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Exhaust flow calibration for a large-scale calorimetry system using tracer gas dilution

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Abstract

Exhaust flow measurements are a significant source of uncertainty for measurements of heat release rate in large-scale fire experiments. Irregular flow distributions are often present in the exhaust ducts making it difficult to measure flow accurately. Tracer gas dilution (TGD), a measurement method for volume flow, is not sensitive to flow distribution and has been applied to calibrate flow measurement devices at the exhaust ducts of a large-scale open calorimetry system. The in-line calibration reduced the bias in the exhaust flow measurement by as much as 6% improving the overall measurement accuracy of the heat release rate. Experimental results provide evidence that the flow calibration is an improvement over the accepted practice of developing a flow correction from the comparison of oxygen consumption calorimetry with the heat output from a gas burner. The flow calibration is valid for a wide range of flow conditions and decouples the oxygen consumption calorimetry measurement from any error in determining the heat release rate from the gas burner.

KEYWORDS
calorimetry, exhaust flow monitoring, flow calibration, flow mixing, heat release rate, tracer gas dilution

1 | INTRODUCTION AND BACKGROUND

The heat released from burning items is a central measurement for large-scale fire testing and the primary measurement for estimating the magnitude of the fire hazard. Oxygen consumption calorimetry is the most widely used method for measuring the rate of heat release, $\dot{Q}_{OC}$, during a large fire experiment. Heat release is proportional to the amount of oxygen consumed by the fire. The simplest quantitative estimate of the rate of heat release, Equation (1), requires an oxygen-based heat of combustion parameter for the burned fuel, $(\Delta_c H_{fuel})_{O_2}$, complete capture of the fire plume for gas analysis, measurement of exhaust volume flow, $\dot{V}_e$, and measurement of oxygen volume fraction, X_{O_2}, at the exhaust stream (flue gas).[1]

$$\dot{Q}_{OC} \cong (\Delta_c H_{fuel})_{O_2} \dot{V}_e \left(X^o_{O_2} - X_{O_2} \right). \quad (1)$$

Accurate measurements of exhaust flow and oxygen volume fraction are necessary to achieve an accurate measure of heat release rate. Multiple studies have cited the exhaust flow measurement as a significant source of uncertainty when measuring the rate of heat release.[2–7] Common methods for measuring flow in exhaust ducts include pressure impact probes (pitot tubes, bi-directional probes, and averaging pitot tubes) and orifice plates. The accuracy of these methods is reduced when less-than-ideal flow characteristics exist, such as skewed velocity distributions, off-axis flow components due to swirl, and turbulence. These conditions can often exist in exhaust systems for large fire testing, especially when there are short lengths of straight sections before and after the measurement location due to space limitations. Specifying volume or mass flow using these methods also requires a measurement of cross-sectional area which can be a significant source of uncertainty if the shape and dimensions of the sampling section cannot be determined with sufficient

accuracy. When such conditions exist, performing an in-line flow calibration can help reduce measurement error.

Consensus standards for open calorimetry fire testing, such as ASTM E2067, ISO 24473, and NFPA 286, provide guidance in the form of a heat release rate calibration (system calibration) that accounts for flow measurement error. For example, the systematic error of the heat release rate measurement and more explicitly the error of the exhaust flow measurement is inferred by comparing the rate of heat release from a gas burner as determined by fuel consumption calorimetry, to that measured in the exhaust flue as determined by oxygen consumption calorimetry. The error is used to estimate the flow coefficient and hence apply a correction to the flow measurement device (ASTM E2067, ISO 24473, NFPA 286); or it is used directly to correct the measurement of heat release rate as determined by oxygen consumption calorimetry (ASTM E1354, ASTM E2257).[8–11]

Correcting the flow measurement based on the comparison with heat release rate determined by fuel consumption calorimetry, a gas burner for example, may be practical in some cases but it is not ideal. This practice couples any error in determining heat content and fuel flow at the burner with that of the calorimeter. When the anticipated heat release rate from the fire under study is much greater than the maximum burner output, the correction is an extrapolation and introduces greater uncertainty. Therefore, conducting an in situ calibration of the flow monitoring device for the full range of conditions is the best practice. ASTM E2067 and ISO 24473 recommend, but do not require, an in situ calibration of the flow monitoring device (bi-directional probe or orifice plate) by conducting a velocity traverse across the exhaust duct to determine the flow distribution. The calibration constant, the ratio of the average velocity determined from the flow distribution and the measurement of the flow monitoring device, becomes the flow correction.

In this study, two methods of flow measurement are discussed, averaging pitot probes (APPs) and tracer gas dilution (TGD). APPs are used to monitor exhaust flow during routine fire experiments in the National Fire Research Laboratory (NFRL). They determine the average flow velocity along a chord of the exhaust duct from a measurement of pressure differential across the device. Combined with a measurement of the exhaust duct diameter (to determine cross-sectional area), volume flow in the exhaust duct is computed. TGD is applied as a reference flow measurement and is utilized to conduct an in-line calibration of the APPs. It is a volumetric or whole-field method that infers volume flow. It does not require a measurement of the cross-sectional area of the duct and is insensitive to irregular or skewed velocity distributions. Volume flow measurements inferred from TGD and the APPs are independent as they are derived from independent measurements—tracer volume flow and volume fraction versus differential pressure and duct diameter, respectively. Therefore, the TGD method is ideal for the in-line calibration.

The method for TGD is described by ASTM Standard E2029. It uses the constant injection technique, assuming an ideal gas and constant flow.[12] For this technique, a known concentration of tracer is injected at a constant rate at an upstream location of the flow stream. The tracer becomes mixed and diluted in the flow stream. At a downstream location, samples of the gas mixture are extracted from the flow stream and transported to an analyzer to measure the diluted volume fraction of the tracer, Figure 1.

