Gas Laws

by Dawn Richardson PhD, Collin College, Preston Ridge Campus; revised by Jim Sizemore PhD, Collin College, Central Park Campus

Introduction:

A gas is a state of matter in which atoms or molecules have large amounts of empty space and are free to move independently of each other under normal conditions. This allows gases to be compressed. Gases lack a definite shape or volume and will therefore adopt the shape of their container and occupy the entire volume available. As the gas particles move they will undergo elastic collisions and the force that they exert per unit area as they strike the surrounding surfaces is called pressure.

There are four basic physical properties of a gas sample: pressure (P), volume (V), amount of gas particles in moles (n) and temperature (T). Regardless of the identity of a gas, all gases exhibit comparable physical behavior. There are simple gas laws that describe the relationship between pairs of the physical properties of gases. For example, Boyle's Law describes the relationship between pressure and volume while the temperature and amount of gas (moles) remains constant. The individual physical behavior of the simple laws can be combined into one mathematical expression referred to as the Ideal Gas Law:

Eqn. 1) $PV = nRT = NkT$

where P is absolute pressure, V is volume, n is number of moles, R is the universal gas constant which equals 8.314 J/mole °K, T is absolute temperature, N is number of molecules, and k is the Boltzmann constant which equals $1.38*10^{-23}$ J/molecule °K. In order to use the Ideal Gas Law, a proportionality or Ideal Gas constant (R or k) is used to enable a direct relationship between the physical properties at standard conditions.

Note that $nR = Nk$ where $N = N_An$. This, therefore, also means $R = N_Ak$. N_A is called Avogadro's number and is the number of molecules in a mole and is a constant value of $6.02214179*10^{23}$. The atomic mass, in grams, of a substance contains Avogadro's number of molecules. Thus (looking this up on the periodic table on the last page) 12.01115 gm of (naturally occurring) carbon has $6.02214179*10^{23}$ carbon atoms in it. O_2 is a molecule so you have to double the atomic mass of oxygen (15.999) to get the mass of a mole of O_2 gas which equals 31.998 gm. A mole of H_2 gas is 2.000 gm, a mole of helium is 4.003 gm, a mole of lithium is 6.939 gm, etc. For more complex molecules simply add the atomic masses of all the constituents. We've already seen examples of two molecules – O_2 and H_2. We just extend this idea. The molecular mass of H_2O, for example, is twice the atomic mass of hydrogen plus the atomic mass of oxygen = 2(1.000)+15.999 = 17.999. So one mole of water has a mass of 17.999 gm. A mole of CO_2 has a mass of 44.00915 gm, a mole of ethanol (C_2H_5OH) has a mass of 46.0213 gm, etc. You will need to apply these principles to calculate the mass of one mole of the substances we will use in the experiment. The number of molecules per gram varies between substances. Therefore chemists find it much easier to work with moles of substances since one mole has a fixed, constant number of molecules. We measure water in liters since it's much easier than calculating the number of water molecules. Similarly moles quantities are much easier to work with in chemistry.

Gases can be produced from a wide range of chemical reactions. Once such reaction involves metal carbonates reacting with an acid to produce gaseous carbon dioxide as shown in the following net ionic equation:

Eqn. 2) $CO_3{}^{2-}{}_{(aq)} + 2H^+{}_{(aq)} \rightarrow H_2O_{(l)} + CO_{2\,(g)}$

We will use a weak acetic acid solution (vinegar about 4% to 5% acetic acid, CH_3COOH, in water) mixed with baking soda which is nearly 100% sodium bicarbonate ($NaHCO_3$). The net chemical reaction is:

Eqn. 3) $NaHCO_{3\,(s)} + CH_3COOH_{(l)} \rightarrow H_2O_{(l)} + CO_{2\,(g)} + CH_3COONa_{(aq)}$

Breaking this reaction down into its part, first consider acetic acid dissolved in water:

Eqn. 4) $CH_3COOH_{(l)} \rightarrow H^+{}_{(aq)} + CH_3COO^-{}_{(aq)}$

Next, consider the baking soda dissolved in water:

Eqn. 5) $NaHCO_{3\,(s)} \rightarrow Na^+{}_{(aq)} + HCO_3{}^-{}_{(aq)}$

When combined the Na^+ ion attaches to the acetate ion (CH_3COO^-) to make sodium acetate (CH_3COONa) and the H^+ attaches to the bicarbonate or hydrogencarbonate ion ($HCO_3{}^-$) to make carbonic acid (H_2CO_3). Let's go back and think about Equation 2. A carbonate ion ($CO_3{}^{2-}$) plus two hydrogens ($2H^+$) makes H_2O and CO_2. The hydrogencarbonate ion already has one hydrogen – we're just adding another to result in H_2O and CO_2, but with the intermediate stage of carbonic acid. Formally we add Equations 4 and 5 to get:

Eqn. 6) $NaHCO_{3\,(s)} + CH_3COOH_{(l)} \rightarrow H^+{}_{(aq)} + CH_3COO^-{}_{(aq)} + Na^+{}_{(aq)} + HCO_3{}^-{}_{(aq)}$

After the Na^+ ion attaches to the acetate ion (CH_3COO^-) to make sodium acetate (CH_3COONa) and the H^+ attaches to the bicarbonate or hydrogencarbonate ion ($HCO_3{}^-$) to make carbonic acid (H_2CO_3), we have the following:

Eqn. 7) $NaHCO_{3\,(s)} + CH_3COOH_{(l)} \rightarrow CH_3COONa^+{}_{(aq)} + H_2CO_{3\,(aq)}$

Finally the carbonic acid disassociates into CO2 and water leading to Equation 3. Convince yourself of this process using the molecular model kits.

Objective:

Equation 3 predicts that for each mole of sodium bicarbonate consumed it results in a mole of CO_2. We will experimentally verify this by measuring the mass of sodium bicarbonate consumed and measure the volume of CO_2 produced. From the mass and volume we will determine the number of moles consumed and produced. They should be equal and we will verify this. However under certain circumstances our calculations will (erroneously) show inequality and we will learn the reasons why.

Materials:

- Baking soda (100% sodium bicarbonate)
- Vinegar (4% to 5% acetic acid solution)
- Triple beam balance with a minimum of 0.1 gm resolution (more precise balance preferred)
- Vernier caliper (preferred, but other ruler acceptable)
- Funnel with narrow mouth about 1 cm diameter (preferred, but optional)
- 10 & 20 mL graduated cylinder (or test tube or similar vial)
- Latex balloons – a few for each lab group
- Goggles and apron strongly recommended – while not dangerous it could irritate the eyes or leave a temporary stain on clothing
- Barometer (optional, but preferred)
- Thermometer (optional, but preferred)
- String (optional)
- Scissors (optional)
- Lab scoop or teaspoon set (optional)
- Weighing paper (optional)

Questions to Consider:

1) What is the Ideal Gas Law?
2) How can the volume of the gas collected be calculated? (Hint: $V = \frac{4}{3}\pi r^3$)
3) How can the number of moles of a gas sample be calculated from a gas law?
4) What is the balanced chemical reaction for this experiment?
5) How can the number of moles of sodium bicarbonate be calculated?
6) The balanced chemical reaction for this experiment predicts for each mole of sodium bicarbonate consumed, one mole of CO_2 is produced. Is this true? Why or why not?
7) What is the Law of Definite Proportions?
8) Explain how this experiment confirms the Law of Definite Proportions.
9) Why is the Law of Definite Proportions important in chemistry, physics, and our understanding of the makeup of matter?

Prelab Questions

1) How are the number of moles related to the number of molecules?

2) Why do we count moles instead of molecules?

____

____

3) What is the current room temperature and pressure? In the absence of a barometer or thermometer make a reasonable guess. For example, room temperature at sea level of 25°C and 101,300 Pa.

Temperature = ____ °C

Barometric Pressure = ____ Pa

You may need to convert your pressure or temperature readings. Here are conversion factors:

14.7 psi = 101.3 kPa = 1.013 bars = 101300 Pa = 76 mm Hg = 30 in Hg.

$T_C = \frac{5}{9}(T_F - 32)$; $T_F = \frac{9}{5}T_C + 32$; and $T_K = T_C + 273.15$

Show your units conversion below.

4) Get a working equation from the Ideal Gas Law (Equation 1) expressing how volume of a gas is related to pressure, temperature, and number of moles.

____

____

____

5) How must we transform temperature to apply this equation? Hint: The Ideal Gas Law requires absolute temperature and pressure.

____

____

6) If you use SI (Standard International metric, that is, Pa pressure units, R = 8.314 J/mole °K, °K temperature units) units, the volume calculated is in units of m^3. Calculate the volume 1 mole of gas occupies at your measured barometric pressure and room temperature. Show calculation below.

