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DIESEL ENGINE SMOKE MEASUREMENT

Foreword—This Reaffirmed Document has been changed only to reflect the new SAE Technical Standards Board Format.

1. Scope—Measurement of diesel smoke in an accurate and consistent manner has been a serious problem for engine and vehicle manufacturers, users, and agencies charged with enforcing smoke limits. Several instruments, based on different principles and using different scales, are commonly used. In addition to these, human observation and judgment are often used to relate smoke to a variety of standards.

The purpose of this SAE Information Report is to provide an understanding of the nature of diesel smoke, how it can be measured, and how the various measurement methods can be correlated. Except for defining the various types of smoke, the report deals solely with the steady-state measurement of visible, black smoke emitted from diesel engines.

For the benefit of those who wish to study various aspects of the subject in greater depth, a list of useful references is included in Section 2.

This document is divided into the following sections:

2. *References*

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein.

2.1.1 Other Publications

Federal Registers, Vol. 33, No. 108, June 4, 1968; and Vol. 35, No. 219, Nov. 10, 1970. Washington, DC: U.S. Government Printing Office.

F. J. Hills, T. O. Wagner, and D. K. Lawrence, "CRC Correlation of Diesel Smokemeter Measurements," Paper 690493 presented at SAE Midyear Meeting, Chicago, May 1969.

A. W. Carey, Jr., "Steady-State Correlation of Diesel Smoke Meters—An SAE Task Force Report," Paper 690493 presented at SAE Midyear Meeting, Chicago, May 1969.

W. D. Conner and J. R. Hodkinson, "A Study of the Optical Properties and Visual Effects of Smoke Stack Plumes," Cooperative Study Project, Edison Electric Institute and U.S. Department of Health, Education, and Welfare.

Bureau of Mines, Informational Circulars No. 8333 and 7718.

1974 EMA—Tech. Paper, "Ringelmann Numbers vs. Opacity," prepared by the Diesel Smoke Subcommittee of the Engine Manufacturers Association.

"The Measurement of Diesel Exhaust Smoke," Motor Industry Research Association (MIRA) Report, 1965.

"Evaluation of Test Methods for Diesel Engine Exhaust Smoke Measurement," Coordinating European Council (CEC), Fuels Committee Report, October 1968.

2.2 Related Publications—The following publications are provided for information purposes only and are not a required part of this document.

2.2.1 Other Publications

R. D. Henderson, "Air Pollution and Construction Equipment," Paper 700551 presented at SAE Earthmoving Industry Conference, Peoria, IL, April 1970.

Design and Test Specifications for Smoke Inspection Guides, U.S. Public Health Service (42 CFR Part 75).

R. D. Fleming, W. F. Marshall, and R. W. Hurn, "The Fuel Factor in Diesel Emissions," Oral presentation made at SAE Midyear Meeting, Detroit, May 1970. (Note: Oral only, nonretrievable.)

R. Burt and K. A. Troth, "Influence of Fuel Properties on Diesel Exhaust Emissions," Institute of Mechanical Engineers, London, November 1968.

J. B. Durant and L. Eltinge, "Fuels, Engine Conditions, and Diesel Smoke," Paper 3R presented at SAE Annual Meeting, Detroit, January 1959.

B. W. Millington and C. C. J. French, "Diesel Exhaust—A European Viewpoint," SAE Transactions, Vol. 75 (1967), Paper 660549.

R. C. Schmidt, A. W. Carey, and Roy Kamo, "Exhaust Characteristics of the Automotive Diesel," SAE Transactions, Vol. 75 (1967), Paper 660550.

M. Vulliamy and J. Spiers, "Diesel Engine Exhaust Smoke—Its Measurement, Regulation, and Control," Paper 670090 presented at SAE Automotive Engineering Congress, Detroit, January 1967.

C. O. Miller, "Diesel Smoke Suppression by Fuel Additive Treatment," Paper 670093 presented at SAE Automotive Congress, Detroit, January 1967.

W. F. Marshall and R. W. Hurn, "Factors Influencing Diesel Emissions," SAE Transactions, Vol. 77 (1968), Paper 680528.

Ralph C. Stahman, George D. Kettredge, and Karl J. Springer, "Smoke and Odor Control for Diesel Powered Trucks and Buses," SAE Transactions, Vol. 77 (1968), Paper 680443.

R. G. Kolb and I. O. Kamm, "Diesel Air Pollution Study for New Jersey State Department of Health," Stevens Institute Report, June 1967.

H. E. Styles, J. Vrebos, and J. Lawther, "Public Health Aspects of Air Pollution from Diesel Vehicle," World Health Organization Report, 1967.

John R. Kinosian, John A. Maga, and John R. Goldsmith, "The Diesel Vehicle and its Role in Air Pollution," California Department of Public Health Report to California Legislature, December 1962.
"Measuring Diesel Exhaust Smoke," Ethyl Corp. Technical Notes, May 1968.
"1962 CRC Smokemeter Tests," CRC Report 371, August 1963.
"1967 CRC Diesel Smokemeter Calibration Tests," CRC Report 421, June 1969.
"Aircraft Gas Turbine Engine Exhaust Smoke Measurement," SAE Aerospace Recommended Practice, May 1970.
SAE J1157, "Measurement Procedure for Evaluation of Full Flow, Light-Extinction Smokemeter Performance," August 1976.
1977 CRC Report, "A Laboratory Comparison of In-Line and End-of-Line Full Flow Diesel Smoke Opacity Meters," prepared by Smoke Panel of CRC-APRAC Program Group on Composition of Diesel Exhaust.

3. Definitions, Terminology, and Abbreviations—The following apply to definitions, abbreviations, and/or terms as used in this document:

3.1 Diesel Smoke—Particles, including aerosols, suspended in the engine's gaseous exhaust stream which obscure, reflect, and/or refract light.

3.1.1 BLACK SMOKE—Particles composed of carbon (soot), usually less than 1 µm in size, which have escaped the engine's combustion process.

3.1.2 WHITE AND BLUE SMOKE—Particles composed of essentially colorless liquid (droplets) which reflect and refract the observed light.

NOTE—The observed color results from the refractive index of the liquid in the droplets and the droplet size. White smoke is usually due to condensed water vapor or liquid fuel droplets. Blue smoke is usually due to droplets resulting from the incomplete burning of fuel or lubricating oil.

3.2 Instrumental Smoke Measurement—Any technique which involves direct measurement of an intrinsic property of the smoke without recourse to human judgment or comparison.

3.2.1 LIGHT EXTINCTION METHOD—Any technique which involves a measurement of the amount of light which fails to penetrate a column of smoke.

