SOCIETY OF AUTOMOTIVE ENGINEERS, INC. • TWO PENNSYLVANIA PLAZA • NEW YORK, NEW YORK 10001

LAND SEA AIR SPACE

TECHNICAL REPORT J255

DIESEL ENGINE SMOKE MEASUREMENT (STEADY STATE)—SAE J255

SAE Information Report

Report of Automotive Emissions and Air Pollution Committee approved June 1971.

Introduction—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 in common use. In addition to these, human observation and judgment are often used to relate smoke to a variety of standards.

The purpose of this 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 black smoke.

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 the bibliography.

This document is divided into the following sections:

1. Definitions and Terminology
2. Procedures for Smoke Evaluation
   - 2.1 Visual
   - 2.2 Photographic
   - 2.3 Instrumental
3. Correlation of Steady-State Smoke Measurements
4. References

1. Definitions and Terminology—The following apply to definitions and/or terms as used in this report:

1.1 Diesel Smoke—White, blue, or black particles, including aerosols, suspended in the engine's gaseous exhaust stream which obscure, reflect, and/or refract light.

1.2 White and Blue Smoke—Composed of essentially colorless liquid particles (droplets) which reflect and refract the observed light. 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.

1.3 Black Smoke—Composed of carbon (soot) particles, usually less than 1 micron in size, which have escaped the engine's combustion process.

1.4 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).

1.5 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.

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

1.7 Opacity—That fraction of light transmitted from a source which is prevented from reaching the observer or instrument receiver. (Opacity = 1—transmittance.)

1.8 Transmittance—That fraction of light transmitted from a source, through a smoke-obscured path, which reaches the observer or instrument receiver. (Transmittance = 1—opacity.)

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

$$\text{Opacity} = 1 - e^{-KL}$$

where: e = base of natural logarithms
K = attenuation (or extinction) coefficient
L = path length through the smoke, in

2. Procedures for Smoke Evaluation

2.1 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 percieved 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-1960's, jointly by the U.S. Public Health Service and the Edison Electric Institute (4)[1]. 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 on one day and accepted on another, or 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."

2.1.1 Ringelmann Rating—The standard for this method was published as U. S. Bureau of Mines Chart No. 917-891 (1). See Fig. 1. This chart consists of white cards ruled with black cross-lines to approximate various smoke densities. A card in which 20% of the area is black is the standard termed No. 1 Ringelmann, the standard for No. 2 Ringelmann is 40% black lines, No. 3 is 60%, and No. 4 is 80%. It is assumed that 0 is completely white, and No. 5 completely black. Pocket-sized adaptations of the original Ringelmann charts are available. An example is shown in Fig. 2. The observer looks at the smoke plume through the center hole and compares his perception of its grayness with the five standards arranged around the hole. If, for example, the observer judged that the smoke opacity corresponded to the 20% standard, the smoke would be rated as "No. 1 Ringelmann."

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 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 (4).

2.1.2 Photographic Gray Scales—Standards with varying shades of blackness on a transparent film base have been developed and are available as guides for smoke evaluation. One now in use is referred to as the "U. S. Public Health Service Film Strip" and is available commercially.[2]

[1]Numbers in parentheses designate references at end of report.
[2]Environmental Research Corp., 3760 N. Dunlap St., St. Paul, Minnesota 55112 (specify Model 110 with calibration). See Refs. 2 and 3.

