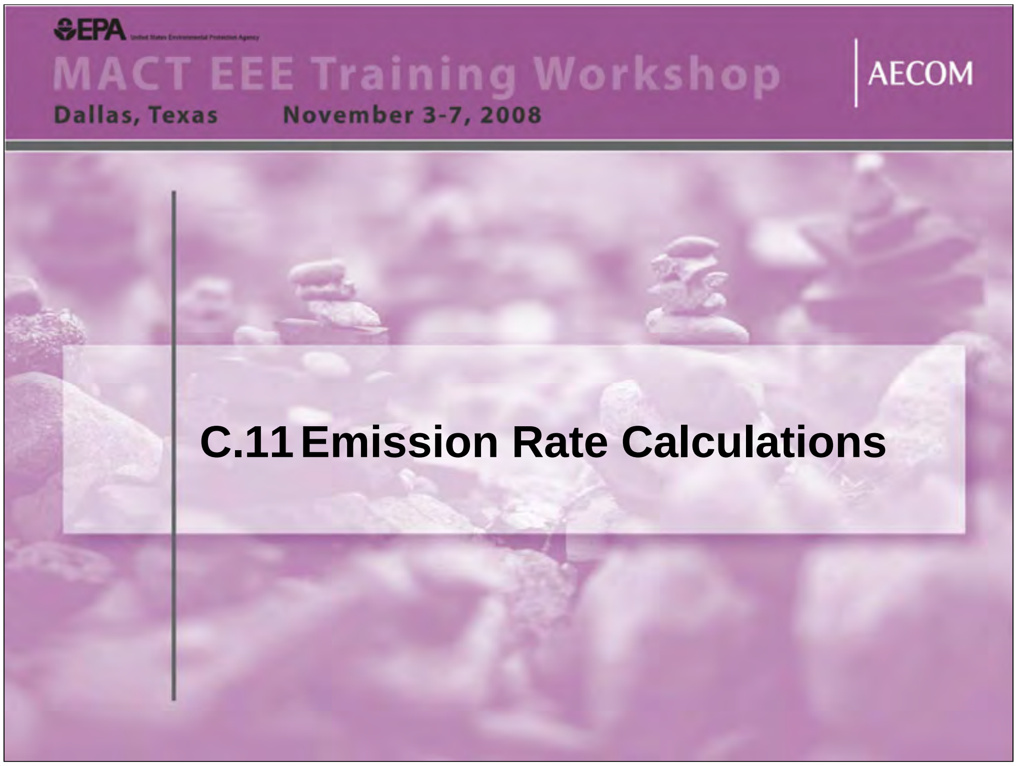

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MACT EEE Training Workshop

Dallas, Texas November 3-7, 2008

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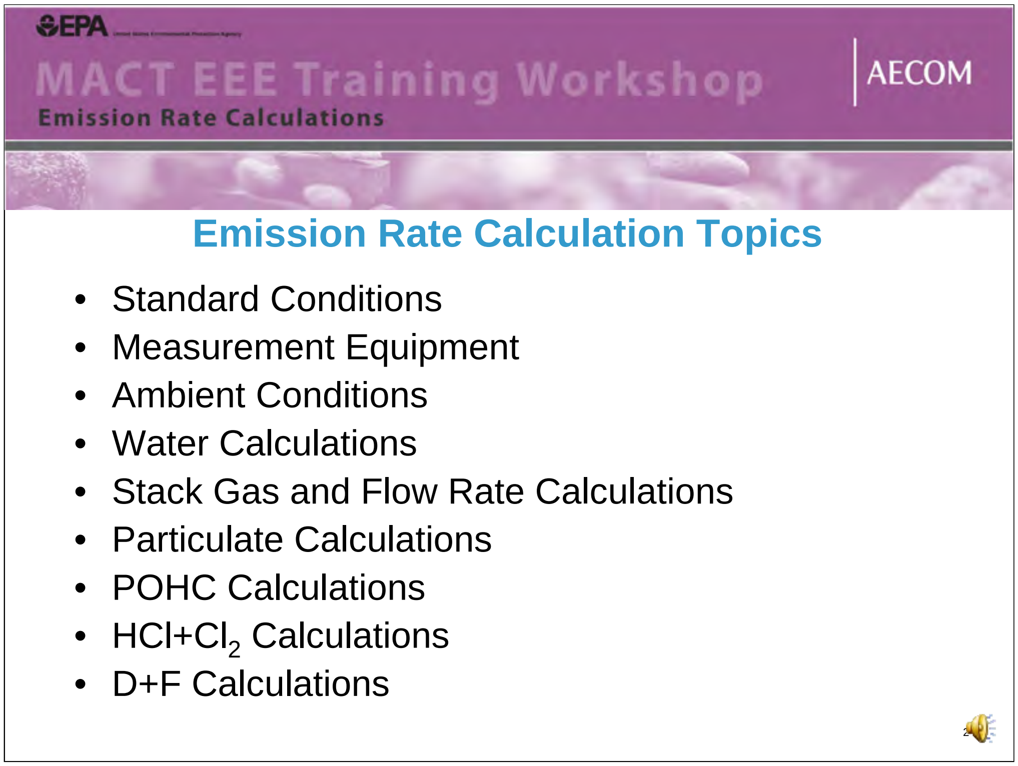
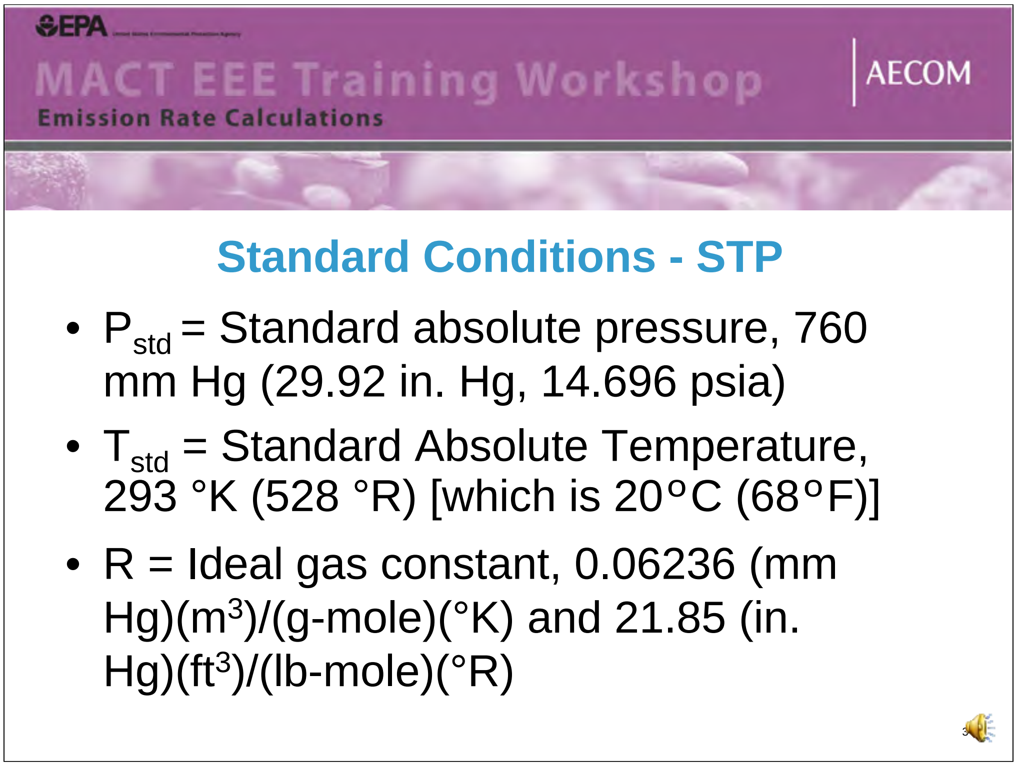
C.11 Emission Rate Calculations



Emission Rate Calculation Topics

- Standard Conditions
- Measurement Equipment
- Ambient Conditions
- Water Calculations
- Stack Gas and Flow Rate Calculations
- Particulate Calculations
- POHC Calculations
- $HCl+Cl_2$ Calculations
- D+F Calculations

In this module, we will address calculations associated with emissions, mainly from stack testing activities. We will review standard conditions, measurement equipment, ambient conditions, calculations associated with water vapor, stack gas and flow rates, particulate, principal organic hazardous constituents (POHC), hydrogen chloride and chlorine, identified as $HCl+CL_2$, and dioxin and furans, identified as D+F.



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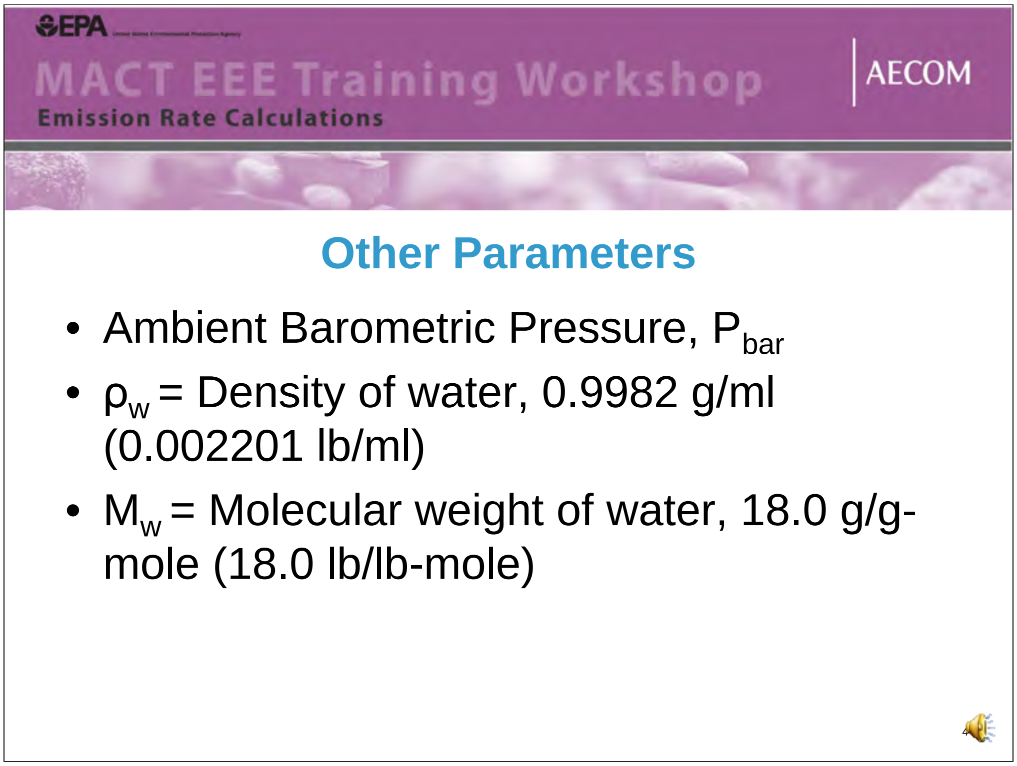
Standard Conditions - STP

- P_{std} = Standard absolute pressure, 760 mm Hg (29.92 in. Hg, 14.696 psia)
- T_{std} = Standard Absolute Temperature, 293 °K (528 °R) [which is 20°C (68°F)]
- R = Ideal gas constant, 0.06236 (mm Hg)(m^3)/(g-mole)(°K) and 21.85 (in. Hg)(ft^3)/(lb-mole)(°R)

Standard Conditions, sometimes referred to as standard temperature and pressure, or STP, are the conditions to which gases are referred so that comparisons can be made at different conditions. Standard pressure is 760 millimeters of mercury, which is equivalent to 29.92 inches of mercury and 14.696 pounds per square inch absolute. Standard temperature is 68 degrees Fahrenheit, which is the same as 20 degrees Celsius, 293 degrees Kelvin and 528 degrees Rankin.

