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AN ANALYSIS OF THE HIGH-TEMPERATURE PARTICULATE COLLECTION PROBLEM

by

Richard Razgaitis

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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October 1977

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AN ANALYSIS OF THE HIGH TEMPERATURE PARTICULATE COLLECTION PROBLEM

Richard Razgaitis

ABSTRACT

Particulate agglomeration and separation at high temperatures and pressures are examined, with particular emphasis on the unique features of the direct-cycle application of fluidized-bed combustion. The basic long-range mechanisms of aerosol separation are examined, and the effects of high temperature and high pressure on usable collection techniques are assessed. Primary emphasis is placed on those avenues that are not currently attracting widespread research. The high-temperature, particulate-collection problem is surveyed, together with the peculiar requirements associated with operation of turbines with particulate-bearing gas streams

SUMMARY

The context of the present analysis is particulate separation and collection in the high-temperature high-pressure environment associated with direct-cycle application of fluidized-bed coal combustors.

The problem of high-temperature collection has been actively studied for at least four decades without a wholly adequate solution. The 15-year effort of the Locomotive Development Committee of the Bituminous Coal Research Institute was directed toward developing a cyclonic device and represents the most comprehensive known investigation. In contrast to this work, most of the current research activity is committed to utilizing the granular bed concept. Recent surveys of this problem published by Stone and Webster for the Electric Power Research Institute and by the Midwest Research Institute for the U.S. Environmental Protection Agency have also generally favored filter and bed-type collectors.

One of the central difficulties in evaluating collector concepts is the lack of an adequately precise and realistic turbine specification for allowable inlet concentration as a function of particulate diameter. The Aerospace Research Laboratory of Australia has concluded after 25 years of study that, for relatively low-tip-speed rotors, particulate smaller than 5 to 7 μm diameter does not cause significant erosion, even in relatively high concentrations. However, domestic turbine manufacturers who are accustomed to high-rotor-speed turbines have concluded that the concentration is critical even for relatively small particles and have established concentration specifications which are only slightly above the ambient level of an urban environment. Thus, the current performance envelop for a collector system requires cleaning from ca. 40 000 mg/m^3 at the bed outlet down to ca. 1 mg/m^3 at the turbine outlet.

There are two basic kinds of separation potentials: external field and streamline modification. None of the six known concepts employing external field separation appear to be usable in the envisioned environment of 1000°C and 10 atmospheres. Separation by streamline modification can be accomplished by either perimeter devices, which rely upon intense centrifugal velocity fields, or by distributed devices, which accomplish separation in two stages--first by precipitation onto an obstructing media and then deprecipitation of the media in a regeneration step external to the collector. Currently, the concept of distributed collection is receiving the primary attention of researchers.

As a result of the analysis presented, it is shown that perimeter devices such as cyclones and gas centrifuges are theoretically capable of meeting much higher standards of efficiency than have been demonstrated. Very little is known about the separation fluid mechanics of aerosols within cyclones, and this has handicapped the development of advanced-technology devices.

Five agglomeration concepts which can be used to enhance the collection step are surveyed. Agglomeration by turbulence and acoustic field appear to be the only techniques suitable to the envisioned environment, and these can dramatically improve the total system efficiency when used with a cyclonic collector.

The five principal conclusions and recommendations of this analysis are as follows:

1. Develop a thorough compendium of the data developed in high-temperature collection over the past four decades;
2. Clearly establish the bounds of the collector performance requirements for efficiency as a function of particle diameter;
3. Begin a fundamental study of the fluid mechanics of separation in cyclonic flows to develop an understanding of the turbulence structure and how it presently impedes the achievement of higher efficiencies;
4. Develop advanced generation perimeter collectors such as cyclones with modified boundary conditions, gas centrifuges, and eddy-baffle assemblies;
5. Determine the agglomeration kinetics of acoustic fields on aerosols emitted from fluidized beds at high temperatures and pressures.

INTRODUCTION

The purpose of this report is to present the conclusions and analysis of a four-month study performed by the author on the problem of particulate removal under high-temperature, high-pressure conditions. The report is organized into five major parts:

PART I. Engineering Relevance and a Survey of Pertinent Research
II. Gas Turbine Constraints and Implications
III. Particulate Separation at High Temperature and Pressure
IV. Particulate Agglomeration at High Temperature and Pressure
V. Conclusions and Recommendations

The scope of this analysis includes a survey of all known particulate removal principles and techniques that appear to be usable in a high-temperature/high-pressure environment. Two promising techniques, particulate conditioning by acoustic agglomeration and particulate removal by vortex tubes developed at the Aerospace Research Laboratory (ARL) of the U.S. Air Force, are examined and evaluated in some detail. A survey of gas turbine erosion and performance degradation experienced with dust-laden gases is presented because no acceptable values have been conclusively established for the particulate inlet number/mass density, size distribution, and trace element concentrations. These considerations are critical to any assessment of a cleanup strategy.

The primary objective of this study was to develop a research plan that would contribute to a solution of the hot-gas cleanup problem. Although this work was intended to assist the development of the direct-cycle concept of the fluidized combustion of coal in a bed of calcium-containing solids, it is also relevant to a number of other applications.

High-temperature particulate removal is necessary for direct-cycle applications using fuels other than coal: wood wastes (hog fuel), municipal solid wastes, and heavy residual oil. Power generation by means of the magnetohydrodynamic effect (MHD) will require the retrieval of valuable seed material dispersed in a high-temperature medium. High-temperature particulate removal will also be necessary for the high-temperature gas-cooled reactor (HTGR) employing CO_2 coolant flowing through a bed of radioactive BeO spheres. Small particles of BeO from these spheres will inevitably be entrained and must be removed. Also proposed are coal-fired fuel cells in which high-temperature particulate collection would be required to prevent blockage in the cells (which would cause hot spots to develop). In addition, many industrial high-temperature removal applications are presently solved at the expense of being exceedingly wasteful of energy: a typical case is the use of scrubbers to cool and agglomerate particulate (initially at ca. 1000°C) in the exhaust of a cupula furnace used to produce gray iron. If an efficient removal technique were available that could operate effectively in this environment, this high-temperature medium could be used as an energy source in a heat exchanger. In instances where such energy recovery is already practiced, a need still exists for greatly improved gas cleaning since the convection surfaces erode/corrode quickly, necessitating frequent replacement which is both expensive and disruptive.

PART I. ENGINEERING RELEVANCE AND A SURVEY OF PERTINENT RESEARCH

A PRIMER ON AEROSOLS

This section serves as a brief primer on aerosols and as a glossary for terms used throughout the report. All micrometer dimensions quoted will refer to particle diameter unless otherwise noted. The terms "high-temperature" and "high-pressure" are intended to mean approximately 1000°C and 10 atm (1 MPa), respectively; the phrase "hot-gas conditions" is usually employed as an abbreviation for a "high-temperature, high-pressure environment." Symbols which refer to particulate properties are designated by the use of a tilda: *e.g.*, $\tilde{V}$ is used for particulate velocity.

A relatively long-lived distribution of very small solid or liquid* particulate in a gaseous medium is called an "aerosol,"† and the field of study dealing with the combined motion of the particulate and medium is called the "Mechanics of Aerosols." The removal of the particulate from the medium, termed "collection," is but one of the specializations of this very diverse field of engineering and is based upon both the science of colloids (within the branch of physical chemistry) and fluid mechanics. A bibliography of the literature of aerosols is presented in Appendixes 1 and 2 and is taken largely from a recently published handbook on the subject.[1],‡

Aerosols are classified by the uniformity, origin, and size of the dispersed particulate. If the particulate is very nearly of a single size, it is termed "monodisperse" as distinct from "polydisperse" (a spectrum of sizes). Aerosols can originate in two ways: (1) by "dispersion," which is a purely mechanical process (such as grinding or pulverizing) and tends to create large (>1 μm), irregularly shaped, polydisperse particulate chemically identical to its parent or (2) by "condensation," which is a physico-chemical process (such as combustion, condensation, or sublimation) forming small particulate (<1 μm) which may be spherical, monodisperse, and chemically different from its parent. Two subtypes of each of these categories are frequently identified. Dispersion aerosols are divided into "dust" and "grit" usually based upon an arbitrary size criterion such as the 200-mesh sieve ("dust" would then designate dispersion particulate ranging in size from 1 to 74 μm). Condensation aerosols are occasionally classified as "smoke" or "fume" although this distinction is often ambiguous; fumes most often occur as a result of metal ore processing, whereas smokes usually result from the combustion of organic substances.

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*Because the application envisioned here involved a high-temperature environment, aerosols consisting of liquid particulate will not be considered further.

†The term aerosol is herein reserved to designate the two-phase particulate-medium state; the state of the system of dispersed particles themselves is identified by the term, particulate.

‡Superscript numbers refer to references listed near the end of this report.

A final important distinction accorded aerosols concerns the size range of the particulate. The ultimate bounds on the particulate diameter that can form an aerosol are 10^{-3} to 10^{+3} μm, although the practical range of interest for assessing removal concepts is 0.1 to 100 μm. Particulate larger than approximately 2 μm is influenced predominantly by gravitational settling, rather than Brownian motion, and is here termed "coarse;" aerosols whose particulate is smaller than this size are referred to as "fines." The 2 μm demarcation, which corresponds to that usually employed by physical chemists to distinguish colloids from suspensions, can only be unambiguously applied to monodisperse aerosols, although it is useful for the polydisperse case when the concept of a mean diameter is used.

Fines can be further classified into two categories: (1) particulate smaller than ca. 0.2 μm (about three mean-free-path lengths at standard conditions), which are dominated by Brownian motion and (2) those between 0.2 and 2 μm, which represent a transition size for which the effects of the Brownian phenomena and of gravitational settling (sedimentation) are of the same order. Transitional fines are the most difficult to analyze because of the influence of both of these effects and, at the same time, they are extremely important for both physiological and meteorological reasons. Even for relatively large particulate number densities, the spacing between individual particles is relatively large (on the order of ten particle diameters), and hence interparticle interactions can often be ignored. Yet, because the particulate is both small and disperse, aerosols are especially sensitive to surface chemistry phenomena (which admits the possibility of occurrences such as the sublimation of small particles followed by condensation onto large ones to form even larger particles). This accounts for many of the analytical and experimental difficulties associated with this subject.

Aerosols, which are not a fundamental state of matter, are unstable. This instability takes two related forms: "agglomeration" and "precipitation." Agglomeration (the term "coagulation" is also used) occurs because of attractive intermolecular forces such as the van der Waals force; these forces are significant only for very small particle-to-particle spacings and are effective only because Brownian motion permits particles to randomly approach a neighbor. The result is an "aggregate" which can be very stable ("hard") or very friable ("soft"), depending on the characteristics of the particulate itself. Agglomeration can also result when the fluid dynamic environment encourages particle encounters such as occur when polydisperse aerosols flow in any kind of an oscillatory environment--for example, within an acoustic field or through turbulent eddies. As noted earlier, sublimation causes an effect similar to agglomeration: a net disappearance of the smaller-sized particulate, a subsequent decrease in the number density, and an increase in the mean particulate diameter. The calculation of the rate at which agglomeration occurs in a general physical setting is a prodigious analytical problem. For the simple case of a nondisperse aerosol that is continuously mixed so as to maintain a homogeneous dispersion, Smoluchowski[2] has shown that the agglomeration rate is equal to the product of a constant (which is a function of the temperature of the medium) and the square of the number density when only Brownian motion is considered. Thus, this phenomenon is most important only for those aerosols which have a high initial particulate number density.

Precipitation, the other form of aerosol instability, occurs because the particulate density differs from that of the medium; the ever-present gravitational field causes stratification and, ultimately, adhesion to a bounding, lower surface. As will be noted later, the sedimentation rate is proportional to the particulate diameter squared (over a wide range of diameters) and is thus most important for aerosols consisting of large-sized particles. This phenomenon is related to agglomeration in that it provides the mechanism by which the aggregates formed can separate from the medium. In addition to precipitation by sedimentation, other force fields can cause particles to stratify. Temperature, concentration, electrical, and centrifugal fields, which can arise quite naturally in a practical flow field, will cause precipitation--primarily of the large-sized particles.

Thus, there are two aerosol types which are highly unstable and may be thought of as bounding extremes: aerosols which consist of very large particulate (in either small or large concentrations), and aerosols which initially consist of high concentrations of particulate (of any diameter). Aerosols which fall between these two extremes--modest particulate concentration and diameter--are still strictly unstable, but agglomerate and precipitate slowly enough so that they can be considered to be permanent. This consideration can be quantified by comparing the magnitude of the sedimentation velocity with that of a characteristic flow velocity and by calculating the time for the number density to decrease substantially (perhaps by one order of magnitude) with a characteristic residence time.

In addition to the aerosol propoerties presented, several others deserve mention: aerosols vary widely in terms of electrical resistivity, stickiness, friability, combustibility, corrosiveness, and toxicity. Each of these properties can be important in assessing a precipitation strategy.

An elegant presentation depicting many physical aerosol properties and flow characteristics is reproduced (by permission) as Fig. 1.[3]

ENGINEERING RELEVANCE

The design of collection schemes for aerosols is an old and well-established art. Aerosol collection has been widely applied for both material recovery and environmental protection purposes as the final step before discharge under virtually every kind of industrial process at low temperature (250°C and less) and low pressure (atmospheric pressure $\pm$ 2%). Two new problems presently require satisfactory solution: fines removal and particulate removal in a hot-gas environment--and the possibility of both requirements have to be met simultaneously.

Since the current U.S. Environmental Protection Agency (EPA) New Source Performance Standards[4] for particulate matter, 0.1 lbm/10^6 Btu,* do not distinguish between rocks and 10^{-2} μm smoke, the fines removal requirement

*This translates to approximately 140 mg/m^3 (0.06 grain/ft^3) at standard conditions for the combustion of coal at 15% excess air.

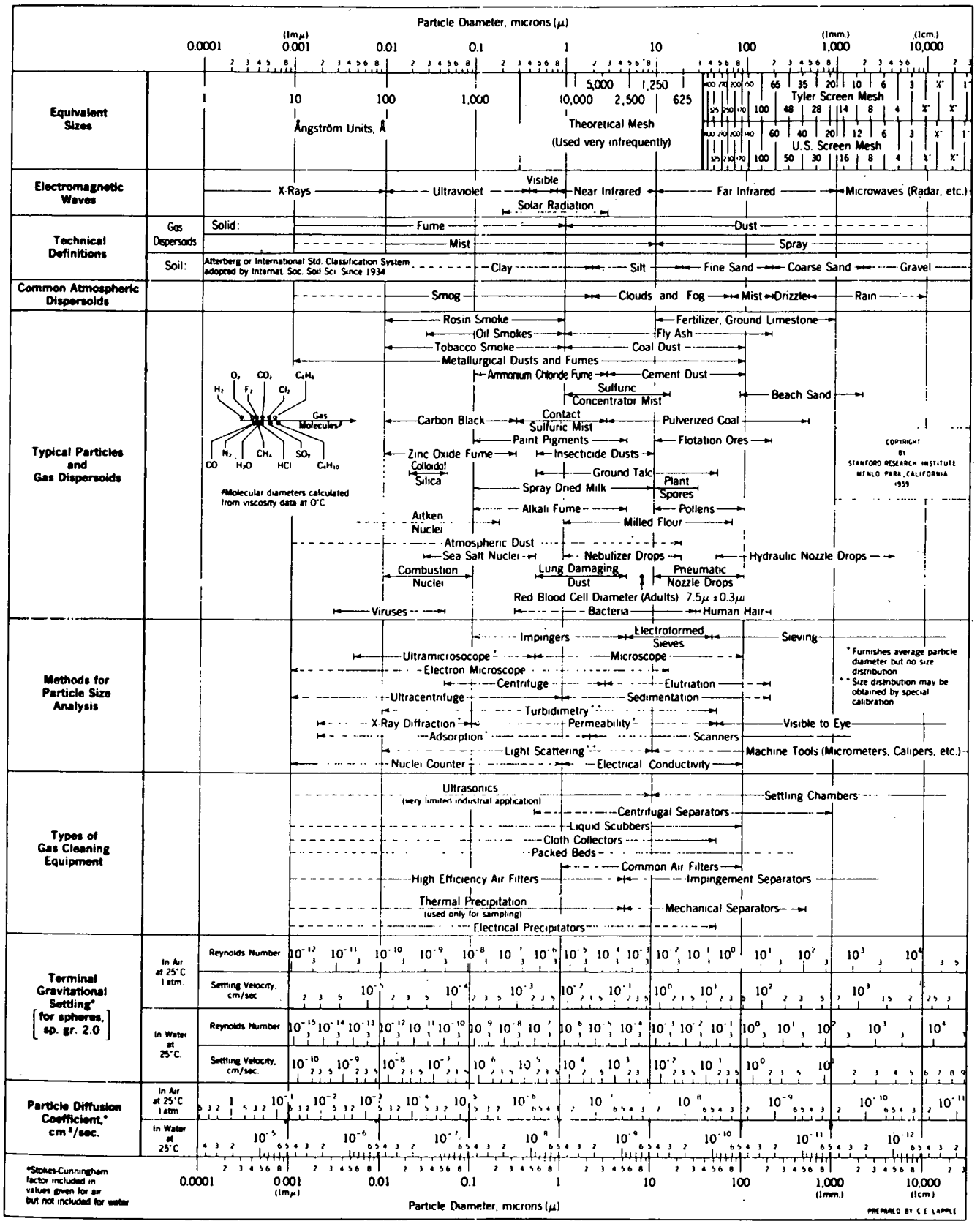

Fig. 1. Characteristics of Aerosols. Reproduced by permission of the Stanford Research Institute, Menlo Park, California, 1959[3]

has pertained only to certain special applications such as hardware protection, material recovery, and radioactive material filtering. It should be noted, however, that concern for the physiological hazards associated with fines emission has heightened greatly in recent years. The reason for this increased apprehension is that particulate smaller than about 2 μm passes the human filtration system (nose, trachea, bronchi, and bronchioles); if particles are larger than about 0.1 μm, they will precipitate within the alveoli of the lungs. A further complication associated with particles in the size range of 0.1 to 2 μm* is that they may contain enhanced concentrations of mercury, lead, and other potentially carcinogenic elements which can remain in the lungs for many years. The practical consequence of these considerations is that any long-term technology presently under development should eventually be capable of meeting very tight emission standards for both fines and total particulate mass burden within the lifetime of the process.

In contrast to extensive work on the fines-removal problem, there has been very limited experience with particulate removal under hot-gas conditions (~1000°C, 10 atm). Although this environment results in a favorable 60% reduction in the volume of gas (compared to a 250°C, 1 atm gas) requiring treatment, there are nearly insuperable difficulties associated with all particulate collection concepts. In addition to severely limiting the kinds of materials that can be used for a collector structure, these conditions have adverse consequences upon the separation mechanics of aerosols. The coup de grace is that the purification standards are significantly higher for high-temperature particulate removal than they are for ambient-temperature removal because the former environments are usually intended for gas turbine application and domestic turbine manufacturers have placed very tight constraints upon both maximum particulate size (ca. 2 μm) and inlet mass concentration (approximately 1 mg/m^3†). Also, acceptable values for the concentrations of trace elements (such as sodium, potassium, vanadium, calcium, lead, and copper) are stringently specified.

These purification requirements have so discouraged some organizations working on direct-cycle, low-Btu, fixed-bed gasifier systems that they favor cooling the outlet product from the gasifier upstream from the gas cleanup stage; the cleaned gas would then be "pre-heated" and combusted upstream from the gas turbine. Direct cycle concepts employing either a fluid-bed combustor or an entrained-bed gasifier do not allow such an option, and failure to develop a solution to meet the particulate collection requirements would be the death knell for gas turbine utilization with these devices.

Data from the Argonne National Laboratory (ANL) fluidized-bed program for coal combustion in a dolomite bed,[5-6] indicate that the particulate exit concentration from the combustor varies from 10 to 50 g/m^3,‡ depending upon the fluidizing velocity, the calcium-to-sulfur ratio, and the size distribution

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*Often termed "respirable dust," which is nearly identical to the previously defined "transitional fines."

†A concentration value which is closer to that of a typical U.S urban environment (0.1 mg/m^3) than it is to the EPA standard (ca. 140 mg/m^3).

‡A commercial version of a fluidized-bed combustor may generate concentrations somewhat higher than this value: Keairns *et al.*[7,8] estimate 40 to 160 g/m^3 at hot-gas conditions (or 16 to 69 g/sm^3).

of the particles making up the bed, as shown in Fig. 2. The mass-mean particulate size emitted from the bed varies from ca. 100 to 250 μm and is also a function of fluidization velocity as shown in Fig. 3. Particle size distributions in Fig. 4 are for fluidized combustion in an Alundum bed (Figs. 2 and 3 were obtained with a dolomite bed) and thus represents only the fly-ash contribution to the particulate concentrations shown in Fig. 3.

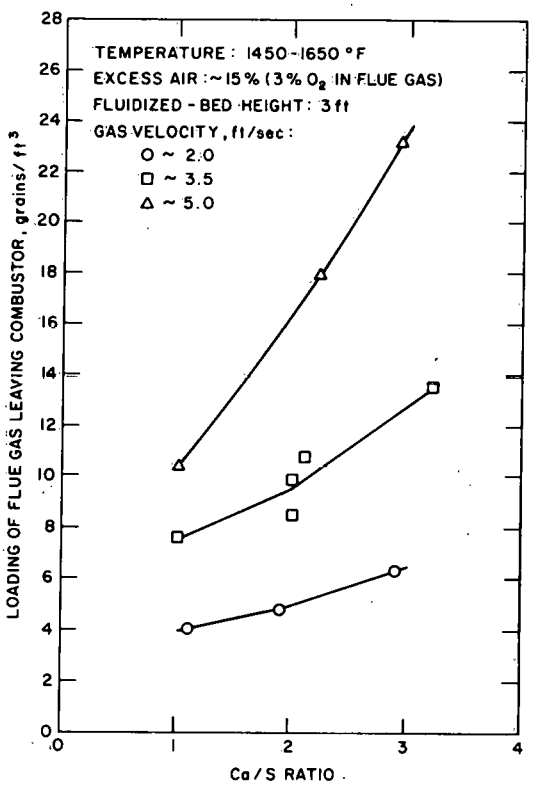

Fig. 2. Particulate Concentration at the Exit of the ANL Fluidized-Bed Combustor (reproduced from Ref. 5, p. 57)

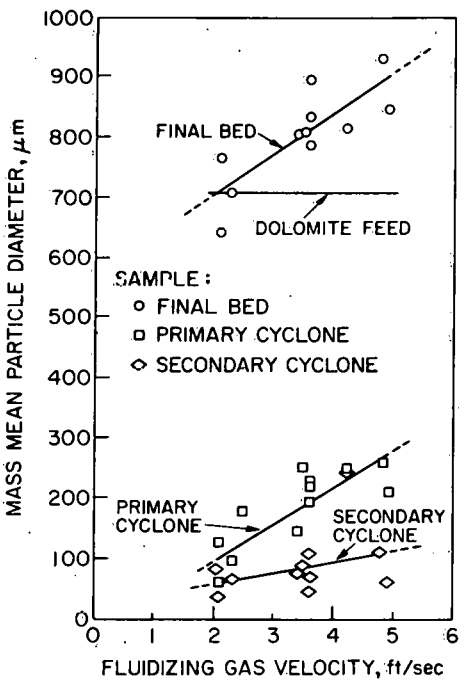

Fig. 3. Mean Particulate Diameter in the ANL Fluidized Bed and the Primary/Secondary Cyclones (reproduced from Ref. 5, p. 58)

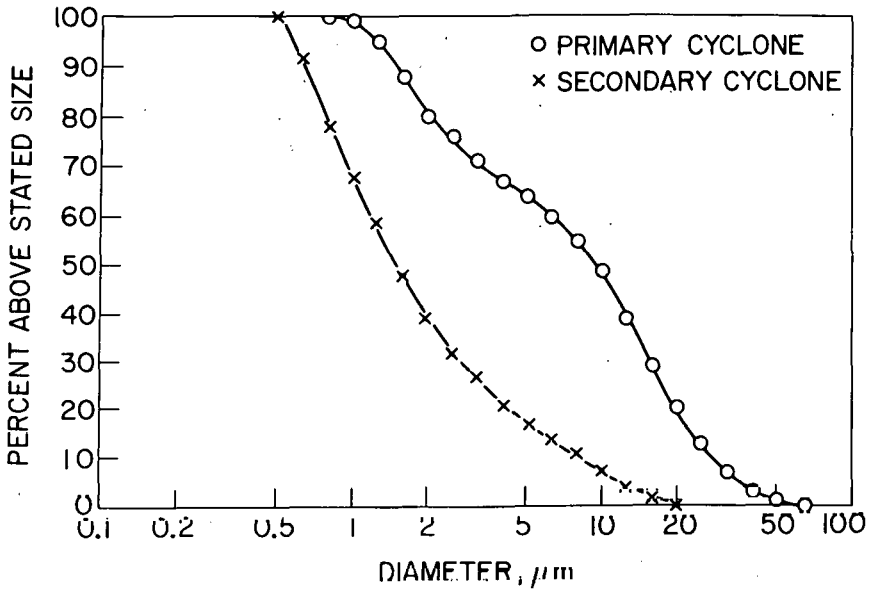

Fig. 4. Particulate Trapped by the Cyclones in the Cleanup System of the ANL Fluidized-Bed Combustor (reproduced from Ref. 5, p. 81)

Many of the trace elements of concern to turbine manufacturers have also been detected in the separated particulate as shown in Table 1,[9] and work is continuing to precisely determine the history of these elements in a fluidized-bed combustor.[10,11]

The engineering problem at hand, then, is to perform the following operations under hot-gas conditions:

(1) Remove virtually all particulate larger than a critical size, probably in the range of 2 to 10 μm,*
(2) Reduce the particulate concentration density by more than four orders of magnitude to approximately 1 mg/m^3, and
(3) Keep within allowable tolerances all trace element concentrations leaving the collection system.

*It may also be necessary to remove the transitional fines, 0.2 to 2 μm, to meet future environmental standards, although it appears that this higher-level requirement needs to be satisfied only downstream from the gas turbine stage.

Table 1. Trace Element Concentrations on a Combustible-Matter-Free Basis (Reproduced from Ref. 9, p. 147)

Element	Concentration, ppm					
		TR-3		TR-5A		
	Coal	Primary Cyclone	Secondary Cyclone	Primary Cyclone	Secondary Cyclone	Filter
As	63 ± 9	52 ± 8	N.D.	N.D.	D[b]	N.D.
Ba	D	740 ± 370	1200 ± 180	940 ± 140	1200 ± 600	1800 ± 900
Be	9.1 ± 0.9	5.4 ± 0.5	8.7 ± 0.9	3.6 ± 0.4	8.2 ± 0.8	7.9 ± 0.8
Ce	D	40 ± 20	19 ± 10	51 ± 26	26 ± 13	25 ± 12
Co	23 ± 3	23 ± 3	28 ± 3	22 ± 3	26 ± 3	33 ± 3
Cr	300 ± 130	390 ± 39	430 ± 43	880 ± 88	560 ± 56	560 ± 56
Dy	2.5 ± 0.4	3.8 ± 0.9	4.2 ± 0.4	N.D.	3.7 ± 1.8	5.6 ± 2.8
F	350 ± 70	42 ± 8	15 ± 3	55 ± 11	15 ± 3	5.7 ± 1.1
Fe[c]	13 ± 1	12 ± 1	5.2 ± 0.5	15 ± 2	7.4 ± 0.7	7.3 ± 0.7
Hf	N.D.	6.1 ± 3.0	8.7 ± 4.4	4.7 ± 2.4	7.6 ± 1.1	N.D.
Hg	1.4 ± 0.1	1.0 ± 0.1	0.7 ± 0.07	0.23 ± 0.02	0.48 ± 0.05	0.51 ± 0.05
K	7,300 ± 3,600	7,700 ± 3,800	7,200 ± 3,600	N.D.	N.D.	11,000 ± 5,500
La	53 ± 5	65 ± 6	75 ± 8	45 ± 22	N.D.	D
Mn	330 ± 33	230 ± 34	210 ± 32	550 ± 280	250 ± 38	290 ± 140
Na[c]	0.9 ± 0.1	0.9 ± 0.1	1.0 ± 0.1	1.2 ± 0.1	1.6 ± 0.2	2.5 ± 0.2
Pb[d]	21 ± 0.2	-	-	23 ± 0.2	16 ± 0.2	25 ± 0.2
Pb[d]	380 ± 38	200 ± 20	300 ± 38	-	-	-
Sb	3.8 ± 1.9	6.3 ± 3.2	8.9 ± 1.3	N.D.	N.D.	N.D.
Sc	21 ± 2	19 ± 2	28 ± 3	20 ± 2	30 ± 3	36 ± 4
Ta	N.D.	N.D.	N.D.	1.6 ± 0.8	3.7 ± 1.8	4.5 ± 2.2

[a] N.D. = not detected.
[b] D = detected qualitatively.
[c] Concentrations in wt %.
[d] The measured concentrations of lead in the coal samples used in the two experiments differed considerably. Therefore, lead mass balances for the two experiments were based on the respective lead concentrations in each starting coal sample. Concentrations of the remaining elements in the two samples did not differ significantly.

Thus the emphasis in the ensuing analysis will be on the aerosol mechanics of particulate larger than approximately 1-μm diameter and smaller than 300 μm with a mean diameter of ca. 200 μm (from Fig. 3); the collection of fines smaller than 1 μm in the high-temperature environment does not appear to be necessary and will not be considered. Since the interparticle spacing is always greater than 10 particle diameters (varying from ca. 30 diameters at the maximum concentration of Fig. 2 to more that 1000 diameters at the 1 mg/m^3 condition), interactions between particles will be neglected while they remain dispersed. Ther aerosol under consideration is both highly dispersed and consists of both small and large particulate, the latter being quite unstable. The common objective of all collection strategies is to provide a fluid dynamic environment which will increase this natural instability, resulting in a high particulate removal rate which permits cleanup to be accomplished in a reasonably sized device.

In addition to these purely technical considerations, the gas cleaning operation must be performed in a manner that will satisfy the requirements and expectations of participants employed in public utilities. Proposed particulate collection systems must be highly reliable, capable of handling exceptionally large gas volumes, adaptable to the daily load-following environment, require relatively moderate capital and operating expenditures (consumption of power and materials, maintenance, *etc.*), and have long lifetimes.

PERTINENT LITERATURE

The problem of particulate collection at temperatures above ambient is most often associated with either the combustion/gasification of coal or the processing of metal ores. Since both of these operations are old and environmentally offensive, there exists a vast body of literature on gas-cleaning devices. A great danger (and temptation) of working in this area is the failure to be cognizant of the work of others. The intent of this section is to provide a brief history of the problem and a summary of recent and current assessment studies. The details of these and other investigations will be discussed in a later section of this analysis.

A Brief History

> Widely divergent statistics have been published about our oil reserves, and there is some doubt what the true situation is. Nevertheless, there is little question but that in a national emergency, fuel oil would be in short supply, just as it was in the last war.[12]

This observation, made in 1949, is also true today and is a reason for continuing the assault on an as yet unsolved problem: finding workable and economic methods to utilize the abundant, domestic coal reserves to produce direct power.

Coal has been used to produce power--both mobile, rotating-shaft power and stationary electrical power--in three contexts: (1) indirect to produce steam via a convection/radiation surface, (2) direct in an internal combustion

engine (ICE), and (3) direct in a turbine. In the first application, steam raising, the convection tubes act as flow baffles and become fouled due to the deposition of fly ash (the entrained portion of the total ash content of the coal fuel). At present, this deposition can be satisfactorily controlled by periodically blowing off the accumulations by means of high-velocity jets; this circumvents the need for ash or particulate separation. The principal reason for the success of coal utilization in this case is that the surfaces subject to the flow of this aerosol are not "performance surfaces" since it is only required that these surfaces maintain steam system integrity. Although this concept of coal utilization conveniently avoids the need for a high-temperature particulate collection device, it does so at the cost of an enormous loss of availability. Since a coal power plant is a heat engine, its efficiency is bound by the Second Law, which can be expressed by the Carnot relation: $\eta_t = 1 - (T_0/T_1)$, where T_0 and T_1 are the absolute temperatures at which energy is rejected and received across the system boundaries. Thus, for a combustion process which naturally proceeds at 2100°C (stoichiometric air with low-rank coal of 10% moisture at 10-atm pressure under near adiabatic conditions)[13] in an environment to which energy can be rejected at 30°C, the efficiency with which the chemical energy stored in the coal may be transformed into useful work (*i.e.*, electrical energy) could be as great as 87% (*i.e.*, 87% of the energy is available). At present, system temperatures for steam generation are limited to 550°C,* which reduces the achievable efficiency (availability) to 63%. Thus, 24% of the energy or 28% of the availability originally in the coal is lost because of energy transfer across a 1550°C temperature difference.† In addition to this performance penalty, steam raising requires a substantial amount of hardware to make it work: boiler tubes, superheat/reheat tubes, feedwater heaters, deaerators, demineralizers, and other equipment.

Improved performance and reduced system complexity can be obtained with either of the direct applications of coal power--ICEs and turbines. However, in these applications, the surfaces exposed to the high-temperature aerosol (cylinder walls or turbine blades) are performance surfaces and hence very sensitive to deposition/erosion/corrosion. A device for high-efficiency removal of ash (particulate) that can operate in this environment is necessary. After more than eight decades‡ of effort, the failure to develop such a device remains one of the fundamental barriers to the development of direct, coal-fired, power-generation systems.

In addition to coal utilization, two other principal "fuels" have been discussed in the literature which result in a high-temperature aerosol product and have been used for direct power generation: blast furnace gas with turbines and, more recently, a variety of top gases which are available in many chemical processes with expanders.

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*This limit is due primarily to the high corrosivity of steam above this temperature.

†To adhere to the steam-raising concept as the proper application of coal availability is to irreversibly destroy more than one-fourth of the useful energy present in the coal reserves of the earth.

‡Rudolf Diesel's original efforts, in 1898, were directed toward the application of using powdered coal as the fuel for a mobile, efficient internal combustion engine.[14]

It is the intention in this subsection to provide a synoptic overview of the principal research efforts that have been associated with the general problem of high-temperature particulate removal from ca. 1930 to 1973.

Germany. Because of its position of having abundant coal and scarce oil reserves, Germany has had a long history of using coal and other dusty fuels for power production. Since the 1930s, blast furnace gas (Gichtgas) has been used to power gas turbines despite its high particulate concentration.[15] Professor K. Bammert of the Technische Universitat Hannover has authored 21 papers during the period, 1959 to 1976.[16-36] During WW-II, efforts were made to develop a coal-burning gas turbine, but these were not successful due to excessive erosion. This result led to the development of a pressurized coal gasifier which was to power a gas turbine and which presented a less formidable particulate collection problem. Although the latter program appeared to be capable of successful completion, work was stopped after the war when other much more economical sources of fuel became available. Pfenninger briefly summarized the experience of Brown Boveri with this project.[37]

Australia. The Aerospace Research Laboratory (ARL) of Australia began work on a coal-burning gas turbine in 1948. By 1958, they were testing a 0.9-MW(e), two-stage Ruston and Hornsby turbine. Serious erosion with this device led to an extensive testing program which was to quantify the significant parameters and mechanisms causing blade failure. By 1970, a newly designed turbine was available for testing and, in 1973, a final report on the 25-year project was issued.[38] Unlike conclusions from similar work in South Africa and the United Kingdom (BCURA, Leatherhead), their conclusions were of a positive, encouraging nature, even to indicating that multimegawatt units could be built immediately (personal communication to E. E. Soehngen).[15]

United States. Domestically, the first work with a coal-fired, open-cycle turbine was begun by the Locomotive Development Committee (LDC) of Bituminous Coal Research, Inc. (BCR) in 1944. In 1946, they began building combustors, turbines, and more importantly, ash-separation equipment. By 1955, they had accumulated more than 1000 hr of operating experience on turbines as large as 3.2 MW(e).[39-42] In 1959, after more than 4000 hr of operation, LDC turned over their equipment and experience to the U.S. Bureau of Mines (BOM) in Morgantown, West Virginia. After an initial assessment study,[43] BOM commenced work on a testing program designed to demonstrate a turbine configuration capable of enduring 50,000 to 100,000 hours of operation. In 1963, testing was begun and, after 878 accumulated hours, the ultimate life of the rotor blades was estimated to be 10,000 hours.[44] By 1966, almost 2000 hours of operation had been completed with an estimated life of 20,000 hours for the rotor.[45] Today, the BOM organization (now the Morgantown Coal Research Center, U.S. ERDA) is continuing its particulate removal activity for application to stirred-bed coal gasifiers for which direct-cycle operation is highly desirable (if not essential).

The Office of Coal Research (OCR) of the U.S. Dept. of the Interior--now also within ERDA--commissioned a study by Westinghouse[7,8] on the direct-cycle application of coal via both gasifiers and combustors. The original terms of the contract were not consumated since the study was terminated by OCR after six months work.

Combustion Power Co., Inc. (CP) began work in 1967 with the support of OCR and the U.S. Environmental Protection Agency (EPA) to develop a turbine operated using pressurized flue gas from a fluidized-bed combustor fired by several solid fuels: municipal solid wastes, wood wastes, and high-sulfur bituminous coal. In 1970, work began on the construction of a municipal solid-waste-fired, turbine power plant for the city of Menlo Park, California. The plant was intended to provide approximately 5% of that city's electrical power from its own garbage.[46] To date, more than 1000 hours of operation of a turbine (a 1-MW(e) Ruston TA 1500) has been completed in conjunction with a 4-atm fluidized-bed combustor.[47-49] Combustion Power now claims that the current process development unit (PDU) warrants the next step--a pilot plant module consisting of four fluidized-bed combustors producing a total of 50 MW(e); such a system could be available within 2 or 3 years. United Technologies Research Center (UTRC) of United Technologies, Inc. has completed several studies,[50-52] including an evaluation of high-temperature collection devices.[51]

In addition to the above mentioned work, other literature exists that pertains to high-temperature particulate collection. One body of literature could be classed under the category of General Studies of the Erosion Mechanism; Smeltzer *et al.*[53] provides a relatively recent sample and bibliography of work in this area. Another body of literature can be found under the general heading of Expanders, which have begun to find widespread use in the chemical industry* for energy conservation; Stettenbenz[54] has briefly surveyed the status of this work.

An enormous number of papers have been written on particulate collection and collectors (as can be verified by looking under the heading, "Dust Collection," in a recent issue of Engineering Index), but surprisingly little work has appeared that is directed toward evaluating high-temperature applications. Thring and Strauss[55] and Strauss and Lancaster[56] have written the only known papers that deal with a survey of collection mechanisms under hot-gas conditions. One difficulty of working in this area is the problem of locating many diffusely published papers which rarely contain adequate literature surveys. As an example, in 1955 Yellott and Broadley published a paper detailing the high-temperature and pressure fly ash removal work of the LDC.[42] Although this remains a significant paper in the area of high-temperature collection, a search of every issue of Science Citation Index from 1961 through September 1975 reveals that not a single paper in the data base of ca. 2000 journals cited this work. Further, the device developed by the LDC--which they called a Dunlab Tube--is not mentioned in any known paper published since 1955; computer searches of both journal and document data bases did not yield a single citation.

Current Research Activity

The fines-removal problem† has recently begun to attract widespread

*"Every major oil company is practicing power recovery in at least one of their refineries via 3rd stage cyclones." (F. A. Zenz, Ref. 61, p. 1-7).

†The question of fines removal is included here because of its possible impact upon proposed devices expected to be required by future, anticipated environmental restrictions.

attention, for the reasons noted earlier. Iammartino[57,58] has written general surveys on the problem and the proposed collection techniques. Midwest Research Institute (MRI) has completed a very detailed study of the subject for the EPA.[59,60] In this study, they have analyzed all known collection and agglomeration mechanisms and have assessed approximately 20 "emerging" systems (defined as having sufficient data to permit an evaluation) and "proposed" systems (concepts with little or no data). Most of these systems were based upon some variation of water-scrubber technology, which is totally unsuitable for hot-gas application. Acoustic agglomeration was discussed briefly and was deemed to have "significant potential," while the ARL* vortex tube was not mentioned at all. Southern Research Institute has also done a similar survey on fine particulate control for EPRI.[75]

Stone and Webster of Boston, Mass., is under contract to the Electric Power Research Institute (EPRI) to survey particulate collection techniques suitable for high-temperature application at the outlet of a low-Btu gasifier, and they have issued a preliminary report.[61] Their initial recommendations favored high-temperature metal filters and granular beds as the most likely candidate concepts. No mention was made of either acoustic agglomeration or the ARL vortex tube. Currently, however, both Stone and Webster[62] and EPRI[63] favor the abandonment of high-temperature processing for their application and, instead, favor cooling the gas to permit conventional techniques to be used. Low-temperature cleaning is particularly appealing in this process because the removal of H_2S is also required. There is, or course, a thermal efficiency penalty to be paid, depending upon the operating temperature of the gasifier under study (some fixed-bed gasifiers operate at less than 550°C), but direct cycle operation is at least possible because the cleaning operation precedes combustion. A final report on this investigation is expected sometime in 1976.