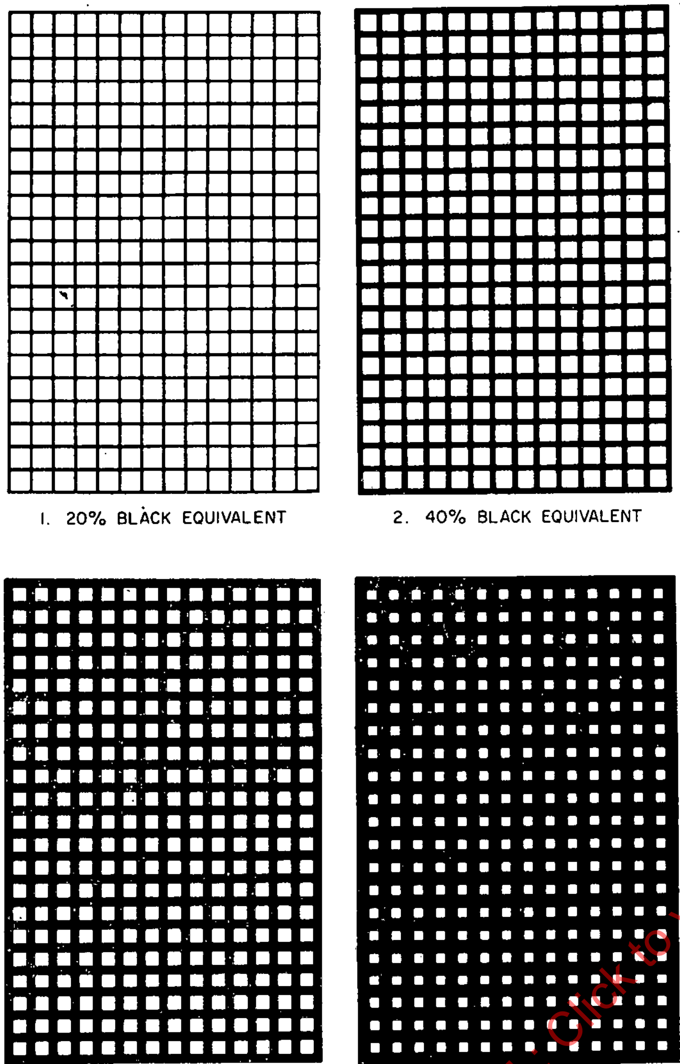

FIG. 1—RINGELMANN SCALE FOR GRADING DENSITY OF SMOKE

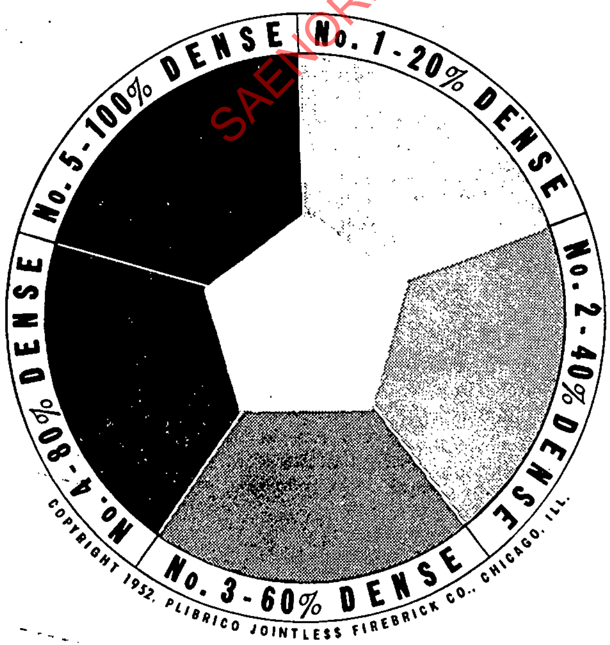

FIG. 2—RINGELMANN TYPE SMOKE CHART

An advantage of the photographically produced gray scale is that smoke and the standard are compared against similar backgrounds with similarly transmitted light. The photographic gray scale can be calibrated accurately with a precision densitometer, and its continuous gray segments are more easily compared to the smoke than are the cross-hatched Ringelmann standards.

2.1.3 Reference Smoke Generators—Efforts to obtain a frame of reference for visual methods of smoke evaluation have resulted in generators designed to produce controllable black or white smoke. These generators, usually of the oil burner type, utilize a device for air/fuel ratio control to regulate smoke density. Opacity is monitored by a light path photoelectric cell apparatus, and is commonly related to the Ringelmann five-step scale.

Observers use these generators to practice with visual smoke rating forms and to "recalibrate" themselves periodically, depending upon requirements. This procedure has been used for some time in Los Angeles, Calif. 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.

