INTERNATIONAL

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Standard Test Method for Determining the Opacity of a Plume in the Outdoor Ambient Atmosphere[1]

This standard is issued under the fixed designation D7520; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes the procedures to determine the opacity of a plume, using digital imagery and associated hardware and software. The aforementioned plume is caused by particulate matter emitted from a stationary point source in the outdoor ambient environment.

1.2 The opacity of emissions is determined by the application of a Digital Camera Opacity Technique (DCOT) that consists of a Digital Still Camera, Analysis Software, and the Output Function's content to obtain and interpret digital images to determine and report plume opacity.

1.3 This method is suitable to determine the opacity of plumes from zero (0) percent to one hundred (100) percent.

1.4 Conditions that shall be considered when using this method to obtain the digital image of the plume include the plume's background, the existence of condensed water in the plume, orientation of the Digital Still Camera to the plume and the sun (see Section 8).

1.5 This standard describes the procedures to certify the DCOT, hardware, software, and method to determine the opacity of the plumes.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

2.2 *U.S. Environmental Protection Agency (USEPA) Document:*[3]

USEPA Method 9 Visual Determination of the Opacity of Emissions from Stationary Sources, 40 CFR, Part 60, Appendix A-4

2.3 *Institute of Electrical and Electronics Engineers (IEEE) Document:*[4]

IEEE 12207-2008 Systems and Software Engineering—Software Life Cycle Processes (ISO/IEC 12207:2008(E)), Edition: 2nd, Institute of Electrical and Electronics Engineers, 01-Feb-2008, 138 pages, ISBN: 9780738156637

2.4 *Japanese Electronic and Information Technology Industries Association (JEITA) Document:*[5]

Exchangeable Image File Format (EXIF) for Digital Still Cameras Joint Photographic Experts Group: JPEG file format version 2.21, JEITA CP-3451-1 (English version) dated 2003-09

2.5 *International Organization for Standardization (ISO) Standard:*[6]

ISO 9001:2000(s) Quality Management Systems – Requirements

[1] This test method is under the jurisdiction of ASTM Committee D22 on Air Quality and is the direct responsibility of Subcommittee D22.03 on Ambient Atmospheres and Source Emissions.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from United State Environmental Protection Agency (USEPA), Ariel Rios Bldg, 1200 Pennsylvania Ave., NW, Washington, DC 20460, http://www.epa.org.

[4] Available from Institute of Electrical and Electronics Engineers, Inc., (IEEE), 1828 L St., NW, Suite 1202, Washington, DC 20036-5104, http://www.ieee.org.

[5] Available from http://www.jeita.or.jp/english/standard/list/list.asp?cateid=1&subcateid=4.

[6] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology D1356.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *analysis software*—software that when combined with a defined operating environment: (*a*) inputs images captured by the Digital Still Camera image capture devices; (*b*) produces opacity measurements from the combination of human interaction, open or proprietary calculations and algorithms, and image content viewing; (*c*) and then outputs said opacity measurement along with Analysis Software's configuration, image source documentation and other environmental parameters.

3.2.2 *certified*—for the purpose of this standard, certified refers to achieving or excelling the requirements described in this method.

3.2.3 *DCOT certification package*—for the purpose of this standard, certification package refers to 300 images (150 white smoke and 150 black smoke) captured against at least two different backgrounds.

3.2.4 *DCOT operator*—refers to the human operating the DCOT system who records the digital still images with the Digital Still Camera and then determines plume opacity with the Analysis Software.

3.2.5 *Digital Still Camera*—an image capture device used to collect store and forward digital still images to the Analysis Software for analysis as defined by the DCOT vendor's certification documentation.

3.2.6 *image transfer file*—an electronic file that contains the image captured by the Digital Still Camera and its associated environment documentation that is consistent with EXIF 2.1 JPG (or higher) format and is input to the Analysis Software; all of the digital images obtained by a DCOT system shall be reviewed by a qualified human DCOT operator to assess if the digital images are acceptable (for example, no obvious errors in the digital images).

3.2.7 *opacity*—measurement of the degree to which particulate emissions reduce the intensity of transmitted photopic light and obscure the view of an object through an effluent gas stream of a given path length in ambient air.

3.2.8 *opacity source*—any source that produces emissions that are visible to the human eye.

3.2.9 *output function*—human readable information documenting the image being analyzed and configuration of the Analysis Software used, the opacity measurement and the other required environment variables defined (for example, view angle, wind direction).

3.2.10 *run*—for the purpose of this standard, run or smoke school run refers to 50 consecutive images (25 white and 25 black); smoke schools identify Runs with a number (normally 1–10), a date, and a location; smoke schools may allow certification between numbered runs (that is, black smoke from Run 1, and white smoke from Run 2.)

4. Summary of Test Method

4.1 A Digital Still Camera is used to capture a set of digital images of a plume against a contrasting background. Each image is analyzed with software that determines plume opacity by comparing a user defined portion of the plume image where opacity is being measured in comparison to the background providing the contrasting values. The Analysis Software is used to average the opacities from the series of digital images taken of the plume over a fixed period of time. The software is also used to archive the image set utilized for each opacity determination including the portion of each image selected by the operator.

4.2 The following conditions must be followed to make a valid opacity determination:

4.2.1 The image must be captured in a JPEG format that adheres to the EXIF 2.1 (or higher) standard.

4.2.2 The image must be captured with the sun located behind the Digital Still Camera and within a 140° sector directly behind the Digital Still Camera (see Table 1 for schematic).

