Optical Dust Deposition Meter

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***Abstract*—Coal dust is produced in coal mines during normal mining operations and by the movement of men and machines. This fine float coal dust, typically less then 74 μm, entrained in the ventiliating air is carried into the return airway, where it settles on exposed surfaces. In the event of an explosion this float dust can be re-entrained into the air, where it can propagate an explosion. The degree of combustion hazard associated with float coal dust is related to the surface density of the deposited coal dust, and the entry cross-sectional area. The operation of a prototype optical dust deposition meter used to measure the mass loading density of stratified coal and rock dust layers, to assess the float coal dust hazard, is described. The meter determines the surface loading density of a dust layer by measuring its optical reflectivity. The theory of the prototype unit's operation is developed and compared with experiment. The studies showed that the prototype unit is capable of measuring coal dust and rock dust surface loading densities of up to 7 mg/cm^2 for coal and 10 mg/cm^2 for rock dust. This is well within the hazard range, with an accuracy of about ± 5 pct. The results of the laboratory and experimental mine testing of a second portable meter is also reported.**

Introduction

COAL DUST is produced in coal mines during normal mining operations at conveyors, at transfer points, and by the movement of men and machines. Float dust, usually defined as dust particles less than 74 μm in diameter, can be entrained by the mines ventilating air and carried into the return airways, where it settles on the mine surfaces. In the event of an explosion this float dust can be re-entrained into the air and contribute to the explosion propagation. The degree of hazard is related to the concentration of float coal when dispersed in the contained air. In the U.S. the coal dust deposit is usually rendered nonflammable by rock dusting [1]. The Mine Safety and Health Administration (MSHA) requires 80-wt pct incombustible content material in the dust deposit in return airways and 65-wt pct incombustible material elsewhere in the mine, except for the last 40 ft from the face. In the presence of methane the amount of rock dust required in the return entry is increased 1-wt pct for each 0.4 pct methane in the ventilating air.

However, if a fresh layer of coal dust corresponding to an air/dust mixture greater than about 50 mg/l (or, equivalently, a coal dust layer density of 9.0 mg/cm^2 in a 1.8-m-high by 2.7-m-wide entry) is deposited on top of a properly rock-dusted substratum, this new layer can be skimmed off the underlying rock dust by a relatively weak methane–air explosion. Such a hazardous coal-dust layer is only 0.08-mm thick in a 1.8-m-high by 2.7-m-wide entry [2]. In an effort to comply with the law and provide protection against such an occurrence, mine operators often place rock dusters in the returns to periodically dispense rock dust into the return airways. Other methods include periodic raking of the entry or re-dusting the rock of the entire entry. Presently, very little data are available regarding float-dust deposition rates in U.S. mines, and operators are forced to rely on visual methods to determine the condition of the float-dust deposits. Therefore the frequency with which new rock dust should be dispersed or raked to protect the new coal-dust deposit is unknown. The result is that current rock-dusting practices cause some mine operators to rock dust excessively in some areas at the expense of others. This report presents the initial results of an investigation to develop a float coal dust layer meter that can be used to monitor the amount of airborne coal dust deposited near the face, belt transfer points, and other areas susceptible to high deposition rates. It can also be used to evaluate the deposition behavior of airborne rock dust along the airway. The ultimate objective is to develop a device to detect a hazardous coal dust layer and automatically start rock-dusting operations to render the coal layer nonflammable.

Paper PID 87-36, approved by the Mining Industry Committee of the IEEE Industry Applications Society for presentation at the 1987 Mining Industry Committee Technical Conference, Pittsburgh, PA, June 9–11. Manuscript released for publication August 23, 1987.

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IEEE Log Number 8719032.

Theory

Since coal dust is black and rock dust white, and since a float coal dust layer density of 10 mg/cm^2 is optically opaque, it is reasonable to believe that the thickness of such a coal dust layer deposited on a rock dust substrate (or *vice versa*) could be determined by measuring the layer's optical reflectivity (the IR optical reflectivity of an opaque layer of coal dust is nine times smaller than a corresponding layer of rock dust). It is on this principle that the float dust meter is based.

