Information Circular 9357

Using Light-Scattering Intensities To Discriminate Waterdrops From Coal Mine Dusts

By Robert P. Vinson

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES

Library of Congress Cataloging in Publication Data:

Vinson, Robert P.
Using light-scattering intensities to discriminate waterdrops from coal mine dusts / by Robert P. Vinson.

p. cm. — (Information circular; 9357)

Includes bibliographical references (p. 12).

1. Mine dusts—Measurement. 2. Moisture—Measurement. 3. Aerosols—Measurement. 4. Light—Scattering. 5. Coal mines and mining—Dust control. I. Title. II. Series: Information circular (United States. Bureau of Mines); 9357.

TN295.U4 [TN312] 622 s—dc20 [622'.82] 93-17726 CIP

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

mm	millimeter	nm	nanometer
μm	micrometer	V	volt

USING LIGHT-SCATTERING INTENSITIES TO DISCRIMINATE WATERDROPS FROM COAL MINE DUSTS

By Robert P. Vinson[1]

ABSTRACT

The U.S. Bureau of Mines evaluated a light-scattering technique for discriminating between spherical and nonspherical particles. This evaluation was a three-step procedure.

The first step required collecting light-scattering data for a variety of particles. This was accomplished with a particle analyzer called the DAWN-A. The DAWN-A measured the scattered light intensities of individual particles at a forward scattering angle of 40°. These DAWN-A measurements of individual particles are called scattering signatures by the Bureau researchers.

The second step in this evaluation was to calculate a sphericity index number using the scattering signatures produced by the DAWN-A. The sphericity index number can range from 0 to 1. A calculated sphericity index of 1 would show that based on the intensity of scattered light, the particle was a perfect sphere.

The third and final step of this evaluation was the comparison of the calculated sphericity indices of the various particles. Comparing these indices made it possible to discriminate between the nearly spherical waterdrops and the nonspherical coal and rock dust particles.

[1]Physicist, Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

The U.S. Bureau of Mines conducts research to protect the health of the Nation's coal miners. The Bureau is pursuing a research program to eliminate coal workers' pneumoconiosis (CWP) by the reduction of respirable coal mine dust in the mine air. A basic requirement for this task is instrumentation to measure respirable coal mine dust concentrations quickly and accurately.

A variety of real-time dust monitoring systems, designed specifically for use in coal mines, are commercially available. Some of these, such as the RAM-1[2] and Miniram from Mie, Inc., and TM Digital and TM Data from the Hund Corp. (*1-2*),[3] are portable, hand-held instruments. Others, such as the OSIRIS from Revel Engineering Ltd. and the TM Stat from Hund, are stationary monitoring systems. These real-time dust monitors use the principles of light scattering to detect respirable-size coal mine dusts.

Dust monitors that use the principles of light scattering are called photometers. Photometers measure the total light scattered at a preset scattering angle θ (also called polar angle) or range of angles. For example, the RAM-1 detects scattered light between 45° and 95° in the forward scattering direction. Photometers detect light scattered from a continuous flow of a mixture of particles and measure the number of particles per volume of air, which is then used to determine the mass of dust per unit volume. They have some unique advantages over standard gravimetric methods. Photometers eliminate the time and cost of weighing dust filters and calculating the concentrations. They also eliminate the potential for human error or tampering of dust filters. Most photometers have digital displays that show real-time dust concentrations. Most importantly, photometers can provide information about short-term fluctuations of dust concentration (*3-4*) in contrast to gravimetric samples. For that reason, engineers and researchers use photometers extensively to determine the effectiveness of present dust controls and those now being developed.

Unfortunately, photometers presently in use have shortcomings that limit their ability to provide reliable measurements of respirable coal mine dust. As now designed, photometers are unable to discriminate between light scattered by liquid or solid aerosols (*5-6*). They must be calibrated with the dust they are to sample if reasonable accuracy is to be expected. Researchers have found that photometers respond differently to coal dust from different coal seams (*6-7*).

Recent advances in light-scattering technology and electronics may help minimize the shortcomings of current photometers (*8*). The Bureau's research program is applying these advances to develop a photometer that can discriminate between various coal mine aerosols. One objective of this program is to collect scattering signatures of coal mine aerosols. Scattering signatures are the intensities of light scattered by aerosols as a function of angle. Bureau researchers used an instrument, called the DAWN-A, to collect the scattering signatures of various coal mine aerosols for analysis and comparison. This report describes and discusses this work.

BACKGROUND

For generations, the coal miner's most chronic health hazard has been CWP or black lung. Black lung is the result of the lung's reaction to long-term inhalation and deposition of respirable coal mine dust. At present, there is no known cure for CWP. The families of stricken miners have to endure the suffering of a family member and the burden of long-term medical expenses. To alleviate the latter, the U.S. Government passed the Black Lung Benefits Act in 1972. These benefits have reduced the financial burden to the miners and their families, but the cost of black lung benefits to government and industry is enormous. The U.S. Department of Labor, Black Lung Claims Div., records show that, in calendar year 1990, $571 million was paid out in black lung claims. CWP will continue to cause untold human suffering and place a heavy financial burden on government and industry until it is eliminated.

Prolonged inhalation of respirable-size coal mine dust causes CWP. Removing respirable coal mine dust from the coal miner's environment could eliminate CWP. The United States and other major coal-producing countries of the world have research programs directed to accomplish this.

The passage of the Federal Coal Mine Health and Safety Acts of 1969 and 1977 authorized the Bureau to conduct research to improve the health and safety of coal miners.

---

[2]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

ACKNOWLEDGMENTS

The Bureau recognizes the contribution of Jerry Bottiger, physicist, U.S. Army Chemical Research and Development Center, Aberdeen Proving Ground, MD. Bottiger developed the sphericity index concept for his research and shared this technique with the Bureau.

The Bureau also recognizes the contributions by Richard Reynolds, II, a technician at the Bureau's Pittsburgh Research Center, Pittsburgh, PA. He developed computer programs and LOTUS 1-2-3 macros to aid in the analysis and graphing of the DAWN-A data. He also wrote a program to transfer American Standard Code for Information Interchange (ASCII) formatted DAWN-A data to LOTUS 1-2-3 worksheet files.

INTENSITY OF LIGHT SCATTERING BY SMALL PARTICLES

In 1908, Gustav Mie developed the general theory of light scattering by aerosols. The mathematical expression of the Mie theory for light scattering from a sphere is—

$$I(\theta) = I_o \frac{\Gamma^2 \quad [i_1(\alpha,m,\theta + i_2(\alpha,m,\theta)]}{8\pi^2 R^2}, \quad (1)$$

where I = intensity,

I_o = intensity of incident light,

Γ = wavelength,

i_1 = Mie intensity parameter for perpendicular polarization,

α = size parameter,

m = refractive index,

i_2 = Mie intensity parameter for parallel polarization,

and R = distance from particle.

This is the form of the Mie equation when the light incident is unpolarized and the particle is a sphere. The equation is for elastic scattering of light; that is, light that does not change in frequency when scattered.

