# POPPING UNDER PRESSURE: THE PHYSICS OF POPCORN 

Aleksandr Arkhipov, Carly Becker, David Bergamo, Veronica Demtchouk, Andrew Freddo, Edward Kreider, Michael Lee, Joseph Montalbano, David Richards, Elizabeth So, Jasper Wang

Advisor: Paul Quinn<br>Assistant: Sally Warner


#### Abstract

Popcorn is produced by heating kernels until the internal moisture expands and pops through the outer shell of the kernel, allowing the starch within to expand and cool. Scientists have researched new ways of making popcorn with the goal of creating a larger and better tasting snack. In this experiment, the pressure surrounding the kernels is reduced in order to increase the size of the popcorn. The results show that decreasing the pressure surrounding the popcorn kernels increases the volume of popcorn produced while also reducing the amount of wasted kernels.


## INTRODUCTION

## The History of Popcorn

Popcorn, the snack that Americans love to consume at movie theaters and at home, was first introduced by Native Americans tribes. Back in the sixteenth century, Aztecs strung popcorn on garlands to decorate themselves for ceremonial dances and to adorn the statues of their gods. The oldest popcorn ears were found in a bat cave in west central New Mexico. These ears are less than 2 inches long and about 4,000 years old [1].

Popcorn popularity has greatly fluctuated throughout the twentieth century. The popcorn business expanded through the Great Depression because popcorn was relatively inexpensive, ranging between 5 or 10 cents a bag. During World War II, because sugar was sent overseas for fighting soldiers, Americans at the home front were unable to make or consume much candy, so they turned to popcorn to tickle their tastebuds. Popcorn consumption tripled due to these circumstances, but fell dramatically after the 1940's because the introduction of television to the home turned people away from buying movie theaters' popcorn. A decade later, sales for the snack soon rebounded as an advertising collaboration with Coca-Cola and Morton Salt incited the "largest home-consumption growth period for the popcorn industry." The 1980's also brought a rise in popcorn consumption when convenient microwave popcorn was created [2].

## The Popcorn Industry

With the ever-growing popularity of popcorn, studies have been executed to examine the particulars concerning the food. According to the National Agricultural Library, the U.S. Department of Agriculture has conducted research on popcorn for decades. This research includes, "all aspects of cultivation, from seed selection, fertilizers and soils, to insect and disease control, to harvesting, storing, and marketing." One test also measured the popcorn's
expansibility, because a higher volume ratio of popped corn to kernels is usually sought after by industry and consumers [2].

Popcorn is proven to be one of the most wholesome and economically proven foods available. Recent statistics show that [4], Americans consume nearly 17 billion quarts of popcorn every year. This statistic equates that an individual eats approximately 54 quarts annually. Nevertheless, Americans seem to overlook that in the past decade, $10-12 \%$ of heated kernels or almost one million popcorn kernels remain unpopped and are wasted [4]. The money that could be saved if the popcorn industry used a more efficient method would be extremely beneficial. Since the popcorn industry mass produces popcorn by mass and sells it by the volume, a new method of popping that increases the volume of popped kernels would be an improvement for the industry. The goal of our project is to find a way to decrease the unpopped kernels and increase volume.

The following three parameters set by the food industry are used to analyze popcorn data

$$
\begin{gathered}
\sigma=\frac{\text { total popped volume }\left(\mathrm{cm}^{3}\right)}{\text { original sample weight }(\mathrm{g})} \\
\pi=\frac{\text { the total popped volume }\left(\mathrm{cm}^{\frac{3}{3}}\right)}{\text { number of popped kernels }} \\
\omega=\frac{\text { the number of unpopped kernels }}{\text { original number of kernels }}
\end{gathered}
$$

The industry sorts through the kernels to take out any mutant-kernels that are small or abnormally shaped before popping during laboratory testing. In doing this, the industry tries to remove any chance of unpopped popcorn, although they rarely completely remove this occurrence. Industry puts the popcorn kernels under ideal conditions when performing tests. The maximum expansion volume of a popcorn kernel, known as $\sigma$, was observed at $45 \mathrm{~cm}^{3} / \mathrm{gm}$. $\pi$, which is the measurement of flake size measured in $\mathrm{cm}^{3}$ per kernel, reaches its maximum value at $8 \mathrm{~cm}^{3}$ per kernel. Under normal conditions, in a microwave or air popper, the average for $\sigma$ is observed to be between 36 and $40 \mathrm{~cm}^{3} / \mathrm{gm}$, which is much lower than the maximum size observed in the laboratories. The average for $\pi$ is also much lower than the maximum seen in the ideal laboratory conditions. This average is detected to be between 5 and $7 \mathrm{~cm}^{3}$ per kernel.

