Design of a Frozen Fruit Smoothie Machine

by

Teddy A. Toussaint

Submitted to the
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Signature of Author______________________________
Department of Mechanical Engineering
May 10, 2013

Certified by______________________________
Alexander H. Slocum
Neil and Jane Pappalardo Professor of Mechanical Engineering
MacVicar Faculty Fellow
Thesis Supervisor

Accepted by______________________________
Annette Hosoi
Professor of Mechanical Engineering
Undergraduate Officer

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ABSTRACT

A smoothie machine known as the FruziFridge is being deterministically designed to dispense frozen fruit smoothies. The design is scalable so it can be made available in homes as a built-in module of a refrigerator or in public as a vending machine. The design is compared to previously existing smoothie machine technology and succeeds in fulfilling functional requirements that cater more to the health conscious consumer. The FruziFridge is still a work-in-progress so this text only shows the strategy and concept phase of design and the early stages of the detailed engineering and development phase of design, including verification of the most critical module's concept.

Thesis Supervisor: Alexander H. Slocum
Title: Neil and Jane Pappalardo Professor of Mechanical Engineering

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First, I thank Professor Alexander H. Slocum who not only to helped me develop this smoothie machine, but helped me develop as a Mechanical Engineer.

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Finally, I thank my parents, who have always supported me.

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Chapter 1

Introduction

1.1 Motivation: Broken American Food Industry

The food industry is often under public scrutiny for its negative contribution to public health. Fortunately, this scrutiny has caused people to act. One of the most controversial initiatives to curb the negative effects of the food industry was the ban on the sale of large containers of soft drinks in New York City. Not to be outdone, venture capitalists and innovators are joining the movement to reverse the unhealthy trends in the food industry by forming food start-ups centered on technologies that deliver healthy, minimally processed foods with no preservatives or food additives.[i] The FruziFridge, the smoothie machine presented in this text, was designed to contribute to the movement to repair the American food industry.

1.2 Fruit Smoothie

A fruit smoothie is a beverage made by liquefying fruit through some means of crushing or cutting, among other possible methods. Two or more fruit ingredients can be mixed in different proportions and combinations to create a vast selection of different smoothies. Fruit smoothies are a healthy and tasty alternative to the sodas and high-fructose juices that have inundated the food industry. Other ingredients, such as milk or vitamin supplements can be added to a smoothie for additional health and taste benefits.

1.3 Identifying Functional Requirements for Smoothie Machine

The design of a smoothie machine can go in many directions. For guidance, the functional requirements in table 1 were identified.

Table 1. Smoothie Machine Functional Requirements

Functional Requirements	Justification for Requirement
Critical Requirements	These functional requirements must be met or design fails.
Food Safe	Keep dangerous microbes from growing in machine
Extends Storage Life of Ingredients	The storage life of the fruit ingredients should be as long as possible to avoid wasting fruit and money.
Avoids Use of Preservatives and/or Food Additives	The safety of certain preservatives and food additives is an unsettled debate. To be safe, health conscious consumers avoid foods that have preservatives

	and/or food additives.
Makes High "Quality" Smoothies	Here quality is to be understood the way it is in manufacturing- low variation. This means the machine can make the same smoothie with the same ratio of ingredients with high precision or with little variation. Since taste is subjective this seems to be a more measurable functional requirement.
Makes Smoothie Quickly	A consumer should be able to get the smoothie quickly. Otherwise, there may be times when she is forced to choose to consume a less healthy food because she doesn't have time to wait for a smoothie.
Scalable Design	The smoothie machine design should be compact enough to be put in homes to serve individuals and families. Still it should be able to be resized to make a vending machine capable of serving consumers in public or in the work place.
Non-Critical Requirements	These functional requirements are good to keep in mind but will not mean failure if they are not fully met.
Fruit Ingredients Used in Machine are Minimally Processed	It is nearly impossible have a food product that is not processed since processing can even include simply cutting fruit into slices. Still many consumers avoid foods that they feel are overly processed so it is best to minimize processing.
Minimizes Food Waste	This saves money and makes design more sustainable.
Machine is energy efficient	This saves money and makes design more sustainable.

1.4 Smoothie Machines: Prior Art

Studying the prior art on smoothie machines was helpful for two reasons:

1) It helped generate ideas through reverse engineering.
2) Identifying the weak points in the design of prior art helped give context for where the most effort should be placed in developing a new smoothie machine.

1.4.1 Blender

A blender is the simplest smoothie machine. The process by which a blender makes a smoothie is given in table 2.

Table 2. Blender Smoothie Making Process

Step 1
User gathers fruit ingredients.
Step 2
Consumer adds fruit ingredients to blender.
Step 3
When consumer turns blender on, a rotating blade cuts fruit ingredients and induces a flow within the blender that mixes different fruit ingredients.
Step 4
Consumer enjoys smoothie.
Step 5
Consumer cleans blender.

Simply examining the process by which a blender makes a smoothie tells a lot about which functional requirements it does and does not meet. This is shown in table 3.

Table 3. Blender and Functional Requirements

Functional Requirements	Justification for Requirement
Critical Requirements	
Food Safe	Marginally Successful- Although blenders can be cleaned to prevent the growth of harmful microbes, they require another mechanism or user to do this.
Extends Storage Life of Ingredients	Requirement Not Met
Avoids Use of Preservatives and/or Food Additives	User Dependent
Makes High "Quality" Smoothies	User Dependent
Makes Smoothie Quickly	Marginally Successful- Although blending can be quick, gathering and preparing ingredients is more time consuming.
Scalable Design	Marginally Successful- The blender is certainly successful at small-scale levels of operation in the home. When its smoothie production is scaled up, however, it must be used in a smoothie shop, which incurs many capitol and operational costs.

Non-Critical Requirements	
Fruit Ingredients Used in Machine are Minimally Processed	User Dependent
Minimizes Food Waste	Successful
Machine is Energy Efficient	Successful

1.4.2 Blend-Tec Smoothie Dispensing Machine

The Blend-Tec is a smoothie machine that can be found in college campus convenience stores. There is a Blend-Tec in the MIT student center.

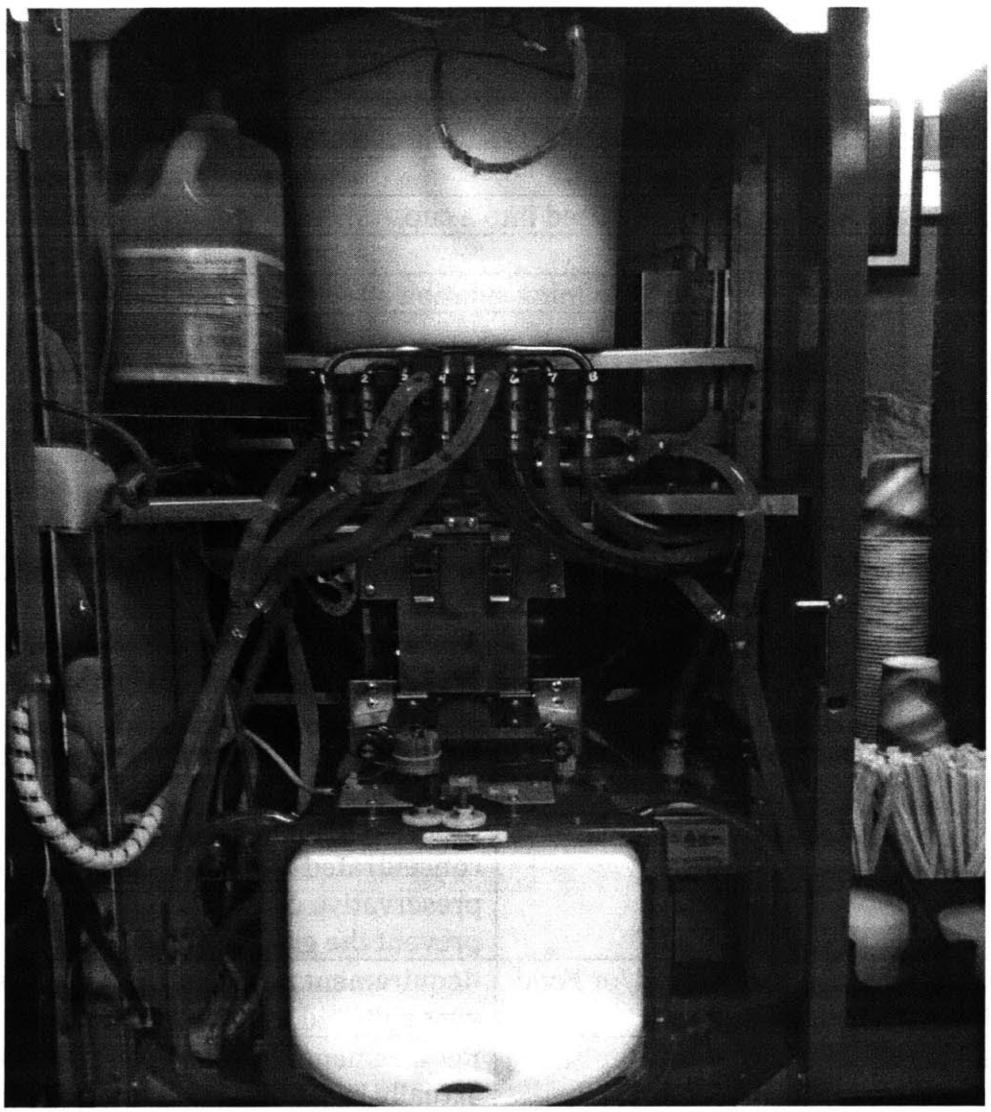


Figure 1 The inner-workings of a Blend-Tec. Most of the tubes are connected to separate unrefrigerated boxes of crushed fruit and fruit concentrate, which is in a cabinet underneath the Blend-Tec. One of the tubes is connected to a water supply. The tubes all lead to a blender. The fruit ingredients are driven from their separate boxes to the blender (hidden in the metal casing below the white bucket) via a peristaltic pump situated in the bottom-right-back corner of the Blend-Tec. The white bucket above the blender produces and dispenses ice into the blender. To the left of the white bucket is a bottle of disinfectant used to clean the blender after each use.

The Blend-Tec Smoothie Dispensing Machine makes many important improvements over the simple blender. For example, the Blend-Tec is self-cleaning. The process by which it makes a smoothie is given in table 3.

Table 3. Blend-Tec Smoothie Making Process

Step 1
Boxes of pureed fruit and fruit concentrate with the preservative culture dextrose are hooked to intake lines of machine.
Step 2
A consumer requests a smoothie.
Step 3
Blend-Tec uses a peristaltic pump to get fruit puree from boxes to a central blender where ice cubes are added.
Step 4
Ingredients are blended and dispensed into a cup.
Step 5
Blend-Tec cleans blender with a cleaning solution and a water rinse.

Despite the improvements the Blend-Tec smoothie machine makes over a simple blender, there are still important functional requirements the Blend-Tec Smoothie Dispensing Machine fails to meet. These are outlined in table 4.

Table 4. Blend-Tec and Functional Requirements

Functional Requirements	Justification for Requirement
Critical Requirements	
Food Safe	Successful- The Blend-Tec cleans its blending compartment by using a disinfectant and a water rinse cycle.
Extends Storage Life of Ingredients	Successful- The Blend-Tec extends the shelf life of the fruit ingredients by processing some of the ingredients into a concentrated form and using the preservative cultured dextrose to prevent the growth of microbes.
Avoids Use of Preservatives and/or Food Additives	Requirement not met- The Blend-Tec uses cultured dextrose.
Makes High "Quality" Smoothies	Requirement not met- The Blend-Tec actually has some issues creating the same smoothie with precision. See section 1.4.2.2 for an explanation.
Makes Smoothie Quickly	Successful- The Blend-Tec can make a smoothie in a matter of seconds after a consumer has completed a smoothie request.