A study somewhat parallel to that of Stone and Webster is being performed by UTRC for the EPA. A report covering the work done during the first three phases of a four-phase program has recently been issued.[52] The primary focus of this investigation was upon the system performance of the direct-cycle, combined gas and steam concept with both low and high temperature coal gasifiers. The gas-cleaning problem addressed was primarily that associated with sulfur compound removal, and more than forty such processes were discussed. On the subject of particulate removal, only brief mention was made of panel-bed filters, granular filters, and conventional cyclones. The problem of the specification of acceptable particulate sizes and concentrations was addressed, although it is still not considered to be a settled issue.[64]

MRI has studied hot-gas cleaning in another investigation for the EPA.[65,66] This effort appears to be the most comprehensive to date (although it does replicate some of the work of Strauss[55,56]). In reference 65, p. 4, it is concluded that ". . .very little theoretical or experimental work [has been] conducted in the past on effects of high temperature and/or high pressure on gas cleaning... [and] considerable development is required before any system

*It is unfortunate, but two different organizations are widely known as ARL. The one referred to here is the now-dismantled Aerospace Research Laboratory of the USAF, Dayton, Ohio.

is commercially available." Their very detailed report indicates that a large number of investigations are already in progress using granular-bed and fabric filters, a few with high-energy cyclones, and fewer still with acoustic agglomeration. The literature on the ARL vortex tube was not reported. The Aerotherm Division of the Acurex Corp. has also reported to the EPA on the hot-gas cleanup problem.[67] Their study was primarily associated with low-Btu gas applications and is a less-detailed study which preceded that by MRI.[65] The EPA is currently sponsoring two ongoing studies--one by Mitre[68] to update the MRI work and the other by Air Pollution Technology[69,70] whose purpose includes experimental investigations of various devices in addition to basic studies. The EPA is also currently evaluating the responses to an RFP (which fell due in January 1976) for further work with specific collection devices.[71] There has also been at least one internal, unpublished paper study in this area.[72]

ERDA is sponsoring the study of several specific removal concepts,[73,74] and it appears that they will be expanding further in this research area.

In addition to the aforementioned general survey studies, a number of specific investigations pertinent to high-temperature collection and particulate measurement are currently active. Table 2 presents a summary of known sponsored research activity on these subjects--work which is either current or has been completed within the past two years. Internal corporate-sponsored research is very difficult to identify (since it is frequently viewed with the same perspective as trade secrets) and is not included in this table. The details of several of these studies will be considered in subsequent sections.

Table 2. Recent and Current Sponsored Research on Particulate and Collectors

Agency	Officer	Subject	Status	Contractor	Personnel
EPA	L. Shackelford	Fine Particulate Removal	Complete[60]	Midwest RI	L. Shannon
	D. Harmon	Braxton Acoustic Agglomerator	Complete	GCA Corp & Braxton	R. Dennis E. Kent
	D. Drehemel	Acoustic Agglomeration Evaluation	Complete	Midwest RI	R. Hegarty
		RFP For Novel High Temperature Devices	Evaluation		
	L. Sparks	High Temperature Removal Survey	Complete[66]	Midwest RI	A. Rao
		Basic Studies, Experiments at High Temp.	68-02-2137	Air Pol Tech	S. Calvert
		EP[a] at High Temperature	68-02-2104	Res Cottrell	
	J. Kilgroe	High Temperature Removal Survey	Complete[67]	Aerotherm Div	R. Fulton
	W. Rhodes	Gas Turbines	Complete[52]	UTRC	F. Robson
	(unknown)	High Temperature Survey	Active	Mitre	B. Truitt
ERDA	W. Fedarko	Fluidized-Bed Collector	Pending	Exxon Res	(proprietary)
	C. Grua	Iron Oxide Bed Collector	Active	ERDA, Morgantown Air Prod & Chem	E. Oldaker
		Molten Salt Scrubber	E 45-1-1830	Battelle NW	R. Moore
		Particulate Measurement Survey	E 49-18-2220	Gilbert Assoc	B. Murthy
		High-Temperature EP[a]	Pending		
	(unknown)	Coal Utilization Experience	Active[15]	Soehngen	E. Soehngen
		Baffle-Array Collector	Active[174]	Const Eng Res	E. M. Honig
		Coal Gasification System	Active[8]	Westinghouse	D. L. Keairns
EPRI	M. Gluckman	Hot Gas Cleaning Survey, I	Complete[61]	Stone & Webster Hall Assoc, Inc Zenz Consultant	E. Zabolotny H. Hall F. Zenz
		Hot Gas Cleaning Survey, II	RP 243	Stone & Webster	C. Jones
	S. Alpert	Panel Bed Filter	RP 257	CCNY	A. Squires
	O. Tassicker	EP for Low Conductivity Ash	RP 386	Air Pol Sys	J. Cooper
		EP Performance Evaluation	RP 413	Southern RI	R. Bickelhaupt
		Dry Scrubber Evaluation	RP 491	Bechtel Corp	
		Conditioning for EP[a]	RP 724	Southern RI	(pending)
		Particle Migration in EP[a]	RP 363	Wash St U	D. Strock
		Acoustic Agglomeration with EP[a]	RP 539	SUNY-Buffalo	(pending)
		Foam Collection for Fines	RP 362	Wash St U	R. Mahalingam
		Measurement via Diffusion Battery	RP 723	Air Pol Tech	(pending)
		Spectroscopy of Fly Ash	RP 631	Stanford U	(pending)
		Fly Ash Testing Facility	RP 629	Babcock & Wilcox	(pending)
		Agglomerator & Collector for EP[a]	RP 533	Stanford U	(pending)
	H. Kornberg	Particulates & Health Effects	RP 571	Sci Appl Inc	R. Ziskind
	A. Stankunas	Measurement with Ionization Dectector	RP 675	Midwest RI	L. Altpeter
	R. Carr	Measurement with Cascade Impactor	RP 414	U Washington	G. Farwell
		Measurement with In-Stack EP[a]	RP 463	Meteorology Res	D. Ensor
	(unknown)	Control of Fine Particulate	Complete[75]	Southern RI	(unknown)
		Evaluation of Coal Conversion	Complete[76]	U Michigan	(unknown)

[a]Electrostatic precipitator (precipitation).

PART II. GAS TURBINE CONSTRAINTS AND IMPLICATIONS

Despite the enormous literature on gas turbine operation with high-temperature aerosols, there remains a great deal of uncertainty as to the precise requirements for a particulate collection device to be used with a given particulate and application. The two most important aerosol parameters that govern turbine life are the particulate size (specified either as a mass mean value or as a distribution curve) and the particulate concentration. It is these quantities that will be emphasized here.

FACTORS WHICH AFFECT TURBINE LIFE

Turbine operating life is governed both by the aerodynamics of the aerosol and by materials considerations: the former essentially determines the number and intensity of particle impacts (deposition/erosion) on both rotating and stationary surfaces; the latter centers on the erosive/corrosive influence of the impacts/deposition.

Materials considerations pertain to the reactivity of the turbine blade material (and its coating) in the presence of the elements contained in the particulate at the operating temperature of the medium. The resistance of the turbine surface to particle impacts can be determined fairly easily and correlates well with stiffness (Young's modulus) of the surface and with stiffness of the particulate (*i.e.*, degree of "hardness").[53] Coal combustion below the ash-softening temperature, such as occurs in a fluidized-bed combustor, tends to produce soft particulate--however, the elutriated calcium stones (which constitute the major fraction of the particulate loading) are considered to be hard and therefore erosive. Quantifying the corrosiveness of the particulate/blade system is much more difficult. When alkali metal compounds are present, liquid films of sulfate and sulfate-chloride mixtures can form on turbine blades over temperature ranges of interest. If these films attack the protective oxide layer, catastrophic oxidation leading to blade failure will result.[6] In addition, tar will condense from the aerosol at temperatures less than ca. 500°C and will interact with deposits on the blading. In principle, it is possible to reduce these deleterious effects to virtually any desired level by designing very thick (and aerodynamically inefficient) blades protected by highly exotic (and expensive) coatings.

Aerodynamic considerations include specification of the streamlines of the flow field and of the secondary flows, the relative velocity between the particulate and the turbine blades, and the particulate size/concentration mentioned previously. These factors determine the percentage of the particulate present that will impact a surface, the angle at which the impact will occur, and the kinetic energy associated with each impact. As with materials condiserations, a wide latitude exists within which performance may be traded for decreased erosion.

The large number of parameters present in this problem, together with the subjective judgments intrinsically required, make it impossible at present to determine "how clean is clean."

PARTICULATE COLLECTION PERFORMANCE ENVELOPE

A critical issue that must be settled before any assessment can be made of particulate collection for high-temperature aerosols is the quantitative specification of the necessary turbine inlet conditions. The emphasis in this section is upon particulate size and concentration. Issues such as particulate reactivity and relative blade velocities, though important, will not be addressed here. The presence of complicated secondary flows results in a subtle and potentially important difficulty: since the inlet aerosol can be expected to comprise different size distributions depending upon both the original source of the high-temperature aerosol and the collector used, these particles will stratify in different concentrations due to the presence of these local centripetal fields and thus experience different streamline and impaction histories. The practical consequence of this situation is that it may not be possible to predict the erosive influence of a new aerosol source or collector system when the performance of a baseline system is known, even if both aerosols have precisely the same chemical composition, mass mean particulate diameter, and particulate concentration.

A graphic display of the known data on turbine erosion and its particulate collection implications is presented in Fig. 5 in the form of particulate concentration (loading) as a function of mass mean particulate diameter. The ordinate on the right side represents the permitted penetration--defined as one minus the efficiency (*i.e.*, 99% collection efficiency corresponds to 1% penetration). Penetration is based on a given particulate inlet concentration: namely, 37.8 g/m^3,* which corresponds to 7 grains per standard cubic foot and is represented by the triangle symbol. This value represents a typical concentration exiting from a fluidized-bed combustor for moderate calcium to sulfur ratios and fluidizing velocities; it was used by Westinghouse as the baseline level in their study.[8] Commercialized versions of such combustors may generate higher concentrations of particulate. The mass mean particulate diameter was taken to be 225 μm, based on the data of Fig. 3. This inlet condition, 37.8 g/m^3 and 225 μm, corresponds to operation at 5 ft/s fluidizing velocity and Ca/S = 2 with the ANL combustor. This concentration, although typical of many industrial aerosols (10 grains/std ft^3 is common), is much lower than that generated by fluid catalytic crackers now used to power gas turbines in the oil industry.[61]

Six performance levels for collector outlet conditions are given in Fig. 5. The EPA limit, the most lenient bound, has been converted from standard to hot-gas conditions such that, if Level 1 should be achieved by the collector system, no further gas treatment would be required downstream to satisfy environmental restrictions. The most stringent bound was presented in a somewhat different form in the UTRC report[52] and originates from a cited petrochemical source.[77] This line represents a constant value of turbine life, 10,000 hours, and is the only known specification of its kind. It assumes a simple inverse relationship between turbine life and both particle size and concentration; thus for constant turbine life to be maintained,

*All concentration values presented in Fig. 5 are based upon actual gas conditions at 10-atm pressure and 1000°C.

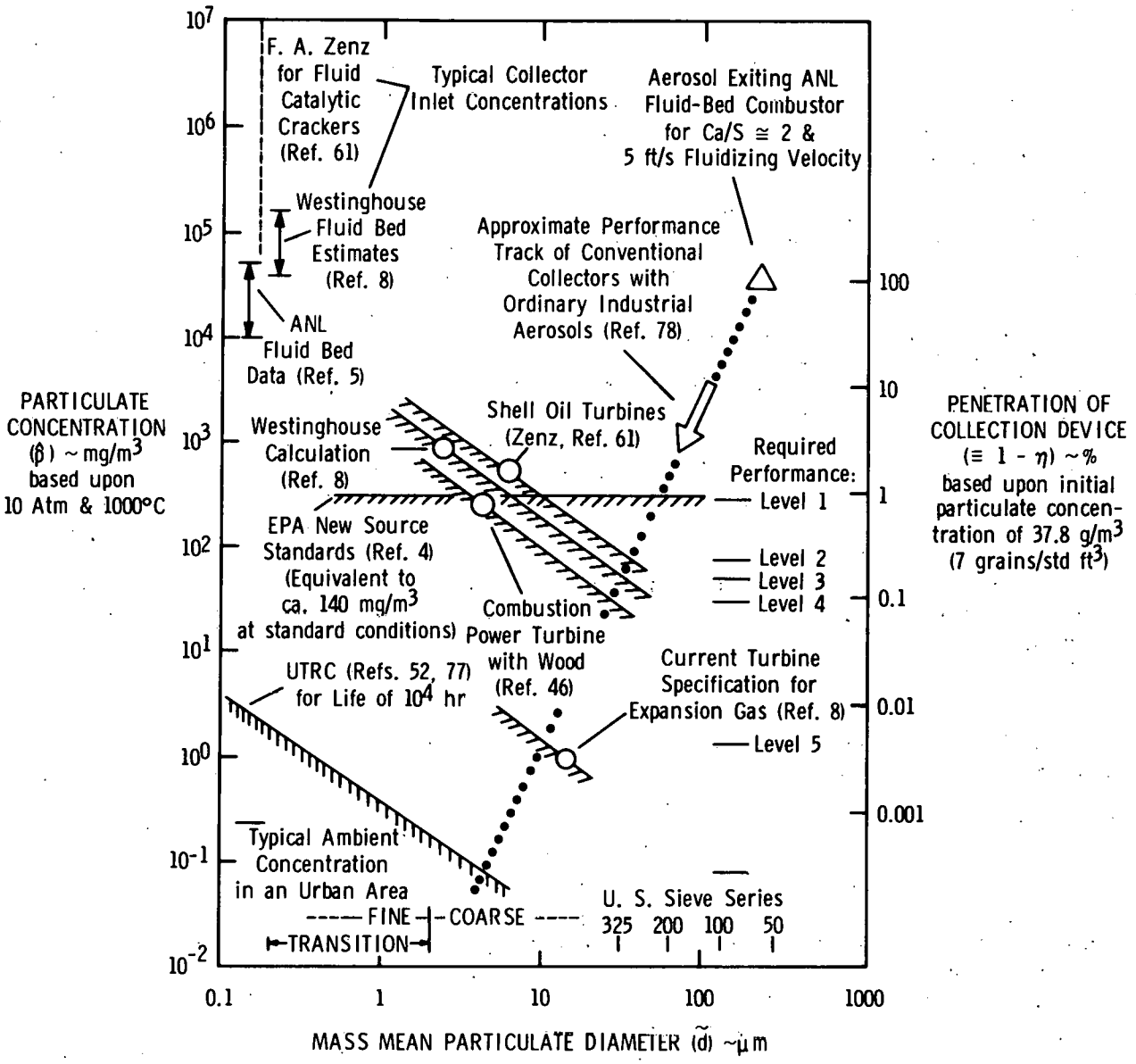

Fig. 5. Collector Performance Implications

increasing the particle size by one order of magnitude requires that the concentration be decreased by one order.

The four circle symbols in Fig. 5 represent the known particulate concentration/diameter pairs that have been discussed in the literature in terms of acceptable turbine wear. The lines extending these symbols were developed by this author. The most exhaustive study to date, that of the Australians,[38] concluded that for a fixed particulate size, the erosion rate is proportional to the concentration (a result consistent with Ref. 77). For a fixed concentration, the erosion rate of a single particle increased approximately by the cube of the diameter.* However, when one is dealing with an aerosol, the concentration will also decrease by the cube of the particle diameter and thus reduce the number of impacts proportionally. If this were the complete picture, erosion with an aerosol would be independent of particle size--a false conclusion. The mission element in the analysis is the sensitivity of the rate at which individual particles drift across fluid streamlines as a function of their diameters, a topic that is developed in Part III of this report. The Australian study presented data for the erosion rate experienced with three different relative velocities (600, 900, and 1200 ft/s) for particulate diameters of 7 to 15 μm. According to these data, the erosion rates were proportional to the diameter raised to powers of 1.17, 1.22, and 1.00 for the three velocities studied (a result which is in approximate aggreement with that given in Ref. 77). Thus, the lines extending the circle symbols were all based on

$$\text{Life} \sim (\hat{\rho})^{-1} \ (\tilde{d})^{-1.2}$$

where $\hat{\rho}$ is the concentration of the particulate in the medium and $\tilde{d}$ is the particulate diameter.

F. A. Zenz, in the Stone and Webster report,[61] details some of the experience of turbine power recovery in a typical refinery (Shell Oil); ". . .using a multiplicity of relatively small diameter cyclones which reportedly resulted in turbine feed gas particle contents of 0.044 to 0.059 grains per actual cubic foot {100 to 135 mg/m^3} of gas. . ." (p. I-3) and "It has been found that particles up to 15 and even 20 microns in diameter at concentrations of 0.08 to 0.12 grains of catalyst per ACF {183 to 275 mg/m^3} of gas crease no significant increased rate of blade erosion." (p. I-4) and ". . .the catalyst loading leaving the second stage cyclones can be expected to be in the range of 0.2 to 0.4 grains/actual cubic foot {458 to 915 mg/m^3} of effluent gas. . ." (p. I-3). Also presented is a size distribution range: 40 to 80% less than 2 μm, 15 to 40% from 2 to 4 μm, 5 to 17% from 4 to 10 μm, and 3% from 10 to 20 μm. By assigning a specific concentration percentage at the mass mean diameter of each of the above four ranges, the mass mean diameter of the total particulate can be found for any selected concentration. A value of 500 mg/m^3 was chosen distributed as 300 mg/m^3 at 1.59 μm, 150 mg/m^3 at 3.30 μm, 45 mg/m^3 at 8.10 μm, and 15 mg/m^3 at 16.5 μm, yielding a mass mean diameter for the particulate of 5.8 μm.

*However, "It has been shown that particles smaller than 5 microns do not contribute to erosion. . ." (Ref. 38, p. 211).

The Westinghouse study[8] analyzed the erosive effects of three different particulate distributions at two concentrations for two impact velocities. The "probable ash" concentration was 0.16 gr/std ft^3 (864 mg/m^3) distributed as follows: 0.13 from 0 to 1 μm (mean = 0.79 μm), 0.02 from 1 to 2 μm (1.65 μm), 0.01 from 2 to 5 μm (4.05 μm), and 0.002 from 5 to 10 μm (8.25 μm). Thus, their probable ash can be depicted as 864 mg/m^3 at a mass mean diameter of 2.3 μm, as shown in Fig. 5. The estimated erosion of this concentration/size particulate was 4 amd 30 mils per year (based upon 5000 hr/yr) for 500 and 1000 ft/s impact velocity. Although these rates are not intolerably high, they do not take into account either stratifying effects due to local streamline curvature which will cause nonuniform erosion rates or corrosion due to the presence of trace elements. For these reasons,* they concluded that the allowable concentration for commercial operation will have to be substantially smaller: below ca. 0.5 mg/m^3 for particulate larger than 2 μm.

Combustion Power Co. has had limited experience operating a turbine directly from a fluidized-bed combustor.[46] They reported concentrations of 0.047 gr/std ft^3 (254 mg/m^3), with 97% of the mass having a diameter below 5 μm. The mass mean average diameter for their particulate was taken to be 4 μm. Based upon their wood-waste fuel experience, Furlong and Wade claim ". . . there is good reason to believe that many turbines can survive such an inert particle loading profile. Although not yet confirmed by long duration tests, a similar situation is anticipated for coal firing." (Ref. 46, p. 8).

The current turbine specification line shown in Fig. 5 was taken from the Westinghouse report,[8] where it was given as a concentration of less than 2×10^{-4} gr/std ft^3 (1.08 mg/m^3) with 95% of the particulate less than 20 μm and an absolute top size of 100 μm. This specification has been included in Fig. 5 by assuming a mass mean diameter for the given concentration of 15 μm.

In order to utilize the above six performance bounds to specify the required collection efficiency, it is necessary to know the "performance track" of the aerosol/collector combination as the gas is cleaned in going from its initial state, the triangle symbol, to its final state. This track is clearly a function of the aerosol properties (*e.g.*, size, distribution, specific gravity of the particulate, concentration, and temperature/pressure of the medium) and of the collector (separation potential, drift distance, residence time, secondary flows, *etc.*), and sufficient data do not exist to establish such a line *a priori*. If, however, it can be assumed that the collection process does not differ too widely from that of industrial dust cleaned by conventional devices, it is possible to at least estimate the slope of this track. Reference 78 (p. 890) presents a cleaning slope that can be represented as follows:

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*Another important reason for conservatism was noted by Robson[64]--all previous experience of commercial turbines has been with soft particulate, whereas the fluidized-bed application will present high concentrations of relatively hard particulate.

$$\hat{\rho} \sim (\tilde{d})^{2.45-3.64}$$

for "ordinary industrial dusts." It was originally developed by S. Sylvan of American Air Filter Co., Inc. The performance track shown as a dotted line in Fig. 5 was obtained by using an intermediate value of 3.25 for the exponent. It must be emphasized that this track is a strong function of both the initial size distribution and the separation mechanics of the collector. For example, if a collector could be designed to separate only the very small particles while leaving the large ones unaffected, the track would have a negative slope since the mean size would be increasing with a decrease in concentration.

There are, then, three principal assumptions upon which Fig. 5 is based: the slope of the constant turbine life curves, the slope of the collector performance track, and the concept of characterizing the properties of the aerosol by a mass mean diameter. If these assumptions are justified, the six required levels of collector performance are as shown: to 99^{+}% to meet the current EPA requirement (Level 1), to 99.9^{+}% to meet the Combustion Power data (Level 4), to 99.99^{+}% to meet current specifications (Level 5), and, finally, to 99.999^{+}% to meet Ref. 77 requirement for 10 000 hours (Level 6).

IMPLICATIONS OF COLLECTOR REQUIREMENTS

It remains to be established where the final turbine specification line will fall; it will certainly be a function of the other factors mentioned earlier (trace elements, relative velocity, *etc.*). Level 6 appears to be extreme since it would require concentrations lower than that present in a typical urban atmosphere. With the notable exception of the Australian community, most investigators have concluded that Levels 2-4 will not be given an adequate turbine lifetime. Further quantitative work is needed to settle this issue concretely. In this regard, it is very important that a full account be made of the worldwide experience available that extends back more than four decades; in particular, the work of Dr. Bammert,[16,36] which to the author's knowledge has not been cited by any of the references, needs to be carefully examined.

These high efficiences would constitute nearly impossible collector requirements were it not for the large initial diameter of the particulate (note the constrast between the size distribution for fly ash in Fig. 4 and that of the aerosol given in Fig. 3). With conventional combustion (which generates fly ash), the EPA limit cannot be met readily with cyclone technology alone. Current practice is to use either an agglomeration technique--namely, water scrubbing--to increase the particulate size so that it may be removed with cyclone-type devices or to use an electrostatic precipitator (EP). For reasons presented in Part III, neither of these current, commercial techniques is applicable to the high-temperature and pressure environment.

The two families of collection concepts commonly suggested are either advanced technology cyclones or high-temperature filters (fiber or granular); cyclones are relatively cheap and filters are relatively more efficient. Which of these concepts will ultimately find commercial acceptance remains to be seen; the turbine requirements will act as the fulcrum in the decision.

A plot of the annualized cost (capital plus operating) of both the collector and the turbine as a function of turbine particulate inlet concentration is likely to take the form shown in Fig. 6; there are two bounding systems--the high-performance turbine which will probably require a granular filter and the modest-performance turbine which may operate acceptably with a cyclonic solution (perhaps together with a particulate agglomerator). If these cost curves can be developed--which would be a formidible task--then the optimum, minimum-cost solution can be established.

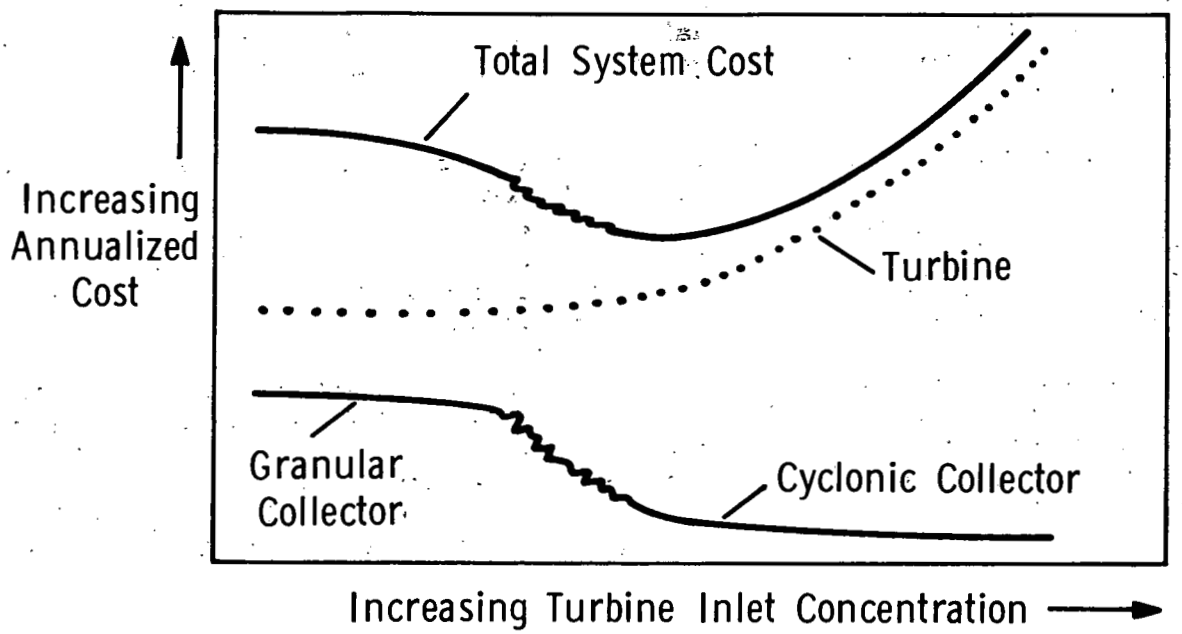

Fig. 6. General Cost Trends of Proposed Turbine/Collector Systems

PART III. PARTICULATE SEPARATION AT HIGH TEMPERATURE AND PRESSURE

BASIC PRINCIPLES

The process of segregating an aerosol into predominantly solid-phase and predominantly vapor-phase streams is termed "collection." Four separate and distinct subprocesses occur during collection: separation, agglomeration, precipitation, and removal. Separation is the subprocess which stratifies the particulate to establish a local, nonuniform concentration by means of an action-at-a-distance force. Agglomeration is the phenomenon whereby particles randomly collide, adhere, and grow in size. Precipitation is similar to agglomeration except that the adhesion forces are between particulate and a system boundary. The final stage of the collection process involves the removal of the separated/agglomerated/precipitated particulate from a system boundary.

The extent to which each of these four subprocesses is important varies with the collector concept. Cyclonic devices, for instance, do not cause significant precipitation. As a result, the removal step is relatively uncomplicated since intermolecular bonds need not be broken. Filters operate with relatively weak separation forces and work only because of substantial precipitation; thus, the removal problem is much more complex.

These subprocesses can be divided into two categories depending upon the character of the associated aerosol: disperse or concentrated. Agglomeration, precipitation, and removal of all involve relatively concentrated particulate and the effects of short-range, intermolecular forces are predominant. This category of collection is discussed under the Part IV heading of "particulate conditioning," which deals with the effect of the short-range mechanism.

The separation process occurs while the particulate is still highly disperse, with interparticle spacing one order or more larger than the particle diameter. Separation occurs only if the particulate phase experiences a force that the medium does not; this can only be accomplished by an action-at-a-distance body force and is termed the long-range mechanism. The essential objective of the long-range mechanism is to establish a velocity component normal to the fluid streamlines, as shown in Fig. 7. This drift velocity will result in a nonhomogeneous distribution of the particulate (stratification) with a small interparticle spacing that permits the action of short-range mechanisms to complete the collection process.

A numberous and diverse assortment of long-range separation mechanisms has been investigated and it is impossible to develop a complete and unambiguous classification system on the subject. Nontheless, because it is fruitful to examine similar mechanistic families and an imperfect classification is better than none at all, the author has attempted to establish such familial relationships (Table 3). The four most commonly known collectors--settling chambers, electrostatic precipitators, inertial collectors, and filters--are in quotation marks. Scrubbers and other agglomerating devices are not separate entries in this table since they are not separation mechanisms but particulate conditioning techniques and as such can be used in conjunction with any listed separator concept.

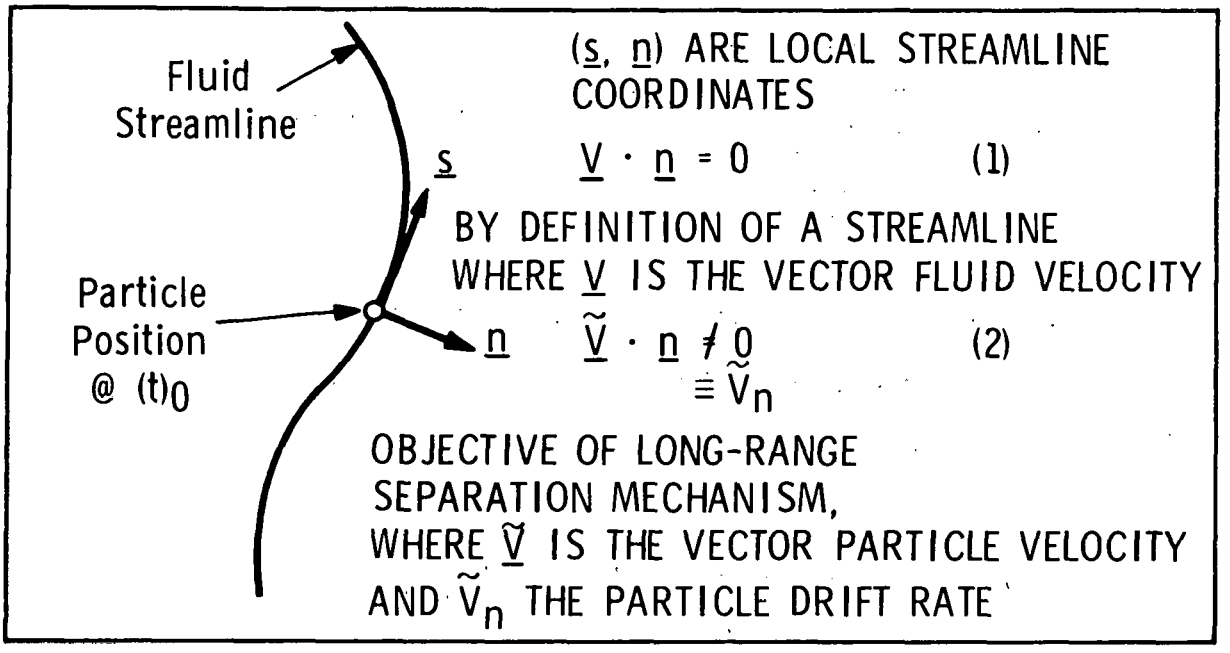

Fig. 7. Illustration of the Long-Range Separation Mechanism

As in all classification schemes, a number of factors arise which tend to obscure distinctions between the various categories. It is frequently desirable to combine devices from two different families into a single, hybrid system, such as the use of a cyclone in series with an electrostatic precipitator. A further complication exists when more than one mechanism is applied within a single device, such as combination of an electrical field with a surface filter. Also, the single mechanism of separation indicated for a particulate device (such as streamline modification with a filter) may be supplemented to a significant degree by effects not shown; for an electrified filter, separation is also influenced by interception, Brownian motion, and other phenomena not directly related to the issue of streamline shape.* Despite these limitations, it is believed that the classification scheme presented in Table 3 is a valuable aid to the comprehension and interpretation of collector performance. It will serve as the organizational outline of the discussion of particulate separation.

*In general, these secondary influences become of increasing importance as the length scale of action decreases; for instance, with particles smaller than ca. 0.5 m, the effect of Brownian motion exceeds that of centripetal motion.

Table 3. A Classification of Long-Range Particulate Separation Mechanisms

I. Separation by an External Field
A. Gravitational: "Settling Chamber"
B. Electrical: "Electrostatic Precipitator"
C. Magnetic
D. Thermal
E. Photon
F. Concentration
II. Separation by Streamline Modification
A. Perimeter Collection: "Inertial Collector"
1. Baffle
2. Scroll
a. Static
b. Dynamic
3. Cyclone
a. Direct/Reverse Flow
b. Tangential/Axial Inlet/Exit
4. Centrifuge
B. Distributed Collection: "Filter"
1. Baffle-Array
2. Granular-Bed
a. Fixed
b. Moving
c. Fluidized
3. Fibrous Mesh
a. Surface
b. Depth

PROPERTIES CONSIDERATIONS

Three properties of the media--density, viscosity, and mean free path--are affected by variations in temperature and pressure. It will be assumed that the medium has the properties of air.

For the range of interest, 27 to 1000°C and 1 to 10 atm (10^5 to 10^6 Pa), these properties may be calculated using the algebraic relationships given in Table 4 and are based on the data compiled in Ref. 66.

Table 4. Properties of Air

Algebraic Relation	Accuracy[a]	Reference Value[b]
$\frac{\rho}{\rho_o} = \left(\frac{P}{P_o}\right)^{1} \left(\frac{T}{T_o}\right)^{-1}$	Exact	$\rho_o = 1.176$ kg/m^3[c]
$\frac{\mu}{\mu_o} = \left(\frac{P}{P_o}\right)^{0} \left(\frac{T}{T_o}\right)^{2/3}$	$\pm 3\%$	$\mu_o = 1.830 \times 10^{-5}$ kg/m-s
$\frac{\lambda}{\lambda_o} = \left(\frac{P}{P_o}\right)^{-1} \left(\frac{T}{T_o}\right)^{7/6}$	$\pm 3\%$	$\lambda_o = 0.0653$ μm

[a] For $P < 20$ atm and $240 < T < 1400$ K.
[b] At $P_o = 1$ atm and $T_o = 300$ K.
[c] Gas constant = 287.2 N-m/kg-K.

AEROSOL MECHANICS OF SEPARATION

Force Balance and Separation Velocity

The separation mechanics of aerosols involves the analysis of two forces on the particulate: the separation body force and the retardation surface force. The retardation force is essentially the sum of the viscous and wake drag forces that the individual particle experiences as a result of its motion relative to the medium--primarily V_n, the drift velocity. The drag force is customarily analyzed in a nondimensional fashion as the drag coefficient, defined by

$$C_D' = F_D/(\pi\alpha\tilde{d}^2/4)\ (\rho\tilde{V}_n^2/2) \qquad (3)$$

where F_D is the drag force on the particle, $\tilde{d}$ is the particle diameter, and V_n is the relative velocity of the particle with respect to the medium; α is a particle shape parameter which permits an account to be made of the particle area-asphericity as it affects the drag force, although it will be assumed to be unity throughout.

The behavior of the drag coefficient for continuum flows (designated by C_D, without the prime) past spheres is well established.[79] Three regimes have been identified: a viscous (called Stokes) regime for very low Reynolds numbers, a turbulent (sometimes called Newtonian) regime at large Reynolds numbers, and a transition regime connecting the two. For very small particulate, the actual drag coefficient (C_D') is found to be somewhat lower than that predicted by continuum relations (C_D). This condition arises because the dimensions of the spheres are approaching the scale of the mean free path (*i.e.*, the Knudsen number, defined as the ratio of the mean free path to the particle radius, is approaching 1), a circumstance known as slip flow. For

Knudsen numbers <<1, the particles behave essentially as if they were gas molecules, and this regime is called free-molecular flow; there is, of course, a transition regime between slip and free-molecular flow. Thus, six flow regimes can be identified in decreasing Re-Kn order: turbulent, transition, Stokes, slip, transition, and free-molecular. The influence of the latter three regimes upon C_D' are most conveniently handled by using the Cunningham correction factor, C_C, defined as

$$C_D' = C_D/C_C \tag{4}$$

The Cunningham factor can be expressed[66] as a function of the Knudsen number

$$C_C = 1 + Kn\{1.246 + 0.42\ \exp(-0.87/Kn)\} \tag{5}$$

for air, where

$$Kn \equiv 2\lambda/\tilde{d} \tag{6}$$

This factor increases with increasing temperature and decreases (*i.e.*, approaches 1.0) with both increasing pressure and increasing particulate diameter. A portrayal of the conditions under which the Cunningham factor is not significantly larger than one--specifically, $C_C > 1.2$--is given in Fig. 8. It can be seen that for hot gas conditions (10 atm/1000°C), less than 20% error ($C_C < 1.2$)* results by taking C_C to be unity for the analysis of particles larger than ca. 0.5 μm. Since the particle sizes of most interest are 20-μm diameter plus or minus one order, this factor can justifiably be taken to be 1.0 throughout all subsequent discussions. For conventional particulate separation environments, Fig. 8 shows that particles must be larger than ca. 2 μm for $C_C < 1.2$.

Thus, the drag force retarding particulate motion can be evaluated by utilizing the available data for continuum flow since for $C_C = 1$, $C_D' = C_D$. The drag coefficient data† for the three continuum regimes can be expressed[80,81] as a function of the particulate Reynolds number as

$$\text{Stokes:} \quad \tilde{Re} < 3; \qquad C_D \simeq 24/\tilde{Re} \tag{7a}$$

$$\text{Transition:} \quad 3 < \tilde{Re} < 10^3; \qquad C_D \cong 14/\tilde{Re}^{0.5} \tag{7b}$$

$$\text{Turbulent:} \quad \tilde{Re} > 10^3; \qquad C_D \cong 0.44 \tag{7c}$$

where

$$Rc \equiv \rho V_n \tilde{d}/\mu \tag{8}$$

The effect of variable medium properties upon particulate Reynolds number can be seen by forming the ratio of the product of particulate velocity and

---

*This corresponds to Kn ≃ 0.12. Thus, the three lines of Fig. 8 are approximately lines of constant Knudsen number (0.12) for the three particle diameters shown.

†Fuchs[82] has summarized other functional relationships for the drag coefficient which are obtainable from purely theoretical considerations.

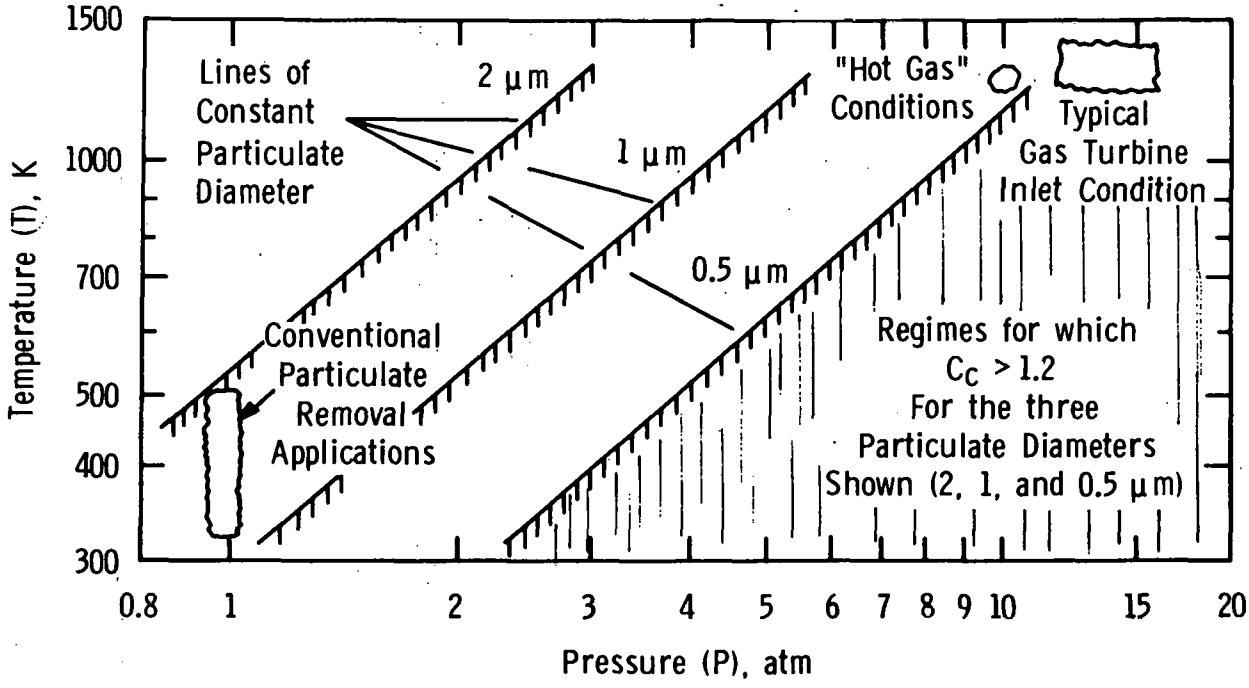

Fig. 8. Portrayal of the Slip-Flow Regime

diameter at hot-gas conditions to that at reference conditions

$$\frac{\tilde{V}_n \tilde{d}}{(\tilde{V}_n \tilde{d})_o} = \left(\frac{\tilde{Re}}{\tilde{Re}_o}\right)\left(\frac{P}{P_o}\right)^{-1}\left(\frac{T}{T_o}\right)^{5/3} \tag{9}$$

Thus, at like Reynolds numbers, the quantity $V_n d$ at 10 atm/1000°C is actually 11% larger than at reference conditions (1 atm, 27°C) but is 37% smaller than at conventional collection conditions (1 atm, 150°C).

The separation force per unit mass, or acceleration, is derivable from a scalar separation potential, Φ, for conservative force fields as

$$\underset{\sim}{F}_n''' = -\nabla_n \Phi \tag{10}$$

where ∇_n designates the directional derivative in the $+\underline{n}$ direction (Fig. 7) which reduces to the gradient operator if lines of constant Φ are parallel to the streamlines (as they should be for optimum performance). Dropping the

vector notation and introducing the particulate density and volume yields the separation force*

$$F_n = \tilde{\rho}(\pi\beta\tilde{d}^3/6)(-\nabla\Phi) \tag{11}$$

where β is another particle shape parameter which accounts for volume-asphericity and will be taken as unity, as was done for α.

Each particle will accelerate under action of the separation potential until the separation force and retarding drag are equal. The particle velocity for this equilibrium condition can be expressed by Eqs. 3 and 11 and solving for V_n

$$\tilde{V}_n = \left(\frac{4}{3}\right)\left(\frac{\tilde{\rho}}{\rho}\right)\left(\frac{\beta}{\alpha}\tilde{d}\right)\left(\frac{C_c}{C_D}\right)(-\nabla\Phi) \tag{12}$$

Substituting the data for C_D from Eqs. 7 and setting α, β, and C_c equal to 1.0 yields:

Stokes:	$\tilde{V}_n = (\tilde{\rho}\tilde{d}^2/18\mu)(-\nabla\Phi)$	(13a)
Transition:	$V_n = 0.209(\tilde{\rho}^2\tilde{d}^3/\rho\mu)^{1/3}(-\nabla\Phi)^{2/3}$	(13b)
Turbulent:	$V_n = 1.74(\tilde{\rho}\tilde{d}/\rho)^{1/2}(-\nabla\Phi)^{1/2}$	(13c)

A summary of the influence of particulate, medium, and field properties upon the separation velocity is presented in Table 5.

