Understanding Drying Parameters During the Production of SDCs
Sponsored by Ocean Spray®

A Major Qualifying Project Report
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By:

Mbolle Akume (ChE)

Michael Fabian (ChE)

Nahomy Medrano (ChE)

Joseph Moutinho (ChE)

Approved by:

Professor Stephen J. Kmiotek
Chemical Engineering, WPI

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Abstract

The purpose of this Major Qualifying Project (MQP) is to study and understand the drying parameters during the production of Ocean Spray's Sweetened Dried Cranberries (SDC) and recommend best practices on how to adjust such parameters. This was accomplished by converting the full-scale drying process at Ocean Spray to a working lab-scale model in a WPI laboratory oven. A common misconception that occurs with the process of drying the fruit in an oven is that they are being "cooked". Rather, food drying is a method of food preservation in which food is dried, dehydrated, or desiccated. The main variables that were studied throughout this project were air temperature, drying time, and bed depth. By understanding how these variables affect the final cranberry product, the drying process at Ocean Spray can be improved and optimized. Due to COVID-19 restrictions, the group was unable to execute this project to the extent that was planned, therefore, the conclusions found in this paper should be used by future researchers as a starting point from which to expand upon.

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Chapter 1: Introduction

Ocean Spray Cranberries Inc. is an American agricultural cooperative of over 700 cranberry and grapefruit farmers in the United States, Canada, and Chile. This cooperative accounts for about 70% of North American cranberry production with their products including cranberry sauce, fruit juices, fruit snacks, fresh fruit, supplements, sparkling beverages, and dried cranberries (trademarked Craisins®)[1]. The objective of this background section is to provide an understanding of the drying process of Ocean Spray's Sweetened Dried Cranberries (SDC) and the purpose of this project.

1.1 Summary of Ocean Spray's Full-Scale SDC Process

Ocean Spray has five main steps in the manufacturing process of Craisins®, shown below.

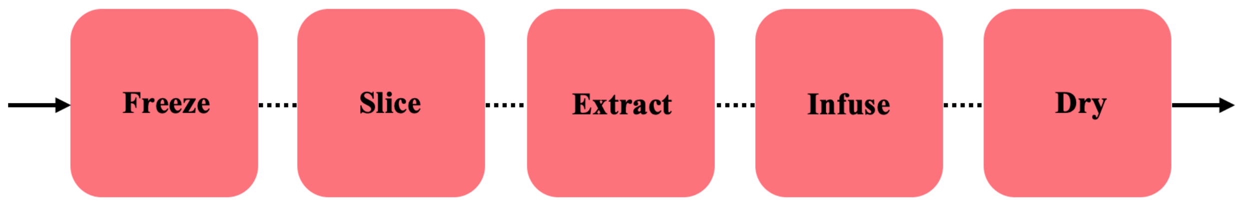


Figure 1: Ocean Spray Full-Scale Craisin® Manufacturing Process

Once cranberries are harvested and cleaned, they are frozen by placing them in 42" W x 48" L x 46" H wooden crates and into industrial-sized freezers at 4°F. Since cranberries can only be harvested a few weeks out of the year, this allows Ocean Spray to sell products year-round. When the cranberries are ready to be used, they are sent through slicers to be cut and some remain whole. They are then sent through an extractor to remove some natural juices. During this step, the cranberries are partially dried due to the removal of the moisture by about 10%. These natural juices are then sweetened and injected back into the cranberries in the infusion step.

Finally, in the last step, the cranberries are sent through a three-stage continuous dryer. The cranberries are dropped on a conveyor belt that runs through three sections labeled A, B, and C, where each section is set at a different temperature. Stage A is run at 260°F, Stage B is run at 230°F, and the final stage, Stage C, is run at 200°F. A common misconception that occurs with the process of drying the fruit in an oven is that they are being "cooked". Rather, food drying is a method of food preservation in which food is dried, dehydrated, or desiccated. Drying the cranberries inhibits the growth of bacteria, yeasts, and mold by removing the majority of the water.

1.2 The Drying Process

In this project, our group converted the full-scale drying process used at Ocean Spray to a lab-scale model. Doing this allowed our team to change different variables in the process and assess how those changes altered the final sweetened dried cranberry product. The main variables that were experimented on in this project were air temperature, drying time, and bed depth during the drying process.

1.3 Literature on Drying Fruits and Methods

The process of drying fruits is well established. The importance it plays in the conservation of food has led to many studies and innovations being made to the fruit drying process since it was initially developed.

Faculty members of Engineering and Surveying at the University of Southern Queensland investigated the fruit drying process looking for specific parameters that affected the final outcome. Their experimental procedure controlled for turbulent airflow and constant humidity, when desired, within the dryer. The main parameters that were investigated in their study were the influence on drying time, the effects of air temperature and humidity on fruit temperature, and the energy required in the dryer to reach a desired final fruit product. In general, the experiment conducted shows that reducing the equilibrium moisture content (the point in which the fruit is neither gaining nor losing moisture) shortens the time it takes to reach the desired end point for the dried fruit. The experiment also proved that lowering the relative humidity in the dryer will result in faster drying of the fruit. The location of the dryer also has an effect on drying time, as the atmospheric conditions affect the speed at which drying occurs. A graph can be seen below for four different atmospheric conditions and how they affect drying time.

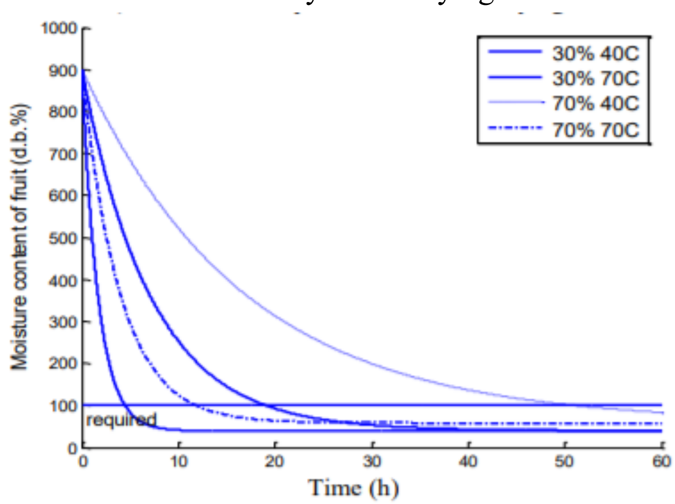


Figure 2: Effect of Atmospheric Condition on Drying Time

An additional study was conducted by the Department of Agricultural and Biosystems Engineering at the Macdonald Campus of McGill University that looked at the effect that four different drying methods had on the quality of osmotically dehydrated cranberries. The four different methods of drying were microwave-assisted convective drying, hot air convective drying, freeze-drying, and vacuum drying. As our experiment was hot air convective drying, that will be the main point of focus regarding this study. The study noted what while there are combinations of methods that can significantly increase drying rates, such as a microwave and freeze-drying combination, hot air drying is generally viewed as the simplest and most economical method. There are four main factors that can affect the rate and total time of drying; the physical properties of the food (particle size and geometry), the physical arrangement of the food with the air, the physical properties of the air (temperature, humidity, and velocity, and the design characteristics of the drying equipment. Focusing on hot air convective drying, the main disadvantages that come along with it are the nonuniformity of the dried sample, slow drying rates, and the quality of the resulting fruit product. The hot air sample was placed as a single layer of fruit on a tray, and was removed from the dryer once a moisture content of 15% was reached. In addition to analysis on drying characteristics, upon reaching a desired level of moisture and having a final dried fruit product, a sensory evaluation was performed that consisted of comparing the characteristics of the fruits for all drying methods. These characteristics include surface color, texture, water activity, rehydration capacity. The hot air convection drying method took the longest time to reach the 15% moisture content level. A graph can be seen below comparing all of the times. The hot air convection berries were voted to have the best appearance due to the uniformity of color in the sample. All drying styles had no discernable difference in taste and minimal difference in water activity. The rehydration ratio was most exceptional in the freeze-drying and relatively lower in all other drying methods. Images of the scoring method and results for the sensory evaluation can be seen below.

