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STATE OF THE ART: 1971. INSTRUMENTATION FOR MEASUREMENT OF PARTICULATE EMISSIONS FROM COMBUSTION SOURCES. VOLUME I: PARTICULATE MASS - SUMMARY REPORT

Thermo-Systems, Incorporated
St. Paul, Minnesota

April 1971

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INSTRUMENTATION FOR
MEASUREMENT OF PARTICULATE EMISSIONS
FROM COMBUSTION SOURCES
VOLUME I PARTICULATE MASS - SUMMARY REPORT

by

Gilmore J. Sem
John A. Borgos
John G. Olin
John P. Pilney
Benjamin Y. H. Liu
Nicholas Barsic
Kenneth T. Whitby
Frank D. Dorman

Thermo-Systems Inc.
2500 North Cleveland Avenue
St. Paul, Minnesota 55113

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16. Abstracts

All known sensing techniques available for application to automatic, continuous measurement of the rate of particulate mass emissions from large fossil-fuel combustion facilities are discussed. Emphasis is on the measurement of particle mass rather than other particle parameters, and emissions downstream rather than upstream of any control equipment. Although sensors for permanently-installed effluent monitoring systems are emphasized, much of the information is also applicable to portable and research instruments. Brief surveys are presented of all known particle sensing techniques. A brief discussion of the principle of operation is followed by a list of inherent and practical strengths and weaknesses of each technique. A list of commercial manufacturers of related equipment and a list of 1,352 references helps the reader who needs more information on a specific technique. Recommendations for further development outline areas of needed improvement for techniques which offer some promise for stack monitoring. The introduction includes general comments which apply to all sensing techniques, and ranks all techniques in order of present apparent potential. A separate chapter summarizes typical conditions found in large fossil-fuel effluent gases and sets the necessary specifications for a particulate monitoring instrument which operates in an effluent gas atmosphere.

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THERMO-SYSTEMS INC

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FOREWORD

The compilation of the information contained in this publication was performed pursuant to Contract 70-23 with the Air Pollution Control Office, Environmental Protection Agency.

The information was compiled by Thermo-Systems Inc , and their sub-contractor, North Star Research and Development, during the period 12 February 1970 to April 1971.

Volume I of this report is written for the engineer or planner who needs to know a few basic facts about a particulate mass measurement technique and wishes to minimize the time required to obtain this information. Volume I is intended for use as a quick reference guide.

Volume II of this report is designed as a detailed in-depth report on operating principles, techniques, historical data, and discussion of the more viable techniques for particulate mass monitoring. Volume II is designed for the plant engineer, abatement and control officials, and others who may not be familiar with the detailed technology of these areas. Included are sections on power plant emissions properties and extraction sampling probes.

Volume III of this report is a comprehensive survey of particle sizing techniques which may be used by the plant engineer, abatement and control officials, and others as a quick reference guide or as a source of more detailed information, including references to original work.

Volume IV of this report describes an experimental evaluation of the beta radiation attenuation and piezoelectric microbalance techniques for mass concentration measurements on a coal-fired power generating plant. Problem areas requiring further development are identified for personnel concerned with improving the techniques.

This report is reviewed and approved.

F. C. Jaye
Project Officier
Environmental Protection Agency

ABSTRACT AND CONCLUSIONS

This report discusses all known sensing techniques available for application to automatic, continuous measurement of the rate of particulate mass emissions from large fossil-fuel combustion facilities. The report emphasizes the measurement of particle mass rather than other particle parameters, and emissions downstream rather than upstream of any control equipment. Although the report emphasizes sensors for permanently-installed effluent monitoring systems, much of the information is also applicable to portable and research instruments.

Volume I (this volume) contains brief surveys of all known particle sensing techniques. A brief discussion of the principle of operation is followed by a list of inherent and practical strengths and weaknesses of each technique. A list of commercial manufacturers of related equipment and a list of references helps the reader who needs more information on a specific technique. Recommendations for further development outline areas of needed improvement for techniques which offer some promise for stack monitoring. The introduction includes general comments which apply to all sensing techniques, and ranks all techniques in order of present apparent potential. A separate chapter summarizes typical conditions found in large fossil-fuel effluent gases and sets the necessary specifications for a particulate monitoring instrument which operates in an effluent gas atmosphere.

Volume II contains detailed discussions of particle sensing techniques as applied to emissions monitoring. Each discussion analyzes possible problems, and their solutions, in using the technique for emissions monitoring, and includes an analysis of what particulate parameter the technique senses, how closely the measurement correlates with particulate mass, inherent measurement errors, practical design problems and possible solutions, the potential sensitivity and response of each technique, the complexity of the potential instrument, the present state of development of the technique, and recommendations for further development. Each discussion includes a complete bibliography. A separate chapter describes typical conditions found in large fossil-fuel effluent gases in greater detail than found in Volume I. Another separate chapter summarizes many of the problems encountered in the design of sampling probes required by most of the particle sensing techniques.

Accurate measurement of the particulate mass emissions rate requires an instrument which directly senses the true mass of the particles. Sensors that are not sensitive to particulate mass, even though they may be calibrated against a mass sensor, do not and cannot yield satisfactory correlation with particle mass emissions during periods of changing and/or abnormal plant operating conditions. Effluent characteristics, such as particle size and density, change often in stacks. This may be a result of changes in combustion efficiency, fuel composition, collector performance, or other system variables.

All existing mass sensors require at least partial extraction of a representative effluent sample from the stack. No present commercial mass sensors meet the requirements for accurate, long-term, continuous monitoring. Two techniques could probably be developed into next-generation commercial stack monitors within 1 - 3 years beta radiation attenuation and piezoelectric microbalance. Beta radiation attenuation has been partially developed for stacks with several first-generation commercial instruments available. These instruments appear to need design improvements First-generation piezoelectric microbalance instruments exist for ambient air monitoring, but no stack monitoring development has been done.

Optical, or light, transmission is presently the most commonly used particulate monitoring technique. It measures the optical density of stack effluents very accurately if the instrument is carefully designed. Unfortunately, few of the presently available transmissometers are well-designed for accurate long-term optical density measurements Although light transmission offers several significant instrument design advantages, the measurement does not correlate well with particulate mass measurement, especially during changing effluent conditions.

Volume III contains discussions of automatic or semi-automatic particle size measuring techniques as applied to emissions monitoring. The dicussions emphasize the particulate parameter (mass, number, surface area, etc.) which each technique senses as well as the method of classifying particles into size ranges (aerodynamically, electrostatically, optically, etc.). Included are major features of each technique, including practical problems which may be encountered when applying the technique to effluent streams. Also included is a brief, but comprehensive, survey of the many methods of expressing particle size, and an evaluation of which are most useful for effluent particles.

Volume IV is the final report containing preliminary results of an experimental evaluation of the beta radiation attenuation technique and the piezoelectric microbalance technique. Most of the experimental work was performed on an effluent duct of a large coal-fired power generating plant. The experimental sampling system and the method of evaluation are described.

INTRODUCTION

Measurement of the total mass flow of particulate emissions from large combustion facilities is a major problem facing plant owners, pollution control officials, and emission control equipment manufacturers. Plant owners need such measurements to more carefully control the combustion and air pollution control efficiency of the facility. Pollution control officials need permanent records of stack mass emissions to aid in air pollution abatement. Emission control equipment manufacturers need more efficient ways to evaluate the performance of their equipment. Instrumentation that automatically and continuously records particulate mass emissions is rapidly gaining importance as a desirable tool to accomplish these goals.

In the past, particulate emissions measurements have been made by sampling a known volume of effluent gas through a filter, and weighing the filter before and after sampling to find the particle mass concentration. By traversing the effluent gas stream cross-section to measure gas velocity as well as to obtain the filter samples, an estimate of the total mass of particles emitted per hour could be made. Such measurements require considerable equipment, labor, and time. One series of measurements typically takes about four hours with perhaps three additional man-days of labor for planning, equipment transport, setup, sampling, and data reduction. This method cannot be used economically on a regular basis for measuring combustion efficiency, for monitoring pollutant emissions, or for extensively evaluating pollution control equipment.

Thus, the emphasis of this report is on automatic and continuous monitors of particulate mass emissions. Automatic means that the instrument is capable of unattended operation for extended periods of time, at least 24 hours, but preferably more than a week. Continuous means that measurements are either made instantaneously in real time, or measurements are made with a frequency great enough for most practical monitoring purposes. A measurement every few minutes is probably sufficient for monitoring pollutant emissions while nearly instantaneous measurements may be needed for some evaluations of pollution control equipment. Often, a gain in the speed with which a measurement can be made results in a sacrifice in accuracy.

The primary goal of this discussion is to define the relative merits of particle-sensing instruments with regard to the measurement of particulate mass or mass concentration. Notice that the emphasis is on the direct measurement of mass, not some other particle parameter. Any instrument which measures some other form of particle concentration, whether it is number, area, or some other parameter, can be calibrated to read mass concentration under specific conditions. However, if those specific conditions change, the mass calibration is no longer valid and inaccurate measurements result. Parameters such as the size distribution and specific gravity of emissions particles can, and do, change drastically with minor changes in combustion efficiency or coal composition within a specific facility. Therefore, instruments which do not directly sense particle mass, or a parameter closely related to mass, must be severely discounted for reliable mass emissions measurement. In the following discussions of measurement techniques, special emphasis is given to the parameter of the particles which each technique measures.

Particle sensing techniques have many monitoring applications ranging from clean rooms to pneumatic conveying systems. Only a few of the techniques are applicable to the sensing of particles in effluent gas streams from combustion sources. Fewer yet are applicable to the sensing of particulate mass in such streams. The measurement of primary interest from a pollution standpoint is the particulate mass flow rate, i.e., the total mass of particles leaving the stack per hour. Most particulate mass sensors, on the other hand, measure particle concentration in terms of the mass of particles per unit of gas volume. This discussion assumes that the measurement of particulate mass concentration is sufficient to define particulate mass flow rate. The volumetric gas flow rate must be measured separately or estimated from the operating conditions of the process.

A complete particulate mass concentration monitoring system generally consists of three components: a sampling system, a sensing system, and a data processing and recording system. The subject of this report is the sensing system. Data processing and recording is only discussed in cases where it becomes significantly simpler or more complicated than usual.

The sampling system, including the nozzle, probe, and sample conditioner, usually contributes as much to the measurement error as the sensing system. The design of an optimum sampling system is a difficult problem. Indeed, at the present time, sampling systems are a highly controversial subject. The brief report on sampling probe design included in Volume II of this report does not pretend to be complete, but does introduce many of the problems encountered in designing such a system.

Several particulate emissions monitoring systems consist of only two major components: a sensing system and a data processing and recording system. They do not require a sampling system with its accompanying measurement errors. As will be seen later, however, all of the techniques which do not need a sampling system have other problems which may result in even greater errors in the measurement of particulate mass.

There is a question about the relative merits of integrated versus point measurements of particle concentration. The most commonly used particle monitors, light transmissometers, are integrating instruments. They measure the average particle concentration along the measuring path. Most other potential and existing particle monitoring instrument measure the particle concentration at a point within the duct. If the gas velocity and particle concentration profiles are relatively homogeneous across the duct, either integrated or point sampling can yield good results with little trouble. However, such conditions seldom exist. Not only is the gas velocity profile usually skewed, but the particle concentration profile may be skewed in a different way. Thus, in general, it is not clear which sampling method will result in the most representative measurement. Each specific situation must be analyzed in detail. One conclusion is certain, however: the placement of any instrument within an effluent duct must be done carefully so that a representative measurement is made.

The operating environment strongly affects the application of any instrument for measuring particulate emissions. A separate chapter defines typical effluent gas stream conditions for large, modern, fossil-fuel combustion facilities. The data was obtained through an extensive survey of the open literature and private reports. There is a rather severe lack of detailed information about emissions from combustion sources, primarily caused by the difficulty in making the measurements. The information about effluent gas conditions was used to define a set of desirable instrument specifications for monitoring particulate effluents. A more detailed description of effluent gas streams is included in Volume II of this report.

Since the effluent from oil combustion facilities is relatively free of particles and since only about 10% of the electric power in the U. S. is generated by such plants, the remainder of the discussion is directed primarily toward coal combustion facilities.

Particulate emissions from coal combustion facilities are usually measured in the breeching, a section of rectangular duct between the collector equipment and the vertical stack. Because the breeching is usually quite short and is seldom straight, ideal sampling conditions seldom occur. The choice of the sampling location is very important, and should be considered carefully whenever emissions measurements are made. In most cases, the accuracy of the measurement depends as much on the representativeness of the sample as on the accuracy of the sensor.