Equations 13 may only be applied within the Reynolds number bounds of Eqs. 7 which are also functions of $\tilde{V}_n$. This dual dependency may be eliminated by solving Eqs. 7a and 13c for V_n and likewise using Eqs. 7c and 13c, yielding

$$\tilde{d}(\tilde{\mu}m)\Big|_{@Re=3} = 197\left(\frac{P}{P_o}\right)^{-1/3}\left(\frac{T}{T_o}\right)^{7/9}[-\nabla\Phi(m/s^2)]^{-1/3} \tag{14a}$$

$$\tilde{d}(\tilde{\mu}m)\Big|_{@Re=10^3} = 3610\left(\frac{P}{P_o}\right)^{-1/3}\left(\frac{T}{T_o}\right)^{7/9}[-\nabla\Phi(m/s^2)]^{-1/3} \tag{14b}$$

for which the reference values of P_o and μ_o have been substituted and a particle density of 2 g/cm^3 assumed, resulting in the units indicated. These bounds are shown for reference and hot-gas conditions in Fig. 9 by dashed and solid lines, respectively. The lines of constant separation velocity within Stokes and turbulent regimes are obtained from Eqs. 13a and 13c and are terminated, at which point slip flow effects become appreciable (from Fig. 8). Constant $\tilde{V}_n$ lines represent lines of constant Y/t_R where Y is the

*For the analysis of a gravitational field, the buoyant force should be used which causes $\tilde{\rho}$ to be replaced by $\tilde{\rho} - \rho$; however, since $\tilde{\rho}$ is three orders larger than ρ for aerosols, this effect will be ignored.

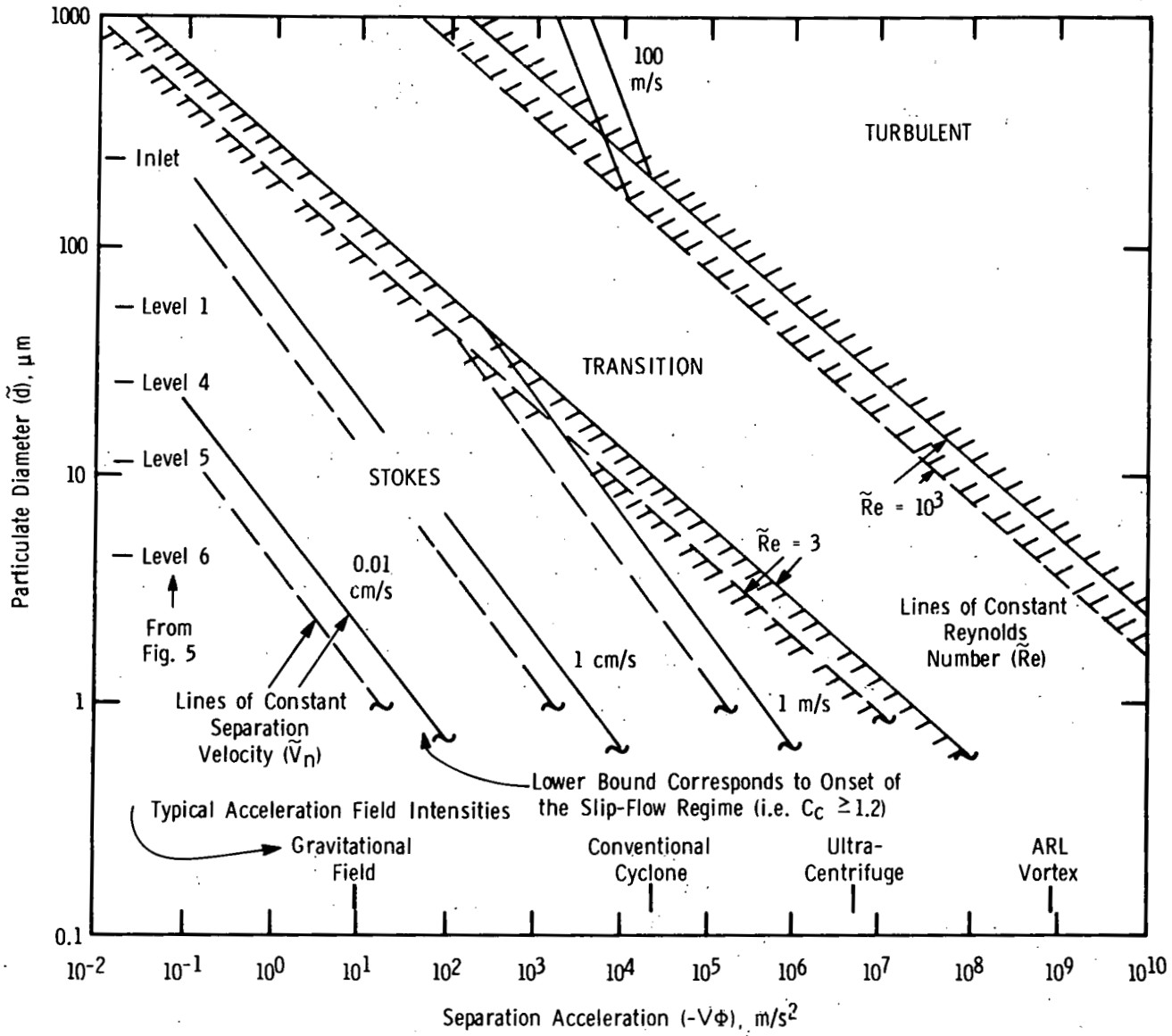

Fig. 9. Particulate Flow Regimes and Separation Velocities as a Function of Particulate Diameter, Medium Properties and Separation Potential for $\tilde{\rho}$ = 2 g/cm^3. (Solid lines correspond to hot-gas conditions and dashed lines to standard conditions.)

separation distance and t_R the residence time; larger values of $\tilde{V}_n$ permit either a shorter residence time (higher throughput) or larger separation distance (more convenient collection). The effect of high temperature and pressure is to require an acceleration field a factor of 2.64 more intense than that at reference conditions to achieve any given $\tilde{V}_n$ for particulate separation in the Stokes regime.

Table 5. Separation Velocity ($\tilde{V}_n$) Parameters

Properties	Flow Regime		
	Stokes	Transition	Turbulent
Particulate	$\tilde{d}^2$	$\tilde{d}^1$	$\tilde{d}^{1/2}$
	$\tilde{\rho}^1$	$\tilde{\rho}^{2/3}$	$\tilde{\rho}^{1/2}$
Medium	p^0	$p^{-1/3}$	$p^{-1/2}$
	$T^{-2/3}$	$T^{1/9}$	$T^{1/2}$
Field	$(-\nabla\Phi)^1$	$(-\nabla\Phi)^{2/3}$	$(-\nabla\Phi)^{1/2}$

For a mean collector inlet particle size of 225 μm (Figs. 3 and 5), it can be seen from Fig. 9 that the particulate will initially be in the turbulent regime for separation fields on the order of 10^4 m/s^2 (a typical cyclone). At the collector exit, the various levels presented in Fig. 5 would correspond to either the Stokes or transition regime for this separation field intensity. Two general observations should be made: (1) analytically, the separation problem is very difficult because the particulate Reynolds number varies over a wide range and (2) the separation velocities obtainable even at modest acceleration fields under hot-gas conditions are quite substantial, which suggests that no fundamental barrier exists to achieving the required separation efficiency by purely cyclonic techniques.

Governing Equations and Dimensionless Parameters

All separation processes can be divided into two categories (from Table 3)--"field separation" or "streamline separation." The governing equations and significant parameters for each of these types are very different and will be presented separately.

Field separation is the least complex since it can, and usually does, utilize straight streamlines.* Two regimes can be identified: the transient condition for which a particle is accelerating due to the imbalance of the separation and retardation forces, and a steady-state condition. If the transient condition corresponds to a small fraction of the separation time, then the particulate position is simply found from the product of $\tilde{V}_n$, from Eqs. 13 and the residence time; as a result, similarity considerations are pointless for this case. The collection efficiency can be expressed simply as the ratio of the residence time to the separation time

$$\eta = \frac{t_{res}}{t_{sep}} = \frac{\tilde{V}_n X}{\tilde{V}_s Y} \tag{15}$$

*It is assumed throughout these discussions that the separating particulate does not appreciably affect the flow streamlines, permitting them to be calculated *a priori*, independently of any imposed field potential.

where the result shown is based on a simple, rectangular geometry for which X is the overall length and Y the mean distance of the particulate from the precipitation surface. The effect of high temperature and high pressure enters the separation mechanics in two ways. First, it impairs V_n because of higher drag, as shown in Table 6. Therefore, hot gas conditions will require on the order of twice as intense a separation acceleration to achieve a separation velocity similar to that required under a low-temperature, low-pressure environment. The physical reason for this situation is an increase in the retardation force with increasing temperature and/or pressure. Secondly, high temperature may or may not also affect the formation of the potential field. In the case of gravitational attraction, media properties clearly have no influence upon $\nabla\Phi$. For electrostatic precipitation, however, aerosol properties greatly influence both the field potential and the precipitation process itself (because particulate resistivity is a strong function of temperature)--matters which are discussed in a later section.

Table 6. Effect of High Temperature and Pressure Upon Separation Potential Required to Maintain Constant Separation Velocity ($\tilde{\rho}$, $\tilde{d}$ constant)

Separation Acceleration Ratio for Equal Separation Velocities	Flow Regime		
	Stokes	Transition	Turbulent
General Form $\frac{(-\nabla\Phi)_a}{(-\nabla\Phi)_b} =$	$\left(\frac{P_a}{P_b}\right)^0\left(\frac{T_a}{T_b}\right)^{2/3}$	$\left(\frac{P_a}{P_b}\right)^{1/2}\left(\frac{T_a}{T_b}\right)^{-1/6}$	$\left(\frac{P_a}{P_b}\right)^1\left(\frac{T_a}{T_b}\right)^{-1}$
Hot Gas to Reference a. 10 atm/1000°C b. 1 atm/27°C	2.62	2.49	2.36
Hot Gas to Conventional a. 10 atm/1000°C b. 1 atm/150°C	2.08	2.63	3.32

For the transient regime of field separation, analytical solutions are much more cumbersome. The drag force is higher than that predicted by Eqs. 13 during this period and is used to define a modified drag coefficient, C_{DA}. Data exist for this coefficient and, if it can be assumed to be approximately constant during the acceleration period, then direct *a priori* integration is possible. Strauss[83] reviews these data and presents the results of the integration process.

Streamline separation is sufficiently complex mathematically that general solutions do not exist, and so dimensional analysis plays an important role. Two general approaches may be taken: (1) nondimensionalize the governing equations to identify the significant groups or to collect all the significant geometric, kinematic, and dynamic dimensional quantities and (2) apply the Buckingham Π Theorem to reduce the total number of original quantities by (ideally) the number of physical dimensions (three in this case).

The governing equations of motion can be obtained most directly by using a Lagranian perspective. The local accelerations in the tangential and radial directions ($\underline{s}$,$\underline{n}$) are given by

$$\frac{d\tilde{V}_s}{dt} = r\frac{d^2\theta}{dt^2} + 2\frac{d\theta}{dt}\frac{dr}{dt} \tag{16a}$$

$$\frac{d\tilde{V}_n}{dt} = \frac{d^2r}{dt^2} - r\left(\frac{d\theta}{dt}\right)^2 \tag{16b}$$

where r, θ are the instantaneous cylindrical coordinates of the particle positioned at t_o in Fig. 7. Equating these accelerations to the tangential and axial forces per unit mass yields

$$\frac{d}{dt}\left(r^2\frac{d\theta}{dt}\right) = 0 \tag{17a}$$

$$\frac{d^2r}{dt^2} - r\left(\frac{d\theta}{dt}\right)^2 = -\frac{18\mu}{\tilde{\rho}\tilde{d}^2}\left(\frac{dr}{dt}\right) \tag{17b}$$

where it has been assumed that the particle tangential velocity is always identical to the local streamline velocity so that the tangential force is identically zero and the radial force is given by the Stokes drag relation. These equations may be nondimensionalized by using a reference length, R_o, and velocity, $\tilde{V}_{so}$, where

$$r^* \equiv r/R_o \tag{18a}$$

$$t^* \equiv \tilde{V}_{so}\, t/R_o \tag{18b}$$

to yield

$$\frac{d}{dt^*}\left(r^{*2}\frac{d\theta}{dt^*}\right) = 0 \tag{19a}$$

$$\frac{d^2r^*}{dt^{*2}} + \frac{18\mu}{\tilde{\rho}\tilde{d}^2}\frac{R_o}{\tilde{V}_{so}}\left(\frac{dr^*}{dt}\right) - r^*\left(\frac{d\theta}{dt^*}\right)^2 = 0 \tag{19b}$$

Integrating the tangential equation and evaluating the constant yields

$$r^{*2}\frac{d\theta}{dt^*} = C \tag{20}$$

where C is a nondimensional constant. This constant can be evaluated by observing that

$$r^*\frac{d\theta}{dt^*} = \tilde{V}_s^* \equiv \tilde{V}_s/\tilde{V}_{so} \tag{21}$$

and so

$$C = r^* \tilde{V}_s^* = \frac{r V_s}{R_o \tilde{V}_{so}} \tag{22}$$

Thus, if R_o and V_{so} represent the initial radius of curvature of the flow streamline and if the tangential velocity and subsequent motion is assumed to be irrotational (potential flow), then this constant is identically 1, and so

$$\frac{d\theta}{dt^*} = 1/r^{*2} \tag{23}$$

Substituting Eq. 23 into 19b and defining the following nondimensional group as the Stokes number

$$Sk \equiv \frac{\tilde{\rho}\tilde{d}^2\tilde{V}_{so}}{18\,\mu\,R_o} \tag{24}$$

yields the final result

$$\frac{d^2r^*}{dt^{*2}} + \frac{1}{Sk}\frac{dr^*}{dt^*} - \frac{1}{r^{*3}} = 0 \tag{25}$$

This is a nonlinear differential equation for which no general solution exists. Numerical solutions which can be provided are functions of the Stokes number only and establish a nonlinear, direct relationship between separation performance (*i.e.*, large values of r* for fixed t* or small t* for fixed r*) and Sk. Clearly, streamline separation works best with dense, large particulate flowing at high velocities along streamlines of small radius of curvature through a medium of low viscosity. The effect of high temperature and high pressure is solely through the viscosity factor in the Stokes parameter and thus Sk decreases with absolute temperature to the two-thirds power.

The primary limitation of the preceding development lies in the assumed Stokes drag law used in the radial force balance. Re-expressing the right-hand side of Eq. 17b for a more general drag coefficient relationship, namely

$$C_D = A/\tilde{Re}^a \tag{26}$$

yields

$$-\frac{(3A/4)\mu}{\tilde{\rho}\tilde{d}^2}\left(\frac{dr}{dt}\right)\tilde{Re}^{1-a} \tag{27}$$

If $a \neq 1$, there remains a particulate Reynolds number dependence which greatly complicates the analysis since the equations must then be solved stepwise in time. Solutions to Eq. 25 are valid only if the particulate Reynolds number history is such that $Re < 3$ at all times, which from Fig. 9 requires both relatively small particulate and weak accelerations.

Another difficulty with this analysis is that the acceleration field for virtually all streamline separation geometries is nonuniform. In general, this problem is approached by assuming that the system geometry will generate a unique acceleration field based upon the fluid Reynolds number and so it should be possible to correlate separation efficiency to two dimensionless parameters: fluid Reynolds number, $\rho V_s D/\mu$, where D is a characteristic dimension of the geometry, and some form of the Stokes number.

The use of the Buckingham Π Theorem requires judicial selection of the significant physical parameters of the problem. If it is assumed that the particulate separation efficiency, η, is dependent upon only the following quantities

$$\eta = \eta(\tilde{\rho},\ \rho,\ \mu,\ V_s,\ \tilde{V}_n,\ \tilde{d},\ D,\ R_o) \tag{28}$$

then the theorem establishes that η must be a function of only five dimensionless groups. The procedure by which these groups can be generated is straightforward and precise, although the groups thermselves are in no sense unique. In this instance, however, it is easy to develop them by inspection: two arise from length ratios, a third by a density ratio, and a fourth by a velocity ratio

$$\Pi_1 = \rho/\tilde{\rho} \tag{29a}$$

$$\Pi_2 = \tilde{d}/D \tag{29b}$$

$$\Pi_3 = R_o/D \tag{29c}$$

$$\Pi_4 = \tilde{V}_n/V_s \tag{29d}$$

The fifth group can be found in a variety of ways; one procedure is to form the ratio of the instantaneous centrifugal force to the Stokes drag force

$$\Pi_5 = \frac{(\pi\tilde{\rho}\tilde{d}^3/6)V_s/R_o}{3\pi\mu\tilde{V}_n\tilde{d}} \tag{29e}$$

$$= \left(\frac{\tilde{\rho}\tilde{d}}{18\mu R_o}\right)\left(\frac{V_s^2}{\tilde{V}_n}\right)$$

Thus, the separation efficiency functional relationship can be expressed as follows:

$$\eta = \eta\left(\frac{\rho}{\tilde{\rho}},\ \frac{d}{D},\ \frac{R_o}{D},\ \frac{\tilde{V}_n}{V_s},\ \frac{\tilde{\rho}\ \tilde{d}^2\ V_s^2}{18\mu\ R_o\ \tilde{V}_n}\right) \tag{30}$$

Since $\tilde{\rho}$ is of three orders larger than ρ for aerosols and remains relatively unchanged for all systems of interest, the influence of Π_1 can justifiably be neglected. The same assessment can also be made of Π_2 and for the same reason: $\tilde{d} << D$.* Finally, a hypothesis is proposed that permits the number of significant dependent variables to be reduced from 3 to 2: it is assumed that the separation efficiency is not separately dependent upon Π_4 and Π_5, but only on their combined product (noting that $V_s = \tilde{V}_s$ throughout these considerations)

$$\Pi_5' = \Pi_4 \, \Pi_5 = \frac{\tilde{\rho} \, \tilde{d}^2 \, V_s}{18\mu R_o} \tag{31}$$

This quantity is identical to the Stokes number which arose from the dimensionless radial equation of motion. Thus, if these three hypotheses are valid

$$\eta = \eta \left(\frac{R_o}{D}, \, Sk \right) \tag{32}$$

As a final step, let it be assumed that Π_3, R_o/D is fixed (and so R_o is as convenient and meaningful a nondimensionalizing length as D) and rescale Sk on D instead of R_o, yielding

$$\Pi_5'' = \frac{\tilde{\rho} \, \tilde{d}^2 \, \tilde{V}_s}{18\mu \, D} \equiv Im \tag{33}$$

so then, finally

$$\eta = \eta(Im) \tag{34}$$

where Π_5'' has been defined as the impaction number to distinguish it from Sk. (Various names have appeared in the literature for this quantity: impaction parameter,[60] particle parameter,[84] separation number,[85,86] inertia parameter,[87] and the Stokes number itself.[66,82,88])

The physical significance of this dimensionless group can be appreciated by calculating the stopping distance of a particle initially traveling at $\tilde{V}_s$ acted on by Stokes drag alone

$$\tilde{\rho}(\pi\tilde{d}^3/6) \frac{d\tilde{V}_s}{dt} = -3\pi\mu\tilde{V}_s\tilde{d} \tag{35}$$

Integrating and solving for $\tilde{V}_s(t)$ yields

$$\tilde{V}_s(t) = \tilde{V}_{so} \exp(-t/\tau) \tag{36}$$

*Filtration can violate this consideration because the fiber diameter can approach the diameter of the particulate to be collected.

where τ is given by

$$\tau = \frac{\tilde{\rho}\,\tilde{d}^2}{18\mu} \tag{37}$$

and represents the relaxation time (*i.e.*, the time required for a particle to slow to 1/e, or 63%, of its initial velocity). Because the particle does not stop in a finite time, the stopping distance, L, is given by

$$L = \int_0^\infty V_{so} \exp(-t/\tau)dt \tag{38a}$$

$$L = V_{so}\tau \tag{38b}$$

Therefore, the impaction number is simply the ratio of the Stokesian stopping distance to a characteristic geometric dimension

$$Im = L/D \tag{39}$$

and is a measure of the particulate's inability to miss an obstacle.

The authentication of the fruit of this dimensionless analysis -- namely, Eq. 34 -- is given in Fig. 10, which is from Davies[84] and is based on the experiments of Landahl and Hermann[89] for the target efficiency* as a function of the impaction number for a very simple geometry, that of a cylinder.

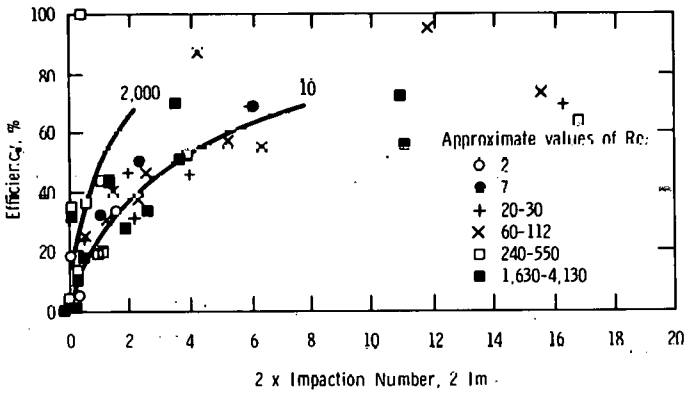

Fig. 10. Efficiency of Impingement of Particles on Cylinders[84]

Comparison of experiments by Landahl and Hermann with theoretical results for Re = 2,000 and 10, when a/R is negligible. a ≡ d/2, R ≡ d/2, cylinder radius. Reproduced by the permission of the Institution of Mechanical Engineers from *Proceedings of the Institution of Mechanical Engineers*, Vol. 1B, 1952

*Defined as the ratio of the actual mass rate of particulate impacting the baffle divided by the mass rate of particulate flowing within the theoretical capture planform area of the target.

The data clearly indicate that for a given target shape, the efficiency is primarily a function of Im but is also sensitive to the Reynolds number of the flow. This Reynolds number dependency can be appreciated by examining Π_3, R_o/D, which essentially represents the characteristic streamline shape since it depends on a characteristic target dimension and can be expected to be a function of Re. Relationships between η and Im, Re are not readily available for many geometries of practical interest. For many separation concepts, it is not possible to characterize the geometry by a single linear dimension (D); for instance, the efficiency of a cyclone is known to depend upon the length of the cylindrical section and the inlet/exit dimensions in addition to a primary dependence upon diameter. Also, for intense separation acceleration fields, the particulate Reynolds number will exceed the Stokes bound, and a more complex dependence upon flow Reynolds number can be expected. The effect of high temperature and pressure upon streamline separation influences the efficiency in two ways: First, the efficiency has been shown to be directly dependent upon Sk or Im, parameters which are temperature dependent

$$\frac{Sk}{Sk_o} = \frac{Im}{Im_o} = \left(\frac{T}{T_o}\right)^{-2/3} \tag{40}$$

and at 1000°C are thus only 36% of the reference condition or 48% of the conventional collection condition. It is not possible to directly correlate this change in Im to a change in η, as was done in Table 6 for field separation (other than to note that it has an unfavorable influence) because the functional dependence of Eq. 34 is not explicitly known. A second influence of variable properties is via the flow field Reynolds number; for a fixed velocity and characteristic dimension

$$\frac{Re}{Re_o} = \left(\frac{P}{P_o}\right)^{1} \left(\frac{T}{T_o}\right)^{-5/3} \tag{41}$$

and results in the hot-gas Reynolds number being 90% of the reference value but 159% of the conventional collection value. This increased Reynolds number with respect to conventional collection at similar throughput and collector size is a favorable influence since the ability of fluid streamlines to perceive downstream influence is diminished, with the result that a more intense, local acceleration field is generated.

SEPARATION CONCEPTS EMPLOYING AN EXTERNAL FIELD

Six distinct varieties of separation fields can be used to provide a particulate drift velocity (see Table 3). Only two, gravitational and electrostatic, have been widely used for gas cleaning. From Eq. 15, it can be seen that the preferred operation of field separation devices is at low throughput velocities in long, narrow channels with lines of constant potential parallel to fluid streamlines. Precipitation then occurs on large system-surface areas, necessitating careful design of removal schemes. Reentrainment of separated/precipitated particulate is also an important problem area because of the need for small separation distances (Y).

Gravitational Field

This mechanism of separation exploits the density difference between the particulate and the medium by using the uniform acceleration field of the earth. The particulate drift velocity, $\tilde{V}_n$, is simply the terminal velocity (neglecting the acceleration period) obtained by balancing the weight of a particle and the drag force. For the Stokes regime, this results in

$$\tilde{V}_n = \frac{\tilde{\rho}\tilde{d}^2}{18\mu} g \equiv \tau g \tag{42}$$

and decreases with the two-thirds power of absolute temperature. By substitution of this result into Eq. 15, the collector efficiency can be correlated in terms of a form of the Stokes number

$$\eta = \left\{\frac{\tilde{\rho}\tilde{d}^2\tilde{V}_s}{18\mu(V_s^2/g)}\right\}\left(\frac{X}{Y}\right) \equiv Sk_g \left(\frac{X}{Y}\right) \tag{43}$$

where Sk_g is based upon a characteristic flow length, V_s^2/g, analogous to R_o in Eq. 24.

These devices represent the simplest possible collector and operate at a low pressure drop. Although in principle it is possible to separate all particulate down to Brownian fines by gravitational settling, these devices are impractical for sizes below ca. 50 μm due to the dependence of $\tilde{V}_n$ upon the square of particulate diameter. If a separation efficiency of 99% is required for a flow velocity of 1 m/s of 2 g/cm^3 particulate at 1000°C, then the ratio of flow length (X) to separation distance (Y) for a 10-μm-diameter particle would need to be

$$\frac{X}{Y} = \frac{\eta}{Sk_g} = \frac{0.99}{2.27 \times 10^{-3}} = 436 \tag{44}$$

This is clearly an impractical requirement.

Electrical Field

The use of a unidirectional electrical field to establish a drift velocity for electrically charged particulate, a process called electrophoresis, is a very old and well known technique: electrostatic phenomena were known to the Greeks 2500 years ago although it was Hohlfeld in 1824 who developed the first device using this principle to precipitate an aerosol, a concept later rediscovered by both Lodge and Clark in England (1883) and Cottrell in the U.S. (1906). General surveys of the basic principles of electrostatic precipitators (EP) by Strauss[83] and Robinson[90] are available; the latter includes a very detailed history and a bibliography of 494 references.

The application of EP to high-temperature and/or high-pressure environments has been the object of a great deal of research. Surveys including

this aspect of EP performance have been published by Strauss[55,56] and Robinson[90] and more recently by Aerotherm,[67] Stone and Webster,[61] and Midwest Research Institute.[66] Much of the actual research activity has been performed at the Bureau of Mines (C. C. Shale et al.) and Research-Cottrell, Inc. (H. J. Hall, M. Robinson, R. F. Brown, A. B. Walker, et al.). Currently, the known sponsored activity (Table 2) includes a Research-Cottrell project for the EPA designed to experimentally examine EP performance in a 1100°C/21 atm environment; EPRI is sponsoring seven separate projects. A complete survey of the published work in this area is included with Hall's recent analysis.[91] Current typical use of EP is 150 to 450°C with a conventional limit of 540°C and/or 11 atm, although capable of operating at 930°C and 60 atm and "feasible" at 1700°C/21 atm.[91]

The process by which electrophoresis takes place is relatively simple. An electrostatic potential is maintained between two surfaces which is greater than the threshold voltage required to produce a corona at the charging electrode but less than the voltage which would produce sparkover to the collecting surfaces (both these voltages are strong functions of medium density). Ions, either positive or negative, produced by the corona migrate toward the collecting surface and bombard the particulate, resulting in each particle becoming charged and thus providing the mechanism for the field force to cause precipitation; typical drift velocities, $\tilde{V}_n$, are in the range of 10 to 20 cm/s for 10 to 40 μm particulate and are not a strong function of $\tilde{d}$. Drift velocities are adversely affected by greater medium viscosity because of increased drag. After precipitation, the particle gradually loses its charge (the rate being a function of its resistivity) and is held in place by a combination of van der Waals and electrostatic forces. The resistivity of the particulate, a temperature-dependent property, is a critical performance parameter: if it is too low (<ca. 10^4 ohm-cm), it will lose its charge too rapidly and because the van der Waals force is relatively weak and the flow geometry consists of narrow passages, precipitated particles will become re-entrained; if the resistivity is too great (>ca. 5×10^{10} ohm-cm), the precipitate will create a steep voltage gradient which will decrease the effective separation potential and ultimately can cause a second ("back") corona which will create ions of opposite charge and completely negate particle migration. Precipitate is removed by periodic cleaning of the collecting surface, by either irrigation or pulsation (hammers or vibrators), which breaks the interparticle/surface bonds and creates large aggregates which fall readily into a collecting hopper.

Thus, high temperature and high pressure affect EP performance because of separation fluid mechanics considerations ($\tilde{V}_n$ is dependent on T and perhaps on P), field considerations (acceptable voltage potential band is dependent on ρ, and particulate charging rate is dependent upon T), and precipitation considerations (the resistivity of the particulate must be between ca. 10^4 and 5×10^{10} ohm-cm).

The particle drift velocity at steady state can be expressed[90] by equating the separation force

$$F_n = 2\pi\varepsilon_o \left(\frac{1 + \tilde{\kappa}}{2 + \tilde{\kappa}}\right) \tilde{d}^2 (-\nabla\Phi)^2 \qquad (45)$$

where ε_o is the permittivity of free space and $\tilde{\kappa}$ the relative dielectric constant of the particulate. This equation presumes that the charging mechanism is ion bombardment (valid for $\tilde{d} > 1$ μm) and that the potentials of the charging and precipitating fields are equal; equating this result to the Stokes drag force yields[90]

$$\tilde{V}_n = \frac{2}{3}\frac{\varepsilon_o}{\mu}\left[\frac{1+\tilde{\kappa}}{2+\tilde{\kappa}}\right]\tilde{d}(-\nabla\Phi)^2 \qquad (46)$$

This result differs significantly from that derived in Eq. 13a: the drift velocity is proportional to the first power of $\tilde{d}$ (instead of the second power) and the second power of $\nabla\Phi$ (instead of the first). The reason for this lies in the nature of the separating force field given in Eq. 45, compared to the general form given in Eq. 11 -- a difference which can be attributed to the nature of the particle-charging mechanism, which is a distinct process not directly related to particle separation. Thus, Fig. 10 is not applicable to this model of an EP process.

For a given voltage potential, Eq. 46 shows that $\tilde{V}_n$ decreases with the two-thirds power of absolute temperature. However, because of an increase in medium density at high pressure and moderate temperature, it is possible to operate at higher potential -- how much higher is very difficult to predict because acceptable threshold/sparkover voltages are also very sensitive to collector geometry. In addition, field stability considerations become increasingly important under these conditions.

The theoretical collection efficiency as a function of $\tilde{V}_n$ can be calculated using Eq. 15 for a rectangular geometry. The actual data for efficiency show an exponential variation with residence time, rather than the linear relation of Eq. 15 and can be understood by recognizing that the flow in the separation passages consists of a turbulent core so that the unprecipitated particulate is continually being remixed in this region until it ultimately enters the laminar wall layer to be permanently separated. This expression for the efficiency is known as the Deutsch equation and is given by

$$\eta = 1 - \exp(-\tilde{V}_n X/\tilde{V}_s Y) \qquad (47)$$

for rectangular passages. Typical values for $\tilde{V}_s$ and $-\tilde{V}_n$ are 1 to 2 m/s and 10 to 20 cm/s, respectively, for particulate of 10 to 40 μm diameter.* At 1 m/s flow velocity, 10 cm/s drift velocity, and 99% efficiency, Eq. 47 indicates that the ratio of flow length to separation distance must be

$$\frac{X}{Y} = \frac{-\ell n(1-\eta)}{\tilde{V}_n/\tilde{V}_s}$$

$$= \frac{4.61}{1/0.1}$$

$$= 46 \qquad (48)$$

*The data show that $\tilde{V}_n$ is dependent upon $\tilde{V}_s$, with a maximum occurring at $\tilde{V}_s \cong 2$ m/s.

or approximately one order of magnitude smaller than that required for a settling chamber, Eq. 44. This dramatic performance improvement has been obtained at a large capital cost. EPs are customarily the most expensive first-cost collector: on the order of $7200 per actual m^3/s for sizes of 470 m^3/s and, although the pressure drop across the device is low (ca. 1 mm Hg), the yearly operating and maintenance cost (ca. $100/actual m^3/s) is still a significant amount.[92]

The feasibility of operating EPs at 1000°C/10 atm remains to be demonstrated. Its principal advantage is that the drift velocity decreases with $\tilde{d}$ to the first power, whereas most devices decrease exponentially with $\tilde{d}$, and so EP should be capable of removing much finer particulate. However, from Figs. 3 and 5, it would appear that this feature is not as critical as it would be in a conventional application since the particulate here is relatively large. Two primary disadvantages associated with EP can be noted. First, they are inherently large devices which, at 10-atm pressure and high temperatures, cause the structure requirements to become exceedingly expensive. Secondly, the efficiency is very strongly dependent upon particulate resistivity which in turn is a function of composition and temperature. Soo[93] points out that an EP operating at $\eta = 0.95$ with 5% sulfur coal will only perform at $\eta = 0.70$ for low sulfur coal (0.5%). This has led to the need for "conditioning," either by means of chemical seeding[94] (*e.g.*, H_2O, SO_3, NH_3) or by specification of the required operating temperature.[95] The control of temperature is not possible for the fluidized-bed combustor application because the bed temperature is fixed by other considerations and cleanup must precede the turbine. Conditioning the aerosol by adding sulfur compounds is a frustrating option not only in terms of potential turbine materials problems but also because it is contrary to one of the basic purposes of fluidized-bed combustion: to prevent the addition of sulfur compounds to the atmosphere. Sulfur addition (however small) to satisfy the needs of an ancillary device would be difficult to accept.

Magnetic Field

In an analogous manner to the electrostatic case, a particulate phase that has been charged by ion bombardment can be separated by a magnetic field. This technique has been noted in Strauss[83] and in two MRI studies[60,66] and can be assessed by equating the Lorentz force

$$F_n = nq\tilde{V}_s B \tag{49}$$

where n is the number of elementary charges q, and B is the magnetic field strength. By equating the force with the Stokes drag, the drift velocity may be found

$$\tilde{V}_n = \frac{nq\tilde{V}_s(-\nabla\Phi)}{3\pi\mu\tilde{d}} \tag{50}$$

In order to develop a parallel expression to Eq. 46, a relation is needed for the particulate charging rate associated with the mechanism by which ions are to be generated. This technique, known as magnetophoresis, apparently was not put to any practical use (Ref. 83, p. 422). In a survey of photophoresis by Preining,[96] he notes the influence of a magnetic field upon particulate motion associated with understanding the atmospheric aerosol.

No additional literature on this topic is known.

An alternative approach to ion-magnetic separation can be postulated which exploits the magnetic properties of the particulate phase. A recent survey article[97] noted that of 104 elements, 3 are ferromagnetic (Fe, Co, Ni), 55 are paramagnetic, 30 diamagnetic, and only 16 are apparent duds. Thus, in theory, 88 out of the 104 elements can be magnetically discriminated from the medium. In order to achieve separation in reasonable residence times, an exceedingly powerful magnetic field is necessary -- a requirement which is at least conceivable with the use of superconducting magnets. The concept -- termed high-gradient magnetic separation -- is feasible, based upon preliminary information,[97] for hydrosol applications such as water purification. Such a process has been widely used to separate iron particulate (which, of course, is ferromagnetic) from clay slurries, ceramic glaze, and even printers ink and paints (Ref. 98, p. 503).

The 19 different elements identified in Table 1 as present in the particulate generated in the ANL combustor, may be classified[97] as follows: two are ferromagnetic (Fe, Co), six exhibit paramagnetic properties in both pure form and in compounds (Ce, Cr, Dy, Mn, Sc, Ta), four exhibit paramagnetic properties in pure form but are diamagnetic in compounds (Ba, Hf, La, Na), one exhibits paramagnetic properties only in compounds (K), and the remaining six elements are either diamagnetic or complete duds (As, Be, F, Hg, Pb, Sb). Thus, in principle, it appears possible to achieve particulate separation without a need for ion bombardment by using a high-gradient magnetic field.

The influence of high temperature upon separation performance is to decrease $\tilde{V}_n$ with the two-thirds power of temperature, as shown in Eq. 50. What influence hot gas conditions will have upon ion charging and/or ferro/paramagnetic properties remains to be determined.

Thermal Field

The phenomenon of particulate drift down a temperature gradient, known as thermophoresis, was first observed by Tyndall in 1870 and has attracted the interest of many investigators. The actual mechanism by which this drift occurs is very complex and is a function of particle size. The general form of the imposed force of this thermal field on an individual, large (>ca. 1 μm, *i.e.*, Kn → 0) particle can be expressed as

$$F_n = \frac{9\pi\tilde{d}\mu^2(-\nabla\Phi)}{\rho T} f(k/\tilde{k}) \qquad (51)$$

where $f(k/\tilde{k})$ is a nondimensional function of the ratio of the thermal conductivities of the medium and the particulate and Φ is simply the absolute temperature (T). By equating this expression with the Stokes drag relation, the particulate drift velocity may be found

$$\tilde{V}_n = \frac{3\mu(-\nabla\Phi)}{\rho T} f(k/\tilde{k}) \qquad (52a)$$

For low-conductivity particulate, the theory of Epstein[99] adequately expresses f as

$$f_E(k/\tilde{k}) = \frac{0.5}{2 + k/\tilde{k}} \qquad (52b)$$

Equation 52 predicts that the drift velocity is independent of particle size and actually increases with absolute temperature to the two-thirds power. For a required separation efficiency of 99% at 1 m/s flow velocity ($\tilde{V}_s$) with a length to width ratio (X/Y) of 50, a drift velocity of 2 cm/s is needed, based upon the laminar form of the efficiency relation given in Eq. 15. The ratio of $k/\tilde{k}$ for air/limestone is approximately 1/6 at ca. 1000°C. For hot-gas conditions, the required temperature gradient to meet these requirements would be approximately 2 x 10^4°C/cm -- a highly impractical result.

The subject of thermophoresis is addressed in Strauss[83] and by the MRI studies,[60,66] and general surveys have been published.[100-102] Although a collection concept employing a temperature field has been patented,[103] it has actually been used only as a particulate sampling device.[83] However, this separation mechanism may have a significant enhancing effect in certain situations: Strauss[55] suggests that the observation of higher performance of granular beds with hot gases when the bed is initially cold can be attributed to this phenomenon. Nevertheless, to utilize this effect would exact a serious thermal efficiency penalty since the aerosol must necessarily be cooled.

Photon Field

In the absence of a temperature gradient and electromagnetic effects, particles will exhibit a drift velocity as a result of a simple beam of light -- a phenomenon known as photophoresis. Although this effect is important in understanding the behavior of the atmospheric aerosol at high altitudes and for certain other applications, the intensity at which photons can presently be generated does not provide large enough values of $\tilde{V}_n$ to permit its use as a particulate separator. Preining[96] has written a general survey on photophoresis which includes more than forty references.

Concentration Field

For the case of an aerosol medium which is a multicomponent mixture, the potential for gas diffusion exists if a concentration gradient for any one phase can be established. For such a gradient to be maintained, the diffusing component must be continually removed (condensed, absorbed, etc.) at a collecting surface. This environment will cause particulate to also precipitate at the gas-collecting surface as a result of momentum interchange with the diffusing component. The establishment of a particulate drift in this manner is known as diffusiophoresis.

Following Waldmann,[100] the diffusion-imposed force for a binary medium can be expressed as

$$F_n = 3\pi\mu\tilde{d}\sigma_{12}D_{12}(-\nabla\Phi) \qquad (53)$$

where σ_{12} is the diffusion slip factor, D_{12} is the binary gas diffusion coefficient, and Φ is the concentration of the gas component which is being collected. Equating this force with the Stokes drag yields

$$\tilde{V}_n = \sigma_{12} D_{12} (-\nabla\Phi) \qquad (54)$$

Both theoretical and empirical expressions are available[100] for σ_{12} and D_{12}. This result shows that the drift velocity is independent of particulate diameter and will increase with increasing temperature because of D_{12}.

The essential limitation to applying this concept is the difficulty of maintaining concentration gradients of sufficient magnitude to provide reasonable $\tilde{V}_n$. At present, the most feasible method is by condensing water vapor at the collecting surface -- an untenable solution at hot-gas conditions. The current research activity in this area is focused on improving scrubber performance by utilizing this mechanism. Surveys of the physics of diffusiophoresis are available.[60,66,88,100]

SEPARATION CONCEPTS EMPLOYING STREAMLINE MODIFICATION

The mechanism of streamline separation differs from field separation (see Table 3) in two significant particulars: nothing that is external (power, equipment, etc.) to the flow system boundary is required, and the separation efficiency generally increases with increasing throughput.* Separation is achieved by the establishment of local acceleration fields due to streamline curvature and can be classified by the manner in which the particulate is collected. Perimeter collection concepts permit the continual, uninterrupted separation of the inlet aerosol into gas and particulate streams. Distributed collection concepts make use of particulate precipitation upon a very large and disperse system surface; this concept requires a two-stage collection process, which usually necessitates intermittent operation of the device.

Perimeter Collection

This class of devices is usually known as "inertial" or "mechanical" collectors and comprises four basic types: baffled geometries, scrolls, cyclones, and centrifuges (in order of increasing potential efficiency). These types can be distinguished by examining the trajectory of a collected particle. Baffles cause flow streamlines to diverge around the implanted obstruction and result in an acceleration field which acts over less than a π-radian sweep angle. Scrolls make use of a confined flow in a short, quasicylindrical geometry to provide a ca. 2π-radian streamline rotation. Cyclones and centrifuges are designed to establish several streamline rotations by the use of a relatively long cylindrical tube.

