THERMODYNAMICS OF POPCORN PRODUCTION

Michael Bachmann, Tony Ghaly, Kathlyn Herrick, Sean Rodney Ireland, Brian Lewis, Mohit Moondra, Neel Patel, Evan Rosenman, Juliet Savits

Advisor: Paul Victor Quinn Sr.
Assistant: Evan Kimberly

ABSTRACT

The production of popcorn is a key process in one of America's leading snack industries. In our experiments, we use simple gas laws of thermodynamics to examine the production of popcorn. By assuming that the expansion of a popcorn kernel into a flake is an adiabatic process, we developed a process for improving the efficiency of popcorn production. By lowering the pressure of the popcorn during the popping process, we induce an increase in popcorn size and a decrease in the number of remaining unpopped kernels. In this project, we ran numerous experiments using the three most common popcorn popping devices, a movie popcorn maker, a stove pot, and a microwave. Our results show a significant increase in volume of the popcorn and a decreased number of unpopped kernels as pressure is lowered.

INTRODUCTION

Since its invention roughly 4000 years ago, popcorn has played an integral role in human society. The oldest ears of popcorn were found in a cave in New Mexico. In Aztec culture, popcorn was not just eaten, but was also used to decorate religious shrines with garlands and jewelry. Among the first European explorers, Cortes and his men were intrigued by the native's use of popcorn, leading to its introduction into European society. By the mid 1800s an improvement in plow technology led to a boom in corn harvesting [1]. By the 1890's, popcorn was being sold on the side of the street by push-cart vendors in America. In the difficult times of the Great Depression, the cheap luxury that popcorn provided led to a boom in production. Some farmers with little left of their dusty lands were able to return to a respectable lifestyle due to the stability and success of the popcorn industry. During World War II's sugar rationing, the candy industry was crushed with production at near standstill. With little candy available on the home front, popcorn became a very appealing alternative snack. In the past sixty years, the invention of the microwave and its use in popping popcorn has allowed the production of popcorn to skyrocket. In addition, the introduction of snack bars at movie theaters and stadiums has caused a large number of Americans to partake in the consumption of the fluffy snack. It is estimated that an American eats about 54 quarts of popcorn per year [2]. It is obvious in our times that popcorn has become a staple in the American snack food industry.

The popcorn industry is still thriving today. America alone consumes over one billion pounds of popcorn each year. America is the headquarters for popcorn production. In fact, most of the world's popcorn originates from fields in Nebraska and Indiana [3]. Naturally, the industry is very interested in creating larger popcorn, and thus, improving its volume per kernel. An increase in the volume of each individual popcorn piece would expand profit margins and create a more aesthetically-pleasing and tasty product for the consumer. The introduction of a method for increasing the volume and efficiency of popped popcorn would be greatly welcomed in the popcorn industry.

Recent developments in the biofuel industry has increased the demand for efficient popcorn production. Ethanol is quickly becoming a popular and widely used alternative fuel. As a result, mass production of ethanol is becoming an immediate reality, with 117 distilleries currently operating in the United States. A full 27% of the American corn crop will be allocated toward ethanol production in 2007, compared to 21% in 2006. Furthermore, with the American ethanol producing capacity forecasted to double by 2010, corn reallocation shows no signs of slowing. The consequences are already being felt; despite a 19% rise in corn production over the past year, the price per bushel has risen more than 37% [4]. The most pronounced effects have been seen in Mexico, where the doubled price of tortillas has led to unrest, protests, and a widespread call for reform [5]. Yet the popcorn industry is also suffering, with a 40% rise in prices since 2006 [4].

A simple analysis of the popcorn industry reveals the degree to which it could benefit from more efficient popcorn production. About 30% of American popcorn consumption occurs outside the home, amounting to roughly five billion quarts consumed at sports games and movie theaters [2]. Furthermore, pre-popped popcorn is also widely consumed in the home. Thus, mass production of popcorn is a widespread practice and creates a realm of possible economies of scale. While the benefits of decreasing the pressure in a popping chamber are too small to offset the cost to an everyday consumer, mass producers of popcorn could benefit enormously from even a small increase in efficiency. A new 16 oz. popper, for instance, costs north of $1,200 dollars but, at movie theater prices, can generate more than $30 dollars each time it is popped [6]. Were its efficiency to be improved, the potential profit differential could easily offset the cost of a depressurizing device. The potential economic ramifications of improved popcorn efficiency are thus tangible and noteworthy.

Research into the popping process of popcorn has presently been limited to developing new types of popcorn. Hybridization of corn has been used to create different textures, sizes, and colors of popcorn. Across the world, kernels have been bred to increase the size of the popped treat. Since the Native Americans first introduced the snack to Europeans however, little research has been conducted on how to externally control the size of popcorn. Using the basic laws of thermodynamics, we have conducted a number of experiments in an attempt to increase the size of popcorn flakes.

THEORY

Before properly analyzing and discussing methods of increasing popcorn size, it is important to first understand the process through which popcorn pops. Each kernel is characterized by a center of starchy endosperm surrounded by a tough dry outer shell, referred to as the pericarp. As heat is applied to the kernel, the starchy center begins to liquefy, settling into a jelly-like consistency. Meanwhile, the water within the endosperm begins to heat. When the heated kernel passes the boiling point of water, the moisture evaporates, putting pressure on the pericarp. When the pressure of the vapor exceeds the yield or breaking point of the pericarp, the shell breaks and the water vapor rapidly expands. The expanding water, already mixed with the gelatinous starch, causes the starch to rapidly expand as well. The starch cools rapidly as it comes into contact with the air, giving popcorn its “popped” look. This popping process can be modeled as an adiabatic expansion because its extreme speed does not allow heat to be transferred to the air while the popcorn expands. After the expansion, the pressure within the popcorn is changed to atmospheric pressure.

Because the popping is based on the expansion of water vapor, we can predict the volume using the Ideal Gas Law:

$$PV = nTR, \tag{1}$$

where P is pressure, V is volume, n is the number of moles, T is the temperature, and R is the universal gas constant. Because volume and moles of water vapor are both held constant during the initial heating process, and R is a constant, the expansion is controlled by a relationship between pressure and temperature which can be seen in the following equation:

$$R = \frac{PV}{nT} \tag{2}$$

When the kernel heats up and finally expands, the process is now treated as an adiabatic relationship, governed by the following equation:

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} = C_0 \tag{3}$$

where P is the yield pressure of the pericarp and V is the volume of the kernel at a respective time. The variable $\gamma = C_p/C_v$ is the ratio of specific heats at constant pressure and constant volume. Because we are modeling this equation for water vapor, we use the accepted value of γ = 1.3. Since this process is an adiabatic expansion, we need not worry about the temperature of the kernel at the instant it pops since there is no heat transfer to surroundings. Our goal is to measure the final volume, V_2, herein referred to as V_f.

