ANALYSIS OF THE PHYSICAL AND MECHANICAL PROPERTIES OF THE PINE NUT AS CRITERIA IN THE DESIGN OF A PINE NUT SHELLER

A Thesis

by

JESUS MENCHACA LARA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 1996

Major Subject: Agricultural Engineering

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ABSTRACT

Analysis of the Physical and Mechanical Properties of the Pine Nut as Criteria in the Design of a Pine Nut Sheller. (August 1996)

Jesus Menchaca Lara, B.S., Universidad Autónoma Agraria Antonio Narro

Chair of Advisory Committee: Dr. Wayne A. LePori

Among the hundred species of pines, a third are classified as soft pines, largely on the basis of wood and leaf anatomy. Eleven species of soft pine make up the group known variously as the piñon, pinyon, or North American nut pines. *Pinus cembroides Zucc* belongs to this category and is the species used in this study. The seeds of this species form an important part in the diet for humans.

Most pine seeds are presently shelled by hand. Mechanical shelling has been attempted, but the shellers damage the nuts and reduce value of the product. Improved mechanical shelling techniques are needed to provide a quality product at reasonable prices.

The overall goal of this work was to develop information to establish design criteria for applying engineering principles for shelling pine nuts. The scope of the work included measurement of physical and mechanical properties of pine nuts and evaluation of one engineering principle for rupturing the seed shell.

Based on the study of the physical and mechanical properties, design criteria for applying engineering principles for shelling pine nuts were developed. These summarized criteria are: 1) cracking unsoaked seeds with about 8.9% moisture content enhances shattering of shells at rupture, 2) deformations ranging from 0.82 mm to 1.14 mm is required to fracture seeds of different sizes, 3) void spaces differ according to seed size allowing deformation of shell without contacting the nut, grouping seeds in size classifications is needed to minimize nut damage, 4) compression forces to crack seeds of different size range from 159.76 N to 304.69 N, 5) a continuous feed process to crack seeds is needed to obtain adequate shelling, and 6) pine nut shells ruptured and shattered at low loading rates, so impact loading is not necessary for the shelling process.

The engineering principles for cracking nuts were analyzed and a mechanical shelling device using counter rotating rollers for cracking nuts was constructed and tested. Results of the tests showed that the counter rotating roller principle can adequately crack 70% in a continuous shelling method for shelling pine nuts.

ACKNOWLEDGMENTS

The author of this work wishes to express sincere appreciation to Dr. Wayne A. LePori, who served as committee chair and provided academic counseling throughout my degree program. His patience, encouragement, and personal interest made this project a tool that for sure will be useful in the future.

I also would like to express my appreciation to Dr. Rosana Moreira for her guidance during the compression force analysis, her kindness, and friendship. Appreciation is also given to Dr. Ron Lacey for his advice in testing the performance of the prototype, and Dr. Lloyd Rooney who provided his individual expertise in the seed qualification area.

Thanks are expressed to Richard Epting who helped in the construction of the experimental apparatus. Special thanks are given to Alfonso Pérez for his suggestions in writing this work.

This project would not have been possible without the financial support of the Office of Graduate Students at Texas A&M.

Thanks are given to CONACYT (The National Council of Science and Technology of Mexico) for their support for my M.S. program at A&M.

A sincere appreciation to my friends Quiang Zeng, Diptish, Kim, Chang Min, and Ezekiel for their friendship during my stay at A&M.

I want first to dedicate this work to God, who always takes care of me and has filled my life with love and happiness. I also want to dedicate this thesis to my parents, Velia and Jesús María who have always given me their love and patience.

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CHAPTER I

INTRODUCTION

Pines are cone-bearing evergreen trees which have woody seed cones made up of cone scales arranged in spirals around the central axis. The seeds are borne on the upper surface of the cone scales. There are approximately a hundred pine species. About a third of these, among them the pinyons, are classified as soft pines, largely on the basis of wood and leaf anatomy. The wood of the soft pines is usually soft, even-textured, creamy white, and is not good for timber.

Eleven species of soft pines make up the group known variously as the piñon, pinyon, or North American pine tree. Pinyon is the anglicized version of the Spanish piñón, for the edible seeds of these desert conifers. The trees are, in Spanish, pinos piñoneros, or nut-bearing pines. The eleven species of pinyon (piñon) pine are: Singleleaf piñon (*Pinus monophylla*), Colorado piñon (*Pinus edulis Englem*), Mexican piñon (*Pinus cembroides Zucc*), Border piñon (*Pinus dicolor*) , Texas piñon (*Pinus remota Little*), Nelson piñon (*Pinus nelsonii*), Pince piñon (*Pinus pinceana*), Potosi piñon (*Pinus culminicola*), Martinez piñon (*Pinus maximartinezii*), Sierra Juarez piñon (*Pinus juarezensis*), and Johannis piñon (*Pinus johannis*). (Lanner, 1981).

This thesis follows the style and format of the *Transactions of the ASAE.*

Pinyon trees are characterized by edible seeds and short leaves. While the seeds of most species have membranous wings, those of pinyon pines and of a number of other species are unwinged. This wing allows most pines to disseminate their seeds widely by the wind, but the pinyons lack this ability.

The habitat in which they develop is of semi-arid origin. In Mexico, *Pinus cembroides Zucc* is the species for commercial sale of seeds. This pine tree is usually 5-10 m tall, though occasionally reaching 15 m, and 30-60 cm in diameter. The seeds of this pine are dark brown, 13 mm long and 7-8 mm wide; wingless, with a thick hard seed coat 0.5-1.0 mm thick; number per kilogram varies from 2,500- 3,000; and the nut is pink with a nice, delightful flavor. (Niembro, 1986)

In the U.S., the pine nut tree has its natural habitat in the semi arid high lands of Southwestern United States in California, Arizona and New Mexico. In Mexico, this species is found distributed in the Western mountain chain which ranges from the United States border (Arizona and New Mexico) Southward in the states of Chihuahua, Durango, Zacatecas, Aguascalientes and Jalisco. There, its range extends Eastward into the states of Guanajuato, San Luis Potosí, Querétaro and Hidalgo. In the Eastern mountains, its distribution extends from the United States border (Texas) Southward into the states of Coahuila, Nuevo Léon, and Tamaulipas. (Collingwood and Warren, 1974).

While *Pinus cembroides* does not bear heavy yield of seeds each year, usually every second or third year will bring a very heavy yield which forms an important part of the diet for humans as an ingredient for different dishes. According to the United

States Department of Agriculture Forest Service, pine nuts have been staple food for humans and wildlife as early as human signs can be traced. A Spanish explorer botanist named Junipero Serra (1713-1784) was the first to mention the pine nuts in his writings. This seed was important in the diet of the Indian tribes in the Southwest portion of the U.S. and Northern Mexico (Menniger, 1977). However, now they are primarily used in the production of candy, or as an ingredient in cooking, blended in combination with lamb, pork, and fish. They are combined in cakes, puddings, and sauces. Besides the use of pine nuts in cookery, the oil can be extracted and used. It has a high concentration of unsaturated fatty acids (oleic and linoleic acids) and a lower concentration of saturated fatty acids. Since no toxic properties have been observed or reported throughout the time in which the nut of *Pinus cembroides* has been consumed, they can be recommended for human nutrition (Sagrero-Nieves, 1992).

In addition, the pine nuts are harvested and sold in markets. They fill a very important need in the lives of thousands of families that inhabit Mexico´s high, semi-arid lands. When pine nuts are harvested, the quality of the seed, size, color, weight, etc., becomes an essential factor in the course of marketing. Furthermore, the quality of the nut that is extracted is a function of whether or not it is extracted manually or with efficient mechanical devices. The extraction process directly influences the price of nuts in the market. While *edilus* shells are easily shelled with the teeth, those of Mexican piñon require judicious use of hammer or pliers. (Lanner, 1981).

OBJECTIVES

The overall goal of this work was to develop information to establish design criteria for applying engineering principles for shelling pine nuts. The scope of the work included measurement of physical and mechanical properties of pine nuts and evaluation of one engineering principle for rupturing the pine nut shell.

The specific objectives of the study were:

1.- To determine the physical characteristics of the pine nut seed.

2.- To evaluate the mechanical properties of the pine nut when it is subjected to uniaxial compression loading.

3.- To determine the effect of the loading rate on the force during compression test.

4.- Analyze the properties of the nut to establish engineering design criteria for shelling pine nuts.

5.- Test one combination of engineering principles for a continuous feed pine nut shelling process.

CHAPTER II

REVIEW OF LITERATURE

THE PINE NUT TREE IMPORTANCE

The first pinyon pine to be recognized by science was *Pinus cembroides*, the Mexican piñon. This species was first collected by Whilhelm Karwinsky in the state of Hidalgo, probably in 1831, and was described by the botanist Zuccarini in 1832 (Lanner 1981). This species generally occurs on dry, rocky slopes of mountain foothills. It is adapted to dry climates and survives in places with an annual rainfall of 305-356 mm. Its range is so broad that no particular soil type appears to be associated with it; however, moisture and altitude are important ecological factors in its distribution. It is found in regions where the altitude ranges between 1500-2800 m. The tree is usually a small pine 5-10 m tall, though occasionally it reaches 15 m. It has a diameter of 30-60 cm.

Three successive growth seasons are necessary to produce mature cones for production of pine nut seed. The pinyon pine has a slow growth and does not reproduce until it reaches an age of 75 years. The cones are globular and symmetrical in shape. They are borne singly or in groups of 2-5. The size of the cone when open is 3-4 cm long and 3-6 cm wide. The mature cones are lustrous reddish to yellowish brown, ripen in the late fall to winter, and opening when mature.