Scalable Design	Marginally Successful- The Blend-Tec preforms well in a large-scale production, public setting. However, because of its size, its need to be calibrated, and its need for technical maintenance it doesn't scale down very well to be used in the typical American home.
Non-Critical Requirements	
Fruit Ingredients Used in Machine are Minimally Processed	Requirement not met- The Blend-Tec uses fruit concentrate.
Minimizes Food Waste	Requirement not met- Because the Blend-Tec uses to peristaltic pump to remove fruit ingredients from a box there is a considerable amount of food waste. See section 1.4.2.2 for explanation.
Machine is Energy Efficient	Marginally Successful

1.4.2.2 Smoothie Quality, Food Waste, and Energy Efficiency in the Blend-Tec

Smoothie Quality

Smoothie quality, here, refers to the precision with which the Blend-Tec can make a number of smoothies of the same type. There are a number of features in the Blend-Tec's design that make it unable to make smoothies with high quality. One reason is that its box of ingredients has no way of maintaining a uniform distribution of ingredients. Although the effect is not as quick, similar to how water and oil spontaneously separate after being mixed, the fruit and water in the Blend-Tec's fruit storage containers are also separating. Each box is labeled with a sticker that says to shake the box before hooking it up to the machine, but after some time, the ingredients will separate and the pump will draw an overly concentrated portion of whatever ingredient happens to settle closest to the exit valve of the fruit storage container. Some people who have bought smoothies from the Blend-Tec in the MIT student center found that their smoothies were sometimes extra watery. It is possible that this is a result of the ingredients separating in the box. This problem is avoided in the FruziFridge because, as you will read in section 1.5, all of the ingredients are kept frozen, which means the mobilities of the ingredients are essentially zero and the will not separate even after long periods of time.

Food Waste and Energy Efficiency

The Blend-Tec uses a peristaltic pump to move ingredients from its fruit storage box to the blender. Unfortunately, because of the way peristaltic pumps work the Blend-Tec has to choose between energy efficiency and minimizing food waste. A peristaltic pump works by squeezing the tubing that a fluid is in and pressing the fluid inside forward, like a toothpaste dispenser. When the tube is no longer being compressed it should return to its normal shape creating a low-pressure region that pulls more fluid forward until the low-pressure region is filled. In a closed system, like the Blend-Tec, however, the fluid source reaches a state of low pressure because it is being evacuated of fluid. At some point, the pressure becomes so low that it pulls against the low-pressure region that is created when a compressed tube returns to its original shape, hindering the ability of the pump to pull any more fluid from the source. One way to increase the strength of the pump would be to increase the stiffness of the tube. That way when it returns to its shape it pulls harder. Unfortunately, this also means a machine must push harder to compress the tube, meaning it is using more energy. A designer must decide how much energy he is willing to expend to waste less fruit in the Blend-Tec. You will find that this dilemma in choosing between energy efficiency and food efficiency does not arise in the design of the FruziFridge.

1.5 The FruziFridge

Just as the Blend-Tec made important improvements on the design of the blender, the FruziFridge improves on the design of both the Blend-Tec. Table 5 explains the process that makes the FruziFridge so successful.

Table 5. FruziFridge Smoothie Making Process

Step 1
Frozen fruit puree is added to machine in a special container. This container minimizes the amount of energy/force necessary to remove frozen fruit from its container.
Step 2
A consumer requests a smoothie.
Step 3
FruziFridge dispenses frozen fruit from container into a blending compartment.
Step 4
Ingredients are blended and dispensed into a cup.
Step 5
FruziFridge cleans blender with a cleaning solution and a water rinse.

The smoothie making process of the FruziFridge and Blend-Tec are actually quite similar. Still, the small difference between the two processes proves to be quite impactful. Table 6 shows just how effective using freezing to preserve fruit ingredients is in producing a smoothie machine and process that meets functional requirements.

Table 6. FruziFridge and Functional Requirements

Functional Requirements	Justification for Requirement
Critical Requirements	

Food Safe	Successful- The FruziFridge will use the same technology used in the Blend-Tec to clean out the compartment where its fruit ingredients are converted into a smoothie.
Extends Storage Life of Ingredients	Successful- The FruziFridge extends the storage life of fruits from several days to several months by holding it in a frozen state until it is dispensed from its storage container.
Avoids Use of Preservatives and/or Food Additives	Successful- The FruziFridge uses no preservatives.
Makes High "Quality" Smoothies	Due to the precision of its fruit dispensing method the FruziFridge is capable of producing high "quality" smoothies.
Makes Smoothie Quickly	Successful- The FruziFrige can make a smoothie within seconds of a consumer completing her request for a certain smoothie.
Scalable Design	Successful- The FruziFridge has a design that can be scaled down in size and complexity to be used in the home. It can also scale up to be used in public as a vending machine.
Non-Critical Requirements	
Fruit Ingredients Used in Machine are Minimally Processed	Marginally Successful- The fruit ingredients will have to be processed into a pureed form and immediately frozen but it avoid going as far as using fruit concentrate.
Minimizes Food Waste	Successful- The method the FruziFridge uses to dispense smoothies doesn't waste considerable amounts of fruit.
Machine is Energy Efficient	Marginally Successful

Chapter 2

Strategy and Concept of FruziFridge Design

This chapter focuses on the high-level decisions that were made early in the design process about the design of the FruziFridge as well as the thought process that led to these decisions.

2.1 Review Functional Requirements

Table 7. Smoothie Machine Functional Requirements

Functional Requirements
Critical Requirements
Food Safe
Extends Storage Life of Materials
Avoids use of Preservatives and/or Food Additives
Makes High "Quality" Smoothies
Makes Smoothie Quickly
Scalable Design
Non-critical Functional Requirements
Minimizes Food Waste
Fruit Ingredients in Machine are minimally processed
Minimize Food Waste
Machine is Energy Efficient

2.2 Justification of Machine Overall Machine System and Strategy

In the early stages of design, there seemed to be two major possibilities for how the machine would work, which are presented in tables 8 and 9.

Table 8. Pre-mixed Strategy

Step 1
Smoothie ingredients are already mixed according to a recipe for different smoothies and each recipe is stored separately in small containers.
Step 2
When a consumer requests a smoothie she chooses the type of smoothie she wants and the whole contents of one container corresponding to that smoothie is used to make the consumer's smoothie.
Step 3
Fruit ingredients are converted into smoothie and served to consumer

Table 9. Separated Ingredients Strategy

Step 1
Each type of fruit ingredient is stored separately in a bulk in a container (i.e. There is a container for bananas and a separate container for strawberries, etc.)

Step 2
When a consumer requests a particular type of smoothie the machine dispenses any fruit ingredients required for that smoothie from its corresponding container to a central location
Step 3
In said centralized location, fruit ingredients are convert to smoothie
Step 4
Smoothie is dispensed to consumer

The Pugh chart in table 10 was used in order to help choose which strategy to pursue.

Table 10. Pugh Chart for Overall Dispensing Strategy of FruziFridge

Strategy	Consumer has choice	Scalable Design	Make Smoothie Quickly	Total
Pre-Mixed Ingredients	0	0	0	0
Separated Ingredients	2	0	-2	0
Pre-mixed in Home Version and Separated in Public Vending Version	2	1	-1	2

As the Pugh chart shows, its best to simply allow the home based smoothie machines to use pre-mixed ingredients while public smoothie vending machine use ingredients that are separate to begin with. This strategy makes sense for a number of reasons. For example, the pre-mixed strategy works best when space is limited as it could quite possibly be in a home. The separated ingredients strategy works best when there is space because the high number of different smoothies that can be produced due to different combinations of ingredients is well worth the extra cost in space.

2.3 Justification for Freezing Fruit for Preservation during Storage

There are various methods for preserving fruit. One might guess, therefore, that it would be difficult to decide which strategy is best. The choice, however, was actually very simple. While freeze-drying or drum drying fruits are very effective methods of preserving fruit, dried fruit is a horrible smoothie ingredient. Dried fruit smoothies just taste bad. Frozen fruit smoothies, on the other hand, are great.

Table 11. Dispensing Strategy with Frozen Fruit Preservation

Step 1
Machine is Stocked with Frozen Fruit
Step 2
Frozen Fruit is stored and kept frozen in machine
Step 3
Dispense Controlled Amount of Frozen Fruit from Storage
Step 4
Convert Frozen Fruit into Smoothie

Table 12. Dispensing Strategy with Powdered Dried Fruit Preservation

Step 1
Stock Machine with Freeze Dried Fruit Powder
Step 2
Freeze Dried Fruit Powder is stored and kept dry in Machine
Step 3
Controlled amount of Freeze Dried Fruit Powder is Dispensed
Step 4
Freeze Dried Fruit Powder is added to "snow" made from a snow machine module within Smoothie Machine
Step 5
Through mixing of Freeze Dried Fruit Powder and snow create smoothie

Table 13. Dispensing Strategy with Dried Fruit Preservation

Step 1
Whole or Sliced Dried Fruit is added to Machine
Step 2
Controlled amount of Dried Fruit is dispensed from storage
Step 3
Water (liquid or ice) is added to Dried Fruit
Step 4
Dried Fruit and water mixture is converted into smoothie

2.4 Justification of Method for Dispensing Frozen Fruit Ingredients

After it was decided that the fruit should be frozen for preservation and best taste during storage, it became important to develop a means to dispense a frozen fruit puree in a controlled and energy efficient manner. This, it turns out, was a non-trivial task because of the high adhesion forces that would arise between the frozen fruit and its container wall.[ii] There was a high risk that the frozen fruit would require too much force to be pushed out of its container. This high risk was an early indication that a module for dispensing frozen fruit ingredients would be the most critical module of the FruziFridge. Several concepts were considered in order to solve this problem. The following four concepts are presented because they give a sense of the spectrum of ideas that were conceived to tackle the design problem of a frozen fruit dispenser.