According to the Bouguer–Beer–Lambert law the transmission of light through a homogeneously dispersed cloud of dust particles is given by the relation

$$I_t = I_i e^{(-QANX)} \tag{1}$$

where I_i and I_t are the incident and transmitted light, respectively, Q the dimensionless extinction coefficient, A is the cross-sectional area of a particle, N the number density of particles, and X the thickness of the cloud. The coefficient Q takes into account the loss of light due to both absorption and scattering. Q is a function of the particle size, the wavelength of light, and the complex retractive index of the particles. For particles larger than the wavelength, Q asymptotically approaches a constant value of 2. If all of the scattered light reached the detector and only the light absorbed by the particles were lost, the effective value for Q would be 1 for absorbing particles larger than the wavelength. If we assume that (1) holds for a dust layer as well as a cloud, then the light transmitted to a depth X in a dust layer is determined by (1), and if the reflectivity I_r per unit depth of the layer is α, the light exiting the dust layer surface (see Fig. 1) can be written as

$$I_r = I_i \int^X \alpha e^{-2QANx}\, dx + \alpha_0 I_i e^{-2QANX}. \tag{2}$$

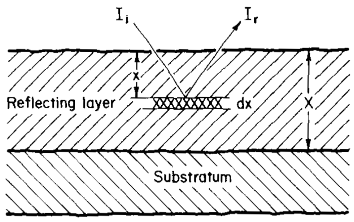

Fig. 1. Reflection of infrared radiation by stratified dusts.

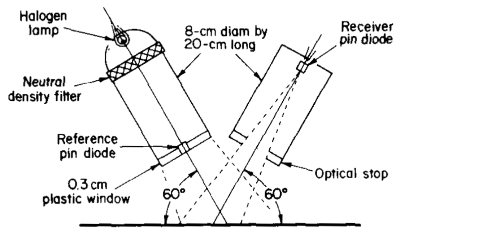

Fig. 2. Apparatus used to measure infrared reflectivity of stratified dust.

The last term on the right accounts for the light reflected from the substrate. Integrating (2) yields

$$I_r = I_\infty(1 - e^{-2QANX}) + I_0 e^{-2QANX} \tag{3}$$

where $I_\infty = I_i\alpha/QAN$ is the intensity of the light reflected from an infinitely thick layer of float dust; and $I_o = \alpha_o I_i$, where I_o is the intensity of the light reflected from the substrate with no surface dust layer. It has been found [3] mathematically expedient to define a new variable ϕ according to the expression

$$\phi = (I_r - I_{cd})/(I_{rd} - I_{cd}) \tag{4}$$

where I_{cd} and I_{rd} are the intensity of light reflected from an infinitely thick layer of coal dust and rock dust, respectively, and I is the reflected light. In the case of rock dust depositing on coal dust, (4) becomes

$$\phi_{rd} = e^{-2QANX} \tag{5}$$

where A and N refer the rock dust particles, and for coal dust deposited on rock dust, (4) becomes

$$\phi_{cd} = 1 - e^{-2QANX} \tag{6}$$

where A and N now pertain to the coal dust. If the layer is composed of spherical particles with surface-weighted mean diameter d, then

$$A = \pi d^2/4.$$

The mass (m) of particles per unit volume V is the layer of concentration C expressed as

$$C = m/V = \pi d^3 \rho N/6$$

$$\sigma = CX$$

and where σ is the layer surface dust density in mg/cm^2.

Using the above expressions to eliminate A and N from (5) one obtains

$$\phi_{rd} = e^{-(3Q\sigma_{rd}/2\rho_{rd} d_{rd})}. \tag{7}$$

Correspondingly, (6) for coal dust layers can be written

$$\phi_{cd} = 1 - e^{-(3Q\sigma_{cd}/2\rho_{cd} d_{cd})}. \tag{8}$$

Equations (7) and (8) constitute the theory on which the design of the dust deposition meter is based.