3.2.2 FILTERING METHOD—Any technique which involves a measurement of the amount of soot particles collected by passing exhaust gases through a filtering medium.

3.3 Visual Smoke Measurement—A measurement technique which relies upon human observation of an engine's smoke plume to rate that plume's appearance against an established scale of blackness or opacity (usually a gray scale on either a transparent or opaque white base).

3.4 Photographic Smoke Measurement—A measurement technique which relies upon an instrumental or visual comparison of the photographic image of a smoke plume with an established scale of blackness or opacity to determine the opacity of the original smoke plume.

3.5 Transmittance (T)—That fraction of light transmitted from a source, through a smoke-obscured path, which reaches the observer instrument receiver, expressed in percent (%),

$$\left(T = 1 - \frac{\text{opacity}}{100}\right) \quad \text{(Eq. 1)}$$

3.6 Opacity (N)—That fraction of light transmitted from a source which is prevented from reaching the observer or instrument receiver, expressed in percent (%), N = 100 (1 - T).

3.7 Beer-Lambert Law—For purposes of diesel smoke measurement an equation expressing the relationship between the opacity of a smoke plume, the effective optical path through the plume, and the opacity of the smoke per unit path length, may be used:

$$T = \frac{\text{Transmitted light}}{\text{Incident Light}} = e^{-KL} \quad \text{(Eq. 2)}$$

and

$$N = 100(1 - e^{-KL}) \quad \text{(Eq. 3)}$$

3.8 Absorption Coefficient—The absorption coefficient, K, (or m^{-1}), of a plume is defined in the following manner, a form of the Beer-Lambert Law:

$$K = -\frac{1}{L} l_n\left(1 - \frac{N}{100}\right) \quad \text{(Eq. 4)}$$

where L is expressed in meters, m.

3.9 Effective Optical Path Length—The length of light beam between the emitter and the detector that is intersected by the exhaust stream, corrected for nonuniformity due to density gradients and fringe effects.

3.10 Abbreviations

°C = degrees Celsius
°F = degrees Fahrenheit
% = percent
m = meters
N = opacity, %
e = base of natural logarithms
K = absorption coefficient (smoke density), m^{-1}
L = effective path length through the smoke (meters)
T = transmittance
l_n = natural log

4. Procedure for Smoke Evaluation

4.1 Instrument Methods for Smoke Measurement—Instruments for measuring diesel smoke may be classified generally as follows:

a. Opacimeter, Full-Flow Type—Measures opacity of the full smoke plume. Can be either the exhaust stack (in-line) or at the outlet of the stack (end-of-line) type.
b. Opacimeter, Sampling Type—Measures the opacity of a portion of the exhaust gas which has been extracted from the exhaust pipe and passed through a measurement chamber of standardized size.
c. Filtering Method—Smoke soot particles are collected on a filter medium as a sample of the exhaust is forced through. The filter may be evaluated by comparison with standards, by photoelectric reflectance measurement methods, or by determining the mass of the sample.

A representative example of these general types of instruments will be described. With the exception of the direct soot measurement systems, each is commercially available.

4.1.1 OPACIMETER, FULL-FLOW TYPE

4.1.1.1 End-of-Line Opacimeter

4.1.1.1.1 Introduction—An example of this type is the USPHS (EPA) Diesel Smokemeter (Figure 1), developed by the U.S. Public Health Service.

The light source and photocell are located on opposite sides of the smoke plume, a few inches from the open end of the exhaust pipe (Figure 2). Output of the photocell may be read remotely on the calibrated milliammeter or by an optional chart recorder. The meter furnished with the instrument may be calibrated in either 0 to 100% light transmittance or opacity. The unit can be battery operated and requires a clean supply of compressed air, which is used as an air curtain to keep the light source and photocell free of soot. Calibration is accomplished by blocking the light beam for 100% opacity and by clean air (remove from plume or shut engine down) for zero capacity. Calibration between 0 and 100% can be established with neutral density filters which should be referenced to NIST standards. The instrument system is sensitive to smoke density and the effective optical path length (diameter of smoke plume). Therefore, it is important to define the location of the meter above the stack and the stack diameter when comparing readings with other smokemeters. Changes in opacity due to path length differences may be calculated by using the Beer-Lambert Law.

