	3,680	40,480
10. Granular Bed Filters	2,452,200	1,207,800	3,660,000
11. Balance of Plant Materials and Installation	--	1,066,800	1,066,800
SUBTOTAL	$ 5,334,214	$ 3,571,566	$ 8,905,780

*Costs are based on mid-1975 dollars.

size distribution which is approximately log-normal with a mass median diameter of about 4 μm and a geometric standard deviation of 3.

In recent years cyclones and granular bed filters have received the most attention as potential tertiary collection devices. To date, neither device has been demonstrated to be efficient enough to satisfy the emissions regulations or the turbine specifications. It is apparent that the current state of the technology is not sufficient and more reliable and efficient cleanup devices are required.

Economic studies of the pressurized fluidized bed combustion process have generally assumed that granular bed filters in their current state of development will be sufficient, or at least representative of the tertiary collector costs. Recent experience at the Exxon miniplant has indicated that granular bed filters need further development before they can be considered commercially viable for PFBC applications. The economic feasibility of pressurized fluidized bed combustion processes must remain highly speculative until a satisfactory solution to the hot gas cleanup problem has been demonstrated.

Cyclones

Background

The application of cyclone separators for particulate removal at high temperature and pressure has been considered for over thirty years. Parent (1946) tested small sampling cyclones (2 and 3 inch diameter) at temperatures up to 1,400°F and pressures to 6.8 atm (100 lb/in^2). Dust loadings from 0.34 to 6.86 g/Nm^3 (0.15 to 3.0 gr/SCF) were also considered. His results are shown in Figure 8.

Figure 8a shows the decrease in overall efficiency as temperature increases for a constant pressure drop. Figure 8b indicates that an increase in pressure drop from about 10 cm W.C. to 25 cm W.C. is required to maintain the overall collection efficiency at 95% when the temperature increases from 24°C to 540°C. Parent 's data also indicate that there was no significant effect of mass loading on the efficiency for the parameters studied.

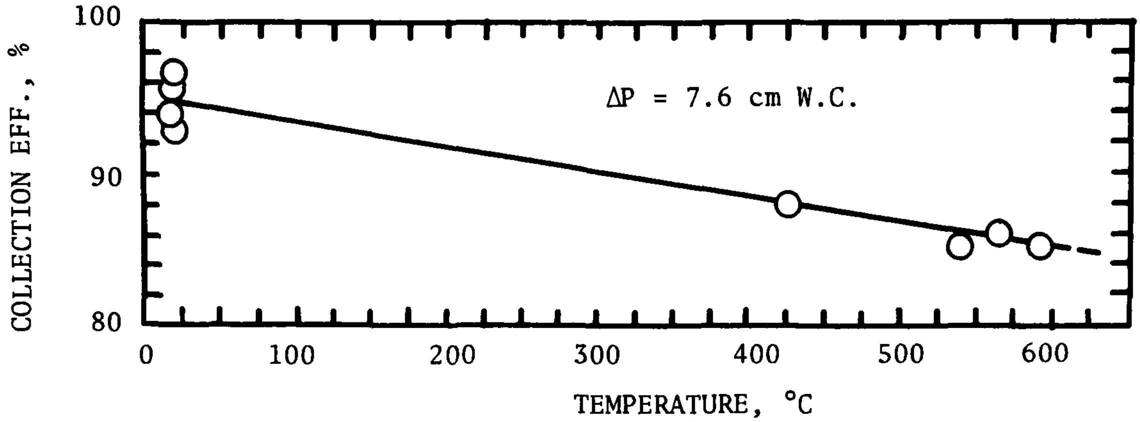


Figure 8a. Efficiency vs. temperature for high temperature cyclone (from Parent, 1946).

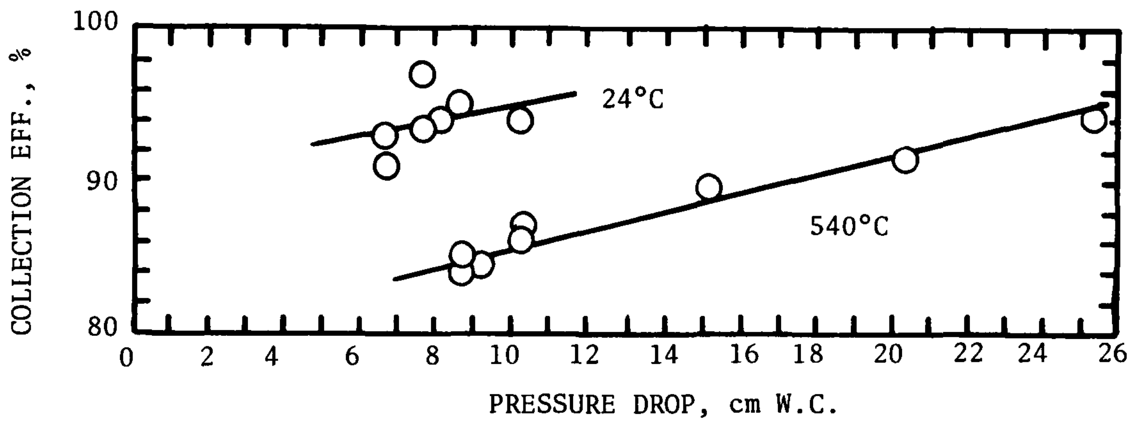


Figure 8b. Efficiency vs. pressure drop for high temperature cyclone (from Parent, 1946).

Yellott and Broadley (1955) studied the efficiency and pressure drop of cyclones operating at high temperatures. They also found that efficiency decreased with increasing temperature. Their study included a 10-inch multiclone for which the fractional efficiency is presented in Table 7. These data are for fly ash particles at 1 atm and 538°C (1,000°F).

TABLE 7. FRACTIONAL EFFICIENCIES FOR MULTICLONE AT 538°C (FROM YELLOTT AND BROADLEY, 1955)

Pressure Drop, kPa	Air Flow, m^3/min	Particle Size, μm			
		0-10	10-20	20-44	+44
0.75	21.4	50.3%	91.5%	97.5%	99.0%
1.00	24.1	55.2	92.0	97.5	99.0
1.34	28.0	60.6	92.6	97.5	99.0
Size analysis of dust		46.3	17.8	15.8	20.1

Advanced Cyclone Designs

Experience with cyclones and multiclones generally confirms that these devices are not sufficient either for protecting the turbine or for satisfying environmental regulations.

Recent data obtained at the Exxon miniplant (Bertrand, et al., 1978) show unusually high collection efficiency for a tertiary cyclone of conventional design. Efficiencies in excess of 80% for 1 μm diameter particles were reported. The size distribution of particles entering the cyclone was not measured directly and it may be that particles were agglomerating somewhere upstream. These results need to be looked at more carefully in order to identify the cause of the high efficiencies measured.

Rotary flow cyclone - A rotary flow cyclone design by Aerodyne Corporation has the potential for higher collection efficiency than conventional cyclones or multiclones and has been proposed as a possible tertiary cleanup device. This cyclone is illustrated in Figure 9.

In the rotary flow cyclone, the primary flow (to be cleaned) enters through a set of vanes located at the base of the unit. A secondary flow is introduced around the circumference of the unit at the top through tangential inlet nozzles. The secondary flow is approximately 60% of the primary flow.

As particles in the primary flow are forced towards the wall they are swept downward to the collection hopper by the secondary flow. The secondary flow may be either clean or dirty gas.

A commercially available Aerodyne rotary flow cyclone, rated at 2.3 m^3/min (80 CFM), was tested at Westinghouse Research Laboratories (Ciliberti and Lancaster, 1976). They used a portion (30 CFM) of the dirty gas stream as the secondary flow. Their results are presented in Figure 10. Also shown are their theoretical predictions. Both their theoretical and experimental performance curves showed lower efficiency than the manufacturers performance curves which claim 50% efficiency for approximately 0.5 μm particles.

From the Westinghouse data, it seems unlikely that the rotary flow cyclone will be able to collect any particles smaller than about 1 to 2 μm. From particle size data obtained at the Exxon miniplant, approximately 30% of the mass leaving the secondary cyclone is smaller than 2 μm. This corresponds to a mass loading of roughly 0.69 g/Nm^3 (0.3 gr/SCF).

Westinghouse plans further tests on the Aerodyne cyclone at high temperature and pressure. Although it may not be sufficient as a tertiary collector, it may be a useful alternative to multiclones as the secondary collection device.

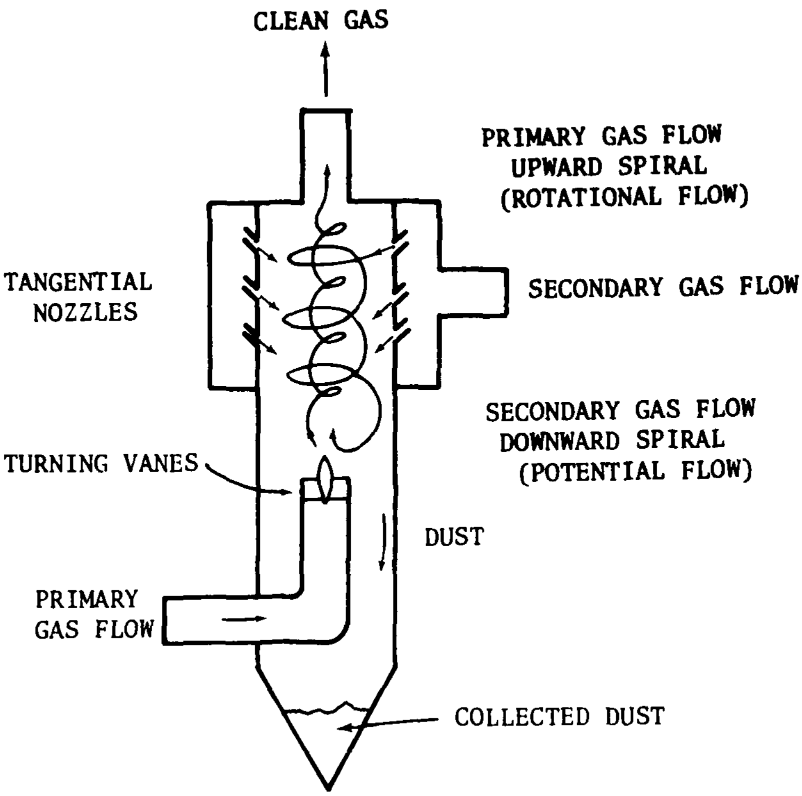


Figure 9. Rotary flow cyclone.

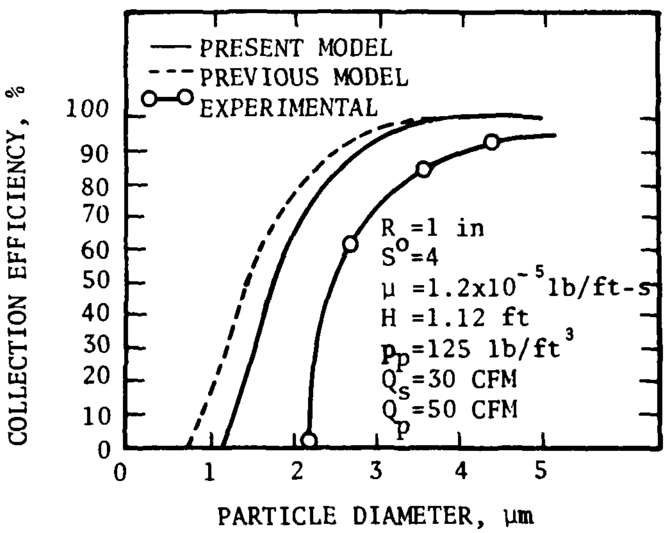


Figure 10. Performance of rotary flow cyclone (from Ciliberti and Lancaster, 1976).

Klett, et al. (1977) reported on a high temperature and pressure design for the Aerodyne cyclone in which the inlet gas is split to provide both primary and secondary flows. They predicted outlet loadings from this cyclone based on the manufacturers performance curves and available data on emissions from PFBC processes. Their predictions are presented in Table 8. Even if this level of performance is attained the emissions will exceed the anticipated emissions regulations (approximately 57.2 mg/Nm^3 or 0.025 gr/SCF for a PFBC process).

TABLE 8. ESTIMATED PERFORMANCE OF AERODYNE CYCLONE (from Klett, et al. 1977)

Particle Diameter μm	Inlet Loading, mg/Nm^3 (gr/SCF)		Outlet Loading, mg/Nm^3 (gr/SCF)		Efficiency, %
0-2	460.0	(0.201)	96.1	(0.042)	79
2-3	153.3	(0.067)	22.9	(0.010)	85
3-4	153.3	(0.067)	13.7	(0.006)	91
4-5	153.3	(0.067)	9.2	(0.004)	94
5-6	153.3	(0.067)	6.9	(0.003)	96
6-10	460.0	(0.201)	4.6	(0.002)	99
10-20	766.6	(0.335)	0.0	(0.000)	99.9
+20	13,032	(5.695)	0.0	(0.000)	100
TOTAL	15,332	(6.700)	153.4	(0.067)	99.0

Cyclocentrifuge - Mechanical Technology, Inc. is developing a gas cleanup device which they call a "cyclocentrifuge" (McCabe, 1977). The basic design of this device is illustrated in Figure 11. It is a hybrid device using a rotating assembly

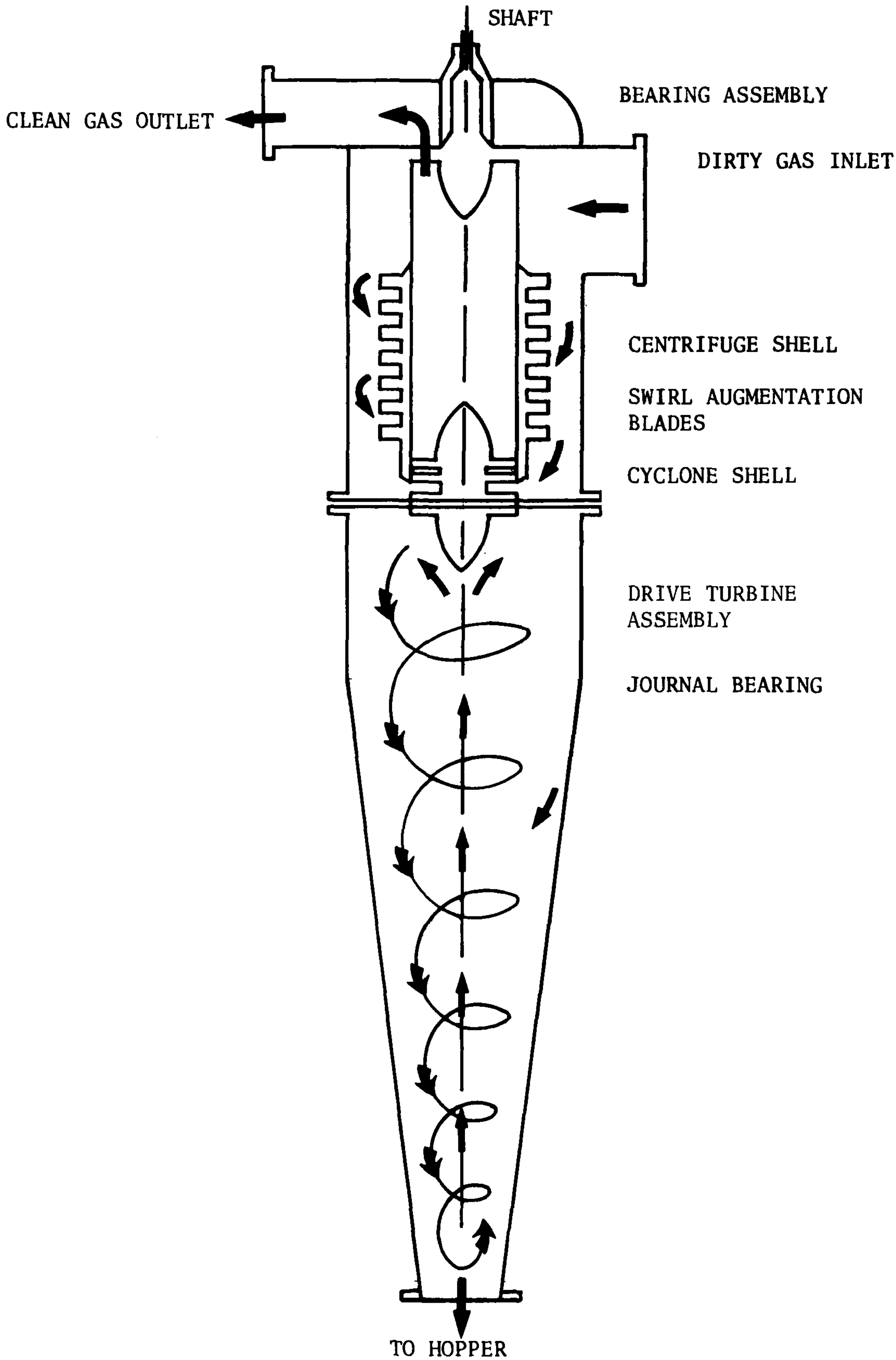


Figure 11. Cyclocentrifuge (from McCabe, 1977).

called the "centrifuge" and a stationary assembly called the "cyclone". The centrifuge is driven by a high reaction axial turbine driven by energy extracted from the process gas.

The predicted fractional efficiency for this device was presented by McCabe and is shown as Figure 12. The design parameters are listed below.

- Volume flow — 3,457 Nm^3/min (125,260 SCFM)
- Inlet pressure — 17 atm (250 lb/in^2)
- Inlet temperature — 538°C (1,000°F)
- Pressure drop — 1 atm (14.6 lb/in^2)

The explanation given for the improved efficiency as compared to a conventional cyclone is as follows:

- The length from the inlet duct to the centrifuge is longer than in a conventional cyclone.
- The centrifuge collects particles that are reentrained from the cyclone section.
- The centrifugal force in the centrifuge is larger than in a cyclone.
- Agglomeration will be increased by the increased centrifugal force field.

If the cyclocentrifuge works as predicted, the outlet loading still may exceed the environmental regulations, depending on the mass loading of particles smaller than 2 μm.

One of the most attractive aspects of cyclones for dust removal is that they have no moving parts. This is not true for the cyclocentrifuge. Operation of the centrifuge bearings at high temperature and pressure in a dirty environment is likely to present the most difficult development problem with this device.

Assuming the predicted performance can be achieved and mechanical problems are not severe, the economic analysis presented by McCabe indicates that the cyclocentrifuge is economically viable for low-BTU coal gasification processes.

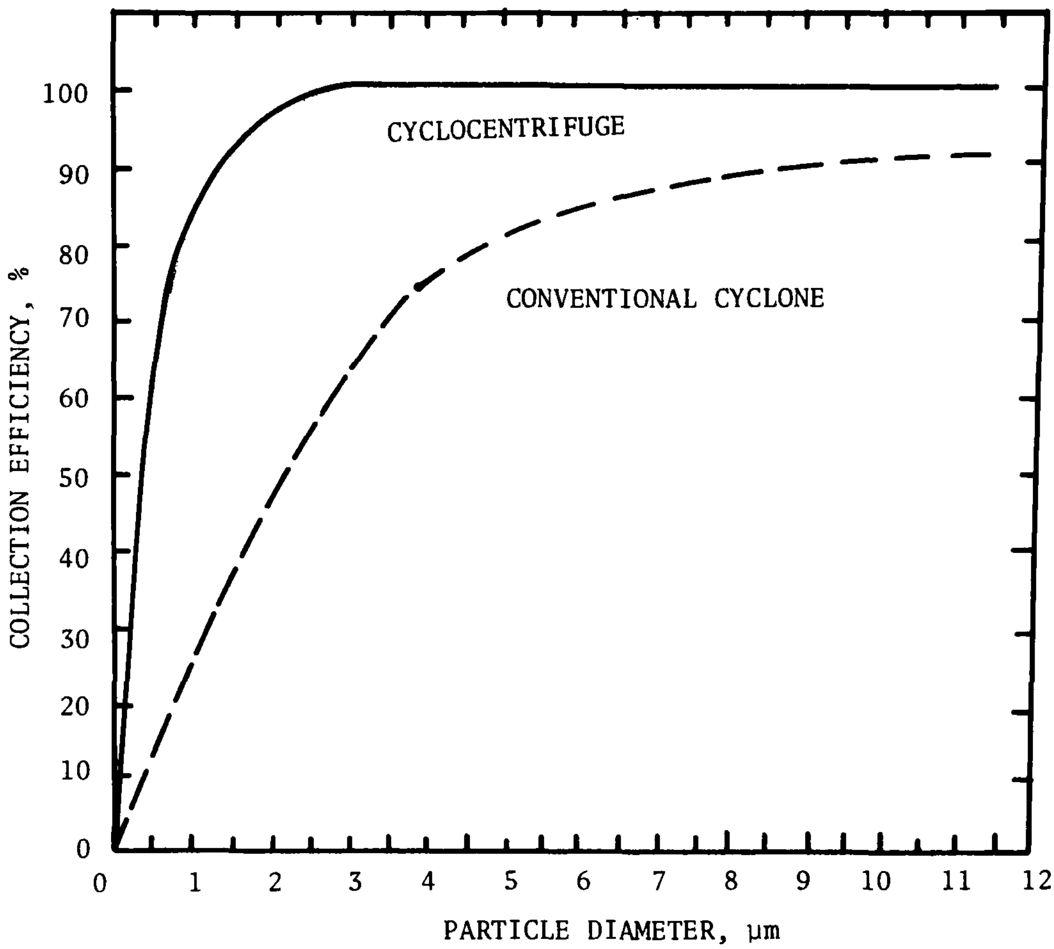


Figure 12. Comparison between estimated performance of cyclocentrifuge and conventional cyclone (from McCabe, 1977).

Granular Bed Filters

Granular bed filter technology has recently been reviewed by Yung, et al. (1977a, 1977b, 1978) to assess the state-of-the-art and to evaluate the feasibility of granular bed filters for high temperature and pressure applications.

Granular bed filters may be defined as any filtration system comprised of a stationary or slowly moving bed of discrete, relatively closely packed granules as the filtration medium. With respect to motion of the granules, granular bed filters may be classified as continuously moving, intermittently moving, and fixed bed filters.

Moving Bed Filters

The continuously moving bed filter is usually arranged in a cross-flow configuration. The bed is a vertical layer of granular material held in place by louvered walls. The gas passes horizontally through the granular layer while the granules and collected dust move continously downward and are removed from the bottom. The dust is separated from the granules by mechanical vibration. The cleaned granules are then returned to the overhead hopper and the panel by a granule recirculation system.

The Combustion Power Company's dry scrubber is an example of a continuously moving bed filter. The system is shown in Figure 13. The granular bed material flows downward between two concentric cylinders. The gas passes through the bed and is filtered by the granules. The granules are recycled pneumatically and the collected dust particles are disengaged from the granules and sent to a conventional baghouse.

The performance of this device has been reported by Wade, et al. (1978). They conducted extensive cold flow tests to investigate the effects of bed depth, granule diameter, amd other parameters on the collection efficiency. Test parameters for the nominal, thick bed, and small collector granule configurations are listed in Table 9. Particulate loadings ranged from 0.46 to 4.6 g/Nm^3

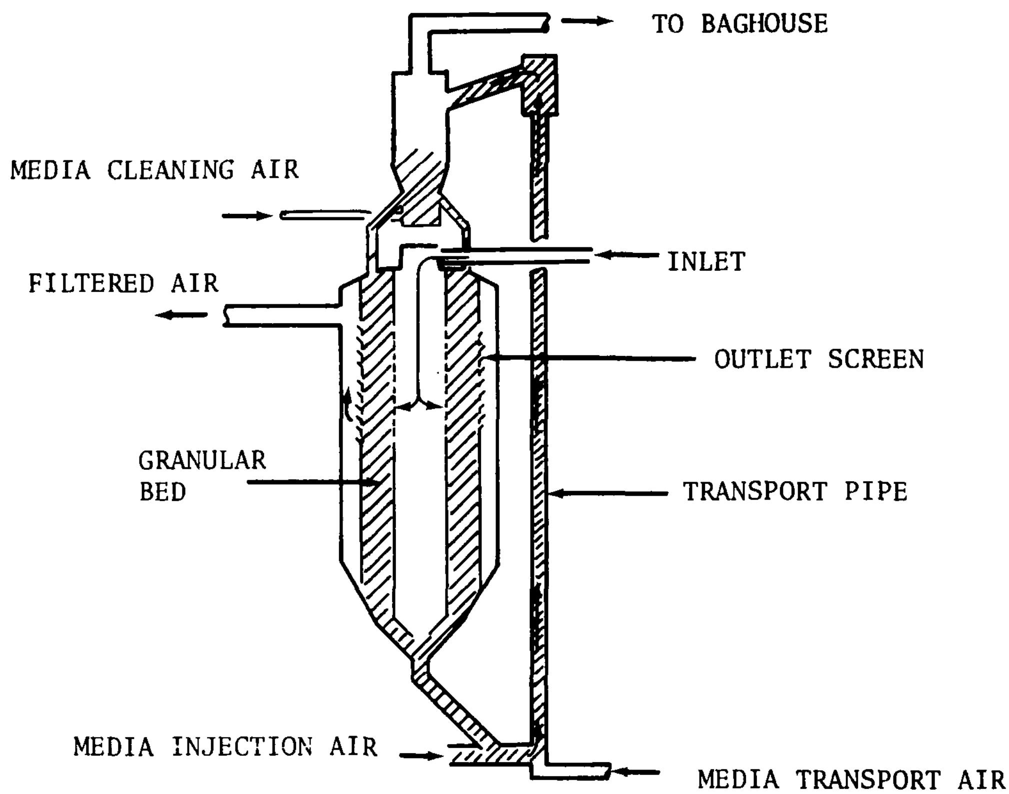


Figure 13. Cold flow granular bed filter parameters.