Recently, engine manufacturers have cooperated in the design and development of a diesel engine smoke generator 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.

The diesel engine smoke generator is a commercial diesel engine, modified to produce smoke by a suitable loading means and an air supply restriction device. Features include an engine inlet air restriction valve and an exhaust system surge chamber to minimize the puffy appearance of smoke at low engine speeds and high inlet restriction. The final 3 ft of exhaust pipe can be changed to demonstrate the effect of pipe diameter on opacimeter readings and plume appearance. Smoke of 2-80% opacity can be generated by adjusting engine speed, loading, and inlet restriction. Engine acceleration transient smoke can also be produced by the generator.

2.2 Photographic Methods—Between 1965 and 1967, an SAE Task Force (5) actively sought to establish an acceptable procedure for the measurement and documentation of diesel smoke using photographic techniques. Early in 1967, the Task Force reported to its parent committee, the Diesel Smoke Measurement Subcommittee of the SAE Truck and Bus Technical Committee, 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 or projected image with an apparent smoke density 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 measurement technique.

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

Opacimeter, Full-Flow Type—Measures opacity of the full smoke plume.

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.

Filtering Systems—Smoke soot particles are collected on a filter paper 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.

2.3.1 Opacimeter, Full-Flow Type (6)

2.3.1.1 *Introduction*—Fig. 3 shows the USPHS Smokemeter, developed by the U. S. Public Health Service for measuring diesel smoke. The light source and photocell are located on opposite sides of the

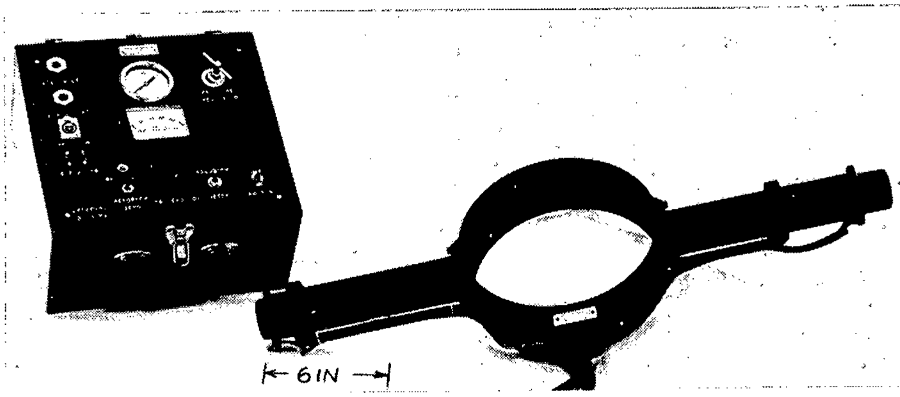

FIG. 3—OPACIMETER, FULL-FLOW TYPE

smoke plume, a few inches from the open end of the exhaust pipe (Fig. 4). 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 0-100% 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 opacity. Calibration between 0 and 100% can be established with neutral density filters which should be calibrated against NBS standards. The instrument system is sensitive to smoke density and length of path (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 difference may be calculated by using the Beer-Lambert Law.

At this writing, several in-line full-flow opacimeters are under development. Successful completion would provide a useful alternative to the present requirement of making measurements at the stack outlet.

2.3.1.2 *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:

General—Shock mount the photocell, solder all electrical connections, strengthen mechanical parts, and use a frosted lamp to minimize the effect of filament vibration.