Particulate emissions are usually not measured in the vertical stacks for several reasons. In cases where several sections of breeching feed one vertical stack, measurements in the breeching allow the operator to monitor the performance of each precipitator separately. Well-developed flow conditions exist only near the top of the stack, if at all, where instrument installation is very difficult if not impossible. Most present-day instruments require regular maintenance, making installations high on a stack very inconvenient. Installation near the bottom of the stack usually has no signficant advantage over installation in the breeching. In the few instances where installation near the top of the vertical stack is convenient, such installation is definitely preferred. However, in the foreseeable future, most instruments will be installed in the breeching at a location which is a compromise between the best location from a flow consideration and the most convenient location from a consideration of installation and maintenance difficulties.

SUMMARY OF STACK EMISSIONS PROPERTIES

Table 1 summarizes the effluent characteristics from large coal- and oil-fired combustion facilities. The information presented is based upon information obtained from a search of the literature, from visits to power plants, and from discussions with the operating personnel and engineers in power plants. Obviously much more information than is presented in Table 1 is needed to define completely the environment in which a continuous mass monitoring instrument must operate. However, to obtain more and better information requires better instrumentation than now commercially available.

A list of specifications for an acceptable instrument to monitor continuously the mass emissions of particles from the stacks of large coal- and oil-fired power plants is presented following Table 1. The specifications are based upon the information presented in this section, especially that presented in Table 1, plus a knowledge of instruments and techniques that exhibit a potential for measuring mass emissions of particles in stack gases.

INSTRUMENT SPECIFICATIONS

The specifications for an acceptable instrument (permanently installed) to monitor the mass emissions of particles downstream from a control device on a large stationary coal- and oil-combustion facility are as follows:

<u>Performance Characteristics</u>

- Measurement must correlate with total emissions of particles into the atmosphere.
- Capability of sensing particle mass concentration in the range of 0.01 - 4.0 grams per cubic meter.
- Must cope with particulate mass concentration profiles which vary by typically ± 50 percent spatially, by a factor of 10 with time, and by a factor of 4 during sootblowing.
- Preferably senses the mass of particles from 0.01 to 300 microns. However, it would be acceptable if it senses mass from 0.1 to 50 microns for coal-firing emissions or from 0.1 to 10 microns for oil-firing emissions, which would include over 90 percent of the mass of particles.

TABLE 1 SUMMARY OF EFFLUENT CHARACTERISTICS FOR COAL AND OIL COMBUSTION

	COAL COMBUSTION EMISSIONS (Controlled and uncontrolled as noted)						OIL COMBUSTION EMISSIONS (Uncontrolled)
Particulate Mass Concentration	(units of grams/cubic meter)*	Before Collector	After Collector				
	Pulverized fired	2.0 - 15.0	0.03 - 4.0				Typical: 0.06 - 0.2
	Stoker fired	0.2 - 10.0	0.06 - 3.0				Range 0.02 - 1.0
	Cyclone fired	0.4 - 4.0	0.03 - 1.0				
Mass Concentration Variations							
Spatially across duct	Typical: ± 50%						Typical. ± 50%
with time	No information available						As much as 10-fold increase over typical
During sootblowing	No information available						About 4-fold increase over typical
Particle Size	(units of microns diameter)	Before Collector			After Collector		Typical: 0.01 - 1.0 microns Usually uncontrolled
		Rg. of MMD**	5% of Mass less Than	95% of Mass Less Than	Mech. 95% of Mass Less Than	Elect. 95% of Mass Less Than	
	Pulverized fired	7-20	1.0	70	40	25	
	Stoker fired	15-70	2.0	100	40	25	
	Cyclone fired	3-10	1.0	50	40	25	
Extreme particle size range	0.01 - 300 microns diameter						0.01 - 40 microns diameter
Particle specific density	0.5 - 10.0 gm/cm³ (variable within each stack)						0.5 - 5.0 range (variable within each stack)
Flue gas velocity	Range: 30 - 120 fps Average. 50 - 60 fps Average velocity fluctuates less than ± 3 fps in most stacks						Range. 30 - 120 fps Average 50 - 60 fps Average velocity fluctuates less than ± 3 fps in most stacks
Flow condition	Turbulent and nonuniform						Turbulent and non-uniform
Periodicity of flow fluctuations	30 - 120 cycles per minute						30 - 120 cyles per minute
Flue gas temperature	Range 270 - 400°F Typical 290-330°F (varies less than ± 5°F in most stacks)						Typical. Slightly higher than coal-fired
Dew point of flue gases	Water. 140°F Acid: 220 - 270°F						No quantitive information available
Moisture content of flue gas	5 - 10% by volume						No information available
Existing sampling port size	3 - 8 inch I.D. hole typical						3 - 8 inch I.D. hole typical
Distance across duct from port	Range. 5 - 30 ft. Typical: 7 - 15 ft.						Range: 5 - 30 ft. Typical 7 - 15 ft.
Static pressure at sampling ports	Range: 5" positive to 15" negative water pressure Typical: 0" to 10" negative water pressure						No information available

*1 grain/cubic foot = 2.29 grams/cubic meter
**MMD = mass median diameter of the particle size distribution

- Reproducibility between two identical instruments of ± 20%.
- Calibrated accuracy of ± 30%.
- Should record such items as zero and span every 1 to 6 hours on data recordings.
- Preferably have an instantaneous readout of the total mass of particles emitted into the atmosphere per unit time, or at least one average readout every 15 minutes.
- Outputs compatible with standard strip chart or digital recorders and with computer data inputs.

Environmental Requirements

- Operate with flue gas velocities of 30 to 120 feet per second.
- Operate in a variety of stacks, each having widely different velocity profiles.
- Not adversely affected by turbulent flow with characteristic eddy dimensions of 6 inches to 6 feet.
- Operate with flue gas temperatures ranging from 250 to 400°F and with temperature fluctuations of ± 5°F for short range periods (less than 1 day) and of ± 20°F for long range periods (more than 1 day).
- Operate in corrosive flue gas containing sulfur trioxide, both combined and uncombined.
- Must not restrict the flue gas flow in any significant way.
- Must withstand such environmental conditions as vibration with amplitudes as high as 1/2 inch and frequencies on the order of 0.1 - 1.0 Hz, all types of meteorological conditions, and direct sunlight.
- Must operate with flue gas static pressures from 15" negative to 5" positive water pressure (atmosphere reference), and with fluctuations of ± 3" water pressure.

Maintenance and Operational Considerations

- Rugged enough to last several years without major repair.
- Little or no maintenance except for regular weekly maintenance and for major maintenance only during regular power plant maintenance shutdowns (usually every 6 months).
- Little or no calibration or adjustment while in operation.
- Easily accessible during and after installation for weekly maintenace and for calibration or adjustments.
- Easy for plant operators to understand, operate, and to make minor repairs.
- Operate on 110V or 220V, 60 Hz electrical power and requires little power, preferably no more than 1500 watts.
- May use up to 10 scfm of 90 psig compressed air in many facilities.

Economic Factors

- Installs easily within a week by 2 men in present and future stacks with little stack modifications other than holes, flanges, and utilities.
- Preferably cost $10,000 or less but definitely not more than $20,000.
- Power industry personnel must be willing to buy it.

SUMMARY OF PARTICLE SENSING TECHNIQUES

This section briefly describes a number of particle sensing techniques. Some are more applicable to the monitoring of particulate mass emissions than others Several techniques have been developed into commercial stack monitors while others have never before been used for particle measurements. The reader who is interested in more detail about a specific measurement technique is referred to the listed references (see complete bibliography in the back of Volume I of this report) and/or the more detailed discussion in Volume II of this report (see table of contents).

Particle measurement techniques which offer some promise for particulate mass emissions monitoring from fossil-fuel combustion sources are listed below in three categories related to the present state-of-the-art:

A. Very promising, commercial instruments exist for stacks, more testing needed:

   1. Beta Radiation Attenuation

B. Very promising, commercial instruments exist for ambient air, development for stacks needed:

   1 Piezoelectric Microbalance

C. Promising, considerably more research and/or development needed

   1 Resonant Frequency

   2 Capacitance - Dielectric Change Technique

   3 Gravimetric Weighing

   4 Rotating Masses

   5 Capacitance-Impact Sensing

Other particle measurement techniques which cannot accurately measure particle mass emissions are listed in three categories below, not necessarily in any order

A. Useful for measuring other particle properties in stacks as sold commercially or with minor adjustment:

   1. Electrostatic Contact Charge Transfer Konitest

2. Light Transmission

3. Soiling Potential

4. Optical Counters and Photometers

5. Condensation Nuclei Counters

6. Collection of Particles in Liquid Suspensions

B. Potentially useful for measuring other particle properties in stacks after considerable research and development:

1. Lidar

2. Holography

3. Angular Light Scattering

4. Gas Adsorption

5. Electrostatic Ion Capture and Ion Current Attenuation

6. Electrostatic Contact Charge Transfer: Probe-In-Nozzle

7. Filter Pressure Drop

8. Alpha and Gamma Radiation Attenuation

9. Volume Measurement

10. Impact Momentum Sensing

C. Little potential for particulate concentration monitoring in stacks:

1. Acoustical Attenuation and Dispersion

2. Acoustical Particle Counter

3. Flame Photometry

4. Flame Ionization

5. Hot-Wire Anemometry

6. Radioactive Tagging and Sensing

7. Pressure Drop in Nozzles

8. Electrostatic Contact Charge Transfer: Bounce

INDEX OF PARTICLE SENSING TECHNIQUES

BETA RADIATION ATTENUATION

PRINCIPLE OF OPERATION

When beta particles (electrons) pass through a medium, some are absorbed and some reflected, resulting in a net reduction in the beam intensity. The reduction in beam intensity, known as beta radiation attenuation, depends statistically on the electron density of the medium. Thus, correlation of attenuation with mass depends on a constant relationship between the number of electrons per molecule (atomic number) and the mass of the molecular nucleus (atomic weight). The ratio is between 0.45 and 0.50 for essentially all elements found in coal and oil combustion effluents except hydrogen which does not contribute enough to particle mass to cause any significant error. Therefore, beta radiation attenuation is a more direct measure of particle mass than any other known technique except gravimetric weighing, vibrational weighing, and centrifugal sensing.

Instruments using this technique consist of a beta radiation source (a radioisotope) and detector. In most instruments, particles from a known volume of effluent gas are collected on a filter tape and then placed between the radiation source and detector. The difference in the count rate of the detector before and after the particles are collected is a measure of the mass of the particles. Common detectors are Geiger-Muller counters, proportional counters, scintillation counters, or semiconductor counters. Common particle collectors are filters, impactors, cyclones, electrostatic precipitators, or combinations thereof.

Beta radiation attenuation is not capable of sensing airborne effluent particles without first collecting the particles and concentrating them because gas molecules also attenuate beta radiation. Since the mass of gas molecules in effluent streams is several orders-of-magnitude greater than the corresponding mass of particles, radiation attenuation caused by suspended particles cannot be accurately separated from attenuation caused by gas molecules.

COMMERCIAL EQUIPMENT

Five companies manufacture beta radiation attenuation instruments:

Gelman Instrument Company
P.O. Box 1448
600 South Wagner Road
Ann Arbor, Michigan 48106

Research Appliance Company
Route 8 & Craighead Road
Allison Park, Pennsylvania 15101

Verewa, Hans Lgowski & Co.
433 Mulheim an der Ruhr
Postfach 1845
Eppinghofer Strasse 92/94
West Germany

Frieseke & Hoepfner GMBH
D 8520 Erlangen-Bruck
Postfach Nr. 72
West Germany

Saphymo-Srat
51, Rue de l'Amiral Mouchez
75 Paris 13e
France

All five use an indexing filter tape as the particle collector. A sixth company:

Environmental Research Corporation
3725 North Dunlap Street
St. Paul, Minnesota 55112

is reportedly developing a commercial beta radiation attenuation instrument using a combination cyclone-filter particle collector.

REFERENCES (See BETA RADIATION ATTENUATION in Volume II).

A. Principle of Operation. 1224, 1179, 1144, 1000, 1149, 1056, 579, 961, 991, 248, 1011, 1107, 335

B. Applications: 227, 1179, 555, 1085, 1138, 1000, 576, 225, 579, 961, 1045, 1107, 821, 705

C. Data: 1189, 1117, 1224, 1179, 555, 1085, 961, 543, 1049, 573, 248, 1107, 335, 821, 705

D. Specific Instrument Descriptions: 227, 1117, 1179, 555, 1085, 1061, 225, 1048, 248, 1107, 335, 821, 705

DISCUSSION

A. Advantages

1. Directly senses a parameter closely related to particle mass.

2. Commercially available with some stack experience.

3. Needs little calibration.

4. Appears to have capability for fair reliability during long-term use.

5. Can probably operate at high temperatures.

6. Can be used with several particle collectors giving the designer greater flexibility in developing reliable instruments.