The most important product is the seed. It is brown in color, 13 mm long and 7-8 mm wide; has a thick hard seed coat (0.5-1.0 mm thick) that encases a pink nut which is the edible portion, sometimes termed meat.

According to Woodroof (1979) pine nuts consist of 42% shells by weight. The other 58% is the edible part which contains 3.1-4.9% moisture. It is 12.5-31.2% protein, 48.4 to 60.6% oil, and 6051 to 6790 calories per kilogram. The carbohydrates contain 4.3% ash, 1.0% fiber, 4.3% sugars and no starch. Characteristics of the oil are iodine value 102.1, oleic acid 56.7%, linoleic acid 31.6%, and saturated acids 8.5%. (Kester 1949).

In Mexico during the harvest period (October-November), the cones are cut from the tree before complete ripeness and then dried outdoors until they open and release the seed. Cones lose about 7-15% moisture content during the 30 days after harvest. Excellent seed quality is maintained when stored below 50% relative humidity. They can be marketed after as much as three years of common storage, if unshelled. However, when shelled they become rancid in 3 to 6 months. Long storage is due in part to the very low moisture in nuts and surrounding air. A comparison of the dietary values of pine nuts and other commercial nuts is shown in table 1.1.

PINE NUT HARVESTING AND PROCESSING

After the frosts come in the fall, the mature cones open and the seeds fall to the ground. The oldest and most common method of harvesting is to pick them off the ground by hand. A fast picker can gather 9 kg. a day. The seeds are so small that pine nuts often average 3300 per kilogram. The U.S. Forest Service is able to provide information on regulations, permits, rates for commercial permits, period of harvesting, maps, etc. for harvesting pine nuts. The official allowance in the U.S. for families is up to 11 kg. of nuts at no cost; permits are required for commercial uses.

Improvements in methods of harvesting include the use of suction machines similar to a vacuum cleaner, and tree shakers which shake the cones and allow seeds to fall onto a canvas spread beneath the trees. In either case, there are pine needles, cones and other litter to contend with. Most of this can be removed by successive screening through hardware cloth. (Woodroof 1979).

Table 1.1. Dietary value of pine nuts and other commercial nuts.

	FOOD CONTENT		
Type of nut	Protein (%)	Fat (%)	Carbohydrate (%)
Colorado piñon	14	62-71	18
Mexican piñon	19	60	14
Parry piñon	11	37	44
Digger pine	30	60	9
White pine	28	52	7
Italian stone pine	34	48	7
Siberian stone pine	19	51-75	12
Chilgoza pine	14	51	23
Pecan	10	73	11
Peanut	26	39	24
English walnut	15	68	12

Percentages are approximate and are based on shelled nuts.

PHYSICAL PROPERTIES OF BIOLOGICAL MATERIALS

In modern agriculture, vegetable and animal products are processed by several means such as mechanical, thermal, electrical, optical and ultrasonic techniques, but very little is known about the physical characteristics and mechanical properties of most agricultural materials (Mohsenin 1986). Physical properties are peculiar attributes of materials. The form, size, volume, density, surface area, porosity, color, and appearance are some of the most important physical characteristics in designing a specific processing machine or in the analysis of the product behavior.

The mechanical properties include deformation, resistance to compression, impact, and shear, as well as the friction coefficient. Knowledge of these properties is essential in design of machines, structures, and processes. Also, they are beneficial in analysis and determination of the efficiency of a machine or a process and evaluation of the product quality.

BACKGROUND RESEARCH

Previous work has demonstrated the value of knowledge about the physical and mechanical properties of different nuts and seeds. These studies have demonstrated use of this knowledge in design of machines, structures, and processes. In addition, it has been used in analyzing and determining the efficiency of machines or processes. To appreciate the need for information on physical properties of nuts and seeds, some examples of previous studies are reviewed.

Pearson et al. (1994), studied the physical characteristics of early splitting pistachios nut shells. A significant difference in weight, length and height between early split and late split pistachios was found. They developed a seed classification system to predict time of splitting by measuring these characteristics.

Braga et al. (1995), studied the mechanical behavior of the macadamia nut when it is subjected to a uniaxial compression load. They studied the effects of shell moisture content, size, and rupture position on the force, energy and deformation to rupture of the nut. They concluded that these are major factors influencing this mechanical behavior.

In similar work accomplished by Paulsen (1977), the effect of the compression force, position, moisture content, and deformation of soy seeds was studied. It was found that the force required to rupture was reduced as the moisture content was increased. Also they found that the position of the seed during breaking significantly influenced the magnitude of the force.

Sarig et al. (1980), studied deformation curves of macadamia nuts during compression tests accomplished in a universal testing machine. A large difference was found for the force required to rupture nuts of the same size where the deformation was not variable. This can be used as criterion in designing a macadamia nut cracker. Finally, they concluded that for a high performance cracking process, the nut must first be sized.

Shelef and Mohsenin (1969), studied the effect of moisture content of millet seed on compression force. They measured the modulus of elasticity and deformation.

They concluded that all values of the parameters decrease when moisture content is increased.

Another study by Inda and Rha (1978), using Yucca Filifera seed with an average moisture content of 6.5% dry basis, evaluated the effect of compression force on energy to rupture. They concluded that there is no effect of the rate of strain on the force and work required to rupture the seeds for rates of strain varying from 0.24 to 24.2 percent per second. Also the failure of the seed was always accompanied by the formation of a single crack through the seed along the loading direction.

FORCE DEFORMATION CURVE

Standards have been developed for compression of food materials (ASAE Standards, 1995). These standards provide typical characteristic force-deformation curves and define terminology used to evaluate results. A typical force-deformation curve is shown with three important engineering parameters identified in figure 2.1. These are: 1) point of inflection (PI), 2) bioyield point, and 3) rupture point.

A typical force deformation curve is first concave up and then concave down (figure 2.1). The point at which the rate of change of slope (second derivative) of the curve becomes zero is called the point of inflection. This point is designated as PI. The change in slope suggests that some type of failure is beginning. Also, this point can be found by using a straight edge to follow the change of slope of the curve and to determine the point at which the slope begins to decrease. Bioyield occurs where an increase in deformation results in decrease or no change in force. Rupture point is the point on the force deformation curve at which the loaded specimen shows a visible or invisible failure in the form of breaks or cracks. This point is detected by continuous decrease of the load in the diagram (figure 2.1).

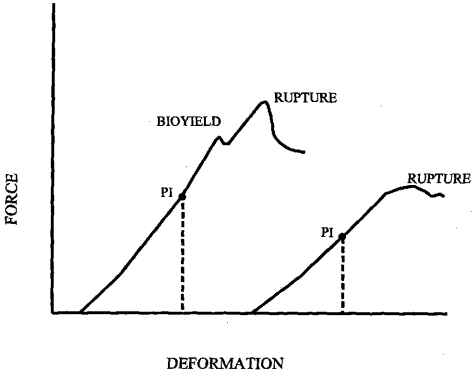

Figure 2.1. Force deformation curve.

PHILOSOPHY OF DESIGN

Design is defined in engineering as the process in which scientific principles and tools of engineering, mathematics, computers, and graphics are used to produce a plan which, when carried out, will satisfy a human need (Shigley et. al. 1989). The concept of design involves past experience of analysis, synthesis, and judgement. Hand books and catalogs also provide useful information designing machines.

Design requires that a configuration be devised and created to perform a function, safety, reliability, cost, manufacturability, and marketability. The complete process requires many steps and generally is an iterative process with feedback at each step. The general process for machinery design is discussed here in relation to the specific problem of developing a pine nut sheller.

THE PROCESS OF DESIGN

Recognition of the need

The first step leading into design is the recognition of the need. It is the engineers responsibility to act on this need. The need I visualize is for an improved mechanical pine nut sheller that can obtain clean undamaged raw pine nut endosperm. This need is based on the fact that pine nut seeds are too hard and small to manually shell in significant commercial quantities. Very few mechanical shellers are in use because of the high percentage of damage that is produced.

Background research

Information on previous research and product background is necessary to fully define and understand the problem. This information can be used to restate the goal. There is very limited information available related to pine nut shelling. Work done on products that are similar in nature to pine nuts can provide useful information for design of a mechanical pine nut sheller. The previous work by Pearson et al. (1994) , Braga et al. (1995), Paulsen (1977), Sarig et al. (1980), Shelef and Mohsenin (1969), and Inda and Rha (1978) have provided ideas and concepts which can be applied to pine nut shelling.

Definition of the problem

The problem needs to be defined in quantitative engineering terms. For example, the acceptable limits of damage to endosperm, rate of shelling, seed shape, force to rupture shells, etc. need to be specified. Also specifications are required on the input and output quantities, the characteristics and dimensions of space the process must occupy, and the limitations on these quantities.

Function

After problem identification, and before a solution is sought, functions need to be determined. Function of a machine is "what" the machine must accomplish not how it is to accomplish the task. Combining functional requirements with the limitations imposed by the biological characteristics of the products with which the machine will interact will allow synthesis and analysis of practical solutions.

Synthesis based on product biological properties

When designing a system to process biological materials, the physical characteristics of the product such as shape, size, volume, surface area, density, porosity, color, and appearance are important. Also, the mechanical properties such as stress-strain behavior, resistance to compression, impact and shear, coefficient of friction, etc. are of vital importance. By analyzing these properties we can synthesize and select the engineering principles and the form they should take when processing the required biological material. Force deformation measurements to rupture pine nut shells under different moisture conditions can lead to engineering principles adaptable to rupture the shell. Synthesis is also sometimes called the invention step in which the largest possible number of creative solutions is generated.

Analysis and optimization

As mentioned above, the possible solutions to the previous step are analyzed, and either accepted, rejected or modified. Design is an iterative process in which we proceed through several steps, evaluate the results, and then return to an earlier phase of the procedure. Thus we may synthesize several components of a system, analyze and optimize them, and return to the synthesis to see what effect this has on the remaining parts of the system.