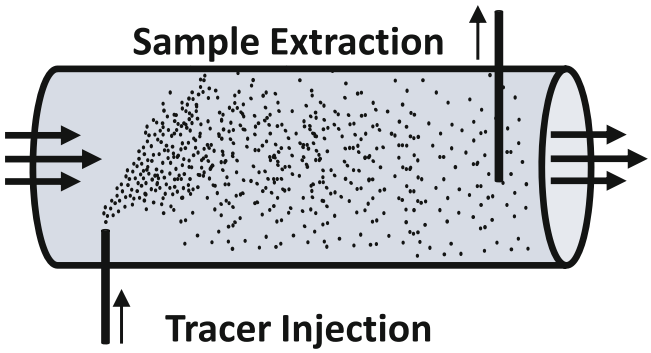


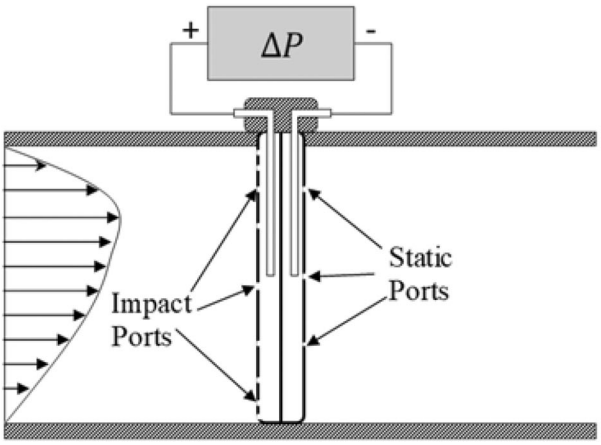
FIGURE 1 Conceptual representation of the method for tracer gas dilution.

The constant-injection technique requires precise metering of the injected tracer, sufficient mixing of the tracer into the transport stream, and accurate detection of the diluted tracer. When these requirements are satisfied, the volume flow in the duct can be determined from the following equation:

$$\dot{V} = \frac{X_{T,I} - X_{T,D}}{X_{T,D} - X_{T,U}} \dot{V}_{T,I}, \tag{2}$$

where $X_{T,I}$ is the known volume fraction of the injected tracer ($X_{T,I} = 1.00$ in the case of a pure tracer); $X_{T,D}$ is the volume fraction of the diluted tracer measured at the downstream sample location; $X_{T,U}$ is the volume fraction of the tracer measured upstream of the injection point (ambient environment); and $\dot{V}_{T,I}$ is the measured volume flow of the injected tracer.

APPs (also known as flow-averaging tubes or multi-port averaging pitot tubes) are impact pressure devices that measure the difference between total and static pressure, ΔP, induced by a flowing gas or liquid. Like the standard pitot tube, Bernoulli's principle is used to infer the fluid velocity from measurements of pressure differential and fluid density, ρ. The averaging pitot extends across the entire diameter of the pipe and has multiple impact and static ports positioned at equal annular locations, Figure 2. The number of impact ports and their spacing can be designed to meet specific applications, but they are usually spaced to account for a log-linear distribution of velocity.[13] Averaging of the spatial distribution of pressure occurs inside the impact and static chambers of the probe. The resulting measurement of differential pressure is used to determine the mean gas velocity along the chord, V_c. This relationship is described in the following equation, where K_a (ranging from 0.6 to 0.8) is the flow coefficient for the averaging pitot.[14] This velocity measurement is combined with a measurement of duct inner diameter (ID), D, to determine volume flow, $\dot{V}_e$.



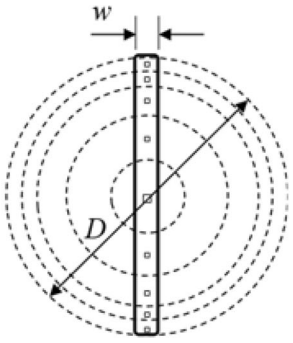


FIGURE 2 Generic installation for an averaging pitot probe.

$$V_c = K_a \sqrt{\frac{2\Delta P}{\rho}}. \quad (3)$$

APPs are off-the-shelf technology widely used to monitor flows for industrial processes. Their application in the NFRL has provided additional evidence of skewed velocity distributions in large exhaust ducts and the need for in-line calibrations to improve flow measurement accuracy.[15,16] This report will describe the methodology and equipment used to conduct in-line flow calibrations for a flue gas exhaust system using TGD. Full details of the experimental procedures have been described in previous publications and are summarized here.[17,18] The objectives of this study are to demonstrate best practices for improved flow measurements in intermediate to large-scale open calorimetry systems and to provide evidence of improved accuracy in measurements of heat release resulting from those best practices.

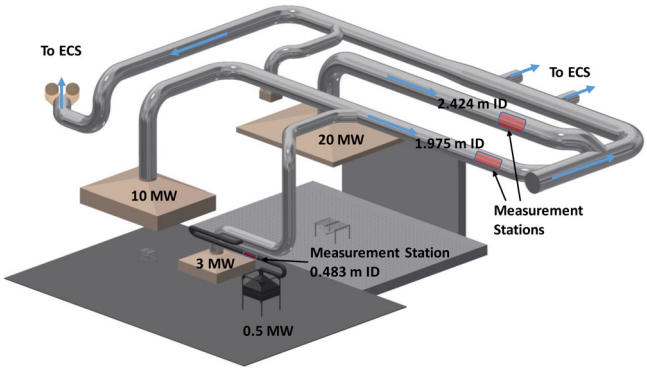


FIGURE 3 Digital rendering of the flue gas exhaust system. Blue arrows indicate flow direction. ECS, emissions control system, ID, inner diameter.

2 | EXPERIMENTAL METHODS AND MATERIALS

2.1 | Flue gas exhaust system

NFRL has four oxygen consumption calorimeters and each is equipped with a large-canopy exhaust hood to capture fire effluents, Figure 3. The insulated steel hoods are suspended above the test floor and serviced by large exhaust ducts that pull smoke and combustion products from the test area to an emissions control system (ECS) for conditioning before release into the atmosphere. Each calorimeter is denoted by its fire capacity, 0.5, 3.0, 10, and 20 MW. Flow dampers are installed at various locations (exhaust duct and canopy hood) to isolate a specific calorimeter for use. NIST Technical Notes 2077 and 2220 provide additional details of the system.[15,18]