7. Problems appear to be basically engineering problems which can be solved.

B. Disadvantages

1. Requires sampling probe and is subject to probe loss errors.

2. Requires conditioning of the sampling stream.

3. Requires particle deposition.

4. Requires an automatic advancing mechanism for the sample deposit.

5. Readout not instantaneous or continuous:
   1 data point every 1 - 15 minutes

6. Filter tape in present models needs replacement every 1 - 4 weeks.

7. Moderately expensive: ≈ $8,000 - $12,000.

8. Little reliable data has been reported although most reports are positive.

C. Recommendations for Further Development

We recommend further testing, evaluation, and accompanying development of this technique. Well designed experimental testing programs, such as described by Schnitzler, et al (Ref. 1189), will undoubtedly lead to improvements, particularly for automatic, unattended operation. The optimum particle collection system remains to be found. The relative merits of various particle sampling systems needs evaluation, e.g., sample heating versus sample dilution and mounting the sensor inside the stack rather than outside. Some question remains regarding the effects which different materials, nonuniform particle deposits, and particle size have on beta radiation attenuation. The present data readout system may not be the best way of doing the job. A type of aerosol concentrator which allows detection of the particles in their airborne state would eliminate many of the operation problems of this technique, but no such concentrator is known to the authors.

D. Conclusions

Beta radiation attenuation is presently the best technique for monitoring the mass of particulate emissions from stacks, primarily because it senses a particle parameter closely related to mass and its feasibility for stack monitoring is proven. Only the piezoelectric microbalance and the capacitance impact techniques offer as much promise for such measurements at this time. These three techniques offer the most promise for the longer-range future. Considerable testing must be done to fully evaluate the error of the beta radiation attenuation technique, but basic feasibility has been proven. At least five commercial models are now available, none of which appears to be obviously superior.

PIEZOELECTRIC MICROBALANCE

PRINCIPLE OF OPERATION

Piezoelectricity is a property of certain crystals which results in an electrical charge on certain surfaces of the crystal when the crystal becomes mechanically stressed. Conversely, a piezoelectric material becomes mechanically strained if an electrical charge is placed on certain of its crystal faces. A piezoelectric crystal, when placed in an appropriate electronic oscillating circuit, will cause the circuit to oscillate at the natural vibrational frequency of the crystal.

When foreign material adheres to the surface of a vibrating piezoelectric crystal, the natural frequency of vibration of the crystal decreases. The magnitude of the frequency change is directly proportional to the mass of the deposited foreign material. Some piezoelectric materials, such as quartz, vibrate at very precise natural frequencies, so that frequency changes of one part in ten million are significant and easily detectable. This principle has been used recently to measure the mass of aerosol particles deposited onto the sensing surface by an electrostatic precipitator or an impactor.

A piezoelectric microbalance instrument for use in stacks would consist of the sampling probe and sample conditioning system, the particle collector, the piezoelectric microbalance, a crystal cleaning system, and suitable data readout equipment. Sample conditioning would probably consist of sample line heating and/or dilution with clean, dry ~~air~~ to prevent condensation. An impactor or electrostatic precipitator would probably be the particle collector, the choice depending on whether or not small submicron particles must be collected. The piezoelectric microbalance includes the crystal and its oscillating circuit. The data readout system would permit recording of particle mass concentration in some convenient form.

COMMERCIAL EQUIPMENT

Two companies manufacture piezoelectric microbalance systems for use in monitoring ambient air and auto exhaust aerosols. One instrument uses an electrostatic precipitator to collect particles and heats the sampling head to prevent condensation of auto exhaust vapors:

Thermo-Systems Inc.
2500 N. Cleveland Ave.
St. Paul, Minnesota 55113

The second instrument uses an impactor which collects particles above a certain critical size:

Atlantic Research Corporation
3333 Harbor Boulevard
Costa Mesa, California 92626

Several companies manufacture piezoelectric microbalance instruments for a wide range of applications, such as dew point indication and monitoring of the thickness of evaporated or sputtered thin films.

REFERENCES (See PIEZOELECTRIC MICROBALANCE and RESONANT FREQUENCY in Volume II)

A. Principle of Operation: 244, 1221, 252

B. Applications: 244, 1223, 252, 1187

C. Data: 244, 1222, 1223, 252

D. Specific Instrument Descriptions: 244, 1222, 1223, 252, 1187

DISCUSSION

A. Advantages

1. Directly senses a parameter closely related to particle mass.
2. Highest mass sensitivity of any direct mass sensing device.
3. Needs no calibration.
4. Can be used with several particle collectors giving the designer greater flexibility in developing reliable instruments.
5. Compact sensing head.
6. Commercial ambient air samplers available from 2 domestic companies, auto exhaust samplers available from 1 company, some actual experience.
7. Offers some chance for mounting completely within the effluent gas stream eliminating several sample conditioning problems.

B. Disadvantages

1. Not yet developed or proven for stack monitoring:
   a. May not sense large particles (>20μm),
   b. May not be able to operate at stack temperatures (350°F).
2. Requires sampling probe and is subject to probe loss errors.
3. Requires conditioning of the sample stream.
4. Requires particle deposition.

5. Requires crystal cleaning with its related system complexity.

6. Readout not instantaneous or continuous:
   1 data point every 5 sec. – 5 min.

7. Moderately expensive. ≈ $7,000 – $12,000.

C. Recommendations for Further Development

We recommend that the feasibility of this technique for stack monitoring be established soon. Feasibility tests should include tests in stack environments with typical stack particles. If feasibility is established, we recommend immediate development of the technique into practical, commercial stack monitors. Such development should include evaluation of the optimum type of crystal sensor, the relative merits of various particle sampling and collection techniques, alternate ways of cleaning the crystal, and the optimum data readout system. The development program, and the evaluation program which must follow, should include actual stack sampling to provide conclusive data on applicability and viability.

D. Conclusions

The piezoelectric microbalance technique is potentially the best method for monitoring the mass of particulate emissions from stacks, primarily because it senses particle mass directly and it has relatively high sensitivity. However, feasibility for use in stacks must yet be established. The technique shares many of the advantages and features of the beta radiation attenuation technique, but offers much greater sensitivity and time resolution than beta radiation attenuation. The total instrument package could probably be quite small making the piezoelectric microbalance instrument especially convenient as a portable monitor used by pollution abatement personnel.

RESONANT FREQUENCY

PRINCIPLE OF OPERATION

The resonant, or natural, frequency of a vibrating spring-mass system decreases if the mass is increased. This is true of any mechanical system vibrating at its resonant frequency. Thus, the change in resonant frequency when particles are added to the system is a direct measure of the mass of the added particles. Piezoelectric microbalances, discussed in a separate report, are one subgroup of the resonant frequency technique.

COMMERCIAL EQUIPMENT

No commercial equipment using this principle is available other than piezoelectric microbalances. Very little laboratory equipment exists.

REFERENCES (See PIEZOELECTRIC MICROBALANCE and RESONANT FREQUENCY in Volume II)

A. Principle of Operation: 1228, 1239

B. Applications: 1228

C. Data: 1228

D. Specific Instrument Descriptions: 1228

DISCUSSION

A. Advantages

1. Directly senses particle mass.

2. Needs little calibration.

3. Can be used with several particle collectors.

4. Should be relatively simple to operate.

5. Should make a rugged instrument.

6. Technique is very similar to piezoelectric microbalances which are commercially available for some particulate mass monitoring applications.

B. Disadvantages

1. Almost no development of the technique has been done, feasibility not well proven.

2. Requires sampling probe and is subject to probe loss errors.

3. Requires particle deposition.

4. May require conditioning of the sample stream.

5. Requires periodic cleaning of the deposit surface.

6. Readout not instantaneous or continuous: Probably capable of 1 data point every 1 second to 1 hour.

7. A possible problem is lack of required sensitivity.

C. Recommendations for Further Development

We recommend that feasibility testing of this technique be done soon. If such tests indicate high potential for stack monitoring, we recommend further development into a practical instrument. Since this technique does measure mass and has no apparent major disadvantages, it definitely merits further investigation. If feasibility is proven, it appears that development into commercial stack monitoring instruments will take at least two years.

D. Conclusions

This technique measures mass directly and has no apparent major problems except its infant state of development. Piezoelectric microbalances, a subgroup of this technique, have proven useful for many particle mass monitoring applications. If the sensitivity of other resonant frequency devices proves high enough for stack monitoring, the technique has great promise of development into a rugged, reliable instrument in a relatively short time. Development of this technique definitely appears justified.

GRAVIMETRIC WEIGHING

PRINCIPLE OF OPERATION

A gravimetric weighing device consists of a pivot point about which two equal and opposing torques act. One torque is set up by the weight of the particle sample whose mass is to be determined. The other torque is usually controlled such that a "null" position is reached where both torques are equal. Several techniques are possible for measuring and controlling this opposing torque.

When this technique is used for measuring particle mass concentration, a means of collecting the particles is needed. The collector can be an electrostatic precipitator, an impactor, a filter, or a cyclone. The collection surface must be locked while the particles are being collected and freed when weighing is done. Air flow must be turned off or diverted during weighing to avoid disturbing the balance. A mechanism for automatic cleaning or replacing of the collection surface is needed.

COMMERCIAL EQUIPMENT

Several commercial balances exist for manual weighing of samples and most components needed for automating the technique exist. However, no commercial equipment exists using this technique to measure particle mass concentration automatically.

REFERENCES (See GRAVIMETRIC WEIGHING in Volume II)

A. Principle of Operation 243, 1097, 938, 1096

B. Applications: 243, 225

C. Data 243

D. Specific Instrument Descriptions: 243

DISCUSSION

A. Advantages

1. Directly senses particle mass.

2. Needs little calibration.

3. Has been tested in stack environments.

4. Can be used with several particle collectors.

5. Problems appear to be basically engineering problems which can be solved.

B. Disadvantages

1. Potential instrument appears expensive, perhaps around $12,000 - $15,000.
2. Requires sampling probe and is subject to probe loss errors.
3. Requires conditioning of the sample stream.
4. Requires particle deposition.
5. Requires an automatic advancing mechanism for the sample deposit.
6. Automatic designs require many moving parts with reliability a potential problem.
7. Sensitive to vibration.
8. Readout not instantaneous or continuous: 1 data point every 1 - 30 minutes
9. Not available commercially.
10. Little data available on research prototype units.

C. Recommendations for Further Development

We recommend that any further development of this technique be postponed pending the results of development on the beta radiation attenuation and piezoelectric microbalance techniques. Since the feasibility of this technique seems to be proven, any further development should concentrate on engineering design of the mechanism for automating the cleaning or replacing of the collecting surface. Improvement would also seem possible in the sensing of the torque on the balance.

D. Conclusions

Gravimetric weighing is the most familiar method for directly measuring the mass of particles. However, automation of the technique leads to a system with considerable mechanical complexity with the associated problems of high cost and low reliability. For this reason, the beta radiation and piezoelectric microbalance techniques offer greater promise for the continuous monitoring of the mass of particles in effluent streams. Gravimetric weighing may find a place in research measurements of particle mass.

ROTATING MASSES

PRINCIPLE OF OPERATION

The mass of a given sample of particles can be sensed by the change in inertia which they cause when placed in a centrifuge. A sample of particles can be collected at a point on a rotating body such that a dynamic off-balance is set up, causing the body to vibrate as it rotates. The off-balance caused by the particles is a function of the mass of the collected sample, and can be detected by a displacement detector which is sensitive to the magnitude of dynamic vibrations.

A similar means of sensing particle inertia is to deposit the particles on a rotating body, apply a constant torque, and measure the angular acceleration of the body. The difference in acceleration before and after the deposit of the particle sample is a direct measurement of the angular momentum added by the particles, and, therefore, is a measurement of the mass of the particles. In this case, the particles must be deposited at a known radius from the axis of rotation, and a sensitive accelerometer must be used to measure acceleration changes.

COMMERCIAL EQUIPMENT

No commercial or laboratory equipment exists at present which uses this principle to measure particle mass concentration.

REFERENCES

This technique was suggested by K. T. Whitby in private conversations. No published information has been found.

DISCUSSION

A. Advantages

1. Directly senses a parameter closely related to particle mass.
2. Needs little calibration.
3. Can be used with several particle collectors.
4. Should be relatively simple to operate.

B. Disadvantages

1. Time resolution may be limited by the requirement of a large mass of collected particles.
2. No equipment has been developed so feasibility is not proven.
3. Requires sampling probe and is subject to probe less errors.

4. Requires conditioning of the sample stream.

5. Requires particle deposition.

6. Requires an automatic cleaning mechanism.

7. Requires tight manufacturing tolerances to provide sensitive detection of acceleration or displacement.

C. Recommendation for Development

We recommend that any further development of this technique be postponed pending the results of development on the beta radiation attenuation and piezoelectric microbalance techniques. However, development programs should be considered in the future in which instruments using this principle are built and tested. Since this technique does measure mass and the instrumentation should be simple to operate, the principle definitely merits some investigation.

D. Conclusions

This technique does measure the mass of a collected sample of particles and is definitely a promising candidate for measuring stack emissions at some time in the future. However, since no work has been done using this principle, the feasibility is not fully proven and much work will be needed to develop practical monitoring instruments. Development of this technique definitely appears justified.