Because we are solving for V_f, we can manipulate (3) to isolate the V_f variable:

$$V_f^{\gamma} = \frac{P_y V_0^{\gamma}}{P_f} \tag{4}$$

$$V_f = \left(\frac{P_y V_0^{\gamma}}{P_f} \right)^{\frac{1}{\gamma}} \tag{5}$$

$$V_f = V_0 \left(\frac{P_y}{P_f} \right)^{\frac{1}{\gamma}} \tag{6}$$

We cannot change the original volume of water in the kernel (V_0) nor modify the yield pressure of the pericarp (P_y). Therefore, the controlling factor of this equation is P_f, the pressure on the kernel immediately after it has popped. Thus, we hypothesize that if the pressure of the popcorn is decreased during the popping process the volume will increase proportionally.

Since we are trying to come up with a simple relationship, we can safely assume that we can model the popcorn flakes as spherical and the expansion as adiabatic. Using the variable v_n as the outward expansion speed of a point perpendicular to the surface of the flake, we model that speed as:

$$v_n = K(P_f - P_0) \tag{7}$$

where K is defined as the proportionality constant determined by the material. This is equivalent to a change in the radius over time. Therefore, if the proportionality constant is known, one could solve for the radius. Since we are modeling the popcorn as spherical, we use the standard formula for the volume of a sphere to model the volume of the popcorn:

$$V_f = \frac{4}{3}\pi r^3 \tag{8}$$

If this equation is used in conjunction with (3), we substitute in the volume in order to obtain the pressure in relation to the radius.

$$P_f = \frac{C_0}{\left(\frac{4}{3}\pi r^3\right)^{\gamma}} \tag{9}$$

Now solving for the radius we derive:

$$R = \left(\frac{KC_0(3\gamma+1)}{(4/3\,\pi)^{\gamma}}t\right)^{\frac{1}{3\gamma+1}} \tag{10}$$

The pressure is initially very high inside the kernel as the water vapor is heated. However, the pressure after the pop, will be equivalent to the outside pressure surrounding the kernel. Therefore, by lowering the pressure outside the kernel, we effectively increase the size of a popped flake. If we lower the pressure of the popping chamber with a vacuum pump, we should an increase in the size of the popped kernels. [7]

In our experiment we condensed our goals to be expressed in three variables also used in the popcorn industry. σ is the expansion volume, π is the flake size, and ω is the percentage of unpopped kernels or percentage waste. We ran our experiment to test these three different factors of the popped product. The variables are defined as follows:

$$\sigma = \frac{\text{total popped volume (cm}^3\text{)}}{\text{original sample weight (g)}}$$

$$\pi = \frac{\text{total popped volume (cm}^3\text{)}}{\text{number of popped kernels}}$$

$$\omega = \frac{\text{number of unpopped kernels}}{\text{original number of kernels}}$$

In this project, we will use three apparatuses to test for these three variables and see if our process increases their values. We are not looking at the expansion of each corn kernel, but rather we are analyzing the overall trend in the volume at decreased pressures. [8]

PROCEDURE

Three separate and unique apparatuses were used in this experiment. Low pressure popcorn testing was done using a microwave apparatus, a movie popcorn apparatus, and a popcorn pot. All three of these machines were depressurized using standard vacuum pumps. According to the aforementioned theory, when the pressure is decreased the volume should increase, regardless of the heating apparatus used. Therefore, by testing all three apparatuses, we can determine how accurate the theory is and whether there were other limitations on this theory. In addition, the testing of all three apparatuses, allows us to determine how practical this popping technique is for the popcorn industry. Following normal popcorn cooking procedures for their respective apparatuses we tested the affect of low pressures on popcorn production.

Microwave Machine

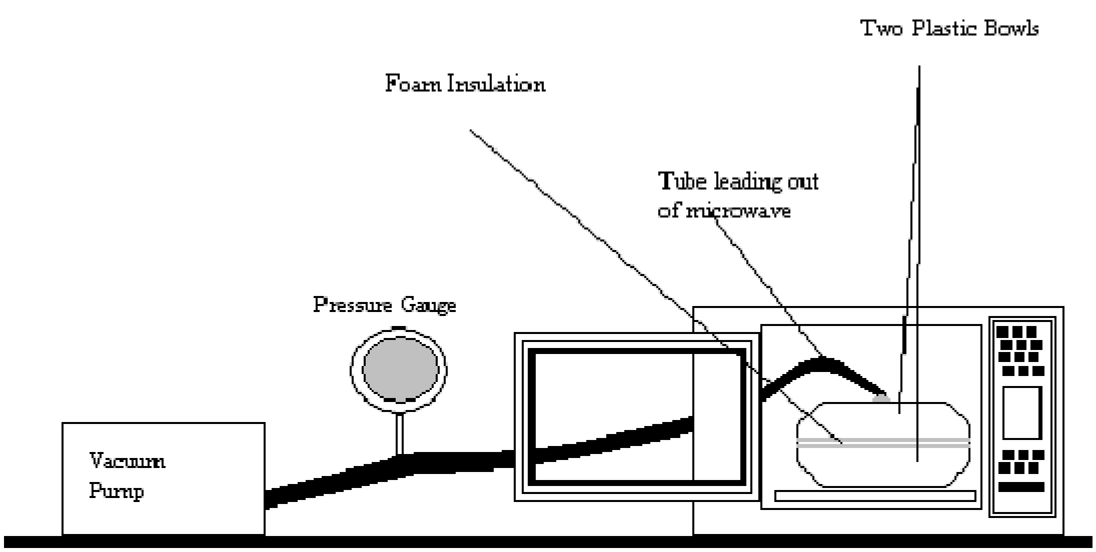

Figure 1: This is a diagram of the Microwave Apparatus showing all major components.

The Microwave Apparatus (Figure 1) was chosen to observe the effects of vacuum pressure in the most common popping apparatus, a household microwave. We used two plastic bowls lined with weather-stripping to create a sealed apparatus into which we could place the popcorn. A rubber tube was inserted into a hole on the top of one of the bowls and, through a hole drilled into the side of the microwave. It was then connected to the vacuum pump used to lower the pressure in the bowls. This allows testing of the popcorn at reduced pressures.

Once the rubber tube was properly fitted into both the vacuum apparatus and the bowl, we put pre-weighed popcorn bags into the bowls (pressure container) and closed it, making sure the seals were aligned. We turned on the vacuum pump and used the gauge to adjust the pressure to a desired level. Once the pressure inside the container reached this level and remained steady, we set the microwave to a desired time and started it. During the popping interval, we made sure to monitor the pressure gauge to ensure that the pressure remained constant. Upon completion of popping, we turned off the vacuum and slowly released the pressure by turning the gauge knob. Once the container reached atmospheric pressure we opened the door and removed the popcorn bag from the container. All measurements are taken at this point, including the volume of popped corn. We then used the data to calculate values of expansion volume, flake size, and percent waste. While measurements were being taken, we took care to properly allow the microwave and container to cool for the next round of testing.