4.2.3 The image must be captured perpendicular to the direction of plume travel.

4.2.4 The ambient light must be sufficient to show a clear contrast between the plume and its background.

4.2.5 The portion of the plume selected for opacity determination shall not contain condensed water vapor.

4.2.6 The selected portions of each image representing the visible plume and the uniform background must contrast sufficiently for the software to differentiate between the plume and its background.

4.2.7 The portion of the plume selected for opacity determination shall represent the part of the plume with the highest apparent opacity, excluding water vapor, as determined by the DCOT operator.

4.2.8 The area of the digital image to be analyzed for opacity shall be centered in the digital image when taking the photograph.

4.2.9 Each DCOT vendor shall provide training for operators of their DCOT system. The training shall include the content of the "Principles of Visual Emissions Measurements and Procedures to Evaluate those Emissions Using the Digital Camera Optical Technique (DCOT)" (Annex A1) and a description of how to operate that specific DCOT system that passed smoke school.

5. Significance and Use

5.1 Air permits from regulatory agencies often require measurements of opacity from stationary air pollution point sources in the outdoor ambient environment. Opacity has been visually measured by certified smoke readers in accordance

TABLE 1 Example of Field Data Record when Determining Plume Opacity with DCOT

Company name:

Company location:

Test Identification No.:

Date:

Type of facility:

Process unit:

Operating capacity or mode for process:

Control device:

Operational status of control device:

Height of emission point and estimation method:

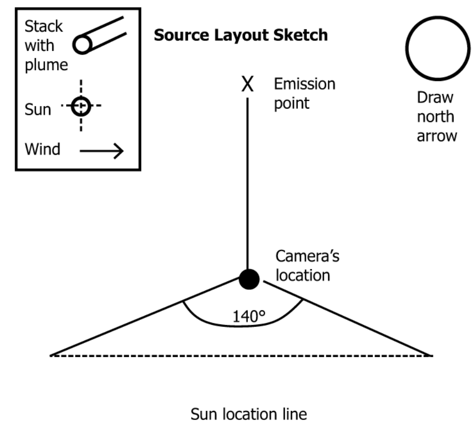
Operator name:

Operator affiliation:

DCOT certification date:

DCOT certified by:

Camera's manufacturer, model, and serial number:



	Initial	Final
CLOCK TIME		
CAMERA LOCATION		
Distance to discharge		
Vertical angle of emission point to camera		
Angle of sun to back of camera		
Height of emission point relative to camera		
ENVIRONMENTAL CONDITIONS		
Background of plume		
Wind direction		
Wind speed		
Ambient temperature		
Relative humidity		
Sky condition (for example, clear, partially cloudy, overcast)		
PLUME DESCRIPTION		
Color		
Distance between discharge and location where opacity is determined		
NUMBER CAPTURED IMAGES		
ADDITIONAL INFORMATION		

Operator signature: ______________________________ Date: ____________

with USEPA (USEPA Method 9). DCOT is also a method to determine plume opacity in the outdoor ambient environment.

5.2 The concept of DCOT was based on previous method development using Digital Still Cameras and field testing of those methods.[7,8] The purpose of this standard is to set a minimum level of performance for products that use DCOT to determine plume opacity in ambient environments.

6. Interferences

6.1 *Contrast*—As the contrast between the color of the plume and the background decreases, the observed opacity decreases. To achieve maximum opacity, the opacity shall be measured at a point where the maximum contrast exists between the plume and the background.

6.2 *Luminescence*—Low light levels adversely impact the determination of plume opacity. Adequate natural light must be available to illuminate the plume and background during the

[7] Du, K., Rood, M. J., Kim, B. J., Kemme, M. R., Franek, B. J., and Mattison, K., Quantification of Plume Opacity by Digital Photography, *Environmental Science and Technology*, Vol 41, No. 3, DOI: 10.1021/es061277n, 2007a, pp. 928–935.

[8] Du, K., Rood, M. J., Kim, B. J., Kemme, M. R., Franek, B. J., Mattison, K., and Cook, J., Digital Optical Method to Quantify the Visual Opacity of Plumes in the Field, *Journal of the Air and Waste Management Association*, Vol 57, DOI:10.3155/1047-3289.57.7.836, 2007b, pp. 836–844.

period the images are captured. This method shall only be used during daytime conditions.

6.3 *Steam Plumes*—Steam plumes (or condensed water vapor) cause significant errors in measuring opacity, and occur in two distinct modes as either attached plumes or detached plumes.[9] When either condition is noted to exist, the camera operator must record sufficient images to document the type of plume observed and the relative position of the exhaust stack with relationship to the point the opacity measurement is made.

6.3.1 *Attached Steam Plumes*—When condensed water vapor is present within the plume as it emerges from the emission outlet, opacity images shall be made beyond the point in the plume at which condensed water vapor is no longer visible. The operator shall record the approximate distance from the emission outlet to the point in the plume at which the images are made (Table 1).

6.3.2 *Detached Steam Plume*—When water vapor in the plume condenses and becomes visible at a distinct distance from the emission outlet, the opacity of emissions shall be evaluated at the emission outlet prior to the condensation of water vapor and the formation of the steam plume.

6.4 *Angle of View*—The position of the camera operator with respect to the smoke plume and sun will impact the perceived contrast between the smoke plume and the background. Changes in apparent contrast will impact the measurement of opacity using this technique and must be minimized by following the procedures specified in Section 8 of this method.

6.5 *Slant-Angle*—The path length of the plume is lengthened when a Digital Still Camera is too close to a stack. The plume shall be observed at least three stack heights away, where the slant-angle is 18° or less to reduce the effect of slant angle on the perceived opacity of the plume.

