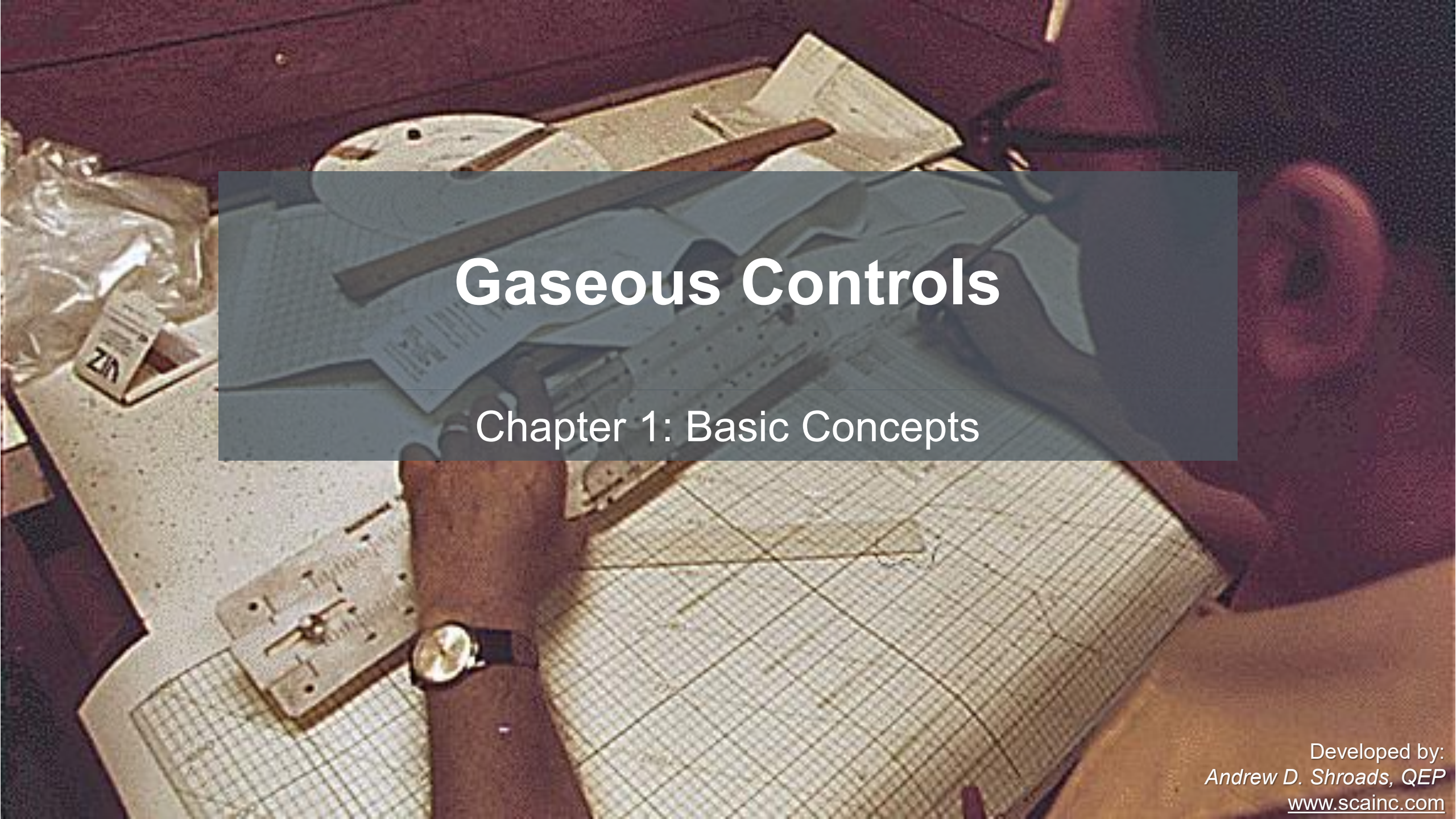


Gaseous Controls

Chapter 1: Basic Concepts

Developed by:
Andrew D. Shroads, QEP
www.scainc.com

Chapter 1: Basic Concepts
Objective

To improve understanding of the scientific and mathematical principles associated with air pollution control technologies

- Gas Temperature
- Gas Pressure
- Molecular Weight
- Ideal Gas Law
- Dry Standard Conditions
- Flammable Range
- Control vs Capture

Air Pollution is a Gas!

- Air pollutants emitted with exhaust air
  - Particulate matter (PM) & metal hazardous air pollutants (HAP) light enough to be carried out with exhaust air
- Air pollutants may be gaseous
  - Ammonia (NH_3)
  - Carbon monoxide (CO)
  - Nitrogen oxides (NO_X)
  - Sulfur dioxide (SO_2)
  - Volatile organic compounds (VOC)
  - Volatile organic HAP (VOHAP)



Gas Properties

- Gases (and air pollutants) have variable characteristics
  - Temperature
  - Pressure
  - Volume (for Flow Rate)
  - Mass Calculations
  - Ignition (Flammability)



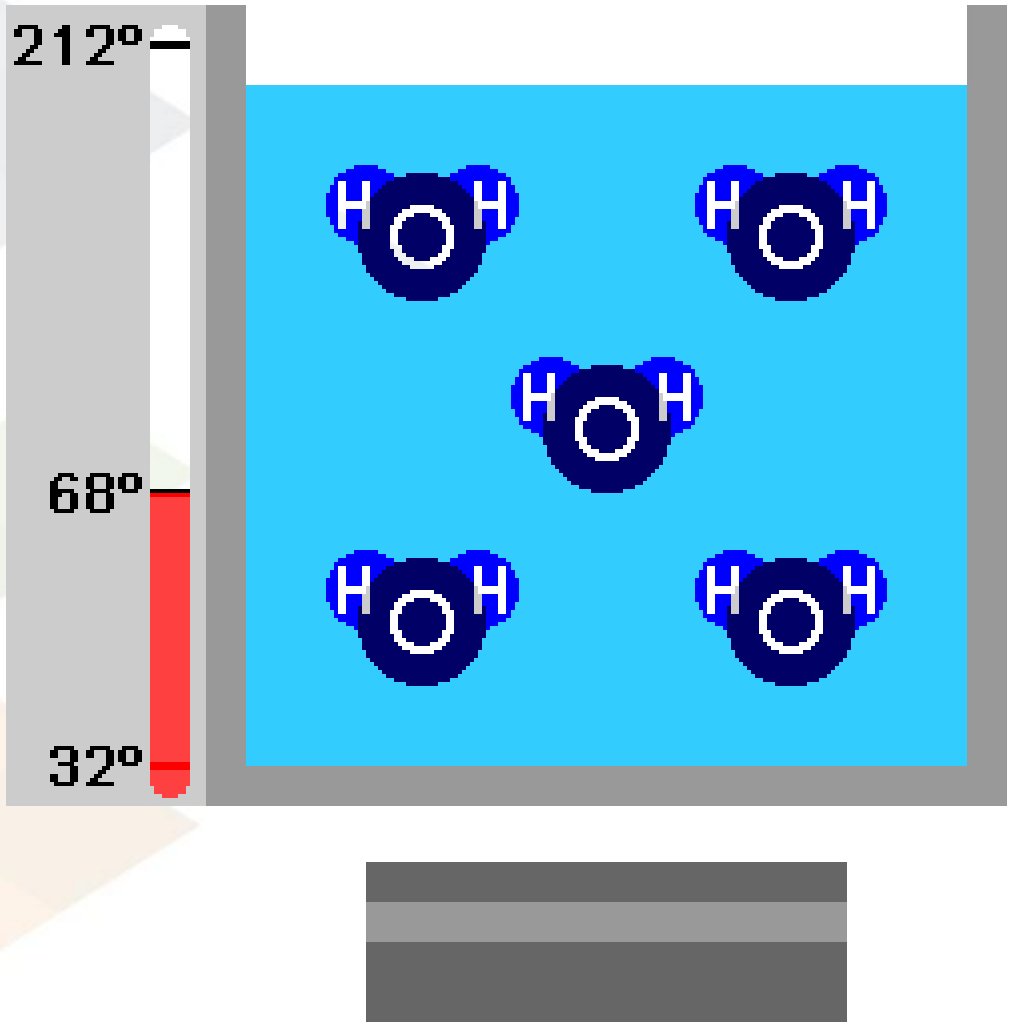






Temperature is a measure of heat

- Heat is generated by molecular motion (kinetic energy)
  - More energy = more heat
  - Less energy = less heat
  - Absolute zero = no heat / no energy
- Temperature is the scale that measures thermal state
  - Heat is the transfer of thermal energy



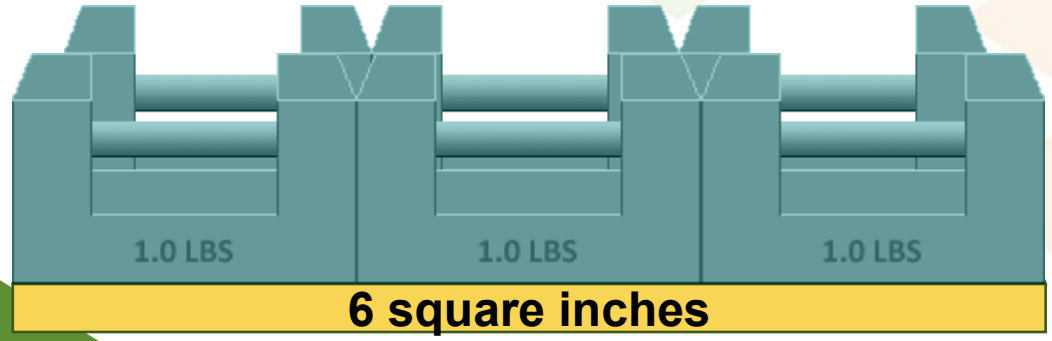
Chapter 1: Basic Concepts
Temperature Scales

	Fahrenheit (ºF)	Celsius (ºC)	Rankine (ºR)	Kelvin (K)
Steel Melts	2,597ºF	1,425ºC	3,057ºR	1,698 K
Water Boils (at sea level)	212ºF	100ºC	672ºR	373 K
Human Body	98.6ºF	37ºC	558ºR	310 K
EPA “Standard” Temperature	68ºF	20ºC	528ºR	293 K
Water Freezes (at sea level)	32ºF	0ºC	492ºR	273 K
Absolute Zero	-460ºF	-273ºC	0ºR	0 K
	Invented 1724 180º between water freeze / boil	Invented 1742 100º between water freeze / boil	Invented 1859 Fahrenheit scale beginning at absolute zero	Invented 1848 Celsius scale beginning at absolute zero

