

Determining the General Gas Law Constant, R

OVERVIEW

Recently in my physics class my imagination caught fire. My teacher derived the gas law equation $PV = \frac{1}{3}Nmc^2$ using classical mechanics: equations of motion, impulse, etc., that is, using pure theory alone. My mind was ready for further exploration, and so when we were told about an IA for physics I once again turned my attention to the gas laws, specifically the universal gas constant, denoted " R ".

The universal gas law constant is important because it is applicable to all gases in the ideal gas law, and it is also applied in various equations in the scientific field in different forms.

That such a law is possible has fascinated me since I first learned about it in physics class.

The purpose of my investigation, then, is to experimentally determine the value of the universal gas constant. First, the experimental value of Boyle's law constant was determined—the product of pressure P and volume V for a constant temperature T and a fixed mass m of air. Then, I measured the mass of air indirectly and looked up the molar mass of air. Next I determined the number of moles in my experiment's air sample. With these values, the universal gas law constant R was calculated from the equation $PV = nRT$.

My experimental value for R was $8.05 \text{ J mol}^{-1} \text{ K}^{-1}$ whereas the accepted¹ or textbook value is $8.3144621 \text{ J mol}^{-1} \text{ K}^{-1}$. Comparing the two values my result is only off by about 3%. However, accounting for experimental uncertainties (in the worst case) by results are good to 8%. This is still somewhat acceptable.

BACKGROUND

In the 17th century Robert Boyle investigated the relationship between the pressure and volume of a gas; he discovered that for a fixed temperature and constant mass, the product of pressure and volume were constant. In the early 1800's the study of gas became important, as the use of hot air balloons was popular; scientists wanted to improve the efficiency of hot air balloons. Jacques Charles investigated the effects of temperature on a gas, and Joseph Louis Gay-Lussac formulated what is now known as Charles's law: namely, that volume was proportional to temperature for a fixed mass and constant pressure.^{2,3} Boyle's and Charles' results can be combined with a proportionally constant r unique to each type of gas, and it was written as $PV = rT$.

This equation requires a different proportional constant r for each specific gas. And yet scientists were not satisfied with this equation. What they wanted was one constant that could be used for every type of gas. Then, with Avogadro's discovery that at a given temperature and pressure, that equal volumes of any gas contain an equal number of molecules, the general gas law was formulated. By carefully investigating the relationship

Comment [1]: Personal Engagement. As we will see, the student is excited, even inspired, to conduct an IA concerning the general gas law.

Comment [2]: Personal Engagement. The student is clearly interested in this, and now they will measure the constant experimentally.

Comment [3]: Exploration. This is a standard high school experiment, but the student puts much thought and critical skills into the experiment. The method is nicely stated, and is ambitious to say the least.

Comment [4]: Exploration. The scientific context is nicely described.

between the gas constant and the molar mass of a gas, scientists realized that there was a constant ratio between them, which is the **universal gas constant**, denoted R . The general gas law is written as $PV = nRT$. Although this constant is for an ideal gas, it is approximately appropriate for real gases given the limit range of pressure, temperature and volume values.

Comment [5]: Exploration. The student has demonstrated a thorough understanding of their topic.

The general gas law constant R is one of the **most important physical quantities** in the natural sciences. It describes the relationship of individual gas constants and molar mass. It appears in various aspects of science, including the ideal gas law in thermo-physics and the Nernst equation in electrochemistry⁴. Moreover, ideologically the universal gas constant is equivalent to the Boltzmann constant⁵, which helps define entropy statistically and has an important role in science.

Comment [6]: Exploration. The student offer more insightful background and context to the universal gas constant.

INTRODUCTION



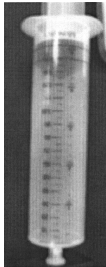
The ideal gas law equation⁶ of pressure P , volume V , the number of moles n and the temperature T will be used to experimentally determine the universal gas constant R .

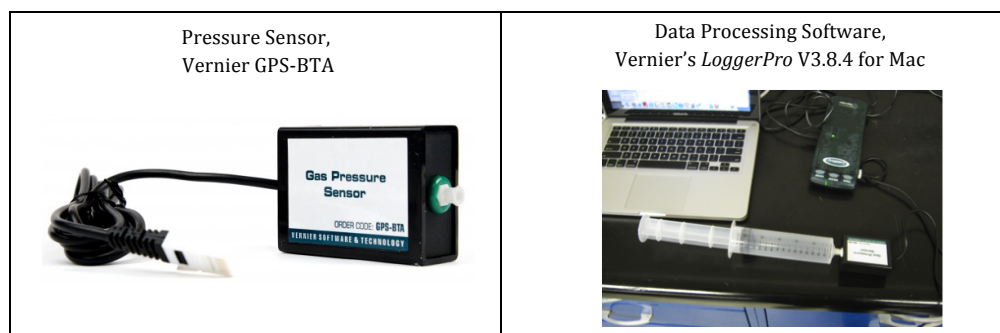
First I establish the proportionally constant of Boyle's law ($PV = \text{constant}$) for a given sample of air at room temperature. Then I establish the molar volume of the sample and hence calculate R as follows:

$$PV = \text{constant} \rightarrow PV = nRT \rightarrow R = \frac{\text{constant}}{nT}$$

Comment [7]: Communication. Sections are easy to understand, and the logical flow makes good sense. The student offers a number of insights as well as a sound scientific study.