Simple Ram Concept

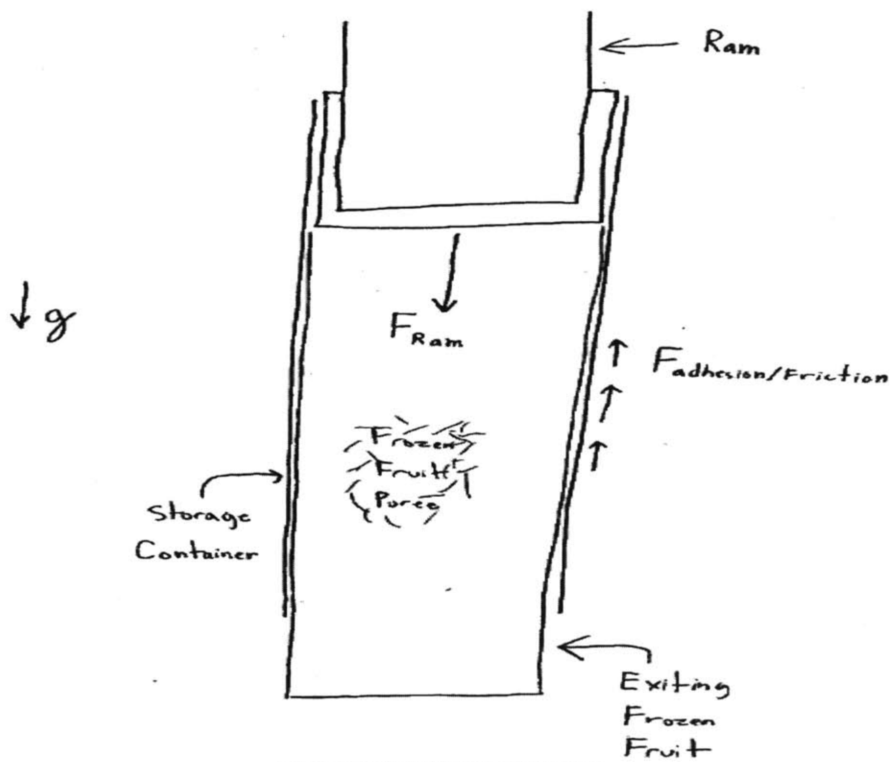


Figure 2 Simple Ram Concept

Table 14. Simple Ram Concept FRDPARRC

Functional Requirement
Drive controllable amount of frozen fruit out of container
Design Parameters
Ram drives plate and pushes frozen block of fruit out of container
Analysis
Thrust force generated by ram must overcome adhesion forces/friction at walls
References

Direct Extrusion
Risks
Friction/Adhesion between container wall and fruit is too high causing jam.
Counter-Measures
Apply high hertz contact stress along container wall so fruit directly underneath container wall is yielded to failure and adhesion interface is destroyed

Simple Ram Concept with Hertz Contact Stress Applicator

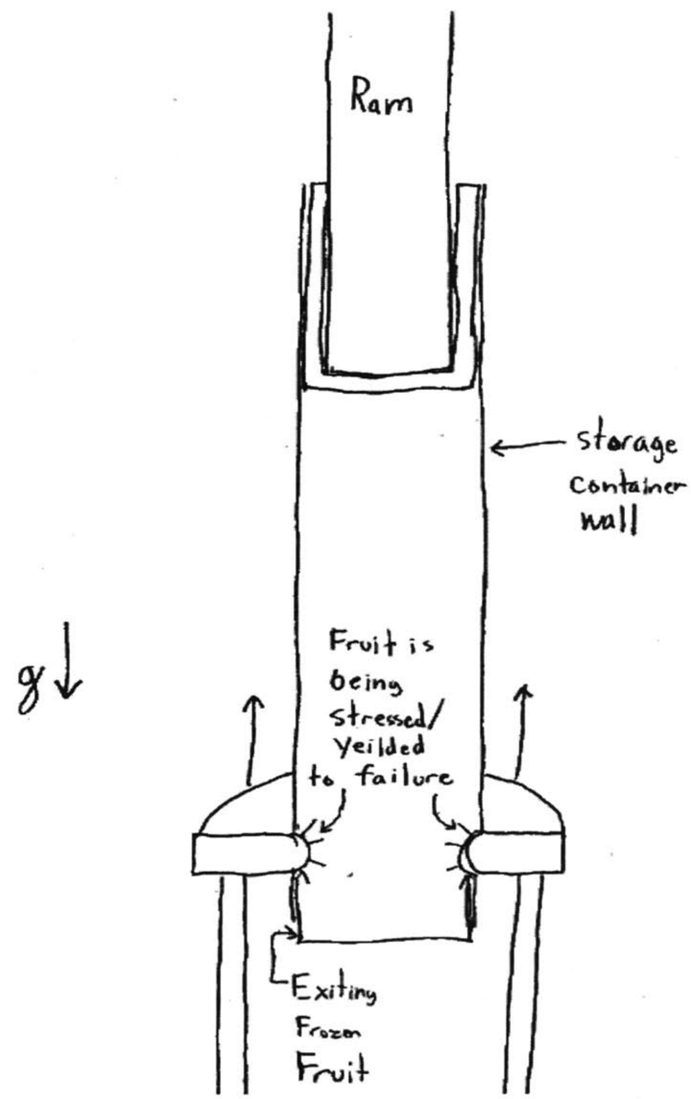


Figure 3 Simple Ram Concept with Hertz Contact Stress Applicator

Table 15. Simple Ram with Hertz Contact Stress Applicator Concept FRDPARRC

Functional Requirement
Drive controllable amount of frozen fruit out of container
Design Parameters
1) Hertz Contact Applicator chokes container applying contact stress as it slides

up fruit container 2) Fruit below container wall is yielded to failure destroying adhesion interface between fruit and container wall 3) Now much easier for ram to push fruit out of container
Analysis
1) Amount of stress required to yield frozen fruit 2) Friction force between contact stress applicator and container wall
References
1) Direct Extrusion 2) Zipper
Risks
1) The friction between the hertz contact stress applicator and container wall is excessively high 2) Lubricant could seep into fruit and become inadvertent food additive
Counter-Measures
1) Apply lubricant on outside of container wall to reduce friction 2) Lubricant should be non-toxic, edible, and preferably organic

Gumball Concept

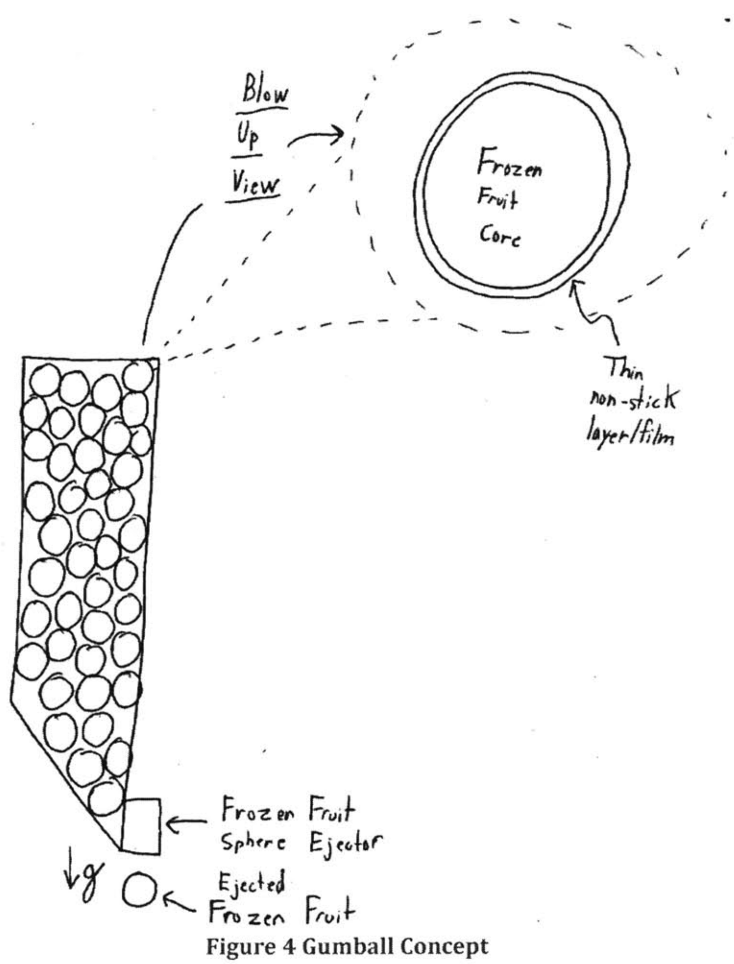


Figure 4 Gumball Concept

Table 16. Gumball Concept FRDPARRC

Functional Requirements
Dispense Controlled Amount of frozen fruit spheres from container
Design Parameters
1) Frozen Fruit spheres are coated with an edible substance that keeps the balls from sticking too each other 2) Ejector dispenses individual frozen fruit spheres which fall into blending compartment
Analysis
There is a lot of wasted space in container in between frozen fruit spheres
References
1) Gumballs 2) Gumball Machine
Risks
Spheres jam at dispense/eject location
Counter-Measures
Something to hit ejector location and shake loose any sphere that get stuck

Indirect Extrusion Concept

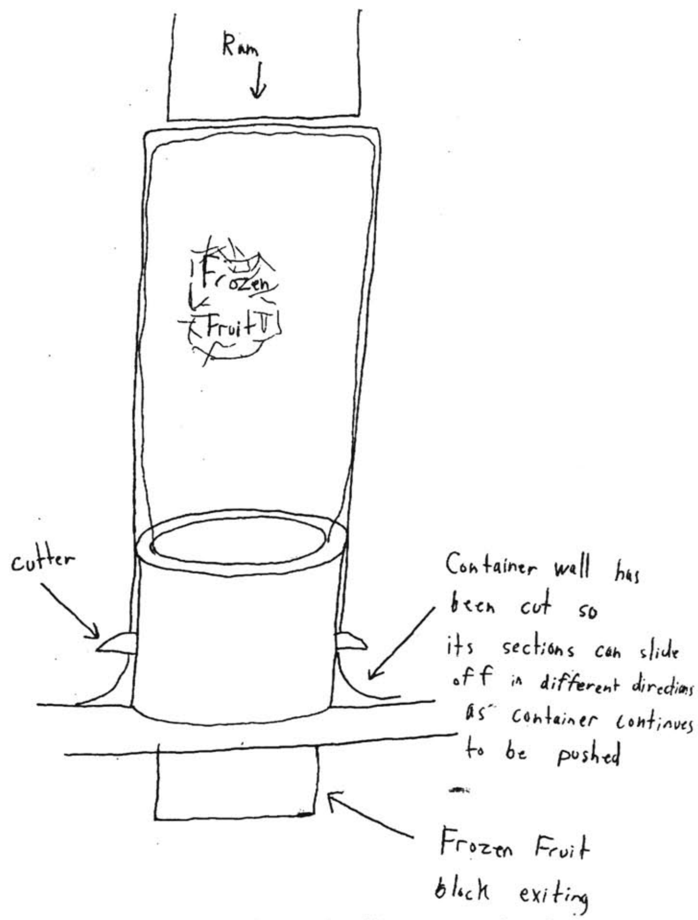


Figure 5 Indirect Extrusion Concept

Table 17. Indirect Extrusion Concept FRDPARRC

Functional Requirements
Expose/remove frozen fruit from a container using minimal force and energy
Design Parameters
1) Fruit container and frozen fruit mass move together. 2) Frozen Fruit mass is pushed out as container walls are peeled away leaving frozen fruit exposed. 3) Cutting tool to separate container walls and allow walls to separate and slide in different directions
Analysis
Don't have to overcome adhesion forces with wall since fruit and container wall move together/ have to relative motion to each other.
References
1) Indirect Extrusion

Risks
1) Frozen Fruit Puree has to deform to enter the die as the container wall is being cut. If the yield strength of frozen fruit is high then even mild cross-sectional area reductions in frozen fruit will require excessive force. See Appendix A for more information. 2) Fruit is left in extrusion die channel it can adhere to die wall over time leaving us with our original adhesion problem.
Counter-Measures
Use Banana Peel Concept