Testing with the microwave was performed for both store-bought and homemade bags of popcorn. When testing, we attempted to use samples from the same box (in the case of the brand name popcorn) and the same batch (in the case of the homemade bags). Thus, by using kernels of similar origins, we minimized the number of possible variables.

For this experiment we attempted to make our own homemade microwave popcorn bags. Using a brown paper bag, we cut about three inches off the top. We pre-measured our popcorn before putting the popcorn into the bottom of the paper bags. After recording all relevant data about the popcorn on the outside of the bag, we proceeded to flatten the bag along the pre-folded lines. Starting from the bottom, air was pressed out towards the top of the bag. We then made a fold about one half inch wide at the top of the bag and secured it with glue so that the fold was flat.

Movie Popcorn Apparatus

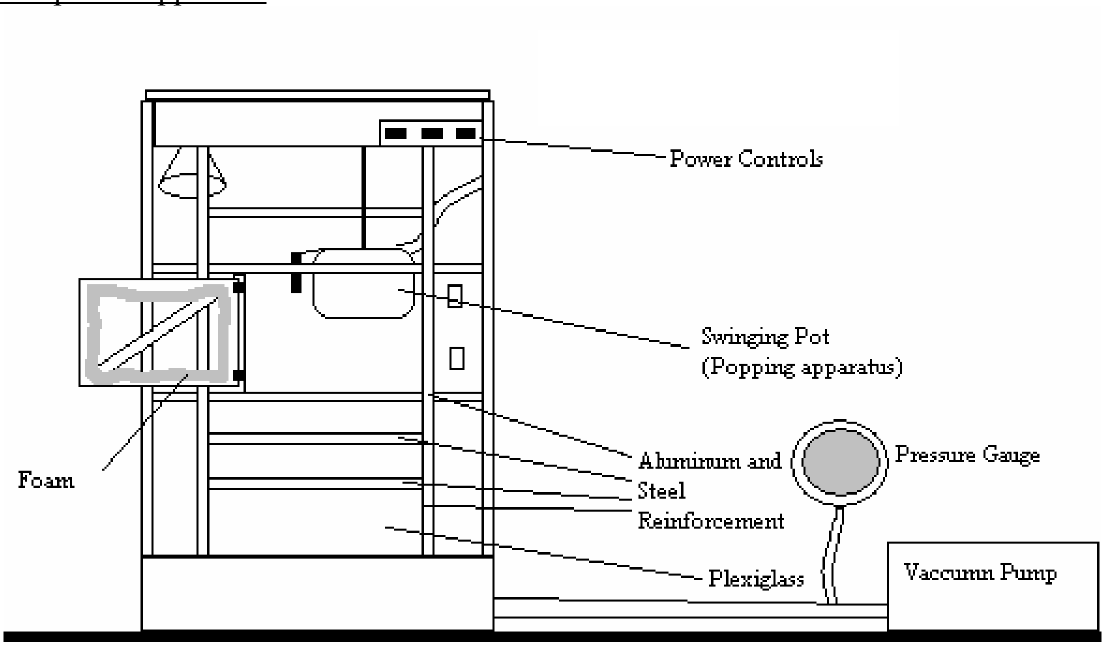

Figure 2: This is a diagram of the Movie Popcorn Apparatus showing all major components.

The Movie Popcorn Apparatus (Figure 2) was chosen in order to see if the effect of lowering the pressure could be achieved with this popular movie theater style popper. A movie popcorn machine was reinforced with Plexiglas, which replaced the ordinary glass found on all sides of the machine. Aluminum was used to reinforce the back of the machine and aluminum bars were placed inside the machine to further reinforce the Plexiglas. In addition, extra steel reinforcements were added to the top and bottom of the machine. To fully seal the apparatus, waterproof silicone sealant was used to fill in all detectable leaks. A special cover made of Plexiglas with a weather-stripping seal was created to be placed over the switches once the machine was working to stop air from leaking through the switches.

First, a pre-weighed sample consisting of 85 grams of kernels mixed with cooking oil was placed into the swinging pot. Once the sample was placed inside the pot, we secured the pot in its upright position. We closed the door of the apparatus and checked to make sure the apparatus was tightly sealed. We turned on the vacuum pump and using the gauge, adjusted the pressure to the desired amount. During the popping, the pressure was maintained by controlled use of the pressure valve. If the apparatus were to leak, the pumps would be immediately turned off to avoid implosion. Once the popping process is complete the vacuum was shut off and the swinging pot released to prevent any popcorn inside from burning. Now all measurements were taken, including volume of popped corn and the number of unpopped kernels. Then the data was used to calculate expansion volume, flake size, and percent waste. While measurements were being taken, the apparatus was cooled in preparation for the next trial.

Popcorn Pot Apparatus

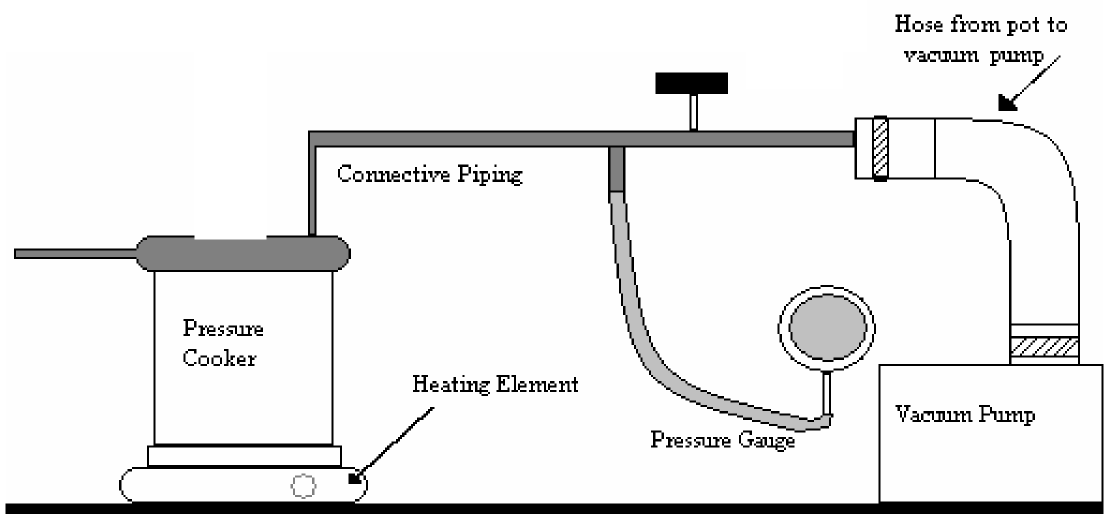

Figure 3: This is a diagram of the Popcorn Pot Apparatus showing all major components.