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*As can be observed from Eqs. 42, 46, 52 and 54 for the field drift velocity when combined with the equation for efficiency, Eq. 15 or Eq. 47, η decreases with increasing $\tilde{V}_s$; the exception is for the case of the magnetic field, Eq. 50, for which η is independent of $\tilde{V}_s$.

Baffles. The concept of baffle separation is depicted in Fig. 11.

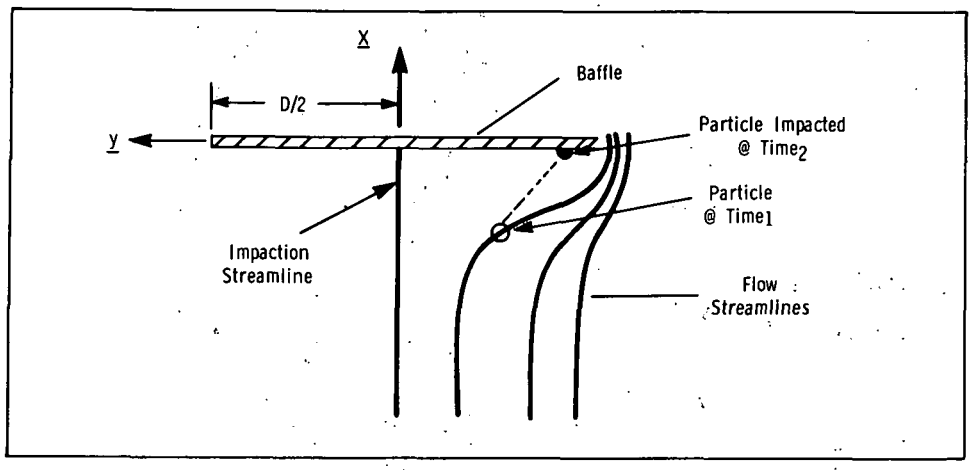


Fig. 11. Baffle Separation

The efficiency of such devices can be predicted and the data correlated using the Stokes and Impaction numbers developed in Eqs. 31-34. Data in the form of Fig. 10 exist for a wide variety of baffle shapes as a function of Im and Re. These devices are capable of very high efficiency when used at high Im and Re and are, in fact, used to obtain submicron particulate samples in a configuration known as a cascade impactor.* As a collector, however, baffles are usually limited to a large particulate applications (ca. >30 μm) because of excessive pressure drops associated with operation at high Impaction number. They are also popularly employed in an arrangement somewhat similar to venetian blinds, called "louvers"; this application is especially useful for aerosols of low particulate concentration, for example, as a conditioner upstream from a cyclone (a process known as "enrichment") since the efficiency of cyclonic separation is known to increase with an increase in grain loading.

The current research interest in this separation concept is associated with investigating its utility as a particulate sampler at hot-gas conditions.

Scrolls. The separation residence time and collection efficiency can be improved by providing a geometry which will cause the streamlines to turn over longer angular distances than are achievable with a simple baffle-geometry. The scroll collector utilizes approximately a 2π-radian rotation of the streamline velocity, as shown in Fig. 12.

Despite the longer residence time within the acceleration field, separation efficiency is still relatively low unless extremely high velocities (with

*For instance, an impactor designed for a $\tilde{V}_s$ of 30 m/s at a streamline radius of curvature of 1 cm would impose a local centripetal acceleration four orders of magnitude larger than that of gravity.

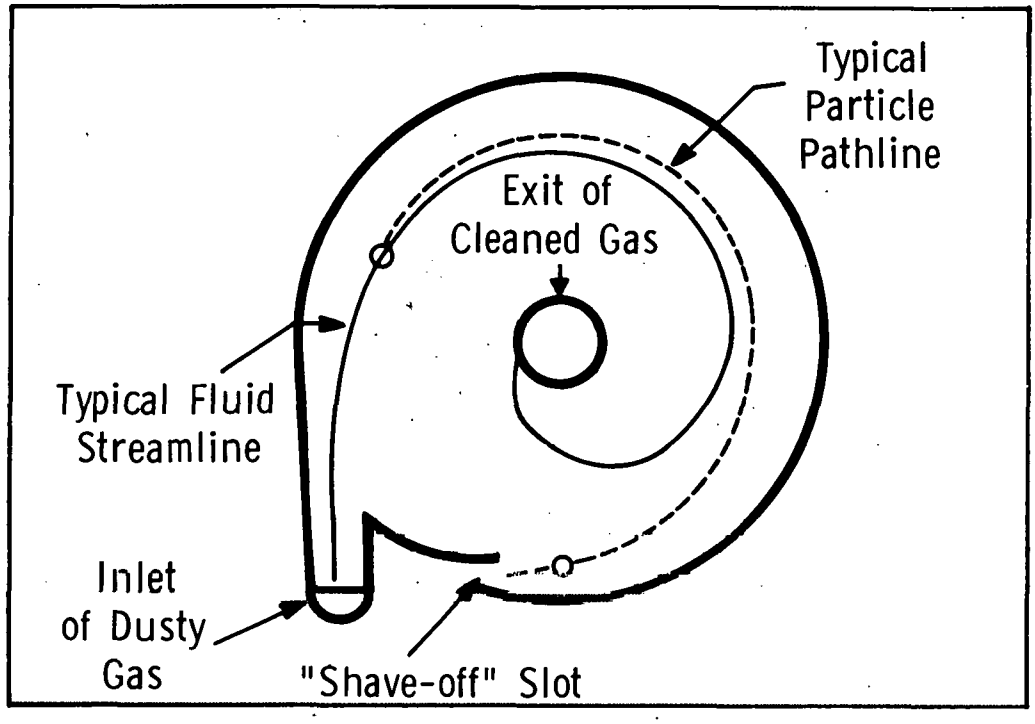


Fig. 12. Scroll Separation

attendant large pressure drops) are used.

An interesting adaptation of the scroll collector involves the use of a powered centrifugal impeller mounted with the collector itself -- a "dynamic" scroll. One version (the "Rotoclone" manufactured by American Air Filter Corp.) is shown in Fig. 13.

Other geometries employing the same dynamic concept have also been developed (*e.g.*, "Sircocco Cinder Fan" manufactured by American Blower Corp.) which are similar to the scroll shown in Fig. 12 except that a rotating set of fan blades is added. Unlike every other collector to be considered in this report, the dynamic scroll collector can operate with an attendant pressure rise instead of a pressure drop.

Although very intense centrifugal forces can be developed with such devices, they are nonetheless of limited efficiency due to either the short residence time available (Fig. 12) or the long separation distance that must be traversed (Fig. 13). In addition, there are serious erosion difficulties associated with operating the impeller in a dusty environment.

One configuration closely related to a dynamic scroll that is potentially very efficient is that of a powered axial-flow geometry. This device, closely resembling an axial-flow compressor, would provide both a long residence time and a short separation distance. Further, these devices are most suited for relatively large flow rates at low heads which would be highly compatible with a particulate separation environment.

Separated particulate could be removed continuously by means of a dust slot extending the length of the compressor. Blade erosion could be reduced

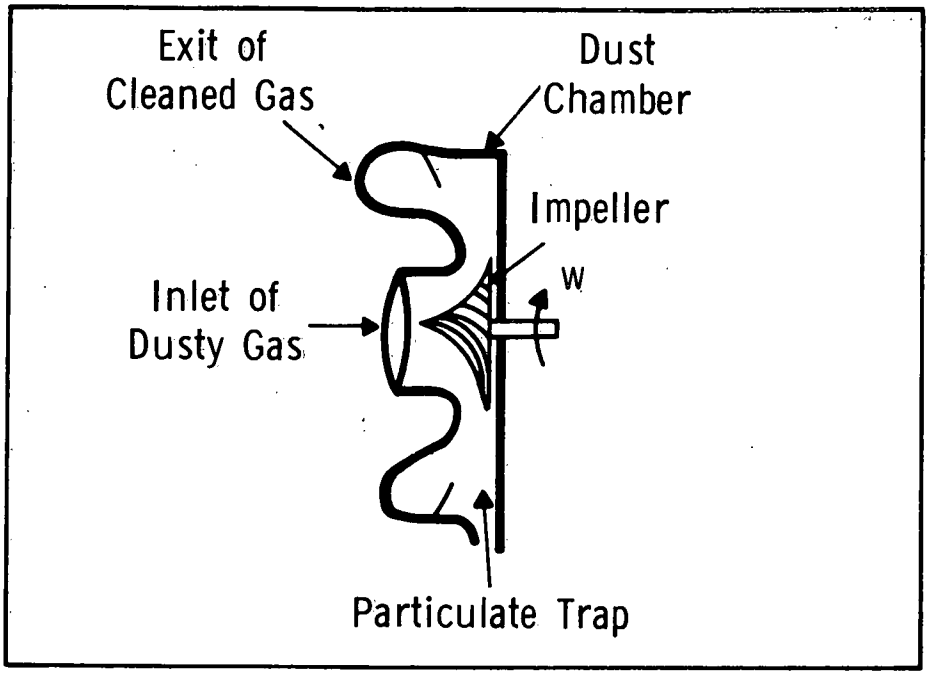


Fig. 13. Impeller-Scroll Collector (Side View)

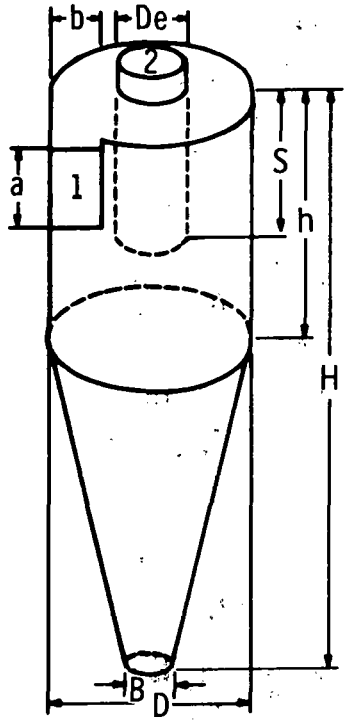
by preremoval of the large particulate by means of a conventional cyclone and by designing the flow field such that the relative blade velocities are low; although this latter step reduces compressor efficiency, the result may still be adequate since its primary mission is separation. A number of obvious disadvantages can be cited -- the principal ones being the relatively high cost that would be associated with such a device and the short life due to erosion. This latter problem, however, may not be insoluble since it has been experimentally determined[38] that blade erosion rates are proportional to relative velocity raised to a power between 3 and 5; hence, if very low speeds are tolerable, it may be possible to reduce erosive effects to acceptable levels. A search of the literature has failed to uncover any discussion of such a device.*

General discussions of the performance of both static and dynamic scroll collectors are available[83,104] These devices have efficiencies intermediate between baffled geometries and cyclones. Unless a greatly improved dynamic concept can be developed, scrolls are not capable of meeting the high-efficiency requirements associated with turbine operation.

Conventional Cyclones. The variety of configurations of the cyclone that have evolved in the more than 100 years since its invention boggles the imagination. Yet, the most commonly employed geometry -- available from more than sixty domestic manufacturers[105] -- remains remarkably similar to the device which

*A particular gas centrifuge, known as a "turbocyclone," has been suggested which closely resembles the axial compressor/separator. However, because both the blades and the outer casing rotate in this device, it is discussed under the heading, "centrifuges."

received a German patent in 1855: a typical design with geometrical proportions is shown in Fig. 14.



Recommended Duty	D	a/D	b/D	De/D	S/D	h/D	H/D	B/D
High efficiency[107]	1	0.5	0.2	0.5	0.5	1.5	4.0	0.375
High efficiency[108]	1	0.44	0.21	0.4	0.5	1.4	3.9	0.4
General purpose[109]	1	0.5	0.25	0.5	0.625	2.0	4.0	0.25
General purpose[108]	1	0.5	0.25	0.5	0.6	1.75	3.75	0.4
High throughput[a107]	1	0.75	0.375	0.75	0.875	1.5	4.0	0.375
High throughput[106]	1	0.8	0.35	0.75	0.85	1.7	3.7	0.4

[a]Scroll type gas entry used.

Fig. 14. Standard Cyclone Geometry and Proportions (schematic reproduced from Ref. 133 with permission of Chemical Engineering Progress)

Cyclones may be distinguished from scroll collectors by observing that the streamline is designed to traverse more than one complete revolution (usually ca. 5). They can be classified in a number of ways: direct (or uniflow) versus vane rotation; simple-flow versus flow with auxiliary injection; and induced draft versus forced draft. In addition, cyclones are also approximately classed based upon their diameter: "large," which corresponds to roughly 0.5 to 4 m diameter and is used for high-throughput applications where low efficiency is acceptable; "medium," of approximately 20 to 100 cm diameter for moderate throughputs and efficiency; and "small" or "multiclones," in the range of 5 to 30 cm diameter and used for the highest efficiency requirements.

Numerous data exist for cyclone performance at moderate temperatures and at atmospheric pressure (*e.g.*, Refs. 78, 80, 83-86, 92, 104, 106-111). These data are usually presented in the form of a plot (which is termed a "grade efficiency curve") of efficiency versus particle size for a prescribed pressure drop.

If the particulate distribution is known for the gas stream to be cleaned, then the overall separation efficiency can be calculated by weighted step calculations. Data of a more detailed nature, such as velocity profiles, is available[112-119] though not abundant: more fundamental studies, such as a mapping of the three-dimensional turbulence stress field, have still to be done. Although it is not possible at present to provide a simple design parameter that will predict the separation efficiency based upon gas and particulate properties, velocity, and geometry, it is possible to indicate what must be done in general to increase the efficiency.

Table 7. Parameters which Affect Cyclone Efficiency

Type	Trend Required to Increase Efficiency
Geometry	Decrease Diameter
	Increase Length
Medium	Increase Tangential Velocity
	Decrease Viscosity
Particulate	Increase Density
	Increase Diameter
	Decrease Surface-to-Volume Ratio
	Increase Concentration

Decreasing the cyclone diameter has proved to be the most convenient design parameter and is the basis of the multiclone concept: an array of small cyclones in parallel is more efficient than a single larger one.

Factors which adversely influence collection efficiency in cyclones are: deagglomeration, reentrainment, deprecipitation, infiltration, recirculation, and plugging. Deagglomeration occurs when friable particulate enters a highly turbulent environment. Secondary flows and viscous effects can cause the wall boundary layer (which contains a high particulate concentration) to periodically separate, with the result that the particulate which had been separated returns to the flow field; this phenomenon is called reentrainment. Adhesion failure of the particulate surface bond can occur when the fluid shear stress in the vicinity of the wall is too large and results in deprecipitation. Infiltration can occur for cyclones which operate at subatmospheric pressure. Recirculation and plugging can occur in multiclone arrays which use a common hopper and very small tube exit diameters. In general, the influence of these adverse factors increases with increasing inlet tangential velocity and ultimately negates any increase in collection efficiency despite improved separation mechanics.

The theory of confined vortex flows is presently woefully inadequate to unravel the fluid-dynamic mysteries of the cyclone. Even the very simplest

of geometries, that of tangential injection throughout the length of a cylindrical tube with a single exit hole in one end plate, can only be solved for very special families of flows due to needed similarity criteria.[120] For the cyclone geometry shown in Fig. 14, there is a double vortex (one inside the other) with two flow exists, which makes the problem analytically insurmountable. In addition, complex internal recirculation zones exist,[121] at both the top and bottom of the cyclone, causing a strongly three-dimensional flow.

The governing equations of motion are, naturally, highly nonlinear. Since the flow along the diameter of the cyclone is viewing a concave surface, the formation of a Görtler longitudinal vortex structure[122,123] is likely, which adversely affects performance by reentraining separated particulate. The wall boundary layer is also known to be unstable to inward displacements, which is the cause of the often-observed dust streaks or striations.[124,125] The internal flow field of cyclones is, of course, turbulent; but it is a non-homogeneous and highly anisotropic turbulent field for which the many closure hypotheses developed for quasilinear flows are not applicable.[126] Confined vortex flows also present other peculiarities such as extreme sensitivity to downstream boundary conditions[127] and the formation of vortex bubbles or breakdown.[128] These and other analytical difficulties have been summarized in a recent survey paper on confined swirl flows.[129]

Despite these prodigious problems, it is not uncommon to find statements such as the following in the literature: "The theory conforms with experience so that performance limits and capabilities are easily calculated" (Ref. 130, p. I-7). Although expressions are available to predict both pressure drop and grade efficiency, these should be taken as semiempirical rules of thumb for already established geometries and not "solutions" to the generic problem. The distinction between solutions and empirical design expressions is an important one because it suggests that marked improvements may be possible in the performance of devices employing a confined centripetal acceleration field -- particularly for novel geometries and new flow regimes. Because these devices have been so successful routinely in many different industrial applications, they have been the subject of very little fundamental research: "...cyclones have been designed to fit a standard-sized sheet metal rather than a specific application..." (Ref. 131, p. 414). The primary research effort on cyclones was accomplished, for the most part, in the period ca. 1930-1950 before the advent of electronic hot-wire probes/correlators, laser-doppler velocimeters, etc. and while the theory of turbulence was still in its infancy; not even the existence of Görtler vortices and the Ranque-Hilsch effect -- two peculiar phenomena of confined vortex flows -- was known in the United States until the end of this period (ca. 1950).

Over the years, a large number of quasiempirical correlations have been developed for predicting both the pressure drop and the efficiency of cyclones.[110-132] Leith and Licht[133] have developed a theoretical result based upon a continual backmixing assumption -- that turbulence acts to maintain a uniform particulate concentration throughout the flow field.* They also assumed that the particulate was spherical, highly dispersed, and acted upon

*A condition which is the basis of the Deutsch equation (Eq. 47) and is characteristic of any turbulent flow in long, narrow geometries.

by Stokes drag. The second order term of the governing equation, Eq. 25, was dropped to making it linear and first order. The flow streamlines were assumed to be strictly circular (*i.e.*, no radial component) and the tangential velocity was expressed in a power law relation with the radius defined by a power exponent, n, as

$$\tilde{V}_s r^n = \text{constant} \tag{55}$$

where $\tilde{V}_s$ and V_s were assumed to be identical. In the core of a confined vortex flow, approximately bounded by the diameter of the exit tube (De of Fig. 14), the flow exhibits solid body rotation (concentrated vorticity) and n = -1 in the region. In the annular region between the core and the boundary layer on the outside wall, the flow approximates potential flow (vortex-free) such that $n \cong +1$. In the wall boundary layer, $\tilde{V}_s$ decreases rapidly with increasing r and hence $n >> 1$. Data for the tangential velocity profile from the core boundary, which is the location of maximum $\tilde{V}_s$, to the wall boundary layer indicate that $n \cong 0.5 \rightarrow 0.8$, depending upon collector geometry and media properties (primarily flow Reynolds number). The only known means of predicting n is by the empirical relationship given by Alexander[134]

$$n = 1 - \left\{1 - 0.351[D(cm)]^{0.14}\right\}\left\{[T(°K)/283]^{0.3}\right\} \tag{56}$$

where D is the cyclone diameter in cm and T is the medium temperature in °K. The motion becomes less vortex-free (*i.e.*, $\rightarrow -1$) with decreasing D and/or increasing T.

The results of this analysis[133] yield

$$\eta = 1 - \exp[-\sqrt{B}] \tag{57a}$$

where

$$B = 4[n + 1)\mathrm{Im}C]^{1/(n+1)} \tag{57b}$$

where C is strictly a geometrical parameter based upon the dimensions of Fig. 14, and Im is as given in Eq. 33 with $\tilde{V}_s$ evaluated at the radius of the cyclone wall* (*i.e.*, D/2). Thus, the efficiency is predicted to increase with increasing C and Im; η also increases with increasing n except for very large values of C Im. This predictive model has been compared[133] with the data of Tengbergen[135] as shown in Figs. 15 and 16 for a cyclone 28 cm in diameter. From the slope of the data in Fig. 16, n can be found to be 0.43. From the value of the ordinate where $\tilde{d} = 1$ (*i.e.*, abscissa = 1), C can be found to be 17.6. The predicted values of n (from Ref. 134) and of C (Ref. 133) based upon the cyclone geometry are 0.60 and 23.8, respectively. Thus, the collection efficiency of cyclones can be empirically well-correlated in terms of an impaction number and a flow Reynolds number-dependent exponent, n; the methods of calculating n and C *a priori* yield only approximate estimates of their true values.**

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*Strictly speaking, this must be outside the boundary layer but since $D >> \delta$ (the boundary-layer thickness), there is little error in ignoring this difference.

**The calculation of C by Leith[133] for two sizes of cyclones used by Tengbergen[135] (28 and 47 cm) yielded identical values (*i.e.*, 23.8), but the data require a change by a factor of 2 (8.78 and 17.6, respectively).

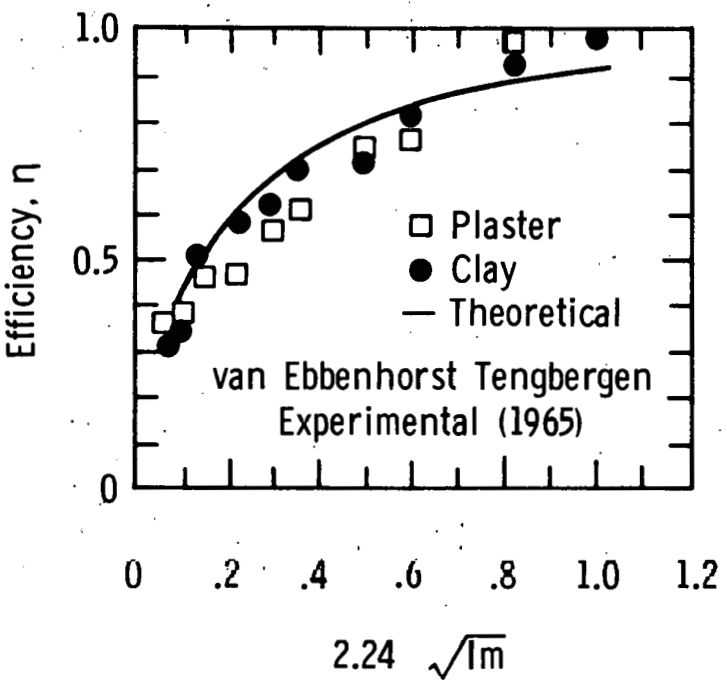

Fig. 15. Comparison of Theory of Leith and Licht[133] with the Data of Tengbergen[135] Reproduced with permission from AIChE Symposium Ser. *68*(126), 196-206 (1972)[133]

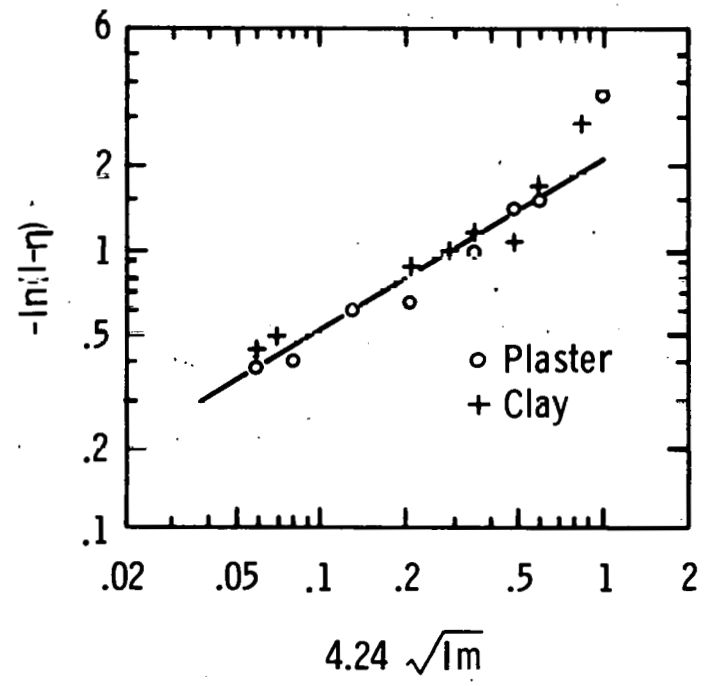

Fig. 16. Data of Tengbergen[135] Reproduced with permission from AIChE Symposium Ser. *68*(126), 196-206 (1972)[133]

The effect of high temperature and high pressure upon the performance of a given cyclone geometry (*i.e.*, fixed C) can be predicted by calculating the effect upon Im and n. As was noted by Eq. 40, Im decreases with the two-thirds power of T. Using Alexander's Eq. 56 for a fixed D yields

$$\frac{1 - n}{1 - n_o} = \left(\frac{T}{T_o}\right)^{0.3} \tag{58}$$

By taking $n_o = 0.7$ and C = 20 at 300 K with an efficiency of 0.990,

$$B_o = [\ell n(1 - \eta_o)]^2$$

$$= 21.2 \tag{59a}$$

$$Im_o = (B_o/4)n^{0 + 1/C(n_o+1)}$$

$$= 0.501 \tag{59b}$$

At 1273 K, using Eqs. 58, 40, and 57, the predicted performance can be determined

$$n = 1 - (1 - n_o)(T/T_o)^{0.3}$$

$$= 0.537 \tag{60a}$$

$$Im = Im_o(T/T_o)^{-2/3}$$

$$= 0.191 \tag{60b}$$

$$B = 4[(n + 1)\ IM\ C]^{1/(n + 1)}$$

$$= 12.7 \tag{60c}$$

$$\eta = 0.971 \tag{60d}$$

Thus, the efficiency based upon this model for these particular values of η_o, n_o, and C can be expected to decrease less than 2% (*e.g.*, 1.9%) for an increase in temperature from 27°C to 1000°C.

This analysis may be compared with the technique suggested by Caplan[136] where

$$\frac{1 - \eta}{1 - \eta_o} = \left(\frac{\mu}{\mu_o}\right)^{0.5} \simeq \left(\frac{T}{T_o}\right)^{1/3} \tag{61}$$

Using $\eta_o = 0.990$ at 300K as before, this method yields $\eta = 0.984$ at 1273K, a decrease of 0.6%. This result predicts a much less adverse change in efficiency than that obtained following Leith: 0.6% vs. 1.9% decrease. In both analyses, the pressure of the medium does not enter into consideration.

Although the decrease in cyclone efficiency with increasing temperature is small, the effect is nonetheless significant because the envisioned application, Fig. 5, presents such stringent requirements. The efficiency data of cyclones is given as a function of particulate diameter (which is

usually a mass-mean value for polydisperse aerosols) and pressure drop (which is directly relatable to inlet velocity, $\tilde{V}_S$) based upon a fixed cyclone diameter (the primary geometrical parameter). For multiclones of D = 10-30 cm, at pressure drops of 7-11 mm Hg, efficiencies of 0.95 are possible with particulate as small as 5-μm diameter.[92] By using a device known as a fines eductor (a continuous dust removal slot along the entire length of the cyclone), efficiencies as high as 0.955 on fly ash ($\tilde{\rho}$ = 2.5 g/cm^3, 45% minus 10 μm, 150°C) are possible with cyclones 150 cm in diameter at a pressure drop of 11 mm Hg.[137] Some manufacturers (*e.g.*, Fisher-Klosterman[138]) claim η = 0.999 on particulate as small as 4 μm via a "super-cyclone." If it is assumed that a given cyclone geometry can demonstrate η = 90% at $\tilde{d}$ = 10 μm at an acceptable pressure drop, then Eq. 57 would predict that efficiencies on the order of 99.99% can be achieved on particulate of 70-μm diameter--a highly promising prospect based upon the requirements of Fig. 5.* Therefore, for a fluidized-bed application, the use of cyclonic separation appears feasible despite the high inlet particulate concentration because the mean particle diameter is sufficiently large that the high collection efficiencies required appear to be obtainable.

Although high-temperature operation of cyclones is not common, it is readily possible. Cyclones have been used at temperatures as high as 1100°C (Ref. 140, p. 111), and at least one manufacturer quotes off-the-shelf usage at 980°C. There are two general structural approaches possible: use of an external pressure shell (*i.e.*, double-wall structure) or use of a refractory lining inside a single shell. Thus, no fundamental barrier exists to the application of cyclones to the high-temperature and pressure environment.

Locomotive Development Committee (LDC) Dunlab Tubes. The only known program to develop cyclone technology for high-temperature/high-efficiency application was that of the LDC, established by BCR from 1944 to 1959 and carried on for a time by BOM (Morgantown), as was noted in Part I.[39-45] Yellott's paper[42] details the principal results of the LDC effort and Smith's paper[45] of the BOM effort.

Four types of cyclones were tested by and for the LDC: the Aerotec (a very small diameter multiclone) by the Institute of Gas Technology, a multiclone (10 VSX) by Western Precipitation Corp., an American Blower ST 361 by Northrup Corp., and the "Dunlab Tubes" by the Dunkirk Laboratory of the LDC. The geometries of these devices are shown in Fig. 17. The typical operating environment of these devices was 2 to 5 atm pressure and 370-700°C at an inlet particulate concentration of ca. 5 g/m^3. The original target concentration at the exit was ca. 0.5 g/m^3, which corresponds to a collection efficiency of 90%. A major problem associated with using these collectors was the need to separate very fine, hot ash particulate that had carbon contents as high as 50%. The carbon burned "vigorously" unless the collected particulate was removed by using a continuous blowdown of approximately 1 to 2% of the throughput. Much of the design effort was related to solving this difficulty.

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*By fitting data to $\eta = a\tilde{d}^b$, typical values of the exponent based upon manufacturer's specifications[139] yield b ≅ 0.07 for $\tilde{d}$ ≅ 10 → 35 μm.

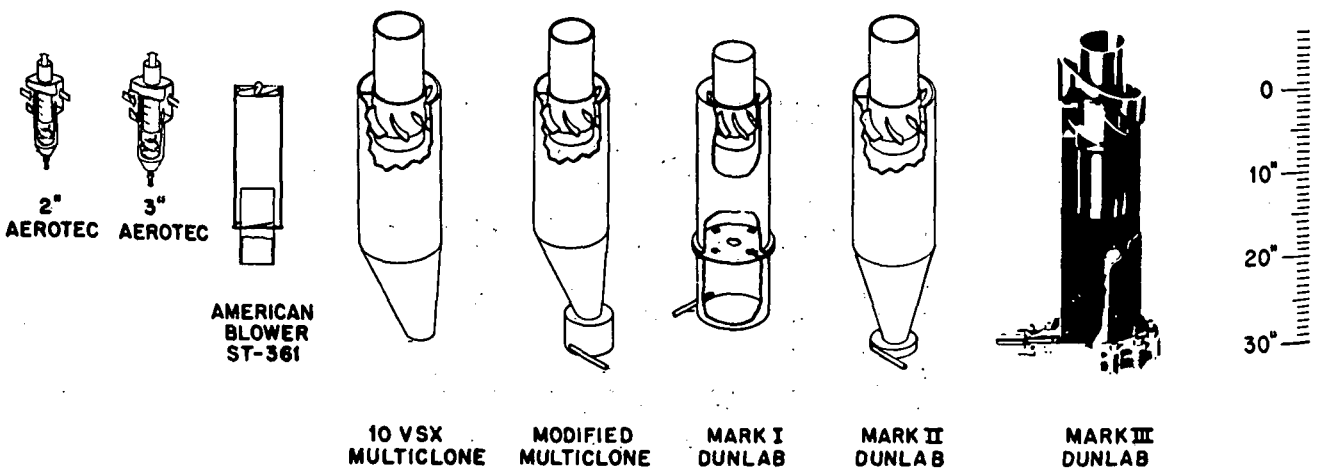

Fig. 17. Cyclones Tested by LDC Program[42]

Tube Designation	Diameter, Inches: Barrel	Diameter, Inches: Discharge tube	Over-all Length, Inches	Vane Angle,°	Blowdown: Type	Blowdown: Size of line, inches
Aerotec, 2 inches	2	1.375	8.25	..	....	....
Aerotec, 3 inches	3	2	13	..	....	....
Am. Blower ST 361	8.25	6 O.D.	21	17	10%	Slotted ring, area 0.6 sq. inch
Multiclone 10VSX	10	6	35.5	45	....	....
Modified Multiclone	10	6	35.5	45	Tangential from 6 x 5 inch pot	0.75
Mark I Dunlab, 10 inches	10	6	27	30	Tangential	0.75
Mark IA Dunlab, 16 inches (no razor plate)	16	9	59	30	Tangential	1.25
Mark II Dunlab	10	6	27	30	Conical radial	0.75
Mark III Dunlab	10	6	27	30	Annular radial	0.75

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The effect of these parameters--particulate size, medium temperature, and mass throughput--was examined in detail. Typical particulate distributions for the fly ash used and the performance of the Mark III Dunlab tube with three different distributions are shown in Fig. 18. It is clear that the efficiency is very dependent upon the relative concentration of the small particulate in the aerosol. For fluidized-bed combustion, the efficiency of these devices would be very high.

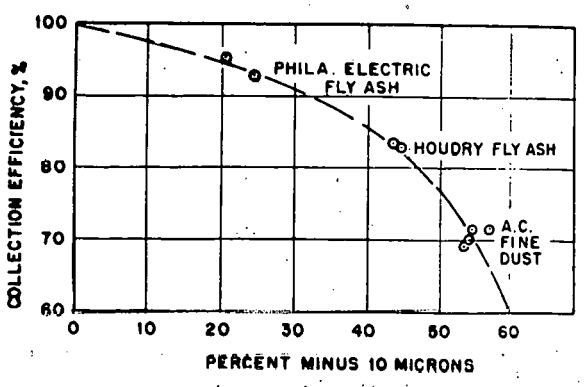

Fig. 18. The Effect of Particulate Fly-Ash Distribution upon the Efficiency of the Mark III Dunlab Tube at 700°C

	Specific Gravity	Particle Diameter, μm 0-10	10-20	20-40	+40
1 State Line fly ash	2.5	57.0	23.0	13.4	6.6
2 Tube mill dust, Western Precipitation Corp.	2.72	36.7	11.6	22.1	29.6
3 Blended fly ash, B, Western Precipitation Corp.	2.52	64.1	13.9	13.7	8.3
4 Philadelphia Electric Co., fly ash A	2.2	40.0	8.0	17.0	35.0
Philadelphia Electric Co., fly ash B	2.2	24.2	15.0	13.4	47.4
5 Detroit Edison, fly ash A	2.45	29.6	18.8	24.6	28.2
6 Detroit Edison, fly ash B	1.9	24.0	26.6	22.3	8.9
7 Houdry unit ash, 30-40% carbon	2.2	44.4	31.0	17.4	6.2
8 A.C. fine test dust	2.9	53.3	18.1	14.8	17.1
9 State Line fly ash	2.55	41.7	24.1	23.6	10.5

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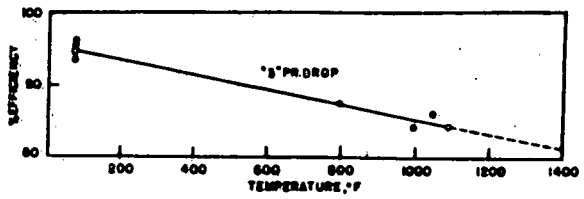
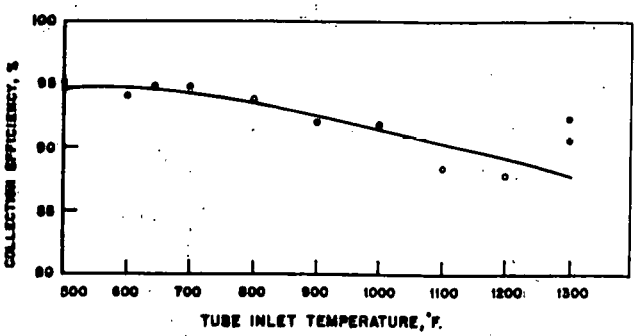
The effect of temperature upon collection efficiency for a given particulate can be seen in Fig. 19.

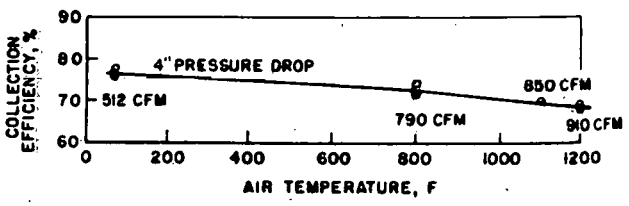
The efficiency data for all cyclone types can be presented as a function of amss flow rate (which can be translated to flow Reynolds number), as shown in Fig. 20.



3" Aerotec (State Line Fly Ash)



ST-361 (Detroit Edison Fly Ash B)



10-VSX (Blended Fly Ash)

Fig. 19. The Effect of Temperature upon the Efficiency of Three Cyclones for a Fixed Particulate.[42] Reproduced with permission, from J. I. Yellott and P. R. Broadley, Ind. Eng. Chem. *47*(5), 944-952 (May 1955). Copyright by the American Chemical Society.

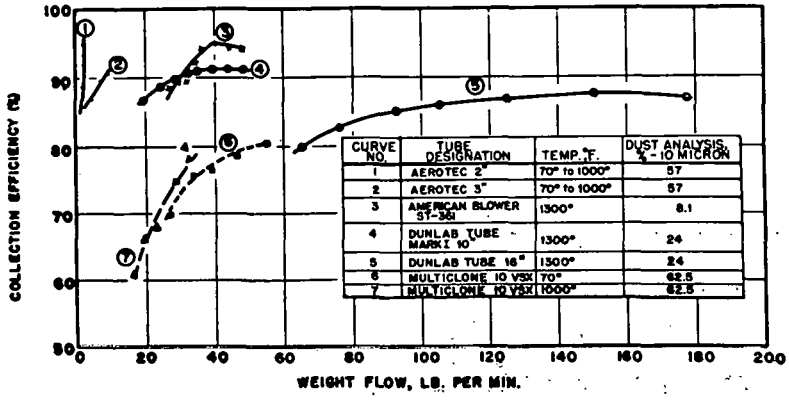


Fig. 20. The Effect of Mass Flow Rate and Temperature on the Collection Efficiency.[42] Reprinted with permission, from J. I. Yellott and P. R. Bradley, Ind. Eng. Chem. *47*(5), 944-952 (May 1955). Copyright by the American Chemical Society.

A small spinner was placed in a scale-model of a Mark I Dunlab tube and its rotation was measured by a stroboscope and found to be as high as 15,000 revolutions per minute which, for the 10-in. tube, implies that the centripetal acceleration was 3×10^5 m/s^2 (3×10^4 times the acceleration of gravity). From Fig. 9, this acceleration intensity should result in a drift velocity greater than 1 m/s for $\tilde{d} > 1$ μm. In the absence of secondary effects, particulate larger than 1 μm should reach the tube wall from any point within the cyclone in 25 ms. The mean residence time for a Mark I tube at 50 lbm/min is on the order of 1 s or 40 times the maximum residence time required to separate the most unfavorably positioned 1-μm particle. The discrepancy between the implications of this analysis and the data can be attributed to the presence of secondary flows (Görtler vortices, wall-layer separation, recirculating flows, etc.) and the continual mixing effect of the flow-field turbulence. These phenomena can be expected to preclude any improvement in η with increasing $\tilde{V}_s$ and are in fact reflected in the data (*e.g.*, curve 5 of Fig. 20). The proper conclusion of this circumstance is that the microflow structure needs to be examined for mechanisms which will inhibit the deleterious effects of secondary flows and turbulence upon the separation potential. The relatively poor performance of the LDC cyclones should be qualified by observing that these devices were being used for very small particulate and compromises were made in their design to deal with the combustibility of the collected material.

After the BOM took over the LDC program, they first redesigned the turbine blades to make them more resistant to erosion. After 2000 hr of operation using a bank of 26 Dunlab tubes in parallel at 5 atm and 670°C, it was concluded[45] that further improvements in the ash-removal system and coal combustor were required before the concept of a coal-burning turbine would be practical. An axial flow ash separator, shown in Fig. 21, was proposed as a second stage collector or as a replacement for the Dunlab multiclones.

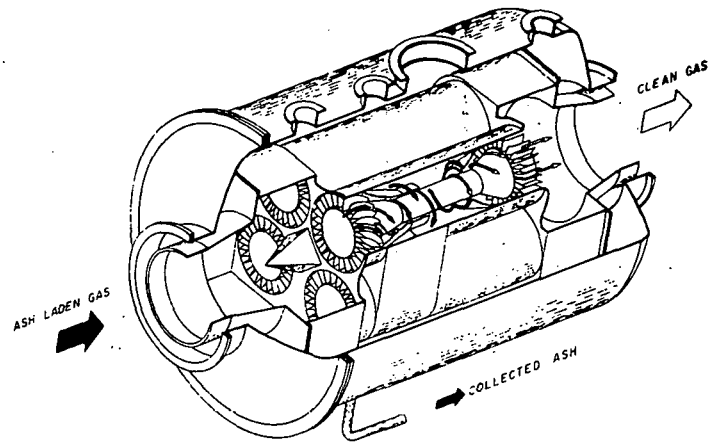


Fig. 21. Bureau of Mines (Morgantown) Proposed Axial-Flow Ash Separator[45] (reproduced with permission, from Trans. ASME, J. Eng. Power)

Further tests of the direct-cycle coal combustor were to be performed. However, a search of the Science Citation Index through September 1975 yielded only one citation[141] of the Smith paper.[45] The Corporate Source Index did not produce a single journal citation by any of the authors of Ref. 45 over this same period, suggesting that this work was either terminated or unpublished.

ARL Vortex Tubes. During the period 1961-1975, the Aerospace Research Laboratories of the U.S.A.F. at Wright-Patterson AFB, Ohio, sponsored a series of activities related to confined vortex flows. Among their interests were applications to (1) fission-material containment for a vortex nuclear rocket, (2) stabilization and heat transfer associated with a plasma-jet arc, and (3) improved cyclonic separation. General research into the problems of confined vortex flows was also sponsored and has been surveyed.[142] Their results in the area of heat transfer were recently summarized.[129] No such summary of their work on cyclones is known to exist.