Another parameter used in calculations of gases is the Ideal Gas Constant, represented as R. This constant is 0.06236 (mm Hg)(m^3)/(g-mole)(°K) or 21.85 (in. Hg)(ft^3)/(lb-mole)(°R), and is a constant, therefore, it does not change.

The most important part of these types of calculations is to make sure that the units of measurement are consistent.



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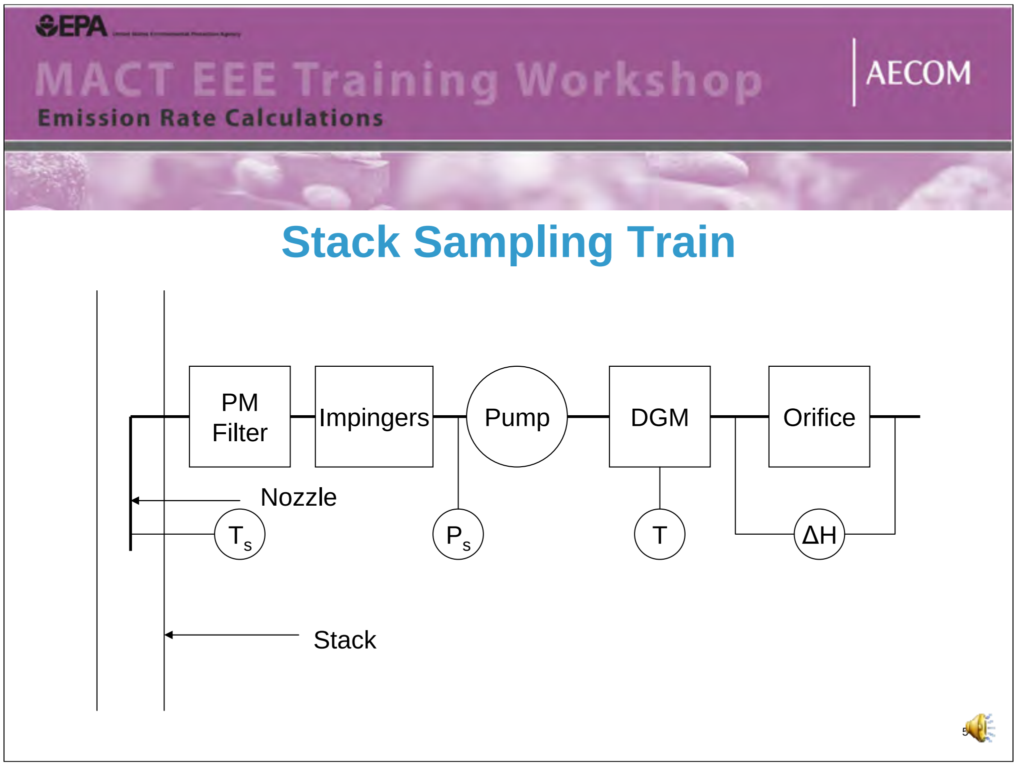
Other Parameters

- Ambient Barometric Pressure, P_{bar}
- ρ_w = Density of water, 0.9982 g/ml (0.002201 lb/ml)
- M_w = Molecular weight of water, 18.0 g/g-mole (18.0 lb/lb-mole)

Other parameters used in stack gas calculations are barometric pressure, density of water, and the molecular weight of water. Barometric pressure is the ambient pressure measured during a test so that the results can later be referenced back to standard pressure. The density and molecular weight of water are constants in these calculations and are as listed in the slide.



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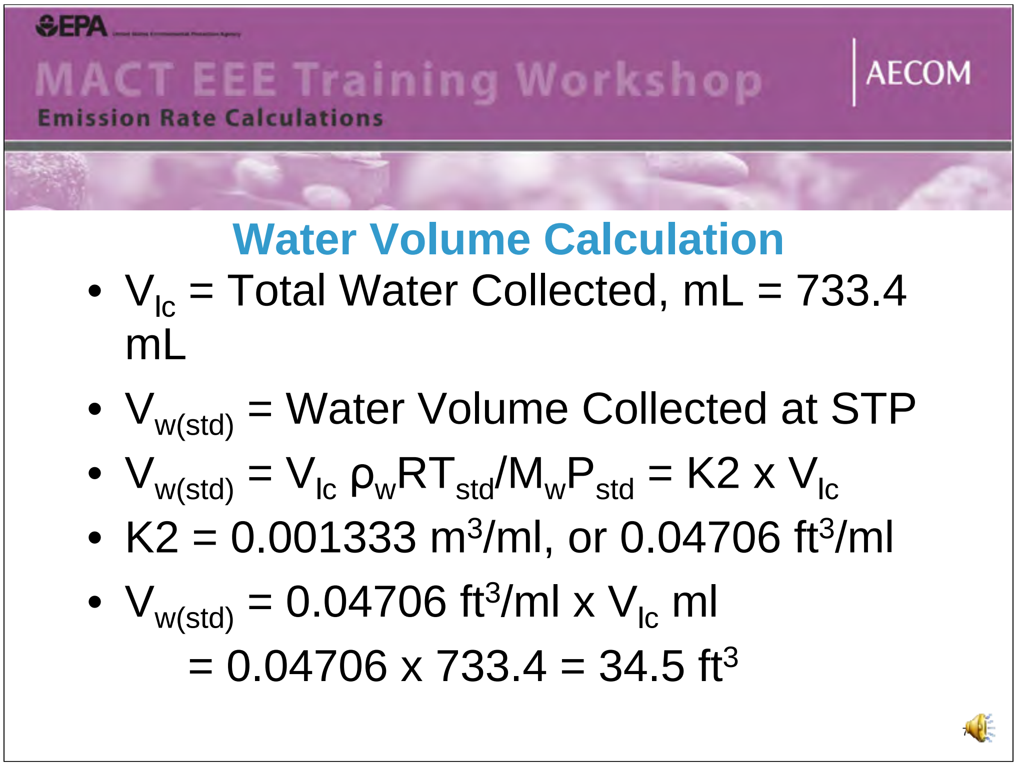
Stack Sampling Train

This diagram depicts a stack sampling train to provide a visual understanding of the placement of measurement devices during a stack test. The parameters indicated will be discussed further in later slides.

Measurement Equipment Parameters

- Nozzle Diameter, D_N
- Dry Gas Meter (DGM) Calibration Factor, C_{DGM}
- Pitot Coefficient, C_p

Several parameters are dependant on the sampling equipment used. The nozzle diameter, dry gas meter calibration factor and pitot tube coefficient are parameters that are based on the equipment used during a specific test.



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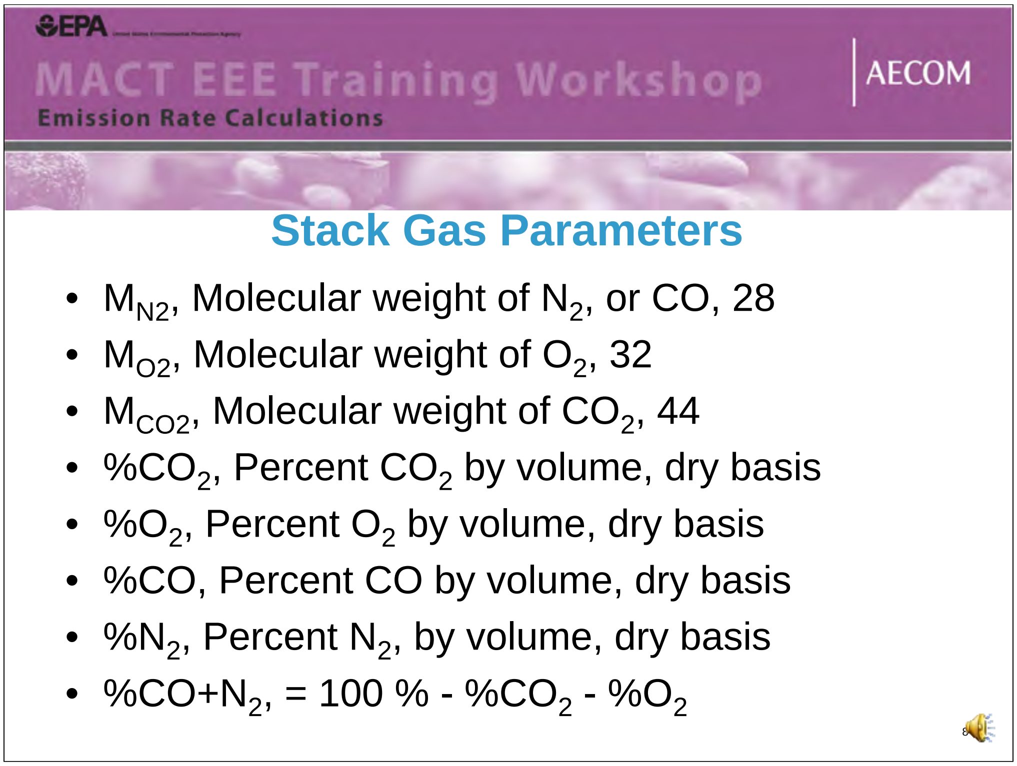
Water Volume Calculation

- V_{lc} = Total Water Collected, mL = 733.4 mL
- $V_{w(std)}$ = Water Volume Collected at STP
- $V_{w(std)} = V_{lc}\ \rho_w R T_{std} / M_w P_{std} = K2 \times V_{lc}$
- $K2 = 0.001333\ m^3/ml$, or $0.04706\ ft^3/ml$
- $V_{w(std)} = 0.04706\ ft^3/ml \times V_{lc}\ ml$
  $= 0.04706 \times 733.4 = 34.5\ ft^3$

We will begin the calculations with the water volume calculations. First the total water collected in impingers during the test, V_{lc} is obtained from the test data. The water volume collected referred to STP, $V_{W(std)}$ is calculated by the presented formula, which is reduced to a constant, K2, times the total water collected. The resulting volume, 34.5 cubic feet, represents the amount of water vapor in the gas stream during the test.