## THE SCIENCE OF POPCORN

## The Physics of Popcorn

Three elements of the kernel make the production of this popular snack possible. These include: moisture and starch inside the kernel and the pericarp of the kernel, as shown in Figure 1 [7].

Moisture is extremely important to a popcorn kernel, and unless the percentage of moisture in the kernel is just right (a moisture content of 16-20 \%) the small-scale explosion of the kernel will not occur [7]. The kernel's shell allows for the moisture to expand and increase internal pressure without leaking out. When the kernels are heated, the corn shell acts like a
pressure cooker that locks moisture inside the kernel. By heating the kernels, the moisture within the hard shell of the kernel also heats up. The heated moisture leads to a pressure buildup [8], as the moisture tries to escape [6]. If there is enough pressure inside the kernel, its outer shell gives way, and the kernel explodes, allowing most of the super-heated water to turn to steam. This sudden mass transition from liquid to steam also cools the kernel, which is why it does not burn immediately after popping [5]. The starch within the hard shell of the kernel also plays its role. As the steam inside the kernel breaks through the shell, the starch inside the kernel does not actually explode. Instead, these gelatinized starch granules expand into thin, jelly-like bubbles. Neighboring bubbles fuse together and solidify, forming a three-dimensional network much like a sink full of soapsuds. This then cools to become the white fluffy solid we eat [7].

Errors in the production process will also have an effect on the end product. It is necessary to have maximal distribution of heat throughout the corn before the explosion. If the heat is too low, the steam can leak out slowly, resulting in a less 'light' kernel. If the heat is too high or is unevenly distributed, only a portion of the kernel will be hot enough to pop, resulting in a partially popped kernel [5].


Figure 1. Structure of the corm kernel

## The Thermodynamics of Popcorn

An important part in the development of our model for popping a kernel of popcorn was the incorporation of thermodynamics. This field of physics involves macroscopic properties of materials, such as heat, pressure, and temperature. The topics of most interest to us were heat transfer and expansion, since the kernel expands as it pops.

We made the assumption that the water vapor inside the kernel prior to popping behaves as an ideal gas. The temperature of such a gas can be found using the ideal gas law,

$$
\begin{equation*}
P V=n R T \tag{1}
\end{equation*}
$$

where $P$ is the pressure of the gas, $V$ is its volume, $n$ is the number of moles of gas molecules, $R$ is the gas constant, and $T$ is the temperature of the gas.

As seen with the ideal gas law, the state of a gas is determined by three factors: pressure, temperature, and volume. Changing any or all of these variables will change the state of the gas through some process. An adiabatic process is one in which no work is done on or by the system. An adiabatic process is the most appropriate model for the kernel's expansion, since the actual
pop is quick. In this type of process, there is no heat exchange between the system and the surroundings during the process.

The first law of thermodynamics essentially states that no energy can be created or destroyed. In the general case, this equation can be expressed as the following

$$
\begin{equation*}
\Delta U=Q+W \tag{2}
\end{equation*}
$$

where $\Delta U$ is the change in internal energy, $Q$ is the energy in the system, and $W$ is the work done on (or by) the system. In an adiabatic expansion $Q=0$ so $\Delta U=W$. Even though there is no heat exchange, the temperature of the gas will decrease if it expands.