IMPACT MOMENTUM SENSING

PRINCIPLE OF OPERATION

When particles strike a surface, they exchange momentum with the surface. If the velocity of all particles striking a surface is constant, the momentum exchange is directly related to the mass of the particles. This principle can be used in several ways for particulate mass concentration measurements.

When a single particle hits a piezoelectric crystal, the crystal vibrates because of the momentum transfer. The vibration causes an electrical signal in the attached circuit. The amplitude of the signal is related to the particle's initial momentum. In this system, an impactor can apply the constant velocity to the particles. Suitable electronic signal manipulation could result in an indication of particle mass concentration. Only particles above 30 microns can be sensed by this method.

If particles strike the sensing plate of a sensitive gravimetric microbalance, the plate deflects a certain distance depending on the momentum of the particles. Again, an impactor can apply constant velocity to the particles. The deflection of the sensing plate, sensed electronically, is a measure of the mass of the particles striking it. The deflection of the microbalance sensing plate caused by the air jet is a potentially major problem. This method resembles the capacitance-impact technique described separately in this report.

COMMERCIAL EQUIPMENT

No commercial instruments using this technique are known to exist. The piezoelectric impact technique has been used as a micrometeorite detector on spacecraft.

REFERENCES

Reference [illegible] and 25[illegible] discuss the theory of the piezoelectric momentum transducer.

DISCUSSION

A. Advantages

1. Can sense a particle parameter closely related to mass.

2. Can detect individual particles, perhaps as small as 30 microns diameter.

3. Has been used for micrometeorite detection.

B. Disadvantages

1. Can sense only particles larger than about 30 microns diameter.

2. Probably cannot detect concentrations as high as those in smoke stacks.

3. Small particles would interfere with the detection of large ones by contaminating the impact surface.

4. Has not been used for purposes other than micrometeorite detection on spacecraft.

5. The gravimetric microbalance technique would have severe interference by the air jet from the impactor.

6. Contamination of the sensor would probably cause measurement errors; periodic cleaning is required.

7. Different responses will probably result depending on whether or not the particle sticks to the sensor.

8. Requires sampling probe and is subject to probe loss errors.

9. Probably requires conditioning of the sample stream.

C. Recommendations for Further Development

We recommend no further development of this technique for particulate mass monitoring in smoke stacks at this time. However, clever design combinations could appear in the future calling for reevaluation of the technique, especially if particle sizing could be done by the same instrument and if the technique becomes useful for particles as small as 1 micron.

D. Conclusions

A variation of this technique is capable of detecting the mass of individual particles larger than 30 microns diameter. However, it is not sensitive enough to detect smaller particles with the present known technology. Other variations have similar problems as listed above. The technique may be useful for some particle sizing applications of large particles, but does not look promising for mass concentration monitoring at this time.

CAPACITANCE-IMPACT SENSING

PRINCIPLE OF OPERATION

If a particle hits one plate of a capacitor with enough momentum, the plate moves slightly causing a change in the capacitance of the system. In its simplest form, this principle can monitor the momentum of moving particles. If airborne particles are first accelerated to a constant velocity in a nozzle, the magnitude of the measured change in capacitance becomes independent of particle velocity and dependent only on particle mass.

An instrument of this type for particulate mass concentration monitoring consists of a nozzle which accelerates the particles to near sonic velocity, an aerodynamically stablized, very thin, capacitor lamella, and a RMS voltmeter, as an indicator. Such an instrument has been used to monitor mass concentrations above 15 mg/m^3 of particles in the 1 - 20 micron size range. The lower size limit is set by the impaction efficiency of the system (probably 0.3 - 1.0 um). The upper size limit is probably above 100 um.

COMMERCIAL EQUIPMENT

No commercial equipment of this type exists. Only three research prototypes have been reported.

REFERENCES

Reference 1248 discusses this technique.

DISCUSSION

A. Advantages

1. May sense a parameter closely related to the mass of particles.

2. In a second mode of operation, the same instrument can obtain some particle size information.

3. High sensitivity, can sense concentrations at least down to 10 mg/m^3.

4. Can probably operate at temperatures as high as 1000°F.

5. Essentially instantaneous and continuous readout

6 Appears to be simple and inexpensive, potential cost of commercial instrument is in the \$2,000 - \$5,000 range.

7 Compact sensing head.

B Disadvantages

1 Almost no development has been done for any applications, only three prototypes have been reported.

2. Correlation with mass is not presently established.

3. Requires lamella cleaning or replacement periodically with some related system complexity.

4. Requires the lamella to be aerodynamically stable with no flutter.

5. Requires sampling probe and is subject to probe loss errors

6. Requires particle deposition.

7. May require some conditioning of the sample stream.

C Recommendations for Further Development

We recommend that the only reported research on this technique, performed in France, be investigated in detail. If the technique looks promising after more details of the French work are known, feasibility studies for stack monitoring should have high priority Cleaning or replacing the lamella for automatic operation may be a major problem. Problems with maintaining aerodynamic stability of the lamella limit the lowest concentration which the sensor can detect The ability of the technique to sense mass must be tested

D. Conclusions

This technique is potentially one of the best methods of monitoring particulate mass concentration in smoke stacks, primarily because it may sense a parameter closely related to the mass of particles, the technique and apparatus is very simple and inexpensive, and it can give instantaneous and continuous readout. It is not clear how closely the measurement correlates with mass. Potential problems appear to be periodic cleaning or replacing of the lamella for automatic operation and maintaining aerodynamic stability of the lamella The technique is very new with only three prototype instruments constructed. Development is needed to make the technique into a reliable instrument for stack monitoring. The reported prototype instruments (see Ref. 1248) should be investigated further, and feasibility tests for stack monitoring should proceed if the investigation indicates high potential. The apparent low cost and simplicity recommend it highly for such studies.

ELECTROSTATIC CONTACT CHARGE TRANSFER: KONITEST

PRINCIPLE OF OPERATION

As particles slide along a wall, they exchange electrostatic charge with the wall. In the Konitest, particles whirl through a tube in a helical path. Centrifugal force causes many particles, especially the larger, heavier ones, to hit and slide along the wall, exchanging electrostatic charge with the wall. An electrometer measures the current flowing from the electrically-floating wall. The current level can be calibrated to read particle concentration. A second design, with the same name, uses an electrically-floating venturi as the surface which exchanges charge with particles. The second design differs little from the probe-in-nozzle technique discussed separately in this report.

The first Konitest design differs from other electrostatic techniques in that centrifugal force causes particles to strike the cyclone wall and slide or bounce along the surface. Thus, larger particles containing most of the mass have a greater effect than smaller ones. If there is no secondary interference by submicron particles, the calibrated output current can correlate reasonably well with particulate mass in certain effluent streams. Little is known about the actual charge transfer process.

COMMERCIAL EQUIPMENT

Until recently, the Konitest was manufactured by J. C. Eckardt A. G., 7000 Stuttgart-Bad Cannstatt, Postfach 347, West Germany. However, this company no longer makes the instrument. No other manufacturer is known.

REFERENCES (See ELECTROSTATIC MEASUREMENT METHODS in Volume II)

A. Principle of Operation: 923, 241

B. Applications: 1189, 659, 923, 225

C. Data. 1189, 923, 241, 1188

D. Specific Instrument Descriptions: 923, 241

DISCUSSION

A. Advantages

1. Continuous, nearly instantaneous readout.

2. Can operate at stack temperatures, eliminating several sample conditioning problems.

3. Senses larger particles which contain most mass.

4. Self-cleaning if some particles are large, somewhat abrasive, and not sticky.

5. Operates over a wide concentration range.

6. Has been marketed commercially in the past.

7. Available data appears to show surprisingly good correlation with particulate mass concentration.

8. Sensor is compact and easy to operate.

B. Disadvantages

1. Several investigators mention high sensitivity to submicron particles leading to highly erroneous mass concentration measurements.

2. Response depends strongly on particle size and composition, on surface characteristics of the particle and probe, and may depend on the initial charge on the particle.

3. Principle of operation is largely unknown.

4. Does not sense particle mass, but may sense something close to it for some aerosols, periodic calibration of each instrument installation appears necessary.

5. Requires some large, non-sticky, abrasive particles to keep the tube clean.

6. Requires measurement of low currents in effluent atmospheres.

7. Requires sampling probe and is subject to probe loss errors.

C. Recommendations for Further Development

We recommend an intensive investigation of past experience with the Konitest, primarily in Germany where it has been sold for about 10 years. Several investigators indicate excellent correlation with particulate mass concentration in coal-fired effluent streams. Others report overwhelming sensitivity to submicron particles which do not have much mass. These reports appear to conflict, as do the reports on operational problems with the Konitest. If the recommended investigation uncovers better documented evidence supporting the reported excellent mass correlation, we recommend further testing and development of this technique.

D. Conclusions

The Konitest is reported to have excellent correlation with particulate mass concentration with coal-fired effluents. If this is true, the instrument could be an excellent, truly continuous, fast response, compact, reliable, automatic stack monitor. However, conflicting reports claim very poor mass correlation because of high sensitivity to submicron particles. The theory is not well developed and, therefore, does not resolve the problem. Only further discussions with past users, perhaps followed by a testing and development program, can resolve the conflicting reports. In any case, since the Konitest does not measure particulate mass directly, periodic calibration of every installation would be required of any instrument using this principle. This may be a severe limitation. Another probable negative feature of the instrument is that, although mass correlation may be excellent during the large majority of the time when the process is under control, mass correlation may be very poor during the times when something happens to the process causing severe changes in emissions. This is precisely the time when accurate mass measurements are most valuable.

ELECTROSTATIC CONTACT CHARGE TRANSFER: BOUNCE

PRINCIPLE OF OPERATION

Particles will bounce between the plates of a high voltage electric capacitor as they are carried through by an airstream. As particles enter the capacitor, they are attracted electrically to one capacitor plate or the other, because of any initial electrostatic charge or because of charge picked up in the capacitor's electric field. Upon hitting the first plate, the particle loses its old charge and gains a new charge with the same polarity as the first plate. The repulsion of the particle by the first plate, caused by their like polarity, forces the particle to migrate toward the second plate, carrying electrical charge with it. When it hits the second plate, it again loses its old charge and picks up a new charge with the same polarity as the second plate. The new charge causes the particle to migrate toward the first plate, carrying electrical charge with it, where the entire process is repeated. The net current flow across the capacitor plates is a measure of the concentration of particles passing through. The technique reportedly works well for dry, non-sticky particles, especially above 100 µm, but sometimes as small as 1 µm.

COMMERCIAL EQUIPMENT

No commercial equipment exists and little laboratory equipment exists.

REFERENCES (See ELECTROSTATIC MEASUREMENT METHODS in Volume II)

Reference 226 discusses all aspects of this technique including a description of a prototype instrument.

DISCUSSION

A. Advantages

1. Continuous, nearly instantaneous readout.

2. Senses large particles which contain most mass.

B. Disadvantages

1. Does not sense particle mass or a parameter very close to mass.

2. Works only with large, dry, non-sticky particles, almost certainly would not work in coal- or oil-fired effluent stacks.

3. Not well developed; only one investigator is known.

4. Probably contamination sensitive.

5. Requires measurement of low current levels in effluent atmospheres.

6. Requires sampling probe and is subject to probe loss errors.

7. Probably requires conditioning of the sample stream.

C. Recommendations for Further Development

We recommend no development of this technique for stack effluent monitoring.

D. Conclusions

This technique cannot be used to monitor stack effluents because of the reason listed as disadvantage 2 above.

ELECTROSTATIC CONTACT CHARGE TRANSFER: PROBE-IN-NOZZLE

PRINCIPLE OF OPERATION

When particles bounce off a surface, they usually exchange some electrostatic charge with the surface. The quantity and polarity of the exchanged charge depends on the composition of the particles and surface, on the surface characteristics of both, on the intensity of the collison, and on the initial charge carried by both. The process is not understood well enough to analyze mathematically.

An instrument using this principle has been designed. A cone-shaped probe points upstream within the throat of a venturi nozzle. Most large particles passing through the nozzle strike theprobe and bounce off, resulting in a charge transfer. An electrometer attached to the probe indicates the magnitude of the charge transfer, which can be related to aerosol concentration by suitable calibration.

COMMERCIAL EQUIPMENT

No commercial equipment exists which uses this principle for measuring particle concentration. Only laboratory equipment exists.