Power Supply—Inverters, gasoline engine generators, or batteries may

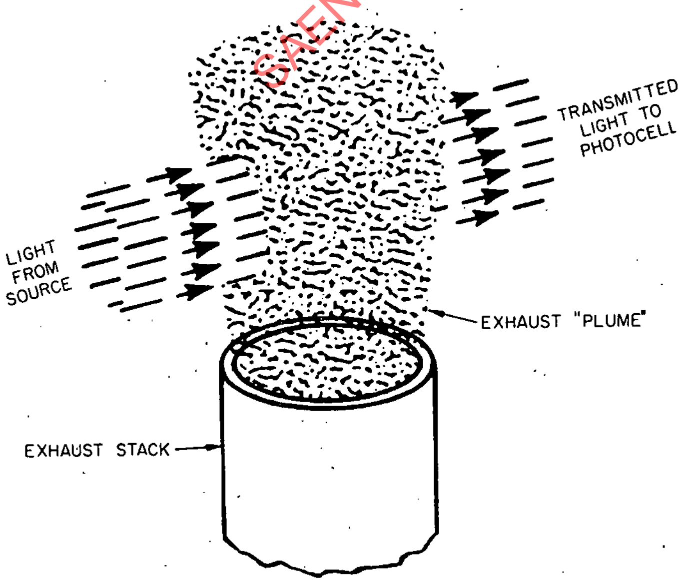

FIG. 4—METHOD OF OPERATION OF FULL-FLOW TYPE OPACIMETER

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.

Air Supply—Bottled nitrogen and vehicle brake air supply, properly filtered and dried, may be used.

(b) The compressed air supply must be free of oil, water, and dirt, any of which may obscure light and introduce error in the readings.

(c) Chart recorder response characteristics can affect the reading obtained. The Federal Register (6) 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 or an oscilloscope), the smoke puffs from individual cylinders of a multicylinder engine may be observed.

(d) 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 system should not influence the shape of the exhaust plume. Exhaust noise and room ventilation also must be considered when testing indoors.

Correlations presented in this report are based on black smoke, but the meter is useful for white smoke measurement in laboratory engine development programs.

2.3.2 OPACIMETER, SAMPLING TYPE

2.3.2.1 *Introduction*—Fig. 5 shows the B. P. Hartridge smokemeter, an example of this type.

Fig. 6 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 measurement 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 by the time required to fill the sampling tube (transport time approximately 0.2-0.6 s) and by the length of tube which serves to integrate the sample. The unit is battery powered.

2.3.2.2 *General*—The photocell used is sensitive to heat; therefore, cooling of the exhaust sample is usually required. Also, 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 exists, an impact sampling probe at the stack outlet may be used. A pressure relief valve and temperature gage are built into the instrument for flow regulation and temperature indication. Exhaust temperature and pressure at the instrument must be within the limits specified for the instrument before the readings are valid. Transient smoke measurements with this type of instrument are not recommended. Isokinetic sampling probes are suggested.

2.3.2.3 *Operating Precautions*

(a) Hardware for cooling the exhaust sample is not supplied with the basic B. P. Hartridge instrument. However, cooling is necessary