Banana Peel Concept

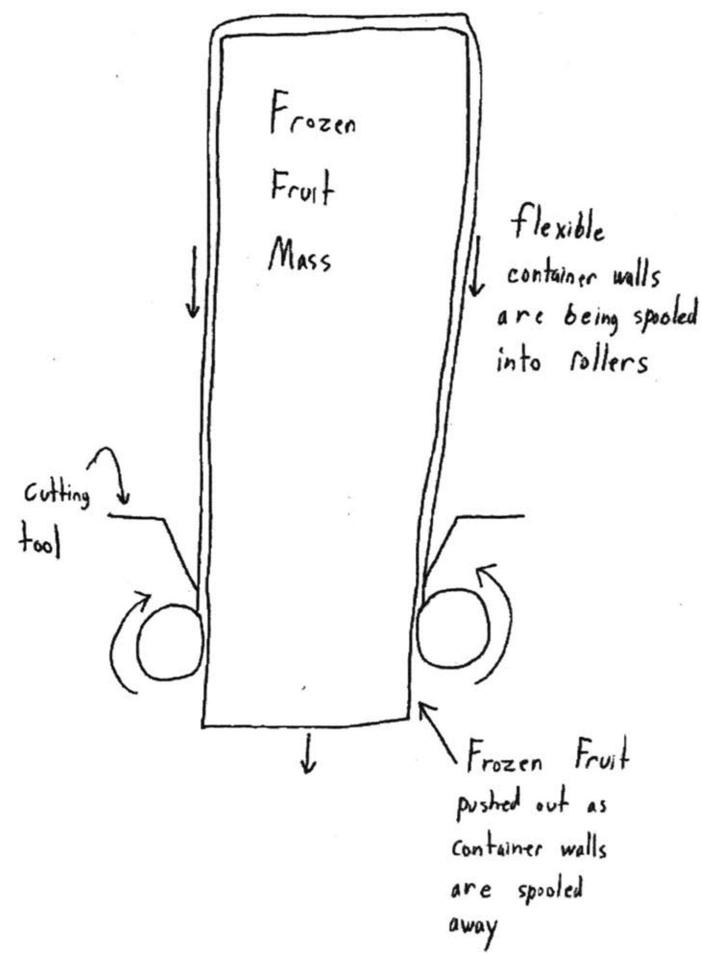


Figure 6 Banana Peel Concept

Table 18. Banana Peel Concept FRDPARRC

Functional Requirements
Expose/remove frozen fruit from a container using minimal force and energy
Design Parameters
1) Rollers rotate pulling in flexible container/spooling in flexible container walls away from frozen fruit mass

2) Frozen Fruit mass is pushed out as container walls are peeled/spooled away leaving frozen fruit exposed. 3) Cutting tool to separate container walls and allow walls to spool unto separate rollers
Analysis
Relative to simple ram concept, this reduces the energy required to eject fruit.
References
1) Peeling Banana
Risks
Frozen Fruit thaws and slips out of container
Counter-Measures
Turn apparatus up side down.

A Pugh chart like the one in table 19 was used to identify the most viable concept for designing a successful frozen fruit dispenser.

Table 19. Pugh Chart for Dispensing Frozen Fruit from Container Concept

Concept	Energy Efficient/Low Forces Involved with Process	No Food Additives	Total
Simple Ram Extruder	0	0	0
Ram Extruder with Hertz Contact Applicator	1	-1	0
Gumball Concept	2	-1	1
Indirect Extrusion Concept	0	1	1
Banana Peel Concept	2	1	3

The banana peel concept was found to be the most viable concept for designing a successful frozen fruit dispenser for the smoothie machine.

2.5 Justification of Method for Converting Fruit Ingredients into Smoothie

The last major conceptual design decision to be made was, of course, the mechanism that converts the frozen fruit that was dispensed from its container into an actual smoothie. The following two concepts were the most promising.

Blender Concept

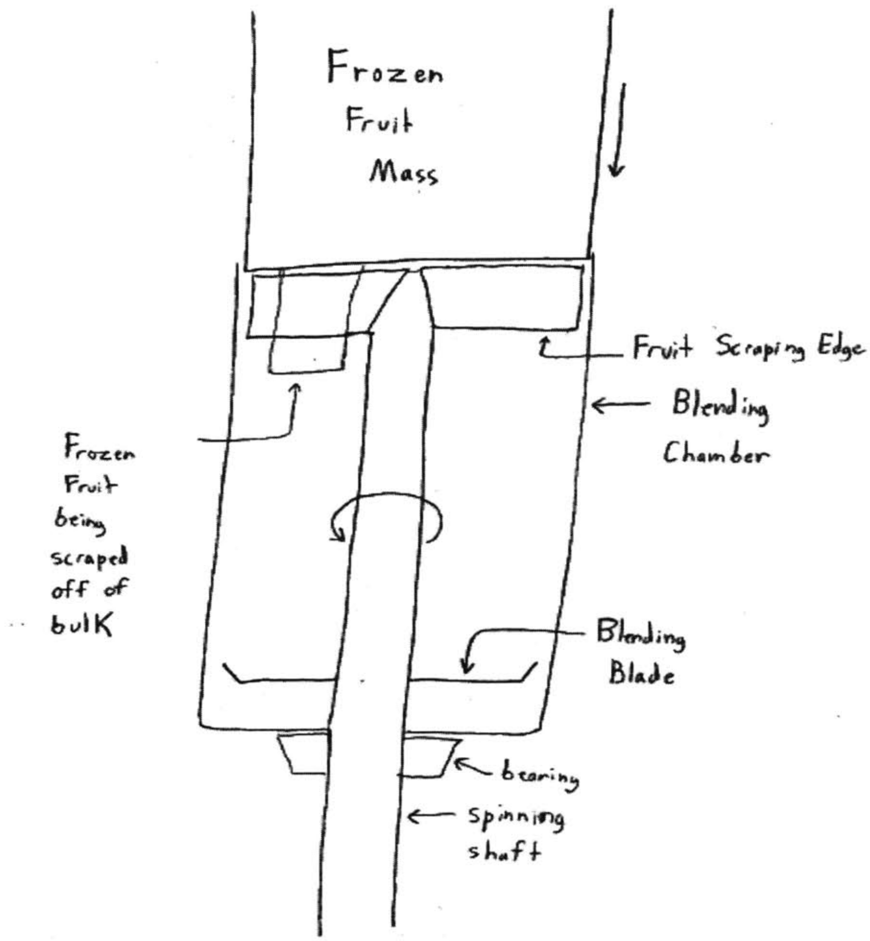


Figure 7 Blender Concept

Table 20. Blender Concept FRDPARRC

Functional Requirements
Convert Frozen Fruit in Smoothie
Design Parameters
Spinning Blade cuts and indirectly heats frozen fruit caused by shearing of contents in flow
Analysis
Torque required to blend
References
Conventional Blender
Risks
Residual smoothie will sit in blender and act as growth site for microbes.
Counter-Measures
Blender will be cleaned after each use.

Extrusion Die Concept

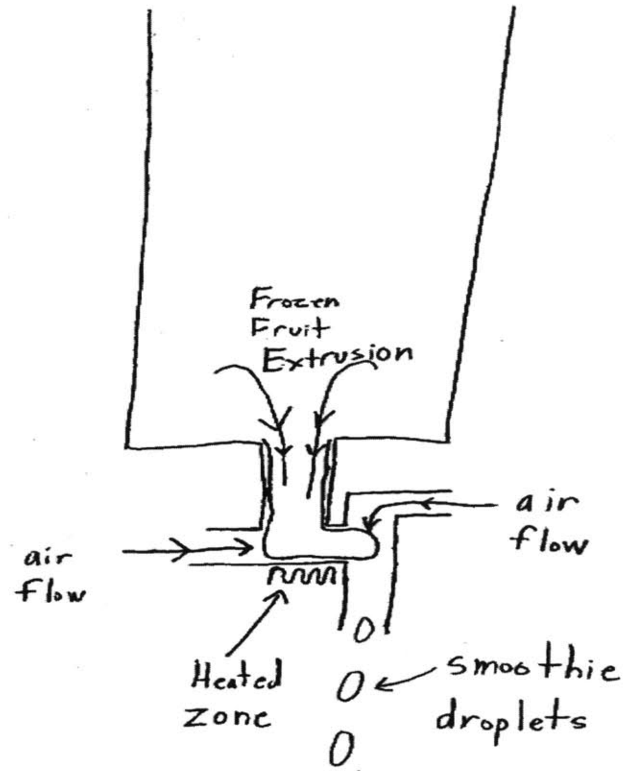


Figure 8 Extruder Die Concept

Table 21. Extruder Die Concept FRDPARRC

Functional Requirements
Convert Frozen Fruit in Smoothie
Design Parameters
1) Frozen fruit is deformed into die. 2) Frozen fruit forms thin column, which is easy to heat with heating wire. 3) Frozen pureed fruit liquefies. 4) Airflow is used to break up/cut continuous stream of pureed fruit to form smoothie.
Analysis
1) The amount of surface area that is exposed 2) Pressure required to drive fruit smoothie through die. 3) Viscosity of fruit smoothie 4) Heat required to thaw frozen fruit ingredients.
References
Extrusion
Risks
1) Residual smoothie will sit in die and act as growth site for microbes. 2) High Force Required to extrude frozen fruit. See Appendix A for more

information.
Counter-Measures
1) Die will be cleaned after each use. 2) Must use Blender Concept.

The Pugh chart in table 22 was used to identify the most viable concept for converting the frozen fruit into a smoothie.

Table 22. Pugh Chart for Converting Fruit into Smoothie Concept

Concept	Energy Efficient/Low Forces Involved with Process	Cleanable or Low surface area in contact with thawed fruit	Total
Blender Concept	0	0	0
Extrusion Die Concept	-2	1	-1

The blender concept was found to be the most viable concept for converting frozen fruit into a smoothie. I was pretty disappointed by this because I was excited about the extrusion die concept. The extrusion die would have had much less surface area to clean compared to a blender. Nevertheless, it was best to use the blender concept to liquefy the frozen fruit into a smoothie.

Chapter 3

Detailed Engineering and Development of Most Critical Module

In chapter 2, it was already mentioned that the module for dispensing frozen fruit ingredients from their containers would be the most critical module of the FruziFridge. More than any of the other modules that are conceived during the strategy and concept phase of design, the most critical module or MCM possess a combination of two attributes:

1) There is a high level of risk that the design for the module will not fulfill its functional requirements. This can happen because something intrinsic to the system being designed is somehow opposing the function of the design. This can also happen because the engineer is designing a system with a physical mechanism she that is not fully understood yet or with an important physical property that is difficult to measure or quantify.
2) The module is central to the fundamental design of the machine. That is, if the module didn't work there would have to be significant changes made to the design of the whole machine in order for it to fulfill its functional requirement or, worse, the machine, even with an altered design, can not fulfill its functional requirement with the technology and resources readily available.

In the case of the design of this smoothie machine, the module for dispensing frozen fruit ingredients is the MCM for two reasons:

1) The adhesion forces between the frozen fruit and the frozen fruit storage container walls are high and prevent the frozen fruit from simply being pushed out.
2) It is central to the design of the smoothie machine. If there is no reliable way to dispense frozen fruit from its container without the use of excessive force then the smoothie machine can longer involve freezing fruit to fulfill the functional requirement of extending the life of the fruit. The design would have to incorporate a new strategy to preserve the fruit.