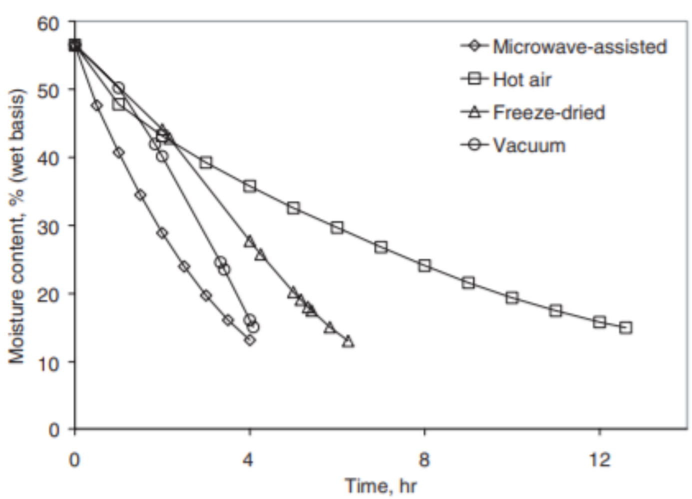


Figure 3: Effect of Variation in Drying Methods

Table 1. Score Rating Characteristics

Score	Description
1	Like extremely
2	Like very much
3	Like
4	Neutral
5	Dislike
6	Dislike very much
7	Dislike extremely

Table 2. Overall Ratings of Drying Methods

Drying method	Overall appearance	Taste	Water activity	Rehydration ratio
Microwave-assisted drying	2.6	2.4	0.676^{a}	1.29^{c}
Conventional hot air drying	1.7	2.5	0.648^{a}	$1.32^{b,c}$
Freeze-drying	2.4	2.1	0.664^{a}	1.50^{a}
Vacuum drying	2.4	2.3	0.602^{a}	1.39^{b}

An additional paper was published by the Department of Machinery and Irrigation at the Technological Educational Institute of Larissa in Larissa, Greece regarding the application of a thin layer equation for the drying data of fruits. The thin-layer equation has been used to estimate and predict drying times as well as the creation of drying curves. The equation can be seen below:

$$\frac{dM}{dt} = -K(M - M_{eq})$$

In this equation, k is defined as the drying rate constant, M is defined as the moisture content at time *t*, and M_e (also referred to as M_{eq} in other documents) is defined as the equilibrium moisture content. The thin layer equation suggests that during the drying period, the rate of change of moisture content is proportional to the difference between the berry moisture content and the expected moisture content when in equilibrium with the drying air. In the thin-layer equation, it is assumed that the conditions of the drying air (humidity & temperature) are held constant throughout the material due to the thinness of the material and the high air velocity. This equation introduces a new variable, R_m, the dimensionless moisture ratio, and can be further solved in order to help estimate the M_{eq} value with the aid of drying curves. The new form is shown below:

$$R_m = \frac{M - M_{eq}}{M_i - M_{eq}} = exp(-Kt)$$

1.4 Model of Diffusion in a Slab

Mathematical models based on mass transfer are used to study the behavior of drying procedures and operations. Assumptions related to mass transfer properties such as initial and boundary conditions, transport equations and partial differential equations, are solved and further used to simulate the drying process. The drying phenomenon of cranberries specifically can be described utilizing mass transfer properties and balances. Water vapor at the surface of a cranberry is transferred to the airstream, resulting from a difference in water vapor concentration. This action leads to a decrease in the amount of water in the cranberry being dried, and to mass diffusion from the inner to outer surface of the cranberry. At the cranberry surface, convective mass transfer occurs as a result of moisture flux between the water vapor at the surface, and the water vapor in the air. For any given time duration, the amount of water vapor in the air increases and the moisture at the surface is removed.

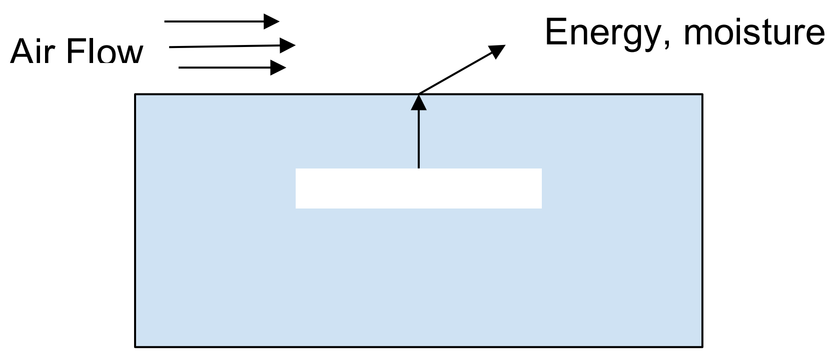


Figure 4: Schematic diagram of mass transfer during drying process of cranberry

The assumptions made for drying the cranberries as a slab were that mass transfer occurred in one dimension at a non steady-state, in the direction of the thickness (on the x-axis). The mass equations were written out for a symmetrical slab and the coordinate axis was set up at the center of the cranberry.

The governing one-dimensional mass transfer differential equation and boundary conditions for the problem statement can be formulated as:

$$\frac{\partial N_{Ax}}{\partial x} + \frac{\partial N_{Ay}}{\partial y} + \frac{\partial N_{Az}}{\partial z} + \frac{\partial c_A}{\partial t} - R_A = 0 \qquad \text{Eq. 1}$$

$$\frac{\partial N_{Ax}}{\partial x} = -\frac{\partial c_A}{\partial t} \text{ or } D_{AB}\frac{\partial^2 c_A}{\partial x^2} = \frac{\partial c_A}{\partial t} \qquad \text{Eq. 2}$$

The differential equation and boundary conditions were changed to dimensionless parameters to simplify the solution and were defined as follows :

$$\psi = \frac{(c_A - c_{A,\infty})}{(c_{A,0} - c_{A,\infty})} \qquad \text{Eq. 3}$$

$$\tau = \frac{D_{AB} t}{L^2} \qquad \text{Eq. 4}$$

$$\eta = \frac{x}{L} \qquad \text{Eq. 5}$$

Where $\psi, \tau,$ and η are the dimensionless variables of concentration, time, and distance respectively. $c_A$is the moisture concentration within the cranberry slab, $c_{A,0}$is the moisture concentration at t=0, and$c_{A,\infty}$ is the bulk moisture concentration. $D_{AB}$is the diffusion coefficient, L is the associated thickness of the cranberry being dried, t is the drying time, and x is the distance.

Substituting in terms of the dimensionless parameters yields the equation:

$$\frac{\partial^2 \psi}{\partial \eta^2} = \frac{\partial \psi}{\partial \tau} \qquad \text{Eq. 6}$$

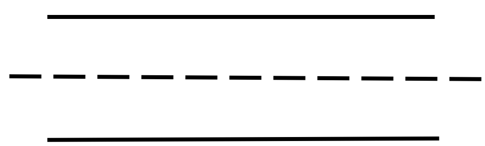


Figure 5: Sketch of symmetric cranberry slab

For a cranberry as a symmetrical slab, our boundary conditions for the problem included:

$$At\ t = 0: \ c_A = c_{A,\infty} \ ; \ At\ \tau = 0: \psi = 0$$

$$At\ x = 0: \frac{\partial c_A}{\partial x} = 0 \ ; \ At\ \eta = 0: \frac{\partial \psi}{\partial \eta} = 0$$

$$At\ x = L, -L: \ -D_{AB} \frac{\partial c_A}{\partial x} = k_x (c_A - c_{A,\infty})$$

$$At\ \eta = 1, -1: \frac{\partial \psi}{\partial \eta} = \ -Bi_m \psi$$

Where $Bi_m = \frac{k_x L}{D_{AB}}$is the Biot number and k_x is the mass transfer coefficient.
Computing our problem gives us the following solution of:

$$\psi = \sum_{n=1}^{\infty} \quad A_n e^{(-\lambda^2{}_n \tau)\ cos\ (\lambda_n \eta)}$$

Eq. 7

Where the eigenvalues, λ_n are the number of roots that may exist for the equation

$$\lambda_n tan \lambda_n = Bi_m, \qquad \text{Eq. 8}$$

And $A_n$is the expansion coefficient depending on particular values of λ , but can be denoted for the nth value of λ , as

$$A_n = \frac{4sin\lambda_n}{2\lambda_n + sin(2\lambda_n)}. \quad \text{Eq. 9}$$

Therefore, the flux from each surface of the cranberry can be determined by:

$$N_A = -D_{AB}\frac{\partial c_A}{\partial x}\Big|_{x=L} = \frac{-D_{AB}(c_{A,0} - c_{A,\infty})}{L}\sum_{n=1}^{\infty} A_n e^{(-\lambda^2{}_n\tau)}\, sin\,(\lambda_n)$$

Eq. 10

Using the above equations, we can develop a model that will simulate the convective drying process of cranberries represented as slabs, and can solve for it using the commercial software COMSOL Multiphysics. With this program, both a numerical solution as well as a two-dimensional model representing the cranberry slab, can be obtained.

Chapter 2: Methodology for Lab-Scale Process

This section describes the experimental procedure used to define the lab-scale drying process of the Ocean Spray's SDC done in WPI's laboratories, along with equipment specifications, and unit operation controls.

2.1 Equipment Specifications

The ovens used during these experiments were the Curtin Matheson Scientific D1540 oven rated at 1190W and the Precision Scientific 31578. After testing the ovens, both produced the same results when running the same experiments in them. To test the brix percentage of the dried product our team used the Digital Hand-Held Pocket Refractometer PAL-1, seen below in Figure 5. The procedure used to find the brix percentage can be found in Appendix A.

Figure 6: PAL-1 Refractometer

Mesh stainless steel sheets were used to make custom 8 inch by 8 inch trays with raised, flattened edges of 1" to allow for stacking of the trays. Three of these were made to allow us to run multiple experiments at a time, as well as stacking the trays on top of each other.

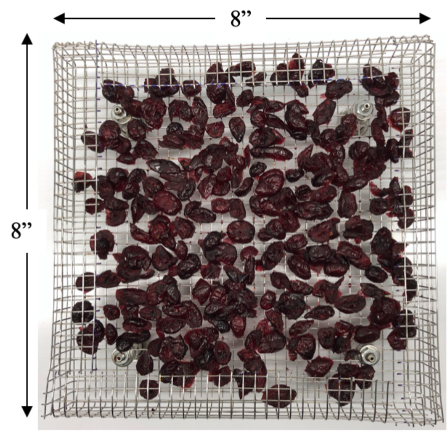


Figure 7: Example of One of the Mesh Stainless Steel Trays Made by the Team

A Habor 022 Thermometer was placed at the openings at the top of the ovens to check the air temperature within the ovens throughout the entire experiment to ensure consistency. A digital scale was used throughout the experiments to weigh the cranberries periodically throughout the drying process, as well as the water used in the procedure for the refractometer.