7. System Description

7.1 The DCOT system is formulated into three distinct and severable components: *(1)* Digital Still Camera, *(2)* Analysis Software and its associated computing platform, and *(3)* the Output Function. This section describes each of the components and the dependency each component has to the others.

7.1.1 The first component of the system is the Digital Still Camera. The Digital Still Camera's sole purpose with respect to the DCOT system is the acquisition of images and documentation of the pictorially represented emission source. All manufacturers of a Digital Still Camera used with the DCOT system shall meet ISO 9001 Quality Standards. The DCOT operator shall use the Digital Still Camera in accordance with the certification documentation of the DCOT, for example, camera settings matching the certification documentation of the DCOT. The Analysis Software shall verify that such conditions were used when obtaining the digital images. The Analysis Software shall define the areas to determine plume opacity and the acceptable size of areas used to determine plume opacity. The entire digital image shall remain in its native state. The Digital Still Camera must be capable of generating EXIF 2.1 JPG (or higher) formatted output files (JEMA EXIF 2.1 JPG, 1995) and the Analysis Software shall stipulate the required values of the EXIF 2.1 JPG (or higher) file as defined in its certification documentation as described in A2.1. The Digital Still Camera performs the image acquisition function and thus images must be captured in accordance with the procedures described in Section 8 to ensure that interferences are reduced as discussed in Section 6. Once the images have been captured and stored into the resulting EXIF 2.1 JPG (or higher) file per the minimum EXIF 2.1 JPG (or higher) data requirements in Annex A2 of this standard the image capture component is complete and the Analysis Software takes over. The Digital Still Camera is dependent on the minimum image requirements of the associated Analysis Software and thus must conform to the requirements for image capture as dictated by the Analysis Software component.

7.1.2 The second component of the DCOT is the Analysis Software which reads the images captured by the Digital Still Camera, performs analysis of the image and calculates the opacity level of the pictorially represented emission from the Digital Still Camera. Analysis Software modifications are subject to procedures established in Annex A3. The Analysis Software portion of the DCOT enforces the specific requirements of the Digital Still Camera (that is, JPEG 2.1 output, or higher) and the minimum requirements of the system to support required output capabilities (that is, compliant with Method 9 and certification documentation (IEEE 12207-2008)). The configuration documentation describing the Analysis Software must include a listing of all non-proprietary components of the software, such as: *(1)* the required hardware platform (that is, processors supported), *(2)* basic input output system (BIOS) supported, *(3)* storage media required and supported, *(4)* video drivers and Dynamic Link Libraries (DLLs) required and supported, *(5)* visual display requirements, (for example, VGA, SVGA), and *(6)* image viewers required and supported (for example, Internet Explorer 6.1, Microsoft Picture Manager 2.1). The configuration of the Analysis Software must also include the source version numbering definition, and the version control plan for the proprietary components of the Analysis Software, such as required by IEEE 12207. The Analysis Software shall be locally hosted on personal computing platforms, mobile devices and/or network hosted. The certification documentation defines the Analysis Software and its host platform environment under which certification of this standard was achieved.

7.1.3 The third and final component of the DCOT is the Output Function. The Output Function serves as the audit capability for the DCOT as well as the formal reporting of the output of the DCOT. Each DCOT shall establish its own representation of output as long as the minimum set of information that is described in Section 8 and A2.1 is included in the Output Function file. The minimum required content from the header of the EXIF 2.1 JPG (or higher) file is described in Annex A2. Further the output must contain the version of the Analysis Software and the configuration of prerequisite components used in the determination of the opacity of the image and/or image set being analyzed.

[9] Water droplets in steam plumes will scatter light resulting in increased plume opacity until the water evaporates, and shall not be included in the determination of opacity.

7.1.4 Each combination of the Digital Still Camera make and model number, Analysis Software, and Output Function shall determine a specified DCOT configuration for testing and possible certification by this ASTM method. The DCOT is certified to this standard as a single entity with requisite definitions of the components embedded in the certification documentation. For instance a single configuration of the Analysis Software and Output Function meets this requirement with multiple Digital Still Cameras with the same make and model number and a single Digital Still Camera make and model number is certifiable to this standard to operate with multiple specified Analysis Software and Output components.

8. Procedures

8.1 The DCOT operator must be knowledgeable about observing plumes to determine their opacity in accordance with "Principles of Visual Emissions Measurements and Procedures to Evaluate those Emissions Using Digital Camera Optical Technique (DCOT)" (Annex A1). The DCOT operator shall use the following procedures for determining the opacity of emissions in the ambient environment. All equipment shall be maintained in accordance with the manufacturer's specifications.

8.2 The Digital Still Camera of the certified DCOT shall be held as steady as possible or be tripod mounted at a distance sufficient to provide a clear view of the plume with the sun oriented in the 140° sector behind the Digital Still Camera's line of sight and toward the plume (Table 1). Consistent with maintaining the above requirement, the Digital Still Camera shall, as much as possible, capture digital images from a position such that the Digital Still Camera's line of sight is perpendicular to the plume's direction and, when photographing opacity of emissions from rectangular outlets (for example, roof monitors, open baghouses, noncircular stacks), approximately perpendicular to the longer axis of the outlet. The Digital Still Camera's line of sight must be such that any plume shall be isolated from its background and analyzed independent of other sources, and in any case the Digital Still Camera's line of sight shall be perpendicular to the longer axis of such a set of multiple stacks (for example, stub stacks on baghouses). The relative areas of the plume and its background in the digital image are dependent on the software used and will be described with training associated with the software that is used to analyze the digital images. The observation shall be restarted at a time when the conditions are appropriate to restart the observation if ambient conditions change to inappropriate conditions during the observation (for example, change in wind direction causing the plume's path to change direction). Quality assurance of the camera shall occur by the human operator viewing the camera to visually assess the operating conditions of the camera.