Pressure is force (weight) applied over surface (area)

- Units in weight (pounds) per area (square inches)
- The same weight applied over a smaller area "feels" heavier
  - 6,600 lb. elephant: 35 pounds per square inch (psi)
  - 100 lb. woman in high heels: 1,600 psi

6 pounds ÷ 6 square inches = 1 psi



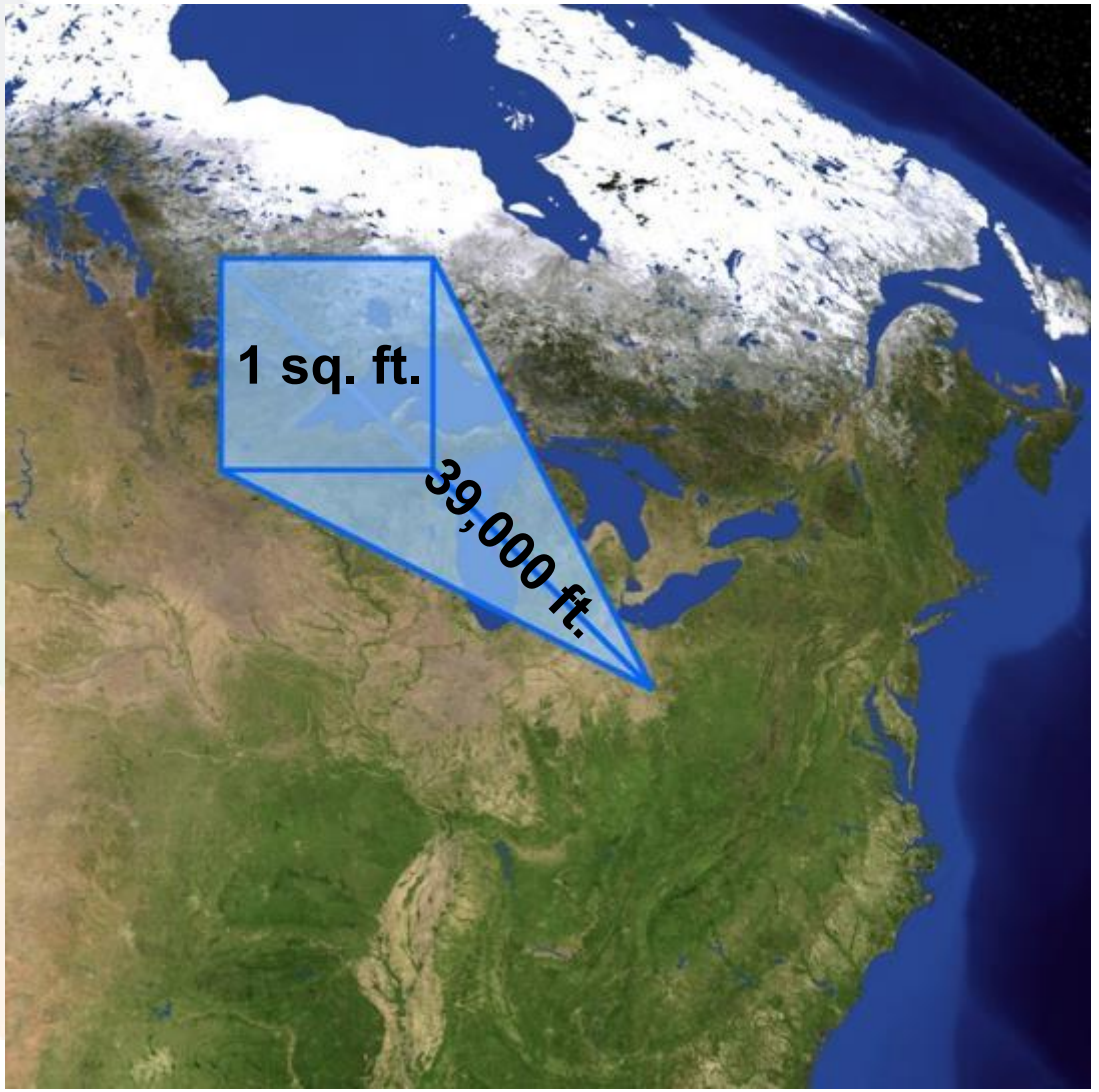
6 pounds ÷ 1 square inch = 6 psi



Chapter 1: Basic Concepts
Atmospheric Pressure

- Our atmosphere has weight
- 1 square foot 7.4 miles high
  = 39,000 cubic feet of air
  = ½ Olympic swimming pool
  = ~2,100 pounds of air

- 2,100 pounds ÷ 144 sq. in.
  = 14.7 psi
  = 1 atmosphere (atm)



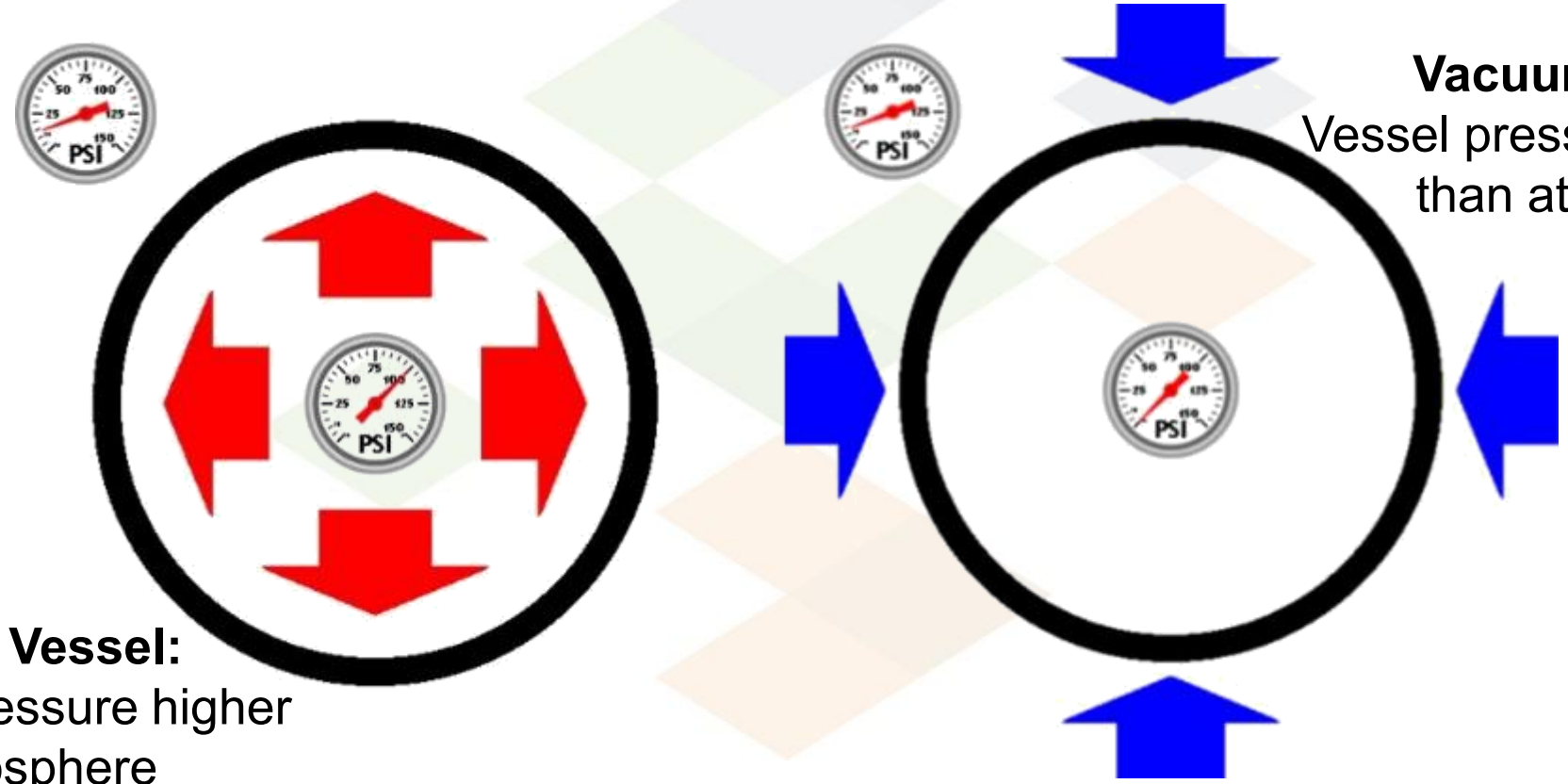
Chapter 1: Basic Concepts
Pressure Scales

	Atmosphere (atm)	Pounds / Square Inch (psi)	Pascal (Pa)	Inches of Water Column (”W.C.)
Lethal Pressure[1]	4.1 atm	60 psi	414,000 Pa	1,662” W.C.
Car Tire Pressure	2.4 atm	35 psi	241,316 Pa	970” W.C.
MSL[2] Atmosphere	1.0 atm	14.7 psi	101,300 Pa	407” W.C.
Baghouse Upper[3]	0.025 atm	0.36 psi	2,488 Pa	10” W.C.
Baghouse Lower[3]	0.012 atm	0.18 psi	1,244 Pa	5” W.C.
	Bar	**Torr[4] / Millimeter Mercury (mmHg)**	**Inches Mercury (in Hg)**	**Notes:**
Lethal Pressure	4.14 bar	3,103 mmHg	122 in Hg	[1] From blast wave
Car Tire Pressure	2.41 bar	1,810 mmHg	71 in Hg	[2] Mean Sea Level
MSL Atmosphere	1.01 bar	760 mmHg	30 in Hg	[3] Typical
Baghouse Upper	0.025 bar	18.6 mmHg	0.73 in Hg	[4] Torr = 1 atm/760
Baghouse Lower	0.012 bar	9.3 mmHg	0.36 in Hg	

- Barometric Pressure: Atmospheric pressure at elevation.
  - Decreases at higher altitudes
  - Historical record ranges from 1.07 atm to 0.858 atm
- Gauge Pressure: Pressure of container
  - Ignores atmospheric pressure, gauge is at atmospheric pressure
  - Measured in psig
- Absolute Pressure: Barometric + Gauge Pressure
  - The actual pressure on the container
  - Absolute pressure = Barometric Pressure + Gauge Pressure
  - 0 psig = 14.7 psia (standard atmospheric pressure at sea level)

Pressure Differential: Change in relative pressure

- Measured difference between high-pressure and low-pressure



Vacuum Vessel:
Vessel pressure lower than atmosphere

Pressure Vessel:
Vessel pressure higher than atmosphere

Tank Pressure Differential

- Used to establish ratings for tanks
  - Tanks rated at pressures above atmosphere (high pressure / explosion) or pressures below atmosphere (vacuum / implosion)