EXPERIMENTAL MATERIALS

<p>Mercury Thermometer</p> 	<p>Data-Logger Interface, Vernier's LabPro</p> 	<p>140 cc Monoject Plastic Syringe</p> 
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MEASUREMENTS & UNCERTAINTIES

Volume. The syringe is calibrated in cubic centimeters with markings every 5 cc. It is safe to estimate the measurement to 1 cc; hence the uncertainty will be ± 1 cc. The uncertainty ranges from 0.7% at the largest volume up to just under 3% for the smallest volume.

$$\Delta V_n \% = \frac{1 \text{ cc}}{V_n} \times 100$$

The percentage for each proved to be so small so I decided to ignore them and not plot them on my graphs.

Pressure. Pressure was measured with Vernier's GPS-BTA⁶ pressure sensor. This sensor measures absolute pressure and the manufacture claims it needs no calibration. The gas sensor specifications⁷ also states that the sensor has a resolution of 0.05 kPa. This is the uncertainty in the measured absolute or raw data values of pressure, $\Delta P = \pm 0.05 \text{ kPa}$.

My experiment utilizes the average of fives sets of pressure measurements. I then determined the average pressure. The uncertainty used for each averaged pressure value is \pm one-half the range, although this is the uncertainty for the raw data and not a statistical uncertainty for the average pressure.

This absolute uncertainty varied from $\pm 0.2\%$ for the largest volume up to just over $\pm 2\%$ for the smallest volume. The error bars for this would be even smaller than the error bars for the volume, which we excluded from my graph because they could not be seen. However, this percentage of uncertainty in the range is greater than the uncertainty in the average of the range. For the uncertainty in the averages I found the statistical value of standard deviation, and this was much smaller than 2%. In fact, for the smallest volume of 35 cc (with the greatest range uncertainty of 2%) the standard deviation is $\sigma = 1.7$, and this is a statistical uncertainty of only $\pm 0.8\%$. For the largest volume, the standard deviation in the pressure values was only 0.2 kPa or about one-third of one-percent of the measured pressure value. These calculations were made using a web site⁸.

Comment [8]: Exploration. Here and in other places the student is fully aware of errors, uncertainties and assumptions.

Comment [9]: Exploration. Five repeated measurements for any given volume is more than adequate, and the range is acceptable given the equipment available in the high school lab.

Because the uncertainty is so small it is safe to assume that the uncertainty in the reciprocal of pressure is the same percentage, even though the reciprocal function is non-symmetrical. When you consider significant figures the asymmetry of the reciprocal functions disappears when the percentage is small. Hence I feel it is safe to not include error bars in Graph 2.

Room Temperature. The room temperature was measured and recorded just before I performed the experiment. The work was in the physics lab basement. The altitude here is approximately 1958 m above sea level. The thermometer read 21.0 °C with an estimated uncertainty of $\pm 0.1^\circ\text{C}$. This is less than 0.5%. I made no effort at calibrating values from the thermometer and barometer due to the possible change in mercury density (as I was told that would be a very minor change).

EXPERIMENTAL PROCEDURE

After measuring and recording the room temperature, I sealed the syringe with 140 cc of air in it to the pressure sensor. This was connected to the *LabPro* data processing unit by *Vernier* and then to a computer interfacing with *Vernier's LoggerPro* software.

I compressed the syringe in steps of 5 cc and recorded the pressure. This was done over a range from 140 cc down to 35 cc. At volumes from around 60 cc to 35 cc the pressure was extreme, and so I had a friend help hold the syringe as I recorded the data.

After recording the volume and pressure measurements over the given range I then repeated the experiment for a total of five times. I used the average pressure for a given volume when making calculations.

DATA

The spreadsheet function of *Logger Pro* was programmed to perform the obvious calculations of averaging the five sets of data, taking the reciprocal of the average pressure data, finding the product of pressure and volume, finding the uncertainty in the volume, converting units, etc. The complete data table in *Logger Pro* was too big to show all these detail, but I have included in the data table the important raw data and averaged data and a few other calculations.