TABLE 9. TEST PARAMETERS FOR CPC MOVING BED FILTER (FROM WADE ET AL., 1978)

Configuration	Bed Depth, mm	Medium Diameter, mm	Mass Median Particle Diameter, μm
Nominal	203.2	2.0	3.2
Thick Bed	406.4	2.0	2.6
Small Granules	203.2	0.8	7.0*

* Correlation was not materially influenced by deletion of four data points resulting in an average median diameter of 2.5 μm

(0.2 to 2.0 gr/SCF). The superficial gas velocity was varied from 20 to 80 cm/s (40 to 160 ft/min). The medium flow rate was varied from 0.4 to 1.6 kg granules/kg air. Pressure drop ranged from 1.2 to 5.7 kPa (5 to 23 in. W.C.).

Fractional efficiency curves are shown in Figures 14a, b, c. The overall penetration (and efficiency) are correlated with the pressure drop function, Θ, in Figures 15a, b, c. The pressure drop function was defined in English units as:

$$\Theta = \frac{\Delta P \; L_i}{V \; \dot{M}} \qquad (1)$$

where ΔP = pressure drop, in.W.C.
L_i = mass loading of dust, gr/SCF
V = superficial velocity, ft/min
$\dot{M}$ = media rate, lb granules/lb air

In general the CPC moving bed filter was found to be capable of particulate removal efficiencies in excess of 98% for particles in the 1 to 10 μmA diameter range. Submicron particles were collected at an efficiency in excess of 90% in cases with high velocities, high loadings, and low granule rates. Beds with larger thickness to granule diameter ratios were most effective in the capture and retention of particles in the 2 to 5 μmA diameter range. Also, intermittent granule movement was shown to improve efficiency by a few percent. However, the economics of this operational technique have not been analyzed.

High temperature tests of the moving bed filter are planned. No high temperature data are available at this time.

The major advantage of the moving bed filter design is that the bed granules are removed and cleaned out of the primary gas stream. This enables efficient cleaning and a relatively steady collection efficiency. Also it is not necessary to isolate filter units during cleaning so that the total filter area open to gas flow is available for filtration at any time.

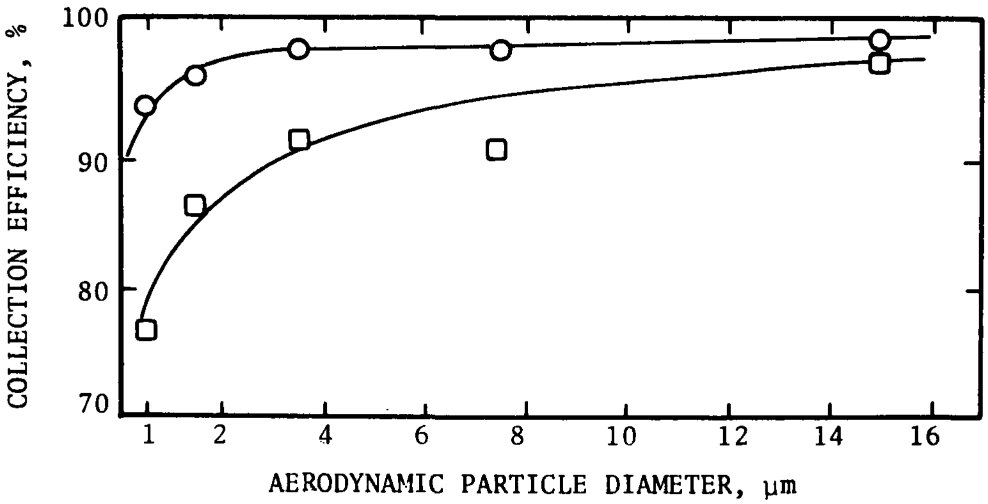


Figure 14a. Fractional collection efficiency, nominal configuration.

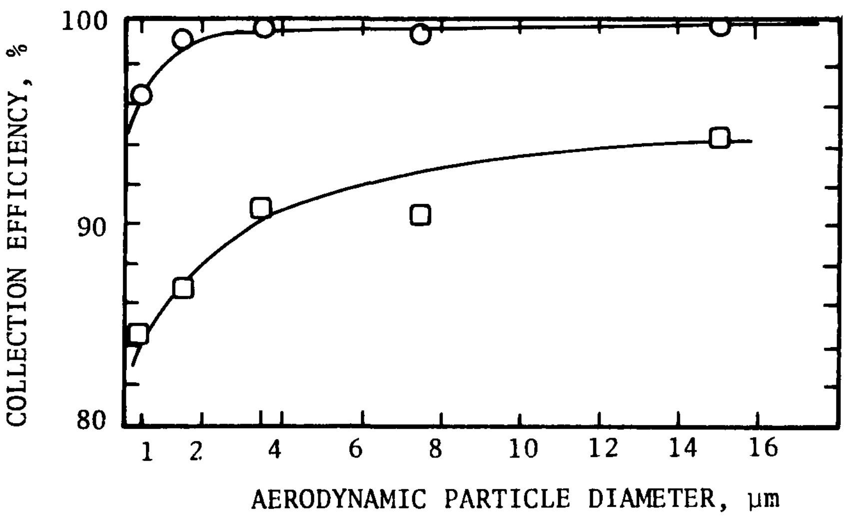


Figure 14b. Influence of operational parameter combinations on fraction efficiency (16" filter, 2mm media).

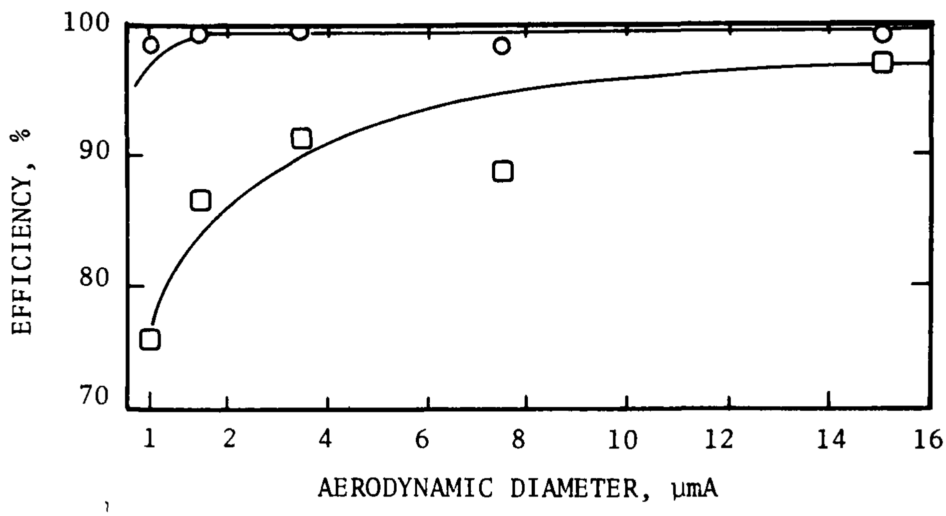


Figure 14c. Fractional efficiency performance, small media configuration.

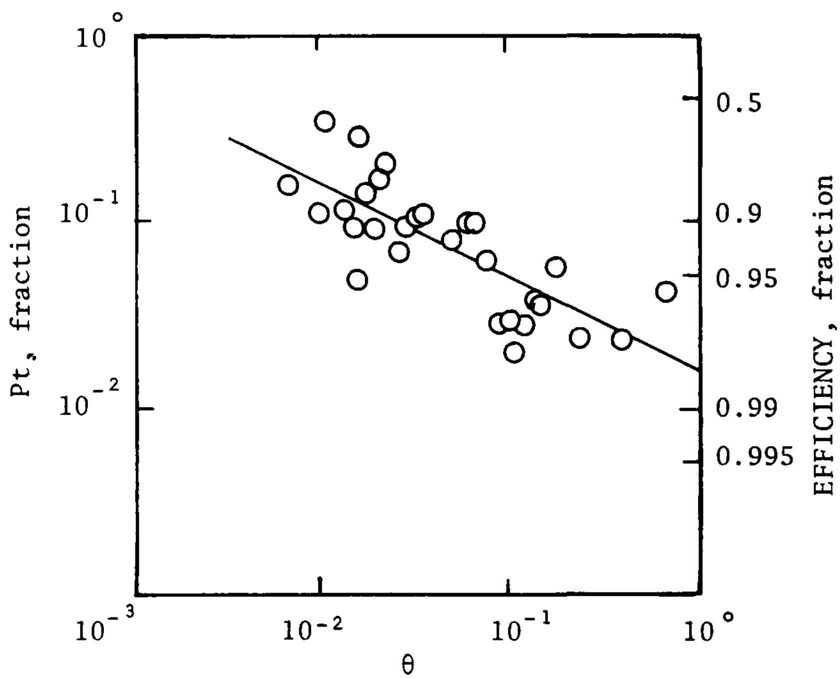


Figure 15a. Influence of pressure drop function on overall collection efficiency, nominal configuration.

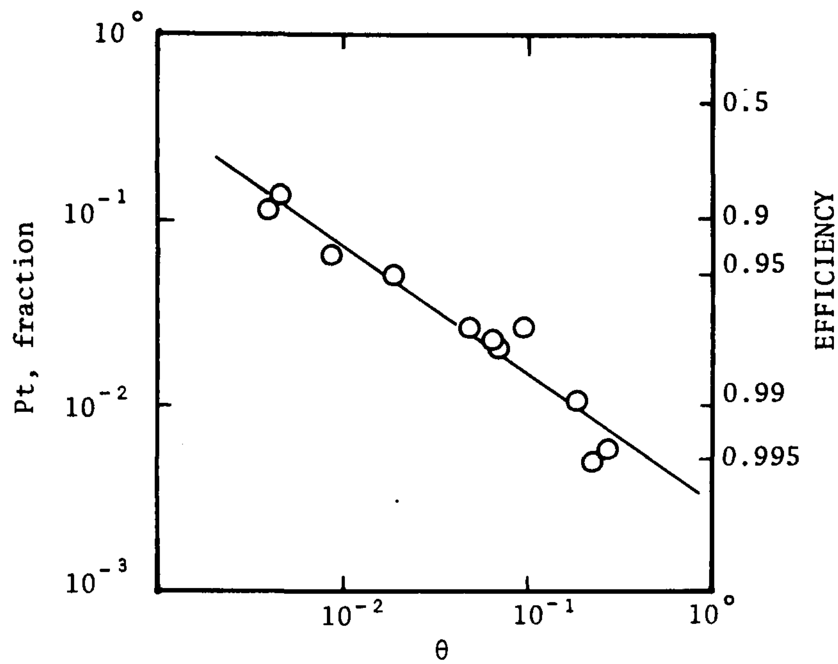


Figure 15b. Influence of pressure drop function on overall collection efficiency, thick bed configuration.

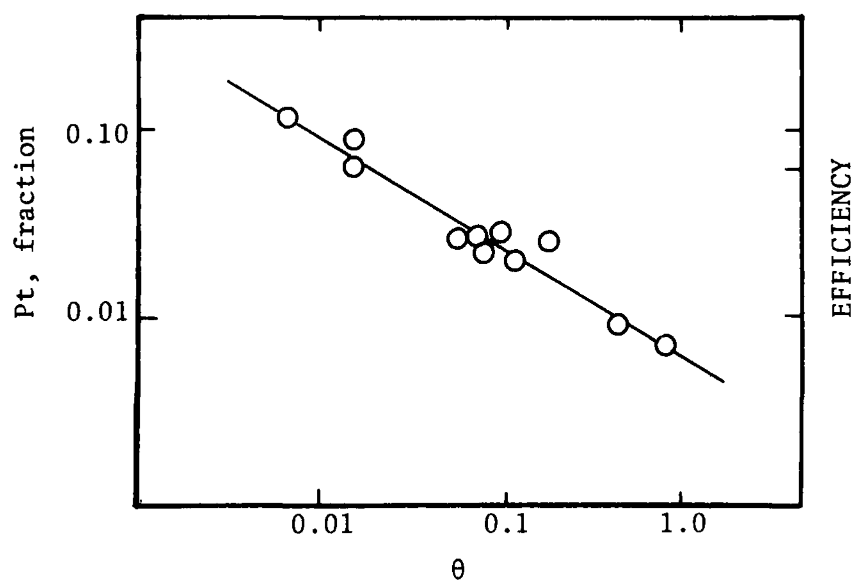


Figure 15c. Influence of pressure drop function on overall collection efficiency, small media.

The moving bed design also has some limiting operating characteristics. The granule recirculation system adds significantly to the operating cost. Particle reentrainment caused by the relative motion of the granules limits the granule flow rate and affects the overall collection efficiency. Erosion of the retaining grids, louvers, and transport system components may be a problem, especially in high temperature and pressure systems. The collected dust particles cannot form a filter cake so that the operating efficiency will be essentially that of a clean bed. Temperature losses may be large and will be proportional to the energy required to keep the granules hot during recirculation.

It may be possible to resolve most of these problems through further development and testing. Performance data at high temperatures and pressures will be important in identifying the most serious operational problems.

Intermittently Moving Bed

In the late 1950s, Squires modified the continuously moving bed design to obtain a fixed bed device with an intermittent movement of granular solids. The bed is stationary during filtration. The accumulated filter cake and the surface layer of granules are ejected from the panel by a sharp backwash pulse and fall to the bottom of the filter vessel. The expelled granules are immediately replaced by downward movement of fresh granules from the overhead hoppers.

Intermittent movement is normally limited to vertical panel filters. The granules are intermittently removed in a cross-flow arrangement panel bed. The advantage of this type of bed structure is the capability for external granule/dust separation with minimum disturbance to the rooting cake. A rooting cake is the foundation for the formation of a surface cake. After cleaning, the surface cake is formed readily without disturbing the rooting cake and filtration efficiencies can be much higher.

The intermittently moving bed also has the advantage that granule cleaning is off-line and potentially more effective.

The major disadvantage is that the gas capacity is lower than for other granular bed filter designs and this results in high capital costs for a given installation. During cleaning, about two to three layers of granules are removed from the bed. To prevent the dust from being carried deep into the bed by the gas, CCNY recommends the velocity be kept as low as possible to reduce the aerodynamic drag force. They usually operate the panel bed filter at about 15 cm/s (30 ft/min). This velocity is about one third the velocity used in the fixed bed and continuously moving bed GBFs. Thus, more filtration area is required.

Bed plugging also can be a problem if the surface cake is not formed properly. Erosion of the retaining grids, louvers, and other components may be a problem. Granule recirculation temperature losses, and the requirement for blow-back air pulses during cleaning add to the overall operating costs.

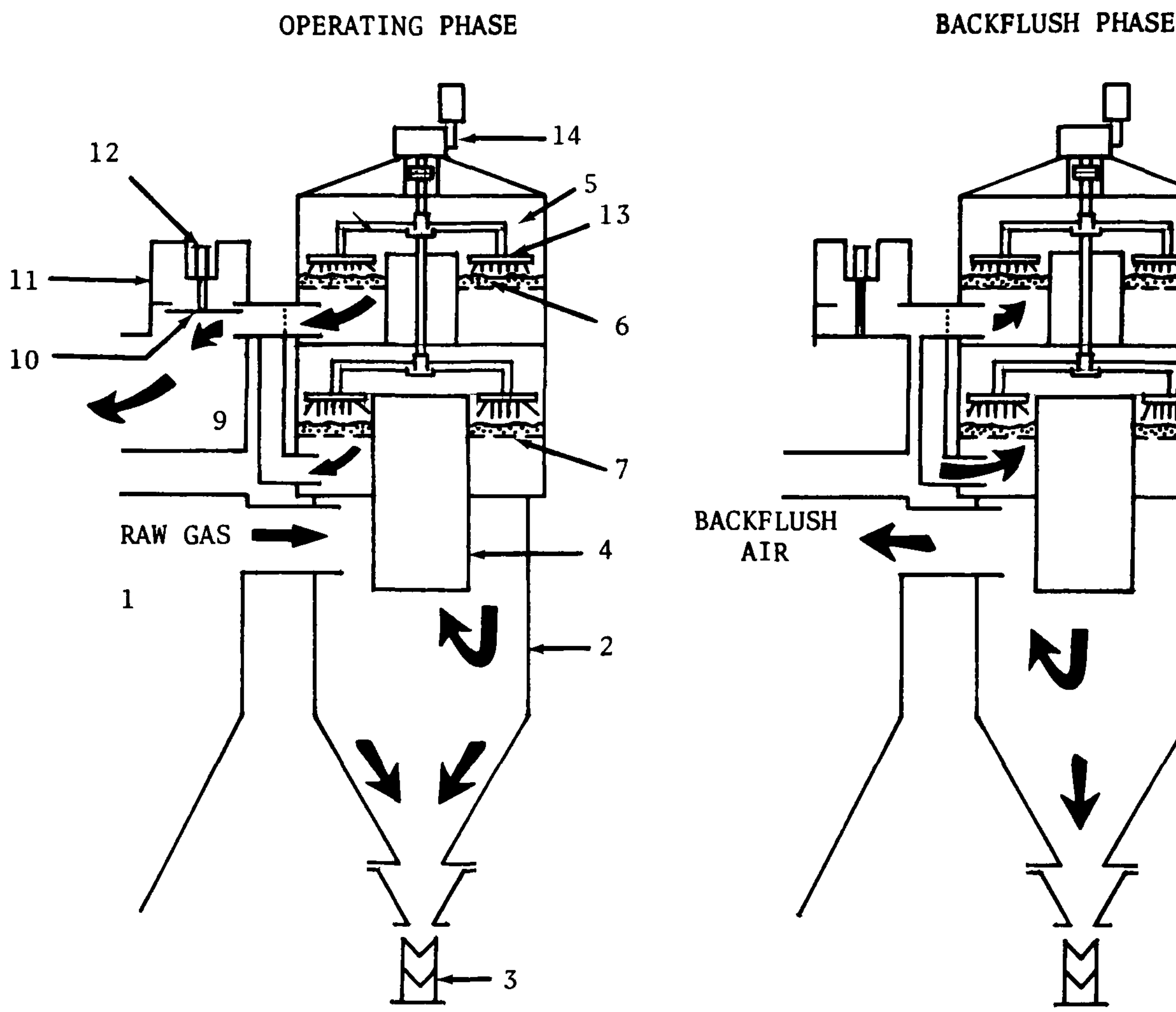
Recent work on the CCNY panel bed was reported by Lee, et al. (1977).

Fixed Bed Filters

Fixed bed filters operate in two modes; the filtration mode and the cleaning mode. During filtration the bed is stationary. The gas passes through the bed and collected particles are deposited within the bed and on the bed surface. During cleaning the bed is isolated from the main flow and agitated mechanically or pneumatically by a reverse flow of gas.

There are two fixed bed devices currently being developed; the Rexnord gravel bed filter and the Ducon granular bed filter. The Rexnord filter (Figure 16) uses a rake-shaped stirring device to agitate the bed during cleaning. This loosens the filter cake which is then removed by a reverse flow of clean air.

Rexnord granular bed filter - No Rexnord filters have been tested at high temperature and pressure, however, McCain (1976) reported the results of a performance test on a Rexnord filter used to control the emissions from a clinker cooler in a Portland cement plant.



1. INLET CHAMBER
2. PRIMARY COLLECTOR (CYCLONE)
3. DOUBLE TIPPING GATE (DUST DISCHARGE)
4. VORTEX TUBE
5. FILTER CHAMBER
6. GRAVEL BED
7. SCREEN SUPPORT FOR BED
8. CLEAN GAS COLLECTION CHAMBER
9. EXHAUST PORT
10. BACKWASH CONTROL VALVE
11. BACKWASH AIR INLET
12. VALVE CYLINDER
13. STIRRING RAKE
14. STIRRING RAKE MOTOR/REDUCERS

Figure 16. Rexnord gravel bed filter.

Samples were taken simultaneously at the filter inlet and outlet with cascade impactors. The operating conditions of the gravel bed were:

Gravel diameter = 4 mm
Face velocity = 73 cm/s
Gas temperature = 174°C
Pressure drop = 25.4 cm W.C.

The grade penetration curves for these tests are shown in Figure 17. The predicted curve was obtained using the model presented by Yung, et al. (1977b) which assumes the bed is clean and particulate collection results from the inertial impaction mechanism only.

Ducon granular bed filters - The Ducon granular bed filter cleans the bed by a reverse flow of gas which fluidizes the bed and elutriates the fine collected particles. The filtration and cleaning modes of the Ducon filter are illustrated in Figure 18.

The Ducon filter was tested on the effluent from a fluid bed catalytic cracking unit regenerator at an oil refinery (Kalen and Zenz, 1973). The gas was at 370°C to 480°C and 1 to 1.5 atm. The dust loading ranged from 0.34 to 1.94 g/m^3 (0.15 to 0.85 gr/ACF). A collection efficiency of 85-98% was obtained on dust with a mass median diameter of 35 μm and a geometric standard deviation of about 4. Yung, et al. (1978) estimated fractional penetrations from their data and the results are shown in Figure 19.

A high temperature and pressure design of the Ducon filter was tested at the Exxon miniplant (Hoke, et al., 1978). Initially severe plugging of the bed retaining grids was encountered. This problem was resolved by eliminating the grids and redesigning the bed housing to provide sufficient freeboard above the bed to allow cleaning of the bed without loss of bed material. The modified filter module is illustrated in Figure 20.

A number of operating problems were encountered during the

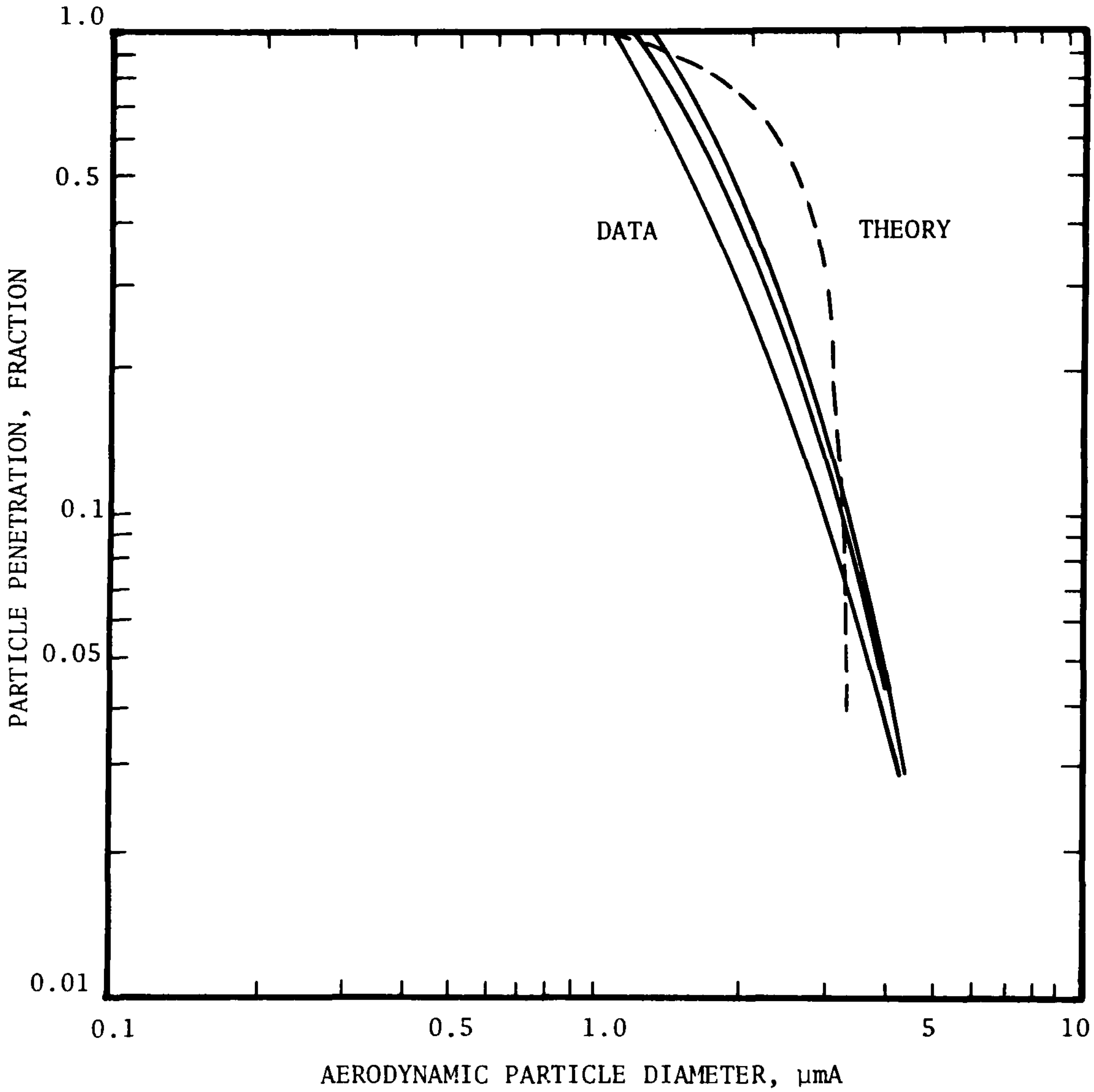


Figure 17. Experimental grade efficiency curve of a Rexnord gravel bed filter (McCain, 1976).