Evaluation

Evaluating is a significant phase of the total design process. Evaluation is the final proof of a successful design and usually involves the testing of a prototype in the laboratory. Here I wish to discover if the design really satisfies the need or needs. Statistical tools an experimental design is used to determine whether the prototype performance is good or not.

Presentation

Communicating the design to others is the final, vital step in the design process. Basically, there are only three means of communication. These are the written, the oral, and the graphical forms. The process of design requires good communication between the engineer, the manufacturing shop, assembly plant, and management. If ideas are not accurately and fully understood, the project might be canceled and a good idea shelved.

Discussion and engineering drawings are both part of this communication process. Communication of a design begins with the drawing. A good layout needs to be drawn so it can easily be reproduced. Computer graphic systems can assist in generating drawings. Computer aided design (CAD) is the common term used for these computer drafting systems.

SUMMARY

Review of literature shows little work on pine nuts. Research made on other nuts and crops such as pistachio nut, macadamia nut, soy seed, millet seed, and Yucca Filifera seed gives procedures that can be applied to pine nuts for identifying physical properties and analyzing the mechanical behavior. This work will fill this void of information for pine nuts, and will be used as criteria in the design of a pine nut shelling device.

CHAPTER III

MATERIALS AND METHODS

INITIAL CONDITIONS

This work was accomplished in the laboratories of the Agricultural Engineering Department at Texas A&M University. Pine nut seeds of the variety *Pinus cembroides Zucc* were manually harvested in the Eastern Mother mountains, near the city of Saltillo, Mexico, 10-15 kilometers south along highway 57.

The results in this work were expressed in terms of force and total deformations and not in terms of stress and strains. The primary reason is because the contact area between the seeds and the compressing head can not be accurately measured. Another reason is that the components of seed have different mechanical properties and physiological arrangements which as a whole violate the requirements of homogeneity, isotropic, and continuity that are usual assumptions used to solve elementary material science problems.

Understanding of the force and deformation behavior of the whole seed is important in analyzing the failure characteristics of the shell. Therefore, no attempt was made to cut the seeds or other wise modify their shape to obtain specimens of constant cross sectional area to define stress-strain characteristics as has been done in the study of other materials (Shelef and Mohsenin 1969).

GENERAL SAMPLE PREPARATION

First, the seeds were cleaned manually to eliminate impurities. Based on other preliminary research work the seeds were sized through circular meshes: # 26 (10.22 mm diameter), # 24 (9.42 mm), # 20 (7.82 mm), and # 18 (7.03 mm). The seeds retained by mesh # 24 were termed large size seeds. The seeds retained by mesh # 20 were termed medium size, and the ones retained by mesh # 18 were termed small size.

The average moisture content of the seeds was 8.9% wet basis, as determined by the oven drying method used by the USDA Forest Service.

Measuring seed moisture

Moisture content was determined according to standard methods described by the manual of measurement and management of tree seed moisture, (Bonner 1981).

Seeds were dried at 103±2°C for 17±1 hr. Weighing samples before and after drying provides the data for calculation of moisture content, and all weight loss is considered to be moisture. Ten samples of five seeds each were placed into ten containers of noncorrosive metal that had a flat bottom and cover. Each sample was spread evenly on the bottom of the container to allow good air circulation. A convection oven was used to dry the seeds. Timing the 17-hr period was not started until the oven temperature reached 103°C with the containers inside. Space approximately equal to the diameter of the containers was left open between containers during drying to allow air circulation. The containers and their seed material were cooled in desiccators for 40-50 minutes before dry weights were recorded. All weights were measured to three decimal places using a Sartorius* analytical balance. Moisture content was expressed as a percentage of the wet weight of the sample. Equation 3.1 is used to calculate the moisture content.

$$\text{percent moisture} = \frac{\text{wet weight - dry weight}}{\text{wet weight}} \qquad (3.1)$$

PHYSICAL DIMENSIONS

To determine the physical dimensions of the pine nut seed and its parts, the following procedure was used:

1) Vernier calipers (Craftsman 40181 DJ) were used to measure the length, width, and height from three random samples of 30 seeds each. Length was defined as the distance from the calyx end to the stem; the height was assumed to be the distance from the bottom to the top when the seed is held in stable natural rest position, and the width of the seed was measured at its widest point. Figure 3.1.

2) Thirty seeds from the last procedure were carefully cut with a micro saw along the transverse and longitudinal axes.

3) After cutting the shells the thickness at 6 critical shell points were measured as shown in figure 3.2.

4) The mass was measured by weighing 40 individual seeds with an electronic balance (Sartorius), and then separating them into groups of 10.

5) The volume of seeds were measured using the air pycnometer method with four

* Use of product names is for identification purposes only and does not imply an endorsement of this product by the author.

replications of ten seeds each. The seeds were shelled by hand to obtain 40 nuts and remaining shells.

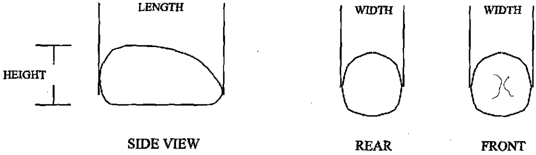

Fig 3.1. Pine nut dimensions.

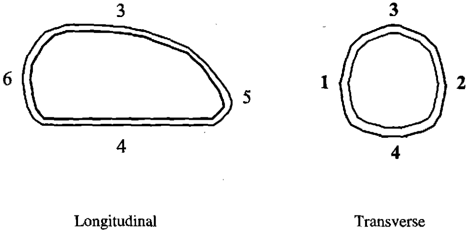

Fig 3.2. Shell thickness.

6) The remaining shells were separated into four individual sub samples, and the volume was measured from each of the four sub samples by the air pycnometer.

7) The mass of each subsample was determined by weighing each group of shells.

8) The volume of nuts was measured using four replications of ten nuts each by the air pycnometer method.

9) The mass of 40 nuts were determined by weighing four groups of ten each.

10) The length, width, and height were measured from the 40 nuts with calipers. The length, width and height were defined similar to the seeds.

11) The density of seeds, nuts, and shells was calculated by using equation 3.2.

$$\text{Density} = \frac{\text{mass of sample}}{\text{volume of sample}} \qquad (3.2)$$

Pycnometer method description

The air pycnometer is an instrument specifically designed to measure the true volume of various quantities of solid materials. The technique employs Archimedes' Principle of fluid displacement to determine the volume. The displaced fluid is nitrogen which can penetrate the finest pores to assure maximum accuracy. Its behavior as an ideal gas is also desirable.

The pycnometer determines the true density of solid samples by measuring the pressure difference when a known quantity of nitrogen under pressure is allowed to flow from a precisely known reference volume into a sample cell containing the solid material.

Roundness and sphericity

As a criteria for describing the shape of pine nuts, the roundness and sphericity were determined. For roundness, the projected area of the pine nut along its narrowest two diameters is assumed to be an ellipse. This parameter is a measure of the sharpness of the corners of the nut with respect to its natural rest position. The method proposed to estimate roundness is given by equation 3.3 and illustrated in figure 3.3. A roundness value of 1.0 would indicate a circular cross section shape.

$$\text{Roundness} = \frac{A_p}{A_c} \qquad (3.3)$$

Where A_p = largest projected area of object in a natural rest position
A_C = area of smallest circumscribing circle

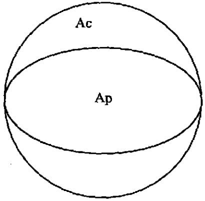

Figure 3.3. Roundness to describe shape of pine nut.

The geometric foundation of the concept of sphericity rest upon the isoperimetric property of a sphere. Sphericity is given by equation 3.4 and illustrated in figure 3.4.

$$\text{Sphericity} = \frac{di}{dc} \qquad (3.4)$$

Where di = diameter of largest inscribed circle
dc = diameter of smallest circumscribing circle

Sphericity provides information relative to three dimensions, and value of 1.0 would indicate that the nut is spherical in shape.

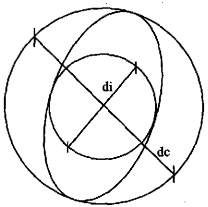

Figure 3.4. Sphericity to describe shape of pine nut.

MECHANICAL PROPERTY EVALUATION

The TA.XT2 texture analyzer was used for measuring mechanical properties of the seeds. The TA.XT2. has a probe speed range from 0.1 mm/s to 10 mm/s. The unit is also equipped with a computer for control, data acquisition, and data analysis.

The determination of compressive properties requires the production of a complete force-deformation curve. A curve satisfying ASAE Standard S368.3 can be obtained from the uniaxial compression test performed by the TA.XT2. Figure 3.5 shows a typical force-deformation curve obtained from the texture analyzer. Deformation is indicated by the crosshead displacement by the texture analyzer as it contacts the nut in compression.

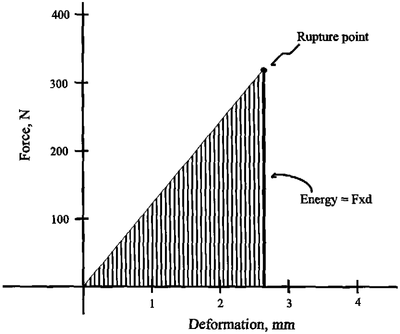

Figure 3.5. Force deformation curve obtained from compression test.

SEED ORIENTATION

There is only one orientation where the seed will be stable when placed on a flat surface. This is termed its stable natural rest position, and it is used for positioning seeds for compressing tests. For the uniaxial compression test, two orientations were used relative to the three axes shown in figures 3.6 and 3.7.

