

# **Accounting for Uncertainty in Opacity Monitoring**

**The latest opacity measurement technology represents the last word in opacity monitoring.**

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## **ABSTRACT**

Smoke and dust emissions are regulated in the United States and Canada through emission limit values for opacity. Pending regulatory developments would require stationary sources to measure and report particulate mass emissions instead of opacity. With the appropriate analyzer, however, both opacity and mass concentration can be measured using the same device. Recent developments in monitoring technology, along with associated standards published by ASTM International, allow very low levels of opacity to be measured accurately. The limiting factors are the optical performance of the monitor, the actual characteristics of the particular installation, and the stability of the applicable calibration standards. The following parameters define the key technology features one would want in the latest opacity/dust monitoring systems.

## **INTRODUCTION**

Opacity monitoring remains the most widely used method for measuring emissions of smoke and particulate matter from stacks. Although other techniques are available, opacity monitors offer a number of features that make them especially attractive. These include the ability to calibrate the analyser using a traceable neutral density filter. Opacity measurements also can be compared to a visual estimate made according to US Environmental Protection Agency (EPA) Method 9<sup>1</sup>, giving a simple remote check of the indicated value. Additionally, some opacity monitors are able to measure both opacity and dust concentration simultaneously.

Traditionally, opacity monitors have been used only in applications where the emission limit value is at least 10% opacity. However, there have been a number of applications in electric arc furnaces and elsewhere where emission limit values of 6% or even 3% opacity have been applied. These values present serious challenges even to the latest generation of opacity monitors. In any case, while opacity continues to be the regulated parameter for EPA reporting, there are considerable advantages to installing a combination dust/opacity monitor where ever the dust concentration levels are within the sensitivity of the opacity measuring technology.

## SOURCES OF MEASUREMENT UNCERTAINTY

US federal law<sup>2</sup> requires all compliance opacity monitors to comply with ASTM D6216-03<sup>3</sup>. The specification limits for the various measurement uncertainties given in D6216-03 set a minimum uncertainty budget. However, the standard omits a number of significant sources of uncertainty, which cannot readily be evaluated in the laboratory and so any budget based on D6216-03 will tend to underestimate the actual uncertainty.

In Europe, the UK MCERTS<sup>4</sup> and German Minimum Requirements<sup>5</sup> set minimum performance standards for dust monitors, but these must be calibrated to measure dust and so the uncertainty limits cannot be expressed in terms of opacity. MCERTS expresses the allowed uncertainties in terms of the minimum specified range, which allows some comparability if we assume that the minimum range is 0% to 10% opacity.

The principal sources of uncertainty for an opacity monitor are shown in Table 1 along with the allowed uncertainties from both the D6216 and MCERTS standards.

Source of uncertainty	D6216-03	MCERTS*
Sensitivity to supply voltage variations	1.0%	0.2%
Thermal stability (change per 22.2°C)	2.0%	0.6%
Sensitivity to ambient light	2.0%	Not specified
Effect of misalignment in the transmitter or transceiver	2.0%	Not specified
Effect of misalignment in the receiver or retro	2.0%	Not specified
Calibration error and nonlinearity	3.0%	0.2%
Accuracy of window dirt compensation	Not specified	Not specified
Repeatability of the external zero device	1.0%	Not specified
Thermal drift of the external zero device	Not specified	Not specified
Long-term stability of external zero device	Not specified	Not specified
Temperature and spectral characteristics of the audit filters	Not specified	Not specified
Scintillation and refractive effects causing systematic bias	Not specified	Not specified

\*assuming 0% to 10% range

**Table 1**

*Uncertainties specified in ASTM D6216 and MCERTS standards*

Clearly, both standards omit a number of significant sources of uncertainty and so any budget based on them will tend to underestimate the actual uncertainty. We shall consider the most pertinent sources of uncertainty individually.