The size parameter $\alpha = \pi d/\Gamma$ relates the particle size d (the diameter of the particle) to Γ, the wavelength of the incident light. The refractive index $m = n_r - in_{im}$, where n_r is the real part of the refractive index and n_{im} is the imaginary part. The imaginary part of the refractive index accounts for light absorbed by particles such as coal.

The scattered light intensity is a function of the size parameter α, which is the ratio of the diameter of the sphere scattering the incident light to the wavelength of the incident light. The scattered light intensity is also inversely proportional to the square of the distance from the point of scattering. These parameters affected the scattering signature data collected by the DAWN-A.

DAWN-A PARTICLE ANALYZER

The DAWN-A is an instrument that detects and stores the scattering signatures of micrometer-size aerosols. Scattering signatures are defined as the measured intensities of light scattered by particles as a function of the scattering angle θ. Wyatt Technology, Inc., Santa Barbara, CA, designed and built the DAWN-A for the U.S. Army Chemical Research and Development Center (*9*). The Bureau now owns the original DAWN-A (fig. 1).

SCATTERING CHAMBER

A sealed scattering chamber is the most important component of the instrument (fig. 2). It is here that the DAWN-A produces and detects scattering signatures of aerosols. The scattering chamber is made of two flanged, hollow-aluminum hemispheres. When bolted together at their flanges, the hemispheres form the scattering chamber, which is a hollow aluminum sphere with an inside diameter of 40.0 mm that has several holes through the surface. The holes in the chamber are for the aerosol-ladened airstream, a laser beam, and light collimators for measuring light intensity.

AIRFLOW SYSTEM

The two openings on the chamber's vertical axis are the inlet and outlet for the aerosols. The inlet contains a nozzle made of two concentric tubes. Filtered air passes

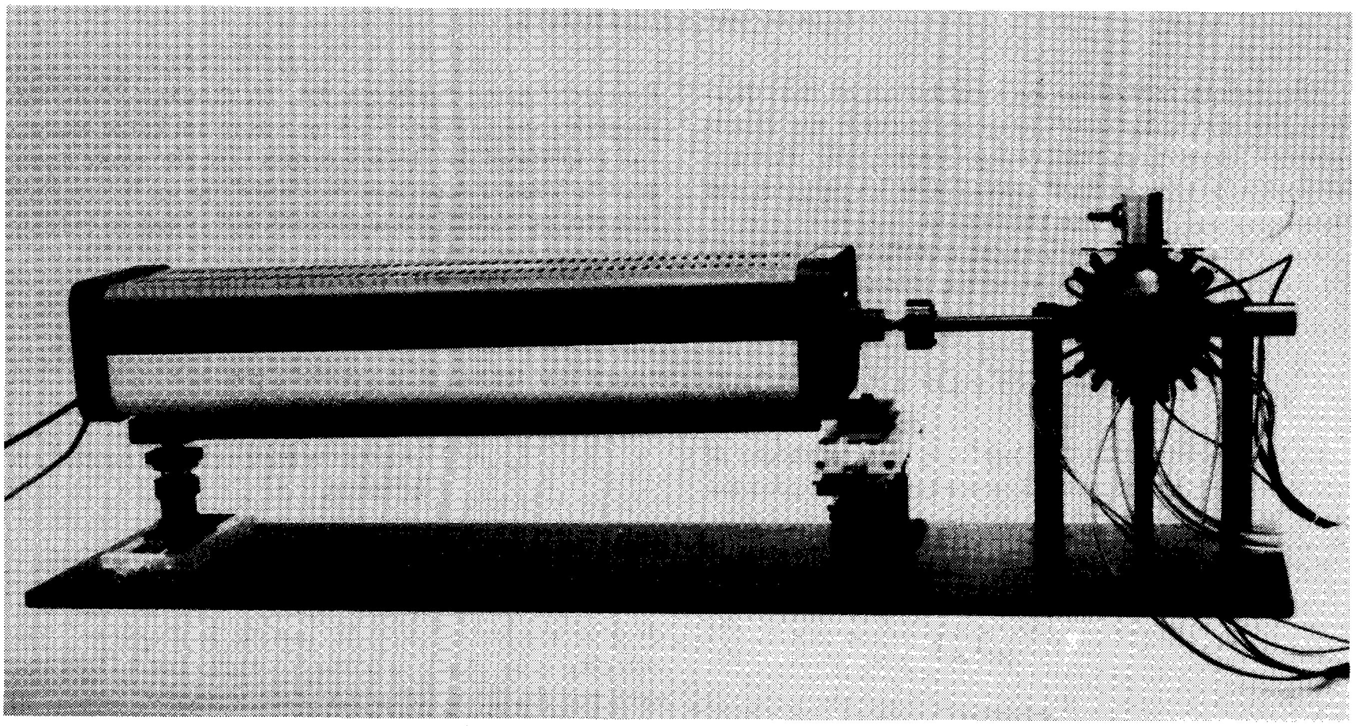

Figure 1.—DAWN-A.

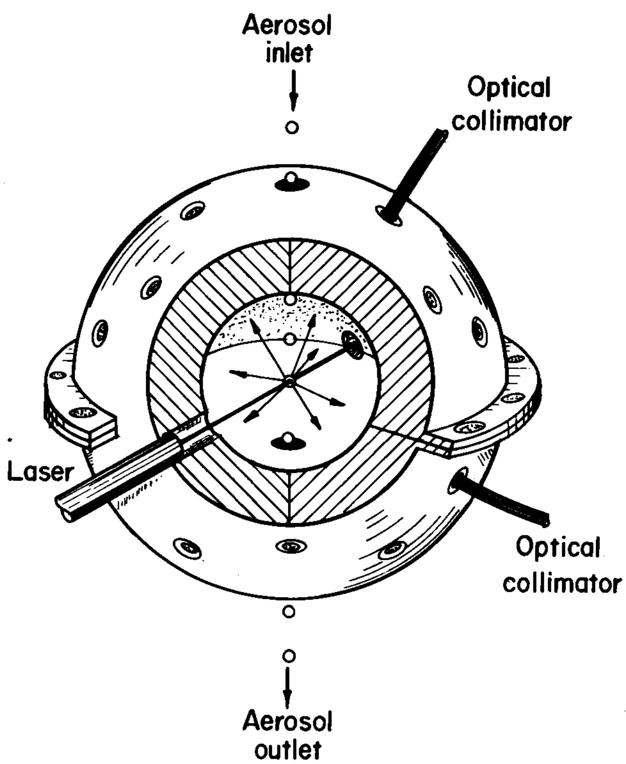

Figure 2.—Sectional view of DAWN-A light-scattering chamber.

through the outer tube. This sheath of air keeps the aerosol-ladened air from the inner tube in a narrow 1.016-mm-diameter stream. An air pump, connected to the outlet at the bottom of the chamber, pulls this air-stream through the center of the chamber. Aerosols in this regulated airstream scatter the laser beam that is perpendicular to it.

LASER

The laser beam passes through two holes in the horizontal axis of the scattering chamber. A light trap that stops the beam and prevents beam reflection covers the beam outlet hole.

The laser is helium-cadmium, emitting plane polarized light with a wavelength of 442 nm. The beam is 0.3 mm in diameter. The energy output of this beam is axially symmetrical, having its maximum energy at its center.