____

V = ____ m^3

7) Express the value in Item 6 as cm^3. Use proper units conversion methodology and show calculation below. Recall 1 ml = 1 cc = 1 cm^3.

____

____

V = ____ cm^3

8) How many moles of gas at the temperature and pressure you measured would a sphere of radius 5 cm contain? Show your work completely.

____

____

____

Moles in a 5 cm radius sphere = ______________________________________ moles

9) How do we find the mass of 1 mole of sodium bicarbonate?

____

____

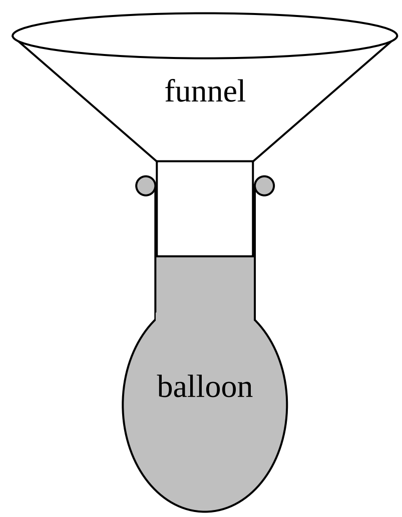
10) Use the chemical formulas and periodic table (one is attached at the end of this document) to calculate the mass of 1 mole of sodium bicarbonate.

Mass of one mole of $NaHCO_3$ = ______ gm

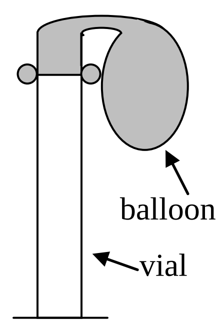
11) How many moles is 1 gm of $NaHCO_3$?

Moles $NaHCO_3$ in 1 gm = ______ moles

Procedure



1) Weigh out about 1 gm of baking soda and record the exact mass in Data Table 1. Don't worry if you get a little more or a little less. If you get between 0.8 gm and 1.2 gm you'll be fine. If below 0.8 gm try adding a little more. If too much – weighing paper helps. Just remove a little. If you're not using weighing paper, go with the quantity you have and Trial 2 can be the 1 gm trial.
2) Put it in the balloon. This is where the funnel comes in – it makes it easier to get the baking soda into the balloon. See the diagram at right.
3) Fill the 10 ml graduated cylinder or, alternatively, an approximately 10 ml test tube or other suitable container (about 10 ml) full to the brim with ordinary household white vinegar (about 4% to 5% acetic acid in water).



4) Do not allow the baking soda to come into contact with the vinegar as you perform this step. Fit the mouth of the balloon over the graduated cylinder (or alternative vial). Allow the portion of the balloon with baking soda to hang loosely along the side of the graduated cylinder (or alternative). See figure at right.
5) With the balloon tightly sealed (this is where the string can help) over the graduated cylinder (or alternative), mix the vinegar with the baking soda.
6) The balloon will expand to a certain size and stop. Reject the data and start over with a new balloon if balloon springs a leak.
7) Measure the size of the balloon in the x, y, and z directions and record in Data Table 1.
8) Is there any baking soda left over? If you set the balloon/vial upright it should settle to the bottom of the vial and appears to be a wet white powder. Record this observation in Data Table 1.

9) Repeat Steps 1 to 8 using different quantities of baking soda. You may reuse the balloon and vial, but thoroughly rinse all vinegar and baking soda out before the next trial. If you had residue per Step 8, either use less baking soda or use the same amount of baking soda and a larger vial, for example, a 20 ml graduated cylinder. Perform at least 2 trials where no residue is observed, but if you have time perform 3 or more trials without residue.

Data Table 1

Trial	Mass of $NaHCO_3$ (gm)	Excess $NaHCO_3$? (y/n)	l_x – size of balloon in x direction (cm)	l_y – size of balloon in y direction (cm)	l_z – size of balloon in z direction (cm)