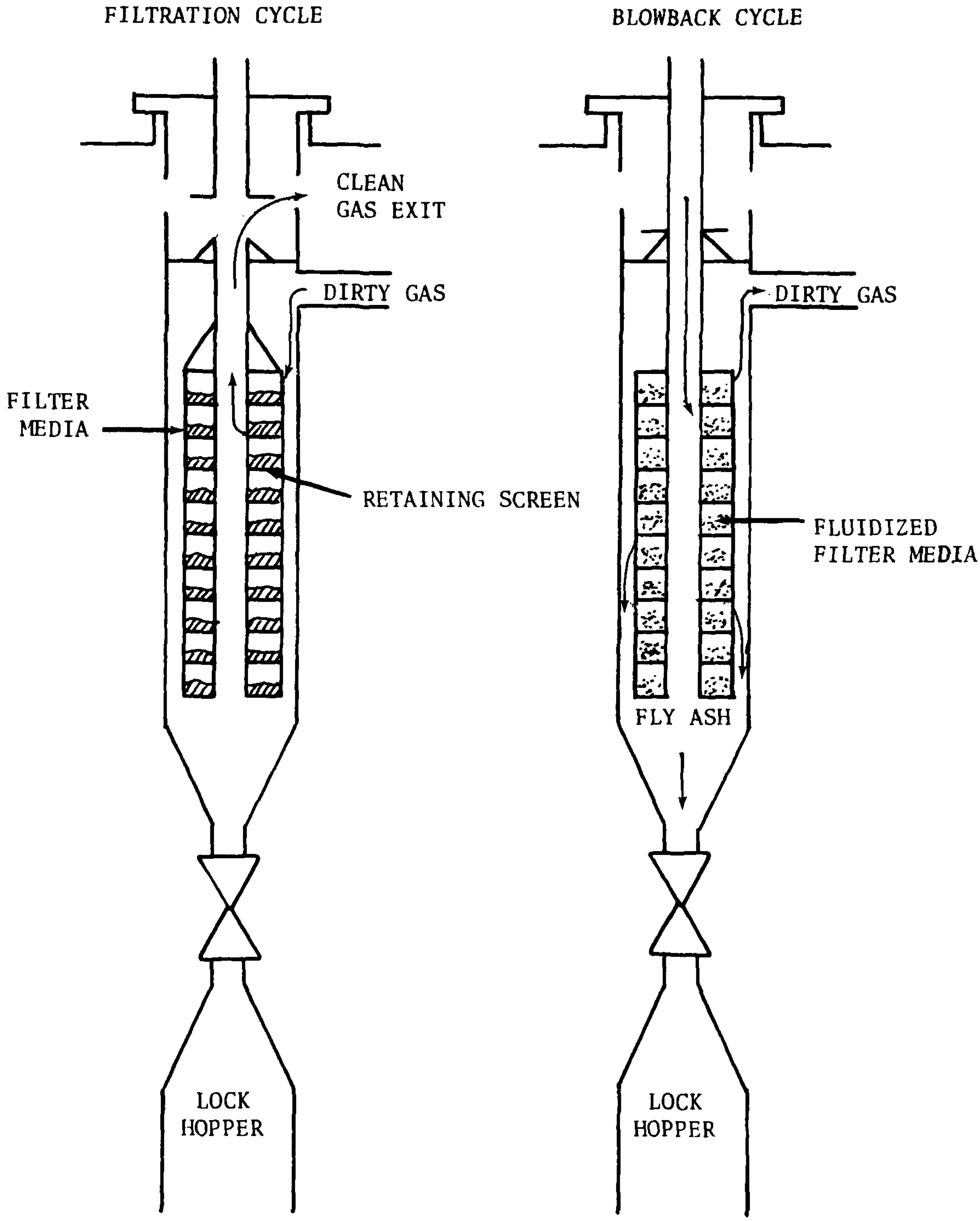


Figure 18. Ducon granular bed filter.

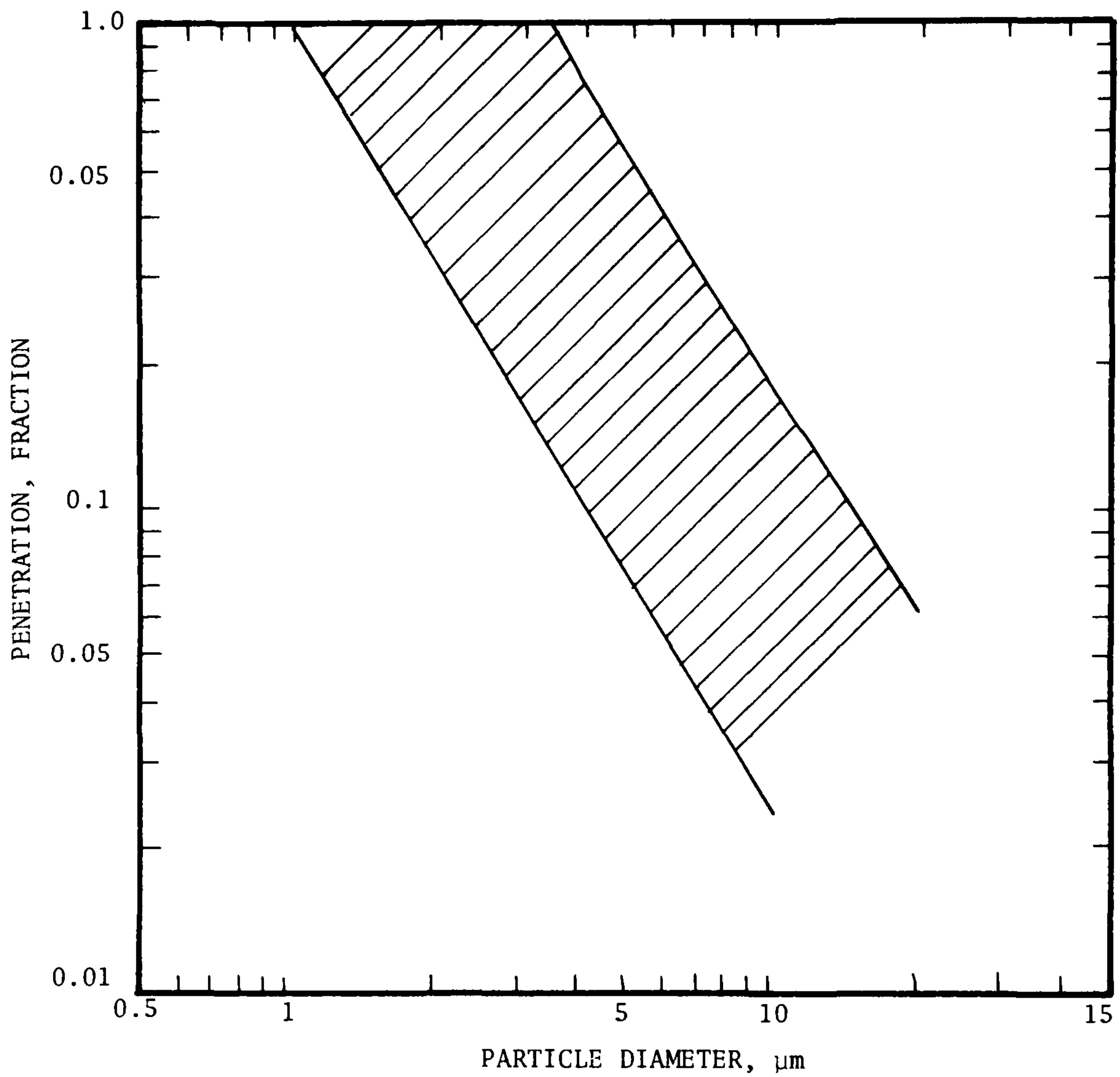


Figure 19. Fractional penetration for Ducon **granular** bed (from Kalen and Zenz, 1973).

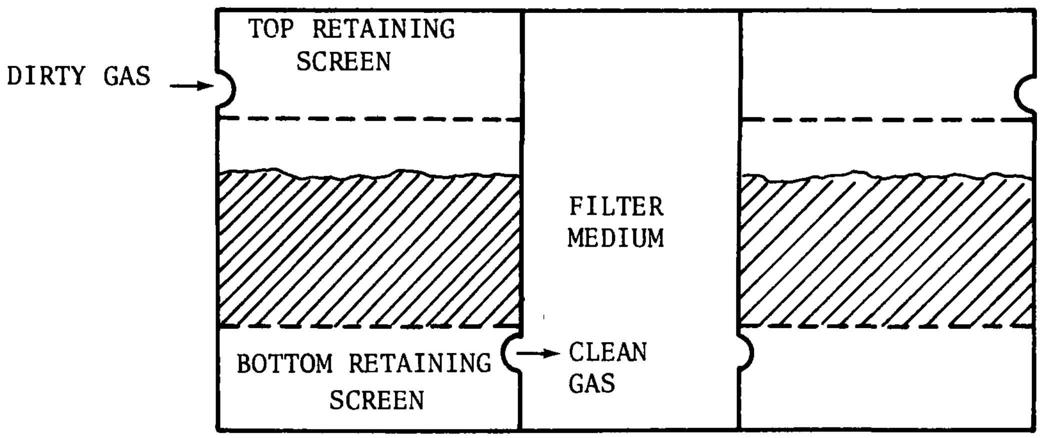


Figure 20a. Schematic of a single Exxon filter bed.

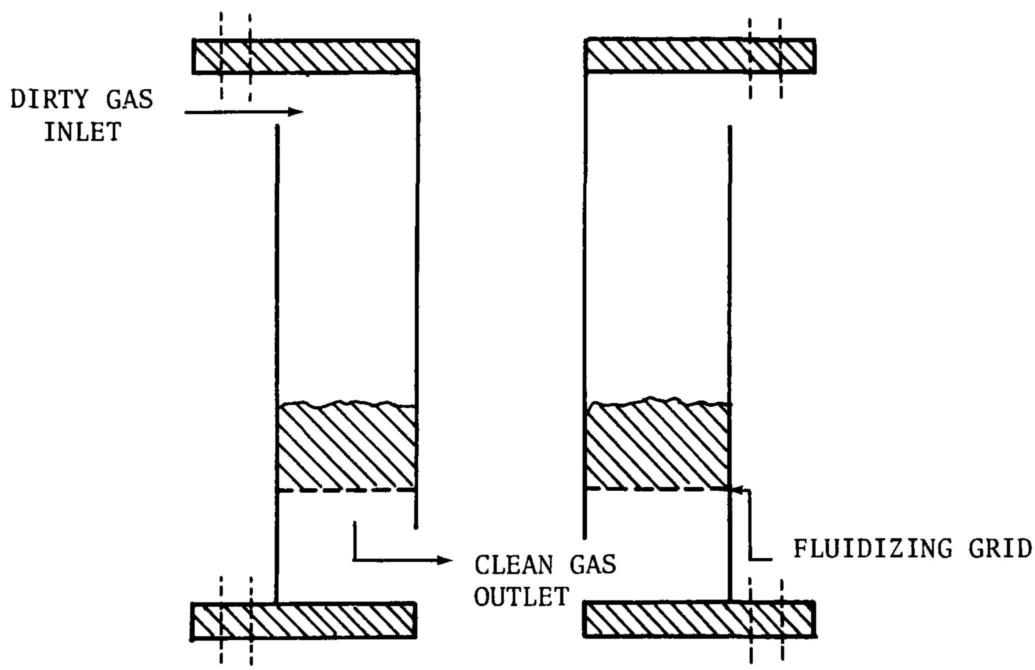


Figure 20b. Modified filter bed.

Exxon tests of the modified Ducon filter. The lowest demonstrated particulate outlet concentration was 68.6 mg/Nm^3 (0.03 gr/SCF) which was considered to be too large to protect a gas turbine and borderline for meeting current emissions regulations. The use of smaller filter media could be expected to improve efficiency. However, at times the filtration efficiency was very poor and the outlet particulate concentrations were as high as 700 to 1,200 mg/Nm^3 (0.3 to 0.5 gr/SCF). It was also observed that the efficiency decreased with time in the longer runs, dropping from 90% initially to about 50% later in the run. Loss of filter medium during blow back was another recurring problem. Further attempts were made to use 50 mesh retaining screens but they failed because of plugging. Additional tests made with 10 mesh screens also resulted in significant screen plugging.

A large buildup of particles in the filter beds also was observed amounting to about 30% of the weight of the filter medium. A possible steady long term increase in filter pressure drop may result because of this. However, no significant increase in filter pressure drop was noted during any of the shakedown runs.

It was observed that the particles were not only building up in the beds, but were uniformly mixed with the filter medium. It is possible that the buildup and mixing of particles in the bed could be responsible for the increase in the particle concentration in the outlet gas with time.

Another potential problem with the current design was its vulnerability to upsets. When upsets occurred, such as bed plugging or loss of filter medium, the operating problems caused by such upsets required shutdown of the system. Another problem which may be unique to the miniplant was the interaction of the granular bed filter with the rest of the FBC system during the blow back cycle. An increase in system pressure was noted during blow back resulting in problems with the coal feed system which is controlled by the differential pressure between the coal feed vessel and combustor. This required modifications to the coal feed control system to minimize these effects.

Granular bed filter performance data for all runs through November, 1977 are listed in Table 10. The efficiencies are based on an inlet concentration of 2.3 g/Nm^3 (1.0 gr/SCF) which is the average for the emissions from the secondary cyclone. Fractional efficiency data are presented in Figure 21.

The granular bed filter test program was suspended in November, 1977. In all runs in which more than one outlet concentration was measured, it was observed that the outlet concentration increased with time. They were not able to demonstrate that the current EPA emission standard (0.1 lb/10^6 BTU or 0.05 gr/SCF) could be met for more than a few hours of operation. In no run was the anticipated new standard (0.05 lb/10^6 BTU or approximately 0.025 gr/SCF) satisfied.

Further tests are planned on a 0.85 m^3/min (30 ACFM) slip stream from the miniplant combustor. The slipstream will be at 870°C and 9 atm pressure. If the filter can be modified to satisfy the EPA regulations for a prolonged run, it will be tested on the full miniplant flow stream.

Summary

At this time granular bed filters have not been demonstrated to be efficient enough to perform as tertiary collectors in high temperature and pressure gas cleanup systems.

High collection efficiencies may be obtained if a filter cake is formed on the surface of the bed. This has been accomplished with the CCNY (Squires) design at low temperature and pressure operating conditions. Efficiencies in excess of 99.9% have been measured. However, when this filter was tested at the Morgantown Energy Research Center at 1,000°F, no filter cake was formed, although 99% efficiency was obtained.

Operation of the Ducon granular bed filter at the Exxon miniplant also indicated that no filter cake was formed.

TABLE 10. GRANULAR BED FILTER PERFORMANCE (FROM BERTRAND ET AL., 1977)

Run Number	Outlet Concentration gr/SCF	g/m^3	Collection Efficiency* (%)
54	0.69	1.57	31.0
57	0.04-0.08	0.09-0.18	92.0-96.0
59 (Sample 1)	0.08	0.18	92.0
59 (Sample 2)	0.28	0.64	72.0
59 (Sample 3)	0.54	1.23	46.0
61	0.46	1.05	54.0
62.1	0.03	0.07	97.0
62.3	0.21	0.48	79.0
63 (Sample 1)	0.05	0.11	95.0
63 (Sample 2)	0.07	0.16	93.0
63 (Sample 3)	0.12	0.27	88.0
64 (Sample 1)	0.28	0.64	72.0
64 (Sample 2)	0.29	0.66	71.0
64 (Sample 3)	0.27	0.61	73.0
65 (Sample 1)	0.05	0.11	95.0
65 (Sample 2)	0.06	0.14	94.0
66	0.06	0.14	94.0

* Based on a 2.3 g/Nm^3 (1.0 gr/SCF) inlet concentration

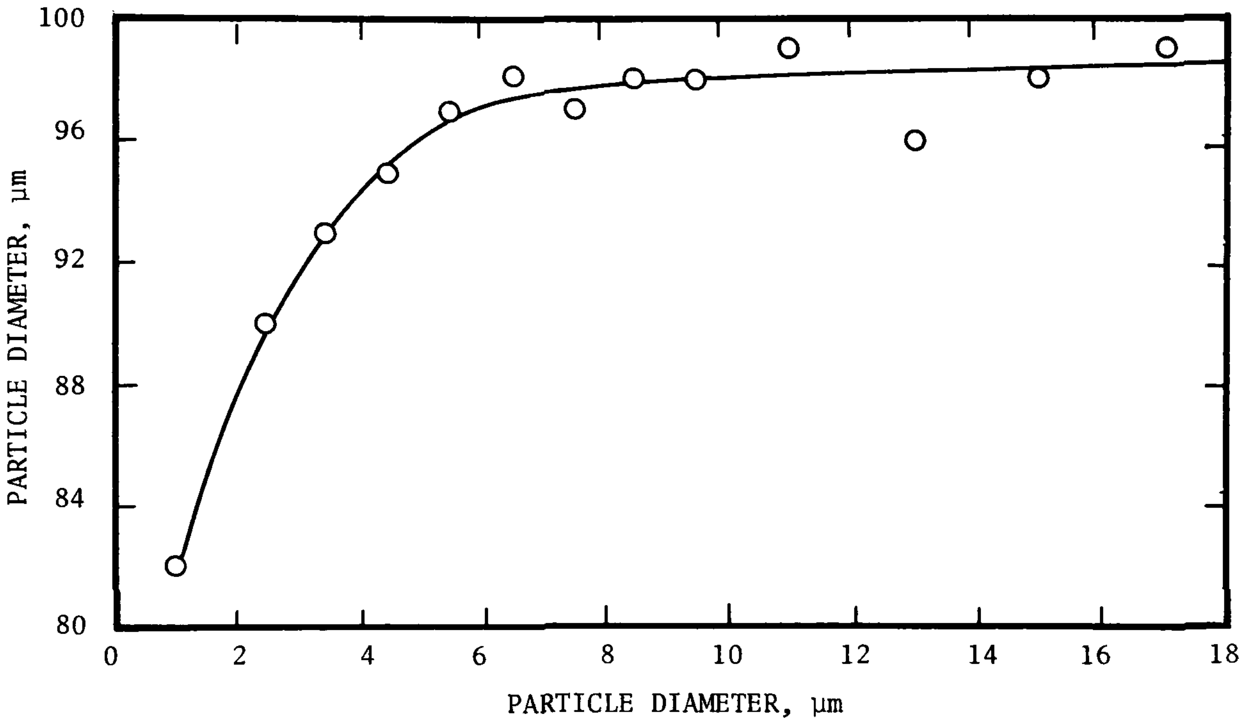


Figure 21. Fractional efficiency data for Ducon GBF (from Bertrand, et al.) 1977).

Therefore, the current state of development of granular bed filters for high temperature applications seems to be predominantly limited to clean bed filtration.

The model developed by Yung, et al. (1977b, 1978) can be used to predict performance for clean bed granular bed filters. This has been done using typical operating parameters from the Exxon tests, as listed below.

Granule diameter	= 400 μm
Bed depth	= 3.8 cm
Superficial velocity	= 45 cm/s
Particle mass median diameter	= 3.5 μm
Particle density	= 1.5 g/cm^3
Bed porosity	= 0.25

The results are presented as Figure 22. The collection efficiency decreases (penetration increases) radically as the gas conditions go from ambient to high temperature and pressure. This effect should be remembered when interpreting low temperature and pressure performance data for granular bed filters.

There are many operational problems and uncertainties which need to be resolved before HTP granular bed filters can be considered sufficiently reliable for commercial application. These problems include the needs to:

1. Prevent particle seepage through the bed (during cleaning or filtration.
2. Reduce temperature losses (especially during cleaning).
3. Improve the efficiency and reduce the cost of granule regeneration and recirculation.
4. Prevent attrition of granules causing particle reentrainment.
5. Prevent sintering of granules.
6. Prevent plugging of retaining grids.
7. Reduce pressure drop across the bed.

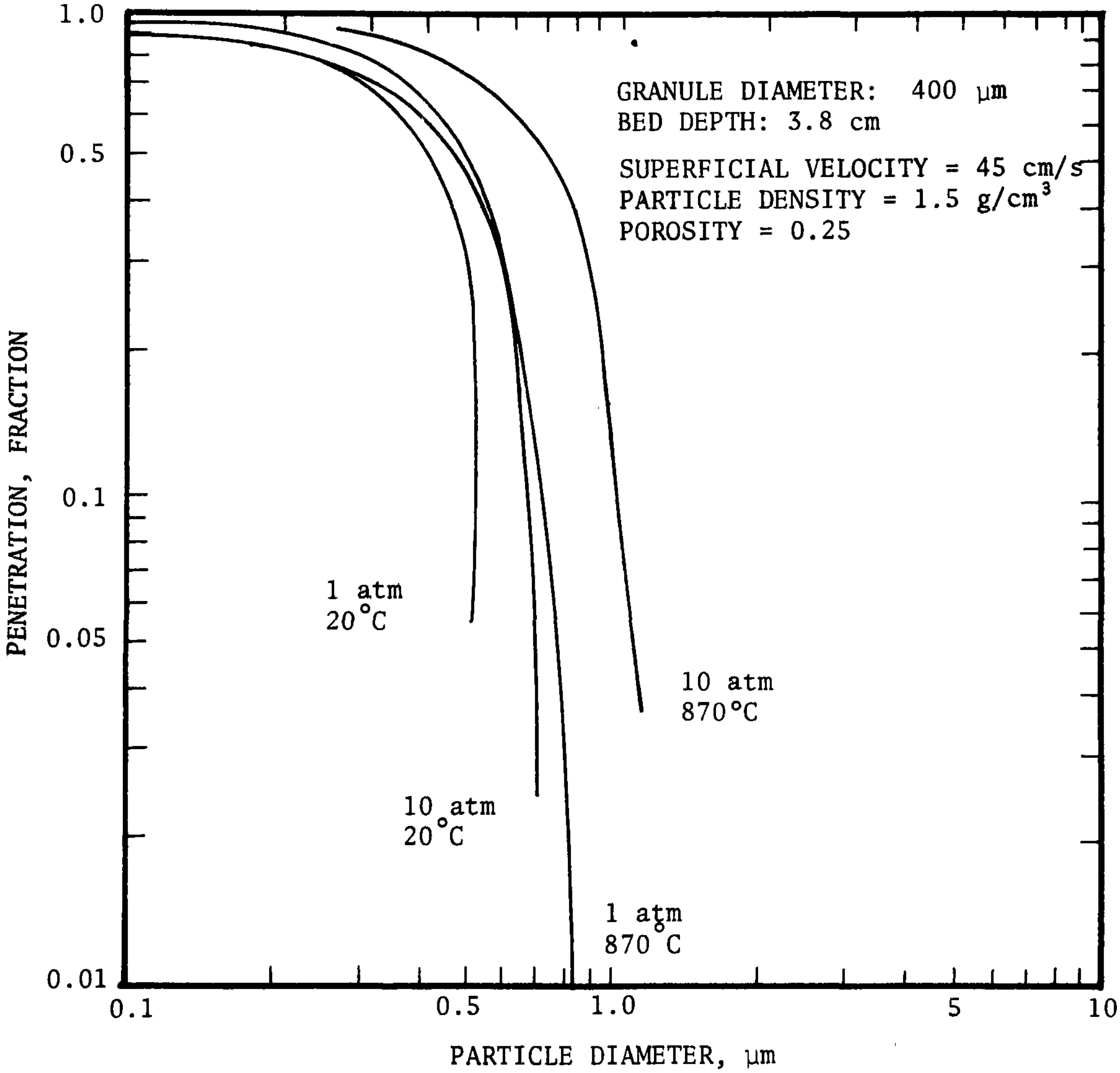


Figure 22. Predicted GBF performance.