The cyclone work was begun in 1961 and was conceived[15,143] by Dr. Hans von Ohain.* The basic objective of this effort was to find geometrical configurations with secondary injection for which the secondary flows inextricably associated with confined vortices aided rather than inhibited particulate separation. The devices which germinated from this concept were called

*Dr. von Ohain is presently Chief Scientist of the Aero-Propulsion Laboratory of WPAFB, Dayton, Ohio.

"reversed flow vortex chambers." The documentation of this 15-yr program did not receive a wide circulation and, as a result, their work is not widely known. A computer key-work search of the Engineering Index (ca. 2000 journals since 1970) and the National Technical Information Service (reports since 1964) data bases failed to yield a single citation on "reversed-flow vortex chambers." The published literature of this organization's work on cyclonic separation has been compiled (with the assistance of E. E. Soehngen[15]) and is given as Ref. 144-159.*

Poplawski and Pinchak[145] have presented some of the preliminary work on dust separation. Three different chambers were constructed: one for high-pressure work and two for low pressure applications (one forced low flow and one induced high flow). The high-pressure separator is shown in Fig. 22.

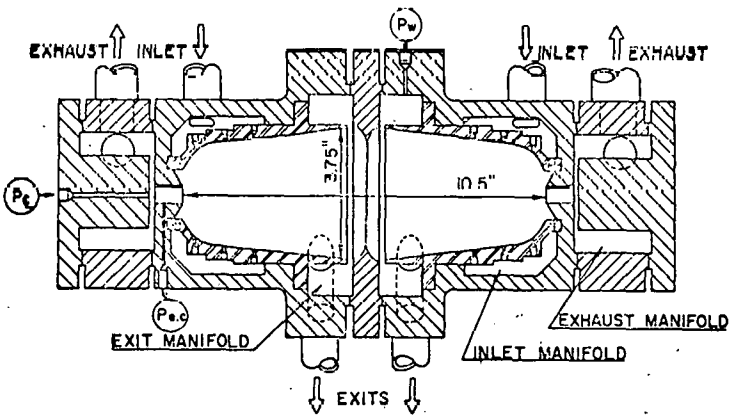


Fig. 22. The High-Pressure ARL Vortex Tube (reproduced from Ref. 145)

Tangential injection from the inlet manifold was by menas of 48 nozzles, of 1.6-mm diameter, located at four different radii. The cleaned air was removed at the exhaust manifold at each end; the particulate was removed near the center at a pair of "exits." By construction of the chamber in two mirror-image halves, one end-wall boundary layer (and its associated secondary flows) was eliminated. The vortex generated by this device was exceedingly intense--tangential Mach numbers of ca. 1.2 and anemometer rotational speeds of 480,000 revolutions per minute, which translates to an acceleration field 100 million times that of gravity (see Fig. 9). No particulate separation data was reported for this chamber.

The low-pressure, low-flow (forced), vortex chamber tested is shown in Fig. 23. No provision was made for continual removal of separated particulate, and so all data were taken on a batch-run basis, using weighed quantities of

*Many of these documents are now difficult to obtain. The author has not yet been able to secure copies of Refs. 144 and 146-154.

"Arizona road dust" which had a top size of ca. 5 μm. Visual examination of this chamber in operation revealed that a cloud of 1-2 μm particulate stabilized in a region ca. 5 cm thick on either side of the geometrical center. This separated particulate cloud was lost if the secondary injection at R_1 of Fig. 23 was reduced by approximately 50%. The rotational velocity in this chamber was estimated to be 55,000 revolutions per minute or one-tenth that of the high-pressure chamber.

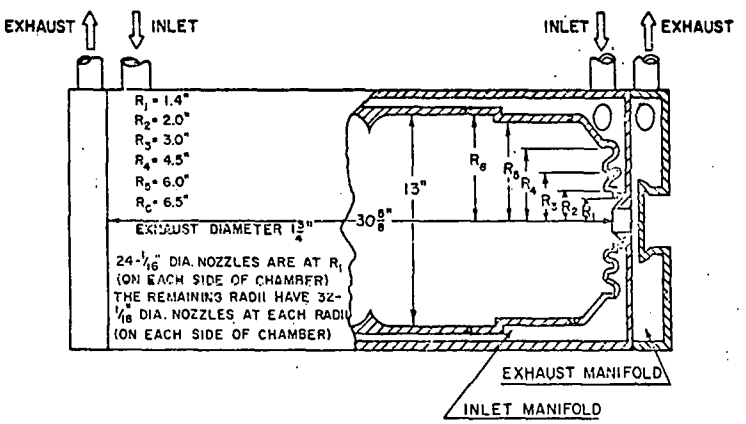


Fig. 23. The Low-Pressure, Low-Flow ARL Vortex Tube (reproduced from Ref. 145)

The second low-pressure chamber utilized an induced-flow geometry that resulted in a much higher volumetric flow rate. A schematic of this separator is shown in Fig. 24. Many different geometrical variations of this device were used: two different conical end sections (lengths of 7.75 or 15 in.) and a number of differently shaped coaxial tube inserts. Continuous particulate removal was accomplished at the periphery of each end and was aided by means of auxiliary air injection. Two inlet particulate size distributions were used--"coarse" (0-200 μm) and "fine" (0-15 μm). No size distribution curves for these particulates were given. The independent variable was the volumetric flow rate, which was varied from 0 to 0.3 m^3/s (0-600 ft^3/min). The data for two geometries and several flow rates are given in Table 8. For the range of flow rates reported in Table 8, the rotational speed was ca. 10,000 revolutions per minute.

From these data, it is not possible to evaluate the merits of these separators. Efficiencies of 95% for particulate larger than 50 μm and 75% for ca. 5-μm particulate are readily achieved with conventional devices (at much lower pressure drops), and so the detailed size distributions of the dust must be known before these results can be assessed.

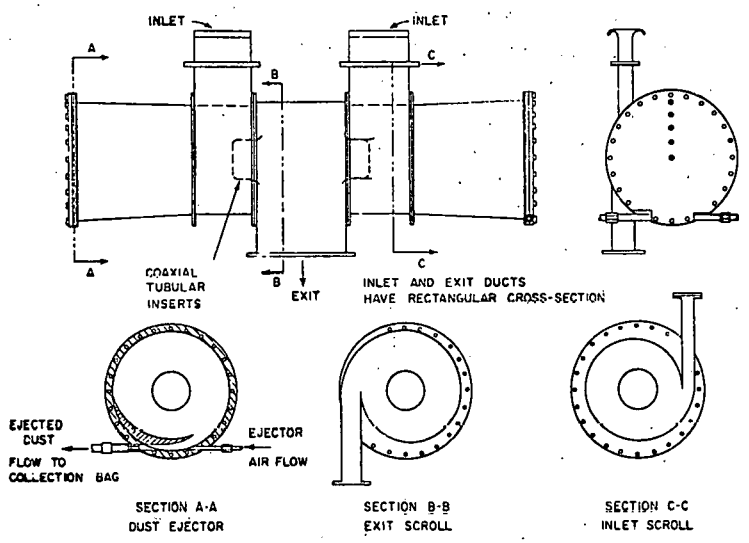


Fig. 24. The Low-Pressure, High-Flow ARL Vortex Tube (reproduced from Ref. 145)

Table 8. Separation Efficiency Data for the Low-Pressure, Low-Flow ARL Vortex Tube[145]

Geometrical Configuration			Volumetric Flow Rate,	Chamber Pressure Drop,	Dump Time,	Dust Size Range,	Separation Efficiency,
Coaxial Diameter, in.	Insert Length, in. (Shape)	End Cone Length, in.	cfm	in wg	min	μm	%
5.10	3 (Cone)	15	524	9.05	1	0-200	93
5.10	3 (Cone)	15	498	8.60	3	0-200	95
5.10	3 (Cone)	15	508	8.60	3	0-5	74
5.10	3 (Cone)	7 3/4	478	8.47	3	0-5	68
5.10	3 (Cylinder)	7 3/4	584	7.80	1 1/4	0-200	89
5.10	3 (Cylinder)	7 3/4	584	7.70	3	0-200	88
5.10	3 (Cylinder)	7 3/4	584	7.80	1	0-5	65
5.10	3 (Cylinder)	15	591	7.80	3	0-5	71

It should be noted that these data were obtained from the first prototype tested, and improved configurations of both geometry and auxiliary injection should be possible as the separation mechanics become better understood. At the time the report[145] was written, twenty scientists and technical support personnel were actively at work on this problem.

Current High-Energy Cyclones. Despite the apparent absence of government-sponsored research on improved-technology cyclones, several devices are being developed by various manufacturers. These devices fall into two groups: multiclones and auxiliary injection cyclones.

Shell Oil Company has developed a high-efficiency multiclone arrangement that has permitted effluent from catalytic crackers to be used with turbines.[130] Babcock and Wilcox Company has developed a proprietary collector based on advanced cyclone technology that has been tested under ambient conditions on a hydrocarbon mist.[61,66]

The Corad Division of Donaldson Company has developed[160] a "TAN-JET™ Cyclone System" which is essentially a multiclone concept employing auxiliary injection in each cyclone, as shown in Fig. 25.

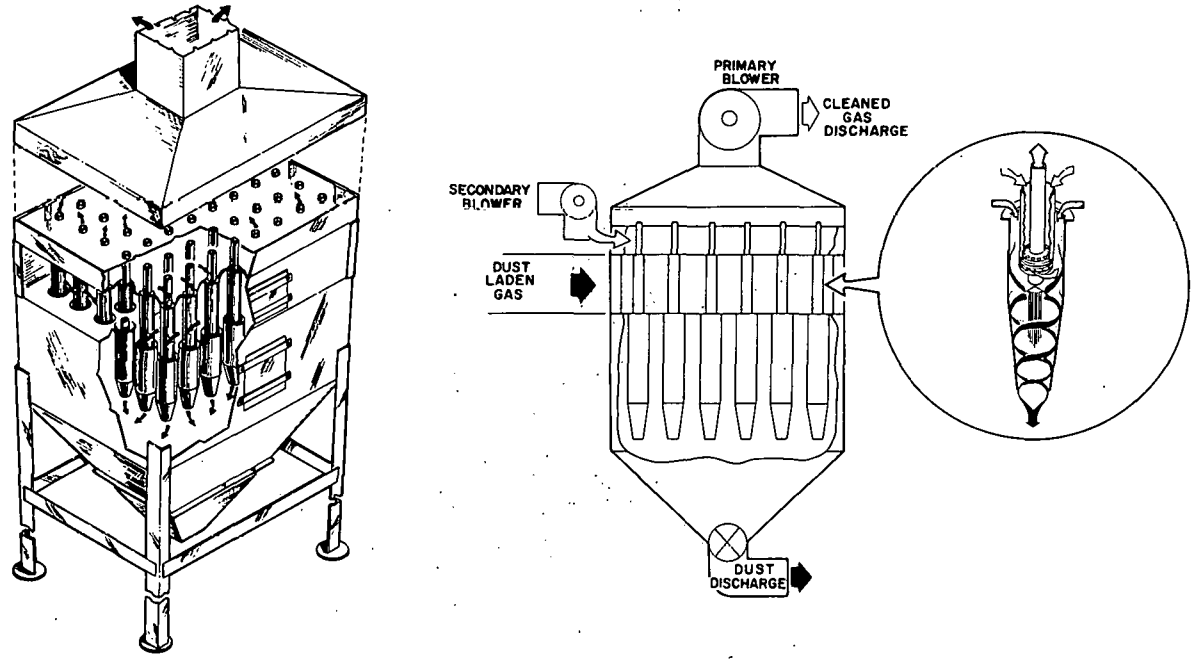


Fig. 25. The Donaldson TAN-JET™ Multiclone[160] (reproduced with permission of Donaldson Co., Inc.)

Each cyclone is 22 cm in diameter and 67 cm long with a capacity of 3 m^3/min (100 std ft^3/min) and requires 15-20% of the primary air flow for auxiliary injection. Off-the-shelf usage to 315°C is quoted, with higher temperature systems available on request. The collection efficiency claimed for their system is given in Fig. 26 for silica dust possessing the shown distribution.

The most widely applied new-technology cyclone has been developed by System Siemens and is available domestically by license from the Aerodyne Development Corporation.[161] These separators are direct-flow cyclones with vane-axial injection that employ auxiliary injection and are available for either dry or scrubber application. The dry version is shown in Fig. 27.

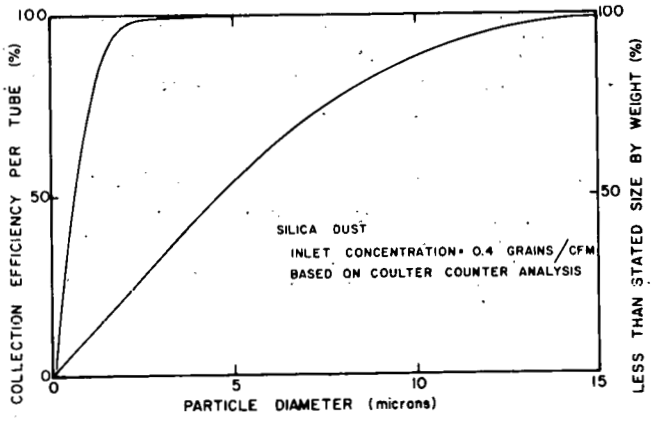


Fig. 26. TAN-JET™ Grade Efficiency Curve[160] (reproduced with permission of Donaldson Co., Inc.)

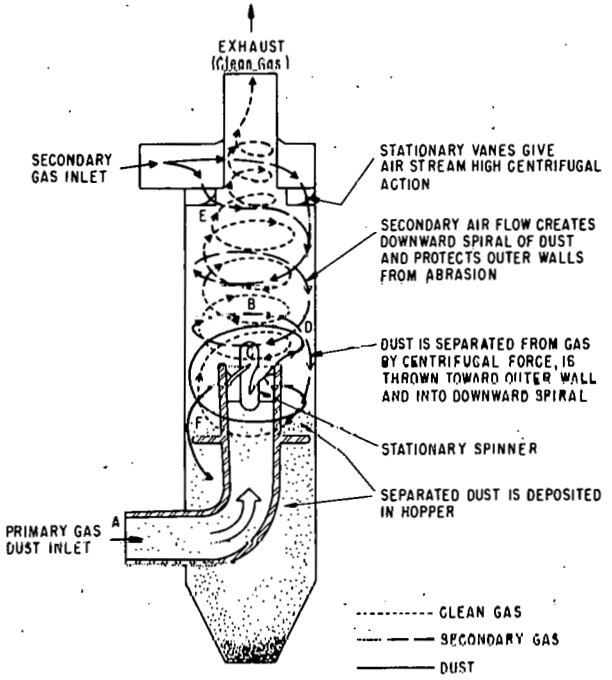


Fig. 27. Aerodyne SV Cyclone[161] (reproduced with permission of Aerodyne Development Corporation)

More than 1500 of these collectors have been installed throughout the world.[66] They have been operated at 500°C/30 atm and are projected to be usable to 900°C/30 atm.[66] They have been tested by Westinghouse at 760°C and 0.7 m^3/s (1500 ft^3/min) and have demonstrated collection efficiencies of 90% for 1-μm particulate at pressure drops of 1.5 cm Hg.[61,67] Combustion Power Company has also tested these devices in connection with their CPU-400 program.[46-49]

The claimed performance of this cyclone is shown in Fig. 28.

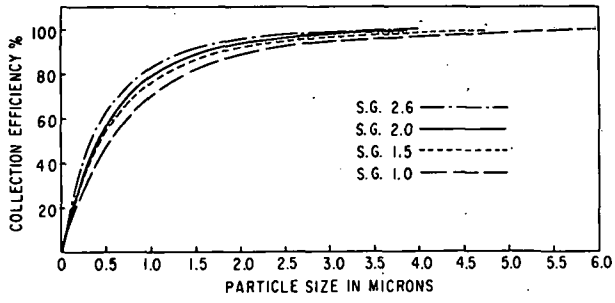


Fig. 28. Aerodyne Grade Efficiency Curve[161] (reproduced with permission of Aerodyne Development Corporation)

Despite the apparent capabilities of this cyclone, both Westinghouse and Combustion Power have elected to develop their own collector systems based on granular-bed technology.[66,67] These decisions are probably due to the high concentrations of small particulate present in the direct combustion (*i.e.*, non-fluidized-bed) concept. Aerodyne has submitted a proposal to Foster-Wheeler Corporation to use this collector for particulate collection at 930°C/10 atm and 43 m^3/s (91,000 ft^3/min) with a fluidized-bed combustor.

The separation performance of conventional cyclones can be improved by operating at a higher throughput and pressure drop. However, there is a definite limit to the improvement realized by simply increasing the flow rate (because of secondary flows, turbulence, etc.) and it is under these conditions that the auxiliary injection technique can result in an increase in efficiency albeit at a cost of additional complexity.

Centrifuges. In addition to the deleterious effects of secondary flows and turbulence upon separation performance for confined vortices, there exists an apparent fluid-dynamic limitation upon acceleration separation. Hasinger in two papers[157,159] has shown that for small particulate (ca. 5 μm) in a Rankine vortex, there exists a significant radially inward surface force on an individual particle as a result of the velocity gradient across its diameter. The conclusion of this analysis is that, although complete separation must occur for particulate in solid-body rotation velocity fields (in the absence of radial in-flow), for vortex flows this condition is not true and a particle can attain a position of radial equilibrium away from the wall in spite of the imposed body force. He concludes[159] for this case that the particulate density must be 200 to 600 times that of the medium in order to ensure separation (again ignoring secondary flows). It is this circumstance that makes the concept of a gas centrifuge attractive.

Solid body rotation also exhibits another favorable fluid-dynamic characteristic: it tends to suppress turbulence. Experiments performed with rotating-tube heat exchangers have shown that heat transfer actually diminishes with increasing rotation speed; this is attributed to increasing the critical Reynolds number for transition from laminar to turbulent flow.[162,163] Thus, for a centrifuge, the theoretical particulate drift velocity found from Fig. 9 can be expected to be realistic. The problem can be analyzed by equating the acceleration body force and the Stokes drag under equilibrium

$$\pi\rho\tilde{d}^3 r\omega^2/6 = 3\pi\mu\tilde{d}\left(\frac{dr}{dt}\right) \tag{62}$$

where $\tilde{V}_n$ has been replaced by the derivative of the radial position. Integrating from time equals zero to the residence time (t_{RES}) yields

$$R/r_i = \exp\{\tilde{\rho}\tilde{d}^2\omega^2 t_{RES}/18\mu\} \tag{63}$$

where R is the radius of the centrifuge and r_i is the initial radial position of the particle to be separated. For $\tilde{\rho} = 2$ g/cm^3, $\tilde{d} = 1$ μm, $\omega = 3000$ rpm, and μ evaluated at 1000°C/10 atm, Eq. 62 yields $R/r_i = 1.26$; this means that, for a 1-m-diameter centrifuge, all 1-μm particulate initially at a radius larger than 40 cm will separate in 1 s or less.* Despite this very promising figure, gas centrifuges have not attracted attention as collectors--no doubt due to the prodigious mechanical difficulties associated with their operation on a continuous (rather than batch) basis.

Wilson[164] has reported on the development of a "Turbocyclone" in Australia. The device consists of two concentric rotating sleeves with attached turbine blades which serve to accelerate the incoming axial flow to solid-body rotation more rapidly. The diameters of the inner and outer sleeves are 10 and 15 cm, and the rotation rate is 5000 rpm. The measured efficiency of this device is shown in Fig. 29 for 5000 rpm operation on an aerosol obtained by a glass sintering torch used to produce spheres 0.5 to 50 μm with a density of 2.23 g/cm^3. Field tests were conducted on a sodium sulfate aerosol from a paper mill and on the aerosol produced by a sulfuric acid plant. The principal difficulty noted was the inability to remove separated particulate that was not a liquid or soluble solid. Despite these generally favorable results, a search through Science Citation Index up to September, 1975, revealed only one paper, Schmidt,[165] which has cited Wilson's work.

Schmidt's paper is very brief and gives only two additional references (in German) on this subject.[166,167] Insofar as the separation mechanics are concerned, the gas centrifuge remains a very attractive solution to high-temperature, high-efficiency collection. A somewhat surprising finding is that the power requirements are comparable to those of multiclones, bag filters, and electrostatic precipitators (ca. 2 kW per 1 m^3/s).[164]

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*The required length of the centrifuge will depend on the axial velocity profile and is a more complex calculation.

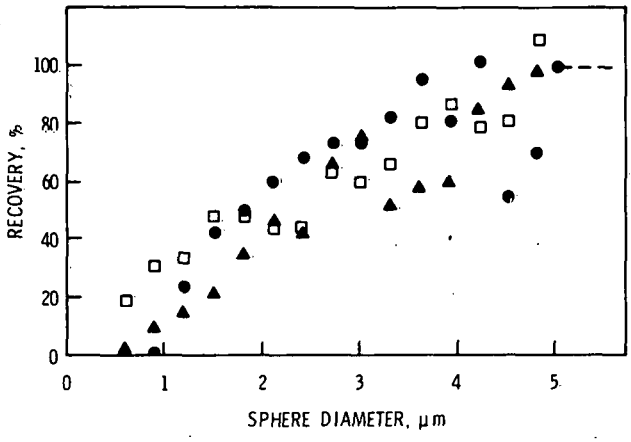


Fig. 29. Turbocyclone Grade Efficiency Curve[164] (reproduced with permission of Commonwealth Scientific and Industrial Research Organization, Australia)

Distributed Collection

This class of collection, generically called "filtration," can be classified into three subcategories: baffle-arrays, granular beds, and fibers (in order of increasing efficiency). The primary collection mechanism for all three types is impaction separation (via streamline modification), for which the characteristic parameter is given by Eq. 33. The fluid dynamic environment under which filters operate is quite different from that of cyclones and similar devices: the separation acceleration potential in filters is very small since $\tilde{V}_n$ is typically 1 to 2.5 cm/s (*i.e.*, laminar flow), and very high efficiencies are obtained only by establishing very small separation distances by means of a distributed collection surface. Because of this collection surface geometry and the associated high separation efficiency for very small particulate, a number of additional mechanisms need to be noted.

If a filter collector was tested at a fixed particulate approach velocity ($\tilde{V}_s$) to determine separation efficiency as a function of particulate diameter ($\tilde{d}$), the data would show a decrease in η with decreasing $\tilde{d}$ (as would be expected from Fig. 10), but there would be a minimum efficiency at ca. 5 μm; as $\tilde{d}$ decreased below this value, η would actually increase. In a similar fashion, if the test were carried out based on a fixed $\tilde{d}$ but with varying $\tilde{V}_s$, for particulate larger than ca. 5 μm, η would increase with $\tilde{V}_s$ (*i.e.*, the impaction mechanism) but for particulate smaller than 5 μm, the efficiency would decrease with increasing $\tilde{V}_s$. The secondary effect that dominates for very small particulate is a result of precipitation by particles randomly contacting the collector surface because of Brownian motion and is known as the diffusion mechanism. Another secondary effect which becomes increasingly important for smaller collecting surfaces is direct interception: particulate on streamlines which pass within $\tilde{d}/2$ of the surface will contact and perhaps precipitate. The primary mechanism (impaction) and the two most important secondary mechanisms (diffusion for very small $\tilde{d}$, and interception, for very small D) are illustrated in Fig. 30.

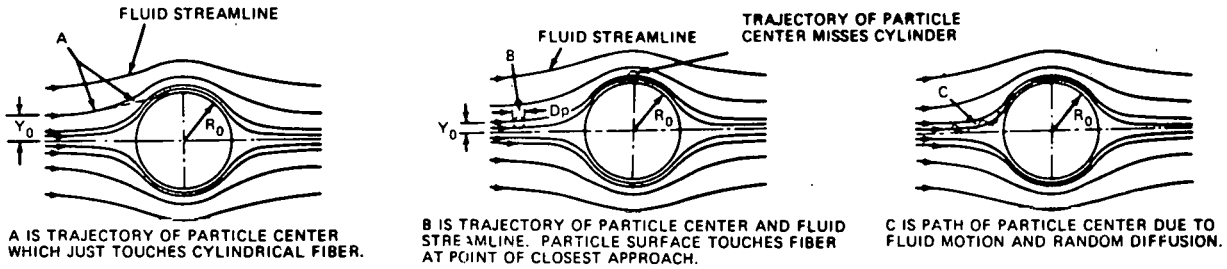


Fig. 30. An Illustration of the Impaction, Diffusion, and Interception Mechanisms Associated with Filtration (reproduced from Ref. 1)

In addition to these two secondary mechanisms, there exists also the potential influence of electrostatic attraction between the particulate and the collector and of sedimentation due to gravity. Further, for filters of appreciable depth, particulate agglomeration as a result of the tortuous flow path will become important. Filter cake formation usually plays an important role; the efficiency of a new filter customarily increases dramatically during the first thirty minutes of operation.

Because of these complications, the theory of filtration is very complex and a large literature exists on the subject (Ref. 1,55,56,60,80,82,83,87, 109,131,168,169). In spite of the analytical difficulties, these devices have found widespread industrial use--most commonly in the form of "baghouses." However, they suffer from severe limitations. For the 27 filter materials commonly used, the maximum allowable operating temperature is 290°C.[140] The approach velocity, expressed as the "air-to-cloth ratio," must be low because of structural, pressure-drop, and efficiency considerations: 0.6 to 1.5 m^3/min of flow per m^2 of surface (2 to 5 cfm/ft^2); as a result, these collectors require large volumes, which is very costly for pressurized applications. Also, the particulate removal step is relatively complex. Typically, removal takes place by shutting down the filter to be regenerated and either shaking the surface or applying a reversed air flow. Finally, the filter lifetime is very sensitive to the character of the precipitate; if the precipitate is very sticky and/or corrosive, the maintenance costs can be excessive. For these reasons, filters have not been accepted by the electric utility industry.*

Current research and development work on the application of filtration to high-temperature environments is relatively extensive, involving approximately 18 organizations. The idea of sand or granular beds is not new[170,171] although it has not been widely adopted because of its cost (estimated to be

*The only baghouse installation known to be at a utility power plant is at the Sunbury Station of Pennsylvania Power and Light.

ca. 25% greater than the cost of an electrostatic precipitator[60]). Recent surveys[55,56,60,61,66,67] have discussed this collector type in great depth.

Baffle Arrays. A device using baffles for collection can be classed under distributed collection, if it resembles a filter more, or under perimeter collection if it resembles a filter less. Louvers are one common form of baffle array. Recently, a new concept of collection that falls in this category has been invented and patented by H. G. Rigo[172,173] and is being developed as a "Particulate Precipitating Heat-Transfer Surface (PPHTS)."[174] Figure 31 illustrates the cross section of the baffle and the vortex mechanism by which particulate is trapped within the cusps. The collection efficiency

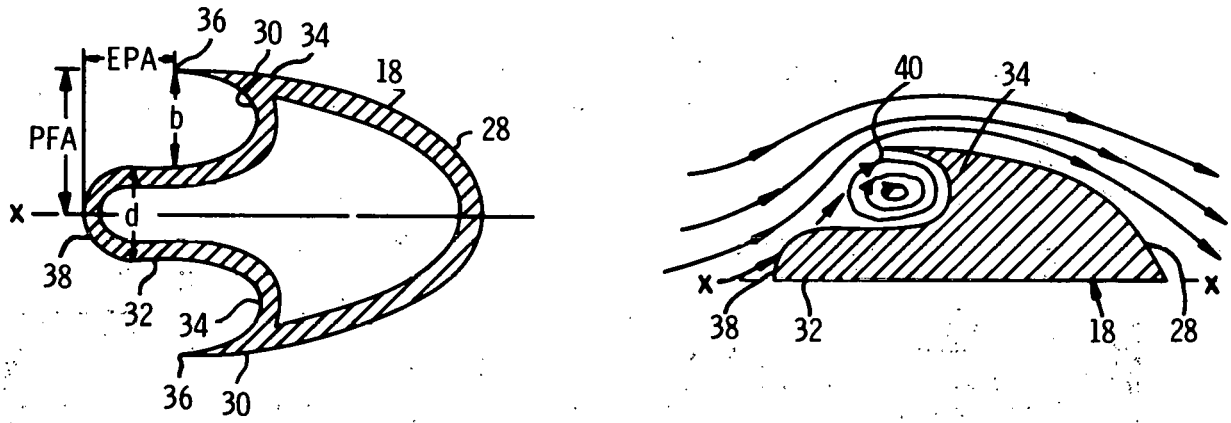


Fig. 31. Particulate Precipitating Heat-Transfer Surface Invented by H. G. Rigo (reproduced from Ref. 172)

has been correlated in terms of a "scaling" parameter, ψ, which is equal to the square root of the impaction number defined in Eq. 33. The performance of a single baffle is shown in Fig. 32.

U. S. ERDA is sponsoring the development and testing of a prototype device by the Construction Engineering Research Laboratory at Champaign, Ill., of the Department of the Army. Currently, work is progressing on the construction of a test section housing 70 baffles of "Style 1" and 18 of "Style 2," each of which is 1.3 m long (52 in.), as shown in Fig. 33. The angle at which these baffles will be mounted with respect to the vertical ("angle of attack") will be varied from 0 to 30 degrees. This test section is being constructed on the site of the Alexandria Fluidized Bed-Test Facility operated by Pope, Evans, and Robbins, Inc.

The separated particulate is expected to flow continuously down the length of the baffle into a hopper, thereby eliminating the need for intermittent operation and secondary removal techniques such as vibration. This concept is very attractive for those applications for which simultaneous heat recovery is desired since this can be readily accomplished by providing a flow passage in the baffle itself.

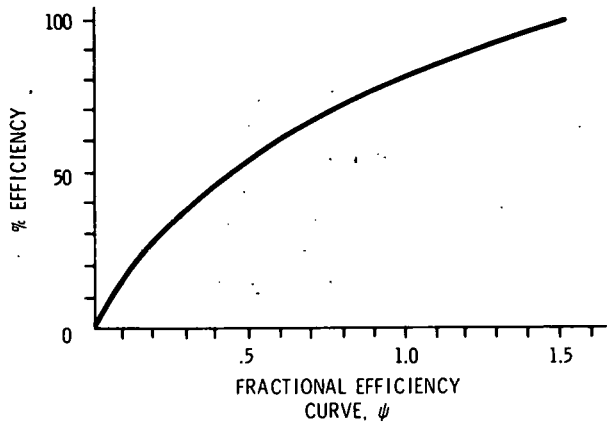


Fig. 32. Separation Efficiency of PPHTS as a Function of Impaction Number ($\Xi\psi^2$) (reproduced from Ref. 172)

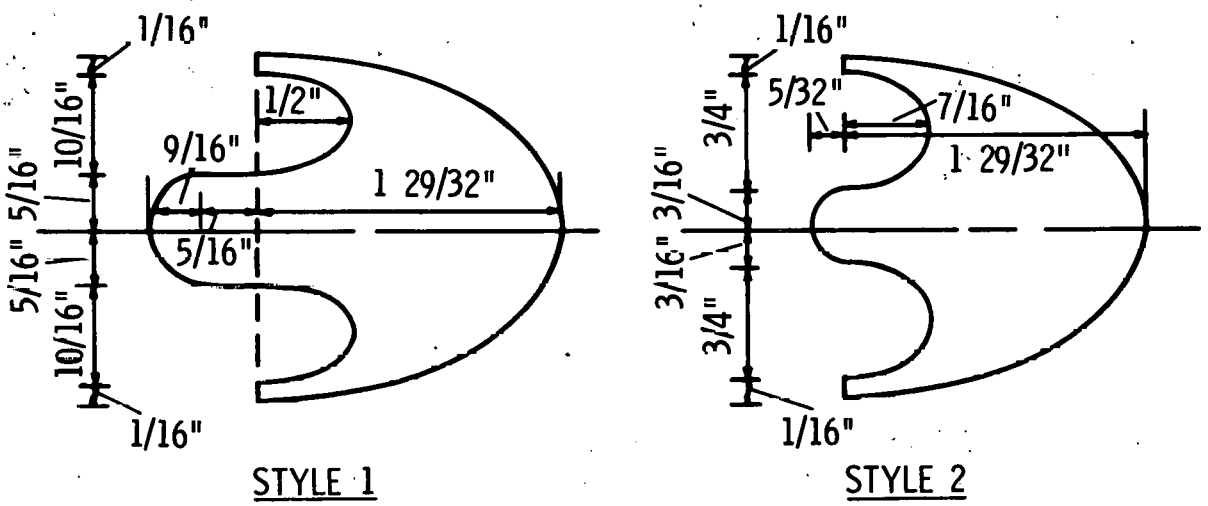


Fig. 33. Styles of PPHTS Currently Being Constructed
Note: All Curves are Ellipses
(reproduced from Ref. 174)

Granular Beds. Collector concepts employing granular beds can be classified on the basis of the condition of the collector surfaces during precipitation: fixed, moving, or fluidized. A summary of the devices currently attracting active research and/or development is given in Table 9. The first four listed collectors are illustrated in Fig. 34. The means by which these beds are regenerated varies: fixed-backflush (panel bed), stirred-backflush (Rex) fluidized-backflush (Ducon), and moving vibration (dry scrubber). In addition to these configurations, a large number of others have been proposed--by Westinghouse and BOM (Morgantown);[8] by Dorfman (Impingo), Consolidation Coal Company, Carnegie-Mellon, and Lurgi M-B;[60] and by Pall Trinity Micro Corp. (sintered porous metal).[67]

Table 9. Granular-Bed Collectors Under Active Development

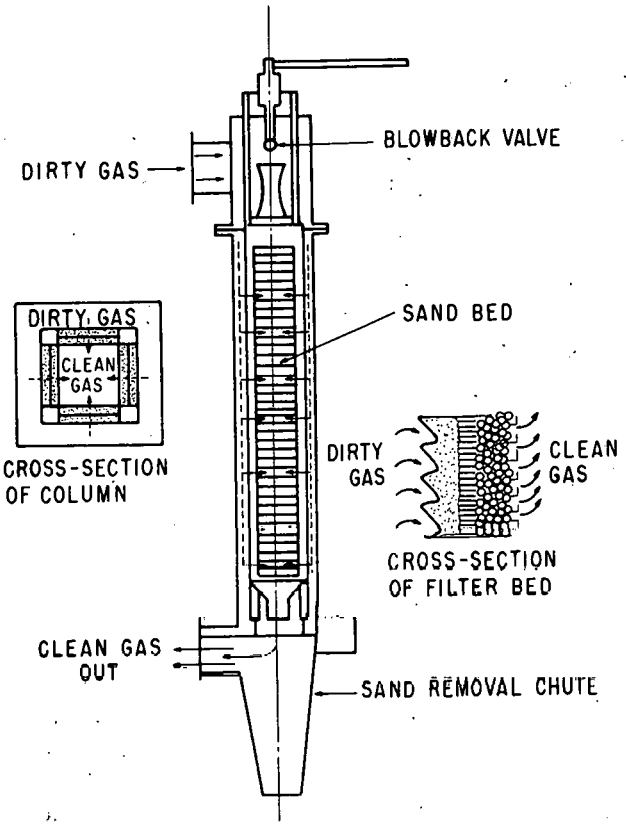
Type	Device	Organization	Ref.
Fixed	Panel Bed	CCNY (Arthur Squires)	175
	Rex Gravel Bed	Rexnord (by license)	176
	Ducon	Ducon Co.	177
Moving	Dry Scrubber	Combustion Power Co.	178
	CANMET	Physical Res. Lab.-Ottawa	179
Fluidized	Exxon	Exxon Research, Inc.	171

Shannon has reviewed the literature on fluid-bed collectors and has concluded that they have "...been studied only to a limited extent and their potential as particulate filters has not been completely characterized" (Ref. 60, p. 200). No citation is known for the Exxon Research fluid-bed collector concept.

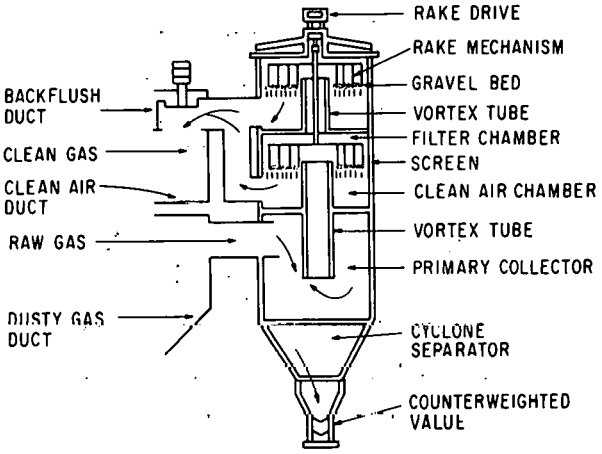
These devices may be generally characterized as highly efficient although complex* (*i.e.*, costly) collectors that appear to be well suited to high temperature applications. In principle, there appears to be no insurmountable difficulty in achieving the needed separation efficiencies of Fig. 9. But in addition to the high cost of these collectors, there remains unanswered how well they can be regenerated in the presence of potentially "sticky" particulate without decrepitation. The concept of collection without regeneration (*i.e.*, once through)--such as by means of sulfated dolomite destined to be discarded--avoids the difficulties of particulate removal; however, since this material includes small particulate, it will be difficult to avoid elutriation of the collector itself during the precipitation process.

Fibrous Mesh. This type of distributed collector is very commonly employed at moderate temperatures. Research on high-temperature applications of fibrous collectors has centered on developing materials which can withstand ca. 1000°C and can be distributed over large areas in small dimensions. The known work is summarized in Table 10, which is based on Ref. 61. The range of applications intended for these materials extends from less than 820°C (Norton ceramic) to 1200°C (alumina-borica-silica by 3M and Brunsmet by Brunswick). Due to structural limitation, the approach velocity will necessarily be low and the regeneration techniques gentle. It does not appear

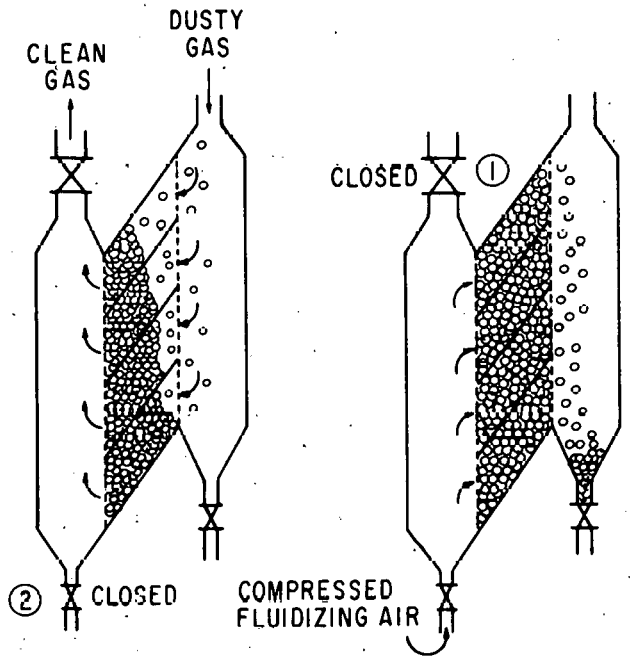
*The Combustion Power Co. "dry scrubber," for instance, is a pressurized vessel 75 ft tall with a cross section of 13.5 by 27 ft.[49]



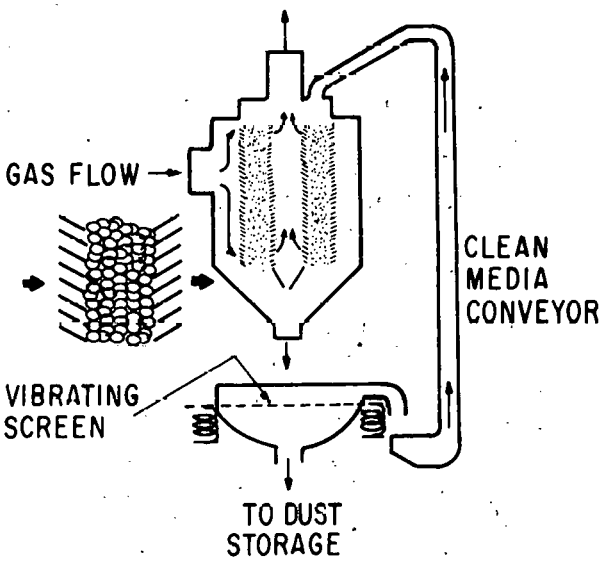
a. Panel Bed[175]



b. Rex Gravel Bed[176]



c. Ducon Fluidizable Bed[177]



d. Dry Scrubber[178]

Fig. 34. Four Granular-Bed Collectors Currently Under Active Development (reproduced from Ref. 66)

Table 10. Fibrous Mesh Collectors Under Active Development

Type	Material	Organization
Glass	Inorganic-bond Fiberglas	Owens Corning Co.
Silica	Silica Fiber	J. P. Stevens Co.
	Alumina-Borica	3M Corporation
	Zirconia	3M Corporation
Metal	Brunsmet	Brunswick Corp.
Ceramic	Norton	Norton Company

that any of these concepts will be able to meet the high-capacity, long-life requirements associated with a power generation application.*

Augmented Concepts. The concept of employing two distinct separation potentials in a single collector is currently being studied in several contexts. The Rex filter is essentially a cyclone and a fixed granular bed in series within one housing. American Precision Industries, Inc. is developing a combined fabric filter and electrostatic precipitator ("APITRON")[61]--a concept which could also be applied to granular beds. J. M. Beeckmans has examined acoustical enhancement of both granular[180,181] and fibrous filters.[182]

EVALUATION OF SEPARATION CONCEPTS

Each of the three general categories of separation mechanisms--field (I. in Table 3), perimeter streamline (II.A), and distributed streamline (II.B)--has the potential to be applied to high-temperature, high-pressure environments, although each has unique disadvantages. Electrostatic precipitation (EP), the only field technique that appears usable, requires careful control of both particulate properties (resistivity) and medium properties (breakdown and sparkover voltages); also, the drift velocities generated are relatively small, which requires large value of X/Y and small values of $\tilde{V}_n$ in order to attain high efficiency (Eq. 47); this results in large collector volumes. Cyclones have fluid dynamic limitations which are not well understood; high efficiency is presently attainable only at large pressure drops or by the use of multicyclones, which results in high operating costs or large collector volumes, respectively. Fibrous and granular filters also

*The Stone and Webster report,[61] however, deemed the Brunsmet filter to have potential.

require a large volume and, in addition, present acute difficulties associated with removal of the precipitate (also a problem area with EP).