There is an equation that describes the change in states of an adiabatic expansion. This equation is given by

$$
\begin{equation*}
P_{0} V_{0}^{\gamma}=P_{f} V_{f}{ }^{\gamma} \tag{3}
\end{equation*}
$$

where $\gamma=C_{p} / C_{v}$ is the ratio of specific heats at constant pressure and volume. $P_{o}$ and $V_{o}$ are the pressure and volume the instant before the kernel pops, while $P_{f}$ and $V_{f}$ are the pressure and volume the instant after it pops. This equation can be derived as follows. First, for any process, the work done on the system is equivalent to

$$
\begin{equation*}
W=-\int P d V \tag{4}
\end{equation*}
$$

Additionally, for an ideal gas, the total internal energy is

$$
\begin{equation*}
U=\int C_{v} d T \tag{5}
\end{equation*}
$$

Since $U=W$ for an adiabatic expansion, we can set the integral of (4) and (5) equal to each other, resulting in

$$
\begin{equation*}
C_{v} d T=-P d V \tag{6}
\end{equation*}
$$

From Eq. 1, we can replace $P$ with $n R T / V$. Separating the variables and integrating both sides, we obtain

$$
\begin{equation*}
C_{v} \ln \left(\frac{T_{f}}{T_{0}}\right)=-n R \ln \left(\frac{V_{f}}{V_{0}}\right) . \tag{7}
\end{equation*}
$$

If we use

$$
\begin{equation*}
\gamma=\frac{C_{v}+R}{C_{v}} \tag{8}
\end{equation*}
$$

we can rearrange (7) to obtain (3) [9]. Since the final volume is what we are concerned with for this project, we solved for $V_{f}$. Our final equation for this was:

$$
\begin{equation*}
V_{f}=\left(\frac{P_{0}}{P_{f}}\right)^{\frac{1}{\gamma}} V_{0} \tag{9}
\end{equation*}
$$

With this equation, we now know how to increase the volume of the popcorn. The final pressure is the pressure surrounding the popcorn. If we lower the pressure outside the kernel, we will increase the final volume. Therefore, popping the kernels in a vacuum will lower the final pressure, increasing the final volume of the popped corn.

Our next goal was to derive a model of the expanding corn that related its radius to its thermodynamic properties at any given time. We start with a differential equation for the expanding radius of the popcorn as a function of time and used Euler's method to numerically determine the solution.

Our model used the following assumptions:
(a) popcorn is spherical during its entire expansion,
(b) the expansion is rapid enough to be considered adiabatic.

The velocity of the expanding outer shell $v_{n}$ is the time derivative of the radius $R$ and is related to the pressure $P$ of the inside of the popcorn using the equations

$$
\begin{equation*}
v_{n}=\frac{d R}{d t} \text { and } v_{n}=\kappa\left(P-P_{o u t}\right) \tag{10}
\end{equation*}
$$

where $P_{\text {out }}$ is the pressure of the inside of the pot in which the popcorn is popped and $\kappa$ is a proportionality constant.

The spherical idealization of the popcorn relates the volume and the radius by

$$
\begin{equation*}
V=\frac{4}{3} \pi R^{3} \tag{11}
\end{equation*}
$$

We now use the thermodynamic identity for the adiabatic expansion

$$
\begin{equation*}
P V^{\gamma}=C \tag{12}
\end{equation*}
$$

in which $C$ is a constant to relate the pressure and volume of the popcorn at any point during its expansion.

We then work with Eq. 9 through Eq. 12 to find a differential equation for $R$. First, we used (11) to substitute for $V$ into (12) and solved the result for $P$ :

$$
\begin{equation*}
P=\frac{C}{\left(\frac{4}{3} \pi R^{3}\right)^{\gamma}}, \tag{13}
\end{equation*}
$$

Lastly, we substituted (10) and (13) into (10) to get the differential equation in $R$

$$
\begin{equation*}
\frac{d R}{d t}=\kappa\left(\frac{C}{\left(\frac{4}{3} \pi R^{3}\right)^{\gamma}}-P_{\text {out }}\right) \tag{14}
\end{equation*}
$$