Apparatus and Procedures

Fig. 2 shows a drawing of the apparatus used to measure the dust layer's optical reflectivity: The light source consists of a 7.6-cm-diameter 20.3-cm-long sheet-metal tube equipped with a miner's halogen lamp, parabolic reflector, and provision for placement of a 0.9-μm-wavelength neutral density filter in the light path. A 0.3-cm Lexan plastic window[1] with a TRW Corp. 3CDP p-i-n diode attached (to measure the intensity of the incident beam) covers the transmitter tube end while the lamp is attached to the opposite end. The window of the reference diode was covered with a 9-pct-transmittance neutral density filter to avoid saturation of the p-i-n diode. The receiver consists of a similar sized tube with a 3CDP p-i-n diode positioned in the center of the far end and a 2.54-cm internal diameter optical stop with a 1-mm plastic film covering the near end. The spot illuminated by the source is about 5.0 cm in diameter at 10 cm from tube outlet. The illuminated area seen by the receiver diode is the 2.54-cm internal diameter central area of the illuminated spot. Both tubes were positioned at an angle of 60° to the horizontal, and the internal surface of both was painted flat black to reduce internal reflections. Since the current of p-i-n diodes at zero bias voltage exhibits a linear dependence with light intensity, the output voltage of the circuit is a linear function of the light intensity as long as the bias current of the operational amplifier is small compared to the diode current. In these studies the diode current ranged from 50 nA to 5 μA, whereas the maximum measured operational amplifier bias current was 10 nA.

Fig. 3 shows a schematic of the circuit used to measure the ratio of the intensities of the reflected-to-incident light intensity. Because the halogen lamp draws about 1 A from the 4.5-V wet cell, a small but continuous drop in the battery voltage resulted, which in turn caused a corresponding decrease in the lamp intensity and a small but measurable shift in its spectra (lower current means lower lamp filament temperatures and therefore a shift to longer wavelength radiation). By measuring the ratio of the reflected-to-incident intensities we were able to compensate for this drift.

The uniformity of the light intensity within the illuminated area was measured by placing 45° pie-shaped white paper sections (cut from one piece of white construction paper) on a black construction paper background with the pie section apex located at the intersection point of the tube axes. The average of these measurements is shown in Fig. 4. The results show that the area visible to the receiver exhibits radial illumination symmetry. This same experiment was repeated using black pie sections on a white background, and three lamp intensities—100, 60, and 30 pct (the lamp's intensity was attenuated with a

[1] The use of a trade name does not constitute endorsement by the U.S. Bureau of Mines.

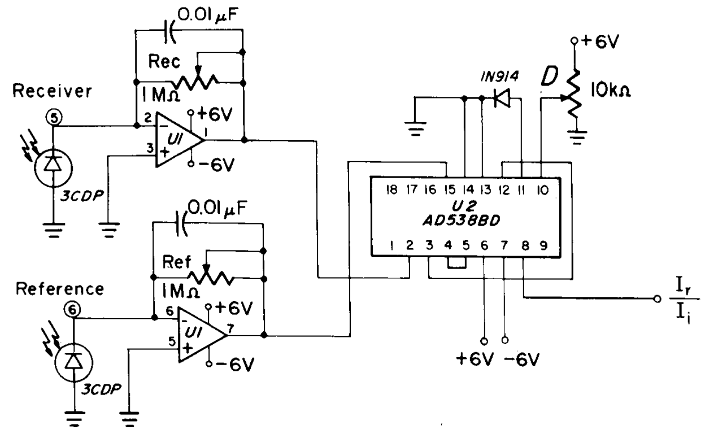

Fig. 3. Circuit used to measure ratio of reflected-to-incident radiation.

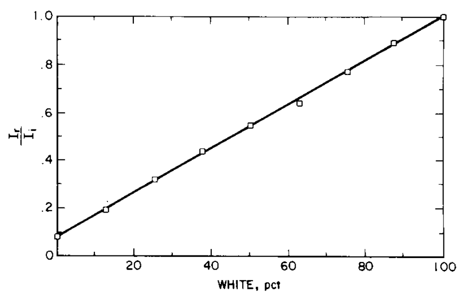

Fig. 4. Ratio of reflected-to-incident infrared radiation as function of pct white paper covering black substratum.