2.2 | Exhaust flow measurement—APPs

The flow sensors used in the exhaust ducts are APPs with a tee-shaped cross section (Rosemont 485 Annubar).[1] They are installed at the measurement stations shown in Figure 3. The probes are made of 316 stainless steel and have a width of 2.7 cm. Probe lengths are sized to match the inner diameter of the exhaust ducts. A pair of probes (A and B) are installed in each exhaust duct, with the exception of the 0.483 m duct (servicing the 0.5 MW calorimeter) which has a single probe. The pressure differential, ΔP, at each probe is measured with a high-precision capacitance manometer (MKS 220D Baratron). Each probe is equipped with two bare-bead thermocouples (Omega, Type K) for monitoring the gas temperature inside the duct. The two probes are installed on orthogonal chords of the duct cross section and 45° relative to horizontal as shown in Figure 4. The minimum separation distance between the two probes is one duct diameter. The average velocity for the two probes, chord *A* and chord *B*, is reported as the flow velocity measured in the exhaust duct:

$$V_{e,\mathrm{APP}} = \frac{V_{c,A} + V_{c,B}}{2}. \quad (4)$$

Mass flow is routinely monitored and reported for NFRL's calorimetry system. For the purpose of comparison with the TGD method, volume flow, $\dot{V}$, is reported as described by Equation (5). Additional

details of the installation and use of APP at the NFRL are available from previous publications.[15,16,18]

$$\dot{V}_{e,\mathrm{APP}} = V_{e,\mathrm{APP}} \frac{\pi D^2}{4}. \quad (5)$$

2.3 | Exhaust flow measurement—TGD

A constant-injection system for TGD measurements was assembled and integrated into NFRL's flue gas exhaust and gas sampling systems. The tracer, sulfur hexafluoride (SF_6, 99.99 ± 0.02%), was injected under the canopy hood at the inlet of the exhaust duct and sampled at the flow measurement station using the facility's existing gas sampling and gas conditioning equipment.[15] A schematic representation of the constant-injection system is shown in Figure 5. The volume flow of the injected tracer was adjusted using a mass flow controller (MKS Instruments, Inc.; Model: M100B53CS1BV), while injection flow was precisely measured using a laminar flow element (Fluke; Model: molbloc-L 1E3-VCR-V-Q with molbox1 terminal) located downstream of the mass flow controller. The temperature and pressure of the injected flow are measured at the laminar flow element and used to convert actual volume flow to volume flow at reference conditions 273.15 K and 101 325 Pa. All volume flow measurements reported here are referenced to these conditions.

A ring made of copper tubing with equally spaced ports was used to distribute the tracer into the exhaust duct, Figure 6, where it mixed with the bulk flow through bends and more than 10 diameters of straight run before being extracted. At the measurement stations, gas samples were extracted from the exhaust flow using a multi-port sampling tube. The stainless-steel tube has equally spaced ports and is mounted horizontally across the exhaust duct, as shown in Figure 4. The gas samples represent the average concentration of tracer gas in the exhaust flow.

Conditioning of the gas sample included filtering to remove particulates and drying to remove water vapor before analysis. A portion of the conditioned sample was directed to a gas analyzer (LumaSense Technologies; Model INNOVA 1412i) to detect trace amounts of SF_6 ($X_{T,U}$ and $X_{T,D}$) in real-time using photoacoustic spectrometry.[19,20] In this technique, the gas sample is irradiated with infrared light where a portion of the light is absorbed by the gas which then generates an

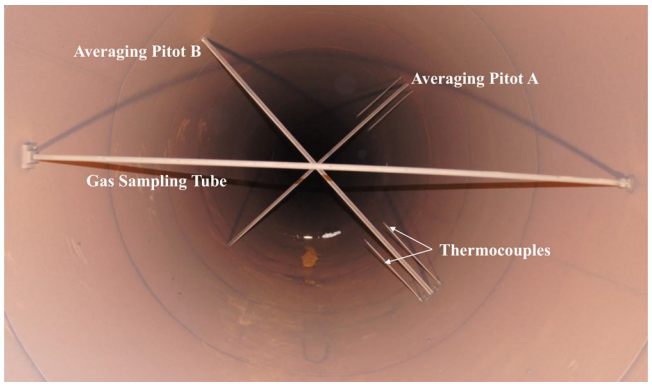


FIGURE 4 Installation of two averaging pitot probes and the gas sampling tube in the 1.98 m exhaust duct. The photograph view is upstream and into the flow.

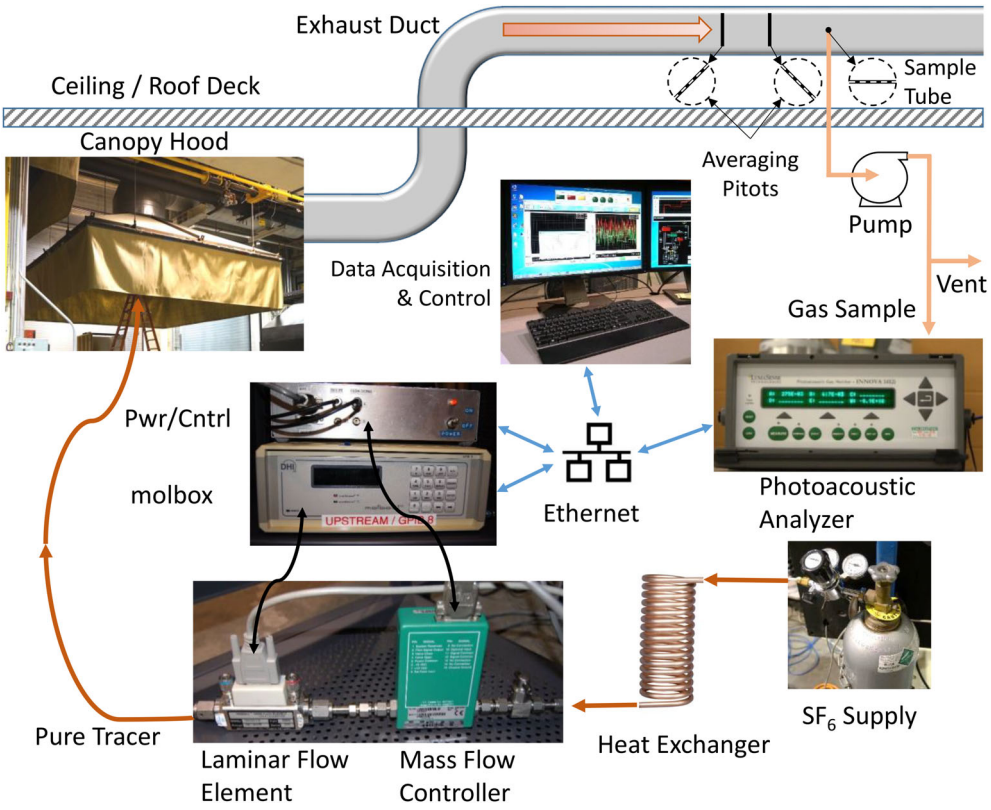


FIGURE 5 Diagram of the tracer gas dilution measurement using constant injection as arranged at the National Fire Research Laboratory calorimetry system.

