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A Survey of Processes for High Temperature-High Pressure Gas Purification

J. P. Meyer
M. S. Edwards

OAK RIDGE NATIONAL LABORATORY
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HIGH TEMPERATURE-HIGH PRESSURE GAS PURIFICATION

J. P. Meyer
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Prepared for the
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A SURVEY OF PROCESSES FOR HIGH TEMPERATURE- HIGH PRESSURE GAS PURIFICATION

J. P. Meyer
M. S. Edwards

ABSTRACT

In order to ensure the optimum operating efficiency of a combined-cycle electric power generating system, it is necessary to provide gas treatment processes capable of operating at high temperatures ($> 1000^{\circ}\text{F}$) and high pressures [> 10 atm (absolute)]. These systems will be required to condition the inlet stream to the gas turbine to suitable levels of gas purity (removal of particulate matter, sulfur, nitrogen, and alkali metal compounds) to be compatible with both environmental and machine constraints. In this work, a survey of the available and developmental processes for the removal of these various contaminant materials has been conducted. Based on the data obtained in this study from a variety of sources, an analysis has been performed to evaluate the performance of a number of potential cleanup processes in view of the overall system needs. Results of this study indicate that commercially available, reliable, and economically competitive hot-gas cleanup systems (for the removal of H_2S , particulate matter, alkali, and nitrogen compounds) capable of conditioning raw product gas to the levels required for turbine use will not be available for some time.

1. INTRODUCTION

As a result of both national policy and economic mandate, it has become apparent that the use of coal, in either direct combustion or gasification, will play an increasing role in the generation of stationary electric power in the United States in the near future. Such a decision, while based on economic reality, presents major engineering obstacles whose solution will be required before environmentally safe and optimally efficient generating systems can be built.

Among the many schemes that have been proposed for power production, one for which considerable interest has been shown is the combined-cycle system. As illustrated in Fig. 1, this process uses both a gas turbine and a steam turbine in sequence. The key feature of the system lies in the augmentation of a conventional steam cycle by a gas turbine which operates by using the pressure and temperature differentials existing between the combustion unit and the waste heat boiler. From thermodynamic considerations, it is easy to show that maximum process efficiencies will be obtained if the product gas is conditioned to meet turbine requirements at process conditions rather than undergoing cooling, cleaning, and regeneration.

In terms of economics, low-temperature purification (cooling, cleaning, and regeneration) is a viable option for gasification applications. However, in the case of pressurized fluidized-bed combustion (PFBC), high temperature-high pressure (HTHP) gas purification is necessary to ensure the economic viability of the combined-cycle system. This need arises because PFBC effluent contains no combustible product whose ignition would compensate for the irreversible thermal losses incurred during the cooling and regeneration phases of a low-temperature gas cleanup process.

In order to ensure an acceptable turbine life, the turbine expansion gas must contain a minimum amount of particulate material and alkali metals. In general, the permissible levels for these contaminants are quite small and if the limits are exceeded, rapid degradation of the turbine components can occur, resulting in reduced performance or even in catastrophic failure. To circumvent this problem, HTHP purification systems must be available, typically at temperatures $> 1000^{\circ}\text{F}$ and pressures > 5 atm (absolute).

ORNL DWG 78-353

Fig. 1. Combined cycle with hot-gas cleanup (Source: ref. 35).

In this study, the initial emphasis was placed on the identification of available and potentially available HTHP gas cleanup processes; however, such identification is insufficient to solve the hot-gas purification problem. To put the work in perspective, it is necessary to

- Identify the existing and projected turbine impurity allowances.
- Generically characterize the contaminant load of both gasifier and PFBC effluent.
- Identify available and developmental hot-gas cleanup systems and ascertain their performance characteristics.
- Assess the state of the art of instrumentation compatible with HTHP environments.

To achieve these objectives, our approach has involved (1) contacting equipment manufacturers, architectural-engineering firms, design-constructor firms, and specialists in high-temperature gas purification technology to obtain their evaluation of the current state of the art, and (2) independently assessing the operational characteristics of several potential particulate cleanup systems, using available grade efficiency data and projected particle-size distributions. Such an approach will provide not only the germane information but also an appropriate perspective with which to assess the problem.

Data relating to the firms and individuals contacted during the course of this study together with the inquiry letters used can be found in Appendices A through D.

During the past year a similar study, whose focus was to identify various pieces of process equipment suitable for HTHP gas purification, was undertaken concurrently by the authors in addition to this

work. Because of background similarities between these two endeavors, a number of sections in this report will necessarily resemble those appearing in the topical report for the other study, *Survey of Industrial Coal Conversion Equipment Capabilities: High Temperature-High Pressure Gas Purification* (ORNL/TM-6072). Background information necessary for both studies includes Sects. 3, 4, 5, 8, 10, 11 and all of the Appendices. Where possible, material in these sections has been updated and amended as new information has become available. By inserting similar material into each report, the continuity of the presentation is retained, and the need for cross-referencing of data is avoided.

2. SUMMARY

The development of a particulate removal system capable of operating reliably at high temperatures and high pressures and able to meet the stringent cleanup requirements needed to ensure acceptable turbine life is a formidable task. Even if existing turbine particulate allowances (0.0002 gr/scf) were increased by two orders of magnitude and the particulate carryover from either a low-Btu gasifier or a pressurized fluidized-bed combustor (PFBC) were held to 5 gr/scf, an overall cleanup efficiency of at least 99% would have to be achieved. As a point of reference, it should be noted that even in low temperature-low pressure applications, the removal of fine particulates to this level is still demanding.

In addition to the stringent cleanup demands, the presence of condensable hydrocarbons in several gasification processes will

require the operation of HTHP filtration systems at temperatures above 1000°F. Below this temperature, HTHP particulate removal may not be a viable option because of problems caused by condensation. In addition, major advances in HTHP filtration technology will be necessary to make it an economically attractive option.

In the case of pressurized fluidized-bed combustion, the development of an HTHP gas filtration system is essential to ensure the economic viability of the combined-cycle system. Unlike gasification, where it is possible to cool, clean, and regenerate the raw gas stream, PFBC effluent contains no combustible product whose ignition would compensate for the thermal losses incurred during the cooling and regenerating phases of the low-temperature cleanup process.

At present, most conceptual designs of HTHP departiculation processes include two stages of inertial separation (cyclones) prior to final gas treatment by a tertiary device that conditions the product gas to the levels of purity required for turbine application. To date, only one of these systems has been built (Exxon Pressurized Fluidized Combustor Miniplant), and preliminary data indicate significant problems associated with its use. Among these are (1) the inability of the system to achieve outlet grain loadings below 0.05 gr/scf, (2) cleaning problems associated with the formation of a dense filter cake on the inlet retaining screens of the tertiary granular bed unit, and (3) system susceptibility to upsets, which requires shutdown in order to restore operation. From these results, it is apparent that significant technical advances will have to be made before this system becomes a viable HTHP filtration technique.

In order to expedite the development of HTHP departiculation processes, Combustion Power Company's dry scrubber at the Morgantown Energy Research Center (MERC) should be tested. By doing so, several significant questions concerning its use and reliability in HTHP applications could be answered.

A review of the possible concepts for hot-gas H_2S removal suggests the following:

1. To date, the MERC iron oxide-fly ash (or silica) process is the closest to full-scale application.
2. Conoco's fluid-bed half-calcined dolomite process offers potential advantages over the MERC process but requires further experimental efforts to ascertain technical feasibility.
3. In addition to requiring further research to validate its technical feasibility, the use of alkali salts by Battelle's molten salt scrubber presents problems that appear to preclude its use in systems designed to condition fuel gas for turbine operation.

Although significant research efforts have been devoted to the development of HTHP departiculation and H_2S removal systems, no effort has been devoted towards developing similar systems capable of removing nitrogen compounds from raw product gas streams. Unless such systems are available, NO_x emissions from the combustion of low-Btu gas may exceed current EPA standards for coal-fired power plants.

At this time, it appears that commercially available, reliable, and economically competitive hot-gas cleanup systems (for removal of

H₂S, particulate matter, alkali, and nitrogen compounds) capable of conditioning raw product gas to the levels required for turbine use will not be available for some time.

3. THE MEASUREMENT PROBLEM

The absence of suitable measurement techniques with which to assess particulate loadings in HTHP environments is a major obstacle in the development of a hot-gas cleanup technology. Without a proven measurement system, it is impossible to obtain even the most elementary information needed to establish such important design parameters as effluent loading, device efficiency, and turbine particulate allowances. Without this information, any kind of process design will at best be approximate and more than likely conjectural.

3.1 Previous Work

Until very recently, little emphasis had been placed on the development of HTHP particulate measurement technology.^{1,2} For cases in which measurements have been made, the techniques normally used have involved direct adaptation of existing low temperature-low pressure (LTLTP) methodologies including filters, cyclones, and cascade impactors to HTHP systems. A summary of the historical experience associated with these attempts is presented in Table 1.

Table 1. Review of high temperature-high pressure measurement applications

Facility	Temperature (°F)	Pressure (psia)	Source	Analytical technique
Australian Aeronautical Research Laboratory	1200		Direct coal combustion	Cyclones--absolute filter
U.S. Bureau of Mines-- Morgantown Energy Research Center	1000-1100	115-315	Stirred-bed gasifier	Bulk filter
British Coal Utilization Research Association	820-925	60-75	Fluidized-bed combustor	High-efficiency cyclone
Westinghouse Research Laboratories	1400-1600	150	Fluidized-bed combustor	Scalping cyclone followed by cascade impactor
Argonne National Laboratory	1450-1650	150	Fluidized-bed combustor	Cascade impactor--optical methods
Exxon Miniplant	1200-1600	135	Fluidized-bed combustor	Cascade impactor

3.2 Problems in HTHP Measurement

In order for HTHP particulate measurements to be meaningful, they should be obtained in situ--that is, at the temperature and pressure of the sampled stream. By altering either the stream temperature by cooling or the sampling pressure by expansion, significant problems can be encountered, including (1) changes in the aerodynamic character of the particle due to altered gas viscosity, (2) distributional changes due to agglomeration, (3) condensation and aerosol generation caused by tar and oils,³ and (4) condensation of low-boiling solids for solid/gas mixtures. If any of these problems occur, the measured particle-size distribution will differ from that which actually exists in the HTHP gas.

3.3 Optical and Aerodynamic Sizing

Two basic methods exist for measuring particle-size distributions-- optical and aerodynamic. When these methods are applied to the same dust-laden stream, they produce different results. For this reason, it is often difficult to decide which result is the "correct" distribution. Since the methods use different bases to construct the distribution (in one case an optical property and in the other case an aerodynamic property), neither result is absolutely correct. At best, one can say that the two results are related, yet different by virtue of the properties they measure.

3.3.1 Optical sizing

Optical sizing usually entails the measurement of either a reflectance or transmittance property of a light beam as it passes through a dust-laden stream. In general, it has the advantages of being

1. suitable for in situ measurements without affecting stream properties,
2. capable of on-line data acquisition with extremely short response times, and
3. operationally simple.

Unfortunately, it has the following disadvantages:

1. susceptible to interference from infrared radiation,
2. can undergo loss of coherent resolution over its optical path-length due to turbulence and density gradients,
3. has difficulties associated with the maintenance of an optically clear path,
4. may require dilution at high dust concentrations, and
5. limited to particle sizes greater than the wavelength of the light used.

The underlying principle used in optical sizing is that it constructs distributions based on the measurement of an apparent linear dimension of a particle--that is, the diameter of a spherical particle having the same projected area as the particle silhouette. In so doing, it does not account for the variations in particle density or in particle shape, but rather assumes a spherical and opaque nature.

3.3.2 Aerodynamic sizing

Aerodynamic sizing is based on the use of conventional devices such as cyclones, filters, and impactors specially designed and adapted to HTHP environments. These techniques have the advantages of

1. measuring particulate loadings directly, and
2. sizing particles according to their aerodynamic behavior.

Similarly, they have difficulties associated with

1. being limited to extractive batch operations,
2. problems regarding the maintenance of probe performance and integrity under extreme conditions, and
3. uncertainties caused by the need for short sampling times in the presence of high-particulate loadings.

Aerodynamic sizing, as opposed to optical sizing, characterizes particle distributions according to their aerodynamic properties--how an individual particle acts in a flow field. In a real sense, this basis relates more directly to particle behavior expected in an actual hot-gas cleanup device. Because of the fluid dynamic nature of the measurement, physical properties such as gas viscosity and particle density play an important role in the measurement procedure. Because of these latter considerations, aerodynamicists have found it convenient to circumvent problems associated with the dependence of particle density on particle size by dealing in terms of an equivalent aerodynamic diameter of a sphere having the same falling velocity as the original particle and a density equal to 1 gm/cm^3 .⁴ Many of the instruments used in aerodynamic analysis give this measure directly.

3.3.3 Comparisons

Discounting the disadvantages associated with either measurement scheme, the fundamental difference between optical sizing and aerodynamic sizing is that they construct particle-size distributions by measuring entirely different particle properties.

Because particulate matter is seldom, if ever, perfectly spherical, entirely opaque, or uniform in density, optical sizing and aerodynamic sizing normally provide different results. In cases for which comparisons of results from the two methods have been made, significant differences occur. The early work of Stein⁵ as shown in Fig. 2 indicates that optically sized particles (r_p) show a significant variation in diameter over a uniquely sized aerodynamic range (r_e), whereas the later work of Kuykendal⁶ as presented in Fig. 3 infers that aerodynamic sizing predicts a mean particle diameter larger than that optically measured. These data illustrate that the two methods give different results; as pointed out earlier, neither method can be said to be absolutely correct.

3.3.4 Recommendations

A research program is needed to resolve the differences that exist between optical and aerodynamic sizing techniques. This program should include (1) a side-by-side comparison of HTHP experimental results from the two measurement systems and (2) a statistical or theoretical analysis aimed at deriving a correlation between the two methods.

3.4 Existing Technology

The following evaluation sheets list either available or developmental instrumentation systems suitable for HTHP particulate measurement.

ORNL DWG 78-310

Fig. 2. Ratio between projected area diameter and equivalent aerodynamic diameter for particulates in Pittsburgh air (Source: ref. 5).

ORNL DWG 77-1663

Fig. 3. Comparison between optically sized and aerodynamically sized particle distributions for different inlet grain loadings (Source: ref. 6).

ACUREX PARTICULATE SAMPLING SYSTEM⁷Manufacturer

Acurex Aerotherm
485 Clyde Avenue
Mountain View, Calif. 94042 ATTN: William Masters

Analysis performed

1. loading
2. particle size distribution
3. chemical composition of particulate (optional)

Operating parameters

Temperature, °F	1200-1800
Pressure, atm	3-20
Particle size, μm	0.3-25
Loading, gr/ft^3	0-15
Response time, sec	Extractive batch
Calibration requirements	Function of analysis technique

Theory

The heart of the Acurex unit lies in the design of its HTHP probe, which is capable of being extended into and withdrawn from a sampling duct. In operation with the probe extended, gas particulate samples are isokinetically withdrawn from the duct at a velocity equal to the local gas velocity at the probe tip and are analyzed. Analysis is performed via an instrument train consisting of specially adapted HTHP cyclones and/or impactors and absolute filters which are housed in the pressure vessel enclosing the sampling arm. Sizing of the particles is based on their aerodynamic, rather than their optical, character.

High temperature-high pressure problems

1. Small sampling times must be used for high dust loads to avoid saturation.
2. This is not an on-line instrument
3. The cost of this system is relatively high.

Stages of development

This instrument is being used to evaluate filtration efficiency of various devices at the Exxon PFBC Miniplant in Linden, New Jersey.

PARTICLE MONITOR MODEL P-5A⁸Manufacturer

Environmental Systems Corporation
1212 Pierce Parkway
Knoxville, Tenn. 37921 ATTN: Robert Nusplinger

Analysis performed

Loading

Operating parameters

Temperature, °F	500 (can be adapted for more)
Pressure, atm	1 (can be adapted for more)
Particle size, μm	0.1-10
Loading, gr/ft^3	0.001-10
Response time, sec	5
Calibration requirements	In situ zeroing done manually

Theory

As suspended particles pass through an optical beam, incident light scattering occurs. By using a monochromatic light source, such as a laser, it is possible to quantitatively relate the intensity of the back-scattered light to the total particulate load in the sample volume. If the particle density is known, the total mass loading can be calculated directly.

High temperature-high pressure problems

This system is not currently used in HTHP applications but is believed to be adaptable to them.

Stage of development

Research is needed for HTHP adaptation.

PILLS VI⁸Manufacturer

Environmental Systems Corporation
1212 Pierce Parkway
Knoxville, Tenn. 37921 ATTN: Robert Nusplinger

Analysis performed

Particle-size distribution

Operating parameters

Temperature, °F	≤ 400 (can be extended)
Pressure, atm	1 (can be extended)
Particle size, μm	1-15, 3-45
Loading, gr/ft ³	5 x 10 ¹⁰ particles/ft ³
Response time, sec	300
Calibration requirements	Calibration module containing particles of known sizes is furnished

Theory

This equipment is based on the principle of measuring the back scattering of light from single particles in sampling volume.

High temperature-high pressure problems

This system is not currently used in HTHP applications but is believed to be adaptable to them.

Stage of development

Research is needed for HTHP adaptation.

MICROTRAC⁹Manufacturer

Leeds & Northrup Company
Technical Center
North Wales, Pa. 19454 ATTN: Harold Frock

Analysis performed

1. mean particle diameter of volume distribution
2. mean particle diameter of area distribution
3. loading

Operating parameters

Temperature, °F	1500-2000
Pressure, atm	≤ 10
Particle size, μm	1.3-15
Loading, gr/ft ³	0.05-3.00 (1-in. pathlength, ρ = 1)
Response time, sec	50-100
Calibration requirements	None necessary

Theory

This instrument bases its analysis on the low-angle forward scattering of light by suspended particles. A diffracted flux pattern is caused by the interference of particles passing through a laser light beam. It is assumed that the particles are spherical and opaque, and that the particle density is low enough so that multiple scattering is negligible.

High temperature-high pressure problems

1. Filtering is needed to eliminate infrared radiation emitted by the particles and the walls of the ducts.
2. An air purge must be provided to keep the quartz windows clean and at a temperature < 1000°F.
3. The optical components must be scaled for across-the-duct sampling.

Stages of development

This unit is undergoing evaluation at the Argonne National Laboratory in an analysis of their PFBC effluent.

LASER INTERFEROMETER¹⁰Manufacturer

Spectron Development Laboratories, Inc.
3303 Harbor Boulevard
Costa Mesa, Calif. 92626 ATTN: Dr. James Trolinger

Analysis performed

1. size distribution based on particle diameter
2. velocity of particles
3. calculation of flux and loading

Operating parameters

Temperature, °F	1500-2000
Pressure, atm	≤ 10
Particle size, μm	2-200
Loading, gr/ft ³	
Response time, sec	Function of particle loading and gas velocity
Calibration requirements	None

Theory

This instrument bases its analysis on the interference fringes caused by the passage of a particle through a probe volume defined by a region in which two laser beams mix. Individual particles are counted and accumulated in registers corresponding to various interval widths (i.e., 1 to 3μm, 5 to 7μm, etc.). If two or more particles enter the sample volume, the count is rejected. One count takes about 20 μsec, and about 1000 counts are needed to characterize a distribution. Particles are assumed to be spherical and opaque.

High temperature-high pressure problems

1. Optical clarity of windows must be maintained.
2. High temperature infrared radiation must be filtered.
3. Electronic noise must be minimized.

Stage of development

This unit is currently undergoing evaluation at Argonne National Laboratory using PFBC effluent.

4. CHARACTERIZATION OF PARTICULATE LOADING

Without a proven measurement technique, it is almost impossible to characterize the particulate effluent from either a gasifier or a fluidized-bed combustor. Not only is it difficult to characterize the effluent from a specific unit or process, but it is virtually impossible to relate the effluent from one system to that produced by another. Neither the empirical evidence nor the theoretical analysis exists with which to model accurately the underlying physical phenomena.

4.1 Gasifiers and Fluidized-Bed Combustors

Generally, PFBCs operate in an oxidizing atmosphere with an excess amount of air, whereas gasifiers operate in a reducing atmosphere in the presence of excess hydrogen. Because of differences in the process environment, PFBCs tend to produce particulate matter composed primarily of elutriated ash, which has a high mineral but relatively low carbon content. On the other hand, gasifier particulate matter can contain a significant amount of unreacted carbon due to incomplete reaction in the combustion zone as well as soot, ash, and unburned hydrocarbons. In both cases, the total amount of elutriated material is a strong function of the specific design configuration of the gasifier or PFBC and the operating conditions. For PFBCs, the elutriation rate is directly correlated with the fluidizing velocity, ash content of the coal, and feed rate. For gasifiers, the amount of carry-over increases from fixed- to fluidized- to entrained-bed units.

Characteristic values of the operating conditions of several commercial and developmental gasifiers are given in Table 2.¹¹ Although gasifiers operate over a wide variety of conditions, PFBC operation has thus far been limited to the temperature range 1450-1650°F and pressures up to 10 atm (absolute).^{12,13}

4.2 Required Data

In general, several sets of information, including total loading, particle-size analysis, and chemical composition, are needed to characterize particulate effluent carry-over. To date, only the first and third members of this triad have been amenable to analysis using existing measurement techniques. Recently, however, some information on particle-size distributions in the HTHP regime has been obtained because of current advances in HTHP instrumentation. Tables 3 (refs. 12 to 15) and 4 (ref. 16) summarize much of the available data on total loading and particulate chemical composition.

4.3 Particle-Size Distribution

Almost without exception, particle-size distribution is a far more important parameter than total dust loading because the removal efficiency of a gas cleanup device is a strong function of particle size. Hence, to assess the applicability of a specific control technology, it is important to know not only the collection characteristics of the device but also the distribution of particle sizes that it will be required to treat.

Table 2. Typical operating conditions for different gasifiers

	Temperature (°F)	Pressure (psia)	Higher heating value (Btu/scf) dry
Entrained bed			
Rahcock & Wilcox	1800	315	100 (air) - 300 (oxygen)
Bigas	1500-1700	500-1500	355 (oxygen)
Brigham-Young	1200-2500	15	350
Combustion Engineering	1600	15	130 (air)
Foster Wheeler	1800-2100	365	180 (air)
Ignifluid ^a	2000-2400	15-75	125
Koppers-Totzek ^a	2700	15	285 (oxygen)
Texaco	400-500	300-1200	250 (oxygen)
Fluidized bed			
Battelle/Union Carbide	1600-1800	115	330
Bituminous Coal Research	1700-2000	250	160 (air)
CO ₂ Acceptor	1500	165	380
Cogas	1600	30-60	335
Hydrane	1000-1500	1000	785 (hydrogen) ^b
Hygas	600	1200	370 (oxygen)
Synthane	1400	1000	165 (air) - 355 (oxygen)
U-Gas	1550-1900	65-365	155 (air)
Westinghouse	1600-1800	145-215	135 (air)
Winkler ^a	1150-1450	15	125 (air) - 290 (oxygen)
Fixed bed			
DOE-MERC	1200	15-300	140 (air)
Gegas	700-1000	300	160
Lurgi ^a	700-1000	350-450	285 (oxygen)
Wellman-Galusha ^a	800-1200	15	145 - 170 (air)
Woodall Duckham/ Gas Integrale ^a	250-1200	15	175 (air) - 280 (oxygen)

^a Commercially available.

^b Products from the Hydrane processes are principally high-Btu gas and coal char. The process needs an external source of hydrogen, which is used for fluidizing the bed at high temperature and high pressure. Under these conditions, cracking of the devolatilized coal fraction occurs, which when followed by hydrogenation, produces a high-Btu gas.

Table 3. Total particulate carry-over from selected processes

Process	Particulate output (lb/10 ⁶ Btu)	Grains per standard cubic foot
<u>Gasifiers</u>		
Entrained bed:		
Ignifluid	40	35
Koppers-Totzek	36	72 (oxygen)
Fluidized bed:		
CO ₂ Acceptor	4	11
Westinghouse	3.6	3.4
Winkler	0.84	0.7 (air) - 1.7 (oxygen)
Fixed bed:		
DOE-MERC	1.5	1.5
<u>Fluidized-bed combustors</u>		
Westinghouse	3.6	6.7
Argonne National Laboratory	0.9-4.9	1.6-9.2
Exxon Miniplant	4.9-5.4	9-10
<u>New source performance standards</u>	0.1	0.089 (gasification) 0.056 (combustion)

Table 4. Chemical composition of elutriated carry-over from selected gasification processes

Process	Particulate (gr/scf)	Particulate		Condensables
		% Carbon	% Ash	
Fixed bed				
DOE-MERC	0.2-2.5	75-80	10-25	Tars — heavy HC ^a
Lurgi	0.2-2.5	75-80	10-25	Tars — heavy HC
Fluidized bed				
CO ₂ Acceptor	6.5	8	88	No tars — no heavy HC
Synthane	2-5	80	20	Tars
Winkler		30	70	No tars — no heavy HC

^aHC — hydrocarbon.

Until recently, most of the available distributional data for PFBC and gasifier effluent was limited not only in absolute amounts but also in accuracy. The bulk of this information is presented in Fig. 4, and includes

1. The British Coal Utilization Research Association (BCURA)^{17,18} data on PFBC carry-over,
2. Acurex Aerotherm data on the Ignifluid Gasifier process,¹⁴ and
3. The Industrial Gas Cleaning Institute's data on "typical" fly ash from a pulverized coal-fired boiler¹⁹ for comparison.