2.2 Full-Scale to Lab-Scale Procedure

The first objective of this project was to take the full-scale SDC drying model and turn it into a lab-scale procedure that could be executed in the laboratory at WPI. The oven was preheated to 260°F with a piece of parchment paper on the very bottom larger than the cranberry tray to catch possible dripping. In a clean mesh metal tray, a single layer (none of the cranberries were overlapping) of defrosted cranberries was spread out and weighed. Once the oven reached the temperature of 260°F, the temperature of the cranberries was taken before inserting the tray into the oven. The temperature and relative humidity were watched for any changes and recorded for 35 minutes. After 35 minutes, the cranberries were taken out of the oven to take the temperature of the cranberries, reweigh the tray, and remeasure the depth. While measuring these characteristics the temperature of the oven was dropped to 230°F and the cranberries were placed back into the oven for another 35 mins. After 35 mins, the measurement process was repeated and the cranberries were placed back into the oven for 90 more minutes at 200°F. The cranberries were then removed and the temperature, weight, and depth were measured along with the Brix percentage in hopes to achieve at least 85%.

2.3 Experimental Procedures

A series of experiments with multiple runs per experiment were run to analyze the effect of a variety of variables on the drying process of cranberries in a small-scale stationary oven. These variables consisted of air temperature and moisture content within the oven, along with the bed depth of the layer of berries within the oven at one time. In order to collect the data necessary to identify possible relationships, five experiments were developed. The experiment procedures in detail can be found in Appendix D.

The first experiment was a basic recreation of the process used in the full-scale Ocean Spray factory. The main purpose of this experiment was to determine the time required to dry a monolayer of berries in the stationary oven at the temperatures specified by the process engineers at Ocean Spray in order to reach the required Brix percent (85%). This value was given by Ocean Spray as a requirement for food safety.

The second experiment built off the first experiment and introduced a new variable, the berry bed-depth. Starting with the times determined in order to dry the monolayer of berries at the specified temperatures, the required Brix percent wasn't reached for the 0.75-inch layer of berries. The experiment was then performed for a second time with the determined times increased by a factor of 1.5 with the bed depth of 0.75 inches.

The third experiment used the same monolayer bed depth thickness as experiment 1, however, the total berry mass within the oven was increased by about a factor of two by introducing a separation of layers. This meant that there were two monolayer thickness trays stacked on each other within the oven at the same time. This was meant to identify the effect of a similar amount of berries as the increased bed depth in experiment two but with more available surface area of the berries through the separation of layers.

This experiment was then run again as experiment 4, but with an increased bed depth of 0.75 inches for both layers within the oven. This was meant to allow for the comparison of a larger amount of berry mass with relation to increased surface area through the separation of layers.

The fifth experiment was an exact recreation of the first experiment, but broken down by each stage and half stage in order to get a better understanding of the brix percent within the berries throughout the whole drying process.

Each experiment was planned to be developed through multiple runs to allow for the maximum amount of data collection, however time was cut short through inaccessibility to the lab.

2.4 Experimental Calculations

In effort to gain a better understanding of the data collected from the experiments run, the drying constant rate was found along with the use of an energy and equilibrium balance around the system.

The drying constant rate was determined through the use of the thin-layer equation:

$$\frac{dM}{dt} = -k(M - M_{eq}) \rightarrow R_m = \frac{M - M_{eq}}{M_i - M_{eq}} = exp(-kt)$$

Where k is the drying constant rate, M is the moisture content at time t, and Meq is the equilibrium moisture content. The thin layer equation suggests that during a drying period, the rate of change of moisture content is proportional to the difference between the berry moisture content and the expected moisture content when in equilibrium with the drying air. It's assumed that the berry layer is thin enough and the air velocity is high, so that the conditions of the drying air (humidity, temperature) are constant throughout the berries. The solution to the thin layer equation is what we see on the right, where Mi is the initial moisture content and Rm is the moisture ratio. The thin layer equation is a function of the moisture content at different stages and the estimated equilibrium moisture content. From this equation, we are able to create a drying curve to find the rate constant as the slope of the line for the thin-layer equation.

Next for the energy balance, the two equations that were utilized are as follows:

$$Q = mc_p\Delta T$$

$$L_v = \Delta H_{vap} * m$$

The one on the left is for heat energy, where Q is the heat energy, M is the mass, Cp is the specific heat, and delta T is the change in temperature. The one on the right is for Latent heat of vaporization of water, where: Lv is the latent heat of vaporization, delta Hvap is the heat of vaporization, and m is the mass. With these equations, we were looking to determine how much energy was needed to heat up the air and evaporate the water moisture, providing a total energy consumption for each experiment. Allowing us to compare the energy consumption for each experiment and make hypotheses based on them.

For our final analysis, we are looking at equilibrium within the complete system using the following equation:

$$y_i = K_{eq} * x_i$$

Where yi is the humid ratio, Keq is the equilibrium constant which is dependent on the berry temperature, pressure and properties, and xi is the concentration of water in the berries. However, in order better analyze the equilibrium balance, we found the heat loss for each experiment. This was done by first calculating for the water loss out of the vent by first calculating for the amount of water the berries put out into the atmosphere and subtracting away the water still in the oven when equilibrium was reached. These water loss values were solved for using the dry bulb temperature and relative humidity to calculate the humid ratio. The water loss out of the vent was then used to solve for the heat loss during the process in order to reach equilibrium. The heat loss across the experiment was compared in order to better justify the ideal variables to focus on for the drying process of sweetened dried cranberries.

Chapter 3: Results and Discussion

The following graphs show the percent moisture within the berries based on dry-bulb temperature collected as the experiments took place. The solid and water mass collected from the berries throughout the runs were used to calculate percent moisture for wet bulb and dry bulb. Looking at the dry bulb percent moisture versus time allowed us to analyze the drying curve for each run and compare how variations in the key variables affect the process.

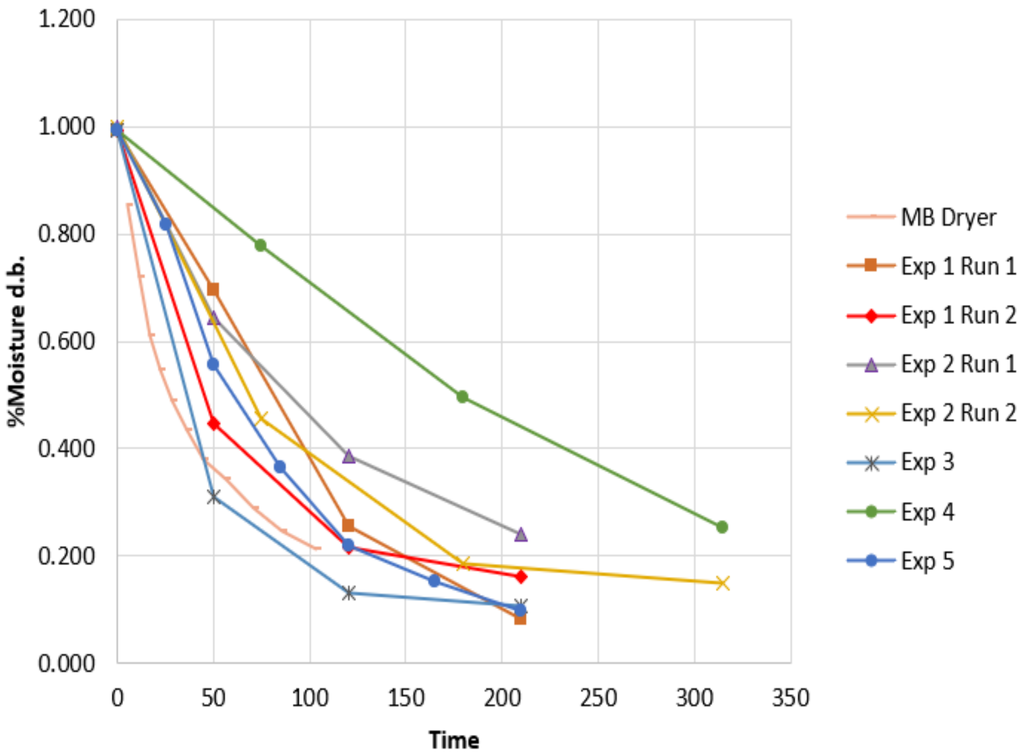


Figure 8: Drying curve of all down-scaled experiments along with Ocean Spray's monolayer run during commissioning

Table 3. All experiment descriptions, Meq, and k values

Experiment	**1**		**2**		**3**	**4**	**5**	**MB Dryer**
Description	Monolayer	Monolayer 2	0.75" B.D.	0.75" B.D. 2	Stacked Monolayer	0.75" B.D. Stacked	Monolayer	Monolayer
Meq	0.05	0.14	0.15	0.13	0.10	0.06	0.08	0.09
k	-0.0161	-0.0175	-0.0071	-0.0124	-0.0235	-0.0050	-0.0122	-0.0172

The graph above in Figure 8 is a comparison of all the data that was collected in the down-scale drying process at WPI compared to the drying curve for the monolayer dryer run by Ocean Spray in Middleboro, MA during commissioning a few years ago. It's important to note that the temperatures throughout all of the down-scaled experiments were the same, which was 260°F for stage A, 230°F for stage B, and 200°F for stage C.