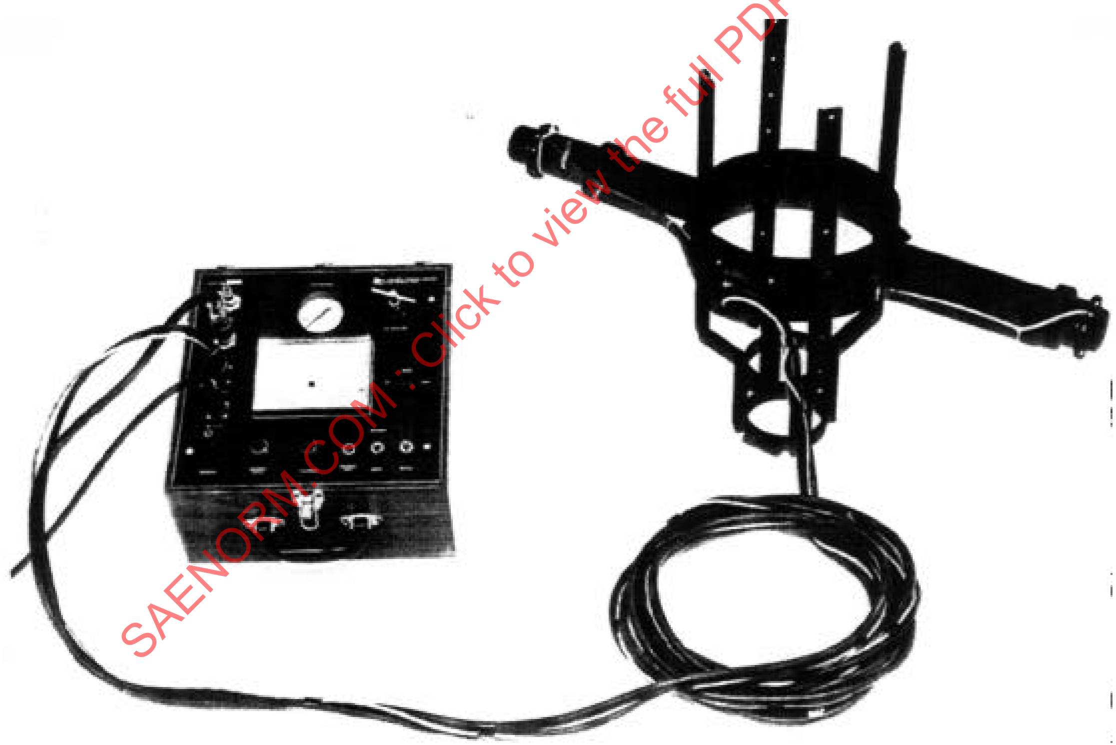

FIGURE 1—USPHS (EPA) DIESEL SMOKEMETER

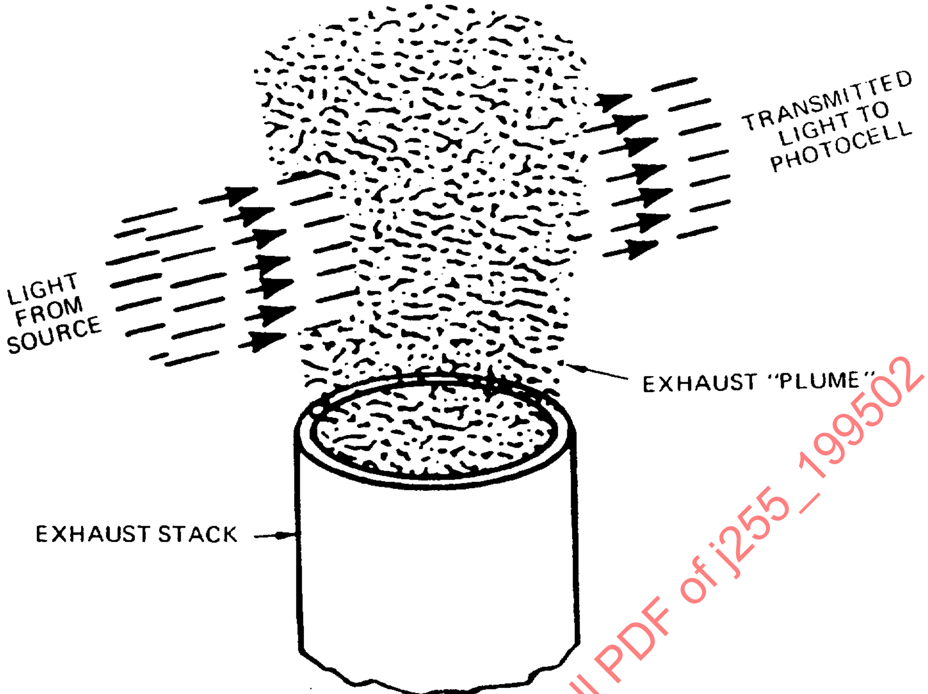

FIGURE 2—METHOD OF OPERATION OF FULL-FLOW TYPE OPACIMETER

4.1.1.1.2 Specific Operating Precautions

a. Do not rigidly mount the optical unit on the engine exhaust pipe. Engine vibration can shake the lamp filament which may register as noise on recorders. It may also shake lenses and loosen other mechanical and electrical components within the unit.

   If adaptation of the instrument for portable vehicular operation is attempted, several modifications are suggested:

   1. General—Shock mount the photocell, solder all electrical connections, strengthen mechanical parts, and use a frosted lamp to minimize the effect of filament vibration.
   2. Power Supply—Inverters, gasoline engine generators, or batteries may be used to power the optical unit and recorder. Vehicle electrical systems should not be used for power, since voltage fluctuations result in instrument zero shift.
   3. Air Supply—Bottled nitrogen or vehicle brake air supply, properly filtered and dried, may be used.

b. The open stack, a relatively critical location for the optical unit, and the need to calibrate on clean air are features not particularly well suited to laboratory engine testing. Hoods or funnels have been used successfully, but the particular exhaust gas disposal system must be considered when this smokemeter is used. The smoke ventilation systems should not influence the shape of the exhaust plume. Exhaust noise and room ventilation also must be considered when testing indoors.

   CAUTION—Exhaust stacks larger than 5 in in diameter should not be used.

4.1.1.2 In-Line Opacimeter

4.1.1.2.1 Introduction—An example of this type is the Celesco Model 107 Smokemeter (Figure 3). The light source (pulsed light-emitting diode) and detector (photodiode) are located on opposite sides of the smoke plume in the sensor mounts as shown. Output from the photodiode may be read remotely on the microammeter or by an optional recorder. The unit requires a clean supply of compressed air, flowing through the sensor mounts to keep the light source and detector free of soot. Water-cooled sensor mounts are used for temperature isolation (recommended for ambient temperatures above 49 °C (120 °F). Calibration is accomplished by electrically blocking the detector circuit (to minimize source diode thermal drift) for 100% opacity and clean air (shut engine down) for zero opacity. Calibration between 0 and 100% can be established with natural density filters which should be referenced to NIST standards.

This instrument system is sensitive to smoke density and the effective optical path length.

4.1.1.2.2 Specific Operating Precautions

a. Mount the meter sensor unit in a straight section of pipe downstream of any curved sections.
b. Provide clean purge air to the photocell and light source to avoid soot contamination.
c. For in-line meters used with laboratory engines and sufficiently large inertia dynamometers, a hot zero can be attained by running the engine at high speed, then closing the throttle, and removing the load simultaneously to allow the engine to decelerate against the dynamometer inertia. This allows a period of approximately 2 to 5 s of no smoke while the engine is purging the stack with clean air during which time the meter can be zeroed.

FIGURE 3—CELESCO MODEL 107 SMOKEMETER

4.1.1.3 General Operating Precautions

a. The compressed air supply must be free of oil, water, and dirt, any of which may obscure light and introduce error in the readings. For oil contaminated lines, it is necessary to thoroughly flush the supply air system back to the air filters.
b. Chart recorder response characteristics can affect the reading obtained. The Federal Register (2.1.1) specifies recorder response for certification testing. This is especially important for transient smoke tests, and it should be established that the readout instrumentation used has proper response for transient work. The optical system of the opacimeter is extremely fast, and with suitable recorders (light beam type of an oscilloscope) the smoke puffs from individual cylinders of a multicylinder engine may be observed.
c. Since neutral density (ND) filters used in the calibration of opacimeters are not truly neutral, the filters should be calibrated at the same mean effective wavelength as the meter.

4.1.2 OPACIMETER, SAMPLING TYPE

4.1.2.1 Introduction—Figure 4 shows the Hartridge MK3 smokemeter, an example of this type.

FIGURE 4—HARTRIDGE MK3 SMOKEMETER

Figure 5 illustrates the operating principle which involves measuring the opacity of a portion of exhaust gas continuously flowing through the sample tube. Zero reference is achieved by a switching arrangement which utilizes a second tube containing clean air, free of smoke. An internal electric fan purges the instrument case (of smoke) and clears soot from the light source and photocell. The calibrated milliammeter reads in units from 0 (clear) to 100 (completely opaque). Since the smoke tube length is fixed and known, these readings can be related to smoke measurements made with other instruments by means of the Beer-Lambert law. The smoke reading is not affected by exhaust pipe diameter. Transient response is limited to the time required to fill the sampling tube (transport time approximately 0.2 to 0.6 s) and by the length of tube which serves to deliver the sample.