This differential equation cannot be solved analytically. We investigated simplifying (13) by applying the approximation $P_{\text {out }}=0$, which appears to be a reasonable estimate since the pressure of the inside of the pot is very small compared to $P_{i}$, the kernel's yield pressure. Under this assumption, (14) reduces to

$$
\begin{equation*}
\frac{d R}{d t}=\frac{\kappa C}{\left(\frac{4}{3} \pi R^{3}\right)^{\gamma}} \tag{15}
\end{equation*}
$$

which can be solved analytically using separation of variables to yield

$$
\begin{equation*}
R^{3 \gamma+1}=\kappa C \frac{3 \gamma+1}{\left(\frac{4}{3} \pi\right)^{\gamma}} t \tag{16}
\end{equation*}
$$

Eq. 16 predicts that if the external pressure is zero, the radius of the popcorn tends towards infinity, since there is no pressure to resist the popcorn's growth. This model is inaccurate for large times because real popcorn, of course, does not grow infinitely large as $t$ gets infinitely large.

An accurate prediction of the popcorn's final size can be found by returning to the original Eq. 14 and expressing the final radius $R_{f}$ as a function of $P_{\text {out }}$. The radius of the popcorn converges to the value $R_{f}$ at which no further change in radius occurs, when $\frac{d R}{d t}=0$. Substituting this into (14) yields

$$
\begin{equation*}
0=\kappa\left(\frac{C}{\left(\frac{4}{3} \pi R_{f}^{3}\right)^{\gamma}}-P_{\text {out }}\right), \tag{17}
\end{equation*}
$$

which we algebraically solve for $R_{f}$ to obtain

$$
\begin{equation*}
R_{f}=\left(\frac{C}{P_{\text {out }}}\right)^{\frac{1}{3 \gamma}}\left(\frac{3}{4 \pi}\right)^{\frac{1}{3}} . \tag{18}
\end{equation*}
$$

In order for us to calculate the final radius, it was necessary to determine the constant $C$. To do so, we applied the thermodynamic identity (3) to the state after the popcorn has just popped, yielding

$$
\begin{equation*}
P_{f} V_{f}^{\gamma}=C . \tag{19}
\end{equation*}
$$

We approximated the constant $\gamma$ for the inside of the popcorn as that of water vapor which is expanding, $\gamma=1.3$.

To find the volume $V_{f}$ of a popped piece of corn, we filled a graduated cylinder with sand and noted the displacement shown when popcorn was put into the graduated cylinder before pouring in the sand. We repeated this for five different popped pieces and found an average value of $V_{f}=5.3 \mathrm{~mL}=5.3 \times 10^{-6} \mathrm{~m}^{3}$.

Based on these measurements,

$$
\begin{equation*}
C=P_{f} V_{f}^{\gamma}=3377 \times\left(5.3 \times 10^{-6}\right)^{1.3}=4.678 \times 10^{-4} \mathrm{~Pa} \bullet \mathrm{~m}, \tag{20}
\end{equation*}
$$

giving

$$
\begin{equation*}
R_{f}=\left(\frac{C}{P_{\text {out }}}\right)^{\frac{1}{3 \gamma}}\left(\frac{3}{4 \pi}\right)^{\frac{1}{3}}=\left(\frac{4.678 \times 10^{-4}}{P_{\text {out }}}\right)^{\frac{1}{3.9}}(0.2387)^{\frac{1}{3}}=\frac{0.0869}{P_{\text {out }}^{0.256}} \mathrm{~m} \tag{21}
\end{equation*}
$$

The predicted relationships of $V_{f}$ and $R_{f}$ as a function of $P_{\text {out }}$ are shown in Fig. 2. As expected, lowering the pressure of the container in which the popcorn is popped causes an increase in the popcorn's final volume.


Figure 2. Graphs of the theoretical relationship between the pressure of the chamber in which popcorn is popped, and the volume and radius of the resulting popcorn.