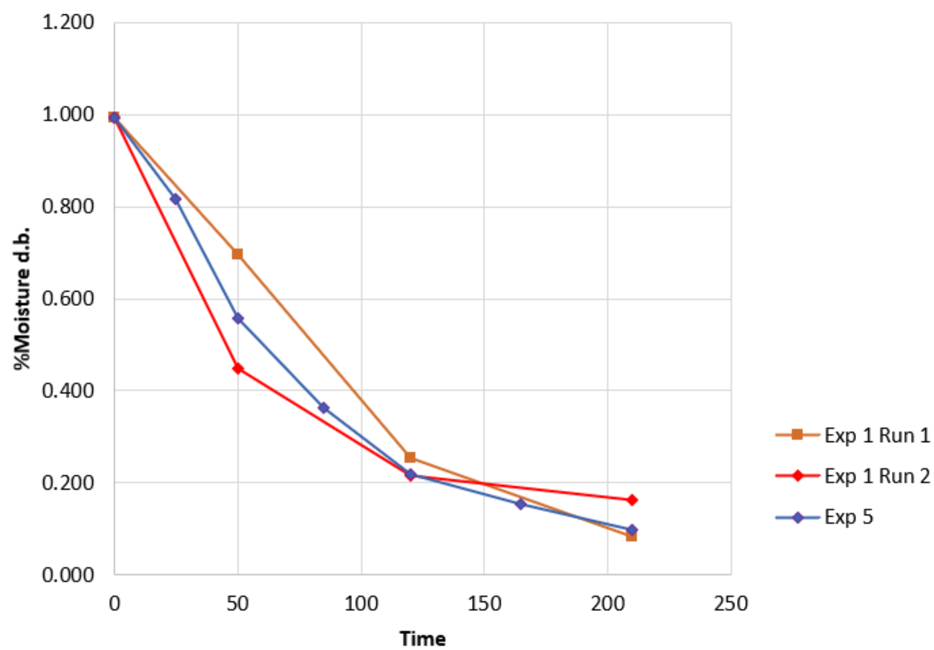


Figure 9: Drying Curve of Experiment 1 Monolayer and Monolayer 2 and Experiment 5 Monolayer

Table 4. Experiment 1 monolayer and monolayer 2 and experiment 5 monolayer Meq, k, and energy consumption values

Experiment	**1**		**5**
Description	Monolayer	Monolayer 2	Monolayer
Meq	0.05	0.014	0.05
k	-0.0161	-0.0175	-0.0143
Energy Consumption (kJ / kg berries)	2950.7	2825.8	2948.7

Figure 9 above compares the drying curves of both runs of experiment 1 and experiment 5, where all three experiments had the same monolayer depth, stage temperatures, and duration within the dryer. This was used to find the Meq and rate for a monolayer depth in the process of recreating Ocean Spray's process. In Table X, it can be seen that the Meq in monolayer 2 is significantly different from that of the monolayers of experiment 1 or 5. This change is thought to have occurred because of the smaller berry mass in the oven, resulting in the higher Meq values.

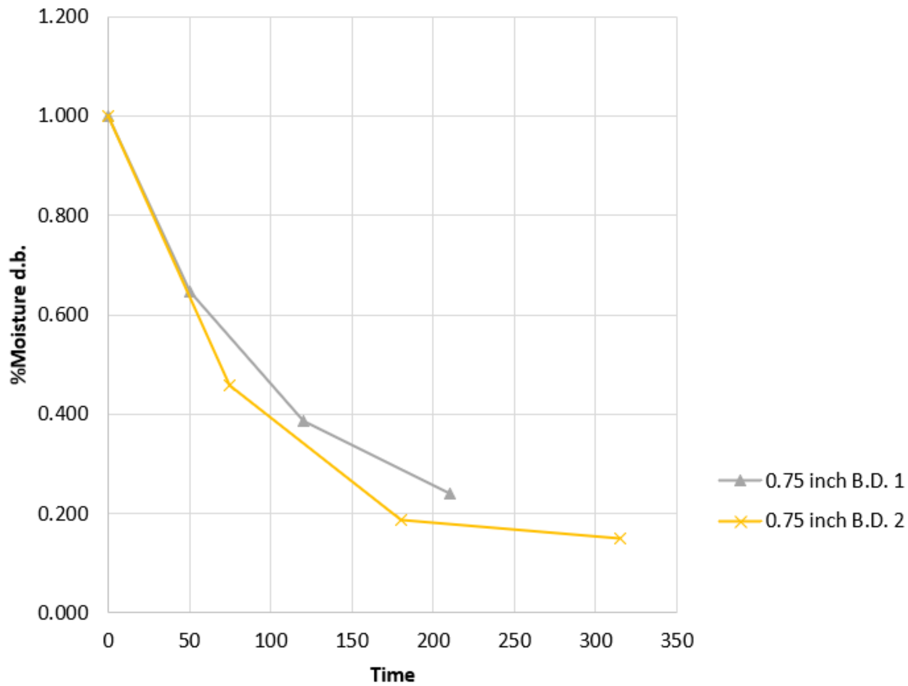


Figure 10: Drying curve for both runs of experiment 2 with bed depths of 0.75”

Table 5. Experiment 2 runs with Meq, k, and energy consumption values

Experiment	**2**	
Description	0.75” B.D**.**	0.75” B.D. 2
Meq	0.15	0.13
k	-0.0106	-0.0124
Energy Consumption (kJ / kg berries)	2546.7	2737.7

Figure 10 compares the drying curves of both runs of experiment 2, where both experiments had the same 0.75-inch bed depth and drying temperature in the ovens. The difference in these two runs is the longer amount of time the second run took at each stage. The first run had stage durations of 50, 70, and 90 minutes within the drier and did not reach the desired 85 brix percentage in the final product, falling short at 78 brix %. This meant that the stage durations needed to be lengthened and thus they were increased 1.5 times the original durations for run 2; stage A was 75 mins, stage B was 105, and stage C was 135 minutes. The second run then produced a final brix percent of 87 in the final product with the new lengthened times. This explains two things; why the Meq of run 1 was higher than the Meq of run 2 and also why the rate of run 1 was slower than the rate of run 2. From this analysis, the team inferred that a longer time spent in each stage creates a lower equilibrium moisture content and increases the overall rate.

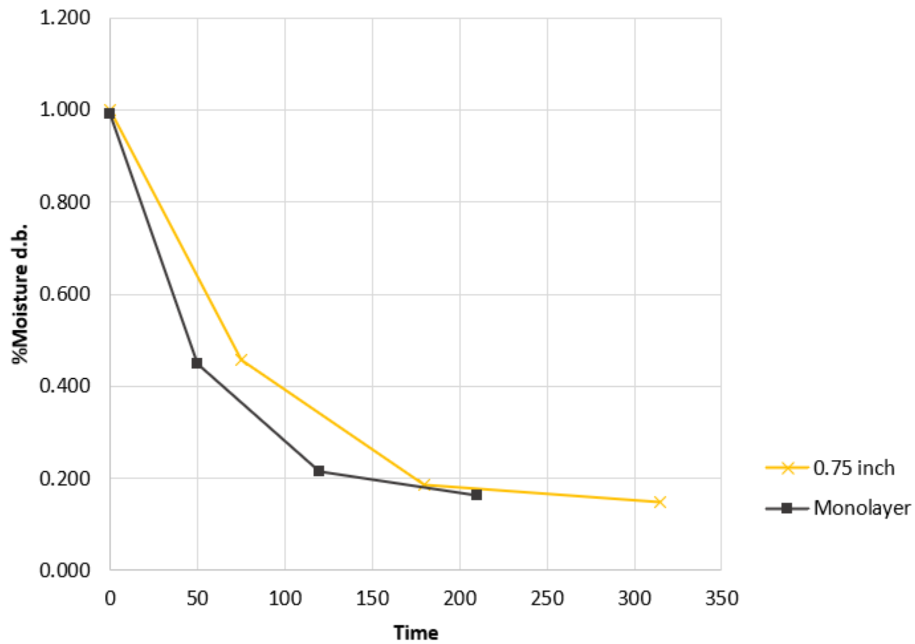


Figure 11: Drying curve of experiment 2 run 2 with the 0.75" bed depth versus experiment 1 monolayer

Table 6. Experiment 2 run 2 and experiment 5 monolayer with Meq, k, and energy consumption values

Experiment	**2**	**1**
Description	0.75" B.D. 2	Monolayer 2
Meq	0.13	0.14
k	-0.0124	-0.0175
Energy Consumption (kJ / kg berries)	2737.7	2825.8

Figure 11 compares experiment 2 run 2 with a bed depth of 0.75-inches and final brix percent of 87 and experiment 5 monolayer that had a final brix percent of about 92. The two variables that were changed in these two experiments to reach Brix percent requirement was the stage duration and bed depth. Experiment 2 had stage durations of 75 minutes for stage A, 105 for stage B, and 135 minutes for stage C while experiment 5 had stage durations of 50, 70 and 90 minutes respectively. The Meq and rate was determined for the 0.75-inch depth and compared to that of experiment 5. It was observed that an increase in bed depth of about a multiple of 3, requires an increase in each stage durations of about 1.5 times the original. Therefore, it was inferred that if the thickness of the bed depth increases, then an increase in the stage durations is required to achieve similar Meq and rate values.