3.1 Review of Concept for Most Critical Module

Banana Peel Concept

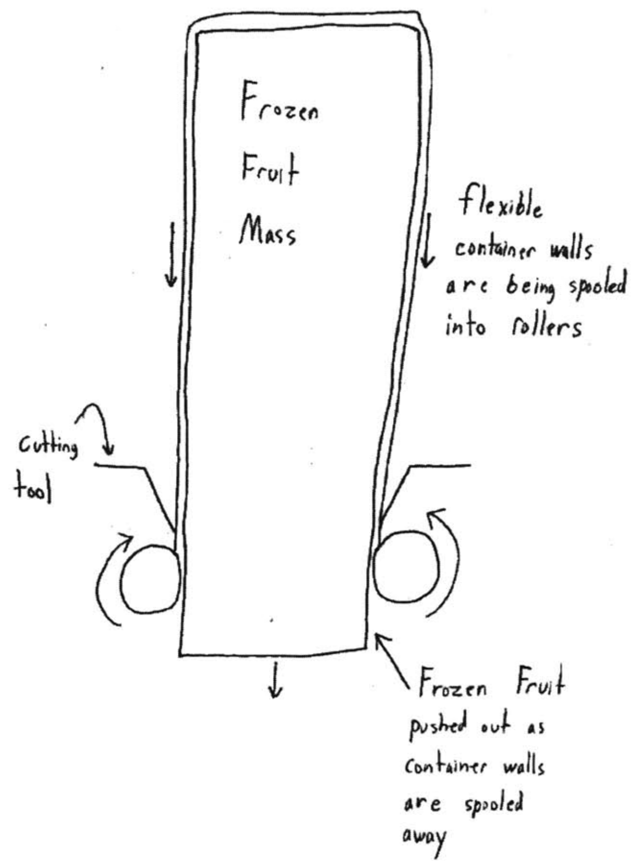


Figure 9 Most Critical Module, Banana Peel Concept

Table 23. Banana Peel Concept FRDPARRC

Functional Requirements
Expose/remove frozen fruit from a container using minimal force and energy
Design Parameters
4) Rollers rotate pulling in flexible container/spooling in flexible container walls away from frozen fruit mass 5) Frozen Fruit mass is pushed out as container walls are peeled/spooled away leaving frozen fruit exposed. 6) Cutting tool to separate container walls and allow walls to spool unto separate rollers
Analysis
Relative to simple ram concept, this reduces the energy required to eject fruit.
References
2) Peeling Banana
Risks

Frozen Fruit thaws and slips out of container
Counter-Measures
Turn apparatus upside down.

3.2 Verification of Feasibility of Cutting Container Wall

3.2.1 First-Order Approximation of Cutting Force

First, in order to begin verifying the feasibility of the cutting a frozen fruit container wall it helps to perform a quick first-order approximation. This is done by relating the force required to cut through a strip of PET (a material of used to manufacture beverage containers) to the shear strength of PET.

To make this first-order approximation, we make the assumption that the PET is being cut because its material is failing in shear as a cutter pushes on it. Looking at figure 10 we can see the area that is directly affected by the cutter. Since the cutter is acting at the surface of the material, Saint Venant's principle suggests that most of the shear stress imparted on the material is supported by a region that extends about 3 cutter diameters deep in the material.

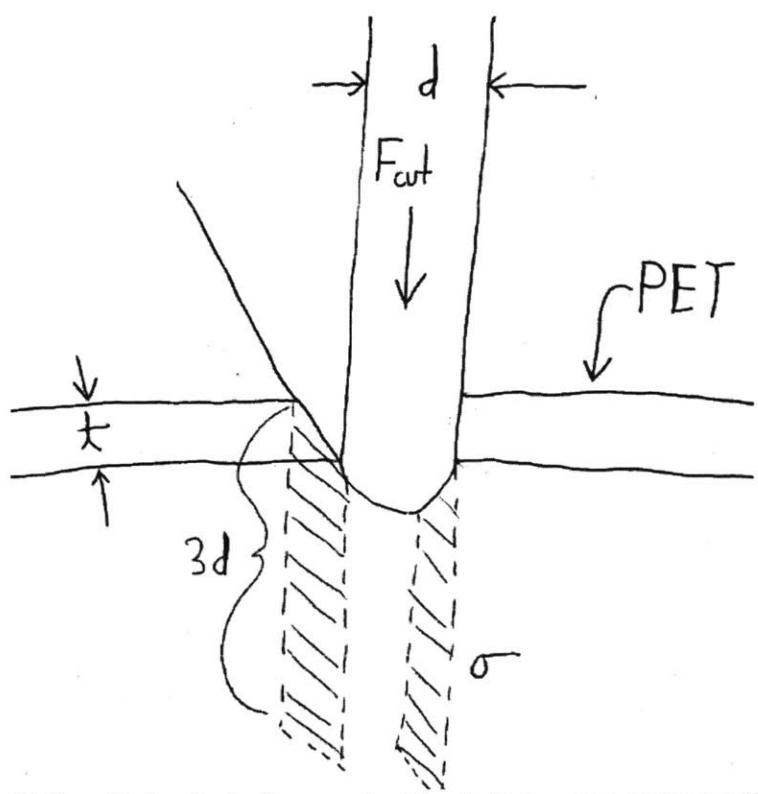


Figure 10 Close Up free body diagram of cutting fruit storage container wall

Since the ultimate shear strength of PET was not readily available at the time the calculation was made it was approximated as $1.5\sigma_{UTS}$, where σ_{UTS} is the ultimate tensile strength of the PET. Thus, based on the geometry of the problem it was predicted that the cutting force,

$$F_{cut} = 2\times(1.5\times\sigma_{UTS})\times t\times(3d).$$

(Eq.1)

This simplifies to,

$$F_{cut} = 9td\sigma_{UTS}$$

(Eq. 2)

Table 24. Important Dimensions for Cutting Force Prediction

Thickness, t	3.05 x 10^{-4} m (0.012 in)
Diameter of cutting Edge, d	2.2 x 10^{-3} m (0.085 in)
Ultimate Tensile Strength of PET, σ_{UTS}	22 MPa

Given the information in table 24, then F_{Cut} = 130 N. It is fair to suspect that 130 N is an overestimation and that the measured value of F_{Cut} will be smaller than this value simply because the calculation:

1) probably overestimates the shear strength of PET
2) does not take into account the stress concentration at the point of cutting will probably weaken the material
3) only takes into account one component of stress that arises in the PET strip to predict when fracture will occur.

3.2.2 Measurement of F_{Cut}

Table 25. Cutting Force Experiment

Material: PET	
Average Thickness of Material: 3.05 x 10^{-4} m	
Diameter of cutting edge of cutting tool: 2.2 x 10^{-3} m	
Temperature: 24.4°C	
Approximate Speed/Rate of Cut (m/s)	Max Measured Force During Cut (N)
0.15	19.4
0.007	14.1
0.005	17.4
0.14	40.1
0.52	23.6
0.83	60.5

3.2.3 Discussion

The experiment confirmed the first-order analysis derived prediction that F_{Cut} of PET of that particular geometry and that particular cutting tool geometry would be less than 130 N. The experiment also revealed the rate-dependence of F_{cut}.

3.3 Verification of Feasibility of Peeling Container Wall

The banana peel concept drastically reduces the energy and force required to remove frozen fruit from its container because it eliminates the need for the whole frozen fruit to slide or shear past the container wall. This is highly effective since the shear strength of the whole adhesion interface is very high. Instead, the container wall is literally being peeled off of the fruit. It, thus, becomes important to make sure that the peeling forces are not too high. All of the background for peeling theory is presented in appendix B, along with experimental results. A short calculation based on the information in the appendix is presented below to show the feasibility of peeling the container wall off from the fruit.

3.3.1 Calculating Peel Force

The peel force per unit width is given by

$$P = \frac{W_s}{1-\cos\Theta} \qquad \text{(Eq.3)}$$

where W_s is the work of separation per unit area and Θ is the peeling angle. We are assuming $\Theta = 90°$ and we know that the work of separation for polyethylene coated-freezer paper stuck on frozen pureed strawberries is $W_s = 40.86 \pm 488.3\ J/m^2$. Thus, we can estimate that the peel force per unit width of this system is 530 N/m. This means that even if a polyethylene coated-freezer paper wall were 7.6 mm (3 inches) wide it would only require about 40 N to be peeled. This is an acceptable amount of force.

3.4 Verification of Feasibility of Spooling Container Wall

In order to ensure that spooling the container wall would not require too much energy or torque, a very simple experiment was devised to measure the required torque. The apparatus for this experiment as well as a loaded specimen is shown in figure 10.

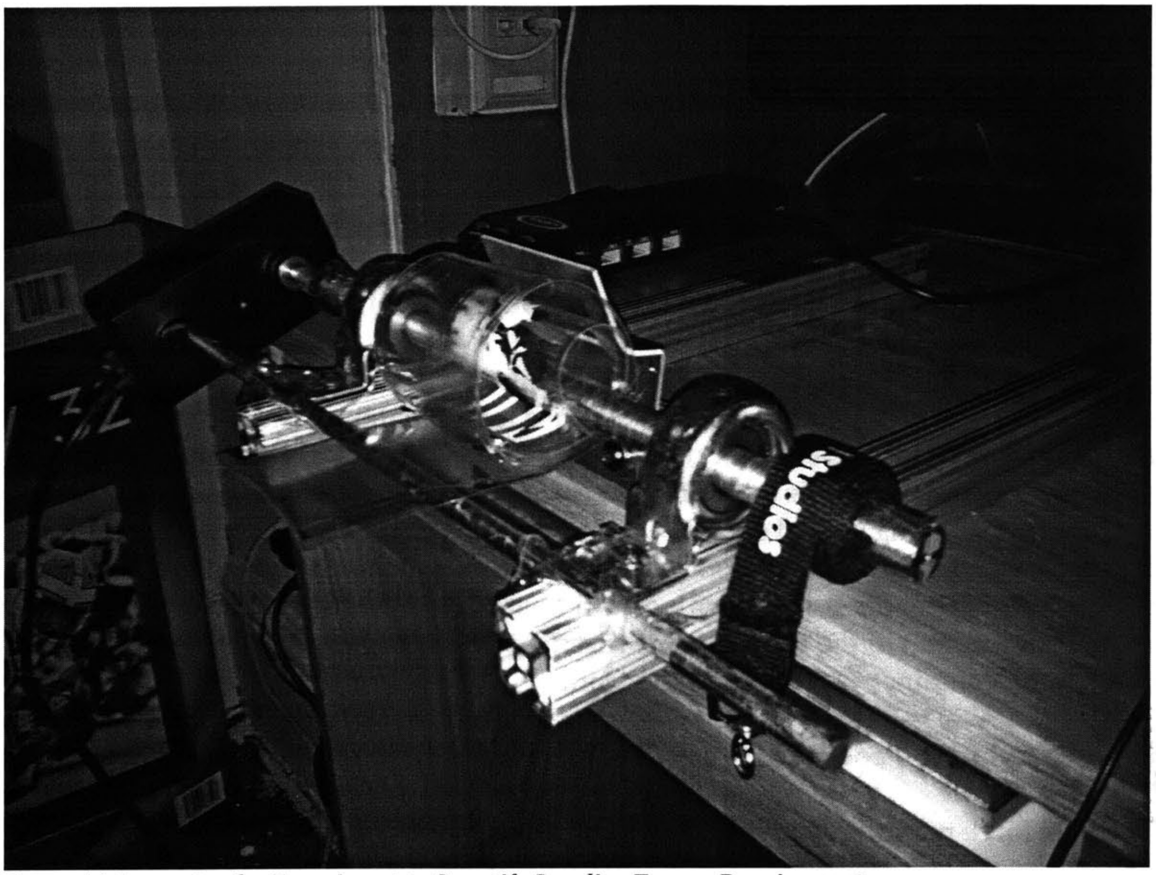


Figure 11 Apparatus for Experiment to Quantify Spooling Torque Requirement

Table 26. Spooling Torque Experiment

Material	PET
Average Thickness of Specimen	5.33 x 10^{-4} m
Average width of Specimen	0.06 m
Unrolled Length of Specimen	0.38 m
Temperature	Room temperature
Measured Torque at Fully Spooled State	0.6 Nm

3.5 Estimation of Torque Requirement for Most Critical Module

Now that we have quantified the torque and force requirements for each of major actions in MCM, we can sum the torques to get the overall torque requirement for implementing the banana peel concept.