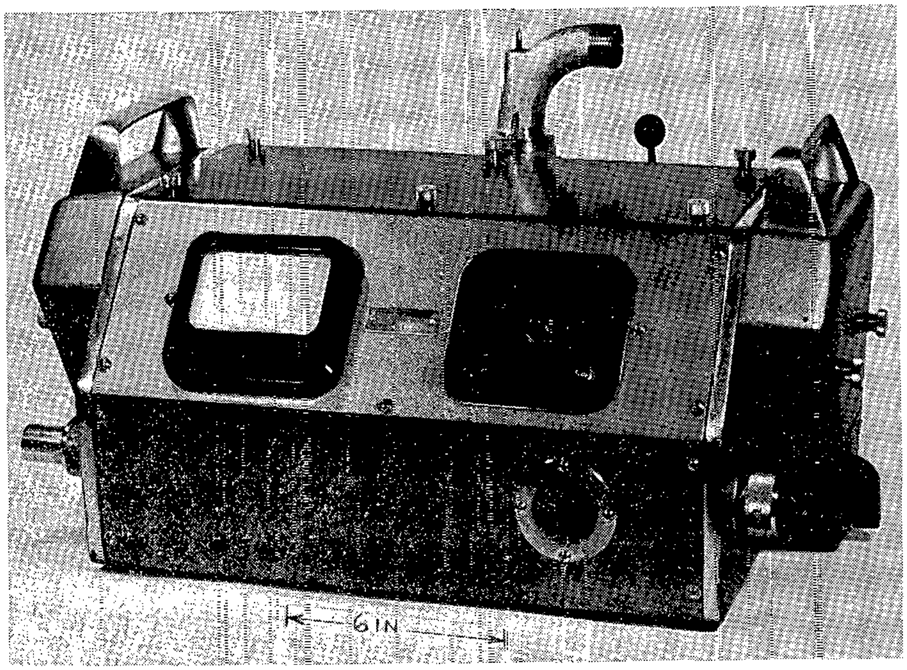

FIG. 5—OPACIMETER, SAMPLING TYPE SMOKEMETER

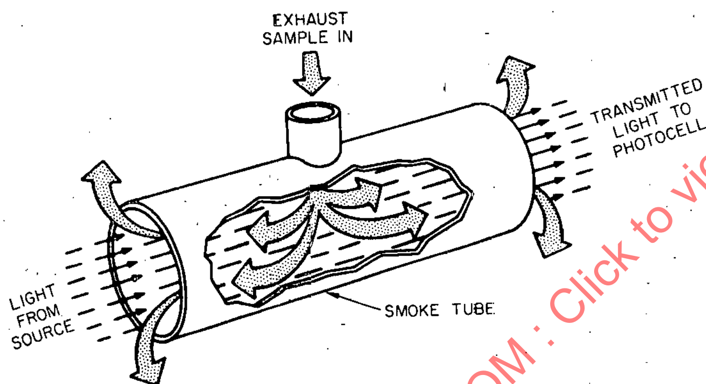

FIG. 6—METHOD OF OPERATION OF SAMPLING TYPE OPACIMETER

before the gases are allowed to pass through the plastic hose or to reach the photocell. This can be accomplished with commercially available air-to-water heat exchangers. The choice here depends upon the test setup. An air-to-air exchanger may be convenient where a storage battery can be used to power a fan for aircooling. Water-to-air coolers may be more convenient for laboratory testing. The instrument may be used without external cooling of the sample, but only for very short sampling periods. When used this way, 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. Extreme care must be exercised in this mode of operation because diesel exhaust will often exceed 1000 F on a loaded engine.

(b) Outdoor operation 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.

2.3.3 FILTERING SYSTEMS

2.3.3.1 *Bosch Spotmeter*

2.3.3.1.1 Introduction—An example of this type is the portable Bosch "Spot" smokemeter as shown in Fig. 7. A spring-operated sampling pump pulls a fixed volume (⅓ l) of exhaust gas from the exhaust stream through a controlled density paper filter disc. Soot from the sample is deposited on the filter disc, causing it to darken in relation to the exhaust gas soot content (density). A separate, battery-powered photoelectric device measures the light reflected from the darkened filter. Readout is by a milliammeter calibrated in 0-10 deg of darkening. Fig. 8 shows the operating principle of the photoelectric evaluation system. Calibration is accomplished with a calibrated, perforated grid (supplied with the instrument), which corresponds to a 5.0 Bosch reading.

Variations of this type of instrument include a filter system with a roll of filter paper instead of individual discs and a remote release system.

2.3.3.1.2 Operation Precautions—Some precautions and techniques are suggested:

(a) Engine vibrations may loosen the smoke probe shield. This should be checked frequently whenever vibration is encountered.

(b) 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.

(c) Locate sampling tube so that water cannot drain down into the sampling pump. Sampling location should be 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.

(d) At least two samples should be taken after purging the collection tube of accumulated soot. Purging is done by depressing the plunger to the "ready" position without a disc in place. Back-flushing with shop air will improve results during heavy smoke operation.

(e) Frequently check plunger travel time and clean the sampling pump when sluggish. Periodically check the sampling pump and hose for leaks.

(f) This meter is intended for measurement of black smoke and should not be used for white or blue smoke.

(g) Sampling under transient conditions is not recommended because of transport time lag and integration of the sample on the filter.

2.3.3.2 *Direct Soot Measurement*—Diesel smoke of the black variety can be measured and described by determining the mass of particulate soot per unit volume of exhaust gas. In general, the procedure is to pass a measured amount of exhaust gas through a nearly "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