The absolute uncertainty in the volume was $\Delta V = \pm 1\text{cc}$ and the absolute uncertainty in the raw pressure data was $\Delta P = \pm 0.05\text{ kPa}$, and the other uncertainties are discussed in this report. Graph 2 uses SI units of meter-squared for volume and Pascals for pressure, and in my calculations of the number of moles will use mass in grams.

Comment [10]: Exploration. The method is most appropriate. The student clearly knows what they are doing.

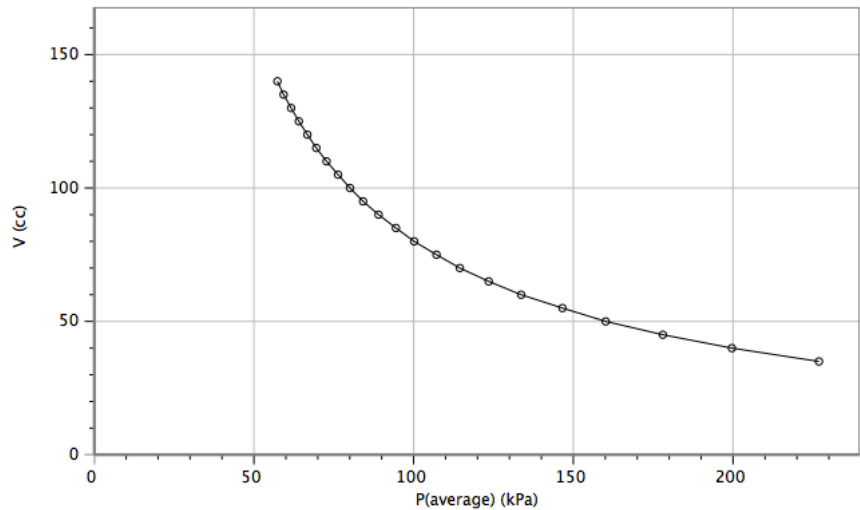
Comment [11]: Analysis. The student has selected, recorded and processed the data in a beautifully executed way. They have also interpreted the data in a most relevant and appropriate way.

	Data Set									
	Volume (cc)	Pressure Set 1 (kPa)	Pressure Set 2 (kPa)	Pressure Set 3 (kPa)	Pressure Set 4 (kPa)	Pressure Set 5 (kPa)	Average Pressure (kPa)	1/P(Average) (kPa ⁻¹)	P V (kPa * cc)	V Uncertainty (%)
1	140.0	57.59	57.17	57.24	57.25	57.58	57.366	0.017432	8031.240	0.71
2	135.0	59.50	59.12	59.22	59.24	59.4	59.296	0.016865	8004.960	0.74
3	130.0	61.80	61.39	61.57	61.76	61.74	61.652	0.016220	8014.760	0.77
4	125.0	64.08	63.85	64.01	64.36	64.05	64.070	0.015608	8008.750	0.80
5	120.0	66.83	66.61	66.73	66.83	66.75	66.750	0.014981	8010.000	0.83
6	115.0	69.46	69.46	69.57	69.64	69.57	69.540	0.014380	7997.100	0.87
7	110.0	72.67	72.3	72.72	72.98	73.04	72.742	0.013747	8001.620	0.91
8	105.0	76.66	75.98	76.16	76.62	76.33	76.350	0.013098	8016.750	0.95
9	100.0	79.94	79.97	80.05	80.19	80.31	80.092	0.012486	8009.200	1.00
10	95.0	84.26	83.95	84.1	84.15	84.4	84.172	0.011880	7996.340	1.05
11	90.0	89.33	88.93	88.76	88.87	89.31	89.040	0.011231	8013.600	1.11
12	85.0	94.52	95.01	93.73	94.36	94.72	94.468	0.010586	8029.780	1.18
13	80.0	100.16	99.98	99.68	100.41	100.59	100.164	0.009984	8013.120	1.25
14	75.0	107.08	107.02	106.83	107.35	107.52	107.160	0.009332	8037.000	1.33
15	70.0	114.54	114.34	114.26	114.99	114.17	114.460	0.008737	8012.200	1.43
16	65.0	123.32	123.45	123.34	123.75	123.69	123.510	0.008097	8028.150	1.54
17	60.0	134.06	133.59	132.82	134.66	133.2	133.666	0.007481	8019.960	1.67
18	55.0	146.44	147.36	144.85	147.33	147.02	146.600	0.006821	8063.000	1.82
19	50.0	160.83	160.87	158.13	160.94	159.91	160.136	0.006245	8006.800	2.00
20	45.0	177.98	178.02	176.72	179.7	177.77	178.038	0.005617	8011.710	2.22
21	40.0	200.70	200.29	197.18	199.38	200.62	199.634	0.005009	7985.360	2.50
22	35.0	226.27	226.89	224.9	229.63	226.77	226.892	0.004407	7941.220	2.86

BOYLE’S LAW CONSTANT FOR AIR

The first analysis is to determine the Boyle’s law constant for the given mass of air at room temperature sealed in the syringe. Here in Graph 1 you can see the inverse relationship between volume and pressure.

