Designation: D7520 − 16

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 and health practices and determine the applicability of regulatory limitations prior to use.*

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:*

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[5]

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

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

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

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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.

interaction, open or proprietary calculations and algorithms, and image content viewing; (*c*) and then output 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 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.

[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.

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:

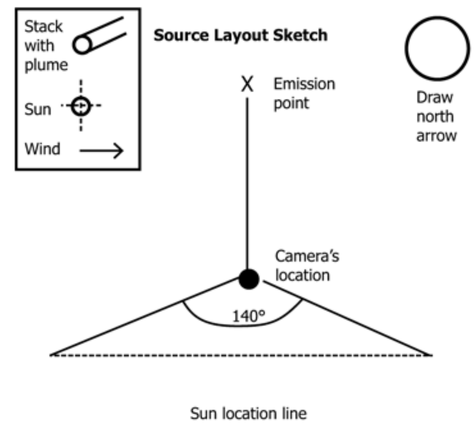
Operator name:

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: __________

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 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.

[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.

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.

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-second intervals. These 24 images constitute a record set. Each image taken shall be deemed to represent the average opacity of emissions for a 15-second period.

8.5 Opacity shall be determined as an average of 24 consecutive images recorded at 15-second 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 section 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 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

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

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]

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.

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.

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 (0-100), and segregated their data based on

[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.

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 (0-100). 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 %.

10.3.2 Table 3 shows the bias associate 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.

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.

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 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.

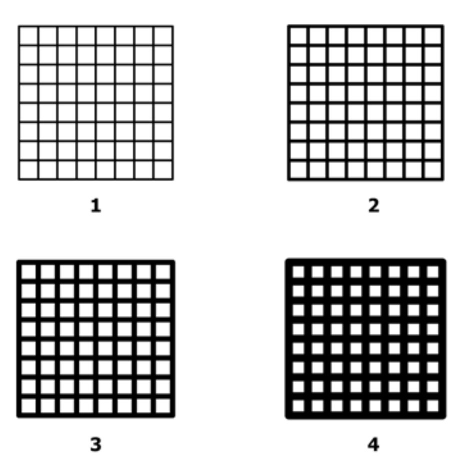


FIG. A1.1 Ringelmann Chart

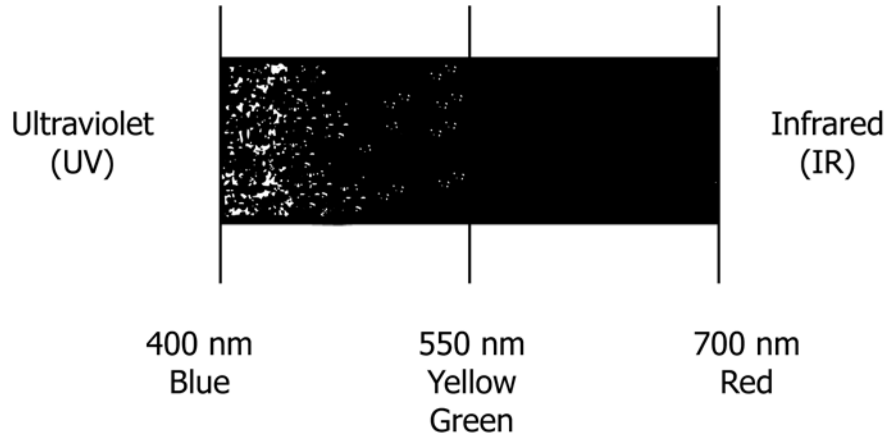


FIG. A1.2 Electromagnetic Spectrum

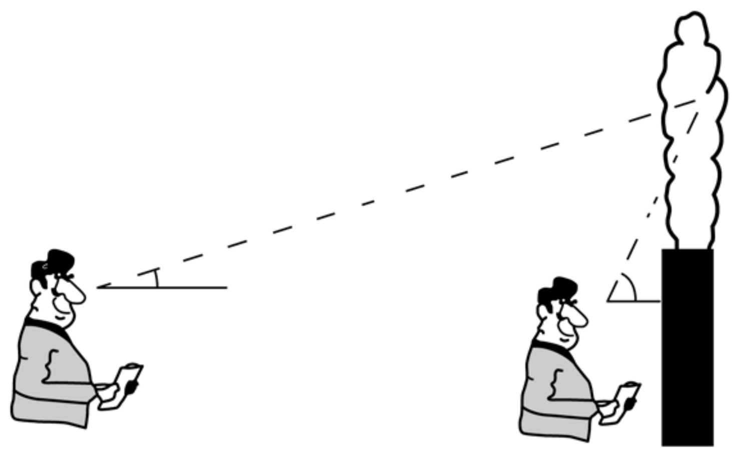


FIG. A1.3 Dependence of Slant Angle on Distance between the Observer and Plume

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

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:

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

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

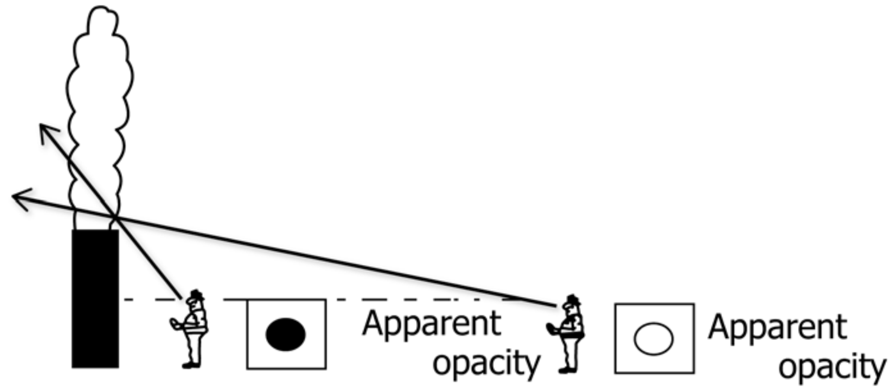


FIG. A1.5 Effect of Slant Angle on Path Length and Apparent Opacity

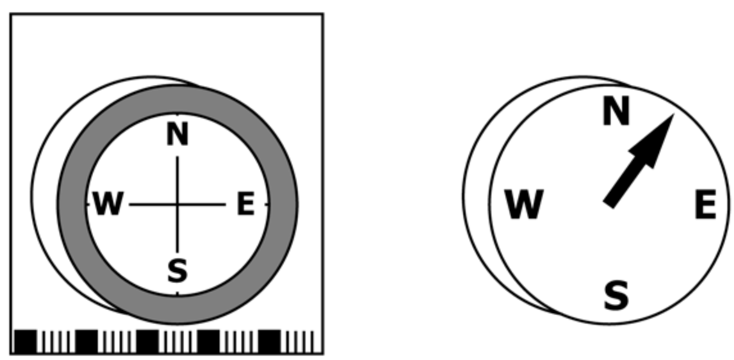


FIG. A1.6 Card-Type and Needle-Type Compasses

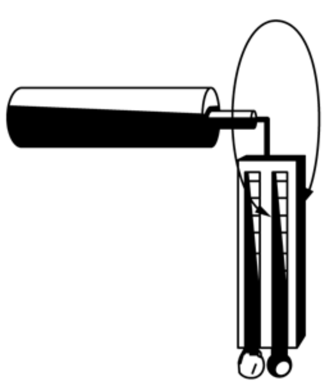


FIG. A1.7 Sling Psychrometer

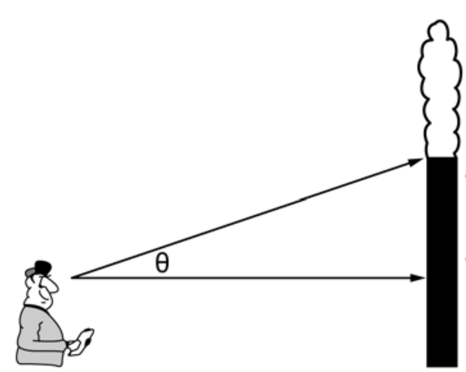


FIG. A1.8 Slant-Angle Determination

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 [1973].) In the remand, the court directed USEPA to reconsider, among other things, the use of the opacity standards."

A1.5.1.2 All other versions of Method 9 are based on the USEPA promulgation remanded in this historic case.

A1.5.2 *The Reference Method is one of Observation:*

A1.5.2.1 USEPA established that Method 9-type observations take precedence even when Transmissometers are used:

"USEPA will accept as probative evidence in certain situations and under certain conditions the results of continuous monitoring by transmissometer to determine whether a violation has in fact occurred."

A1.5.2.2 The revision makes clear that even in such situations the results of opacity readings by Method 9 remain presumptively valid and correct.

A1.5.2.3 Aerosols can form after the transmissometer within the stack or above the stack by gas-phase reactions, condensation, or accumulation. Consequently, the best measure of opacity at the stack exit is presumed to be the visible emissions readings obtained by applying Method 9.

A1.5.3 *Opacity Variances:*

A1.5.3.1 USEPA recognized that in some limited cases, opacity can be an unfair measure of emissions:

"The provisions in paragraph (e) provide a mechanism for an owner or operator to petition the Administrator to establish an opacity standard for an affected facility where such facility meets all applicable standards for which a performance test is conducted under 60.8 but fails to meet an applicable opacity standard. The intent of this provision is primarily applied to cases where a source installs a very large diameter stack that causes the opacity of the emissions to be greater than if a stack of the diameter ordinarily used in the industry were installed."

A1.5.3.2 The effect of stack diameter on opacity is not inconsequential. Transmission (and, consequently, opacity) is directly proportional to the square of the path length. A plume with an opacity value of 20 % will have an opacity value of 36 % if the stack diameter is doubled.

A1.5.4 *Changes in USEPA Procedures:*

A1.5.4.1 After a series of extensive field tests, USEPA determined that some revisions and clarifications in applying Method 9 were in order. In evaluating the accuracy of results from qualified observers following the newly revised Method 9 procedures, USEPA determined that observers trained and certified in accordance with the procedures prescribed under Method 9 are consistently able to read opacity with positive errors not exceeding 7.5 % based on single sets of an average of 24 readings.

A1.5.5 *Analysis of Error:*

A1.5.5.1 The preamble states:

"An introductory section was added. This included a discussion of the concept of visible emission reading and described the effect of variable viewing conditions. Information was also presented concerning the accuracy of the method, noting that the accuracy of the method must be taken into account when determining possible violations of applicable opacity standards."

A1.5.6 *Averaging was Introduced to Increase Accuracy:*

A1.5.6.1 At the time Method 9 was proposed, a commonly used standard technique for reducing data was to count the number of observations at or above the standard and to multiply by 15 seconds to determine the amount of violation time (15 seconds represents the lapse of time during an observation). This violation time was compared to the time exemption in the rule. At the time of the Portland cement remand, USEPA had not determined the accuracy of this approach. Consequently, USEPA modified the method to use an averaging approach to ensure the accuracy of the observations.

A1.5.6.2 The preamble states:

"Provisions were added which specify that the determination of opacity requires averaging 24 readings taken at 15-second intervals. The purpose for taking 24 readings is both to extend the averaging time over which the observations are made and to take sufficient readings to ensure acceptable accuracy."

A1.5.6.3 After taking an average of 20 or more values, statistical accuracy is not greatly enhanced by adding more data. Thus, 24 readings over a six-minute period produce a statistically significant average and demonstrate that the plume is not a momentary puff of excess emissions.

A1.5.6.4 This change of method indirectly had an immense impact on the states that were using the time-aggregation technique. In accordance with regulatory provisions later promulgated in CFR part 52.12.(c), federal enforcement required states that do not clearly specify a method in their State Implementation Plans (SIPS) to use averaging as the data-reduction technique.

A1.5.7 *Sun Position became an Issue:*

A1.5.7.1 The preamble states:

"More specific criteria concerning observer position with respect to the sun were added. Specifically, the sun must be within a 140° sector to the observer's back."

A1.5.7.2 Of all the changes in the method, this one increased the accuracy of the observations the most.

A1.5.8 *Slant-Angle Considerations were Introduced:*

A1.5.8.1 The preamble states:

"Criteria concerning an observer's position with respect to the plume were added. Specific guidance was also provided for reading emissions from rectangular emission points with large length-to-width ratios, and for reading emissions from multiple stacks. In each of these cases, emissions are to be read across the shortest path length."

A1.5.8.2 This section was included to minimize positive bias inherent to the effect of path length on visible emissions observations.

A1.5.8.3 Slant-angle effects occur when the observation path length through the plume is longer than it should be. The path length through the plume is lengthened when an observer either gets too close to a tall stack or observes a plume along its line of travel (Fig. A1.3). The best rule of thumb for observing tall stacks with vertical plumes is to be positioned at least three stack heights away, where the slant-angle is 18° or less.

A1.5.9 *The Issue of Steam Source Plumes was Introduced:*

A1.5.9.1 The preamble states:

"Provisions were added to make clear that opacity of contaminated water or steam plumes is to be read at a point when water does not exist in condensed form. Two specific instructions are provided: one for the case where opacity can be observed prior to the formation of the condensed water plume, and one for the case where opacity is to be observed after the condensed water plume has dissipated."

A1.5.9.2 For the first time, standardized approaches were included to eliminate the problems of observing plumes formed by the condensation of steam or steam plumes.

A1.5.10 *Smoke Generators were Standardized:*

A1.5.10.1 The preamble states:

"Specifications were added for the smoke generator used for qualification of observers so that state or local air pollution control agency..."

A1.5.10.2 USEPA wanted to standardize the certification procedure by establishing criteria for the generators and opacity-measuring equipment used in training and certifying observers.

A1.5.11 *Minor Changes to the Method:*

A1.5.11.1 The current version of Method 9 can be found in the Federal Standards of Performance for New and Modified Stationary Sources-Code of Federal Regulations (CFR) Part 60, Appendix A-Reference Methods. Some minor variations to the basic method are found in specific standards. The method has essentially been unchanged since its promulgation in 1974, except for two minor changes in 1987. The following discussion reflects the 1987 version of the method.