Because of advances in HTHP particulate measuring equipment,²⁰ Acurex Aerotherm Corporation has recently been able to augment these data and obtain more accurate information on the size distribution of elutriated carry-over from a PFBC. This data, presented in Fig. 5, represents the distribution of effluent leaving the second-stage cyclone of the Exxon Miniplant. In absolute amount, it is *estimated* to account for about 10% of the total elutriated material. This information is significant because in many HTHP cleanup systems, it is envisioned that two stages of cyclones will precede a final removal device. Thus, for the purposes of our analysis, we have assumed that the tertiary cleanup unit in PFBC applications will face a 1-gr/scf loading with a particle size distribution comparable to that obtained by Acurex.

All of these data have been plotted in log-normal form, that is, with the cumulative distribution of particulate given as a function of the logarithm of the particle diameter. This representation is consistent with that of previous work and was selected because:

Fig. 4. Cumulative distribution of particulate vs particle diameter for different combustion processes.

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Fig. 5. Particle-size distribution of effluent leaving second-stage cyclone of the Exxon Miniplant.

1. Naturally occurring aerosols often exhibit log-normal behavior.
2. Attrition processes frequently give rise to this type of distribution, particularly in the fine-particle domain.
3. This representation is a two-parameter distribution which is relatively easy to fit and convenient to work with.

If a given distribution plots as a straight line on log-probability paper, it is then log normal in character and is mathematically described by the expression:

$$F(x) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left\{ - \left[\frac{\ln(x) - \ln(\bar{d}_p)}{\sqrt{2} \sigma} \right]^2 \right\},$$

where

$F(x)$ = probability density function for particle with diameter x ,

x = particle diameter (μm),

$\bar{d}_p$ = mean particle diameter (μm),

σ^2 = distributional variance.

To estimate the values of the distribution parameters $(\bar{d}_p, \sigma^2)$, a simple procedure is followed. First, the value of the mean particle diameter is obtained by finding that value of the particle diameter at which the cumulative distribution function reaches 50%. Second, the variance is computed via the algorithm,

$$\sigma = \ln \left(\frac{\bar{d}_p}{d_{15.4}} \right),$$

in which $d_{15.4}$ corresponds to that value of the particle diameter at which the cumulative distribution function equals 15.4%.

Examination of the data in Fig. 5 illustrates that a log-normal model can accurately characterize the distribution of particulate

leaving the second-stage cyclone at the Exxon Miniplant. To establish the distributional parameters $\overline{dp}$ and σ , the previous algorithms are used and the values 5 μm and 1.43 are obtained respectively. Because most of the proposed HTHP departiculation processes include at least two stages of cycloning prior to final cleanup, we will assume that a similar configuration will exist in any HTHP cleanup system we examine in this study. Consequently, our analysis will begin at the exit of the second-stage cyclone with the assumption that 90% of the particulate matter has already been removed by inertial separation and that the remaining uncollected 10% exhibits a log-normal distribution identical in form to that presented in Fig. 5.

4.4 Recommendations

Both the data and the methodology with which to reduce the data are necessary to characterize either gasifier or PFBC effluent carry-over. The elucidation of these uncertainties awaits the development of suitable measurement techniques capable of analyzing HTHP particulate streams and the extension of existing theoretical treatments of elutriation dynamics.^{21,22} Such work should be undertaken in the future.

5. TURBINES

The current focus of any hot-gas cleanup technology is to provide an acceptably clean hot-gas stream compatible with the particulate allowances of a power recovery turbine. These requirements must include allowances for both total particulate loading and specific particle size which will, in general, vary with different turbine inlet conditions. Because random fluctuations occur in the normal operating cycle, process cleanup requirements should be set at the extreme operating point to ensure that adequate protection is provided over the entire operating spectrum.

5.1 Previous Work

Several attempts have been made in the last 25 years to operate a gas turbine using direct-fired coal combustion to generate the expansion gas. None of these endeavors have reached the commercial stage, although the results of these studies have illuminated many of the underlying problems associated with coal combustion power recovery. In a large number of cases, it has been shown that erosion is the single most limiting factor in reducing turbine life. Ingested particulate material entering the turbine, in either ash or char form, severely grinds away the rotor and stator internals and dramatically reduces machine performance.

Most previous attempts to effect inlet-gas cleaning have relied on the use of conventional cyclones for particulate removal. Unfortunately, these units have failed to achieve the degree of cleaning

necessary for acceptable turbine life. A summary of this experience is presented in Table 5.

5.2 Existing Specifications

To date, the true tolerances of turbines to particulate matter have not been determined with sufficient accuracy to predict turbine life. In general, manufacturers conservatively limit the particulate material of the expansion gas to about 2×10^{-4} gr/scf (0.4 ppm weight), which affords them more than adequate protection in most industrial applications. In addition, it is normally stipulated that turbines with inlet velocities between 1100 and 1200 ft/sec should not ingest material greater than 5 μ m in diameter, although it is unclear exactly how this diameter is to be measured.

Table 6 provides a synopsis of existing turbine tolerances which have been culled from a variety of sources. Two entries are provided in the table--one for expansion gas and the other for low-Btu fuel gas. The expansion gas values are characteristic of the tolerances PFBCs will have to meet, whereas the low-Btu fuel gas values correspond to those to be met by gasifiers. Using combustion air gives a decided advantage to low-Btu gas combustion since dilution will reduce gas cleanup needs.

Work has recently been undertaken by DOE to quantify reasonable estimates of turbine tolerances for coal gasification applications. The maximum allowances of 0.0002 gr/scf for particulate loading and material sizes $\leq 6 \mu$ m have emerged as the projected benchmark values from the High-Temperature Turbine Technology Program (HTTTP).²³

Table 5. Summary of high-temperature, coal-fired gas turbine experience

Facility	Inlet turbine temperature (°F)	Dust loading (gr/scf)	Source of power	Date	Comments
Locomotive Development Committee ^a	1250	> 0.120	coal	1951-58	Severe erosion.
	1050	> 0.120	coal	1951-58	Negligible erosion and deposition after 500 hr.
United States Bureau of Mines	1250	0.120	coal	1959-64	Blade life of redesigned vanes estimated to be 500 to 7000 hr, depending on erosion.
Aeronautical Research Laboratories (Australia) Australian Joint Coal Board ^a	1200	0.170	coal	1959-63	Severe erosion and ash deposition problems at gas velocity of 1200 ft/sec.
	1200	0.170	coal	1969-70	At reduced inlet velocity of 800 ft/sec, erosion was avoided and slight deposition occurred. Blade life estimated to be between 25,000 and 50,000 hr.
Combustion Power Company ^b	1400	0.052-0.208	coal-FBC ^c	1974	Severe erosion

^aHigh Temperature Turbine Technology Program, Phase I: Program and System Definition, Topical Report: Fuels Cleanup and Turbine Tolerance, Generation Systems Division, Westinghouse Electric Corp. for ERDA, FE-2290-27 (February 1977).

^bInterim Report No. 1 on Energy Conversion from Coal Utilizing CPU-400 Technology, Combustion Power Company for Dept. of Interior, NTIS PB-273-028 (November 1974).

^cFluidized-bed combustor.

Table 6. Particulate tolerances for various turbine manufacturers

Manufacturer	Particulate loading (gr/scf)	
	Turbine expansion gas	Low-Btu fuel gas ^a
Brown-Boveri ^b	3.2×10^{-4} (0.6 ppm weight)	2.9×10^{-3}
General Electric ^c	1.7×10^{-4} ^d (0.3 ppm weight)	1.5×10^{-3}
Ingersoll-Rand (Turbo Expanders) ^e	7.0×10^{-2} (125 ppm weight)	6.3×10^{-1}
United Technologies: (Pratt & Whitney: Turbo Power & Marine) ^c	2.2×10^{-4} (0.4 ppm weight)	2.0×10^{-3}
Westinghouse ^f	2.0×10^{-4} (0.4 ppm weight)	1.8×10^{-3}
HT ³ Recommendation ^g	2.0×10^{-3} (4 ppm weight)	1.8×10^{-2}
Westinghouse PFBC Projection ^f	2.0×10^{-3} to 2.0×10^{-2} (4 to 36 ppm weight)	1.8×10^{-3} to 1.8×10^{-2}

^aBased on air/fuel ratio of 8:1 for 225 Btu/scf gas with dust-free air and turbine inlet temperature of 1800°F.

^bStanley Stys, Brown-Boveri Corp., North Brunswick, N.J., private communication.

^cFred L. Robson et al., Fuel Gas Environmental Impact: Phase Report, United Technologies Research Center for EPA, EPA-600/2-75-078, PB 249 454 (November 1975).

^dBased on air/fuel ratio of 40:1 for 1000 Btu/scf gas with dust-free air and turbine inlet temperature of 1800°F.

^eRichard A. Worthen, Ingersoll-Rand Research, Inc., P. O. Box 301, Princeton, N.J., private communication.

Turbo expanders are unfired units similar in design to turbines but generally operated at inlet conditions below 1300°F. Because of this reduced inlet temperature, they are able to accommodate higher inlet particulate loadings.

^fAdvanced Coal Gasification System for Electric Power Generation, Quarterly Progress Report, Fiscal Year 1976, Westinghouse Electric Corp., Heat Transfer Division for ERDA, FE-1514-1/6 (Oct. 15, 1975).

^gHigh Temperature Turbine Technology Program, Phase I: Program and System Definition, Topical Report: Fuels Cleanup and Turbine Tolerance, Generation Systems Division, Westinghouse Electric Corp. for ERDA, FE-2290-27 (February 1977).

Throughout the remainder of this study, these values will be used as reference points to assess the potential of various hot-gas cleanup devices.

5.3 Acceptable Turbine Life

The term *acceptable turbine life* is ill-defined unless a particular gas turbine application is specified. For example, in the electric utility industry, an acceptable operating life is normally regarded as being on the order of 25,000 to 30,000 hr of operation. On the other hand, in a number of industrial applications, an operational life of 5,000 to 7,000 hr may be entirely acceptable. Under similar inlet conditions (temperature and pressure), the difference in operating lifetime is directly related to the differences in particulate loading ingested by the two machines.

Because significant variations can occur in acceptable turbine life that are almost entirely related to economic conditions, we have chosen to analyze the problem of HTHP filtration in a parametric manner. That is, we shall look at the performance of a number of different removal systems as a function of varying inlet and outlet loadings. In this way, the range of performance for a given system can be analyzed. As a point of reference, however, we shall use the data provided by DOE's HTTP (0.0002 gr/scf, $< 6 \mu\text{m}$) to assess the suitability of each filtration system. At this time, these values represent the best, if not the only, information available on allowable particulate levels for gas turbines operating in combined-cycle systems at high temperature.

5.4 Particulate Behavior in Turbines

Three mechanisms exist whereby turbine performance is diminished by the presence of particulate matter: erosion, corrosion, and deposition. In most previous coal-fired applications, erosion and deposition have been the principal components of turbine failure. A brief synopsis of each mode of destruction is given below.

5.4.1 Erosion

Erosion results from the mechanical degradation of the internal elements of a turbine through the grinding and abrasion caused by particulate impaction on internal surfaces. The degree of erosion is strongly influenced by (1) particle size, (2) particle physical properties, (3) blade hardness, and (4) the impact velocity and impact angle of the particulate matter.²⁴ Studies have shown that particles having a diameter greater than 1 μm may have sufficient impact with turbine components to cause material removal if the gas velocity is sufficiently high. Indeed, the preliminary experimental results of Mogul,²⁵ as shown in the following table, confirm the severity of the problem as a function of particle size and type.

Curtis-Wright experimental results for particulate erosion on turbine materials (Mogul)^a

Particulate	Diameter (μm)	Time (hr)	Erosion
Alumina	10	100	Severe
Silica	10	100	Severe
Silica	3	200	Little

^aTest conditions: temperature, 1600°F; pressure, 1 atm; flux, 1.5 gr/ft³; velocity, 300 ft/sec.

Because of the inherent difficulties associated with an extensive experimental program, investigators have developed an alternative assessment technique involving a computer analysis of particle dynamics and impaction phenomena to predict erosion characteristics. In this way, Westinghouse²⁶ has been able to produce the data estimates presented in Figs. 6 and 7, which confirm Mogul's experimental results by showing an almost exponential increase in erosion damage as the particle size is increased from 3 to 10 μm . Even the relatively light grain loading of 10^{-4} gr/scf used in the study is still sufficient to produce substantial damage. As a result of the HTTP analysis, it has been recommended that an erosion tolerance of 0.002 gr/scf (4 ppm weight) with no particles greater than 6 μm may be acceptable for a 20-MW turbine.²³ This figure is substantially more stringent than the 0.05 gr/scf value with no particles greater than 22 μm that was recommended by the Australian Aeronautical Research Board as a result of their work on direct coal-fired gas turbine operation. In this latter case, the discrepancy may be related to the fact that in the Australian experience, the turbine inlet velocity was reduced from 1100 to 800 ft/sec.

5.4.2 Corrosion

Sulfidation and oxidation are the two principal modes of corrosive attack in HTTP coal-fired environments.²³ The rate associated with each mechanism is a strong function of blade temperature and the amount of impurities in the gas stream.

To prevent hot-corrosive oxidation, the amount of vanadium pentoxide (V_2O_5) present in the turbine expansion gas must be limited. This material vaporizes in the combustion process, passes through the

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Fig. 6. Variation in the computed rates of erosion of turbine rotor elements with particle size for different particle densities (Source: ref. 26).

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Fig. 7. Variation in the computed rates of erosion of turbine stator elements with particle size for different particle densities (Source: ref. 26).

hot-gas purification system, and condenses on the cooler turbine stator and rotor blades. In so doing, it fluxes (or dissolves) the protective oxide coating of the blades and renders the metal substrate susceptible to attack through a variety of subsequent mechanisms. Fuel additives such as MgO are used to protect against vanadium oxide attack by forming vanadates, which tie up vanadium in high-melting solid phases.²⁷

Below 1670°F, sulfidation is promoted principally by the presence of alkali-metal chlorides and sulfides. When these compounds condense on a turbine blade (alkali chlorides at 1030°F, alkali sulfates at 1485°F), they form a eutectic mixture with the surface protective oxide layer, weakening its resistance to resist sulfur attack.²⁷ Though the mechanism is poorly understood, it has been proposed that sulfur is absorbed at the metal surface and migrates inward along the grain boundary, reducing blade strength and eventually resulting in catastrophic failure.²⁴ The onset of sulfidation is generally considered to occur at 1525°F, which corresponds to the melting point of the K_2SO_4 - Na_2SO_4 eutectic.

Laboratory tests have indicated that one method of reducing alkali attack is to dope the combustion coal with aluminum silicate ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) in the form of clay or kaolin. This additive works by reacting with sodium and potassium to form feldspars ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$ and $K_2O \cdot Al_2O_3 \cdot 6SiO_2$), which tie up the elements in a solid phase.²⁷

Below 1670°F, it is believed that oxidation rather than sulfidation will be the controlling mechanism of corrosion attack. At higher temperatures, the ash constituents, including calcium sulfate and metal oxides, supply a natural liquid-like environment necessary to produce sulfidation.²⁸

Typical results of the dependence of corrosion rates of blade material on temperature and alkali-metal concentration are presented in Fig. 8.²³

5.4.3 Deposition

Four steps are involved in the deposition process: (1) arrival at the blade surface, (2) adhesion to the interface, (3) growth, and (4) removal.²³ The first of these is related to the aerodynamic behavior of particles in gas streams. The remaining three steps are physiochemical in nature and are understood only qualitatively at this time.

Currently, it is believed that the deposition process is strongly influenced by the presence of alkali salts in the gas stream. Because these compounds have a relatively low melting point (alkali chlorides at 1030°F), they can condense in liquid form on turbine blades and hence establish the initial bond between particulates and structural members. Once initiated, the deposition process can grow in a continued particulate-alkali compound layered pattern.²⁴

Because the presence of alkali metals can also influence other deterioration modes, it is important to point out that the significant variable in this regard is the ratio of the binding material to the bulk of the deposits. If this value is high, corrosion occurs. Deposition occurs at medium values, and erosion takes place if the value is low. Unfortunately, the values high, medium, and low are hard to quantify.

Temperature is another important variable in determining deposition rate. As the temperature increases, deposition increases because of an

Fig. 8. Dependence of corrosion rates of various turbine blades materials on inlet gas temperature (Source: ref. 23).

acceleration in the rate of reaction which forms the alkali-particle bond necessary to make particles stick. In effect, this process enhances the deposition of fine particulate, since it reduces the residence time needed for the adhesion of small particles that would otherwise be removed by the turbulent eddies surrounding the blade. Confirmation of this hypothesis is suggested by the results presented in Fig. 9.²³

Recently it has been observed that above 870°F fly ash sticks rather than erodes and that deposition may well be the principal problem facing PFBC and gasifier combined-cycle operation.²⁹ Not only does the material stick, but it is hard, essentially 100% dense, and does not appear to depend on alkali salts to effect deposition. This behavior is attributed to the high impact velocities coupled with the sensible heat of the particles, which can supply 80% or more of the heat of fusion, depending on the velocity. This means that under the best filtration conditions practically attainable with current technology (0.03 gr/ft³),²⁹ the rate of deposition is 0.0005 in. per hour or 0.10 in. in 200 hr. Under typical operating conditions in a turbine with a 6 to 1 compression ratio, this can occur in approximately 30 hr.²⁹ Data germane to this hypothesis is presented in Figs. 10 and 11.

Previous experience²⁴ in gas turbine operation with coal-produced expansion gases has shown that if the turbine inlet temperature is held below 1050°F, deposition will not be a problem. Ultimately, this may be the simplest way to avoid deposition phenomena, although it may result in uneconomic gas turbine plant design.

Fig. 9. Dependence of deposition phenomena in turbines on variations in particle size and inlet gas temperature (Source: ref. 23).

Fig. 10. Deposition-erosion characteristics of two ashes vs temperature (Source: ref. 29).

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Fig. 11. Deposition thickness vs time as a function of inlet grain loading (Source: ref. 29).

5.4.4 Recommendations

Much of the critical information relating to particulate loading tolerances of gas turbines is being obtained under DOE's High-Temperature Turbine Technology Program. Future recommendations should await the results obtained from this study.

6. THE ALKALI-METAL PROBLEM

Although coal contains a significant amount of alkali-metal compounds (Table 7), it is not known to what extent they are volatilized during the combustion process. Nonetheless, the presence of these materials and the potential for their release pose two significant problems for systems containing gas turbines and HTHP gas purification equipment. The first problem is metallurgical in nature, and the second is concerned with the condensation characteristics of alkali compounds.

As indicated in Sect. 5, both rotor and stator blade materials are extremely susceptible to alkali attack. When these elements reach the metal surface, they react with the protective oxide coating to form a eutectic mixture that is unable to resist sulfidation significantly. The phenomena has been known to metallurgists for some time, and as a precaution, turbine manufacturers have limited the alkali content in gas turbine fuel to minimal amounts. Table 8 has been prepared using existing liquid fuel specifications and engineering estimates of air to fuel ratios, listing the equivalent alkali levels allowable in low-Btu fuel for a number of major turbine units. From this data, it can be concluded that in the absence of any significant metallurgical breakthroughs, gasifier raw product gas will have to be conditioned to

Table 7. Contaminant levels in typical U.S. coals

Element	Level (ppm weight)
Sodium	500 $\pm$ 400
Potassium	1600 $\pm$ 600
Chlorine	1400 $\pm$ 1400

Source: High Temperature Turbine Technology
Program: Phase I, Program System
Definition Topical Report: Fuels
Cleanup and Turbine Tolerances,
Westinghouse Electric Corp. for ERDA,
FE-2290-27 (February 1977).

Table 8. Limits on alkali metal content (Na + K) of low-Btu gas^a for different turbine manufacturers

Manufacturer	Na + K (ppm weight)
Brown-Boveri ^b	0.05
General Electric ^c	0.1
Westinghouse ^d	0.05
United Technologies ^e	0.20
HT ³ Recommendations ^d	0.05

^aBased on fuel/air ratio of 0.22 for low-Btu gas and a fuel/air ratio of 0.02 for liquid fuels.

^bFuel specifications supplied by Z. Stanley Stys, Brown-Boveri Corp., North Brunswick, N.J.

^cFuel Flexibility in Heavy Duty Gas Turbines, General Electric Gas Turbine Reference Library GER-222K, General Electric Co., Schenectady, N.Y.

^dHigh Temperature Turbine Technology Program: Phase I, Program System Definition Topical Report: Fuels Cleanup and Turbine Tolerances, Westinghouse Electric Corp. for ERDA, FE-2290-27 (February 1977).

^eF. L. Robson, A. J. Giramonti, and W. A. Blechor, Fuel Gas Environmental Impact: Phase Report, United Technologies Research Center, EPA-NTIS PB-249-454 (November 1975).

contain no more than 0.1 ppm total alkali content. In the case of PFBC, this value corresponds to a level of 0.015 ppm that will have to be achieved.

Aside from being metallurgically destructive, alkali-metal compounds also have the tendency to condense at relatively low temperatures (alkali chlorides at 1030°F, alkali sulfates at 1485°F).²⁹ The implication of this phenomena is that should process cleanup temperatures fall below 1400°F or possibly to as low as 1000°F, alkali condensation would occur simultaneously with departiculation. Because condensing alkali metals tend to act as bonding agents between adjacent particles, it is conceivable that dense layers of particulate matter would form whose ability to adhere to various substrates would pose significant removal problems. For devices that rely either on the development of a surface layer to effect filtration or on internal pore filtration (fabric-metal-ceramic filters), the potential of irreversible clogging exists, and consequently these units may be inapplicable in HTHP purification systems.

To circumvent problems associated with alkali-metal compounds, several investigators have examined materials that suppress alkali-metal release in the combustion mixture. Experimentally, the addition of clays and kaolin suppresses alkali release by forming feldspars ($\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ and $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$), which tie up the elements in a solid phase.²⁷ Only bench-scale work in this area has been performed, and estimates of the cost or applicability of these systems in commercial operation are not available. In addition, the kinetics of these reactions are largely unknown, and hence it is impossible to assess whether or not equilibrium levels below 0.1 ppm can be achieved.

7. THE NO_x PROBLEM

The oxides of nitrogen are highly reactive compounds that play a central role in the generation of photochemical smog. From both a chemical and physical point of view, smog is an undesirable atmospheric constituent capable of producing adverse health and welfare effects. One method of retarding its formation is to limit the amount of NO_x present in the atmosphere. Because large quantities of nitrogen oxides are generated during the combustion of fossil fuels, several regulations have been promulgated that severely limit the amount of NO_x emissions allowed to the atmosphere from these processes.

During the combustion of low-Btu fuel gas, two separate mechanisms are responsible for the formation of NO_x emissions--the thermal fixation of N₂ and the oxidation of fuel nitrogen compounds (for example, NH₃, HCN).³⁰ Experimental observations have shown that although both mechanisms are dependent on the amount of oxygen present in the combustion zone, thermal fixation exhibits an exponential dependence on temperature, whereas the oxidation of nitrogen compounds appears to be relatively temperature insensitive.³¹ Because of the inherent differences in these two reactions, two alternative control strategies for NO_x control have been formulated.

Because of the strong dependence of the rate of thermal fixation of nitrogen with temperature, it has been suggested and demonstrated that adequate NO_x control results from reduction of the flame combustion temperature.^{32,33} In practice, this would involve the use of either staged combustion or a combustor with a modified design. Current research indicates that this technique is capable of sufficiently

controlling NO_x emissions to limits well within current environmental tolerances, provided that the sole source of NO_x emissions is the thermal fixation of nitrogen.

At present, no processes are available for the removal of fuel nitrogen compounds in the high temperature-high pressure domain, although there are a number of such systems available for the low-temperature regime. In addition, the rate of NO_x formation via oxidation of fuel nitrogen compounds is relatively insensitive to temperature; hence the previously described control strategies are inadequate for NO_x control. To circumvent this problem, a number of investigators have suggested that the catalytic decomposition of ammonia (NH_3), the major low-Btu gas nitrogen compound constituent, into its elemental forms (N_2 and H_2) may be a potentially useful method of reducing NO_x emissions.^{23,34} Ammonia has been experimentally observed to exist in many high-temperature, low-Btu coal gases at concentrations well above its equilibrium value. For example, Robson et al. provide a value for the ammonia concentration in the product gas of a BCR gasifier at 1750°F and 475 psi of 4260 ppm. If this ammonia is allowed to equilibrate, its concentration would decrease to between 200 and 460 ppm depending on the final temperature. Unfortunately, the kinetics of ammonia decomposition are slow, and hence it would be necessary to use a catalyst in commercial operations. Because those catalysts that are the most active for ammonia decomposition are also those that are the most readily poisoned by sulfur compounds, a sulfur resistant material would have to be available. Robson has suggested³⁴ that iron oxide may potentially be such a catalyst. It

may possess not only the desirable property of enhancing ammonia decomposition, but it can also simultaneously act as a sulfur sorption agent (similar to the MERC iron oxide process). An experimental investigation of this premise is needed, however, to support the utility of this concept.

Unless significant efforts are devoted to the development of HTHP fuel nitrogen compounds removal systems in the near future, existing environmental constraints may well preclude the use of HTHP gas purification systems.

8. HOT-GAS CLEANUP PROCESS EQUIPMENT

In previous surveys of hot-gas cleanup technology,³⁵⁻⁴¹ much of the emphasis has been placed on the identification of various HTHP purification systems and a detailed description of their mode of operation. In this work, the approach used has been to characterize each individual piece of equipment in terms of its design parameters and service in HTHP environments. Consequently, the use of illustrations to depict candidate units has been limited to only those cases in which a verbal description of the unit would be unsatisfactory.