## Random Noise

Any device employing an optical detector will show some random noise, and an opacity monitor is no exception. Even where the monitor is completely insensitive to an influence such as mains voltage or temperature, there is a strong likelihood that any test will give a small non-zero result because of noise. Therefore, any test criterion must allow for a small uncertainty and so it is impractical to specify an uncertainty limit below 0.2% opacity for any source of uncertainty.

## Sensitivity to Supply Voltage Variations

Modern opacity monitors use switched mode power supplies, which give a constant dc output irrespective of the mains voltage, and these should be completely insensitive to changes. Some older designs still use linear power supplies and these can exhibit some response to changes in mains voltage, but measurements on new units should be limited by random noise.

## Thermal Stability

Almost all electronic and optical components have some sensitivity to ambient temperature and so it is inevitable that some thermal drift will occur. LED emission patterns, transmissivity and reflectivity of optical components, detector responsivity, amplifier gain and filter passbands can all change with temperature. Careful attention to component specifications and mechanical stability can minimise the effect but drift values below 0.3% per 22°C have been difficult to achieve consistently.

One surprising source of error is a temperature-dependent absorption within a large-diameter corner-cube reflector. Although BK-7 has a very small absorption coefficient in the visible region, the coefficient does change measurably over the usual operating temperature range of an opacity monitor (typically -20°C to +55°C). By utilizing an innovative multi-element design<sup>8</sup> (Fig 1), one can reduce the length of the optical path within the glass and so reduces the temperature coefficient of the retroreflector close to the noise level of a typical opacity monitor.

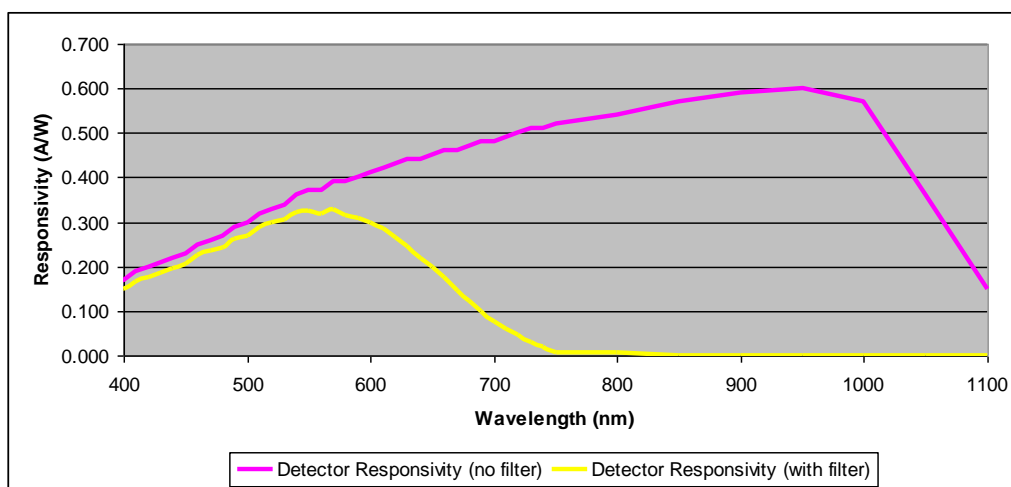


**Figure 1**

*Multi-element retroreflector displaying minimal thermal drift*

## Sensitivity to Ambient Light

An opacity monitor mounted close to the stack exit will be exposed to high levels of ambient light, especially in the summertime. This can lead to an offset if the optical detector or preamplifier is nonlinear. Some older designs used unmodulated light sources, and these were very susceptible to ambient light effects. In extreme cases, the detector or amplifier can saturate, leading to very large uncertainties. For this reason, D6216 requires that the opacity monitor is able to function correctly when exposed to  $900 \text{ W.m}^{-1}$  of sunlight. In practice, a well-designed opacity monitor, which has a narrow field of view and a modulated light source, should be limited by random noise.