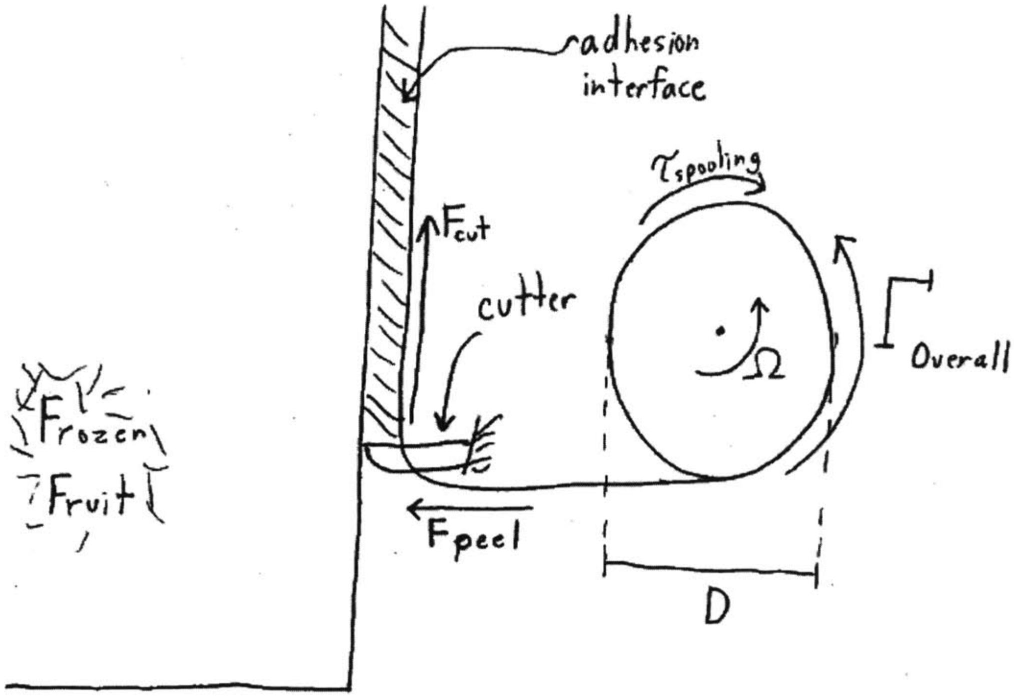


Figure 12 Free Body Diagram of Banana Peel Concept. This only shows one roller peeling off one of the container walls from the frozen fruit.

From the free body diagram in figure 12 we find that the overall torque

$$\Gamma_{Overall} = \tau_{spooling} + \frac{D}{2}(F_{Cut} + F_{Peel}) \qquad \text{(Eq.4)}$$

By setting the diameter, D = 0.0254 m (1 inch) and plugging in the most conservative values found for the cutting and peeling force and spooling torque, we find that the overall torque requirement, $\Gamma_{Overall}$ = 1.9 Nm. This is a very reasonable torque requirement that many small, off-the-shelf motors can fulfill.

Chapter 4

Future Work

The strategy and concept phase and the early stages of the detailed engineering and development phase of this smoothie machine's design have been fruitful. The next step is to continue the detailed engineering and development of the MCM of the smoothie machine so that it's the first module to be completed and tested. Meanwhile, simple bench-top experiments should be devised to verify that the concept for all of the other modules in the smoothie machine are, in fact, as viable as they appeared during the strategy and concept phase. By the end of the detailed engineering and development phase, every most viable concept for each non-critical module should be verified or altered if concept can't actually fulfill its functional requirements in practice.

Appendix A

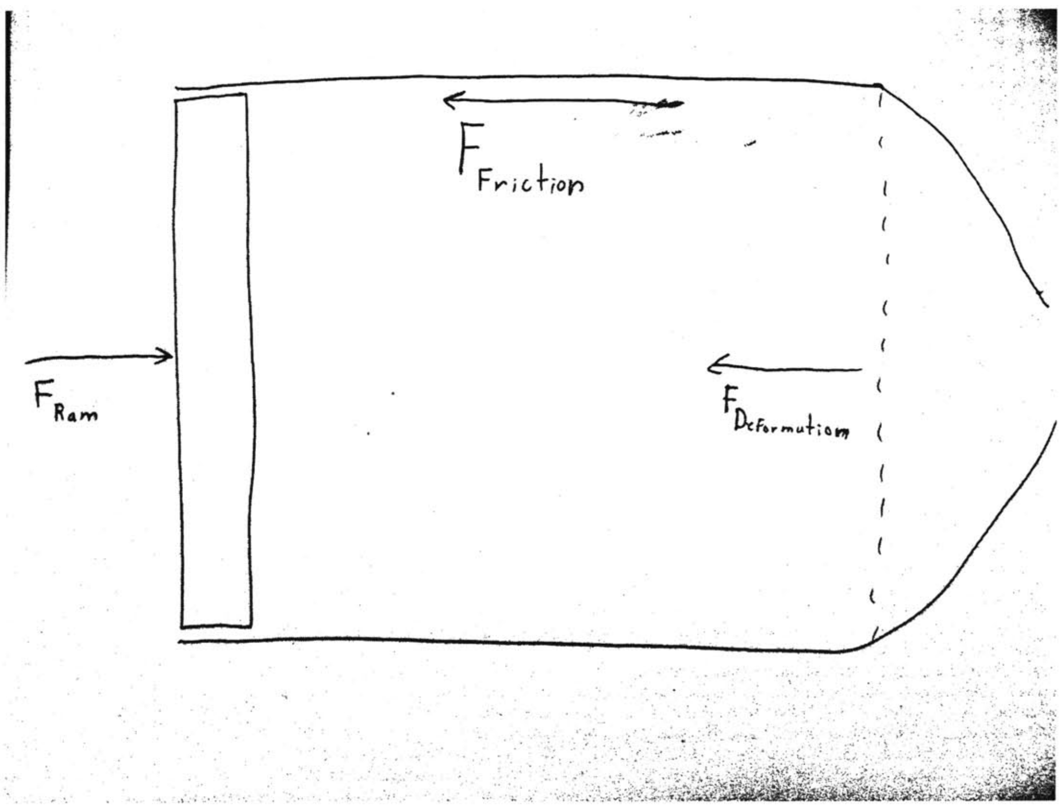
Extrusion of Frozen Fruit Purees

Abstract

A simple ram extruder apparatus was designed to quantify the forces and pressures required to extrude frozen bananas through die with different area reduction ratios.

1. Theory

As depicted in the simple free body diagram, the force the ram must exert on the frozen fruit puree billet is equivalent to the sum of the back force that is generated as a result of the frozen fruit undergoing deformation as it passes through the die and the friction forces of the frozen fruit puree with the extruder walls.



Thus,

$$F_{Ram} = F_{Deformation} + F_{Friction}$$

An extremely accurate expression for $F_{Deformation}$ could be quite involved because of the complicated flow field that develops as the fruit puree is squeezed through the die. In order to simplify this expression and achieve a first-order estimate, $F_{Deformation}$ was modeled as the force required to elongate the frozen fruit puree as its cross-sectional area is reduced passing through the die. Saving a derivation that can be found in literature,

$$F_{SimpleDeformation} = A\sigma_Y \ln\left(\frac{A_0}{A}\right)$$

(Eq. 1)

where A_I is the original cross-sectional area of the frozen fruit puree at the closed end of the extruder, A is the final cross-sectional area of the fruit puree at the die exit of the extruder, and σ_Y is the yield stress of the frozen fruit.[iii] The quantity $\frac{A_0}{A}$ is known as the area reduction ratio.

A very accurate expression for $F_{Friction}$ could also be quite involved. Since friction forces tend to be much smaller than deformation forces in extrusion, we will neglect the friction forces.

Thus, using first-order methods we find that

$$F_{Ram} = A\sigma_Y \ln\left(\frac{A_0}{A}\right).$$

(Eq. 2)

This, of course, means that the amount of pressure experienced by the ram as it pushes out the frozen fruit will be

$$P_{Ram} = \frac{A}{A_0}\sigma_Y \ln\left(\frac{A_0}{A}\right).$$

(Eq. 3)

2. Experimental Apparatus

In order to test the theory laid out in section 1 a simple ram extruder was constructed from a pipe and pipe cap. The ram that fit into the extruder was also made to connect to an Instron machine so force measurements could be taken.

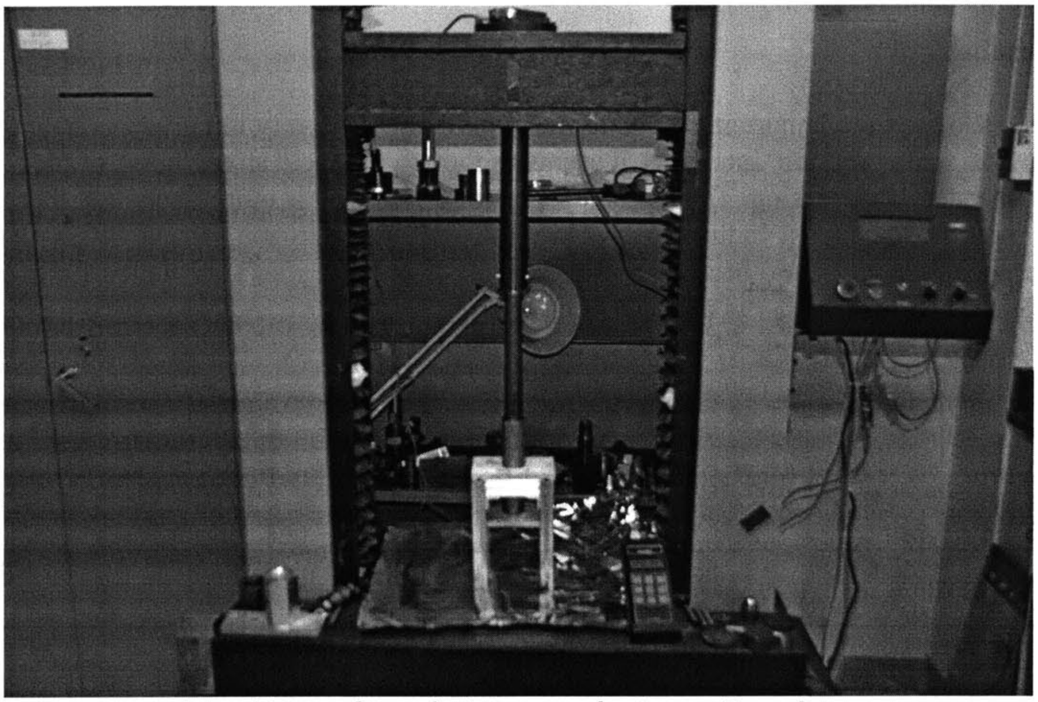


Figure 13 Ram of Extruder is connected to Instron Force Gauge.