Orientation 1

This is obtained when the seed is held in its stable natural rest position on a flat surface. At this point, 3 perpendicular axes are set up with the origin in the center of the seed. The z axis runs parallel to the longest seed dimension. Figure 3.6.

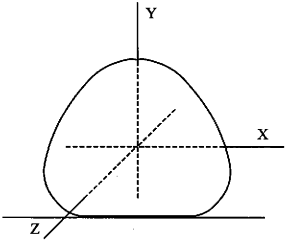

Figure 3.6. Orientation 1.

Orientation 2

The second orientation is obtained when the seed is rotated 90° from its stable natural rest position around the z axis. In this orientation an unstable position is obtained, and loading is still along the y axis. Figure 3.7.

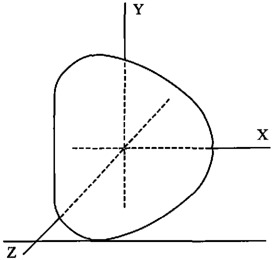

Figure 3.7. Orientation 2.

EXPERIMENTAL DESIGN

Experiment 1

The effect of seed moisture content, and orientation during rupture. To evaluate the effect that seed moisture content and the orientation have on the force, deformation, and energy to the shell rupture point, ten treatments were run.

They were obtained from the combination of 5 moisture contents of the seed with 2 compression orientations. Ten repetitions were run in a completely randomized design experiment. Pine nut seeds were used which passed through a # 24 mesh screen, but retained by a # 20 mesh. Five different moisture contents were obtained by soaking the seeds in water at five different soaking times: 0, 1, 2, 4, and 6 hr. Compression loads were applied for orientations 1 and 2 described above, and the loading rate was 1 mm/s until shell rupture was registered.

To evaluate the significance of the experiment among the 5 soaking times, (moisture content) a least significance difference test (LSD) was run. The null hypothesis Ho to be evaluated in this experiment was: There is no difference among responses of the combination of 5 soaking times (moisture contents) of the seed with the 2 orientations during compression test. The null hypothesis was tested with $\alpha = 0.05$.

The dependent variable for the test is the force. The completely randomized experiment design testing the effect of 5 moisture content levels with two orientations on the force is shown in table 3.1.

Table 3.1. Completely randomized experiment design testing the effect of 5 moisture content levels with two orientations on the force.

Source	df	Expected Mean square
Moisture Content	4	$\sigma^2_\epsilon + 5/4\sum m_i$
Error	45	σ^2_ϵ
Total	49	

Experiment 2

The effect of the orientation and size of the seed on the force, deformation, and energy requirements to rupture the shell. The compression force, deformation, and energy were measured. Six treatments were performed by the combination of three sizes: small, medium, and large (obtained from seeds passed through a # 20, # 24, and # 26 sieves); and two orientations when loading. Ten repetitions in a complete randomized design test were run. Pine nuts seeds with an average shell moisture content of 8.9% were used. The loading rate was also 1 mm/s.

To evaluate the significance of the experiment among 3 seed sizes, a least significance difference test (LSD) was run. The null hypothesis Ho to be evaluated in this experiment was: There is no difference among responses of the combination of 3 sizes and 2 orientations during compression test. Null hypothesis tested with $\alpha = 0.05$.

The dependent variable for this test is the force. The completely randomized experiment design testing the effect of 3 seed sizes with the two orientations on the force is shown in table 3.2.

Table 3.2. Completely randomized experiment design testing the effect of 3 seed sizes with two orientations on the force.

Source	df	Expected Mean square
Seed Size	2	$\sigma^2_\epsilon + 3/2\sum m_i$
Error	27	σ^2_ϵ
Total	29	

Experiment 3

The effect that the rate of loading has on the force over the seed during compression test. A compression test for pine nut seeds in a complete randomized design with 5 loading rates (0.1, 0.5, 1.0, 5.0, and 10.0 mm/s) and 5 repetitions was performed for orientation 1. The size of the seeds were those passing through a # 24 mesh. One seed moisture content was used for this experiment (8.9% wb).

To evaluate the significance of the experiment among the 5 rates of loading, a least significance difference test (LSD) was run. The null hypothesis Ho established for this experiment was: There is no difference among responses of the combination of_5 rates of loading for orientation 1. The null hypothesis was tested with $\alpha = 0.05$.

The dependent variable is the force. A completely randomized experiment testing the effect of 5 loading rates with orientation 1 on the force is shown in table 3.3.

Table 3.3. Completely randomized experiment design testing the effect of 5 loading rates with orientation 1 on the force.

Source	df	Expected Mean square
Rate of loading	8	$\sigma^2_\epsilon + 5/8\sum m_i$
Error	16	σ^2_ϵ
Total	24	

Sheller experiments

For purposes of evaluating the performance of an engineering principle for a shelling device the description of experiments is given in chapter V.

CHAPTER IV

RESULTS AND DISCUSSION

Results are presented in two parts: the physical characteristics of the seed and the mechanical behavior when it is subjected to uniaxial loading. Mechanical behavior was evaluated for the following three cases:

1. The effect of seed moisture content and orientation on the force, deformation and energy requirements to rupture.
2. The effect of the size and orientation of the seed on the force, deformation and energy to rupture.
3. The effect of the loading rate on the pine nut seed during compression.

PHYSICAL CHARACTERISTICS

Seeds were classified as small, medium, and large. The difference in whole seed and nut dimensions for each size classification were determined by measuring the seed, nut, and shell dimensions.

Seed dimensions

The statistics of the physical properties of small, medium and large sizes are shown in table 4.1. It can be observed that there is a difference in the dimensions of the seeds, as well as the nut. The shell thickness was found to vary according to position. For positions described in figure 4.1, the position 5 is the thickest part of the shell and the position where the changes in the shell curvature is greatest. The differences suggest that shell strength is less near positions 1 and 2. Forces to rupture the shell would be expected to be lower when applied at these positions.

Table 4.1. Physical properties of seed, nut, and shell.

PROPERTY	MED	SMALL	LARGE	SD*	VC**
WHOLE SEED					
Height (mm)	8.57	7.15	10.27	0.800	9.33
Length (mm)	13.87	11.75	16.36	1.200	8.69
Width (mm)	7.49	6.14	9.04	0.730	9.82
Mass (gr)	0.44	0.41	0.49	0.043	9.69
Volume (ml)	0.36	0.33	0.40	0.045	12.38
Dens (g/ml)	1.24	1.23	1.24	0.004	0.33
MC (% wb)	8.99	8.14	9.65	0.380	3.53
NUT					
Height (mm)	5.85	4.70	7.00	0.580	9.96
Length (mm)	10.99	9.30	12.80	0.790	7.24
Width (mm)	4.68	3.88	5.81	0.537	11.47
Mass (gr)	0.14	0.12	0.16	0.019	13.54
Volume (ml)	0.13	0.11	0.15	0.022	17.13
Dens (g/ml)	1.08	1.081	1.084	0.0017	0.64
MC (% wb)	1.41	1.31	1.52	0.104	7.30
SHELL THICKNESS					
Point 1 (mm)	0.98	0.56	1.35	0.255	26.09
Point 2 (mm)	1.05	0.65	1.60	0.288	27.40
Point 3 (mm)	1.18	0.74	1.35	0.231	21.06
Point 4 (mm)	0.99	0.60	1.44	2.810	28.34
Point 5 (mm)	1.55	1.05	2.10	0.323	21.14
Point 6 (mm)	0.92	0.76	1.19	0.138	14.97
Mass (gr)	0.30	0.28	0.32	0.023	7.64
Volume (ml)	.225	0.21	0.24	0.023	10.20
Dens (g/ml)	1.34	1.33	1.34	0.001	0.12
MC (% wb)	5.84	5.77	6.02	0.160	2.84

* Standard deviation ** Coefficient of variation

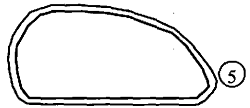

Figure 4.1. Longitudinal shell section showing the thickest part.

Void space

The shell and nut void space is shown in figure 4.2. Void space between shell and nut was determined for three size classification using equation 4.1 and are given in table 4.2. According to the results, the small seed size has a void space of 0.92 mm for orientation 1. In shelling, this means that a deformation of 0.92 mm can occur before force is exerted on the nut. For orientation 2, the deformation would be 1.24 mm without shell nut contact. For medium size seeds with orientation 1, the total space between shell and nut is 0.64 mm, and with orientation 2, it is 0.69 mm. Medium sized seed with orientations 1 and 2 can be deformed up to 0.64 and 0.69 mm respectively before contact is made. Finally, large size nuts have a total void space of 0.44 mm with orientation 1, and 0.32 mm with the orientation 2. To rupture the shell of large sized seeds without making shell nut contact, the deformation should not exceed 0.44 and 0.32 mm respectively.

$$VS = OD - (Th1 + Th2) - ID \quad (4.1)$$

Where

VS = Void Space
OD = Outside diameter
Th1 = Thickness 1
Th 2 = Thickness 2
ID = Inside diameter

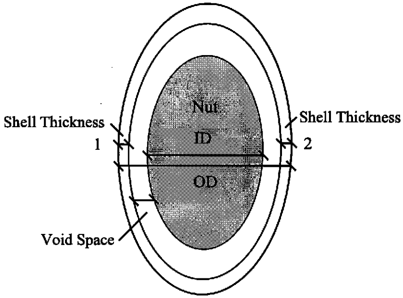

Figure 4.2. Void space between shell and nut.

Table 4.2. Values of void spaces for three seed sizes.