8.3 The DCOT operator shall record at a minimum the name of the facility, emission location, facility type, operator's name and affiliation, the date of the field data record, and the Digital Still Camera's make, model and serial numbers (for example, Table 1). The time, estimated distance to the emission location, location of the Digital Still Camera with respect to the emission source and sun, approximate wind direction, estimated wind speed, description of the sky condition (presence and color of clouds), and plume background are recorded on a field data record at the time the Digital Still Camera captures the images to be used by the Analysis Software to determine opacity.

8.4 A minimum of 24 consecutive opacity images shall be taken at 15-s intervals. These 24 images constitute a record set. Each image taken shall be deemed to represent the average opacity of emissions for a 15-s period.

8.5 Opacity shall be determined as an average of 24 consecutive images recorded at 15-s intervals. Divide the recorded images into sets of 24 consecutive images. A set is composed of any 24 consecutive images with the opacity values from each digital image rounded to the closest 5 %. Sets need not be consecutive in time and in no case shall two sets overlap. For each set of 24 images, calculate the average by summing the opacity of the 24 observations and dividing this sum by 24. If an applicable standard specifies an averaging time requiring other than 24 images, calculate the average for all images made during the specified time period.

9. Certification of DCOT and DCOT Operator

9.1 *Certification Requirements of DCOT*—To be certified to this standard as a qualified DCOT, the specified DCOT must be tested and demonstrate the ability to assign opacity readings in 5 % increments to 25 different black plumes and 25 different white plumes, with an error not to exceed 15 % opacity on any one reading and average error not to exceed 7.5 % opacity in each category. Specified DCOT configurations shall be tested in accordance with the procedures described in 9.2. Smoke generators used pursuant to 9.2 shall be equipped with a smoke meter which meets the requirements of A3.1. Valid certification for that DCOT will last for 3.5 years[10] for the documented DCOT configuration as described by the manufacturer, model name, and model number of the Digital Still Camera the version of the Analysis Software, and the Output Function. Re-certification to this standard is required if the documented configuration of the original DCOT is revised. Each DCOT shall provide a self-test facility upon startup. The self-test shall utilize existing certification data to ensure that no impacts to the configured DCOT have occurred due to operating system updates. The procedure shall utilize the same comparison methodology as the certification. For instance, if the DCOT identifies an area in the plume as compared to an area outside the plume (background) to derive opacity, the exact same areas/dimensions must be used for the self-test. If a different result on any reading is returned, a re-certification is required, or the OS update must be rolled back, restoring the DCOT configuration to a version consistent with what was certified.

9.2 *DCOT Certification Procedure*—The specific DCOT shall be certified to determine the opacity of plumes once it passes six runs of 50 plumes, in front of various backgrounds of color and contrast representing conditions anticipated during field use. The certification package must include at least two different backgrounds. Four (4) independent Analysis Operators must successfully apply the software to determine the

[10] http://olegkikin.com/shutterlife and http://www.weibull.com/hotwire/issue22/hottopics22.htm.

visible opacity of the 300 certification plumes within a six month period as described in 9.1. The DCOT must enforce the configuration settings of the Digital Still Camera per its certification requirement, for example, if auto focus is used in certification, auto focus must be enforced on all imagery processed by that certified DCOT. The DCOT must include in the certification documentation the results of all smoke school tests. Those results shall include whether the DCOT passed or failed the tests and for the time periods between and during the six successful smoke school tests. Each individual run consists of collecting images of a complete run of 50 plumes: 25 black plumes and 25 white plumes-generated by a calibrated smoke generator. Plumes within each set of 25 black and 25 white runs shall be presented in random order and distributed over the entire range of opacities (that is, 0 to 100 % opacity values for black and white plumes). The DCOT operator shall ensure the Digital Still Camera is set in accordance with DCOT certification documentation. The Analysis Software shall verify that such conditions were used when obtaining the digital images. The Analysis Software shall define the areas to determine plume opacity and the acceptable size of areas used to determine plume opacity. The entire digital image shall remain in its native state. The DCOT must capture the image of the measured plume and assign an opacity value to each along with the required environment information listed in Section 8 of this standard. At the completion of each run of 50 readings, the score of the DCOT is determined. If a DCOT fails to qualify, the complete run of 50 readings must be repeated in any retest. The smoke test shall be administered as part of a smoke school or training program.

9.3 *Certification of DCOT Operator*—The DCOT operator shall be certified to acquire digital images from the Digital Still Camera to determine plume opacity by meeting the requirements specified by the training course for the specified DCOT system. The operator will use and shall be knowledgeable of the content described in "Principles of Visual Emissions Measurements and Procedures to Evaluate those Emissions Using Digital Camera Optical Technique (DCOT)" as provided in Annex A1. The DCOT Operator shall be certified to perform analysis with the DCOT system by attending a smoke school, acquiring images, and successfully performing analysis on smoke school imagery with the DCOT system. The jurisdiction of the smoke school may conduct schools differently. The intent here is to have DCOT analyst candidates, under whatever prevailing weather conditions exist, successfully capture and analyze 25 white plumes and 25 black plumes in a "run" as defined by the jurisdiction and smoke school operator.