Resolving these problems may provide a solution to the HTP particle collection problem, and will improve granular bed filter technology for many other applications, especially where hot, corrosive gases are encountered.

Scrubbers

Wet scrubbers are not generally suitable for high temperature and pressure gas cleaning because they necessarily cool down the gas. It is possible to cool the gas in a regenerative heat exchanger and then use a wet scrubber to clean the gas at high pressure before the gas is reheated. Wet scrubbers also are used for tar removal, H_2S removal, and particulate removal in many coal gasification process designs.

Dry scrubbers and molten glass or metal salt scrubbers are being developed for hot gas cleanup applications. These systems are described and available data are reported below.

A.P.T. Dry Scrubber

A.P.T., Inc. is developing a dry scrubber system, called the PxP (particle collection by particles) system which can be used for high temperature and pressure gas cleaning. This system has been reported by Calvert et al.(1977) and Patterson, et al.(1978).

The PxP system is somewhat similar to a venturi scrubber system in that it uses relatively large particles as collection centers for the fine particles in the gas stream. The principal advantage with this system is that it maximizes the collection efficiency of individual collector particles and thereby reduces the number of collectors that need to be cleaned and recycled.

The collector particles introduced to the gas stream collect fine particles by mechanisms such as diffusion, inertial impaction, interception and electrophoresis. The larger size of the collector particles allows easy separation from the gas stream by methods such as cyclones and gravitational settling.

Figure 23 is a functional diagram of the process steps for a representative PxP system. The functions represented on this diagram could occur concurrently or separately in several

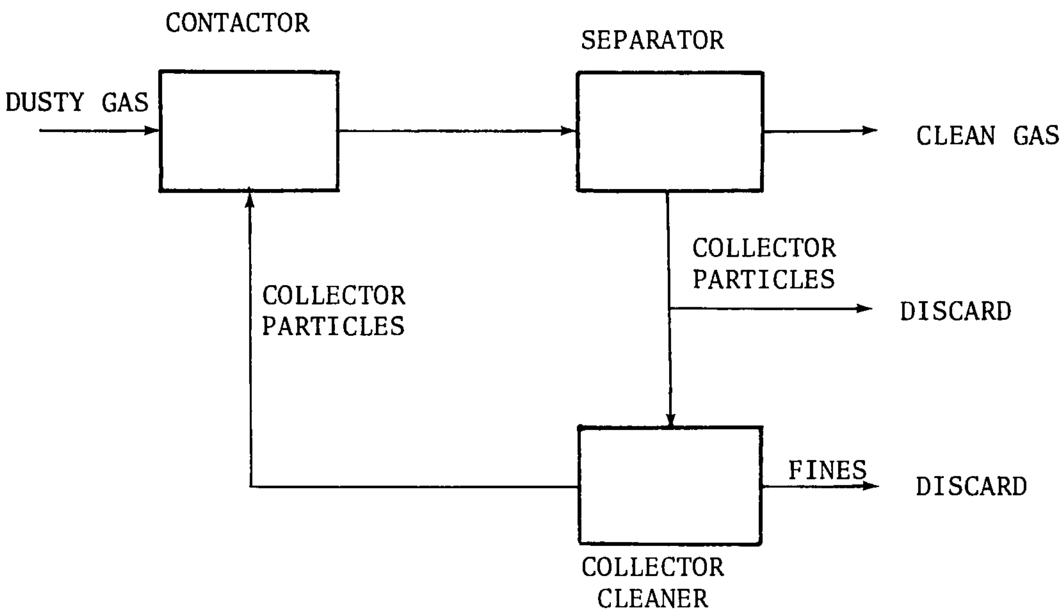


Figure 23. Schematic diagram of A.P.T. dry scrubber system.

types of equipment.

The first step involves introducing the collectors to the gas stream. This process can involve pneumatic or mechanical injection. The second stage involves contacting the collectors with the gas in such a way as to encourage the movement of the fine particles towards the collectors. A venturi device can be used for the contactor in which case the system would be analogous to a venturi scrubber with solid collectors used instead of liquid drops.

The next process step is to remove the collector particles after they have captured the fine particles initially present in the gas. This is accomplished by using the large size and mass of the collector particles to separate them from the gas. A cyclone separator, gravity settler, or virtual impactor could be used for this step. Two streams are shown leaving the separator: the cleaned gas leaves the process at this point and the second stream represents the flow of collector particles to the next step. The final process involves either discarding the collector particles or cleaning them for recycle and disposing of the particulate matter collected from the gas stream.

The particle collection efficiency and pressure drop for an A.P.T. dry scrubber with cocurrent flow can be predicted with the same relationships that define cocurrent wet scrubber performance. The theoretical performance of the PxP scrubber has been determined based on the venturi scrubber performance model of Yung, et al. (1977). Figure 24 shows the predicted efficiency at 20°C and 820°C. Efficiencies will be somewhat lower at high pressure for the same pressure drop.

Experimental work has been done by A.P.T. to determine fine particle collection efficiency in a PxP scrubber in order to confirm the predictions obtained from available mathematical models. A dibutylphthalate (DBP) aerosol was used in collection efficiency experiments with 100 μm mean diameter sand as collector particles. The DBP aerosol had a mass median aerodynamic diameter of 1.3 μmA and a geometric standard deviation of 2.0.

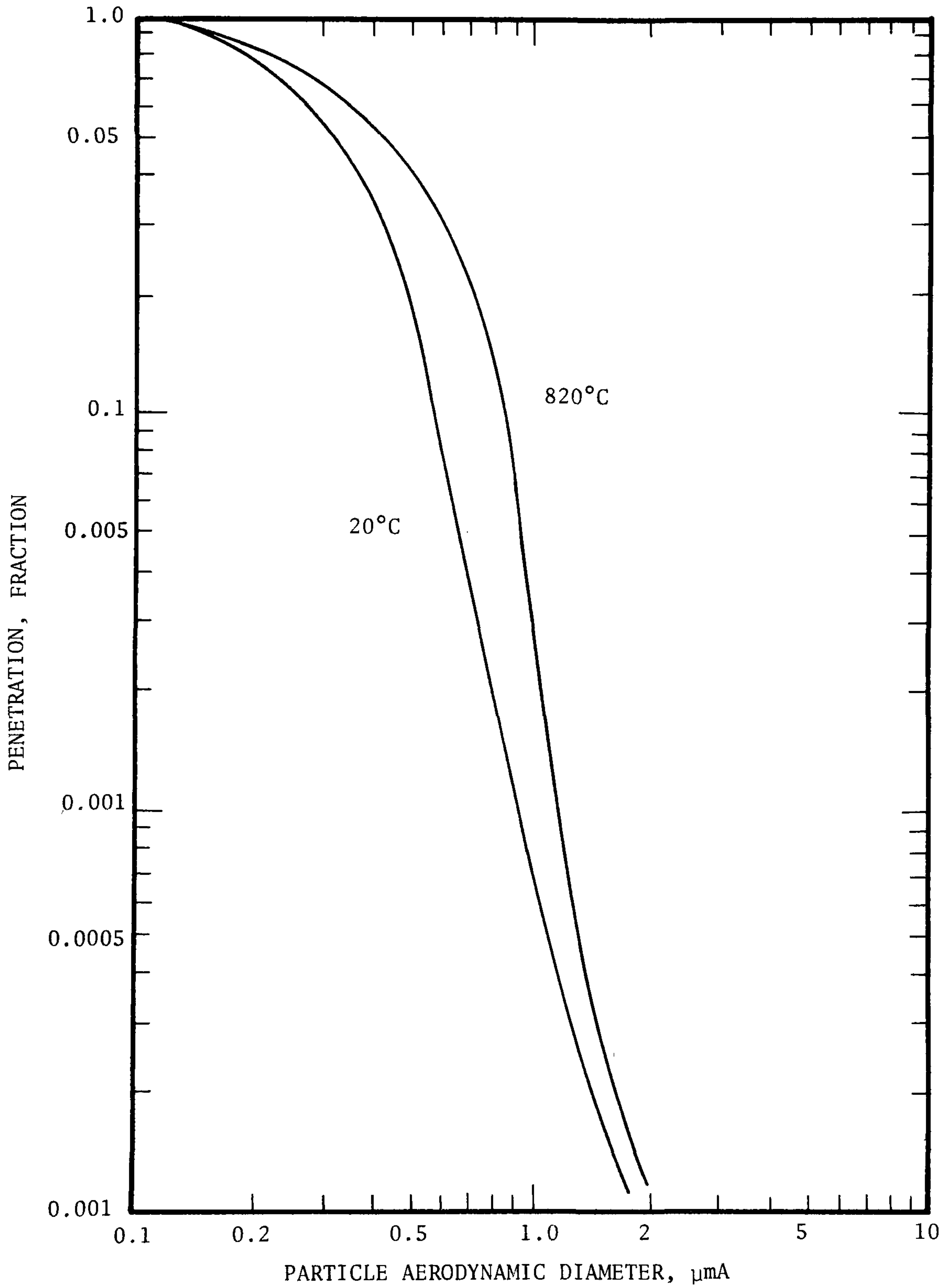


Figure 24. Predicted performance for A.P.T. dry scrubber.

The resulting penetration data are shown in Figure 25. The prediction is also shown in Figure 25 and compares well with the experimental curve. Higher collection efficiencies can be achieved using denser collector particles. For this reason experiments were also conducted with 125 μm nickel beads.

Particle penetration data for all runs with nickel and sand collectors are represented in Figure 26 in terms of the 50% cut diameter as a function of gas pressure drop. The line represents the best available relationship for industrial scale wet venturi scrubbers. Therefore the A.P.T. dry scrubber follows the same primary collection efficiency/power relationship as venturi-type wet scrubbers.

The overall efficiency of the PxP system will depend on the reentrainment characteristics of the specific system configuration in addition to the primary collection efficiency. Particle and collector properties, system geometry, flow rates, and other parameters will influence reentrainment.

A.P.T. has built an atmospheric fluidized bed coal combustor which will be used for testing a pilot plant PxP system at high temperature. Electrostatic augmentation is also being investigated as a means of increasing the collection efficiency independently of pressure drop, and possibly improving the adhesion of fine particles to collector particles. The economics of the PxP system for high temperature and pressure particulate control will be analyzed in connection with the pilot plant test program.

Molten Salt Scrubber

Battelle-Northwest has constructed a process demonstration unit for the molten salt scrubber. The scrubber is designed to remove H_2S as well as particulates from the high temperature and pressure gases produced in low-BTU coal gasification processes. Minor impurities such as halogens, volatile metals and non-metals, and ammonia also potentially could be removed from the gas with this system.

Details of the system design and pilot plant data were presented by Moore, et al. (1977). The system consists of a

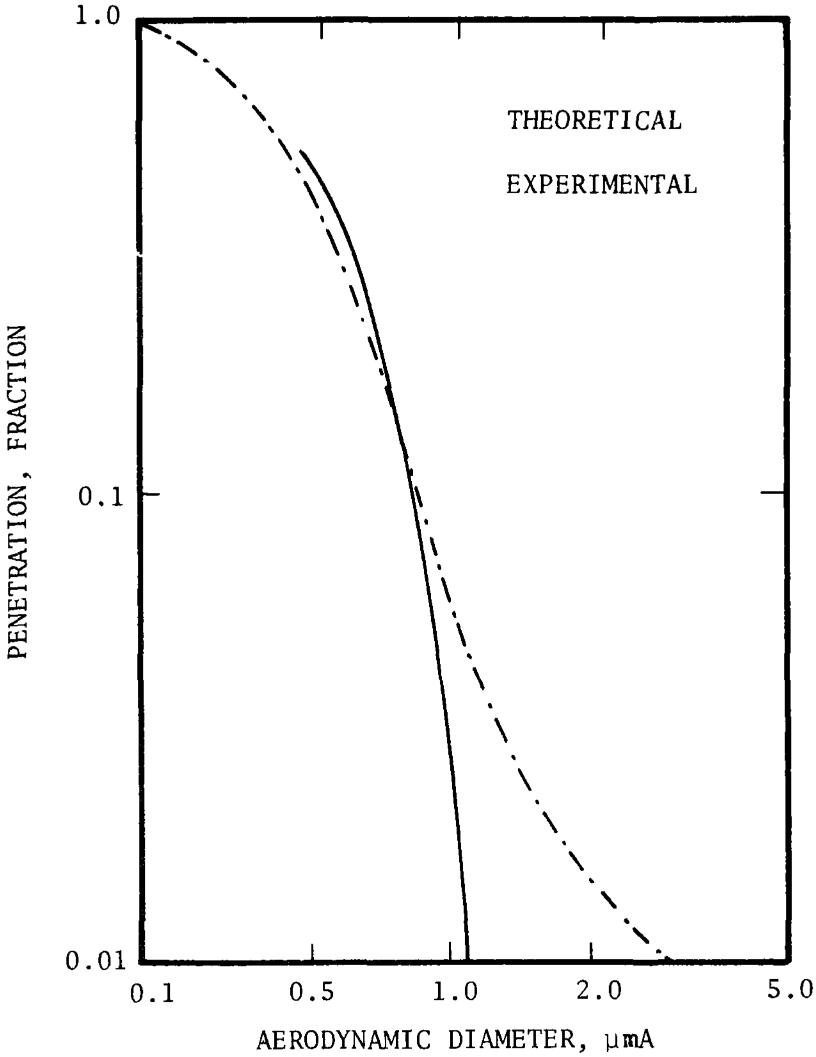


Figure 25. Comparison of experimental with theoretical particle collection characteritics of the A.P.T dry scrubber.

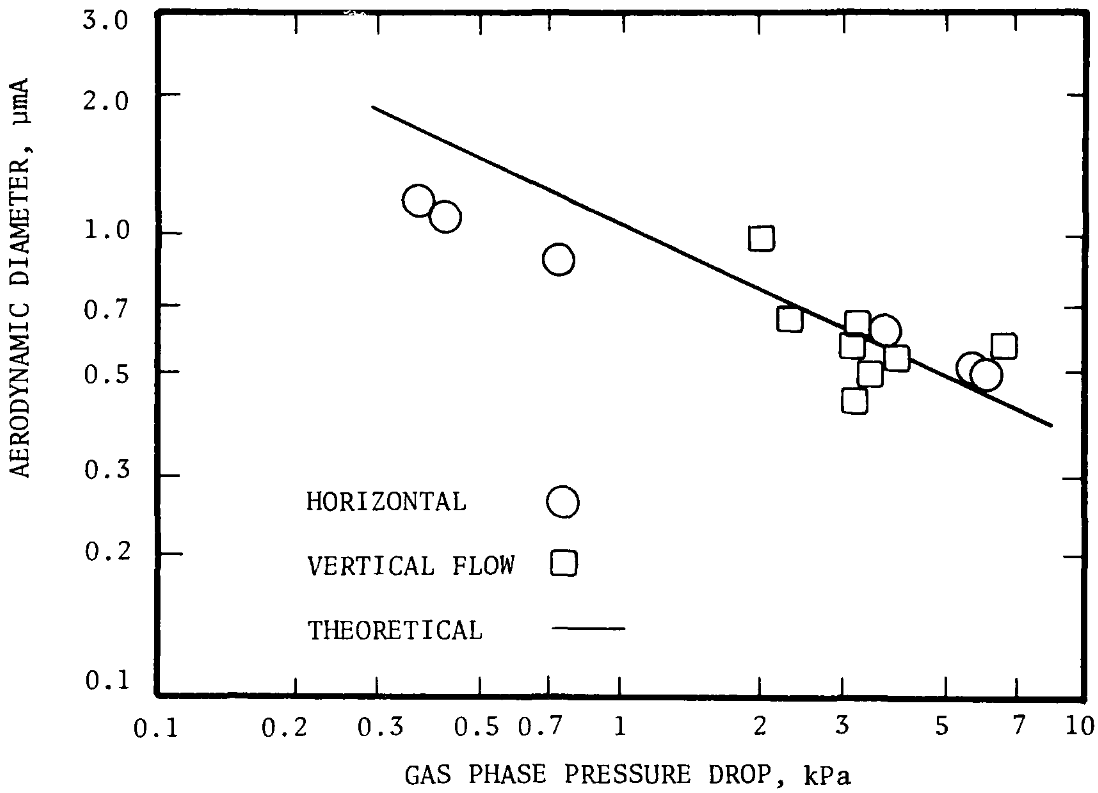


Figure 26. Comparison of particle characteristics of the A.P.T. dry scrubber with the A.P.T. cut/power relationship.

venturi scrubber followed by a packed tower entrainment separator. The venturi is operated vertically to avoid the need for a mechanical pump to feed the molten salt.

The salt composition used is shown in Table 11. The particulate removal efficiency was measured using an Andersen impactor. The particle size distribution and mass loadings leaving the scrubber are shown in Tables 12 and 13.

Poe, et al. (1977) evaluated the molten scrubber process for particulate control. They pointed out numerous potential problems including material corrosion, alkali metal vapor emissions, line clogging due to precipitation of metal oxides, particulate buildup in the molten salt and particulate solubility in the molten salt.

Their analysis indicated that, from an economic standpoint, molten scrubbing appears to be a promising approach for high temperature fine particle collection. They did not consider the effect of gas density on the scrubber performance at high pressure. Theoretical considerations based on the venturi scrubber model of Yung, et al. (1977) indicate that high temperature and high pressure operation may be less favorable in terms of the pressure drop required to achieve a desired efficiency.

Hot Gas Cleanup by Molten Glass

The General Electric Company is investigating the use of coal slag based glasses for hot gas cleanup. Preliminary work has been presented by McCreight, et al. (1977) and Fedarko, et al. (1978).

Figure 27 shows viscosity curves for typical coal slags as a function of temperature. Particulate collection studies are being carried out by inertial impingement onto plates coated with glycerine. In the temperature range -20 to 30°C glycerine has a similar viscosity to that of coal slag in the range 1,200 to 1,600°C.

The work is in a very early stage and there are no data available to indicate the potential particle collection efficiencies and operational problems that can be expected for large scale molten glass scrubbing equipment.

TABLE 11. SALT COMPOSITION USED IN PDU DEMONSTRATION RUNS (FROM MOORE, ET AL., 1977)

Component	Mole %	Weight %
Li_2CO_3	18.0	13.0
Na_2CO_3	37.3	36.0
K_2CO_3	29.6	37.3
$CaCO_3$	15.1	13.8

TABLE 12. PARTICLE SIZE DATA; MOLTEN SALT PILOT PLANT RUN NUMBER 3 (FROM MOORE, ET AL., 1977)

Inlet Gas; Total Particle Burden = 0.109 gr/SCF, % H_2O = 9.1

Outlet Gas; Total Particle Burden = 0.077 gr/SCF, % H_2O = 4.5

Anderson Head Particle Size Distribution

Plate No.	Wt. Gain g	Calculated Effective Cut-off Dia, μm	%	Concentration in Gas gr/SCF	g/Nm^3
1	0.0048	17. 6	1.5	0.00114	0.0026
2	0.0042	11.2	1.3	0.00099	0.0023
3	0.0327	7.5	10.1	0.00774	0.0176
4	0.0498	5.3	15.3	0.0118	0.0270
5	0.0405	3.5	12.5	0.0096	0.0220
6	0.0381	1.7	11.7	0.0091	0.0208
7	0.0289	1.0	8.9	0.0069	0.0158
8	0.0314	0.7	9.7	0.0075	0.0172
Filter	0.0948	--	29.2	0.0224	0.0513
Total	0.3253				

TABLE 13. PARTICLE SIZE DATA; MOLTEN SALE PILOT PLANT RUN NUMBER 6 (FROM MOORE, ET AL., 1977)

Inlet Gas; Total Particle Burden = 0.074 gr/SCF, % H_2O = 11.2

Outlet Gas; Total Particle Burden = 0.024 gr/SCF, % H_2O = 3.3

Anderson Head Particle Size Distribution

Plate No.	Wt. Gain g	Calculated Effective Cut-off Dia, μm	%	Concentration in Gas gr/SCF	g/Nm^3
1	0.0015	20.1	5.0	0.0012	0.0027
2	0.0013	10.5	4.3	0.0011	0.0025
3	0.0016	7.0	5.3	0.0013	0.0030
4	0.0019	5.0	6.3	0.0015	0.0034
5	0.0026	3.1	8.6	0.0021	0.0048
6	0.0029	1.6	9.6	0.0021	0.0048
7	0.0030	1.0	10.0	0.0024	0.0055
8	0.0047	0.6	15.6	0.0038	0.0087
Filter	0.0106	--	35.2	0.0086	0.0197
Total	0.0301				

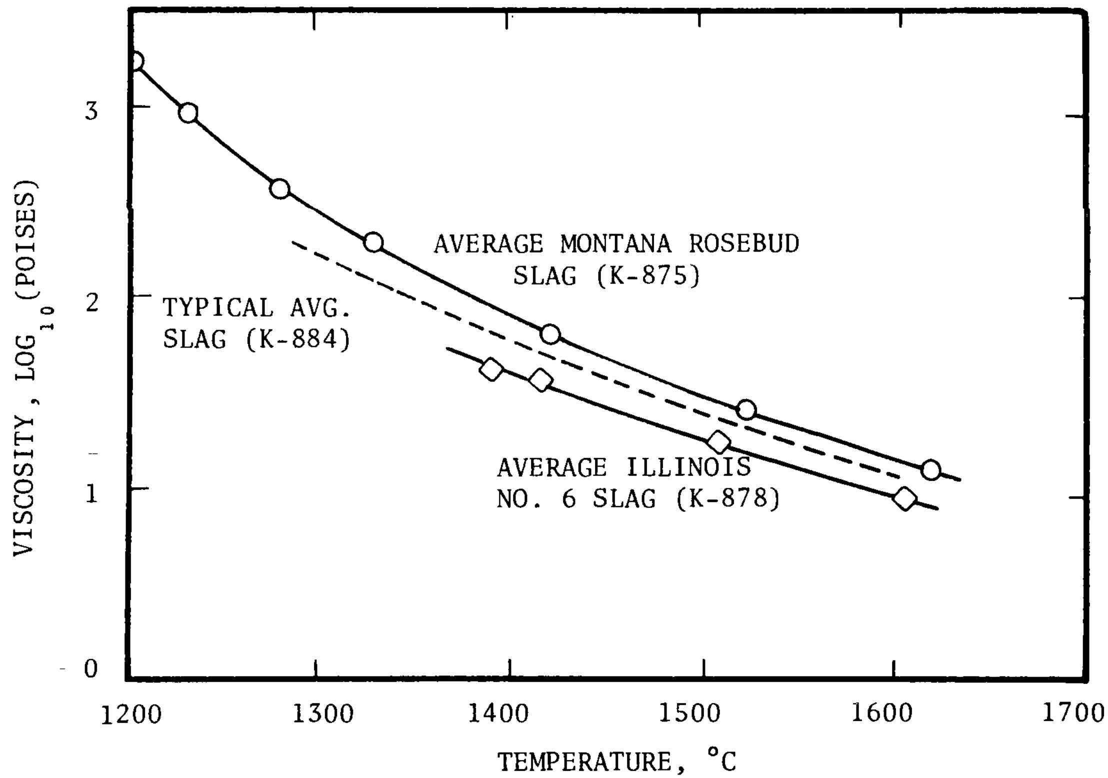


Figure 27. Viscosity/temperature relationship determined by NBS on synthetic slags formulated to represent the average compositions of fly ash from Montana Rosebud and Illinois No. 6 coal types.

Electrostatic Precipitation

The normal operating temperature range for industrial electrostatic precipitators is 20 to 300°C. In a few special applications they are used at temperatures up to about 550°C. The application of electrostatic precipitation at higher temperatures and pressures has been considered in many studies over the past 30 years.

