Analyzing Cigarette Smoke

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INTRODUCTION

According to the Surgeon General smoking is the number one preventable cause of death in the United States. In the United States alone:

- Approximately 400,000 people die from smoking related illnesses each year;
- The average smoker starts by age 15;
- 3000 teenagers per day start to smoke;
- By age 6 more than 90% of all children can identify "Joe Camel".

Numerous legal and educational initiatives have targeted smoking and smokeless tobacco use by children. Many of these focus on preventing children from purchasing cigarettes or smokeless tobacco, restricting advertising of tobacco products, or educating young people about the hazards of smoking and smokeless tobacco. In this latter category it should be possible to utilize young people's natural inquisitiveness about their personal environment to investigate the composition of cigarette smoke in laboratory science classes. In this way we can allow students to reach their own conclusions based on, at least in part, data that they acquire themselves. In this paper we describe several experiments using readily available laboratory equipment to measure the tar and carbon monoxide concentrations of cigarette smoke. It is also possible that these experiments could be performed by the teacher as a demonstration.

Cigarette smoke contains an amazing array of gaseous and particulate matter. This includes (in approximate order by mass): carbon dioxide, water, carbon monoxide, particulate matter (mostly tar), nicotine, nitrogen oxides, hydrogen cyanide, ammonia, formaldehyde, phenol and dozens of other well known toxic compounds. Some of these compounds are present in extremely high concentrations. For example cigarette smoke contains higher concentrations of carbon monoxide than the auto exhaust from a well maintained vehicle. This concentration of CO would be lethal if inhaled continuously. Interestingly, some students don't believe this fact and are eager to investigate this phenomenon for themselves. Because of the relatively high concentrations of some of these constituents (e.g. tar and carbon monoxide) it is possible to conduct science experiments without using very sophisticated equipment. In addition the visual and olfactory clues obtained in the course of doing these labs are in themselves powerful information which the students cannot fail to process.

Standard methods for collection of cigarette smoke have been developed by the Federal Trade Commission (FTC). The FTC method is intended to approximate a typical smoking pattern and consists of one 35 cm^3 "puff" of 2 seconds duration, once per minute. Mainstream (MS) smoke is the smoke which is directly inhaled by the smoker whereas sidestream (SS) or secondhand smoke is the smoke which is released to the environment from the burning cigarette. Measurements on both SS and MS smoke have been made for many of the toxic constituents in cigarettes. The ratio of the mass for many compounds released in SS vs MS smoke is ~1-10 for a typical smoking pattern. This means that for most of the toxic compounds, a greater mass is released in the sidestream than the mainstream smoke [Guerin et al., 1987; Guerin 1991]. For particulate matter and carbon monoxide the SS/MS ratios are in the range of 0.4-2 and 2-8, respectively, however there is a large amount of variation depending on the cigarette type and how it is smoked. Past and current research is quantifying both the MS and SS emissions from cigarette smoke.

Because the quantities and concentrations of the toxic constituents in cigarette smoke are quite high we believed it should be possible to measure these using low technology methods available to secondary science students. In developing these laboratory exercises, our goals was to minimize the complexities as much as possible, while still maintaining a scientifically valid approach. In this light we chose to ignore the differentiation between MS and SS smoke and to focus instead on a total smoke sample obtained by continuously "smoking" the cigarette. Certainly many of the same methods described in this paper could be applied to the MS and SS smoke separately, however to date we have not done so.