The Popcorn Pot Apparatus (Figure 3) is a modified pressure cooker used to hold the popcorn under reduced pressure. It uses a standard steel pressure cooker connected to a vacuum pump. For our experiments, the popcorn pot was heated by placing it on a standard hot plate. A rubber tube was connected to the pot and then connected to the vacuum pump. The vacuum pump lowered the pressure in the pot allowing us to test popcorn volume at different reduced pressures.

To begin trials we preheated the cooker for about 30 minutes. This was done in order to establish a uniform temperature for the pot. When it was ready, we placed the popcorn kernels into the pressure cooker. Next, while holding the pressure cooker away from the heat source, the vacuum pump was used to adjust the pressure to the desired value. We observed how long the popping process took by periodically shaking the pressure cooker to determine the approximate amount of unpopped kernels remaining. Once only a few kernels could be heard, the pressure was released and the popcorn was transferred into a beaker to be measured. Each trial was timed, making sure to keep the popping times relatively close, thus reducing the impact of the time variable. Now all measurements were taken, including volume of popped corn and the number of unpopped kernels. From this data of expansion volume, flake size, and percent waste were calculated. While measurements were being taken, we proper care was taken to allow the apparatus time to cool for the next round of testing.

DATA AND ANALYSIS

Microwave Apparatus

The results show that with reduced pressure on the bag containing the popcorn kernels, the volume of the individual flakes of popcorn (π) increased. The average volume per mass (σ) value also increased as pressure decreased. The percentage of unpopped kernels (ω) decreased as pressure decreased. The overall results showed more popped kernels, higher volume per flake, and a rise in total volume, when measured at a constant time of two minutes and fifteen seconds.

As seen in Figure 4, the total volume of the popped popcorn showed growth as the pressure decreased. At atmospheric pressure, the average expansion volume (σ) was 11.25ml/g. When the surrounding pressure was lowered by 30 in-Hg, σ increased to 45.0ml/g. Its increase can best be modeled as $y = -31.5e^{-.122x} + 43.5$. The increase in σ supports the theory that with reduced pressure, the volume of the popcorn will be enlarged.

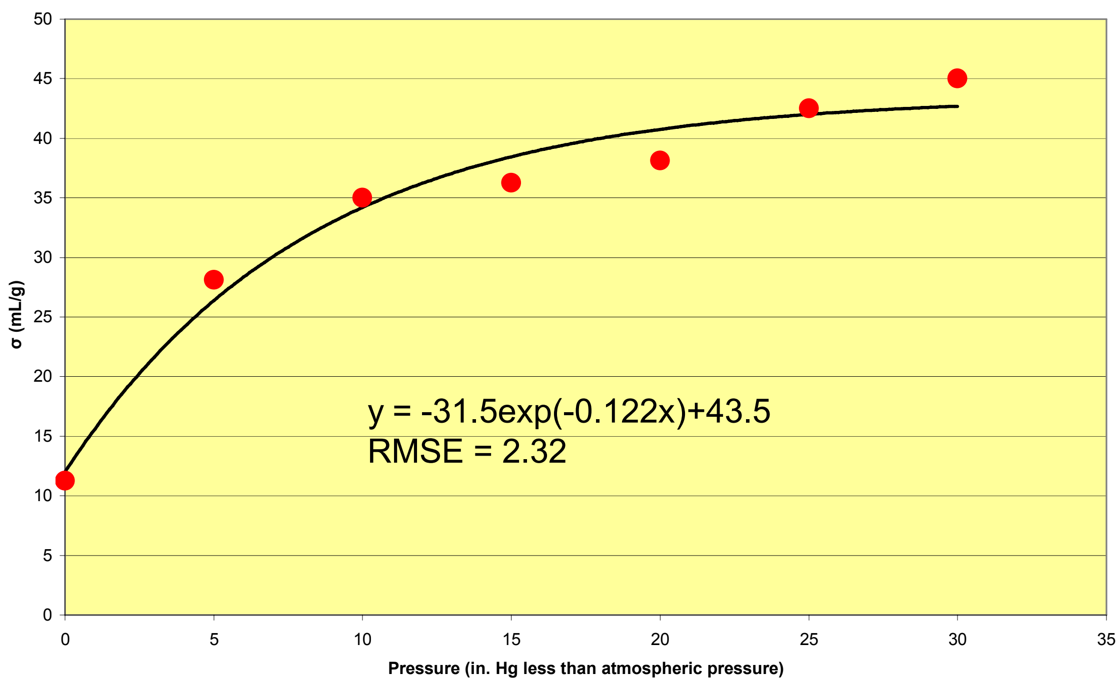

Figure 4: Expansion Volume vs. Pressure graph for microwave apparatus. This graph shows a natural exponential growth in volume per gram as the pressure is decreased.

As seen in Figure 5, the flake size (π) increased with a natural exponential growth. At regular pressure, π was 5.42 ml/flake of popcorn. This individual expansion dropped slightly when the popcorn was subjected to 30in-Hg below atmospheric pressure but this was because the increased number of popped kernels was restricted in volume due to the limitations of the bag but hit a maximum value at 25 in-Hg of 7.508 mL/flake of popcorn. The data can best be modeled as $y = -3.04e^{-.0395x} + 8.43$.

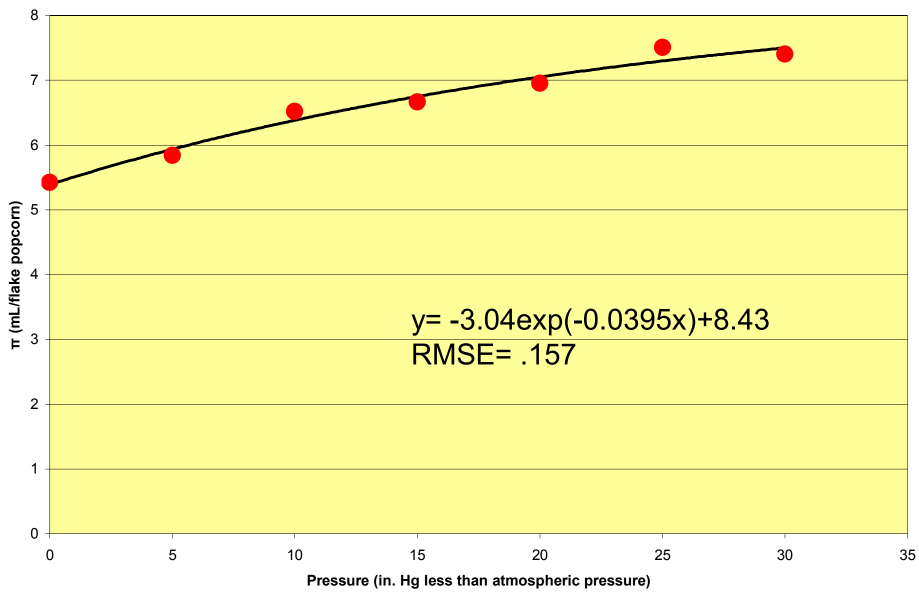

Figure 5: Flake Size vs. Pressure graph for the microwave apparatus. This graph shows the natural exponential growth in volume per kernel as pressure is decreased.