Railroad Tank Car Implosion



Storage Tank Explosion



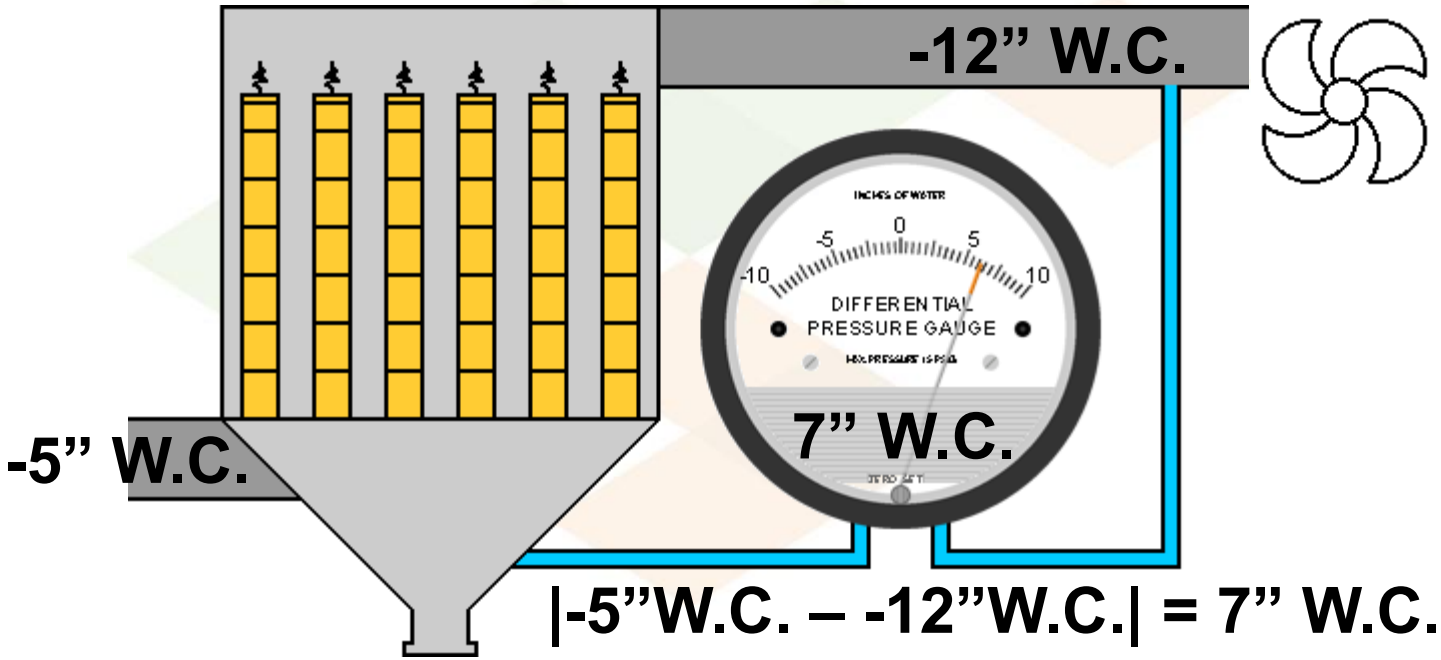
Chapter 1: Basic Concepts
Video

1.0 - Tank Implosion

1.1 - Boiling Point and Pressure

Control Device Pressure Differential

- Commonly used to monitor particulate control devices
  - The more particulate trapped in a filter, the harder for air to pass
  - Fans usually operate after control (induced draft / negative pressure)

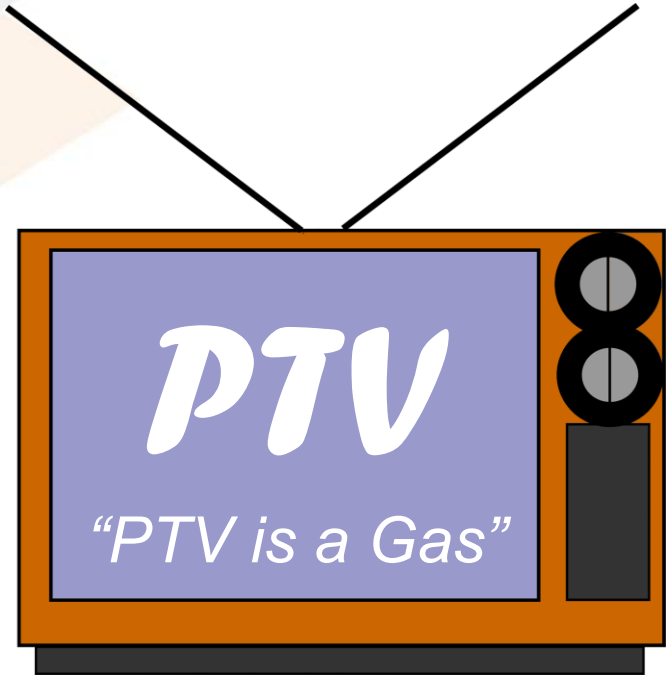


Gas Pressure / Temperature / Volume Relationship

Pressure, temperature, and volume all influence each other

- At constant pressure, temperature / volume are proportional
- At constant temperature, pressure / volume are inversely proportional
- At constant volume, temperature / pressure are proportional

Pressure **T**emperature **V**olume



Constant Pressure – Charles' Law


Jacques Alexandre César Charles

$$V \propto T$$

Constant Pressure

P T V

Constant Temperature – Boyle's Law


Robert Boyle

$$V \propto \frac{1}{P}$$

Constant Temperature

P T V

Constant Volume – Gay-Lussac's Law


Joseph Louis Gay-Lussac

$$P \propto T$$

Constant Volume

P T V

Combined Gas Law

The Combined Gas Law combines the three gas laws and approximates gas properties at different conditions

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Combined Gas Law

- Compare exhaust gas volume at actual (measured) versus standard conditions (1 atm / 68ºF)

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$V_1 = V_2 \left(\frac{P_2}{P_1} \right) \left(\frac{T_1}{T_2} \right)$$



Winter Conditions

- Colder air is denser
  - Nov-Feb generally has higher barometric pressure



Clear Conditions

- High barometric pressure indicates fair weather
  - Rising pressure can cause headaches and sinus pain



Summer Conditions

- Warmer air is lighter
  - May-Aug generally has lower barometric pressure



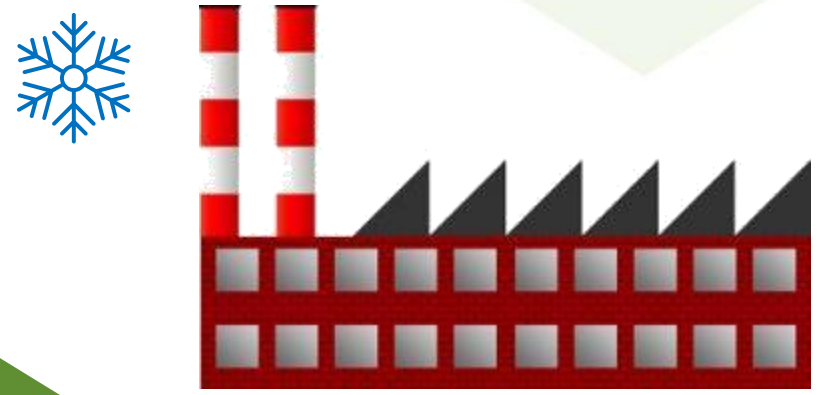
Stormy Conditions

- Low barometric pressure indicates storms
  - The lower the pressure, the stronger the storm
  - Measure of hurricane strength

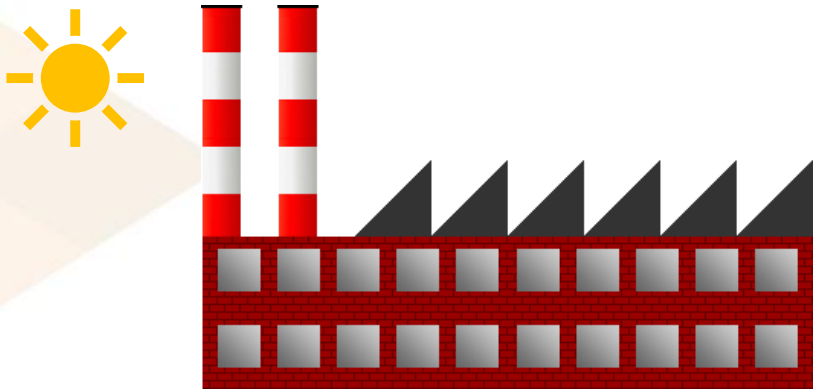
Do we really need to know this?

- Air pollution is a gas (CO, VOC) or emitted with a gas (PM)
  - The exhaust properties of the gas determine pollutant concentrations

Factory in Toledo, OH – January Stack Test
Temperature: 35ºF / 495ºR
Barometric Pressure: 30.42 in Hg
Airflow: 1,000 acfm



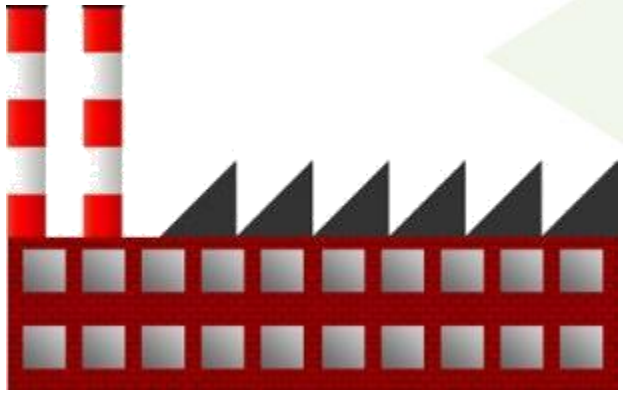
Factory in Toledo, OH – June Stack Test
Temperature: 91ºF / 551ºR
Barometric Pressure: 29.74 in Hg
Airflow: 1,139 acfm (14% increase in volume)



Chapter 1: Basic Concepts
Combined Gas Law Purpose

Stack Test (1-hour)
Airflow: 60,000 acf
Collected PM: 1,790 grains
Limit: **0.0300 gr/cf**
Operates Ambient Conditions