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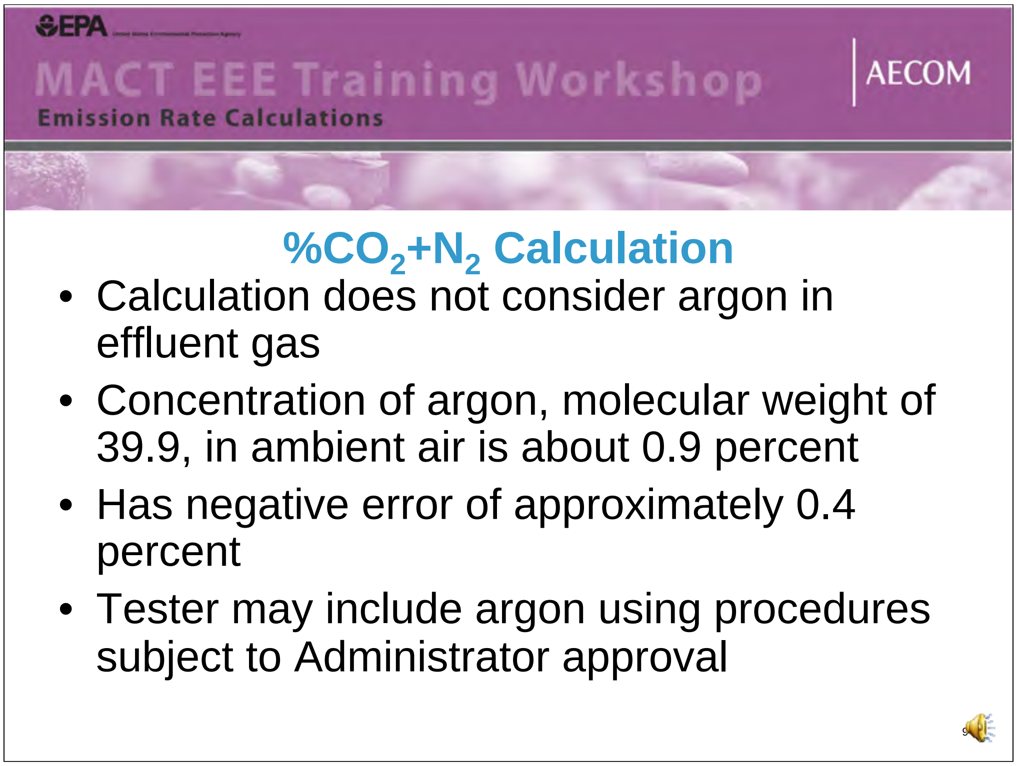
Stack Gas Parameters

- M_{N2}, Molecular weight of N_2, or CO, 28
- M_{O2}, Molecular weight of O_2, 32
- M_{CO2}, Molecular weight of CO_2, 44
- $\%CO_2$, Percent CO_2 by volume, dry basis
- $\%O_2$, Percent O_2 by volume, dry basis
- %CO, Percent CO by volume, dry basis
- $\%N_2$, Percent N_2, by volume, dry basis
- $\%CO+N_2$, = $100\ \% - \%CO_2 - \%O_2$

Other stack gas parameters are molecular weight and percent concentration of the major gas constituents nitrogen, carbon monoxide, oxygen and carbon dioxide. Of these, % Oxygen and % carbon dioxide are measured in the stack during the test. Normally the factor representing the % nitrogen and % carbon monoxide are determined by the equation presented in the slide.



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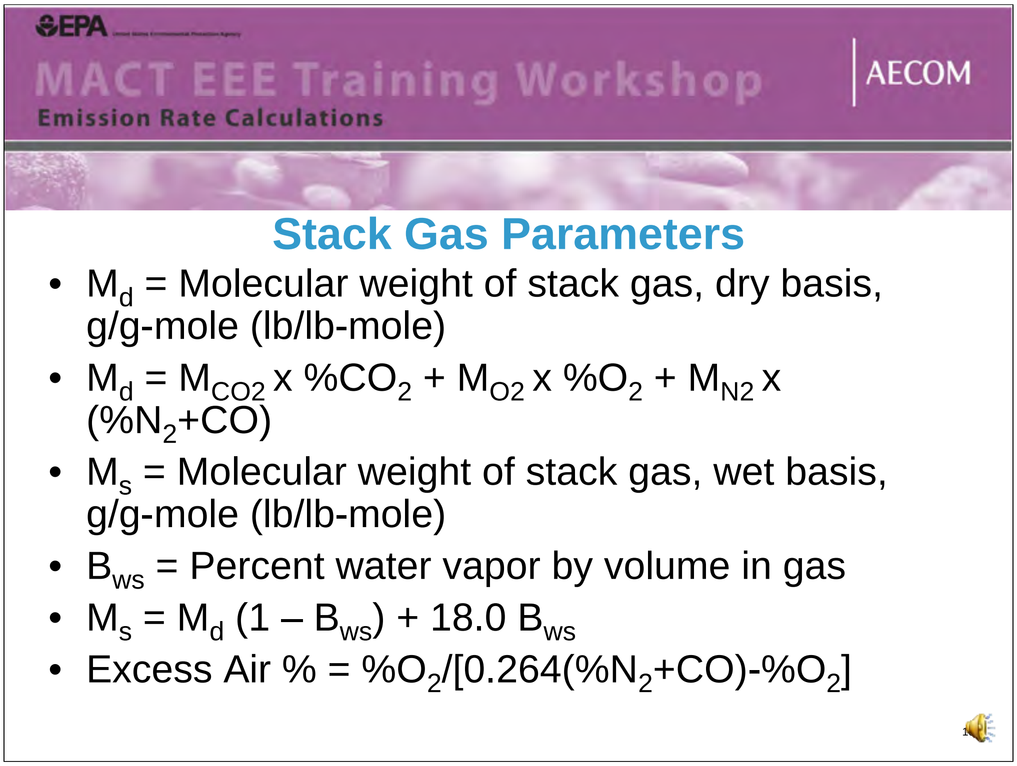
%CO_2+N_2 Calculation

- Calculation does not consider argon in effluent gas
- Concentration of argon, molecular weight of 39.9, in ambient air is about 0.9 percent
- Has negative error of approximately 0.4 percent
- Tester may include argon using procedures subject to Administrator approval

The calculation of percent carbon dioxide and nitrogen does not consider the argon that is present in air. Argon represents about 0.9 percent of air, therefore, not considering this constituent introduces a negative error of approximately 0.4 percent. This small error is normally disregarded in stack testing, however, a tester may include argon by obtaining approval from the Administrator to use a specific procedure.



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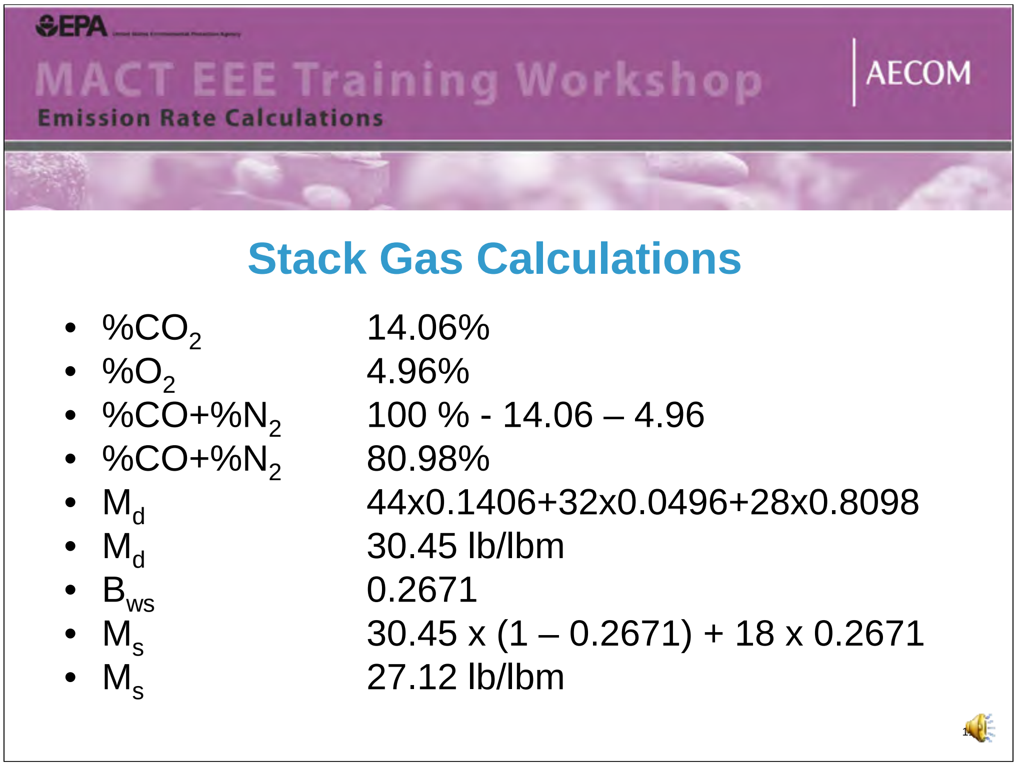
Stack Gas Parameters

- M_d = Molecular weight of stack gas, dry basis, g/g-mole (lb/lb-mole)
- $M_d = M_{CO2} \times \%CO_2 + M_{O2} \times \%O_2 + M_{N2} \times (\%N_2+CO)$
- M_s = Molecular weight of stack gas, wet basis, g/g-mole (lb/lb-mole)
- B_{ws} = Percent water vapor by volume in gas
- $M_s = M_d (1 – B_{ws}) + 18.0 B_{ws}$
- Excess Air % = $\%O_2/[0.264(\%N_2+CO)-\%O_2]$

The molecular weight of stack gas, on a dry basis, in units of measure of grams per gram-mole or pounds per pound-mole, is calculated by the presented formula for M_d. The molecular weight of stack gas, on a wet basis, in units of measure of grams per gram-mole or pounds per pound-mole, is calculated by the presented formula for M_s. B_{ws} is the portion by volume of water vapor in the stack gas. As can be seen by the formula for wet gas molecular weight, the calculation is based on the amount of water vapor in the gas stream.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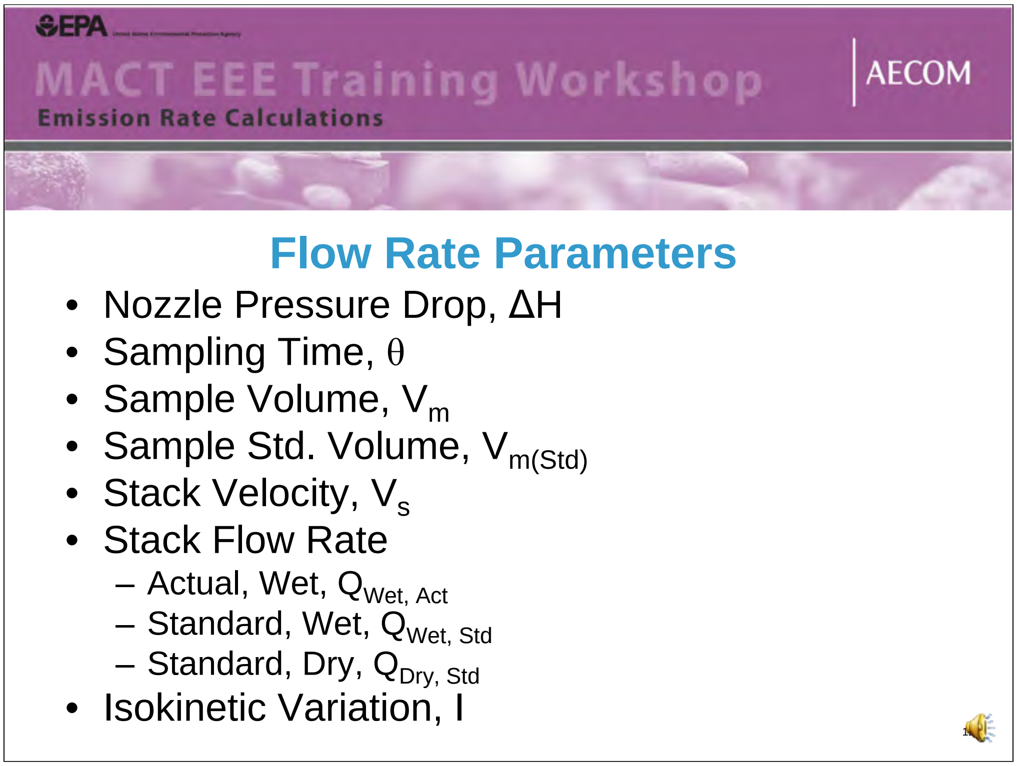
Stack Gas Calculations

$\%CO_2$	14.06%
$\%O_2$	4.96%
$\%CO+\%N_2$	100 % - 14.06 – 4.96
$\%CO+\%N_2$	80.98%
M_d	44x0.1406+32x0.0496+28x0.8098
M_d	30.45 lb/lbm
B_{ws}	0.2671
M_s	30.45 x (1 – 0.2671) + 18 x 0.2671
M_s	27.12 lb/lbm

Using sample test data, the calculations are made as shown on the slide. Percent carbon dioxide and oxygen are determined from testing, and from those data is percent carbon monoxide plus nitrogen calculated. With these data, the molecular weight of the stack gas on a dry basis is calculated. The testing resulted in a B_{ws} of 0.2671 and from this amount the molecular weight of the stack gas on a wet basis is calculated.