4.1.2.2 *General*—The instrument does not have a system to draw the sample into the meter, so a butterfly valve or other restriction is needed in the exhaust stack to create sufficient exhaust pressure to force the sample through the meter. If sufficient exhaust gas velocity exits, an impact sampling probe at the stack outlet may be used. Isokinetic sampling probes are suggested. A manometer is provided with the meter because the pressure of the exhaust sample at the meter must be maintained within specified limits. A pressure relief valve is also provided to aid in maintaining this pressure. Temperature gauges are provided for exhaust sample temperature to the meter and within the smoke tube. These temperatures must be maintained to prevent condensation of water vapor in the exhaust at low temperatures, damage to the meter at high temperatures, or inaccurate meter readings at high or low temperatures. (A more recent version of the meter contains a heated smoke tube.) Transient smoke measurements with this type of instrument are not recommended due to slow system response, problems of obtaining a representative exhaust sample, and inability to maintain temperatures and pressures within specified limits during transient operation of an engine.

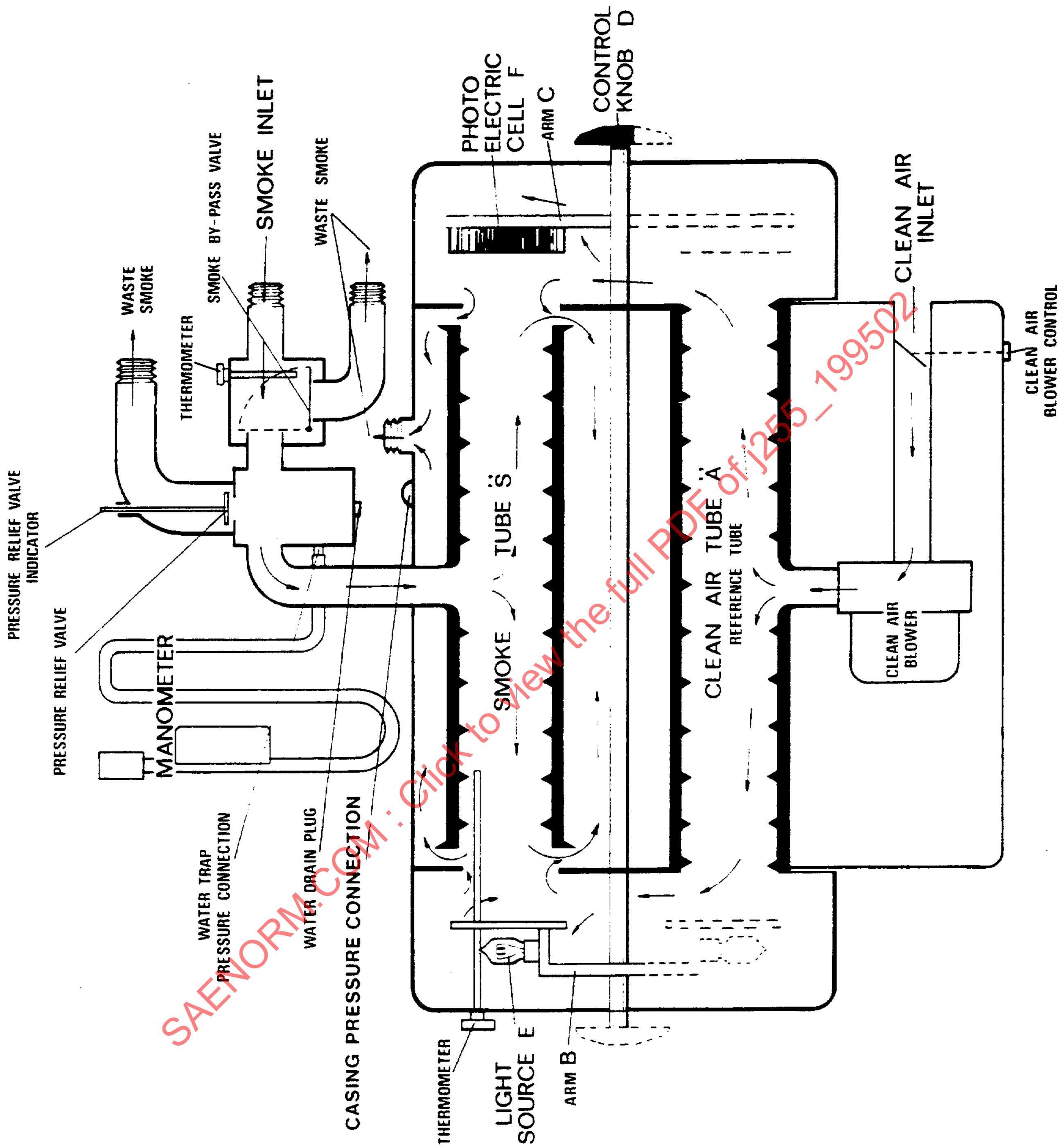

FIGURE 5—OPERATING PRINCIPLE INVOLVING MEASURING THE OPACITY OF A PORTION OF EXHAUST GAS CONTINUOUSLY FLOWING THROUGH SAMPLE TUBE

4.1.2.3 Operating Precautions

a. An external means of cooling the exhaust sample to the meter is normally required because diesel exhaust will often exceed 1000 °F on a loaded engine. This hardware is not provided with the basic Hartridge MK3 instrument, but this can be accomplished with commercially available air-to-water or air-to-air heat exchangers. The choice depends on the test setup. The air-to-water exchangers may be more convenient for laboratory testing, whereas the air-to-air exchangers may be more convenient for field operation if a storage battery can be used to power a fan for air cooling. The instrument may be used without external cooling of the sample if the exhaust temperature is quite low or if very short sample periods are used. When short sample periods are used the probe should be removed from the exhaust stream between readings. The sample tube should be allowed to cool between readings since its heat capacity serves to cool the sample. External care must be exercised in this mode of operation to prevent damage to the meter due to overheating.
b. Outdoor operations in cold weather or overcooling of the exhaust may result in condensation in the sampling hose or within the smoke tube. This is usually noticeable at the pressure relief valve and may cause the valve to stick. Excessive condensation can foul the photocell, smoke tube, and light source causing zero shift. Condensed water will also cause erroneous readings by scattering the light beam.
c. This type of smokemeter has displayed repeatable results when properly applied. It is intended for use on black diesel smoke, and correlations herein are on that basis. Attempts to measure white or blue smoke will usually be unsuccessful because of the liquid particles which will cause problems similar to those mentioned for condensed water vapor.