EXPERIMENTAL

Part A: Measuring the mass of tar and other particulates

Materials:

High, medium and low tar cigarettes

Balance capable of weighing to 0.001 gram

Small vacuum pump (~$75), house vacuum line or aspirator

47 mm filter holder (~$20 each, available from Cole-Parmer, Niles, IL)

Control valve (~$10) or pinch clamp

Flow meter (optional, ~$20)

Rubber stopper and rubber or Tygon™ tubing

A typical cigarette (regular size) has a mass of ~ 1 gram. Since the main constituent of the cigarette is cellulose, its combustion can be approximated by the following equation (assuming complete combustion):

$$(C_6H_{10}O_5)_n \quad + \quad 6\,O_2 \quad \Rightarrow \quad 6\,CO_2 \quad + \quad 5\,H_2O \qquad [\textit{Equation 1}]$$

$$1.00\text{ gm} \quad + \quad 1.19\text{ gm} \quad \Rightarrow \quad 1.63\text{ gm} \quad + \quad 0.56\text{ gm}$$

where the mass given below each compound in equation 1 is the mass consumed or produced in the combustion of a 1 gram cigarette. The fact that the cigarette is not completely consumed (ash is produced) and that the combustion is incomplete will reduce the amounts of CO_2 and H_2O produced, but nonetheless, it must be kept in mind that CO_2 and H_2O will always be the dominant constituents in the cigarette smoke.

In this first experiment tar in the cigarette smoke is collected on 47 mm filters and weighed. In our early attempts at this we used glass wool as the collection medium and weighed it before and after the tar was collected. However, the mass collected on the glass wool was always several times greater than the mass of tar which should have been present, according to the FTC data. In addition the mass of material collected was not constant, but would slowly decline over a few days. We attribute this excess mass to water produced from the combustion which was also being collected on the glass wool.

We experimented with glass wool, 47 mm Teflon filters, 47 mm quartz fiber filters, and 47 mm Whatman 41 paper filters. The glass wool and quartz fiber filters collected a large amount of water along with the tar and even with drying gave irreproducible results. The Teflon filters gave very low collection amounts due to the fact that the Teflon filters would clog soon after lighting the cigarette and the flow through the cigarette and filter would quickly drop to zero. The most reproducible results, and those closest to the FTC data, were obtained with the Whatman 41 paper filters.

The experimental setup for collecting the tar in the smoke is shown in Figure 1. If a flow meter is used, we aim for a flow of between 0.5-1 liter per minute which is similar to the flow when a smoker inhales. We have performed the experiment both with and without the flow meter and found it helpful, but not essential. To start the experiment the equipment is assembled in a fume hood and a piece of clean filter paper is weighed to the nearest milligram (0.001 gram) or tenth of a milligram (.0001 gram). The filter is put in the filter holder and the vacuum pump (or aspirator) turned on. The air flow is adjusted using the valve or pinch clamp to get a flow of between 0.5-1 liter per minute or a burn time for the cigarette of between 2-3 minutes and then the cigarette is lit. More consistent results are obtained if the flow is kept constant from one run to the next and this takes a little bit of practice with the valve or pinch clamp. Once the cigarette is completely burned, the pump is turned off and the filter paper removed and immediately weighed. The filters can also be weighed after letting them sit overnight to dry, although we have found that this has very little effect using the Whatman 41 paper filters.

The filters must be weighed carefully so as not to lose any material. Each filter must be weighed individually before and after sampling. If a milligram (0.001 gram) or a tenth of a milligram (0.0001 gram) balance is not available it is possible to collect the smoke from more than 1 cigarette on each piece of filter paper or to collect and weigh all of the filter papers together from the entire class and divide by the number of filters weighed.

EXPERIMENTAL DATA

Table 1: Results using Whatman 41 paper filters*

Tar content	**Brand**	**Avg. mass collected (mg)**	**Number of trials**	**Standard deviation (mg)**	**FTC tar content (mg per cigarette)**
High	Lucky Strike	33.3	6	4.3	26
Medium	Camel Filters	11.5	6	1.5	18
Low	Carlton	4.3	6	1.0	1

*Filters were weighed prior to sampling and immediately after collecting the smoke sample

It is possible that using this method we collect other compounds besides tar. Also, since we are collecting a total smoke sample (MS+SS) we might expect our mass to be larger than the FTC value which reports only MS values. However it must be kept in mind that the conditions under which we "smoke" these cigarettes are quite different from the FTC procedure. Although we should not expect good agreement between our data and the FTC tar content, our data indicate that we can clearly differentiate between the high tar and low tar brands and that we are collecting about the right amount of material. It would certainly be interesting to repeat this measurement using a procedure which approximates the FTC method and that is something that could be done by a secondary science class.