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Emission Rate Calculations

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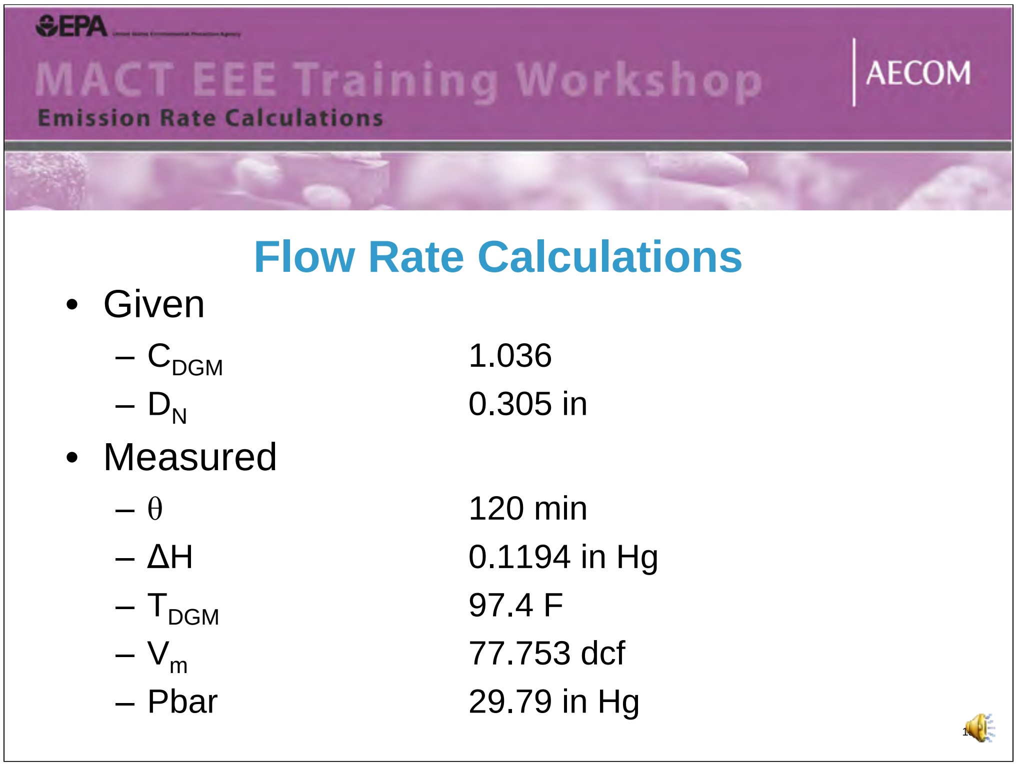
Flow Rate Parameters

- Nozzle Pressure Drop, ΔH
- Sampling Time, θ
- Sample Volume, V_m
- Sample Std. Volume, $V_{m(Std)}$
- Stack Velocity, V_s
- Stack Flow Rate
  - – Actual, Wet, $Q_{Wet,\ Act}$
  - – Standard, Wet, $Q_{Wet,\ Std}$
  - – Standard, Dry, $Q_{Dry,\ Std}$
- Isokinetic Variation, I

This slide lists the flow rate parameters, some of which are measured and some are calculated by data from measurements. Nozzle Pressure Drop, Sampling Time, Sample Volume are measured parameters and the sample standard volume, stack velocity stack flow rate and isokinetic variation are calculated.



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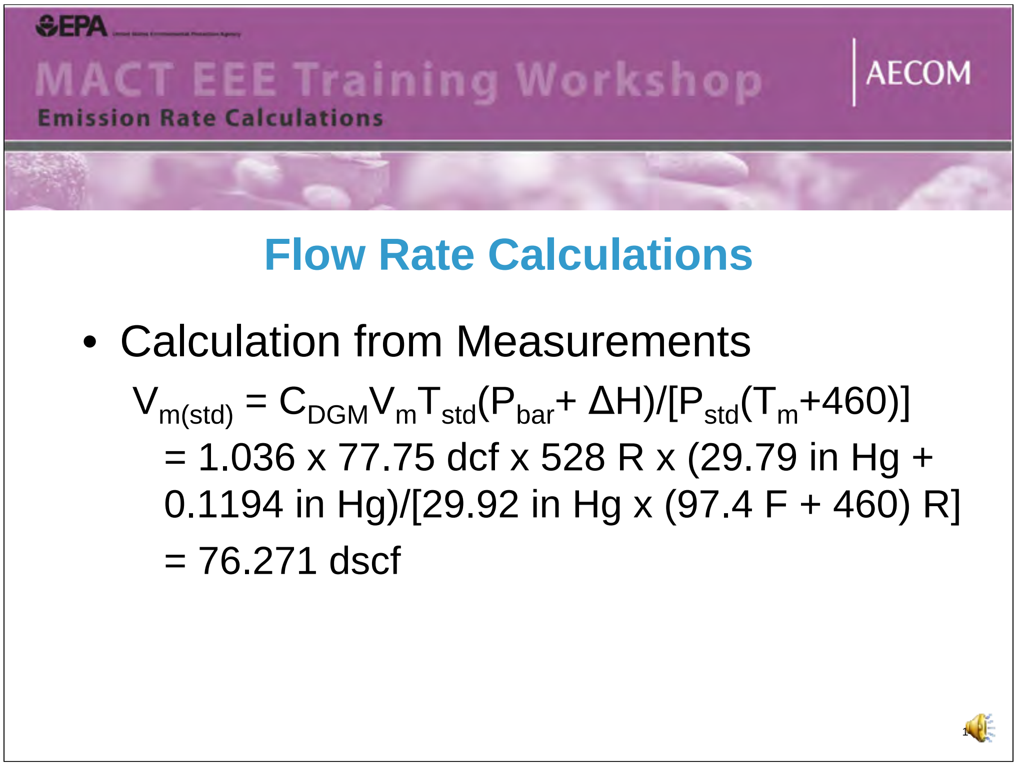
Flow Rate Calculations

- Given
  - – C_{DGM} 1.036
  - – D_N 0.305 in
- Measured
  - – θ 120 min
  - – ΔH 0.1194 in Hg
  - – T_{DGM} 97.4 F
  - – V_m 77.753 dcf
  - – Pbar 29.79 in Hg

For an example calculation, this slide lists the parameters of the test equipment, the dry gas meter calibration factor and the nozzle diameter. The measured values are the sampling time, the pressure drop, the temperature of the dry gas meter, the volume of gas measured during the test and the barometric pressure.



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Emission Rate Calculations

Flow Rate Calculations

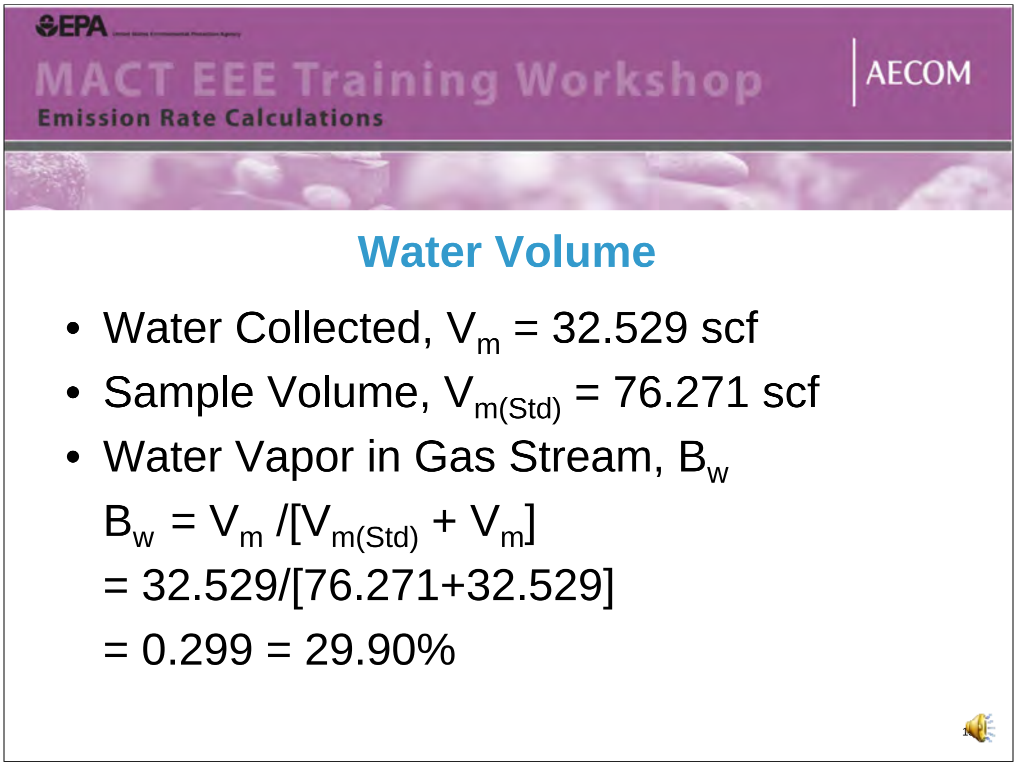
- Calculation from Measurements

$V_{m(std)} = C_{DGM} V_m T_{std}(P_{bar} + \Delta H)/[P_{std}(T_m + 460)]$

$= 1.036 \times 77.75 \text{ dcf} \times 528 \text{ R} \times (29.79 \text{ in Hg} + 0.1194 \text{ in Hg})/[29.92 \text{ in Hg} \times (97.4 \text{ F} + 460) \text{ R}]$

$= 76.271 \text{ dscf}$

The first value to calculate is the flow rate during the test. The equation shown in the slide is used to calculate the dry standard cubic feet of gas that was measured during the test, which is calculated to be 76.271 dry standard cubic feet.