Having found the theoretical maximum radius of the popcorn, we continued by finding a numerical model for the radius at any point in the time during the expansion. To do this, we chose to use Euler's method, a first-order algorithm used for finding numerical solutions to differential equations. In order to apply this method, we first linearized the differential Eq. 14 into the form

$$
\begin{equation*}
R(t+\Delta t)=R(t)+\Delta t \frac{d R}{d t} \tag{22}
\end{equation*}
$$

Substituting $\frac{d R}{d t}$ from (14) gives the expression

$$
\begin{equation*}
R(t+\Delta t)=R(t)+\Delta t \kappa\left(\frac{C}{\left(\frac{4}{3} \pi R^{3}\right)^{\gamma}}-P_{\text {out }}\right) \tag{23}
\end{equation*}
$$

To continue with the analysis, it was necessary to use the numerical estimates for all the relevant constants found previously. The expansion coefficient $\kappa$, however would have been difficult to determine experimentally. We overcame this problem by assuming $\kappa=1 \mathrm{~m} /(\mathrm{s} \bullet \mathrm{Pa})$ and using an appropriate adjustment in timescale.

We also needed to determine the starting radius $R(0)$, which would be the starting value for the iteration. To do so, we used a caliper to measure the diameter of a ten different kernels of popcorn five different ways. We found half the average of all the values which gave our estimate, $R(0)=0.0031815 \mathrm{~m}$.

We used $P_{\text {out }}=\frac{1}{30} \mathrm{~atm}=3.38 \times 10^{3} \mathrm{~atm}$ as the outside pressure, since that was the vacuum pressure at which we tested our popcorn.

So, plugging in values for the constants in Eq. 23, we have found an equation for obtaining the solution

$$
\begin{equation*}
R(t+\Delta t)=R(t)+\Delta t\left(\frac{4.678 \times 10^{-4}}{\left(\frac{4}{3} \pi R^{3}\right)^{1.3}}-3.38 \times 10^{3}\right) \tag{24}
\end{equation*}
$$

We ran 3,118 loops of the iteration for Euler's Method on Microsoft Excel. Experimenting with different intervals for $\Delta t$, we found that $\Delta t=1 \times 10^{-9}$ was effective in generating the function. Note that the value $\Delta t=1 \times 10^{-9}$ does not correspond to $10^{-9}$ seconds, since we had made the timescale arbitrary in order to eliminate $\kappa$ from the equation.

Plotting the 3,118 data points in the program Graphical Analysis, it was evident that the function $R(t)$ was convergent, and the value of the convergence appeared to be the predicted final radius of 0.01082 m . We used the program to fit a curve of the form $R(t)=A-B e^{-C t}$ to the data, and the result was an accurate fit with parameters $A=0.0106 \mathrm{~m}, B=0.00478 \mathrm{~m}$, $C=2.69 \times 10^{6} \mathrm{~s}^{-1}$ and root-mean-square error $R M S E=0.000173$. The curve fit converges to the value $R=A=0.0106 \mathrm{~m}$. The plot of the data points with the curve fit $R(t)$ is shown in Figure 3.


Figure 3. A plot of the expansion of the popcorn's radius as predicted by numerical integration by Euler's Method, along with a curve of best fit.

## METHODS AND MATERIALS

## Description of Apparatuses

In order to test the thermodynamic effects of pressure on $\sigma, \pi$, and $\omega$, a standard pressure cooker and a household microwave oven were utilized for research purposes. Throughout the experiment, the apparatuses facilitated the adiabatic expansion of the popcorn kernels, producing popcorn through methods somewhat comparable to industrial processes. When attempting to increase the volume of popped kernels, a vacuum pump was utilized to create an environment in which the popcorn kernels could expand in decreased pressure as shown in Fig. 4.


Figure 4. The Hot Plate Apparatus

Popcorn kernels were placed in the metal pressure cooker and were heated with a hot plate that on average reached a temperature of $210^{\circ} \mathrm{C}$ as measured with a thermometer attached to the side of the pot. A vacuum pump attached to the lid of the pot worked to remove the air inside the apparatus. The pressure was determined with a pressure gauge and could be released slowly with a shut-off valve. The experiment progressed at predetermined pressures, ranging from 1 to $1 / 30$ of an atmosphere.

More specifically, the apparatus utilized in the experiment to reduce pressure was a rod and crank pump. The rod and crank pump worked by trapping escaped water vapor and air into the fluid, decreasing the pressure in an efficient manner [10]. Also, after initial tests, it was observed that kernels inside the apparatus were heated unevenly along the bottom of the pot. Thus, in some experiments, a wire mesh platform was placed inside the pot to distribute heat uniformly to the kernels.