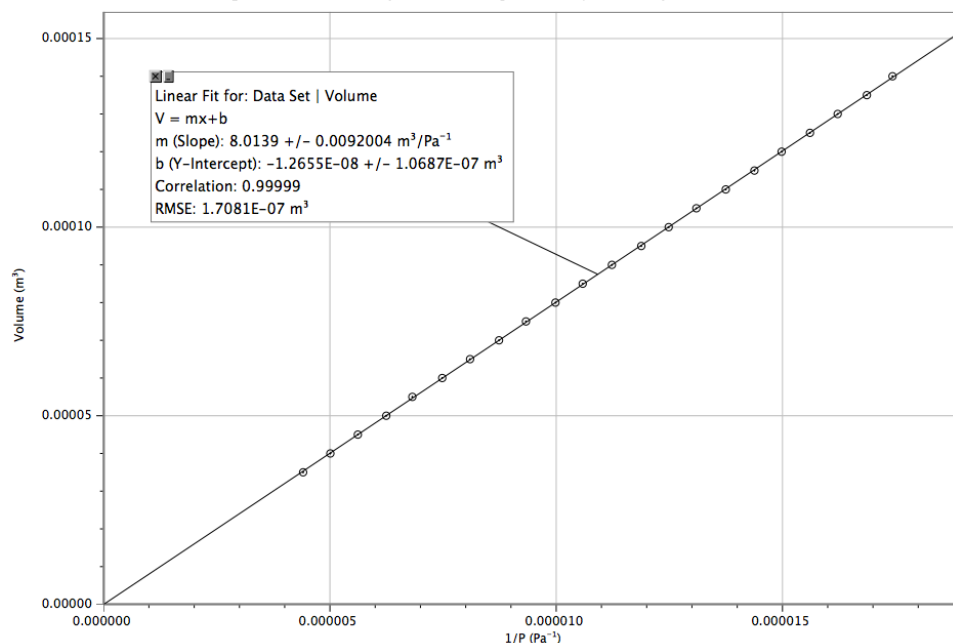
Graph 1, Volume against Average Pressure



Comment [12]: Communication. The data presentation, the graphs, and the text all make for easy understanding of what the student is doing.

Boyle's law states that $P_1V_1 = P_2V_2 = P_nV_n$ which is to say that as the volume gets smaller the pressure gets larger. If $PV = \text{constant}$ then volume is inversely proportional to the pressure, that is, $V \propto \frac{1}{P}$. This is illustrated in Graph 2.

Graph 2, Volume against Reciprocal of Average Pressure



The best-fit line is clearly linear and, accounting for uncertainty in the gradient, includes the origin, hence the relationship is proportional (within experimental error). The most significant uncertainty is in the volume measurement, and when a graph including error bars of $\pm 1 \text{ cc}$ is added, the bars were too small to see so I did not include them here. Instead, I will use the statistical uncertainty generated by the computer, namely a gradient of 8.0139 ± 0.0092004 with a negative volume intercept of $-1.2655\text{E-}8 \pm 1.068\text{E-}7$. These values simplifies as follows:

$$\text{slope} = (8.014 \pm 0.009) \text{ m}^3 \text{ Pa}$$

$$y - \text{axis intercept} = -1.26 \times 10^{-8} \text{ m}^3$$

The gradient thus has an uncertainty of about 0.1%. The y-intercept is as close to zero as one would expect. The uncertainty here should not be expressed as a percentage as the ideal value would indeed be zero. If the y-intercept is in the order of 10^{-8} and the values of

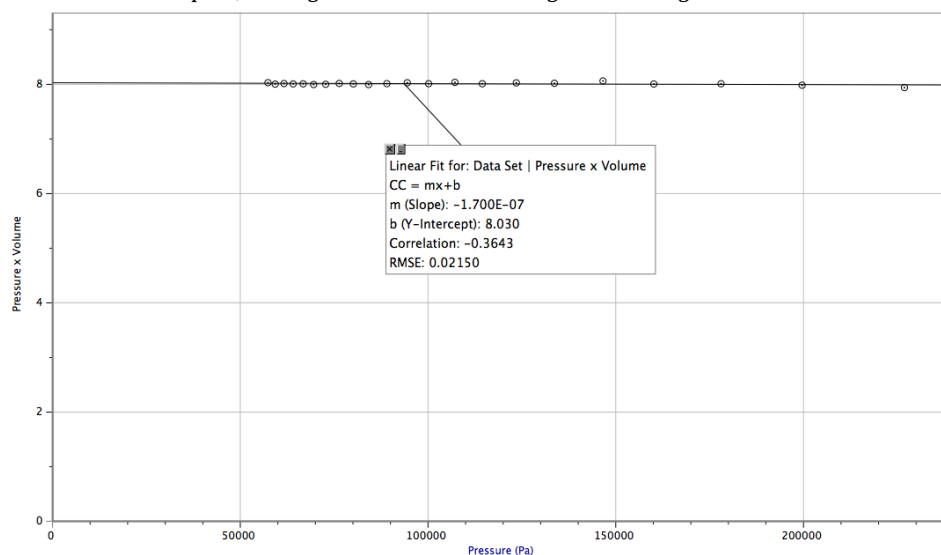
volume are in the order of 10^{-4} and 10^{-5} then we can appreciate any systematic shift as insignificant, probably due to rounding errors.