1,790 gr ÷ 60,000 acf =
0.0298 gr/acf **(Pass)**



Stack Test in January
Air Temperature: 35ºF
Barometric Pressure:
30.42 in Hg

Standard Conditions
Temperature: 68ºF
Pressure: 29.92 in Hg

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

60,000 acf = 65,072 scf

1,790 gr ÷ 65,072 scf =
0.0275 gr/scf **(Pass)**

Stack Test in June
Air Temperature: 91ºF
Barometric Pressure:
29.74 in Hg

Standard Conditions
Temperature: 68ºF
Pressure: 29.92 in Hg

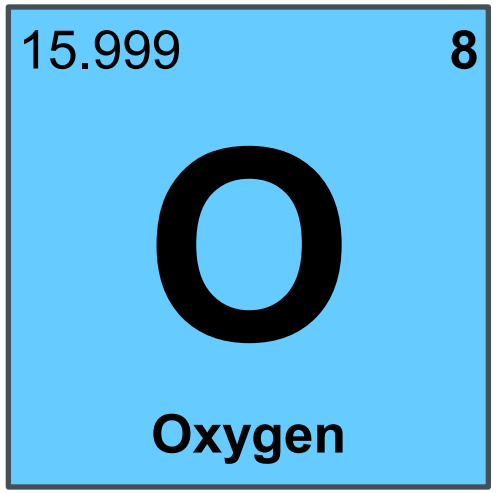
$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

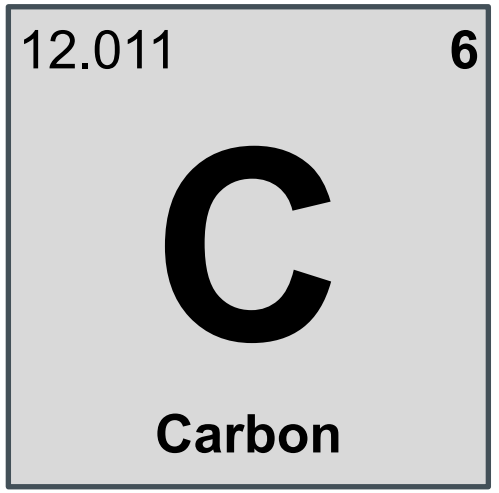
60,000 acf = 57,148 scf

1,790 gr ÷ 57,148 scf =
0.0313 gr/scf **(FAIL)**

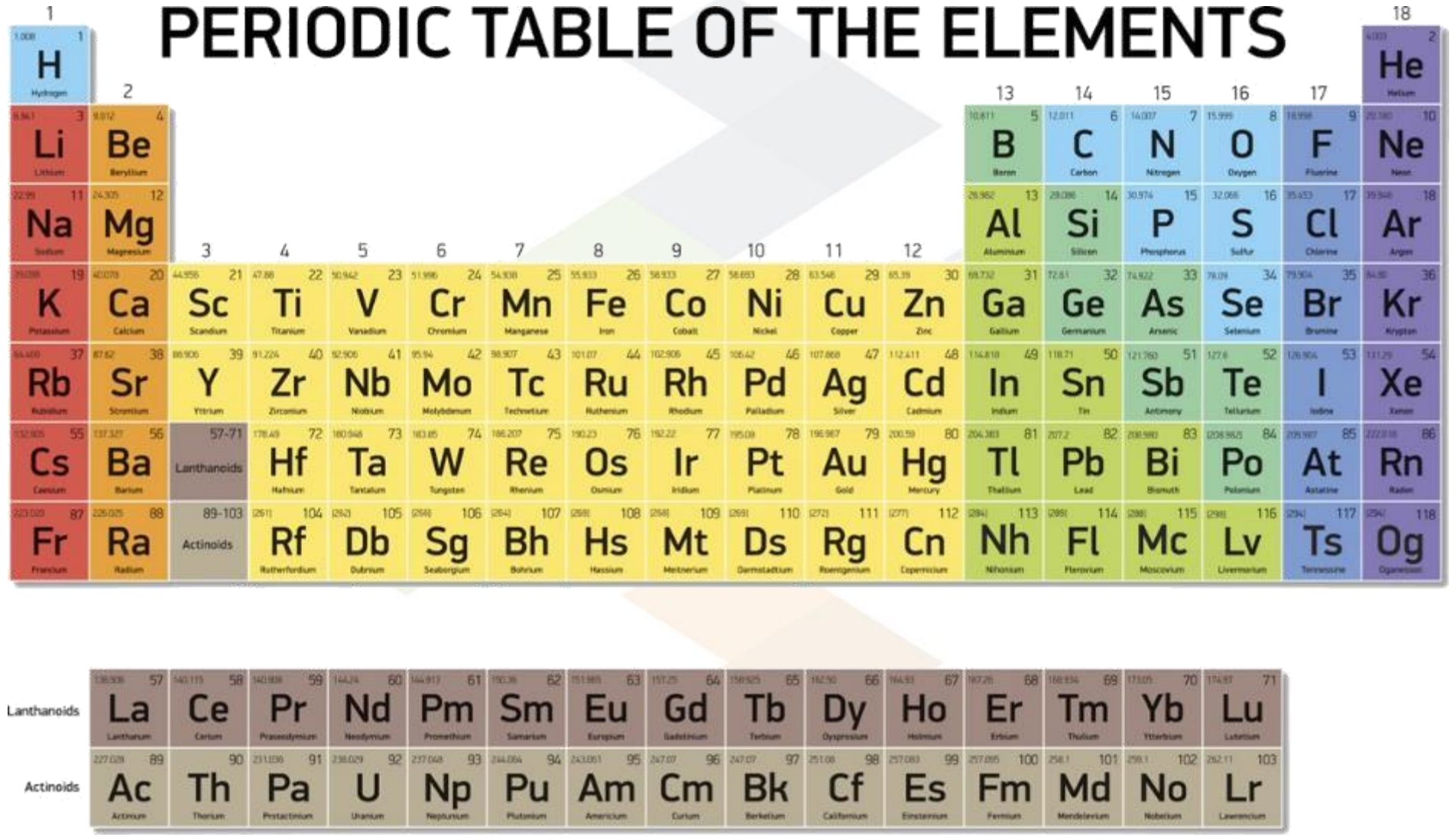
Molecular Weight

- Atoms all have different masses (weight)
  - Atomic weights are specified in the periodic table
  - Oxygen has an atomic weight of 15.999
  - Carbon has an atomic weight of 12.011
- Molecules have the combined weights of their component atoms
  - Atmospheric oxygen (O_2) has a molecular weight of (15.999 × 2) = 31.998 (32)
  - Carbon dioxide (CO_2) has a molecular weight of 12.011 + (15.999 × 2) = 44.009 (44)





Chapter 1: Basic Concepts
Periodic Table



The molecular weight of a gas mixture is the weighted average of its component gases

Molecular Weight of Dry Air

Compound	Atomic Weight	Molecular Weight	Molar Percentage	Total Molar Mass
N_2	14.01	28.02	78.1%	21.88
O_2	16.00	32.00	21.0%	6.72
Ar	39.95	39.95	0.9%	0.36
Dry Air			**100%**	**28.96**

Mole: Unofficial Mascot of Chemistry



- A chemical mole (n) is the number of **mole**cules that make the molecular weight equal to weight units we use (gram / pound)
  - Because atoms are so small, you need 6.022×10^{23} of them to measure them in grams
  - There are almost a million times more carbon atoms in a gram of carbon than there are grains of sand on Earth



- 1 mole of atmospheric oxygen (O_2) weighs 32 grams
  - 32.0 g of O_2 contain 1 g-mol of O_2 and 0.00223 lb-mol of O_2
  - Gram-mole (g-mol) can be converted to pound-mole (lb-mol) by converting grams to pounds (dividing by 453.592 grams/pound)

Volume and Amount of Gas – Avogadro's Law



Lorenzo Romano
Amedeo Carlo Avogadro

$$V \propto n$$

The Ideal Gas Law (or equation of state) combines all four gas laws and approximates gas properties at different conditions

$$pV = nRT$$

p = absolute pressure (psia)

V = gas volume (cubic feet)

n = moles of gas (lb-mol)

T = absolute temperature (ºR)

R = constant (10.73 psia•ft^3/[lb-mol•ºR])

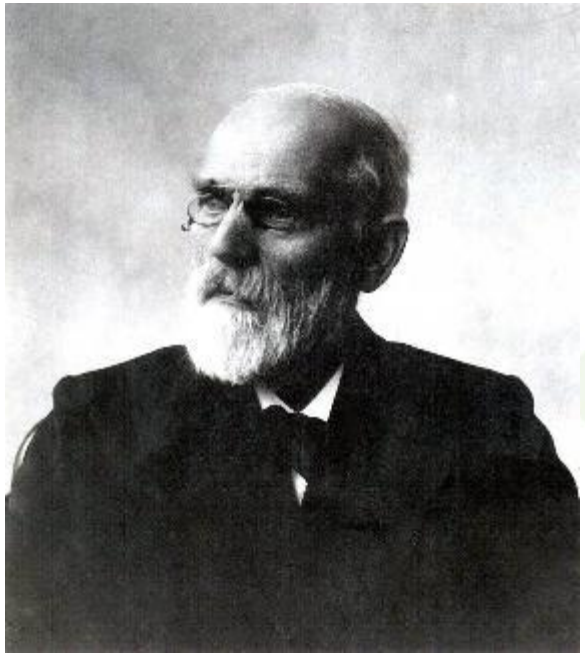
Chapter 1: Basic Concepts
Ideal Gas Law

	Pascal (Pa)	Atmosphere (atm)	Pounds / Square Inch (psi)	Millimeter Mercury (mmHg)
Ideal Gas Law Constant (R)	8.314 $Pa \cdot m^3/(g\text{-}mol \cdot K)$ or $Joule/(g\text{-}mol \cdot K)$	0.73024 $atm \cdot ft^3/(lb\text{-}mol \cdot {}^oR)$	10.73 $psi \cdot ft^3/(lb\text{-}mol \cdot {}^oR)$	62.36 $mmHg \cdot l/(g\text{-}mol \cdot K)$

The ideal gas law works at high temperatures (≥ ambient) and low pressures (≤ ambient)

- Considered acceptable for air pollution
  - Less accurate for cryogenic conditions or compressed gases
  - Less accurate for volatile organic compounds, sulfur dioxide, and ammonia

Real Gases are Fluids



Johannes Diderik van der Waals

- Hypothesized that real (non-ideal) gases are affected by interactions between molecules
  - Attraction and repulsion between molecules as electrons move around in electron cloud
- Created van der Waals equation of state
  - Accounts for intermolecular attraction and volume occupied by particles

van der Waals equation for fluid dynamics (gases and liquids)

$$\left(p+\frac{an^2}{V^2}\right)(V-nb)=nRT$$

p = absolute pressure (psia)