A final note on this experiment: An important part of this experiment is the visual and olfactory, but non-quantitative, data obtained by each student. After the smoke from one cigarette has been collected the filters (see Photo A) have a dark brown appearance and intense odor. The students can not fail to notice this "data" and process it as part of their overall learning about cigarettes.

Part B: Non-quantitative analysis of the Carbon Monoxide content of cigarette smoke.

Materials:

High, medium and low tar cigarettes

250 or 500 ml Erlenmeyer flask with sidearm

Small vacuum pump, house vacuum line or aspirator

Control valve or pinch clamp

Rubber stopper and rubber or Tygon™ tubing

Commercially available visual indicator badges for CO (e.g. "Dead stop" badge, ~$1 each, manufactured by Houston Atlas, 2001 Northpark Drive, Kingswood, TX. 77339-3804)

Cigarette smoke contains approximately 0.5-5 % CO (expressed as a mole fraction, which means that at a level of 1%, for example, 1 out of every 100 molecules in the smoke is CO). The range is due to variations in the cigarette and how they are smoked. By comparison, a well tuned car will have CO concentrations which are much lower than 0.1%. In many regions of the country vehicles must be tested annually for CO emissions; the CO standard for auto emissions is 1% v/v. It is a remarkable fact that cigarette smoke contains much higher CO than all but the dirtiest vehicles and exhaling cigarette smoke into the vehicle exhaust analyzer would likely register a failing concentration! It is also rather remarkable to realize that the concentration in cigarette smoke is lethal if inhaled continuously for 30 minutes. Of course smokers do not inhale the smoke continuously, but nonetheless there are serious health implications from these very high levels of CO in the smoke. Smokers have much higher incidence of many cardiovascular disease, stroke, etc. which is due, in part, to the fact that CO tightly binds to hemoglobin in the bloodstream. Smokers have between 2-5% of the hemoglobin in their blood unavailable for O_2 transport because it is tightly bound to CO.

The point of this lab is to qualitatively show that cigarette smoke contains dangerous levels of CO. For this experiment the cigarette is connected using a small piece of Tygon™ tubing which is connected to glass tubing which runs into the one-hole rubber stopper in the Erlenmeyer flask. In earlier experiments the cigarette was inserted directly into the rubber stopper in the top of the flasks, but due to leaks this was changed. The vacuum is pulled through the sidearm of the flask (see figure 2 and Photo B). If the glass tubing is put through the stopper and into the flask a striking visual effect is observed when the cigarette is lit. The flow adjustments are made using the valve or pinch clamp as described in part A. The CO visual indicator badges are designed to warn of a potentially toxic concentration. Several inexpensive types are readily available in aviation supply stores or through suppliers of lab safety equipment. The badges we used in this experiment are called "Dead Stop" and have a bright orange indicator section which turns to black upon exposure to dangerous levels of CO (greater than around 100 parts per million). The badge is placed inside the Erlenmeyer flask.

The procedure for this lab is quite simple. The vacuum is turned on and the flow is adjusted to an appropriate value as in the tar experiments above. Once the cigarette is lit a striking (and rather beautiful) pattern of smoke appears in the flask. At first the smoke may be so dense that the indicator badge disappears. However once the smoke clears it will be obvious that the badge has changed color to indicate a dangerous level of CO. Once exposed to high levels of CO, the badges do not return to their original color. We attempted to use the badges as a semi-quantitative measure of CO by measuring the time it took for the color change to take place. Unfortunately the color change is very rapid and so we were unable to use this approach to get any quantitative results. This should not be surprising since the badges are intended to turn color at ~100 parts per million v/v and we are exposing them to ~1% v/v, or about 10,000 parts per million. Thus cigarette smoke has CO levels which are ~1000 times greater than the level considered dangerous.