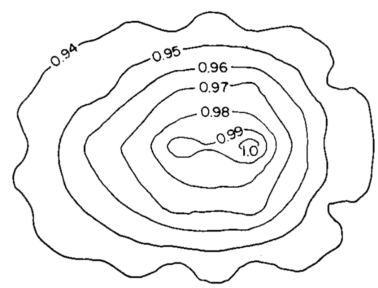

Fig. 5. Infrared intensity contours seen by p-i-n diode receiver. Where superscripts indicate measurements made at different intensities, then ϕ is independent of variations in I_i. This definition of ϕ was used in subsequent studies.

0.9-μm-wavelength neutral density filter). The results were identical to the previous results.

In a second study of the illumination uniformity, a 0.5-cm-diameter circle of white construction paper was positioned at various points on the black construction-paper background in the illuminated region and the receiver signal recorded.

Fig. 5 shows a contour map of these measurements. The figure shows that the light intensity, although not perfectly symmetrical, should be adequate for purposes of this research.

ϕ, as defined in (4), is not invariant to changes in the lamp's intensity. However, dividing each term of (3) by I_i (as measured by the reference p-i-n diode) results in an equation whose terms are independent of I_i. Therefore, if we redefine ϕ as

$$\phi = (I'/I_i' - I''_{cd}/I_i'')/(I'''_{rd}/I_i''' - I''''_{cd}/I_i'''') \qquad (9)$$

where the superscripts indicate measurements made at different intensities, then ϕ is independent of the variations in I_i. This definition of ϕ was used in the subsequent studies.

Fig. 6 shows a drawing of the apparatus used to prepare uniform float-dust deposits in the laboratory. To prepare a dust layer using this apparatus an accurately weighted quantity of dust is placed in the dust reservoir and dispersed upward, by means of compressed air, inside a 2-m-high 20.3-cm-diameter section of stove pipe. At the base of the pipe is placed a 7.6-cm-diameter Petri dish to catch the settling dust. Knowing the weight of the dish before and after depositing the dust, one can calculate loading density. The tests have shown that such layers have a reflectivity uniform to within 3 pct. Fig. 7 shows the measured particle diameter distributions of the Pittsburgh Pulverized Coal (PPC) dust and rock dust used in these studies.

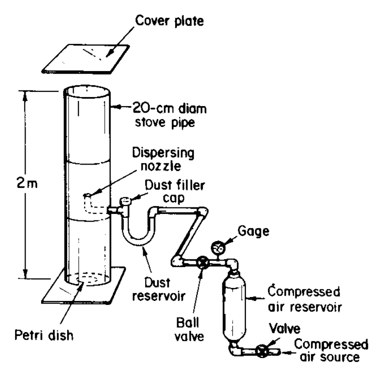

Fig. 6. Dust deposition apparatus.

To conduct an experiment, optically dense (20 mg/cm^2) layers of rock dust were deposited in a Petri dish and the ratio of the intensity of the incident and reflected light recorded. On top of this was deposited a 1 mg/cm^2 layer of coal dust, and the ratio of the intensities measured again. Successive 1-mg/cm^2 layers of coal dust were deposited until two successive

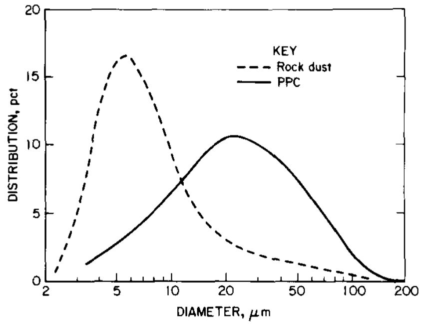

Fig. 7. Particle diameter distribution of dust (PPC) and rock dust particles.

layers exhibited the same intensity ratio. The same procedure was followed for rock dust deposited on a coal dust substrate.