For these studies, a quartz-quarter-wave retardation plate was installed in front of the laser beam. This improved the uniformity of the scattered light intensity along the azimuth of the scattering angle θ. The quarter-wave plate transformed the linearly polarized laser beam to a circularly polarized beam.

LIGHT-DETECTION SYSTEM

The scattering chamber contains several apertures for light detection. The scattering angle θ and the azimuth angle Φ, as shown in figure 3, determine the location of each aperture. Figure 3*A* shows the orientation of the laser beam along the X axis, which is perpendicular to the aerosol-ladened airstream along the Z axis in the scattering chamber.

The scattering angle θ is referenced to the direction the laser beam propagates. In the DAWN-A scattering chamber, 0° polar is where the beam exits the chamber and 180° polar is where it enters the chamber. The scattering angle is illustrated in the scattering plane in figure 3*B*. The scattering plane is the plane containing a vector in the direction of the incident light and a vector in the direction of the scattered light.

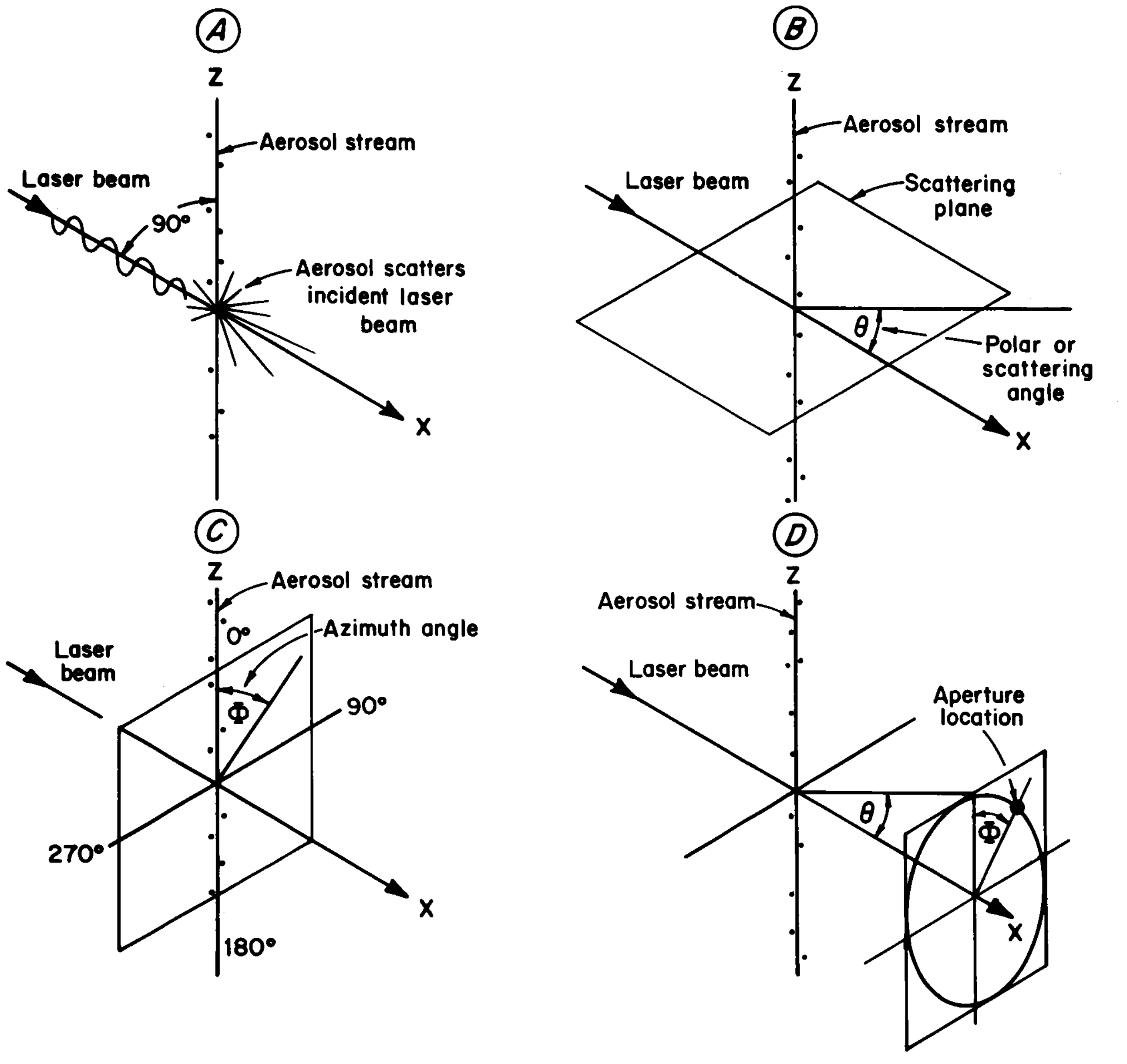

Figure 3.—Scattering chamber geometry. *A*, Laser beam and aerosol stream; *B*, scattering angle θ; *C*, azimuth angle Φ; *D*, aperture location.

The azimuth angles Φ determine the location of the apertures along a plane that is perpendicular to the direction of the laser beam (figs. 3*C-D*). With the quarter-wave plate removed, the laser propagates a vertically polarized beam. The vertical polarization of the laser beam sets the location of 0° azimuth. Apertures are located along the circumference of the scattering sphere at 0°, 45°, 90°, 135°, 180°, 270°, and 315° azimuth.

Optical collimators collect the scattered light at the apertures in the scattering chamber (fig. 2). An optical collimator is a 100-μm-diameter fiber-optic cable with a lens attached to one end. The lens has a refractive index that varies parabolically as a function of its radius. This variation in refractive index causes the incident light rays to follow a sinusoidal path along the length of the lens. The full acceptance angle of this lens is 2.5°. The lens focuses a small wedge of scattered laser light that is within the acceptance angle onto the fiber-optic cable.

Each collimator connects to a photomultiplier tube (PMT) that receives the collected light. The light enters the photocathode of the PMT and causes it to emit electrons. An electron multiplier then increases the number of electrons. The PMT then emits these electrons as an electrical signal, which is then amplified.

An amplified signal from a preselected PMT triggers the light-collection process. A signal from this PMT that exceeds the preset trigger voltage initiates a sample hold circuit. When this signal exceeds the preset trigger voltage, the output signals from all of the PMT's are sent to an analog-to-digital converter board installed in an IBM-compatible personal computer (PC).

COMPUTER-INTERFACE SOFTWARE

The IBM-compatible PC controls the DAWN-A with a menu-driven program written in Microsoft C called AEROSOL. The operation and explanation of this program is in appendix A.

DATA ANALYSIS AND GRAPHICS SOFTWARE

Besides the software provided by Wyatt Technology, the Bureau developed Fortran programs and various macros for LOTUS 1-2-3 to analyze and graph the DAWN-A light-intensity data. The most important of these is a program called DATAPROC. This program transfers ASCII-formatted DAWN-A data to LOTUS 1-2-3 worksheet files in a revised format. The new format makes it possible to analyze and graph the data in a variety of ways using customized LOTUS macros.