Koller and Fremont (1950) studied the corona characteristics of precipitators at temperatures to 500°C and pressures to 5 atm. Thomas and Wong (1958) conducted a similar study to 800°C and 8 atm. Both studies showed that the current-voltage characteristics were predominantly a function of gas density rather than temperature and pressure independently. Thomas and Wong experienced regions of instability at temperatures above approximately 800°C at atmospheric pressure. At 815°C and pressures above 4.6 atm (relative density $\geq$ 1.25) adequate electric field can be maintained for effective electrostatic precipitation.

Shale and Fasching (1969) reported on the operation of a high temperature (800°C) and pressure (6.4 atm) electrostatic precipitator. Dust removal efficiency ranged from 91 to 96% for negative corona with a voltage of 36.5 kV and power input averaging 6.4 kW. For positive corona the efficiency was only 75 to 77% even though a higher operating voltage was possible (54 kV) at a lower power input (2.0 kW). The particulate matter had a mass median diameter of approximately 30 to 40 μm. There was no significant mass below 5 μm.

The input power-removal efficiency relationships at high temperature (800°C) compared favorably with those found in conventional industrial precipitation. No apparent insurmountable electronic problems were encountered, however, thermal misalignment of the tube and mechanical difficulties with the tube rapper presented problems.

Brown and Walker (1971) operated an electrostatic precipitator at about 900°C and 4.4 atm. Particle removal efficiencies ranged from 25% for positive polarity to 87% for negative polarity. Test data are summarized in Table 14.

TABLE 14. TEST DATA SUMMARY FOR ESP AT 900°C, 4.4 ATM (FROM BROWN & WALKER, 1971)

Run No.	Polarity	Applied Voltage, kV	Current, mA	Field Strength, kV/cm	Power, W	Efficiency, %	Effective Migration Velocity, cm/s
1	Negative	29	1.9	2.9	55	37.7	1.8
2	Positive	47.5	4.6	4.6	230	25.0	0.9
3	Negative	34	3.7	3.3	126	59.5	3.4
4	Positive	25.5	2.4	2.5	61	16.0	0.6
5	Negative	42	3.5	4.1	147	73.5	5.2
6	Negative	44.5	11.0	4.4	490	78.1	5.8

The effective migration velocity for negative polarity averaged about 4.0 cm/s. This is about half that expected for a conventional precipitator operating at a similar field strength and low temperature. The lower migration velocity can be accounted for adequately by considering the effect of high temperature on the gas viscosity.

More recent work on high temperature and pressure electrostatic precipitation has been reported by Feldman, et al. (1977, 1978) and by Robinson (1978). They reported work conducted at Research-Cottrell which demonstrated that stable operating conditions can be maintained at temperatures and pressures up to 1,100°C and 35 atm.

Their major conclusions are summarized below:

1. There are no temperature or pressure limitations to electrostatic precipitation over the range studied. Practical high temperature precipitation may be limited by thermal ionization at temperatures exceeding 1,100 to 1,300°C.

2. High temperature and pressure enables operation at higher voltages than is possible at standard conditions. This is in part due to the supression of back-corona by operation at high pressure. The higher operating voltage should more than compensate for the adverse effect of high temperature gas viscosity on the migration velocity and collection efficiency.

3. The critical pressure (above which sparkover results) increases with temperature. Negative polarity gives higher critical pressure than positive polarity.

4. In most cases negative currents are larger than positive currents.

They prepared a preliminary design for a high temperature and pressure electrostatic precipitator to be used in a pressurized fluidized bed combustion unit. The operating temperature and pressure are 815°C, 10 atm. Their recommended design parameters are presented in Table 15.

TABLE 15. RECOMMENDED DESIGN PARAMETERS FOR HTP ESP (FROM FELDMAN ET AL., 1977)

Number of Precipitators per Boiler Module	1
Pipes per Precipitator	320
Pipe Size	0.229 x 3.05 m
Vessel Diameter	7.0 m
Vessel Height	10.7 m
Steel Thickness	0.038 m
Vessel Weight	52.8×10^3 kg
Capacity	19.82 m^3/s
	42,000 ACFM
	106,000 SCFM
MW of Plant capacity	75 MW
Collecting Surface Area	700.5 m^2
Discharge Electrode Length	975.4 m
Specific Collection Area	35.3 $m^2/m^3/s$
	180 $ft^2/10^3$ ACFM
Expected Efficiency	98-99%
Power Supply	
Voltage	150 kV
Current	3,000 mA
Discharge Electrode	3.08 mA/m

TABLE 15. Continued

Current Density/Collecting Surface	4.31 mA/m^2
Specific Power	1.462 x $10^4 W/m^3/s$
	6.9 W/ACFM

<u>Capital Costs</u>

Per Precipitator - Less Engineering	
Stainless steel internals	$1,945,000
Inconel internals	$2,185,000
Per 300 MW Plant - Including Engineering	
Stainless steel internals	$7,980,000
Inconel internals	$8,940,000
Per kW of Plant Capacity	
Stainless steel internals	$26.60/kW
Inconel internals	$29.80/kW

The recent Research-Cottrell work did not include the effects of dust particles on the electrical performance. In general, the presence of dust particles suppresses current flow and creates a space charge between the electrodes. This enables higher operating voltages than are possible in a clean gas. However, as dust accumulates on the collection surface the sparkover voltage decreases and may to some extent nullify the effect of space charge.

Many practical problems are likely to be encountered in the further development and demonstration of HTP electrostatic precipitation. The very low electrical resistivity of ash particles at temperatures above 400-500°C may result in excessive reentrainment during electrode rapping operations. Also mechanical problems such as electrode alignment and strength after many rapping cycles will need to be resolved.

Also it will probably be necessary to follow the precipitator with a barrier collection device such as a granular bed filter because even brief outages of the precipitator can cause catastrophic damage to the gas turbine.

Plans are being considered for testing the Research-Cottrell high temperature and pressure electrostatic precipitator on a slip stream from the Exxon PFBC miniplant. It would operate at 870°C 9 atm, and would handle 0.85 m^3/min (30 ACFM) of gas containing 2.3 g/Nm^3 (1.0 gr/SCF) of fly ash particles with a mass median diameter of about 4 μm and a geometric standard deviation of approximately 3.

Fiber Filtration

Conventional fabric filters are limited to operating temperature below 250°C. The maximum temperature varies with the specific fabric and is determined as the temperature at which accelerated fabric deterioration or abrasion occurs.

Glass fiber bags are the most common type used for higher temperature applications and are limited to about 300°C. The glass fibers are coated with a silicone, silicone-graphite, or equivalent finish in order to provide lubrication between the fibers. Unfinished glass fibers experience extreme abrasion and unsatisfactory bag life. The temperature limit of glass fiber fabrics is directly related to the temperature limit of the finish.

Lundgren and Gunderson (1976) reviewed the filtration characteristics of glass fiber filters at elevated temperatures (to approximately 500°C). Their review indicated that in practice the effect of temperature and pressure on filtration mechanisms was not a determining factor in the application of high efficiency filters. The main problems are the physical and chemical effects of a high temperature environment on the filter materials. These effects may appear as reduced mechanical strength and resilience or loss of adhesion, leading to mechanical leakage, decrease in efficiency and eventually mechanical failure.

High Temperature Filtration Studies

Filtration media for extreme temperatures and pressures has been investigated by many authors. Silverman and Davidson (1956) suggested the use of ceramic fibers sandwiched between layers of woven metallic or ceramic fabrics for filtration at temperatures to 1,100°C and higher. Billings, et al. (1955) and Silverman (1962) discussed the use of metallic fiber "slag/wool" filters for high temperature filtration of open-hearth furnace fume. They tested the slag-wool filter at temperatures from 300 to 650°C and dust loadings from 0.1 to 1.1 g/Nm^3 (0.1 to 0.5 gr/SCF). Efficiencies ranged from 75 to 98%. A continuous slag-wood filter was designed and tested at 300-400°C. The efficiency ranged from 10 to 80% for Fe_2O_3 particles with a mass median diameter of 0.65 μm.

First, et al. (1956) and Kane, et al. (1960) reported on the use of ceramic fiber filters capable of withstanding temperatures up to 1,100°C. First, et al. (1955) measured collection efficiencies at 21°C and 760°C. The mass median particle diameter was 8.5 μm with a particle density of 6.4 g/cm^3. The effect of temperature on efficiency for individual fiber diameters is shown in Table 16.

TABLE 16. EFFECT OF TEMPERATURE ON FILTRATION EFFICIENCY (FROM FIRST, ET AL. 1955)

Filter Diameter, µm	Filter Depth, cm	Superficial Velocity	Efficiency, Wt. %	
		cm/s	21°C	760°C
20	10.16	203.2	85	82
8	3.81	203.2	99	94
4	2.54	203.2	98	91

TABLE 17. FRACTIONAL EFFICIENCY FOR COMPOSITE FILTER TESTS (FROM FIRST, ET AL., 1955)

Particle Diameter Range	Collection Efficiency
0-1 µm	28.4%
1-2 µm	95.4%
2-5 µm	99.4%
>5 µm	99.4%

A composite filter comprised of fibers from 4 μm to 20 μm in diameter gave over 99% collection for all temperatures. The fractional efficiency for the composite tests is shown in Table 17.

Theoretical Predictions

Filtration theory has been reviewed by many authors including Davies (1973) and Pich (1966). We have used the theory presented by Davies to predict the collection efficiency of a clean fiber filter at high temperature and high pressure. The following parameters were assumed:

Filter weight	= 0.026 g/cm^2
Fiber density	= 2.53 g/cm^3
Fiber diameter	= 5.0 μm
Superficial velocity	= 12 cm/s
Particle density	= 2.5 g/cm^3
Air properties at:	
Temperature	= 20°C and 1,100°C
Pressure	= 1 atm and 15 atm

These parameters simulate a typical aluminum-silicate ceramic paper. The results are presented in Figure 28.

At high temperature and low pressure the Brownian diffusion regime becomes very significant and the collection efficiency of particles smaller than approximately 0.5 μm increases dramatically. At high temperature and high pressure this effect is less apparent.

In the inertial impaction regime, high temperature and high pressure reduce the collection efficiency from that obtained at standard conditions. Even at high temperature and pressure, however, the predicted collection efficiency is effectively 100% for particles larger than 2 μm. This is consistent with the data reported earlier from the work by First, et al. (1955).

Current Development Work

Recent development work on high temperature and pressure ceramic fiber filters is being carried out by Acurex Corporation

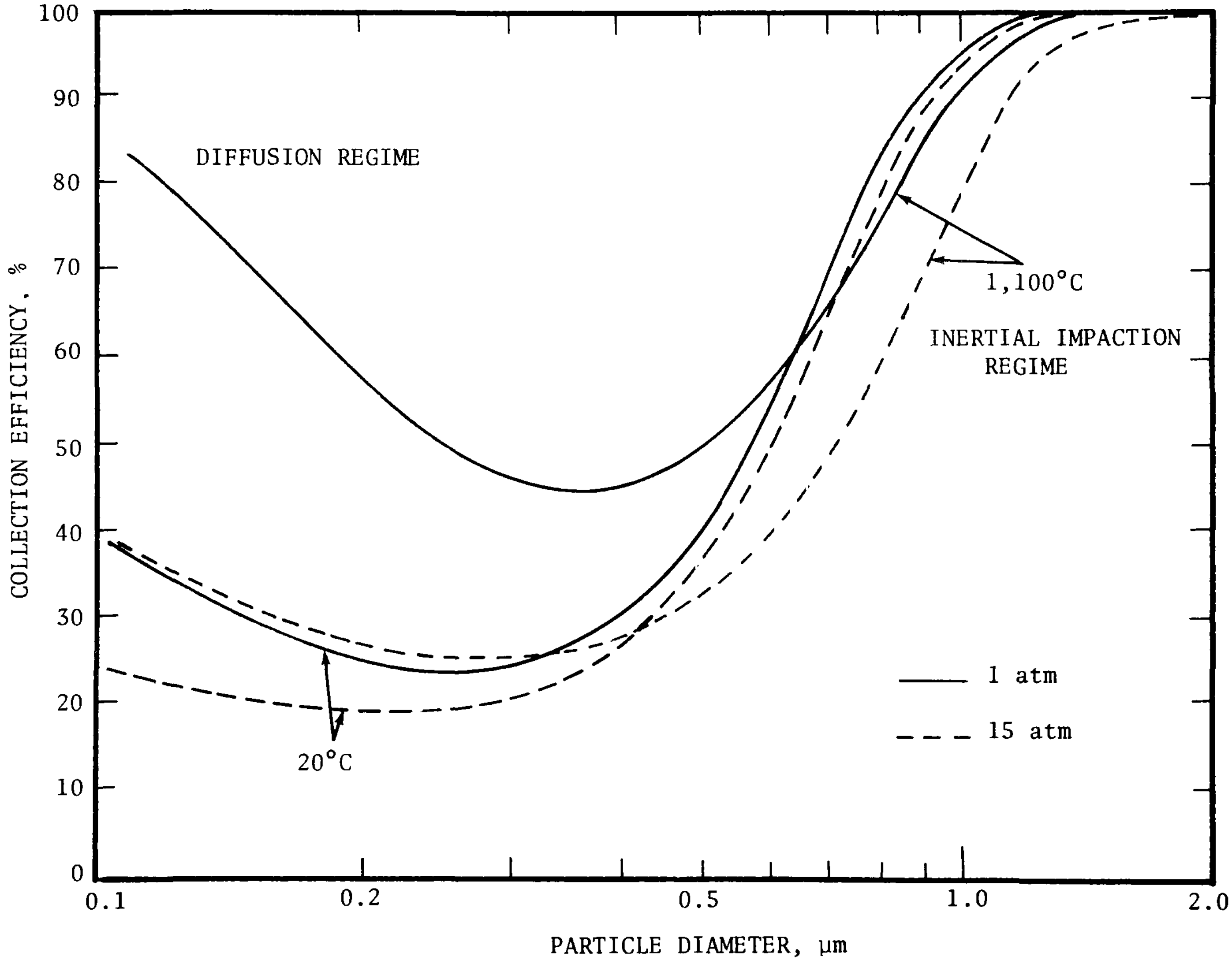


Figure 28. Predicted performance for ceramic fiber filter.

and has been reported by Shackelton (1977, 1978).

They have conducted a detailed survey and evaluation of ceramic fiber media with potential for high temperature filtration. Available ceramic fiber configurations can be classified into the following three groups of materials:

1. Woven structures - Cloth woven from long-filament yarns of ceramic fibers.
2. Papers - Ceramic structures produced from short lengths of fibers, generally held together with binders.
3. Felts - Structures produced to form mats of relatively long fibers. These materials are known as blankets in the insulation industry. They tend to be less tightly packed than conventional felt materials.

A summary of room temperature data is presented in Table 18. The last three materials are conventional fabric filter media which are only included for purposes of comparison. A number of the media show high collection efficiencies for 0.3 μm diameter DOP aerosol particles. It should be noted that this is the efficiency of a clean filter media and higher efficiencies can be anticipated for a dirty filter operating with some residual dust deposited between the fibers.

Permeability is measured as the flow per unit area at a constant pressure drop. Thus, a material with low permeability offers a high restriction to gas flow and one with high permeability allows more gas to penetrate for a given pressure drop. Table 18 shows that some ceramic materials are available which have low permeability, while others have high permeability. Most of the paper and felt materials have permeability similar to that of commonly used filter materials.

Ceramic fiber filters have two major drawbacks regarding application at high temperature and pressure. First of all they must be very durable. Conventional filter bags are expected to last at least one year (see Billings and Wilder, 1970). Bag life at the Nucla Power Plant was estimated to be 5$\pm$ 1.3 years

TABLE 18. CERAMIC FIBER TEST DATA (FROM SHACKLETON AND DREHMEL, 1978)

(W) Woven (P) Paper (F) Felt	Basis Weight g/m^2	Permeability $cm^3/s/cm^2$ 1.27 cm H_2O	$ft^3/min/ft^2$ at 0.5 in. W.C.	Percent Efficiency on 0.3 μm DOP at cm/s 2.68	5.35	14.22
1. Carborundum Fiberfrax cloth (W) with nichrome wire insert	1366	8.7	17.1	45	47	50
2. Zircar Zirconia felt ZFY-100 (F)	615	10.9	21.4	75	78	72
3. ICI Saffil alumina paper (P) with binder	165	9.3	18.3	82	65	62
4. ICI Saffil mat (F)	355	12.4	24.4	79	80	73
5. Babcock & Wilcox Kaowoll (F)	746	8.1	15.9	96.5	93.5	86
6. Carborundum Fiberfrax (F) durablanket	1363	5.6	11.0	97.1	94.6	90.5
7. John-Mansville Fiberchrome (F)	1297	11.9	23.4	78	73	74
8. Stevens Astroquartz (W) style 581	283	37.2	73.3	0	9	12
9. Hitco Refrasil C-100-96 (W) heat cleaned	1284	1.2	2.4	0	19	34
10. Hitco Refrasil C-100-48 (W) not heat cleaned	667	3.1	6.1	0	11	10
11. Stevens Astroquartz cloth (W) style 570	667	22.8	44.8	0	13	32

continued

TABLE 18. Continued

(W) Woven (P) Paper (F) Felt	Basis Weight g/m^2	Permeability $cm^3/s/cm^2$ 1.27 cm H_2O	Permeability $ft^3/min/ft^2$ at 0.5 in. W.C.	Percent Efficiency on 0.3 µm DOP at cm/s 2.68	5.35	14.22
12. 3M AB-312 basket weave (W) cloth	311	13.6	26.7	0	5	8
13. 3M AB-312 twill weave (W) cloth	231	28.4	56.0	0	3	2
14. HITCO Refrasil cloth (W) UC-100-48	643	8.7	17.1	0	4	3
15. Zircar Zironia cloth (W) ZFY-30A	608	5.8	11.4	29	37	34
16. FMI-Stevens Astroquartz (W) cloth crowfoot satin	352	16.6	32.6	0	5	6
17. 3M AB-312 twill weave (W) cloth coated with 3M coating	227	65.2	128.3	0	3	10
18. 3M AB-312 basket weave (W) cloth coated with 3M coating	281	47.6	93.7	0	7	0
19. 3M AB-312 twill weave (W) cloth Menarde coating	254	51.2	100.8	0	6	10
20. HITCO Refrasil cloth (W) UC-100-96 not heat cleaned	1249	3.4	6.7	0	11	16
21. Carborundum Fiberfrax (W) no insert wire L-126TT	1544	7.4	14.7	55	55	57
22. HITCO Refrasil batt B100-1 (F)	807	8.9	17.5	84	79	72

TABLE 18. Continued

(W) Woven (P) Paper (F) Felt	Basis Weight g/m	Permeability $cm^3/s/cm^2$ 1.27 cm H_2O	Permeability $ft^3/min/ft^2$ at 0.5 in. H.C.	Percent Efficiency on 0.3 μm DOP at cm/s 2.68	5.35	14.22
23. HITCO Refrasil standard (W) not heat cleaned very thin UC-100-28	335	11.9	23.4	0	1	0
24. HITCO Irish Refrasil (W) chromized C-1554-48	683	5.2	10.1	2	8	10
25. Carborundum Fiberfrax (P) paper (with binder) 970J	604	26.9	53.0	99.5	99.0	97.6
26. ICI Saffil Zirconia paper (P) (with binder)	212	8.8	17.1	83	78	74
27. Carborundum Fiberfrax (P) paper (no binder) 970-AH	152	12.4	24.4	88	--	73
28. 3M AB-312 double thick (W) plain weave	1035	84.8	167.0	0	10	41
29. FMI crowfoot satin cloth (W) astroquartz	905	62.1	122.2	0	10	32
30. 3M AB-312 12 harness satin (W) weave	675	75.5	148.7	0	8	24
31. 630 Tuflex fiberglass* (W)	564	16.0	31.6	10	9	19
32. 15-011-020 woven filment* (W) polyester	175	6.8	13.4	6	0	4
33. 25-200-070 polyester felt* (F)	524	11.9	23.4	34	24	29

*These materials are conventional (not ceramic) media.

(Ensor, et al. 1976). For typical cleaning pulse frequencies, a bag may have to withstand a few million pulses in its lifetime. For this reason, blanket or felted ceramic fiber materials are expected to be the most promising. They combine good filtration properties with relatively high strength.

The second drawback is the size of typical fabric filter installations. Most conventional fabric filters operate at superficial velocities in the range of 1 to 3 cm/s. Somewhat higher velocities up to 10 or 20 cm/s are possible with some felted fabrics although bag life will be shortened.

In comparison, granular bed filters operate at superficial velocities from 40 to 80 cm/s. For a given gas flow rate, fabric filters will require from 4 to 20 times the surface area required by granular bed filters. This is especially important at high pressure where the cost of the pressure vessel can be a significant fraction of the capital cost. Both baghouses and GBFs will have to be designed so as to maximize the surface to volume ratio.

These problems are being considered in the EPA-sponsored development program. Preliminary experience at high temperature and pressure indicate that at least three configurations show promise, having survived 50,000 cleaning pulses at 815°C and 9 atm. Test conditions were as follows:

Temperature - 815°C
Pressure - 930 kPa (9 atm)
Air-to-cloth-ratio - 5 to 1 (2.54 cm/s)
Cleaning pulse pressure - 1,100 kPa
Cleaning pulse interval - 10 s
Cleaning pulse duration - 100 m/s
Dust - redispersed fly ash

The three filter media configurations tested were:

1. Saffil alumina mat contained between an inside and an outside layer of 304 stainless steel knit wire screen.
2. Woven Fiberfrax cloth with nichrome wire scrim insert.
3. Fiberfrax blanket contained between an inside and an

outside cylinder of 304 SS square mesh screen similar to common window screen. The ceramic fiber blanket was held in position between the screens with 302 SS wire sewn between the screens.

Pressure drop during the tests was controlled by rapid cleaning pulses and in general remained less than about 5 kPa (20 in.W.C.). Formation and removal of the filter cake for these configurations and test conditions presented no problems.

The average outlet loading during the Fiberfrax blanket test was 0.0055 g/Nm³ (0.0024 gr/SCF). The fly ash dust dispersion apparatus used was suitable for filter loading tests but may not be representative of the dust characteristics and size distribution to be encountered in a real application.

In order to obtain test data in a real PFBC application, the Acurex ceramic baghouse is to be tested on a slipstream at the Exxon miniplant. Installation has begun and the test program is scheduled to start in late November, 1978.

Membrane Filtration

Several available ceramic materials in many configurations have been evaluated as possible high-temperature filters by Ciliberti (1977) and Poe, et al. (1977). One of the most promising materials tested was a ceramic cross flow monolith produced by 3M Company under the trade name of Thermacomb. This material is composed of alternate layers of corrugations separated by thin filtering barriers. This type of configuration affords a large amount of filter surface in a very small volume. Figure 29 shows a piece of this material and indicates the cross flow configuration. The material has an average pore size of 10 μm with a range as shown in Figure 30.

The Thermacomb cross flow structure is made up of several layers in the following pattern: a thin (0.25 - 1.5 mm) porous cordierite sheet, a layer of cordierite corrugations similar in

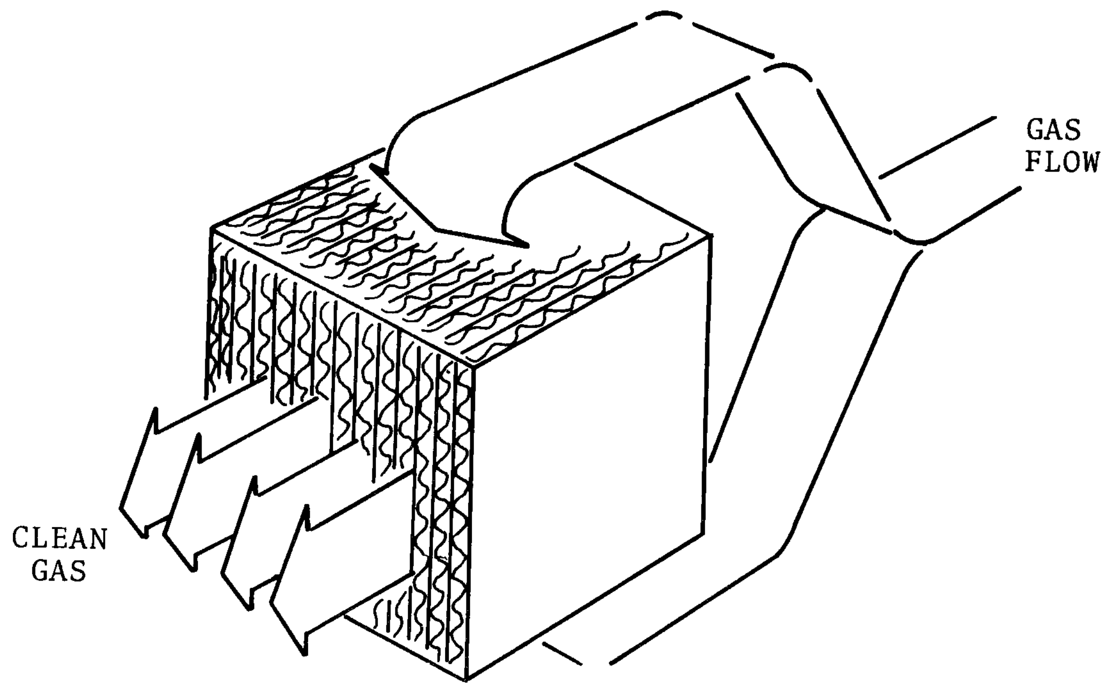


Figure 29. 3M crossflow ceramic monolith.