The assessment of these three collector concepts can be summarized by noting that they represent two basic approaches: (1) a high-efficiency/high-cost solution by means of EP and filters versus (2) a moderate-efficiency/low-cost solution by means of cyclones; multiclones would fall somewhere in between. An illustration of this point is given in Fig. 35.

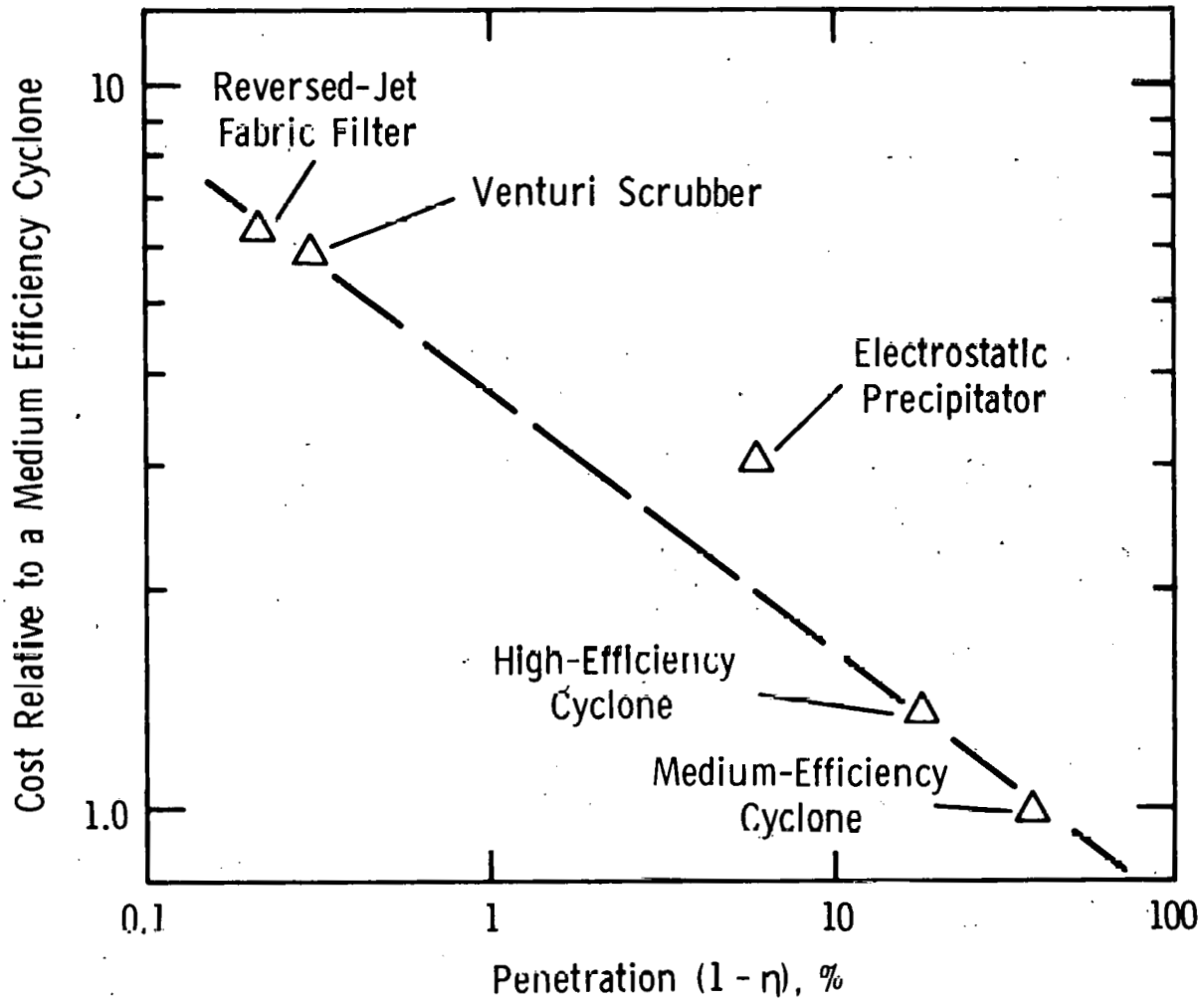


Fig. 35. Relative Cost of Several Conventional Collectors as a Function of Performance (based on the data of Ref. 183)

The optimum device will be strongly dependent on the required performance level which, in turn, is influenced by available trade-offs in turbine design and the relative concentration of small particulate present in the original

source; the latter differs greatly, depending upon whether it is simple fly ash or elutriated fluidized-bed material.

It is significant to contrast the intense level of research and development activity being applied to the high-efficiency/high-cost solution (Tables 9, 10, and 27) with that being applied to the moderate-efficiency/low-cost cyclones, multiclones, centrifuges, and baffles. The only known sponsored research in the latter area is associated with the baffle array of Fig. 33.

The deleterious effect of pressure drop across the collector upon system operation has been examined[184] for Brayton cycle applications and can be estimated as a 1% loss in efficiency for each 1% loss in pressure. For a combined cycle in which the turbine exhaust is used for steam raising, this loss is even smaller because the entropy production step which results in the pressure loss also causes a temperature rise which can, in part, be recovered because the turbine cycle only contributes ca. 20% to the total plant power. Keairns[7] estimates that each 1% loss in pressure (*i.e.*, 7.6 mm Hg at 10 atm) will cause a drop of only 0.1% in total plant efficiency.

A pertinent question regarding all collector development concepts relates to what is the ultimate, theoretical efficiency and how closely present devices approach this bound. Several papers[185,186] have treated this issue. The answer can be ascertained by examining the minimum work required by the Second Law to unmix the particulate and the medium. For aerosols, this quantity is simply the total kinetic energy of motion of the particulate phase as given below:*

$$W_{min} = \eta(\tilde{\rho}/\rho)(\tilde{V}_s^2)/2 \qquad (64)$$

where W_{min} is the ideal work required per unit mass of mixture, and η is the collection efficiency. The Second Law performance index, η_s, is then given by

$$\eta_s \equiv W_{min}/W_{act} \qquad (65)$$

and has been called the "energy efficiency."[186] Typical collector performance under conventional conditions has been evaluated by Stukel and Rigo[186] and is shown in Fig. 36 based upon actual power consumption data. Since all devices are less than 0.1% efficient on a Second Law basis, it is clear that no fundamental barrier exists to greatly improving separator performance.

*There is, in general, a second term in Eq. 64 which is important for gaseous pollutant separation but can usually be ignored for particulate separation.

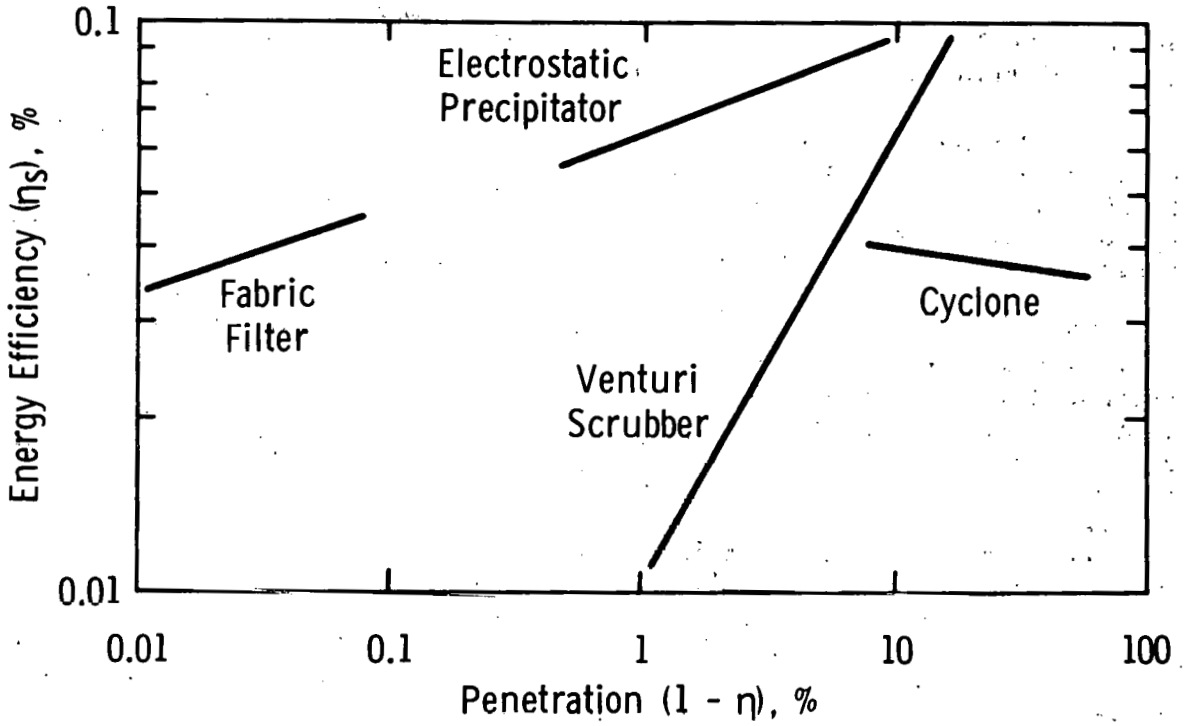


Fig. 36. Second Law Efficiency for the Four Most-Common Collectors (based upon the work of Ref. 186)

PART IV PARTICULATE AGGLOMERATION AT HIGH TEMPERATURE AND PRESSURE

GENERAL CONSIDERATIONS OF PARTICULATE CONDITIONING

Agglomeration* is but one aspect of the general subject of particulate conditioning. Conditioning is a pertinent consideration for the collection steps (for example, agglomeration, precipitation and removal) that involve high concentrations of particulate (since in such steps,) interparticle and particle-surface interactions are predominant. These processes are governed by short-range mechanisms and can be substantially affected by modifications of particulate properties.

One example of conditioning is the use of a seed material to control the resistivity of a particulate to be subjected to electrostatic precipitation. The general subject of adhesion treatment--the securing of the precipitate until it is ready to be removed--also falls within this area. In addition to standard texts on colloid chemistry that detail the influence of particulate properties upon aerosol behavior, a number of specialized references exist that are relevant to collect.[187-189] The complexity of the short-range mechanisms that are known to exist can be appreciated from Table 11.

The motivation for promoting agglomeration can be seen by examining the various drift velocity relations developed in Part III. In general, $\tilde{V}_n$ increases with increasing $\tilde{d}$, and usually be the second power. Agglomeration occurs inadvertently in many collectors. Cyclones, for instance, are known to demonstrate increasing efficiency with increasing particulate inlet concentration. This is due to large particulate experiencing a higher separating force† than does small particulate, yielding a larger drift velocity. As a result, large particulate overtakes and impacts the small particles en route to the outer wall. This effect will be more pronounced with highly polydisperse aerosols. In granular beds, the flow field is such that a significant relative motion exists between the large and small particulate, which results in a natural agglomeration.

The general objective of agglomerating techniques is to enhance the natural tendency of polydisperse particulate to self-impact. Schemes to accomplish this can be developed as a pretreatment step, prior to the collector or *in situ*. These techniques can be put into five general categories which are described in the next section.

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*The synonymous term "coagulation" is used by many authors (especially chemists).

†$F_n \sim \tilde{d}^3$ and $F_D \sim \tilde{d}^2$ so that $F_n/F_D \sim \tilde{d}$, where F_n is the centrifugal force and F_D is the Stokes drag.

Table 11. Short-Range Binding Mechanisms[189] (reprinted from W. B. Pietsch, J. Eng. Ind. *91*(2), 435-449 (May 1969)

I Solid bridges
  1 Mineral bridges
  2 Chemical reaction
  3 Partial melting
  4 Hardening binders
  5 (a) Crystallization of dissolved substances
    (b) Deposition of suspended colloidal particles
II Adhesion and cohesion forces in not freely movable binders
  1 Highly viscous binders, adhesives
  2 Adsorption layers (below ca. 30-50 Å thickness)
III Interfacial forces and capillary pressure at freely movable liquid surfaces
  1 Liquid bridges
  2 Capillary forces at the surface of aggregates filled with liquid
IV Attraction forces between solid particles
  1 Molecular forces: Van-der Waals forces, Chemical binding forces (Valence forces)
  2 Electrostatic forces
  3 Magnetic forces
V Interlocking bonds

PARTICULATE AGGLOMERATION TECHNIQUES

Brownian Agglomeration

As a result of Brownian motion, particles collide and agglomerate. For the Smoluchowski model[2] of a monodisperse, continuously honogeneous aerosol

$$\dot{N} = -K_o N^{2/2} \tag{66a}$$

where N is the number of particles (aggregates) and K_o is the agglomeration constant

$$K_o = 2\pi\tilde{d}D^* \tag{66b}$$

where D^* is the diffusivity

$$D^* \simeq k\, C_C T/3\pi\mu\tilde{d} \tag{66c}$$

where K is the Boltzmann constant and C_C the Cunningham correction factor. Eliminating K_o and D^* yields

$$\dot{N} = -(kC_C/\mu)TN^2 \tag{67}$$

Since C_C increases with increasing T and decreasing P and $\tilde{d}$, and $\mu \sim T^{2/3}$, Eq. 67 indicates that Brownian agglomeration will be most effective for small, populous particulate in a high-temperature, low-pressure medium. For the general case of a polydisperse, nonhomogenous aerosol, the result is a nonlinear integro-differential equation for which no general solution exists.

Because the agglomeration rate is most strongly dependent upon the particulate number density, it is not possible to readily enhance this rate by conditioning techniques. For the case of hydrosols (*e.g.*, locophobic colloidal solutions), however, there exists the "zeta potential" (the electrical double layer) which may be overcome by the use of floccolating agents and thus render appreciable assistance to Brownian motion. For aerosols, no such enhancement is possible since no such inhibition exists.

Turbulent Agglomeration

On a scale larger than Brownian motion, turbulence causes random particulate motions and therefore agglomeration. the scale of turbulent eddies usually present in a flow varies--from scales on the order of the dimensions of the flow passage (for which viscous effects are small) down to very small eddies (for which the viscous effects are dominant). The large-scale eddies tend primarily to create stratification (since these motions are, in effect, local centripetal acceleration fields) and agglomeration is a secondary effect. Turbulent agglomeration occurs primarily as a result of the small or microscale motion.

This subject has been discussed by Fuchs;[82] analytical models[190] and data[191] (for $\tilde{d}$ larger than the microscale of turbulence) have been developed and the implications upon particulate collection surveyed.[60] Turbulence has been found to be only effective in agglomerating particulate larger than ca. 0.2 μm. Also, estimates of the energy required to grow a 0.5-μm particle to ca. 2-3 μm are discouraging: on the order of 1 kW/m^3 (40 hp/1000 ft^3) for a process that takes one minute.[60] The effect of high temperature and high pressure is primarily through a change in the flow Reynolds number (Eq. 41) as the data for the coagulation constant[191] can be approximately correlated by $K \sim Re^a$ where $a \simeq 2$ for particulate ca. 0.3-0.8 μm. Thus, the influence of hot gas conditions is a favorable one in comparison to conventional collection conditions.

Generalization of the agglomerating characteristics of large-scale turbulence is much more difficult since the flow field is strongly dependent on the particular geometry employed. The idea of using large-scale eddy motions to agglomerate particulate is not new: a rotary "screw agglomerator" was suggested in 1957.[192] The baffle array invented by Rigo[172] (Fig. 31) makes use of a turbulent eddy to trap and agglomerate particles. Insofar as is known, this technique has received very little attention despite its promise.

Electro/Magnetic Agglomeration

Electromagnetic force can be used to agglomerate particulate in two ways: by using this effect to provide an interparticle force (*e.g.*, electrically charged particles or electrical/magnetic dipoles) or by imposing an external oscillatory field upon charged or magnetic particles. The former concept has received the most attention[60,80] although the latter ("directed"

coagulation) has also been noted.[193,194]

The effect of high temperature and pressure upon the theoretical agglomeration rate for bipolar-charged particles is very complex, although it has been estimated to increase approximately with the square root of absolute temperature.[66]

Acoustic Agglomeration

The agglomerating influence of an acoustic field has been known for 100 yr and has undergone a remarkable history of development: cycles from wild enthusiasm to complete disdain. This subject is discussed in detail in a later section.

Scrubbing/Condensation Agglomeration

Introduction of additional particles, either by injection (scrubbing) or by a phase change (condensation), is not, strictly speaking, agglomeration but particle growth--a distinction which is not pressed further. Scrubbing via water droplet injection is a very popular technique for conventional collection environments because it has a high efficiency, even with small particulate (Fig. 35), but it is of course unsuitable for the hot-gas environment. Likewise unsuitable is agglomeration by the condensation of water around particulate acting as nuclei.

Scrubbing can only be accomplished by using a substance which is molten at ca. 1000°C, such as a metal or a salt. Battelle Northwest is pursuing molten salt scrubbing with ERDA support[74] in a geometry very similar to a conventional venturi scrubber. The peculiar advantage of this technique would be its application to a high-sulfur aerosols since the scrubbing action of an alkali carbonate readily removes SO_2[195], in addition to causing particle growth. The disadvantage for turbine applications is that salt mist not removed would potentially have a corrosive action. Battelle has provided sapphire filters manufactured by Alcoa to ensure complete demisting.[61]

IGT is apparently developing a molten metal scrubber which is intended to provide H_2S removal in addition to agglomeration.[67] No other work in this area is known.

A SURVEY OF ACOUSTIC AGGLOMERATION

Basic Concepts

The essential objective of acoustic agglomeration* (AA) is the growth of particles which are ca. 0.5 μm (too large to be affected by Brownian motion) to ca. 10 μm in diameter so that they may be separated by inexpensive cyclonic devices. Thus, the mean particle size must increase by a factor of about 20, which requires that the particulate concentration must decrease by four orders

*A dazzling array of names have appeared in the literature for this phenomenon: permutations of acoustic, sonic, ultrasonic, and supersonic with agglomeration, coagulation, and flocculation.

of magnitude. Although the agglomerating process is exceedingly complex, the rate of increase can be approximated by equations of the type for the Smoluchowski model (Eq. 66a) -- which illustrates the extreme sensitivity of the agglomeration rate to the instantaneous concentration. This circumstance suggests that this technique will become exponentially more costly as N decreases in order to maintain the agglomerating rate at acceptable values.

Six parameters have been found to be of primary importance: the frequency (f) and intensity (J) of the acoustic field, the concentration ($\hat{\rho}$), the relative particulate density ($\tilde{\rho}/\rho$), the particulate diameter ($\tilde{d}$), and the physical properties of the particulate matter itself.

The acoustic fields which have been studied originate from a variety of sources: fluid generators (whistles or sirens), mechanical piston-generators, or electrical piston-generators (piezoelectric, magnetostrictive, or electromagnetic). Both standing-wave and travelling-wave fields have been examined. Frequencies and field intensities have varied from 500 to 30 000 Hz and from 135 to greater than 170 dB, respectively.

Literature Surveys

Because the subject of AA is relatively old and the interest in it widespread, a large number of surveys of the basic principles of acoustical fluid mechanics relevant to agglomeration and summaries of specific applications have appeared. Table 12 presents a summary of these surveys.

Table 12. Summary of Surveys on Acoustic Agglomeration (AA)

Authors	Year	Ref. (pages)
D. Sinclair	1950	196 (pp. 72-76)
H. Johnstone *et al.*	1956	197 (p. 13-71)
A. C. Stern *et al.*	1956	110 (pp. 47-48)
C. E. Lucas	1963	85 (p. 18-88, p. 20-96)
G. Nonhebel	1964	183 (p. 718)
H. L. Green & W. R. Lane	1964	87 (pp. 170-186, 333)
N. A. Fuchs	1964	82 (pp. 80-95, 315-319)
E. P. Mednikov	1965	198 (180 pp.)
G. Zebel	1966	193 (pp. 52-55)
W. Strauss	1966	83 (pp. 402-416)
N. A. Fuchs	1968	199 (pp. 27-37, 41, 127-128)
H. L. Shirokova	1973	200 (pp. 476-539)
L. J. Shannon	1974	60 (pp. 23-24, 51, 89-92)
A. K. Rao *et al.*	1975	66 (pp. 42-43)
R. Hegarty & L. Shannon	1976	201 (45 pp.)

The total literature of AA exceeds 500 references, with the majority of the papers being of Soviet origin (especially since 1950). The principal survey work is that of Evgenii Mednikov,[198] which was originally published in Russian in 1963. This book includes more than 300 references on AA.

A Historical Synopsis

In 1866, Kundt[202] observed that particulate spheres, placed in a tube with an imposed standing wave, migrated toward the nodes and agglomerated. König,[203] in 1891, analyzed the hydrodynamic forces between two spheres in a vibrating medium and showed that they attract one another when their line of centers is perpendicular to the vibration vector and repel when it is parallel to the vector. These observations remained relatively unnoticed until the Patterson and Cawood paper[204] in 1931, which showed how a sound field could be used to create aggregates which then readily precipitated. This paper sparked worldwide interest: Andrade in England, Brandt-Freund-Hideman in Germany (who later obtained several German and British patents in 1936 and 1937), and Amy in the U.S. who, in the same year, demonstrated an acoustic system that could disperse fogs (for which he later received a U.S. patent [205]). The Metallurgical Division of the Bureau of Mines (H. W. St. Clair) began to work on a "sonic flocculator" and gave a demonstration at the 1937 annual meeting of the AIMetE in New York. In 1940, several additional U.S. patents were issued.[206,207]

In this early period, the principal difficulty was associated with the poor efficiency of the acoustic generators then available. During WW-II, when the potential military applications of fog dispersion became apparent, an intense effort was initiated to develop a high-energy/high-efficiency siren. The result was a "victory" siren manufactured by Chrysler Corp. which had a 37 kW radiation power at an efficiency of 70-90%.[208] Experiments on fog dispersion were performed at Columbia University, and later (1943) a field test was performed at Lunken Field, the Cincinnati, Ohio, airport. At calm conditions, four victory sirens were able to double the visibility in about one minute.

During the postwar period, Ultrasonics Corp. developed a siren agglomerating chamber (150+ dB at 3-5 kHz), which was used in series with a large-diameter cyclone as a collection system.[209-211] The first commercial installation (in 1948) was for the collection of a soda ash fume at a paper mill in Maine. Later installations were completed for sulfuric acid fog (1949) and furnace black (1950). Although environmental problems were associated with the intense sound levels needed (problems which ultimately led to the dismantling of at least one installation[85]), these systems were competitive with electrostatic precipitators. Although they were not as efficient, acoustic-agglomerator systems cost approximately 20% less (Ref. 85, pp. 20-96) and required a modest amount of power: ca. 4-11 kW per m^3/s of gas to be treated.[209,212]

By 1952, the electrostatic precipitator had won the performance/cost war, and interest in acoustic agglomerators waned to virtually nil in the U.S. At the same time, however, intense interest was generated in the Soviet Union (lamp black, ZnO_2, drilling dust, etc.), Hungary (cementation furnace gases), Poland (metallurgical furnaces), Japan (cracking gas purification), and a number of other countries. This foreign interest has continued to the present. As a result, the U.S. has been left behind in both developing this technology and maintaining the requisite scientific interest. Table 13 summarizes many of the commercial applications of AA and is based on the work of Mednikov.[198]

Table 13. Summary of Acoustic Agglomeration Experience
(from Ref. 201, based upon Ref. 198)

	Aerosol and Gas Stream Properties				Agglomeration Chamber					Collector System		
Aerosol Type	Particle Radius r (μm)	Conc. by Weight (g/m^3)	Temp. (t, °C)	Vol. Treated (Q, m^3/hr)	Type, Dimensions ($D_c \times H_c$, m)	Type of Siren	Freq. f (kc/sec)	Intens. J (w/cm^2)	Length of Sonic Treatment t_o (sec)	Type	Percentage Removed Without Sound η_n (%)	Percentage Removed With Sound η_{si} (%)
Gas furnace black	0.03-0.07	1.2-12.6	40	1,700-2,000	Exp. direct flow 1.1 dia. × 6.6	Dynamic, radial	4	0.5-1.0	4.5	Two cyclones 1.3 in dia. (in series)	40	83-90
Gas furnace black	0.03-0.07	1.2-2.1	40	1,700-2,000	The same, with water addition	The same	2-4	0.5-1.0	1.2	The same	8-32	99
Aggregated gas black	0.5-15	0.5-2.5	--	600	Exp. reverse flow with water 0.5 dia.	Dynamic, axial	3	0.1	10	One or four cyclones (in parallel)	68-72	95
Atomized carbon black	0.1-0.2	26	82	45	Exp., rising stream 0.29 dia. × 1.9	Static with pump-off	4.6	1.0	7	Two cyclones and a glass cloth filter (in series)	(30)[a]	99.98 (97)[a]
Hard coal black	0.5-1.0	0.5-2.4	80-90	90-100	Exp., reverse, flow, 0.2 dia. × 2.5	Dynamic, axial	3.6	0.10-0.14	3-4	Cyclone 0.15 m dia.	68-74 (81)[b]	87 (97)[b]
Sulfuric acid fog	0.5-5.0	5-40	180	1,700	The same, 0.6 dia. × 6	The same	2.15	0.1	3	Multicyclones (in parallel)	84	99.6-99.9
Natural sulfuric acid fog	0.25-2.5	1	50	40,000	Indust., composite flow, 2.4 dia. × 10.5 (2 sets)	Dynamic, radial	2.25	0.1	4	Two cyclones (in parallel)	--	90
Dilute sulfuric acid fog	2.5-50, predominant 7.5	0.5-1.2	20	1,800	Exp., reverse flow, 0.64 dia. × 11	Dynamic, axial	1-2	0.1	7	Four cyclones (in parallel)	69-72	78-82

Table 13. (contd)

Aerosol Type	Aerosol and Gas Stream Properties: Particle Radius r (μm)	Conc. by Weight (g/m^3)	Temp. (t, °C)	Vol. Treated (Q, m^3/hr)	Agglomeration Chamber: Type, Dimensions ($D_c \times E_c$, m)	Type of Siren	Freq. f (kc/sec)	Intens. J (w/cm^2)	Length of Sonic Treatment t_o (sec)	Collector System: Type	Percentage Removed Without Sound η_n (%)	Percentage Removed With Sound η_{si} (%)
Zinc oxide sublimate from roasting zinc ore	0.5-5.0, predominant 2.5	1-2	40-100	1,600	Exp., reverse flow, 0.75 dia. × 10	Dynamic, axial	3-3.5	0.1	10	Cyclone	84-87	94-98
Zinc oxide sublimate from copper smelting	0.5-4.0	0.5-20	50-350	1,300-2,160	The same, 1.0 dia. × 9	Dynamic, radial	3-9	0.12	10	Cyclone 1.35 m dia.	70	90-95
Zinc oxide sublimate from brass melting	0.4-0.6	10	400	?,000	The same, 0.7 dia. × 10	Dynamic, axial	0.7	0.6	2.5	Cyclone 0.15-0.3 m dia. and filters (in series)	--	99.8
Coke gas (tar)	0.5-5.0, predominant 2.5	30-70	40-60	1,300-2,100	The same, 0.5-0.64 dia. × 9	The same	4	0.2	5-8.5	Two cyclones (in parallel)	88	99-99.8
Cracking gas (condensate)	0.5-5.0	5-70	35	1,200	The same, 0.5 dia. × 9	The same	4	0.1	5	The same	76-82	97.5-99.3
Cracking gas (condensate)	0.5-5.0, predominant 3.0-3.5	6-15	40	12,000	Indust., reverse flow, 1.6 dia. × 11 (2 sets)	The same	3.5	0.1	6	Two Pelouze tar extractors (in parallel)	73	95
Open-hearth furnace smoke	2.5 (55%)	2	150	5,000	Exp., reverse flow with water addition	Dynamic	2.2	—	--	Wet type W rotoclone	45	90.7

Table 13. (contd)

	Aerosol and Gas Stream Properties				Agglomeration					Collector System		
Aerosol Type	Particle Radius r (μm)	Conc. by Weight (g/m^3)	Temp. (t, °C)	Vol. Treated (Q, m^3/hr)	Type, Dimensions ($D_c \times H_c$, m)	Type of Siren	Freq. f (kc/sec)	Intens. J (w/cm^2)	Length of Sonic Treatment t_o (sec)	Type	Percentage Removed Without Sound η_n (%)	Percentage Removed With Sound η_{si} (%)
Carbide furnace smoke	0.5-15, predominant 0.5	0.25-2.8	120	500	Exp., reverse flow	Static	7-10	--	4-6	Multi-cyclones (in parallel)	11	94
Carbide furnace smoke	The same	0.25-2.8	120	500	The same, with water addition (5 g/m^3)	Static	10.5	--	4.6	The same	--	86

[a]Result without cloth filter, in parentheses.

[b]Result from water addition, in parentheses.

Several observations should be made regarding the premature demise of AA. First, because the aerosol mechanics of AA were poorly understood,* the designs originally developed for commercial application did not in any sense represent optimum configurations. This point is very important since the aggregates formed by this process tend to be very delicate: "Turbulence, in an intense sound field, breaks up the larger aggregates. Aggregates formed during ultrasonic coagulation are generally not very strong and often crumble on deposition. Break-up of aggregates is the reason for the ineffectiveness of ultrasonics for removing fly ash." (Ref. 82, p. 317). In addition, these devices were applied to relatively fine aerosols, using moderate and low efficiency cyclones which demand a large particle growth factor for the AA conditioning stage. Finally, although the electrostatic precipitator has a history of demonstrated superiority (with the above two points noted), there are a number of settings for which it is poorly suited: very high-temperature environments, combustible particulate (explosion hazard), corrosive atmospheres, particulate resistivity outside an acceptable band, etc. For these circumstances, the cost-effective method might be AA.

Research Activity Since 1970

In 1970, Braxton Corp.† announced[213] the development of a prototype AA -- the "Alternating Velocity Precipitator" (AVP) -- capable of handling 7 m^3/s and using a very low frequency sound field (400 Hz) driven by an electromagnetic piston. The agglomerating chamber is 75 cm in diameter and 4.3 m high (adjustable to provide 4.5 wavelengths) and has a provision for ingestion of water and/or steam to assist the agglomerating process. A series of patents were secured for the concept and several of its components.[215-218] The very low frequency field has attracted theoretical analyses by S. Tsai of Northeastern University.[219,220] In 1974, the U.S. EPA contracted with the GCA Corp. to formally test this prototype AA in what was called a field evaluation.[221] Nineteen test runs were performed at flow rates of 2.2 to 3.7 m^3/s and inlet concentrations of 0.9 to 6 g/m^3 at sound power levels of 2.3 to 3.6 kW with various combinations of sound plus water and/or plus steam (but never with sound only). The results showed only a small improvement with the use of steam; the influence of water injection was almost as significant as the use of sound. Although the system efficiency was higher with sound and water than when the system was operating as a simple high-efficiency cyclone, the results were disappointing in view of the complexity of the process. One test which was run without sound, water, or steam gave an indication of at least one shortcoming of the system: the particulate distribution was appreciably shifted to smaller sizes as a result of flowing through the system--*i.e.*, the device is so highly turbulent that it acts as a deagglomerator. Since this study was done, there has been essentially no new development work

*Although it should be noted that aerosol mechanics remains an enigma to this day -- in part because of the complexity of the governing equations and in part because of the data: "Experimental data on ultrasonic coagulation of aerosols are for the most part of no use for comparing with theory since they have usually been obtained for polydisperse aerosols of unknown particle size and concentration." (Ref. 82, p. 316).

†This organization began in 1964. Caperton Braxton Horsley, who was formerly associated with the Ultrasonics Corp., was one of its principals.[214]

by Braxton Corp., and the prototype AVP at Bedford, Mass., remains the only installation.[214]

In addition to Braxton Corp., only two other organizations are known to advertise the availability of AA: American Van Tongeren Corp. of Columbus, Ohio, and Beltran Assoc. of Brooklyn, NY.[222]

Prof. D. S. Scott of the University of Toronto has examined AA in a series of papers[223-229] with the support of the Ontario Research Foundation and the National Research Council of Canada. In a recent paper,[229] he advocated new sound field concepts: progressive saw-tooth waves and pulse-jet generation. A prototype research facility is being constructed at the Ontario Research Foundation.

The concept of using an acoustic field to augment filtration has been pursued by Prof. J. M. Beeckmans of the University of Western Ontario.[180-182] The aerosol being examined is of sufficiently low concentration that agglomeration does not occur upstream from the filter and so this concept represents augmented collection rather than AA.

The U.S. EPA has sponsored several studies at the Midwest Research Institute (MRI) on fines collection[60] and high-temperature collection[66] which have included reviews of the AA concept. Recently, MRI completed[201] an evaluation of AA and concluded that the energy requirements are prohibitive: at 165 dB (3.2 W/cm^2) for growth ratios of 20 in 5 sec, 8.2 kW per m^3/s would be needed. In comparison, typical high-efficiency fibrous collectors require 1.6 to 32 kW per m^3/s. What must be noted, however, is that the possibility exists that only a small improvement in cyclone performance may be required to meet performance specifications (*e.g.*, EPA New Source Standards, turbine manufacturer specifications, etc.); just a small change in particulate diameter (perhaps by a factor of 2 to 5) may provide the needed impetus.* Also, for high-temperature applications, the energy requirements associated with alternative solutions(granular beds, silica fibers, etc.) may also be very high and even when 8.2 kW is added to the energy needs of a cyclone, the result may still be competitive.

EPRI is supporting a program at SUNY-Buffalo (Prof. Shar[214]) -- RP 539 -- that will examine the use of an acoustic field in concert with an electrostatic precipitator. No other activities are known to be currently receiving sponsored support in the U.S. Computer searches of Engineering Index and NTIS data bases on the subject of AA (and all its permutations) yielded, in addition to the literature already cited, one Harvard study[230] and Soviet papers.[231-234]

Agglomerating Mechanisms and Data

That an acoustic field is capable of causing particulate agglomeration is a well-established and widely accepted fact. How the agglomeration process takes place, *i.e.*, the mechanism(s) of AA, remains an engima despite

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*The Impaction number is dependent upon the square of $\tilde{d}$, and so this amount of growth will cause Im to increase by a factor of 4 to 25. The net impact on collection efficiency can not be determined a priori since general functional forms of η(Im) are not known.

four decades of research:

> "The exact interrelation of these mechanisms of sonic agglomeration has not been found ..." (Ref. 83, p. 408)
>
> "Very little progress has been made in the past few years in understanding sonic coagulation." (Ref. 82, p. 318)
>
> "A completely satisfactory theory of acoustic coagulation, which will account quantitatively for the manner in which vibration and acoustic forces increase the rate of collision of particles, has yet to be developed." (Ref. 87, p. 172)
>
> "Although the acoustic coagulation of aerosols enjoy widespread applications in industry, the theory of the process has still not been fully developed." (Ref. 200, p. 535)

Agglomeration is known to occur for all degrees of dispersion (more to highly polydisperse), with both liquid and solid-phase particulate yielding aggregates comprising several thousand particles.[87] The rate of agglomeration generally diminishes rapidly with increasing time and/or decreasing particulate concentration. More than ten separate agglomerating mechanisms have been suggested in the literature which occur in one of two basic modes: "distributed" and "local" agglomeration.

Distributed agglomeration occurs as a result of enhanced particulate relative motion, throughout the flow field, much in the manner of Brownian motion, whereas local agglomeration is caused by localized stratification of the particulate phase as a result of the acoustic field creating a region of relatively small interparticle spacing that allows the short-range forces to form aggregates. The problem is sufficiently complex that not only is "the" mechanism not known, it probably does not exist since AA occurs in a diverse variety of ways, depending upon the nature of the aerosol, the acoustic field, the flow geometry, etc. Thus, the conclusions of particular study may be seemingly contradicted by other experiments, whereas it is entirely possible that both sets of data are equally valid and are depicting different dominant mechanisms under different circumstances. The dependence of AA upon acoustic frequency is an example of this situation; some investigators have concluded that it is an important parameter while others have concluded that it is not, and it appears that both groups are correct.

It is intended that this section briefly survey the various mechanisms of AA that have been propounded in order that the data may be analyzed within some analytical framework.

Orthokinetic Vibration was proposed as the AA mechanism for polydisperse aerosols by Brandt, Freund, and Hidemann in the mid-1930's. Since each particle possesses a unique diameter ($\tilde{d}$) and density ($\tilde{\rho}$), it responds to a changing flow field at a characteristic rate: namely, the relaxation time ($\tilde{\tau}$) developed in Eq. 37. In an acoustic field, the particles with short relaxation times closely follow the vibrational motion of the medium (*i.e.*, viscous-dominated regime) while those with a large $\tilde{\tau}$ remain almost stationary with respect to the mean flow (the inertial regime). Thus, the action of acoustic wave to an observer stationed on a large $\tilde{\tau}$ particle is

to cause the vibrational motion of smaller $\tilde{\tau}$ particles in a surrounding envelope. Within an "aggregation volume," the particles with small time constants approach near enough to a parent particle of large $\tilde{\tau}$ that the short-range forces result in a capture and the creation of a particle of still larger relaxation time. Since this mechanism of AA is probably the most significant, the governing equations will be developed in detail.

The general solution for particulate oscillation in a medium of appreciable inertia has been developed by Fuchs.[82] For a comparison of this result with that obtained by neglecting the mass of the medium, Fuchs has shown that the error is negligibly small. Equating the acceleration of a single, spherical particle to the Stokes drag force and making use of the inertia-less medium approximation yields

$$\frac{\pi}{6}\tilde{\rho}\tilde{d}^3 \frac{\tilde{dV}}{dt} = 3\pi\tilde{d}\mu(V_o - \tilde{V}) \tag{68a}$$

where V is the vibrational velocity of the medium and can be expressed as

$$V = V_o \sin(\omega t) \tag{68b}$$

This equation of motion is restricted to the low Reynolds number/low Knudsen number flow regime, *i.e.*,

$$\tilde{Re} \equiv (V_o - \tilde{V})\ \tilde{d}/\nu \quad \tilde{<} 2 \tag{69a}$$

$$Kn \equiv 2\lambda/\tilde{d} \quad \tilde{<} 0.1 \tag{69b}$$

since the simple Stokes law has been presumed.

Rearranging Eq. 68a yields

$$\tau \frac{d(\tilde{V}/V_o)}{dt} = \sin(\omega t) - (V/V_o) \tag{70a}$$

where

$$\tau \equiv \tilde{\rho}\ \tilde{d}^2/18\mu \tag{70b}$$

The general solution of this first-order differential equation is given by the sum of two terms, one representing the transient effect and one the steady state condition

$$\frac{\tilde{V}}{V_o} = \frac{(\omega\tau)e^{-t/\tau}}{1 + (\omega\tau)^2} + \frac{\sin(\omega\tau - \phi)}{\sqrt{1 + (\omega\tau)^2}} \tag{71a}$$

where the phase angle ϕ is given by

$$\tan\phi = \omega\tau \tag{71b}$$

Since the time constant of those particles satisfying Eq. 69a is very small, the transient term can be justifiably ignored. It is clear, then, that the particulate motion can be expressed as

$$A^* \equiv \frac{\tilde{X}_o}{X_o} = \frac{\tilde{V}_o}{V_o} = \frac{1}{\sqrt{1+\omega^2\tau}} \qquad (72a)$$

where

$$\tilde{V} = \tilde{V}_o \sin(\omega t - \phi) \qquad (72b)$$

$$\tilde{X} = \frac{d\tilde{V}}{dt} \qquad (72c)$$

The nondimensional ratio of the modules of the particulate motion to the medium motion, namely, A^*, is known as the entrainment coefficient and varies from zero to unity as a function of the product $\omega\tau$.

The significance of Eq. 72 is that for a flow field with a single imposed vibrational frequency, the particulate dispersion will vibrate at characteristic values of A^* as governed by the time constants of each particle. The very large $\tilde{\tau}$ particles will remain essentially motionless, whereas the very small τ particles will vibrate essentially with the medium. Thus, significant relative motion is established between the various-sized* particulate and hence contact and agglomeration can be expected to occur. In addition to a distribution of relative maximum vibrations, AA also causes the particulate to undergo periodic motion at various phases, as governed by Eq. 71b.

At 1000°C, particulate of specific gravity 2.85 g/cm^2 (dolomite) has time constants given by the following expression:

$$\tau(s) = 3.30 \times 10^{-6} [\tilde{d}^2(\mu m)]^2 \qquad (73)$$

Since the acoustic frequency is simply ω divided by 2π, Eqs. 72 and 73 can be expressed as

$$f(Hz) = 4.82 \times 10^4 \sqrt{1/A^{*2}-1} \; / \; [\tilde{d}(\mu m)]^2 \qquad (75)$$

for the hot-gas condition. This equation is depicted in Fig. 37 for two values of the entrainment coefficient: 0.10 and 0.90. The significance of this graph can be seen by examining the influence of a 10-kHz acoustic field on a highly disperse aerosol (*e.g.*, 0.1 to >300 μm particulate) such as would be produced by fluidized-bed combustion: all particulate larger than ca 15 μm will be essentially stationary with respect to the vibrating

*Since the time constant expression involves particulate density, even a monodisperse aerosol can agglomerate by this mechanism provided it is nonhomogeneous.