10. Precision and Bias

10.1 *General Considerations:*

10.1.1 The precision and bias of this test method has been evaluated by using the statistical procedures described in Practice E691 and the guidance provided by the ASTM "Blue Book."[11] The only tests available with an accepted reference value were Method 9 smoke school (smoke generator) comparison tests using a certified DCOT "DOCS II" using a Digital Still Camera, default auto focus settings, default auto exposure settings, image stabilization set off, flash set off, using optical zoom through the standard lens, with a resultant EXIF 2.1 JPG per the detailed values in A2.1. There were 57 full tests of 50 smoke plumes (25 black plumes and 25 white plumes) conducted at eleven different smoke school locations.

10.1.2 The level of opacity being generated by the smoke generator and being read by the DCOT affects the achievable precision of the measurement. Table 2 describes the 95 % repeatability and 95 % reproducibility for each opacity level during the smoke school tests.[12,13]

10.2 *Precision:*

10.2.1 The precision for DCOT was calculated at every 5 % interval of opacity because that is the procedure dictated by USEPA Method 9 and an operational constraint of smoke school operators. Further USEPA Method 9 dictates that only absolute error be used in determining the bias of the opacity reading, for example confidence intervals are not used in USEPA Method 9. ASTM standards typically follow Practice E691 in determining bias and requires a 2.8 multiplier on absolute error to determine the confidence interval of 95 %. It also makes sense that the absolute precision might be expected to vary based on opacity level. The database included 96 to 256 tests at each opacity level from eleven (11) smoke school runs. This precision statement may be updated with additional data prior to each reauthorization of the method. The precision, in terms of repeatability and reproducibility, of the smoke school tests are shown in Table 2.

TABLE 2 Repeatability and Reproducibility[A, B]

Opacity Level	Repeatability (r) Absolute Opacity, %	Reproducibility (R) Absolute Opacity, %
0	3	4
5	7	8
10	10	12
15	11	11
20	11	16
25	16	16
30	11	14
35	15	17
40	10	17
45	9	17
50	13	17
55	12	17
60	10	17
65	12	14
70	8	17
75	10	16
80	7	17
85	9	17
90	10	16
95	10	14
100	5	11

[A] Large uncertainties are the consequence of using Practice E691 to present repeatability and reproducibility. However, the raw datasets used to determine these values meet the requirements of Method 9 for individual and average opacity errors.

[B] Data utilized to create Precision and Bias tables came from images acquired under smoke school conditions.

[11] "Form and Style for ASTM Standards," March 2009.

[12] The 95 % repeatability and reproducibility were calculated using a coverage factor of 2.8 as prescribed by Practice E691 and the ASTM Blue Book.

[13] There are 21 opacity levels between 0 and 100 % opacity.

10.2.2 The repeatability and reproducibility values are in percent opacity absolute. For example, if 15 % opacity is presented by the smoke generator, then there is a 95 % probability that the DCOT will read between 26 % and 4 % opacity (15 % ± 11 %). As a point of clarification, the percent opacity absolute is the absolute opacity value. For example, the absolute opacity difference between 20 % opacity and 10 % opacity is 10 % opacity. It is critical to understand the USEPA, in support of Method 9, utilized average error over the spectrum of opacity (0 to 100), and segregated their data based on white or black smoke to report precision and bias type information. Consequently, to understand the method described herein as relates to Method 9, one would apply Precision and Bias calculations as performed in this method, per the ASTM Blue Book to Method 9 data. For instance, if the data supporting the USEPA method 9 reported an average error of 5 % for white smoke, apply 5 % equally across the spectrum of opacity (0 to 100). Thus there is a 95 % probability that the trained human reader would read between 29 % and 1 % opacity if presented a known opacity of 15 %.

10.3 *Bias:*

10.3.1 Bias is a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value. Variables such as the angle at which images of the plume are captured, portion of the plume analyzed, direction of plume travel versus angle of image captured, luminescence and color contrast between the plume and the background against which the plume is viewed exert an influence upon the appearance of the plume and affect the ability of the technology to assign accurate opacity values. Studies of the theory of plume opacity have demonstrated that a plume is most visible and presents the greatest apparent opacity when viewed against a contrasting background (USEPA Method 9). Accordingly, the opacity of a plume viewed under conditions where a contrasting background is present is assigned with the greatest degree of accuracy. DCOT's opacity results must document the bias variables in order to minimize their effects on the resulting opacity determination. Captured images must document the environment under which the image was captured to determine the applicability of the opacity measurement. Mandatory environment variables are described in Section 8 of this standard. DCOTs certified to this standard are instructed to round to the nearest 5 % increment. DCOTs report opacity in increments of 5 %.

TABLE 3 Bias

Opacity Level	Bias, % of reading
0	NA[A]
5	-7 %
10	0 %
15	0 %
20	0 %
25	-5 %
30	-4 %
35	-5 %
40	0 %
45	6 %
50	0 %
55	-3 %
60	-3 %
65	-5 %
70	0 %
75	-5 %
80	–1 %
85	–4 %
90	–3 %
95	0 %
100	NA[A]

[A] NA is utilized in Table 3 because 0-100 is the range of acceptable values. One cannot attain a number <0 for an opacity, nor can one attain an opacity of >100. As such the values for bias at 0 and 100 are not applicable.

10.3.2 Table 3 shows the bias associated with the smoke school data. As expected, the bias varied from opacity level to opacity level.

10.3.3 Bias was determined by comparing the mean difference between the readings and the smoke generator reference value. If the absolute value of the mean difference was greater than the 95 % confidence coefficient, then a bias was calculated by dividing the mean difference by the mean DCOT value. The database included 96 to 256 tests at each opacity level from eleven (11) smoke schools' runs.