POSSIBLE DEAD SPACE IN VOLUME MEASUREMENTS

The small value of the y-intercept on Graph 2 could represent the dead space in the syringe and pressure sensor, but it was so small I ignored it. However, I want to double-check my values here. To do this I graphed the product of average pressure and volume against volume. A small and negative gradient represents the dead space⁹.

Comment [13]: Analysis. The student is insightful here, both to account for the dead space and the manner in which they determine the dead space. A graph of PV against V was on an IB exam paper.

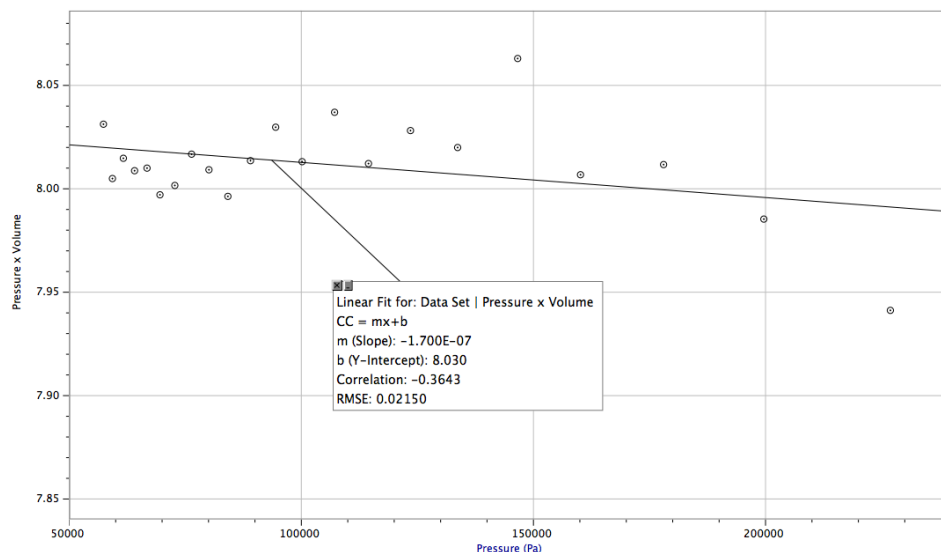
Graph 3, Average Pressure x Volume against Average Pressure



The slope is a $-1.7 \times 10^{-7} \text{ m}^3$. This is much larger than the offset represented in Graph 2, which was $-1.3 \times 10^{-8} \text{ m}^3$ or about 13 times larger. In either case, the negative slope is extremely small. The difference may be due to rounding errors in the calculations. And in either case it is much smaller than the $\pm 1 \text{ cc}$ uncertainty of any given measurement. I will therefore not assume this value represents the dead-space. However, both Graphs 2 and 3 suggest a possible negative value of volume that indeed represents the dead space and should be added to all volume measurements.

Graph 4 is a close up view of the scatter of data. Although this may look almost random, if you consider the scale we can say there is ever so slight a negative slope (representing dead space).

Graph 4, A Close Up View of
the Average Pressure \times Volume against Average Pressure



CALCULATING THE UNIVERSAL GAS CONSTANT

First I found the number (or fraction thereof) of moles in the air sample. Using a sensitive digital balance from the chemistry department I measured the syringe with 140 cc of air in it and again without air in it. The difference is the mass of air that I used in my experiment.

$$m_{\text{air}} = m_{\text{syringe with air}} - m_{\text{syringe without air}} = (73.323 - 73.225)\text{g} = 0.098\text{g}$$

Next I found the molar mass of air. Air is a gas made of up different percentages of various gases, such as N_2 , O_2 , Ar, and CO_2 . I used an Internet calculator to determine the molar mass and was given as an effective average of 28.97 g/mole. This was confirmed by another web site.¹⁰

The number of moles of air in my syringe is thus calculated as:

$$n = \frac{m_{\text{air}}}{\text{molar mass of air}} = \frac{0.098\text{g}}{28.97\text{g/mol}} = 3.38281 \times 10^{-3}\text{ mole}$$

From Graph 2 we find that the Boyle's law constant (for the given mass of air and constant temperature) from the gradient of the graph, PV , is equal to $8.0139\text{ m}^3\text{ Pa}$.