Part C: Quantitative analysis of the carbon monoxide content of cigarette smoke and/or auto exhaust.

Materials:

Filtered and/or unfiltered cigarettes

250 or 500 ml Erlenmeyer flask with sidearm

Small vacuum pump, house vacuum line or aspirator

Control valve or pinch clamp

Rubber stopper and rubber or Tygon™ tubing

Commercial detection system for CO (available from Lab Safety Supply, Janesville, WI) consisting of:

Visual indicator tubes for CO in the range of 0.3-7.0% v/v (~$5 each)

Calibrated hand pump for use with the indicator tubes ($300-325.)

In a previous publication [Jaffe and Herndon, 1995] we developed a lab for freshmen college chemistry classes to quantify the CO concentration in auto exhaust. Recently we have extended this approach to also quantify the CO content in cigarette smoke [Jaffe and Chavasse, 1997]. This approach is used by students in our freshmen chemistry classes at the University of Alaska to compare the CO content in auto exhaust and cigarette smoke. However, since these labs use a gas chromatograph to measure CO this approach is not likely to be useful for secondary science classes. Instead, we have also used a simple commercial system to quantitatively determine CO in cigarette smoke and, if desired, auto exhaust.

For ~$400 it is possible to purchase a direct indicating quantitative CO detection system, suitable for cigarette smoke or auto exhaust. This system uses a small, calibrated hand operated pump and direct reading, indicating tubes for CO concentrations in the % range. These are made by several different manufacturers. For the data reported below we used a Dräger Accuro® handpump with Dräger indicating CO tubes purchased from Lab Safety Supply (Janesville, WI, 1-800-356-0783). The pump draws a measured volume of air through the indicating tubes which contain a material that changes color in the presence of CO. After the air sample is drawn through the tube, the CO concentration is read off the tube based on how far the color change extends down the tube. The indicating tubes used for this lab can detect CO in the range of 0.3-7.0%. This range should always detect CO in cigarette smoke and in the exhaust from a poorly operating vehicle, but will not detect CO in the exhaust from a well tuned vehicle. Indicating tubes for lower CO concentrations can also be purchased, but the CO content in cigarette smoke will saturate the tubes and not yield quantitative data.

The data reported below were obtained by burning Camel 100 filter cigarettes in an apparatus very similar to that shown in Figure 2 and Photo B. Both gas chromatography and the indicating tubes were used to determine the CO concentration in the smoke from the same samples. However the samples for the two methods were obtained somewhat differently. For the gas chromatography the samples were obtained by inserting a syringe into the tubing immediately after the Erlenmeyer flask and withdrawing the sample. For the indicator tubes, the sample was obtained by removing the cigarette, inserting the indicating tube where the cigarette was and withdrawing the sample directly into the tube with the handpump. In both cases the flow through the system was turned off before the sample was collected.

Table 2. CO concentration (% v/v) in the smoke from 4 cigarettes as determined by both gas chromatography and Dräger indicating tubes.

Method	**Gas chromatography results (% v/v)**	**Indicating tubes results (% v/v)**
Mean	2.6	2.0
S.D.	0.7	0.5
Range	1.6-3.0	1.5-2.7

In general, the analysis by gas chromatography gave higher CO concentrations than the indicating tubes. Because gas chromatography makes a direct comparison of the CO concentration with a known calibration standard it should be more accurate than the indicating tubes. However the differences in sampling could also explain some of the differences in the data.