AEROSOL-DISPERSING SYSTEM

A TSI Inc. model 3433 small-scale powder disperser disperses the solid test aerosols and feeds them into a particle-free airstream. This airstream, containing only the test aerosols, then feeds the TSI aerodynamic particle sizer (APS) or the DAWN-A (fig. 4). The APS measures the size distribution of the test aerosols (table 1), while the DAWN-A measured their scattering signatures.

A simplified waterdrop generator produced the waterdrops used for this series of tests (fig. 5). A constant flow pump injects prefiltered water at a constant rate through a hypodermic needle into a tee fitting. The injected water forms waterdrops at the tip of the hypodermic needle. A prefiltered high-velocity airstream, directed perpendicular to the water injection needle, blows the waterdrops off into the particle-free airstream that feeds the APS and DAWN-A.

Table 1.—APS particle statistics, in micrometers

Particle type	Mean	Median	Mode	Standard deviation
Illinois 6 coal	1.415	1.099	0.8355	0.9220
Limestone	1.356	1.077	.8355	.8002
Pittsburgh coal	1.024	.8006	.7235	.6922
Pocahontas 4 coal ..	1.018	.8129	.6251	.6063
Waterdrops	.7536	.6733	.6251	.3197
2.02-μm spheres ...	1.859	1.969	1.981	.4518

APS Aerodynamics particle sizer.

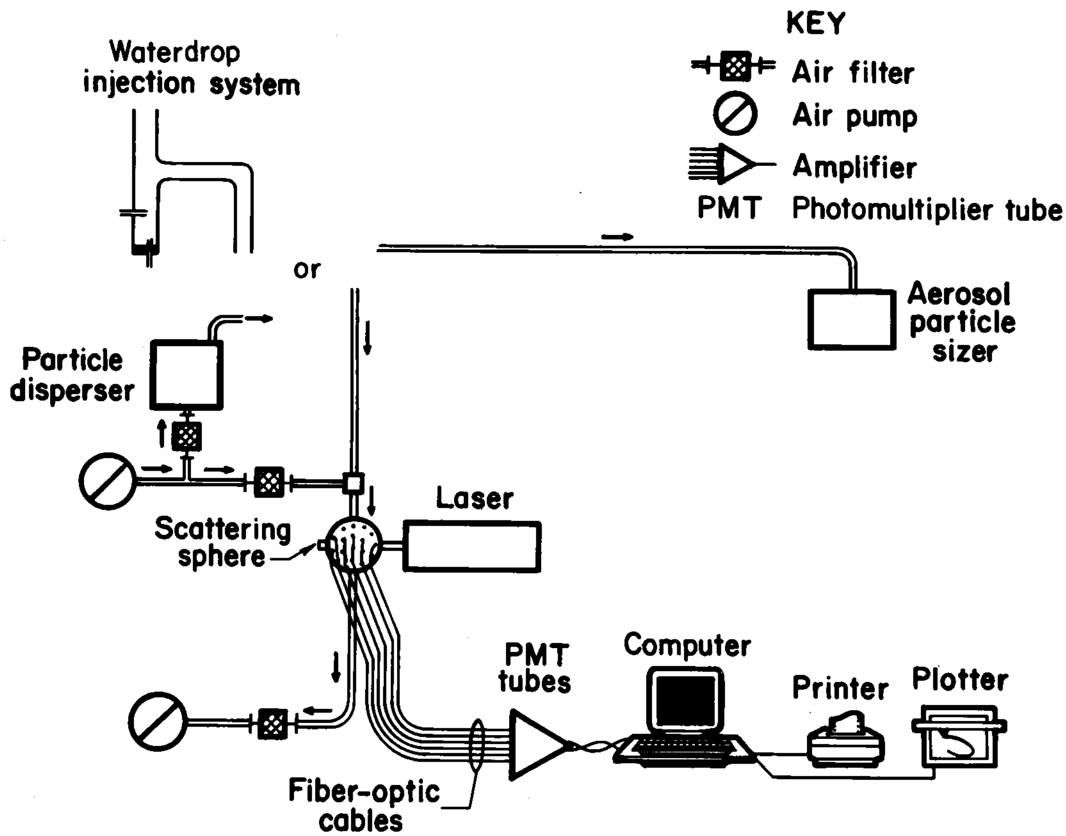

Figure 4.—Schematic of DAWN-A test setup. NOTE.—Either the waterdrop injector or the particle disperser can be connected to the system.

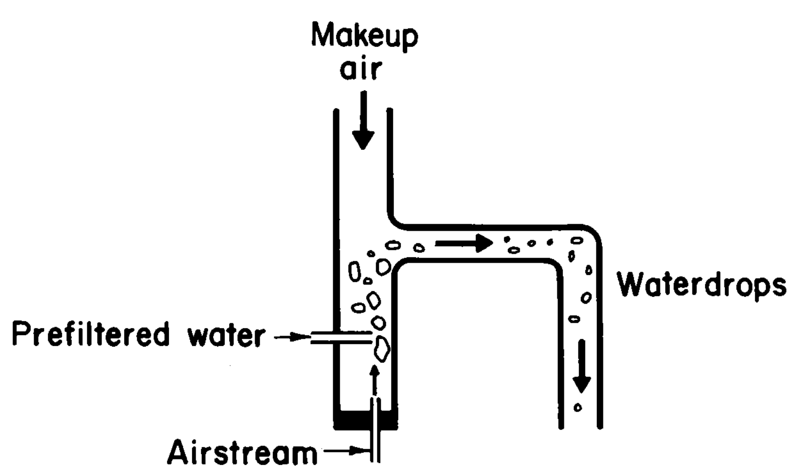

Figure 5.—Waterdrop injection system.

SPHERICITY INDEX

As previously stated, Jerry Bottiger of the U.S. Army Chemical Research and Development Center developed a technique for measuring the sphericity of micrometer-size aerosols using light-intensity data obtained by the DAWN-A. To evaluate Bottiger's technique, seven collimators are positioned at the same 40° scattering angle θ, but at different azimuth angles Φ on the DAWN-A scattering chamber. With this setup, the DAWN-A measures and stores the scattered light intensities at seven locations for each particle it detects. These data, called scattering signatures, reveal the degree of uniformity of the light scattered by aerosols as they pass through the circularly polarized laser beam.

Under ideal conditions, a perfect sphere passing through the center of the laser beam will scatter light at uniform intensity at any particular scattering angle θ. Each collimator at the same scattering angle θ will detect the same light intensity. On the other hand, a nonspherical micrometer-size particle passing through the center of the laser beam will not scatter light at uniform intensity and the collimators at a particular scattering angle θ will detect different intensities of scattered light.

For each particle the DAWN-A detects, it measures and stores a set of light-intensity data in a PC. These data are then used in an equation for determining the sphericity index of the particle. The equation is—

$$1 - \frac{\text{standard deviation}}{\text{mean} \times \left(\sqrt{n - 1}\right)} = \text{sphericity index}. \quad (2)$$

For this work, the mean and standard deviation are calculated from the light intensities, measured by seven collimators positioned at a scattering θ angle of 40°. The term $\sqrt{n - 1}$ is called the degrees of freedom. N is the sample size, which is 7 for these tests. Under ideal conditions, a sphericity index of 1 means that a perfect sphere passed through the center of the DAWN-A laser beam and thus scattered the incident laser beam in a perfectly uniform manner. A sphericity index less than 1 would indicate that the detected particle was not spherical or that it did not pass through the center of the laser beam.