A1.5.11.2 The method states:

"Many stationary sources discharge visible emissions into the atmosphere; these emissions are usually in the shape of a plume. This method involves the determination of plume opacity by qualified observers. The method includes procedures for the training and certification of observers, and procedures to be used in the field for determination of plume opacity."

A1.5.12 *Appearance and Controllable Observational Variables:*

A1.5.12.1 The method states:

"The appearance of a plume as viewed by an observer depends upon a number of variables, some of which are controllable in the field. Variables which can be controlled to an extent to which they no longer exert a significant influence upon plume appearance include: Angle of the observer with respect to the plume; angle of the observer with respect to the sun; point of observation of attached and detached steam plume; and angle of the observer with respect to a plume emitted from a rectangular stack with a large length to width ratio. The method includes specific criteria applicable to these variables."

A1.5.12.2 These variables are discussed in the next few pages. It is interesting to note that the controllable variables generally give a positive bias to any observations if the specific criteria in the method are not followed.

A1.5.13 *Appearance and Uncontrollable Observational Variables:*

A1.5.13.1 The method states:

"Other variables which may not be controllable in the field are luminescence and color contrast between the plume and the background against which the plume is viewed. These variables exert an influence upon the appearance of a plume as viewed by an observer, and can affect the ability of the observer to accurately assign opacity values to the observed plume."

A1.5.13.2 Generally speaking, the uncontrollable errors lead to negative bias in observations. In other words, these errors tend to result in Method 9 opacity readings that are lower than the actual opacity of the plume.

A1.5.14 *High-Contrast Backgrounds:*

A1.5.14.1 The method states:

"Studies of the theory of plume opacity and field studies have demonstrated that a plume is most visible and presents the greatest apparent opacity when viewed against a contrasting background. It follows from this, and is confirmed by field trials, that the opacity of a plume, viewed under conditions where a contrasting background is present, can be assigned with the greatest degree of accuracy. However, the potential for a positive error is also the greatest when a plume is viewed under such contrasting conditions."

A1.5.14.2 The key word is *potential*. "Potential for positive error" does not mean that observations always or even often will be higher than the actual opacity. An additional series of tests sponsored by USEPA determined that the most likely outcome is for observers to estimate opacity correctly or to underestimate opacity.

A1.5.15 *Low-Contrast Backgrounds:*

A1.5.15.1 The method states:

"Under conditions presenting a less-contrasting background, the apparent opacity of a plume is less and approaches zero as the color and luminescence contrast decrease toward zero. As a result, significant negative bias and negative errors can be made when a plume is viewed under less contrasting conditions. A negative bias decreases rather than increases the possibility that a plant operator will be cited for a violation of opacity standards due to observer error."

A1.5.15.2 Simply put, as the amount of visual information to help determine plume opacity decreases, negative bias increases. It is hard to distinguish a black cat at night; likewise, it is hard to distinguish a white plume against an overcast sky. In the real world, it is most likely that the observer will encounter factors that tend to result in negative bias because of low contrast between the plume and the background. Plumes from tall stacks must always be evaluated against a blue or cloudy sky in which the color contrast is low and the luminous contrast is poor.

A1.5.16 *Positive Error Defined:*

A1.5.16.1 USEPA has on several occasions quantified the errors associated with Method 9. In the original promulgation, data were presented from a series of field studies conducted by the Agency.

A1.5.16.2 The method states:

"Studies have been undertaken to determine the magnitude of positive errors which can be made by qualified observers while reading plumes under contrasting conditions and using the procedures set forth in this method. The results of these studies (field trials), which involve a total of 769 sets of 25 readings each, are as follows:

(1) For black plumes (133 sets at a smoke generator) 100 % of the sets were read with a positive error of less than 7.5 % opacity; 99 % were read with a positive error of less than 5 % opacity.

(2) For white plumes (170 sets at a smoke generator, 168 sets at a coal-fired power plant, and 298 sets at a sulfuric acid plant), 99 % of the sets were read with a positive error of less than 7.5 % opacity; 95 % were read with a positive error of less than 5 % opacity."

A1.5.16.3 Note that black smoke was only slightly easier to evaluate. Note also that two levels of error are addressed in each set of results. For black smoke, the reported levels of confidence were 100 and 99 %. For white smoke, the levels were 99 and 95 %. These data indicate that there is no single level of error for Method 9. In addition, note that the method does not address negative error at all. USEPA is simply addressing the issue of wrongfully identifying a compliant source as a violator.

A1.5.17 *Positive Observational Error:*

A1.5.17.1 The method states:

"The positive observational error associated with an average of twenty-five readings is therefore established. The accuracy of the method must be taken into account when determining possible violations of applicable opacity standards."

A1.5.18 *Principle:*

A1.5.18.1 The method states:

"The opacity of emissions from stationary sources is determined visually by a qualified observer. Again, this is a method that involves human observation. The observer must be certified before completing observations for record."

A1.5.19 *Applicability:*

A1.5.19.1 The method states:

"This method is applicable for the determination of the opacity of emissions from stationary sources pursuant to 60.11 (b) and for qualifying observers for visually determining opacity of emissions."

A1.5.19.2 In addition to sources subject to NSPS, other sources are evaluated using Method 9. Often, states incorporate Method 9 into their SIP rules and regulations by reference. If a state SIP is unclear as to an exact method or if the cited method has not gone through formal rulemaking, Section 52.12(c) of CFR Part 52 allows USEPA to apply Method 9 in making a compliance determination. Thus, the observer should be careful to check the standard to which a source is subject and to determine whether any other methods apply for observations.

A1.5.20 *Procedures:*

A1.5.20.1 The method states:

"The observer qualified in accordance with paragraph three of this method shall use the following procedures for visually determining the opacity of emissions."

A1.5.20.2 An observer must follow specific procedures to complete a valid visible emission evaluation. These procedures are described below.

A1.5.21 *Observer Position Relative to the Sun Notes:*

A1.5.21.1 One of the most important aspects of visible emissions evaluation is the relative positions of the observer, the sun, and the plume (Fig. A1.4). If the observer looks toward the sun, the appearance of the plume is enhanced, resulting in a high bias.

A1.5.21.2 The method states:

"The qualified observer shall stand at a distance sufficient to provide a clear view of the emissions with the sun oriented in the 140° sector to his/her back. The cone behind the operator represents a 140° sector where the sun should be located when the observer is looking at the plume."

A1.5.21.3 Adherence to this rule prevents forward scattering of the light by the plume from interfering with the observation. On an overcast day when no shadows are observed and the lighting is diffuse or flat, this rule might not be as important from a scientific standpoint as on a bright, sunny day. Observers might have trouble defending their positions in court if they disregard the rule. The best practice for an observer is always to have the sun at his/her back, even if it is not visible and no shadows are cast.

A1.5.22 *Observer Line of Sight:*

A1.5.22.1 The method states:

"Consistent with maintaining the above requirement, the observer shall, as much as possible, make his/her observations from a position such that his/her line of vision is approximately perpendicular to the plume direction, and when observing opacity of emissions from rectangular outlets (for example, roof monitors, open baghouses, non-circular stacks), approximately perpendicular to the longer axis of the outlet."