4.1.3 FILTERING SYSTEMS

4.1.3.1 Bosch Spotmeter

4.1.3.1.1 Introduction—An example of the filtering type system is a portable Bosch "Spot" Smokemeter shown in Figure 6. A spring-operated sampling pump draws a fixed volume of exhaust gas from the exhaust stream through a controlled density paper filter disc. Soot particles from the sample are deposited on the filter disc, causing it to darken in proportion to soot particle concentration. A separate 110 V AC or battery-powered photoelectric device measures the light reflected from the darkened filter disc. Readout is by a milliammeter calibrated in 0 to 10 units. Figure 7 shows the operating principle of the photoelectric evaluation system.

Calibration of the photoelectric readout consists of:

a. A zero adjustment with the instrument switched on with the detector exposed to clean filter.
b. A mid-scale calibration using a black perforated grid (supplied with the instrument) corresponding to a 5.0 Bosch reading.
c. Full scale reading (2.1.1) Bosch is set with the switch off. (A mechanical meter adjustment.)

A variation of this type of instrument made by AVL includes an automated sampling system with remote actuation and readout. This automated system utilizes a roll of filter paper in place of the individual discs.

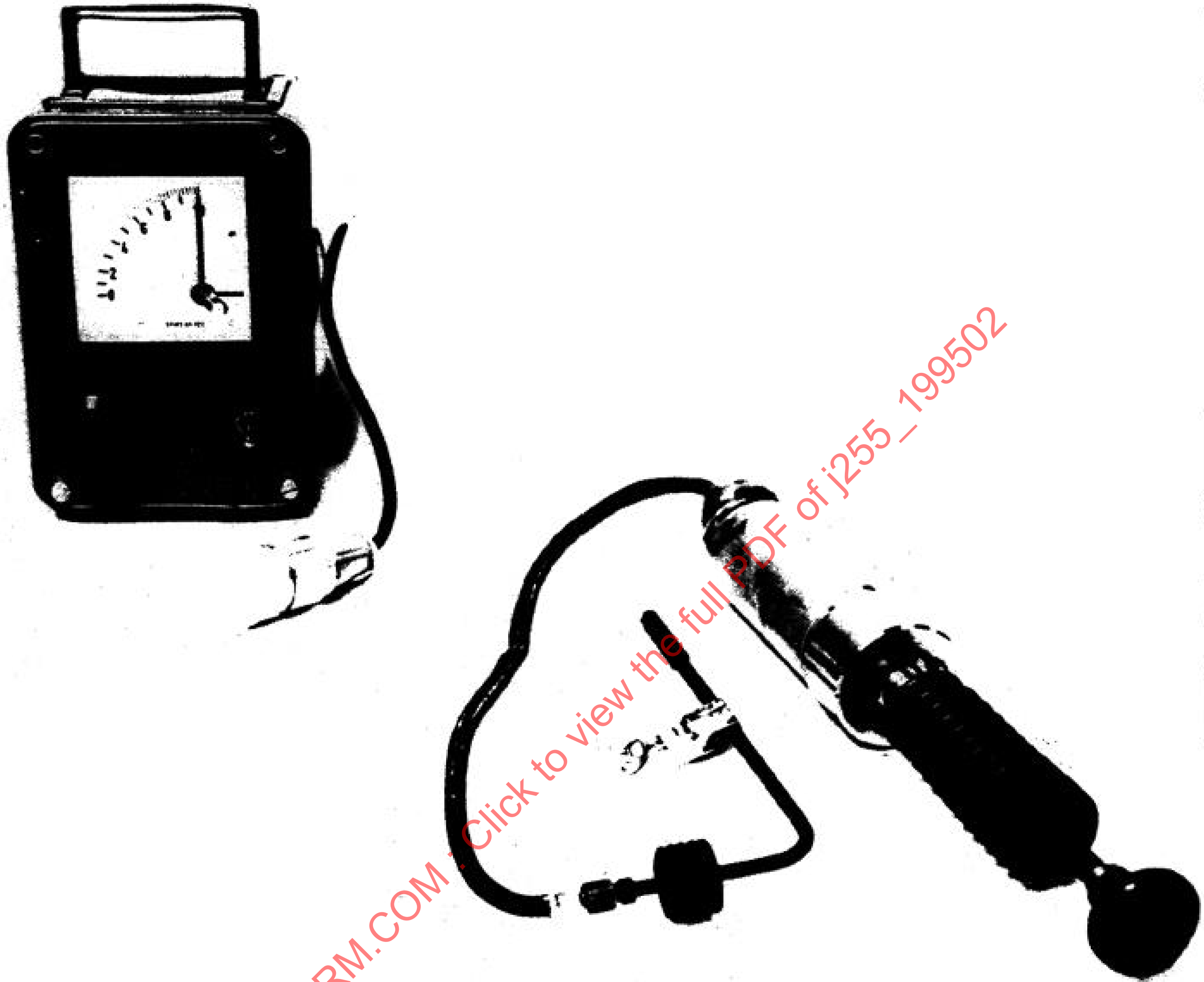

FIGURE 6—PORTABLE BOSCH "SPOT" SMOKEMETER

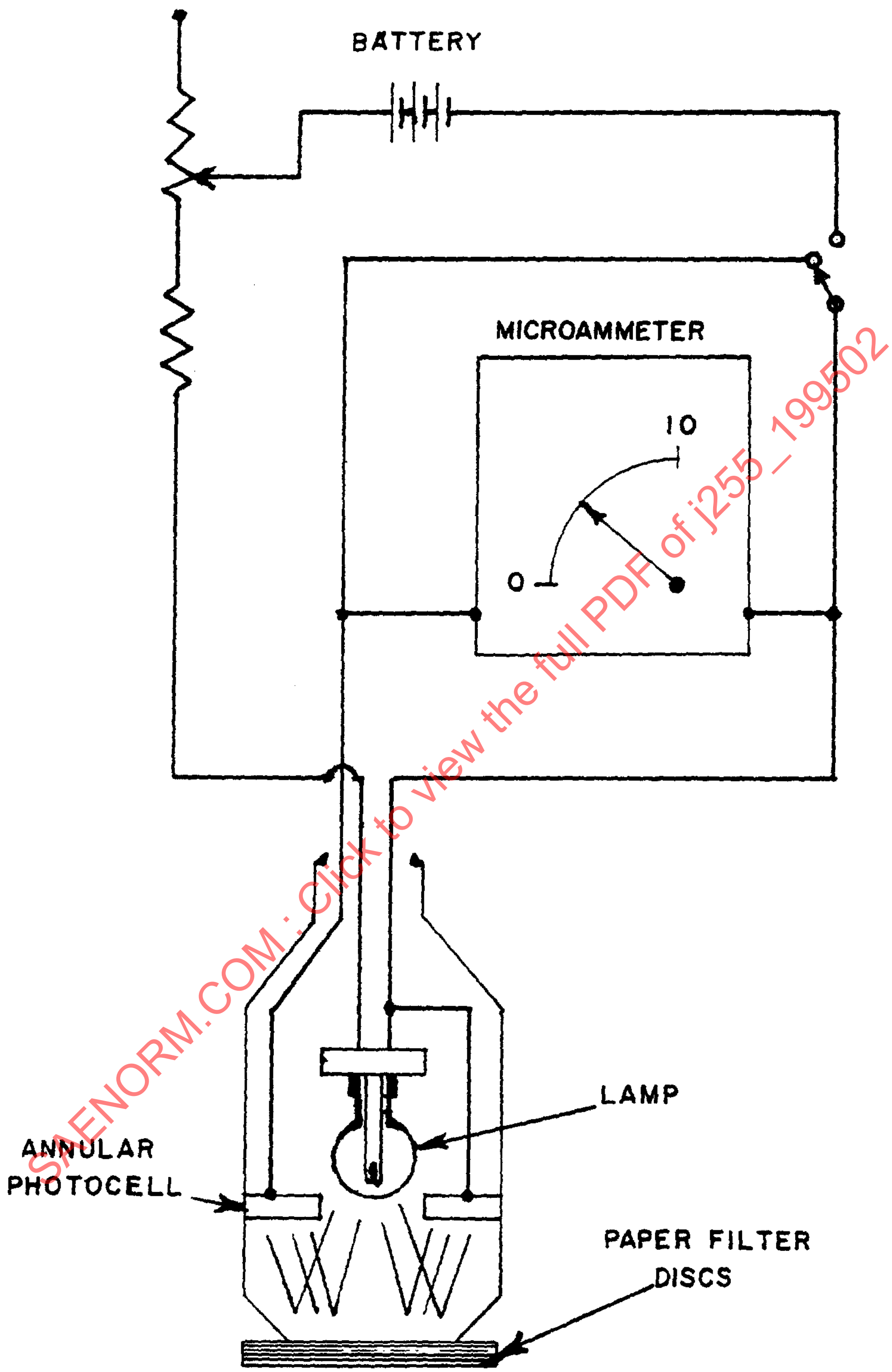

FIGURE 7—OPERATING PRINCIPLE OF THE PHOTOELECTRIC EVALUATION SYSTEM

4.1.3.1.2 Operating Precautions

a. Engine vibrations may loosen the smoke probe shield. This shield may be pinned to the probe and should be checked frequently whenever vibration is encountered.
b. Locate sampling tube so water cannot drain down into the sampling pump. Sampling probe should be located at the open end of the exhaust pipe, whenever possible, to avoid the pressure, velocity, or pulsation effects which may occur closer to the engine manifold.
c. When performing the mid-scale readout calibration or when reading a sooted filter disc, the perforated grid or sooted filter disc should be placed on top of a minimum stack of 10 clean filter discs. Discard sample discs which become smudged with water vapor or smeared by the operator. Keep plenty of clean discs available and handle both clean and used discs carefully.
d. Three samples should be taken at each engine operating condition. The first sample will clean the filter holder and collect any accumulation of water vapor or soot from the sample line. This sample disc should be discarded. To prevent soot and water vapor accumulation, shop air may be applied to the sample line. Caution should be exercised to be certain that the shop air is turned off during sampling.
e. The mid-scale calibration of the photoelectric readout should be checked prior to reading each set of sooted discs. Check to be sure that the proper side of the paper filter disc is measured.
f. At light smoke levels it is difficult to determine which side of the filter has been exposed to the exhaust gases. Therefore, check to be sure that proper side of filter disc is measured.
g. Frequently check sample pump plunger travel time and periodically leak-check the sample pump hose as outlined in the manufacturer's maintenance instructions.
h. This smokemeter is intended for measurement of black engine smoke and should not be used for white or blue smoke.