TEST RESULTS AND DISCUSSION

Under ideal conditions, all of the test spheres would be perfectly uniform in size and shape and they would all pass precisely through the center of the laser beam. Under these conditions, the scattering signatures would be very uniform and the calculated sphericity indices would all be 1. However, as in any test situation, ideal conditions seldom, if ever, exist. Because the conditions are not ideal, errors occur, resulting in sphericity indices that are not always 1, even for uniform latex spheres. These errors include the 2.02-μm-diameter latex spheres that have a diameter standard deviation of 0.0135. Also, the scattering sphere inlet orifice of the particle-laden airstream is larger in diameter than the laser beam. The latex spheres may pass through the laser beam anywhere from its outer edges to the center. This causes the scattered light intensity to be nonuniform along the azimuth of a given scattering angle θ. Obviously, when using these intensity data to calculate the sphericity index, the result will not always be 1. This is shown in the scatter plot in figure 6 for 2.02-μm-diameter latex spheres when detected with the DAWN-A set at 3-V trigger voltage. Figure 7 shows these normalized histogram plotted from these same data. This plot shows the relative frequency of the sphericity index data. The sphericity index of 0.9 has the highest relative frequency (about 0.8), indicating a high degree of sphericity.

EFFECT OF TRIGGER VOLTAGE SETTINGS

The Mie light-scattering equation shows that for a given incident light beam, the intensity of the forward scattered light is related to the size of the particle that scatters the light. The larger the particle diameter, the greater the intensity of the forward scattered light. Correspondingly, a smaller aerosol with all other conditions unchanged will scatter light in the forward direction at a lower intensity.

This has a direct relation to the trigger voltage setting of the DAWN-A. If the trigger voltage is set too high, the intensity of light scattered by smaller particles and collected by the collimators will not be great enough to produce a voltage to exceed the trigger voltage. The scattering signatures from the smaller particles will not be measured, since the DAWN-A does not collect data until the trigger voltage is exceeded. This will bias the scattering signature data toward the larger particles.

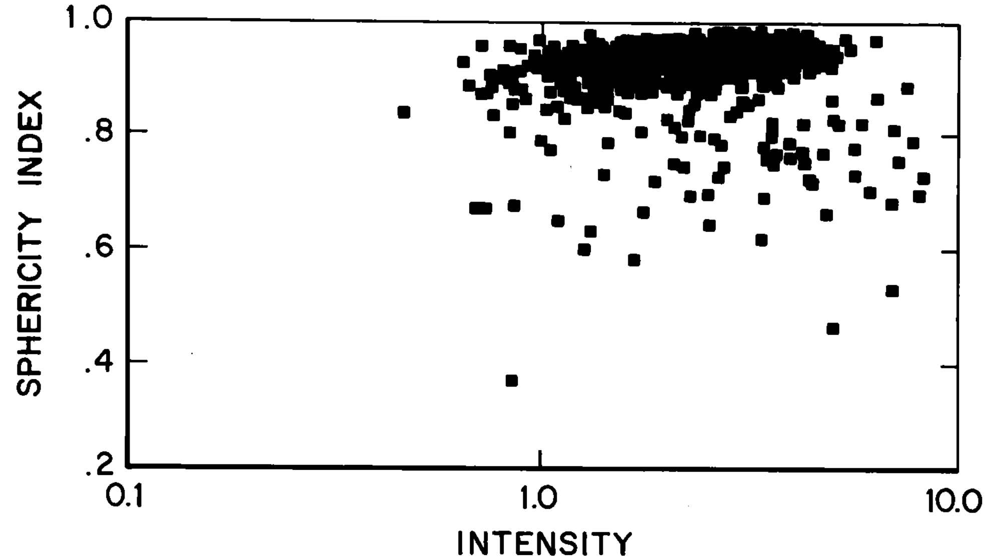

Figure 6.—Sphericity indices of 2.02-μm-diameter latex spheres.

The Mie equation also shows that the scattered light intensity decreases at a rate that is proportional to the square of the distance between the point that the light is scattered and detected. This also affects the trigger voltage setting of the DAWN-A. If the trigger voltage is set too low, the DAWN-A will collect scattering signatures from particles that passed through the outer edge of the Gaussian-shaped laser beam where the light intensity is weak. Under this condition, the scattered light is weak and at unequal distances from the collimators. The DAWN-A will detect a nonuniform scattering signature that is not representative of the particle.

These effects made it necessary to examine the scattering signatures of monodisperse spheres measured at different trigger voltages. The DAWN-A measured scattering signatures of 2.02-μm-diameter latex spheres at trigger voltages of 1.5, 3.0, and 5.0 V (fig. 8).

At a trigger voltage of 1.5 V, the DAWN-A data produced a low relative frequency at a sphericity index of 1 for the 2.02-μm spheres. At this low trigger voltage, the DAWN-A detected the scattered light intensities of many spheres that passed through the edge of the laser beam and detected scattering signatures that are not representative of the uniform latex spheres.

With the DAWN-A trigger voltage set at 3 V, there was a significant improvement. The relative frequency of a sphericity index of 0.9 increased from below 0.5 to a little over 0.8. This shows that at the lower trigger voltage, the collected scattering signatures were not representative of the latex spheres.

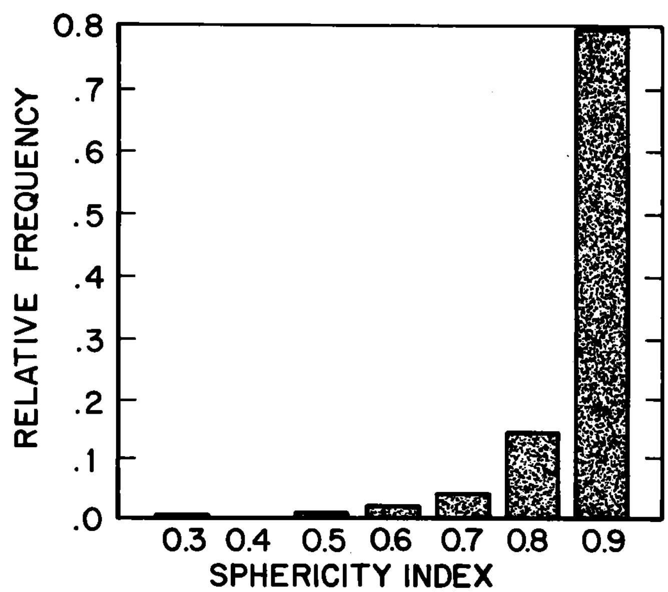

Figure 7.—Relative frequency of sphericity indices of 2.02-μm-diameter latex spheres.

The relative frequency of the sphericity index at 1 remained about the same when the DAWN-A trigger voltage was increased to 5.0 V. As previously stated, the ideal relative sphericity frequency should be 1 at a sphericity index of 1. The lack of improvement from 3.0 to 5.0 V means that a sphericity index frequency of 0.8 for a sphericity index of 1 was the best the instrument and test setup could provide.