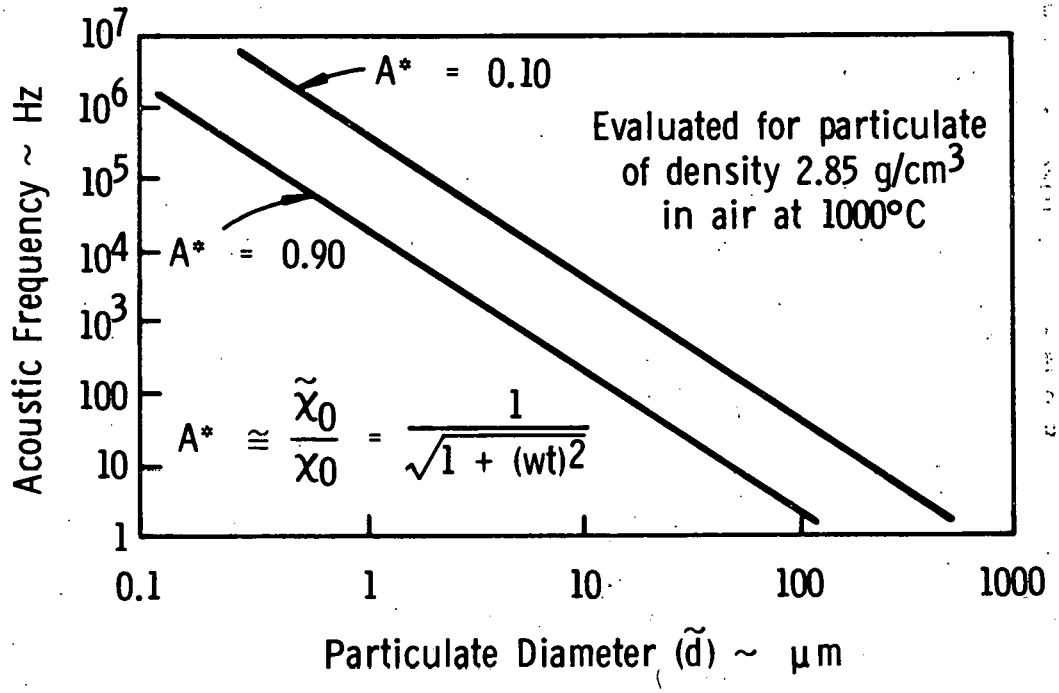

Fig. 37. Acoustic Frequency as a Function of Particulate Diameter for Two Entrainment Coefficients for Dolomite Particulate in 1000°C Air.

medium whereas all particulate smaller than ca. 2 μm will be vibrating essentially with the medium. Hence, for this frequency, particulate on the order of 10 μm and larger can be considered as stationary parents which act as agglomeration sites for particulate of the order of 1 μm and smaller. In fact, all particles are vibrating to some degree and at different phase angles -- as a consequence of Eq. 71b--but the highly desirable phenomenon of growing small, difficult-to-collect particles onto the large particles present can clearly be expected to occur.

Because high-frequency acoustic fields attenuate rapidly, it is probably impractical to attempt to maintain a standing wave in a large agglomerating vessel at frequencies in the kHz range. It is possible, however, to use a progressive wave field such that the aerosol is originally subjected to a high frequency field which acts to agglomerate submicron particulate into the transmicron range. Then, by providing a lower frequency field, the same high entrainment coefficient can be maintained for the continued efficient agglomeration of the now larger particulate. As the small-size particulate reaches the 10 μm range, the optimum acoustic frequency for agglomeration decreases to less than ca. 1000 Hz. One concept utilizing such a frequency variation has been recently proposed by Scott.[229]

Several important second-order effects regarding the succeeding analysis have been developed by Mednikov:[198] the flow-around factor (α_1) and the phase-difference factor (α_2). Both of these corrections have the effect of decreasing the aggregation volume of an agglomeration pair.

In addition to orthokinetic vibration, numerous additional mechanisms or phenomena have been proposed as significantly affecting the agglomerating characteristics. Since the essential role of these additional effects appears to be that of enhancing or inhibiting the primary mechanism of orthokinesis, they will be treated only briefly.

Radiation Pressure. An acoustic wave impinging upon a particle will result in reflection, scattering, absorption, and diffraction, causing a net transfer of energy (momentum) from the wave system to the particulate phase. For a traveling wave, this results in the particulate experiencing a relative force with respect to the medium in the direction of the wave motion; for a standing wave, this force acts to establish a drift velocity toward the nodes and antinodes. (The radiation as pressure vanishes at both the nodes and antinodes, although only at the latter location is it possible for the particulate to stably congregate.) This mechanism was first proposed by King in 1934[235] to explain the observed clouds by Kundt in 1866[202] which formed at the antinodes when a standing acoustic wave was imposed on a nonflowing aerosol in a tube. St. Clair,[236] who did much of the early work on AA in the U.S., was a strong proponent of this mechanism. As a result of his analysis, he was able to calculate a decrease in particulate concentration at the nodes and a corresponding increase at the antinodes purely as a result of radiation pressure.

Hydrodynamic Attraction/Repulsion. For particles of relatively long relaxation time with respect to the acoustic period, the effect of the oscillating medium is to establish a relative velocity parallel to the direction of the vibration vector. For a particulate system aligned perpendicular to this vector, the relative medium velocity causes the spherical particles to be attracted to one another as a result of the increased medium velocity and, therefore decreased fluid pressure, between the spheres. Conversely, for a particle system aligned parallel to the vibration vector, this effect causes a relative repulsion. This mechanism was originally postulated by König in 1891[203] as an explanation of the dust figures in Kundt's tube and is often referred to in the literature as the Bernoulli force.

Parakinetic Attraction. If the Reynolds number of relative velocity of the medium with respect to the particulate is larger than one (which can readily occur for high acoustic intensities and/or large particulate), it is known that streamline asymmetry occurs fore-aft of each particle. As a result of this asymmetry in the streamline field, short-relaxation-time particulate, which cycles back and forth in the vicinity of long time particles, finds itself on different streamlines after each cycle. Such a hysteretic motion will cause small particles originally within a narrow band above and below a stationary particle (for a horizontal vibration vector) to drift toward that particle regardless of its initial horizontal position, whereas particles initially outside this narrow band will experience a net drift away from the stationary particle.

Wake Attraction. For the large Reynolds number condition, the velocity field as well as the streamline field is asymmetrical. Two particles of similar but unequal relaxation time then alternately experience each other's wake. Because of the velocity deficit in the wake, this cyclic action causes the trailing particle to approach the lending particle during each

cycle, although this effect is resisted to a degree by the hydrodynamic repulsion force noted above.

Stokes Force. Since the Stokes drag force relation involves the medium viscosity to the first power, this force will vary with the temperature of the medium. Since any turbulent velocity field evidences a temperature turbulence field (even if the system is adiabatic), there will be a periodicity to the Stokes drag force. This effect can be compounded if the agglomerating process takes place in a diathermal environment.

Acoustic Streaming. This phenomenon occurs as a result of the acoustic field interacting with solid obstacles, which causes recirculation motions of the common, gross variety around the entire obstacle, as well as very minute motions within the boundary layer itself (microstreaming). Shirokova[200] has postulated that the microstreaming which occurs when an acoustic wave strikes the particulate phase explains why she observed that particles within a prescribed capture solid angle were attracted to a reference particle while those outside this angle were repelled.

Turbulence Inception. Since turbulence causes relative microscale motion between particles, in the manner of Brownian agglomeration, the augmentation of turbulence due to a high-intensity acoustic field can be expected to also increase the agglomeration rate.

Electrostatic Charge. It is well known that the particulate phase in an aerosol possesses various intensities of electrostatic charge even in the absence of an impressed potential. This charge arises in part because of the relative motion between the medium and the particle and can be an important factor in either assisting or opposing agglomeration and collection. Since an acoustic field enhances this relative motion, it is expected that the electrostatic charge effects will also be more important for AA.

Acoustic Agglomeration Kinetics

For highly polydisperse aerosols, the dominant effect causing agglomeration is orthokinetic vibration. The other mechanisms supplement this agglomeration process in two ways. First, they provide a means of refilling the emptied aggregation volume after each half-cycle of vibration by the small-size particulate phase. If this refilling did not occur, the agglomeration rate would decrease dramatically after the first cycle. Secondly, these supplemental mechanisms cause long-time-period gross motions of the entire particulate phase, resulting in nonhomogeneous distributions. One example of this effect is the tendency of particulate to stratify near the nodes in standing wave systems or to gradually follow the wave front in a traveling wave system.

The first, and most important, influence of these supplemental mechanisms has been portrayed by Shannon and Hegarty, as shown in Fig. 38.

In order to assess the kinetics of the entire process, a number of simplifications must be made. The entire influence of the refilling mechanisms will be contained in a single parameter, β, where it is defined as

$$\beta \equiv n_A/n \tag{76}$$

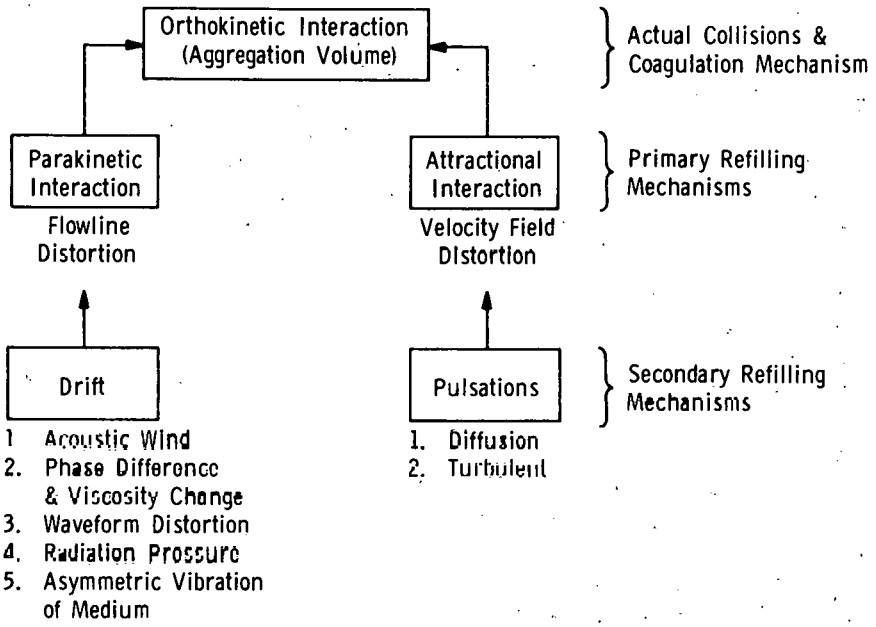

Fig. 38. An Illustration of the Hypothesized Relationships Among Various Acoustic Agglomeration Mechanisms (reproduced from Ref. 201).

where n_A is the number density of small size particles maintained within the aggregation volume of the parent particle and n is the ambient number density of the small size particulate outside this volume. Mednikov refers to this factor as the "filling coefficient," which may be considered a measure of the efficiency with which the various refilling mechanisms maintain the aggregation volume filled with the instantaneous ambient concentration of particulate to be agglomerated.

The kinetic equation of the agglomeration rate due to orthokinetic vibration may be assumed to be of the form

$$\frac{dn}{dt} = -K_A n^a \tag{77}$$

If the kinetics of this process were similar to Brownian agglomeration as governed by Eq. 66a, the exponent would be 2. However, since self-agglomeration is not the dominant mode (*i.e.*, small particles do not tend to agglomerate upon each other but onto large particles), it might be expected that the exponent would be unity as for a unimolecular chemical reaction

$$\frac{dn}{dt} = -K_A n \tag{78a}$$

$$\therefore \frac{n}{n_o} = \exp(-K_A t) \tag{78b}$$

where at t = 0, the number density is n_o. The available data tend to support this first order reaction model over a wide range in operating variables.

For instance, Mednikov (Ref. 198, p. 117) has, on the basis of data by Podoshevnikov,[235] found that

$$\frac{n}{n_o} = \exp[-0.08(pt) + 0.0002(pt)^2] \qquad (79)$$

for acoustic agglomeration of 0.28 μm dioctylphthalate fog droplets at 13 kHz where p is the sound pressure in kilobars and the time is given in seconds. For moderate values of (pt), the second order term may be justifiably neglected.

The functional form for the AA kinetic coefficient K_A may be inferred by observing that it represents the fraction of n particles present in small size that are captured in time dt and can be expressed as

$$K_a = (2f)\cdot(n_A Q_A)\cdot(N)/n \qquad (80)$$

where 2f represents the number of passes of the small particulate by the agglomerating centers in dt, $n_A Q_A$ represents the number of particles within the agglomerating volume, N represents the number density of stationary large phase particles, and n represents the number density of the small phase particles. By substituting Eq. 76 for the filling coefficient, this reduces to

$$K_A = 2f\beta\, Q_A N \qquad (81)$$

The agglomerating volume can be viewed as an approximate circular cylinder of cross-sectional area $\alpha_1 \pi \tilde{D}^2/4$ where $\tilde{D}$ is the diameter of the large-size particle and α_1 is a correction factor to reduce the area due to secondary effects (which Mednikov terms the capture coefficient) and a length $2\alpha_2 A_g$ where A_g is the maximum gas amplitude and α_2 is another correction factor which reduces the potential length of this volume due to phase shifts and other influences. The maximum gas amplitude may be expressed in terms of the frequency (f) and acoustic power density (J) by

$$A_g = \frac{1}{2\pi f}\,(2J/\rho c)^{1/2} \qquad (82)$$

where ρ and c are, respectively, the density and speed of sound in the medium.

Substituting these relations into Eq. 81 yields

$$K_A = \gamma \tilde{D}^2 \sqrt{J\,\rho c}\; N \qquad (83a)$$

where

$$\gamma \equiv \sqrt{2}\;\beta\alpha_1\alpha_2/2 \qquad (83b)$$

and thus

$$n/n_o = \exp(-\gamma \tilde{D}^2 \sqrt{J/\rho c}\; Nt) \qquad (84)$$

showing that the agglomeration rate is most strongly dependent upon the diameter of the large size particulate phase and is least strongly dependent upon J, ρ, and c.

This result may be conveniently assessed in two contexts: agglomeration of a monodisperse aerosol for a desired growth ratio of the particulates and for the agglomeration of the small size phase onto the large size phase for a binary aerosol.

The first case, that of a monodisperse aerosol, was evaluated by Hegarty and Shannon[201] in the EPA-sponsored study and led to very pessimistic conclusions as to the practicality of AA. But it is important to observe that they evaluated the least adaptable configuration for AA. For the monodisperse aerosol, a mass balance yields

$$n_o \frac{\pi}{6} \tilde{\rho} \tilde{d}_o^3 = n \frac{\pi}{6} \tilde{\rho}' \tilde{d}^3 \tag{85}$$

where $\tilde{\rho}'$ is the density of the aggregated particulate and can be expected to be somewhat smaller than ρ for smokes and dusts, which tend to form chain and flake-like structures. Solving for n/n_o and substituting it into the kinetic equation yields

$$t = \frac{3}{K_A} \ell n \left[\frac{\tilde{d}}{\tilde{d}_o} \left(\frac{\tilde{\rho}'}{\tilde{\rho}} \right)^{1/3} \right] \tag{86a}$$

where

$$K_A = \gamma \tilde{d}^2 \sqrt{J/\rho c}\, n \tag{86b}$$

Since the agglomerating centers diminish in number as they form from the small size particles, it is apparent that the above equations are much more complex than originally anticipated by the kinetic model since K_A continually changes due to changes in $\tilde{d}$ and n. Hegarty and Shannon circumvented this difficulty by merely analyzing the following form:

$$t\sqrt{J} \cong 3\ \ell n[\tilde{d}/\tilde{d}_o] \tag{87}$$

for growth ratios of 5 to 20 (also known as the agglomeration index) which requires

$$t\sqrt{J} = 5 \rightarrow 9$$

By using the data of Neumann and Norton,[237] they reexpressed the above equation as

$$tJ = 6 \rightarrow 20$$

in order to achieve this range of growth ratios. Thus, a sound intensity of 1 W/cm^2 (160 dB) is needed to provide a growth ratio of approximately 8 in 10 sec of residence time. Next, by assuming various efficiencies for the acoustic generator, compressor, and the agglomerating chamber, they were

able to estimate the size and power requirements for such an agglomerator system. As a typical result, for a growth ratio of 15 at 160 dB, a residence time of 8 seconds is required in a chamber 4 m in diameter and 11 m tall with an energy consumption of 9.1 kW-hr per 1000 m^3 of gas treated (21 hp/1000 cfm). Since this energy requirement would be in addition to that associated with the pressure drop across the collection cyclone downstream (ca. 4 hp/1000 cfm), the total power requirement would exceed that of even the highest venturi scrubber system (ca. 20 hp/1000 cfm). Hence, they concluded: "The utility of a sonic agglomerator as an aid to controlling fine particulates seems doubtful at best." (Ref. 201, p. 39).

This study, together with the poor performance of the Braxton sonic agglomerator (also tested by EPA), has resulted in a very pessimistic attitude toward AA in many quarters. However, because the Hegarty and Shannon study evaluated the concept of AA in its least adequate setting (*i.e.*, a monodisperse aerosol of fines) and because the poor performance of the Braxton agglomerator can be explained on other grounds, this assessment of AA should not be casually extended to other potential application for which the aerosol characteristics and system requirements are more suitably matched with the capabilities of AA.

To assess AA in the context of pretreating an aerosol that has been produced by fluidized-bed combustion and cleaned by a medium-efficiency cyclone, the model of a binary aerosol is developed: a large-size particulate phase which acts as agglomeration centers and a small-size phase which is diminished in concentration as a result of agglomeration onto the large particulate. The triangular point of Fig. 5 will be used as the baseline aerosol: $\hat{\rho} = 37.8$ g/m^3 and $(\bar{d})_{avg} = 225$ μm. Since the efficiency of cyclones decreases significantly for particulate below ca. 20 μm, the agglomeration process should be designed primarily to decrease the concentration of the particulate below this size. For instance, this aerosol can be approximated as consisting of a large phase of 37.7 g/m^3 at a size of 230 μm and a small phase of 100 mg/m^3 at 10 μm. From grade efficiency curves available from cyclone manufacturers, approximately 0.1% of the large phase and 90% of the small phase will escape the collection system. Thus, with no AA, the concentration at the cyclone outlet would be approximately

$$\begin{aligned}(\hat{\rho})\ \text{outlet} &= 0.001(37\ 700) + 0.90(100) \\ &= 38 + 90 \\ &= 128\ \text{mg/m}^3 \end{aligned} \tag{88}$$

which corresponds to the EPA upper bound of Fig. 5. By using AA at a frequency of ca. 1 kHz (from Fig. 37), the concentration of the small-size phase will vibrate with the medium and the large phase will be motionless, causing a reduction in small phase concentration in proportion to the product $K_A t$ as given by Eq. 78, namely,

$$\begin{aligned}K_A t &= -\ell n(n/n_o) \\ &= -\ell n(\hat{\rho}_e/\hat{\rho}_i) \end{aligned} \tag{89}$$

where the subscripts i and e denote inlet and exit to the agglomerating chamber. If the concentration is to be reduced by one order of magnitude, then

$$K_A t = -\ell n(0.1)$$
$$= +2.3 \qquad (90)$$

For this degree of agglomeration, the small phase concentration would diminish by 10 mg/m^3 and the large phase would increase to 37 790 mg/m^3; by assuming the same cyclone efficiencies, the cleaned aerosol would then be

$$(\hat{\rho})_{\substack{\text{outlet} \\ \text{cyclone/AA}}} = 0.001(37\,790) + 0.90(10)$$
$$= 38 + 9$$
$$= 47 \text{ mg/m}^3 \qquad (91)$$

or a reduction in aerosol concentration of 63% (in comparison to no AA) at an expenditure of $K_A t = 2.3$. This exit concentration corresponds to approximately level 4 of Fig. 5. A graphic portrayal of this model is given in Fig. 39 for various expenditures of acoustic energy and/or treatment time.

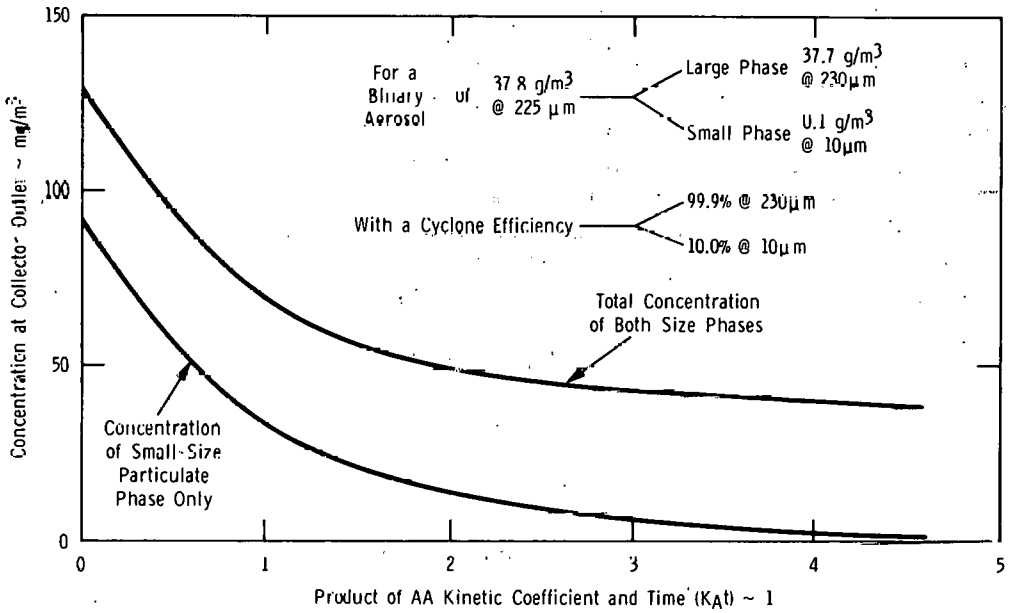

Fig. 39. Estimated Influence of AA for a Binary Aerosol.

In order to compute the requisite acoustic power, the agglomeration coefficient for the conditions of the given binary aerosol at high temperature and pressure must be given. No such data are known to exist. From Eq. 83, it can be seen that K_A is expected to be given by

$$K_A = 0.707\beta\alpha_1\alpha_2\tilde{D}^2\sqrt{J/\rho c}\ N \tag{92}$$

By assuming a perfect gas model

$$p = \rho/RT \tag{93a}$$

$$c = \sqrt{kRT} \tag{93b}$$

this may be expressed as

$$K_A = 0.707\beta\alpha_1\alpha_2\tilde{D}^2\left(\frac{J}{\rho}\right)^{1/2}\left(\frac{RT}{k}\right)^{1/4} N \tag{94}$$

where N is the number of agglomeration centers and can be written as

$$N = \frac{\hat{\rho}_o}{\frac{\pi}{6}\tilde{\rho}'\tilde{D}^3} \tag{95}$$

where $\tilde{\rho}'$ is the density of the aggregate, which is expected to be somewhat smaller than $\tilde{\rho}$. Substituting for N yields

$$K_A = 1.35(\beta\ \alpha_1\ \alpha_2)\left(\frac{R}{K}\right)^{0.25}\left(\frac{T}{p^2}\right)^{0.25}\left(\frac{\tilde{\rho}_D}{\tilde{\rho}'\tilde{D}}\right)J^{0.50} \tag{96}$$

Hegarty and Shannon simply assumes that all the factors multiplying $J^{0.50}$ combined to unity, *i.e.*,

$$K_A/\sqrt{J} \tilde{=} 1 \tag{97}$$

If it is assumed that all the factors in Eq. 96 correspond to the Hegarty and Shannon values except that due to the pressure and temperature of the aerosol, one finds that for 1000°C/10 atmospheres

$$K_A/\sqrt{J} \tilde{=} 0.45 \tag{98}$$

if Eq. 97 is based upon 23°C/1 atmosphere.

Substitution of this relation into Eq. 89 yields

$$K_A t = 0.45t\sqrt{J}$$

$$= -\ln(\hat{\rho}_e/\hat{\rho}_i) \tag{99a}$$

or

$$t\sqrt{J} = -2.2\ \ln(\hat{\rho}_e/\hat{\rho}_i) \tag{99b}$$

The above result can now be used to calculate the combination of residence time and power density to achieve the estimated particulate concentrations after the cyclone given in Fig. 39. This result is shown below.

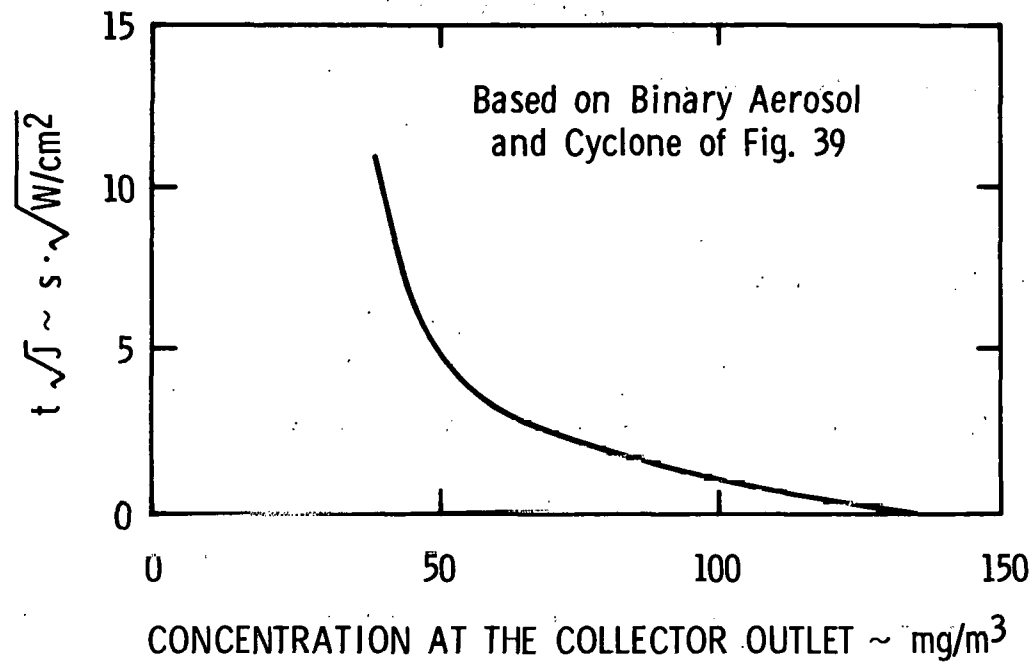

Fig. 40. Estimated Acoustic Power and Residence Time to Achieve Indicated Concentrations, Using a Standard Cyclone.

For an acoustic power of 160 dB (1 W/cm^2), the ordinate reads as simply the residence time required in seconds. Using the same assumptions for the efficiency of the acoustic generator and associated agglomerator components, the 47 mg/m^3 point, which requires $T\sqrt{J} = 5$, translates to a total treatment power estimate for AA of 21 hp/1000 cfm and required a chamber 4 m in diameter and 6 m high.*

It is exceedingly difficult to calculate a priori the efficiency of an AA/cyclone system due to the absence of pertinent data for kinetic coefficients. It is entirely possible that the actual performance would exceed the values indicated above.

There are several possible favorable influences that have not been accounted for in the previous analysis. The mean diameter of both the small and large phase particulate will increase as a result of AA (in addition to a shift in concentration from the small to the large phase), and this will increase the efficiency of cyclonic collection. This effect should be especially important for the collection of the small phase. Another favorable influence is the high degree of size dispersity present with a fluid-bed aerosol. Virtually all available data have been obtained with essentially monodisperse aerosols. It is also possible that the refilling and gross drift mechanisms may be more efficient in the high-pressure environment. Until actual kinetic data are developed for these conditions,

*This power requirement is coincidently identical to that computed in the Hegarty and Shannon study, but the required AA volume is 50% smaller.

A typical example of data presently available is shown below. It is due to Krebs,[238] who used an AA/cyclone on the very fine, essentially monodisperse aerosol formed in the flue of a pulverized coal boiler.

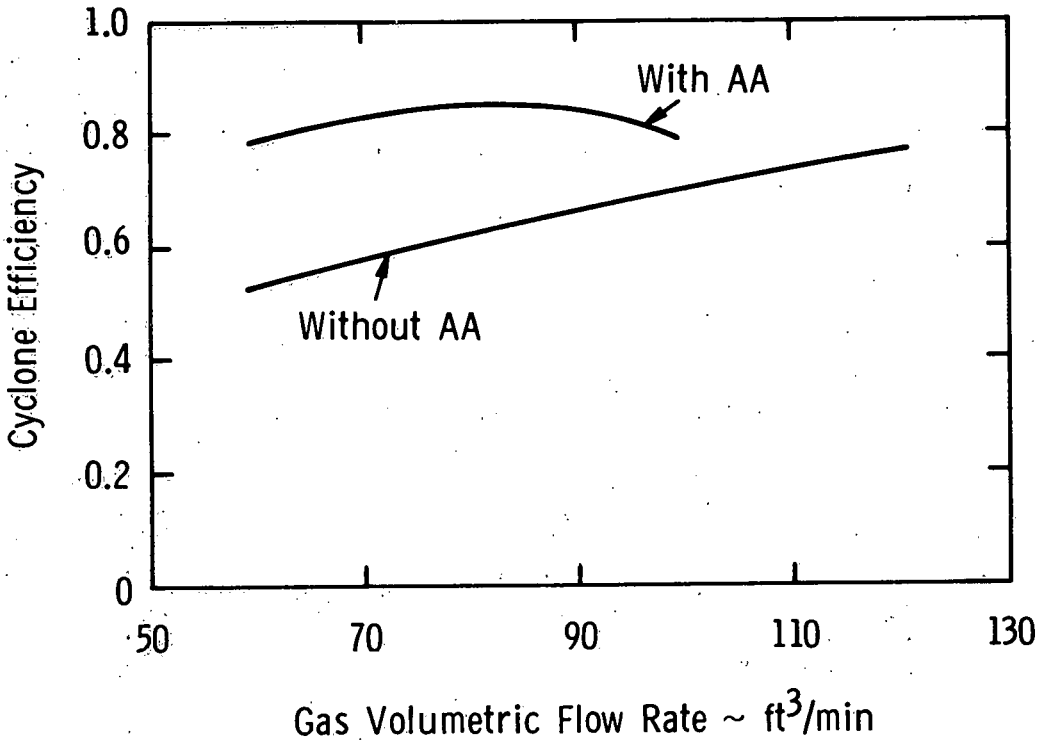

Fig. 41. Effect of AA on Cyclone Collection Efficiency (based on Ref. 238).

PART V. CONCLUSIONS AND RECOMMENDATIONS

The five principal conclusions and recommendations of this analysis are presented below.

(1) Efficient particulate separation and collection from high-temperature media has been the object of many years of research, yet remains a research frontier because of ever-increasing efficiency requirements and even higher particulate concentrations in the aerosols to be treated. Because much of the research was accomplished 30 and 40 years ago, there is general ignorance today of pertinent data and results available. For this reason, a comprehensive and intelligent compendium of the data on high-temperature collection would be of great benefit to workers in this area.

(2) The performance requirements of a collector situated between a fluidized-bed combustor and a turbine are, at present, very poorly defined, as can be seen in Fig. 5. In particular, the turbine tolerance for particulate concentration as a function of mean diameter must be determined with a great deal more specificity. Complicating this task is the inherent tendency of designers of fluid beds and turbines to maximize the performance of their particular device, with the consequence that specifications for the intervening collector system require cleaning of an exceedingly concentrated aerosol (on the order of 10^5 mg/m^3) to limits approaching that of ambient air (*i.e.*, 10^{-1} mg/m^3). If this situation is permitted, the entire concept of direct utilization of a fluidized-bed combustor will fail since no practical collector system appears capable of economically cleaning high volume aerosol flows by six orders of magnitude. Clearly, some very pragmatic constraints will have to be established for the minimum tolerable fluidizing velocity and maximum turbine inlet concentration.

(3) The separation mechanics of aerosols remains an unsolved science--particularly for the nonhomogeneous velocity fields characteristic of cylonic devices. From Fig. 9, there is every indication that cyclones should be capable of achieving very high efficiencies on particles as small as and smaller than 1 μm in diameter. The principal reason this is not experienced in practice is the turbulence structure of the wall boundary layer. Very little work has been done on understanding the fundamental fluid mechanics of cyclonic flows, and almost no turbulence data exist under actual separation conditions. A study needs to be made of the influence of changes in the geometry and thermal boundary conditions upon the turbulence process and hence particulate reentrainment kinetics. One theoretically promising device is the gas centrifuge. Although the centripetal acceleration achievable with this device is not as great as in a cyclone, the boundary conditions tend to suppress turbulent bursts and thus they should be capable of very high separation efficiencies. Yet only two or three studies have pursued this concept. Figure 36 clearly shows that since the highest operation efficiency of any collector is still below 0.1% of what is achievable, a great deal of progress is yet to be made in all areas of separation fluid mechanics.

(4) There are two categories of collectors that are workable in the high-temperature and high-pressure environment: the perimeter and distributed classes (IIA and IIB in Table 3). They represent interesting contrasts

in that the one is simple, relatively cheap, and highly reliable (the perimeter devices) whereas the other has the potential for highest efficiency (the distributed devices). Clearly, if an aerosol is passed through a bed of rocks deep enough, virtually any level of cleaning desired may be realized--an analogy which does not extend to cyclone-like devices. However, unlike perimeter collectors, the distributed type collector must be regenerated, and it is this aspect of the process that has proved to be most difficult. The precipitation of an aerosol onto a granular substance represents a small fraction of the total process that must be successfully accomplished: the collection of the particulate phase into a single, concentrated mass. The size of particle bed collectors, such as the Combustion Power moving bed system which is 25 m tall, is proof of the complexity of this concept. Cyclonic devices, on the other hand, have traditionally been of limited utility when high collection efficiencies have been required. The primary reason for this limitation has been that the concept of "high efficiency," for most industrial aerosols, requires the removal of substantial fractions of 1 μm and smaller particulate (in contrast to fluidized-bed aerosols, which have large-size particulate) and the turbulent reentrainment of already separated particulate continually frustrates this process. From a study of Figs. 5 and 9 and the achievable efficiency of currently available cyclones, the gap between what is required and what is available is sufficiently close that, in view of their simplicity and low cost, research activity employing this concept should be pursued. This pursuit must be of a more fundamental nature than merely trying to increase the Impaction number and/or decreasing the cyclone diameter since it is clear from the BLM and ARL experience that the point of diminishing return has already been reached with these two approaches.

It should also be noted from Table 2 that the primary efforts at high-temperature gas cleaning are being directed toward distributed collectors. The absence of any known sponsored research in advanced technology cyclones is strikingly apparent.

(5) The extreme polydispersity and large initial number density of aerosols form fluidized-bed combustors are characteristics ideally suited to agglomeration concepts. Of the five agglomeration techniques discussed in Part IV, only turbulent and acoustic agglomeration appear promising. The technique of AA is particularly attractive for this environment because it is not confronted with the overwhelming limitations of most aerosols, such as metallurgical fumes. Further, since the collection system for this application must protect a highly valuable component, it is possible to justify higher expenditures to meet higher standards than are customary for purely environmental considerations.

In summary, the following recommendations are offered:

1. Develop a thorough compendium of the data developed in high-temperature collection over the past four decades;

2. Clearly establish the bounds of the collector performance requirements for efficiency as a function of particle diameter;

3. Begin a fundamental study of the fluid mechanics of separation in

cyclonic flows to develop an understanding of the turbulence structure and how it presently impedes the achievement of higher efficiencies;

4. Develop advanced-generation perimeter collectors such as cyclones with modified boundary conditions, gas centrifuges, and eddy-baffle assemblies;

5. Determine the agglomeration kinetics of acoustic fields on aerosols emitted from fluidized beds at high temperatures and high pressures.

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REFERENCES

1. R. Dennis, Ed., *Handbook on Aerosols*, for U.S.ERDA, NTIS, Springfield, Va. (1976).

2. M. Smoluchowski, Z. Physik. Chem. 92, 129 (1917).

3. C. E. Lapple, SRI J., 5(94) (Third Quarter 1961).

4. "Standards of Performance for New Stationary Sources," U.S. Environmental Protection Agency, Federal Register, 36(247), Part II. (Thursday, December 23, 1971).

5. G. J. Vogel *et al.*, *Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion and Regeneration of Sulfur-Containing Additives, Annual Report, July 1973-June 1974*, Argonne National Laboratory Report ANL/ES-CEN-1007 and EPA-650/2-74-104 (1974).

6. A. A. Jonke *et al.*, *Fluidized-Bed Combustion: Development Status*, Trans. Soc. Min. Eng. AIME, 258, 159-167, (June 1975).

7. D. L. Keairns *et al.*, *Design of a Pressurized Fluidized Bed Boiler Power Plant*, AIChE Symp. Ser. 69(126), 267-275 (1972).

8. *Clean Power Generation from Coal*, Research and Development Report No. 84, prepared by Westinghouse Research and Development Center for the Office of Coal Research, U.S. Department of the Interior (January 1973).

9. G. J. Vogel *et al.*, *A Development Program on Pressurized Fluidized-Bed Combustion, Annual Report, July 1974-June 1975*, Argonne National Laboratory Report ANL/ES-CEN-1011 (1975).

10. G. J. Vogel *et al.*, *A Development Program on Pressurized Fluidized-Bed Combustion, Quarterly Report, July 1975-September 1975*, Argonne National Laboratory Report ANL/ES-CEN-1013 (November 1975).

11. G. J. Vogel *et al.*, *A Development Program on Pressurized Fluidized-Bed Combustion, Quarterly Report, October 1975-December 1975*, Argonne National Laboratory Report ANL/ES-CEN-1014 (January 1976).

12. C. K. Steins, *Some of the Problems Involved in the Coal-Burning Gas Turbine Locomotive*, Proc. Midwest Power Conf., 11, 362 (1949).

13. M. A. Field, *Combustion of Pulverized Coal*, BCURA, Leatherhead, U.K. (1967).

14. J. R. Allen and J. A. Bursley, *Heat Engines*, McGraw-Hill, p. 484 (1941).

15. E. E. Soehngen, E. Soehngen and Associates, Dayton, Ohio, letter to R. Razgaitis (December 19, 1975).

16. K. Bammert *et al.*, *Die Gasturbine in deutschen Huttenwerken (The gas turbine in German steel mills)*, V.I.K. Berichte Nr. 94 (Vereinigung Industrielle Kraftwirtschaft, Essen) (1959).

17. K. Bammert *et al.*, *Entwicklundsstand der ortesgesten Gasturbine (State of development of the stationary gas turbine)*, Vereinigung Industrielle Kraftwirtschaft, Essen) V.I.K. Berichte Nr.121/122 (1961).

18. K. Bammert *et al.*, *Betriebserfahrungen mit Gasturbinen (Operation experieinces with gas turbines)*, Vereinigung Industrielle Kraftwirtschaft, Essen) V.I.K. Berichte Nr. 136 (1963).

19. K. Bammert *et al.*, *Verluste beim Betrieb von Dampfturbinen (Losses in operation of steam turbines)*, Vereinigung Industrielle Kraftwirtschaft, Essen) V.I.K. Berichte Nr. 141/142 (1963).

20. K. Bammert *et al.*, *Über Korrosion, Erosion und Verschmutzung bei Gichtgasturbinen (On corrosion, erosion, and pollution in blast-furnace gas turbines)* Vereinigung Industrielle Kraftwirtschaft, Essen) V.I.K. Berichte Nr. 164 (1965).

21. K. Bammert and F. Fiedler, *Der Reibungsverlust von rauhen Turbinenschaufelgittern (The friction loss in rough turbine blade cascades)* Brennstoff-Wärme-Kraft 18, Nr. 9, S. 430-36 (1966).

22. K. Bammert and K. Fiedler, *Hinterkanten- und Reibungsverlust in Turbinenschaufelgittern. (The trailing edge loss in the friction loss in turbine blade cascades)*, Forsch. Ingenieurwes. 32 Nr. 5., S. 133/41 (1966).

23. K. Bammert and H. Sonnenschein, *Der Einfluß verdickter und verdünnter Turbinenschaufeln auf die Gittereigenschaften. (The influence of thickened and thinned turbine blades on cascade characteristics)*, Arch. Eisenhuettenw. 38 Nr. 4, S. 287/99 (1967).

24. K. Bammert, *Einfluß der Profiländerung auf die Eigenschaften von Turbinenschaufelgittern. (Influence of profile changes on the characteristics of turbine blade cascades)*, Wiss. Z. Techn. Univ. Dresden 16 Nr. 2, S. 369/75 (1967).

25. K. Bammert, *Die Auswirkung der Profilveränderungen auf den Turbinen- und Kreislaufwirkungsgrad von Gaturbinen (The effect of profile changes on the turbine and cycle efficiency of gas turbines)*, Zagadniena Maszyn Przeplywowch, Problems of Fluid-Flow Machines, Wydawnictwo Jubilenszowe, Panstwowe Wydawnictwo Naukowe-Warszawa - Jubilee Edition, S. 71/84 (1968).

26. K. Bammert and H. Stobbe, *Messungen an einer mehrstufigen Axial-turbine mit normalen, verdünnten und verdicten Schaufeln (Measurements on a multi-stage axial turbine with normal, thinned, and thickened blade profiles*, Motortech. Z. 31 Nr. 5, S. 189/98 (1970).

27. K. Bammert and H. Stobbe, *Der Einfluß von Profile-Fertigungstoleranze auf die charakteristischen Kenngrößen mehrstufiger Axialturbinen (The influence of profile manufacturing tolerances on the characteric values of multi-stage axial turbines)*, VDI Z. 112 Nr. 11, S. 686/92 (1970).

28. K. Bammert and H. Stobbe, *Der Einfluß von Korrosion, Erosion und Verschmutzung auf das Betriebsverhalten von Turbine und Kreislauf einer Gasturbinenanlage (The effect of corrosion, erosion, and contamination on the operation behavior of turbine and circuit of a gas turbine and circuit of a gas turbine plant),* Arch. Eisenhüttenw. 41, Nr. 11, S. 1055/68 (1970).

29. K. Bammert and H. Stobbe, *Results of experiments for determining the influence of blade profile changes and manufacturing tolerances on the efficiency, the enthalpy drop, and the mass flow of multi-stage axial turbines,* ASME Paper No. 70 WA/GT-4.

30. K. Bammert and H. Sandstede, *Measurements Concerning the Influence of Surface Roughness and Profile Changes on the Performance of Gas Turbines,* Trans. ASME, J. Eng. Power, Ser. A, 94 Nr. 3, S. 207/13 (1972).