At home, people typically make popcorn inside of store-bought bags placed inside microwaves for specific amounts of time. The microwave oven used in the popcorn experiment was one conventional to the household (Fig. 5). It circulates electromagnetic waves inside the central compartment and heats by vibrating moisture inside of the kernel, creating an environment for adiabatic expansion [11]. Inside the microwave apparatus, two plastic dog bowls, one facing up and the other overturned upside-down and over the first, enclosed a compartment in which kernels could be popped. A ceramic plate was placed on the bottom of the dog bowl assembly for kernels to be positioned and a hole in the upper dog bowl, gelled with pump grease, allowed for a connected vacuum pump to created reduced pressure conditions. When the vacuum pump was turned on, a suction seal was made possible by weather stripping placed between the two dog bowls.


## Procedure

Essentially, the objective of our experiment was to quantify the differences found when popcorn kernels are popped in chambers having different pressures. We aimed to show that, by removing the air from the popping process, the kernels would become all-around better pieces of popcorn, as based on the three parameters set by the food industry, $\sigma, \omega$, and $\pi$.

The popcorn industry's goal is generally to maximize $\sigma$ and $\pi$ while minimizing $\omega$. We also hoped to show that the popcorn made in lower pressure chambers were superior in terms of qualitative properties, such as taste, flavor, shape, "fluffiness," and "squishiness."

The procedures for the first-half of our experimental runs, those popped at atmospheric pressure, were rather straightforward. After picking a brand, Orville Redenbacher, we separated all the seeds into "good" and "bad" piles. The "bad" ones were misshapen, discolored, or too small. By being selective of which kernels to use, we could ensure that our results stemmed only from the popping processes and not the uneven quality of the original test seeds. The bad ones were thrown out, and the rest were deemed satisfactory for use in the experiment. We followed this screening process because it is similar to what industry does when conducting their own tests.

We then proceeded to measure out 20 g of the "good" seeds and counted the exact number of kernels. The sample was placed in an unheated pot, upon which a lid was placed. The pot was immediately lifted onto a hot plate and left there until all the kernels were popped.

Although the decision of when to remove the pot was a bit subjective, the rule of thumb was to keep the pot on for no more than 15 minutes total, and then remove it when the intervals of silence between pops was greater than roughly 5 seconds.

The newly-popped kernels were taken from the pot and poured into a graduated container, upon which we measured the total volume of the popcorn. We then counted every popped and unpopped kernel. Having now gathered all the necessary data, we calculated the $\sigma$, $\pi$, and $\omega$ values. Also, we recorded any relevant information involving the taste, shape, and "fluffiness."

The procedures for the second-half of our experimental runs, those popped in a low pressure environment, were slightly more complicated. The steps taken were the same as those of the first, up until the point where the pot was placed on the hot plate. Some connective piping attached the lid to a vacuum pump, and, in order to remove the air from within the pot, the pump was turned on. Only after we lowered the pressure within the pot was the pot actually placed onto the stove. After the popping stopped, the vacuum was turned off, and the collected air within the piping was slowly released out through a valve. We then measured the volume as well as the popped and unpopped kernels, just as before. The entire process was done multiple times. The sets of collected data could now be compared with one another, and we could begin to determine the differences between the kernels popped at various pressures.

Our experiments were not limited to those done with the pot and stove. Since so many families buy the microwavable popcorn bags, we decided to test the popping of kernels at different pressures inside a microwave, as well. A vacuum connecting to the dishes in the microwave could remove air to a desired pressure. Once the pressure was lowered, the microwave was turned on for exactly two minutes. Afterwards, the collected air was slowly released out of a valve, and the necessary data was collected from the popcorn kernels. Organic popcorn kernels in particular were used in the microwave trials.

Up until this point, the only variable discussed was the pressure. Of course, there was a plethora of other factors with which we could experiment. These variables included the mass of the sample, the specific time that the pot spent on the stove, the temperature of the stove, the setting of the microwave, the presence or absence of oil during the popping process, or the presence or absence of mesh wiring at the bottom of the pot. Any one of these variables could be altered, allowing us to see how a change in any of them affected the quality of popcorn.