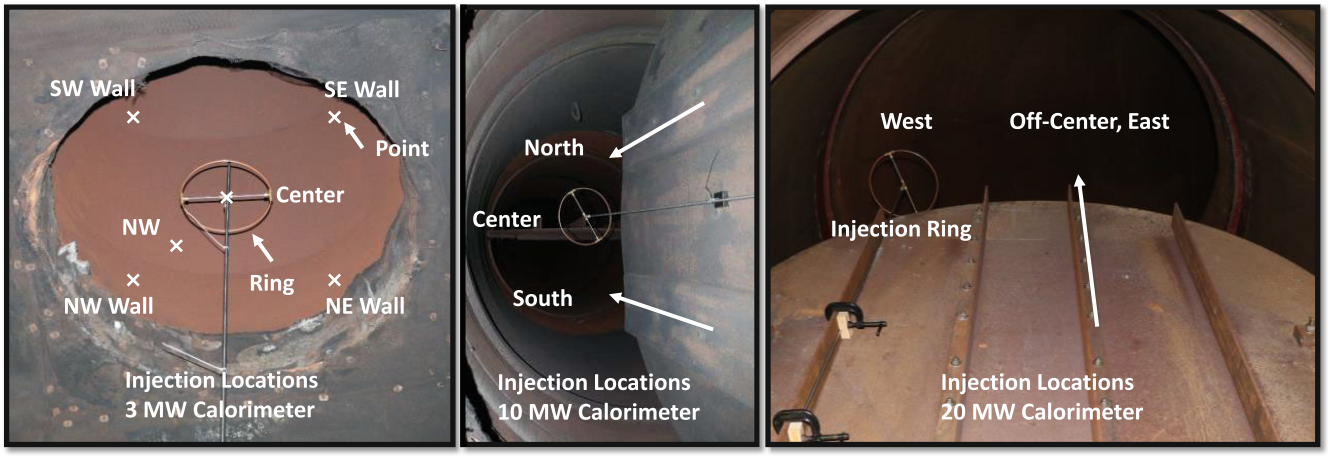


FIGURE 6 Tracer injection ring mounted at the inlet of the exhaust ducts for each calorimeter. The arrows indicate additional locations of the injection ring to confirm sufficient mixing. The "X"s indicate point injection locations for preliminary experiments to test for sufficient mixing.

acoustic signal that can be detected by a microphone. The analyzer uses optical filters to select which wavelengths of light irradiate the gas sample and therefore which gases are selected for detection.

ASTM E2029 provides a list of candidate tracers, such as helium, carbon dioxide, halocarbons, and so on.[12] For the present application, the tracer must be nontoxic to maintain personal health and safety; it must be nonreactive to preserve the exhaust system and instrumentation; and it must be detectable in the range of (0.001–100) nL/L, using off-the-shelf measurement technology. For this investigation large exhaust flows are studied. Therefore, tracers with higher limits of detection, such as carbon dioxide, require a large amount of injected flow to provide a detectable amount of tracer in the diluted gas sample. Since SF_6 has strong absorption in the infrared, it is highly detectable by the photoacoustic spectrometer. Therefore, manageable amounts of SF_6 (<5 L/min) can be precisely injected into the flow and detected in the diluted sample. Sulfur hexafluoride also has very low ambient volume fractions (≤0.012 nL/L),[21] is nontoxic and nonreactive; making it the logical choice of tracer gas for this investigation. The disadvantage of using SF_6 as a tracer is its high potential for global warming and decomposition into toxic compounds at high temperatures.

Prior to drying the gas sample, the volume fraction of water vapor, $X_{H_2O,i}$, was measured with a thin film capacitive detector (Vaisala; Model: HMT337). This measurement was used to account for the water vapor in the exhaust gas by revising Equation (2) to compute the volume flow for the wet conditions:

$$\dot{V}_{e,\mathrm{TGD}} = \frac{X_{T,I} - X_{T,D}(1 - X_{H_2O,D})}{X_{T,D}(1 - X_{H_2O,D}) - X_{T,U}(1 - X_{H_2O,U})} \dot{V}_{T,I}. \quad (6)$$

2.3.1 | Measurement uncertainty

The accuracy of the TGD method depends on how well the tracer mixes with the transport stream. Sufficient mixing ensures that the dilution of the tracer is representative of the overall flow. Basic guidance to promote sufficient mixing is provided by ASTM E2029 and includes: (1) establishing as much distance as possible between the injection plane and sample plane to allow for greater mixing time; (2) injecting the tracer upstream of flow components such as bends, turns, or fans, to assist mixing; and (3) injecting the tracer from multiple points to promote greater distribution. These best practices should result in less than 10% variation of tracer concentration across the duct.[12]

This study employs the aforementioned practices and a multi-port sampling tube to collect an average tracer concentration and reduce the potential for measurement error. To confirm sufficient mixing, tracer injection was located at various positions at the inlet of the exhaust duct, as shown in Figure 6. If the tracer does not completely mix with the flow at the downstream sample location, then any change in the location of tracer injection at the upstream injection plane should influence the distribution of the tracer at the downstream sample plane and induce an erroneous change in the measured volume flow. However, a spatially integrated sample, as for the present case, should be insensitive to small changes in the downstream distribution of the tracer.[18]

Preliminary experiments to confirm sufficient mixing were conducted at the 3 MW calorimeter. Figure 6 shows the inlet at the exhaust duct of the 3 MW calorimeter and the single-point injection locations, annotated by "X"s in the far left photo. The injection locations are also displayed as a diagram in the upper right of Figure 7. The tracer was injected at the various inlet locations while flow conditions were held steady. Figure 7 shows the standard deviation of volume flow, measured using TGD, to be less than 0.5%; confirming the measurement essentially held steady across all injection positions and mixing was sufficient. The injector ring was used for subsequent experiments to ensure the tracer was well distributed at the inlet. For the 10 and 20 MW calorimeters, the injection ring was relocated between repeat measurements, as shown in Figure 6 (middle and right

photos), to confirm sufficient mixing. The average ratio of the volume flow measurements, $\dot{V}_{e,TGD}/\dot{V}_{e,APP}$, for each injection location was used to analyze mixing. The standard deviation of this ratio was less than 1% of the average and provides an estimate of the potential error due to inadequate mixing, Table 1.