The temperature was $T = 21.0^\circ\text{C} = (21.0 + 273.15)\text{K} = 294.15\text{K} \approx 294.2\text{K}$

Comment [14]: Evaluaiton. The student answers the research question in magnificent detail, with full appreciations of the strength and limitations of the experimental results.

Now for **the final result of my exploration**, the experimental value of the universal ideal gas law constant. My result is rounded to three significant figures.

$$R_{\text{experiment}} = \frac{PV}{nT} = \frac{\text{gradient}}{nT}$$

$$R_{\text{experiment}} = \frac{8.0139 \text{ m}^2 \text{ Pa}}{(3.38281 \times 10^{-3} \text{ moles})(294.15 \text{ K})} = 8.05373 \text{ J mol}^{-1} \text{ K}^{-1}$$

$$\therefore R_{\text{experiment}} \approx 8.05 \text{ J mol}^{-1} \text{ K}^{-1}$$

Compare this with the textbook or **accepted value** of:

$$R_{\text{accepted}} = (8.3144621 \pm 0.0000075) \text{ J mol}^{-1} \text{ K}^{-1} \approx 8.31 \text{ J mol}^{-1} \text{ K}^{-1}$$

Compared to the accepted value, my result is low by about 3%.

CONCLUSION AND IMPROVEMENTS

My experimental value was about 3% off the accepted value, and on the low side. However, when I calculate 3% of my answer I get an uncertainty of $\pm 0.24 \text{ J mol}^{-1} \text{ K}^{-1}$, and this is in the first decimal place, the tenths. Perhaps my conclusion should be

$$R_{\text{exp}} = (8.1 \pm 0.2) \text{ J mol}^{-1} \text{ K}^{-1}$$

With this expression my result almost reaches the accepted value. Recall that the uncertainty in the volume ranged from 0.2% to 2% and the uncertainty in the slopes was only 0.1% while the two significant figures in the air mass determination represents an uncertainty of 1%. These are all very small, and my best determination of the quality of my results can be based on comparison to the accepted value, again at about 3%.

My purpose in this exploration was to establish the universal gas law constant by experiment. Overall, I was really excited when my conclusion confirmed to a reasonable degree the accepted value. I can hardly believe that this was possible.

IMPROVEMENTS TO THE EXPERIMENT

- (1) My biggest uncertainty is in the measurement of the number of moles. It is this area that would need improvement. Two significant figures in the mass measurement limited the mole number precision. My teacher said that were more sensitive balance scales are available but my school did not have one.

Comment [15]: Evaluaiton. The student compares their experimental result with the accepted value, and appreciate the uncertainty range in both value.

Comment [16]: Evaluation. The student clearly discusses improvement that are relevant to their work. The student even mentions an interesting extension (about determining the atmospheric pressure).

- (2) My raw data did not account for the sensor's dead space. Although my two calculations are significantly different for the dead space in the sensor, I still believe that there is dead space and this volume should be added to each raw data value of volume. If I could account for this before performing all investigation my results would be more accurate. *Vernier's* technical specification says that no calibration is needed but they do not mention dead space. A personal email from *Vernier's* Jake Hopkins at www.vernier.com/til/582/ stated the dead space should be 0.8 mL (that is 0.8 cc). My uncertainty for volume was 1 cc. perhaps there is an unknown systematic error in all my data that somehow cancels out the dead space.

To account for the **dead space** (if I were to repeat my experiment) I could (a) open the sensor valve so that air goes in and remains at room pressure. (b) Then I could move the piston of the syringe down so the volume reading is zero. (c) Next I would close the valve and connect the syringe to the sensor, and then move the piston on the syringe so that the volume reads zero. The reading should be close to one atmosphere, but I would note the exact pressure reading. (d) Finally, I would pull the piston out slowly, noting the pressure reading. When the reading drops to half of its original reading, I would have double the volume. Hence the new piston reading is the volume of the pressure sensor and the tube up to the syringe. Unfortunately, I cannot spend more time on this project.

Comment [17]: Evaluation. The student offers a most impressive appreciation of the dead space.

- (3) With more time I would like to repeat the investigation using a larger syringe and perhaps with air at different temperature (as well as different gases).
- (4) **An alternative investigation that fascinates me** would be to seal a syringe with the plunger 90% of the way in at normal atmospheric air pressure. Then I would hang masses (converted to force units of weight) and record the hanging weight as a function of syringe's partial vacuum volume. By measuring the diameter of the plunger and extrapolating from an appropriate graph the normal air pressure in the room (in units of N m^{-2}) can be determined. I would love to do this with more time.

Comment [18]: Personal Engagement. Another expression of the student's enthusiasm.