REFERENCES (See ELECTROSTATIC MEASUREMENT METHODS in Volume II)

A. Principle of Operation: 187, 104, 5, 659

B. Applications: 20, 1036, 684, 659

C. Data: 20, 104, 1036, 684, 922, ~~5,~~ 659

D. Specific Instrument Descriptions: 20, 104, 1036, 684, 922, 5, 659

DISCUSSION

A. Advantages

1. Continuous, nearly instantaneous readout.

2. Senses large particles which contain most mass.

3. Self-cleaning if some particles are large, somewhat abrasive, and not sticky.

4. Operates over a wide concentration range.

B. Disadvantages

1. Does not sense particle mass or a parameter closely related to mass.

2. Response depends strongly on particle size and composition, on surface characteristics of the particle and probe, and on the initial charge on the particle.

3. Requires some large, non-sticky, abrasive particles to keep the probe clean.

4. Requires measurement of low currents in effluent atmospheres.

5. Requires sampling probe and is subject to probe loss errors.

6. May require some conditioning of the sample stream.

C. Recommendations for Further Development

We recommend no development of this technique for coal- or oil-fired effluent monitoring.

D. Conclusions

This technique is not suitable for use in monitoring stack effluents because of reasons listed as disadvantages 2 and 3 above.

ELECTROSTATIC ION CAPTURE AND ION CURRENT ATTENUATION

PRINCIPLE OF OPERATION

If a constant supply of unipolar ions flows perpendicularly across a stream of airborne particles toward the grid of an electrometer, some of the ions will strike the particles, become captured, and be carried away, thus reducing the ion current as measured by the electrometer. The reduction in ion current, known as ion current attenuation, is a measure of the particle flow rate.

The ion capture technique measures the other portion of the total ion current: the portion carried away by particles. The particles must be collected downstream of the charging region by some means such as filtration or electrostatic precipitation, the charge from the particles must leak through an electrometer.

COMMERCIAL EQUIPMENT

No commercial equipment exists for monitoring stack effluents. One company manufactures a sophisticated version of ion capture as a submicron particle sizing instrument:

Thermo-Systems Inc.
2500 North Cleveland Avenue
St. Paul, Minnesota 55113

Several laboratory prototypes of stack monitors exist.

REFERENCES (See ELECTROSTATIC MEASUREMENT METHODS in Volume II)

A. Principle of Operation: 68, 1211, 8, 916, 554, 122, 245, 1040, 284, 242

B. Applications: 659, 552, 916, 554

C. Data: 659, 1040, 302, 8, 554, 122, 245, 1040, 284, 242

D. Specific Instrument Descriptions: 659, 242, 581, 68, 302, 916, 554, 122, 284

DISCUSSION

A. Advantages

1. Continuous, nearly instantaneous readout.

2. Can operate at stack temperatures, eliminating several sample conditioning problems.

3. Several investigators have operated instruments in coal-fired effluents with some success.

4. Sensor is compact and easy to operate.

5. Simple technique available for drawing particles through the sensor eliminating many isokinetic sampling problems and much equipment.

6. Unique suction technique makes readout proportional to particle flow rate rather than particle concentration, making auxiliary measurements of gas velocity unnecessary.

B. Disadvantages

1. Does not sense particle mass or a parameter closely related to mass.

2. Response depends strongly on particle size with very high sensitivity to submicron particles which do not contain much mass.

3. Requires periodic cleaning by an auxiliary technique.

4. Requires measurement of low currents in effluent atmospheres.

5. Requires sampling probe and is subject to probe loss errors.

C. Recommendations for Further Development

We recommend no further development of this technique for particulate mass measurements. However, further development as a monitor for other particle concentrations or flow rates, such as total surface area flow rates, is strongly recommended.

D. Conclusions

This technique cannot measure particulate mass flow rate or concentration. However, the technique is a strong candidate for other particle concentration measurements, for example, measurements based on total surface area of the particulate cloud. The point sampling feature, the compactness, and the instantaneous, continuous readout should recommend this technique for some research applications as well as for evaluating specific portions of an electrostatic precipitator.

CAPACITANCE-DIELECTRIC CHANGE

PRINCIPLE OF OPERATION

If the dielectric strength of the material between the plates of a capacitor changes, the capacitance of the system changes. If the composition of the material remains constant, the change in dielectic strength depends primarily on the mass of material between the plates. This technique has been used to detect the presence of the powder particles in both pneumatic and belt conveying systems. The resolution of these instantaneous readout devices is apparently not high enough to accurately measure flow rates, even in systems with high particle concentrations. However, it may be possible to collect enough particles on a suitable substrate, such as a filter or impaction plate, so that the mass of material could be periodically measured in a batch process. The instrument would consist of a particle collector, a capacitance sensor with an appropriate electrical circuit, and a system to move the substrate for each batch from the collector to the sensor.

COMMERCIAL EQUIPMENT

No commercial equipment exists. Several powder detection prototypes have been tested.

REFERENCES

This technique was suggested for aerosol measurements by B. Y. H. Liu in private conversations. References 4 and 1031 discuss the powder detecting systems.

DISCUSSION

A. Advantages

1. Detects a parameter related to the mass of particles for a given particulate composition.

2. Can be used with several particle collectors.

3. May need little calibration within each stack if the dielectric constant of the material remains constant.

4. Should be relatively simple to operate.

B. Disadvantages

1. Almost no development of the technique has been done, feasibility not yet proven.

2. May lack sufficient sensitivity.

3. Dielectric constant of stack effluents may not remain constant, probably requires an initial calibration for each installation at each operating condition.

4. Readout not instantaneous or continuous.

5. Requires sampling probe and is subject to probe loss errors.

6. Requires particle deposition.

7. May require conditioning of the sampling stream.

8. Requires replacement or cleaning of the collection substrate for every measurement.

C. Recommendations for Further Development

We recommend that preliminary feasibility tests of this technique be made soon. Further development should depend on the results of such tests. A serious problem may be a lack of sufficient sensitivity.

D. Conclusions

This technique has more promise than most techniques, primarily because it measures a parameter somewhat related to particulate mass if the dielectric constant of particulate matter remains constant. However, the possible lack of sensitivity may severely restrict the the use of this principle. The feasibility of the technique has not yet been tested. This technique requires several years of development to reach the commercial instrument stage, and offers somewhat less promise than techniques listed earlier.

LIGHT TRANSMISSION

PRINCIPLE OF OPERATION

When light, or other electromagnetic radiation, passes through an aerosol, its intensity decreases because of scattering and absorption by the particles. The transmission or attenuation of light through an aerosol is a measure of the aerosol concentration. In order to measure the particle mass concentration, particle size, shape, optical characteristics and density must remain constant. The relationship between particle mass concentration and light transmission must be established by calibration of each instrument within every stack under every plant operating condition.

Despite the severe limitation in terms of mass concentration measurement, light transmission is now the most widely used principle for continuous monitoring of smoke emissions from stacks. The technique has several impressive practical advantages, and the measurements correlate quite well with the visual appearance of the effluent. Although light transmission may remain an important effluent monitoring technique, measurements made in this way must not be confused with the mass concentration of particles in the effluent. In practical situations, particle mass concentration must be measured by other techniques.

COMMERCIAL EQUIPMENT

A number of companies manufacture and/or sell light transmission instruments for installation in smoke stacks including:

Airflow Developments (Canada) Ltd.
244 Newkirk Road
Richmond Hill, Ontario, Canada

Bailey Meter Company
29801 Euclid Avenue
Wickliffe, Ohio 44092

Cleveland Controls, Inc.
1111 Brookpark Road
Cleveland, Ohio 44109

Combustion Equipment Associates, Inc.
120 Park Avenue
New York, New York 10017

Durag Apparatebau Gmbh
2 Hamburg 61
Killanstrasse 105,
West Germany

Electronics Corporation of America
Photoswitch Division
3 Memorial Drive
Cambridge, Massachusetts 02142

General Electric Company
Communication and Control Devices Department
Waynesboro, Virginia 22980

Infra-Red Industrial Systems Division
Ovitron Corporation
1425 Milldale Road
Cheshire, Connecticut 06410

Intertech Corporation
262 Alexander Street
Princeton, New Jersey 08540
(U.S. representative for Irwin Sick
Optik Elektronik
Neuried, West Germany)

Leeds & Northrup Company
4901 Stenton Avenue
Philadelphia, Pennsylvania 19144

Mac Leod & Stewart Company, Inc.
43 Rome Street
Farmingdale, Long Island, New York 11735

Nebetco Engineering
1107 Chandler Avenue
Roselle, New Jersey 07203

Photobell Company, Inc.
12 East 22nd Street
New York, New York 10010

Photomation, Inc.
280 Polaris Avenue
Mountain View, California 94040

Reliance Instrument Manufacturing Corporation
141 Laverance Avenue
Hackensack, New Jersey 07601

Sentry Controls, Inc.
P.O. Box 116
Pearl River, New York 10965

Robert H. Wager Company, Inc.
Passaic Avenue
Chatham, New Jersey 07928

REFERENCES (See LIGHT TRANSMISSION and MULTI-WAVELENGTH LIGHT TRANSMISSION in Volume II)

A. Principle of Operation: 1211, 485, 147, 1201, 1214, 1215, 843, 1212, 1199, 1250, 33, 1213, 34

B. Applications. 487, 13, 718, 964, 485, 34, 637, 1189, 225, 1230

C. Data: 485, 1201, 1211, 1215, 846, 847, 848, 1181, 1200, 33, 1213, 718, 964, 34, 1189, 225, 1230

D. Specific Instrument Descriptions: 950, 963, 850, 851, 193, 1033, 487, 13, 485, 34, 637, 225, 1230

DISCUSSION

A. Advantages

1. Measures the optical density of suspended particles in a portion of the stack without removing them or depositing them.

2. High reliability easily possible because of relative mechanical simplicity.

3. Lower initial cost than most other techniques if necessary calibration is ignored.

4. Several commercial instruments exist.

5. No moving parts are necessary.

6. Instantaneous, continuous measurement readout which is easy to record.

7. Measures average concentration over a long path, an advantage in some applications if carefully used.

B. Disadvantages

1. Does not detect particle mass, but some other parameter which is poorly related to mass concentration.

2. Requires extensive repeated calibrations of each installation under each plant operating condition for correlation with particle mass concentration. Small changes in plant operating conditions can result in measurement uncertainties of typically $^{+200}_{-100}$ % without such calibration.

3. Yields erroneous measurements during normal plant operations such as rapping and soot-blowing.

4. Becomes very expensive with the necessary calibrations.

5. Even with careful calibration, plant operating conditions must be known at all times in order to interpret the data.

6. Does not fit most existing sampling access ports, requiring higher cost of installation.

7. Requires careful placement, installation, and alignment.

8. Present manufacturers have a somewhat established market in the United States, making the introduction of new, more accurate mass concentration monitors more difficult.

9. Present commercial instruments often show poor correlation with each other.

C. Recommendations for Further Development

Although we reject this technique for particle mass concentration measurements, we recommend extensive development and testing of light-transmission instruments for use as optical density monitors. Different models of present commercial instruments show poor correlation with each other, suggesting the need for standardization of instrument design. Before that, however, extensive development and testing is needed to identify the "best" design. We recommend that a carefully-planned, long range program be undertaken which will result in an instrument design worthy of standardization. Such a program must also increase the knowledge of what light transmission instruments in stacks really measure.

D. Conclusions

Measurements made with this technique correlate very poorly with the mass concentration of aerosol particles. Thus, for most stack monitoring applications, the light transmission technique must be rejected for measurements of particle <u>mass</u> concentration. However, the technique will undoubtedly be used for monitoring optical density in stacks for some time to come because the measurement does correlate somewhat with the visual appearance of the plume and because instruments using the technique have several important practical advantages. A number of companies manufacture light transmission instruments. Considerable development of both theory and hardware is necessary to evaluate what is being measured. The lack of good correlation between the many light transmission instruments is disturbing. Although careful design could improve the correlation of light transmission measurements with particle mass concentration, this technique is not capable of accurate <u>mass</u> measurements.

LIDAR

PRINCIPLE OF OPERATION

Lidar, the optical analog of radar, uses the backward reflection of light from particles as a way of measuring particle concentration. The lidar light source is a laser and the detector is a photomultiplier. The source and detector are generally located close to each other. Most instruments have been made to study aerosol clouds 100m to 100 km from the lidar unit.

A typical lidar system consists of a laser, sending telescope, receiving telescope, and signal detector. Light pulses of very short duration (30×10^{-9} sec) and high energy (45 megawatts) are directed through the sensing telescope toward the cloud. Energy returned by the atmosphere is collected by a similar telescope and sensed by a photomultiplier. As with most optical particle sensing methods, the size and optical properties ofthe particle must be known for accurate data interpretation. Lidar has proven itself useful in defining the boundaries of aerosols plumes and clouds at some distance from the observer.

COMMERCIAL EQUIPMENT

Only research prototype lidar units exist.

REFERENCES (See LIDAR in Volume II)

A. Principle of Operation: 66, 221, 149

B. Applications: 280, 221, 569, 514, 149, 89, 66

C. Data: 280, 221, 569, 514, 89, 149

D. Specific Instrument Descriptions: 286, 802, 221, 89

DISCUSSION

A. Advantages

1. Measures some concentration of particles remotely from the observer.
2. Requires no sampling or particle deposition.
3. Senses a wide range of concentrations.
4. One instrument, located at some central location outside the stack, can monitor a number of stacks in turn.
5. Can measure the particles just after entering the atmosphere from the stack.