For our purposes, the format chosen for presenting the data on particulate removal devices has been to provide a small generic summary of each class of equipment including:

1. inertial separators,
2. surface filters,
3. granular-bed filters,

4. electrostatic precipitators, and

5. novel devices--molten salt scrubber and electrofluidized bed.

Each summary is accompanied by detailed evaluation sheets for each device in that particular class. Because this data is largely tabular in nature, it has been included in Appendix E in order to condense the main body of the report.

Similar evaluation sheets are provided in Appendix F for hot-gas H₂S removal systems.

9. ANALYSIS

Although it is impossible to specify exactly the requirements to be met by any single hot-gas purification system, it is plausible to analyze the overall problem parametrically in such a way as to assess the range of efficiencies required for successful operation of an HTHP filtration system. This is done by allowing the effluent grain loading to assume preselected values and then to compute required process clean-up efficiencies as a function of projected turbine particulate tolerances. Such an approach was used to construct Table 9, in which the effluent grain loadings of 5, 15, and 35 gr/scf were designated as generically typical of fixed-bed, fluidized-bed, and entrained-bed gasifiers, respectively. The turbine tolerances of 0.05, 0.002, and 0.0001 gr/scf encompass the range of the most severe and least severe allowances to date, as well as the projected value for future turbine operation.

The data in Table 9 confirm the formidable nature of any approach to hot-gas cleanup. The requirements for particulate removal, even

in the most liberal application, will be at least 99%. Most likely, these limits will be even more stringent.

Table 9. Overall process cleanup efficiencies (%) needed for acceptable turbine life as a function of gasifier effluent loading and inlet turbine specifications

Effluent loading (gr/scf)	Cleanup efficiencies (%)		
	Turbine tolerance (gr/scf)		
	0.05	0.002	0.0001
35	99.86	99.99	99.99
15	99.67	99.99	99.99
5	99.00	99.96	99.99

9.1 Filtration Mechanisms

In general, the ten collection mechanisms responsible, in varying degrees depending on the device, for filtration are^{42,43}

1. direct interception,
2. inertial impaction,
3. Brownian diffusion,
4. electrical migration,
5. thermophoresis,
6. diffusio-phoresis,
7. centrifugal forces,
8. gravitation forces,
9. particle agglomeration, and
10. magnetic separation.

Of these ten, only Brownian diffusion and particle agglomeration are enhanced by HTHP operation,⁴² whereas the remaining eight are either diminished or not enhanced at all. Because these modes are of second-order importance in most collection devices, it has been concluded by Rao⁴² and by Calvert and Parker⁴³ that HTHP filtration will be less effective than LTLP operation using the same device. The primary reason for this reduction is that gas viscosity is a strong function of temperature and that increased viscosity enhances fluid resistance, which prevents movement of the contaminant particle from the gas stream to the surface of the collecting device.

9.2 Limiting Case Analysis

Because the particle collection efficiency of a given device will be maximum under ambient conditions, a limiting case to be analyzed is the low-temperature behavior of a particular unit. Clearly, if a potentially suitable device can be shown to be ineffective at low temperatures, then it can be concluded that its operation at high temperature would fare no better and, consequently, should be excluded from further consideration.*

Fortunately, the studies of Shannon et al.⁴⁴ and Kalen and Zenz⁴⁵ provide a generic classification of the collection efficiencies of several cleanup devices, which facilitates such an analysis. Using

*An exception to this rule will of course be drawn for those cases in which either Brownian diffusion or particle agglomeration is a principal mode of collection for a particular device. In this study, neither of these mechanisms is dominant for the devices cited.

their data as shown in Fig. 12 in conjunction with the previously proposed log-normal mass distribution,

$$F(x) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left\{ - \left[\frac{\ln(x) - \ln(\bar{dp})}{\sqrt{2} \sigma} \right]^2 \right\} ,$$

it is possible to predict the overall collection efficiencies of the individual devices.

Although it is desirable to know the collection characteristics of individual devices, the main purpose of this work is to determine the overall efficiencies of particulate removal processes. To facilitate this analysis, we have adopted the approach that any HTHP departiculation train will consist of two stages of cycloning followed by a final departiculation device capable of conditioning the gas to meet turbine requirements. This approach is consistent with that proposed by Exxon,⁴⁶ Combustion Power Company,⁴⁷ and Westinghouse.⁴⁸ Further, it will be assumed that the data obtained by Acurex Aerotherm at the Exxon Miniplant is both accurate and characteristic of PFBC and gasifier operation in general. This means that two stages of cycloning will be considered capable of removing 90% or 9 gr/scf of the elutriated material emanating from the coal consuming unit and that 10% or 1 gr/scf will have to be posttreated by a final cleanup device. In addition, the particle-size distribution of this remaining material is assumed to be well characterized by a log-normal distribution in which the parameter $\bar{dp}$ and σ have the values of 5 μm and 1.43 respectively.

Table 10, which presents results computed by using all of the previous assumptions, is based on:

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Fig. 12. Extrapolated collection efficiencies as a function of particle size for various filtration devices (Source: ref. 44).

Table 10. Estimated overall process collection efficiencies for various hot-gas cleanup systems consisting of two stages of cycloning followed by selected tertiary treatment devices

Tertiary treatment device	Overall process collection efficiency (%)
Fabric-ceramic-metal filter	99.7
Venturi scrubber	99.7
Tornado cyclone	99.6
High-efficiency ESP ^a	99.4
High-efficiency scrubber	99.3
Medium-efficiency ESP ^a	99.0
Low-efficiency ESP ^a	98.4
Granular-bed filter	98.3
Low-efficiency scrubber	98.2
Multiclone	97.5
High-efficiency cyclone	96.3
Medium-efficiency cyclone	95.3

^aElectrostatic precipitator.

1. The assumption that the particle mass distribution supplied to the tertiary treatment unit is log-normally distributed with respect to particle size:

$$F(x) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left\{ - \left[\frac{\ln(x) - \ln(\bar{dp})}{\sqrt{2} \sigma} \right]^2 \right\} ,$$

where

$F(x)$ = probability density function for particle with diameter x ,

x = particle diameter (μm),

$\bar{dp}$ = mean particle diameter ($5 \mu\text{m}$),

σ^2 = variance (in this case, taken as 2.04).

2. The collection efficiencies of various devices can be represented by the error function,

$$\eta = \text{ERF} \left[\frac{(\ln(x) - \ln(\gamma))}{\theta} \right] ,$$

where

η = collection efficiency,

ERF = error function,

x = particle diameter (μm),

γ = device mean particle diameter,

θ^2 = device variance,

as presented by Shannon.⁴⁵ Values of γ and θ are presented in Table 11, and device efficiencies are shown graphically in Fig. 12.

3. Limits of integration for the particle-size distribution are from 0.01 to $10^6 \mu\text{m}$.

Table 11. Parameters used in predicting device efficiencies

Device	Parameters	
	γ	θ
Metal-ceramic-fabric filter ^a	0.068	1.15
Venturi scrubber	0.185	0.92
High-efficiency scrubber	0.335	1.15
Tornado cyclone		
($d > 1.5 \mu\text{m}$)	0.830	0.77
($d \leq 1.5 \mu\text{m}$)	0.439	1.95
High-efficiency ESP ^b	5.41×10^{-6}	8.81
Medium-efficiency ESP ^b	0.032	3.59
Low-efficiency scrubber	0.950	1.15
Granular-bed filter		
($d > 2.3 \mu\text{m}$)	0.100	2.48
($d \leq 2.3 \mu\text{m}$)	1.00	0.69
Low-efficiency ESP ^b	0.335	2.30
Multiclone	1.34	1.35
High-efficiency cyclone	2.51	1.40
Medium-efficiency cyclone	4.38	1.04

^aBelow $0.4 \mu\text{m}$, filter efficiency assumed to be 0.95.

^bElectrostatic precipitator.

When comparing these results to those on the levels of purity required for turbine operation, it is easily seen that HTHP particulate removal is a formidable task. To obtain a perspective, one should bear in mind that the HTHP cleanup system of the Exxon PFBC Miniplant is capable of achieving an overall removal efficiency of 99.5% (based on 90% removal by inertial separation), yet is unable to obtain outlet grain loadings lower than 0.05 gr/scf. This level is about 250 times higher than existing turbine requirements and 25 times higher than projected standards.

9.3 Limitations and Assumptions

Admittedly, a large number of assumptions were involved in the foregoing analysis. Without these assumptions, an analysis would have been impossible. It is impossible to determine to what extent the distributional data taken from one plant at one time are representative of the entire spectrum of operation. Nonetheless, in the absence of other information, such data must be considered at least typical, if not characteristic, of one subset of conditions that could be encountered in actual operation.

At this time, we are unable to compare the results of this study with actual system performance data because no such data exist. However, from what little data are available on the performance of individual devices in HTHP applications, it appears that the behavior of several generic devices as predicted by Shannon compares favorably with the actual behavior computed from manufacturers' data or experimentally

derived values.⁴⁹ Exceptions to this rule occur in the cases of tornado cyclones (overestimated by Shannon) and granular-bed filters (underestimated by Shannon); these differences in performance may be attributable to uncertainties associated with the generic rather than specific nature of Shannon's results.

10. ECONOMICS

The economic advantages of a hot-gas cleanup system must be demonstrated in order to validate its selection over an alternative cold gas purification process involving heat exchange, gas treatment and thermal regeneration. In a recent study by Jones and Donohue⁵⁰ for EPRI, which compared the economics of the high-temperature Morgantown iron oxide desulfurization process to those of the low-temperature Benfield potassium carbonate process, it was shown that only under limited circumstances would the high-temperature route be clearly the favored choice.

As a basis of this comparison, they examined the behavior of the following five gasification processes for plants having a net electrical capacity of 1000 MW.

1. Lurgi pressurized moving bed, air-blown gasifier;
2. Lurgi pressurized moving bed, oxygen-blown gasifier;
3. British Gas Corporation (BGC) pressurized-type, moving bed gasifier, oxygen-blown and slagging;
4. air-blown, entrained-bed gasifier currently under development by Foster Wheeler Corporation; and
5. oxygen-blown, entrained-bed gasifier currently under development by Foster Wheeler Corporation.

In all cases, it was assumed that high-temperature dust removal (100%) was available using cyclones, bed filters, and metal cloth units. In addition, the following economic criteria were assumed:

1. mid-1975 dollar with no escalation;
2. 36-month construction period;
3. 10% construction loan interest, compounded quarterly;
4. 70% operating load factor;
5. 25-year plant life;
6. 50:50 debt to equity ratio;
7. 8% bond interest, compounded semiannually; and
8. 12% return on equity after taxes, compounded semiannually.

The results obtained from this study are summarized in Tables 12 and 13, in which data on process thermal efficiencies and capital costs are presented. Examination of this data reveals that only the Lurgi gasification system will benefit from the development and use of a high-temperature gas purification system. This advantage is attributed to the following reasons:

1. The Lurgi gasifiers were the only systems in the study considered to have a net production of tars. 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 to 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 to 40%).

2. The Lurgi gasifiers consume large quantities of steam to prevent ash matter from clinkering in the bottom. Most of the steam passes through the gasifier unconverted and is condensed in the gas

Table 12. Summary of estimated thermal efficiencies

Purification	Cold Benfield	Hot Morgantown	Cold Benfield	Hot Morgantown
Gas turbine inlet temperature, °F	1,950	1,950	2,400	2,400
Lurgi (O ₂) Thermal efficiency ^a	29.4	35.4	32.4	39.9
Heat rate ^b	11,628	9,630	10,544	8,558
Lurgi (air) Thermal efficiency	31.0	37.0	34.5	41.2
Heat rate	10,994	9,223	9,907	8,285
Slagging (O ₂) Thermal efficiency	36.5	37.5	39.6	40.6
Heat rate	9,352	9,095	8,624	8,409
Entrained bed (air) ^c Thermal efficiency	38.0	38.4	40.8	41.6
Heat rate	8,982	8,879	8,359	8,215
Entrained bed (O ₂) ^c Thermal efficiency	35.4	36.6	37.8	39.3
Heat rate	9,641	9,334	9,028	8,688

$$^a \text{Thermal efficiency (\%)} = \frac{(\text{delivered kW})(3412.75)(100)}{(\text{coal lb/hr})(\text{coal HHV Btu/lb})}$$

^b Heat rate in Btu/kWhr.

^c Foster Wheeler gasifier.

Source: C. H. Jones and J. M. Donohue, Comparative Evaluation of High and Low Temperature Gas Cleaning for Coal Gasification - Combined Cycle Power Plants, Stone & Webster Engineering Corp., Process Industries Group, One Penn Plaza, New York, N.Y., for EPRI, EPRI AF-416 (April 1977).

Table 13. Summary of estimated capital requirements^a for 1000-MW gasification – combined-cycle power plants

Purification	Cold Benfield	Hot Morgantown	Cold Benfield	Hot Morgantown
Gas turbine inlet temperature, °F	1950	1950	2400	2400
Lurgi (O ₂ dry ash)	1117	739	1046	703
Lurgi (air dry ash) Total capital	1000	667	936	642
Slagging (O ₂) Total capital	643	629	629	606
Entrained bed (air) ^b Total capital	619	616	604	597
Entrained bed (O ₂) ^b Total capital	670	679	658	657

^aAll capital estimates are based on mid-1975 dollars with no escalation. Capital requirements (\$/kW) correspond to plant investment with adjustment for Illinois sales tax, preproduction costs, royalty payments, initial catalyst and chemicals, construction loan interest and working capital. The capital requirements tabulated above represent an increase of 34% over the plant investment estimates due to inclusion of these allowances.

^bFoster Wheeler gasifier.

Source: C. H. Jones and J. M. Donohue, Comparative Evaluation of High and Low Temperature Gas Cleaning for Coal Gasification – Combined Cycle Power Plants, Stone & Webster Engineering Corp., Process Industries Group, One Penn Plaza, New York, N.Y., for EPRI, EPRI AF-416 (April 1977).

quench operation, rendering the sensible heat of the steam 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.

3. Both the BGC slagging and the oxygen-blown, entrained-bed gasifier require only 13% of the steam required by the dry ash, oxygen-blown Lurgi gasifier. They convert approximately 90% of the gasifier steam to hydrogen and carbon monoxide. Therefore, steam losses due to the cooling of the gasifier effluents in the quench operation are negligibly small.

Much of the savings associated with the deployment of a Lurgi hot fuel gas purification system are the result of the elimination of equipment necessary in the low-temperature purification case. These include a separate tar-fired boiler with stack gas scrubber and a large water treatment facility to treat the condensed gas liquor. The remainder of the economic difference between the two methods can be directly attributed to the large heat rate advantages associated with systems employing high-temperature gas purification.

In addition, one important reason why hot fuel gas purification shows smaller thermal efficiency advantages than might be expected on a superficial analysis is the thermal cost of hot-sulfur absorbent regeneration. This amounts to a loss of about 1.5 net thermal efficiency percentage points for the coal studied.

In a similar study conducted by United Technologies Corporation, comparative costs were developed for two 1000-MW gasification combined-cycle systems, one using high-temperature cleanup and the other using

low-temperature cleanup. In both cases, a BIGAS entrained-flow gasifier was selected as the principal process unit, and the following configurations constituted the gas purification train:

- Low-temperature purification:

Particulate removal--waste heat boiler followed by
wet scrubbing,

Sulfur removal--Selexol.

- High-temperature purification:

Particulate removal--cyclones followed by a final filter
capable of conditioning the product
gas to conform to turbine particulate
allowances,

Sulfur--Conoco's half-calcined dolomite process.

Results of this study are presented in Table 14. As in the previous study, only marginal benefits in terms of economy and efficiency accrue from the deployment of a high-temperature rather than low-temperature cleanup system.

Although these results are derived for only a small number of gasification processes, they indicate that in addition to circumventing significant technical problems, major advances in HTHP filtration technology will be required to make it economically attractive.

Table 14. Summary of estimated capital costs and operating efficiencies for
1000-MW gasification - combined-cycle power plant
developed by United Technologies Corporation

	BCR-Selexol low-temperature	BCR-Conoco high temperature	Conventional steam FGD ^a
Gasifier and cleanup system cost, \$	231,300,000	210,800,000	94,000,000
Power system cost, \$	285,300,000	296,500,000	415,400,000
Total cost, \$	516,600,000	507,300,000	509,400,000
Net plant output, MW	1088	1126	957
Overall plant efficiency, % ^b	43.5	45.0	36.5
Generating costs, mills/kWhr			
Owning costs	13.2	12.5	14.7
Operation and maintenance	4.4	4.1	4.0
Fuel, \$1.00/MMBtu	7.8	7.6	9.6
Total generating cost, mills,kWhr	25.4	24.2	28.3

^aFlue-gas desulfurization.

^bCoal pile to busbar efficiency.

11. ENVIRONMENTAL EFFECTS

Because of the stringent requirements imposed on the particulate content of the turbine expansion gas, it appears as though the EPA's new source performance standard (NSPS) for direct coal combustion of 0.1 lb/10⁶ Btu can be met easily by any hot-gas purification system satisfying the turbine needs. Although it is true that this figure is only valid for new coal-fired sources, we will assume that it can be used as a benchmark for estimating the allowable emissions from gasification plants. In this event, 0.1 lb/10⁶ Btu translates to roughly 0.056 gr/scf for PFBC operation and 0.087 gr/scf for gasifier operation, both of which are well above the recommended 0.002 gr/scf value needed for acceptable turbine life.

Similarly, if required particulate tolerances can be met, then there appears to be no problem associated with compliance to the opacity regulations regarding plume visibility covered under the secondary standards of the National Environmental Policy Act. This apparent compliance, so to speak, is based on the analysis of Knapp⁵¹ in which Mie scattering is considered the principal mechanism of light attenuation. Mathematically, the model is given as:

$$M = \frac{2}{3} \frac{\bar{D}\rho}{\bar{\phi}L} \ln(T),$$

where

M = mass loading per unit volume,

$\bar{D}$ = area-mean particle diameter,

$\bar{\phi}$ = area-mean extinction coefficient,

ρ = particle density,

L = optical path length,

T = transmission.

The mean extinction coefficient ($\bar{\phi}$) is a function of the particle size, its refractive index, and the wavelength of the incident light. Typical results from this model for various area mean particle diameters are presented in Fig. 13. Should either the particulate loading be allowed to increase or exceptionally small, opaque particles constitute the bulk of the matter in the effluent stream, problems in meeting environmental constraints could arise.

For the other major air pollutants from point sources controlled by federal standards (SO_2 and NO_x), current turbine tolerances are insufficient and may not meet existing EPA restrictions. EPA's NSPS for SO_2 emitted from a direct coal-fired power plant is $1.2 \text{ lb SO}_2/10^6 \text{ Btu}$ fuel input. For NO_x , the appropriate value is $0.7 \text{ lb NO}_2 \text{ (equivalent)}/10^6 \text{ Btu}$. Standards have not been specifically promulgated for plants that convert coal to fuel gas, but it is unlikely that such standards, if promulgated, will permit levels higher than those mentioned.

The required level of sulfur control can be related to the fuel heating value, as shown in Fig. 14. The current NSPS for SO_2 is indicated in this figure.

Many of the processes under development for H_2S removal have demonstrated (at least on a laboratory scale) the ability to remove sulfur below the equivalent of $1.2 \text{ lb SO}_2/10^6 \text{ Btu}$. In some systems, levels lower than this by a factor of 2 or 3 have been reached. However, H_2S removal to these lower levels is sometimes accompanied

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Fig. 13. Variations in opacity with mass concentration in effluent gas stream for different mean particle sizes (Source: ref. 51).

Fig. 14. Sulfur dioxide emissions (lb SO₂/10⁶ Btu) as a function of hydrogen sulfide content of raw product gas (ppmv) for fuels with different heating values.

by significant reductions in throughput capacity. In other systems (principally those using dolomite), basic thermodynamic equilibrium prevents the attainment of very low residual H_2S contents.

Sulfur compounds other than H_2S may play a significant role and must also be included in determination of SO_2 emissions. Most of the systems under development have not been examined for possible control of other sulfur species (e.g., COS, thiophene, CS_2 , mercaptans). However, these are generally present at low levels, and it is apparent that several systems have the potential to meet the current standards for SO_2 emissions even if H_2S were assumed to be the only sulfur compound removed.

In regard to nitrogen compounds, current standards place a maximum limit on NO_x emissions of 0.7 lb NO_2 (equivalent)/ 10^6 Btu. Formation of nitrogen oxides results from two mechanisms--the oxidation of nitrogen compounds in the fuel gas (NH_3 , HCN, etc.) and the thermal fixation of nitrogen during combustion. Both of these mechanisms are complex and are strongly influenced by the concentration of nitrogen compounds in the fuel gas and the combustion conditions. Current research efforts^{30,33,40,52} indicate that thermal fixation of nitrogen by itself can be controlled through combustion techniques to prevent exceeding the allowable NO_x limit. However, the combined effect of thermal fixation and oxidation of nitrogen compounds in the fuel gas could well produce NO_x levels in excess of the limit mentioned. Specific processes for the removal of nitrogen compounds from fuel gas do not exist, and alternative hot-gas cleanup processes (H_2S and particulate removal), as currently envisioned, do not eliminate these compounds.

12. RECOMMENDATIONS AND CONCLUSIONS

Without a doubt, any type of HTHP gas filtration whose final goal is to produce a product stream suitably clean for gas turbine application from either gasifier or PFBC effluent will be a formidable task. At best, at least a 99% overall collection efficiency will be required even under the most favorable conditions.

In addition to the stringent cleanup demands, the presence of condensable hydrocarbons in a number of gasification processes will require the operation of HTHP filtration systems at temperatures above 1000°F. Below this temperature, HTHP particulate removal may not be a viable option because of problems caused by condensation. In addition, it appears as though major advances in HTHP filtration technology will be required in order to make it an economically attractive option.

Unlike gasification in which fuel gas can be cooled, regenerated, and fired, pressurized fluidized-bed combustion demands HTHP filtration to ensure its economic viability. This occurs because PFBC effluent contains no combustible product whose ignition would compensate for the thermal losses incurred during the cooling and regeneration phases of low-temperature cleanup processes.

Currently, most conceptual designs of HTHP departiculation processes include two stages of inertial separation (cyclones) prior to final gas treatment by a tertiary device which conditions the product gas to the levels of purity required for turbine application. To date, only one of these systems has been built, the Exxon Pressurized Fluidized Combustor (PFBC) Miniplant, and preliminary data indicate that significant problems are associated with its use. Among these are:

1. the inability of the system to achieve outlet grain loadings below 0.05 gr/scf;
2. cleaning problems associated with the formation of a dense filter cake on the inlet retaining screens of the tertiary granular bed unit; and
3. system susceptibility to upset, requiring shutdown in order to restore operation.

From these results, it is apparent that significant technical advances will have to be made before this system becomes a viable HTHP filtration alternative.

In order to expedite the development of HTHP deagglomeration processes, the Combustion Power Company's Dry Scrubber at the Morgantown Energy Research Center should be tested. By doing so, significant questions concerning its applicability and reliability in HTHP domains could be answered.

In addition, another choice involving research in HTHP purification that could be undertaken is the synthesis of a hybrid filtration system involving three elements. This would include an electrofluidized bed to capture fine particulate ($< 3 \mu\text{m}$), a cyclone to scalp off most of the heavy material ($> 10 \mu\text{m}$), and a final polishing device to remove the intermediate-range material (3 to $10 \mu\text{m}$). The third and final unit would be either a fabric element, a Brunsmet filter, a Ducon unit, or a CPC dry scrubber, depending on how these devices performed in the previous tests. This program is a research option that should be considered as a potential rather than deliverable choice.

In gas turbine applications, sulfur is a factor in blade corrosion principally through the mechanism of alkali sulfate formation, as discussed in Sect. 5. However, it is not possible to control sulfur contents by high-temperature processes to the levels required to eliminate this problem. Consequently, attempts to reduce such corrosion have generally been limited to control of the alkali content of the fuel. Nonetheless, because of environmental considerations, it is necessary to have available HTHP H_2S removal systems capable of conditioning the effluent to levels compatible with environmental constraints. Currently, there are no commercially available HTHP H_2S removal processes capable of meeting the value of $1.2 \text{ lb } SO_2/10^6 \text{ Btu}$ set by the EPA for sulfur emissions from a coal-fired power plant. Such processes are, however, under development; Appendix F lists several of these proposed systems, all of which have laboratory-scale data indicating that they could meet this level of SO_2 control.

In terms of the development status of selected H_2S removal systems, the following observations can be made:

1. Only the Appleby-Frodingham process has been commercially applied to processes operating at high temperatures ($< 800^\circ F$).
2. The most promising evolving concepts for HTHP application in the near term appear to be the MERC iron oxide-silica process and the Conoco fluid-bed, half-calcined dolomite process. Commercial application of the MERC process would be technically feasible sooner because of its simplicity of operation, current stage of development, and durability of H_2S removal media. On

the other hand, the Conoco process will require more extensive testing to determine its technical feasibility on a commercial scale.

3. In addition to requiring further research to validate its technical feasibility, the use of alkali salts by the Battelle molten salt scrubber presents problems that appear to preclude its use in systems designed to condition fuel gas for turbine operation.

Recommendations concerning future development of H₂S removal systems include pursuit of the MERC iron oxide process for earliest applications, and sufficient investigation of the Conoco dolomite and Battelle molten salt processes to determine the potential economic advantages (if any) of these alternatives.