As seen in Figure 6, the percentage of unpopped kernels is best represented with by a natural exponential decay. At atmospheric pressure, 64% of the kernels remained unpopped. At 30in-Hg below atmosphere, only 4% remained unpopped. This data can be modeled as $y= .534e^{-.276x} + .101$. This shows that the lack of pressure on the outside of the kernel makes it much easier for the pressure inside to break the shell and release the liquid starch.

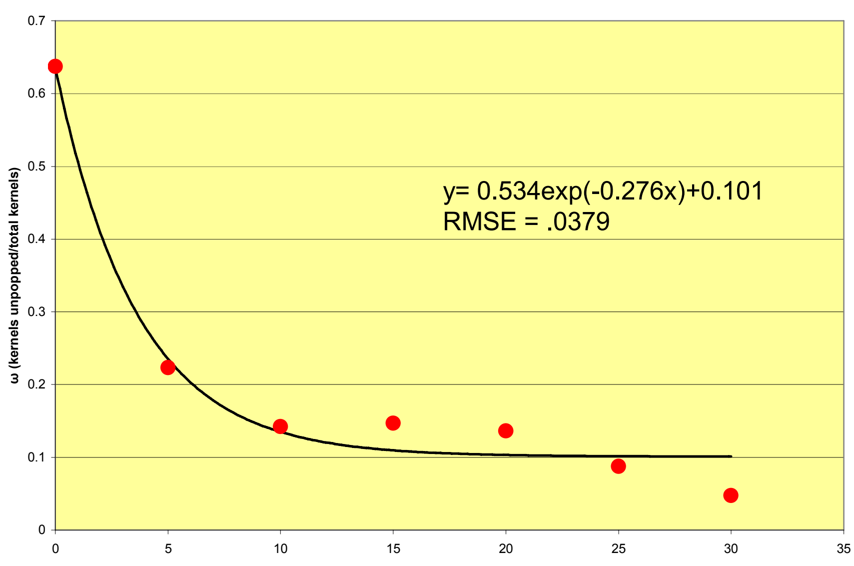

Figure 6: Percentage Waste vs. Pressure graph for microwave apparatus. This graph shows the natural exponential decay of the number of unpopped kernels at decreased pressures.

In Figures 4-6, it can be seen that there is a general increase in volume as pressure decreases. It can also be seen that as pressure decreases the number of unpopped kernels decrease.

There are many limitations which kept the popcorn from expanding to its full potential. For example, when at 30in-Hg below atmospheric pressure, the popcorn expands until the bag prevents it from continuing to do so. Many times the bag will tear from the pressure exerted on it. If kernels fall out of the bag into the depressurized container, they will not pop because the heat is concentrated on the bag. This led to many trials where results were skewed and thus discarded.

Another major problem that our team faced was the functionality of the microwave being used. The microwave periodically stopped working and trials would have to be discarded. If there was about 10 minutes between each trial then the microwave seemed to work at full strength, but if two trials were not separated by enough time, there was a clear lack of microwave power in the second trial. If the microwave was not working to full capacity far fewer kernels would pop, independent of the pressure.

At 30in-Hg below atmospheric pressure, a lot of popcorn would burn when kept at a time of 2 minutes and 15 seconds. At 25in-Hg below atmospheric pressure, some popcorn would burn, but at 20in-Hg below atmospheric pressure no popcorn would burn. The burning popcorn led to many problems regarding the amount of time the popcorn should be microwaved. Originally, the microwave was set to 2 minutes and 30 seconds, but most of the popcorn burned. Then time was dropped to 2 minutes and a number of kernels did not pop. The time was then set to 2 minutes and 15 seconds and kept constant for the remaining duration of the experiment.

The overall effect of the vacuum on the popcorn produced the desired result. The individual and total volumes increased and the percentage of unpopped kernels decreased. This leads one to believe that without the limitations of the bag size the popcorn size would continue to expand under decreasing pressure. In future experiments, the size of the bag could be enlarged to allow greater expansion of the popcorn without the bag's size as a limiting factor. In conclusion, the results attained through the use of a depressurized chamber greatly increased the volume of the popcorn.

Movie Popcorn Apparatus

Our experimental results showed that the samples of popcorn popped under reduced pressure occupied a greater volume. Consequently, expansion volume (σ) and flake size (π) both increased as can be seen in Figures 7 and 8 respectively. We found that the data for the increase in expansion volume was best fit linearly. The best fit for the data of the movie maker apparatus can be modeled as $y= .3001x + 38.177$. Though at first glance the linear model seems strangely out of place, it is important to consider the fact that if we had the vacuum power to lower the pressure in the apparatus we would expect it to transform the line of best fit into a natural exponential line. If considering that the data for this apparatus is a smaller sample set than the other two apparatuses, we can assume that the data shows a smaller section of the relationship trend. Any curve looked at through a small enough window will result in a straight line. We found that there was an asymptotic limit on the size of each popcorn kernel as seen in flake size (π) and, according to our curve of best fit, we calculated it to be approximately 7.5 mL/flake (Figure 11). This may be due to the fact that there is a limited amount of starch held in the pericarp and thus the material acts as limit on the expansion. As shown by our charts, the decreased pressure resulted in higher volumes. The increase in the volume can best be represented as $y = -2.27e^{-.0727x} +7.74$. As the experiments continued, the total volume of the 85 grams of kernels increased from 3225 mL to 3750 mL. Because of these increased volumes, the values of σ and π also increased, ranging from 37.94 mL/g to 44.12 mL/g for σ and 5.457 mL/kernel to 7.205 mL/kernel for π. The only instance in our data that does not reflect the ideas in our introduction is the values for the percent waste. However, this is not an error, but rather a consequence of the way the movie apparatus popped the corn under the lowered pressures. As the volume of each popped kernel increased, unpopped kernels were more easily pushed out of the popping apparatus and were not given a chance to pop. In addition, the nature of the apparatus itself produces a very small amount of wasted kernels. Because of this, the ω values fluctuate for each individual test.