Figs. 8 and 9 show typical results of these measurements. A least-squares fit of (7) and (8) to this data resulted in the expressions

$$\phi_{rd} = e^{-(0.96 \pm 0.14)\sigma_{rd}} \tag{10}$$

and

$$\phi_{cd} = 1 - e^{-(0.24 \pm 0.04)\sigma_{cd}} \tag{11}$$

for rock dust deposited on coal dust and coal dust deposited on rock dust, respectively. Equations (10) and (11) have standard errors about regression of 0.026 and 0.038, respectively. Substituting ρ_{cd} = 1.3 gm/cm^3 and d_{cd} = 31 μm into (7) one finds a value of 0.6 for the extinction coefficient of coal dust and, correspondingly, for rock dust, where ρ_{rd} = 2.7 gm/cm^3, d_{rd} = 10 μm, and Q = 1.7.

As a further test of (11) the coal dust deposition experiment was repeated using a classified coal dust having a surface-weighted mean diameter of 15 μm. Fig. 11 compares the results obtained using the 15-μm and 30-μm sizes of coal dust. According to the theory the extinction coefficient for the 15-μm coal dust should be twice that for the 30-μm coal dust. However, the measured ratio lies between 1.6 and 1.5 and is statistically different from an extinction coefficient of 2 at the 95-pct confidence level. However, the 15-μm dust has a significantly larger pct of dust particles whose sizes lie within the Mie theory scattering region (i.e., ≦ 8 μm), and because it has a larger pct of small particles, it has a greater tendency to agglomerate, and therefore Q should decrease, which is in accordance with the above findings.

An additional study was conducted using rock dust obtained from a different manufacturer as a base layer and a deposit of PPC 30-μm-diameter dust on top. The resulting least-squares fit was statistically indistinguishable from the previous results, suggesting that the results may not depend on the origin of the rock dust as long as its chemical composition is not significantly different.

Because the process of preparing the substrate dust layers was time consuming and considerable care was required in handling the Petri dishes containing the substrate, we experimented using other substrate materials. It was found that using a black construction paper substrate in place of the coal dust substrate, and white construction paper in place on the rock dust substrate, worked satisfactorily. These white and black surfaces had a reflectance ratio of 20.0 compared with 19.0 for

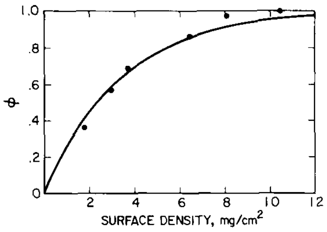

Fig. 8. Reflectance of rock dust deposited on coal dust substratum.

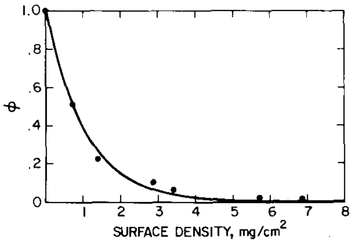

Fig. 9. Reflectance of coal dust deposited on rock dust substratum.

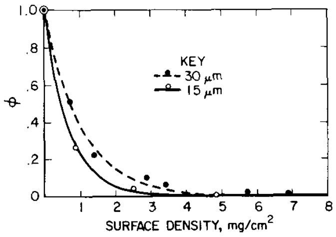

Fig. 10. Reflectance of coal dust particles with surface-weighted mean diameter of 30 μm and 15 μm deposited on rock dust substratum.

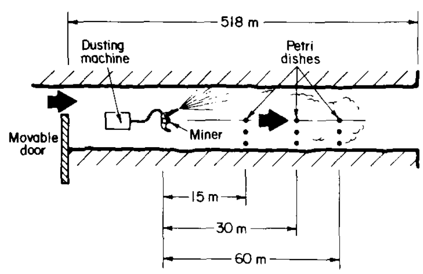

Fig. 11. Pictorial of underground test layout.

rock dust and coal dust. A least-squres fit to (7) and (8) with the data obtained from deposited experiments using the paper substrates gave results that were statistically indistinguishable from the data obtained using the correspondence dust substrates.

Following the studies conducted in the laboratory under controlled conditions, experiments were conducted at the Bureau's experimental mine at Lake Lynn, PA.