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Emission Rate Calculations

Water Volume

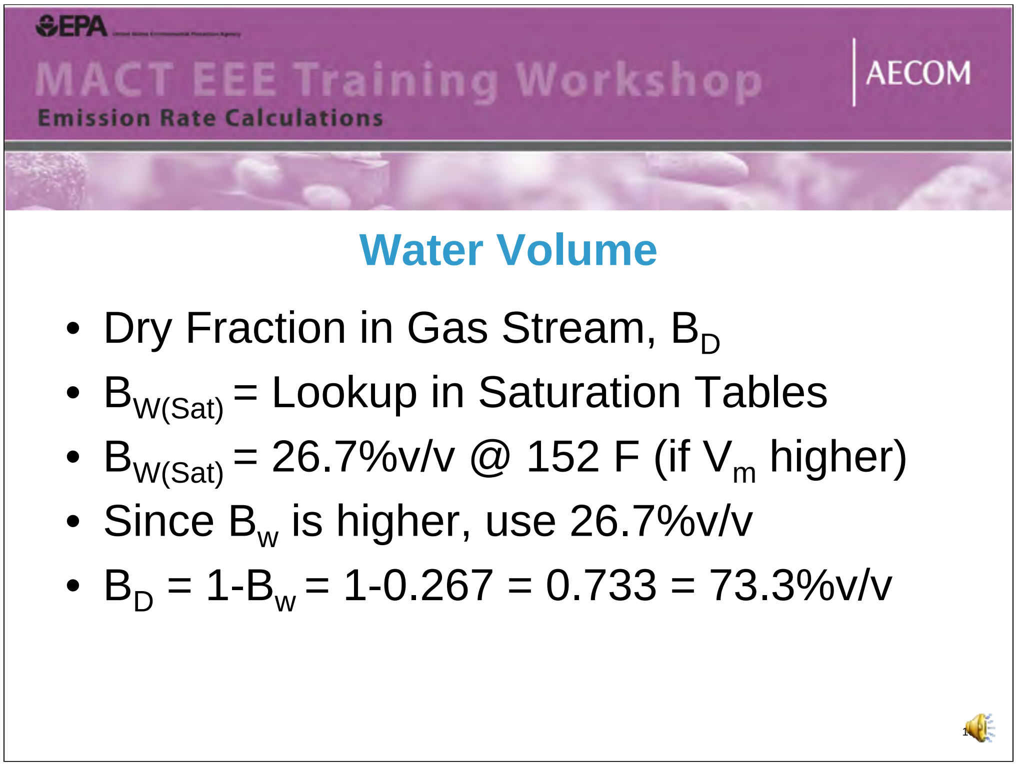
- Water Collected, V_m = 32.529 scf
- Sample Volume, $V_{m(Std)}$ = 76.271 scf
- Water Vapor in Gas Stream, B_w

$B_w = V_m / [V_{m(Std)} + V_m]$

$= 32.529/[76.271+32.529]$

$= 0.299 = 29.90\%$

The water collected during the test was 32.529 standard cubic feet and the sample volume, calculated earlier, is 76.271 standard cubic feet. The water vapor in the gas can then be calculated by the provided equation using the water collected and the sample volume. The resulting water vapor percentage is 29.90%.



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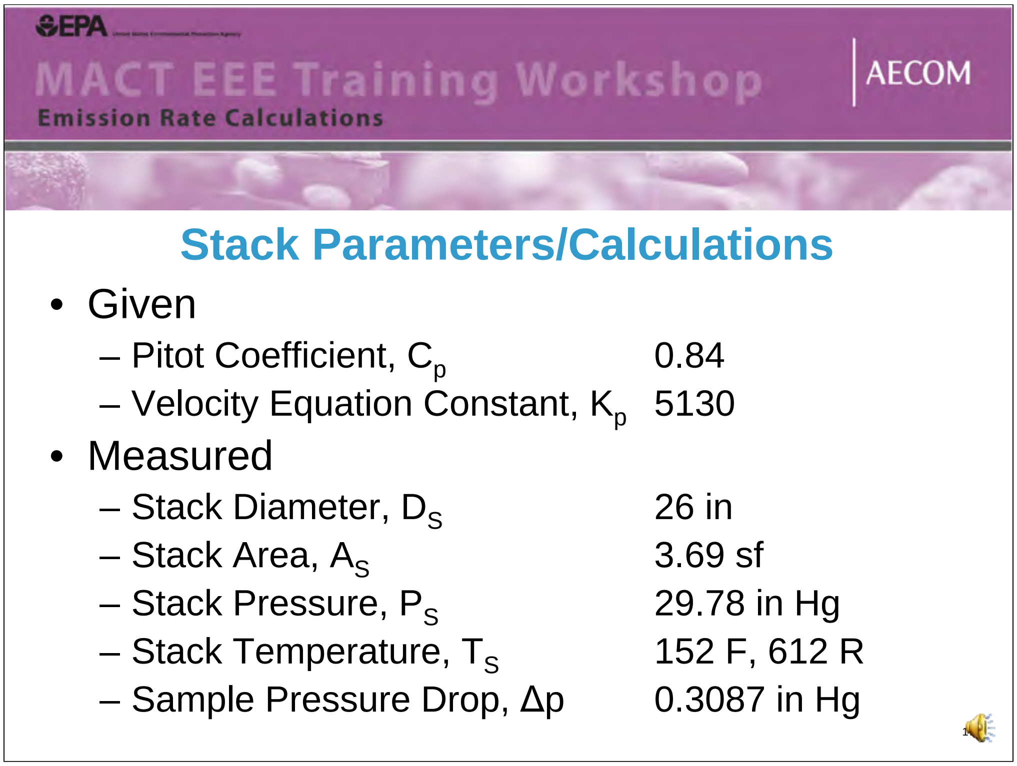
Water Volume

- Dry Fraction in Gas Stream, B_D
- $B_{W(Sat)}$ = Lookup in Saturation Tables
- $B_{W(Sat)}$ = 26.7%v/v @ 152 F (if V_m higher)
- Since B_w is higher, use 26.7%v/v
- $B_D = 1\text{-}B_w = 1\text{-}0.267 = 0.733 = 73.3\%$v/v

Further calculations of water volume in the gas involved calculation of the dry fraction or percentage of water in the gas stream. To make this calculation, the water vapor fraction when the gas is saturated with water vapor is needed. This value is determined using saturation tables and for 152 degrees F, the saturated fraction is 0.267 or 26.7%. Because the calculated value of B_w, the percentage of water vapor in the gas is higher than the saturated value, the saturated value is used. The saturated value is used because the fraction of water vapor cannot exceed the saturated fraction since the water would condense beyond this point. The calculation results in a dry fraction of 0.733 or 73.3%.



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Emission Rate Calculations

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Stack Parameters/Calculations

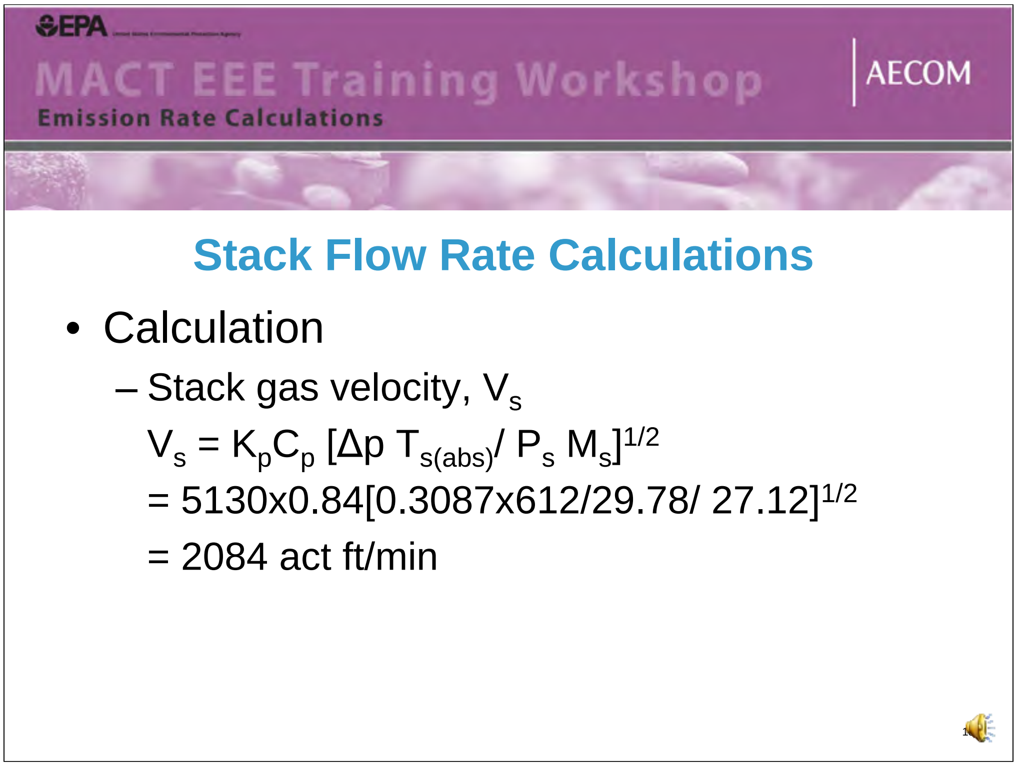
- Given

– Pitot Coefficient, C_p	0.84
– Velocity Equation Constant, K_p	5130

- Measured

– Stack Diameter, D_S	26 in
– Stack Area, A_S	3.69 sf
– Stack Pressure, P_S	29.78 in Hg
– Stack Temperature, T_S	152 F, 612 R
– Sample Pressure Drop, Δp	0.3087 in Hg

Further stack calculations use the pitot coefficient, C_p, and the velocity equation constant, K_p, which depends on the units of measure used. Measured parameters are stack diameter, D_s, stack area, As calculated using the stack diameter, the stack pressure, P_s, the stack temperature, T_s, and the pressure drop across the measuring device, delta P.