In order to test the effects of different area reduction ratios on the amount of force required to extrude the frozen fruit, different dies were designed so they could be inserted and removed from the extruder pipe cap.

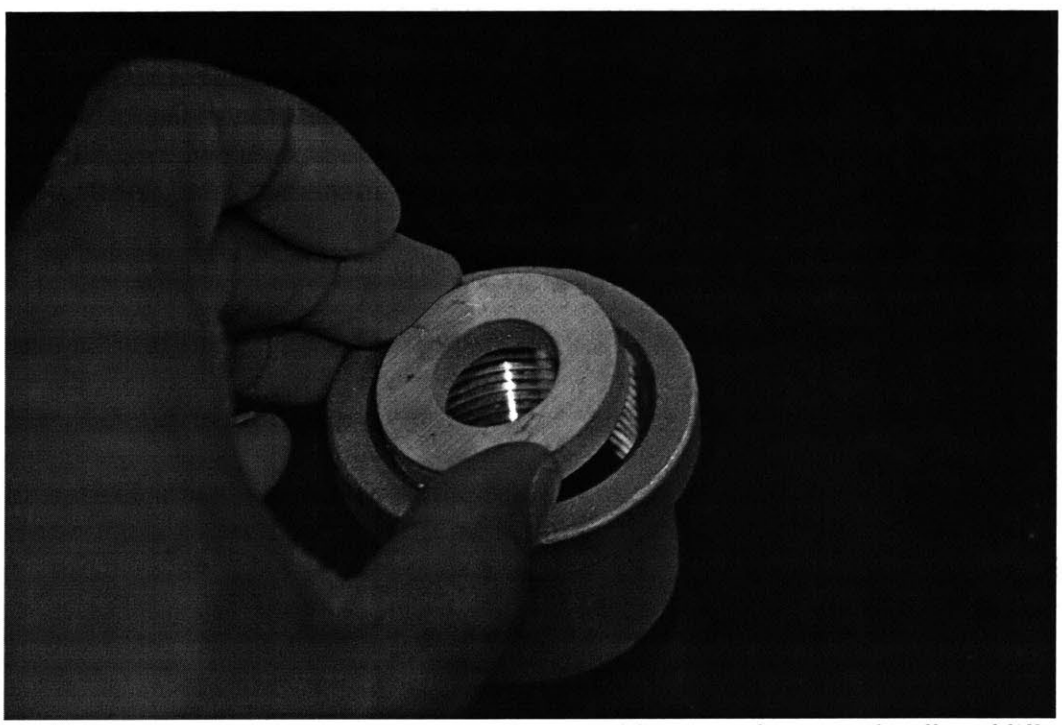


Figure 14 Extrusion die inserts can be inserted and removed from extruder cap so the effect of different area reduction ratios on extrusion forces can be tested.

3. Results

Table 1 shows some important results of the experiment. It is very important to note that as the area reduction ratio increases, it seems as though the yield strength, σ_y, of the frozen banana is increasing. This, of course, is not the case. It is more likely that there is a disproportionate increase in the force required to extrude the frozen banana with a much higher area reduction ratio because of the complex flows that aren't accounted for in our simple model.

Table 1.

Die	A_0	A	A_0/A	Pressure	Force	Effective σ_y
1	9.6×10^{-4} m^2	2.85×10^{-4} m^2	3.37	11.7 MPa	11200 N	32 MPa
2	9.6×10^{-4} m^2	3.2×10^{-5} m^2	30	15.2 MPa	14600 N	100 MPa

4. Design Conclusions

Despite simplifications made in the model and the crudeness of the experimental setup, one thing is still certain: it takes an excessive amount of force to push frozen fruit through a die that has even a small reduction ratio. Thus, when designing the smoothie machine strategies or concepts that involve extrusion dies or pushing frozen fruit through a reduced area should be avoided.

Appendix B

Determining Work of Separation of Freezer Paper/Frozen Substrate Systems

Abstract

The peel test was used to determine the work of separation (energy per unit area) between polyethylene-coated freezer paper and various frozen substrates (ice, frozen pureed bananas, and frozen pureed strawberries). The forces were measured using an electronic force gauge that peeled the polyethylene coated side of the freezer paper samples away from the frozen substrates at a 90° angle above horizontal. The peel force per unit width, P, or work of separation per unit area, $W_s = 7.48 \pm 2.53$ J/m^2 for a freezer paper/ice system. The peel force per unit width, P, or work of separation per unit area, $W_s = 40.86 \pm 488.3$ J/m^2 for a freezer paper/ frozen pureed strawberry system. The peel force per unit width, P, or work of separation per unit area, $W_s = 9.526 \pm 370.5$ J/m^2 for a freezer paper/ frozen pureed banana system.

1. Introduction

This experiment was driven by the need for data regarding the forces and work required to separate freezer paper from various frozen fruit purees and in order to inform the design of a smoothie vending machine. The results, althought not precise, suggest the viability of the design concept for the most critical module of the vending machine that is being investigated.

The work of separation (energy per unit area of interface) between polyethylene-coated freezer paper/frozen substrate systems was determined by using a electronic force sensor to measure the force necessary to peel the freezer paper off of the frozen substrates and digital calipers to measure the width of the peel zone. Assuming peel direction is $\varphi = 90$, the work of separation, W_s, is given by

$$W_s = P \qquad (1)$$

where P is the peel force per unit width length, L_p.

A more comprehensive explanation of peel test theory is given in section 2. The experimental setup is discussed in section 3. The experimental results are presented in section 4. In section 5, conclusions are drawn.

2. Background

2.1 Why Test Freezer Paper

The motivation of this experiment is to determine the force and work necessary to separate a frozen fruit puree from its container walls. Of course, there were several possible materials that could have been chosen to represent the container walls in the experiment. Freezer paper was chosen because it is coated with polyethylene. Hydrophobic materials like polyethylene are known to have very low strength adhesion interfaces with ice compared to hydrophilic materials or materials that interact neutrally with water such as metals. The low adhesion of the freezer paper/frozen substrate system is desirable in order to reduce work and power consumption in the vending machine. Also, freezer paper has the advantage of being easy to manufacture and, as a result, is low in cost.

2.2 The Peel Test: Overview

The peel test is used to measure the interface toughness between a film and a substrate by measuring the peel force per unit width, P, required to peel the film separate from the substrate. In this experiment, the film is the freezer paper and ice, frozen pureed bananas, or frozen pureed strawberries are the substrates.

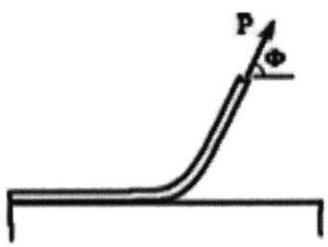


Figure 15 The Peel Test[iv]

2.3 Mechanisms of Peeling

The process involved in peeling is not too complicated. It is important, however, to specify each mechanism in the peeling process. Figure 16 will be used to help describe these mechanisms.

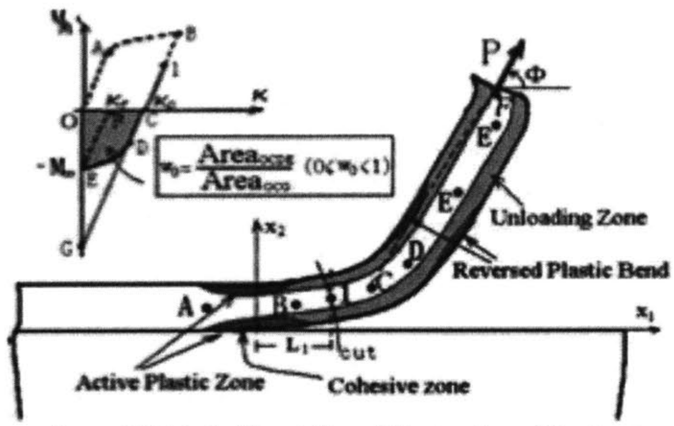


Figure 16 Detailed Depiction of Mechanism of Peeling[v]

2.3.1 Adhesion at Interface

The adhesion, found in the cohesive zone labeled in figure 16, must be overcome in order to separate the film from the interface. The total adhesion at an interface can be the sum of several contributions, such as Van der Waals forces, electro-chemical forces, etc. When enough peel force per unit width, P, is applied to the film, the adhesion is overcome and the film peels back in the direction of the force.

2.3.2 Elastic Deformation

When the peel force, P, is applied to the film both the film and the substrate will elastically deform. Through elastically deforming the adherents the peel force is transferred to the interface or cohesive zone where adhesion occurs.

2.3.3 Intrinsic Plastic Deformation

Intrinsic plastic deformation refers to plastic deformation at the interface that actually transmits the peel force to the interface, opposing the adhesion of the film and substrate. For example, if the freezer paper polyethylene adhered to the frozen pureed banana were to plastically deform as a direct result of pulling at the interface then that plastic deformation is intrinsic to the peeling. Intrinsic plastic deformation occurs in the active plastic zone shown in figure 16.

2.3.4 Extrinsic Plastic Deformation

Extrinsic plastic deformation refers to the plastic deformation that occurs away from the interface. For example, this could be the plastic deformation that occurs on the top surface of the film as the film is curled backwards in the direction of the peel force P. This plastic deformation requires force but does not transmit any of that force to the interface. Extrinsic plastic deformation occurs in the reversed plastic bend zone depicted in figure 16.

2.4 Peeling Conditions

Peeling occurs in two major regimes. Peeling is elastic when an overwhelming majority of the deformation that occurs is elastic. Peeling is elastic-plastic when there is a significant amount of extrinsic plastic deformation occurring along with the elastic deformation.

2.4.1 Elastic Condition in Peeling

In the elastic condition the film and substrate are rigid compared to the adhesive interface. Under these conditions, the work of separation, W_s, correlates to the intrinsic adhesion energy, Γ_o, that previously held the interface together. That is, almost all of the force or work of separation that goes into the film/substrate system is seen by the adhesive interface. Thus,

$$W_s = \Gamma_0 \tag{2}$$

It is important to note that in elastic conditions small amounts of intrinsic plastic deformation also occur but it transmits work to the interface.

2.4.2 Elastic-Plastic Condition in Peeling

In the elastic-plastic condition the film and substrate are ductile compared the adhesive interface. As a result a considerable amount of extrinsic plastic deformation occurs. This extrinsic plastic deformation contributes significantly to the work of separation, W_s, since the peel force must now be used to plastically deform the film or substrate as well as to overcome the adhesive forces at the interface. Under the elastic-plastic conditions,

$$W_s = \Gamma_0 + \Gamma^P \tag{3}$$

where Γ^P is the plastic dissipation energy.

2.4.3 Determining Peeling Conditions

To determine whether the conditions for peeling are elastic or elastic-plastic investigate the ratio of the strain energy in the film per unit area to Γ_0. This ratio, α, is modeled by

$$\alpha = \frac{P}{2Et} \tag{4}$$

where E is the Young's modulus of the film, and t is the thickness of the film. Conditions are elastic when the film and substrate are rigid compared to the interface. In other words, the ratio of strain energy should be low compared to Γ_0. Thus, conditions are elastic when α is much smaller than unity. In contrast, the larger α gets the more elastic-plastic the peeling process.

2.5 Peeling Angle

The angle at which P peels the film affects the work of separation, W_s, that the peel force P is imparting into the system. The relationship between the peel force, P, the peel force direction angle, ϕ, and the work of separation W_s is given by

$$P(1 - \cos\phi) = W_s \tag{5}$$

3. Measuring Work of Separation

The peel force required to separate the freezer paper from its frozen substrate was measured using a Vernier Dual Range Force Senor. Digital calipers where used to measure the width of the peel zone for each sample.