i. Sampling under transient conditions is not recommended because of transport time lag and integration of the sample on the filter.

4.1.3.2 Direct Soot Measurement—Diesel smoke of the black variety can be measured and described by determining the mass of soot per unit volume of exhaust gas. In general, the procedure is to pass a measured amount of exhaust gas through an absolute filter, capable of retaining on its surface all the soot that was suspended in the exhaust gas sample. The weight of soot collected divided by the volume (at a specified temperature and pressure) of exhaust gas sampled, is reported as the soot concentration.

In the Caterpillar Tractor Co. version of this procedure, the weight of soot is determined as the difference in weight of the filter before and after the sampling process. The filter with its sample is heated sufficiently to drive off any absorbed hydrocarbons that might contribute to the soot weight.

In the Ethyl Corp. version of the procedure, an incombustible filter is used. After sampling, the soot residue is burned under carefully controlled conditions. The weight of carbon (soot) is determined from the amount of CO_2 produced.

4.2 Photographic Methods—Still pictures, motion pictures, black and white and color photographic methods and films have been used in attempts to establish an acceptable procedure for the measurement and documentation of diesel smoke.

In the mid-1960s, an SAE Task Force (2.1.1) of the Diesel Smokemeter Subcommittee came to the following conclusions:

a. The density exposure characteristics of color photographic emulsions are such that they will indicate apparent smoke densities in substantial variance with those observed by eye or with a photoelectric light-extinction type opacity meter (opacimeter).

b. To yield a transparency of projected image with an apparent smoke equal to that visually observed or indicated with a photoelectric opacimeter, the exposure must be such that it utilizes the nonlinear portion of the photographic emulsion's response curve. When exposed in this manner, it would be mandatory that transparencies be evaluated with a precision densitometer before they could be accepted as evidence of a particular smoke level.
c. Although a photograph made under ideal conditions may not yield a record directly corresponding to the eye's impression or to a reading from a photoelectric opacimeter, it can be used as the basis for a calculation of smoke opacity.
d. Even under ideal conditions, photographic smoke measurement is incapable of sufficient reproducibility to warrant its use as an objective smoke technique.

In the early 1970s another method of photographic recording was attempted to eliminate some of these variances. This method consisted of two neutral density filter (light attenuators) mounted at the film plane in the aperture plate of a movie camera. Only a small section on either side of the field of view was covered by the filters, and therefore light flux being admitted through the lens was also attenuated in the area of the filters.

The intent was to record on film, simultaneously, the density of smoke plume as well as density filters for comparison without consideration for background conditions, such as, the variation in sky (the normal background) condition: cloudy, hazy, mottled, clear, etc.