31. K. Bammert and R. Milsch, *Boundary Layers on Rough Compressor Blades,* ASME PAper 72-GT-48.

32. K. Bammert and R. Milsch, *Das Verhalten der Grenzschichten an rauhen Verdichterschaufeln (The behavior of boundary layers on rough compressor blades),* Forsch Ingenieurwes. 39 Nr. 4, S. 101/09 (1972).

33. K. Bammert and H. Sandstede, *Strömungsverluste durch die Oberflächenrauhigkeit der Schaufeln in einer Turbine (Flow losses caused by the surface roughness of blades in a turbine),* VDI-Ber. Nr. 193, S. 225/32 (1973).

34. K. Bammert and H. Sandstede, *Influences of Manufacturing Tolerances and Surface Roughness of Blades on the Performance of Turbines,* Trans. ASME, J. Eng. Power, Ser. A, 98 Nr. 1, S. 29/36 (1970).

35. K. Bammert and H. Sandstede, *Gas Turbine Burning Dirty Fuels,* ASME Paper 76-GT-66, New Orleans, La., March 21-26, 1976.

36. K. Bammert, *Status Report on the Closed Cycle Gas Turbines in the Federal Republic of Germany,* presented at the ASME Gas Turbine and Fluids Engineering Conference, New Orleans, La., March 21-26, 1976.

37. E. h. Hans Pfenninger, *Vergangenheit, Gegenwart und Zukunft der Brown Boveri Gasturbinen,* Sonderdruck aus MTZ Motortechische Zeitschrift 27, Jahrgang No. 11, 1-15 (Franckh' sche Verlagshandlung Stuttgart) (Nov. 1966).

38. *The Coal Burning Gas Turbine Project,* Report of the Interdepartmental Steering Committee, Department of Minerals and Energy, Department of Supply, Commonwealth of Australia (1973).

39. J. I. Yellott and C. F. Kottcamp, *Coal-Burning Gas-Turbine Plants,* presented at ASME Semiannual Meeting, Chicago, Ill., June 16-19, 1947.

40. J. I. Yellott and P. R. Broadley, Power 95, 104-107 (June 1951) and 90-91 (August 1951).

41. J. I. Yellott and P. R. Broadley, Engineering 177, 561 (April 30, 1954) and 592 (May 7, 1954).

42. J. I. Yellott and P. R. Broadley, *Fly Ash Separators for High Pressures and Temperatures*, Ind. Eng. Chem. 47(5), 944-952 (May 1955).

43. R. M. Junge and G. W. Scheper, Jr., *Locomotive Development Committee Coal-Fired Turbine Blade Erosion Study*, No. DF-59-GTD-32, General Electric Company, Schenectady, New York (December 1959).

44. W. M. Nabors *et al.*, *Bureau of Mines Progress in Developing the Coal-Burning Gas Turbine Power Plant*, J. Eng. Power 87(2), 215-222 (April 1955).

45. J. Smith *et al.*, *Bureau of Mines Progress in Developing Open and Closed-Cycle Coal-Burning Gas Turbine Power Plants*, J. Eng. Power 88(4), 313-322 (Oct. 1966).

46. D. A. Furlong and G. L. Wade, *Use of Low Grade Solid Fuels in Gas Turbines*, Paper No. 74WA/ENER-5, presented at the ASME Winter Annual Meeting, New York, pp. 17-22 (November 1974).

47. Combustion Power Company, Inc., literature entitled, *Gas Turbines Equipped for Direct Combustion of Coal in Fluidized Beds Provide an Environmentally Acceptable, Cost-Effective and Yet Technically Simple Method for Generating Electric Power Using Our Most Abundant Fuel.*

48. Combustion Power Company, Inc., literature entitled *For Several Years the Federal government has been funding Research on Technology to Advance Solid Waste Technology...*

49. D. Lear, Combustion Power Co., Inc., private communication (Feb. 12, 1976).

50. F. L. Robson *et al.*, *Technological and Economic Feasibility of Advanced Power Cycles and Methods of Producing Nonpolluting Fuels for Utility Power Stations*, UARL Rpt. J-970855-13, NTIS No. PB 198-392 (Dec. 1970).

51. F. L. Robson, *et al.*, *Analysis of Jet Engine Test Cell Pollution Abatement Methods*, Technical Report AFWL-TR-71-18 (May 1973).

52. F. L. Robson *et al.*, *Fuel Gas Environmental Impact: Phase Report*, UTRC Rpt. EPA-600/2-75-078 (Nov. 1975).

53. C. E. Smeltzer *et al.*, *Mechanisms of Metal Removal by Impacting Dust Particles*, J. Basic Eng. 639-654, (Sept., 1970).

54. L. M. Stettenbenz, *Benefits of the Power-Recovery Gas Expander*, Chem. Eng. 93-96 (Jan. 10, 1972).

55. M. W. Thring and W. Strauss, *The Effect of High Temperature on Particle Collection Mechanisms*, Trans. Inst. Chem. Eng. 41(6-7), 248-254 (July-Aug. 1963).

56. W. Strauss and B. W. Lancaster, *Prediction of Effectiveness of Gas Cleaning Methods at High Temperatures and Pressures*, Atmos. Environ. 2(2), 135-144 (March 1968).

57. N. R. Iammartino, *Technology Gears Up to Control Fine Particles*, Chem. Eng. 50-52 (August 21, 1972).

58. N. R. Iammartino, *Gaging the Potential for Fine-Particle Control*, Chem. Eng. 86-90 (June 23, 1975).

59. A. E. Vandergrift, L. J. Shannon, and P. G. Gorman, *Controlling Fine Particles*, Chem. Eng./Deskbook Issue, 107-114 (June 18, 1973).

60. L. J. Shannon, *Control Technology for Fine Particule Emissions*, Midwest Research Institute, EPA report EPA-650/2-74-027 (May 1974).

61. *Purification of Hot Fuel Gases from Coal or Heavy Oil*, Interim Report, EPRI 243-1, Stone and Webster (November 1974).

62. C. Jones, Stone and Webster, private communication (Feb. 9, 1976).

63. Dr. M. Gluckman, EPRI, private communication (Feb. 6, 1976).

64. Dr. F. L. Robson, UTRC, private communication (Feb. 9, 1976).

65. A. K. Rao, M. P. Schrag, and L. J. Shannon, *Particulate Removal from Gas Streams at High Temperature and/or High Pressure*, Midwest Research Institute Project No. 3821-C(30) for U.S.EPA (May 23, 1975).

66. A. K. Rao, M. P. Schrag, and L. J. Shannon, *Particulate Removal from Gas Streams at High Temperature and/or High Pressure*, Midwest Research Institute, report EPA 600/2-75-020 (August 1975).

67. R. W. Fulton and S. Youngblood, *Survey of High Temperature Clean-up Technology for Low Btu Fuel Processes*, Aerotherm Division, Acurex Corp., Aerotherm Report 75-134, EPA contract 68-02-1318 (January 1975).

68. B. Truitt, Mitre Corp., private communication (March 8, 1976).

69. Dr. S. Calvert, Air Pollution Technology Corp., private communication (Feb. 12, 1976).

70. Dr. L. Sparks, U.S.EPA, private communication (Feb. 17, 1976).

71. D. H. Drehmel, U.S.EPA, private communication (Feb. 12, 1976).

72. W. Rhodes, U.S.EPA, private communication (Feb. 12, 1976).

73. W. Fedarco, U.S.ERDA, private communication (Feb. 19, 1976).

74. C. Grua, U.S.ERDA, private communication (Feb. 13, 1976).

75. *Survey of Information Fine-Particle Control*, Southern Research Institute, EPRI 259, PB 248 386 (April 1975).

76. *Evaluation of Coal Conversion Processes to Provide Clean Fuels - Final Report,* Univ. of Michigan, EPRI 206-0-0, PB 234 202 and 234 203 (parts I and II) (Feb. 1974).

77. Dust Erosion Parameters for Gas Turbines, Petro/Chemical Engineering, December 1962 (as cited in Ref. 52, p. 270).

78. *Air Pollution Engineering Manual,* U.S.HEW, Cincinnati, Ohio (1967).

79. H. Schlicting, *Boundary-Layer Theory,* 6th Ed., McGraw-Hill, New York (1968).

80. C. E. Lapple, "Separation of Dusts and Mists," in *Chemical Engineers Handbook,* 3rd Ed., J. H. Perry, Ed., McGraw-Hill (1950).

81 J. O. Ledbetter, *Air Pollution. Part A,* Marcel Dekker, Inc., New York (1972).

82. N. A. Fuchs, *The Mechanics of Aerosols,* The Macmillan Company, New York (1964).

83. W. Strauss, *Industrial Gas Cleaning,* Pergamon Press, New York (1966).

84. C. N. Davies, *The Separation of Airborne Dust and Particles,* Proc. Inst. Mech. Eng. 1B(5), 185-213 (1952).

85. C. E. Lucas, "Gas-Solids Separation," in *Chemical Engineers' Handbook,* 4th Ed., J. H. Perry, Senior Ed., McGraw-Hill, pp. 20-62 to 20-96 (1963).

86. K. J. Caplan, "Source Control by Centrifugal Force and Gravity," in *Air Pollution,* 2nd Ed., A. C. Stern, Ed., Academic Press, pp. 359-407 (1968).

87. H. L. Green and W. R. Lane, *Particulate Clouds: Dusts, Smokes, and Mists,* E. & F. N. Spon Ltd., London (1964).

88. G. M. Hidy and J. R. Brock, *The Dynamics of Aerocolloidal Systems,* Vol. I, Pergamon Press, New York (1970).

89. H. G. Landahl and R. G. Hermann, *Sampling of Liquid Aerosols by Wires, Cylinders, and Slides and the Efficiency of Impaction of the Droplets,* J. Colloid Sci. 4, 103 (1949).

90. M. Robinson, "Electrostatic Precipitation," in *Air Pollution Control,* Part I., W. Strauss, Ed., Wiley, New York, pp. 227-335 (1971).

91. H. J. Hall, "Application of Electrostatic Precipitation to Process Gas Cleaning of High Temperature, High Pressure Coal Gasification System," App. II, *Purification of Hot Fuel Gases from Coal or Heavy Oil,* EPRI 243-1 (Nov. 1974).

92. T. M. Rymarz and D. H. Klipstein, *Removing Particulates from Gases,* Chemical Engineering Deskbook, pp. 113-120 (Oct. 6, 1975).

93. S. L. Soo, *A Critical Review on Electrostatic Precipitators*, AIChE Symp. Ser. 68(126), 185-193 (1972).

94. G. G. Schneider *et al.*, *Selecting and Specifying Electrostatic Precipitators*, Chem. Eng. 94-108 (May 26, 1974).

95. P. P. Bibbo and M. M. Peacos, *Hot Side Precipitators for Cat Crackers Ease Waste Heat Recovery, Pollution Abatement Conflicts*, Combustion 31-32 (March 1976).

96. O. Preining, "Photophoresis," in *Aerosol Science*, C. N. Davies, Ed., Academic Press, 111-136 (1966).

97. H. Kolm *et al.*, *High-Gradient Magnetic Separation*, Sci. Amer. 233(5), 47-54 (Nov. 1975).

98. *Standard Handbook for Electrical Engineers*, 9th Ed., A. E. Knowlton, Ed., McGraw-Hill (1957).

99. P. S. Epstein, Z. Physik 54, 537 (1929).

100. L. Waldmann and K. H. Schmitt, "Thermophoresis and Diffusiophoresis of Aerosols," *Aerosol Sceince*, C. N. Davies, Ed., Academic Press, New York, pp. 137-162 (1966).

101. B. V. Derjaguin and Yu. I. Yalamov, *The Dynamics of Aerocolloidal Systems*, Vol. III, G. M. Hidy and J. R. Brock, Eds., Pergamon Press, New York (1970).

102. J. A. Gieseke, "Thermal Deposition of Aerosols," in *Air Pollution Control*, Part II, W. Strauss, Ed., Wiley-Interscience, New York, pp. 211-254 (1972).

103. T. K. Sherwood, U.S. Patent 2,833,370 (1958).

104. R. Jackson, *Mechanical Equipment for Removing Grit and Dust from Gases*, BCURA, Leatherhead, U.K., 1963.

105. *Emission Control Equipment*, J. Air Pollut. Control Assoc., 26(3), 264-274 (March 1976).

106. D. Leith and D. Mehta, "Cyclone Performance and Design," *Atmos. Environ.* 7, 527-549 (1973).

107. C. J. Stairmand, *The Design and Performance of Cyclone Separators*, Trans. Inst. Chem. Eng. 29, 356-383 (1951).

108. P. Swift, *Dust Control in Industry 2*, Steam Heat. Eng. 38, 453-456 (1969).

109. C. E. Lapple, *Processes Use Many Collector Types*, Chem. Eng. 58, 144-151 (1951).

110. *Cyclone Dust Collectors*, American Petroleum Institute, Washington, D.C., 1955 (reaffirmed 1972).

111. K. Reitema and G. A. Vewer, *Cyclones in Industry*, Elsevier Pub., Amsterdam (1961).

112. C. B. Shepherd and C. E. Lapple, *Flow Pattern and Pressure Drop in Cyclone Dust Collectors*, Ind. Eng. Chem. 31, 972-984 (1939).

113. C. B. Shepherd and C. E. Lapple, *Flow Pattern and Pressure Drop in Cyclone Dust Collectors*, Ind. Eng. Chem. 32, 1246-1248 (1940).

114. A. J. Terlindien, *Investigations into Cyclone Dust Collection*, Proc. Inst. Mech. Eng. 160, 233 (1949).

115. A. J. Terlindien, Proc. Inst. Mech. Eng. 160, 249 (1949).

116. R. H. B. Forster, Proc. Inst. Mech. Eng. 160, 246 (1949).

117. M. W. First, ASME Preprint 49-A-127 (1949).

118. M. W. First, *Fundamental Factors in the Design of Cyclone Dust Collectors*, Ph.D. Thesis, Harvard University, Boston (1950).

119. A. J. Terlindien, Tonind.-Z. 77(314), 49-55 (1953).

120. C. D. Donaldson and R. D. Sullivan, *Examination of the Solutions to the Navier-Stokes Equation for a Class of Three Dimensional Vortices*, Aeronautical Research Assoc. of Princeton, Inc., AFOSR TN 60-1227 (October 1960).

121. F. Wellman, *Feuerungstechnik (Leipzig)* 26, 137 (1938).

122. H. Gortler, *On the Three Dimensional Instability of Laminar Boundary Layers on Concave Walls*, NACA TM1375 (1954).

123. I. Tani, *Production of Longitudinal Vortices in the Boundary Layer Along a Concave Wall*, J. Geophys. Res. 67(8), 3075-3090 (July 1962).

124. J. L. Smith, Jr., *An Analysis of the Vortex in the Cyclone Separator*, J. Basic Eng. 84(4), 609-618 (Dec. 1962).

125. I. L. Smith, Jr., *An Experimental Study of the Vortex in the Cyclone Separator*, J. Basic Eng. 84(4), 602-608 (Dec. 1962).

126. P. Bradshaw, *Effects of Streamline Curvature on Turbulence*, AGARDograph No. 169, NASA Langley (August 1973).

127. J. P. Hartnett and E. R. G. Eckert, Trans. ASME 79, 751-757 (May 1957).

128. M. G. Hall, *Ann. Rev. Fluid Mech.* 4, Annual Reviews, Inc., Palo Alto, Calif., 195-217 (1972).

129. R. Razgaitis and J. P. Holman, *A Survey of Heat Transfer in Confined Swirl Flows*, presented at the Summer Seminar of the International Centre for Heat and Mass Transfer, Dubrovnik, Yugoslavia, Aug. 25-30, 1975.

130. F. A. Zenz, "The Feasibility of Existing Technology for Removal of Particulate Solids from High Temperature Feed Gases," *Purification of Hot Fuel Gases from Coal or Heavy Oil*, EPRI 243-1, pp. I-1 to I-10 (1974).

131. A. C. Stern *et al.*, *Fundamentals of Air Pollution*, Academic Press (1973).

132. D. Leith and D. Mehta, *Cyclone Performance and Design*, Atmos. Environ. 7, 527-549 (1973).

133. D. Leith and W. L. Licht, *The Collection Efficiency of Cyclone Type Particle Collector -- A New Theoretical Approach*, AIChE Symp. Ser. 68(126), 196-206 (1972).

134. R. Mck. Alexander, Proc. Australas. Inst. Mining Met. 152, 202 (1949).

135. H. J. van Ebbenhort Tengbergen, Staub 25, 44 (1965).

136. K. J. Caplan, "Source Control by Centrifugal Force and Gravity," in *Air Pollution*, Vol. 3, 2nd Ed., A. C. Stern, Ed., Academic Press, pp. 359-407 (1968).

137. R. D. Ross, Ed., *Air Pollution and Industry*, Van Nostrand-Reinhold, New York, pp. 348-350 (1972).

138. Fisher-Klosterman, Inc., "Super-Cyclone," *Pollut. Eq. News*, 18 (Feb. 1976).

139. *The Ferro-Tech High Efficiency Centrifugal Dust Collector*, technical literature of Ferro-Tech, Inc., Pittsburgh, Pa.

140. P. N. Cheremisinoff and R. A. Young, *Pollution Engineering Practice Handbook*, Ann Arbor Science Pub. Inc. (1975).

141. V. A. Zysin, *Development of Combined Steam and Gas Turbine Power Plants*, Therm. Eng. 15, 1 (1968).

142. S. N. B. Murthy, *Survey of Some Aspects of Swirling Flows*, ARL 71-0244 (Nov. 1971).

143. S. H. Hasinger, R. H. Mills, and H. J. P. von Ohain, Internal unpublished ARL report.

144. A. C. Pinchak and R. Poplawski, *On the Attainment of Extremely High Rotational Velocities in a Confined Vortex Flow*, AIAA Second Annual Meeting, San Francisco, California, Paper 65-200, July 26-29, 1965.

145. R. Poplawski and A. C. Pinchak, *Aerodynamic Performance of Reversed Flow Vortex Chambers*, ARL 65-219 (Oct. 1965).

146. T. D. Fiorina, Jr. and R. Poplawski, *Experimental Optimization of the Reversed Flow Vortex Chambers*, ARL 65-66 (April 1965).

147. R. Poplawski and A. C. Pinchak, *Aerodynamic Effects of Secondary Flows in Confined Vortices*, Res. Review, Office of Aerospace Research (OAR) No. 11, 18-22 (January 1966).

148. R. A. Miller and R. Poplawski, *The Inertial Particle Separator for Military Turbine Powered Vehicles*, Proceedings of the Office of Aerospace Research (OAR) Research Applications Conference, Washington, D.C., April 5, 1966, pp. 44-69.

149. R. Poplawski, *Potential Scope of Application of the ARL Separator for Turbine Powered Vehicles*, Proceedings of the Counter-insurgency Research and Development Symposium, Advanced Research Projects Agency, Wash., D.C., June 14-16, 1966, pp. 519-539.

150. E. C. Fletcher, G. Gyarmathy, and S. Hasinger, *Separation of Submicron Condensate Particles in a Vortex Chamber*, ARL 66-0218 (November 1966).

151. Roger A. Miller, *Field Testing the ARL Dust Separator*, Res. Rev. (Office Aerosp. Res.) VI(1), 1-6 (Jan. 1967).

152. A. C. Pinchak, *A Review of the State of the Art of Cyclone-Type Separators*, ARL 67-0047 (March 1967).

153. G. Gyarmathy, *Optical Measurement of Radial Density Distributions in a High-Speed Confined Vortex*, ARL 67-0234 (Dec. 1967).

154. R. Poplawski and R. A. Miller, *Microscopic Particle Separation and Applications*, ARL 68-0024 (Feb. 1968).

155. John D. Lee, *An Experimental Study of the Flow in a Low Pressure Swirl Chamber*, The Ohio State University, Air Force Contract No. 33(615)-1063, ARL 68-0072 (April 1968).

156. O. R. Burggraf, *A Linearized Analysis of Mass-Transfer Effects on Confined Laminar Vortex Flows*, The Ohio State University, Air Force Contract No. 33(615)-1063, ARL 68-0071 (April 1968).

157. S. H. Hasinger, *An Experiment with Particles in a Free Vortex*, AIAA J. 6(5) 939-940 (May 1968).

158. J. D. Lee, *Nature of the Flow in a Swirl Chamber Having Endwall Flow Reversal*, The Ohio State University, Air Force Contract No. 33(615)-1063, ARL 68-0131 (July 1968).

159. S. H. Hasinger, *Limit of Centrifugal Separation in a Free Vortex*, AIAA J. 9(4), 644-648 (April 1971).

160. *TAN-JET Cyclone Systems*, technical information literature published by Donaldson Co., Inc., Corad Division, P.O. Box 1299, Minneapolis, Minn. 55440.

161. *AERODYNE Series 'SV' Dust Collector*, technical literature published by the Aerodyne Development Corp., 29085 Solon Rd., Cleveland, Ohio.

162. F. Kreith, "Convection Heat Transfer in Rotating Systems," in *Advances in Heat Transfer*, Vol. 5, T. F. Irvine and J. P. Hartnett, Eds., Academic Press, pp. 129-253 (1968).

163. J. H. Cannon and W. M. Kayes, *Heat Transfer to a Fluid Flowing Inside a Pipe About its Longitudinal Axis*, J. Heat Transfer 91(1), 135-139 (Feb. 1969).

164. B. W. Wilson, *The Turbocyclone: A New Method for Separating Fine Particles from Gas Streams*, Aust. J. Appl. Sci. 4(1), 49-57 (March 1953).

165. P. Schmidt, *Staubzentrifuge*, Chem. Ing. Tech. 47(3), 107 (Jahrg. 1975).

166. K. Barth and L. Leineweber, Staub 24, 41/55 (1964).

167. E. Muchselknautz, Staub 30, 187/195 (1970).

168. R. G. Dorman, *Filtration*, Aerosol Science, C. N. Davies, Ed., Academic Press, pp. 195-222 (1966).

169. J. Pich "Theory of Aerosol Filtration by Fibrous and Membrane Filters," in *Aerosol Science*, C. N. Davies, Ed., Academic Press, pp. 223-286 (1966).

170. H. L. Englebrecht, *The Gravel Bed Filter--A New Approach to Gas Cleaning*, J. Air Pollut. Control Assoc. 15(2), 43 (1965).

171. R. A. Juvinal *et al.*, *Sand-Bed Filtration of Aerosols: A Review of Published Information on Their Use in Industrial and Atomic Energy Facilities*, Argonne National Laboratory Report ANL-7683 (June 1970).

172. H. G. Rigo, *Gaseous Flow Separator and Heat Exchanger*, U.S. Patent 3,815,336 (1974).

173. H. G. Rigo and J. J. Stukel, *High Temperature Dust Control-Improving Energy Efficiencies with a Combination Heat Exchanger and Flow-Phase Separator*, presented at 13th Annual Meeting of the East Central Sec. of APCA, 1973.

174. E. M. Honig and M. K. Lee, *High Temperature Dust Control*, Second Quarterly Progress Report for the Period Nov. 1975-Jan. 1976 for U.S. ERDA by the Construction Engineering Research Laboratory (Dept. of the Army), Champaign, Ill. (Jan. 1976).

175. A. M. Squires and R. Pfeffler, *Panel Bed Filters for Simultaneous Removal of Fly Ash and SO_2: I. Introduction*, J. Air Pollut. Control Assoc. 20, 523 (1970).

176. Anonymous, Environ. Sci. and Technol. 8(7), 600-601 (July 1974).

177. AIChE Symp. Ser. 70(137), 388-397 (1974).

178. R. A. Chapman and R. R. Wocasek, *CPU-400 Solid-Waste-Fired Gas Turbine Development,* presented at the International Incinerator Conference, May 17, 1972.

179. Anonymous, *Novel Filter Cleans Stack Gases,* Can. Chem. Process. 7-8 (Dec. 1975).

180. J. M. Beeckmans and S. Keillor, J. Colloid Interface Sci. 30, 387 (1969).

181. J. M. Beeckmans and P. Sen Gupta, Can J. Chem. Eng. 49, 721 (1971).

182. X. Nguyen and J. M. Beeckmans, *Sonically Enhanced Depth Filtration of Aerosols,* Aerosol Sci. 5, 133-143 (March 1974).

183. G. Nonhebel, *Gas Purification Processes,* George Newnes Ltd., London (1964).

184. J. I. Yellott and E. F. Lype, *Some Effects of Pressure Loss on the Open-Cycle Gas-Turbine Power Plant,* Trans. ASME 69, 903-911 (Nov. 1947).

185. S. L. Soo, *Power Efficiency for Dust Collection,* Environ. Sci. Technol. 7(1), 63-64 (Jan. 1973).

186. J. J. Stukel and H. G. Rigo, *Energy Efficiencies of Air Pollution Control Devices,* Atmos. Environ. 9, 529-535 (1975).

187. A. D. Zimon, *Adhesion of Dust and Powder*, Plenum Press, New York (1969).

188. R. G. Boothroyd, *Flowing Gas-Solids Suspensions,* Chapmand and Hall Ltd., London (1971).

189. W. B. Pietsch, *Adhesion and Agglomeration of Solids During Storage, Flow and Handling--A Survey,* J. Eng. Ind. 91(2), 435-449 (May 1969).

190. S. K. Beal, *Turbulent Agglomeration of Suspensions*, Aerosol Sci. 3, 113-125 (1972).

191. J. D. Yoder and L. Silverman, *Influence of Turbulence on Aerosol Agglomeration and Deposition in a Pipe,* Paper No. 67-33, presented at 60th Annual APCA Meeting, Cleveland, Ohio, June 13, 1967.

192. E. E. Hickey and C. E. Billings, "Agglomeration of Particulate Matter," *Fifth Atomic Energy Commission Air Cleaning Conference,* pp. 130-132 (1957).

193. G. Zebel, "Coagulation of Aerosols," in *Aerosol Science,* C. N. Davies, Ed., Academic Press, New York, pp. 31-58 (1966).

194. S. L. Soo, "Dynamics of Charged Suspensions," in *Topics in Current Aerosol Research,* Pergamon Press, New York, pp. 61-150 (1971).

195. W. V. Botts and R. D. Oldenkamp, *The Atomics International Molten Carbonate Process for SO_2 Removal from Stack Gases,* EPA Rpt. 650/2-73-038 (May 1969).

196. *Handbook on Aerosols*, U.S.AEC, Washington, D.C. (1950).

197. *Air Pollution Handbook*, P. L. Magill *et al.*, Eds., McGraw-Hill, New York (1956).

198. E. P. Mednikov, *Acoustic Coagulation and Precipitation of Aerosols*, Consultants Bureau, New York (1965).

199. N. A. Fuchs, *Advances in the Mechanics of Aerosols*, AD 682 0682 (May 1968).

200. N. L. Shirokova, "Aerosol Coagulation," in *Physical Principles of Ultrasonic Technology*, Vol. 2, L. D. Rozenberg, Ed., Plenum Press, pp. 476-539 (1973).

201. R. Hegarty and L. J. Shannon, *Evaluation of Sonics for Fine Particulate Control*, EPA 600/2-76-001 (Jan. 1976).

202. A. Kundt, *On a New Type of Acoustic Dust Figure and on a New Application of the Same for the Determination of Sound Velocity in Solid Bodies and Gases*, (in German), Pogg. Annales 127, 497 (1866).

203. W. Konig, *Hydrodynamisch-Akustische Untersuchungen: Uber die Kroftzwischen zwei Kugeln in einer Schwingenden Flussigkeit und uber die Entstehung der Kindtschen Staubfiguren*, Ann Physik 42(4), 549 (1891).

204. H. S. Patterson and W. Cawood, *Phenomena in a Sounding Tube*, Nature 127, 3209, 6677 (1931).

205. E. V. Amy, *Dispersing Particles Suspended in Air*, U.S. Patent No. 1,980,171 (1934).

206. H. W. St. Clair, *Sonic Flocculator and Method for Flocculating Smoke and the Like*, U.S. Patent 2,215,484 (1940).

207. J. Y. Houghton and T. H. Brown, *Smoke and Fume Separating*, U.S. Patent 2,216,779 (1940).

208. R. C. Jones, *A Fifty Horsepower Siren*, J. Acoust. Soc. Am. 18(2), 371-387 (1946).

209. H. W. Danser, Jr. and E. P. Neumann, *Industrial Sonic Agglomeration and Collection System*, Ind. Eng. Chem. 41, 24-39 (1949).

210. H. W. Danser, Jr., *Eliminate Stack Dusts and Mists*, Chem. Eng., 158-160 (May 1950).

211. E. P. Neumann *et al.*, "Design, Application, Performance, and Limitation of Sonic Type Fluculators and Collectors," in *Air Pollution*, L. McCabe, Ed., McGraw-Hill, pp. 388-393 (1950).

212. E. P. Neumann *et al.*, Air Pollution Procedures, in *U.S. Technical Conference on Air Pollution, 1952*, McGraw-Hill p, 388 (1952).

213. Anonymous, *Sound-Pulses Clean Foul Air,* Chem. Eng. 52-54 (Aug. 24, 1970).

214. E. F. Kent, V. P. Mech. Eng., Braxton Corp., private communication (Feb. 9, 1976).

215. *Coupling,* U.S. Patent 3,599,748 (Aug. 17, 1971).

216. *Force Dist. Structure,* U.S. Patent 3,606,263 (Sept. 20, 1971).

217. *Method and Apparatus for Removal Material from Stack Gases,* U.S. Patent 3,681,009 (Aug. 1, 1972).

218. *Stimulator,* U.S. Patent 3,708,033 (Jan. 2, 1973).

219. S. Y. Tsai, *Theoretical Analysis of Agglomeration of Aerosols in Acoustic Fields,* Ph.D. Thesis, Northeastern University, Boston, Mass. (1973).

220. S. Y. Tsai, *Particle Collection by Means of Low Frequency Sound Waves,* Atmos. Environ. 8, 873-884 (1974).

221. Richard Dennis *et al., Braxton Sonic Agglomerator Evaluation,* EPA-650/2-74-036 (May 1974).

222. *Emissions Control Equipment,* J. Air Pollut. Control Assoc. 26(3), 264-274 (March 1976).

223. D. S. Scott, *Method of Coagulating Aerosols,* U.S. Patent 3,771,286 (1973).

224. G. A. Davidson and D. S. Scott, *Finite-Amplitude Acoustics of Aerosols,* J. Acoust. Soc. Am. 53, 1712-1729 (1973).

225. G. A. Davidson and D. S. Scott, *Finite-Amplitude Acoustic Phenomena in Aerosols from a Single Governing Equation,* J. Acoust. Soc. Am. 54(5), 1331-1342 (1973).

226. D. S. Scott *et al., On Waveforms and Sound Production in Acoustic Agglomeration of Aerosols,* Proc. Symp. Finito-Amplitude Effects in Fluids, IPC Science and Technology Press, London, pp. 130-133 (1973).

227. D. C. Scott, *Advances in the Sonic Agglomeration of Industrial Aerosol Emissions,* Proc. Symp. Control of Fine-Particulate Emissions from Industrial Sources, pp. 597-621 (1974).

228. D. A. Scott and D. F. Rennick, *On the Dynamics of Small Aerosol Particles,* Aerosol Sci. 5(3), 301-315 (May 1974).

229. D. C. Scott, *A New Approach to the Acoustic Conditioning of Industrial Aerosol Emissions,* J. Sound Vib. 43(4), 607-619 (Dec. 8, 1975).

230. G. M. Fair and R. S. Gemmell, *Some Aspects of Orthokinetic Flocculation,* Progress Report, Oct. 1, 1960 - Sept. 30, 1962, Harvard University, Division of Engineering and Applied Physics.

231. G. Yu. Statnikov and N. L. Shirokova, *Calculation of the Efficiency of Acoustic Aerosol Coagulation*, Sov. Phys. Acoust. (trans.) (USA) 20(1) (July-Aug. 1074).

232. V. A. Kit, V. I. Timoshenko, and Ya. T. Fedoruk, *Choosing the Optimum Conditions for the Acoustic Coagulation of Aerosols*, Sov. Phys. Acoust. (trans.) (USA) 19(2), 181-182 (Sept.-Oct. 1973)

233. R. H. Koefke, *Streaming of a Particulate Aerosol Due to Acoustic Excitation*, Water, Air and Soil Pollut. (Netherlands) 1(2), 212-226, (April 1972).

234. M. Jessel and V. Timochenko, *On the Dynamic Process of Acoustic Coagulation*, Comp. rend. Acad. Sci. Series B, 272(26), 1457-60 (June 28, 1971).

235. L. V. King, Proc. Roy. Soc. (London) A147(233) (1934).

235a. B. F. Podoshevnikov, *Acoustic Coagulation of Aerosols as a Function of the Amount of Sound Exposure*, Zh. Prikl. Khimi. 34(12), 2664-2668 (1961).

236. H. W. St. Clair, *Sonic Flocculator as a Fume Settler: Theory and Practice*, U.S. Bureau of Mines RI 3400 (1938).

237. E. P. Neumann and J. L. Norton, *Application of Sonic Energy to Commercial Aerosol Collection Problems*, Chem. Eng. Progr. Symp. Ser. Sec. 1, 47(1), 4-10 (1951).

238. J. R. Krebs *et al.*, Combustion 23, 45-47 (June 1952).

APPENDIX 1. Bibliography--Periodicals Whose Scope Includes Aerosols (taken from Ref. 1)

American Institute of Aeronautics and Astronautics Journal
Air Pollution Titles
Air Quality Control Digest
American Industrial Hygiene Association Journal
Annals of Occupational Hygiene
Applied Optics
Archiv fuer Meteorologie, Geophysik and Biolimatologie, Series A
Archives of Environmental Health
Atmospheric Environment
Beiträge zur Phyzik der Atmosphere
Colloid Journal of the USSR (English, Translation of Kolloidhyi Zhurnal)
Contamination Control
Environment
Environmental Science and Technology
Icarus
Industrial Engineering Chemistry Fundamentals
I.S.A. (Instrument Society of America) Transactions
Journal of Aerosol Science
Journal of the Air Pollution Control Assoication
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Journal of the Atmospheric Sciences
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Pollution Abstracts
Pollution Atmospherique
Pollution Engineering
Powder Technology
Proceedings of the Royal Irish Academy
Quarterly Journal of the Royal Meteorological Society
Review of Scientific Instruments
Smokeless Air
Staub
Tellus

APPENDIX 2. A Basic Library of Books on Aerosols (taken from Ref. 1)

T. Allen, *Particle Size Measurement*, 1968, Chapman and Hall, Ltd., London.

American Conference of Governmental Industrial Hygienists, 1972, *Air Sampling Instruments*, 4th ed.

R. D. Cadle, 1953, *Particle Size Determination*, Interscience Publishers, a division of John Wiley & Sons, Inc., New York.

J. M. Dalla Valle, 1948, *Micromeritics*, 2nd ed., Pitman Publishing Corporation, New York.

C. N. Davies, 1967, *Aerosol Science*, Academic Press, New York.

P. Drinker and T. Hatch, 1954, *Industrial Dusts*, 2nd ed., McGraw-Hill Book Company, New York.

H. Englund and W. T. Berry (Eds.), 1971, *Proceedings of the Second International Clean Air Congress, held at Washington, D.C., Dec. 6-11, 1970*, Academic Press, Inc., New York.

S. K. Friedlander, L. Silverman, P. Drinker, and M. W. First, 1952, Handbook on Air Cleaning, Harvard University, U.S. Atomic Energy Commission, Washington, D.C.

N. A. Fuchs, 1964, *Mechanics of Aerosols*, The Macmillan Co., New York, and Pergamon Press, Inc., New York.

N. A. Fuchs, 1968, An Attempt at a Classification of Aerosol Literature, *Staub-Reinhalt. Luft*, *28*(9): 1.

N. A. Fuchs, 1971, *Collection of Aerosol Abstracts*, Vol. 1, Viniti, Moscow.

N. A. Fuchs and A. G. Sutugin, 1971, *Highly Dispersed Aerosols*, Pergamon Press, Inc., Oxford.

W. E. Gibbs, 1924, *Clouds and Smokes*, Blakiston's, Philadelphia.

H. L. Green and W. R. Lane, 1964, *Particulate Clouds: Dusts, Smokes, and Mists*, Van Nostrand Reinhold Co., New York.

Handbook on Aerosols, 1950, selected chapters from the summary technical report of Division 10, National Defense Research Committee, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

G. Herdan, 1960, *Small Particle Statistics*, Academic Press, Inc., New York.

G. M. Hidy and J. R. Brock (Eds.), 1970-1972, *International Reviews in Aerosol Physics and Chemistry*, 3 vols. Pergamon Press, Inc., Oxford.

International Atomic Energy Agency, 1967, *Assessment of Airborne Radioactivity*, Symposium Proceedings, Vienna, July 3-5, 1967, International Atomic Energy Agency, Vienna, (STI/PUB/159).

Intersociety Committee, 1972, *Methods of Air Sampling and Analysis*, American Public Health Association, Washington, D.C.

R. Irani and C. F. Callis, 1963, *Particle Size: Measurement, Interpretation, and Application*, John Wiley & Sons, Inc., New York.

M. Kerker, 1969, *Scattering of Light and Other Electromagnetic Radiation*, Academic Press, Inc., New York.

W. E. Kuhn, *et al.* (Eds.), 1963, *Ultrafine Particles*, John Wiley and Sons, Inc., New York.

C. E. Lapple, 1950, Separation of Dusts and Mists, *Chemical Engineers' Handbook*, J. H. Perry (Ed.), 3rd ed., p. 1013, McGraw-Hill Book Company, New York.

C. E. Lapple, 1956, *Fluid and Particle Mechanics*, University of Delaware, Newark, Del.

J. Ledbetter, 1972, *Air Pollution*, Vol. 1, Analysis, Marcel Dekker, Inc., New York.

W. Leithe, 1970, *Analysis of Air Pollutants*, Ann Arbor Science Publishers, Inc., Ann Arbor, Mich.

P. Magill, *et al.* (Eds.), 1956, *Air Pollution Handbook*, McGraw-Hill Book Company, New York.

K. H. Mancy, 1971, *Instrumental Analysis of Air Pollutants*, Ann Arbor Science Publishers, Inc., Ann Arbor, Mich.

W. C. McCrone, *et al.*, 1971, *Particle Atlas*, Ann Arbor Science Publishers, Inc., Ann Arbor, Mich.

E. P. Mednikov, 1965, *Acoustic Coagulation and Precipitation of Aerosols*, Plenum Press, Inc., New York.

T. T. Mercer, *et al.* (Ed.), 1971, *Assessment of Airborne Particles: Fundamentals, Applications and Implications to Inhalation Toxicology*, Charles C. Thomas, Publisher, Springfield, Ill.

C. Orr, 1966, *Particulate Technology*, The Macmillan Co., New York.

C. Orr, 1971, *Filtration--Principles and Techniques*, Marcel Dekker, Inc., New York.

C. Pazar, 1970, *Air and Gas Clean-Up Equipment*, Noyes Data Corporation, Park Ridge, N.J.

E. G. Richardson (Ed.), 1960, *Aerodynamic Capture of Particles*, Pergamon Press, Inc., New York.

A. T. Rossano, Jr., and H. B. Cooper, 1970, *Source Testing Handbook for Air Pollution Control*, Environmental Science Service, Wilton, Conn.

L. S. Ruzer, 1968, *Radioactive Aerosols*, Bureau of Standards, Moscow.

P. A. Sanders, 1970, *Principles of Aerosol Technology*, Van Nostrand Reinhold Company, New York.

R. S. Scorer, 1968, *Air Pollution*, Pergamon Press, Inc., New York.

J. P. Sheehy, W. C. Achinger, and R. A. Simon, Handbook of Air Pollution, U.S. Department of Health, Education and Welfare, National Center for Air Pollution Control, Document 999-AP-44, Washington, D.C.

H. R. Sheperd, 1960, *Aerosols: Science and Technology*, John Wiley & Sons, Inc., New York.

L. Silverman, C. E. Billings, and M. W. First, 1971, *Particle Size Measurement in Industrial Hygiene*, U.S. Atomic Energy Commission, Monograph Series, Academic Press, Inc., New York.

M. Sittig, 1968, *Air Pollution Control*, Noyes Data Corp., Park Ridge, N.J.

D. H. Slade (Ed.), 1968, Meteorology and Atomic Energy--1968, USAEC Report TID-24190.

S. L. Soo, 1967, *Fluid Dynamics of Multi-Phase Media*, Blaisdell Publishing Co., Inc., Waltham, Mass.

W. T. Sproull, 1970, *Air Pollution and Its Control*, Exposition Press, Inc., Jericho, N.Y.

K. Spurny, 1966, *Aerosols: Physical Chemistry and Applications*, Gordon and Breach, Science Publishers, Inc., New York.

E. S. Starkman, (Ed.), 1971, *Combustion-Generated Air Pollution*, Plenum Press, Inc., New York.

A. C. Stern (Ed.), 1968, *Air Pollution: A Comprehensive Treatise*, 3 vols., Academic Press, Inc., New York.

W. Strauss, 1966, *Industrial Gas Cleaning*, Pergamon Press, Inc., New York.

W. Strauss (Ed.), 1970, *Air Pollution Control*, John Wiley & Sons, Inc. New York.

U.S. Weather Bureau, 1955, Meteorology and Atomic Energy, USAEC Report AECU-3066.

H. C. van de Hulst, 1957, *Light Scattering by Small Particles*, John Wiley & Sons, Inc., New York.

H. J. White, 1963, *Industrial Electrostatic Precipitation*, Pergamon Press, Inc., New York.

R. Whytlaw-Gray and H. S. Patterson, 1932, *Smoke*, Edward Arnold, London.

A. D. Zimon, 1969, *Adhesion of Dust and Powder*, Plenum Press, Inc., New York.

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A. L. Conn, Amoco Oil Company
G. G. Copeland, Copeland Systems, Inc.
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R. Covell, Combustion Engineering, Inc.
G. Curran, Conoco Coal Development Co.
D. DeCoursin, Fluidyne Engineering Co.
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