A1.5.22.2 Recognizing that sun angle is the most important factor, the method gives guidance to limit slant-angle effects. Slant-angle effects occur when the observation path length through the plume is longer than it should be. Path length increases when the observer gets too close to a tall stack or observes a plume along its line of travel (Fig. A1.5).

A1.5.22.3 The best rule for observing tall stacks with vertical plumes is to take a position at least three stack heights away, where the slant angle is 18° or less. Under these conditions, the positive error is less than 1 % of the true opacity.

A1.5.22.4 When the plume is horizontal, the same effect holds true. Because of slant angle, observers must take special care in observing plumes from ships' holds. If the slant angle cannot be minimized, calculations can be used to negate the effects and determine the corrected opacity.

A1.5.23 *Multiple Stacks:*

A1.5.23.1 Multiple stacks can create plumes that intermingle.

A1.5.23.2 The method states:

"The observer's line of sight should not include more than one plume at a time when multiple stacks are involved, and in any case, the observer should make his/her observations with his/her line of sight perpendicular to the longer axis of such a set of multiple stacks (for example, stub stacks on baghouses)."

A1.5.23.3 If the observer cannot get perpendicular to the line of stacks, he/she should make sure that no interfering plumes are present. Sometimes just viewing the plumes before they intermingle will achieve this goal.

A1.5.24 *Field Records:*

A1.5.24.1 The method states:

"The observer shall record the name of the plant, emission location, type of facility, observer's name and affiliation and the date on a field data sheet. The time, estimated distance to the emission location, approximate wind direction, estimated wind speed, description of the sky conditions (presence and color of clouds), and plume background are recorded on a field data sheet at the time opacity readings are initiated and completed."

A1.5.24.2 This section contains language not present in the 1974 promulgation. The method now requires a sketch of the relative positions of the sun, the source, and the observer.

A1.5.25 *Observation Point in the Plume:*

A1.5.25.1 The method states:

"Opacity observations shall be made at the point of greatest opacity in that portion of the plume where condensed water vapor is not present."

A1.5.25.2 This provision ensures that the opacity is measured after particles and gas-phase reactions in the plume have formed. The provision could, however, cause problems if the plume is mushrooming in the atmosphere. Mushrooming occurs when the plume velocity cannot be maintained in the atmosphere and the path length increases faster than the natural dilution of the plume. Normally, this is not the case.

A1.5.26 *Attached Steam Plumes:*

A1.5.26.1 When steam is emitted, cools, and condenses, it forms a steam plume. Steam is not defined as particulate matter by the Agency. To address the problem of steam plumes, several modifications to the rule of observing at the densest part of the plume are part of the method.

A1.5.26.2 The method states:

"When condensed water vapor is present within the plume as it emerges from the emission outlet, opacity observations shall be made beyond the point in the plume at which condensed water vapor is no longer visible. The observer shall record the approximate distance from the emission outlet to the point in the plume at which the observations are made."

A1.5.27 *Detached Steam Plumes:*

A1.5.27.1 The method states:

"When water vapor in the plume condenses and becomes visible at a distinct distance from the emission outlet, the opacity of emissions should be evaluated at the emission outlet prior to the condensation of water vapor and the formation of the steam plume."

A1.5.27.2 Note the key words in those last three sections of the method that have been discussed. In the first two, the key word was *shall*, while in the third the key word was *should*. There is no option in the first two cases. In the last case, however, observations could be made before steam plume formation, as suggested, or they could be made after the steam plume re-evaporates. The key to this decision is to follow the first rule and observe at that point where the plume is the densest.

A1.5.28 *Recording Observations:*

A1.5.28.1 The method states:

"Opacity observations shall be recorded to the nearest 5 % at 15-second intervals on an observational record sheet. A minimum of 24 observations shall be recorded. Each momentary observation recorded shall be deemed to represent the average opacity of emission for a 15-second period."

A1.5.28.2 From a technical standpoint, the most important part of this section concerns making momentary observations. Staring at the plume reduces the ability of the observer to make an accurate assessment of the opacity.

A1.5.29 *Data Reduction:*

A1.5.29.1 The method states:

"Opacity shall be determined as an average of 24 consecutive observations recorded at 15-second intervals. Divide the observations recorded on the record sheet into sets of 24 consecutive observations."

A1.5.29.2 Taken out of context, this section has been used by some attorneys to claim that the observer must take the first six minutes and average them, then the next six minutes and average them, and so on. This is not the case.

A1.5.29.3 The method continues:

"A set is composed of any 24 consecutive observations. Sets need not be consecutive in time and in no case shall two sets overlap."

A1.5.29.4 This means that any set of observations in the total data set could contain a violation.

A1.5.30 *Calculation of Opacity:*

A1.5.30.1 The method states:

"For each set of 24 observations, 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 more than 24 observations, calculate the average for all observations made during the specified time period. Record the average opacity on a record sheet."

A1.5.30.2 For a one-hour data set, there are 217 possible six-minute averages that could be calculated using the "rolling average" calculation technique preferred by USEPA.

A1.5.31 *General Certification Requirements:*

A1.5.31.1 The method states:

"To receive certification as a qualified observer, a candidate 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 an average error not to exceed 7.5 % opacity in each category. Candidates shall be tested in accordance with the procedures described in paragraph 3.2 [of Method 9]. Smoke generators used pursuant to paragraph 3.2 [of Method 9] shall be equipped with a smoke meter which meets the requirements of paragraph 3.3 [of Method 9]."

A1.5.32 *Period of Certification:*

A1.5.32.1 The method states:

"The certification shall be valid for a period of six months, at which time the qualification procedure must be repeated for an observer to retain certification."

A1.6 Introduction to Digital Camera Opacity Technique (DCOT)

A1.6.1 The following information describes the: *(1)* typical equipment that is needed to provide a complete dataset when determining plume opacity with DCOT, *(2)* documentation needed to determine plume opacity with DCOT, *(3)* certification requirements and duration for DCOT, and *(4)* requirements for Knowledgeable Users.

A1.6.2 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.

A1.7 Equipment to Determine Plume Opacity in the Field Using Digital Camera Opacity Technique

A1.7.1 *Introduction:*

A1.7.1.1 This section provides information about the typical equipment that is useful when recording digital images with a Digital Still Camera to determine plume opacity with DCOT.

A1.7.2 *Digital Camera Opacity Technique (DCOT):*

A1.7.2.1 DCOT consists of three components as described in more detail in the body of this ASTM Method: *(1)* a Digital Still Camera, *(2)* Analysis Software and its associated computing platform, and *(3)* the Output Function. The Digital Still Camera's sole purpose with respect to the DCOT system is the acquisition and documentation of the pictorially represented emission source. The Digital Still Camera shall provide digital images and shall use the Digital Still Camera's auto-focus and auto-exposure settings and may use the optical zoom feature when recording the digital images of the plumes. The flash, optical filters, digital zoom, and image stabilization of the Digital Still Camera shall not be used when recording the digital images of the plumes. The second component of the DCOT is the Analysis Software that 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. The Analysis Software component of the DCOT dictates the specific requirements of the Digital Still Camera and establishes the minimum requirements of the system output capabilities. The third 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 can establish its own representation of output as long as the minimum set of information is provided that is described in the body of this ASTM Method. The combination of the Digital Still Camera, Analysis Software, and Output Function is considered a DCOT. The DCOT is certified 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 could be certified to this standard with multiple Digital Still Cameras and a single Digital Still Camera could be certified to this standard to operate with multiple Analysis Software and Output components.