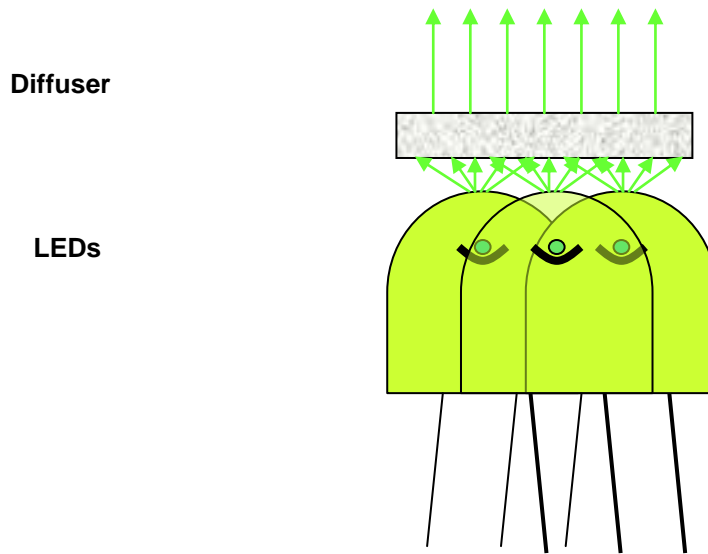


**Figure 2**

*Detector responsivity with and without optical filter*

## Optical Misalignment

Limiting the effect of optical misalignment is a key aspect of any opacity monitor design. An ideal monitor would exhibit no sensitivity to the alignment until the retro is outside the projected beam, but this is difficult to achieve in practice. The retroreflector is generally less sensitive to optical misalignment than the transceiver, but both show some effect. The design of the light source, retro mount and detector design all have an influence. An innovative design of LED light source<sup>5</sup>, shown schematically in Figure 3, has been found to give a minimal sensitivity to misalignment. In this design, the outputs from three LEDs are overlaid and then diffused so that the slight irregularities in each light source are averaged. The image of this light source on the distant retroreflector is, therefore, highly homogeneous. Slight misalignment does not change the intensity of the returned light and so no opacity measurement error is apparent.



**Figure 3**

*Three overlapping LEDs give homogeneous illumination,  
reducing sensitivity to misalignment*

### **Temperature and Spectral Characteristics of the Audit Filters**

Although the inconel-coated glass typically used in calibration attenuators shows very little variation with wavelength, its spectrum is not completely flat. Therefore, changes in the output wavelength of an opacity monitor could lead to measurement uncertainties. The center wavelength of a typical green LED changes by 2 nm between  $-20^{\circ}\text{C}$  and  $+60^{\circ}\text{C}$ . This effect was modelled by multiplying the output spectrum of a green LED by the transmittance value of an actual 23% opacity filter at 10 nm intervals, then repeating the calculation with the LED spectrum shifted by +10 nm and by -10 nm. The respective changes in calculated opacity were  $-0.13\%$  and  $+0.16\%$ .

Similarly, any change in the filter transmittance as a result of changes in temperature would reduce the accuracy of the measurement. The transmittances of four calibration attenuators were measured between  $+5^{\circ}\text{C}$  and  $+40^{\circ}\text{C}$ , a somewhat greater range than is typically found in a laboratory. The results are shown in Table 2

Filter	Average opacity	Maximum deviation
UY92	3.1%	0.06%
RX41	8.5%	0.09%
RX42	17.0%	0.10%
VA29	22.9%	0.12%
RX43	47.2%	0.08%
RX44	60.9%	0.24%

**Table 2**

*Thermal drift of inconel-coated neutral density filters*

Except for the highest-valued filter, the maximum deviation was 0.12% opacity. Although these effects are small, once we allow for the calibration uncertainty of the filters, changes in transmittance with temperature, spectral effects random noise and some actual nonlinearity, it is necessary to allow an uncertainty of at least 1.0% for the measured nonlinearity of the monitor. Higher-range monitors, which are calibrated using attenuators with higher opacity values, are likely to have greater uncertainties, which accounts for the specification of 3.0% in D6216-03.