## RESULTS

Several trials were conducted using the hot plate and the microwave. The different variables included the brand of popcorn, the level of pressure, using a bag (for microwave trials), and application of oil. In each trial, the three variables, $\sigma, \pi$, and $\omega$ were calculated.

Heating stove trials were conducted with oil and a vacuum pump with variable pressure. The results show a decrease in $\omega$, the percent of unpopped kernels. It can be seen from Fig. 6 that $\omega$ is directly proportional to the pressure inside the apparatus. In other words, as pressure increases, the percentage of waste also increases.

In addition to the decreasing percentage of waste, the volume of each popped kernel $(\pi)$ increases when the pressure is reduced. As Fig. 7 indicates, the value of $\pi$ is negatively proportional to pressure. While there is a substantial increase in volume, the popped kernel may not appear significantly larger.

The values of $\sigma$ also increase when the pressure is decreasing. Fig. 8 shows a linear correlation between the volume per gram of popcorn and the pressure of the heating apparatus. As the pressure is reduced, the values of $\sigma$ increase.

In another series of trials, different methods of stovetop cooking were analyzed. Using a different vacuum pump, trials were conducted dry, with a mesh, and with oil. In all three different cooking methods, there was a significant decrease in waste. Fig. 9 indicates that under dry conditions at atmospheric conditions, $28.7 \%$ of the kernels were unpopped. However, when the vacuum pump is activated, the percentage decreases to $1.57 \%$. This reflects a $27.1 \%$ decrease in the amount of unpopped kernels.

Fig. 10 shows that the volume of the popped kernels, $\pi$, increases with all three cooking methods. The most significant increase in volume occurred in the 20 gram oil trial, where the average size of the kernel increased from $3.21 \mathrm{~cm}^{3}$ to $5.25 \mathrm{~cm}^{3}$.

Fig. 11 indicates that the volume per gram of popped kernels increases under oil, mesh, and dry conditions. For example, the 20 gm sample of popcorn used under dry conditions had an $89 \%$ increase in the sigma $(\sigma)$ value from $11.25 \mathrm{~cm}^{3} / \mathrm{g}$ to $21.25 \mathrm{~cm}^{3} / \mathrm{g}$.

Due to the lack of adequate time to develop an effective seal, the microwave trials yielded different results than the heating stove trials. The weather stripping used in microwave trials did not completely seal the cooking chambers, so the vacuum inside the bowls was not perfectly at $1 / 30 \mathrm{~atm}$. Nevertheless, there is a significant decrease in the amount of unpopped kernels, as Fig. 12 illustrates.

As with the heating stove trials, the volume of the popped kernels increased during the microwave trials. Fig. 13 shows that there was a $19 \%$ increase in volume between kernels popped with pressure and with reduced pressure.

The volume per gram of popped kernels, $\sigma$ also increased in the microwave trials. Fig. 14 shows that there is a $51 \%$ increase in $\sigma$ when the kernels are popped under reduced pressure.

After seventy trials, 8,921 kernels of popcorn were popped. There were 862 unpopped kernels, and 8,059 popped kernels. The total volume of the 8,921 kernels was $37,885 \mathrm{~cm}^{3}$.

## Theoretical Model Compared to Laboratory Results

The actual and predicted volumes do not match perfectly because the model is very simplified as compared to the real, complex system. Therefore, we did not calculate a final volume to compare with the experimental values. The point of the project, however, is to show that the theory gives a qualitative prediction of a larger volume with decreased external pressure, which is exactly what our experiment shows. The experiment succeeded in qualitatively proving that reduced pressure yields a decreased $\omega$ value and increased $\pi$ and $\sigma$ values. The model can also demonstrate the qualitative behavior of the popcorn's radius as it expands. But once again, no actual values can be compared due to the complexity of the system. When solving for $\mathrm{R}(\mathrm{t})$, some factors, such as popcorn's elasticity, limited starch and moisture content, perturbations on kernel surface, $\kappa$ value, and other incalculable variables, could not be taken into account because of the mathematical complexities. For example, according to our theoretical model, a graph of volume versus pressure would asymptotically approach infinity as the pressure goes to zero. However, this is not possible because there are physical limitations. So instead of analyzing our data quantitatively, we must analyze it qualitatively. When viewed qualitatively, our physical results follow the predictions of our theoretical model.