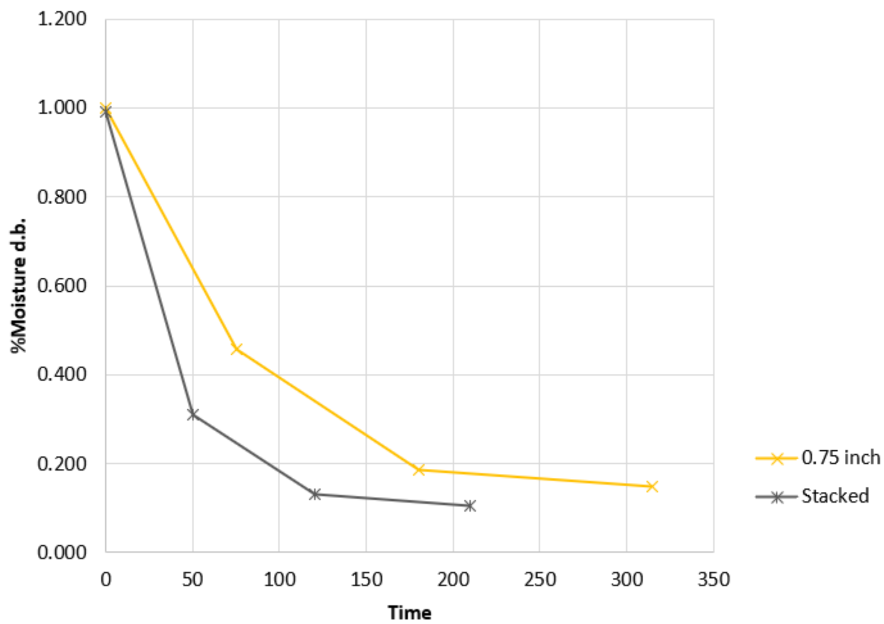


Figure 12: Drying curve of experiment 2 run 2 with 0.75" bed depth and experiment 3 stacked monolayer

Table 7. Experiment 2 run 2 with 0.75" bed depth and experiment 3 stacked monolayer with Meq, k, and energy consumption values

Experiment	2	3
Description	0.75" B.D. 2	Stacked Monolayer
Meq	0.13	0.10
k	-0.0124	-0.0235
Energy Consumption (kJ / kg berries)	2737.7	2847.1

Figure 12 compares experiment 2 run 2 with the bed depth of 0.75-inches to experiment 3, which was two monolayer trays stacked on top of each other. Both of these experiments met the final 85 brix percent requirement. Experiment 2 had stage durations of 75 minutes for stage A, 105 for stage B, and 135 minutes for stage C while the double-stacked monolayer experiment had stage durations of 50, 70, and 90 minutes respectively. The total mass of the cranberries within the oven was very similar for both of these experiments. This fact led the Meq values to be very similar, however, the rate for the double-stacked monolayer of cranberries is greater by about a factor of two. It can be inferred that if the berries are separated into multiple thinner layers, the same mass of berries can be dried two times as fast using the same temperature conditions.

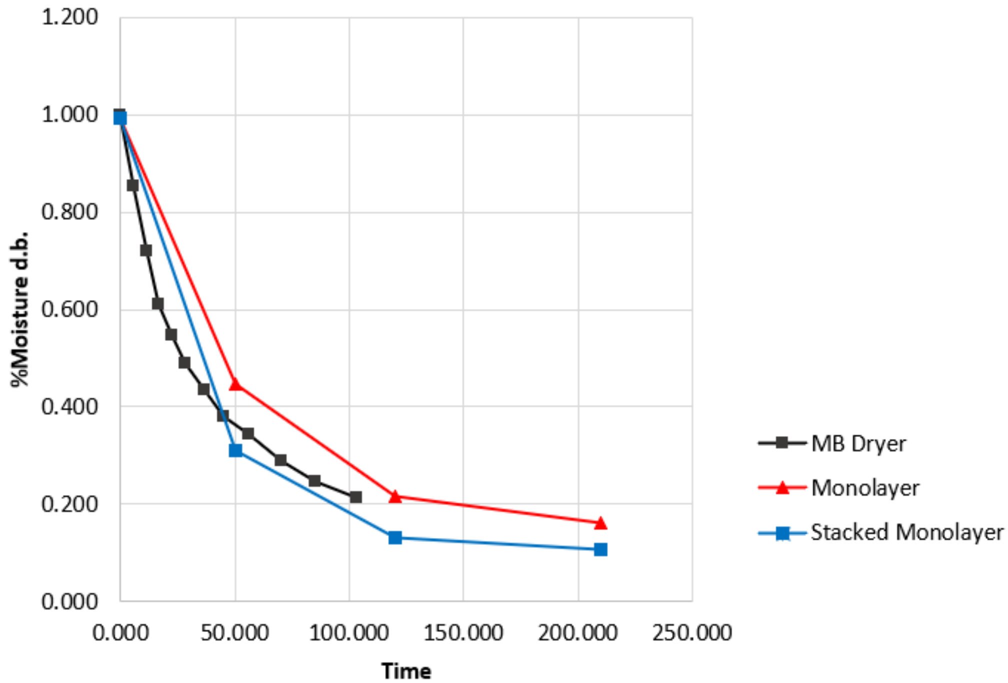


Figure 13: Drying curve of experiment 3 stacked monolayer, experiment 1 run 2, and Ocean Spray's monolayer run during commissioning

Table 8. Experiment 3 stacked monolayer, experiment 1 run 2, and Ocean Spray's monolayer run during commissioning with Meq, k, and energy consumption values

Experiment	**3**	**1**	**MB Dryer**
Description	Stacked Monolayer	Monolayer 2	Monolayer
Meq	0.10	0.14	0.09
k	-0.0235	-0.0175	-0.0172

Figure 13 shows the down-scaled experiments that are most similar to the data collected from the Ocean Spray dryer during commissioning. These two experiments were experiment 3 with the two stacked monolayers and experiment 1 with a single monolayer. The only variable that was different in the two experiments the team performed was this layering of the berries. This difference caused the Meq of experiment 1 to be lower than that of experiment 3. From this it can be inferred that greater massed items will have a higher equilibrium moisture content.

Chapter 4: Conclusion

One of the main objectives of this study was to understand the variables that affect the SDC drying process and the associated implications those variables have on the final SDC product. In order to do this, we had to downscale the drying process used at Ocean Spray and effectively recreate that process in a similar manner inside WPI laboratories. Three key variables were considered when conducting experimentation, those being varied time inside of the oven, bed depth of the berries while drying, and separation of berries. Through energy balance comparison equations, we were able to determine the most efficient way to dry berries considering these variables would be by using a sample of berries with increased mass and a separation of berries present. Based on the drying curves created for each experiment using dry bulb percent moisture vs. time, the equilibrium moisture content (M_{eq}) and mass transfer rate (k) were able to be calculated for each experiment. In addition, the drying curves that were created for our laboratory experiment at WPI are able to be compared to the drying curves of the ovens at Ocean Spray. These different drying curves could be used to prove that the use of a small dryer in a non-industrial setting is comparable to the Ocean Spray drying process in Middleboro, MA.

Chapter 5: Recommendations

5.1 COVID-19 Pandemic

Due to the extraordinary conditions with the COVID-19 Global Pandemic, this project was not executed to the extent that the team planned and wanted to accomplish. This section will be an overview of the other factors that affect the drying process and how we had planned to experiment with them.

5.2 Directions for Future Studies

Our recommendations are that the following team/teams continuing this project expand upon our research by looking into the following parameters:

1. Altering Airflow with the Addition of Dampers
    a. Airflow is the amount of air being blown into the oven. Maintaining a uniform distribution of airflow throughout the entire oven is one of the main problems encountered in the drying process. If the airflow is greater in one specific region compared to another, uneven drying occurs, as the region with the most airflow becomes drier than that of lower airflow. This can ultimately lead to inconsistency in moisture content of the berries being tested. In order to adjust airflow and its consistency, dampers could be implemented to control the area through which air is flowing, and to create a balance of recirculated air throughout the oven, while

preventing any risk for chaotic flow. This uniformity of airflow would better the circulation within the oven and most likely increase the overall efficiency.

2. Utilizing Thermocouples as Temperature Measurement Devices
    a. In our experiments, we were only able to use simple thermometers in order to check the air temperature within the ovens at the top openings. Utilizing more precise devices such as thermocouples would provide future teams with more accurate readings in the oven, as they would effectively and quickly respond to any noticeable temperature changes. These readings would be more consistent and would provide us with better estimations for calculations such as energy balances.

3. Introducing Dehydrators to Change Temperature and Food Quality
    a. The temperature used in the drying process is one of the most influencing factors. Since moisture removal involves a change from liquid to vapor, increasing the energy input to an oven by raising the temperature will increase the drying rate in each zone. However, excessive high temperatures can damage the berries drastically. As heat is continuously increased to drive off moisture, there's a possibility of burning and hardening the berries, which can decrease the nutritional or functional properties. Introducing a dehydrator into the system, as its own stage in the experimental procedure, could have a greater beneficial outcome on the nature of berries as compared to ovens. Maintaining lower temperatures and using less energy than conventional ovens, dehydrators would allow us to increase production quality and obtain final products which are more flavorful and not as burnt.