### **Accuracy of Dirty Window Compensation**

Any opacity monitor that meets D6216-03 must have a means to compensate for any dust accumulation on the transceiver lens or window. However, any fouling of the zero reflector will lead to overcompensation, and a figure of 2.0% has been included in the uncertainty budget. Fouling is expected to be negligible in those opacity monitor designs that fully protect the zero reflector except when it is actually in use.

### **Repeatability, Thermal Drift and Long-term Stability of the External Zero Device**

Once an opacity monitor has been installed on a stack, it is usually impossible to recalibrate it without returning it to a workshop. For this reason, most designs incorporate an external zero device (EZD) that simulates a clear-stack condition. This device is usually set when the instrument is calibrated and kept carefully so that it can be used periodically to check for and correct any drift. As the EZD is used to recalibrate the instrument, any drift from its original state will be replicated in the instrument settings. Such drift may be caused by mechanical instability, temperature effects or deterioration of the optics over time. D6216 specifies a repeatability figure of 1.0%, though a well-designed EZD can show repeatability better than 0.3%. Thermal drift is not addressed in D6216 and, as the EZD must be used at the operating temperature of the analyzer, such drift can be rather large. A representative figure of 1.0% has been chosen. Reducing the operating temperature range of the

EZD and explicitly measuring the temperature coefficient of the EZD reduces the uncertainty and a figure of 0.4% can be achieved over a limited temperature range.

Long-term stability of the EZD is highly dependent on correct storage; an EZD kept in a sealed container in an air-conditioned office is more likely to remain stable than one that has been left on a workshop bench. The estimated figure of 0.5% is based on a properly-stored device.

## COMBINED UNCERTAINTIES

The ISO *Guide to the Expression of Uncertainty in Measurement*<sup>7</sup>, a combined uncertainty can be calculated from a set of individual uncertainty figures by taking the square root of the sum of the squared values:

$$u_c = \sqrt{\sum_p u_p^2}$$

The values for all of the identified uncertainties are shown in Table 3 along with the combined uncertainty. Two cases are given: that of an opacity monitor which complies with D6216 and one which represents the best available technology. Items for which D6216 has no specification are indicated with an asterisk and reasonable values have been chosen.

Parameter	D6216-03 Tolerance	Best-available technology
Sensitivity to Supply Voltage Variations	1.0%	0.2%
Thermal Stability	2.0%	0.3%
Sensitivity to Ambient Light	2.0%	0.2%
Indication of Optical Misalignment in the transmitter or transceiver	2.0%	0.5%
Effect of misalignment in the receiver or retro	2.0%	0.5%
Calibration Error Test	3.0%	1.0%
Accuracy of window dirt compensation	2.0%*	0.0%
Repeatability of the External Zero Device	1.0%	0.3%
Thermal drift of the External Zero Device	1.0%*	0.4%
Long-term stability of External Zero Device	0.5%*	0.5%
Temperature and spectral characteristics of the audit filters	0.2%*	0.2%
Scintillation and refractive effects causing systematic bias	1.0%*	1.0%
Combined Uncertainty	5.8%	1.8%

**Table 3**  
*Combined uncertainty*

## **SUMMARY**

ASTM D6216 was a major step forward in the quality of opacity monitoring because for the first time, it gave a common standard against which all suppliers could test their products. However, many of its specifications are rather conservative, and a monitor that meets its requirements could have an uncertainty in excess of 5.0% opacity – too large for use in applications which have a very low ELV. A high-quality opacity monitor could meet an enhanced specification and such a monitor would have a combined uncertainty better than 2.0% opacity. By remedying the uncertainties described above, one could reach the ultimate level of sensitivity for opacity measurement with an instrument that complies with all practicable opacity measurement requirements. An added advantage of a high-quality opacity monitor is its ability to indicate dust concentration in gravimetric units in addition to opacity.

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## **KEY WORDS**

Opacity, dust, particulate matter, CEMS, stack gases

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