11. Keywords

11.1 digital camera; digital image; digital still camera; opacity

ANNEXES

(Mandatory Information)

A1. PRINCIPLES OF VISUAL EMISSIONS MEASUREMENTS AND PROCEDURES TO EVALUATE THOSE EMISSIONS USING DIGITAL CAMERA OPTICAL TECHNIQUE (DCOT)

A1.1 Abstract

A1.1.1 This document was developed to provide background information pertaining to the principles of visual emission measurement, United States Environmental Protection Agency (USEPA) Reference Method 9 requirements, ASTM Standard Practice for Competence of Air Emission Testing Bodies, equipment needed to collect visual emission data for the Digital Camera Optical Technique (DCOT), documentation needed when measuring visual emissions with DCOT, and the certification and duration of certification of DCOT. DCOT was developed as a possible alternative to Method 9 and this document provides background information about Method 9 that is also applicable to DCOT.

A1.1.2 A note about terminology: the term "observer" is used in this document when referring to Method 9 to describe the person who is making a visual emission evaluation to determine plume opacity. However, "observer" is replaced with "Digital Still Camera" when referring to DCOT as the means to record digital still images that are then used to determine plume opacity. The term "operator" is used when referring to DCOT to describe the operation of the Digital Still Camera that obtains the digital still images and the collection of supporting documentation that are needed to provide a complete dataset for DCOT to determine plume opacity.

A1.1.3 An extensive amount of the information provided below is from the student manual for the "Visible Emission Evaluation Procedures Course," Air Pollution Training Institute (APTI) Course 325, Final Review Draft (January 1995). The principal author of the student manual is Thomas H. Rose with style and editing by Monica L. Loewy.

A1.2 Table of Contents

A1.3 List of Figures

A1.4 *Principles of Visual Emissions Measurement*—This section describes concepts related to opacity and discusses the scientific principles associated with measuring opacity and the practical application of those principles.

A1.4.1 *Ringelmann Method:*

A1.4.1.1 Evaluation of visible emissions evolved from a concept developed by Maximillian Ringelmann during the late 1800s. Ringelmann used a chart of calibrated black grids on a white background to measure dark or black smoke emissions from coal-fired boilers. The grids ranged from approximately

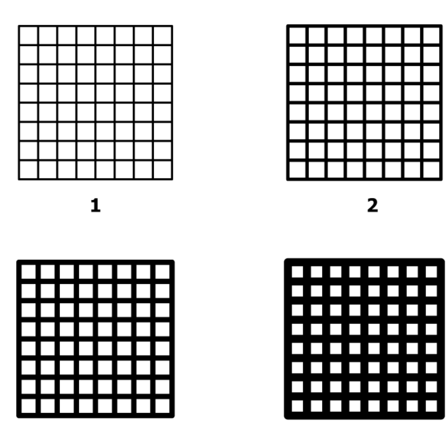


FIG. A1.1 Ringelmann Chart

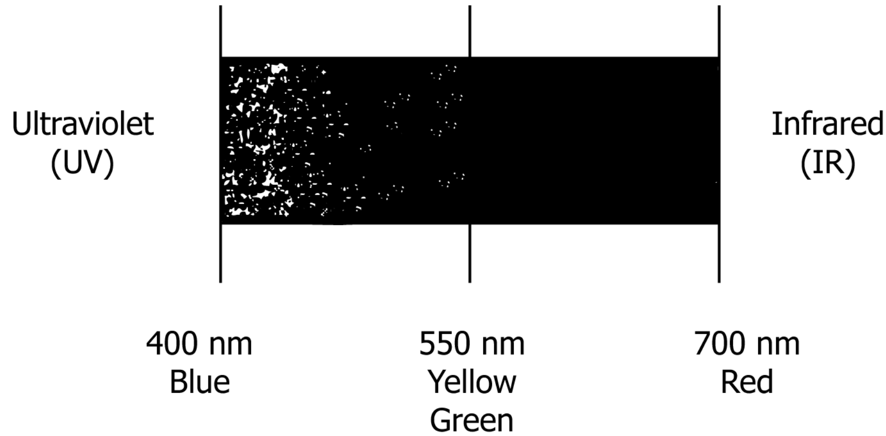


FIG. A1.2 Electromagnetic Spectrum

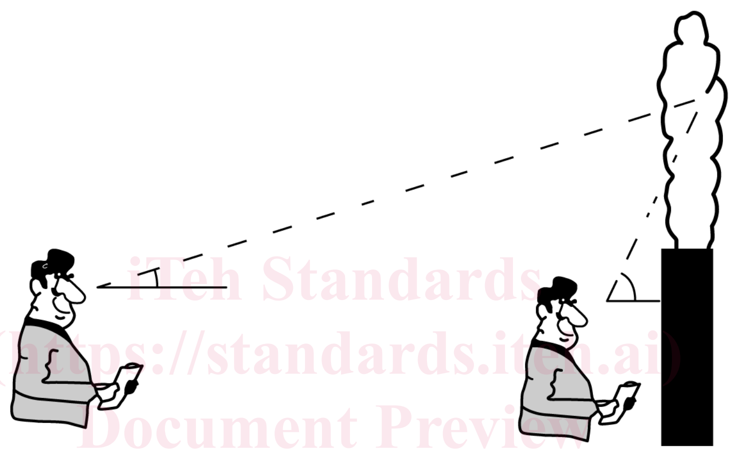


FIG. A1.3 Dependence of Slant Angle on Distance between the Observer and Plume

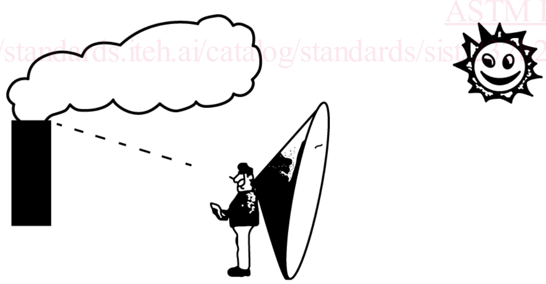


FIG. A1.4 Orientation of the Observer to the Plume and Sun

20 % ink coverage for a Ringelmann #1 through 100 % ink coverage, or solid black, for a Ringelmann #5 (Fig. A1.1). The observer then compared the shade of the smoke with the shade of the card.