The DAWN-A trigger voltage was set at 3 V for the remainder of the tests discussed in this report. Setting the trigger voltage higher might result in missing scattering signatures from smaller aerosols when polydisperse aerosols were passed through the DAWN-A scattering chamber.

WATERDROPS

The previously described waterdrop generator provided a polydispersion of waterdrops to the DAWN-A and APS. The APS measured waterdrops from 0.5 to 9.0 μm in diameter. The mean diameter of these waterdrops was 0.75 μm. This distribution changed somewhat because of evaporation. However, it is a good indication of the size range of the waterdrops that passed through the DAWN-A since the inlets of both instruments were within a few inches of the waterdrop generator.

The DAWN-A measured the scattering signatures of waterdrops at a scattering angle θ of 40°. These data were then used to calculate and plot their sphericity indices (fig. 9). Figure 9 shows that the waterdrops were relatively spherical. The histogram in figure 10 shows the relative frequency of these sphericity indices. The relative frequency for a sphericity index of 0.9 is about 0.7. This means that most of the waterdrops were spherical. Figure 11 is a comparison of the histogram of the waterdrops with the histogram of the 2.02-μm-diameter latex spheres. The data from these two aerosols reveal that they both were highly spherical; they both had a high relative frequency of sphericity indices of 0.9. This suggests that the sphericity index method is a viable candidate for separating spherical from nonspherical particles. It is significant that the waterdrops were of several different diameters. This shows that the sphericity index technique does not depend on particle size for spherical particles.

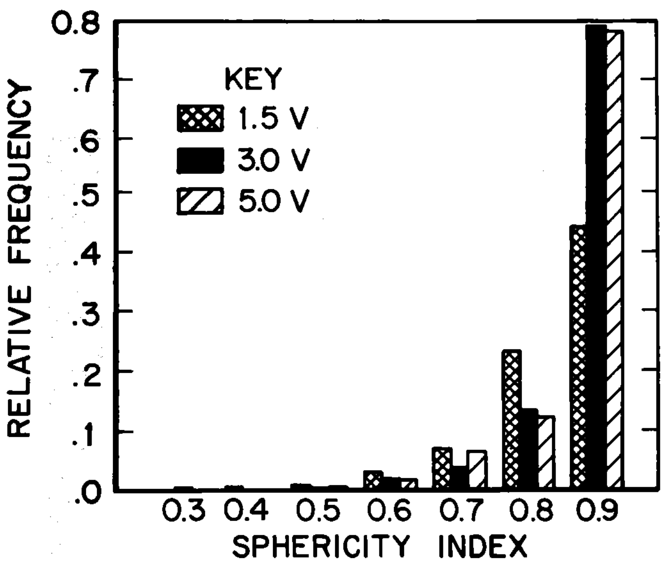

Figure 8.—Relative frequency of sphericity indices of 2.02-μm-diameter latex spheres at three trigger voltages.

COAL DUSTS AND ROCK DUST

The DAWN-A measured the scattering signatures of −325 mesh Pittsburgh coal dust. Figure 12 shows the sphericity indices of the Pittsburgh coal dust. Figure 13 combines the histograms of the relative frequencies of both the waterdrop and Pittsburgh coal dust sphericity indices. The difference in relative frequency of sphericity indices of 0.9 makes it a simple matter to discriminate between waterdrops and coal particles. Figure 13 shows that the sphericity index method can discriminate between the nonspherical Pittsburgh coal dust and the spherical waterdrops.

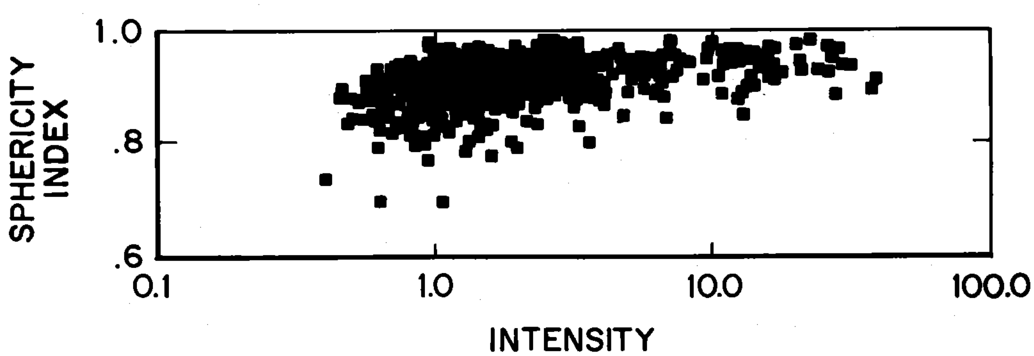

Figure 9.—Sphericity indices of waterdrops.

The DAWN-A also measured the scattering signatures of Illinois 6 coal dust, Pocahontas 4 coal dust, and limestone dust. The scattering signatures then determined the sphericity indices of these dusts. Figure 14 shows a histogram of the relative frequency of the sphericity indices of these dusts. This histogram reveals that the relative frequencies of the three coal dusts are very similar.

Figure 15 is similar to figure 14, but with the addition of the sphericity index data for waterdrops. This histogram again shows that the sphericity index method can discriminate between nonspherical and spherical aerosols.

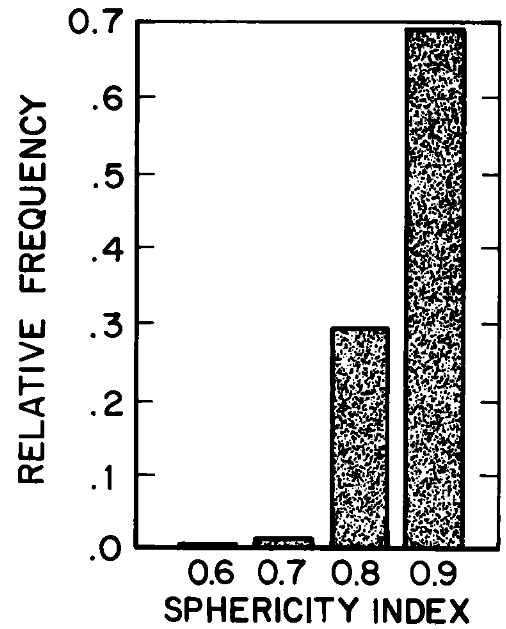

Figure 10.—Relative frequency of sphericity indices of waterdrops.

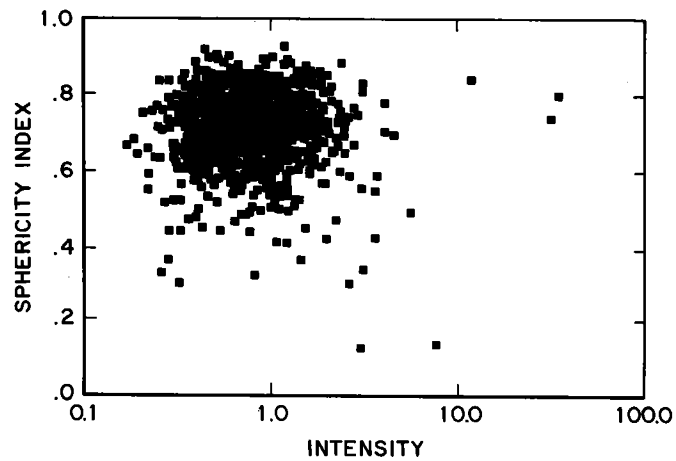

Figure 12.—Sphericity indices of −325 mesh Pittsburgh coal dust.