SIZE	Orientation 1	Orientation 2
Small	0.92 mm	1.24 mm
Medium	0.64 mm	0.69 mm
Large	0.44 mm	0.32 mm

Roundness and sphericity

The roundness and sphericity of small, medium, and large seed sizes were evaluated. Results are given in table 4.3, and calculations using equations 3.3 and 3.4 are presented in appendix E. The values for roundness for all three sizes are well below 1.0, so the cross-section of the pine nuts cannot be considered round. Observations show that shape transitions are smooth, but the shape has a low roundness value. The values for sphericity are also well below 1.0 verifying a more ellipsoidal shape.

Table 4.3 shows the roundness and sphericity values of pine nut seeds.

Table 4.3. Roundness and sphericity values of pine nut seeds.

SIZE	Roundness	Sphericity
Small	0.52 mm	0.52 mm
Medium	0.54 mm	0.54 mm
Large	0.52 mm	0.54 mm

MECHANICAL BEHAVIOR

The results of the experiment of the effect of loading rate on the force showed no significant difference among the five loading rates (appendix C, table C2). This led to the conclusion that the other two experiments could be done for a single loading rate. The load cell velocity of the texture analyzer was selected to achieve a loading rate of 1 mm/s for subsequent tests. This was the median value among the five velocities.

Experiment 1

When exposed to moisture the seed first absorbs water into the shell and after a period of time the water is absorbed by the nut. Although soaking the seed significantly reduces the force to crack them, the quality of the endosperm is reduced dramatically. Soaking the seeds is not a good procedure to crack pine nuts.

Seeds used in this experiment had soaking times of 0, 1, 2, 4, and 6 hours resulting in moisture content of 8.9%, 17.66%, 19.95%, 20.73%, and 26.16% respectively.

For the orientation number 1, the measured force was significantly higher for 0 hour soaking time as compared to longer times (table 4.4). Deformations were also significantly higher for 0 soaking hours as compared to longer soaking times (table 4.5). Measured energy required for 0 and 1 hours soaking time were also significantly higher than longer soaking times (table 4.6).

For orientation number 2, force was significantly higher for 0 hours soaking as compared to longer times (table 4.4). Deformation values were significantly higher for 0, 1, 4, and 6 hours soaking times (table 4.5). Energy for 0 hours soaking was also higher than longer times (table 4.6). The level of significance of the experiment was 0.05.

Table 4.4. Statistical analysis (LSD) comparing the mean force values for five seed moisture content for two orientations during compression test.

FORCE FOR ORIENTATION 1
(LSD)
α=0.05 df=45
Critical value of T=2.01
Least Significant Difference=50.948
Means same letter not significantly diff

T Grouping	Mean N	N	Soak time
A	258.04	10	0 hours
B	166.12	10	6 hours
B			
B	159.06	10	1 hours
B			
B	144.14	10	2 hours
B			
B	143.59	10	4 hours

FORCE FOR ORIENTATION 2
(LSD)
α=0.05 df=45
Critical value of T=2.01
Least Significant Difference=41.49
Means same letter not significantly diff

T Grouping	Mean N	N	Soak time
A	249.65	10	0 hours
B	158.08	10	2 hours
B			
B	157.64	10	4 hours
B			
B	123.96	10	6 hours
B			
B	121.16	10	1 hour

Table 4.5. Statistical analysis (LSD) comparing the mean deformation values for five different seed moisture content affected by two loading orientations.

DEFORMATION FOR ORIENTATION 1
(LSD)

α=0.05 df=45
Critical value of T=2.01
Least Significant Difference=0.2568
Means same letter not significantly diff

T Grouping	Mean mm	N	Soak time
A	1.1320	10	0 hours
B	0.8460	10	2 hours
B			
B	0.8150	10	4 hours
B			
B	0.8050	10	1 hour
B			
B	0.7990	10	6 hours

DEFORMATION FOR ORIENTATION 2
(LSD)

α=0.05 df=45
Critical value of T=2.01
Least Significant Difference=0.3251
Means same letter not significantly diff

T Grouping	Mean mm	N	Soak time
A	1.2040	10	0 hours
A			
B A	1.1930	10	1 hour
B A			
B A	0.9600	10	6 hours
B A			
B A	0.9310	10	4 hours
B			
B	0.8720	10	2 hours

Table 4.6. Statistical analysis (LSD) comparing the mean energy values for five different seed moisture content when it is compressed in two different orientations.

ENERGY FOR ORIENTATION 1
(LSD)

α=0.05 df=45
Critical value of T=2.01
Least Significant Difference=0.0521
Means same letter not significantly diff

T Grouping	Mean Nmm	N	Soak time
A	0.15061	10	0 hour
A			
BA	0.12005	10	1 hour
B			
B	0.08418	10	2 hours
B			
B	0.07313	10	4 hours
B			
B	0.07050	10	6 hours

ENERGY FOR ORIENTATION 2
(LSD)

α=0.05 df=45
Critical value of T=2.01
Least Significant Difference=0.0395
Means same letter not significantly diff

T Grouping	Mean Nmm	N	Soak time
A	0.14882	10	0 hours
B	0.08941	10	4 hours
B			
B	0.08246	10	2 hours
B			
B	0.08246	10	6 hours
B			
B	0.06141	10	1 hour

Figure 4.3 presents data values of the force during rupture as affected by the seed moisture content for the two compression load orientations. Orientation 1 is emphasized with the error range. It can be observed that the mean forces to rupture seeds with a m.c. of 8.9% with orientation 1 is 258.04 N. For seeds with m.c. of 17.66% a drop in the force to 159.06 N is observed.

Figure 4.4 shows data values of the force during rupture as affected by the seed moisture content for the two compression load orientations. Orientation 2 is emphasized with the error range. For seeds of m.c. of 8.9% in orientation 2 a mean value of 249.65 N to rupture seeds is observed. For seeds of m.c. of 17.66%, a drop in the force to 121.16 N is also observed.

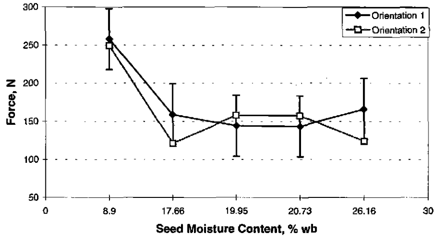

Figure 4.3. Seed moisture content vs force emphasizing error range for orientation 1. Observing the values when loading the seed in two orientations.

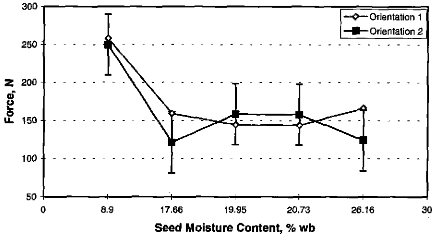

Figure 4.4. Seed moisture content vs force emphasizing error range for orientation 2. Observing the values when loading the seed in two orientations.

Figure 4.5 shows data values of the seed deformation during rupture as affected by the seed moisture content for the two compression load orientations. Orientation 1 is emphasized with the error range. It can be observed that the deformation of seeds with a m.c. of 8.9% with orientation 1 is 1.13 mm. For seeds with m.c. of 17.66% the deformation is 0.81 mm.

Figure 4.6 shows data values of the seed deformation during rupture as affected by the seed moisture content for the two compression load orientations. Orientation 2 is emphasized with the error range. For seeds of m.c. of 8.9% in orientation 2 the deformation is 1.20 mm. For seeds of m.c. of 17.66% a deformation of 1.19 mm is observed. When m.c. is 19.95% the deformation is 0.87 mm.

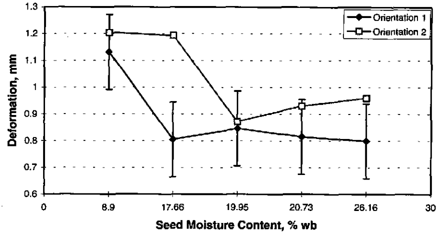

Figure 4.5. Seed moisture content vs deformation emphasizing error range for orientation 1. Observing the values when loading the seed in two orientations.

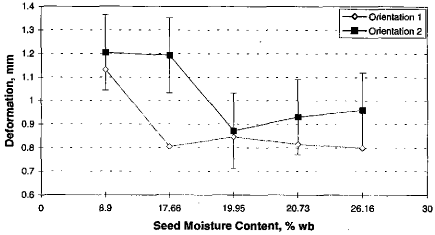

Figure 4.6. Seed moisture content vs deformation emphasizing error range for orientation 2. Observing the values when loading the seed in two orientations.

Figure 4.7 shows data values of the seed energy to rupture as affected by the seed moisture content for the two compression load orientations. Orientation 1 is emphasized with the error range. It can be observed that energy requirements to rupture seeds with a m.c. of 8.9% with orientation 1 is 0.151 Nmm. For seeds with m.c. of 17.66% the energy to rupture drops to 0.120 Nmm.

Figure 4.8 shows data values of the seed energy to rupture as affected by the seed moisture content for the two compression load orientations. Orientation 2 is emphasized with the error range. It can be observed that energy requirements to rupture seeds with a m.c. of 8.9% with orientation 2 is 0.149 Nmm. For seeds with m.c. of 17.66% the energy to rupture drops to 0.061 Nmm.

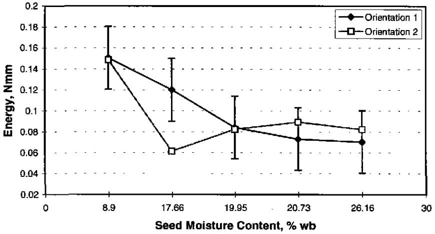

Figure 4.7. Seed moisture content vs energy emphasizing error range for orientation 1. Observing the values when loading the seed in two orientations.

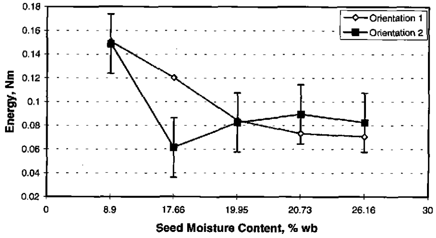

Figure 4.8. Seed moisture content vs energy emphasizing error range for orientation 2. Observing the values when loading the seed in two orientations.