In the future, emphasis should be placed on the general question of the desirability of hot-gas cleanup. It has not yet been clearly established that hot-gas cleanup has the potential effectiveness required for turbine application or that the economic advantages which may accrue from such use justify further development funds. In addition, efforts should be devoted to assessing other potential hot-gas cleanup applications, where more lenient tolerances (especially for particulates and alkali compounds) may offer a better fit for the abilities of hot-gas cleanup systems. An example of such an application would be hot-gas cleanup of a low-Btu gas generated by a gasifier providing process heat to an industrial park. In such circumstances, production of sulfuric acid as a by-product of hot H₂S removal (currently counted a disadvantage in utility applications) may prove a distinct asset.

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41. R. A. Kennedy, H. Dhillon, and J. B. Truet, EPA and ERDA High Temperature/High Pressure Particulate Control Programs, Mitre Corporation, McLean, Va., EPA-600/7-77-013 (February 1977).
42. A. K. Rao, M. P. Schrag, and L. J. Shannon, Particulate Removal from Gas Streams at High Temperature/High Pressure, Midwest Research Institute, 425 Volker Boulevard, Kansas City, Mo., for ERDA, EPA-600/2-75-020 (August 1975).
43. S. Calvert and R. Parker, "Collection Mechanisms at High Temperature and Pressure," paper presented at the Particulate Control in Energy Processes Symposium, San Francisco, Calif., May 11-13, 1976, prepared for EPA-IERL, NTIS PB-260 499 (September 1976).
44. L. J. Shannon, P. G. Corman, and M. Reichel, Particulate Pollutant System Study, vol. II: Fine Particulate Emissions, Midwest Research Institute, 425 Volker Boulevard, Kansas City, Mo. for EPA, NTIS PB-203 521.
45. B. Kalen and F. A. Zenz, paper presented at the 65th AIChE Annual Meeting, N.Y., 1972.
46. R. C. Hoke and M. W. Gregory, "Evaluation of a Granular Bed Filter for Particulate Control in Fluidized Bed Combustion," paper presented at EPA/ERDA Symposium on Particulate Removal, Sept. 20-21, 1977, Washington, D.C.
47. R. Vander Molen, Combustion Power Company, 1346 Willow Rd., Menlo Park, Calif., private communication.
48. Advanced Coal Gasification System for Electric Power Generation Quarterly Progress Report, Second Quarter - Fiscal Year 1976, Westinghouse Electric Co., Heat Transfer Division, for ERDA, FE-1514-45 (January 1976).
49. J. P. Meyer and M. S. Edwards, Survey of Industrial Coal Conversion Equipment Capabilities: Research Needs and State-of-the-Art of High Temperature - High Pressure Gas Purification, ORNL/TM-6072 (June 1978).
50. C. H. Jones and J. M. Donohue, Comparative Evaluation of High and Low Temperature Gas Cleaning for Coal Gasification - Combined Cycle Power Plants, Stone & Webster Engineering Corp., Process Industries Group, One Penn Plaza, New York, N.Y., for EPRI, EPRI AF-416 (April 1977).

51. K. T. Knapp, "New Techniques for Continuous Measurement of Mass Emissions," from Proceeding of the Workshop on Sampling, Analysis and Monitoring of Stack Emissions, Southern Research Institute, Birmingham, Ala., for EPRI, NTIS PB-252-746 (April 1976).
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APPENDIX A:
INITIAL INQUIRY LETTERS AND FOLLOW-UP LETTERS SENT TO
DIFFERENT FIRMS INVOLVED IN THIS WORK

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

February 23, 1977

Dear Sir:

The Oak Ridge National Laboratory is conducting a study for the Energy Research and Development Administration to assess the existing technological and productive capability of U.S. industry to provide components for coal utilization plants. As part of this study, we are investigating the availability of high temperature gas cleaning equipment (hydrogen sulfide and particulate removal systems). The equipment would operate at temperatures above 600°F and possibly up to 2400°F, and at pressures in the range 0 - 750 psig. These conditions are encountered in high efficiency coal conversion technologies such as pressurized fluid bed combustion and low-Btu gasification combined cycle plants.

We are trying to identify potential suppliers of such equipment and would appreciate any help you could give us on a no-charge basis.

To date, we have been able to identify a number of potential processes and items of equipment which we believe capable of removing impurities from coal-derived gases at high temperatures and have included them in Tables 1 and 2. We would appreciate your taking a look at these tables and providing any additional information or comments you may have based on your experience in these areas. Since the lists are not comprehensive, some vendors may have been overlooked. Any information you could provide as to contacts who have information regarding applicability, industrial applications, operating conditions and costs for high temperature gas cleaning equipment would be appreciated. In addition, should you know of other technologies not necessarily related to power generation yet applicable to gas cleanup, please bring them to our attention. For example, information on particulate removal techniques used in catalytic cracking and catalyst regeneration would be most useful.

February 23, 1977

Please note that no purchase is planned at this time. If any questions arise please contact me at (615) 483-8611 (ext. 3-1696) or Michael S. Edwards at the same number, ext. 3-6491.

Very truly yours,

A handwritten signature in dark ink, appearing to read 'James P. Meyer', followed by a long horizontal line.

James P. Meyer
Engineering Coordination and
Analysis Section
Chemical Technology Division

JPM:msb

Attachments

Table 1

High temperature particulate removal
($> 600^{\circ}\text{F}$)

I. Mechanical collectors

A. Cyclones

1. Buell-Norblo
2. Ducon
3. Babcock & Wilcox

B. Aerodyne-Tornado

II. Bed filters

- A. Combustion Power Co. (moving pebble bed)
- B. Ducon (granular bed)
- C. City College of New York (panel bed sand filter)
- D. Rexnord Air Poll. (gravel bed)

III. Surface filters

A. Bag filters

1. J. P. Stevens (silica fiber)
2. Owens Corning (fiberglass with proprietary binding)
3. 3M Co. (alumina-boria-silica, zirconia-silica fibers)
4. Brunswick (metal felt fiber) - Brunsmet
5. Am. Precision, Dustex Div. (electrostatic charged filter) - Apitron

B. Ceramic and porous metal filters

1. Norton Co. (ceramic)
2. Pall-Trinity Micro Corp (sintered metal)
3. Selas

IV. Electrostatic precipitators

- A. Research Cottrell - H. J. Hall Assoc.
- B. BuMines - C. C. Shale - 1960's
- C. Combustion Power (CPU-400 program)

V. Other equipment

- A. Molten salt scrubbing - Battelle NW
- B. Impingement (VEFL) - Babcock & Wilcox
- C. Sonic agglomeration - Braxton

Table 2

High temperature H_2S removal

- I. Solid sorption
 - A. Iron oxide
 - 1. BuMines-Morgantown Energy Research Center (fixed bed)
 - 2. Appleby-Frodingham (fluid bed)
 - 3. Babcock & Wilcox (iron plates)
 - 4. University of Kentucky (flyash)
 - B. Proprietary: Battelle-Columbus
 - C. Dolomite/Limestone
 - 1. Consolidation (half calcined fluid bed)
 - 2. Air products (calcined fixed bed)
 - 3. CCNY (half calcined panel bed)
 - 4. Westinghouse (gasify with limestone)
 - D. Copper oxide - Kennecott Copper
- II. Liquid sorption
 - A. Molten salt
 - 1. Battelle-NW (venturi scrub)
 - 2. Kellogg (molten-salt gasifier)
 - 3. Atomics International (molten-salt gasifier)
 - B. Molten metal-IGT/Meissner
(may also be molten salt)

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

March 15, 1977

Dear Sir:

The Oak Ridge National Laboratory is conducting a study for the Energy Research and Development Administration to assess the existing technological and productive capability of U.S. industry to provide components for coal utilization plants. As part of this study, we are investigating the availability of high temperature gas cleaning equipment, specifically particulate removal systems. The equipment would operate at temperatures above 800°F (700K) and possibly up to 2200°F (1500K) and at pressures in the range 0 - 750 psig (100 - 77,500KPa). These conditions are encountered in high efficiency coal conversion technologies such as pressurized fluid bed combustion and low-Btu gasification combined cycle plants.

We are trying to identify potential suppliers of such equipment and would appreciate any help you could give us on a no-charge basis.

Because of the diversity encountered in the multitude of available gasification schemes, we have characterized the range of operation into the following types of service:

Service	Temperature: °F (K)	Pressure: Atm Abs (KPA)	Particulate Loading: lb/scf (kg/m ³ 289K, 1013KPa)	Particulate Condition
			(kg/m ³ 289K, 1013KPa)	
Low	850 - 1000 (728 - 811)	10 - 20 (1013 - 2026)	2.3 x 10 ⁻⁴ - 1.5 x 10 ⁻³ (3.7 x 10 ⁻³ - 2.4 x 10 ⁻²)	Wet/Dry
Medium	1400 - 1800 (1033 - 1255)	10 - 15 (1013 - 1520)	4 x 10 ⁻³ (6.4 x 10 ⁻²)	Dry
High	1600 - 2200 (1144 - 1478)	1 - 20 (101 - 2026)	1.0 x 10 ⁻³ - 4 x 10 ⁻² (1.6 x 10 ⁻² - 6.4 x 10 ⁻¹)	Dry

All conditions have a log-normal particle size distribution with a mean particle diameter of 130 µm and variance of 10 µm.

March 15, 1977

In this phase of the study we are interested in identifying specific equipment capable of cleaning hot gas streams. Examples of such equipment include the following:

- cyclones or multiclones
- electrostatic precipitators
- filters
- scrubbers
- novel devices

The type of information we are seeking should include:

- temperature and pressure operating range
- removal efficiency as a function of particle size
- capacity (ACFM and loading in lb/scf), or m^3/s and loading in kg/m^3
- pressure drop
- power requirements
- materials of construction
- dry or wet particulate compatibility
- costs (capital, installation and operating)
- current developmental status (if not an off-the-shelf item)
- special maintenance procedures

Please note that no purchase is planned at this time. If any questions arise, please contact me at (615) 483-8611 ext. 3-1696. Thank you very much for your cooperation.

Very truly yours,

James P. Meyer
Engineering Coordination and
Analysis Section
Chemical Technology Division

JPM:msb

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

March 24, 1977

Dear Sir:

The Oak Ridge National Laboratory is conducting a study for the Energy Research and Development Administration to assess the existing technological and productive capability of U.S. industry to provide components for coal utilization plants. At present, the focus of our work is devoted to an assessment of existing hot gas cleanup systems capable of removing particulate matter and hydrogen sulfide from contaminated gas streams. After being cleaned, it is envisioned that these streams will be combusted and used to drive gas turbines for electricity generation.

In order to assess the capabilities of existing hot gas cleanup devices, it is necessary to obtain information regarding turbine inlet gas purity requirements. We would greatly appreciate any help you could give us in this regard on a no-charge basis.

Specifically, the data we are seeking includes:

- Information regarding variations in turbine blade life with changes in inlet particulate loading.
- Data on how particulate loading limits vary with turbine inlet temperature
- Information as to tolerances on inlet particle size distributions
- Information as to the effects of particulate composition

As a point of departure, it may be assumed that we will be dealing exclusively with large horsepower multistage turbines (>10,000 hp)

March 24, 1977

capable of driving electrical utility generators, with inlet temperatures varying from 1400 to 2600°F and inlet velocities in the range of 600 to 1200 ft/sec.

At this time, it should be noted that no purchase is planned. Thank you for your help. We will be glad to supply any additional information you may need.

Sincerely,

A handwritten signature in dark ink, appearing to read 'James P. Meyer', with a long horizontal flourish extending to the right.

James P. Meyer
Engineering Coordination and
Analysis
Chemical Technology Division

JPM:msb

OAK RIDGE NATIONAL LABORATORY

OPERATED BY

UNION CARBIDE CORPORATION

NUCLEAR DIVISION

POST OFFICE BOX X

OAK RIDGE, TENNESSEE 37830

April 1, 1977

Dear Sir:

Recently we sent you a letter requesting your assistance in reviewing a list of available equipment for particulate removal and desulfurization from hot fuel gas streams. We wondered if you have had a chance to look at this yet. This survey is being done for ERDA/Fossil Energy in regard to possible applications to synthetic fuels plants, and we are trying to collect responses by April 15.

Thank you for your help.

Very truly yours,

A handwritten signature in cursive script, likely of James P. Meyer, followed by a horizontal line.

James P. Meyer
Engineering Coordination and
Analysis
Chemical Technology Division

JPM:msb

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

Dear Sir:

Oak Ridge National Laboratory is conducting an investigation for the Major Facility Project Management Division of the Energy Research and Development Administration to determine industrial capabilities in several areas pertinent to coal utilization. One area crucial to the attainment of high process efficiencies is high temperature gas cleanup; the removal of hydrogen sulfide and possibly particulates, ammonia, and alkali metals from fuel gases at temperatures of 600 to 2400°F (590 to 1600K). Equipment capable of high temperature cleaning, at pressures above 100 psig (0.8 MPa), will be required in demonstrating and commercializing high efficiency coal conversion technology such as low Btu gasification combined cycle plants.

We are trying to identify potential suppliers and developers of such equipment and would appreciate any help you can provide on a no-charge basis. A number of potential processes and items of equipment are shown in Table 1, attached. Information on these or other possibilities would be very useful to us in assessing the potential for hot gas H₂S removal. In addition, information relating to possible ammonia or alkali removal processes or equipment under the above conditions is needed. An example of a low Btu fuel gas is shown in Table 2, listing the major components and the important minor and trace constituents. The operating conditions are shown also, although substantial variations are expected in flow rates, temperature, etc. For example, the temperature exiting the gasifier (Texit) is shown as 1700°F (1200K); the actual exit temperature encountered in various gasifiers can range from 1000 to 1900°F or more (800 to 1300K).

Please assume that the sulfurous compounds listed in Table 2 must be removed to below 1000 ppm by volume to meet environmental regulations when discussing process applicability. The type of information we are seeking, insofar as it is known, includes:

- temperature and pressure operating range
- removal efficiency as a function of operating conditions

- capacity (gas flow and/or amount of sulfur)
- pressure drop
- power requirements
- materials of construction
- particulate compatibility
- costs (capital, installation and operating)
- current developmental status (if not an off-the-shelf item)
- special maintenance procedures

Please note that no purchase is planned at this time. If any questions arise, please contact me at (615)483-8611, ext. 3-0159. Thank you for your cooperation in this effort.

Yours truly,

M. S. Edwards
Engineering Coordination
and Analysis Section
Chemical Technology Division

MSE:jt

Attachments

Table 1. High temperature H₂S removal

I. Solid sorption

A. Iron oxide

1. BuMines-Morgantown Energy Research Center (fixed bed)
2. Appleby-Frodingham (fluid bed)
3. Babcock & Wilcox (iron plates)
4. University of Kentucky (flyash)

B. Proprietary: Battelle-Columbus

C. Dolomite/Limestone

1. Consolidation (half calcined fluid bed)
2. Air Products (calcined fixed bed)
3. CCNY (half calcined panel bed)
4. Westinghouse (gasify with limestone)

II. Liquid sorption

A. Molten salt

1. Battelle-NW (venturi scrub)
2. Kellogg (molten-salt gasifier)
3. Atomics International (molten-salt gasifier)

B. Molten metal-IGT/Meissner
(may also be molten salt)

Table 2. Example product gas

Major & Minor Components	Mole %	Trace Components	PPM (by volume)
CO	20.00	HCl	110
CO ₂	8.00	KCl	2.1
H ₂	13.95	NaCl	0.8
H ₂ S	0.70		
COS	0.05		
N ₂	48.00		
CH ₄	3.00		
NH ₃	0.30		
H ₂ O	6.00		
Total	100.00		

Operating Conditions

Coal	Ill. #6
Texit	1700°F (1200K)
Pexit	250 psia (1.7 MPa)
Heating Value (HHV)	150 Btu/scf (132 kJ/mole)

Sample Flow Rates:	<u>lb mole/hr</u>	<u>(mole/s)</u>
Utility Electric Plant	100,000	(12,600)
Industrial Steam Boiler	5,000	(630)

*Reflects a hypothetical air-blown gasifier.

OAK RIDGE NATIONAL LABORATORY

OPERATED BY

UNION CARBIDE CORPORATION

NUCLEAR DIVISION

POST OFFICE BOX X

OAK RIDGE, TENNESSEE 37830

April 18, 1977

Recently we sent you a letter requesting your assistance in identifying gas turbine tolerances (particulate, chemical composition, etc.) for units operating at high inlet temperatures and fired with low Btu gas. We wondered if you had a chance to look at this yet. This work is being done for ERDA/Fossil Energy in regard to possible applications to synthetic fuels plants, and we are trying to collect responses by May 15.

Your assistance in this effort will be sincerely appreciated.

Very truly yours,

A handwritten signature in dark ink, appearing to read "James P. Meyer", with a long horizontal line extending to the right.

James P. Meyer
Engineering Coordination and
Analysis
Chemical Technology Division

JPM:msb

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APPENDIX B:

NAMES AND ADDRESSES OF INDIVIDUALS OR ORGANIZATIONS CONTACTED
REGARDING HOT-GAS CLEANUP

Design-Construction Firms

<p>* Mr. George Frey
United Engineers & Construction Co.
30 S. 17th Street
Philadelphia, Pa. 19101</p> <p>Mr. Lester Pease
Fluor Corp.
Engineers & Constructors, Inc.
P. O. Box 11977
Santa Ana, Calif. 92711</p> <p>* Mr. Charles M. Whitten
Bechtel Inc.
50 Beale Street
P. O. Box 3965
San Francisco, Calif. 94119</p> <p>* Mr. James P. Sheehan
Sleearns-Roger Corp.
702 S. Ash Street
P. O. Box 5888
Denver, Colo. 80217</p> <p>Mr. R. J. Feldman
The Lummus Co.
1515 Broad Street
Bloomfield, N.J. 07003</p> <p>Mr. Warren Mindheim
Ralph M. Parsons Co.
100 W. Walnut
Pasadena, Calif. 91124</p> <p>* Dr. Ernest Zabolotny
Stone & Webster Engineering Corp.
P. O. Box 2325
245 Summer Street
Boston, Mass. 02107</p> <p>* Mr. Thomas H. Holzberger
Pullman Kellogg - R&D
16200 Park Road
Industrial Park 10
Houston, Tex. 77084</p> | <p>Mr. Robert Meichle
Senior Engineer
C. F. Braun & Co.
1000 S. Fremont Avenue
Alhambra, Calif. 91802</p> <p>* Mr. Joseph T. Roe
Senior Consultant
Brown & Root
4100 Clinton Drive
P. O. Box 3
Houston, Tex. 77001</p> <p>Mr. John H. Robertson
Catalytic, Inc.
Centre Square West
1500 Market Street
Philadelphia, Pa. 19102</p> <p>* Mr. Wesley Hunting
The Austin Co.
3650 Mayfield Road
Cleveland, Ohio 44121</p> <p>Mr. Wayne Kramer
Fluidized Combustion Co.
110 S. Orange Avenue
Livingston, N.J. 07039</p> <p>* Mr. Gary Herrin
The Badger Co.
1 Broadway
Cambridge, Mass. 02142</p> <p>* Mr. Bruce McNab
Arthur G. McKee & Co.
6200 Oak Tree Boulevard
Independence, Ohio 44131</p> <p>* Mr. Robert Culbertson
Dravo Corp.
One Oliver Plaza
Pittsburgh, Pa. 15222</p> |
|---|--|

*A response was received.

- * Mr. Charles Best
Environmental Systems
Procon, Inc.
30 UOP Plaza
Algonquin & Mt. Prospect Roads
Des Plaines, Ill. 60016
- * Mr. Donald A. Huber
Burns & Roe, Inc.
283 Route 17 South
P. O. Box 663
Paramus, N.J. 07652
- * Mr. Henry Cruse
Jacobs Engineering Co.
837 S. Fair Oaks Avenue
Pasadena, Calif. 91105
- * Mr. John Lagarias
Kaiser Engineers
Div. of Kaiser Industries Corp.
300 Lakeside Drive
Oakland, Calif. 94666
- * Mr. W. H. Alexander
The Litwin Corp.
110 N. Market
P. O. Box 282
Wichita, Kan. 67201
- Mr. G. Dean Barrett
J. F. Pritchard & Co.
4625 Roanoke Parkway
Kansas City, Mo. 64112
- * Dr. M. F. Nathan
Crawford & Russell, Inc.
733 Canal Street
Stamford, Conn. 06904
- * Mr. E. C. Rowan
Ford, Bacon & Davis
3901 Jackson Street
P. O. Box 1762
Monroe, La. 71201
- Mr. Daniel Newman
Barnard & Burk
200 Sheffield Street
Mountainside, N.J. 07092
- Mr. Frank P. Witmer
The Kuljian Corp.
3624 Science Center
Philadelphia, Pa. 19104
- Mr. Edward Bailey
Davy Powergas, Inc.
P. O. Drawer 5000
Lakeland, Fla. 33803
- Mr. Arthur Trombley
Cunningham - Limp Co.
1400 N. Woodward Avenue
Birmingham, Mich. 48011
- Dr. G. K. Chen
Monsanto Enviro-Chemical
Systems Co.
800 N. Lindbergh Boulevard
St. Louis, Mo. 63166
- Mr. Harry Hart
Dorr - Oliver, Inc.
77 Havemeyer Lane
Stamford, Conn. 06904
- * Mr. Richard Marcel
Scientific Design, Inc.
2 Park Avenue
New York, N.Y. 10016
- Mr. Fred Murad
Combustion Equipment Associates
Air Pollution Control Equipment
& Residue Recovery
555 Madison Avenue
New York, N.Y. 10022
- * Mr. David James
New Products
Babcock & Wilcox
Fossil Power Generation Division
20 S. Van Buren Avenue
P. O. Box 351
Barberton, Ohio 44203
- Dr. Henry Osborne
Air Preheater Co.
C-E Process Equipment
Wellsville, N.Y. 14895

Architectural Engineering Firms

* Dr. Michael Klett
Gilbert/Commonwealth
P. O. Box 1498
Reading, Pa. 19603

Mr. Arthur Brearley
Environmental Division
Sargent & Lundy
55 E. Monroe Street
Chicago, Ill. 60603

* Dr. A. Runchel
Dames & Moore
Suite 1000
1100 Glendon Avenue
Los Angeles, Calif. 90024

Mr. John Jacobs
Charles T. Main, Inc.
Southeast Tower
Prudential Center
Boston, Mass. 02199

* Mr. R. H. Gordon
Gibbs & Hill, Inc.
393 Seventh Avenue
New York, N.Y. 10001

Mr. Frederick Brunner
Sverdrup Corp.
800 N. 12th Boulevard
St. Louis, Mo. 63101

Mr. Elvis Couppis
Manager
Environmental Services
Sanderson & Porter, Inc.
25 Broadway
New York, N.Y. 10004

Mr. Henry Teri
Burns & McDonnell
P. O. Box 173
Kansas City, Mo. 64141

Dr. D. H. Breckenfelder
Stanley Consultants, Inc.
Stanley Building
Muscatine, Iowa 52761

Mr. Alan B. Wolf
Pope, Evans & Robbins
1133 Avenue of the Americas
New York, N.Y. 10036

* Mr. E. B. Beckman
Foster-Wheeler Corp.
110 S. Orange Avenue
Livingston, N.J. 07039

* Mr. J. B. Pohlenz
UOP Process Division
20 UOP Plaza
Algonquin & Mt. Prospect Roads
Des Plaines, Ill. 60016

* A response was received.

Individuals Knowledgeable in Hot-Gas Cleanup Technology

<p>* Mr. Fred Moreno
Acurex Aerotherm
485 Clyde Avenue
Mountain View, Calif. 94042</p>	<p>* Mr. F. M. Veazie
Owens-Corning Fiberglas Corp.
Technical Center
Granville, Ohio 43023</p>
<p>* Mr. Albert Tesoriero
Ducon Co.
Subsidiary of U.S. Filter Corp.
147 E. Second Street
Mineola, N.Y. 11501</p>	<p>* Mr. Richard Shaner
Linde Division
Union Carbide Corp.
P. O. Box 44
Tonawanda, N.Y. 14150</p>
<p>* Mr. E. C. Oldaker
Morgantown Energy Research Center
Department of Energy
P. O. Box 880
Morgantown, W. Va. 26505</p>	<p>* Mr. Bernard Lee
IGT
3424 South State Street
IIT Center
Chicago, Ill. 60616</p>
<p>* Mr. R. Moore
Battelle Pacific Northwest
Laboratories
Battelle Boulevard
P. O. Box 999
Richland, Wash. 99352</p>	<p>* Mr. Samuel Jacobsen
TRW, Inc.
Energy Systems Group
1 Space Park
Redondo Beach, Calif. 90278</p>
<p>* Dr. F. A. Zenz
Technical Director
Particle Solids Research Institute
Riverdale Station
P. O. Box 447
Bronx, N.Y. 10471</p>	<p>* Mr. Richard Vander Molen
Combustion Power Co.
1346 Willow Road
Menlo Park, Calif. 94025</p>
<p>* Dr. Arthur M. Squires
Department of Chemical Engineering
Virginia Polytechnic Institute
Blacksburg, Va.</p>	<p>* Mr. F. H. Bunge
Manager of Research
The Hanna Mining Company
100 Ericview Plaza
Cleveland, Ohio 44114</p>
<p>* Mr. H. J. Hall
H. J. Hall Associates, Inc.
Cherry Valley Road
Princeton, N.J. 08540</p>	<p>* Dr. Joseph Yerushalmi
Department of Chemical
Engineering
City College of New York
Convent Avenue at 138th Street
New York, N.Y. 10031</p>
<p>* Mr. W. A. Baxter
Environmental Elements Co.
Subsidiary of Koppers Co.
P. O. Box 1318
Baltimore, Md. 21203</p>	<p>* Dr. O. J. Hahn
Institute for Mining and
Minerals Research
University of Kentucky
Lexington, Ky. 40506</p>

* A response was received.