A1.7.3 *Tripod:*

A1.7.3.1 Use of a tripod to keep the camera stationary and stable is recommended when reasonably possible.

A1.7.4 *Timer/Watch:*

A1.7.4.1 The operator shall use a timer or watch that signals (for example, beeps) every 15 seconds so that the operator will actuate the Digital Still Camera to capture digital still images at each of those 15 second intervals. In contrast, the time specified by the Digital Still Camera should correspond to the actual time of day. The time provided by the Digital Still Camera is used to record times in the Field Data Record as described below.

A1.7.5 *Direction Finder:*

A1.7.5.1 The operator shall use a compass (Fig. A1.6) or a Global Positioning System (GPS) to determine the direction to the source from where the camera is located and to determine the wind direction at the source. For accurate readings, the compass should have a resolution better than five minutes.

A1.7.5.2 The card-type compass has a circular disk, marked in degrees, that rotates on a pivot. The needle-type compass has a needle with a north marker that indicates magnetic north. The observer should keep the compass level and away from ferrous metals. Even a small amount of ferrous metal, such as the clip on a clipboard, can influence the reading on a compass. This makes the hood of a car an unsuitable place to take a compass reading. It is also important to know the magnetic declination from true north at the observation location. Sizeable documentation errors can be generated when an observer relies on a compass alone for determining direction. For this reason, a map should be used in conjunction with a compass to ensure accuracy. Use of a GPS instead of a compass is recommended to alleviate the issues described above for compasses.

A1.7.6 *Rangefinder:*

A1.7.6.1 A rangefinder measures the observer's distance from the emissions point and should be capable of determining distances to 1000 m with an accuracy of ±10 %. The accuracy of the rangefinder should be checked on receipt and periodically thereafter with targets at known distances of approximately 100 m and 1000 m. The two common types of rangefinders are stadiometric and split image. For ease of use and portability, most observers prefer the stadiometric rangefinder, but either type is acceptable.

A1.7.7 *Clinometric Devices:*

A1.7.7.1 Clinometric devices determine the vertical viewing angle. For visual emission observation purposes, a clinometric device should measure within 5 minutes. An inclinometer is recommended to make such measurement.

A1.7.8 *Anemometer:*

A1.7.8.1 Anemometers, or wind gauges, are devices that determine wind speed. The three basic types are:

(1) Mechanical,

(2) Electronic, and

(3) Pressure.

A1.7.8.2 Mechanical anemometers measure the wind with a rotating turbine. The rate of rotation depends on the wind speed. The rate of rotation is electrically determined and translated into wind speed on a meter or display.

A1.7.8.3 Electronic anemometers usually consist of a hot wire that is cooled by the air flowing past. The faster the air flow, the more cooling occurs. The amount of current required to reheat the wire is then translated to wind speed.

A1.7.8.4 The pressure type anemometer is the simplest anemometer and the most popular among field personnel. It consists of either a hinged pressure plate that rises with wind speed or a variable orifice flow meter (rotameter) with an indicator that rises proportionally to wind speed.

A1.7.9 *Relative Humidity Sensor:*

A1.7.9.1 Relative humidity (RH) can be measured with a wide range of detectors. Examples include capacitive type relative humidity sensors and sling psychrometers (Fig. A1.7). These devices shall be used when the atmospheric conditions might promote steam plume formation. The capacitive type element consists of a film capacitor located on select substrates (for example, glass or ceramic). There is a dielectric that sorbs and desorbs water vapor proportional to the RH of its environment. Such interaction with the water vapor changes the capacitance of the capacitor that is related to RH. Typical capacitive relative humidity sensors are accurate to within 3 % relative humidity. The psychrometer consists of two thermometers, accurate to 0.5°C, mounted on a sturdy assembly that allows the thermometers to be swung rapidly in the air. One thermometer is fitted with a wettable cotton wick tube on the bulb. If for some reason the wick is missing, a cotton shoelace can be substituted. Thermometer accuracy should be checked by placing the bulbs in a fresh-water/ice-water bath and checking to see that they read 0°C.

A1.7.9.2 An operator uses a sling psychrometer by wetting the cotton wick and swinging the assembly through the air until the temperatures of both thermometers stabilize. Because of evaporative cooling, the wet-bulb temperature will be lower than the dry-bulb temperature if the relative humidity is below 100 %. The difference between the two temperatures indicates RH. The RH can be calculated from these two values by using either a psychrometric chart or a slide rule that has the necessary scales.

A1.8 *Documentation Needed to Determine Plume Opacity with DCOT*—Industry is motivated to scrutinize the visible emissions data on a form for error because of the size of the fines. Court cases have been lost or dropped because of poor documentation of opacity violations. Observers in the field simply do not always pay enough attention to the details necessary for litigating a violation successfully. Observers can prevent possible challenges during deposition processes and in court by properly documenting the visible emissions they observe. Initial use of Method 9 demonstrated that more documentation was needed. The example Field Data Record and documentation included in the *Federal Register* with the Method 9 procedure are not always adequate to determine the compliance status of sources subject to opacity standards. An example of a Field Data Record is provided in Table 1 and is followed by information describing the parameters specified in the example Field Data Record. Please note that specific reporting requirements are determined by the agency/organization that is requiring the evaluation of the opacity of the visual emission.

A1.8.1 *Company Name and Location:*

A1.8.1.1 The complete name of the company and its location shall be clearly described. Include the parent company name, division, or subsidiary name when describing the name of the company. The location shall describe the complete street, city and state address of the facility so that the exact physical location of the source is adequately described.

A1.8.2 *Test Identification Number and Date:*

A1.8.2.1 Specify the identification number of the test and the date when the test occurred. Such information is important to be able to relate other ancillary information that was obtained relative to that specific test.

A1.8.3 *Type and Operational Status of the Facility, Process Unit and Control Device:*

A1.8.3.1 Provide descriptions of the type of facility, the process unit that is generating the plume and its operational status, and any control devices that are treating the gas stream and their operating conditions before the gas stream is emitted to the atmosphere. The information should be brief but as quantitative as reasonably possible. This information can be obtained from a representative of the facility. Overall, the information about the facility, process unit, and control device should meet the reporting requirements for the organization or agency where the opacity measurements will be reported.

A1.8.4 *Height of Emission Point and Estimation Method:*

A1.8.4.1 Indicate the vertical distance from the ground to the emission point and the method used to determine that distance. Such distance can be estimated by: *(1)* information in agency files, engineering drawings, or computer databases (such as National Emissions Data System), *(2)* using a combination of a rangefinder and an inclinometer, or *(3)* an estimation by eye sight.