6. Source and detector can be located in one housing, measurement is single-ended and truly remote.
7. Lidars have been used to monitor stack plumes.
8. Remote monitoring removes the problems of high temperature and the otherwise harsh stack environment.
9. Can scan a cloud to obtain concentration profiles and cloud boundaries.
10. Cost can be low for monitoring a number of stacks remotely with one unit.

B. Disadvantages

1. Does not measure the mass of particles.
2. Particle size, density, and optical properties must be known to interpret the data accurately.
3. The measured parameter is not readily defined.
4. Technique not fully understood and developed yet.
5. Only sophisticated research equipment exists.
6. Present units are too expensive for monitoring single stacks.

C. Recommendations for Further Development

We do not recommend development of lidar as a particle mass concentration detector because the technique cannot sense mass. Even though it is not within the scope of this report, we recommend this technique highly as a remote monitor of particulate emissions from a number of stacks with one centrally-located instrument. Further studies should include better definition of the measured particulate parameter.

D. Conclusions

Lidar cannot measure the <u>mass</u> concentration of particles in or from a smoke stack. However, lidar appears to have excellent potential for remotely monitoring a number of stacks with one, permanently - installed instrument. This application would seem to be very useful in identifying possible emissions violators. After such identification, more careful particle mass concentration measurements could be made for more definite proof of violations. Thus, although lidar cannot fill the needs of a particle <u>mass</u> emissions monitor, it appears to be a potentially useful tool for pollution abatement.

HOLOGRAPHY

PRINCIPLE OF OPERATION

Holography is an interferometric technique by which three-dimensional information can be recorded on a two-dimensional photograph. The process consists of photographing the interference pattern that exists when a diffracted or object field (Fresnel or Fraunhofer diffraction pattern of the object) is allowed to interfere with a reference or background wave. The image can be reconstructed in three-dimensions by illuminating the film record with a coherent beam of quasi-monochromatic light.

Holography can be used to find the size and number distribution of an aerosol which passes through a given volume. The reconstructed holograms can be displayed on a TV monitor. Manual or automatic scanning techniques can then obtain the number concentration as a function of particle size in the 1 to 500 μm range. This information could be transformed into the total volume occupied by particles in a given volume of gas.

COMMERCIAL EQUIPMENT

Several companies manufacture and/or market holographic equipment for research purposes. Three companies that market equipment which can be specifically applied to particle holography are:

Stat Volt Company
1130 Channel Drive
Santa Barbara, California 93103

Optics Technology Inc.
901 California Avenue
Palo Alto, California 94304

Technical Operations Inc.
South Avenue
Burlington, Massachusetts 01803

REFERENCES (See HOLOGRAPHY in Volume II)

A. Principle of Operation: 150, 1195, 1197, 128, 682, 253, 126, 132, 784

B. Applications: 1197, 682, 253, 150, 483, 1198, 3, 516, 633

C. Data: 1198, 150, 3

D. Specific Instrument Descriptions: 148, 253, 483, 150, 1196, 3

DISCUSSION

A. Advantages

1. Does not require particle deposition or disturbing the aerosol flow stream.
2. Records permanent, 3-dimensional photographs of particles.
3. Can be used to measure particle size and number concentration plus some particle shape information.

B. Disadvantages

1. Very expensive at the present time and for some time to come.
2. Does not measure true particle mass, although it can measure particle volume.
3. Does not lend itself easily to automation without added expense and complex equipment.
4. Principle of operation is quite complicated.

C. Recommendations for Further Development

We do not recommend development of holography for particle mass concentration measurement at this time. The technique will undoubtedly be useful for studying the size, shape, and number concentration of particles in their natural state. Therefore, development for purposes other than particle mass measurement may be justified.

D. Conclusions

Holography is not a feasible monitor of particulate mass emissions from stacks at this time and probably will not be in the future. The system appears to be much too expensive and complex for such purposes. Undoubtedly, many other uses will be found for holography, including research study of particle size, shape, and concentration in the natural suspended state within smoke stacks.

OPTICAL COUNTERS AND PHOTOMETERS

PRINCIPLE OF OPERATION

An optical counter measures and counts individual particles by light scattering or extinction. Particles in an aerosol cloud are led single-file through a light beam where they scatter and absorb a certain amount of light depending on the particle size, the optical characteristics of the particle, and the light beam characteristics. Most optical counters detect the light scattered in a given direction by means of a photomultiplier. The output data is generally given as the number of particles within a given particle size range per unit gas volume. Modified commercial optical counters are limited to particle diameters of 0.2 μm to about 70 μm. Aerosol concentrations entering well-designed optical counters must be less than about 10^7 particles per cubic foot within the sensing range of the instrument. Some optical counters detect the amount of light blocked out by the particle. Optical counters are also known as single particle optical counters, aerosol counters, particle counters, and dust counters.

Photometers, often called nephelometers, perform their measurement on a cloud of aerosol particles by light scattering. They are useful for measuring aerosol concentration. In a photometer, a light beam shines through the cloud of aerosol particles. A photomultiplier measures the intensity of light scattered at a certain angle by the particles. The intensity of the scattered light depends on the particle size and concentration, on the optical characteristics of the light beam. Correlation with particle mass concentration requires that all these parameters except concentration remain constant. Photometers can measure aerosol clouds with considerably higher concentrations than can the optical counter.

COMMERCIAL EQUIPMENT

A number of companies manufacture optical counters, primarily for use as clean room monitors, but with several models for use as ambient atmospheric aerosol monitoring:

Royco Instruments, Inc.
141 Jefferson Drive
Menlo Park, California 94025

Bausch & Lomb
635 St. Paul Street
Rochester, New York 14602

Climet Instruments, Inc.
1240 Birchwood Drive
Sunnyvale, California 94086

High Accuracy Products Corporation
141 Spring Street
Claremont, California 91711

Coulter Electronics Industrial Division
590 West 20th Street
Hialeah, Florida 33010

Dynac Corporation
Thomson's Point
Portland, Maine 04120

Phoenix Precision Instrument Company
3803-05 North Fifth Street
Philadelphia, Pennsylvania 19140

Envirco
P. O. Box 6098
Albuquerque, New Mexico 87107

Several companies manufacture aerosol photometers for atmospheric aerososl:

Phoenix Precision Instrument Company
3803-05 North Fifth Street
Philadelphia, Pennsylvania 19140

Meteorology Research, Inc.
Box 637
464 West Woodbury Road
Altadena, California 91001

Royco Instruments, Inc.
141 Jefferson Drive
Menlo Park, California 94025

Envirco
P. O. Box 6098
Albuquerque, New Mexico 87107

REFERENCES (See OPTICAL COUNTERS and PHOTOMETERS in Volume II)

A. Principle of Operation: 143, 515, 362, 813, 625, 840, 1083, 1192, 1082, 578, 132, 680, 1211

B. Applications: 711, 732, 731, 840, 124, 919, 69, 928, 285, 225, 288, 1110, 993, 307, 578, 580, 559, 1180

C. Data: 993, 988, 731, 171, 680, 132, 928, 69, 919, 1083, 374, 285, 752, 340

D. Specific Instrument Descriptions: 145, 146, 370, 580, 1210, 756, 670, 615, 120, 1128, 949, 824, 276, 598, 1066, 822, 876, 1082, 362, 346, 840, 124, 928, 288, 1192, 1193, 1194, 969, 287

DISCUSSION

A. Advantages

1. Optical counters can detect very low concentrations (a single particle within the sensitive size range passing through the instrument) and upper concentrations of about 10^7 particles per cubic foot within the specified size range.

2. Optical counters can measure particle size distribution in the 0.2 - 70 μm diameter range if correctly designed.

3. Readout of photometer is instantaneous, continuous, and easy to record.

4. Automatic instruments are commercially available for ambinet air and clean room monitoring.

B. Disadvantages

1. Neither optical counters nor photometers measures particle mass, correlation with mass is not good.

2. Both types of instruments, especially the optical counter, are designed for clean room and other low concentration aerosols.

3. Both instruments require sampling probe and are subject to probe loss errors.

4. Both instruments require conditioning of the sample stream, including considerable dilution to measure stack concentrations.

5. Calibration of the instruments changes with changes in particle optical properties.

6. Both instruments lack the wide size range necessary for mass measurements.

7. Changes in the specific gravity of particles causes errors in estimating particulate mass.

8. Two particles passing through an optical counter at one time are counted as one particle.

9. Fluctuations in the number concentration of particles smaller than the lower size limit of optical counters cause errors in counting of particles in the lower size ranges.

C. Recommendations for Further Development

We recommend no development of these techniques as particle mass concentration monitors. A good dilution and sample conditioning system is necessary for use of either device in specific research applications.

D. Conclusions

These techniques cannot measure the mass concentration of airborne particles. Correlation of these measurements with particle mass concentration is very poor. These instruments share most of the problems of light transmission instruments and also have several additional problems for particle mass concentration monitoring. Optical counters may be useful for particle size distribution measurements of stack effluents after development of a sample conditioning system. Photometers may find specialized research application for measurement of stack effluents.

ANGULAR LIGHT SCATTERING

PRINCIPLE OF OPERATION

Light scattering is the redirection of illumination which is incident upon the object. Scattered light is a combination of transmitted, reflected, and diffracted light, and depends upon characteristics of the object, the surrounding medium, and the incident radiation. Important parameters which influence light scattering are light wavelength, particle size and shape, refractive index of the particle with respect to the medium, and the angle at which an observer is located in relation to the incident light. Light scattered at various angles from the direction of illumination provides a means of studying aerosols. The light intensity as a function of observation angle provides information which describes particle size if the index of refraction and light wavelength are known and the particle is spherical.

COMMERCIAL EQUIPMENT

No commercial equipment is known which uses this principle for aerosol measurements. Only laboratory prototypes exist.

REFERENCES (See ANGULAR LIGHT SCATTERING in Volume II)

A. Principle of Operation: 147, 1201, 1211, 702, 1203, 909, 1233, 70, 842, 38, 474, 805, 85, 1235, 1236, 1237, 1238

B. Applications: 702, 909, 1234, 1237, 1238

C. Data: 474, 805, 85, 1203, 1234, 1232

D. Specific Instrument Descriptions: 842, 1211, 38, 787

DISCUSSION

A. Advantages

1. Can measure particle concentration without depositing the particles onto a surface.

2. Can measure particle concentration more accurately than standard light transmission or scattering because particle size is partially measured.

3. Can detect low concentrations.

4. Potentially, rapid measurements are possible.

B. Disadvantages

1. Cannot measure particle mass or a parameter closely related to mass.

2. Procedure is presently manual and does not lend itself to automatic stack monitoring.

3. Data reduction is complicated and requires expensive equipment.

4. Results with adequate accuracy for stack monitoring are probably not possible.

5. Only research equipment has been constructed.

6. Considerably more theory and development remain to be done if practical instruments are to result.

C. Recommendations for Further Development

We recommend no further development as a particulate mass monitor. Further research and development may be justified for other types of particle measurements in stacks.

D. Conclusions

Angular light scattering cannot measure particulate mass concentration. Some research applications for the technique in stack effluents may be found.

SOILING POTENTIAL

PRINCIPLE OF OPERATION

As a filter becomes loaded with particles, the amount of light which can be transmitted through the filter decreases. The unit of measurement, called the coefficient of haze (Coh), corresponds with the optical density of the filter deposit. Another system with reflectance units of dirt (Rud), measures the stain potential due to light reflection rather than transmission. Soiling potential instruments usually consist of an indexing tape filter with a light source on one side of the filter deposit and a light detector on the other side.

COMMERCIAL EQUIPMENT

Several companies manufacture and/or sell soiling potential instruments for ambient air sampling including:

Research Appliance Company
Route 8 & Craighead Road
Allison Park, Pennsylvania 15101

Gelman Instrument Company
P. O. Box 1448
600 South Wagner Road
Ann Arbor, Michigan 48106

Precision Scientific
3737 West Cortland Street
Chicago, Illinois 60647

Leigh Systems, Inc.
220 Boss Road
Syracuse, New York 13211

Von Brand
Rhinebeck, New York 12572

Some of the ambient air monitors may adapt to stack monitoring with little modification.

REFERENCES (See SOILING POTENTIAL in Volume II)

A. Principle of Operation: 519, 396, 831, 305

B. Applications: 519, 396, 831, 305

C. Data: 519, 396, 831, 305

D. Specific Instrument Descriptions: 519, 396, 831, 305

DISCUSSION

A. Advantages

1. Several commercial models available for ambient air sampling; modification for stacks appears simple.

B. Disadvantages

1. Does not measure the mass of particles.
2. Particle size, density, and optical properties affect the measurement severely.
3. Requires sampling probe and is subject to probe loss errors.
4. Probably requires conditioning of the sample stream.
5. Requires particle deposition.
6. Requires an automatic advancing mechanism for the filter.
7. Difficult to make readout continuous and instantaneous.
8. Filter tape in present models needs replacement every 1 - 4 weeks.