## GRAPHS



Figure 6. A comparison of $\omega$ (unpopped kernels/total number of kernels) values between kernels popped at different pressure levels during heating stove trials.


Figure 7. A comparison of $\boldsymbol{\pi}$ (popped volume/number of kernels) values between kernels popped at different pressure levels during heating stove trials.


Figure 8. A comparison of $\sigma$ (popped volume/weight) values between kernels popped at different pressure levels during heating stove trials.


Figure 9. A comparison of $\omega$ (unpopped kernels/total number of kernels) values between kernels popped at regular atmospheric pressure and at reduced pressure for dry, mesh, and oil methods.


Figure 10. A comparison of $\boldsymbol{\pi}$ (popped volume/number of kernels) values between kernels popped at regular atmospheric pressure and at reduced pressure for dry, oil, and mesh cooking.


Figure 11. A comparison of $\sigma$ (popped volume/weight) values between kernels popped at regular atmospheric pressure and at reduced pressure for dry, mesh, and oil trials.


Figure 12. A comparison of $\omega$ (unpopped kernels/total number of kernels) values between kernels popped at regular atmospheric pressure and at reduced pressure for microwave trials.


Figure 13. A comparison of $\boldsymbol{\pi}$ (popped volume/number of kernels) values between kernels popped at regular atmospheric pressure and at reduced pressure for microwave trials.


Figure 14. A comparison of $\sigma$ (popped volume/weight) values between kernels popped at regular atmospheric pressure and at reduced pressure for microwave trials.

## CONCLUSIONS

Our data has come to show that as pressure within the popping apparatus decreases, so does the amount of waste. Also, lowering the pressure results in greater volume and flake size. Thus, pressure and volume are approximately inversely related. Looking at the mathematical calculations, our theoretical results qualitatively matched the experimental values obtained. The possible sources of error for deviation from theory to experiment include the assumption that popcorn is perfectly spherical and that there is no heat transfer between the popcorn and its surroundings. Also, some of our measurements were subject to human measurement error. These measurements include the volume of the popped kernels and the exact pressure inside the apparatus.

Our experiment showed an improvement on industry's value of $\omega$, and matched industry's values of $\sigma$ and $\pi$. If industry were to use the vacuum apparatus under its ideal conditions, it would see a similar increase in the latter two variables. Furthermore, industry is better capable of creating ideal conditions for popcorn to be popped. Our selections for the popcorn used were subjective and based solely on sight, whereas the industry is more selective in choosing kernels for their moisture content and size. We were able to reduce this error by having the same people sort the kernels for ideal shape and appearance.

Once again, because our laboratory equipment was not as efficient as industry's would be, we were unable to find the desired results when using the microwave apparatus. Some of these problems included a faulty seal and the inability to maintain the reduced pressure within the microwave. Also, we created our own bags of popcorn to test the effects of popping within a sealed bag in the microwave. The results show that using a larger bag yielded better tasting
popcorn that was capable of popping to a greater size than the popcorn used with a smaller bag. We found that bags packed with corn popped worse than bags that had space allowing for popcorn expansion.

Several other factors influenced our results. During the experiments using the pressure cooker, the temperature of the hot plate varied, as did the popping time and the amount of oil used. Also, the oil used was cold before each trial and, therefore, the kernels were heated slowly. Another factor was the environment of the room, which could have affected the moisture content of the kernels. The age of the popcorn also varied, since we used the same containers of popcorn over the course of the experiment.

If we were to have more time, there are several ways in which we could expand on our current experiment. First of all, we could have used spherical harmonics to more accurately model the popcorn for our theoretical values. We also would get better equipment, including different microwaves, a vacuum pump that lowers the pressure below $1 / 30^{\text {th }}$ of an atmosphere, and more effective weather stripping for the microwave bowls. We also would use a wider range of popcorn brands and different sample sizes.

Thus, our experiment enabled us to view the effects of pressure on popping popcorn. The theory behind this experiment could be applied in the future for various industry purposes.

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