A1.8.5 *Description of Operator, DCOT and Digital Still Camera:*

A1.8.5.1 The DCOT operator's and Digital Still Camera operator's name and affiliation shall be recorded in this section so that it is known who operated the DCOT, who completed the form, and the name of the organization that the operator(s) was working for while operating the DCOT/Digital Still Camera to determine plume opacity. This information is important to be able to locate the operator(s) at a later date. The date that the DCOT was certified and the name of the organization that certified the specific DCOT used to determine plume opacity shall also be described in this section. Also, the name of the manufacturer, the model, and serial number of the Digital Still Camera used to obtain the digital images of the plume and its background shall be specified in this section.

A1.8.6 *Source Layout Sketch:*

A1.8.6.1 This section shall identify the camera's position relative to the emission point, plant landmarks, topographic features, and sun position. This sketch should be drawn as a rough plan view and should include as many landmarks as possible (for example, buildings, roads, and ponds). At the very least, the sketch should show the relative positions of the observed outlet of the source and associated buildings so that the specified emission point and landmarks are not confused with other emission points and landmarks at a later date.

A1.8.6.2 Include a sketch of the plume, which also includes the wind's direction. This will assist in subsequent analysis of the conditions when obtaining the digital still images from the Digital Still Camera. The wind direction also must be described in the environmental conditions section of the form as described below.

A1.8.6.3 A north arrow shall be included in the sketch. To determine the direction of north, point the line of sight in the Source Layout Sketch in the direction of the actual emission point. Place the directional device (for example, compass or GPS) next to the circle and draw an arrow in the circle parallel to the directional device that is pointing north. Alternatively, a map can be used to determine the north direction.

A1.8.6.4 The sun's location during the operation of the DCOT shall also be included in the Source Layout Sketch. Verify the location of the sun before recording the digital images that will be used to determine plume opacity. The sun's location shall be within the 140° sector behind the camera as indicated in the Source Layout Sketch. This effort confirms that the sun is within the 140° sector to the camera's back.

A1.8.6.5 The operator can identify the location of the sun by: *(1)* point the line of sight in the Source Layout Sketch in the direction of the actual emission point, *(2)* move a pen upright along the "sun location line" until the shadow of the pen falls across the camera's position, and *(3)* draw the sun at the point where the pen touches the "sun location line" and the pen's shadow remains across the camera's position.

A1.8.7 *Clock Time:*

A1.8.7.1 The operator shall indicate the times at the beginning, intermediate, and end of the operation of the DCOT when observations about the environment or plume are recorded on the Field Data Record. The times recorded in the Field Data Record shall be synchronized with the time specified by the DCOT within one minute. The times can be expressed in a 12-hour or 24-hour format (that is, 1:35 PM or 13:35), but 24-hour time recordings tend to be less confusing and is recommended. Care should be taken to synchronize the time provided by the Digital Still Camera to the time used to describe the operation of the unit that is generating the plume of interest.

A1.8.7.2 The times in the Field Data Record should be within one minute of the times for the Digital Still Camera. The time for the Digital Still Camera should be within five minutes of the actual time (for example, as determined by a GPS or cell phone).

A1.8.8 *Camera's Location:*

A1.8.8.1 Record the distance from the location of the camera to the emission outlet. The distance can be measured with a rangefinder or a map. The operator shall use the same units that were used to record the other height measurements. This measurement of "distance to discharge" must be accurate when the camera is close to the stack (within three stack heights). Accuracy is important because this measurement might be used in conjunction with the outlet height relative to the camera to determine the slant angle at which the observations were made (Fig. A1.8). A precise determination of the slant angle is needed to calculate the positive bias. This bias is inherent in opacity values that were determined when the camera is within a distance of three stack heights from the stack.

A1.8.8.2 Record the vertical angle between the horizontal plane (ground) and the line of sight from the camera to the point where the digital images are obtained. The angle can be determined with an inclinometer.

A1.8.8.3 The horizontal angle of the sun to the back of the camera can be estimated using the Source Layout Sketch and a compass or GPS.

A1.8.8.4 Record the height of the emission outlet relative to the camera's position (that is, higher or lower than outlet of the source). This information is necessary if slant-angle calculations are performed. This parameter should be recorded in consistent units as used above.

A1.8.9 *Environmental Conditions:*

A1.8.9.1 This section describes the background and weather conditions during the observation period when the digital images were obtained to determine plume opacity. These factors could affect the resulting opacity values.

A1.8.9.2 Describe the background against which the opacity is being read. Include characteristics such as texture in the background description (for example, structure behind roof monitor; stand of pine trees; edge of jagged, stony hillside; clear blue sky; stack scaffolding; and building obscured by haze). Also describe the background color, including the shade (for example, new leaf green, conifer green, dark brick red, sky blue, and light gray stone). The operator shall use a background that is in contrast with the plume.

A1.8.9.3 Indicate the direction *from* which the wind is blowing. The direction should be estimated with a compass or GPS. Wind direction can be determined by observing which way the plume is blowing. If the wind direction is not readily discernible from the plume path, it can be determined by observing a blowing flag or a handful of dust that is blown when tossed into the air. The operator should keep in mind that the wind direction at the observation point can be different from that at the emission point; the wind direction at the emission point is the one of interest.

A1.8.9.4 Record the wind speed. Speed should be measured or estimated to ±5 miles per hour. The wind speed can be measured with a hand-held anemometer.

A1.8.9.5 Record the outdoor temperature at the plant site with a thermometer, including the units for the temperature value. The ambient temperature can be used in conjunction with the wet-bulb temperature to determine relative humidity when there are indications of a condensing water droplet plume.

A1.8.9.6 Enter the relative humidity, which can be determined with instrumentation described in the equipment section of this document. This information is used to estimate if water vapor in the plume is likely to condense and form a steam plume.

A1.8.9.7 Record the sky condition by indicating the percent cloud cover of the sky (for example, 10 % overcast or 100 % overcast) or by a qualitative description (for example, clear, scattered clouds, partly cloudy, overcast).

A1.8.10 *Plume Description:*

A1.8.10.1 Include descriptions of the physical characteristics and behavior of the plume that are not addressed elsewhere on the form. Also, the operator shall include the maximum distance at which the plume is visible. Examples of descriptions include "lacy," "fluffy," "copious," "mushrooming," "spreading over horizon," and "detached non-water vapor condensables."

A1.8.10.2 Record the color of the plume. The plume color can sometimes be useful in determining the composition of the emissions. Plume color also serves to document the color contrast between the plume and its background as seen by the operator. If emissions change color during the observation period, the color changes should be noted at the appropriate clock time.

A1.8.10.3 Record the distance between the discharge to the atmosphere and the location where opacity is determined.

A1.8.10.4 Note that information provided in this section may change many times during the observation period. These changes should be noted at the select clock times and in the Additional Information Section of the form.

A1.8.11 *Additional Information:*

A1.8.11.1 Additional information can be provided in this section about the actual conditions and/or deviations. The information should pertain only to conditions that have an influence on the opacity values and that have not been addressed elsewhere on the form (for example, potential interferences and presence of haze).