Details of the mine geometry for the experiments can be found in (4). Fig. 11 illustrates the geometry of the mine passageway, location of the dust dispenser, and the location of the Petri dishes (containing a black or white paper substrate) used to collect the depositing dust. While conducting an experiment the entry ventilation velocity is set to the desired level (15 m/min, 30 m/min, or 60 m/min) by adjusting the opening of a movable door, and nine Petri dishes were laid out on the passageway floor as shown in the Fig. 11. About 46 kg of dust were dispersed from the dusting machine into the ventilating air using a hand-held nozzle discharging at about 46 kg/h.

Following each experiment the Petri dishes are collected and the reflectivity of the deposited layer measured. Figs. 12 and 13 show the results of this study. Least-squares fits of the measurement data to (7) and (8) resulted in the expressions

$$\phi = e^{-(1.3 \pm 0.14)\sigma_{rd}} \tag{12}$$

for rock dust deposited on a black substrate and

$$\phi = 1 - e^{-(0.34 \pm 0.02)\sigma_{cd}} \tag{13}$$

for coal dust deposited on a white substrate. The standard error of ϕ for these two expressions is 0.08 and 0.05, respectively.

The experimental mine data only are shown in Figs. 12 and 13 along with the best-fit traces for both the mine and lab studies. Fig. 13 shows that for rock dust deposited on coal dust the laboratory and mine results are statistically indistinguishable; however, the same is not true for coal dust deposited on rock dust (Fig. 12). However, the agreement is sufficiently close to justify the use of this technique for measuring the loading density of either material on a substrate of the other.

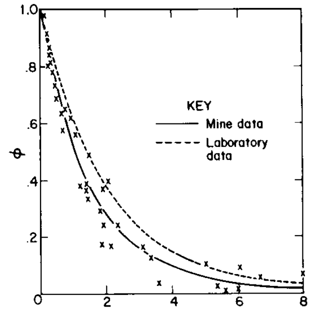

Fig. 12. Reflectance versus surface density of coal dust deposited on rock dust in experimental mine and in laboratory chamber.

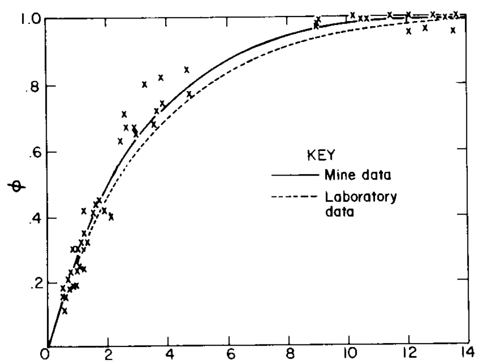

Fig. 13. Reflectance versus surface density of rock dust deposited on coal dust in experimental mine and in laboratory chamber.

Dust Deposition Meter

The last phase of this feasibility study concerned the construction of a portable battery-powered meter that displays the dust loading density directly. Fig. 14 shows a schematic of such a meter powered by two 9-V batteries. In principle the circuit solves the equation

$$\sigma_c = -(1/\alpha_{cd}) \ln \phi, \tag{14}$$

or

$$\sigma_r = -(1/\alpha_{rd}) \ln (1-\phi) \tag{15}$$

where

$$\alpha_i = (3Q/2\rho_i d_i), \qquad i = cd \text{ or } rd. \tag{16}$$

The first stage of the circuit is the same as shown in Fig. 3, the second stage calculates the ϕ function or 1-ϕ (for use with rock dust layers), the third stage calculates ln ϕ (or ln $(1 - \phi)$, the fourth stage forms the product of $-1/\alpha_i$ and ln ϕ (or ln $(1 - \phi)$, and the last stage displays the loading density in mg/cm^2 on a liquid crystal display.

To test the meter design the laboratory-based rock dust deposition experiments were repeated. Fig. 15 shows the results of these tests, and it can be seen that the meter results agree with the rock dust loading density of the prepared mixture to within 5 pct; this is well within the acceptable limits of such a meter.