4. Using Different Ovens to Avoid Inaccurate Data
    a. Each type of oven has its own individual method to undergo moisture removal. Throughout our experiments, we were limited in the specific type of oven we could use. Compared to Ocean Spray's industrial process oven, the ovens that we were provided with, were smaller, not as efficient, and also didn't include a conveyor belt. As a result, we weren't able to obtain the most accurate downscaling because our ovens required us to consistently open and close the door each time we inserted and removed the trays of berries. This definitely played a significant role in altering the airflow and interior temperature, ultimately skewing our data and final results.

5. Varying Berry Quantity, Bed Depth and Layers of Separation
    a. In our double-stacked experiment, we explored the results of a separation of layers with greater berry quantity and bed depth, which proved to be more efficient compared to our other tests. Due to the success we observed in increasing the quantity and thickness of berries in a tray, it would be interesting to look further

into this variable, and discover how this manipulation could also pose a negative impact on the overall berry quality.

6. Infusion Variability
    a. Infusing fruits with sweetened juice is a preservative strategy used to reduce the water content inside them. During this project, the berries we received and studied were already infused from their harvesting. As stated previously, during this harvest process, the berries were sliced, sent through extractors to remove natural juice, partially dried and then injected with the removed sweetened juice. This infusion process expelled a large amount of water content from the berries without being heated, and produced a high yield of the final product. For future studies, teams could look into observing the level of moisture content and drying phenomenon within the berries, if they had not previously been infused with sugar.

7. Uniformity of Bed Depth
    a. To ensure the best possible performance of drying, it's very important to have a uniform bed of berries in the oven. As the bed depth of the berries gets thicker and more inconsistent on one side of the tray, the time it takes for moisture to travel to the surface also increases, meaning that the berries will take longer to dry. Fortunately, the variability of the berries across our study had an average consistency from left to right, staying pretty consistent and even. What could be analyzed further is creating intentional inconsistency in the bed depth of the berries in a single tray and seeing how the results vary, compared to an even layer.

Our team hopes that the addressed parameters above will provide information concerning the implications of our studies, and aid in future research on converting full-scale models to lab-scale models of the drying process.

References

1. Abdulla, S. F., Wen, P. F., Landers, R. F., & Yousif, B. F. (2011, October). Fruit drying process: Analysis, modeling and simulation [PDF file].
2. Beaudry, C., Raghavan, V. G. S., Ratti, C., & Rennie, T. J. (2004, January). Effect of Four Drying Methods on the Quality of Osmotically Dehydrated Cranberries [PDF file].
3. Jesse, Edward V., and Richard T. Roberts. "The Cranberry Industry and Ocean Spray Cooperative: Lessons in Cooperative Governance." *FSRG Monographs*, Jan. 2006, https://aae.wisc.edu/fsrg/publications/Monographs/19cranberryjan06.pdf.
4. Karathanos, V. T., & Belessiotis, V. G. (1999, July 21). Application of a Thin-Layer Equation to Drying Data of Fresh and Semi-dried Fruits [PDF file].

Appendices

Appendix A: Procedure for the Refractometer

1. Leave a bag of cranberries outside of the freezer for about 3 hours to thaw.
2. In a blender, add 100 grams of cranberries and 500 grams of distilled water and blend for 3 minutes on high.
3. Calibrate the refractometer with distilled water.
    a. Press ‘Start’
    b. Pipette enough distilled water onto the refractometer to cover the window (~50-100µL)
    c. Press ‘Zero’ and ensure that the measurement reads zero
4. Clean off the window with a Kim wipe and pipette ~50-100µL of the blended cranberry mixture (enough to cover the window and ensure no chunks are present). Press ‘Start’ and record the temperature and Brix reading.

Table 9: Testing Unfrozen Cranberries to Find Starting Brix Percentage Before Drying

Test	Brix %	Brix %	Brix %
1	8.2	8.3	8.2
2	8.1	8.0	8.1

5. Multiply the Brix % by 6 to get the actual brix percentage

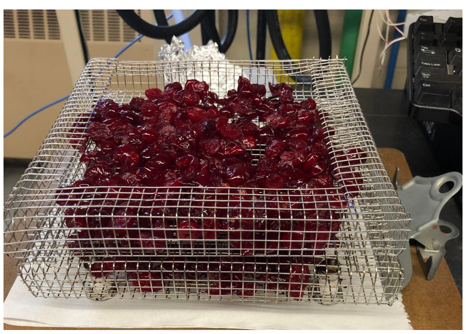
Repeat steps 2-5 on dried cranberry product to find the final brix percentage.
Goal = 85%

Appendix B: Images of Cranberries

Experiment 1 Final Products (Monolayers)

Experiment 3 Run 1 (Two monolayer trays, stacked)

Before Drying



After Stage A (50 mins)

After Stage B (70 mins)

After Stage C (90 mins)

Experiment 3 Run 2 (Two 0.75” trays, stacked)

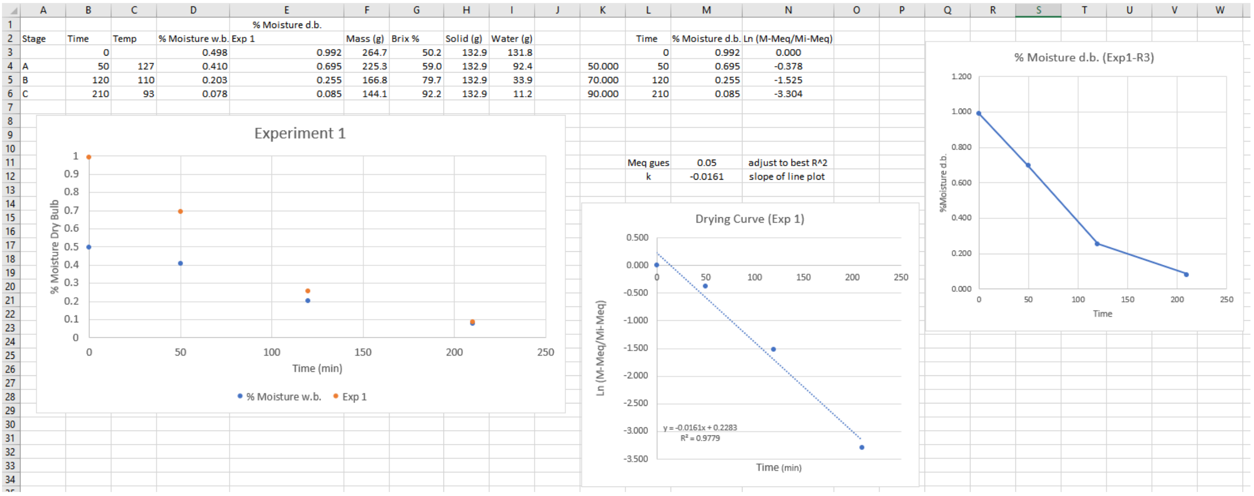
After Stage A

After Stage B

After Stage C

Appendix C: Excel Calculations

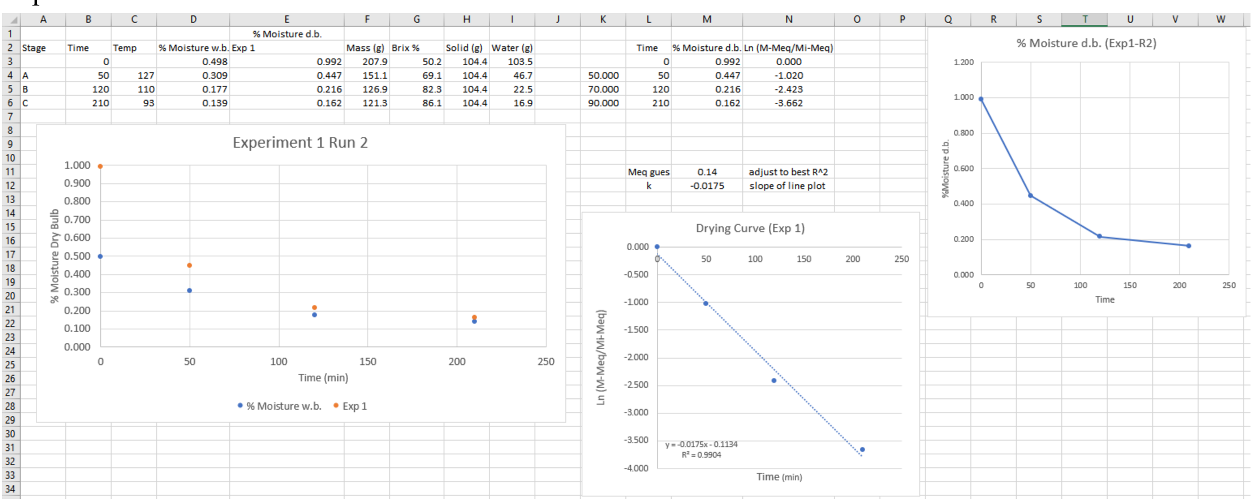
Experiment 1 Run 1



Stage	Time	Temp	% Moisture w.b.	% Moisture d.b. Exp 1	Mass (g)	Brix %	Solid (g)	Water (g)		Time	% Moisture d.b.	Ln (M-Meq/Mi-Meq)
	0		0.498	0.992	264.7	50.2	132.9	131.8		0	0.992	0.000
A	50	127	0.410	0.695	225.3	59.0	132.9	92.4	50.000	50	0.695	-0.378
B	120	110	0.203	0.255	166.8	79.7	132.9	33.9	70.000	120	0.255	-1.525
C	210	93	0.078	0.085	144.1	92.2	132.9	11.2	90.000	210	0.085	-3.304