V = gas volume (cubic feet)

n = moles of gas (lb-mol)

T = absolute temperature (ºR)

R = constant (10.73 psia•ft^3/[lb-mol•ºR])

a / b = constants for specific compound (determined experimentally)

Density

- Ratio of substance mass to its volume
  - Divide mass of liquid or gas by its volume (usually container)
  - Liquids & gases are usually measured by volume; however, calculations and emissions limits usually require mass (or weight)
- Density of liquids & gases changes with temperature
  - Inverse: As temperature increases, density generally decreases
- Density of gases changes with pressure
  - Proportional: Higher absolute pressure increases gas density
  - Pressure has a negligible change to liquid density

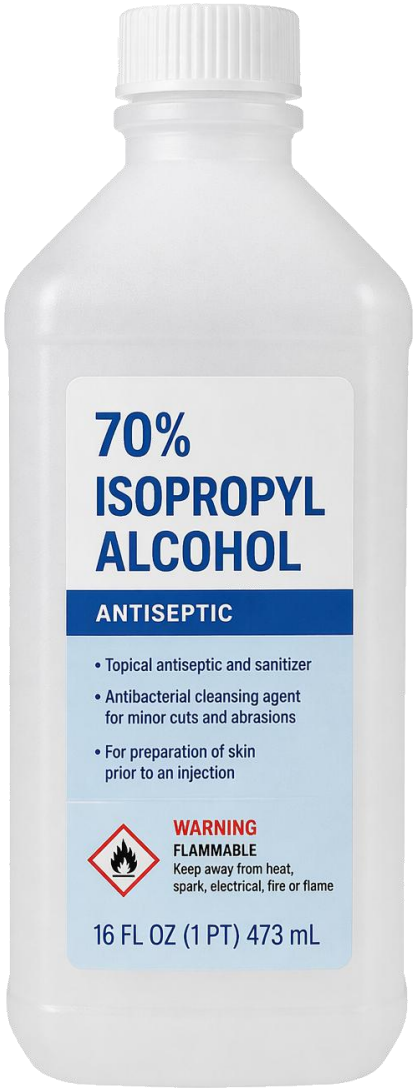
Mixtures

- Consistent volume of chemical mixtures (≥2 chemicals) may be represented in multiple ways
  - Volume Fraction: Amount of liquid (% by volume)
  - Mass fraction: Amount of solid (% by weight)
  - Mole fraction: Amount of molecules (moles)

  Not Equivalent!
- Can convert between volume / mass / molar fractions by knowing density and molar mass of **all** compounds in mixture
  - Density: Mass per unit of volume (lbs./gallon)
  - Molar Mass: Mass per mole (lb./mol or gram/mole) – equivalent to atomic or molecular weight

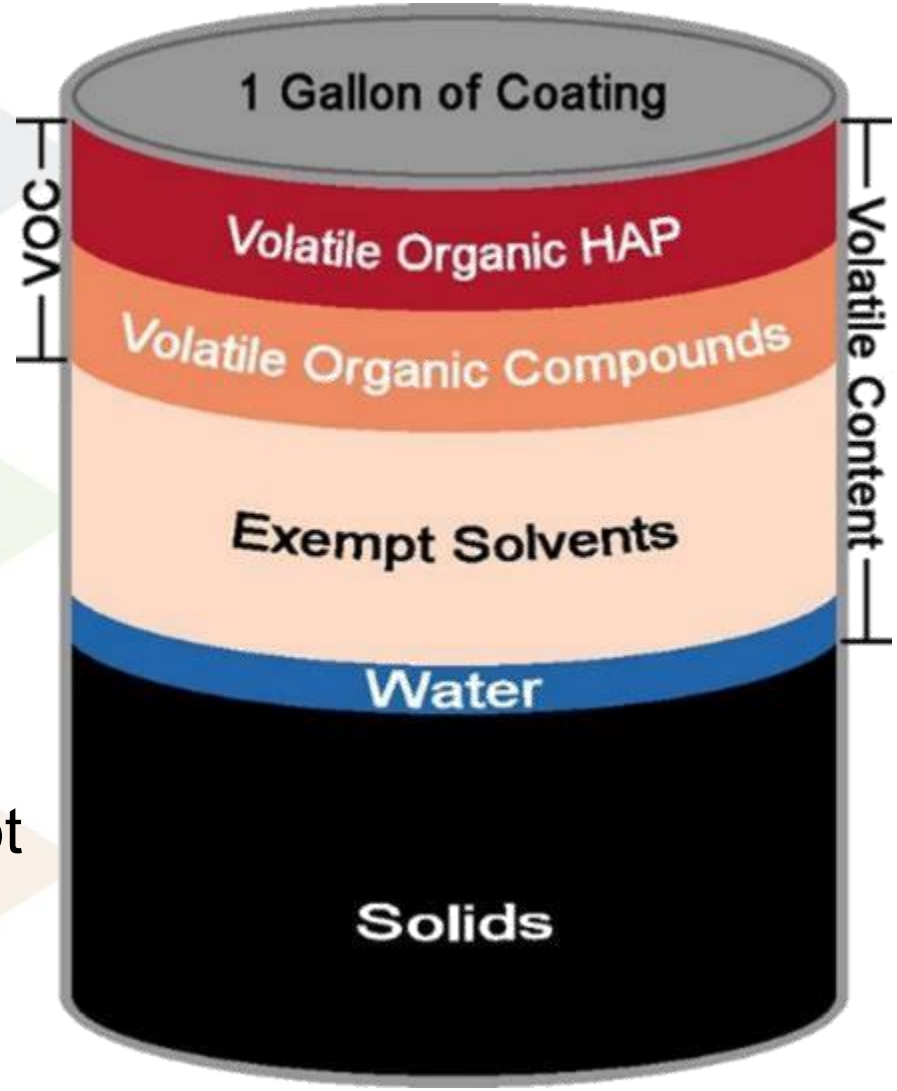
Isopropyl Alcohol (C_3H_8O)

- 70% v/v isopropyl alcohol (Density 0.86 g/mL@ 68ºF)
- 30% v/v water (Density 1.0 g/mL@ 68ºF)
- What is the density of 100% v/v isopropyl alcohol?
  - 331 mL Isopropyl Alcohol (473 mL × 70%)
  - 142 mL Water (473 mL × 30%) = 142 g Water (142 mL × 1 g/mL)
  - 473 mL bottle = 407 g (473 mL × 0.86 g/mL)
  - 265 g Isopropyl Alcohol (407 g - 142 g Water)
- 0.86 g/mL Density of Isopropyl Alcohol (265 g ÷ 331 mL)
  - Real density = 0.785 g/mL or 2% error
- 70% v/v isopropyl alcohol = 64% w/w (265 g ÷ 407 g)



Mixtures (Coatings)

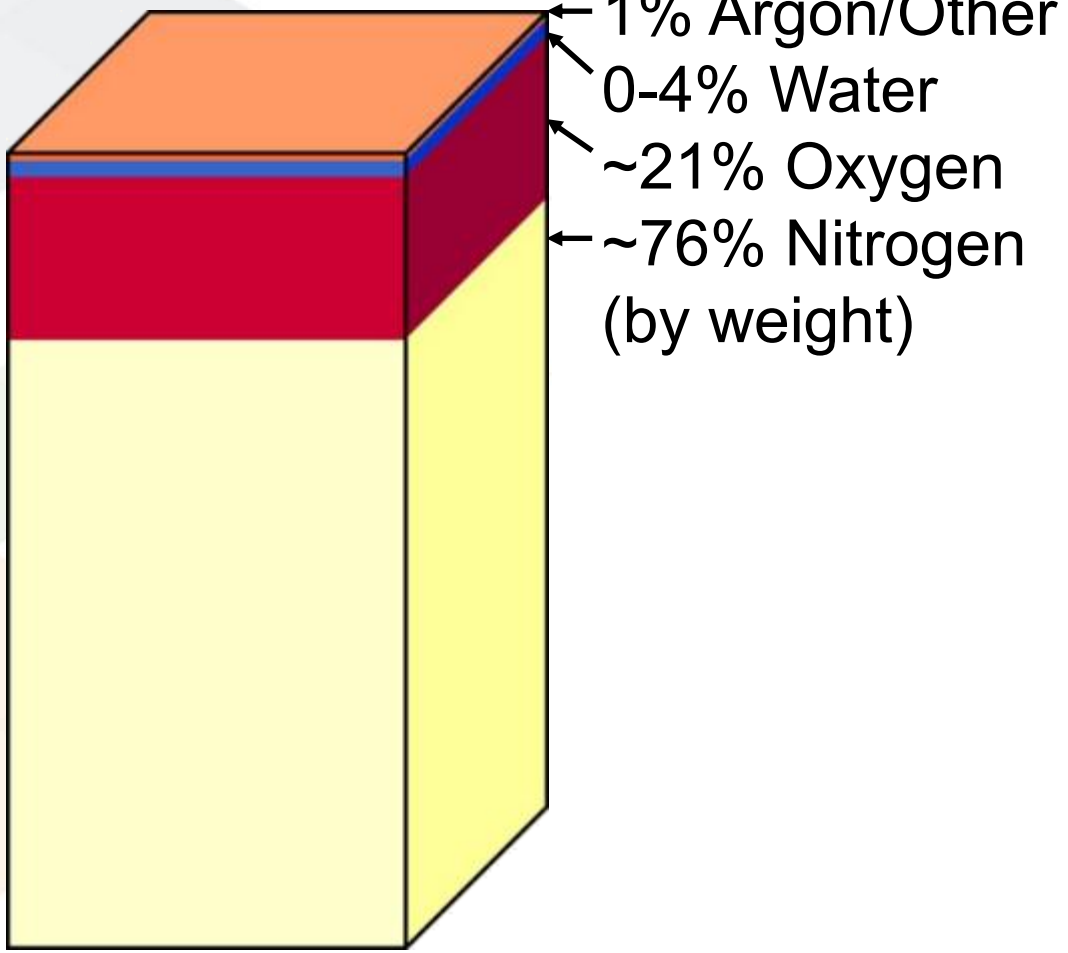
- Coatings are liquid mixtures
- Standards may be based on weight or volume of mixture components
  - VOC % by weight (w/w)
  - VOC lbs./gallon, minus water & exempt
  - VOC lbs./gallon solids
  - VOC lbs./lbs. solids
  - VOC % by volume, minus water & exempt
  - VOC % by volume of volatile matter (v/v)