* Mr. Charles A. Trilling
Atomics International Division
Rockwell International Corp.
8900 DeSoto Avenue
Canoga Park, Calif. 91304

* Mr. George P. Curran
Research Division
Conoco Coal Development Co.
Library, Pa. 15129

^ Mr. L. C. Doelp
Processes & Catalysts
Air Products & Chemicals, Inc.
P. O. Box 427
Marcus Hook, Pa. 19061

Mr. A. W. Lemmon, Jr.
Battelle Columbus Laboratory
505 King Avenue
Columbus, Ohio 43201

* Dr. J. C. Agarwal
Director, Development
Ledgemont Laboratory
Kennecott Copper Corp.
128 Spring Street
Lexington, Mass. 02173

APPENDIX C:
NAMES AND ADDRESSES OF VENDORS CONTACTED REGARDING
HOT-GAS CLEANUP PROCESS EQUIPMENT

Equipment Vendors

<p>* AMF Cuno Div.
AMF, Inc.
402 Research Parkway
Meriden, Conn. 06450</p> <p>* Aerodyne Development Corp.
29085 Solon Road
Solon, Ohio 44139</p> <p>* Aerodyne Machinery Corp.
Subsidiary of General Resource Corp.
201 S. Third Street
Hopkins, Minn. 55343</p> <p>Aeropulse, Inc.
1574 Bridgewater Road
Cornwell Heights, Pa. 19020</p> <p>* Air Correction Division — UOP
Tokeneke Road
Darien, Conn. 06820</p> <p>Air Pollution Industries (Airpol)
95 Cedar Lane
Englewood, N.J. 07631</p> <p>American Air Filter Co., Inc.
215 Central Avenue
Louisville, Ky. 40208</p> <p>American Standard Air
Quality Division
Detroit, Mich. 48232</p> <p>* American Van Tongeren Corp.
3435 Livingston Avenue
P. O. Box 27990
Columbus, Ohio 43227</p> <p>* Ametek, Inc.
3427 Industrial Drive
Durham, N.C. 27704</p> | <p>* Andersen 2000, Inc.
2000 Sullivan Road
P. O. Box 20769
Atlanta, Ga. 30320</p> <p>* Atlas Copco, Inc.
70 Demarest Drive
Wayne, N.J. 07470</p> <p>* BIF
Unit of General Signal Corp.
1600 Division Road
P. O. Box 217
West Warwick, R.I. 02893</p> <p>* Babcock & Wilcox
Fossil Power Generation Division
20 S. Van Buren Avenue
P. O. Box 351
Barberton, Ohio 44203</p> <p>* Belco Pollution Control Corp.
P. O. Box 412
Livingston, N.J. 07039</p> <p>Black, Sivalls & Bryson, Inc.
4242 S.W. Freeway
Houston, Tex. 77027</p> <p>* Brighton Corp.
11862 Mosteller Road
Cincinnati, Ohio 45241</p> <p>* Brunswick Corp.
One Brunswick Plaza
Skokie, Ill. 60076</p> <p>Buckbee — Mears Co.
245 E. Sixth Street
St. Paul, Minn. 55110</p> <p>Buell Emissions Controls
Division of Envirotech
200 N. Seventh Street
Lebanon, Pa. 17042</p> |
|---|---|

* A response was received.

- * Buffalo Forge Co.
490 Broadway
P. O. Box 985
Buffalo, N.Y. 14240
- * Buhler-Miag, Inc.
8925 Wayzata Boulevard
Minneapolis, Minn. 55426
- CEA Carter-Day Co.
500-73 Avenue, NE
Minneapolis, Minn. 55432
- Cambridge Wire Cloth Co.
P. O. Box 399
Cambridge, Md. 21613
- * CE Air Preheater
Wellsville, N.Y. 14895
- CE Tyler Industrial Products
7887 HUB Parkway
Cleveland, Ohio 44125
- * Ceilcote Co.
Unit of General Signal Corp.
140 Sheldon Road
Berea, Ohio 44017
- Chemelex, Inc.
837 Second Avenue
Redwood City, Calif. 94063
- Chemical Construction Corp.
One Penn Plaza
New York, N.Y. 10001
- * Chemineer, Inc.
5870 Poe Avenue
P. O. Box 1123
Dayton, Ohio 45401
- * Chem-Pro Equipment Corp.
87 Daniel Road
P. O. Box 1248
Fairfield, N.J. 07006
- * Chiyoda International Corp.
1300 Park Place Building
1200 Sixth Avenue
Seattle, Wash. 98101
- Clermont Engineering Co.
1300 N. Ninth Street
Philadelphia, Pa. 19122
- * Cleveland Wire Cloth &
Manufacturing Co.
3573 E. 78th Street
Cleveland, Ohio 44105
- * Combustion Equipment
Associates, Inc.
555 Madison Avenue
New York, N.Y. 10022
- * Croll-Reynolds Co., Inc.
751 Central Avenue
P. O. Box 668
Westfield, N.J. 07091
- * Deltech Engineering, Inc.
Century Park
New Castle, Del. 19720
- * Demco, Inc.
Gardener-Denver Co.
845 S.E. 29th Street
P. O. Box 94700
Oklahoma City, Okla. 73109
- Diversified Metal Products, Inc.
1275 Bloomfield Avenue
Fairfield, N.J. 07006
- * Dustex
Subsidiary of American
Precision Industries
2777 Walden Avenue
Buffalo, N.Y. 14225
- Entoleter, Inc.
Subsidiary of American
Manufacturing Co.
P. O. Box 1919
New Haven, Conn. 06509
- * Environmental Elements Corp.
Subsidiary of Koppers Co., Inc.
P. O. Box 1318
Baltimore, Md. 21203
- Eriez Magnetics
389 Magnet Drive
Erie, Pa. 16512

- FMC
Environmental Equipment Division
1800 FMC Drive West
Itasca, Ill. 60143
- Fiber-Dyne, Inc.
8530 San Fernando Road
Sun Valley, Calif. 91352
- Fike Metal Products Corp.
704 S. 10th Street
Blue Springs, Mo. 64015
- * Fisher-Klosterman, Inc.
P. O. Box 11190
Station H
Louisville, Ky. 40211
- Flex-Kleen Corp.
222 S. Riverside Plaza
Chicago, Ill. 60606
- * Fuller Co.
Subsidiary of GATX
124 Bridge Street
Catasaugua, Pa. 18032
- GAFF Corp.
Felt & Filter Products Division
140 W. 51st Street
New York, N.Y. 10020
- Glitsch, Inc.
4900 Singleton Boulevard
Dallas, Tex. 75212
- * Graham Manufacturing Co., Inc.
170 Great Neck Road
Great Neck, N.Y. 11021
- Griffin Environmental, Inc.
One Ecology Park
Baldwinsville, N.Y. 13027
- HR Filters
10445 Glenoaks Avenue
Pacoima, Calif. 91331
- HITCO Materials Corp.
1600 W. 135th Street
Gardena, Calif. 90249
- Hastings Reinforced
Plastics, Inc.
1220 W. State Street
Hastings, Mich. 49058
- * Haveg Industries, Inc.
900 Greenbank Road
Wilmington, Del. 19808
- Heil Process Equipment Co.
Division of Dart Industries, Inc.
12901 Elmwood Avenue
Cleveland, Ohio 44111
- * Justin Enterprises, Inc.
15030 Golden West Circle
Westminster, Calif. 92683
- Maurice A. Knight Co.
P. O. Box 109
Akron, Ohio 44309
- * Norton Company
1 New Bond Street
Worcester, Mass. 01527
- * Koch Engineering Co., Inc.
161 E. 42nd Street
New York, N.Y. 10017
- * George Koch & Sons
P. O. Box 358
Evansville, Ind. 47744
- * L. A. Water Treatment
17400 East Chestnut Street
City of Industry, Calif. 91749
- Lamparts Co.
230 Hamilton Avenue
Cleveland, Ohio 44114
- * Lodge-Cottrell
Dresser Industries
601 Jefferson
P. O. Box 6504
Houston, Tex. 77005
- * Ludlow-Saylor Wire Cloth
Division General Steel
Industries
8474 Delport Drive
St. Louis, Mo. 63114

- Mahon Industrial Corp.
6045 Dixie Highway
P. O. Box 611
Saginaw, Mich. 48606
- * Matheson Gas Products
Division of Will Russ Industries
P. O. Box 85
East Rutherford, N.J. 07073
- * Michigan Dynamics, Inc.
32400 Ford Road
Garden City, Mich. 48135
- * Mikropol
Subsidiary of U.S. Filter Corp.
15 Chatham Road
Summit, N.J. 07901
- * Mine Safety Appliances Co.
Evans City, Pa. 16033
- National Filter Media Corp.
1717 Dixwell Avenue
Hamden, Conn. 06314
- Packed Column Co.
Division of Metex Corp.
970 New Durham Road
Edison, N.J. 08817
- * Pall Trinity Micro Corp.
Subsidiary of Pall Corp.
Route 291 at McLean Road
Cortland, N.Y. 13045
- Patterson Industries, Inc.
1250 St. George Street
East Liverpool, Ohio 43920
- Perry Equipment Corp.
25 Mt. Laurel Road
Hainesport, N.J. 08036
- Pfaulder Co.
Division of Sybron Corp.
P. O. Box 1600
Rochester, N.Y. 14603
- * Poly Con Corp.
185 Arch Street
Ramsey, N.J. 07446
- Purity Corp.
50 Lively Boulevard
Elk Grove, Ill. 60007
- * Research-Cottrell
P. O. Box 750
Bound Brook, N.J. 08805
- * Ed Renneburg & Sons Co.
2639 Boston Street
Baltimore, Md. 21224
- * Rexnord, Inc.
Air Pollution Control Division
3300 Fern Valley Road
Louisville, Ky. 40213
- Riley Stoker Corp.
9 Neponset Street
P. O. Box 547
Worcester, Mass. 01606
- * Schwarzenbach Huber
1185 Avenue of the Americas
New York, N.Y. 10036
- * Selas Corp. of America
1957 Pioneer Road
Huntington Valley, Pa. 19006
- * W. W. Sly Manufacturing Co.
21945 Drake Road
Strongsville, Ohio 44136
- Spencer Turbine Co.
600 Day Hill Road
Windsor, Conn. 06095
- Standard Havens, Inc.
8800 E. 63rd Street
Kansas City, Mo. 64133
- * Stellite Division
Cabot Corp.
1020 W. Park Avenue
Kokomo, Ind. 46907
- * J. P. Stevens Co.
1185 Avenue of the Americas
New York, N.Y. 10036

* Torit Division
Donaldson Co., Inc.
1135 Rankin Street
P. O. Box 3217
St. Paul, Minn. 55165

* Trane Thermal Co.
Brook Road
Conshohocken, Pa. 19428

Tri-Mer Corp.
1400 Monroe
P. O. Box 739
Owosso, Mich. 48867

Union Carbide
Carbon Products Division
120 S. Riverside Plaza
Chicago, Ill. 60606

United Air Specialists
6665 Creek Road
Cincinnati, Ohio 45242

* United McGill Corp.
2400 Fairwood Avenue
P. O. Box 820
Columbus, Ohio 43216

* Western Precipitation
Division of Joy Manufacturing Co.
P. O. Box 2744
Terminal Annex
Los Angeles, Calif. 90051

* Westinghouse Electric Corp.
Sturtevant Division
Damon Street
Hyde Park, Mass. 02136

Wheelabrator-Frye, Inc.
Air Pollution Control Division
600 Grant Street
Pittsburgh, Pa. 15219

* Otto H. York Co.
42 Intervale Road
Parsippany, N.J. 07054

The Young Industries, Inc.
Painter Street
P. O. Box 30
Muncy, Pa. 17756

* John Zink Co.
4401 S. Peoria Street
Tulsa, Okla. 74105

* 3M Company
Product Information Center
3M Center
St. Paul, Minn. 55101

THOMAS REGISTRY

Dust Collecting Systems

Hoffman Filtration Systems
3 Adler Drive
East Syracuse, N.Y. 13057

Hough Brothers, Inc.
Sunfield, Mich. 48890

* Hydronics Engineering Corp.
190 Godwin Avenue
Midland Park, N.J. 07432

Kirk & Blum Manufacturing Co.
3246 Forrer Street
Cincinnati, Ohio 45201

Precipitator Pollution Control, Inc.
P. O. Box 7202
Longview, Tex. 75601

Seneca Environmental Products
78 N. Washington Street
Tiffin, Ohio 44883

Sternvent Company, Inc.
21 Carroll Street
Brooklyn, N.Y. 11231

* W. C. Wiedenmann & Co.
1820 Harrison Street
Kansas City, Mo. 64108

Young & Bertke Co.
2213 Winchell Avenue
Cincinnati, Ohio 45215

* A response was received.

Cyclones

* American Sheet Metal, Inc.
P. O. Box 9
Tualatin, Ore. 97062

Astralloy — Vulcan Corp.
P. O. Box 6206
Birmingham, Ala. 35217

Duplex Mill & Manufacturing Co.
400 Sigler Street
Springfield, Ohio 45501

Pollution Control Systems, Inc.
321 Evergreen Boulevard
Renton, Wash. 98055

Tricon Metals & Services, Inc.
P. O. Box 6634
Birmingham, Ala. 35210

Gas Scrubbers

ACS Industries, Inc.
Villa Nova & Florence Drive
Woonsocket, R.I. 02895

CEA Combustion, Inc.
61 Taylor Reed Place
Stamford, Conn. 06906

American Bridge
600 Grant Street
Pittsburgh, Pa. 15219

* CE NATCO
P. O. Drawer 1710
Tulsa, Okla. 74101

American Environmental
Products Corp.
P. O. Box 200
Glassboro, N.J. 08028

Centri-Spray Corp.
39001 Schoolcroft Road
Livonia, Mich. 48150

Anderson IBEC
19699 Progress Drive
Cleveland, Ohio 44136

Chemical Equipment Corp.
7454 E. 46th Street
Tulsa, Okla. 74145

Bohler Brothers of America, Inc.
1623 West Belt North
Houston, Tex. 77043

M. H. Detrick Co.
220 N. Wacker Drive
Chicago, Ill. 60606

* Carborundum Co.
Process Equipment Branch
600 Aurora Road
Solon, Ohio 44139

Fly Ash Arrestor Corp.
227 N. First Street
Birmingham, Ala. 35201

Hydro Dyne Co.
Westmore & 3rd Streets
Massillon, Ohio 44646

King Tool Co.
P. O. Box 5729
Longview, Tex. 75601

Lindbergh-Hammar Associates, Inc.
5511 Ekwill Street
Santa Barbara, Calif. 93111

* McDowell-Wellman Co.
113 St. Clark Avenue NE
Cleveland, Ohio 44114

Metrol Corp.
P. O. Box 10777
Houston, Tex. 77018

John Mohr & Sons
3205 E. 96th Street
Chicago, Ill. 60617

* Peabody Air Resources
P. O. Box 5202
Princeton, N.J. 08540

Peerless Manufacturing Co.
P. O. Box 20657
Walnut Hill Station
Dallas, Tex. 75220

Smith Industries, Inc.
8000 Hempsted Highway
Houston, Tex. 77008

Stacey Manufacturing Co.
359 Township Avenue
Cincinnati, Ohio 45216

Stansteel Corp.
5001 S. Boyle Avenue
Los Angeles, Calif. 90058

United Utensils Co.
2 Yennicock Avenue
Park Washington, N.Y. 11050

* Wright-Austin Co.
3243 Wright Street
Detroit, Mich. 48207

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APPENDIX D:
NAMES AND ADDRESSES OF INDIVIDUALS CONTACTED REGARDING
PARTICULATE TOLERANCES FOR GAS TURBINES

Turbines

- Mr. James Murray
Detroit Diesel Allison
GM Corp.
P. O. Box 894
Indianapolis, Ind. 46208
- * Mr. Robert Johnson
Avco-Lycoming Co.
550 S. Main Street
Stratford, Conn. 06497
- * Mr. Z. Stanley Stys
Brown-Boveri Corp.
1460 Livingston Avenue
North Brunswick, N.J. 08902
- * Mr. R. N. Schiller
Cooper Energy Services
P. O. Box 751
Mount Vernon, Ohio 43050
- * Mr. Anthony Caruvana
GE Corp.
Gas Turbine Division
Building 56-200
1 River Road
Schenectady, N.Y. 12345
- * Mr. Richard Worthen
Ingersoll-Rand Research, Inc.
P. O. Box 301
Princeton, N.J. 08540
- * Mr. Fred Robson
United Technologies
Pratt & Whitney Aircraft Division
400 Main Street
East Hartford, Conn. 06108
- * Mr. A. R. Stetson
International Harvester Corp.
Solar Division
2200 Pacific Highway
P. O. Box 80966
San Diego, Calif. 92138
- Mr. John Polyansky
Studebaker-Worthington, Inc.
Turbodyne Corp.
711 Anderson Avenue North
St. Cloud, Minn. 56301
- * Mr. Nils Carlson
United Technologies, Inc.
Power Systems Division
P. O. Box 109
South Windsor, Conn. 60674
- * Mr. Donald Jones
Westinghouse Electric Corp.
Turbine Division
Lester Branch
P. O. Box 9175
Philadelphia, Pa. 19113
- * Mr. Erich Schneeberger
Sulzer Brothers, Inc.
Suite 654
1 Greenway Plaza East
Houston, Tex. 77046

* A verbal or written response was obtained.

APPENDIX E:
SUMMARY AND APPRAISAL OF INDIVIDUAL HOT-GAS
CLEANUP DEVICES BY TYPE

PROVISO

When obtaining information for this report about the performance of individual pieces of equipment, we had to rely almost exclusively on the data supplied by the manufacturer. Although efforts were devoted to obtaining independent information for each device, little success was achieved in this area. Consequently, unless otherwise specified, all reported information should be regarded as manufacturer supplied.

Due to the absence of independent data, we have chosen to use the term *demonstrated* to describe the known maximum operating range of a particular device. By this we mean that the manufacturer is unaware of a unit operating at the stated conditions which has undergone mechanical failure. In general, no reference is made concerning its performance. In particular, it is neither stated nor implied that the device will provide results similar to those obtained by an identical device operating under different conditions.

E.1 Inertial Separation Devices and Summary of Experience in HTHP Applications

Conventional cyclones, rotary cyclones, and multiclones constitute the bulk of inertial separation devices. In the most common arrangement, the gas enters the cyclone tangentially at the top of the cylindrical section and spirals downward into the bottom section, which is usually conical in shape. Dust particles, which have a greater applied centrifugal force than gas molecules, accumulate at the wall and are carried downward, being held against the wall by the gas velocity. At the bottom of the cyclone the gas separates from the dust, flows back up in a smaller

spiral, and exits at the top. Solids are collected in a hopper and are removed by a rotary valve, screw conveyor, or other such means.

Conventional cyclones have the advantages of being

1. a proven technology whose design procedures are well established;
2. a simple device with no moving parts; and
3. least expensive, in terms of capital and operating costs, of the available HTHP particle control devices.

They suffer from the disadvantages of having

1. low removal efficiencies for particle sizes less than 5 μm ;
2. erosion problems if material selection and aerodynamic design are not considered carefully; and
3. reduced efficiency at high temperatures due to increased gas viscosity.

To overcome the disadvantages associated with a conventional cyclone, several manufacturers have designed rotary-flow cyclones in which the normal tangential swirl of the inlet gas is augmented by the addition of a secondary air flow introduced at the top of the unit. A theoretical analysis of this design confirmed by a number of experimental results,¹ has shown that this configuration is only marginally better than that of a conventional unit in the $< 10\text{-}\mu\text{m}$ region. In addition, the enhanced costs of providing a pressurized secondary air stream make the unit economically unattractive.

Another way of increasing conventional cyclone performance is to reduce the diameter of the cyclone while maintaining a constant inlet velocity. Multiclone units, which are fabricated from a series of small cyclones, operate on this principle and offer better collection

efficiencies than large-diameter conventional cyclones in the 1- to 10- μ m range. However, plugging may occur, or either too great a pressure drop or too complex an underflow control system may be required to ensure the uniformity of flow distribution necessary for efficient operation. In cases where multiclones have been applied to PFBC operation (Combustion Power Company), both of these problems have been encountered. Efforts to eliminate these problems via the redesign of the inlet flow system have proven unsuccessful.

Inertial separation devices have the following general characteristics in relation to HTHP filtration needs:

1. Capacity - Units can be combined in a variety of configurations to meet virtually any process load.
2. Power requirements - Pressure drops are related to equipment type and size, desired separation efficiency, and gas properties. These drops can range from a few inches of water to several psia. For cases in which energy recovery systems have been employed, Van Tongeren recommends that pressure drops be limited to about 1 psia.
3. Materials of construction - For temperatures above 1600°F, cyclones should be refractory lined. Below this limit, exotic alloys can be used in the fabrication of cyclones and multiclones, provided that they are weldable and compatible with the process environment.
4. Costs - Cost is process specific.

Because of their simplicity of design and proven ability to operate in HTHP domains, cyclones have received considerable attention for combined-cycle applications. Although durable in construction, cyclones suffer from the inherent disadvantage that at elevated temperatures gas viscosity increases and hence their ability to remove particulate matter by inertial separation diminishes. This phenomena has led Westinghouse,² after a comprehensive experimental and theoretical analysis of both rotary and conventional cyclone performance, to conclude that these devices by themselves will be unable to condition raw product gas to the level of purity required for turbine operation.

Cyclone

Manufacturer

The Ducon Company, Inc.
147 East Second Street
Mineola, N.Y. 11501

(No information supplied)

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1200	5
Projected		

Removal efficiency vs particle size

Not supplied

Stage of development

Ducon is a leader in producing cyclones for fluidized catalytic cracking units (1200°F, 5 atm).

Cyclone

Manufacturer

Buell Emissions Controls
Division of Envirotech
200 N. Seventh Street
Lebanon, Pa. 17042

(No information supplied)

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1200	5
Projected		

Removal efficiency vs particle size

Not supplied

Stage of development

Buell is a leader in producing cyclones for fluidized catalytic cracking units (1200°F, 5 atm).

Cyclone³Manufacturer

Van Tongeren
 c/o Aerex Corporation
 1312 Epworth
 Reynoldsburg, Ohio 43068

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1200	5
Projected		

Removal efficiency vs particle size

Van Tongeren quotes the following "typical" fractional efficiency data for a high-efficiency cyclone (1-m diam) treating 4500 cfm:

<u>Particle diameter (μm)</u>	<u>Collection efficiency (%)</u>
0-2.5	23
2.5-5	59
5-7.5	71
7.5-10	87
10-15	93
15-20	96
20-40	98.5
>40	99.5

No reference temperature or pressure is given for the data.

Stage of development

Van Tongeren is a major producer of cyclones used in the fluidized catalytic cracking units (1200°F, 5 atm) of European refineries.

Cyclone - Multiclone⁴Manufacturer

Fisher-Klosterman, Inc.
P. O. Box 1190
Station H
Louisville, Ky. 40211

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	800	High (> 10)
Projected	1600	High (> 10)

Removal efficiency vs particle size

Fisher-Klosterman believes that 95% removal efficiencies at 5 μ m are achievable.

Stage of development

From a performance point of view, Fisher-Klosterman designs are off the shelf. From a structural viewpoint, each unit would have to be custom designed and built.

Cyclone - Multiclone⁵Manufacturer

Environmental Elements Corp.
185 Arch Street
Ramsey, N.J. 07446

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	700	High (> 10)
Projected	2100	High (> 10)

Removal efficiency vs particle size

Grade efficiency data for Environmental Elements Corp. cyclones and multiclones are given in the following figures.

ORNL DWG 78-5161

Source: Poly Con Corporation, Multicyclone Collectors,
Bulletin 7010.

Removal efficiency vs particle size (cont'd)

ORNL DWG 78-5164

CYCLONES

Source: Poly Con Corporation, Cyclone Collectors,
Bulletin 7010.

No reference temperature or pressure is given for this information.

Stage of development

Environmental Elements Corp. has recently completed the construction of four refractory-lined cyclones for an Oak Creek, Wisconsin, gasification plant. They are designed to operate at 2100°F, with a maximum flow rate of 5500 acfm (actual cubic feet per minute) at a water pressure drop of 2 in.

Cyclone⁶Manufacturer

General Electric Company
 Energy Systems Programs Department
 1 River Road
 Schenectady, N.Y. 12345

ATTN: C. M. Thoennes

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	Ambient	Ambient
Projected	1750	9

Removal efficiency vs particle size

Not available

Stage of development

Under a DOE contract, General Electric has constructed a prototype device whose design incorporates an aerodyne-tornado cyclone in the core of a conventional cyclone. In effect using dirty gas to provide secondary flow in the aerodyne unit. The device is scheduled to undergo testing at the Exxon Miniplant at Linden, New Jersey, under the following process conditions:

Temperature	1750°F
Pressure	9 atm
Mass flow rate	0.8 lbm/sec

The cyclone will precede a Ducon filter, and the efficiency of both units will be measured. Recently, grade efficiency tests have been completed under ambient conditions, and results have indicated that it is possible to achieve up to 90% of vendor (Aerodyne) claims in the 5- to 10- μ m range.