The technique also eliminated the need to consider variations in overall film density of the reference filters and smoke plume which are proportionately affected. But the technique was not fully developed for a number of reasons: primarily, the method was not instantaneous and the opacity type meters were emerging as the accepted instrument (standard) of the industry.

4.3 Visual Methods—Visual methods of smoke observation and rating have been developed as simple and direct means for obtaining numerical ratings of black (gray) smoke. The smoke perceived by the observer is subjectively compared with one of several established gray scales. The observer must discipline himself to limit his observation to that portion of the plume immediately above the exhaust stack exit, and to compensate mentally for the factors of background color, illumination, and ambient light level.

To investigate the optical properties and visual effects of smokestack plumes, a research program was conducted in the mid-1960s, jointly by the U.S. Public Health Service and the Edison Electric Institute (2.1.4). Obscuration of objects by smoke and the visual appearance of the smoke itself were studied. The influence of ambient light intensity and orientation was defined.

Two observations in the report on this work summarize the results and indicate the rationale behind the procedures that have since been stipulated by the federal government for diesel smoke certification purposes:

Vision obscuration by smoke plumes and the visual appearance of smoke plumes are far too dependent on environmental conditions of plume illumination to be reliable measures for characterizing the plume as an aerosol. A plume that is assessed by a visual effect could be condemned when viewed from one direction and accepted from another, even when its content had not changed, and The optical property of a plume that is easiest to measure and most simply related to concentration, particle size, composition, and dimensions of the plume is its light transmittance. Although no general inexpensive instrumental technique is available for objectively measuring the transmittance of plumes, there are several special techniques which collectively, under most circumstances, will provide an objective means of measuring the transmittance.

4.3.1 RINGELMANN RATING—The standard for this method was published as U.S. Bureau of Mines Chart No. 917-891 (2.1.1) (Figure 8). It was developed by Prof. Maximilian Ringelmann of Paris, France in the late 1800s. It was originally developed as a guide for operators to adjust excess air for blast smelting furnace efficiency. This chart served as the primary enforcement tool in this country in earlier years.

The Ringelmann system uses a card or a chart of graduated shades of gray produced by varying the width of cross-hatched black lines on a white background. The line widths are varied so that the black occupies approximately 20, 40, 60, and 80% of the total area of the chart. These shades are referred to as Ringelmann No. 1, 2, 3, and 4, respectively.

It is assumed that 0 is completely white and No. 5 is completely black. Pocket-size adaptations of the original charts are available. An example is shown in Figure 9. The observer views the smoke plume through the center hole and compares his perception of its grayness with the five standards arranged around the hole.

It should be noted that the Ringelmann method requires the observer to compare the obscuration of light transmitted or reflected from a background through the smoke plume to that of the light reflected from the standard. Errors in judging the equivalence between the smoke and the printed standard are inevitable. It has been conclusively demonstrated that the evaluation of a smoke plume is strongly influenced by background, light intensity, and light directionality (2.1.1).

The system, as a smoke-measuring device, has come under criticism on innumerable occasions. This is due to the fact that the Ringelmann ratings are subjective and depend on training and conditions. The Engine Manufacturers Association has prepared a complete report and discussion of Ringelmann numbers versus opacity in their paper (2.1.1) which further substantiates the conclusion that there are definite discrepancies in the relationship between the Ringelmann rating and opacity.

4.3.2 PHOTOGRAPHIC SCALES—FILM STRIPS—This type of opacity guide system uses a transparent film base on which segments of graduated density are produced by controlled exposure of photographic silver.

One such guide was developed for visual smoke evaluation by the U.S. Public Health Service in the late 1950s. These guides are designed to allow the transmission of light through the smoke plume to be compared simultaneously with the transmission of light through the guide. With proper usage, the viewer observes the guide against the same background and lighting as the smoke plume.

An opacity rating is determined by comparing the smoke plume to the graduated densities on the film strip guide. Many versions of film strip guides have been available, but in general they are of limited use in determining actual opacity measurements.