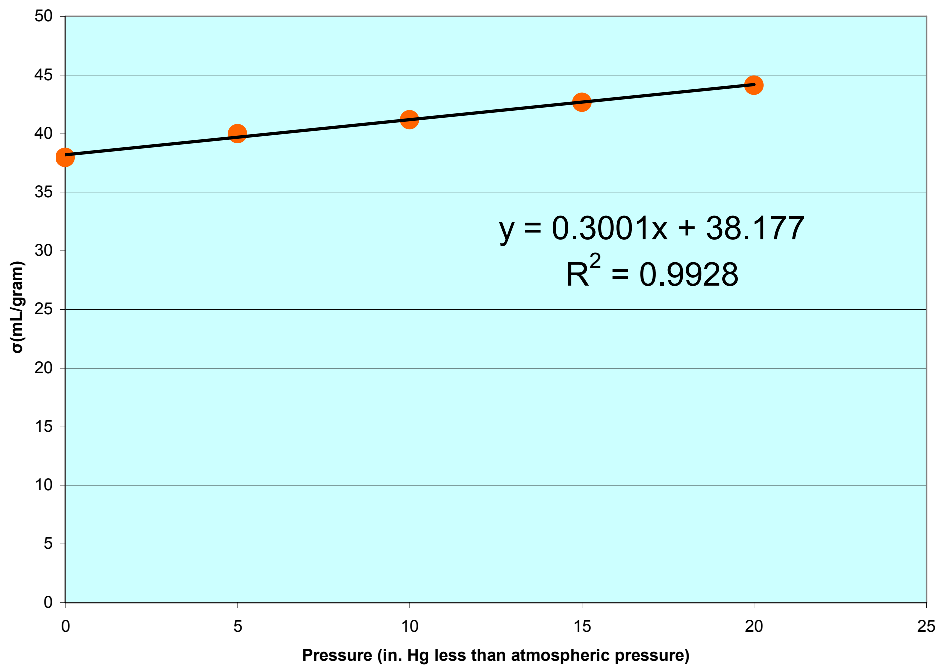

Figure 7: Expansion Volume vs. Pressure graph for the movie popcorn apparatus. This graph shows a natural exponential growth as pressure is decreased.

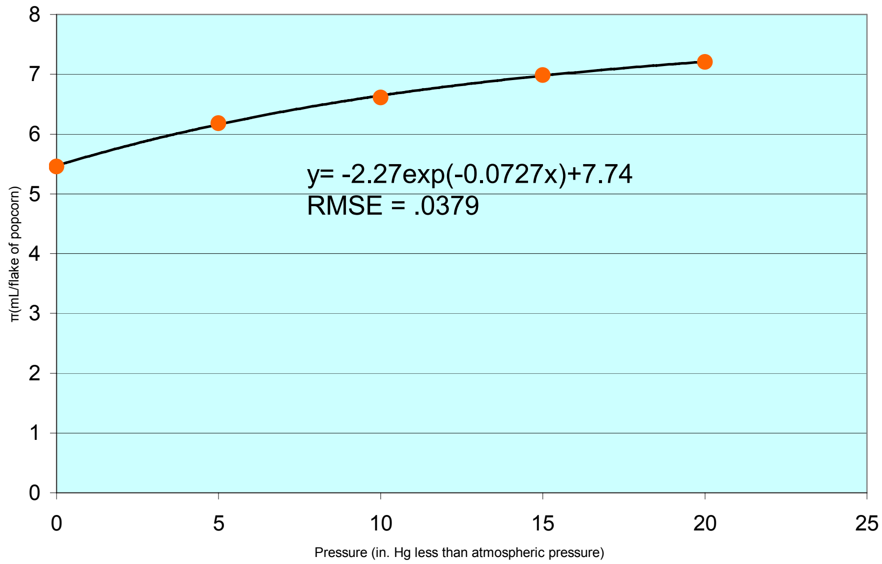

Figure 8: Flake Size vs. Pressure graph for the movie apparatus. This graph shows a natural exponential increase of the volume per kernel as the pressure is decreased.

<u>Popcorn Pot</u>

As predicted in the hypothesis, we produced larger popcorn under lowered pressure in the cooker. As seen in Figure 9, expansion volume (σ), the calculation of the volume of resultant popcorn per gram of kernels popped, followed a natural exponential trend, which was found to be best represented as $y = -24.6e^{-.199x} + 34.5$. The exponential equation indicates an increase in popcorn volume with decreasing pressure.

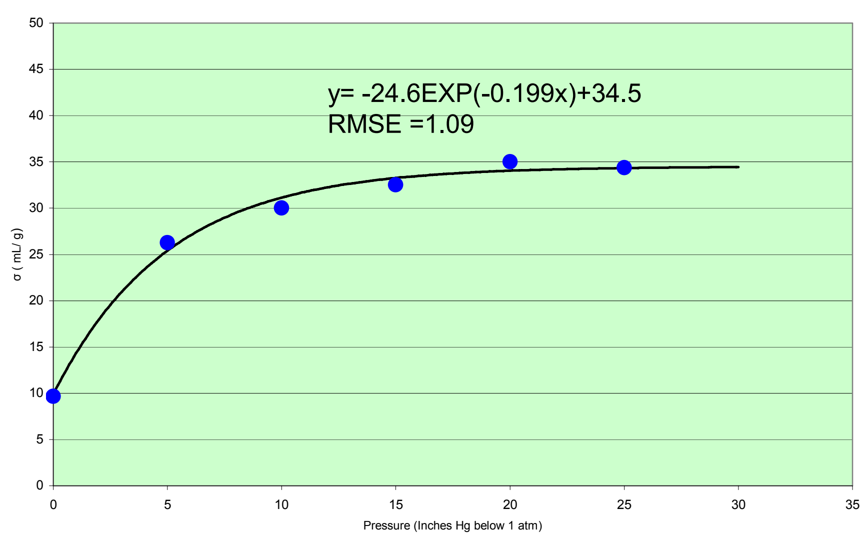

Figure 9: σ vs. Pressure graph for the popcorn pot. This graph shows a natural exponential increase in volume per gram as the pressure is decreased.

As seen in Figure 10, the flake size (π), or the average volume of a popped kernel in a sample, also followed a natural exponential pattern, $y = -2.39e^{-.0712x} + 6.12$. Once again, this shows the enlargement of the average popped kernel's volume as the pressure decreases; emphasizing the effect that lowering pressure increases the size of popcorn.