EPA Dry Standard

- Air is a mixture
- Water vapor in atmosphere and exhaust gas is variable
  - Proportional to humidity
  - Cold air holds less water vapor
- Removes water from exhaust
  - Increases pollutant concentration
  - Ensures consistency between test runs and different processes

Normal Air



EPA Dry Standard

- Emissions (stack) testing establishes actual gas flow rate (Acf) and weight (grains) of pollutant collected
  - Used to establish concentration (grains/cubic foot) and rate (lbs./hour)
- Testing firm corrects stack parameters to U.S. Environmental Protection Agency (EPA) dry standards in method
  - 1 atmosphere / 14.7 psia / 29.92 inches of mercury (Hg)
  - 68ºF / 528ºR (EPA value; science uses 32ºF)
  - 0% moisture content in exhaust gases
  - Dry air molecular weight (O_2 & N_2 concentration of 29.0 lbs./lb-mol), as certain processes (e.g., combustion) reduce O_2 content

Stack Test Calculations:

- Water Content of Stack Gas % by volume (B_{ws})
  - Water Collected (cf) ÷ Total Airflow (cf)

$$B_{WS} = V_{Water\ Vapor} \div (V_{Water\ Vapor} + V_{Dry\ Gas})$$

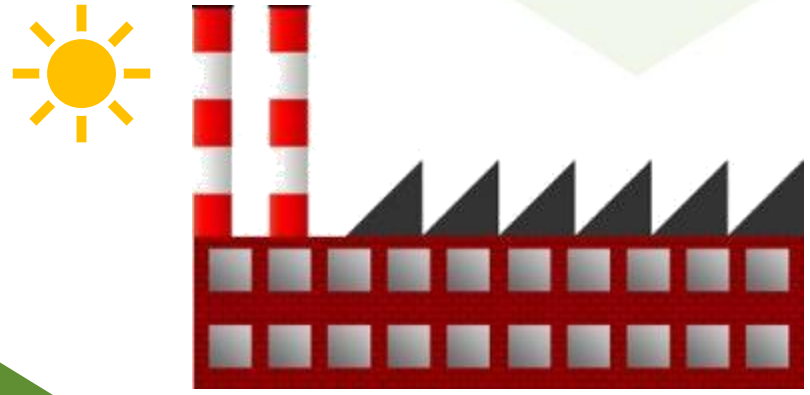
- Molecular Weight of Stack Gas (dry basis) in lb/lb-mol (M_d)
  - 44 CO_2 × % CO_2 + 32 O_2 × % O_2 + 28 N_2 × % (100-CO_2-O_2)



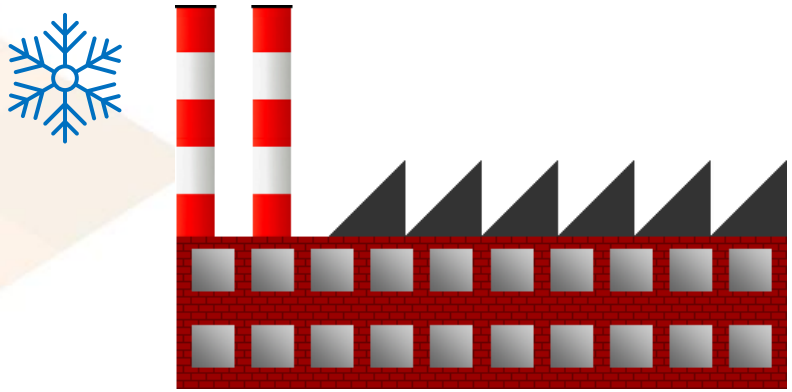
Do we really need to know this?

- Air pollution is a gas
  - Concentration emissions limits are pollutant mass ÷ exhaust volume
  - Actual cubic feet vs standard cubic feet changes exhaust volume

Higher Exhaust Volume (Lower Emissions)
- Dry process (lower water volume in air)
- High process temperature
- Low atmospheric pressure



Lower Exhaust Volume (Higher Emissions)
- Wet process (higher water volume in air)
- Low process temperature
- High atmospheric pressure



Emission Limit: 0.1 grains/cubic foot (gr/cf)

- Stack test report states the following:
  - PM Weight: 8.2 lbs. (in 1 hour)
  - flow rate: 10,000 actual cubic feet per minute (acfm)
  - Temperature: 150ºF
  - Barometric Pressure: 14.49 psia

- What is the PM concentration in grains per actual cubic feet and grains per standard cubic feet?
- Is grains/cubic foot an acceptable emissions limit?

Review Question

- PM concentration in actual cubic feet:
  - Weight: 8.2 lbs./hr × 7,000 grains = 57,400 gr/hr
  - flow rate: 10,000 acfm × 60 m/hr = 600,000 acf/hr
  - PM Emissions Rate: 57,400 gr/hr ÷ 600,000 acf/hr = 0.096 gr/acf
- Conclusion: **PASS** (0.096 gr/acf < 0.1 gr/cf)

Chapter 1: Basic Concepts
Review Question

- PM concentration in standard cubic feet (scf):
  - Weight: 8.2 lbs./hr × 7,000 grains = 57,400 gr/hr
  - flow rate: 10,000 acfm × 60 m/hr = 600,000 acf/hr
  - Temperature: 150ºF / 609.7ºR
  - Standard Temperature: 68.0ºF / 527.7ºR
  - Barometric Pressure: 14.49 psia
  - Standard Pressure: 14.70 psia

$$V_1 = V_2\left(\frac{P_2}{P_1}\right)\left(\frac{T_1}{T_2}\right)$$

Standard flow rate:
600,000 acf/hr×(14.49 psia÷14.70 psia)×(527.7ºR÷609.7ºR)=511,886 scf/hr

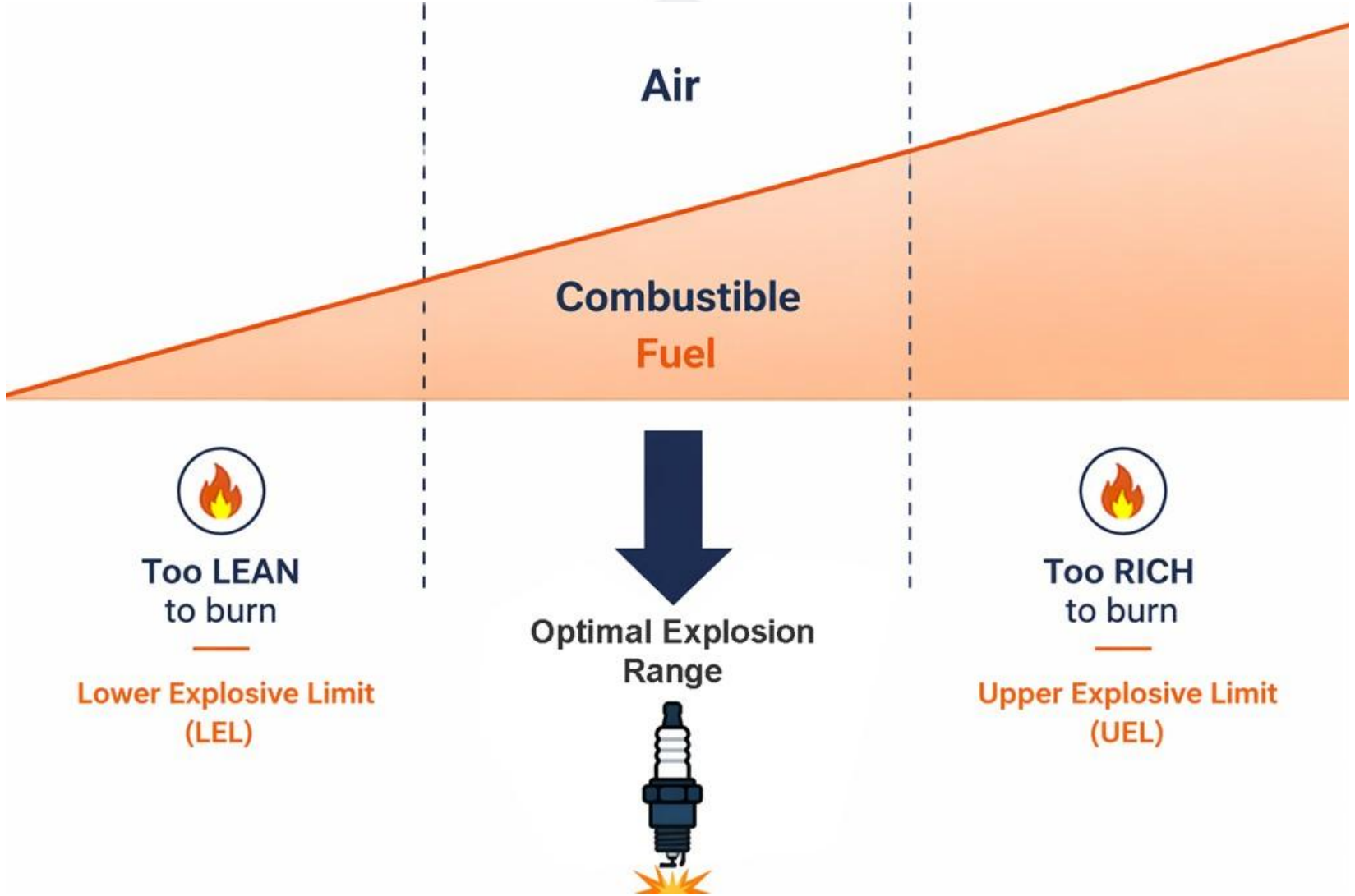
PM Concentration: 57,400 gr/hr ÷ 511,882 scf/hr = 0.11 gr/scf

Conclusion: **FAIL** (0.11 gr/scf > 0.1 gr/cf)

Flammable Range

- Range of gas concentration that supports combustion / explosion
  - Lower Explosive Limit (LEL): Minimum gas concentration for explosion
  - Upper Explosive Limit (UEL): Maximum gas concentration for explosion
- Many gaseous air pollutants have explosive limits
  - CO, NH_3, Hydrogen Sulfide (H_2S), VOC, VOHAP
  - PM may become combustible dust if <500 micrometers (μm) and suspended in air

Chapter 1: Basic Concepts
Flammable Range



Chapter 1: Basic Concepts
Flammable Range

Compound	LEL (% by volume)	UEL (% by volume)
Acetone	2.5%	12.8%
Ammonia	15%	28%
Benzene	1.2%	7.8%
Carbon Disulfide	1.3%	50%
Ethanol	3.3%	19%
Formaldehyde	7.0%	73%
Gasoline	1.4%	7.6%
Hydrogen	2.0%	80%
Methylene Chloride	13%	23%
Propane	2.1%	9.5%
Toluene	1.1%	7.1%
Xylenes	0.9%	7.0%

Potential Ignition Sources

- Static electricity from gas moving through ducts / equipment
- Sparks due to metal-to-metal contact
- Hot surfaces
- Electrically powered instruments within gas stream (fans)

Additional Considerations

- Control devices must account for flammable range
  - Exhaust gases within the flammable range may explode if a spark / heat is introduced
  - Exhaust gases may have multiple compounds with different flammable ranges
  - Control device fires are not uncommon, even for baghouses!