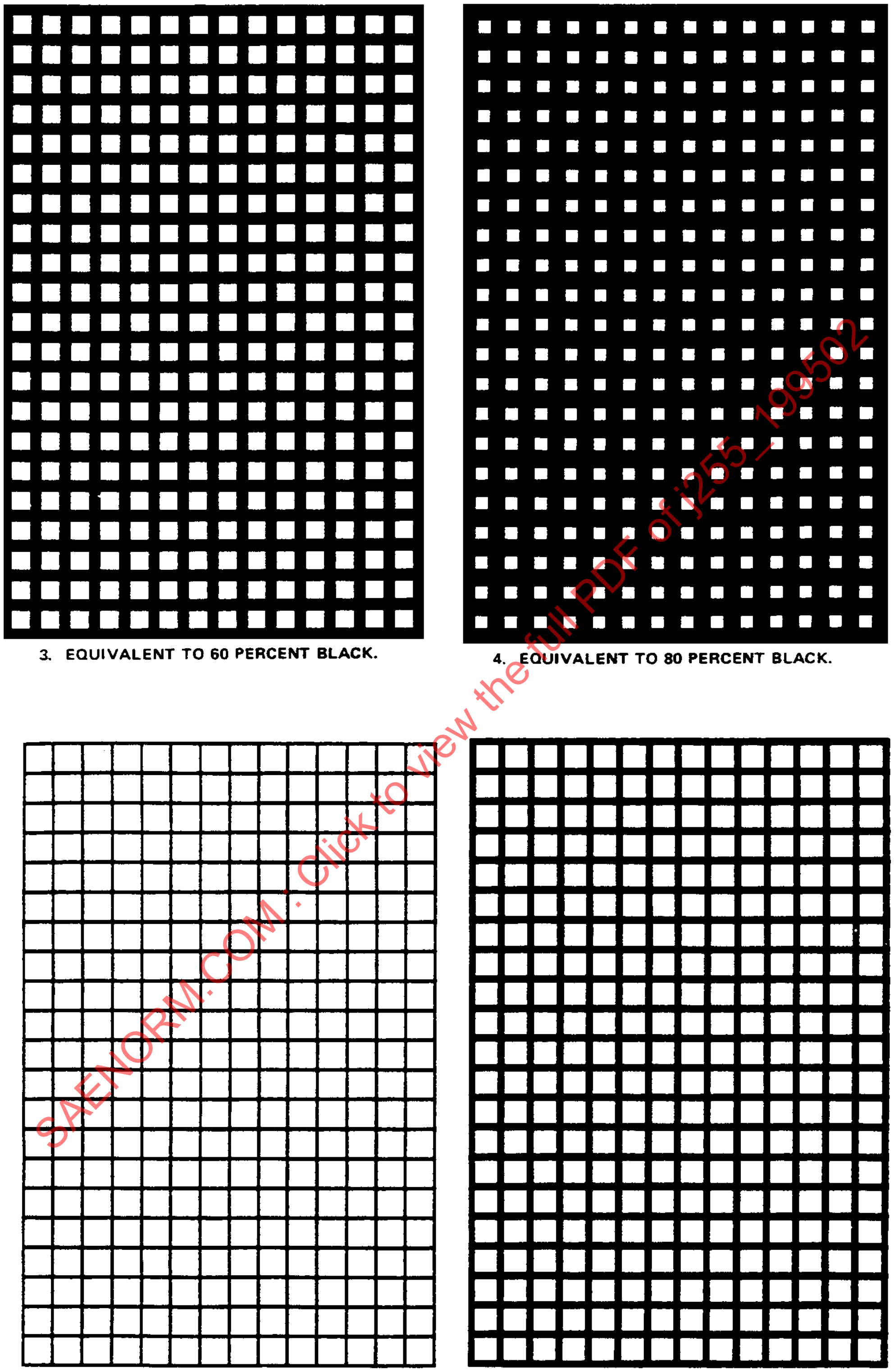

FIGURE 8—RINGELMANN SCALE FOR GRADING DENSITY OF SMOKE

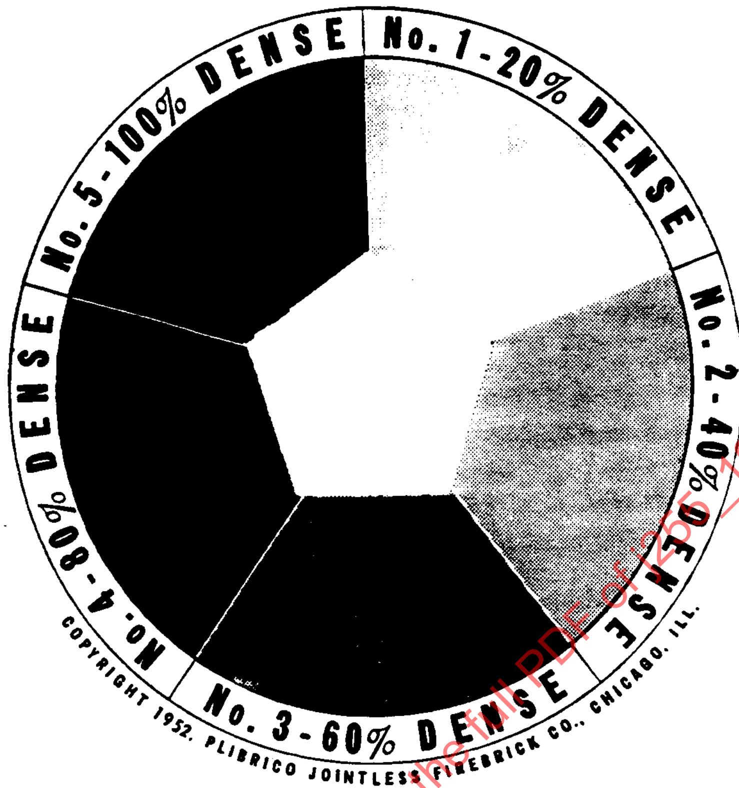

FIGURE 9—RINGELMANN TYPE SMOKE CHART

4.3.3 REFERENCE SMOKE GENERATORS—Efforts to obtain a frame of reference for visual methods of smoke evaluation have resulted in generators designed to produce controllable smoke. These generators, usually of the oil burner type, have been used in Los Angeles, CA to train observers for visual smoke rating. Such smoke generators may be of questionable value for training observers to rate diesel engine smoke because the generator stacks are usually more typical of stationary powerplant practice than of diesel vehicle stack installation.

To help improve the understanding of engine smoke and to establish a better correlation between what the public may see and what an instrument measures, engine manufacturers cooperated in the design and development of a diesel engine smoke generator. It was a commercial diesel engine, modified to produce smoke by a suitable loading means and an air supply restriction device. Engine acceleration transient smoke could also be produced by the generator.

5. Correlation of Steady-State Smoke Measurements—In 1967, an SAE Diesel Smoke Measurement Task Force conducted a series of tests to establish usable correlations between the principal methods of steady-state smoke measurement used by engine research and development organizations. Correlations were established between: opacimeters, full flow type; Robert Bosch Spotmeter; B. P. Hartridge; and exhaust soot content.

It was found that reliable correlations between these methods could be established only if the smoke measurements were taken at the exhaust stack outlet. Sampling smoke at locations in the exhaust line other than the stack outlet would necessitate correlations which would vary from installation to installation and which would also be influenced by engine load and speed.

The results of these tests were reported in May, 1969 (2.1.1). Figure 10 represents the summarized results of the work of the Task Force. Some examples will serve to illustrate how this figure should be used. Figure 11 is a self-explanatory alignment chart, presenting the same results in another form.

Example 1—A Hartridge smoke reading taken at the stack outlet yields a value of 50 HSU (Hartridge Smoke Units). By reading across in Figure 10 from 50 HSU, we find that a Hartridge reading of 50 corresponds to a Bosch Spotmeter reading of 4. Reading down from the 45.7 cm (18 in) Hartridge line, we find that the corresponding soot concentration is approximately 222.5 mg/m^3 (6.3 mg/ft^3), and that the opacity of this smoke when flowing through a 10.2 cm (4 in) stack is 14.5%. If the same smoke were passed through 7.6 cm (3 in) and 15.2 cm (6 in) stacks, then the observed opacities would be 11.5% and 21%, respectively.

Example 2—A Bosch Spotmeter reading of 3.0 is measured at the exhaust stack outlet. Reading across in Figure 10, we find that this would correspond to a Hartridge reading of 35.5 HSU. Reading down, the opacity produced by the smoke passing through a 15.2 cm (6 in) exhaust stack would be 14%; through a 12.7 cm (5 in) stack, 12%; through a 10.2 cm (4 in) stack, 9.5%; and through a 7.6 cm (3 in) stack, 7.5%. The soot content of this smoke would be approximately 148.4 mg/m^3 (4.2 mg/ft^3).

Similar correlative data resulting from studies of others in the field may be explored by consulting publications of the Coordinating Research Council (2.1.1), the Motor Industry Research Association (MIRA) (2.1.1), and the Coordinating European Council (CEC) (2.1.1).

The smokemeter correlation data presented previously is the most acceptable data available. More recent steady-state correlation data is now being evaluated by the EMA Smokemeter Correlation Task Force and the results of that work will be available in the future.