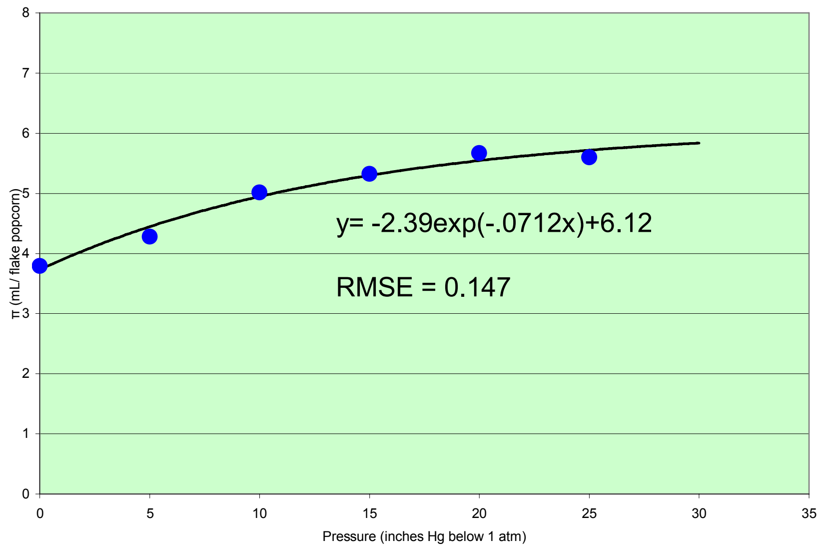

Figure 10: Flake Size vs. Pressure graph for the popcorn pot. This graph shows a natural exponential increase in volume per flake as pressure decreases.

Finally, percent waste (ω), the calculation of the percent of unpopped kernels in a sample, follows an exponential graph, which a function of $y = 56.2e^{-.692x} + 1.92$, as seen in Figure 11. The exponential curve displays an increase in pop success of kernels when the pressure lowers. The ω value decreases as the pressure decreases. Therefore we can infer that the lowered pressure also allows the moisture in the kernels to break the pericarp more efficiently.

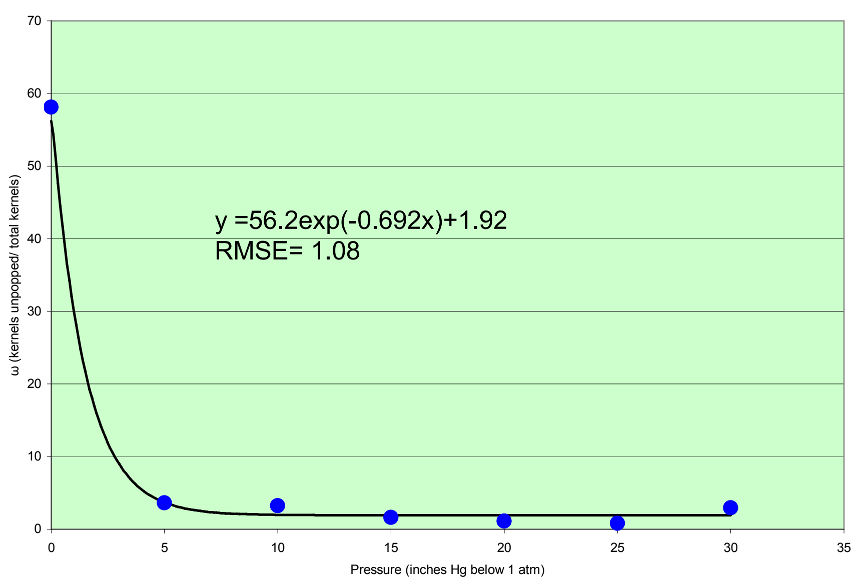

Figure 11: Percent Waste vs. Pressure graph for the popcorn pot. This graph shows an exponential decay in number of unpopped kernels as pressure decreases.

By looking at Figures 9-11 it can be seen that there is a general increase in volume as pressure decreases. It can also be seen that as pressure decreases the number of unpopped kernels decrease.

Through the experiment we ran into some obstacles, like differences in pot temperature and nonconformity in the popcorn kernels. At first, we did not pre-heat the popcorn pot long enough to attain a stable temperature range through the trials, which resulted in inconsistent amounts of time taken to pop the kernels in different trials. However, we decided upon a 20 minute pre-heating period which effectively gave our trials a stable temperature range. Regarding the popcorn kernels, each kernel has a different shape, size, starch content, and moisture content, which means that the kernels do not all pop at the same time. Therefore, some kernels popped early on in the process of heating, which could have allowed those kernels to become somewhat burnt over the remaining heating time.

CONCLUSIONS

Comparison among Popping Devices

Any comparison among the three popping devices we used to test our hypothesis would be incomplete without looking at two pieces of information: which popping method popped popcorn the best overall and which best demonstrated the adiabatic modeling theory. To do so we must compare the relations between pressure and our three variables, expansion volume (σ), flake size (π), and percent waste (ω), as seen in Figures 12-14. As expected, the movie maker apparatus had the highest σ and π values—the values directly correlated to volume popped—and by far the lowest ω, even before pressure was reduced. Once we reduced the pressure, σ and π between the microwave apparatus and the movie maker apparatus were comparable. (It is important to note that the minimum pressure achieved with the microwave apparatus was 30 in. Hg below atmospheric pressure, while the minimum pressure tested with the movie maker apparatus was only 20 in. Hg below atmospheric pressure.) The stove pot behaved similarly, but its σ and π values were never able to match those of the other two devices.

Our data show that the microwave apparatus best demonstrates the theory of the application of adiabatic processes to popcorn popping, with the popcorn pot apparatus in a close second. Both of these devices demonstrated dramatic increases in expansion volume (σ) and flake size (π). In fact, we found that σ in the microwave trials quadrupled as we decreased the pressure from atmospheric to 30 in Hg below atmospheric pressure. The popcorn pot σ values tripled. The increases in π were fairly uniform regardless of the popping method used. Percent Waste (ω), the percentage of kernels that did not pop, dropped from 63.7% to 4.8% in the microwave apparatus and from 58.1% to 2.96% in the pop corn pot apparatus. The movie maker apparatus, the most efficient method of popping corn and hence the one most similar to devices used in industry, began with such a low ω value that reducing the pressure affected no significant change.