Meq gues	0.05	adjust to best R^2
k	-0.0161	slope of line plot

Experiment 1 Run 2



Stage	Time	Temp	% Moisture w.b.	% Moisture d.b. Exp 1	Mass (g)	Brix %	Solid (g)	Water (g)		Time	% Moisture d.b.	Ln (M-Meq/Mi-Meq)
	0		0.498	0.992	207.9	50.2	104.4	103.5		0	0.992	0.000
A	50	127	0.309	0.447	151.1	69.1	104.4	46.7	50.000	50	0.447	-1.020
B	120	110	0.177	0.216	126.9	82.3	104.4	22.5	70.000	120	0.216	-2.423
C	210	93	0.139	0.162	121.3	86.1	104.4	16.9	90.000	210	0.162	-3.662

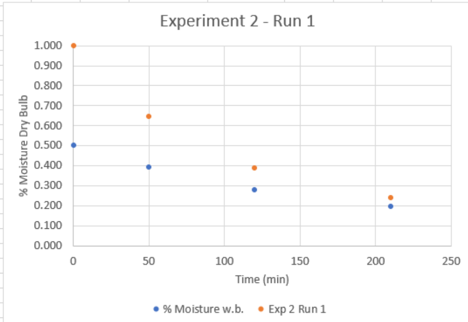
Meq gues	0.14	adjust to best R^2
k	-0.0175	slope of line plot

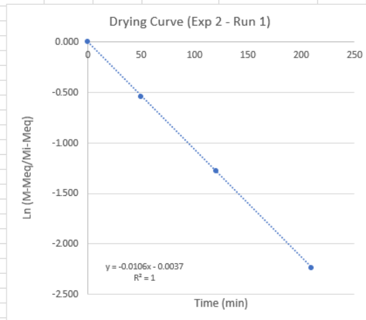
Experiment 2 Run 1

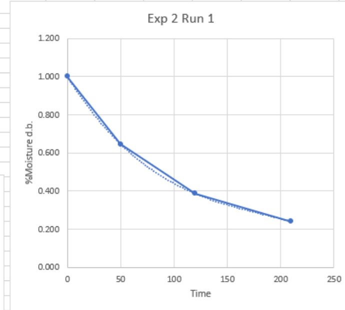
Stage	Time	Temp	% Moisture w.b.	% Moisture d.b. Exp 2 Run 1	Mass (g)	Brix %	Solid (g)	Water (g)
	0		0.500	1.000	424.9	50.2	212.4	212.4
A	50	127	0.392	0.646	349.6	60.8	212.4	137.1
B	120	110	0.279	0.386	294.5	72.1	212.4	82.0
C	210	93	0.194	0.241	263.6	78.0	212.4	51.2

	Time	% Moisture d.b.	Ln (M-Meq/Mi-Meq)
	0	1.000	0.000
50.000	50	0.646	-0.540
70.000	120	0.386	-1.281
90.000	210	0.241	-2.235

Meq gues	0.15	adjust to best R^2
k	-0.0106	slope of line plot





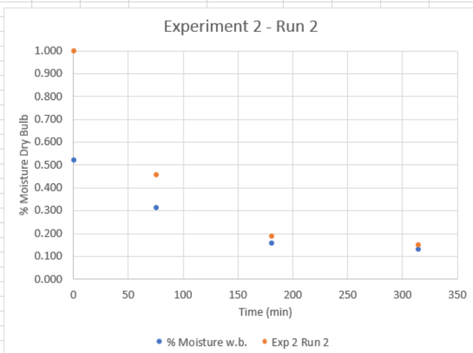


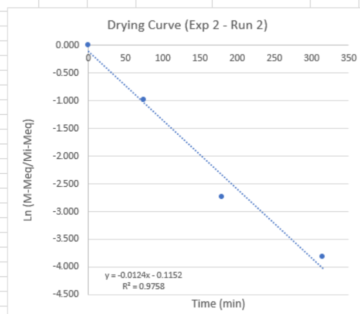
Experiment 2 Run 2

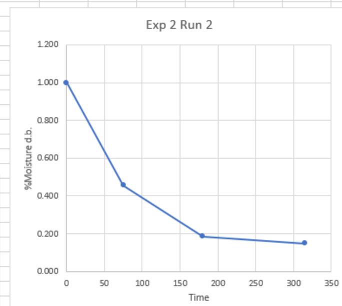
Stage	Time	Temp	% Moisture w.b.	% Moisture d.b. Exp 2 Run 2	Mass (g)	Brix %	Solid (g)	Water (g)
	0		0.519	1.000	415.7	50.2	208.7	207
A	75	127	0.314	0.457	304.1	68.6	208.7	95.4
B	180	110	0.157	0.186	247.5	84.3	208.7	38.8
C	315	93	0.130	0.149	239.8	87	208.7	31.1

	Time	% Moisture d.b.	Ln (M-Meq/Mi-Meq)
	0	1.000	0.000
75.000	75	0.457	-0.978
105.000	180	0.186	-2.745
135.000	315	0.149	-3.823

Meq gues	0.13	adjust to best R^2
k	-0.0124	slope of line plot



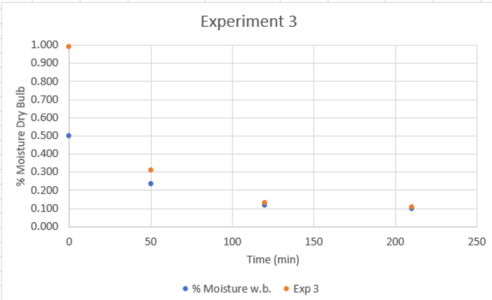


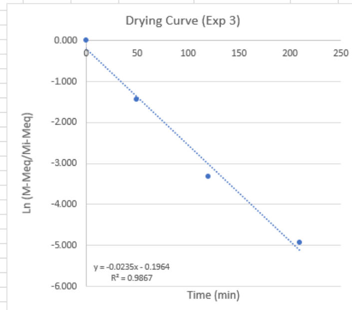


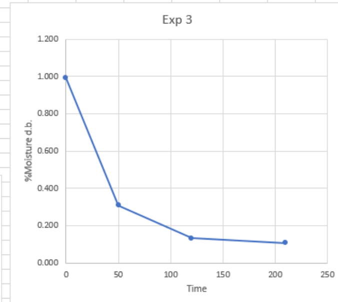
Experiment 3 Run 1

Stage	Time	Temp	% Moisture w.b.	% Moisture d.b. Exp 3	Mass (g)	Brix %	Solid (g)	Water (g)		Time	% Moisture d.b.	Ln (M-Meq/Mi-Meq)
	0		0.498	0.992	375.93	50.2	188.7	187.2		0	0.992	0.000
A	50	127	0.236	0.309	247.07	76.4	188.7	58.4	50.000	50	0.309	-1.450
B	120	110	0.117	0.132	213.59	88.3	188.7	24.9	70.000	120	0.132	-3.331
C	210	93	0.096	0.106	208.79	90.2	188.7	20.1	90.000	210	0.106	-4.927

Meq gues	0.10	adjust to best R^2
k	-0.0235	slope of line plot



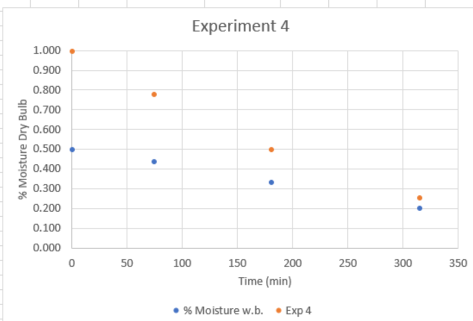


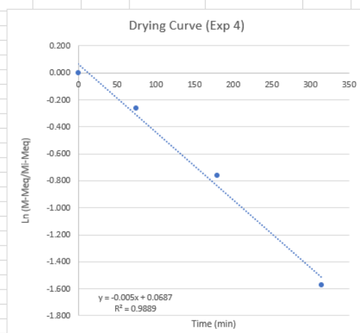


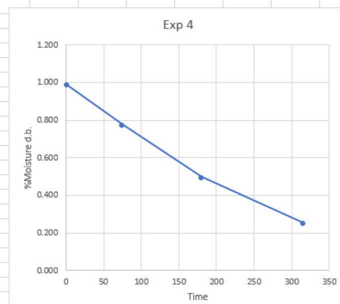
Experiment 4 Run 1

Stage	Time	Temp	% Moisture w.b.	% Moisture d.b. Exp 4	Mass (g)	Brix %	Solid (g)	Water (g)		Time	% Moisture d.b.	Ln (M-Meq/Mi-Meq)
	0		0.498	0.992	862.2	50.2	432.8	429.4		0	0.992	0.000
A	75	127	0.437	0.777	768.9	56.3	432.8	336.1	75.000	75	0.777	-0.263
B	180	110	0.331	0.496	647.4	66.9	432.8	214.6	105.000	180	0.496	-0.760
C	315	93	0.202	0.253	542.4	79.8	432.8	109.6	135.000	315	0.253	-1.573