Oxygen Content

- Oxygen content of exhaust gas above / below “normal”
  - Fossil fuel combustion has lower oxygen in exhaust gas
  - Steelmaking requires pure oxygen to refine iron
  - Correct oxygen content
- Oxygen content of exhaust air affects flammable range
  - Oxygen required for combustion



Stack (Point) Emissions

- One identifiable emissions point (stack, duct, flue)

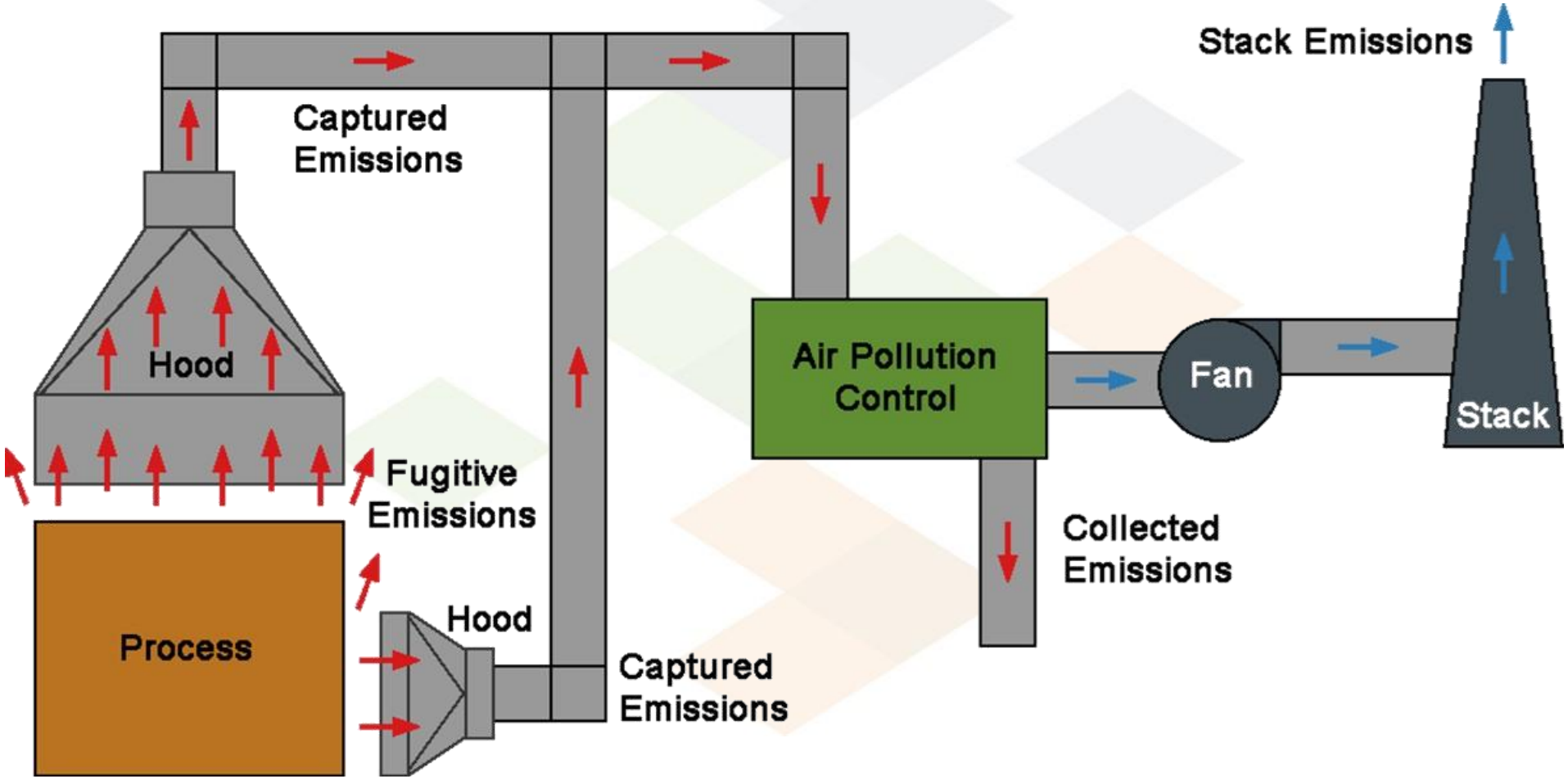


Fugitive Emissions

- Emissions generated over an area (roadways, piles)



Capture, Control, and Collection System



Capture System

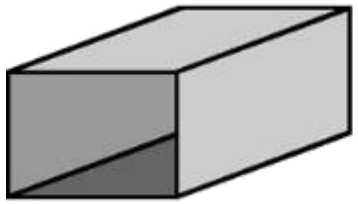
- Hoods and ducts
- Capture Efficiency: Amount of air pollution transferred from process to control device

Control System

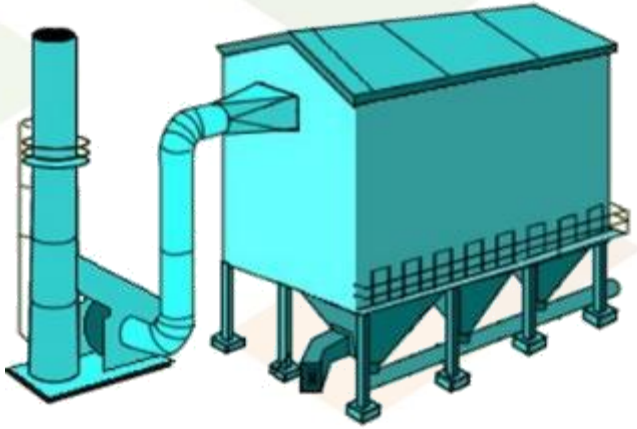
- Baghouse / Oxidizer
- Control Efficiency: Amount of air pollutants collected in control device

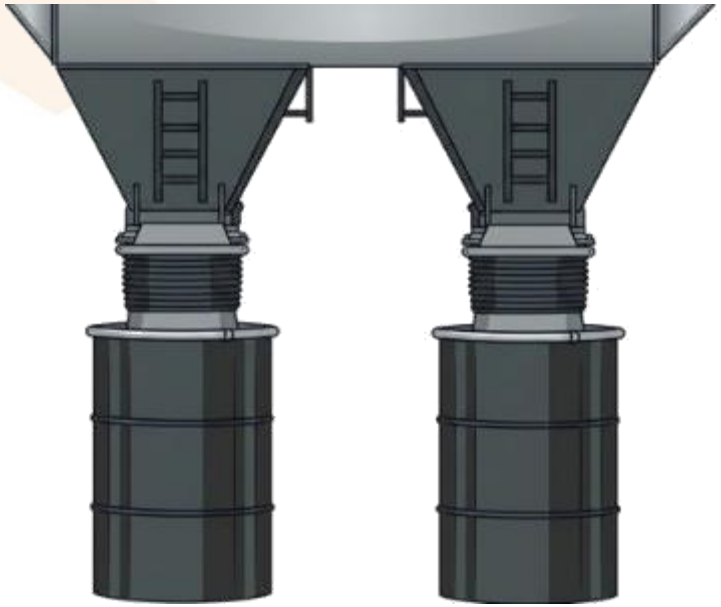
Collection System

- Hoppers and Material Handling Equipment









Capture System

- Capture system is responsible for delivering pollutants to control device
- Insufficient capture efficiency reduces overall control efficiency
  - No capture = no control



Capture Efficiency: Measure of how much air pollution generated by the source is conveyed to the control device

- Dependent on the type of enclosure capturing air pollution and venting it to stack or control device
- Difficult to measure for open systems (e.g., painting operations)

Control Efficiency: Measured ability for equipment or operational restriction to reduce air pollution

- Determined by comparing air pollutant concentration before and after control (e.g., stack / performance test)

! **Overall Efficiency = Capture Efficiency × Control Efficiency**

Capture Principles

- Total enclosure: Entire fugitive emissions area is enclosed
  - Device enclosure – Device is completely enclosed (blast cabinet)
  - Room enclosure – Room is completely enclosed (paint booth)
  - Building enclosure – Hoods or pickup points are placed for entire building (foundry floor)
- Partial enclosure: Fugitive emissions generation relies on vacuum and placement of pickup points for enclosure
  - Flexible hoses for grinding / machining equipment
  - Halogenated solvent degreaser under a hood

Total Enclosure



Partial Enclosure



Capture System (Total Enclosure)



Capture Efficiency

Capture Efficiency: amount of air pollutants transferred from generating area to control device or stack

$$\frac{\text{Captured (lbs.)}}{\text{Generated (lbs.)}} = \text{Capture Efficiency\%}$$

Captured = Control Device Inlet

- How do you determine total air pollutants generated?
- How do you determine total air pollutants captured?