What is clear from the data in Table 2 is that these simple indicating tubes can be used to give quantitative data on CO concentrations in cigarette smoke. This opens up a variety of interesting possibilities for classroom use. For example, one could compare the CO concentration of auto exhaust and cigarette smoke. In a recent comparison that we conducted using gas chromatography, we found that 16 vehicles had a mean CO concentration of 0.24 % v/v as compared to 10 samples of cigarette smoke, which had a mean CO concentration of 2.8% v/v [Jaffe et al., 1997]. We also found that filtered and unfiltered cigarettes showed essentially no difference in the concentrations of CO. Using the indicating tubes we would expect that the exhaust from most vehicles would show non detectable levels of CO whereas we have always detected CO in cigarette smoke using them. If desired, one could also purchase the indicating tubes for the lower concentration levels to allow for a wider range of observations.

Conclusion

Cigarette smoking is a major health concern in the U.S. and around the world. Most smokers start smoking by age 15. One approach to reducing the number of young people who start smoking is to provide them with direct visual, olfactory and quantitative data from which they can draw their own conclusions about smoking. In this paper we present several methods to quantify and qualitatively identify the toxic compounds in cigarette smoke. This type of approach also has a unique appeal among students in that it allows them to directly investigate something in science classes which is directly relevant to their lives. Because of this, most students are very interested in these lab experiments.

Figures

Figure 1. Experimental apparatus used in experiment A for collecting tar on filter papers.

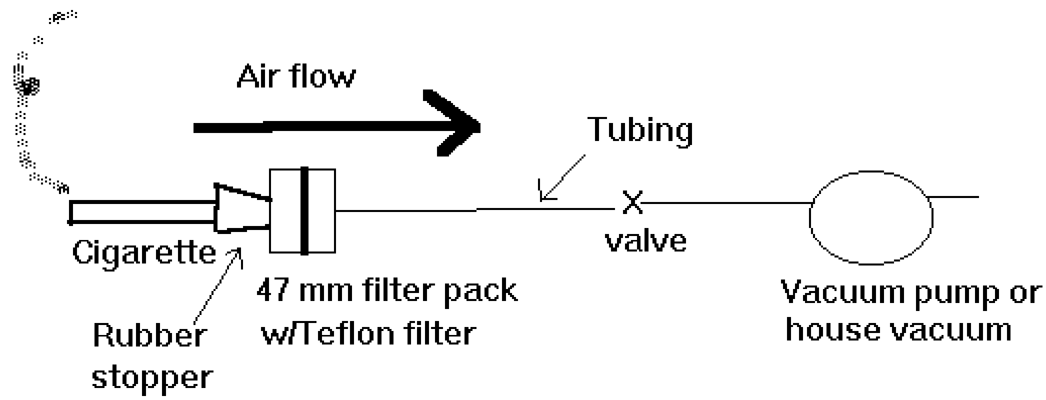
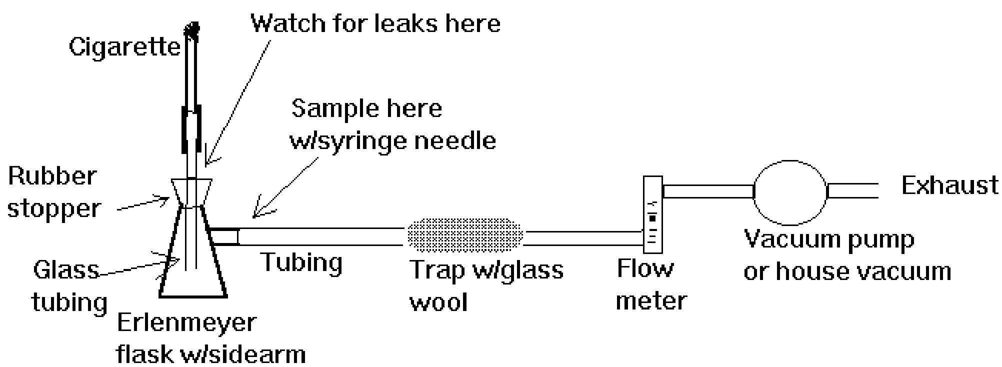
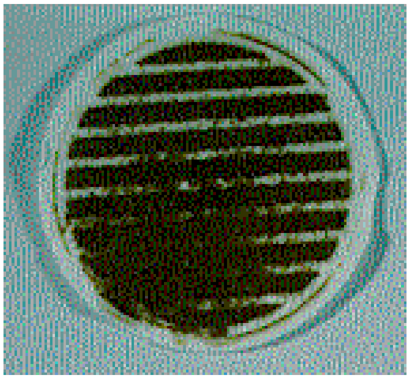