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Stack Flow Rate Calculations

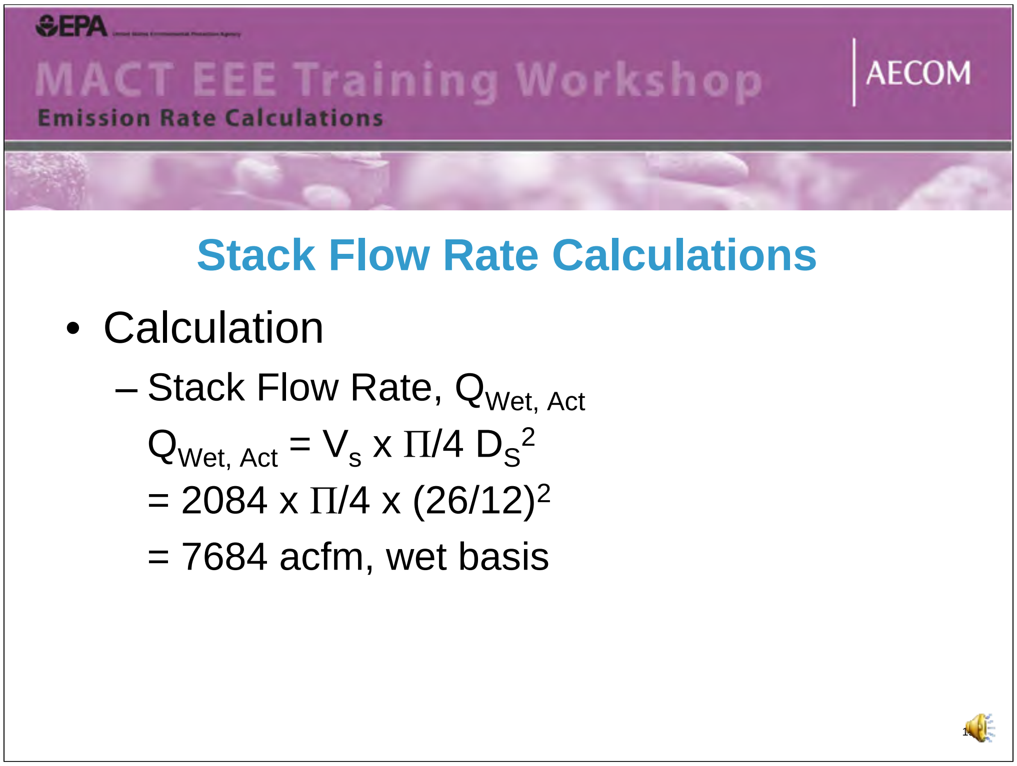
- Calculation
  - Stack gas velocity, V_s

    $V_s = K_p C_p\ [\Delta p\ T_{s(abs)} / P_s\ M_s]^{1/2}$

    $= 5130 \times 0.84[0.3087 \times 612/29.78/\ 27.12]^{1/2}$

    $= 2084$ act ft/min

With the values from the previous slide, the stack gas velocity, Vs, is calculated using the presented equation. The calculation results in a stack gas velocity of 2084 actual feet per minute.



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Stack Flow Rate Calculations

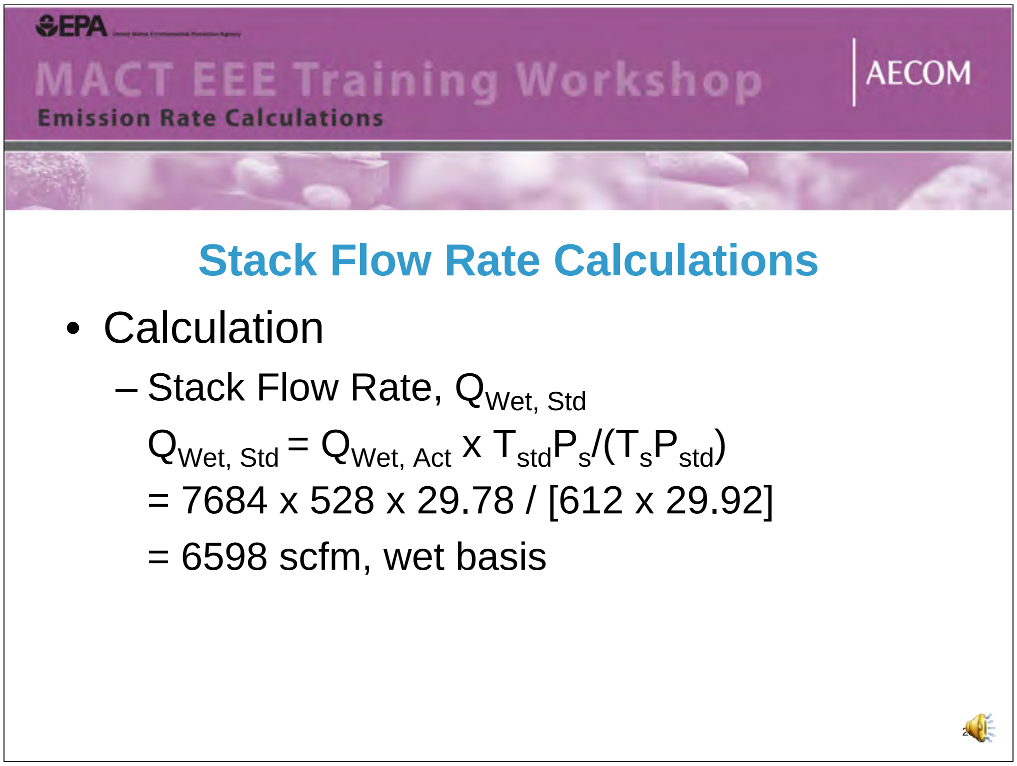
- Calculation
  - Stack Flow Rate, $Q_{Wet,\ Act}$

    $Q_{Wet,\ Act} = V_s \times \Pi/4\ D_S^2$

    $= 2084 \times \Pi/4 \times (26/12)^2$

    $= 7684$ acfm, wet basis

After the stack gas velocity has been calculated, as discussed on the last slide, the stack flow rate can be calculated. The flow rate is calculated as the stack gas velocity, V_s, times the cross-sectional area of the stack at the point where the velocity measurements were made. For this example, the calculation results in 7684 ACTUAL cubic feet per minute on a wet basis.



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Emission Rate Calculations

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Stack Flow Rate Calculations

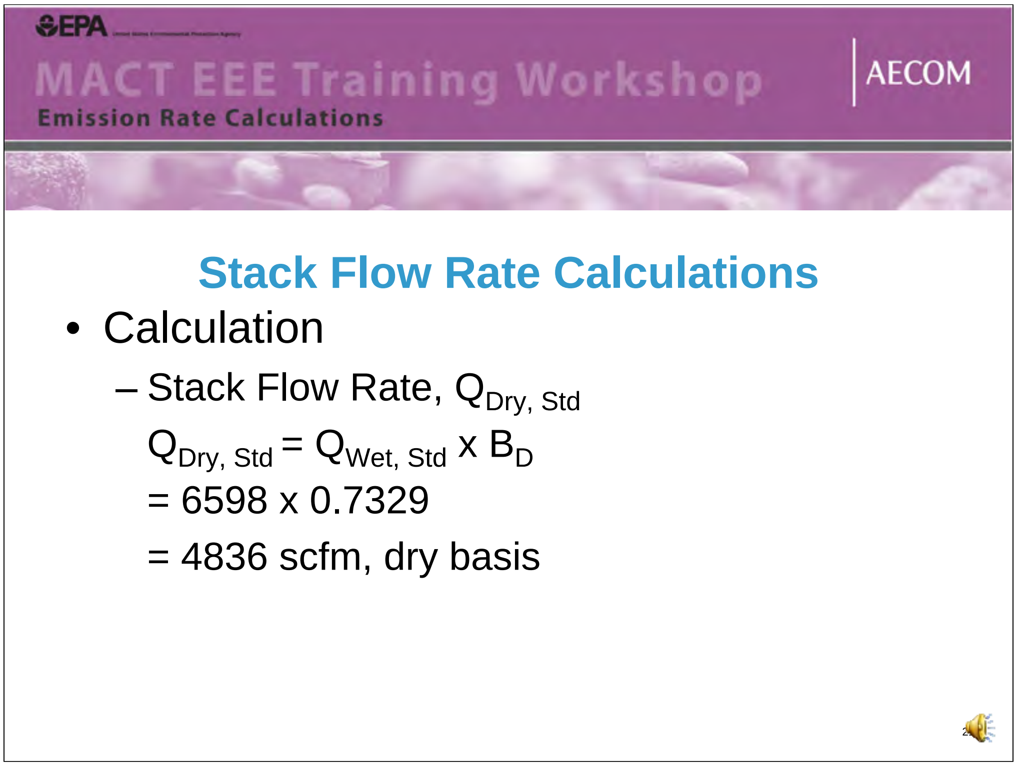
- Calculation
  - Stack Flow Rate, $Q_{Wet,\ Std}$

    $Q_{Wet,\ Std} = Q_{Wet,\ Act} \times T_{std}P_s/(T_sP_{std})$

    $= 7684 \times 528 \times 29.78 / [612 \times 29.92]$

    = 6598 scfm, wet basis

The actual stack flow rate is then referred to standard conditions by the equation presented in the slide. The calculation results in a stack flow rate of 6598 standard cubic feet per minute on a wet basis.



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Emission Rate Calculations

Stack Flow Rate Calculations

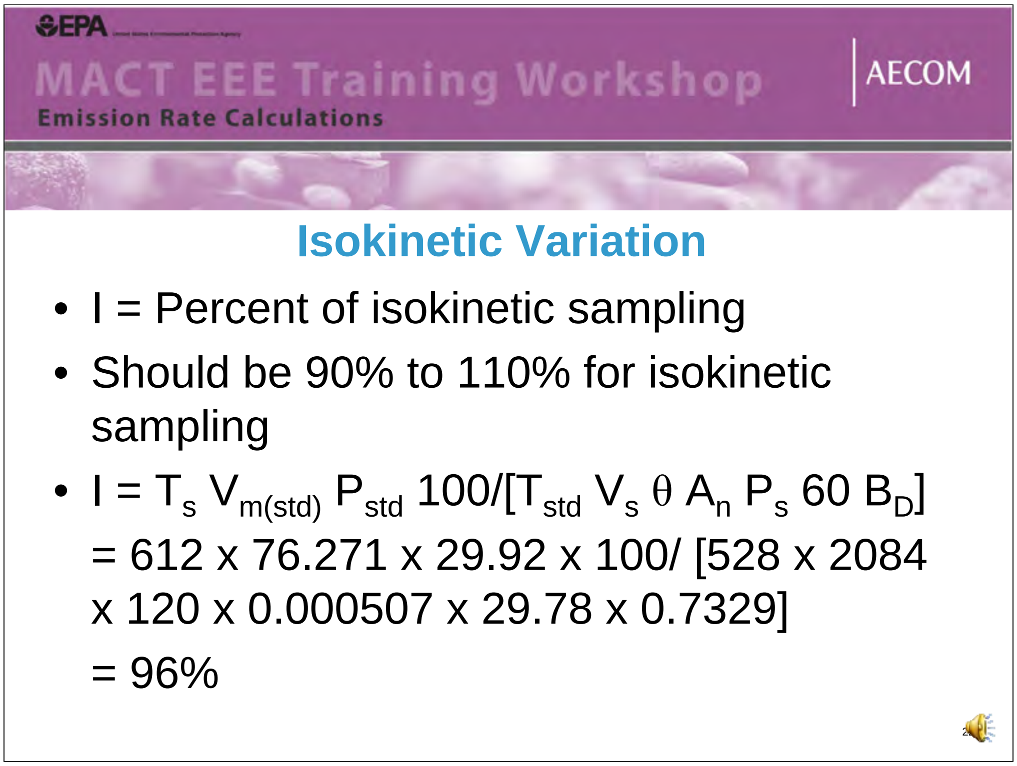
- Calculation
  - Stack Flow Rate, $Q_{Dry,\ Std}$

    $Q_{Dry,\ Std} = Q_{Wet,\ Std} \times B_D$

    $= 6598 \times 0.7329$

    = 4836 scfm, dry basis

The stack flow rate on a dry basis is then calculated. The dry flow rate is determined by multiplying the standard flow rate on a wet basis by the dry fraction of gas, B_D. The calculation results in a stack flow rate of 4836 standard cubic feet per minute on a dry basis.