3.1 Preparing Samples

3.1.1 Ice substrate samples

The following procedure was used to prepare the ice samples. Cold tap water was poured into hand-made aluminum foil trays with different dimensions. Freezer paper was placed with the polyethylene side down on top of the opening of the aluminum trays and pushed down to make contact with the water. The water samples were then placed in a commercial kitchen freezer to freeze.

3.1.3 Frozen Pureed Strawberry Sample

The following procedure was used to prepare the frozen pureed strawberry samples. Ripe strawberries were peeled and dropped into a commercial blender. The strawberries were packed down so the blade could pull the strawberries into the blender's cutting zone. The strawberries were pureed. The pureed strawberries were poured into hand-made aluminum foil trays with different dimensions. Freezer paper was placed with the polyethylene side down on top of the opening of the aluminum trays and pushed down to make contact with the pureed strawberries. The strawberry samples were then placed in a commercial kitchen freezer to freeze.

3.1.2 Frozen Pureed Banana Samples

The following procedure was used to prepare the frozen pureed banana samples. Ripe bananas were peeled and dropped into a commercial blender. The bananas were packed down so the blade could pull the bananas into the blender's cutting zone. The bananas were pureed. The pureed bananas were poured into hand-made aluminum foil trays with different dimensions. Freezer paper was placed with the polyethylene side down on top of the opening of the aluminum trays and pushed down to make contact with the pureed bananas. The banana samples were then placed in a commercial kitchen freezer to freeze.

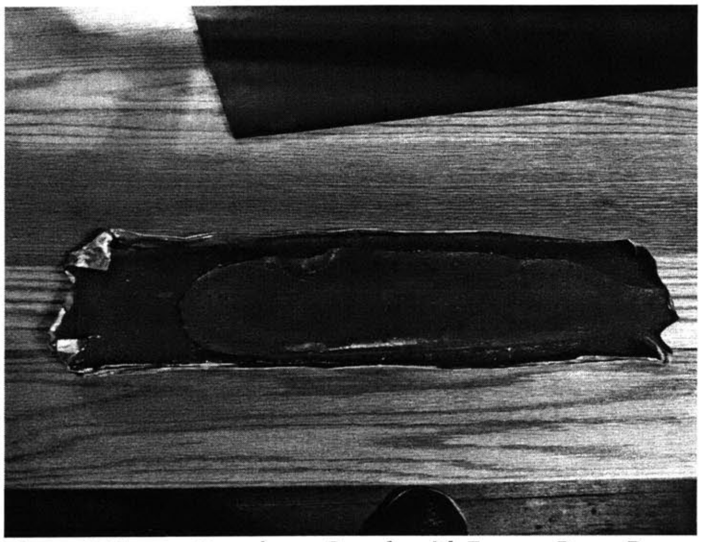


Figure 17 Frozen Strawberry Sample with Freezer Paper Removed

3.2 Testing Apparatus

The testing apparatus was designed to guide the force gauge and samples such that the film was peeled away from the substrate at 90° above horizontal.

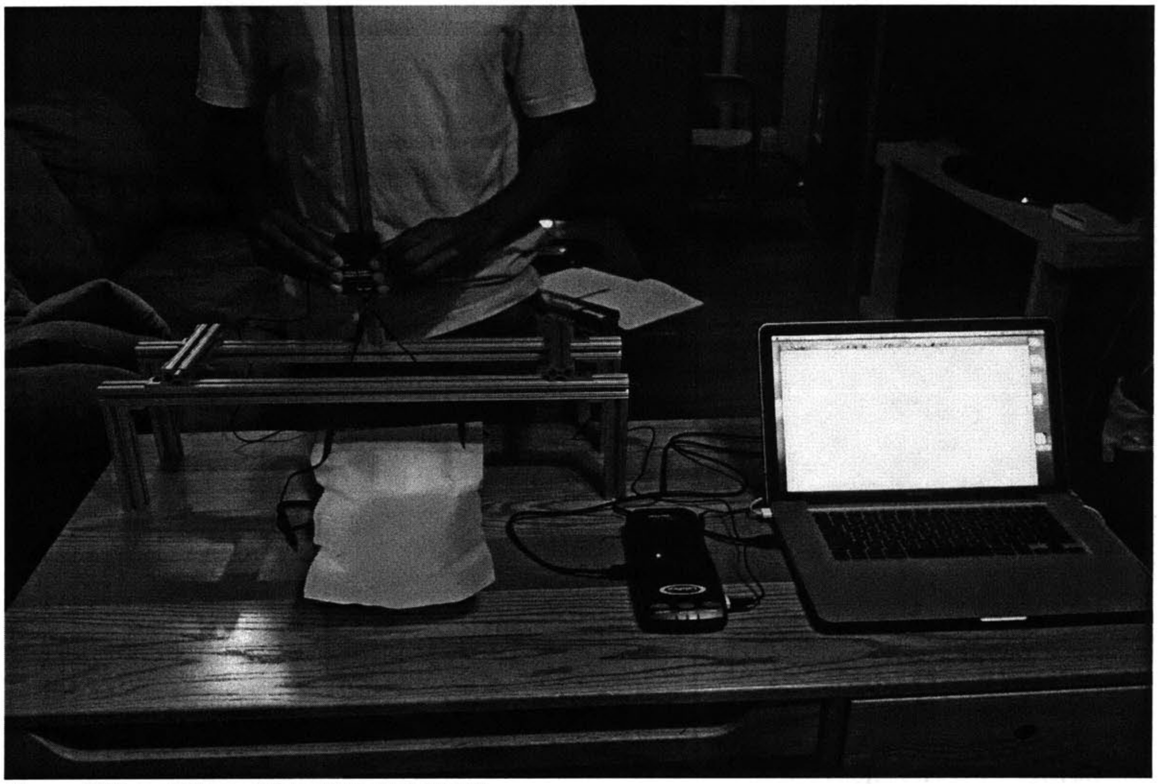


Figure 18 Front View of Experimental Set Up


Figure 19 Side View of Experimental Set Up

4. Results and Discussion

Due to various problems that arose during the experiment, the data collected has low accuracy. If was often difficult to get the freezer paper to peel exactly at 90° above horizontal. This changed the force gauges reading for how much peel force was necessary to separate the freezer paper from the frozen substrates. Another problem was that the freezer paper sometime ran into the apparatus while being peeled upwards. This increased the force gauges reading for the peel force necessary to separate the freezer paper and frozen substrates. For one banana sample, which required a relatively high force to achieve separation, the string connection between the pulling force gauge and the freezer paper broke and had to be repaired during the experiment. This was not ideal since it gave the sample more time to thaw, since the experiments could not be conducted in a freezer. The added thaw time didn't seem to affect the peel force required too much, however. Despite the experiment's failings, the data does succeed in providing an order of magnitude for the forces and work to be expected when separating freezer paper from ice, frozen pureed bananas, and frozen pureed strawberries.

4.1Works of Separation

The peel force per unit width, P, or work of separation per unit area, $W_s = 7.48 \pm 2.53\ J/m^2$ for a freezer paper/ice system.

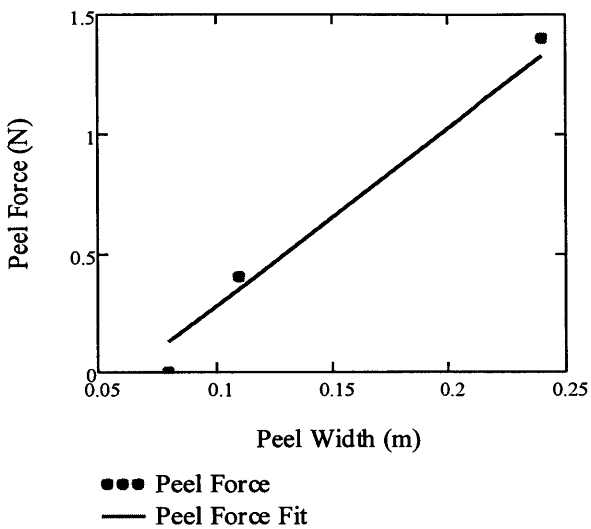


Figure 20 Experimental Results for Freezer Paper/Ice System

The peel force per unit width, P, or work of separation per unit area, $W_s = 40.86 \pm 488.3\ J/m^2$ for a freezer paper/ frozen pureed strawberry system.

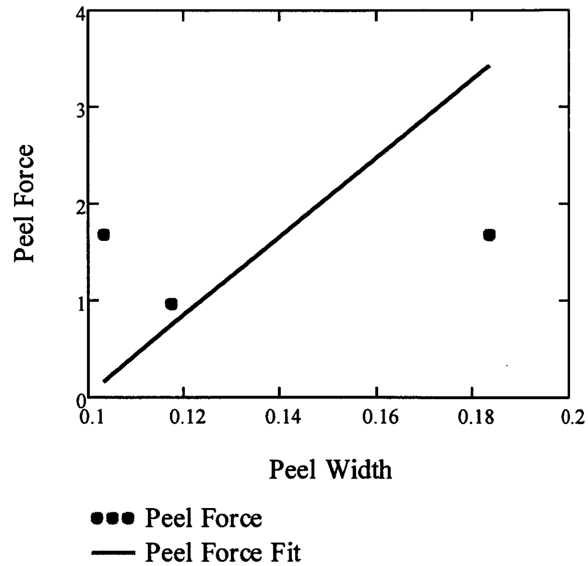


Figure 21 Experimental Results for Freezer Paper/Frozen Strawberry System

The peel force per unit width, P, or work of separation per unit area, $W_s = 9.526 \pm 370.5\ J/m^2$ for a freezer paper/ frozen pureed banana system.

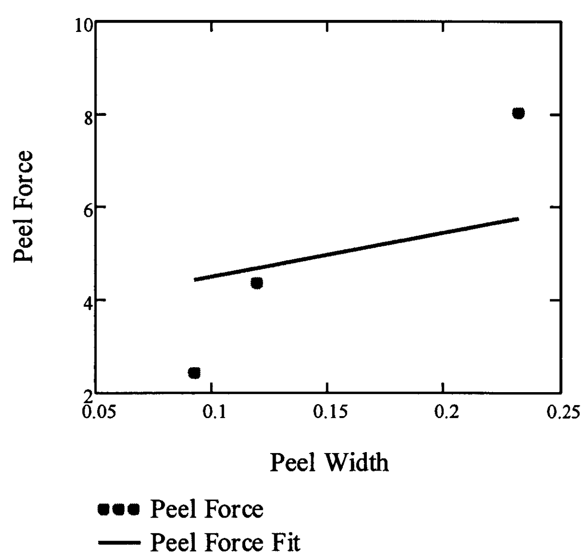


Figure 22 Experimental Results for Freezer Paper/Frozen Banana System

5. Conclusion

The results of this experiment aren't very precise. Still, they give an order of magnitude for the work of separation to be expected for a freezer paper/frozen substrate system. In the future, a more careful experimental setup as well as more sample points will be necessary to generate more precise measurements for the work of separation (per unit area) for the freezer paper/ frozen substrate system.

Despite the lack precision in the experimental results, they still confirm the low adhesion forces of a polyethylene/frozen substrate system. This suggests the feasibility of implementing a certain design concept for the smoothie machine with low power consumption.

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