Multiclone⁷Manufacturer

Peerless Manufacturing Co.
 P. O. Box 20657
 Dallas, Tex. 75220

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1200	High (~ 50)
Projected	< 2200	High (~ 50)

Removal efficiency vs particle size

Peerless dry scrubbers are guaranteed to have the following collection efficiencies based on a flow rate of 20 acfm per tube :

<u>Particle diameter (µm)</u>	<u>Collection efficiency (%)</u>
2-4	85
4-6	90
6-8	99
>8	100

No reference temperature or pressure is given for these data.

Stage of development

Peerless units are available off the shelf. For high-temperature applications, Peerless can build multiclones of almost any weldable material and can provide units to withstand temperatures up to 2200°F. In order to maintain device efficiency, they recommend a maximum capacity of 40 acfm and a minimum of 10 acfm per tube.

Multiclone⁸Manufacturer

Western Precipitator Division
Joy Manufacturing Co.
4569 Colorado Boulevard 90039
P. O. Box 2744
Terminal Annex
Los Angeles, Calif. 90051

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1150	4
Projected		

Removal efficiency vs particle size

Joy's multiclone 9VM model with tricones will collect 98% of all particles over 10 μm and 50% of all material under 10 μm . These data were obtained at 450°F in a 9-in.-diameter tube.

Stage of development

Multiclone separators used for catalytic cracker service (1200°F, 5 atm) have been supplied by Joy Manufacturing Co. Joy is contemplating development work to extend the range of application into the HTHP regime.

Multiclone⁹⁻¹¹Manufacturer

Shell Development Company
One Shell Plaza
P. O. Box 2463
Houston, Texas 77001

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1300	5
Projected		

Removal efficiency vs particle size

Essentially complete removal of particles larger than 15 μm is typically achieved, and efficiency at the 10- μm levels exceeds 95%.

Capacity

Units capable of treating up to 85,000 scfm have been constructed.

Power requirements

Pressure drop across the separator is less than 3 psi.

Materials of construction

The refractory-lined cyclone is constructed with stainless steel and ceramic internals.

Stage of development

Shell separator units are available and require a licensing agreement between Shell Development Company and licensee.

Aerodyne-Tornado Cyclone^{2,12-14}Manufacturer

Aerodyne Development Corp.
 29085 Solon Road
 Cleveland, Ohio 44139 ATTN: Mack Gordon

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1600	5
Projected	1800	10

Removal efficiency vs particle size

Manufacturer's test data for a 1000-acfm Aerodyne Type S rotary cyclone operating at 1600°F and atmospheric pressure are presented below. No data on primary or secondary flows are given.

ORNL DWG 78-5163

Source: Advanced Coal Gasification System for Electric Power Generation, vol. II, R&D Report No. 81, Interim Report No. 2, June 30, 1974, Heat Transfer Division, Westinghouse Electric Corp., Lester, Pa., ERDA/FE 1514-T-8.

Mode of operation

During operation, the dirty gas stream enters the collector chamber past a stationary turning vane which imparts a rotary motion to the flow. Centrifugal force directs the dust outward towards the outer wall of the collector where it is engaged by a secondary gas stream of superior energy and directed spirally downward into a collecting hopper.

Capacity

Aerodyne has manufactured commercial-sized units to treat up to 13,000 cfm at temperatures of 900°F. This corporation is also designing a HTHP unit to operate at 1750°F and up to 10 atm pressure.

Power requirements

Power requirements depend on the amount of secondary air used in operation.

Materials of construction

HTHP designs require refractory lining and special alloy internals.

Costs

Cost is process specific.

Stage of development

Aerodyne's Type S cyclone is a commercially available off-the-shelf item. In an extensive test program conducted by Westinghouse, the unit performed poorly in the 0- to 10- μ m range with overall collection efficiencies averaging usually less than 50% in this interval. Consequently, Westinghouse sees little potential for its use in gasification applications. Nonetheless, General Electric has developed an advanced design incorporating an aerodyne unit inside a conventional cyclone for use in the Exxon Miniplant.

Tanjet Cyclone^{14,15}Manufacturer

Donaldson Company, Inc.
 1400 West 94th Street
 P. O. Box 1299
 Minneapolis, Minn. 55440 ATTN: Thomas Donnelly

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1800	5
Projected		

Removal efficiency vs particle size

Donaldson's Tanjet grade efficiency data are presented in the figure below. No reference temperature or pressure is given for the data, but Westinghouse tests have confirmed that the unit maintains its performance at high temperatures (> 1600°F).

Source: Advanced Coal Gasification System for Electric Power Generation, Quarterly Progress Report, First Quarter, FY 1976, Heat Transfer Division, Westinghouse Electric Corp., Lester, Pa., ERDA/FE-1514-176 (October 1975).

Mode of operation

Donaldson's Tanjet is designed to incorporate a low-volume, high-velocity tanjential gas flow to induce a strong vortex flow on a primary axial flow stream. The tanjential jets are designed to provide a radically outward flow component in the separation zone which aids in particle separation. The strong vortex is generated by pressurized gas released through the tanjential jets from a secondary gas reservoir.

Capacity

In order to facilitate a significant separation in the small particle size range, Westinghouse has operated a single Tanjet unit at 132 scfm with a secondary flow of clean air at 15 scfm at a pressure drop of 33 psi.

Power requirements

4-7 air hp per 1000 scfm of primary flow.

Materials of construction

The Tanjet cyclone is constructed of alloy steels.

Costs

Capital costs are estimated to be between \$10 and \$20 per acfm.

Stage of development

The Tanjet program was discontinued by Donaldson in 1976, awaiting development of an attractive market. Donaldson still considers the collector as a prototype unit and has stated the need for further improvement in the following areas:

1. Because of the extremely strong vortex developed in the cyclone which extends well below the collection point of the tube, the fabrication and design of the collection hopper need further refinement.
2. To be competitive, the collector must offer significantly improved results as compared to conventional cyclones to overcome the cost differential between them.

In addition, from an operational point of view, the use of clean secondary air, at pressure, must be considered as a significant process cost to be included in any overall design.

Solids Separator¹⁶Manufacturer

Dyna-Therm Corporation
 P. O. Box 66629
 Houston, Texas

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1000	High
Projected	1600	10

Removal efficiency vs particle size

Efficiency data for the removal of tungsten dust from steam at 1000°F is quoted by the manufacturer to be:

<u>Particle size (μm)</u>	<u>Removal efficiency (%)</u>
2	70
3	85
4	93
5	98
>5	99

Stage of development

The Dyna-Therm solids separator is available off the shelf, and the vendor will guarantee 99% collection of all particles $\geq 10 \mu\text{m}$ in diameter.

Cyclone-Centrifuge^{17,18}Manufacturer

Mechanical Technology, Inc.
 968 Albany Shaker Road
 Latham, N.Y. 12110 ATTN: Dr. Bernard Sternlicht

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated		
Projected	1000	17

Removal efficiency vs particle size

An efficiency curve derived from theoretical considerations is presented below.

ORNL DWG 78-13930

Source: John T. McCabe, Centrifuges for Coal Conversion and Related Processes, Phase I: Feasibility Study, draft report, Mechanical Technology, Inc. (March 1977).

Stage of development

Mechanical Technology has recently completed a contract with DOE to assess the feasibility of using centrifuges in gasification applications. Their analysis has shown that a cyclocentrifuge, constructed by housing a centrifuge in a cyclone shell, is capable of reducing particulate loadings to below 1 ppm weight. However, they have assumed in their calculations that a linear particle-size distribution occurs in the size range 0 to 5 μm and have also assumed an extremely optimistic efficiency curve. Discounting these assumptions, a basic question that remains is whether or not the centrifuge unit itself will face the same corrosion, erosion, and deposition problems as the turbine, for which it is conditioning the gas.

E.2 Surface Filters

Porous metal elements, ceramic fiber fabrics, and ceramic membranes are the principal elements used in surface filtration. The term surface filtration is used in reference to the fact that as dirty particles flow through a porous medium they deposit in the voids and eventually build up a filter cake on the upstream surface. In large part, this cake is a principal mode of particle separation, and its growth is allowed to continue until the pressure drop increases to a point at which the solids must be removed.

E.2.1 Porous metal filtration

Filtration methods using porous metal media have the advantages of high filtration efficiency and durability. However, the following disadvantages must be considered:

1. Require high differential pressure,
2. Incur expensive initial costs (\$60 to 100 per ft²),
3. Use low face velocities (4 to 6 ft/min),
4. Need an additional "blow back" cleaning system,
5. Are susceptible to corrosion and condensation, and
6. Undergo degradation due to the irreversible capture of fine particulate on the interior of the filter.

In general, their use is not recommended in hot-gas purification systems. An exception to this rule is the potential use of the porous metal filter developed by the Brunswick Corporation, which is able to accommodate high face velocities (~ 100 ft/min) at low pressure drops (~ 10 in. H₂O). The ability to demonstrate grade efficiency data typical of other surface filtration devices in HTHP environments is crucial to the adoption of

this filter. A test to demonstrate this ability is being conducted by EPRI at the Arapaho Generating Station in Denver, Colorado, in summer of 1977.

E.2.2 Fabric filtration

Fabric filtration has been used successfully whenever filtration of fine particulate has been required at low-temperature conditions. In HTHP applications, it has the advantage of having a high filtration efficiency. Some problems, however, have been encountered:

1. high maintenance requirements associated with the failure and replacement of filter bags;
2. the need to develop fiber lubricants compatible with HTHP corrosive environments for fabrics that undergo flexing during cleaning operations;
3. additional costs associated with the installation, operation, and maintenance of a fiber-medium cleaning system; and
4. low air/cloth ratios (2 to 10 ft/min).

Although several ceramic fiber manufacturers sell fabrics that are serviceable in high-temperature environments, many of these are unsuitable for filtration purposes. This is because they lack the required high-temperature inorganic fiber lubricant needed to enable the fabric to withstand the fiber-to-fiber abrasions caused by the repeated flexing that occurs during the cleaning cycle.

Acurex Aerotherm,¹⁹ under EPA-IERL funding, is currently conducting an extensive test program to ascertain the potential of ceramic fabric filtration in a high-temperature environment. Undoubtedly, results from

this study will yield valuable insights into the applicability of this technology for gasification operations.

E.2.3 Rigid ceramic membrane filtration

To date, very little effort has been devoted to development and use of rigid ceramic membranes in HTHP filtration. Although they have the advantages of offering high filtration efficiency and compatibility with corrosive environment, these membranes also exhibit the detriments of

1. being susceptible to thermal shock,
2. having low mechanical strength,
3. requiring low face velocities (6 to 9 ft/min),
4. needing the development of a suitable cleaning system, and
5. needing to be preheated to avoid plugging caused by condensation.

Before rigid ceramic membrane filtration will be realized as an acceptable form of HTHP gas purification, an extensive research program will have to be undertaken.

E.2.4 Summary of experience in HTHP applications

Research programs are underway to evaluate the applicability of metal-fabric-ceramic filters in HTHP applications. The purpose of this work is not only to obtain data on their filtration efficiency, but also to obtain information on their reliability and capacity.

In order for this technology to become a viable HTHP departiculation alternative, it will be necessary to (1) develop systems capable of accommodating high face velocities (> 100 ft/min) so that the required surface area for gas treatment can be kept to a reasonable size, and (2) fabricate materials that can undergo extensive cyclic cleaning

without irreversible degradation or mechanical failure. In addition, it will also be necessary to make sure that these systems operate in a dry, noncondensing environment so that plugging will not occur. Recent experience at the Exxon Miniplant indicates that this could be a major problem in PFBC operation. Similarly, this must be considered a potential problem in gasification systems in which condensable hydrocarbons are present in the raw product gas.

Fiber Filter^{20,21}Manufacturer

Owens-Corning Fiberglass Corp.
Technical Center
Granville, Ohio 43023 ATTN: F. Munro Veazie

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1200	
Projected		

Removal efficiency vs. particle size

Not applicable

Materials of construction

Silica fiber with proprietary inorganic finish.

Costs

Not available

Stage of development

Owens-Corning's "S" fiber material with proprietary finish has been shown to maintain its integrity at temperatures up to 1200°F. In the future, it will be woven into a filter element and tested by the EPA at Research Triangle Park under the direction of Dr. James Turner to assess its high-temperature collection ability.

Fabric Filter²²Manufacturer

Haveg Industries, Inc.
900 Greenbank Road
Wilmington, Del. 19808

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	2500	
Projected		

Removal efficiency vs particle size

Not available

Materials of construction

Refractory silica

Costs

Depending on the grade of material, Haveg's SiltempTM fabric costs:

<u>Material</u>	<u>Price (\$/yd)</u>	<u>Weight (oz/yd)</u>
Siltemp 82	6.35	10.3
Siltemp 84	8.75	18.5
Siltemp 84 CH	7.95	19
Siltemp 188	17.20	38
Siltemp 188 CH	14.95	37

Stage of development

Haveg's Siltemp fabrics are available off the shelf and are coated with a low-temperature organic finish.

Fabric Filter²³Manufacturer

3M Company
Central Research Laboratories
P. O. Box 33221
St. Paul, Minn. 37830 ATTN: Dr. Thomas Shevlin

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1800	
Projected		

Removal efficiency vs particle size

At ambient conditions, EPA tests have shown 99.5% mass efficiency in the removal of typical fly ash.

Materials of construction

3M ceramic fibers consist of 60% alumina, 25% silica, and 15% boria.

Costs

Fabrics in the 10-oz range cost between \$25 and \$50 per square yard, depending on quantity.

Stage of development

3M Company commercially markets stranded fiber suitable for high-temperature filter applications in the temperature range 550 to 1800°F. In addition, the company is also weaving and matting filter fabric material.

Fiber Filter²⁴Manufacturer

Carborundum
Research & Development Laboratories
P. O. Box 1054
Niagara Falls, N.Y. 14302 ATTN: Dr. David Hamilton

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	2200	
Projected		

Removal efficiency vs particle size

Not available

Materials of construction

Boron nitride fiber

Costs

Not available

Stage of development

Carborundum is currently trying to both weave and felt its boron nitride fiber into filter elements that would be compatible with high-temperature, high-efficiency filtration. Because of the nature of the fiber itself, Carborundum believes that an inorganic fiber lubricant, which would enable the element to withstand intrafiber abrasion, will be necessary.

Fiber Filter²⁵Manufacturer

J. P. Stevens Co.
Stevens Tower
1185 Avenue of the Americas
New York, N.Y. 10036 ATTN: John F. Cobianchi

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	500	
Projected	2000	

Removal efficiency vs particle size

Not available

Materials of construction

Quartz fiber

Costs

None

Stage of development

J. P. Stevens' AstroquartzTM is now available off the shelf.

Fiber Filter²⁶Manufacturer

Hitco Materials Corporation
1600 West 135 Street
Gardena, Calif. 90249

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1800	
Projected		

Removal efficiency vs particle size

Not available

Materials of construction

Refractory Silica

Costs

From \$6 to \$17 per square yard, depending on thickness.

Stage of development

Hitco RefrasilTM cloth, fiber, and batting are commercially available.

Porous Metal Filter²⁷Manufacturer

Brunswick Corporation
One Brunswick Plaza
Skokie, Ill. 60074 ATTN: Kenneth Mills

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	700	
Projected	> 1500	

Removal efficiency vs particle size

At ambient conditions in a laboratory environment, collection efficiencies on the order of 99.5% in the 0.5- to 1.5- μ range have been obtained with flow rates of 100 cfm. In some preliminary industrial testing, results have been somewhat lower and, consequently, more laboratory work has been undertaken.

Mode of operation

Unlike conventional filtration in which high efficiency is obtained by filtration through an external filter cake, the Brunsmet filter relies on depth filtration in which filtration occurs by particle capture on individual fibers. This approach reduces the pressure drop and enhances throughput. To retain filter efficiency, Brunswick has developed a proprietary cleaning process which remains confidential.

Capacity

Face velocities vary from 50 to 100 ft/min.

Power requirements

Design criteria call for a maximum pressure drop of 4 in. H₂O.

Materials of construction

Brunswick's Brunsmet stainless steel fiber can withstand temperatures up to 1000°F.

Costs

Not available

Stage of development

The Brunsmet metal filter is largely in the developmental phase. The unit is made from Brunsmet fiber material and has a webbed rather than a porous steel construction. By adjusting the fiber diameter used in its manufacture, as well as the depth of the filter, it is possible to vary the degree of efficiency the filter can achieve.

Currently, the unit is undergoing testing at a Commonwealth Edison plant using a side stream from a coal-fired boiler to collect fly ash. Further testing will occur at the Arapahoe Power Station near Denver in the fall of 1977 under an EPRI test program.

Porous Metal Filter²⁸Manufacturer

Pall Trinity Micro Corp.
Cortland, N.Y. 13045

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1500	High (> 50)
Projected	> 2000	High (> 50)

Removal efficiency vs particle size

Pall Trinity Micro can provide filter elements whose absolute efficiencies (100%) are as low as 1 μ m.

Capacity

Recommended throughputs are on the order of 7 to 10 acfm per square foot of filter material.

Power requirements

Not available

Materials of construction

Stainless steel, Inconel, Monel, and other high-temperature alloys.

Costs

\$60 per square foot of filter material for fabricated cylindrical stainless steel elements.

Stage of development

All Pall Trinity Micro filter media are commercially available.

Porous Metal Filter²⁹Manufacturer

Mott Metallurgical Corp.
Farmington Industrial Park
Farmington, Conn. 06032

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1500	High (> 50)
Projected	1500	High (> 50)

Removal efficiency vs particle size

Mott believes that it is possible to produce a filter which is totally effective in filtering all particles > 1 μ m in size, provided the face velocity to the filter is < 4 ft/min.

Capacity

Recommended air/cloth ratios are 4 acfm per square foot.

Power requirements

Pressure drops for clean filter elements vary between 5 and 9 in. H₂O and will rise to somewhere between 15 to 20 in. H₂O prior to cleaning.

Materials of construction

Inconel

Costs

Not available

Stage of development

Both cartridge and filter sheet material are commercially available.

Porous Metal Filter³⁰Manufacturer

Michigan Dynamics, Inc.
32400 Ford Road
Garden City, Mich. 48135

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1500	High (> 50)
Projected	1600	10

Removal efficiency vs particle size

Dynapore 405705 filter plate, manufactured by Michigan Dynamics, Inc., has a nominal rating of 2 μm and an absolute rating of 10 μm . This means that a clean filter will remove all material > 10 μm from a dust-laden gas stream and has a filtration efficiency of 98% for all particles larger than 2 μm in size. In actual operation, filter cake builds up on the upstream side of the filter and enhances collection efficiency.

Capacity

Michigan Dynamics, Inc., manufactures filter elements rather than filter units per se. Its current capability rests in the manufacture filter panels measuring 3 by 3 ft, or 2 by 4 ft.

Power requirements

Pressure drop for a clean filter would be under 2 psi and could be cleaned at any preset differential value.

Materials of construction

304 and 316 stainless steel

Costs

\$56.50 per square foot of filter material for orders $> 1000 \text{ ft}^2$.

Stage of development

Porous metal filter material by Michigan Dynamics, Inc., is commercially available and is being used as the retaining screen on the Ducon granular filters at the Exxon Miniplant in Linden, N.J.

Porous Metal Filter³¹Manufacturer

Vacco Industries
10350 Vacco Street
South El Monte, Calif. 91733

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1500	High (> 50)
Projected	> 2000	High (> 50)

Removal efficiency vs particle size

Not available

Capacity

Not available

Power requirements

Clean filters normally exhibit pressure drops of < 1 psi and rise to 75 or 80 psi before cleaning.

Materials of construction

Inconel, Monel, and high-temperature alloys

Costs

Process specific

Stage of development

Vacco etched disc filters are commercially available.

Ceramic Membrane Filtration³²Manufacturer

Westinghouse Research Laboratory
1310 Beulah Road
Churchill Borough
Pittsburgh, Penn. 15235

ATTN: Dr. David Ciliberti

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1300	1
Projected		

Removal efficiency vs particle size

Overall efficiencies ranged from 99.6 to 100% for limstone dust (mean particle diameter of 1.4 μ m) at 1300°F and at atmospheric pressure.

Mode of operation

Ceramic membranes identical to those proposed by Acurex Acrotherm are being tested for filtration efficiency.

Capacity

Not available

Power requirements

Not available

Materials of construction

Ceramic membranes are supplied by 3M Company under the trademark of Thermacomb.®

Costs

Not available

Stage of development

Westinghouse has tested the effectiveness of ceramic membrane systems in the high-temperature regime and found them to be effective in the collection of fine dust on a bench-scale basis. However, before going to a full-scale HTHP system, a number of questions need to be resolved. These include those relating to membrane (1) cleanability, (2) structural integrity under cyclic thermal stress, and (3) susceptibility to plugging.

Recent experience at the Exxon Mimiplant indicates that plugging can be a major problem even in less complex systems such as sand-bed filters. It will be necessary to resolve this problem prior to the full-scale testing of ceramic membranes, since they most certainly will suffer adversely from the presence of this phenomena.

Ceramic Membrane Filtration^{33,34}Manufacturer

Acurex Aerotherm
485 Clyde Avenue
Mountain View, Calif. 94042 ATTN: Fred Moreno

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1400	1
Projected	1500	10

Removal efficiency vs particle size

Absolute filtration down to submicrometer particle size can be achieved.

Mode of operation

The accompanying figure illustrates the basic principles and design of Acurex's ceramic filtration module. During the filtration process, the dust-laden gas flows through the honey-combed ceramic block and deposits in the channels in the interior. As the gas is cleaned by diffusing through the porous ceramic wall, it is rotated 90° with respect to the inlet and collected in the outlet plenum located on the opposite edges on the element.

Capacity

To date, 2-in.-square ceramic blocks with 45-in.² filter area have been able to treat particle concentrations between 0.5 and 1.3 gr/scf.

Power requirements

Pressure drops on the order of 10 in. H₂O are expected in an operating unit.

SECTION THRU CORE

Materials of construction

Suitable filter elements can be supplied by the following manufacturers:

1. W. R. Grace Co., 1114 Avenue of the Americas,
New York, N.Y. 10036
2. 3M Company, 3M Center, St. Paul, Minn. 55101
3. Norton Company, Worcester, Mass. 01606
4. Selas Flotronics, 1957 Pioneer Road,
Huntington Valley, Pa. 19006

Costs

Estimated at \$0.83/kW

Stage of development

At this point, Acurex has merely a conceptual design and is seeking funding from its research program. In doing so, it hopes to address the following problem areas:

1. a determination of an optimum cleaning configuration and cleaning cycle,
2. an estimation of the susceptibility of ceramic elements to plugging and an evaluation of their long-term endurance characteristics, and
3. a definition of the mechanical parameters in regard to the thermal and mechanical stresses involved in their design.

Ceramic Fabric Test Program¹⁹Conducted by

Acurex Aerotherm

For

EPA (Dennis Drehmel)
EPA — IERL
Research Triangle Park, N.C.

Program includes

1. Selection of HTHP filtration materials
2. Bench scale screening tests (Phase I)
3. Pilot scale tests (Phase II)
4. Filtration theory/analysis
5. Economic analysis of full scale filtration systems

Ceramic fibers (silica, silica/alumina, alumina, zirconia)

1. Woven
2. Felted

High loading, flyash, 1500°F, 10 atm

E.3 Granular-Bed Filters and Summary of Experience in HTHP Applications

One popular means of removing fine particulate that has been pursued in some detail is the use of granular-bed filters in either a fixed-bed or moving-bed configuration. Such devices have the advantages of

1. using either inert or sulfur-adsorbent material,
2. having a capacity for high filtration efficiency,
3. being able to accommodate high face velocities while incurring a moderate pressure drop, and
4. incorporating relatively simple cleaning procedures.

However, these filters are still in the development phase, which means that information on performance in HTHP environments, optimum operating conditions, and influence of particle attrition on outlet loading is largely unknown. Substantial efforts in development and evaluation need to be performed before these devices find a suitable market in HTHP applications.

Only the Ducon granular-bed filter has undergone any extensive testing in HTHP applications. This work is being conducted at the Exxon PFBC Miniplant in Linden, New Jersey under EPA sponsorship. Several significant problems have been noticed during operating, including

1. irreversible plugging of the inlet retaining screens,
2. degradation of collection efficiency with time,
3. inability to reduce outlet loadings to below 0.03 gr/scf,
4. buildup of particulate in the granular bed, and
5. system vulnerability to process upsets.

One of the unexpected phenomena that has been observed in these tests is that the particulate matter tends to form a dense cake on the filter element that is hard to remove. This suggests that some sort of condensation phenomena is occurring concurrently with departiculation. If this phenomena is common to all PFBC operation, it could very well imply that any device relying on surface filtration for departiculation may be inapplicable.

Granular Bed Filter³⁵⁻³⁸Manufacturer

The Ducon Company, Inc.
147 East Second Street
Mineola, N.Y. 11501 ATTN: Mr. Albert Tesoriero

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	900	2
Projected	1600	10

Removal efficiency vs particle size

Under fluidized catalytic cracker conditions (700 to 900°F, 1 to 2 atm), the Ducon filter achieved overall collection efficiencies ranging from 85 to 98% for gas flows between 475 and 1000 acfm. No specific grade efficiency data are available.

Mode of operation

In service, particle-laden flue gas enters the dusty side of the filter housing, passes through the outer retaining screen downward into the filter bed, and exits through the supporting screen into the clean gas plenum. Cleaning occurs via a blowback mechanism which is actuated when the pressure drop across the unit reaches a preset value.

Capacity

Existing units have operated with flow rates of up to 1000 acfm. In principle, units of any size can be fabricated.

Power requirements

Pressure drop across the system is dynamic in nature and increases as filter cake buildup occurs. By adjusting the blow back cleaning attenuator, the maximum allowable pressure drop can be set at any value.