A1.8.12 *Operator's Signature and Date:*

A1.8.12.1 The operator shall sign and date the form once the form is complete.

A1.9 *Certification of DCOT*—Certification of a DCOT is performed outdoors using a smoke generator to present black or white smoke plumes and a measuring device that determines opacities from 0 to 100 %. The operator of the smoke generator shall generate plumes in accordance with Method 9 certification.

A1.9.1 *Testing Requirements:*

A1.9.1.1 To receive certification as a qualified DCOT, a DCOT operator must 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 an average error not to exceed 7.5 % opacity in each category (black and white) during smoke school as described by Method 9. DCOT certification shall follow the procedures as described by the Smoke School provider.

A1.9.2 *Grading:*

A1.9.2.1 At the conclusion of the test, each DCOT operator shall provide a report as described above that describes the 50 opacity values from the certification test. The reports are then submitted to the personnel operating the smoke school to compare the opacity values determined by the DCOT to the opacity values provided by the smoke generator. The two criteria that are used to determine if the DCOT passes the test:

(1) No individual opacity error, d_i, between the reference and DCOT reported opacity values shall exceed 15 % opacity.

(2) The average absolute error shall not exceed 7.5 % opacity value for the white and then again for the black plumes.

A1.9.2.2 The individual opacity error, d_i, is the absolute error between an individual opacity value, $0_{2,i}$, as measured by the reference opacity, and the opacity value reported by the DCOT, $0_{1,i}$, as described by:

$$d_i = |0_{1,i} - 0_{2,i}| \quad \text{(A1.2)}$$

where:

subscript i = each corresponding reference and DCOT reported opacity values for all fifty tests.

A1.9.2.3 The average absolute opacity error, $\bar{d}$, is defined as:

$$\bar{d} = \frac{\sum_{i=1}^{n} |d_i|}{n} = \frac{1}{n}\cdot\sum_{i=1}^{n} |0_{1,i} - 0_{2,i}| \quad \text{(A1.3)}$$

where:

n = the number of paired observations.

A1.9.2.4 If the opacity record for your DCOT meets both of the criteria stated above, then the DCOT system is certified. A certification record shall be sent to the DCOT operator at the address specified on the registration form within two weeks.

A1.9.3 *Certification of DCOT and Certification Period:*

A1.9.3.1 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 visible opacity of the 300 certification plumes within a six month period as described in 9.1. Results must be included in the certification documentation for all smoke school tests that occurred, whether the DCOT passed or failed the tests, and for the time periods between and during the six successful smoke school tests. Valid certification for that DCOT will last for 3.5 years.

A1.9.3.2 The recertification period of 3.5 years is supported by looking at two distinct areas impacting the life of the Digital Still Camera: *(1)* Electromechanical Failures and *(2)* Electronic failures.

A1.9.3.3 In the Digital Still Camera industry, electromechanical failure rates (for example, optical zoom) are quantified by the manufacturer with cycles (that is, shutter clicks) as opposed to Mean Time to Failure (communicated in hours). The average digital camera in the class contemplated for use herein is 60 000 cycles. In addition, the ability to maintain electro-mechanical parts (that is, repair) exists well into the camera model's lifecycle.[14]

A1.9.3.4 Electronic failures for the Digital Still Camera industry (sensors, integrated circuits, etc.) occur as they do in any electronics-related industry. Basically, electronics will be stricken with infant mortality, however, after the period where

[14] See http://olegkikin.com/shutterlife.

infant mortality occurs (also known as the "burn-in" period), electronic components show low to no failures.[15] This infant mortality always occurs inside warranty windows (assuming a one-year warranty), and given that certification is done to the Model number of the Digital Still Camera, there should only be an impact when a failure occurs between years 2 and 3.5.

A1.10 *Knowledgeable Users*—In many instances the Digital Still Camera operator and the DCOT operator are one and the same (also known as users). However, the functions of Digital Still Camera and DCOT operator are separable, each with its own competency requirements. The DCOT operator will be trained by the DCOT vendor regarding the specifics of operating their software. However, the DCOT operator must also be certified as a Digital Still Camera Operator as described below. The Digital Still Camera Operator must be intimate with rules as well as various field apparatus and required data which together determine a valid, defensible visual observation. Digital Still Camera Operators must understand the information in this document. In order to ensure this is the case, it is critical that the classroom portion of "smoke school" or an equivalent training be attended and documented. The point here is to evaluate via demonstration, or test that a Digital Still Camera Operator has mastered the required information.

A1.10.1 *Testing Requirements:*

A1.10.1.1 To receive certification as a qualified Digital Still Camera Operator, a candidate must demonstrate mastery of the following:

(1) Rules associated with the operation of a Digital Still Camera (Section A1.7 of this annex),

(2) Rules associated with plume observations (Section A1.5 and Section A1.7 of this annex),

(3) Required field data supportive of a valid defensible observation (Section A1.5 and Section A1.8 of this annex), and

(4) Expertise in utilizing field equipment (Manufacturer's Instructions in addition to Section A1.7 of this annex).

A1.10.2 *Grading:*

A1.10.2.1 At the conclusion of the training, and the associated test/demonstration, the participant (Digital Still Camera Operator) will be issued a pass or fail. Those who pass are responsible for maintaining proof of completion of training and successful test/demonstration results. Those who fail may retake the test / demonstration 3 times within a year; thereafter, they must wait until one year from the first attempt.

A1.10.2.2 The testing entity must maintain a record of the questions asked and the practical activities conducted, as well as individual results. Entities with jurisdiction (state and federal regulators) may define the content of training, and/or require modifications to training as necessary.

A1.10.3 *Certification of Digital Still Camera Operators:*

A1.10.3.1 The Digital Still Camera Operator shall be certified to capture plume and related field data if they receive a "Pass" on the training test/demonstration. Valid certification for that Digital Still Camera Operator will last no longer than 3.5 years.

[15] See http://www.weibull.com/hotwire/issue22/hottopics22.htm.

A2. MINIMUM EXIF 2.1 JPG DATA REQUIREMENTS

A2.1 EXIF 2.1 JPG (or higher) data shall be available for each digital image from the Digital Still Camera and shall be provided by the Output Function of the Analysis Software. The minimum EXIF 2.1 JPG (or higher) data requirements for the Digital Still Camera and the digital images from the Digital Still Camera are described in Table A2.1. EXIF data may also include other camera specific information that is important to document but is not part of the EXIF 2.1 JPG (or higher) standard (for example, use of image stabilization). This information is required to describe the: *(1)* manufacturer, model name or model number of the Digital Still Camera used to obtain the digital images, *(2)* operating conditions of the Digital Still Camera, *(3)* when the digital images were created or changed, *(4)* properties of the digital images, and *(5)* name and version of the software or firmware of the Digital Still Camera used to generate the digital images. Such documentation will inhibit the opportunity to modify the digital images and the resulting analysis of the plumes' opacity values.