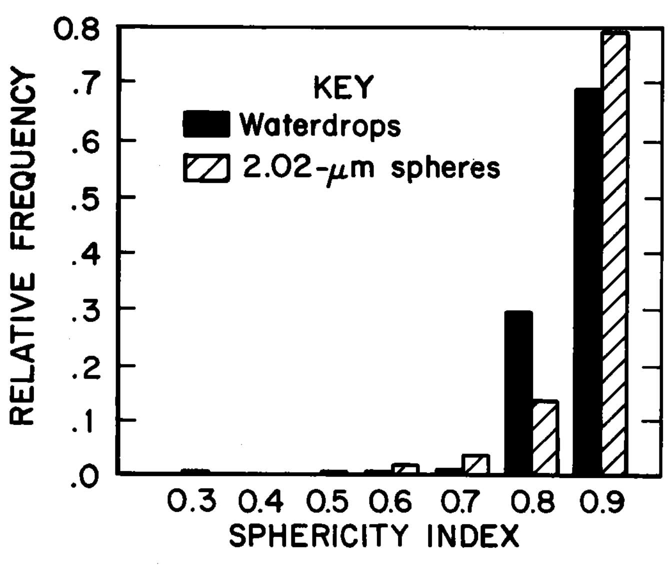

Figure 11.—Relative frequency of sphericity indices of waterdrops and 2.02-μm-diameter latex spheres.

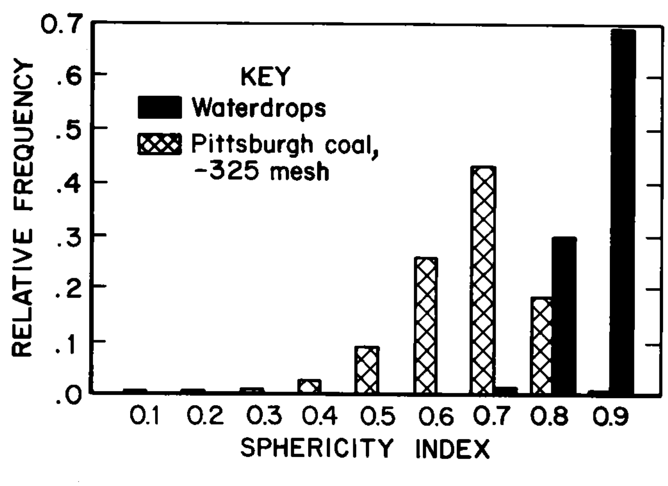

Figure 13.—Relative frequency of sphericity indices of Pittsburgh coal dust and waterdrops.

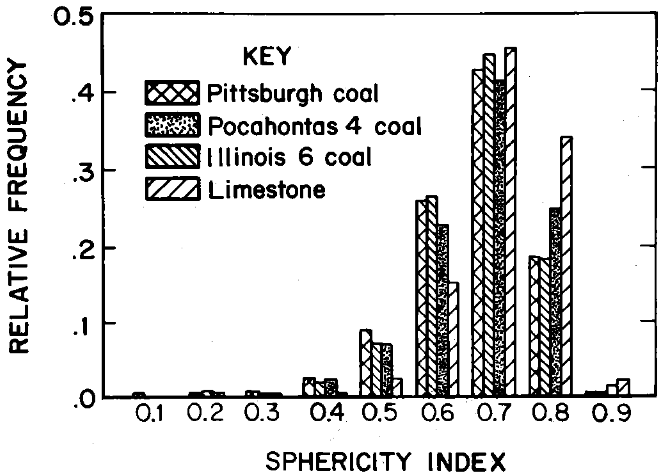

Figure 14.—Relative frequency of sphericity indices of three coal dusts and limestone dust.

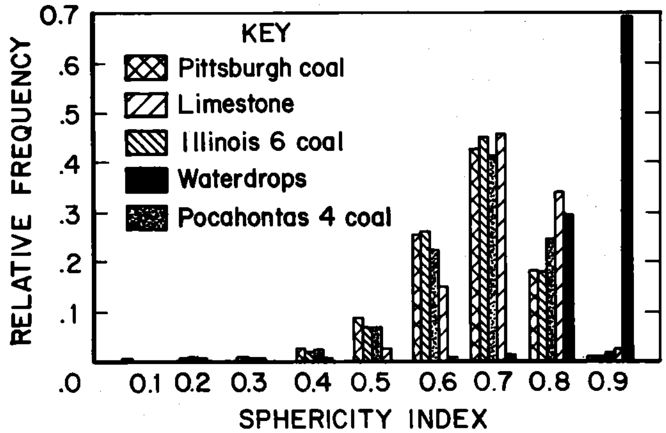

Figure 15.—Relative frequency of sphericity indices of three coal dusts, limestone dust, and waterdrops.

SUMMARY AND RECOMMENDATIONS

The DAWN-A measured the scattering signatures of 2.02-μm-diameter latex spheres, waterdrops, three coal dusts, and limestone at a scattering angle θ of 40°. These data were then used to evaluate the sphericity index method for its ability to discriminate between micrometer-size aerosols. The test results show that the sphericity index method can discriminate between spherical waterdrops and nonspherical coal mine dusts.

The sphericity indices of coal dusts produced by mining machine cutter bits should be measured since the coal dusts for these tests were artificially produced. Likewise, the sphericity indices of waterdrops produced by mining machine water sprays and the sphericity indices of wet coal particles also should be determined.

The DAWN-A should be modified to measure sphericity indices at scattering angles θ less than 40°. At these angles, the scattered light intensity is greater for a given set of conditions. Smaller particles could be more easily detected and a lower power light source would be adequate since a larger portion of the incident light is scattered at small scattering angles θ.

The practicality of implementing the sphericity index method into the design of a discriminating dust monitor should be investigated.

REFERENCES

1. Lilienfeld, P. Improved Light Scattering Dust Monitor (contract HO377092, GCA Corp.). BuMines OFR 90-79, 1979, 48 pp.; NTIS PB 299 938/AS.

2. Lilienfeld, P., and R. Stern. Personal Dust Monitor—Light-Scattering (contract HO308132, GCA Corp.). BuMines OFR 95-83, 1982, 40 pp.; NTIS PB 83-205435.

3. U.S. Bureau of Mines. Instantaneous Sampling Improves Longwall Dust Control. Technol. News 134, Feb. 1982, 2 pp.

4. Kissell, F. N., S. K. Ruggieri, and R. A. Jankowski. How To Improve the Accuracy of Coal Mine Dust Sampling. Am. Ind. Hyg. Assoc. J., v. 47, No. 10, Oct. 1986, pp. 602-606.