C. Recommendations for Further Development

We recommend no development of this technique as a particle mass concentration monitor.

D. Conclusions

This technique cannot measure the mass concentration of airborne particles. The soiling index may be a useful measurement for pollution monitoring programs, but measurements cannot be expected to correlate with particle mass concentration. The technique shares nearly all the problems of light transmission measurements while having the additional problems of extraction sampling.

ACOUSTICAL ATTENUATION AND DISPERSION

PRINCIPLE OF OPERATION

Acoustical attenuation is the decrease in amplitude of an acoustical pressure wave traveling through a media due to such effects as interactions with walls and suspended particles. Two mechanisms account for practically all the attenuation caused by particles. One is viscous energy loss caused by the lagging motion of the particles as the acoustic wave passes. The other mechanism is thermal energy loss caused by the irreversible flow of heat between the suspended particle and the gas during rarefactions and compressions of the sound wave.

Acoustical dispersion is the decrease in sound velocity due to the presence of particulate matter in the gas. Particles added to a gas cause an increase in heat capacity and an increase in the density of the gas-particle mixture. Both result in a lower sound velocity.

COMMERCIAL EQUIPMENT

No commercial equipment using this principle is available for measuring particles. Only laboratory equipment exists.

REFERENCES (See ACOUSTICAL ATTENUATION AND DISPERSION in Volume II)

A. Principle of Operation: 138, 139, 604, 616

B. Applications: 314, 600

C. Data: 103, 138, 139, 605

D. Specific Instrument Descriptions: 314, 557

DISCUSSION

A. Advantages

1. Measures suspended particles without first depositing them.
2. Probably insensitive to contamination of apparatus.

B. Disadvantages

1. Does not sense particle mass concentration.
2. Sensitive only to very high concentrations, not sensitive to stack concentrations.
3. Response is dependent on particle size.

4. Instruments require batch sampling with relatively long stabilizing time.
5. Principle not well understood.
6. No feasible instrument design yet discovered.

C. Recommendations for Further Development

We do not recommend further development at this time. More basic research for developing a better understanding of the principle is needed. New methods for utilizing the principle may result from such programs. However, a number of other particle measurement techniques appear considerably more promising.

D. Conclusions

Acoustic attenuation and dispersion are not practical methods for measuring particle concentration in smoke stacks. Particle-acoustic interactions are in the research stage and little practical use has been found for the technology to date. We see little chance that practical instruments using this technology can be developed in the next 5 - 10 years.

ACOUSTICAL PARTICLE COUNTER

PRINCIPLE OF OPERATION

Particles cause an audible "click" when passing through or leaving a laminar capillary. The intensity of the "click" is somewhat related to particle size, but the exact relationship is not yet known. Although the phenomena is not very well understood, it can be used to count individual particles. Particles below 5 μm cannot be detected. The resulting measurement is the number concentration of particles above 5 μm.

COMMERCIAL EQUIPMENT

No commercial equipment exists using this principle. Only laboratory prototypes exist.

REFERENCES (See ACOUSTICAL PARTICLE COUNTER in Volume II)

A. Principle of Operation: 249, 349, 6

B. Applications: 250, 349, 2

C. Data: 250, 349

D. Specific Instrument Descriptions: 249, 349

DISCUSSION

A. Advantages

1. Sensitive to single particles.

2. Measures suspended particles without first depositing them.

B. Disadvantages

1. Not sensitive to particle mass, but to particle number concentration.

2. Not sensitive to particles below 5 μm.

3. Has not been made to work reliably in the laboratory and would need much more development for stack use.

4. Requires low particle concentrations to prevent coincidence errors.

5. Physical principles poorly understood.

6. Requires sampling probe and is subject to probe loss errors.

7. Requires conditioning of the sample stream.

C. Recommendation for Further Development

We recommend no development of this technique for particle monitoring in smoke stacks.

D. Conclusions

Acoustical particle counting is not a practical method for monitoring particles in smoke stacks, primarily because of the first three disadvantages listed earlier.

ALPHA AND GAMMA RADIATION ATTENUATION

PRINCIPLE OF OPERATION

As with beta radiation, alpha and gamma radiation are also attenuated when passing through a medium. Alpha radiation particles, which are really helium nuclei, are not very energetic. A piece of ordinary paper stops most of them. Gamma radiation is an electromagnetic wave with characteristics identical to those of x-rays of the same energy. Gamma radiation can have either high or low energy, depending on the source. The attenuation of gamma radiation, particularly low-energy gamma radiation, depends strongly on the atomic number of the target material. High energy gamma radiation is not appreciably attenuated by thin layers of particles. Alpha and gamma radiation have not been used much to sense particles.

COMMERCIAL EQUIPMENT

No commercial equipment of this type exists.

REFERENCES (See BETA RADIATION ATTENUATION in Volume II)

Few references discuss using alpha and gamma radiation for monitoring particles. Reference 1085 discusses the use of gamma radiation to measure the ash content of coal.

DISCUSSION

A. Advantages

1. No significant advantages as compared to beta radiation attenuation.

B. Disadvantages

1. Not sensitive to particle mass concentration, very sensitive to particulate composition.
2. Alpha radiation is not energetic enough to penetrate reasonable particle deposits.
3. Gamma radiation penetrates large thicknesses of particles with almost no attenuation and, therefore, has poor sensitivity.
4. Gamma radiation is dangerous if not carefully handled and would require careful shielding.
5. Requires sampling probe and is subject to probe loss errors.

6. Requires particle deposition.
7. Requires conditioning of the sample stream.
8. Requires an automatic advancing mechanism for the sample deposit.
9. Not available commercially.

C. Recommendations for Further Development

We recommend no further development for particle monitoring at this time.

D. Conclusions

Alpha and gamma radiation attenuation have no significant advantages over beta radiation attenuation for particle monitoring in stacks. On the other hand, each has several severe disadvantages compared with beta radiation attenuation. Alpha and gamma radiation attenuation cannot be used for monitoring effluent particle mass concentration.

COLLECTION OF PARTICLES IN LIQUID SUSPENSIONS

PRINCIPLE OF OPERATION

If airborne particles are collected into a liquid, the concentration of the resulting suspension is proportional to the original aerosol concentration. This technique can be used for concentrating particles from a large volume of air into a small volume of liquid. Particle collectors include impactors, electrostatic precipitators, cyclones, and bubblers. Particle sensing techniques include light transmission, light scattering, and electrical resistivity.

COMMERCIAL EQUIPMENT

No equipment is known which is designed specifically for automatic monitoring of this type. However, several samplers are available which deposit or collect the particles directly into the liquid. Also, several particle concentration monitors for liquid suspensions are available. A combination of a sampler and sensor should be very easy to assemble since each can operate nearly independent of the other. Samplers which collect particles directly into liquid are:

1. Common bubbler samplers sold by a number of companies.

2. Impaction and electrostatic precipitation samplers particularly suited to this application are manufactured by:

   Litton Systems, Inc.
   Applied Science Division
   13010 County Road 6
   Minneapolis, Minnesota 55427

   Environmental Research Corporation
   3725 North Dunlap Street
   St. Paul, Minnesota 55112

Sensors which measure the concentration and/or the size distribution of particles in a liquid suspension are sold by a number of companies.

REFERENCES

No references have been found which discuss this specific technique. A large number of references discuss the two components of this technique: the particle collector and the liquid suspension sensor.

DISCUSSION

A. Advantages

1. Because some samplers which leave the particles in liquid suspension operate at high air flow rates, they can collect large samples in a short time.

2. The liquid suspension acts as a particle concentrator, allowing the measurement of a wide range of airborne particle concentrations.

3. Several different collectors and sensors can be used.

4. The particle size distribution can be obtained by the same or a similar method.

B. Disadvantages

1. Liquid particles are lost in the liquid suspension.

2. Solid particles may change their shape, size, surface characteristics, etc., when placed in a liquid.

3. Sensing techniques do not measure particle mass and generally share the same problems as their aerosol counterparts.

4. Requires sampling probe and is subject to probe loss errors.

5. Requires the particles to become wetted and remain in liquid suspension until sensed.

6. Requires liquid handling system, probably including recirculation.

C. Recommendations for Further Development

We do not recommend further development of this technique for particle mass concentration measurements at this time.

D. Conclusions

This technique is not a practical method for monitoring the mass concentration of particles in smoke stacks, primarily becuase of the first three disadvantages listed earlier.

CONDENSATION NUCLEI COUNTER

PRINCIPLE OF OPERATION

If an aerosol of 0.002 - 0.1 µm particles with water vapor is suddenly expanded, the water vapor condenses on most particles causing them to grow. Such particles are called condensation nuclei. Depending on the thermodynamic properties of the system, particles larger than about 20 Å grow while smaller particles do not. After sufficient growth, most particles are in the 0.1 to 1.0 µm size range and are quite uniform in size, composition, and optical properties. A photometer then senses the concentration of the resulting aerosol. The measurement can be calibrated in terms of particle number concentration. The measurement is overwhelmingly dominated by submicron particles which do not contain much mass.

COMMERCIAL EQUIPMENT

At least three companies manufacture condensation nuclei counters:

Environment/One Corporation
2773 Balltown Road
Schenectady, New York 12309

General Electric Company
P. O. Box 43
Schenectady, New York 12301

Singco Inc.
11 Cypress Drive
Burlington, Massachusetts 01813

REFERENCES

A. Principle of Operation: 1133, 683

B. Applications: 1133, 27, 42, 68, 683, 606

C. Data: 1133, 336, 683, 606

D. Specific Instrument Descriptions: 1133, 336, 683, 606

DISCUSSION

A. Advantages

1. Measures suspended particles without first depositing them.
2. Fast response, several measurements per second.
3. Readout is easy to record.

4. Sensitive to submicron particles (see disadvantages).
5. Several commercial automatic instruments available.

B. Disadvantages

1. Measurement of number concentration does not correlate with mass concentration.
2. The number of submicron particles to which this instrument is sensitive fluctuates strongly in most effluents.
3. Requires sampling probe and is subject to probe loss errors.
4. Probably requires conditioning of the sample stream.
5. Calibration of present instrument does not appear to remain constant.
6. Some particles may not allow condensation and will therefore not be sensed.

C. Recommendations for Further Development

We recommend no development of this technique as a particle mass concentration monitor. Some development as a research tool for specialized applications may be justified.

D. Conclusions

This technique cannot measure the mass concentration of airborne particles. The measurement is much too sensitive to submicron particles to correlate with particle mass. Some specialized research applications of this technique to stack effluent measurements may exist.

FILTER PRESSURE DROP

PRINCIPLE OF OPERATION

When particle-laden air is passed through a clean filter, the collection of particles on the filter will cause an increase in the pressure differential across the filter. This is because the particles reduce the effective flow area through the filter, which has the same effect as a constriction in a tube.

This technique measures the particle concentration in an airstream if the pressure drop across a filter is monitored as a function of time. This technique does not sense the mass of the particles. It is rather sensitive to the size and shape of the particles. Its particle-size dependence arises because the size (or cross-sectional area) of a particle determines the amount of air flow it "blocks". The shape of the particle determines its ability to penetrate the filter, and, if a particle is allowed to penetrate to the interior of the filter, its effect will be much less pronounced.

COMMERCIAL EQUIPMENT

No commercial equipment is available which uses this technique to measure particle mass concentration.

REFERENCES

A. Principle of Operation: 136, 482, 674

B. Applications: 482, 674, 932, 1042

C. Data: 482, 915, 932

D. Specific Instrument Descriptions: 225, 482, 921, 1042

DISCUSSION

A. Advantages

1. Insensitive to contamination of apparatus because all particles are collected on the filter.
2. Quite simple to design, construct, and operate.
3. Inexpensive.
4. Present commercial filter tape spot samplers can be adapted quite easily.

B. Disadvantages

1. Does not measure the mass of particles.
2. Theory not developed relating particulate mass loading to pressure drop.
3. Technique is sensitive to particle size and shape to such a degree that changes in these parameters overshadow changes in mass loading.
4. Requires sampling probe and is subject to probe loss errors.
5. Requires particle deposition.
6. May require conditioning of the sample stream.
7. Requires some mechanism for periodically replacing filters.
8. Readout not instantaneous or continuous:

   1 data point every 1 min. - 1 hr.

C. Recommendations for Further Development

We do not recommend further development of this technique at the present time.

D. Conclusions

This technique is not very promising for use in stacks at this time. Although a rugged, practical instrument could easily be fabricated, an accurate reading of particle mass concentration is not possible because the technique is not sensitive to the mass of the particles. Changes in other properties such as size and shape overshadow changes in the mass concentration.