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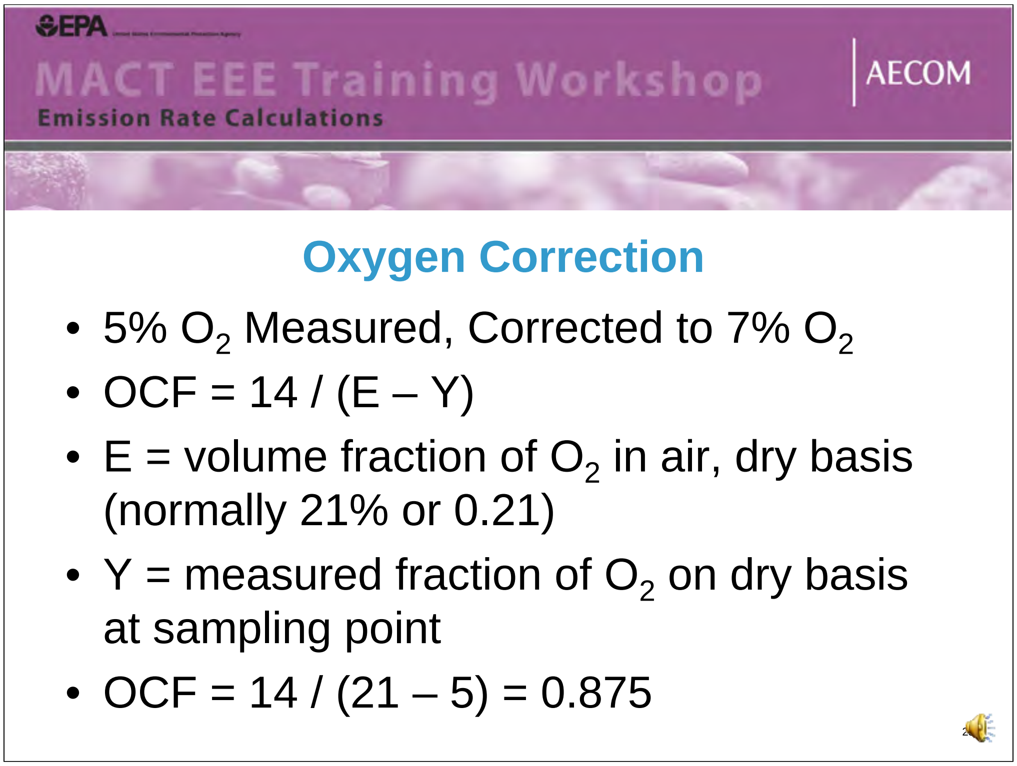
Isokinetic Variation

- I = Percent of isokinetic sampling
- Should be 90% to 110% for isokinetic sampling
- $I = T_s V_{m(std)} P_{std} 100/[T_{std} V_s \theta A_n P_s 60 B_D]$
  $= 612 \times 76.271 \times 29.92 \times 100/ [528 \times 2084 \times 120 \times 0.000507 \times 29.78 \times 0.7329]$
  $= 96\%$

Another important term that is used in stack testing is Isokinetic Variation, represented by I. The sample collected from the stack must be done under isokinetic conditions. As defined in 40 CFR Part 60, *Isokinetic sampling* means sampling in which the linear velocity of the gas entering the sampling nozzle is equal to that of the undisturbed gas stream at the sample point. For a test to be acceptable, the Isokinetic Variation must be between 90 and 110 percent. The equation given in the slide is used to calculate the Isokinetic Variation and, for the example, the calculation resulted in isokinetic variation of 96 percent, therefore, the test was acceptable.



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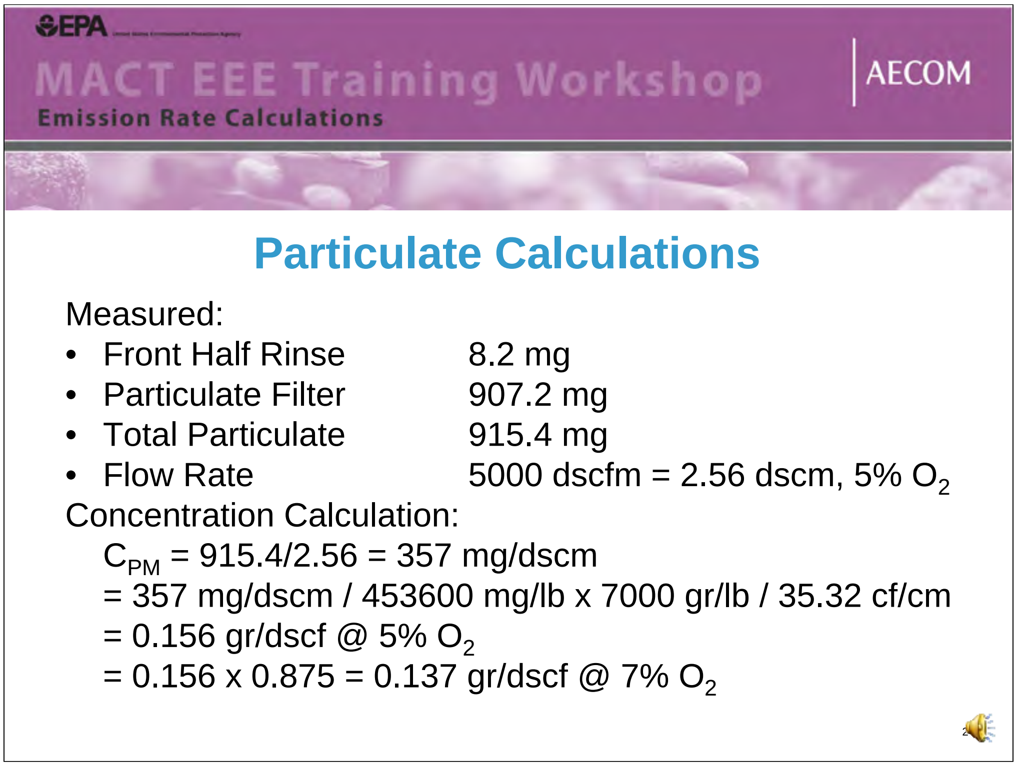
Oxygen Correction

- 5% O_2 Measured, Corrected to 7% O_2
- OCF = 14 / (E – Y)
- E = volume fraction of O_2 in air, dry basis (normally 21% or 0.21)
- Y = measured fraction of O_2 on dry basis at sampling point
- OCF = 14 / (21 – 5) = 0.875

Many calculated values used in MACT EEE and other regulations, are referenced to certain values of oxygen. For an example, a test that was conducted in which oxygen was measured as 5 percent, however, the measurement must be referenced or corrected to an oxygen concentration of 7 percent. The Oxygen Correction Factor, OCF, is calculated as 14 divided by the volumetric fraction of oxygen in air on a dry basis minus the measured fraction of oxygen in the stack. Note that the 14 in the OCF is 21, the normal oxygen concentration in air, minus 7, the concentration of oxygen reference. For this example, the OCF is calculated to be 0.875.



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Particulate Calculations

Measured:

• Front Half Rinse	8.2 mg
• Particulate Filter	907.2 mg
• Total Particulate	915.4 mg
• Flow Rate	5000 dscfm = 2.56 dscm, 5% O_2

Concentration Calculation:

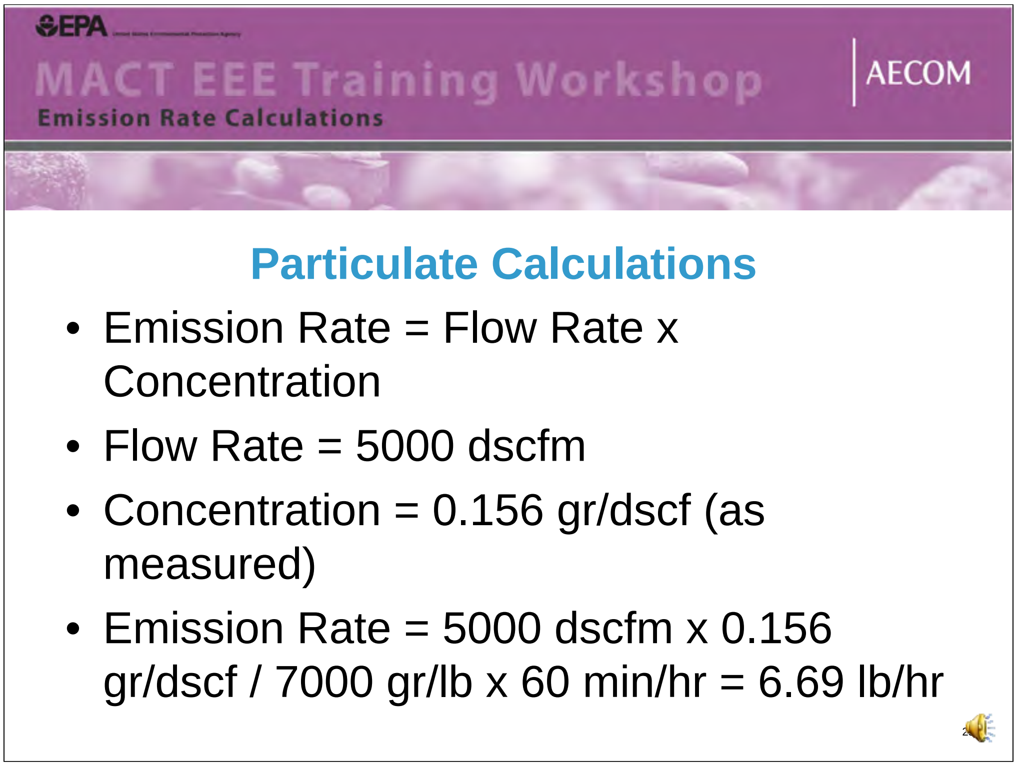
C_{PM} = 915.4/2.56 = 357 mg/dscm

= 357 mg/dscm / 453600 mg/lb x 7000 gr/lb / 35.32 cf/cm

= 0.156 gr/dscf @ 5% O_2

= 0.156 x 0.875 = 0.137 gr/dscf @ 7% O_2

This slide reviews calculations of particulate from stack testing. The measured amounts are the front half rinse particulate plus the particulate from the filter, that results in a total particulate amount. The flow rate was measured at 5000 dry standard cubic feet per minute at 5 percent oxygen, which is equivalent to 2.56 dry standard cubic meters. The concentration of particulate, C_{PM}, is calculated as the total particulate mass in milligrams divided by the flow rate in dry standard cubic meters, which yields a concentration of 0.156 grains per dry standard cubic foot, at 5 percent oxygen. This concentration is then corrected to 7 percent oxygen by multiplying the particulate concentration at 5 percent by the oxygen correction factor to correct it to 7 percent oxygen. The resulting value is 0.137 grains per dry standard cubic foot.