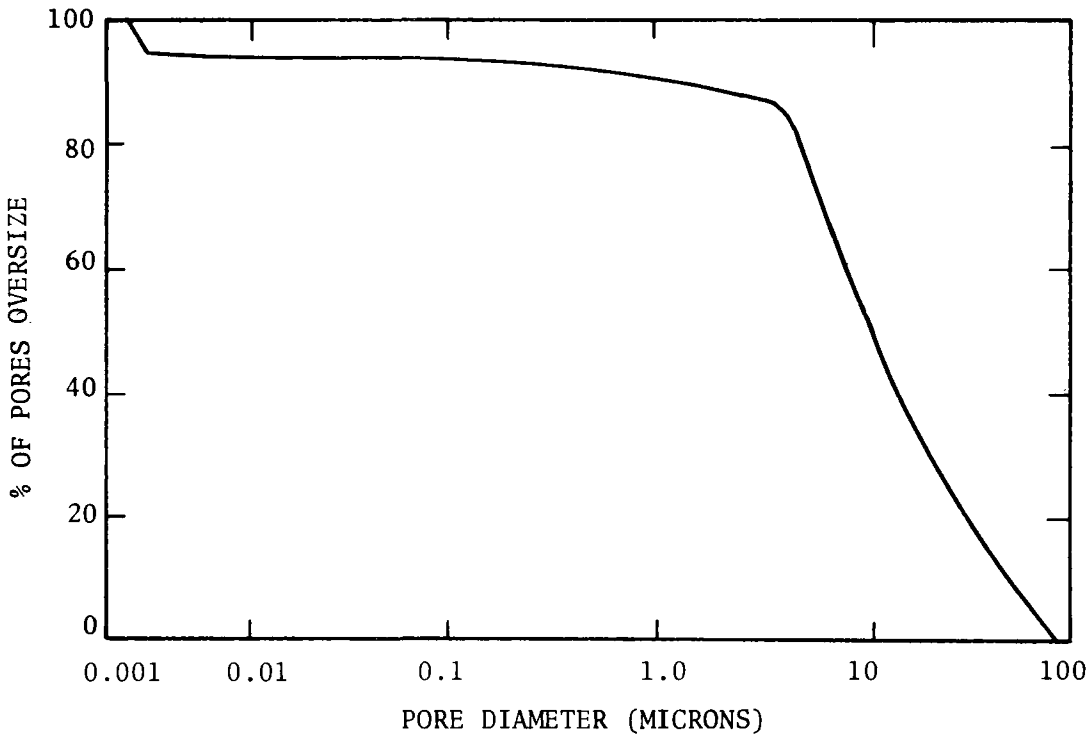


Figure 30. Pore size distribution for Thermacomb ceramic fiber material (from Poe, et al., 1977).

appearance to those used in cardboard, another flat sheet of cordierite followed by another layer of corrugations oriented 90° from the corrugations below. The presently available forms of the material have 1.97, 3.15 or 4.72 corrugations per cm. A similar material is manufactured by W.R. Grace & Company. This material has perpendicular dividers which given rectangular holes rather than the triangular holes seen in the Thermacomb. The Grace material tested had approximately 8.5 holes per cm and an equal number of layers per cm.

These materials have many properties that make them attractive as filters. Among these are (1) working temperature to 1,200°C, (2) very good mechanical strength despite thin separators, (3) excellent resistance to thermal shock, (4) excellent resistance to corrosive atmospheres and, (5) very high surface area to volume ratios. Ciliberti (1977) estimated that the Thermacomb material tested had 3.27 cm^2 filter area per cm^3 of element while the W.R. Grace & Company material had approximately 6.52 cm^2 of usable area per cm^3 of element.

Cascade impactors were used to measure the size of the limestone test dust. The mass median diameter was typically 1.4 μm and the geometric standard deviation was 3.0.

Results of the high temperature Thermacomb tests are presented in Table 19. The overall collection efficiency averaged 96.4% with some tests showing 100% collection. No problems were encountered in cleaning the filter media by reverse pulses of compressed air. It was possible to clean the filter and return to a stable pressure drop even the relatively heavy dust loadings.

Similar results were obtained in a limited number of tests on the W.R. Grace material.

Although ceramic honeycomb filters operated successfully on limestone particulate in bench scale tests, there are a number of uncertainties regarding their application as tertiary cleanup devices. Further development work is needed to resolve the following major questions.

TABLE 19. SUMMARY OF HOT TESTS WITH 3M THERMACOMB (FROM CILIBERTI, 1977)

Temperature, °C	Superficial Velocity cm/s	Inlet Concentration g/m^3	Overall Efficiency, %
815	11.6	1.2-2.2	95.5
750	7.3	1.8-2.1	85.0
720	7.0	8.4-12.0	95.0
360	4.5	3.6	100.0
520	5.7	5.2	100.0
710	7.3	4.5	99.6
700	6.9	2.7-7.9	99.9
680	6.8	2.6	99.6
690	6.8	3.8	100.0
680	6.8	3.2	100.0
695	6.9	5.4	100.0
680	2.9	0.05	100.0
660	2.8	0.11	100.0
650	2.7	0.11	93.0
700	2.2	1.1	99.0
630	1.6	0.06	88.0
620	1.5	0.12	92.0
615	1.4	0.08	81.0

1. Are ceramic honeycombs susceptible to clogging with actual process particulate matter?
2. Can these filter media be redesigned or optimized with regard to particle collection, pressure drop, permeability?
3. What are the temperature and pressure losses associated with alternative cleaning methods?
4. How durable are these media over a prolonged high temperature and pressure run, and how serious are the problems of erosion and degradation of the media ?

HOT VERSUS COLD GAS CLEANUP

INTRODUCTION

Because of the technical and economic uncertainties associated with high temperature and pressure particulate control, there is a possibility that the only practical approach to particulate removal which will allow for reasonable turbine life is low temperature, high pressure cleanup.

In most cases, low temperature-high pressure gas cleaning equipment can be based on conventional technology. However, the specific design configurations for high pressure applications will generally be different than for low pressure applications. For example, tubular electrostatic precipitators are more suitable than parallel plate designs for operation at high pressure. This is essentially a matter of packaging the precipitator in a pressure vessel. However, increased pressure increases precipitation efficiency by reducing ion mobility and thereby enabling operation at higher electrical potential. Therefore particle collection should not present problems.

Fabric filtration baghouses should operate adequately at high pressure. However the expense of high pressure housings may require special design to minimize the baghouse volume and maximize the superficial velocity (air-to-cloth ratio).

Wet scrubbers can also be designed to work well at high pressure. However, large gas densities may require higher liquid-to-gas ratios, and in some configurations high pressure frictional losses may become more significant than in conventional applications.

In general, low temperature-high pressure particulate control technology is feasible and to some extent commercially available. This is the major advantage to cold gas cleanup as compared to hot gas cleanup. On the other hand, hot gas cleanup can achieve higher overall thermal efficiencies and therefore more efficient fuel usage.

The relative process efficiencies for hot and cold gas cleanup depend on the specific process configuration. Hot versus cold gas cleanup for pressurized fluidized bed combustion and low-BTU coal gasification processes are reviewed in this section.

PRESSURIZED FLUIDIZED BED COAL COMBUSTION

Klett, et al. (1977) carried out an analytical study to determine the performance penalties which accompany cold gas cleanup for representative pressurized fluidized bed combustion combined-cycle systems. They considered a cold gas cleanup cycle consisting of a recuperator followed by a baghouse or electrostatic precipitator. The PFBC boiler, air-cooled combustor, and adiabatic combustor designs were considered. The system parameters are listed in Table 20.

PFB Boiler Process

The G.E. 1,000 MW commercial scale combined-cycle design was used as a basis for the water cooled PFBC process. The system is illustrated in Figure 31. Water and steam pass through tubes in the bed to control bed temperature. Combustion is carried out with approximately 20% excess air and the combustion gas is cleaned prior to entering the gas turbine.

The proposed G.E. system cleans the combustion gas at high temperature (955°C) using two stages of cyclone separation and a final gas cleanup stage. Klett, et al. (1977) also considered cold gas cleanup with heat recovery. For all cases, the temperatures out of the bed were held constant at 955°C which are consistent with those chosen by G.E. for their preliminary base case.

The tertiary cleanup device was a moving granular bed filter (GBF). A pressure drop of 0.34 atm and a temperature drop of 14°C across the bed were assumed. A 1% mass flow loss due to medium recirculation and leakage was also assumed for the moving bed filter.

TABLE 20. SYSTEM PARAMETERS FOR PFBC ANALYSIS
(FROM KLETT, ET AL., 1977)

	Adiabatic Combustor (CPC-400 System)		Air Cooled Combustor (Curtiss-Wright System)		Water Cooled Combustor (GE CFCC System)	
	Hot Gas Cleanup	Cold Gas Cleanup	Hot Gas Cleanup	Cold Gas Cleanup	Hot Gas Cleanup	Cold Gas Cleanup
PFBC Temperature (°C)	983	983	899	899	955	955
PFBC Pressure (atm)	6.3	6.3	6.9	6.9	10	10
Excess Air for Combustion (%)	300	300	33	33	20	20
Gas Cleanup Temperature (°C)	969	316	899	316	955	316
RHX Effectiveness	N/A	0.80	N/A	0.80	N/A	0.80
Gas Turbine Inlet Temperature (°C)	933	802	916	864	926	814
Steam Turbine Pressure/ Temperature (atm/°C)	31.6/426-7.14/204	31.6/426-7.14/204	54.4/440	54.4/440	238/538/538	238/538/538
Steam Turbine Pressure/ Temperature (psia/°F)	465/800-105/400	465/800-105/450	800/825	800/825	3500/1000/1000	3500/1000/1000
Stack Temperature (°C)	163	133	149	149	149	149
Gas Turbine Electrical Output (MW)	12.5	9.7	304	280	222	174
Steam Turbine Electrical Output (MW)	7.4	7.8	190	194	731	768

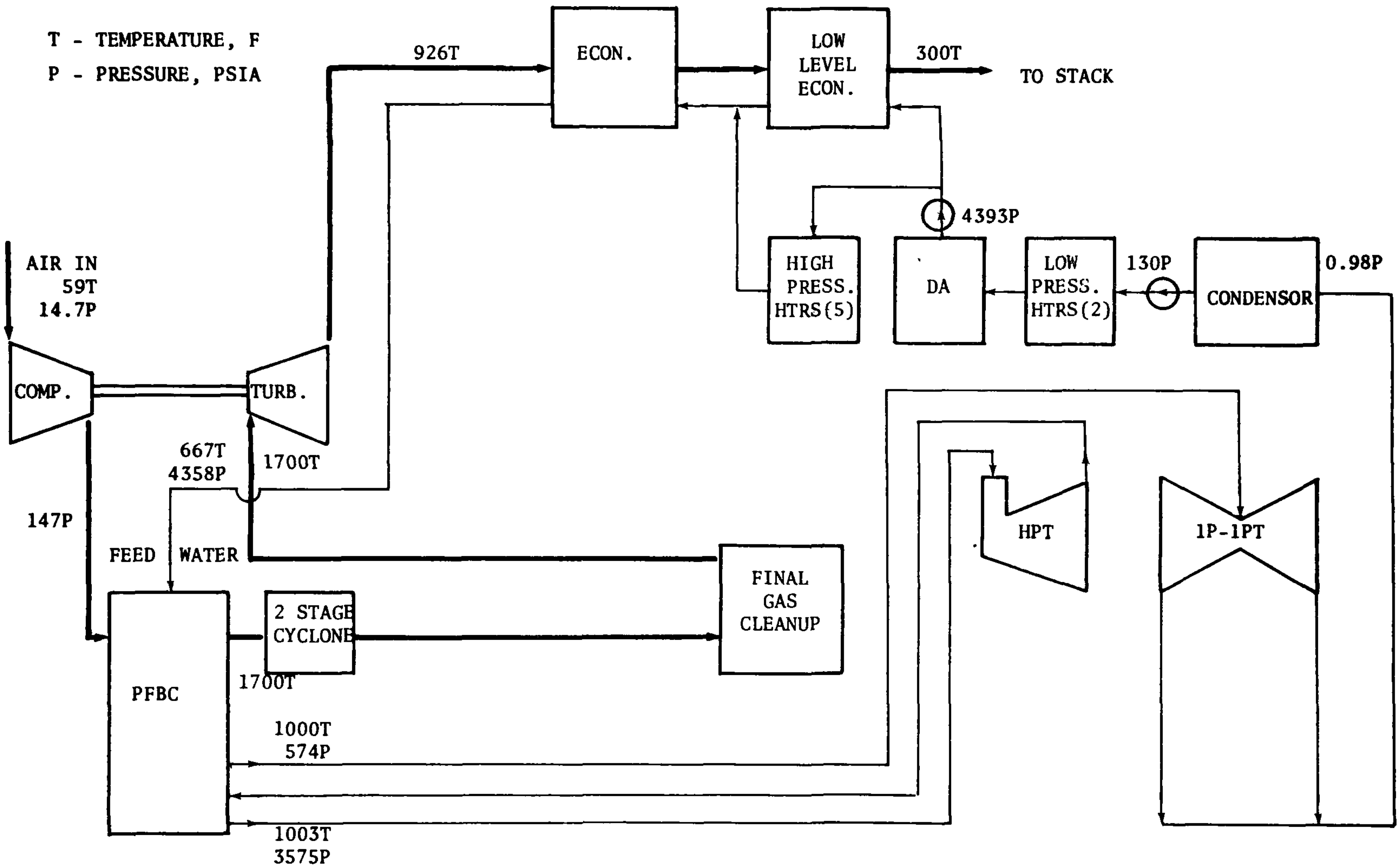


Figure 31a. Pressurized fluidized bed/combined cycle system, water cooled combustor with hot gas cleanup.

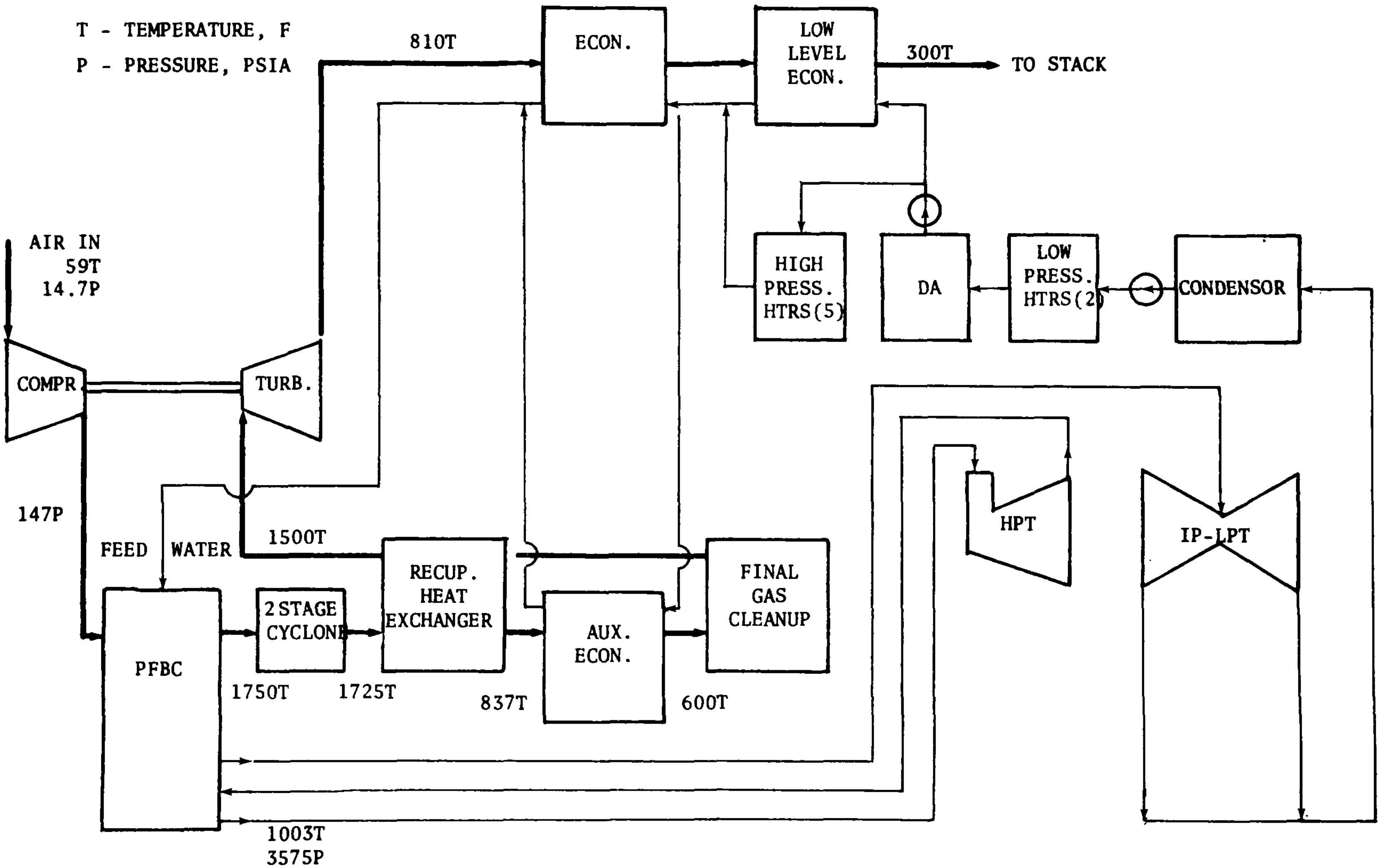


Figure 31b. Pressurized fluidized bed/combined cycle steam, water cooled combustor with cold gas cleanup.

The cold gas cleanup system used a pressurized baghouse, in conjunction with a gas/gas recuperative heat exchanger. An effectiveness of 80% and a pressure drop of 76 cm W.C. per side were assumed for the heat exchanger. These values are consistent with those found on gas/air heat exchangers used on regenerative gas turbines in electric power generation service. Effectiveness ranges for various commerically available recuperative heat exchanger designs are given in Table 21.

The heat removed from the cleanup stream prior to reentering the recuperator was recovered in a bottoming cycle auxiliary economizer. The baghouse filter inlet temperature was set at 316°C based on design limitations for available material.

The results are presented in Table 22.

Air-Cooled PFBC Process

The air-cooled PFBC analysis was based on the Curtiss-Wright 500 MW combined cycle system. This system is illustrated in Figure 32. Approximately two-thirds of the total gas flow is passed as cooling air through tubes in the combustor bed to control the bed temperature. Combustion is carried out with approximately 33% excess air. The combustion gas is cleaned and mixed with the heated air prior to entering the combustion turbine.

The proposed Curtiss-Wright system cleans the combustion gas at high temperature (899°C) using two stages of Aerodyne rotary flow cyclones. Klett, et al. considered alternative hot gas cleanup systems as well as cold gas cleanup with heat recovery. For all cases, the temperature out of the bypass air heat exchanger was held constant at 856°C.

The alternative hot gas cleanup method studied was a gravel bed filter (GBF). Two types of GBF were considered: fixed bed and moving bed. For both filters, a pressure drop of 34.5 kPa (5 psi) and a temperature drop of 14°C across the bed were assumed. A 1% flow loss due to media recirculation and leakage was assumed for the moving bed filter. A 0.25% flow leakage was assumed for the fixed bed filter.

TABLE 21. EFFECTIVENESS RANGES FOR RECUPERATIVE HEAT EXCHANGERS

Heat Exchanger Type	Effectiveness*
Shell & Tube Single Pass	48-57.5%
Shell & Tube Double Pass	60-73%
Shell & Tube Three Pass	81-83%
Rotary (Heat Wheel) (3 or 4 units)	75-80%

*Effectiveness is the percentage of available temperature differential recovered.

TABLE 22. PERFORMANCE OF PFBC PROCESSES WITH HOT AND COLD GAS CLEANUP (FROM KLETT, ET AL., 1977)

Process Configuration	Gas Turbine Inlet Temp. °C	Thermodynamic Efficiency, %	Heat Rate, BTU/kW-hr	Net Power MW
I. PFB Boiler				
A. Hot Gas Cleaning				
1. Moving GBF	926	40.6	8,399	953
B. Cold Gas Cleanup				
1. Pressurized baghouse	814	39.6	8,624	942
II. Air-Cooled PFBC				
A. Hot Gas Cleanup				
1. Two stages Aerodyne cyclones	871	38.8	8,805	458.1
2. Moving GBF	866	37.1	9,200	435.4
3. Fixed GBF	867	37.3	9,154	440.7
B. Cold Gas Cleanup				
1. Baghouse/low pressure heat	828	35.5	9,621	419.3
2. Baghouse/high pressure heat recovery	828	36.0	9,476	425.7
III. Adiabatic PFBC				
A. Hot Gas Cleanup				
1. Moving GBF	932	37.1	9,203	19.9
B. Cold Gas Cleanup				
1. Baghouse high pressure steam with heat recovery	802	32.6	10,450	17.5

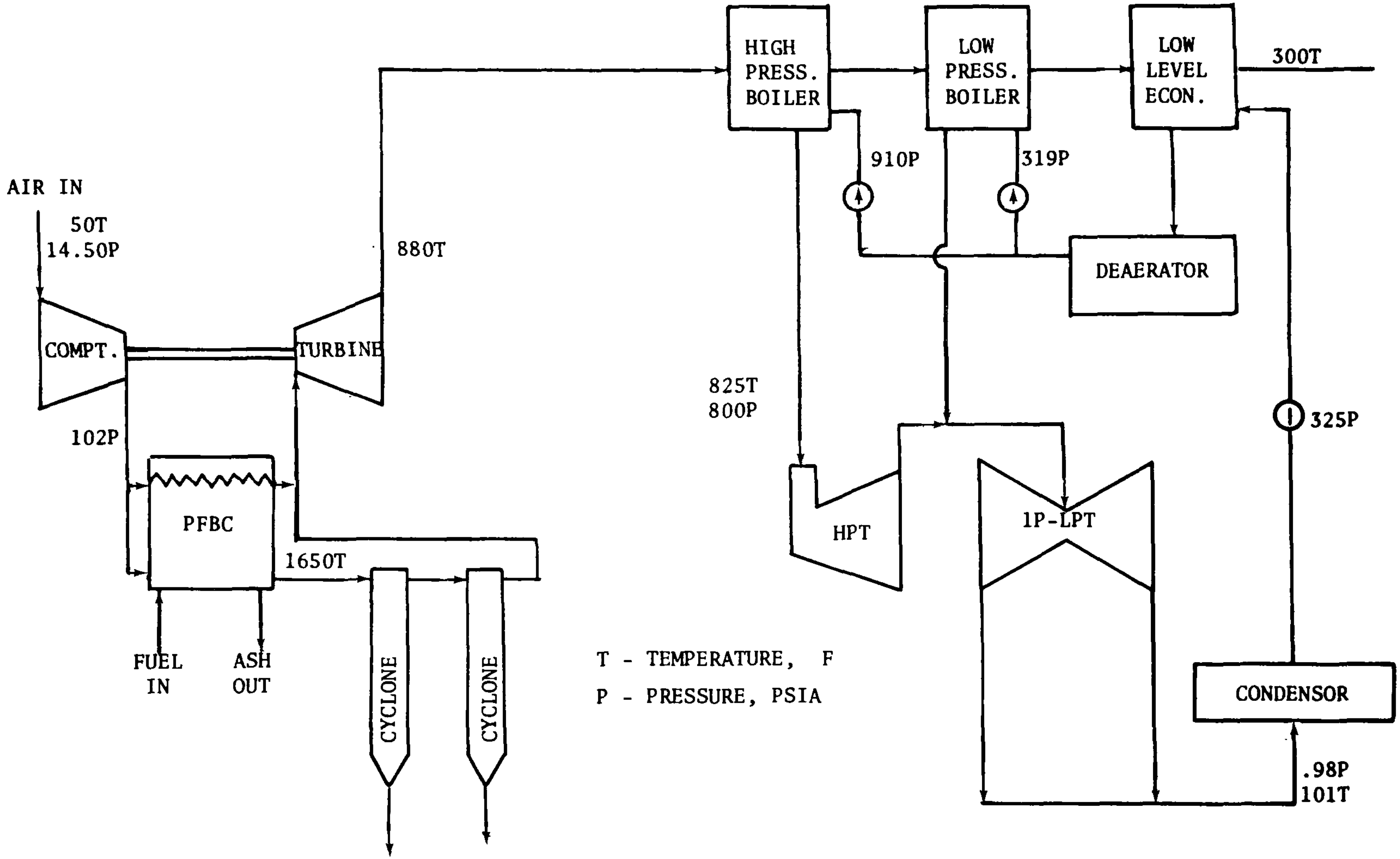


Figure 32a. Curtiss-Wright pressurized fluidized bed/combined cycle system, hot gas cleanup with aerodyne cyclones.