A1.4.2 *Equivalent Opacity:*

A1.4.2.1 During the early 1950s, the Ringelmann concept was expanded to include colors of smoke other than black by introducing "equivalent opacity." Equivalent opacity is the opacity equivalent to the obscuring power of black smoke characterized by a specific Ringelmann grid. Thus, Ringelmann #1 was equivalent to 20 % opacity.

A1.4.2.2 United States Environmental Protection Agency (USEPA) discontinued using Ringelmann numbers with USEPA's Reference Method 9 procedures for New Source Performance Standards (NSPS). Although current procedures are based solely on opacity, some state regulations (notably California's) still specify the use of the Ringelmann Chart to evaluate black and gray plumes. The general trend, however, is toward reading all visible emissions in unit of percent opacity.

A1.4.3 *Opacity and Transmission of Light:*

A1.4.3.1 Plume opacity is defined as one of the following:

(1) The degree to which light transmission through the width of a plume is reduced.

(2) The degree to which the visibility of a background viewed through the diameter of a plume is obscured.

A1.4.3.2 When light strikes an object or substance, the light is attenuated by either absorption or scattering. The amount of light that is absorbed or scattered determines the opacity of the substance. Simply put, in the observation of a plume, opacity is the light obscuring power of the plume.

A1.4.3.3 In terms of physical optics, opacity is related to transmittance (I/I_o) through the plume. Percent opacity and percent transmittance always total 100 %. Percent opacity is defined by the following equation:

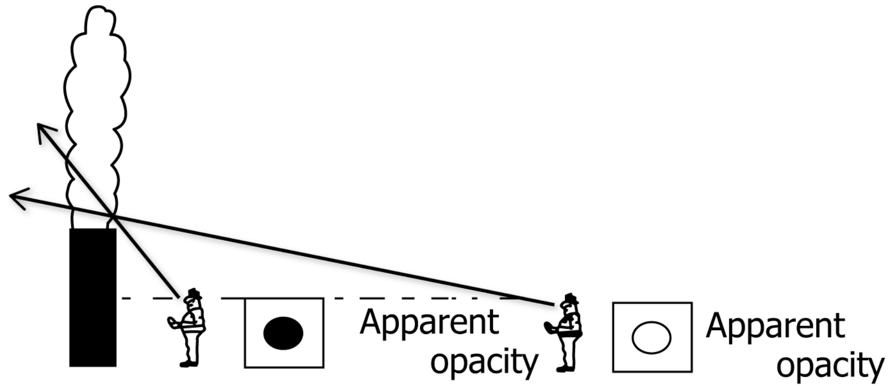


FIG. A1.5 Effect of Slant Angle on Path Length and Apparent Opacity

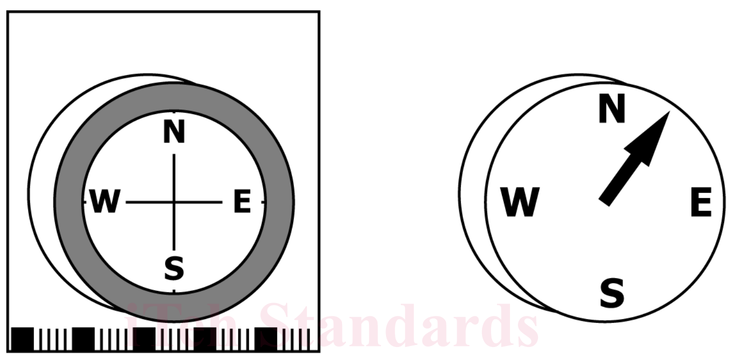


FIG. A1.6 Card-Type and Needle-Type Compasses

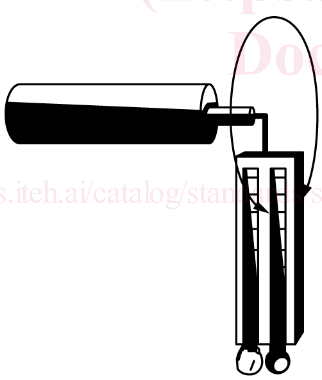


FIG. A1.7 Sling Psychrometer

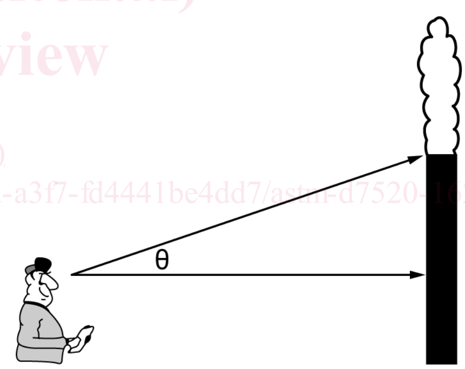


FIG. A1.8 Slant-Angle Determination

$$\text{Percent opacity} = (1 - I/I_o) \times 100 \qquad (A1.1)$$

where:

I = light flux leaving the plume along the same path, and
I_o = light flux entering the plume (incident light flux).

A1.4.3.4 Many factors influence plume opacity readings: particle number density, particle refractive index, particle size distribution, wavelength of light, plume color, plume background, plume width, path length of observation, distance and relative elevation of the observer to the stack's exit, sun angle relative to the observer and plume, and lighting conditions.