TGD serves as the reference method for determining exhaust volume flow. A detailed analysis of the measurement uncertainty for the method has been described previously[17,18] and the resulting uncertainty budgets for measurements at each calorimeter are summarized in Table 1. On average the estimated measurement uncertainty for volume flow determined by TGD is 3% for the experiments described here. Major contributors to the measurement uncertainty were the measurement of downstream tracer volume fraction (tracer detection at the photoacoustic analyzer), measurement repeatability (standard deviation of the mean—SDOM), and error due to inadequate mixing. Contribution from the measurement of injected flow is almost negligible due to the high accuracy laminar flow element. However, its contribution will be greater when utilizing flow monitoring devices with lower accuracy such as rotameters or standard mass flow controllers.

A previous investigation estimated the uncertainty for NFRL's flow measurements using the APPs at 3%.[16] The analysis used the uncertainty estimates from the manufacturer and practical judgment for the given application, based on measurement data from the probes. Skewed flow distributions, which can introduce measurement error, were discovered during the investigation. The investigation also presented a comparison of the heat release rate to the heat output from a gas burner and revealed a measurement bias as large as 6%. The bias could possibly be traced to the flow measurement. Initially, a reference flow measurement based on an independent measurement technique was not available for comparison. TGD is an independent technique, is insensitive to skewed velocity distributions, and therefore anticipated to provide better accuracy. Hence, it is applied as the reference flow measurement for the in-line calibration of the APPs.

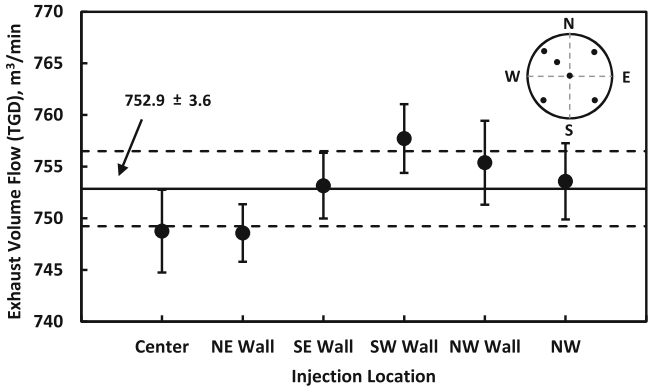


FIGURE 7 Confirmation of sufficient mixing of the tracer with single-point injection for various locations at the exhaust duct inlet. Error bars represent the standard deviation of the mean (SDOM) for 10 or more measurements. The solid and dashed horizontal lines represent the overall mean and standard deviation, respectively, of the volume flow computed from the six locations.

2.4 | Experimental procedures

Calibration experiments consisted of simultaneous measurements of exhaust flow using both APPs and TGD. Each calibration experiment consisted of 3–4 flow settings, targeting approximately 25%, 50%, 80%, and 100% of a calorimeter's flow capacity. A minimum of three repeat experiments were conducted for each calorimeter with repeats occurring on separate days. Because SF_6 decomposes into toxic compounds at high temperatures, fire conditions were not introduced, and all experiments were conducted using the ambient exhaust flow. Figure 8 is a time trace of the volume flow measurements and demonstrates a typical calibration experiment. Measurements from the APPs were logged at 1 Hz, while measurements from the TGD system were logged at 0.025 Hz, due to the longer measurement time required by the photoacoustic analyzer. During periods of steady flow (annotated in Figure 8), the measurements were tagged for later analysis. Volume flow measurements determined by the TGD method are the average of at least 10 consecutive measurements over approximately 7 min of steady flow.

TABLE 1 Estimated uncertainty for measurements of volume flow in the National Fire Research Laboratory exhaust system using tracer gas dilution.

	0.5 MW		3.0 MW		10 MW		20 MW	
Measurement component, x_i	$u(x_i)/x_i$	~%[a]	$u(x_i)/x_i$	~%[a]	$u(x_i)/x_i$	~%[a]	$u(x_i)/x_i$	~%[a]
Downstream tracer volume fraction, $X_{T,D}$	0.011	70	0.011	68	0.011	53	0.011	55
Injected tracer volume flow, $\dot{V}_{T,I}$	0.0007	<1	0.0007	<1	0.0007	<1	0.0007	<1
Repeatability (SDOM)	0.004	9	0.006	20	0.008	27	0.008	28
Error due to inadequate mixing	0.006	21	0.005	12	0.007	20	0.006	17
Standard, $u_c(y)/y$	0.013		0.014		0.016		0.015	
Expanded, $U(y)/y$	0.027		0.028		0.032		0.031	

Note: Expanded uncertainty is reported for a 95% CI, with $k = 2.0$.
Abbreviation: SDOM, standard deviation of the mean.
[a]Percent contribution (rounded approximation) of the component uncertainty to the combined standard uncertainty.

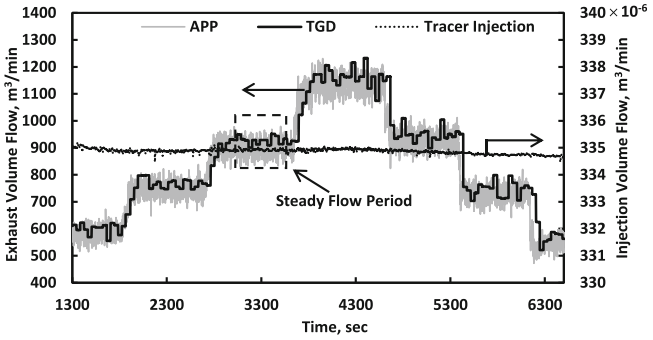


FIGURE 8 Time trace for a flow calibration experiment. Simultaneous measurements of volume flow determined by the averaging pitot probes (APPs) and tracer gas dilution (TGD) are shown on the left vertical axis. The volume flow of the injected tracer is shown on the right vertical axis.