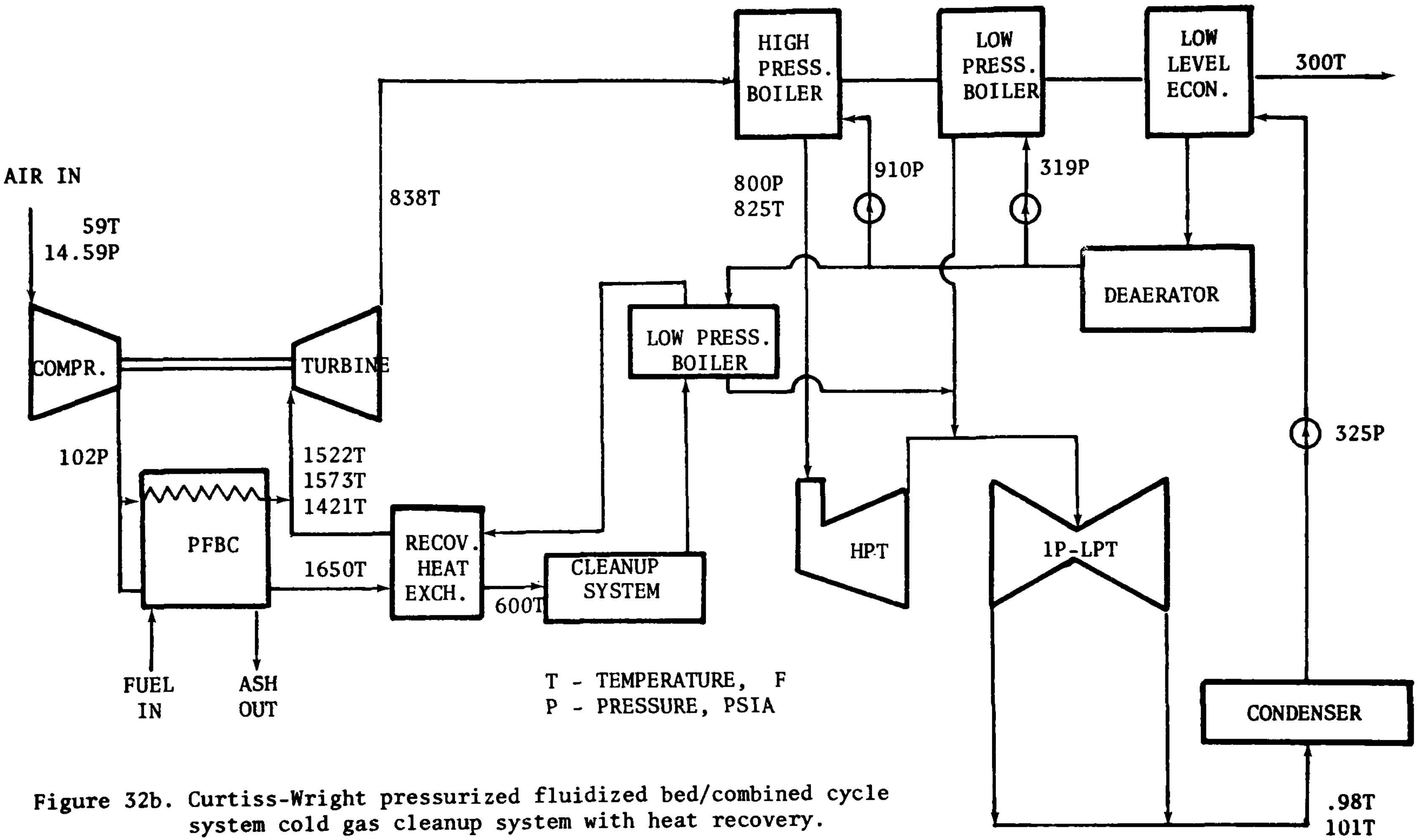


Figure 32b. Curtiss-Wright pressurized fluidized bed/combined cycle system cold gas cleanup system with heat recovery.

A baghouse, in conjunction with a gas/gas recuperative heat exchanger, was considered for cold gas cleanup. As with the preceding study, an effectiveness of 80% and pressure drops of 76 cm W.C. per side were assumed for the heat exchanger. The heat removed from the cleanup stream prior to reentering the recuperator was used to generate additional steam. In one system, a second low pressure evaporator was added to recover the heat. In a second system, the heat was recovered by adding a high pressure economizer.

The results are presented in Table 22.

Adiabatic PFBC Process

The Combustion Power Company's adiabatic PFBC system was used as the basis for the adiabatic process. The system incorporates a moving bed granular bed filter (GBF) for high temperature cleanup of the combustion gas prior to entering the gas turbine. The system is illustrated in Figure 33.

The cold gas cleanup method was a baghouse with fiberglass filters. A pressure drop of 13 cm W.C. through the baghouse was assumed. The maximum operating temperature of the baghouse is about 315°C (600°F). The combustion gas was cooled by means of a gas/gas heat exchanger which was added to the system ahead of the baghouse. The heat exchanger effectiveness and pressure drop per side were assumed to be 80% and 76 cm W.C. The results are presented in Table 22.

The efficiency loss between hot and cold gas cleanup is greatest for the adiabatic combustor configuration, since all the working fluid passes through the bed and therefore must be cooled and cleaned. Future equipment, capable of handling higher product gas temperature, could reduce the performance penalties associated with cold gas cleanup and probably justify the additional hardware complexity.

The systems using air and water cooled combustors appear to be capable of using current cold gas cleanup techniques with fairly small system performance penalties (1 to 2%). The Phase II ECAS studies (Lewis Research Center, 1977 and General Electric

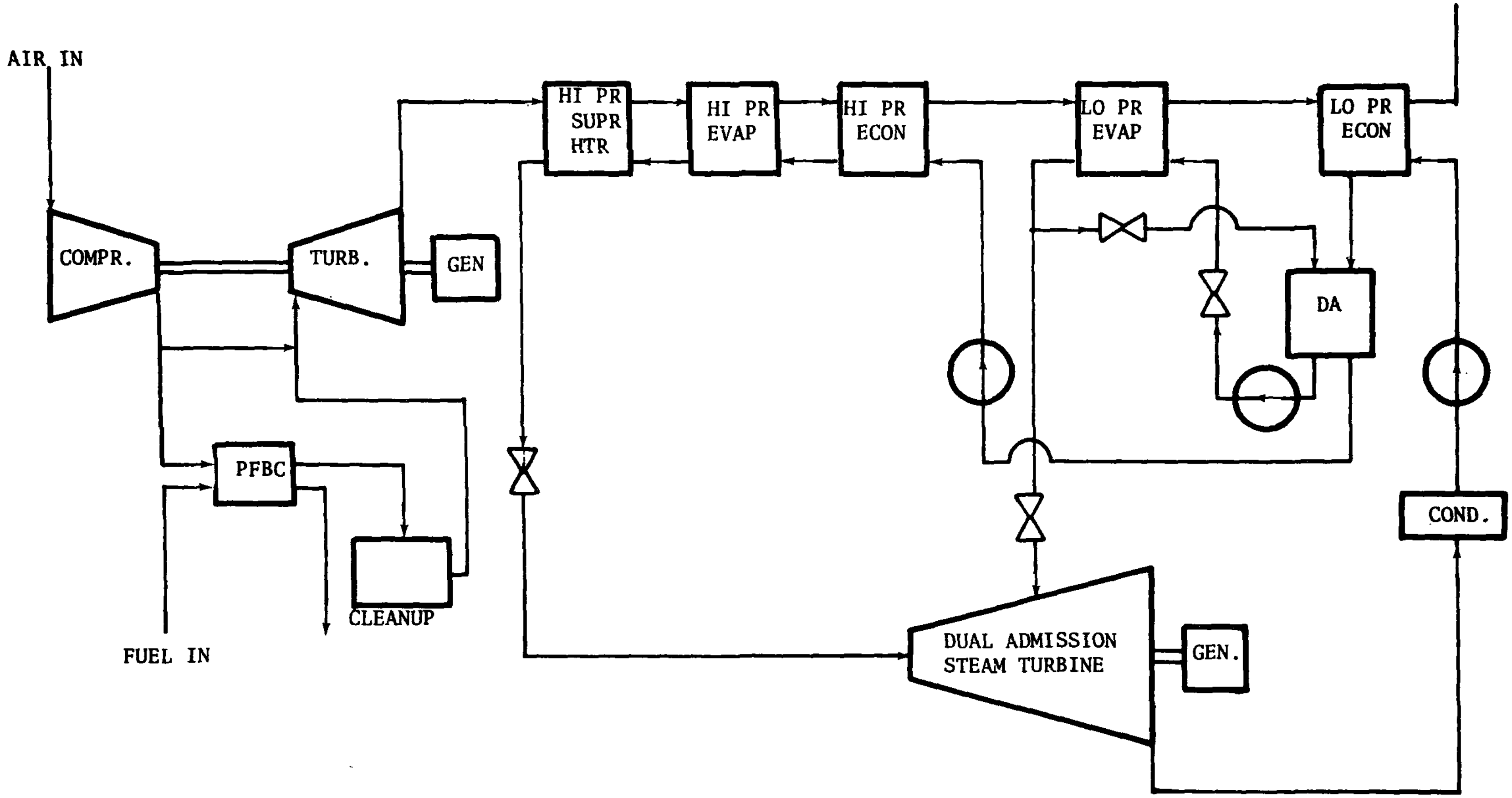


Figure 33a. Pressurized fluidized bed combustion system with dual admission steam turbine.

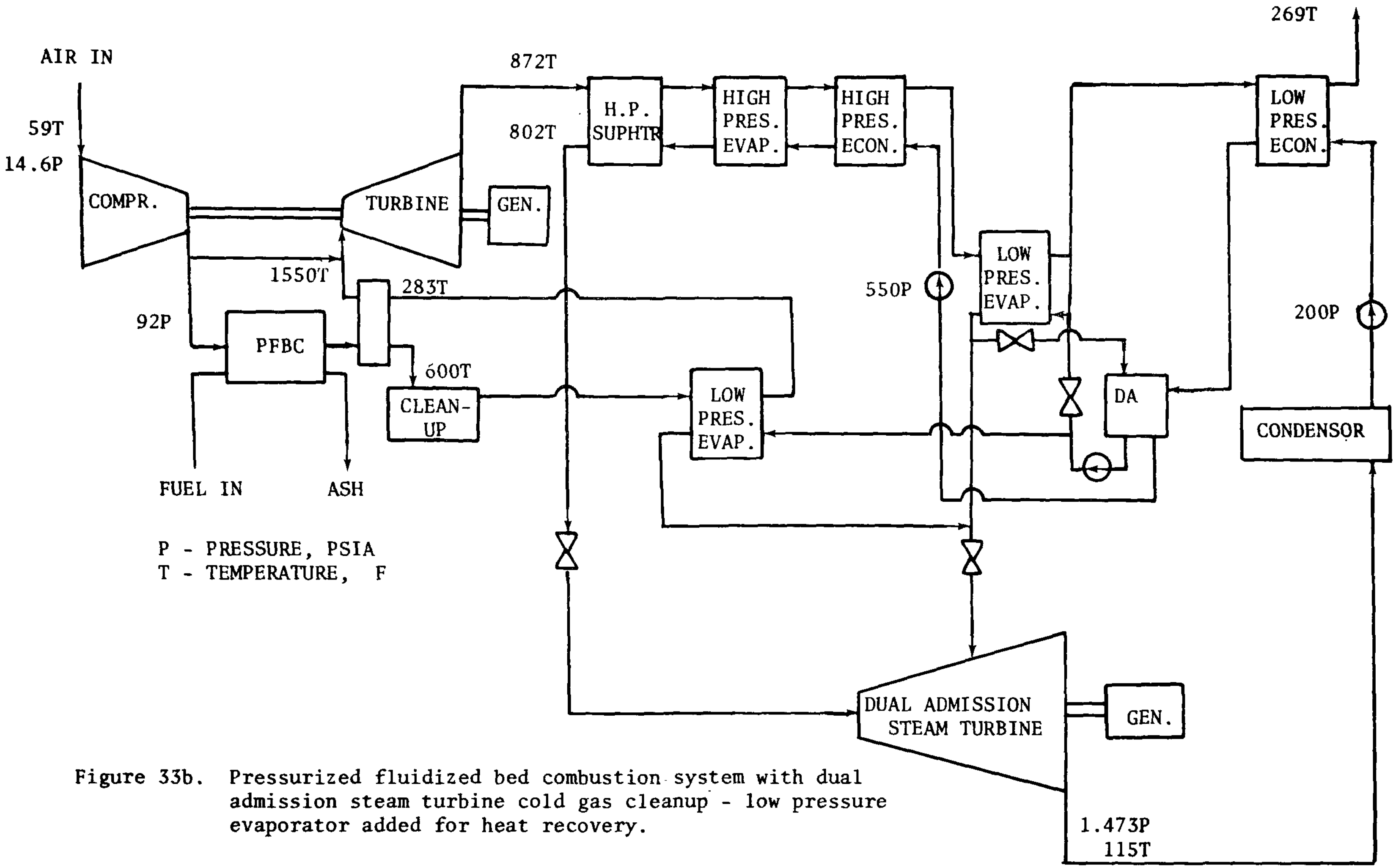


Figure 33b. Pressurized fluidized bed combustion system with dual admission steam turbine cold gas cleanup - low pressure evaporator added for heat recovery.

Company 1976) showed the PFBC boiler process with hot gas cleanup to have a 7% thermal efficiency advantage over conventional coal-fired boilers with wet scrubbers for SO_x control.

In order to fully assess the cold cleanup alternatives, recuperative heat exchangers must be studied more closely, especially regarding effectiveness, availability and cost for high temperature and pressure applications.

Further economic evaluation of hot versus cold gas cleanup must consider the cost and effectiveness of high temperature-high pressure and low temperature-high pressure particulate control devices, recuperator performance and cost, and the specific particulate control requirements. Much more development work is required to provide this information.

Post-Turbine Particulate Control

If gas turbines can be developed which have relatively high tolerance for fine (<5 μm) particles, then it may be feasible to use conventional cyclones and multiclones to protect the turbine. In such cases the emissions regulations would have to be met by applying conventional particulate control equipment downstream from the gas turbine.

Using the Westinghouse ECAS Phase II PFBC design (Beecher, et al. 1976), each gas turbine would handle 345 kg/s of gas flow. At a stack temperature of 150°C, this would correspond to 24,900 m^3/min (879,000 ACFM) of gas to be controlled.

Data from the Exxon miniplant indicate that about 0.23 to 2.3 g/Nm^3 (0.1 to 1.0 gr/SCF) of particulate matter penetrates the second stage cyclone. The proposed New Source Performance Standard for coal-fired boilers of 0.05 lb/10^6BTU corresponds to about 0.046 g/Nm^3 (0.025gr/SCF) for the Exxon system. Therefore collection efficiencies of 80 to 98% may be required downstream from the turbine.

The estimating curves presented by Neveril, et al. (1978) were used to estimate the cost of electrostatic precipitators with design efficiencies of 80, 90, 95, and 98%. Typical effective migration velocities (precipitation rate parameters) of 9 and 12 cm/s (0.3 and 0.4 ft/s) were assumed for these predictions.

The results are shown in Table 23, along with the costs for high temperature and pressure particulate control equipment reported by Beecher, et al. All prices have been adjusted to mid-1978 dollars using the Marshall and Stevens equipment cost index.

When interpreting Table 23 it should be remembered that the granular bed filter costs are highly speculative in that they are based on an unproven technology at high temperature and pressure. Also the electrostatic precipitator costs assume that there are no problems with using standard cold-side designs for this application. High resistivity problems necessitating hot-side electrostatic precipitation will cause the estimated costs to increase by a factor of two or more.

The cost of post-turbine cleanup equipment is noticeably less expensive than hot gas cleanup. However, the post-turbine equipment costs are significant and must be considered in the overall capital cost for gas cleaning equipment. Any economic advantages associated with using post-turbine cleanup very likely will depend on the cost and availability of gas turbines which can tolerate relatively heavy loadings of fine particulate matter.

LOW-BTU COAL GASIFICATION PROCESSES

The incentives for hot gas cleanup in coal gasification processes are different than for PFBC processes. The major differences are:

1. The available sensible heat in the coal gas is only about 20% or less of the total energy available from the gas. Therefore heat transfer inefficiencies associated with the cold gas cleanup approach are less severe.

2. Maximum turbine inlet temperature is assured because of the heat released by combustion of the gas.

3. High temperature particulate removal is coupled to hot H_2S removal. There is little incentive for hot particulate removal if the gas must be cooled for H_2S removal.

TABLE 23. COMPARISON BETWEEN PRE-TURBINE AND POST-TURBINE EQUIPMENT COST

CONTROL DEVICE (Number per Turbine)	TOTAL ESTIMATED MAJOR COMPONENT COST PER TURBINE, $	
A. HOT GAS CLEANUP:*		
1. Primary Cyclones (8)	1,140,000	
2. Multiclones (2), including bleed lines	2,360,000	
3. Granular Bed Filters (8)	2,980,000	
B. POST-TURBINE CLEANUP:		
Electrostatic Precipitators:	Migration Velocity	
(Cold Side)	9 cm/s	12 cm/s
1. 80% collection	400,000	500,000
2. 90% collection	530,000	630,000
3. 95% collection	640,000	750,000
4. 98% collection	750,000	960,000

*From Beecher, et al. (1976) converted to mid-1978 dollars.

4. In some processes quenching is required to remove tars. The presence of tars can plug hot gas cleanup devices unless the tars can be prevented from condensing. Quenching loses the gas sensible heat and the heating value of the tars which can be as much as 20% of the total heating value of the fuel (MERC, 1978). Also tar disposal or recovery from the scrubber liquor can present problems. Hot gas cleanup which enables the tars to be burnt in the gas turbine combustor is highly desirable.

Jones and Donohue (1977) reported on a comparative evaluation of high and low temperature gas cleaning for coal gasification combined-cycle power systems. They were concerned primarily with hot H_2S removal and for the purposes of their evaluation they assumed that suitable high temperature and pressure particulate control equipment would be developed. However, they noted that it is impossible to develop better than rough cost estimates for hot gas cleanup equipment at the current state of development.

Process evaluations were performed for five different coal gasification schemes.

1. Air blown, dry ash, moving bed gasifiers (Lurgi)
2. Oxygen blown, dry ash, moving bed gasifiers (Lurgi)
3. Oxygen blown, slagging, moving bed gasifier (British Gas Corporation)
4. Oxygen blown, two-stage entrained bed gasifier (Foster-Wheeler)
5. Air blown, two-stage entrained bed gasifier (Foster-Wheeler)

The air blown systems and the oxygen blown slagging gasifier system are illustrated in Figures 34, 35 and 36. The Morgantown iron oxide system was used for hot H_2S removal. The CCNY (Squires) granular bed filter system was used for hot particulate control. Cold H_2S removal was achieved using the proprietary Benfield process. Wet scrubbers were used for low temperature particulate removal.

The results of their study are summarized in Table 24. It appears that the greatest thermal benefits are to be derived from applying hot gas purification to Lurgi gasifiers. It is

TABLE 24. SUMMARY OF ESTIMATED THERMAL EFFICIENCIES FOR HOT VERSUS COLD GAS CLEANUP IN COAL GASIFICATION PROCESSES (FROM JONES AND DONOHUE, 1977)

PURIFICATION	COLD GAS CLEANUP	HOT GAS CLEANUP	COLD GAS CLEANUP	HOT GAS CLEANUP
Gas Turbine Inlet Temperature, °C	1,063	1,063	1,315	1,315
	Thermal Efficiency, %* Heat Rate, BTU/kW-hr			
Lurgi (O_2)				
Thermal Eff.	29.4	35.4	32.4	39.9
Heat Rate	11,628	9,630	10,544	8,558
Lurgi (Air)				
Thermal Eff.	31.0	37.0	34.5	41.2
Heat Rate	10,994	9,223	9,907	8,285
Slagging (O_2)				
Thermal Eff.	36.5	37.5	39.6	40.6
Heat Rate	9,352	9,095	8,624	8,409
Entrained Bed (Air)**				
Thermal Eff.	38.0	38.4	40.8	41.6
Heat Rate	8,982	8,879	8,359	8,215
Entrained Bed (O_2)**				
Thermal Eff.	35.4	36.6	37.8	39.3
Heat Rate	9,641	9,334	9,028	8,688

$$\text{*Thermal Efficiency (\%)} = \frac{\text{(Delivered kW) (3412.75) (100)}}{\text{(Coal lb/hr) (Coal HHV BTU/lb)}}$$

**Foster Wheeler Gasifier. The notation Air or O_2 indicates the oxidant employed in each type of coal gasifier.

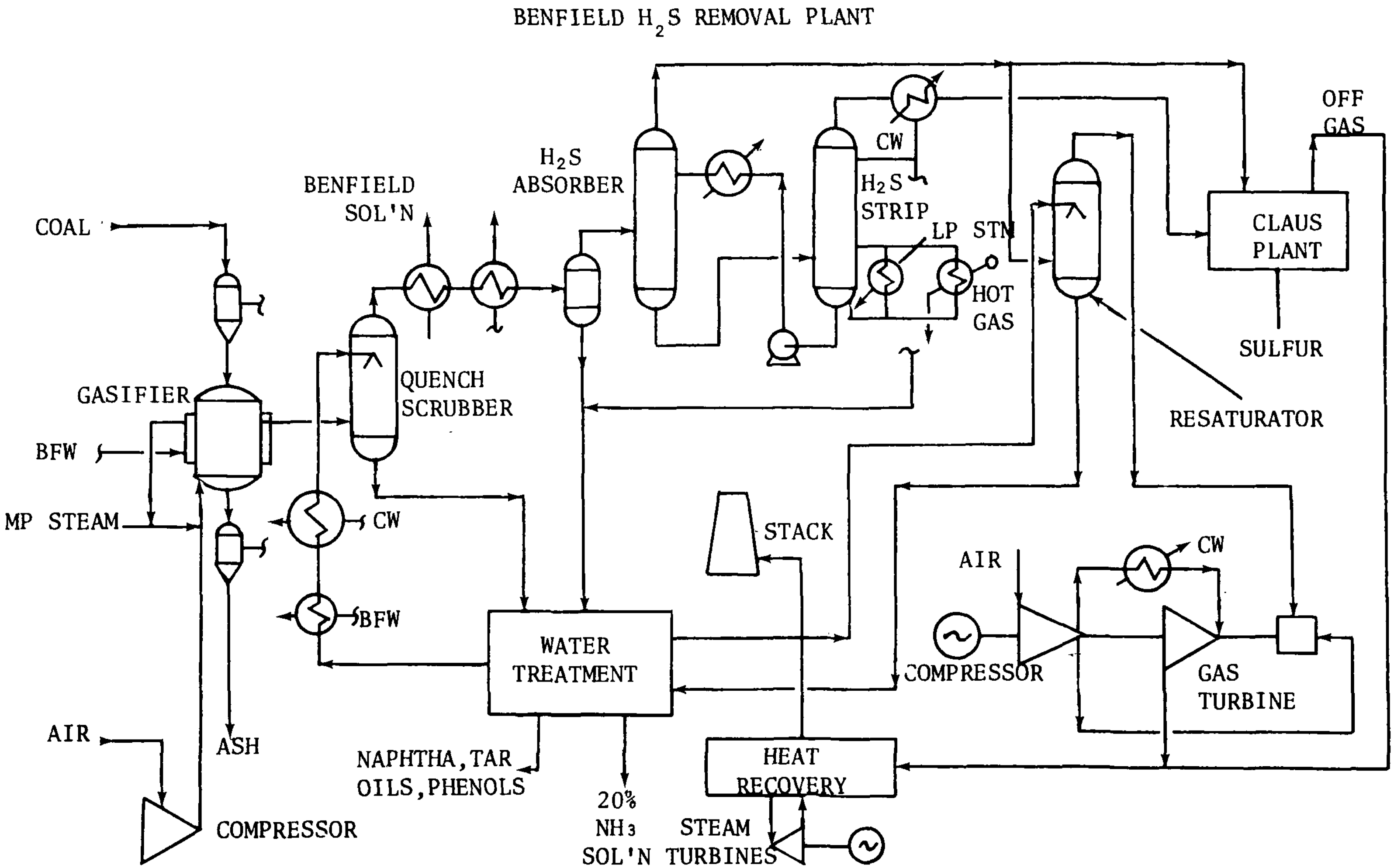


Figure 34a. Lurgi air blow gasifier - cold purification case.