Analysis

1) If a balloon is a perfect sphere then $2r = l_x = l_y = l_z$. and $V = \frac{4}{3}\pi r^3$. However the balloon may be distorted. We have to modify the formula for volume slightly in a way that makes sense. Define 3 new variables a little like radius: $a = \frac{l_x}{2}$; $b = \frac{l_y}{2}$; $c = \frac{l_z}{2}$. The volume of the balloon is better approximated by the formula: $V = \frac{4}{3}\pi abc$. Calculate a, b, c, and volume and record in Results Table 2.
2) The balloon contains CO_2 as a product of the reaction. In Prelab Questions 6, 7, and 8 you learned how to calculate the number of moles in a volume of gas. Do this now for each of your trials and record the number of moles of CO_2 in Results Table 2.
3) In Prelab Question 9, 10, and 11 you learned how to calculate the number of moles given mass of baking soda ($NaHCO_3$). Do this now for each of your trials and record the number of moles of $NaHCO_3$ in Results Table 2.
4) Note in Results Table 2 if there was any residue.
5) Calculate the percent difference between moles of baking soda consumed and CO_2 produced and enter in Results Table 2.
6) Graph moles of CO_2 versus moles of $NaHCO_3$. Note if there was residue on each point of the graph.

Results Table 2

Trial	a (cm)	b (cm)	c (cm)	V (cm3)	CO_2 (moles)	$NaHCO_3$ (moles)	% Diff	Residue? (y/n)

Conclusions and Postlab Questions

1) Does the graph you plotted in Analysis Step 6 show a straight line through the origin? Why or why not? Explain.

____

____

____

2) What conclusion would you draw by observing a straight line through the origin?

____

____

____

3) Does your experiment confirm or deny the Law of Definite Proportions? Explain.

____

____

____

4) Explain why the Law of Definite Proportions was so important to understand chemistry.

5) Calculate the mass of $NaHCO_3$ consumed when 1 liter of CO_2 is produced in the reaction you studied.

LIGHT METALS

PERIODIC TABLE OF THE ELEMENTS

NON METALS

In the periodic table the elements are arranged in order of increasing atomic number. Vertical columns headed by Roman. Numerals are called *Groups*. A horizontal sequence is called a *Period*. The most active elements are at the top right and bottom left of the table. The staggered line (Groups IIIA and VIIA) roughly separates metallic from non-metallic elements.

Group IA includes hydrogen and the alkali metals.
Group VIIA includes the *halogens*.

The elements intervening between groups IIA and IIIA are called *transition elements*.
The elements intervening between groups IIA and IIIA are called *transition elements*.
The elements intervening between groups IIA and IIIA are called *transition elements*.

Short vertical columns without Roman numeral headings are called sub-groups.

Groups- Elements within a group have similar properties and contain the same number of electrons in their outside energy shell.

Periods- In a given period the properties of the elements gradually pass from a strong metallic to a strong non- metallic nature, with the last number of a period being An inert gas.

IA	IIA											IIIA	IVA	VA	VIA	VIIA	VIIIA
Hydrogen 1.0000 H 1																	Helium 4.003 He 2
Lithium 6.939 Li 3	Beryllium 9.012 Be 4											Boron 10.811 B 5	Carbon 12.01115 C 6	Nitrogen 14.007 N 7	Oxygen 15.999 O 8	Fluorine 18.998 F 9	Neon 20.183 Ne 10
Sodium 22.990 Na 11	Magnesium 24.312 Mg 12											Aluminum 26.981 Al 13	Silicon 28.086 Si 14	Phosphate 30.974 P 15	Sulfur 32.064 S 16	Chlorine 35.453 Cl 17	Argon 39.948 Ar 18
Potassium 39.102 K 19	Calcium 40.08 Ca 20	Scandium 44.956 Sc 21	Titanium 47.90 Ti 22	Vanadium 50.942 V 23	Chromium 51.996 Cr 24	Manganese 54.938 Mn 25	Iron 55.847 Fe 26	Cobalt 58.933 Co 27	Nickel 58.71 Ni 28	Copper 63.54 Cu 29	Zinc 65.37 Zn 30	Gallium 69.72 Ga 31	Germanium 72.59 Ge 32	Arsenic 74.922 As 33	Selenium 78.96 Se 34	Bromine 79.909 Br 35	krypton 83.80 Kr 36
Rubidium 115.17 Rb 37	Strontium 87.62 Sr 38	Yttrium 88.905 Y 39	Zirconium 91.22 Zr 40	Niobium 92.906 Nb 41	Molybdenum 95.94 Mo 42	Technetium 99 Tc 43	Ruthenium 101.07 Ru 44	Rhodium 102.91 Rh 45	Palladium 106.4 Pd 46	Silver 107.87 Ag 47	Cadmium 112.40 Cd 48	Indium 114.82 In 49	Tin 118.69 Sn 50	Antimony 121.75 Sb 51	Tellurium 127.60 Te 52	Iodine 126.90 I 53	Xenon 131.30 Xe 54
Cesium 132.90 Cs 55	Barium 137.34 Ba 56	57-71	Hafnium 178.49 Hf 72	Tantalum 180.95 Ta 73	Tungsten 183.85 W 74	Rhenium 186.21 Re 75	Osmium 190.2 Os 76	Iridium 192.2 Ir 77	Platinum 195.09 Pt 78	Gold 196.97 Au 79	Mercury 200.59 Hg 80	Thallium 204.37 Tl 81	Lead 207.19 Pb 82	Bismuth 200.98 Bi 83	Polonium (210) Po 84	Astatine (210) At 85	Radon (222) Rn 86
Francium 22.3 Fr 87	Radium (226) Ra 88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118