FOOTNOTES

- 1 http://en.wikipedia.org/wiki/Gas_constant
- 2 <http://www.chm.davidson.edu/vce/gaslaws/gasconstant.html>
- 3 http://www.newworldencyclopedia.org/entry/Joseph_Louis_Gay-Lussac and <http://www.chm.davidson.edu/vce/gaslaws/>
- 4 Sybil and Parker, *McGraw-Hill Encyclopedia of Science and Technology*, McGraw-Hill Publishers, 1997, page 158.

- 5 "Boltzmann Constant." *Encyclopedia Britannica*, 2010. Encyclopedia Britannica Online. 10 Dec. 2010 in semi-conductor physics.
- 6 Tipler, Paul Allen, "Physics for Scientists and Engineers," Volume 1, Page 632.
- 7 <http://www.vernier.com/products/sensors/gps-bta/>
- 8 <http://www.mathsisfun.com/data/standard-deviation-formulas.html>
- 9 See "More on Systematic Error in a Boyle's Law Experiment" by Richard McCall in *The Physics Teacher*, Volume 50, Number 1, January 2012, pages 22-23.
- 10 The two web sites that derived the molar mass of air were:
http://www.engineeringtoolbox.com/molecular-mass-air-d_679.html
<http://www.wolframalpha.com/input/?i=air+molecular+weight>

Moderation Bullets (in red), Comments and Assessment Marks

Title: **Determining the general gas law constant R**

Personal Engagement x/2	Exploration x/6	Analysis x/6	Evaluation x/6	Communication x/4	Total x/24
2	6	6	6	4	24

Personal Engagement

This criterion assesses the extent to which the student engages with the exploration and makes it their own. Personal engagement may be recognized in different attributes and skills. These could include addressing personal interests or showing evidence of independent thinking, creativity or initiative in the designing, implementation or presentation of the investigation.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1	The evidence of personal engagement with the exploration is limited with little independent thinking, initiative or creativity. <ul style="list-style-type: none"> The justification given for choosing the research question and/or the topic under investigation does not demonstrate personal significance, interest or curiosity. There is little evidence of personal input and initiative in the designing, implementation or presentation of the investigation.
2	The evidence of personal engagement with the exploration is clear with significant independent thinking, initiative or creativity. <ul style="list-style-type: none"> The justification given for choosing the research question and/or the topic under investigation demonstrates personal significance, interest or curiosity. There is evidence of personal input and initiative in the designing, implementation or presentation of the investigation.
Moderator's Award 2	Moderator's Comment Although there are only a few expressions of personal engagement, the excitement the genuine interest is clearly expressed. Moreover, when we appreciate the subtle details demonstrated throughout this investigation it is clear that the student has the curiosity, intellectual interest and determined creativity in developing a most thorough scientific study. The moderator is certain that the student earns full marks for Personal Engagement, level 2 .

Exploration

This criterion assesses the extent to which the student establishes the scientific context for the work, states a clear and focused research question and uses concepts and techniques appropriate to Diploma level. Where appropriate, this criterion also assesses awareness of safety, environmental, and ethical considerations.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1-2	<ul style="list-style-type: none"> The topic of the investigation is identified and a research question of some relevance is stated but it is not focussed. The background information provided for the investigation is superficial or of limited relevance and does not aid the understanding of the context of the investigation. The methodology of the investigation is only appropriate to address the research question to a very limited extent since it takes into consideration few of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of limited awareness of the significant safety, ethical or environmental issues that are relevant to the methodology of the investigation *
3-4	<ul style="list-style-type: none"> The topic of the investigation is identified and a relevant but not fully focused research question is described. The background information provided for the investigation is mainly appropriate and relevant and aids the understanding of the context of the investigation. The methodology of the investigation is mainly appropriate to address the research question but has limitations since it takes into consideration only some of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of some awareness of the significant safety, ethical or environmental issues that are relevant to the methodology of the investigation *.
5-6	<ul style="list-style-type: none"> The topic of the investigation is identified and a relevant and fully focused research question is clearly described. The background information provided for the investigation is entirely appropriate and relevant and enhances the understanding of the context of the investigation. The methodology of the investigation is highly appropriate to address the research question because it takes into consideration all, or nearly all, of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of full awareness of the significant safety, ethical or environmental issues that are relevant to the methodology of the investigation.*
Moderator's Award 6	Moderator's Comment The student states a clear and focused research question and sets the general gas law constant in appropriate scientific context. The techniques and methods are most appropriate for high school lab work. The student is aware of all the major and subtle issues involved. Although no safety issues or environmental concerns are mentioned, we can consider the fourth bulleted descriptor as an outlier for this investigation. The moderator is happy to award the student full marks here, level 6.