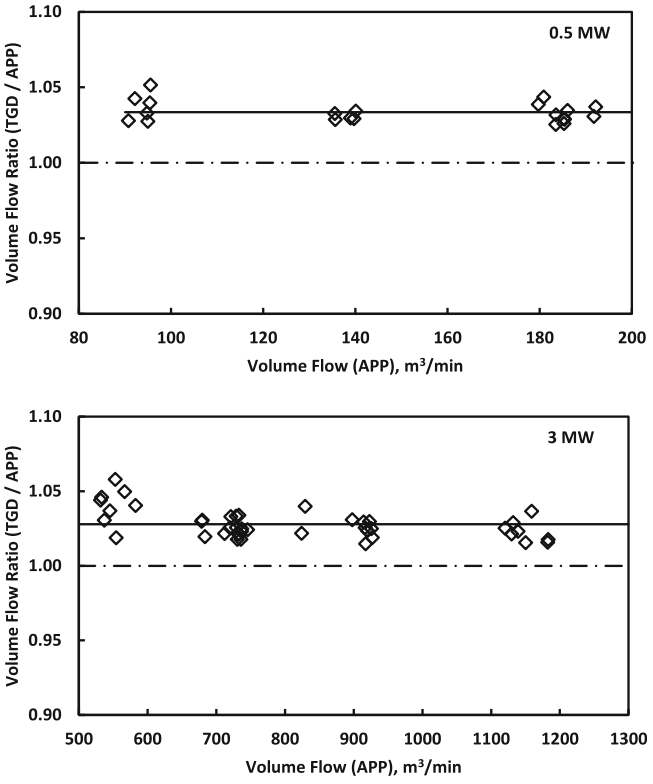


FIGURE 9 Results of flow calibration experiments at the 0.5 and 3.0 MW calorimeters. The symbols represent the ratio of average volume flow measurements (tracer gas dilution [TGD] and averaging pitot probes [APPs]). The solid line represents the average ratio over the operational range of flow for each calorimeter.

3 | RESULTS AND DISCUSSION

3.1 | In-line calibration of APPs

NFRL's exhaust ducts have more than 10 diameters of straight run upstream of each flow measurement location to allow the flow to develop a favorable distribution at the measurement station.

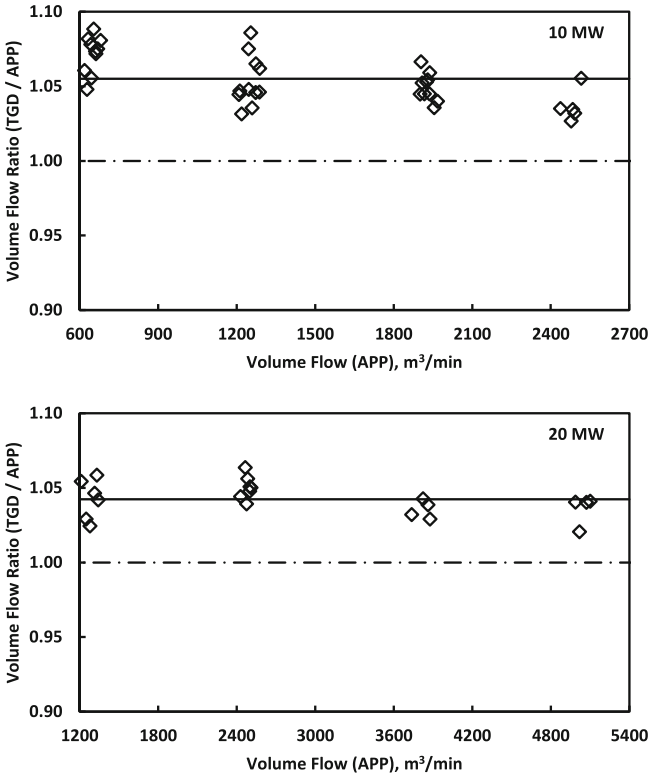


FIGURE 10 Results of flow calibration experiments at the 10 and 20 MW calorimeters. The symbols represent the ratio of average volume flow measurements (tracer gas dilution [TGD] and averaging pitot probes [APPs]). The solid line represents the average ratio over the operational range of flow for each calorimeter.

Flow conditioning methods, such as screens, straightening tubes, or disturbance plates, have not been implemented. For a fully developed exhaust flow, therefore a flow that is symmetrical in all directions of the cross section, the APPs (A and B), installed as shown in Figure 4, should measure the same gas velocity. When the ratio of the measured velocities, $V_{c,A}/V_{c,B}$, deviates from unity, an asymmetric or irregular flow is suspected.[16] The flow coefficients (K_a) provided by the manufacturer of the APPs are the most accurate for a turbulent and fully developed pipe flow. When asymmetry exists, the manufacturer recommends an in-line calibration of the probes to improve measurement accuracy.

The results of the calibration experiments are displayed in Figures 9 and 10 as the ratio of volume flow, $\dot{V}_{e,TGD}/\dot{V}_{e,APP}$. For the NFRL exhaust ducts, the ratio is greater than unity, meaning the measurement determined by the APPs consistently underestimates that determined by TGD. This is consistent with previous comparisons of heat release rate. The comparisons demonstrated oxygen consumption calorimetry measurements, which are proportional to exhaust flow, consistently under predicting the theoretical heat released by a natural gas burner as computed from fuel consumption measurements. The heat release comparison provided more evidence of the need for an in-line calibration.[16]

Figures 9 and 10 show the flow ratio as mostly constant across the operational range of flow for each calorimeter. The calibration

TABLE 2 Flow calibration constants determined from the in-line calibration of the averaging pitot probes using tracer gas dilution.

Calorimeter (MW)	$C_f \pm U_{C_f}$	Volume flow range[a] (m^3/min)
0.5	1.033 ± 0.029	90–200
3	1.028 ± 0.029	500–1300
10	1.055 ± 0.034	600–2700
20	1.042 ± 0.032	1200–5400

Note: Expanded uncertainty is reported for a 95% CI, with $k = 2.0$.
[a]Reference conditions for volume flow are 273.15 K and 101 325 Pa.

constant for flow, C_f, is therefore determined as the average ratio of volume flow, Equation (7).

$$C_f = \frac{1}{N}\sum\left(\frac{\dot{V}_{e,\mathrm{TGD}}}{\dot{V}_{e,\mathrm{APP}}}\right). \tag{7}$$

This correction is applied to flow measurements determined by the APPs. Flow calibration constants for each calorimeter (or exhaust flow path) are listed in Table 2 along with estimates of expanded uncertainty, U_{C_f}. The uncertainty estimates include the uncertainty of the TGD method. Using the calibration constant, a better determination of total flow is achieved and designated the effective exhaust velocity, Equation (8). Correcting the flow measurements with the in-line calibration improved measurement accuracy for the range of flows listed. The uncertainty of the calibration increases for flows outside of the range.

$$V_{e,\mathrm{eff}} = C_f V_{e,\mathrm{APP}}. \tag{8}$$

The results show that measurements from the APPs underestimate the volume flow at NFRL's exhaust ducts by 3%–6%. Major fire test standards (ASTM, ISO) for large fire calorimetry state accuracy requirements for flow measurements at 5%–6%.[8,9,22] The underestimate does not exceed the stated accuracy requirements for flow, therefore NFRL's exhaust flow measurements would still be in compliance with these standards without the flow calibration as demonstrated in a previous publication.[16] However, the overall research goal is to achieve the best accuracy while advancing the state-of-the-art for large-scale calorimetry.