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Emission Rate Calculations

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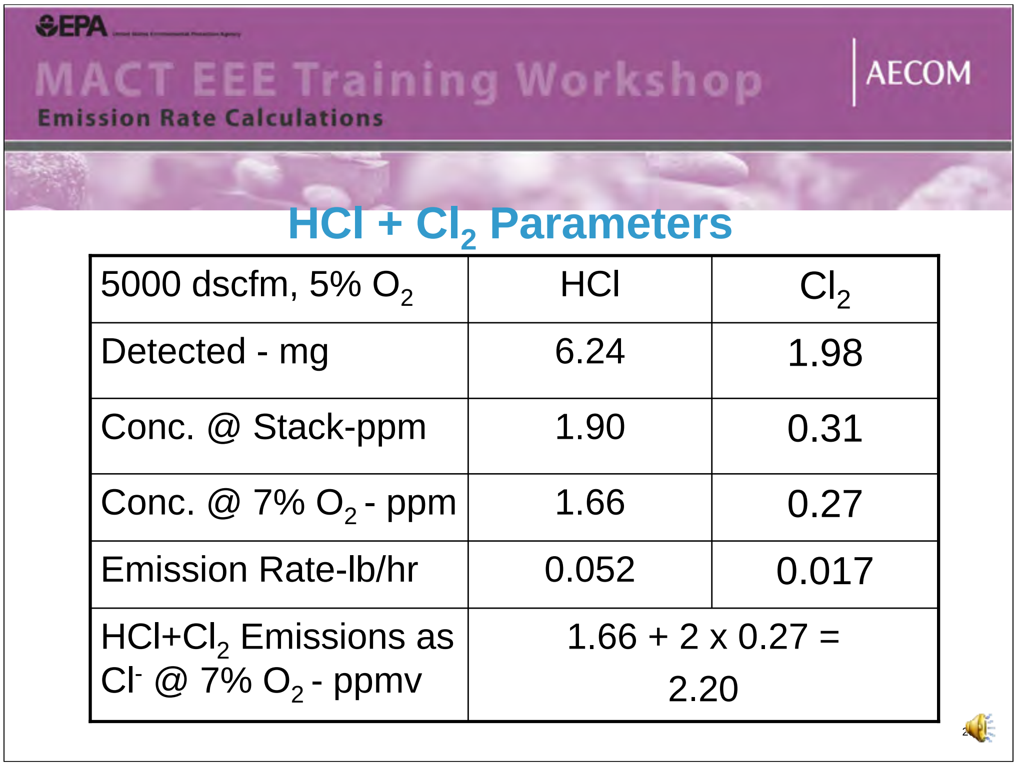
Particulate Calculations

- Emission Rate = Flow Rate x Concentration
- Flow Rate = 5000 dscfm
- Concentration = 0.156 gr/dscf (as measured)
- Emission Rate = 5000 dscfm x 0.156 gr/dscf / 7000 gr/lb x 60 min/hr = 6.69 lb/hr

This slide demonstrates the calculation for particulate emission rate. The particulate emission rate is calculated by multiplying the stack gas flow rate by the measured concentration of particulate, not the concentration that has been corrected to 7 percent oxygen. The resulting calculated value, maintaining conversion for the appropriate units of measure, is 6.69 pounds per hour.



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Emission Rate Calculations

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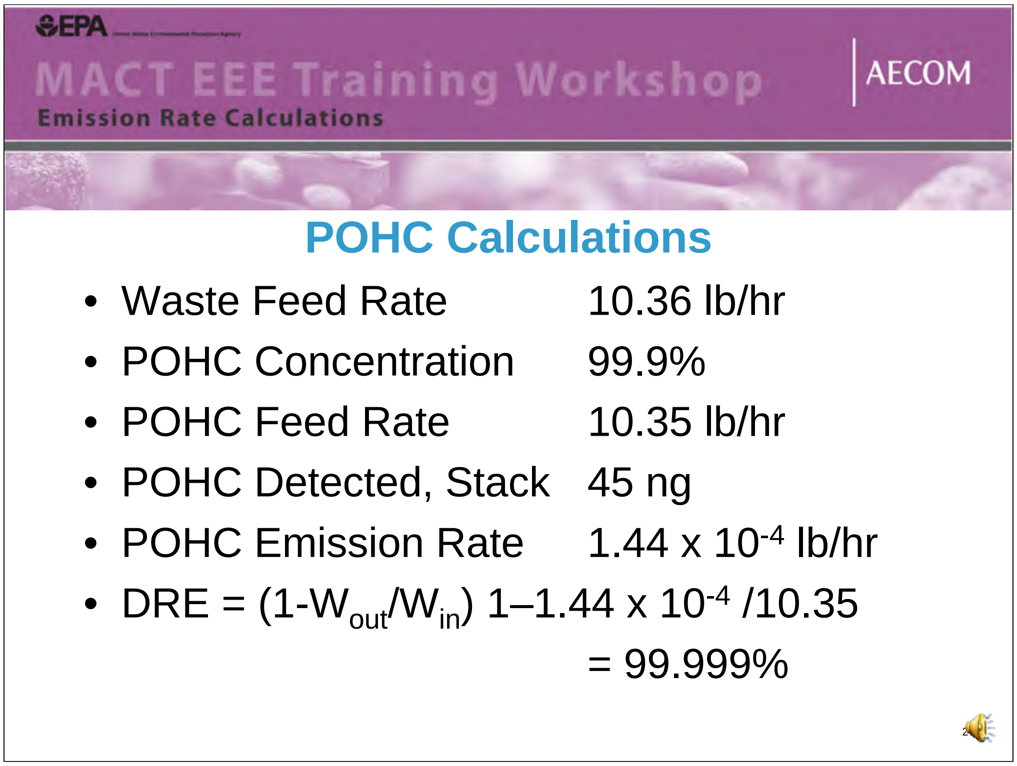
HCl + Cl_2 Parameters

5000 dscfm, 5% O_2	HCl	Cl_2
Detected - mg	6.24	1.98
Conc. @ Stack-ppm	1.90	0.31
Conc. @ 7% O_2 - ppm	1.66	0.27
Emission Rate-lb/hr	0.052	0.017
HCl+Cl_2 Emissions as Cl^- @ 7% O_2 - ppmv	1.66 + 2 x 0.27 = 2.20	

This slide provides for calculations of hydrogen chloride and chlorine parameters for MACT EEE. The detected mass of hydrogen chloride and chlorine are used to determine the stack concentration of each parameter and then corrected to 7 percent oxygen. The hydrogen chloride plus chlorine emission concentration, represented as chlorine, is calculated by adding the hydrogen chloride concentration corrected to 7 percent oxygen to 2 times the chlorine concentration corrected to 7 percent oxygen. The factor of 2 is used because there are two atoms of chlorine in the chlorine gas molecule. The resulting calculation is 2.20 parts per million of hydrogen chloride plus chlorine corrected to 7 percent oxygen.



EPA

MACT EEE Training Workshop

Emission Rate Calculations

AECOM

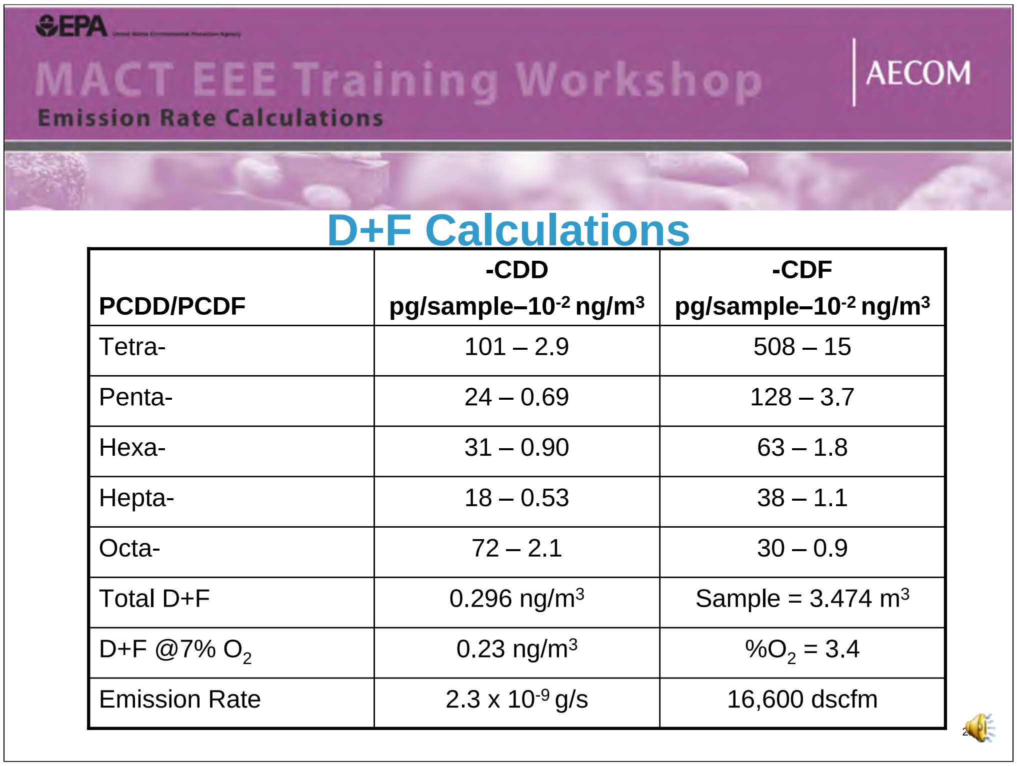
POHC Calculations

• Waste Feed Rate	10.36 lb/hr
• POHC Concentration	99.9%
• POHC Feed Rate	10.35 lb/hr
• POHC Detected, Stack	45 ng
• POHC Emission Rate	1.44×10^{-4} lb/hr

- DRE = $(1-W_{out}/W_{in})$ $1–1.44 \times 10^{-4} /10.35$

  = 99.999%

This slide demonstrates calculations of a principal organic hazardous constituent, POHC. For the example, the waste feed rate was 10.36 pounds per hour with a concentration of the POHC of 99.9 percent. The calculated POHC feed rate is calculated by multiplying the waste feed rate by the POHC concentration. Because the waste feed stream is primarily the POHC, there is not much difference in these values. The mass of POHC detected in the stack after the combustion process has oxidized the POHC was 45 nanograms. The resulting POHC emission rate, determined as explained previously, was 1.44 times 10 to -4, in units of pounds per hour. From the feed rate and emission rate of the POHC, the destruction and removal efficiency, DRE, is calculated as 99.999 percent.



MACT EEE Training Workshop

Emission Rate Calculations

AECOM

D+F Calculations

PCDD/PCDF	-CDD pg/sample–10^{-2} ng/m^3	-CDF pg/sample–10^{-2} ng/m^3
Tetra-	101 – 2.9	508 – 15
Penta-	24 – 0.69	128 – 3.7
Hexa-	31 – 0.90	63 – 1.8
Hepta-	18 – 0.53	38 – 1.1
Octa-	72 – 2.1	30 – 0.9
Total D+F	0.296 ng/m^3	Sample = 3.474 m^3
D+F @7% O_2	0.23 ng/m^3	%O_2 = 3.4
Emission Rate	2.3 x 10^{-9} g/s	16,600 dscfm

This slide shows calculations of Dioxin and Furans. The table in the slide shows the detected amounts of dioxin, under the CDD column, and amount of furan, under the CDF column for isomers of tetra through octa of each compound. The values of dioxins and furans, in units of nanograms per cubic meter, are all added and result in a combined concentration of 0.296 nanograms per cubic meter. The stack gas for the measured values was 3.4 percent, therefore, the dioxin and furan concentration was calculated to be 0.23 nanograms per cubic meter corrected to 7 percent oxygen. The dioxin and furan emission rate can be calculated using the stack gas flow rate as discussed previously and resulted in 2.3 time 10 to -9 in units of grams per second.

This slide concludes the module on emission rate calculations.