Lanthanum 138.91 La 57	Cerium 140.12 Ce 58	Praseodymium 140.91 Pr 59	Neodymium 144.24 Nd 60	Promethium (147) Pm 61	Samarium 150.35 Sm 62	Europium 151.96 Eu 63	Gadolinium 157.25 Gd 64	Terbium 158.92 Tb 65	Dysprosium 162.50 Dy 66	Holmium 164.93 Ho 67	Erbium 167.26 Er 68	Thulium 168.93 Tm 69	Ytterbium 173.04 Yb 70	Lutetium 174.97 Lu 71
Actinium 227 Ac 89	Thorium 232.04 Th 90	Protactinium (231) Pa 91	Uranium 238.03 U 92	Neptunium (237) Np 93	Plutonium (242) Pu 94	Americium (243) Am 95	Curium (247) Cm 96	Berkelium (249) Bk 97	Californium (251) Cf 98	Einsteinium (254) Es 99	Fermium (253) Fm 100	Mendelevium (256) Md 101	Nobelium (254) No 102	Lawrencium (257) Lr 103

Notes to Instructors – these pages are at the end so instructors may reproduce this packet with these notes omitted.

Student Level

This experiment is designed as an introductory chemistry experiment for high school or freshman level college beginning chemistry course or for a chemistry chapter in an introduction to physical sciences course.

Overview

This experiment measures the moles of baking soda consumed and moles of CO_2 produced. No attempt is made to quantify the moles of acetic acid consumed although this is a potential extension of this experiment.

Molar quantities are simply a constant multiplier of the number of molecules. Thus students are led to understand that when one mole of baking soda is consumed, a mole of CO_2 is produced. Furthermore this implies for each molecule of baking soda consumed, a molecule of CO_2 is produced. We lead students to understand the direct correlation between chemical formula and the proportion of reactants.

Finally we teach students how to handle unexpected variations. At about 2 gm of baking soda to 10 ml of vinegar the baking soda will not be fully consumed. Students are challenged to think about what this means and how it influences their results. The calculated number of moles of baking soda is based on mass and, if not completely consumed, it will result in large difference between **calculated** moles of baking soda consumed and CO_2 produced. Students are led to understand this difference is due to incomplete consumption of baking soda.

Sample Data

This experiment was performed and the two Tables with that data used are reproduced here. I rinsed and reused the same balloon, but since the balloon was wet the funnel helped get baking soda into the balloon for the next trial.