Some fire test standards recommend using the difference in heat release rate between burner and calorimetry as the flow correction factor or overall correction factor for the oxygen consumption calorimetry measurement. In-line or in situ calibrations of flow devices is best practice when feasible. A system correction based on a comparison of calorimetry measurements is a practical solution but not the best practice to improve accuracy. It is well known that flow conditions play an important role in the performance of calorimetry measurements using oxygen consumption.[23] If flow conditions are not well characterized and reproducible, corrections based on burner outputs may not be reliable. The in-line flow calibration is more robust since it is valid for a range of flow conditions and decouples any measurement errors for the fuel consumption method from the calorimetry measurement.

3.2 | Heat release rate confirmation—Flow corrected

Experiments to confirm heat release rate values using independent measurement methods are conducted periodically in the NFRL to ensure measurement quality. The experiments are used to generate the full range of anticipated heat release rates and check that all components of the oxygen consumption calorimetry measurement are operating as anticipated. Photographs representing the experiments are shown in Figure 11.

The flow calibration demonstrated that the APP measurement underestimated the exhaust flow. This is consistent with pre-calibration results where oxygen consumption calorimetry measurements of heat release rate, $\dot{Q}_{\mathrm{OC}}$, underestimated the heat release rate computed from fuel consumption measurements for the natural gas burner, $\dot{Q}_{\mathrm{FC}}$.[16] Heat release rate data from the previous confirmation experiments were reprocessed using flow measurements corrected with the flow calibration constants. The relative difference between mean values of heat release rate measured by oxygen consumption calorimetry and mean values of the theoretical heat output, $\bar{\dot{Q}}_{\mathrm{OC}}/\bar{\dot{Q}}_{\mathrm{FC}} - 1.0$, are plotted in Figures 12 and 13, with the open symbols representing the flow-corrected results.

On average, the difference for the flow-corrected measurement is within ±1.5% for the 0.5 and 3 MW calorimeters. This is better than a factor of three less than the typical allowance of 5% among consensus standards for large fire calorimetry systems.[16] In addition, Figure 12 shows the difference is within the uncertainty of the fuel consumption measurement, 1.5%, and demonstrates improved accuracy for the oxygen consumption calorimetry measurement. For the 10 and 20 MW calorimeters, the difference for the flow-corrected measurement is within ±3.0% on average. The greatest improvement in accuracy occurred at the 10 MW calorimeter, as prior to the flow correction, the difference was greater than the 5% allowance (Figure 13). It is noted that the net heat of combustion for natural gas, 12.54 MJ/kg, was used for the oxygen consumption calorimetry measurements to compute the heat release rate for the natural gas fires (pre- and post-flow calibration). This provides greater accuracy compared to the value generally used for common materials, 13.1 MJ/kg.

Heat release rate ranged from 0.1 to 20 MW and exhaust flow ranged from 50% to 100% of each calorimeter's flow capacity, covering the range of routine operating conditions for NFRL's calorimetry system. The confirmation results demonstrate the flow calibration to be effective in reducing the discrepancy between oxygen consumption calorimetry and burner output for fires up to 20 MW. This is almost two orders of magnitude greater than the largest heat output required by the standards (0.3 MW or 30% of the maximum

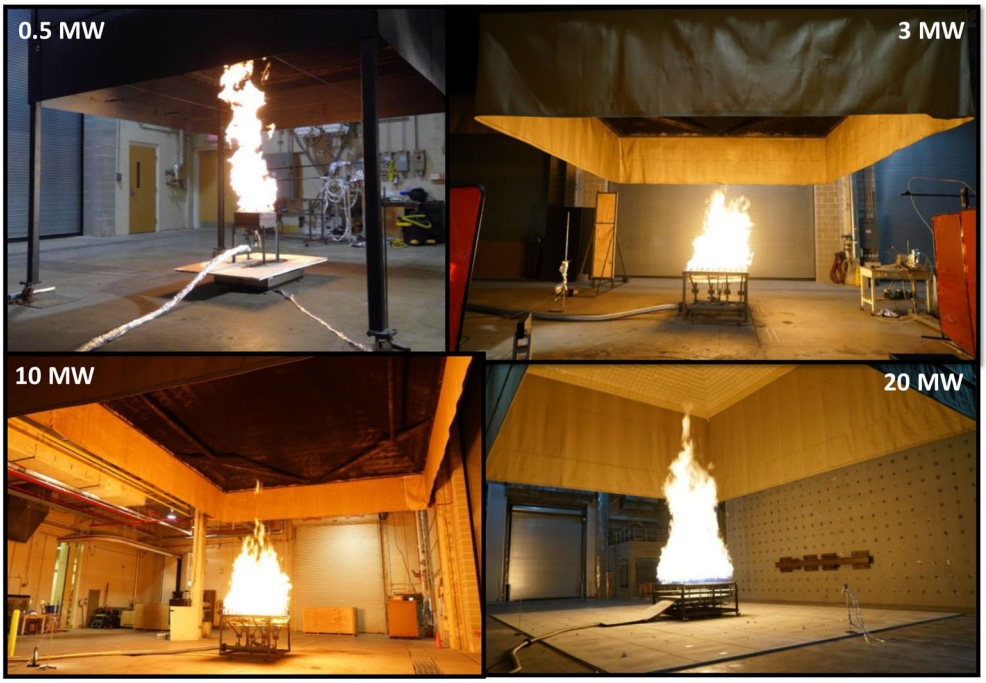


FIGURE 11 Photographs of the oxygen consumption calorimeters and natural gas burners during confirmation experiments.