Materials of construction

304 and 316 stainless steels

Costs

Process specific

Stage of development

The Ducon filter is almost out of the developmental phase and is moving towards commercialization. Current work includes testing a Ducon unit at the Exxon Miniplant in Linden, New Jersey on a PFBC test rig. In operation, the 10-ft² test bed operates at 1600°F and 10 atm absolute pressure at flow rates of up to 1200 scfm. Available plant data indicate that

1. Significant cleaning problems result from the formation of a hard filter cake on the inlet retaining screens. This cake is dense, and efforts to remove it by blowback cleaning have not been successful.
2. It has not been possible to achieve outlet loading concentrations compatible with turbine design requirements (0.002 gr/scf). Most runs have yielded outlet values in the range 0.05 to 0.08 gr/scf.
3. Filtration efficiencies have tended to decrease with time in some of the longer runs, dropping from 90% initially to 50% at the end of the run.
4. A sizable and uniformly dispersed fraction of particulates can build up in the filter bed. It can account for as much as 30% of the total media weight.
5. The system, with its current design, is extremely vulnerable to upsets and normally requires shutdown in order to restore operation.

Moving-Bed Filter (Dry Scrubber)^{39,40}Manufacturer

Combustion Power Co.
1346 Willow Road
Menlo Park, Calif. 94025 ATTN: Robert Vander Molen

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1600	1
Projected	1600	2

Removal efficiency vs particle size

Preliminary, but questionable, data indicate overall collection efficiencies ranging from 85 to 97% at atmospheric pressure with temperatures below 800°F. Condensation of tars and oils complicated the measurement problem when the unit was used in line with the MERC gasifier.

Mode of operation

Combustion Power Company's moving-bed filter is designed to include both mechanical and inertial filtration. The external shell of the scrubber acts as a cyclone, using a tangential feed arrangement to remove the bulk of the larger particles via centrifugal separation. In the interior vortex, the unit houses an annular filter element which retains granular filter media between two vertical, louvered screens. As the gas stream passes through the filtering media, internal impaction removes entrained particulate and the gas emerges into an interior collection plenum. To avoid particulate saturation, the media is continuously recirculated and cleaned using a gravity-fed recirculation system.

Capacity

An experimental unit with a capacity of 10,000 scfh has been delivered to MERC.

Power requirements

Pressure drops of 3 to 10 in H₂O are commonly encountered in atmospheric units operating at a filtering velocity of 125 ft/min.

Materials of construction

316 stainless steel

Costs

Not available

Stage of development

Most of CPC's experience in moving-bed filters has been directed toward applications that operate at atmospheric pressure and temperatures typically below 1000°F. In the few cases where CPC has tried to utilize its dry scrubbing technology in HTHP applications, it has encountered severe difficulties, most notably the structural failure of an 18,000 scfm unit intended to operate at 1600°F and 10 atm. After a thorough engineering review, CPC believes it has solved its mechanical problems and has fabricated a unit to operate at 1200°F and 2 atm. and is treating a 10,000 scfh gas stream at a grain loading of 4 gr/scf or below. This test module has been delivered to Morgantown Energy Research Center (MERC) but has not undergone operational testing. In this new design CPC believes it has circumvented problems associated with pressure letdown devices and lock hoppers by pneumatically recirculating the filter media at the system operating pressure. Although no testing has occurred at high temperatures and high pressures, tests have been conducted at ambient conditions, under an EPA-sponsored program, using the redesigned unit. Test conditions and results are listed below.

Test conditions

Temperature (°F)	Ambient
Absolute pressure (atm)	1
Bed depth (in.)	15.2
Mean face velocity (ft/min)	97.0
Mean inlet loading (gr/scf)	0.504
Mean inlet particle diameter (μm)	7

Results

Mean outlet loading (gr/scf)	0.014
Mean efficiency (%)	96
Mean pressure drop (in. H ₂ O)	10.5

Given the inherent difficulty of collecting 7- μ m material, the overall collection efficiency (96%) is impressive.

Panel-Bed Filter⁴¹⁻⁴⁵Manufacturer

Dr. Arthur M. Squires
c/o Department of Chemical Engineering
Virginia Polytechnic Institute
Blacksburg, Va. 24061

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1000	1
Projected	> 2000	High

Removal efficiency vs particle size

At ambient temperatures and atmospheric pressure, overall collection efficiencies on the order of 99.9% have been obtained from bench-scale apparatus. In a high-temperature application (1000°F) at MERC, overall collection efficiencies in the range 95 to 96% have been recorded. No specific grade-efficiency data are available.

Mode of operation

Filtration occurs via inertial impaction caused by cake buildup on the upstream side of the filter unit. Cleaning occurs by blow back which dislodges the external cake, causing it to fall into a lock hopper. Filter media lost by blow back are replaced using a gravity feed arrangement.

Capacity

Bench-scale studies have operated at 60 scfm. In commercial operation, the unit must be sized to accommodate face velocities on the order of 25 ft/min.

Power requirements

At face velocities of 25 ft/min, pressure drops on the order of 6 in. H₂O occur.

Materials of construction

Unspecified for HTHP applications

Costs

Not available

Stage of development

The panel-bed filter is in the early stages of development. In concept, it has been proven to provide effective filtration only at relatively mild operating conditions. If this efficiency can be extended to include HTHP operating ranges, then the use of the device with a dolomite filter media for SO₂ sorption will prove extremely attractive. However, rigorous testing under extreme conditions and over prolonged periods of time must be conducted to ensure that filtration efficiency and bed integrity are maintained.

In the few preliminary tests performed at high temperatures, the absence of a filter cake buildup was observed and filter efficiencies were less than anticipated. Squires attributes these results to a lack of expertise in performing the tests rather than to any inherent deficiency in the device.

To date, a final report is being prepared for EPRI, and although further support is being sought, no future work is scheduled.

Gravel-Bed Filter^{46,47}Manufacturer

Rexnord
 Corporate Research & Development
 1914 Albert Street
 Racine, Wis. 53404 ATTN: Fred Shulte

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	< 500	1
Projected	1650	10

Removal efficiency vs particle size

Fractional efficiency data taken from a bed operating in a Portland-cement clinker cooler at 350°F and atmospheric pressure are given below:

<u>Particle diameter (μm)</u>	<u>Efficiency (%)</u>
< 1	Negative
1	0
2	30
5	97.5

Mode of operation

Rexnord's gravel-bed filter combines both mechanical collection and gravel filtration in a single unit. When the dust-laden gas inlet stream enters the unit, it undergoes mechanical cycloning which separates the bulk of material > 10 μm in size. As the gas passes upward, it encounters the top of the chamber, reverses direction, and flows downward through an annular gravel bed before being collected in an outlet plenum.

To clean the filter, the airflow is reversed in the system, thus elutriating fines entrained in the gravel bed and collecting them in the cyclone section of the device. During backflush operations, the gravel bed is mechanically raked to enhance bed agitation.

Capacity

Modular units designed to treat 4500 scfm are commercially available.

Power requirements

Test data indicate that power consumption averages ~ 47.7 Btu/1000 scf at a pressure drop of 4.7 in. H₂O gauge.

Materials of construction

Available models utilize mild steel construction and can operate only up to 700°F.

Costs

Not available

Stage of development

Rexnord commercially available units are unacceptable for operation in coal gasification processes. In addition to the current design limitations due to the carbon steel material used in fabrication, the deagglomeration of ash which occurs during backwash and raking cycles actually increases the submicron content of the effluent stream above the actual inlet loading. Consequently, negative collection efficiencies occur. To enter the coal gasification equipment market, Rexnord is seeking DOE funding to develop a HTHP filter (1600°F, 10 atm) whose design will be radically different from that of the existing model.

Granular-Bed Filter^{48,49}Manufacturer

PEEMCO
 292 Main Street
 Nelsonville, N.Y. 10516 ATTN: Dr. Frank Zenz

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated		
Projected		

Removal efficiency vs particle size

Not available

Mode of operation

The restricted circulation gravel-bed filter manufactured by PEEMCO is similar in design, construction, and operation to Squire's panel-bed filter. Differences occur in the fabrication of the louvres and spill pans used to retain the filter media. As a result of PEEMCO's redesign, it is possible to reduce the amount of filter media lost during cleaning operations, as well as almost double the bed surface exposure for filtration.

Capacity

Not available

Power requirements

Not available

Materials of construction

Not available

Costs

Not available

Stage of development

Not available

Granular-Bed Filter⁵⁰⁻⁵²Manufacturer

Westinghouse Research Laboratories
1310 Beulah Road
Pittsburgh, Pa. 15235 ATTN: Dr. Daniel Archer

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	Ambient	1
Projected	1400	10

Removal efficiency vs particle size

Results of filtration efficiency for ambient conditions are given in the following table.

Capacity

Experimental units with a surface area of only 0.25 ft² have been fully tested. A larger model with a 7-ft² surface area capable of operating at 1100°F and atmospheric pressure has been constructed.

Power requirements

Not available

Materials of construction

Because of the unique design, the bed contains no metal internals.

Costs

Not available

Experimental results, dust collection of a
Westinghouse granular-bed filter

Laboratory unit conditions: Gas velocity 30 cfm
Temperature 1100°F
Bed depth 4 in.
Bed material 14-28 mesh alumina
Surface area 7 ft²

Particle size (μ m)	Inlet (%)	Outlet (%)	Collection efficiency (%)
0.0-0.5	11	13	96
0.5-1.1	5	15	88
1.1-2.2	11	25	91
2.2-3.7	16	26	93
3.7-8.2	12	8	97
> 8.2	43	12	99

Overall efficiency: 96%

Comparative efficiency for a low-temperature laboratory unit under similar operating conditions: 99.5%

Source: Advanced Coal Gasification System for Electric Power Generation, Quarterly Progress Report, Second Quarter - Fiscal Year 1976, ERDA-FE-1514-45 (Jan. 15, 1976).

Stage of development

Westinghouse's granular-bed filter is still at the experimental stage. Preliminary results indicate that acceptable filtration efficiencies can be obtained from a design in which the bed contains no metal internals. Motivation for this approach lies in the fact that a filter free of metal elements is unaffected by corrosion that would attack a conventional design in a hot, oxidizing atmosphere.

Although the test unit is able to achieve high collection efficiencies (96%), it does so at the expense of a low face velocity (4.3 ft/min). For economic viability, higher face velocities will most likely be required to keep the bed to a manageable size. In order to avoid fluidization at these increased velocities, a thicker bed having a more significant pressure drop will probably be necessary. In systems for which power recovery is important, this is obviously a counter productive step.

E.4 Electrostatic Precipitators and Summary of Experience in HTHP Applications

In industrial applications at moderate process conditions, fine particulate control ($< 10 \mu\text{m}$) has often involved the use of electrostatic precipitators. These devices exhibit high collection efficiency in the fine particulate range and low pressure drop at normally encountered process conditions; however, they face the following difficulties in HTHP applications:

1. operating instabilities caused by thermal ionization, resulting in sparkover and loss of corona generation;
2. problems associated with material selection and maintenance of good electrode alignment; and
3. inability to collect fine particulate with a high carbon content which lacks sufficient resistivity to be collected electrostatically.

In regard to the last point, it has been observed that electrostatic precipitators (ESPs) operate best when the resistivity of the collected material lies between 10^3 and 2×10^{10} ohm-cm. At values lower than the stated minimum, particles lose their electrical charge on contact with the collecting electrodes. Thus high carbon content particles, typical of those produced in some gasification operations, with low resistivity, are easily reentrained after coming in contact with the collecting electrode. The dependence of resistivity with carbon content as a function of temperature is given in Fig. E-1.⁵³

To date, little interest has been shown by the industrial sector in the development of electrostatic precipitators for HTHP processes. A recent program opportunity notice (PON-FE-7) seeking the development

ORNL DWG 78-314

Fig. E-1. Effect of carbon on resistivity of fly ash.

and test operation of a high-temperature, pressurized electrostatic precipitator went unanswered. Much of this reluctance is due to the monumental engineering problems associated with the development of the device.

Due to the embryotic state of HTHP ESP development, no information is available on unit capacity, power requirements, materials of construction, or costs of these units.

Throughout the 1960s, a considerable amount of research was conducted by C.C. Shale of the then U.S. Bureau of Mines on the development of an HTHP electrostatic precipitator. Results of his work indicated that it was possible to find operating ranges in the HTHP domain in which stable corona could be generated and, hence, particle collection would be feasible. In fact, test results obtained from a semicommercial-sized unit operating at 1470°F and 6.5 atm pressure and using fly ash for particulate indicated that it was possible to obtain removal efficiencies of about 91 to 96% with negative corona and about 75 to 77% with positive corona. Unfortunately, materials with particle diameters of less than 5 μm were not used in the test nor were fractional efficiencies computed.

Electrostatic Precipitator^{54,55}Manufacturer

Research-Cottrell
P. O. Box 750
Bound Brook, N.J. 08805 ATTN: Dr. Ernst DeHaas

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	2000	20
Projected		

Removal efficiency vs particle size

Not available

Stage of development

Research-Cottrell, under an EPA contract, is investigating the feasibility of operating an ESP in the temperature range 700 to 2000°F and 0 to 20 atm. Preliminary results indicate that regimes exist in which stable positive and negative corona generation is possible. Collection efficiencies need to be determined under these conditions.

A cursory economic study has revealed that it is feasible to clean gases using an ESP in HTHP environments. Expansion of the project to the pilot plant stage is being considered.

Electrostatic Precipitator⁵⁶Manufacturer

Electric Power Research Institute
 3412 Hillview Avenue
 Palo Alto, Calif. 94304 ATTN: Owen Tasiker

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1700	8
Projected		

Removal efficiency vs particle size

Not available

Stage of development

Under the direction of Dr. Owen Tasiker, EPRI is funding the development of a HTHP ESP suitable for gasifier and PFBC applications. An experimental unit has been constructed and is scheduled to be tested at the Arapahoe Generating Station in Denver, Colorado, late in 1977.

Dr. Tasiker feels that one of the major problems associated with attaining high performance from ESPs is reentrainment of material in the gas stream which is caused by the rapping of collecting electrodes during cleaning. By a thorough study of adhesion processes and a careful redesign of the cleaning unit, it is believed that the problem can be resolved.

Electrostatic Precipitator⁵⁷⁻⁶⁰Manufacturer

DOE
Morgantown Energy Research Center
P. O. Box 880
Collins Ferry Road
Morgantown, W. Va. ATTN: C. C. Shale

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1470	7
Projected		

Removal efficiency vs particle size

At 1470°F and a pressure of 7 atm, using a negative corona, removal efficiencies ranged from 91 to 96%. For similar conditions, using positive corona, efficiencies ranged from 75 to 77%.

Stage of development

In the early and mid-1960s, C. C. Shale of the then Bureau of Mines was able to demonstrate the feasibility of operating an ESP under HTHP conditions. From his work, it was observed that positive corona was more electrically stable than negative corona in the HTHP domain, although it was less efficient in particle removal. His research was terminated in the late 1960s, after a semicommercial-size unit had been built.

E.5 Novel Devices

Several novel devices have been proposed as nonconventional alternatives for gas purification, including

1. molten salt scrubber,
2. electrofluidized bed,
3. molten glass scrubber,
4. acoustical agglomerator,
5. PXP dry scrubber, and
6. particulate precipitating heat transfer surface.

The advantages and disadvantages of each are discussed below.

E.5.1 Molten salt scrubber

Molten salt scrubbing (MSS) is based on the use of a molten alkali salt as the scrubbing liquor in a conventional venturi scrubbing apparatus. As is true with any venturi scrubber, it has the advantages of having potentially high collection efficiencies. However, there are some unique problems associated with this device:

1. materials handling problems caused by the high corrosiveness of the scrubbing medium,
2. alkali salt carryover of molten liquid droplets which are in excess of gas turbine specifications,
3. molten salt decomposition at 1650°F and reactions with gaseous pollutants, and
4. high energy requirements (7 to 10 kW/Mcfm).

Because of the formidable problems associated with the use of alkali scrubbing liquids, it does not appear that MSS is a viable hot-gas purification technique.

E.5.2 Electrofluidized bed

Since the control of fine particulates represents the major hurdle in HTHP filtration, the use of an electrofluidized bed may be one means of circumventing this problem. In this device, an electric field is internally imposed in a fluidized bed, causing a polarization of the bed media which allows it to act as a collecting electrode. This device, then, has excellent collection efficiencies in the fine particulate range ($< 3 \mu\text{m}$) although it is unable to remove particulate greater than $3 \mu\text{m}$ in size and requires testing in the HTHP range. In concert with other cleanup devices, this unit may offer sufficient efficiency to meet gas turbine requirements, provided that a successful research and development program is able to demonstrate its applicability in the HTHP domain.

E.5.3 Molten glass scrubber

In principle, this device operates by passing molten glass, mixed with coal slag, over collecting plates which are arranged in a baffled configuration. As the gas stream impinges on the collecting plates, particles are entrained in the molten glass and eventually carried to a slag hopper by gravity.

At this time, the device is merely in the conceptual stage and hence it is hard to delineate its advantages and disadvantages clearly. Nonetheless, the use of molten glass in a device designed to condition gas for turbine use appears to diminish particulate at the expense of increasing alkali content. Since turbines have an extremely low tolerance to alkali compounds, this does not appear to be an optimal departiculation strategy.

E.5.4 Acoustical agglomerator

Acoustical agglomeration is based on the concept of improving collection efficiencies by enhancing particle coagulation prior to inertial separation. This aggregation is effected by increasing the number of interparticle collisions occurring in the raw product gas by inducing a velocity difference between large and small particles through the use of acoustical waves. Experience in the past with a device based on a similar operating principle has shown that only marginal increases in overall collection efficiencies could be obtained.

E.5.5 PXP dry scrubber

PXP dry scrubbing is based on the use of dry particulate as the scrubbing media in a conventional venturi scrubber. At this time, little information is publicly available about the unit. However, previous experience with a device based on similar operating principles had encountered problems with the char feed arrangement and was unable to achieve collection efficiencies greater than 50% in the range 0 to 3 μm .

E.5.6 Particulate precipitating heat transfer surface (PPHTS)

The PPHTS consists of a set of combustion heat exchanger tubes with surfaces curved to create aerodynamic forces that remove dust particles from gas streams. Its main disadvantage is that it is unable to achieve overall collection efficiencies greater than 8.2%.

E.5.7 Summary of experience in HTHP applications

Only Battelle's molten salt scrubber has operated in the HTHP regime. Limited test results indicate that it has not been able to

achieve its design efficiency of 99% for all particles greater than 4 μm in size. In addition, problems regarding methods of improving alkali deentrainment, as well as finding materials of construction capable of withstanding corrosive environments, will have to be resolved before it becomes a viable HTHP cleanup alternative.

Molten Salt Scrubber⁶¹⁻⁶³Manufacturer

Battelle Pacific Northwest Laboratories
Battelle Boulevard
Richland, Wash. 99352 ATTN: Raymond H. Moore

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	1500	1
Projected		

Removal efficiency vs particle size

Battelle's molten salt scrubber is designed to collect 99% of all particles 4.0 μm or larger in size. In practice, collection data indicate that this efficiency is not achieved. This reduced efficiency is largely attributable to the retention of droplets of the scrubbing liquor which failed to de-entrain from the gas stream.

Mode of operation

Battelle's scrubber is similar in design to a conventional venturi scrubber which is vertically mounted and uses molten alkali salts (Na_2CO_3 , K_2CO_3 , Li_2CO_3 , CaCO_3 at 1500°F) as scrubbing liquids.

Capacity

An experimental unit capable of treating 75 acfm has been constructed.

Power requirements

For collecting particles in the 0.5- to 2.0- μ range, energy requirements for venturi scrubbers vary from 7 to 10 kW/1000 acfm.

Materials of construction

Special alloys

Costs

In similar designs, capital requirements would be \$17/kW, and annual operating costs would be on the order of 0.95 mill/kWhr (3.53 mills/MCF).*

Stage of development

In an independent study by Acurex Aerotherm Corp., it was concluded that molten salt scrubbing appeared to be a viable concept for fine particulate cleanup in advanced energy systems. However, before effective molten scrubbing systems can be developed for particulate removal, two important problems need to be solved. These are:

1. locating construction materials at an acceptable cost which can adequately withstand the highly corrosive scrubbing medium provided by hot molten liquids.
2. improving gas/liquid separation and mist eliminator designs so that liquid carry-over satisfies both emissions standards and gas-turbine-inlet specifications.

* MCF = thousand actual cubic feet.

Electrofluidized Bed Collector⁶⁴⁻⁶⁶Manufacturer

Dr. James R. Melcher
 Department of Electrical Engineering
 Massachusetts Institute of Technology
 Cambridge, Mass. 02139

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	400	1
Projected		

Removal efficiency vs particle size

Electrofluidized beds have their maximum utility in removing fine particulate ($< 3 \mu\text{m}$). Collection efficiencies on the order of 90% are commonly observed in this range of operation. Beyond the $3\text{-}\mu\text{m}$ limit, they are of marginal utility.

Mode of operation

An electrofluidized bed is established by the application of an electric field internal to a fluidized bed. After being energized, this field induces a polarization of the bed media, causing it to become a collecting electrode which is extremely effective in capturing and retaining submicron-size material. The collection efficiency appears to be a function of:

1. electrical properties of bed particles, especially their electrical conductivity;
2. electrical properties of the collected particulate;
3. the mobility of the particulate and the imposed field strength;
4. the degree of fluidization which influences the degree of bubbling and, hence, nonuniformity in the gas distribution.

Capacity

Not available

Power requirements

Not available

Materials of construction

Not available

Costs

Not available

Stage of development

The electrofluidized bed is still largely in the research phase of its life cycle. Its theoretical basis has recently been elucidated, and prototype models have been developed and operated at temperatures up to 400°F at atmospheric pressure. Preliminary results show promise of its being extremely effective in removing submicron-size particulate ($< 3 \mu\text{m}$). Additional work is needed to test the unit in HTHP applications. No interruptions of its performance are foreseen under these conditions.

Molten Glass Scrubber⁶⁷Manufacturer

General Electric Company
Space Sciences Laboratory
P. O. Box 8555
Philadelphia, Penn. 19101 ATTN: Louis McCreight

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated		
Projected		

Removal efficiency vs particle size

Not available

Mode of operation

Molten glass, mixed with coal slag, is passed over collecting plates which are arranged in a baffled configuration. As the gas stream impinges on the collecting plates, particles are entrained in the molten glass and carried by gravity into a slag hopper.

Capacity

Not available

Power requirements

Not available

Materials of construction

Not available

Costs

Not available

Stage of development

At this time, the molten glass scrubber is largely in the conceptual phase. However, one haunting question that arises from its design is that of using molten glass in the unit. At the outset, it would appear as though this media would enhance the generation of alkali salts. Given the extremely low tolerance of turbines to alkali compounds (< 0.1 ppm), it is questionable as to whether this is an optimal departiculation strategy.

Acoustical Agglomerator^{68,69}Manufacturer

Dr. David Scott
University of Toronto
Toronto, Canada M5S 1A4

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated		
Projected		

Removal efficiency vs particle size

Not available

Mode of operation

Standing acoustical waves are set up by a pulse jet in an agglomeration chamber. The smallest particles oscillate with the gas while the larger particles remain relatively stationary. This produces a velocity difference between smaller and larger particles, and agglomeration occurs via the mechanisms of impaction, interception and diffusion. Because of the removal of small particles and the growth of larger particles, post-treatment of the agglomerator effluent by conventional cyclones enhances the overall system collection efficiency.

Capacity

Not available

Power requirements

Not available

Materials of construction

Not available

Costs

Not available

Stage of development

At this time, the acoustical augmentation is merely a concept and has not been tested. However, previous experience with a device based on similar principles (Braxton Sonic Agglomerator) has shown that only marginal benefits could be obtained from combined sonic agglomeration and cycloning as opposed to cycloning alone. This was due to the fact that small particulate tended to follow low-frequency acoustical waves rather than agglomerate. By using high-frequency as opposed to low-frequency signals, this obstacle may be overcome if sufficient energy densities can be generated. However, by adding energy to the system it may be quite possible to induce particle attrition as well as agglomeration with no net benefit being achieved.

PXP Dry Scrubber^{70,71}Manufacturer

Air Pollution Technology, Inc.
 4901 Morena Avenue
 Suite 402
 San Diego, Calif. ATTN: Dr. Seymour Calvert

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Demonstrated	Ambient	1
Projected		

Removal efficiency vs particle size

Not available

Mode of operation

APT's PXP scrubber would use recycled char as the aggregating media in a venturi scrubber arrangement.

Capacity

Not available

Power requirements

Not available

Materials of construction

Not available

Costs

Not available

Stage of development

At this time, little information is available on APT's PXP scrubber. Historically, however, Babcock and Wilcox tried to develop a similar device but encountered problems with the char feed arrangement and was unable to achieve collection efficiencies above 50% in the range 0 to 3 μm . Babcock and Wilcox discontinued work after preliminary testing when they were unable to obtain external support.

Particulate Precipitating Heat Transfer Surface (PPHTS)⁷²

Evaluated by

Department of the Army
Construction Engineering Research Laboratories
P. O. Box 4005
Champaign, Ill. 61820

Temperature and pressure operating range

	Temperature (°F)	Absolute pressure (atm)
Demonstrated	400	1
Projected	1	

Removal efficiency vs particle size

Maximum overall collection efficiency estimated to be 8.2%.