A1.4.4 *Light and Particles:*

A1.4.4.1 The wavelengths of visible light in the electromagnetic spectrum range from 400 nanometres (nm) for blue light to 700 nm for red light. Below 400 nm is the ultraviolet (UV) wavelength, and above 700 nm is the infrared (IR) wavelength (Fig. A1.2). Human vision peaks in the middle of the visible range, at 550 nm, a yellowish-green color. This color is seen the best, and not coincidentally, it is also the best background for light-colored plumes.

A1.4.4.2 Opacity is a function of the interaction between light over this visible spectrum and particles. This interaction is affected by properties of both the particles and the light that include:

(1) Number and size of the particles,
(2) Particle shape,
(3) Particle color,

(4) Index of refraction of the particles,
(5) Spectral characteristics of the light,
(6) Light direction, and
(7) Amount of light.

A1.4.4.3 When light is attenuated by an aerosol particle, one of two things can happen: the light can either be absorbed or scattered.

A1.4.5 *Absorption:*

A1.4.5.1 If a particle has any color or is black, it will absorb a certain amount of light as the light enters the particle. The energy of the light is converted to thermal energy (for example, heat) or chemical energy (for example, chemical reaction) in the particle.

A1.4.6 *Scattered Light:*

A1.4.6.1 Scattered light is re-directed from its original path of transmission to another direction. The primary light-scattering mechanisms for ambient aerosol particles are Rayleigh and Mie scattering.

A1.4.7 *Rayleigh Scattering:*

A1.4.7.1 When particle size is significantly smaller than the wavelength of light, the light is widely scattered. Rayleigh scattering is important for extremely small particles because they scatter much of the light away from the forward direction at large angles. Rayleigh scattering is responsible for the blue color of the sky: blue light is scattered out from the light coming directly from the sun. Extremely small particles cause a bluish plume even if the individual particles are actually colorless.

A1.4.8 *Mie Scattering:*

A1.4.8.1 Mie scattering occurs when particle diameter and the wavelength of light are approximately the same. Visible light that is scattered from particles with diameters less than 1 µm can be characterized by Mie scattering theory.

A1.4.9 *Particle Size:*

A1.4.9.1 Particle size plays a significant role in opacity given that particles decrease light transmission by both absorption and scattering. Particles with diameters approximately equal to the wavelength of visible light (400 nm to 700 nm) have the greatest scattering effect and cause the highest opacity.

A1.4.10 *Variables Influencing Opacity Observations:*

A1.4.10.1 The appearance of a plume as viewed by an observer depends on a number of variables, some of which are controllable in the field. Variables difficult to control in the field are luminous contrast and color contrast between the plume and the background against which the plume is viewed. These variables influence the appearance of a plume as viewed by an observer and can affect the ability of the observer to assign accurate opacity values to the plume. A plume is most visible and presents the greatest apparent opacity when it is viewed against a contrasting background.

A1.4.10.2 Color contrast is the difference in color between two objects. For instance, red and orange are different colors but the difference between them is not nearly as great as that between red and blue. If the plume color is identical to the background color, the visible emissions observer will have difficulty distinguishing between the plume and the background. To the degree possible, the observer should maximize the color contrast between the plume and the background to get the most accurate readings.

A1.4.10.3 Luminous contrast is the difference in light emanating from two objects, for example, a black plume against a light sky. Two objects that have the same color can show up against each other because of these differences in lighting levels. This effect is important in the case of forward scattering in which plumes become more luminous than their background. Luminous contrast is vital to a color-blind observer. Also, luminous contrast is the primary tool for observing a light-colored plume against a light-colored sky.

A1.4.10.4 When reading light-colored plumes, it is useful to have a patterned background as a target. The degree to which the pattern is obscured is another tool to assist in determining the opacity. Patterned backgrounds can include trees, buildings, towers, power poles, mountains, or even other stacks at the source.

A1.4.11 *Selecting the Background:*

A1.4.11.1 All the factors discussed above are important in selecting the proper background for an opacity determination.

A1.4.11.2 For black smoke, a light-colored background is best and light blue sky is excellent. Because the black smoke does not scatter the light, it is not necessary or desirable to use a textured or patterned background.

A1.4.11.3 For white smoke, a dark-colored background with texture or a pattern is best. The observer is often faced with only a blue-sky background because of stack height. Generally, the deeper the blue for the blue sky background, the more accurate are the observations.

A1.4.11.4 During all observations, it is important that the observer look through the plume toward its background and also at the background without the plume at a nearby location. The observer should compare the background appearances under both conditions and not focus only on the appearance of the background through the emissions. The observer should remember that the goal in determining opacity values is to determine how much the un-obscured background is changed by the emissions.

A1.5 Method 9 Requirements

A1.5.1 *Method 9:*

A1.5.1.1 USEPA Reference Method 9 (or Method 9) is the visible emissions inspection method most frequently used by visible emissions observers. It has been tested in the courts and in practice and has wide acceptance within the regulatory community. The purpose of this section is to describe the details of Method 9 as they are described in the method itself. It is important to know and understand the method to apply it. When USEPA promulgated Method 9, the text of the method was preceded by a preamble that explains USEPA's rationale in developing the method. The preamble also provides some historical perspective on the method:

"On June 29, 1973, the United States Court of Appeals for the District of Columbia remanded to USEPA the standard of performance for Portland cement plants (40 CFR 60.60 et seq.) promulgated by USEPA under section 111 of the Clean Air Act. (*Portland Cement Association v. Ruckelshaus. 486* F.2d 375