<u>Experiment 2</u>

It was observed that seed size directly affected the force required to rupture pine nuts. Different levels of deformation resulted from the variation in seed size. As seed size increases the deformation decreases.

The comparison of the mean values obtained in the mechanical behavior experiment in tables 4.7, 4.8, and 4.9, shows that the force and deformation during rupture are significantly higher for the largest seed with orientation 1. For the rupture energy, there was no difference between the three sizes for orientation 1. It was observed that with orientation 1, large seeds require more force to fracture shells and that the deformation is higher with orientation 1 than orientation 2.

For orientation 2, the values measured between the three sizes of seeds are not significantly different in rupture energy. Concerning the force and the deformation with orientation 2, the values were significantly lower for the smallest size. Also, the energy required to break the shell was the same for the two orientations. The level of significance for the test was 0.05.

Table 4.7. Statistical analysis comparing the mean force values for three seed sizes when subjected to two orientations loading force.

FORCE FOR ORIENTATION 1
(LSD)
α=0.05 df=27
Critical value of T=2.05
Least Significant Difference=45.755
Means same letter not significantly diff

T Grouping	Mean N	N	Size
A	304.69	10	Large
B	256.89	10	Medium
B			
B	223.39	10	Small

FORCE FOR ORIENTATION 2
(LSD)
α=0.05 df=27
Critical value of T=2.05
Least Significant Difference=39.169
Means same letter not significantly diff

T Grouping	Mean N	N	Size
A	253.42	10	Large
A			
A	241.24	10	Medium
B	159.76	10	Small

Table 4.8. Statistical analysis comparing the mean deformation values for three seed sizes when subjected to two orientations loading force.

DEFORMATION FOR ORIENTATION 1
(LSD)
α=0.05 df=27
Critical value of T=2.05
Least Significant Difference=0.249
Means same letter not significantly diff

T Grouping	Mean mm	N	Size
A	1.3370	10	Large
B	1.0800	10	Medium
B			
B	0.8936	10	Small

DEFORMATION FOR ORIENTATION 2
(LSD)
α=0.05 df=27
Critical value of T=2.05
Least Significant Difference=0.2751
Means same letter not significantly diff

T Grouping	Mean mm	N	Size
A	1.1320	1	Large
A			
A	1.1170	10	Medium
B	0.8190	10	Small

Table 4.9. Statistical analysis comparing the mean energy values for three seed sizes when it is compressed in two different orientations.

ENERGY FOR ORIENTATION 1
(LSD)
α=0.05 df=27
Critical value of T=2.05
Least Significant Difference=0.2037
Means same letter not significantly diff

T Grouping	Mean Nmm	N	Size
A	0.28614	10	Small
A			
A	0.23116	10	Large
A			
A	0.21701	10	Medium

ENERGY FOR ORIENTATION 2
(LSD)
α=0.05 df=27
Critical value of T=2.05
Least Significant Difference=0.0815
Means same letter not significantly diff

T Grouping	Mean Nmm	N	Size
A	0.15350	10	Large
A			
A	0.13449	10	Medium
A			
A	0.11067	10	Small

Figure 4.9 shows data values of the force during rupture as affected by the seed size for two compression load orientations. Orientation 1 is emphasized with the error range. It can be observed that the mean forces to rupture small and medium sized seeds with orientation 1 ranges from 223.39 N to 256.89 N. For large sized seeds the force to rupture the seeds is significantly higher at 304.69 N.

Figure 4.10 shows data values of the force during rupture as affected by the seed size for two compression load orientations. Orientation 2 is emphasized with the error range. It can be observed that the force to rupture medium and large sized seeds with orientation 2 ranges from 241.24 N to 253.42 N. For small sized seeds the force to rupture the seeds is significantly lower at 159.76 N.

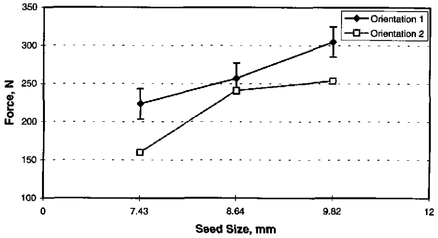

Figure 4.9. Seed size vs force emphasizing error range for orientation 1. Observing the values when loading the seed with two orientations.

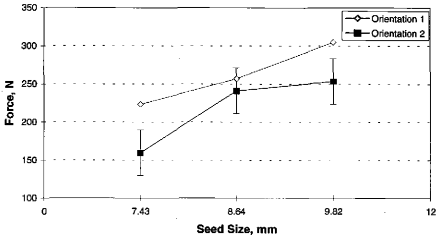

Figure 4.10. Seed size vs force emphasizing error range for orientation 2. Observing the values when loading the seed with two orientations.

Figure 4.11 shows data values of the seed deformation during rupture as affected by the seed size for the two compression load orientations. Orientation 1 is emphasized with the error range. It can be observed that the deformation of small and medium sized seeds with orientation 1 ranges from 0.89 mm to 1.08 mm. For large sized seeds the deformation is significantly higher at 1.34 mm.

Figure 4.12 shows data values of the seed deformation during rupture as affected by the seed size for the two compression load orientations. Orientation 2 is emphasized with the error range. It can be observed that the deformation of medium and large sized seeds with orientation 2 ranges from 1.12 mm to 1.13 mm. For small seeds the deformation is significantly lower at 0.82 mm.

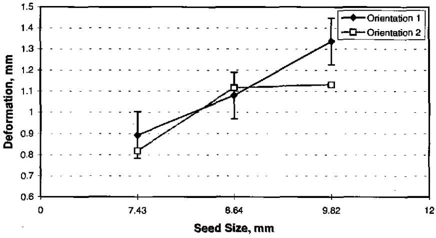

Figure 4.11. Seed size vs deformation emphasizing error range for orientation 1. Observing the values when loading the seed with two orientations.

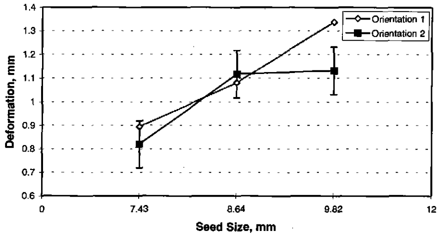

Figure 4.12. Seed size vs deformation emphasizing error range for orientation 2. Observing the values when loading the seed with two orientations.

Figure 4.13 shows data values of the seed energy to rupture as affected by the seed size for the two compression load orientations. Orientation 1 is emphasized with the error range. It can be observed that energy requirements to rupture small seeds for orientation 1 is 0.286 Nmm. For medium size seeds the energy to rupture drops to 0.217 Nmm. The energy requirements are not significantly different.

Figure 4.14 shows data values of the seed energy to rupture as affected by the seed size for the two compression load orientations. Orientation 2 is emphasized with the error range. It can be observed that energy requirements to rupture small seeds with orientation 2 is 0.110 Nmm. For medium size seeds the energy to rupture increases up to 0.134 Nmm. The energy requirements are not significantly different.

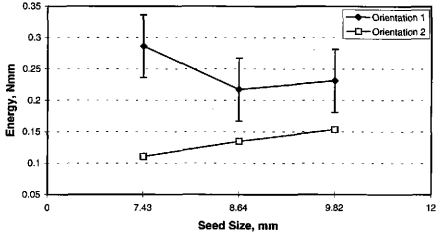

Figure 4.13. Seed size vs energy emphasizing error range for orientation 1. Observing the values when loading the seed with two orientations.

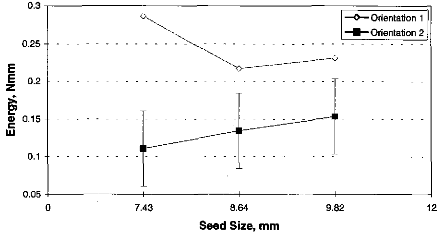

Figure 4.14. Seed size vs energy emphasizing error range for orientation 2 . Observing the values when loading the seed with two orientations.

SUMMARY OF RESULTS

Like previous studies on similar materials, a direct relationship was found between the moisture content and the three measured parameters: force, energy, and deformation. Increasing the moisture content reduces magnitude of force and energy, but increases maximum deformation for rupture. Additionally it was observed that upon wetting, the quality of the nut is reduced.

It was observed that the dry seeds fractured into more parts. The dry seed rupture could be described as a catastrophic failure. This does not happen with shells containing high moisture content.

The deformation for the large sized seeds is greater than for small sized seeds in the stable position. This indicates the need to apply different levels of deformation for fracturing pine nuts of different sizes. Therefore, sizing of the seed is essential for mechanical shelling.

The numerical values that are significant from an engineering design point of view will be summarized in the next chapter.

CHAPTER V

DESIGN CRITERIA FOR MECHANICAL PINE NUT SHELLER

Based on the study of the physical and mechanical properties of the pine nut criteria for mechanical shelling may be summarized as follows:

1. Cracking non soaked pine nuts with about 8.9% moisture content enhances shattering of shells at rupture.
2. Deformations ranging from 0.82 mm to 1.14 is required to rupture pine nuts of different sizes.
3. Void spaces allow deformation of shell without contacting nut, but void spaces differ according to nut size, so grouping seeds in uniform size classifications is needed to minimize nut damage.
4. Compression forces to crack seeds in different size classification range from 160 N to 305 N.
5. A continuous feed process to crack seeds is needed to obtain adequate capacity because of the small seed size.
6. Pine nut shells ruptured and shattered at low loading rates so impact loading is not necessary for the shelling process.