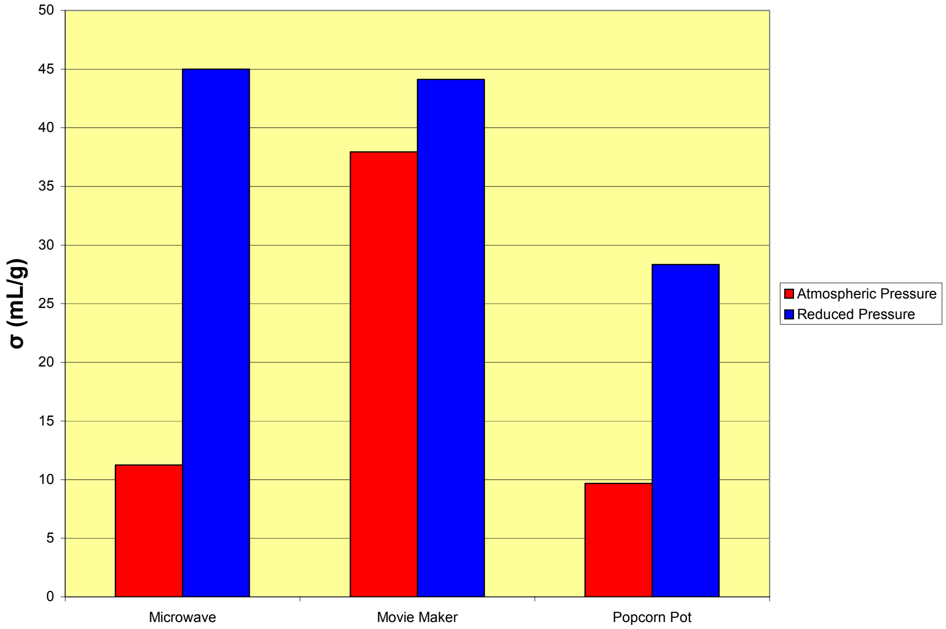

Figure 12: A comparison of expansion volume at atmospheric pressure (left) and maximum attainable pressure reduction (right) between the microwave apparatus, the movie maker apparatus, and popcorn pot.

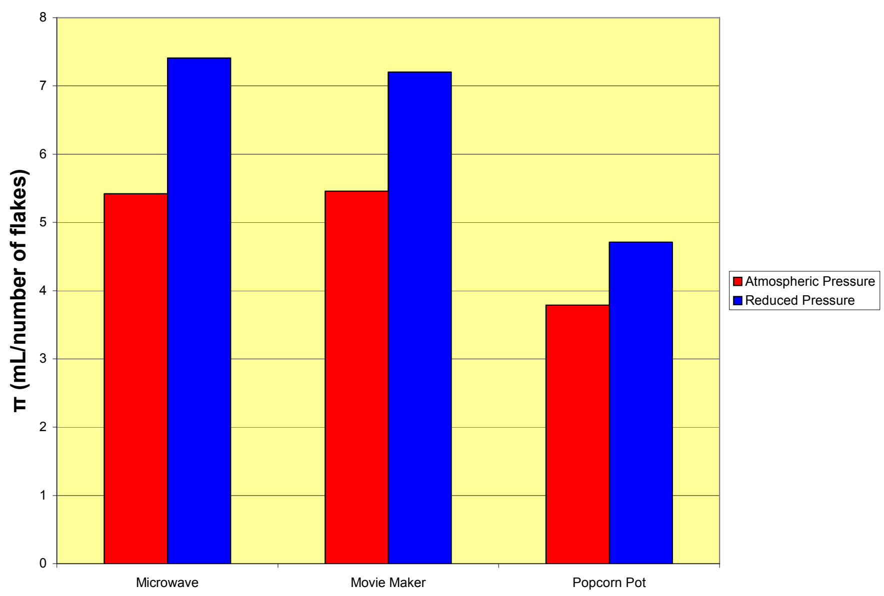

Figure 13: A comparison of the flake size at atmospheric pressure (left) and maximum attainable pressure reduction (right) between the microwave apparatus, the movie maker apparatus, and popcorn pot.

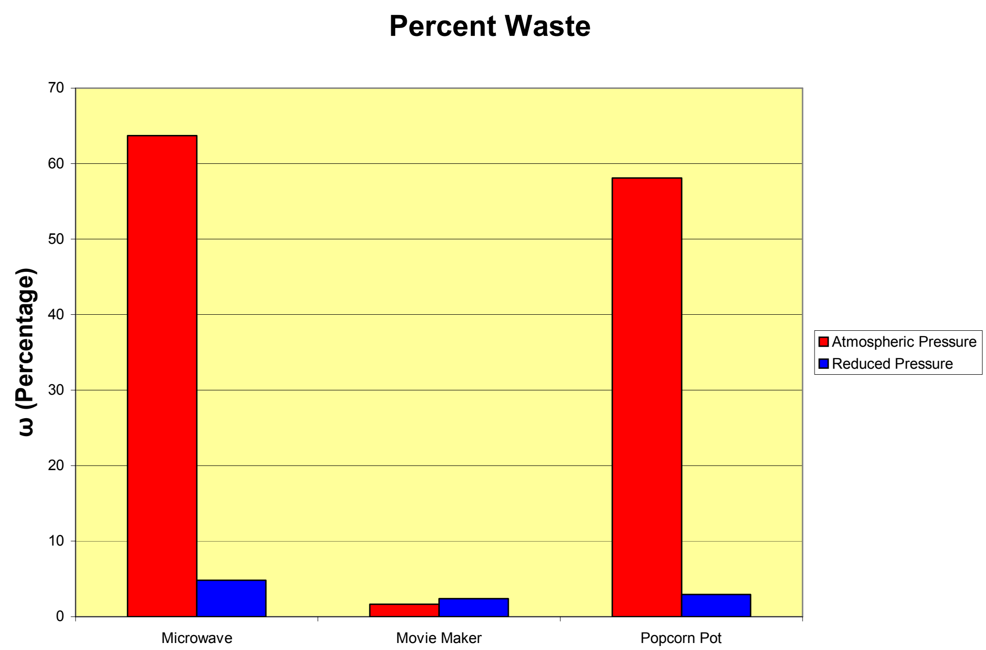

Figure 14: A comparison of percent waste at atmospheric pressure (left) and maximum attainable pressure reduction (right) between the microwave apparatus, the movie maker apparatus, and popcorn pot.

The experiments detailed in the procedures above point conclusively toward a confirmation of the qualitative analysis noted in Ref [4]. Regardless of the popping method, reducing the pressure of the chamber the popcorn pops in results in an increase in the volume of the popcorn, both per kernel and per gram. For those involved in industry, our data means that the devices and methods currently in use could be effectively improved and, above all, that the physical popcorn itself could be changed for the better.

Several important questions remain unanswered. For example, companies in industry would probably require more information on the physical limitation on the size of popcorn before accepting and implementing a variation of the procedure described in this paper in their production. The maximum size that each popcorn kernel can reach has yet to be determined, but the result of such an experiment should be of utmost interest to industry. Other factors besides pressure, such as the temperature of the popping chamber, may interact with the reduction of pressure favorably or unfavorably. The limitations of microwavable popcorn bags and optimization of cooking time could also be important future research. Because of the relative complexity of quantitative control on the size of popcorn, other experiments would need to be performed in order to establish exactly how these factors can be altered in the context of reduced pressure to maximize the effectiveness of the popping mechanism. It should be clear that further research into the effect of pressure and other possible factors is still necessary, but it is clear that the theory correlating popcorn size and popping pressure is true and therefore reliable in its qualitative predictions.

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