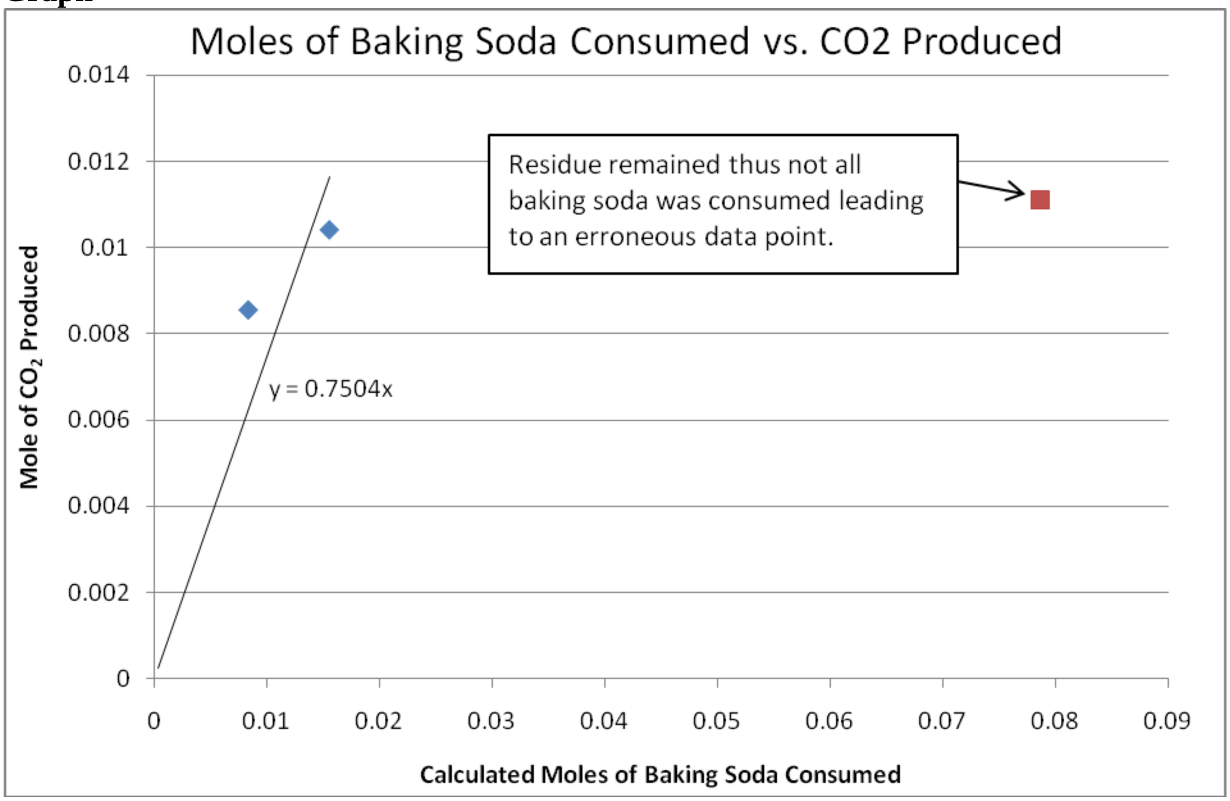
Data Table 1

Trial	Mass of $NaHCO_3$ (gm)	Excess $NaHCO_3$? (y/n)	l_x – size of balloon in x direction (cm)	l_y – size of balloon in y direction (cm)	l_z – size of balloon in z direction (cm)
1	6.6	Y	7.57	7.57	9.08
2	1.3	N	7.58	7.58	8.48
3	0.7	N	7.30	7.30	7.50

Results Table 2

Trial	a (cm)	b (cm)	c (cm)	V (cm3)	CO_2 (moles)	$NaHCO_3$ (moles)	% Diff	Residue? (y/n)
1	3.785	3.785	4.54	272	0.0111	0.0786	151%	Y
2	3.79	3.79	4.24	255	0.0104	0.0155	39%	N
3	3.65	3.65	3.75	209	0.00854	0.00833	2.5%	N

Graph



<u>Prelab Sample Answers</u>

1) A mole contains a constant number ($N_A = 6.02214179*10^{23}$) of molecules no matter what the substance is.
2) Convenience. It's easier to measure 2 moles of hydrogen (H_2) and 1 mole of oxygen (O_2) to yield 2 moles of H_2O rather than $2*10^{23}$ molecules of hydrogen and 10^{23} molecules of oxygen to yield $2*10^{23}$ molecules of H_2O.
3) 25°C and 101,300 Pa (for example). °C and Pa (for absolute pressure) are correct units for the time being.
4) $V = \dfrac{nRT_K}{P}$
5) $T_K = 298°K$
6) $2.45*10^{-2}$ m^3
7) 24,500 cm^3

8) V = 524 cm^3; n = 0.0214 moles
9) Find the sum of the atomic masses of each element in sodium bicarbonate.
10) Sodium bicarbonate is $NaHCO_3$ thus molecular mass is 22.99+1.000+12.01115+3*15.999=83.998 gm
11) 0.0119 moles per gram

Answers to Postlab Questions

1) Yes, however with large error. This is to be expected due to inaccuracy in measuring mass and volume.
2) That there is a one-to-one correspondence between baking soda consumed and CO_2 produced.
3) Our experiment confirms the Law of Definite Proportions.
4) Knowing the chemical formula of a molecule, we can calculate the amount of reactants required to make the compound. It connects molecular structure with macroscopic processes.
5) 3.43 gm