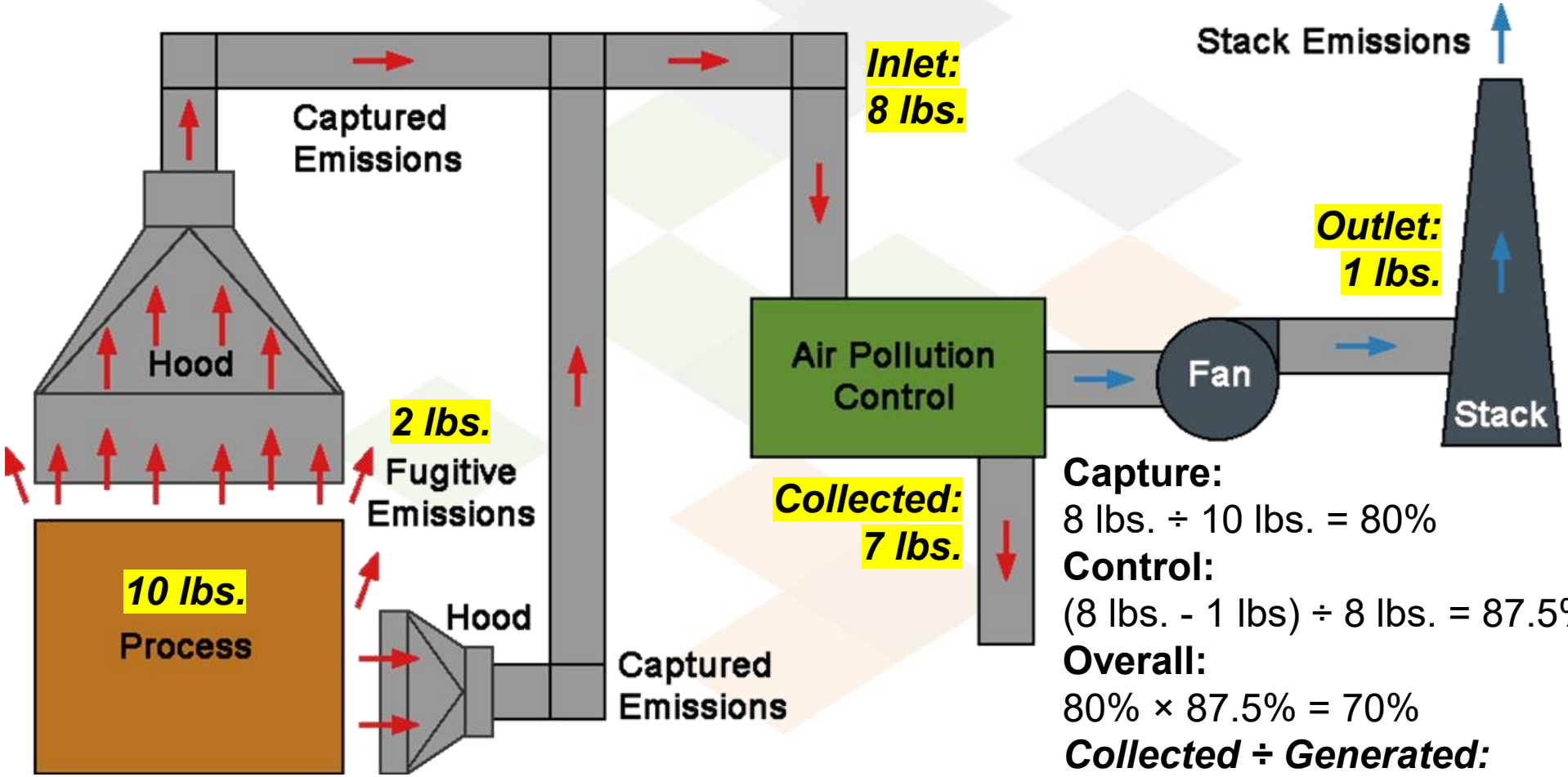
Control Efficiency

Control Efficiency: amount of air pollutants collected in control device

$$\frac{\text{Control Inlet (lbs.)} - \text{Control Outlet (lbs)}}{\text{Control Inlet (lbs.)}} = \text{Control Efficiency\%}$$

Controlled = Control Device Outlet

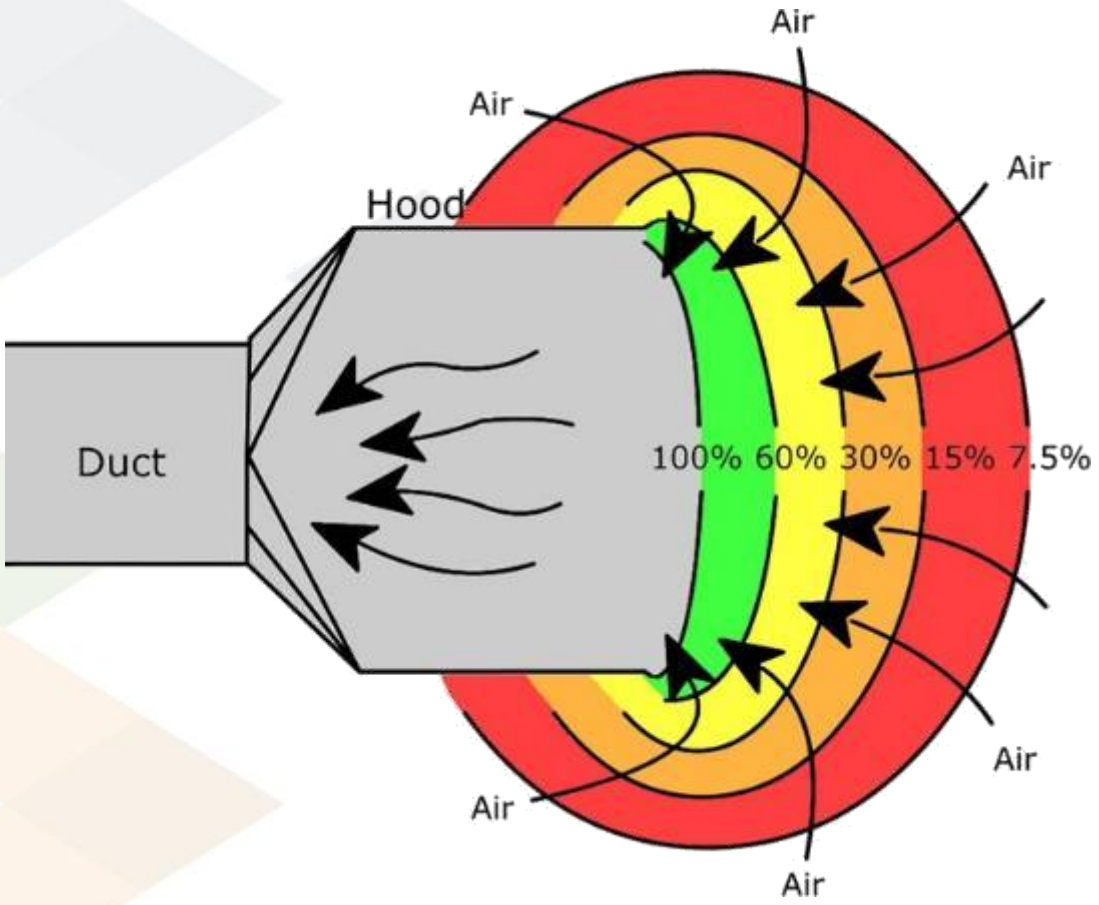
Capture, Control, and Collection System



Capture:
8 lbs. ÷ 10 lbs. = 80%
Control:
(8 lbs. - 1 lbs) ÷ 8 lbs. = 87.5%
Overall:
80% × 87.5% = 70%
Collected ÷ Generated:
7 lbs. ÷ 10 lbs. = 70%

Capture Velocity

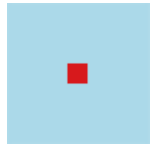
- Hood needs sufficient draw (vacuum) to overcome opposing air currents and capture particulates
  - Air currents within room
  - Toxicity of the pollutant
  - Amount of particulate produced
  - Available area
- Capture velocity decreases **rapidly** with distance



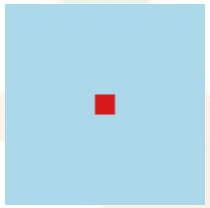
Release Conditions	Typical Capture Velocity (feet/minute)
No velocity into still air	50-100
Low velocity into moderately still air	100-200
Active generation into rapid air motion	200-500
High velocity into very rapid air motion	500-2,000

Capture Velocity

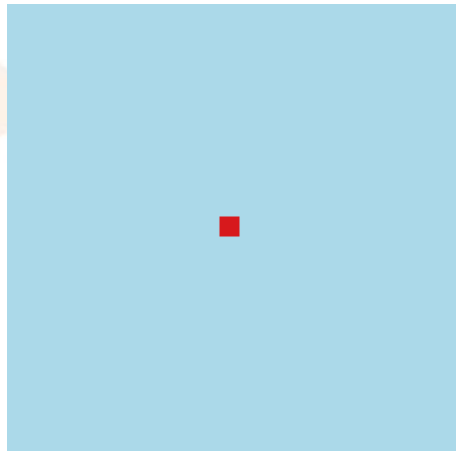
- Increasing airflow reduces air pollution but dilutes air pollutant concentration
  - Pull more air, dilute the pollutant at control (and more expensive)



100 VOC : 5,000 Air
(20,000 ppm)



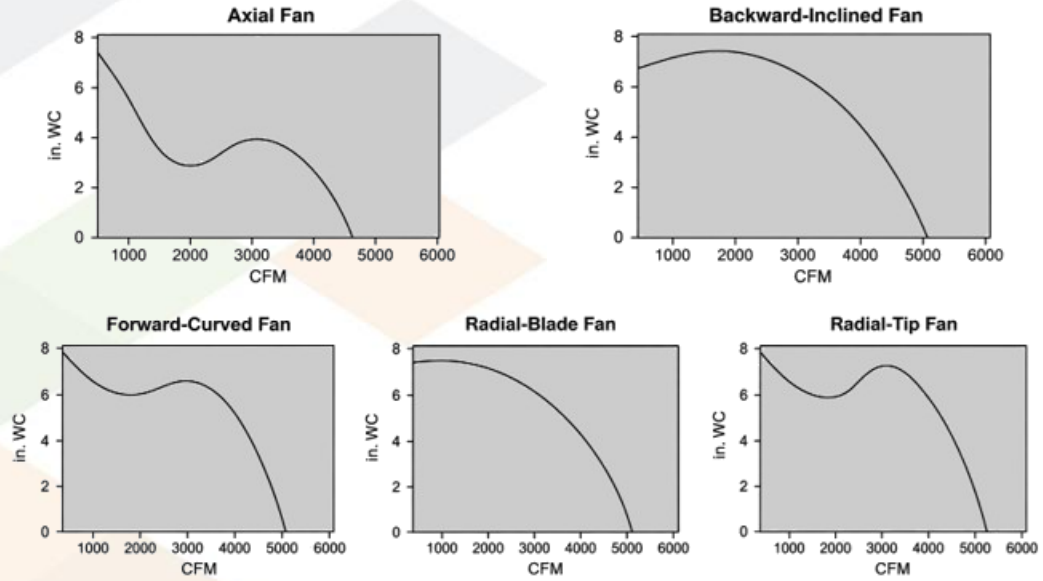
100 VOC : 10,000 Air
(10,000 ppm)



100 VOC : 50,000 Air
(2,000 ppm)

Fans

- Fans pull a different amount of air (flow rate) at different differential pressures
  - Higher pressure drop decreases air flow rate (more resistance)
  - Fan curves are available from manufacturer
- Fans **generally** are located after PM control device



Recap

In this chapter, we discussed:

- Gas Temperature
- Gas Pressure
- Molecular Weight
- Ideal Gas Law
- Dry Standard Conditions
- Flammable Range
- Control vs Capture