RECOGNITION AND SELECTION OF ENGINEERING PRINCIPLES

Numerous engineering principles are available for applying the forces in the manner needed to rupture the pine nut seeds. Based on the criteria established above, a principle that controls the deformation is needed to rupture the shell without damaging the endosperm. Two counter rotating rollers were selected as the principle that can control the deformation and achieve the necessary force levels to rupture the seeds. This method is adaptable for a continuous feed process to crack the seed. The roller principle can be adapted to provide the different deformations for different size classifications. At least four arrangements of the roller principles can provide the deformations required for the different sizes, and are considered below.

One arrangement consists of a set of rollers, where one roller is conical in shape, and the other cylindrical. The gap variation between the rollers can be controlled by the cone angle of the conical roller to provide variations in deformations of different size classifications as shown in the figure 5.1.

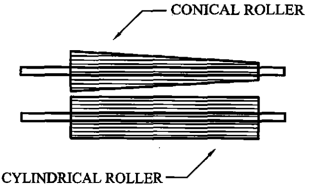

Figure 5.1. Conical-cylindrical roller set.

Another arrangement also has a combination of two roller shapes. One roller is stepped and the other is not. The stepped shape allows different size classifications of pine nuts to be cracked at each step. The number of size classes needed would dictate the number of steps. Figure 5.2.

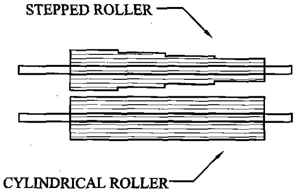

Figure 5.2. Stepped-cylindrical roller set.

A third arrangement is shown in figure 5.3. Two counter rotating cylindrical rollers with one set at angle to the other provides a continuous varying gap from one end to the other. The angle between the two rollers can be adjusted to provide flexibility in use. For example, the rollers could be set parallel when shelling a single size classification, or the angle could be adjusted to provide cracking several different size classifications simultaneously.

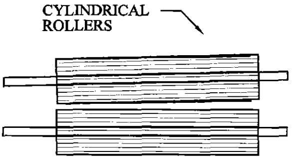

Figure 5.3. Cylindrical-cylindrical roller set.

A fourth arrangement includes cylindrical rollers in series, it is shown in figure 5.4. The cracking of the pine nuts can be achieved without sorting the seeds. Mixed seed sizes are dropped from the top of the rollers. The largest seeds will be break first when passing through the first set of rollers and nut will then pass through the other set of rollers. The seeds not cracked by the first set of rollers will be cracked by one of the other sets of rollers which have successively smaller clearance. Interference between shells and nuts could cause damage to the nuts at each successive set of rollers.

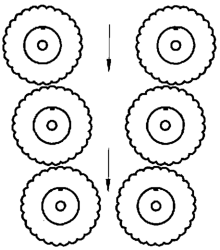

Figure 5.4. Three circular sets of rollers.

ANALYSIS OF MECHANICAL PINE NUT SHELLING PRINCIPLES

The characteristics of the four arrangements were analyzed. All the rollers require some machining, but some require more than others. The conic and cylindrical set of rollers shown in figure 5.1 has the capability of working without adjusting the gap, only one conic roller is needed because this can be set on an angle. The stepped combination can only be used for fixed seed size classifications. To rupture seeds, it is necessary to make a stepped roller with the number of steps equal to the number of seed size classifications. The angular velocity for each step will be the same since they run at the same RPM, but there is a difference in the peripheral velocity on the circumference of each step. This fact could make the process of cracking vary. The advantage is that step lengths are unlimited so large capacities could be achieved with a single machine.

The third set of rollers is the easiest to construct. It can be adjusted to any angle, so any size of seeds can be processed. The deformation also can be controlled for each seed size. The RPM, angular velocity, and peripheral velocity are the same for the two rollers. Although velocity of the force application was not found to be critical in tests, high velocities can increase shelling capacity of a machine.

The fourth arrangement is by far the best idea to crack nuts without sorting them, but this system is more expensive compared to the other three, and most likely to create damage to the nut. Three, four or six set of rollers may be required to cover the broad range of seed sizes.

Although all four roller methods can be built with any metal, the cheapest and easiest to construct are the cylindrical rollers. Thus, the decision to select the cylindrical-cylindrical arrangement for experimental evaluation is based on its ability to process seeds of different sizes along the axis at the same time, and also easy to adjust deformation.

Cylindrical rollers with grooves on the surface are needed to increase friction between the seeds and rollers. Without grooves, the tangential force exerted on the nuts by the rollers may not be great enough to force the nuts through the rollers.

It can also be observed that if the speed of the two adjacent rollers are not the same, a shearing effect may be produced. One roller works as a seed support while the other shears and compress it. Figure 5.5.

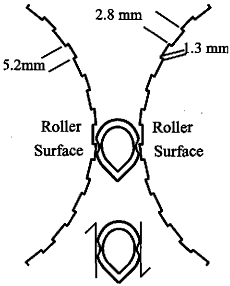

Figure 5.5 Shearing effect on the shell surface.

MATERIALS AND CONSTRUCTION

General description

A device was constructed in the Agricultural Engineering Research Shop to evaluate the counter rotating cylinder principle as a means of rupturing pine nut seeds as part of the shelling process. The design and construction of the experimental device was primarily for evaluating principles, and existing components were used when possible.

The pine nut shells are cracked by means of deformations developed by compressive forces. The seeds are dropped into each size container from the top of the feed hopper and delivered between the two rollers by means of gravity. The feed hopper was built with five separators to deliver the different size classification. The grooves on the counter rotating rollers produce frictional forces on the nut and forces it between the rollers. The seed is compressed and the rollers rupture the shell to obtain the nut.

After the seed has been cracked, nuts and shells fall into the collector. This device was designed to maintain separation of the different size classifications. The components of the device are mounted on a main frame built square steel tubing.

The components that comprise the test apparatus are the power unit, drive system, compression rollers, gap adjusters, feed hopper and cracked nut collector, and frame. Components and parts list are given in appendix F.

All the moving parts are covered by metal screen guards to avoid any possible injury. Figure 5.6 shows the general view of the experimental device. Figure 5.7 shows a close up of the device. Five metal sieves and a mechanical shaker device were also used to sort the seeds before processing.

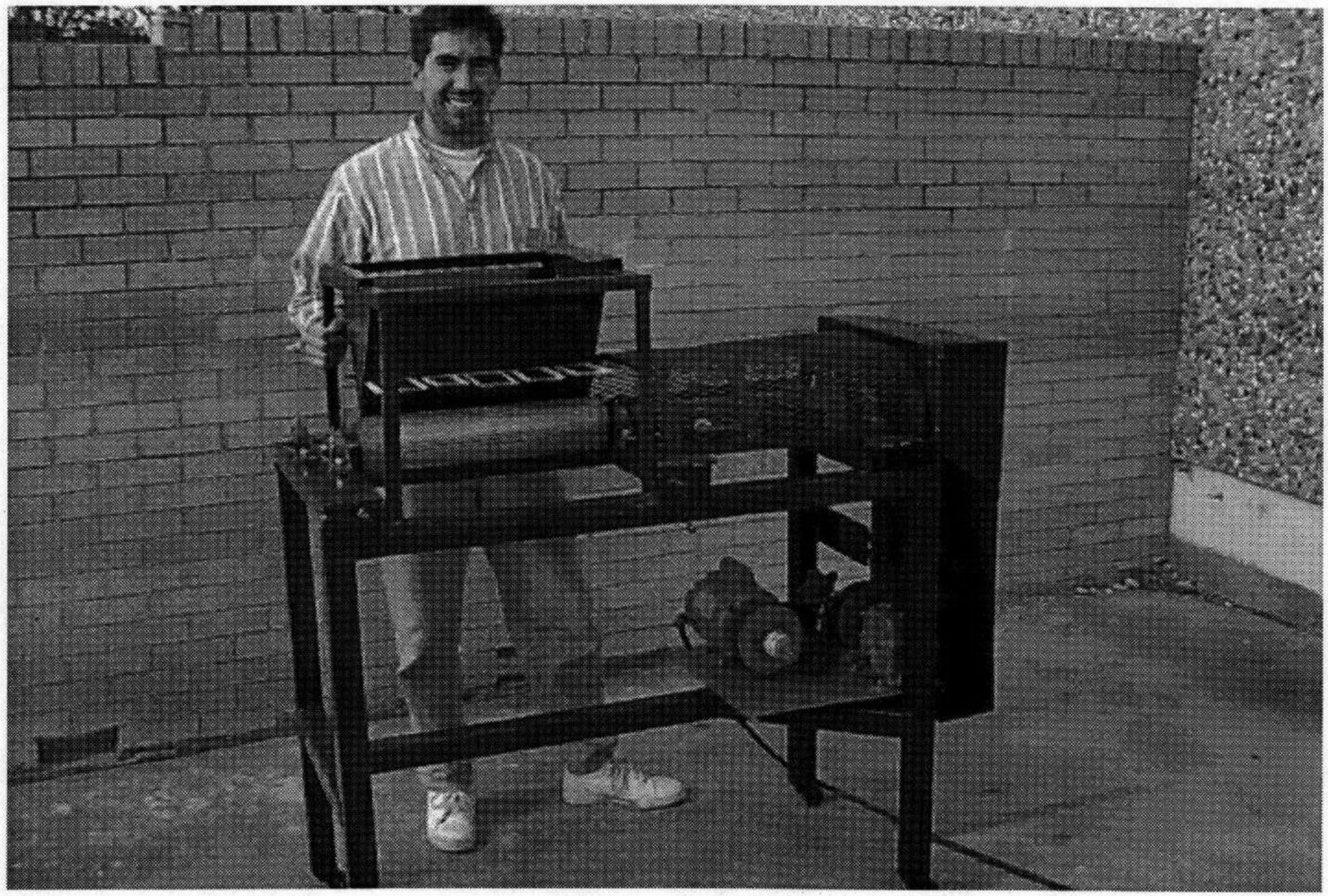

Figure 5.6. General view of the experimental device.