Mode of operation

The PPHTS array consists of a set of combustion system heat exchanger tubes with external fluting on the upstream faces and elliptic curvatures on the downstream faces. These curves create aerodynamic forces that remove dust particles from the gas stream.

Capacity

Not available

Power requirements

Pressure drop is given by the expression $\Delta P = 7.9 \times 10^{-4} N V_o^2$
where

ΔP = pressure drop (IW),
N = number of tube banks,
 V_o = upstream velocity (ft/sec).

Materials of construction

Carbon steel

Costs

Not available

Stage of development

The PPHTS is a patented device (Patent No. 3,815,336)
invented and owned by H. Gregor Rigo.

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APPENDIX F:
EVALUATION SHEETS FOR INDIVIDUAL HOT-GAS H₂S REMOVAL SYSTEMS

MERC Iron Oxide/Fly Ash (Silica) Process⁷³⁻⁸⁰

Vendor (developer)

Morgantown Energy Research Center
P. O. Box 880
Morgantown, W.Va. 26505 ATTN: Ernest C. Oldaker

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Proven ^a	1000-1500	1-2
Projected ^b	1000-1700	2-30

^aIn bench-scale cyclic tests.

^bProjected upper temperature based on the use of silica-based iron oxide sorbent. Pressure range based on laboratory-scale batch tests at Air Products & Chemicals, Inc.

H₂S removal efficiency

Bench-scale data on a fixed bed of 75% fly ash-25% iron oxide pellets gave H₂S removal efficiencies on coal-derived low-Btu gas of 90 to 95%, based on halting the bed operation at an H₂S breakthrough of 800 ppmv. During many of these runs, H₂S content in the effluent was maintained below 500 ppmv. Silica-based iron oxide pellets exhibit similar efficiencies.

Mode of operation

Current operation of the fixed-bed iron oxide/fly ash (or silica) process is cyclic; iron oxide absorbs H₂S during desulfurization until the specified breakthrough of H₂S occurs, at which time a fresh bed is connected to the gas requiring treatment. The spent bed is regenerated by oxidation, using either very low flow rates of O₂, or dilute O₂ with inert gases (e.g., N₂) at higher rates. Regeneration is highly exothermic; a temperature of 1500°F should not be customarily exceeded for fly ash-based sorbents to prevent sintering, fusing, or other particle degradation. Silica-based iron oxide sorbents are more durable; a reasonable maximum operating temperature around 1700°F is currently estimated from limited available data.

Capacity

Ultimate sulfur capacity on 75% fly ash-25% iron oxide is slightly above 10 wt %. Properly prepared 55% silica-45% iron oxide sorbents exhibit sulfur capacities approximately double this value. Actual dynamic sulfur capacity is less than ultimate because a desulfurizing bed is taken off stream before the entire bed has reached equilibrium with regard to H_2S . Data for dynamic runs specifying end of run at an H_2S breakthrough of 10% of inlet H_2S indicate that actual sulfur capacities of 60 to 70% of ultimate are achievable. Multiple cycles have shown negligible capacity decline.

Power requirements

A conceptual design by TVA for hot desulfurization of about 25×10^6 scf of low-Btu gas per hr included about 20 kW(e) for the fixed-bed desulfurization system. About 20 times as much electricity was required for the sulfur recovery plant, which was specified for conversion of the regeneration off-gas (~ 97 vol % SO_2) to elemental sulfur. The O_2 plant designed to supply the regeneration oxidant was estimated to consume ten times the electricity of the preceding two systems combined.

Materials of construction

Reactors would be exposed to both corrosive-reducing and corrosive-oxidizing atmospheres at high temperatures. Use of refractory lining, stainless steel weld overlays, and expensive alloys will likely be required. Avoidance of aqueous-phase corrosion by proper start-up and shutdown procedures is advisable in order to prevent additional materials problems.

Costs

Capital costs for a hot-gas desulfurizer have been estimated for several studies. Because of varying assumptions and applications, the costs estimated for hot desulfurization of sufficient low-Btu gas to fuel a 1000-MW(e) combined-cycle plant have ranged from $\$30 \times 10^6$ to $\$50 \times 10^6$. The fixed-bed iron oxide reactors have each been estimated to cost above \$100,000. Placed on an operating cost basis, and including required supporting systems (sulfur recovery, O_2 plant, etc.), the charge for hot desulfurization has been estimated at about $\$0.50/10^6$ Btu of fuel gas for a 1000-MW(e) combined-cycle plant.

Stage of development

Plans had been announced for operation of the fixed-bed iron oxide process on low-Btu coal-gas, along with tests of a moving-bed filter. Gradual substitution of a strong, abrasion-resistant sorbent (probably silica-based) for the inert solids in the moving-bed filter would have permitted testing of a moving-bed iron oxide system for H₂S and particulate control. Redirection of the efforts at MERC has returned development to further laboratory-scale testing.

Appleby-Frodingham Fluid-bed Iron Oxide Process⁸¹

Vendor (developer)

Appleby-Frodingham Steel Co.
Scunthorpe, England

U.S.A. contact:

Woodall-Duckham U.S.A., Ltd.
1910 Cochran Road
Pittsburgh, Pa. 15220 ATTN: Andrew J. Grant

Temperature and pressure operating range

	Temperature (°F)	Absolute pressure (atm)
Proven ^a	635-788	~ 1
Projected		

^aIn commercial plant for coal-gas desulfurization.

H₂S removal efficiency

In pilot plant tests on coke-oven gas with about 1 vol % H₂S, one bed of fluidized iron oxide (pulverized to approximately 16 x 100 mesh) provided 80% H₂S removal. Use of two beds in series increased the efficiency of H₂S removal to 95-98%. Much of the organic sulfur (e.g., COS) was also removed. In a commercial plant at Exeter, a four-stage fluid bed consistently removed 99.9% H₂S. Almost all of this removal occurred in the first two stages. Removal of organic sulfur (excluding thiophene) ranged from 75 to 90%, with better removal experienced above 750°F in the second stage. Thiophene removal was on the order of 25 to 50%, again exhibiting higher removal at high temperature.

Mode of operation

Cooled coal gas enters the bottom of the fluid-bed reactor. The gas fluidizes the four beds of iron oxide in series, passing upward through the reactor counter to the bulk direction of the solid. Spent sorbent is passed through two fluidized seals in series to the fluid-bed regenerator, using air transport to lift the solids to the regeneration. (Original design presumed use of recycle SO₂ to transport

the spent stone, thus increasing the SO_2 content of the regenerator off-gas. This led to system temperature drops and was discontinued.) Regenerated stone is fed back to the first two absorber beds through additional fluidized seals. Particle attrition, especially in the pneumatic transport systems, leads to a requirement for iron oxide make-up, which is introduced in the fourth absorber bed (at the top of the scrubber).

Capacity

Commercial H_2S scrubber capacities have been standardized at 4.5×10^6 scf/day coal gas throughput per vessel. The units at Exeter were fitted with liners to reduce each unit's capacity from the design 4.5×10^6 to the available 3.9×10^6 scf/day gas flow rate. With greater than 99% H_2S removal from a coal-derived gas averaging almost 1 vol % H_2S , each scrubber removed slightly over 3000 lb of sulfur per day.

Power requirements

Not available

Materials of construction

Not available

Costs

Not available

Stage of development

Commercial operation of the fluid-bed iron oxide process demonstrated technical feasibility over several years on coal-derived gas. Continuous operation and extremely effective H_2S removal are two prime advantages demonstrated at temperatures below 800°F . Shutdown of the Exeter plant in 1965 was principally dictated by economic considerations; gas derived from light distillates was less expensive, and anticipated revenues from by-product sulfuric acid sales were not experienced. A larger plant at Appleby-Frodingham Steel Company in Scunthorpe was also installed in the late 1950s. Design capacity was 32×10^6 scf/day of coke oven gas, using a two-stage iron oxide process to remove about 90% of inlet H_2S . Woodall-Duckham, Ltd., constructed the plant and indicates that it has also been closed down. Technical concerns remaining for any future operations include (1) high iron oxide losses of 120 to 170 lb per 10^6 scf gas treated, (2) low SO_2 off-gas concentrations around 4 to 5 vol %, (3) lack of operating experience at high pressure or temperatures above 800°F , and (4) mechanical problems caused by buildup of iron oxide dust in the system.

B & W Iron Plate Process^{82,83}Vendor (developer)

Alliance Research Center
 The Babcock & Wilcox Company
 1562 Beeson Street
 Alliance, Ohio 44601 ATTN: N. J. Kertamus

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Proven ^a	675-1200	1
Projected	> 1000	

^aIn bench-scale tests using 1/8-in.-diam carbon steel shot.

H₂S removal efficiency

Batch tests on synthesized low-Btu gas were considered complete when effluent sulfur concentration reached 0.1%. H₂S removal efficiencies were then averaged over the on-stream time. Operation at higher temperatures increased the efficiency, which varied from 95% at 675°F to greater than 98% at 1200°F.

Mode of operation

The equipment proposed for large-scale operation would consist of a cylinder subdivided radially into 16 compartments. Each compartment contains carbon steel plates, oriented parallel with the gas flow, with about 100 ft² of surface area. Gas to be treated flows downward in 13 compartments; H₂S reacts with iron oxide scale formed on the carbon steel surface and sulfides the scale. At the same time, the remaining three compartments undergo regeneration. Regeneration air flows upward in the first, crosses over, flows downward in the second, crosses to the third compartment, and flows upward and out of the reactor. The regeneration off-gas is expected to contain 10 to 13% SO₂ by this method. The off-gas would be sent to sulfur recovery for production of sulfuric acid or, preferably, elemental sulfur. The cylinder would rotate at two revolutions per hour; thus each of the 16 compartments should undergo regeneration twice in an hour.

Capacity

In the bench-scale tests with carbon steel shot, sulfur capacity was determined as a function of temperature. End point of the runs was taken to be at an effluent sulfur concentration of 0.1%. At space velocities of 2000 to 2500 hr⁻¹ (vol gas/vol bed • hr), operation at 675°F gave a sulfur capacity of 3.5 scf H₂S per 100 ft² of surface area. Capacity increased linearly with temperature, 1200°F operation removing about 13.8 scf H₂S per 100 ft².

Power requirements

Not available

Materials of construction

The vessel containing the 16 compartments is expected to be constructed from high-alloy steel.

Costs

Not available

Stage of development

Initial work at Babcock & Wilcox fed gas from a coal gasifier to an iron grid desulfurizer. When the operating temperatures exceeded 1200°F, materials problems were encountered. The second phase of testing was on a bench-scale fixed-bed reactor containing carbon steel shot. Synthesized low-Btu gas was used. Feasibility on large-scale equipment has not yet been demonstrated. Further development efforts by Babcock & Wilcox have not been reported; as of 1975 no further effort was planned.

IMMR Coal Ash Process⁸⁴⁻⁸⁶Vendor (developer)

Institute for Mining and Minerals Research (IMMR)
University of Kentucky
Lexington, Ky. 40506 ATTN: O. J. Hahn

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Proven ^a	700-1500	1-11
Projected	1500	

^aIn laboratory-scale fixed-bed tests, T_{max} = 1450°F at 7.8 atm, P_{max} = 11 atm at 1300°F. Laboratory-scale fluid-bed tests run at 1 atm, up to 1500°F.

H₂S removal efficiency

The fluid-bed coal ash process, using gasifier coal ash which contains significant iron oxide, is claimed capable of removing H₂S to its equilibrium value. A calculation by IMMR at 1100°F, 1 atm, and 13.0 vol % H₂O gives the H₂S equilibrium as 340 ppmv. Removal to this level is equivalent to 95% H₂S removal for a typical feed gas containing 0.7 vol % H₂S.

Mode of operation

The IMMR coal ash process uses 60- to 80-mesh coal ash from a fixed-bed gasifier; the tests reported have used ash containing about 23 wt % Fe₂O₃. A possible design for use of the fluid-bed process would require two fluid beds. In the first, coal ash absorbs H₂S from the gas. A continuous solids transfer moves spent ash to the second bed for regeneration of the ash. Air, O₂, or recycled SO₂ has been proposed as the regeneration gas. Use of recycled SO₂ would require extensive gas recycle because of low predicted sulfur yields.

Capacity

The ultimate sulfur capacity of the 23% iron oxide coal ash was found to be strongly dependent on operating conditions. The data from fixed-bed tests were correlated by:

$$\text{CAP} = 1.07C + 0.00247\text{SV} + 0.00139T + 0.0203P - 4.871,$$

where

CAP = sulfur capacity of the ash, wt %;

C = H₂S inlet concentration, vol %;

SV = space velocity, hr⁻¹;

T = bed temperature, °F; and

P = bed pressure, psig.

The statistical correlation coefficient was given as 0.84. The sulfur capacities given for tests of the fluid-bed coal ash process range from 1.1 to 2.3 wt %. The highest capacity was shown at the highest operating temperature, in accordance with the correlation found in fixed-bed tests. The fluid-bed tests were run at 1 atm, so the effect of pressure was not determined. Fixed-bed tests indicate that higher pressures should increase ash sulfur capacity.

Power requirements

Not available

Materials of construction

Not available, but coupon testing of various steels and special alloys is under way.

Costs

Not available

Stage of development

Laboratory-scale fluid-bed tests have shown that coal ash will remove H₂S. Regeneration of the ash at 1200°F with air slightly enhances ash sulfur capacity, at least in initial cycles. The program at IMMR is not yet sufficiently advanced to permit an assessment of economic feasibility.

Conoco Half-Calcined Dolomite Process⁸⁷⁻⁸⁹

Vendor (developer)

Conoco Coal Development Company
Research Division
Library, Penn. 15129 ATTN: Melvyn Pell

Temperature and pressure operating range

	Temperature (°F)	Absolute pressure (atm)
Proven ^a	1500-1600	15
Projected	1700	15

^aIn bench-scale continuous tests.

H₂S removal efficiency

Bench-scale tests with half-calcined dolomite (MgO·CaCO₃) in a fluid-bed operation have demonstrated removal efficiencies of 95% and above. Exit-gas H₂S concentrations of 300 ppmv (dry basis) have been frequently achieved when treating a synthesized low-Btu gas with 1 to 2% H₂S.

Mode of operation

Conoco's system uses two fluid beds; the H₂S removal bed is fluidized by process gas, and the dolomite regenerator is fluidized by a steam-CO₂ mixture at 1300°F, which removes H₂S from the spent stone. Dolomite is cycled continuously between the two units.

Capacity

Design of the fluid-bed process at 1700°F and projected stone residence time of 20 min is based on 3.6 H₂S/CaCO₃ molar hourly space velocity. This space velocity is defined as moles H₂S per hour fed divided by moles CaCO₃ in the bed. Makeup of fresh stone to maintain desulfurization activity will run about 1 to 2% of the circulation rate.

Power requirements

A design by Conoco for a conceptual commercial installation of the fluid-bed desulfurization process for the removal of about 1345 lb-moles H₂S/hr resulted in utilities as follows:

	<u>H₂S removal</u>	<u>Sulfur recovery</u>	<u>Makeup CO₂ (for regenerator)</u>
Electricity, kW	2,478	10,365	340
Cooling water, gpm	2,975	7,744	16,000
Low-pressure steam, lb/hr			78,300
Boiler feed water, gpm		1,584	

Materials of construction

Desulfurizer will require stainless steel lining of carbon steel shell for corrosion protection. The stainless steel lining may need to be alonized, although Conoco data are not sufficient at this time to support such a decision. Refractory lining will be required for insulation (next to the reactor wall) and erosion protection.

Costs

A conceptual commercial design by Conoco for a plant gasifying about 560 tons of coal per hour (4.3 wt % sulfur) provided the following estimates of cost, based on July 1975 dollars:

	<u>Total battery limits investment (\$10⁶)</u>	<u>Offsites and utilities (\$10⁶)</u>
Desulfurization	24	2.6
Sulfur recovery	16.7	4.4
CO ₂ makeup	5	1.4

Adding escalation to January 1980, interest during construction, and operating costs (at 70% plant operating factor), the total cost for these plants can be expressed as:

\$7.40/ton feed coal,
\$0.31/10⁶ Btu HHV feed coal, and
\$0.403/10⁶ Btu HHV product gas.

Stage of development

Continuous operation of a 3-in.-diam reactor and a 2-in.-diam regenerator containing fluidized beds of half-calcined dolomite has been demonstrated. No development work is currently under way. A proposal to scale up to a pilot-plant operation was not funded by DOE. On the bench scale, Conoco noted a logarithmic decline in dolomite desulfurization activity as the stone underwent cycles of desulfurization and regeneration. High-temperature regeneration (at 1400°F) gives an off-gas with a low H₂S content, but a higher activity regenerated stone. Low temperatures (1100°F) produce a much richer H₂S off-gas, but stone activity is greatly reduced. Conoco believes that 1300°F regeneration is a reasonable compromise. The low H₂S content of regeneration off-gas at this temperature necessitates a liquid-phase sulfur recovery system.

CCNY Panel-Bed Dolomite Process⁹⁰⁻⁹²Vendor (developer)

The Clean Fuels Institute
 Department of Chemical Engineering
 City College of the City University of New York
 New York, N.Y. 10031 ATTN: Robert A. Graff

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Proven ^a	1500-1650	21.4
Projected		

^aIn laboratory-scale batch tests.

H₂S removal efficiency

Laboratory tests with half-calcined dolomite (MgO·CaCO₃) were directed principally to the problem of rapidly declining sorbent H₂S activity after repeated cycles of absorption and regeneration. Dynamic H₂S removal efficiencies were not reported, but equilibrium for the H₂S removal reaction was given as:

$$\log_{10} [\text{H}_2\text{O}] [\text{CO}_2] P/[\text{H}_2\text{S}] = 7.253 - \frac{9504.9}{(T+459.7)}$$

where

P = pressure (atm);

T = temperature (°F).

Other experimenters have indicated that H₂S is removed to its equilibrium value at absorption temperatures above 1650°F. H₂S removal efficiencies on the order of 90 to 95% are predicted based on other reports on half-calcined dolomite.

Mode of operation

Arthur M. Squires has proposed using half-calcined dolomite in the panel-bed filter developed at City College. The filter operation is described in Appendix E, Sect. E.3 (granular-bed filtration). After the filter medium (in this case, 40- to 60-mesh dolomite) is dislodged by blowback, it would be cycled through a separate regenerator, then back to the panel bed.

Capacity

Projected design of a commercial filter is expected to be based on a face velocity of 25 to 30 ft/min. This is reported for particulate removal operations. It has not been reported whether inclusion of sulfur-removal capability will affect such design values.

Power requirements

At a face velocity of 25 to 30 ft/min, the pressure drop across the panel bed is expected to be about 0.2 to 0.4 psi.

Materials of construction

Unspecified for HTHP operation.

Costs

Unavailable

Stage of development

The stage of development for the panel-bed filter without use of dolomite is reported in Sect. E.3. Tests of dolomite reported to date have been performed on laboratory-scale thermogravimetric balances. Until the filter testing is extended to HTHP operating ranges with dolomite media, no conclusions can be drawn about operability of the panel-bed system as an H₂S removal process.

Kennecott Copper Oxide Process^{93,94}Vendor (developer)

Ledgemont Laboratory
 Kennecott Copper Corporation
 128 Spring Street
 Lexington, Mass. 02173 ATTN: J. C. Agarwal

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Proven ^a	900-950	1
Projected ^b	900	20

^aIn laboratory-scale fixed-bed system using copper-containing absorbents. Regeneration at 1500°F with air.

^bProjected fluid-bed process; projected fluid-bed regeneration at 1500°F, 20 atm.

H₂S removal efficiency

Removal efficiency is a function of bed temperature and sorbent composition; values calculated at 1 atm for % H₂S removal are:

Temperature (°F)	Sorbent	
	CuO (%)	Equimolar CuO•Fe ₂ O ₃ (%)
800		99.93
980	99.0	99.7
1520		95.2
1700	88.7	
1880		90.6
2240	68.7	80.8
2500		72.2

Laboratory-scale fixed-bed tests demonstrated H₂S removals greater than 90% at 900 to 950°F with gas residence time about 0.5 sec.

Mode of operation

The conceptual design for a commercial plant proposes the use of copper oxide sorbent in two fluidized beds. The first bed contacts hot coal gas from a Lurgi-type gasifier. H_2S is absorbed by the solid CuO at 900°F and 300 psig. Overflow sorbent from the scrubber and solids collected by overhead cyclones are transported to the second bed, an air-blown regenerator. The regenerator off-gas is projected to contain about 9% SO_2 , based on laboratory-scale tests, and is sent to a conventional, double-absorption sulfuric acid plant after particulate removal.

Capacity

The very short gas residence times demonstrated in batch tests of absorption and regeneration using copper oxide (less than 1 sec) and the even shorter required reaction times for 90% H_2S removal (0.2 sec and less) and 99% sulfur regeneration (about 0.03 sec) indicate that high throughputs of gas should be feasible, particularly in fluid-bed systems. The copper oxide utilization in these tests, based on the conversion of copper oxide to Cu_2S , has been calculated at about 100%. Essentially all available copper was believed to be sulfided.

Power requirements

Not available

Materials of construction

Not available

Costs

Capital cost for desulfurizing a low-Btu gas in a conceptual 300-MW(e) power plant has been estimated by the developers. Based on treating 21.9×10^6 scf of low-Btu gas (1.1% H_2S) per hr from Lurgi gasifiers at 300 psig and 900°F , the following battery limits capital costs were estimated (January 1976 base):

	<u>Millions of dollars</u>
Total absorption equipment	4.23
Sulfuric acid plant	6.40
Absorbent recovery and recycle	0.84
Installation, building, yard, and utilities distribution	5.24
Engineering	0.85
Field expense and fee	1.14
Contingency	<u>4.70</u>
Total for hot-gas desulfurization plant	\$23.40

The conceptual design estimated a copper makeup rate of 120 lb/hr. About 1.5×10^6 scf/hr regenerator off-gas at 9% SO₂ was calculated, yielding about 500 tons of sulfuric acid per day for sale.

Stage of development

Batch tests on copper oxide have been completed. Fluid-bed systems are not currently under development. In the developer's view, problem areas remaining before technical and economic feasibility can be assured include:

- Development of hot-gas, high-pressure particulate removal equipment for turbine applications.
- Development of suitable transport mechanism to move hot copper oxide from the regenerator to a fluid-bed scrubber at the rate of 300 tons/hr.
- Flexibility of fluid-bed systems because minimum fluidizing velocities must be maintained.
- Ultimate control of soot, tars, and oil.
- Possible eutectic formation between copper absorbents and coal ash which might cause agglomeration.
- Operation of fluidized beds at high pressures, for example, 300 psig.
- Removal of fly ash from copper oxide fines without excessive copper loss, and minimization of copper loss in general.

Battelle-NW Molten Salt Process⁹⁵⁻⁹⁸Vendor (developer)

Battelle Pacific Northwest Laboratories
 Battelle Boulevard
 Richland, Wash. 99352 ATTN: Raymond H. Moore

Temperature and pressure operating range

	<u>Temperature (°F)</u>	<u>Absolute pressure (atm)</u>
Proven ^a	1200-1700	1
Projected		20

^aIn laboratory-scale batch tests.

H₂S removal efficiency

The use of a single-stage vertical venturi with fresh molten salt demonstrated H₂S removal efficiencies above 95% at 1 atm pressure. This process development unit (PDU) was not integrated with a continuous salt regeneration unit. To achieve high H₂S content during regeneration, the sulfur content of the spent salt solution must be high. Thus, the salt solution in the venturi scrubber in a continuous operation would exhibit a lower H₂S removal efficiency (less than 90%). Battelle proposes use of a supplemental absorber (a counter-current flow contactor) to permit 99% sulfur removal. Theoretical calculations by Battelle for 98% H₂S removal at 20 atm (and 1300°F) indicates over 3 times as many theoretical extraction stages required as compared to operation at 1 atm, 4.8 vs 1.5. Reducing the required H₂S removal to 90% gives theoretical stages of 2.6 for 20 atm operation.

Mode of operation

Battelle's contactor is similar in design to a conventional venturi scrubber which is vertically mounted and uses molten alkali salts (Na₂CO₃, K₂CO₃, Li₂CO₃, CaCO₃) as scrubbing liquids. Laboratory-scale tests operated to 1700°F. Tests with the PDU limited salt temperature to below 1400°F.

Capacity

A process development unit was constructed and operated on up to 75 scf/min of gas from the Battelle-Northwest gasifier using coke. Operation was not integrated with continuous salt regeneration. Salt flow was about 0.9 gal/min. Solution circulation is determined by the particulate removal requirement and exceeds the rate required for H₂S removal appreciably.

Power requirements

The design pressure drop of about 1 psi for the modified PDU currently nearing completion yields an estimated power consumption for a near-atmospheric gas stream of about 10 kW/1000 scfm.

Materials of construction

The modified PDU is being constructed of alonized stainless steel type 304. This is believed to be a suitable material below 1400°F. The PDU is designed for operation below 1300°F, where corrosion studies have thus far proved alonized stainless satisfactory. Alonization is difficult and expensive, especially for large, complex items, and may increase problems in subsequent welding or machining operations. Commercial operation, especially above 1400°F, will necessitate further efforts in material selection and vessel design.

Costs

Unavailable

Stage of development

The PDU has been modified to permit continuous operation with multiple extraction and regeneration stages. The addition of several salt deentrainment devices is hoped to prevent alkali carry-over. At least an order of magnitude better salt recovery from the treated gas stream than heretofore demonstrated is expected to be required for turbine protection. Start-up of the modified PDU is predicted in fourth quarter 1977. (Note: Also see Appendix E, Sect. E.1 for discussion of use of the Battelle molten salt process for removing particulates.)

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