Figure 2. Experimental apparatus used to sample the smoke for carbon monoxide.

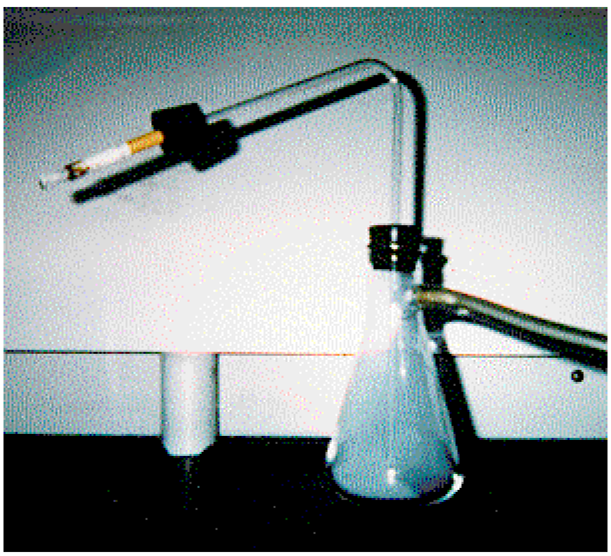


Photos

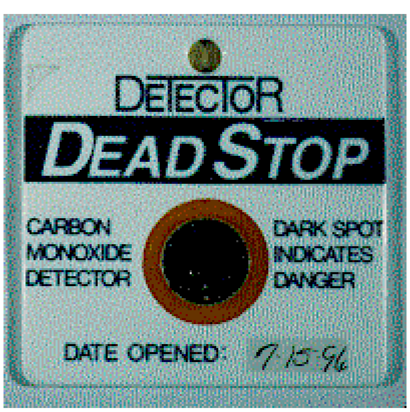
A. Photo of paper filter following collection of tar from a single unfiltered cigarette.



B. Photo of apparatus used to sample cigarette smoke for CO.



C. Photo of the commercial "DeadStop" visual carbon monoxide indicators before and after cigarette smoke exposure.



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Guerin, M.R., Higgins, C.E., and Jenkins, R.A. (1987) Measuring environmental emissions from tobacco combustion: sidestream cigarette smoke literature review. *Atmos. Env.* V. 21, No. 2, 291-297.

Jaffe D.A. and Herndon, S. (1995) The Measurement of Carbon Monoxide in Auto Exhaust by Gas Chromatography, J. Chem. Ed., 72, 364-366.

Jaffe, D.A. and Chavasse, L. Comparing the CO Content of Cigarette Smoke and Auto Exhaust Using Gas Chromatography. Submitted to J.Chem. Ed., July 1997.

Rickert, W.S., Robinson, J.C., and Collishaw, N. (1984) Yields of tar, nicotine, and carbon monoxide in the sidestream smoke from 15 brands of Canadian cigarettes. *Am. J. Public Health* V. 74, No. 3, 228-231.

Internet resources:

FDA home page on Children and Tobacco:
http://www.fda.gov/opacom/campaigns/tobacco.html

CDC's Tobacco Information and Prevention home page (TIPS):
http://www.cdc.gov/nccdphp/osh/

EPA home page on Indoor Air Quality and Secondhand Smoke:
http://www.epa.gov/docs/iedweb00/index.html