FLAME IONIZATION

PRINCIPLE OF OPERATION

When combustible particles pass through a hot flame, they will burn, producing a pulse of electrical ions. The intensity of the ion pulse can be sensed with an electrometer, yielding information about particle concentration and particle size. The magnitude of the ion pulse depends on the mass of the particle, but also on the composition. This technique is analogous to the flame photometry technique.

COMMERCIAL EQUIPMENT

No flame ionization instruments are manufactured for monitoring of particles although several companies manufacture gaseous analyzers using flame ionization.

REFERENCES

A. Principle of Operation: 60

B. Applications: 408

C. Data: 54, 60, 289

D. Specific Instrument Descriptions: 54, 289, 408

DISCUSSION

A. Advantages

1. Measures suspended particles without first depositing them.

2. Can probably operate at stack temperatures.

3. Gives size and concentration data continuously.

4. Probably senses a parameter closely related to particle mass if the composition is acceptable and remains constant.

B. Disadvantages

1. Senses only combustible particles, few of which should exist in stack effluents if the process is under control.

2. Even with combustible particles, the particle composition must remain quite constant.

3. Requires sampling probe and is subject to probe loss errors.

4. Equipment may be expensive.

C. Recommendations for Further Development

We do not recommend further development of this technique for particle mass concentration measurement in stacks.

D. Conclusions

This technique is not a practical method for monitoring the mass concentration of particles in smoke stacks, primarily because of the first disadvantage listed earlier. Flame photometry may be a good indicator of the poor burning of combustible materials and could probably be used in this way to help the plant operator adjust the fuel burning efficiency.

FLAME PHOTOMETRY

PRINCIPLE OF OPERATION

When combustible particles pass through a hot flame, they will burn, producing a bright glow. The intensity of the glow can be sensed by a photometer, yielding information about particle concentration and particle size. The amount of light produced depends on the mass of the particle, but also depends on the composition. This technique is analogous to the flame ionization technique.

COMMERCIAL EQUIPMENT

No flame photometers are manufactured for stack monitoring.

REFERENCES

Reference 53 discusses this technique.

DISCUSSION

A. Advantages

1. Measures suspended particles without first depositing them.
2. Can probably operate at stack temperatures.
3. Gives size and concentration data continuously.
4. Probably senses a parameter closely related to particle mass if the composition is acceptable and remains constant.

B. Disadvantages

1. Senses only combustible particles, few of which should exist in stack effluents if the process is under control.
2. Even with combustible particles, the particle composition must remain quite constant.
3. Requires sampling probe and is subject to probe loss errors.
4. Equipment would probably be quite expensive, especially readout equipment.

C. Recommendations for Further Development

We do not recommend further development of this technique for particle mass concentration measurements in stacks.

D. Conclusions

This technique is not a practical method for monitoring the mass concentration of particles in smoke stacks, primarily because of the first disadvantage listed earlier. Flame photometry may be a good indicator of incomplete burning of combustible materials and could probably be used in this way to help the plant operator adjust the fuel burning efficiency.

GAS ADSORPTION

PRINCIPLE OF OPERATION

If a gas is in equilibrium with a solid surface, the concentration of gas molecules in the vicinity of the surface is always greater than the free gaseous phase. This phenomena, known as adsorption, is independent of the nature of the gas and the surface. The amount of gas, usually nitrogen, adsorbed on a surface can be measured very accurately by means of the Brunnauer-Emmett-Teller (BET) method. This technique measures surface area of a sample. For the monitoring of particles in stacks, a sample must be collected by some auxiliary method and then introduced to the BET apparatus: a batch process.

COMMERCIAL EQUIPMENT

No commercial or research equipment is known to exist for measurement of airborne dusts by this technique. Several companies manufacture BET surface measuring apparatus for manual laboratory measurements of collected particles including:

Micromeritics Instrument Corporation
800 Goshen Springs Road
Norcross, Georgia 30071

Perkin-Elmer Corporation
702 G Main Avenue
Norwalk, Connecticut 06852

REFERENCES

Reference 312 suggests this principle for dust measurement. No references discuss actual instruments or data.

DISCUSSION

A. Advantages

1. Directly measures the surface area of the sample very accurately.
2. Surface area measuring apparatus is well developed and commercially developed.

B. Disadvantages

1. Does not measure the mass of particles, correlation with mass is highly questionable since surface area is measured.
2. Technique not tried on stack effluents, feasibility remains to be proven.

3. Automation of the batch process may be difficult.
4. The batch process may require excessive time to complete one measurement.
5. Requires sampling probe and is subject to probe loss errors.

C. Recommendations for Further Development

We recommend no further development of this techique for particulate mass monitoring. However, the technique is useful for accurate particulate surface area measurements. Automation of the batch process would require considerable development.

D. Conclusions

This technique can measure surface area very accurately. Correlation with mass is poor, and the technique must be rejected for that purpose. However, the technique will be useful in a laboratory for surface area measurements of batches of collected effluent particles.

HOT-WIRE ANEMOMETRY

PRINCIPLE OF OPERATION

Output voltage fluctuations of a hot-wire anemometer placed in an airstream with liquid aerosol are primarily caused by two phenomena: transient cooling of the wire by turbulence of the airstream and evaporative cooling resulting from liquid drops which have impacted on the hot wire. If the thermodynamic properties of the liquid and airstream are known, the two effects can be discriminated by electronic filters. The concentration of liquid droplets can be measured by an electronic counter. Droplets below 3 μm are difficult to detect. Solid particles tend to contaminate the hot wire, resulting in erroneous measurements of gas stream velocity and droplet concentration.

COMMERCIAL EQUIPMENT

Several domestic companies manufacture hot-wire or hot-film anemometers:

Thermo-Systems Inc.
2500 North Cleveland Ave.
St. Paul, Minnesota 55113

Datametrics Division
CGS Scientific Corporation
127 Coolidge Hill Road
Watertown, Massachusetts 02172

Two foreign companies also manufacture this equipment:

Disa Elektronik A/S
Herlev Hovedgade 15-17
Herlev, Denmark

Nihon Kagaku Kogyo Co., Ltd.
4168, Yamadashimo
Suita, Osaka, Japan

REFERENCES (See HOT-WIRE ANEMOMETRY in Volume II)

A. Principle of Operation: 79, 10, 798, 39

B. Applications: 14, 799, 1046, 39, 2

C. Data: 14, 830, 10, 799, 39, 2

D. Specific Instrument Descriptions: 224, 830, 14, 799, 39

DISCUSSION

A. Advantages

1. Can discriminate liquid droplets from solid droplets.
2. Does not require extraction of a sample from the airstream.
3. Can be calibrated to measure droplet size distribution.
4. Several commercial anemometers for air velocity and turbulence measurements have existed for over 10 years.

B. Disadvantages

1. Cannot sense particle mass concentration.
2. Cannot sense solid particles.
3. Cannot sense droplets below 3 μm.
4. Droplet size calibration is only valid if all droplets are the same material.
5. Present hot wires and hot films needed for droplet sensing are somewhat fragile for continuous stack use.

C. Recommendations for Further Development

We recommend no further development for particle monitoring in smoke stacks.

D. Conclusions

Hot-wire and hot-film anemometers cannot be used for monitoring particle mass concentration because of the five listed disadvantages.

PRESSURE DROP IN NOZZLE

PRINCIPLE OF OPERATION

As a gas stream passes through a nozzle, the gas flow rate can be calculated using the well-known relationship between pressure drop and velocity. The presence of particles in the gas stream changes this relationship because the particles lag behind during the rapid velocity changes of the gas stream. Thus, the pressure drop across a nozzle increases if particles are present. The magnitude of the effect caused by particles depends on particle size. Dust concentration of 500 g/m^3 or more are necessary, making it necessary to enrich the concentration of effluent dusts by a factor of at least 1000 in order to measure the concentration with any degree of accuracy.

COMMERCIAL EQUIPMENT

No equipment specifically designed for particle concentration measurement appears to be available. Numerous companies sell nozzles for measureing the flow rate of gas through a tube.

REFERENCES (See PRESSURE DROP IN NOZZLES in Volume II)

A. Principle of Operation: 1067, 225, 1031

B. Applications: 1031, 1067, 225

C. Data: 225, 1031, 1067

D. Specific Instrument Descriptions: 1067

DISCUSSION

A. Advantages

1. Measures suspended particles without first depositing them.
2. Uses simple apparatus which is familiar to most technical people.
3. Reliability of apparatus should be high.
4. Can operate at stack temperatures.

B. Disadvantages

1. Cannot sense particle mass concentration.

2. Cannot sense particle concentrations below 500 g/m^3, requiring particle enrichment of at least 1000 times for stack effluents. Since cyclones are too erratic, no useable enricher is presently known.
3. Requires sampling probe and is subject to probe loss errors.
4. Measurement depends on particle size.
5. Very litle development has been done on this technique.

C. Recommendations for Further Development

We recommend no further development for particle monitoring in smoke stacks.

D. Conclusions

Pressure drop across a nozzle cannot be used for monitoring particle mass concentration, primarily because of the second disadvantage listed above.

RADIOACTIVE TAGGING AND SENSING

PRINCIPLE OF OPERATION

It may be possible to tag airborne particles radioactively so that the activity level is proportional to particle concentration. An activity meter downstream of the "charger" would monitor the activity of the airborne cloud or of the collected (and, thus, concentrated) sample.

COMMERCIAL EQUIPMENT

No instrument of this type is presently available. No reports of research on this technique have been found by the authors.

REFERENCES

No direct references have been found by the authors. Reference 920 discusses some aspects of radioactively labeled aerosols.

DISCUSSION

A. Advantages

1. May offer possibility of monitoring aerosols without first collecting the particles on a surface.

B. Disadvantages

1. Probably would be more proportional to surface area than to mass of particles.
2. Feasibility is not proven, no development has been done.
3. Probably requires sampling probe and is subject to probe less errors.
4. May not operate with stack concentrations.

C. Recommendations for Further Development

We recommend no further development of this technique for particulate mass monitoring unless some radioactive tagging technique is available which places activity on the particles proportional to their mass.

D. Conclusions

Since no feasibility has been done on this technique, it must be rejected for the present. Further evaluation awaits such a study. It appears that this technique would not measure particulate mass but some other particle parameter.

VOLUME MEASUREMENT

PRINCIPLE OF OPERATION

The volume occupied by particles can be measured by several methods. For example, particles collected by a cyclone can settle into a small diameter tube (about 1 mm diameter). The volume of the sample can be measured by monitoring the height of the deposit in the tube after a specified time with a light beam. Another way to measure the sample volume is to measure the amount of liquid needed to fill the tube which holds the particles. Other particle collection and volume measuring techniques can be used.

This technique offers greater promise than most techniques which do not directly sense particulate mass because the volume concentration is related to mass concentration by knowledge of only one other parameter: the average specific gravity of the particles. Most other techniques which do not directly sense mass also require knowledge of the size distribution and other particulate parameters. Unfortunately, average specific gravity of combustion effluent particles fluctuates strongly.

COMMERCIAL EQUIPMENT

No commercial or research instruments of this type are known to exist.

REFERENCES

No references have been found describing this technique.

DISCUSSION

A. Advantages

1. Measures some form of particle volume, a parameter related to mass if one knows particle specific gravity.
2. Principle is simple and easy to analyze for errors.
3. Apparatus could be moderately simple.
4. Time resolution should be quite good, probably about 1 minute per measurement with a cyclone collector.
5. Several particle collectors and sensors can be used, offering the designer greater flexibility in developing instruments.

B. Disadvantages

1. Does not measure particulate mass directly.

2. Particle specific gravity must be known and should be constant for all volume sensing techniques; particle specific gravity within stacks is not well known at this time and may vary considerably with slight plant operating changes.

3. Some volume sensors require knowledge of the packing of the dry deposit, others require a rather complicate liquid-batch process.

4. Readout not instantaneous or continuous:
   1 data point every 1 - 10 minutes.

5. Time required for 1 - 10 micron particles to settle into a chamber may increase the time required for each measurement.

6. Requires particle collection and cleaning of the system for every measurement.

7. No development of this technique appears to have been done although the technique simply combines several well-known procedures.

8. Automation may be difficult.

9. Requires sampling probe and is subject to probe loss errors.

10. May require some conditioning of the sample stream.

C. Recommendations for Further Development

We recommend no development of this technique at this time. The major design problem with this technique appears to be the automation of the system.

D. Conclusions

This technique offers some promise of accurate particulate mass concentration measurements if the specific gravity of the effluent particles remains constant. Unfortunately, the particulate specific gravity within combustion effluents fluctuates quite strongly. Since no instruments of this type have been developed, considerable work remains for development of a reliable instrument. The technique does not measure particulate mass concentration directly and has several other problems listed above. Commercial development would require several years, primarily for the design of the automatic features.

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