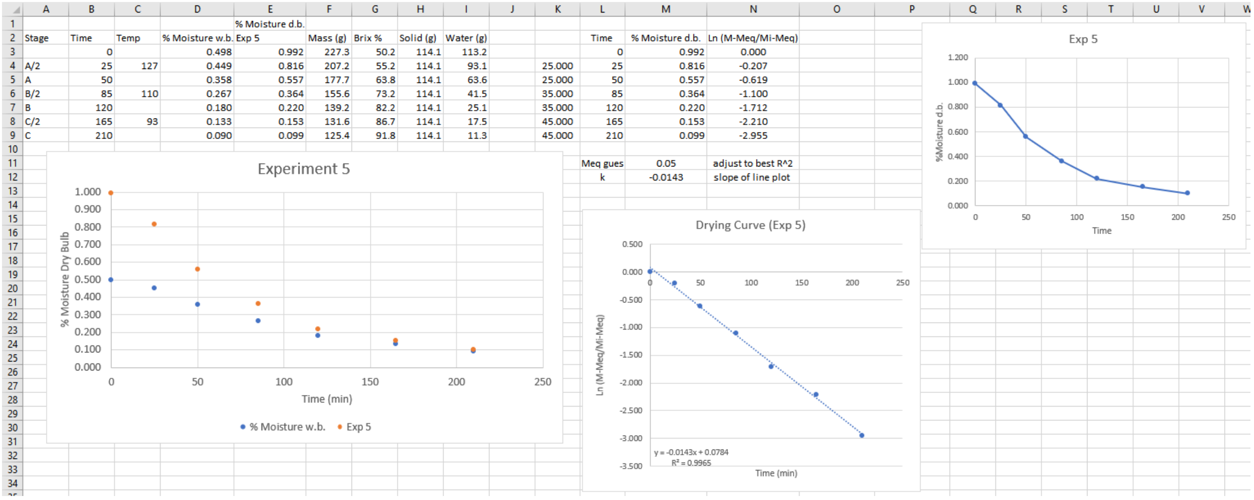
Meq gues	0.06	adjust to best R^2
k	-0.0050	slope of line plot







Experiment 5 Run 1



Stage	Time	Temp	% Moisture w.b.	% Moisture d.b. Exp 5	Mass (g)	Brix %	Solid (g)	Water (g)		Time	% Moisture d.b.	Ln (M-Meq/Mi-Meq)
	0		0.498	0.992	227.3	50.2	114.1	113.2		0	0.992	0.000
A/2	25	127	0.449	0.816	207.2	55.2	114.1	93.1	25.000	25	0.816	-0.207
A	50		0.358	0.557	177.7	63.8	114.1	63.6	25.000	50	0.557	-0.619
B/2	85	110	0.267	0.364	155.6	73.2	114.1	41.5	35.000	85	0.364	-1.100
B	120		0.180	0.220	139.2	82.2	114.1	25.1	35.000	120	0.220	-1.712
C/2	165	93	0.133	0.153	131.6	86.7	114.1	17.5	45.000	165	0.153	-2.210
C	210		0.090	0.099	125.4	91.8	114.1	11.3	45.000	210	0.099	-2.955

Meq gues	0.05	adjust to best R^2
k	-0.0143	slope of line plot

Appendix D: Detailed Procedures

Experiment 1 Procedure

The oven was preheated to 260 degrees Fahrenheit with a piece of parchment paper on the very bottom larger than the cranberry tray to catch possible dripping. In a clean mesh metal tray, a single layer (none overlapping) of defrosted cranberries was spread out and weighed. Once the oven was at 260 degrees Fahrenheit, the temperature of the cranberries was taken before inserting the tray into the oven. The temperature and relative humidity were watched for any changes and recorded for X minutes. After X minutes, the cranberries were taken out of the oven to take the temperature of the cranberries, reweigh the tray, and remeasure the depth. While measuring these characteristics the temperature of the oven was dropped to 230 degrees Fahrenheit and the cranberries were placed back into the oven for X mins. After X mins, the measurement process was repeated and the cranberries were placed back into the oven for X more minutes. The cranberries were then removed and the temperature, weight, and depth were measured along with the Brix percentage in hopes to achieve at least 85%.

Run 1
Objective(s):

- ➢ Run experiment 1 using the drying times given by Ocean Spray to find the correct amount of time our scale-down experiments should be run at for each stage.

Run 2
Objective(s):

- ➢ Run experiment 1 doubling the drying times given by OS using the oven upstairs
- ➢ Reach 85 Brix %

Experiment 2 Procedure

The oven was preheated to 260 degrees Fahrenheit with a piece of parchment paper on the very bottom larger than the cranberry tray to catch possible dripping. In a clean mesh metal tray, an 0.75-inch layer of defrosted cranberries was spread out and weighed. Once the oven was at 260 degrees Fahrenheit, the temperature of the cranberries was taken before inserting the tray into the oven. The temperature and relative humidity were watched for any changes and recorded for X minutes. After X minutes, the cranberries were taken out of the oven to take the temperature of the cranberries, reweigh the tray, and remeasure the depth. While measuring these characteristics the temperature of the oven was dropped to 230 degrees Fahrenheit and the cranberries were placed back into the oven for X mins. After X mins, the measurement process was repeated and the cranberries were placed back into the oven for X more minutes. The cranberries were then removed and the temperature, weight, and depth were measured along with the Brix percentage in hopes to achieve at least 85%.

Run 1

Objective(s):

- ➢ Run experiment 2 with a layer depth of 0.75" using the drying times found from experiment 1 run 2. The drying time will probably need to be increased but this is a starting point.
- ➢ To see the difference in the experimental values collected when the bed depth is increased.

Run 2

Objective(s):

- ➢ Run experiment 2 with a layer depth of 0.75" multiplying the drying time found from experiment 1 run 2 by 1.5.
- ➢ To see if increasing the time will get the experimental values closer to the values collected in experiment 1.

Experiment 3 and 4 Procedure

The oven was preheated to 260 degrees Fahrenheit with a piece of parchment paper on the very bottom larger than the cranberry tray to catch possible dripping. Using two clean mesh metal tray, a single layer (none overlapping) of defrosted cranberries was spread out and weighed on each tray. Once the oven was at 260 degrees Fahrenheit, the temperature of the cranberries was taken before inserting the trays into the oven stacked on top of each other. The temperature and relative humidity were watched for any changes and recorded for X minutes. After X minutes, the cranberries were taken out of the oven to take the temperature of the cranberries, reweigh the tray, and remeasure the depth. While measuring these characteristics the temperature of the oven was dropped to 230 degrees Fahrenheit and the cranberries were placed back into the oven for X mins. After X mins, the measurement process was repeated and the cranberries were placed back into the oven for X more minutes. The cranberries were then removed and the temperature, weight, and depth were measured along with the Brix percentage in hopes to achieve at least 85%.

Run 1

Objective(s):

- ➢ Run experiment 3 with a monolayer using the drying times found from experiment 1 run 2 (50/70/90).
- ➢ To see how having a separation in the layers differs these experimentally collected values from experiment 1 run 2.

Run 2

Objective(s):

- ➢ Run experiment 3 with a bed depth of 0.75" using the drying times found that best suit a 0.75" layer (75/105/135).
- ➢ To see how having a separation in the layers differs these experimentally collected values from and experiment 2 runs 1-2.

For Experiment 4, the procedure for Experiment 3 was used but with a 0.75" bed depth

Experiment 5 Procedure

The oven was preheated to 260 degrees Fahrenheit with a piece of parchment paper on the very bottom larger than the cranberry tray to catch possible dripping. In a clean mesh metal tray, a single layer (none overlapping) of defrosted cranberries was spread out and weighed. Once the oven was at 260 degrees Fahrenheit, the temperature of the cranberries was taken before inserting the tray into the oven. The temperature and relative humidity were watched for any changes and recorded for X minutes. After X minutes, the cranberries were taken out of the oven to take the temperature of the cranberries, reweigh the tray, and remeasure the depth. While measuring these characteristics the temperature of the oven was dropped to 230 degrees Fahrenheit and the cranberries were placed back into the oven for X mins. After X mins, the measurement process was repeated and the cranberries were placed back into the oven for X more minutes. The cranberries were then removed and the temperature, weight, and depth were measured along with the Brix percentage in hopes to achieve at least 85%.

Run 1

Objective(s):

- ➢ Run experiment 4 with a monolayer and the (50/70/90) run time but stop halfway through Stage A.

Run 2

Objective(s):

- ➢ Run experiment 4 with a monolayer and the (50/70/90) run time but stop at the end of Stage A.

Run 3

Objective(s):

- ➢ Run experiment 4 with a monolayer and the (50/70/90) run time but stop halfway through Stage B.

Run 4

Objective(s):

- ➢ Run experiment 4 with a monolayer and the (50/70/90) run time but stop at the end of Stage B.

Run 5

Objective(s):

- ➢ Run experiment 4 with a monolayer and the (50/70/90) run time but stop halfway through Stage C.