5. Ford, V. H. W., R. Minton, and D. Mark. Comparative Trials in Coal Mines of the TM-Digital and Simslin Dust Monitors. Ch. 54 in Aerosols in the Mining and Industrial Work Environments, ed. by V. A. Marple and B. Y. H. Liu. Ann Arbor Sci. Publ. Inc., Ann Arbor, MI, v. 3, 1983, pp. 759-775.

6. Thakur, P. C., R. W. Hatch, and J. B. Riester. Performance Evaluation of Machine-Mounted Respirable Dust Monitors for U.S. Coal Mines. Ch. 49 in Aerosols in the Mining and Industrial Work Environments, ed. by V. A. Marple and B. Y. H. Liu. Ann Arbor Sci. Publ. Inc., Ann Arbor, MI, v. 3, 1983, pp. 665-688.

7. Williams, K. L., and R. J. Timko. Performance Evaluation of a Real-Time Aerosol Monitor. BuMines IC 8968, 1984, 20 pp.

8. Barber, P. W., and R. K. Chang. Optical Effects Associated With Small Particles. World Sci. Publ. Co., 1988, 336 pp.

9. Wyatt, P. J., K. L. Schehrer, S. D. Phillips, C. Jackson, Y. Chang, R. G. Parker, D. T. Phillips, and J. R. Bottiger. Aerosol Particle Analyzer. Appl. Opt., v. 27, No. 2, Jan. 1988, pp. 217-220.

APPENDIX A.—DAWN-A SOFTWARE PROGRAM

To run this software, the operator types AEROSOL and the menu shown below appears on the PC screen:

1. Measure Dark Offsets.
2. Measure Background.
3. Calibration.
4. Collect Data.
5. Process Data.
6. Print/Edit Master Table.
7. Suspend to DOS.
8. Exit Program.

The following procedure must be followed prior to each test series. The first step in operating the program is to configure the software to match the hardware setup of the DAWN-A. This is done by selecting option 6 (Print/Edit Master Table) and typing in the angular locations of the collimators and the voltages of the PMT's.

After this, select option 1 (Measure Dark Offsets) to measure the "dark current" for each PMT. The "dark current" is the current that flows in a PMT when there is no incident luminous radiation on the photocathode.

Next, select option 2 (Measure Background) to measure the "background current" for each PMT. Background current comes from light detected in the scattering chamber when the laser beam is on but no particles are present to scatter light.

Finally, select option 3 (Calibration) to calculate a calibration coefficient for each collimator and its PMT. Each collimator receives light from the same constant light source. The calibration program then uses the output signal of the PMT connected to the collimator receiving this light to produce a calibration coefficient.

Once the above options are completed, select option 4 (Collect Data) to prepare the DAWN-A to measure the light-scattering intensities of particles. The program will then look for amplified PMT outputs and store them on the computer's hard disk.

After the DAWN-A has collected data, option 5 (Process Data) transforms the collected data into ASCII file format. The data can then be transferred to other programs for analysis and graphing.

The two remaining functions on the main menu are option 7 (Suspend to DOS), for temporarily going into DOS and option 8 (Exit Program), for leaving the program.

APPENDIX B.—STATISTICAL ANALYSIS OF DATA

The DAWN-A data were analyzed with a data analysis system called RS1 from Bolt, Beranek and Newman Inc. Software Products, Cambridge, MA. This system contains an extensive range of statistical analysis tools. One of these tools, called "MEASURES," provides descriptive statistics of data.

Table B-1 is the descriptive statistics that the MEASURES procedure developed from the six sets of DAWN-A data used in this study. These six data sets are the scattered light intensities of various particles measured at a near-forward scattering angle θ of 40°.

Another RS1 statistical procedure used by the researchers was "COMPARES." This procedure can analyze two sets of data to determine if they are in the same statistical population. An algorithm first chooses between robust (nonparametric) or classical analyses. (Nonparametric tests are not dependent on the shape of the distribution.) The COMPARES procedure was used to make comparisons between all six of the data sets. The null hypothesis for robust analysis was that the medians of the two populations being compared were equal. The results are shown in table B-2. The null hypothesis for classical analysis was that the mean of populations 1 and 2 were equal. The results are shown in table B-3.

Table B-1.—Light-intensity statistical data

Statistic	Illinois 6 coal	Limestone	Pittsburgh coal	Pocahontas 4 coal	Waterdrops	2.02-μm spheres
Count	800.000	800.000	800.000	800.000	800.000	800.000
Kurtosis	175.836	23.881	270.015	192.681	22.755	30.952
Maximum	34.193	17.603	33.921	17.506	39.416	19.785
Mean	1.108	1.605	.995	.942	2.922	2.691
Median	.792	1.060	.747	.753	1.619	2.482
Minimum	.166	.287	.168	.206	.408	.467
Range	34.028	17.316	33.753	17.300	39.008	19.318
Skewness	11.531	4.260	15.267	10.507	4.357	3.924
Standard deviation	1.793	1.798	1.740	.837	4.402	1.530
Standard error of mean	.063	.064	.062	.030	.156	.054
Sum	886.186	1,283.950	795.845	753.644	2,337.290	2,152.871
Variance	3.215	3.232	3.027	.701	19.377	2.344

Table B-2.—Summary of RS1 COMPARES using robust analysis

Scattered light intensities from—	Compared with—	Null hypothesis
Illinois 6 coal	Limestone	Rejected.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Not rejected.
	Waterdrops	Rejected.
	2.02-μm spheres	Do.
Limestone	Illinois 6 coal	Do.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Do.
	Waterdrops	Do.
	2.02-μm spheres	Do.
Pittsburgh coal	Illinois 6 coal	Not rejected.
	Limestone	Rejected.
	Pocahontas 4 coal	Not rejected.
	Waterdrops	Rejected.
	2.02-μm spheres	Do.
Waterdrops	Illinois 6 coal	Do.
	Limestone	Do.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Do.
	2.02-μm spheres	Do.
2.02-μm spheres	Illinois 6 coal	Do.
	Limestone	Do.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Do.
	Waterdrops	Do.

Table B-3.—Summary of RS1 COMPARES using classical analysis

NLOG's of scattered light intensities from—	Compared with—	Null hypothesis
Illinois 6 coal	Limestone	Rejected.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Not rejected.
	Waterdrops	Rejected.
	2.02-μm spheres	Do.
Limestone	Illinois 6 coal	Do.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Do.
	Waterdrops	Do.
	2.02-μm spheres	Do.
Pittsburgh coal	Illinois 6 coal	Do.
	Limestone	Do.
	Pocahontas 4 coal	Not rejected.
	Waterdrops	Rejected.
	2.02-μm spheres	Do.
Waterdrops	Illinois 6 coal	Do.
	Limestone	Do.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Do.
	2.02-μm spheres	Do.
2.02-μm spheres	Illinois 6 coal	Do.
	Limestone	Do.
	Pittsburgh coal	Do.
	Pocahontas 4 coal	Do.
	Waterdrops	Do.

NLOG Natural logarithm.

INT.BU.OF MINES,PGH.,PA 29785

*U.S.G.P.O.: 1993--709-008/80026