Conclusion

It has been shown that the optical reflectivity of light from superficial layers of rock dust on coal dust or coal dust on top of rock dust can be used to measure the accumulation of explosive dust. The relationship between normalized reflectivity and surface density follows a modified Bouguer–Beer–Lambert law of light transmission through dispersed dust clouds. The agreement between laboratory tests, mine tests, and theory are sufficiently close to justify the use of this technique for measuring and controlling the surface loading density of either rock dust or coal dust on the substratum of the other. If further mine testing confirms the reliability of the technique, mine operators will have a means of controlling the explosive accumulation of float coal dust through efficient rock dusting. A portable meter has been designed and constructed that is capable of measuring the loading density of float coal dust on a rock dust substrate and *vice versa* with an accuracy within 5 pct.

Acknowledgment

The authors wish to acknowledge the valuable support of Greg Moorman at the Electrical Engineering Department of Geneva College under memorandum of agreement 14-09-005-3249. The authors also wish to acknowledge the invaluable technical assistance of Henry Perlee, Ken Cashdollar, and Tom Woods for designing and fabricating the circuit, and to Nevin Greninger and Gene Bazala for laboratory and mine testing of the prototype device.

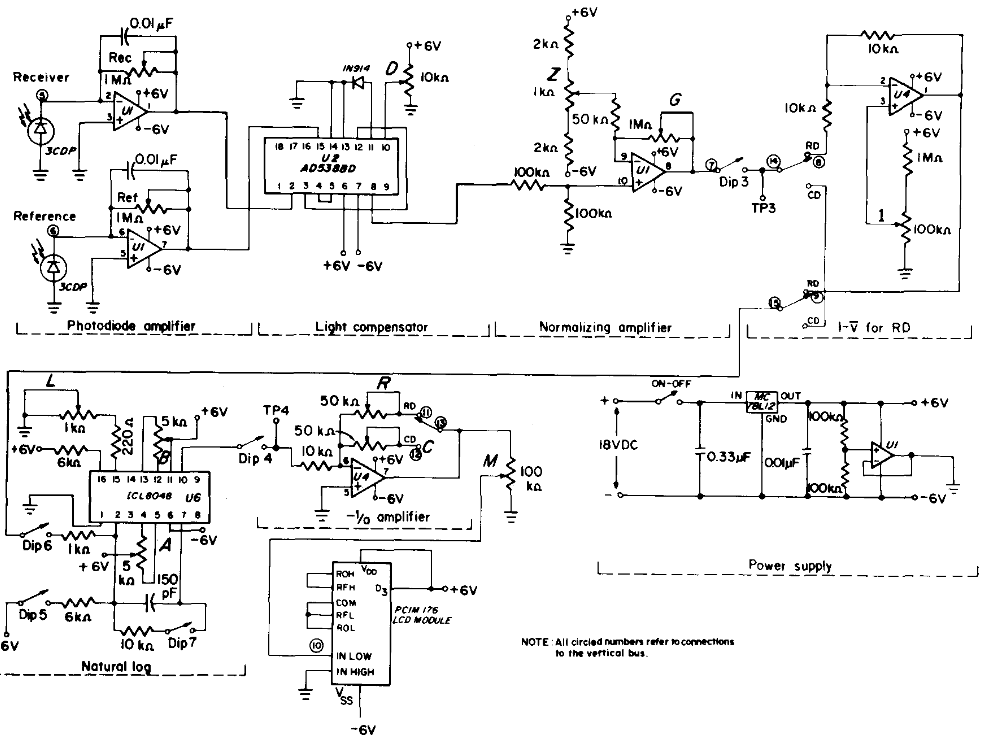

Fig. 14. Circuit schematic for prototype dust deposition meter.

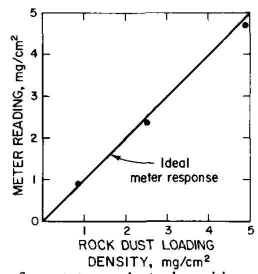

Fig. 15. Response of prototype dust deposition meter for rock dust deposited on coal dust.

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