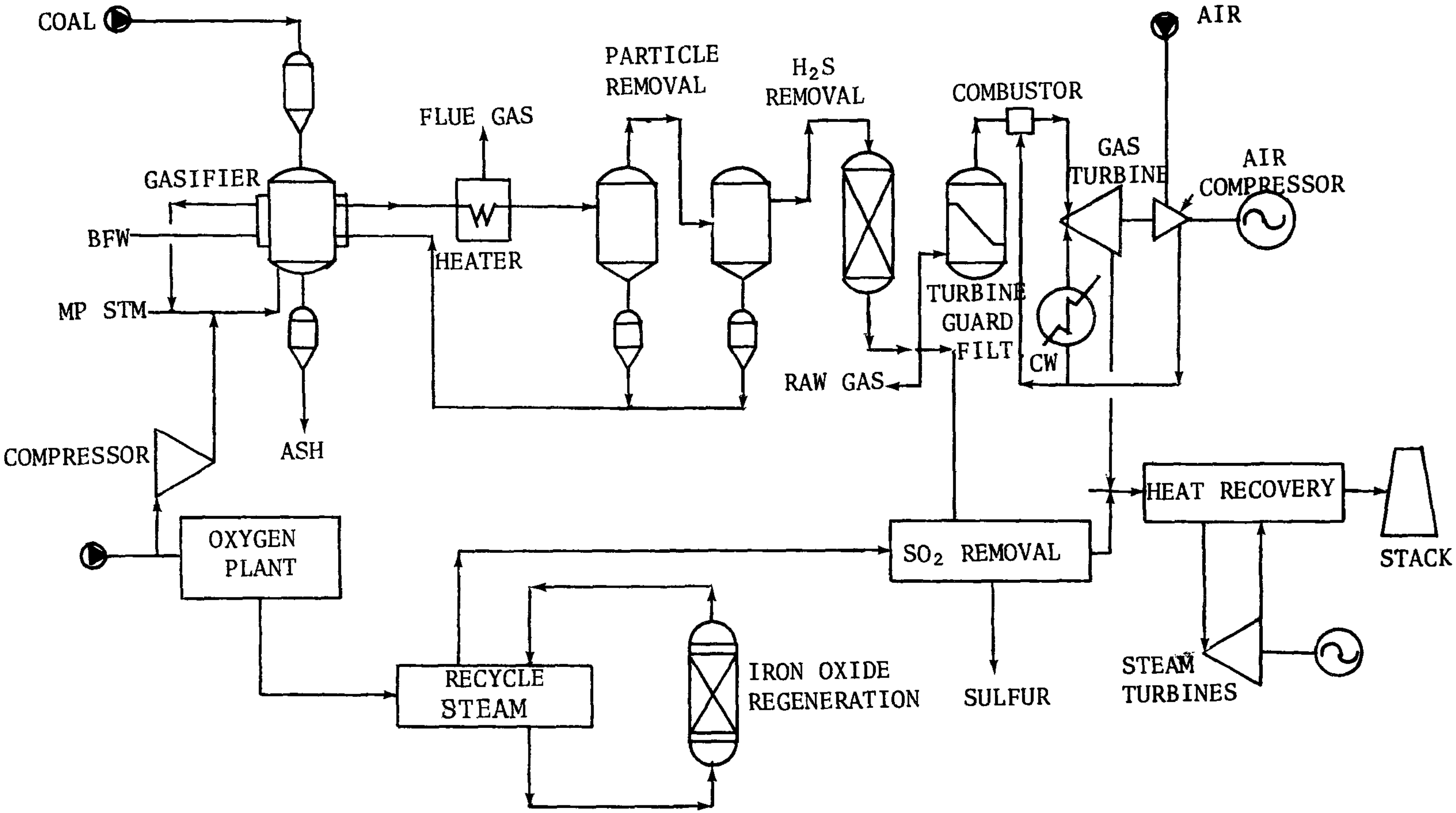


Figure 34b. Lurgi air blown gasifier study - hot purification case.

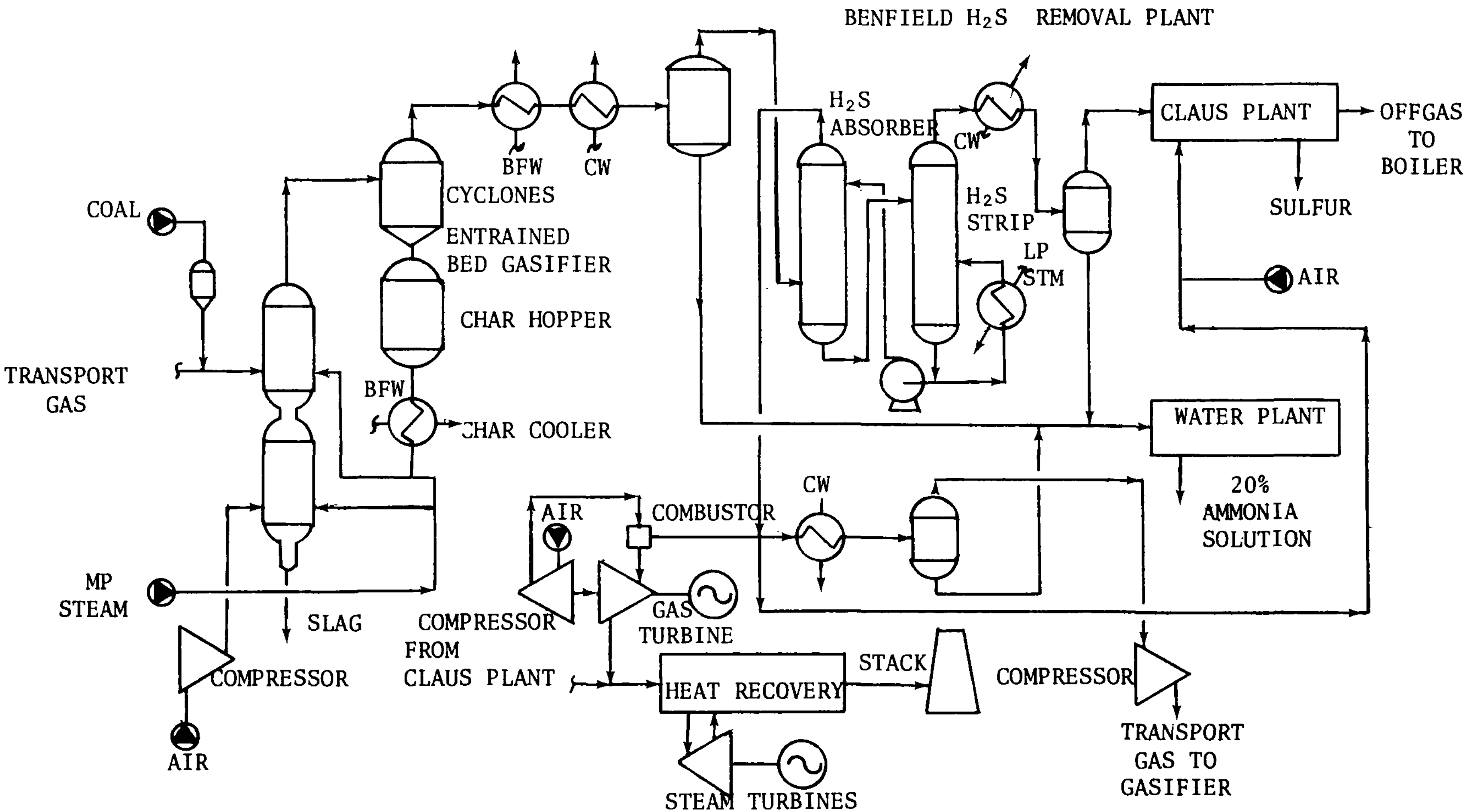


Figure 35a. Air blown entrained bed gasifier study - cold purification case.

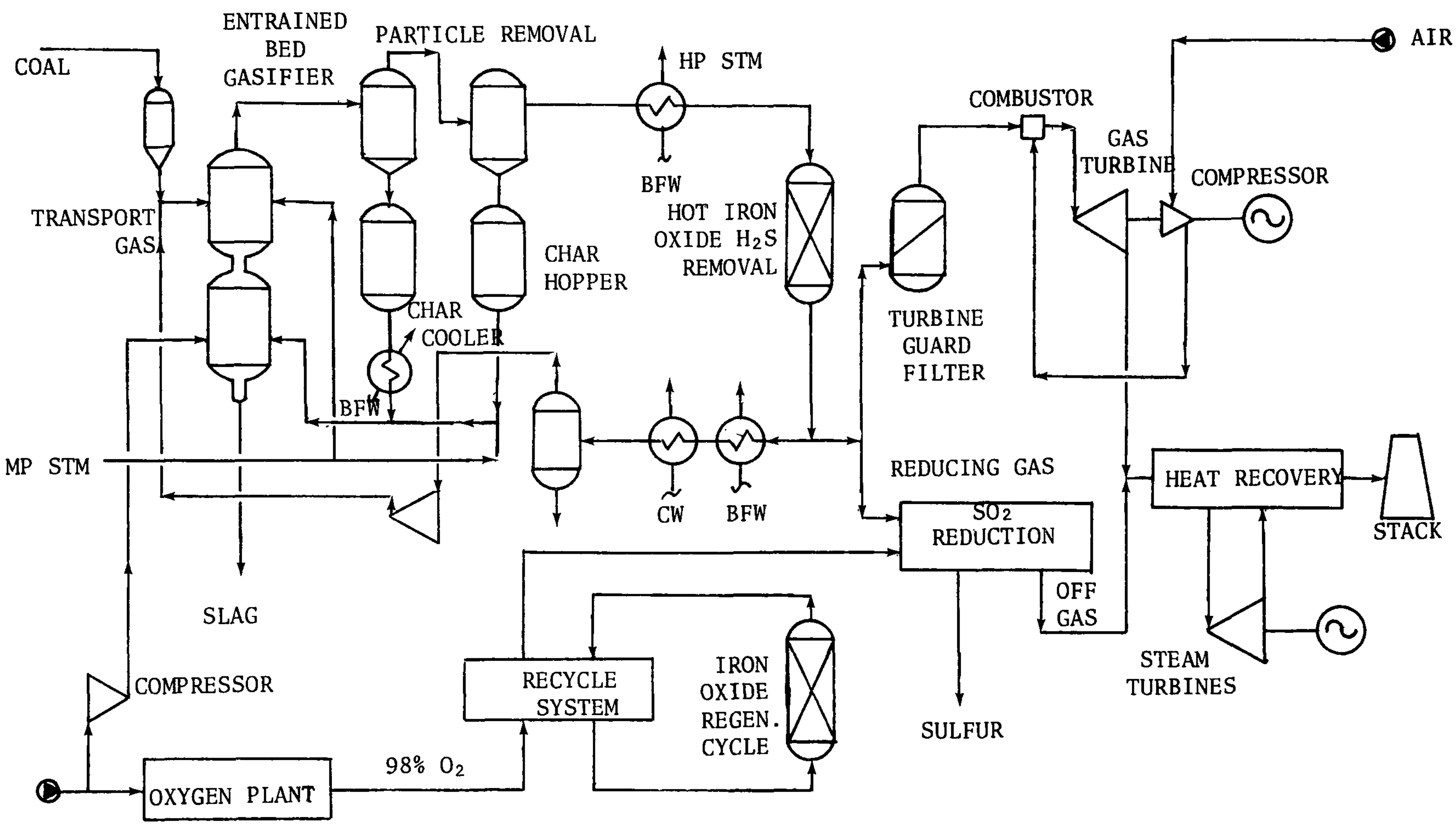


Figure 35b. Air blown entrained bed gasifier study - hot purification case.

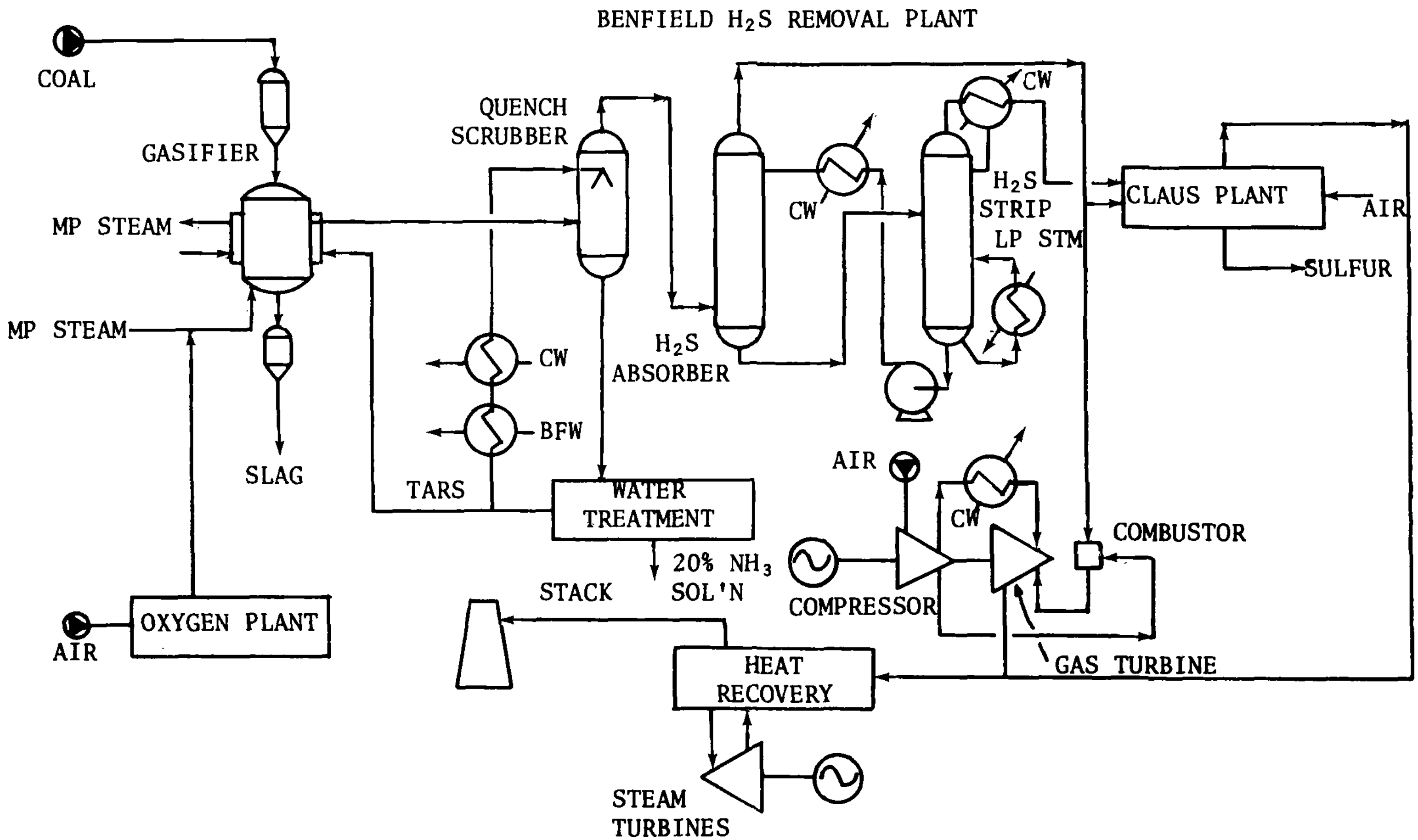


Figure 36a. Slagging gasification study - cold purification case.

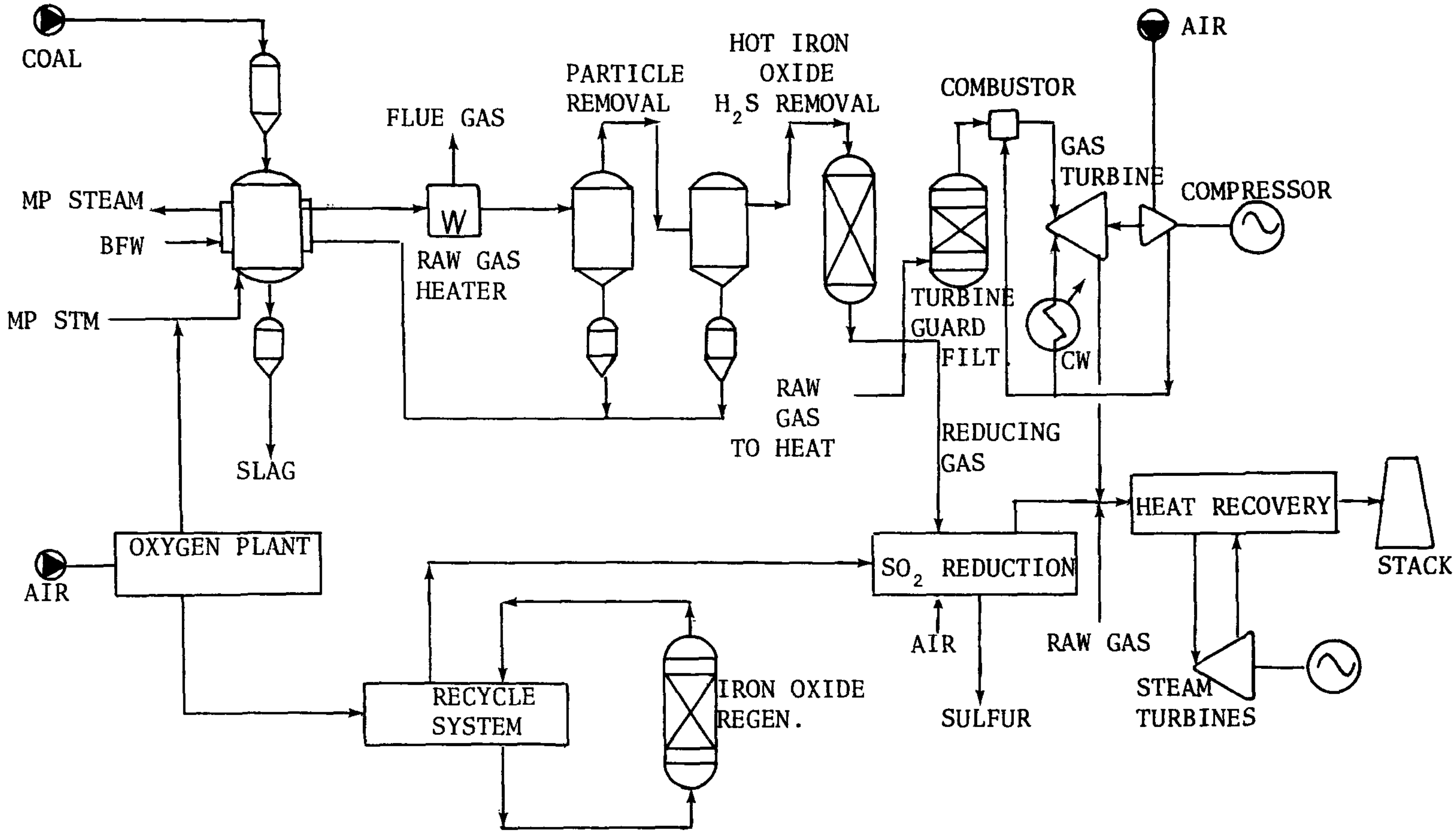


Figure 36b. Slagging gasification study - hot purification case.

important to remember that the underlying assumption used for these cases is that tars will pass uncondensed through the hot iron oxide beds directly into the gas turbine combustor.

For all cases other than the Lurgi dry ash gasifiers, thermal efficiency advantages associated with hot gas cleanup appear to be marginal (1 to 2%). The Phase II ECAS studies (Lewis Research Center, 1977 and General Electric Co., 1976) showed the LBCG combined-cycle system to have a 7% advantage over conventional coal-fired boilers with stack gas scrubbing for SO_x control.

There are two major reasons why high temperature purifi cation proved to be of such benefit to the Lurgi systems and of little advantage to the other gasification systems studied:

1. The Lurgi gasifiers were the only systems considered to have a net production of tars. Tars produced by the BGC slagger were separated from the gas stream prior to desulfurization and were recycled to extinction to the gasifier. Tars were considered to be absent in the crude gas from the entrained gasifier. The presence of tars in a crude fuel gas has major impact on the comparison between high and low temperature cleaning schemes. For the high temperature case, tars are assumed to pass through the iron oxide system and are converted to electricity at combined-cycle efficiency, (40-50%). With low temperature cleaning systems, tars are scrubbed from the crude gas by direct quench and are eventually converted to electricity at only the steam cycle efficiency, (30-40%).

2. The Lurgi gasifiers consume large quantities of steam to prevent ash matter from clinkering in the bottom. Most of this steam passes through the gasifier unconverted and is condensed in the gas quench operation necessary for low temperature gas cleaning. Therefore, if a quench is necessary, most of the sensible heat in the steam is unavailable for power generation. If high temperature desulfurization is employed, the steam passes through the iron oxide beds, and its sensible heat is converted into electricity in the combined-cycle plant.

The BGC slagger required only 13% of the steam required by the dry ash oxygen blown Lurgi gasifier due to the higher bottom temperature required for ash slagging. It also converts approximately 90% of the gasifier steam to hydrogen and carbon monoxide. Therefore, steam losses due to cooling of the slagging gasifier effluent in the quench operation are negligibly small. Steam consumed by both the air and oxygen blown entrained gasifier is approximately the same as that consumed by the slagger resulting in the same negligibly small steam losses on gas cooling.

Thermal efficiency advantages for hot gas cleanup may be even lower than predicted if satisfactory high temperature particulate removal cannot be achieved without significant temperature and pressure losses.

Also both HTP H_2S and particulate removal systems are required. Therefore technology development needs may be greater than for combustion processes.

Existing technology is capable of satisfying cold gas cleanup needs. This should be sufficient for first generation LBCG processes. The development of HTP particulate and H_2S removal systems may be helpful in improving the performance of second generation systems.

HTP control equipment also will make the fixed or moving bed processes more economically competitive by enabling the conversion of sensible heat and tar heating value into electrical energy at combined-cycle efficiency.

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

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/7-79-019		

4. TITLE AND SUBTITLE	5. REPORT DATE
Alternatives for High-temperature/High-pressure Particulate Control	January 1979
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Richard Parker and Seymour Calvert	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Air Pollution Technology, Inc. 4901 Morena Boulevard, Suite 402 San Diego, California 92117	1NE624
	11. CONTRACT/GRANT NO. 68-02-2190
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	Final; 10/77 - 10/78
	14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Dennis C. Drehmel, MD-61, 919/541-2925.

16. ABSTRACT The report gives the status of the most promising high-temperature/high-pressure (HTP) particulate control devices being developed. Data are presented and anticipated performance and development problems are discussed. HTP particulate control offers efficiency and potential economic advantages over cold gas cleanup in pressurized fluidized-bed combustion (PFBC) and low-Btu coal gasification (LBCG) combined-cycle power generation systems. However, considerably more development will be necessary in order to demonstrate the technical and economic feasibility of HTP gas cleanup commercially. The alternative of recuperative heat exchange coupled with low-temperature/high-pressure particulate control is reviewed with regard to power system efficiencies for PFBC and LBCG combined-cycle processes. Successful hot gas cleanup has clear efficiency advantages (1-7%) over cold gas cleanup. The economics of hot gas cleanup, however, are very speculative at the current state of development.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Coal Gasification	Pollution Control	13B
Dust	Gas Scrubbing	Stationary Sources	11G
High Temperature Tests		Particulate	14B
High Pressure Tests		High Temperature/	
Combustion		Pressure Control	21B
Fluidized Bed Processing		Gas Cleanup	
		Combined-cycle systems	13H, 07A

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Unlimited	Unclassified	135
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)