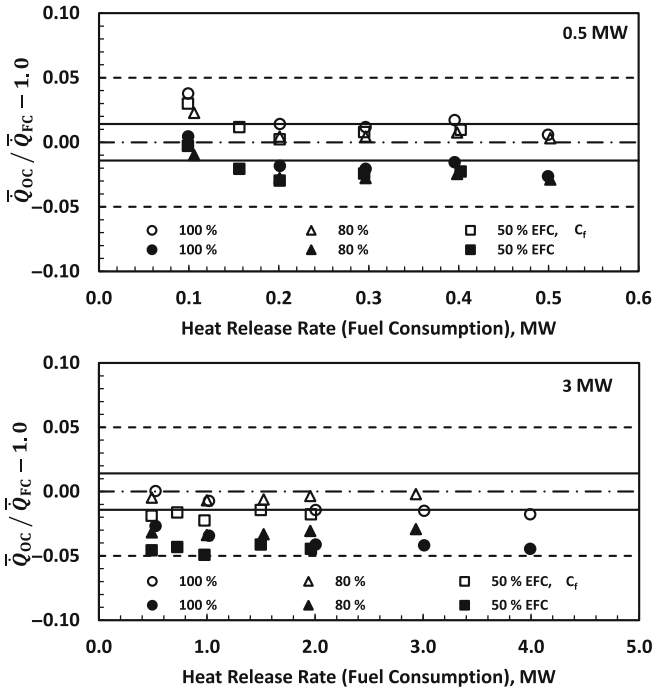


FIGURE 12 Results of the confirmation experiments for the 0.5 and 3 MW calorimeters. The dashed lines represent the relative allowable maximum difference, typical of the consensus standards; solid lines represent the expanded uncertainty (95% CI, with $k = 2.0$) of the heat release rate measurement based on fuel consumption. Symbols represent the percentage of exhaust flow capacity (EFC) for each calorimeter, while open symbols demonstrate the application of flow calibration (C_f).

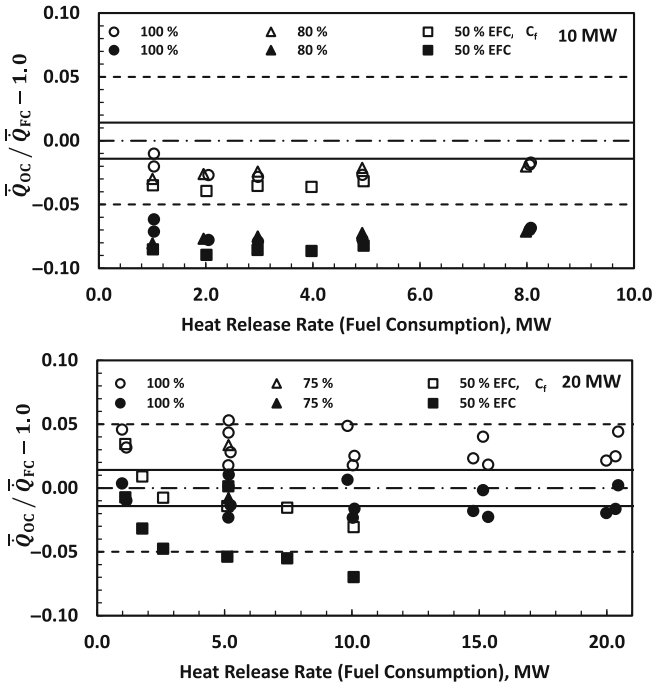


FIGURE 13 Results of the confirmation experiments for the 10 and 20 MW calorimeters. The dashed lines represent the relative allowable maximum difference, typical of the consensus standards; solid lines represent the expanded uncertainty (95% CI, with $k = 2.0$) of the heat release rate measurement based on fuel consumption. Symbols represent the percentage of exhaust flow capacity (EFC) for each calorimeter, while open symbols demonstrate the application of flow calibration (C_f).

anticipated heat release rate) during a system calibration.[16] When the anticipated heat release from the fire under study is much greater than the maximum burner output, the system correction will be based on an extrapolation and introduces greater uncertainty. ASTM E2067 and ISO 24473 acknowledge the potential error due to extrapolation and recommend using higher burner outputs during the system

calibration to improve accuracy.[8,9] The results demonstrate that a well-designed calibration of the flow measurement is a better practice for improving the overall accuracy of the heat release rate measurement as determined by oxygen consumption calorimetry.

4 | CONCLUSIONS

Accurately measuring exhaust flow has long been a major technical challenge for achieving accurate heat release rate measurements in intermediate to large-scale fire experiments. The evidence can be traced to multiple studies of measurement uncertainty for heat release rate and the common requirement among consensus standards for large fire testing to calibrate the heat release rate measurement against a known heat output, thereby correcting any measurement bias due to flow measurement error. For the first time, TGD, a standard test method for determining volume flow in ducts, has been applied to calibrate the devices for determining exhaust flow in a large-scale open calorimetry system. The flow measurement devices used in this study, APPs, underestimated the exhaust flow when compared to the reference flow monitoring. Flow calibration constants determined with the calibration experiments increased the exhaust flow measurements by 3%–6%. The improved accuracy for the flow measurement translates directly to improved accuracy for measurements of heat release rate. The discrepancy between the heat release rate measured by oxygen consumption calorimetry and the heat output of a natural gas burner was reduced to under 5%, the typical allowance among consensus standards for large-scale calorimetry. The flow calibration proved to be effective in improving accuracy for heat release rate measurements ranging from 0.2 to 20 MW, therefore demonstrating in-line (or in situ) calibrations of flow devices as best practice. It is well known that flow conditions play an important role in the performance of calorimetry measurements using oxygen consumption. If flow conditions are not consistent or reproducible, corrections based on the heat output of a burner may not be reliable. An in-line flow calibration is more robust. It can be valid for a wide range of flow conditions and decouples the calorimetry measurement from errors in the fuel consumption measurements as well as extrapolation uncertainty. The results of the study provide evidence that a well-designed calibration of the exhaust flow measurement is a better practice for improving the overall accuracy of heat release rate measurements in intermediate to large-scale open calorimetry systems.

CONFLICT OF INTEREST STATEMENT

The author declares there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTE

[1] Certain commercial entities, equipment, or materials may be identified in this document to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

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