Analysis

This criterion assesses the extent to which the student's report provides evidence that the student has selected, recorded, processed and **interpreted** the data in ways that are relevant to the research question and can support a conclusion.

Mark	Descriptor
0	<i>The student's report does not reach a standard described by the descriptors below.</i>
1-2	<ul style="list-style-type: none"> The report includes insufficient relevant raw data to support a valid conclusion to the research question. Some basic data processing is carried out but is either too inaccurate or too insufficient to lead to a valid conclusion. The report shows evidence of little consideration of the impact of measurement uncertainty on the analysis. The processed data is incorrectly or insufficiently interpreted so that the conclusion is invalid or very incomplete.
3-4	<ul style="list-style-type: none"> The report includes relevant but incomplete quantitative and qualitative raw data that could support a simple or partially valid conclusion to the research question. Appropriate and sufficient data processing is carried out that could lead to a broadly valid conclusion but there are significant inaccuracies and inconsistencies in the processing. The report shows evidence of some consideration of the impact of measurement uncertainty on the analysis The processed data is interpreted so that a broadly valid but incomplete or limited conclusion to the research question can be deduced.
5-6	<ul style="list-style-type: none"> The report includes sufficient relevant quantitative and qualitative raw data that could support a detailed and valid conclusion to the research question. Appropriate and sufficient data processing is carried out with the accuracy required to enable a conclusion to the research question to be drawn that is fully consistent with the experimental data. The report shows evidence of full and appropriate consideration of the impact of measurement uncertainty on the analysis The processed data is correctly interpreted so that a completely valid and detailed conclusion to the research question can be deduced.
Moderator's Award 6	Moderator's Comment There is no doubt that the student has selected, recorded, processed and interpreted the data in a most appropriate and revealing way. Attention to detail, errors and uncertainties, is exceptional. There is more than enough data, limited only by the size of the syringe, and the precision is amazing and the accuracy is good. There is full awareness of the impact of uncertainties. The conclusion, a numerical value for R, is easily established and compared with the accepted value. The moderator is happy to award the student full marks for Analysis, 6.

Evaluation

This criterion assesses the extent to which the student's report provides evidence of evaluation of the investigation and the results with regard to the research question and the accepted scientific context.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1-2	<ul style="list-style-type: none"> A conclusion is outlined which is not relevant to the research question or is not supported by the data presented. The conclusion makes superficial comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are outlined but are restricted to an account of the practical or procedural issues faced. The student has outlined very few realistic and relevant suggestions for the improvement and extension of the investigation.
3-4	<ul style="list-style-type: none"> A conclusion is described which is relevant to the research question and supported by the data presented. A conclusion is described which makes some relevant comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are described and provide evidence of some awareness of the methodological issues* involved in establishing the conclusion. The student has described some realistic and relevant suggestions for the improvement and extension of the investigation.
5-6	<ul style="list-style-type: none"> A detailed conclusion is described and justified which is entirely relevant to the research question and fully supported by the data presented. A conclusion is correctly described and justified through relevant comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are discussed and provide evidence of a clear understanding of the methodological issues involved in establishing the conclusion. The student has discussed realistic and relevant suggestions for the improvement and extension of the investigation.
Moderator's Award 6	Moderator's Comment The student's report provides overwhelming evidence of the evaluation of the investigation and the results within the accepted scientific context. The conclusions (each required measurement) are described and justified, and in far more detail than one normally expects at high school level. Strengths and weakness of the method and data, and the sources of uncertainties are discussed in detail. The methodology is fully understood. The improvements and an extension are relevant and interesting. The moderator is happy once again to award the student full marks, 6.

Communication

This criterion assesses whether the investigation is presented and reported in a way that supports effective communication of the focus, process and outcomes.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1-2	The presentation of the investigation is unclear, making it difficult to understand the focus, process and outcomes. <ul style="list-style-type: none"> The report is not well structured and is unclear: The necessary information on focus, process and outcomes is missing or is presented in an incoherent or disorganized way. The understanding of the focus, process and outcomes of the investigation is obscured by the presence of inappropriate or irrelevant information. There are many errors in the use of subject specific terminology and conventions*.
3-4	The presentation of the investigation is clear. Any errors do not hamper understanding of the focus, process and outcomes. <ul style="list-style-type: none"> The report is well structured and clear: the necessary information on focus, process and outcomes is present and presented in a coherent way. The report is relevant and concise thereby facilitating a ready understanding of the focus, process and outcomes of the investigation. The use of subject specific terminology and conventions is appropriate and correct. Any errors do not hamper understanding.
Moderator's Award 4	Moderator's Comment The entire report demonstrates effective communications; the method stays focused and the logical progression of the investigation follows the presentation. The report is concise despite containing many details. The terminology and scientific conventions are all followed. Overall, this is a most impressive investigation, and the moderator once again awards full marks, 4.