TABLE A2.1 Minimum EXIF Header Reporting Requirements

Tag (hex)	Tag (dec)	IFD	Key	Tag Description
0x0101	257	IFD0	Exif.Image.ImageLength	The number of rows of image data. In JPEG compressed data a JPEG marker is used instead of this tag.
0x0100	256	IFD0	Exif.Image.ImageWidth	The number of columns of image data, equal to the number of pixels per row. In JPEG compressed data a JPEG marker is used instead of this tag.
0x0115	277	IFD0	Exif.Image.SamplesPerPixel	The number of components per pixel. Since this standard applies to RGB and YCbCr images, the value set for this tag is 3. In JPEG compressed data a JPEG marker is used instead of this tag.
0x0212	530	IFD0	Exif.Image.YCbCrSubSampling	The sampling ratio of chrominance components in relation to the luminance component. In JPEG compressed data a JPEG marker is used instead of this tag.
0x0132	306	IFD0	Exif.Image.DateTime	The date and time of image creation. In Exif standard, it is the date and time the file was changed.
0x9202	37378	Exif	Exif.Photo.ApertureValue	The lens aperture. The unit is the APEX (Additive System of Photographic Exposure) value.
0x9000	36864	Exif	Exif.Photo.ExifVersion	The version of this standard supported. Nonexistence of this field is taken to mean nonconformance to the standard.
0x829a	33434	Exif	Exif.Photo.ExposureTime	Exposure time, given in seconds (sec).
0x9209	37385	Exif	Exif.Photo.Flash	This tag is recorded when an image is taken using a strobe light (flash).
0x9201	37377	Exif	Exif.Photo.ShutterSpeedValue	Shutter speed. The unit is the APEX setting.
0x010f	271	IFD0	Exif.Image.Make	The manufacturer of the Digital Still Camera. When the field is left blank, it is treated as unknown.
0x0110	272	IFD0	Exif.Image.Model	The model name or model number of the equipment. This is the model name or number of the Digital Still Camera. When the field is left blank, it is treated as unknown.
0x0131	305	IFD0	Exif.Image.Software	This tag records the name and version of the software or firmware of the camera or image input device used to generate the image. When the field is left blank, it is treated as unknown.
0xA404	41988	IFD0	Exif.Image.DigitalZoomRatio	This tag indicates the digital zoom ratio when the image was shot. If the numerator of the recorded value is 0, then the digital zoom was not used.
927C	37500	IFD0	MakersNote.ImageStabilization	This tag is manufacturer specific. If Image Stabilization capabilities exist, the manufacturer will include a tag in Makers Note area.

A3. QUALIFICATIONS AND TESTING

A3.1 *Smoke Generator Specifications*—Any smoke generator used for the purposes of section 9.2 shall be equipped with a smoke meter installed to measure opacity across the diameter of the smoke generator stack. The smoke meter output shall display in-stack opacity based upon a path length equal to the stack exit diameter, on a full 0 to 100 % chart recorder scale. The smoke meter's optical design and performance shall meet the specifications shown in Table A3.1. The smoke meter shall be calibrated as prescribed in A3.1.1 prior to the conduct of each smoke reading test. At the completion of each test, the zero and span drift shall be checked and if the drift exceeds ±1 % opacity, the condition shall be corrected prior to conducting any subsequent test runs. The smoke meter shall be demonstrated, at the time of installation, to meet the specifications listed in Table A3.1. This demonstration shall be repeated following any subsequent repair or replacement of the photocell or associated electronic circuitry including the chart recorder or output meter, or every 6 months, whichever occurs first.

TABLE A3.1 Smoke Meter Design and Performance Specifications

Parameter	Specification
a. Light Source	Incandescent lamp operated at nominal rated voltage
b. Spectral response of photocell	Photopic (daylight spectral response of the human eye[A]
c. Angle of view	15 maximum total angle
d. Angle of projection	15 maximum total angle
e. Calibration error	±3 % opacity, maximum
f. Zero and span drift	±1 % opacity, 30 minutes
g. Response time	5 seconds

[A] Condon. E. U., and Odishaw, H., *Handbook of Physics*, McGraw-Hill Co., New York, NY, 1958, Table 3.1, pp. 6-52.

A3.1.1 *Calibration*—The smoke meter is calibrated after allowing a minimum of 30 minutes warm-up by alternately producing simulated opacity of 0 % and 100 %. When stable response at 0 % or 100 % is noted, the smoke meter is adjusted to produce an output of 0 % or 100 %, as appropriate. This calibration shall be repeated until stable 0 % and 100 % opacity values are produced by alternately switching the power to the light source on and off while the smoke generator is not producing smoke.

A3.1.2 *Smoke Meter Evaluation*—The smoke meter design and performance are to be evaluated as follows:

A3.1.2.1 *Light Source*—Verify from manufacturer's data and from voltage measurements made at the lamp, as installed, that the lamp is operated within ±5 % of the nominal rated voltage.

A3.1.2.2 *Spectral Response of Photocell*—Verify from manufacturer's data that the photocell has a photopic response; that is, the spectral sensitivity of the cell shall closely approximate the standard spectral-luminosity in (b) of Table A3.1.

A3.1.2.3 *Angle of View*—Check construction geometry to ensure that the total angle of view of the smoke plume, as seen by the photocell, does not exceed 15°. The total angle of view shall be calculated from: $\theta = 2\tan^{-1}(d/2L)$, where θ = total angle of view; d = the sum of the photocell diameter plus the diameter of the limiting aperture; and L = the distance from the photocell to the limiting aperture. The limiting aperture is the point in the path between the photocell and the smoke plume where the angle of view is most restricted. In smoke generator smoke meters this is normally an orifice plate.

A3.1.2.4 *Angle of Projection*—Check construction geometry to ensure that the total angle of projection of the lamp on the smoke plume does not exceed 15°. The total angle of projection shall be calculated from: $\theta = 2\tan^{-1}(d/2L)$, where θ = total angle of projection; d = the sum of the length of the lamp filament plus the diameter of the limiting aperture; and L = the distance from the lamp to the limiting aperture.

A3.1.2.5 *Calibration Error*—Using National Institute of Standards and Technology (NIST) traceable neutral-density filters of known opacity, check the error between the actual response and the theoretical linear response of the smoke meter. This check is accomplished by first calibrating the smoke meter in accordance with A3.1.1 and then inserting a series of three neutral-density filters of nominal opacity of 20, 50, and 75 % in the smoke meter path length. Filters calibrated within 2 % shall be used. Care shall be taken when inserting the filters to prevent stray light from affecting the meter. Make a total of five nonconsecutive readings for each filter. The maximum error on any one reading shall be 3 % opacity.

A3.1.2.6 *Zero and Span Drift*—Determine the zero and span drift by calibrating and operating the smoke generator in a normal manner over a one-hour period. The drift is measured by checking the zero and span at the end of this period.

A3.1.2.7 *Response Time*—Determine the response time by producing the series of five simulated 0 % and 100 % opacity values and observing the time required to reach stable response. Opacity values of 0 % and 100 % shall be simulated by alternately switching the power to the light source off and on while the smoke generator is not operating.