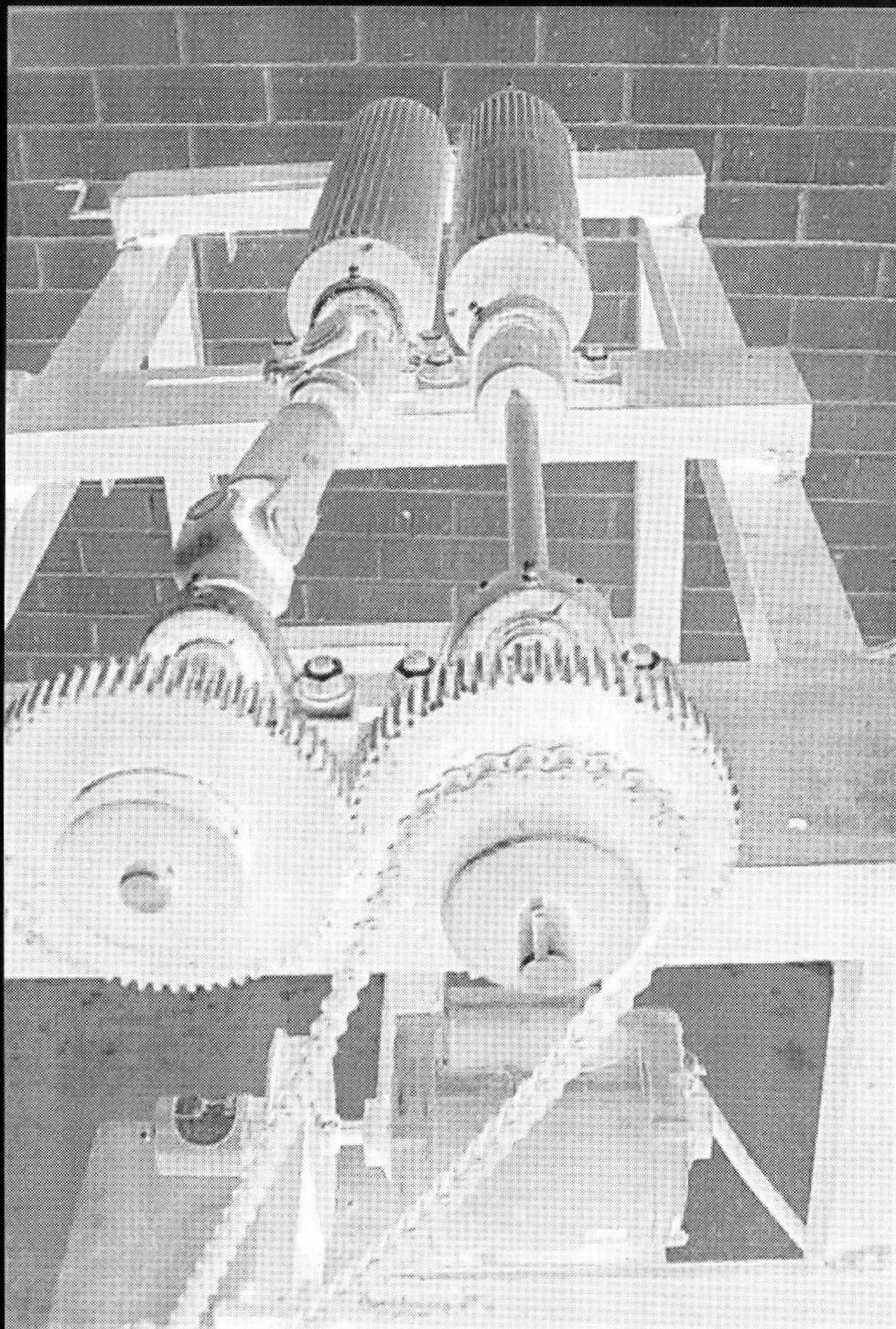

Figure 5.7. Close up of the device.

EVALUATION OF SHELLER EXPERIMENTAL DEVICE PERFORMANCE

Sample preparation

The performance of the counter rotating rollers was tested by assessing seed breakage and nut damage. A sample of 6.06 kg. of pine nuts were cleaned and then sieved in a mechanical shaker. The seeds were sized through circular meshes using a shaker device. Each sieve size was assigned with a successive number from 18 to 26 in a step of 2. The sieve sizes are: # 26 (10.22 mm diameter), # 24 (9.42 mm), # 22 (8.62 mm), # 20 (7.82 mm), and # 18 (7.03 mm). The sieve numbers from 18-20, 20-22, 22-24, and 24-26 denote a difference of 0.8 mm. The seed distribution obtained from the sample is shown in table 5.1. The seed sizes of less than 7.03 mm and more than 10.22 mm are the lower and upper seed size class ranges and are insignificant for the purpose of this test. Four different gap dimensions are required to process the four seed class ranges along the rollers. A further seed division will narrow the range of deformation.

Adjustment of the rollers

The speed of the counter rotating rollers ranged from 46 to 180 RPM, which results in a peripheral speed range of 244 to 957 mm/s. Texture analyzer loading rates ranged from 0.1 mm/s to 10 mm/s, and the results demonstrated no effect of the speed. Since the loading rate from the rollers are much higher than the texture analyzer test, three different speeds of 244, 600, and 957 mm/s were selected to evaluate roller rupturing of individual seeds. The lowest speed of 244 mm/s caused damage to the nut, while the highest speed of 957 mm/s resulted in an incomplete breakage of the shell. The speed of the rollers for subsequent testing was set to 600 mm/s. This speed was a compromise between high cracking percentage and low percentage damage.

The gap between rollers was set in an angle. The largest gap was set to 5.81 mm which is the width of the largest nut. For the smallest gap the smallest nut width size was also used. The smallest gap was set to 3.88 mm. The resulting angle was 1.42 degrees. Figure 5.8 shows the seed entering the rollers and figure 5.9 shows the deformation and cracking of shell.

Table 5.1. Distribution of the seed population.

SIEVE NUM CLASS	SEED SIZE mm. CLASS	AMOUNT	WEIGHT kg.	AMOUNT %	WEIGHT %
less than 18	less 7.03	247	0.0521	1.72	0.93
18-20	7.03-7.82	1962	0.5999	13.64	10.75
20-22	7.82-8.62	5918	2.1391	41.15	38.32
22-24	8.62-9.42	4878	2.0751	33.92	37.18
24-26	9.42-10.22	1245	0.0640	8.66	11.46
26 and more	more 10.22	132	0.0756	0.92	1.36

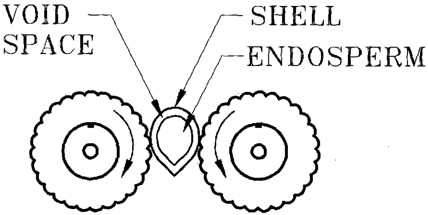

Figure 5.8. Seed entering the rollers.

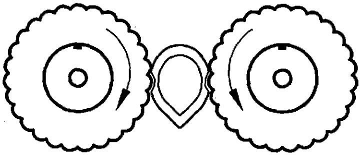

Figure 5.9. Deformation and cracking of the shell.

Procedure of the experiment

For this experiment, seed sizes were named as seed class, and three replications of 100 seeds each were run for each class. Cracking using three different methods to feed the nuts onto the rollers were evaluated. These methods were: 1) one seed at a time for each class, 2) one class at the same time, and 3) the four classes at the same time. To evaluate the significance of the experiment between these three feeding methods a completely randomized design experiment was performed using 12 combinations obtained from the four classes (sieves numbers 18, 20, 22, and 24) and the three feeding methods.

The time to crack the 100 nuts was measured and feed rate in kg/min determined. After the seeds were processed, nuts and shells were collected in the basket. Nuts were separated from shell parts and counted under a magnifying glass. The null hypotheses established to test in this experiment was, Ho: There is no difference among the responses of the combination of four seed size classes and the three feeding methods.

Experiment conditions

Air dried seeds with a moisture content of 8.9% wb approximately. The angle was fixed to provide different roller gaps for different seed size classifications, and the roller speed was constant at 600 mm/s. These variable were held constant for all the experiments. The seeds were placed in the hooper which has separator walls for each class. The seeds were delivered by gravity at the time the gate is opened. A special device was designed to open the gates, either one at a time or all four classes at the same time, depending upon the test. The expected direct variable responses were the total number of shelled seeds, partially shelled seeds, unshelled seeds, and damaged nuts.

Experimental results and conclusions

In general, the statistical analysis reported in appendix D shows insufficient evidence to reject the null hypotheses, that there is no significant difference between seed sizes and the three different ways to feed the seed. The results of the experiment are shown in tables 5.2, 5.3, 5.4, and 5.5.

Table 5.2. Experimental results for seed class 18-20.

	Re	Shelled	Not shelled	Partially Shelled	Damaged	Flow rate Kg/min
FEED TYPE						
INDIVIDUAL	1	80	5	2	10	0.0192
	2	75	13	0	12	0.0192
	3	63	27	0	9	0.0192
ONE CLASS	1	74	17	0	6	0.127
	2	70	8	1	18	0.127
	3	64	3	1	17	0.127
ALL CLASSES	1	69	8	0	13	0.072
	2	73	18	0	5	0.072
	3	66	27	0	5	0.072

Table 5.3. Experimental results for seed class 20-22.

	Re	Shelled	Not shelled	Partially Shelled	Damaged	Flow rate Kg/min
FEED TYPE						
INDIVIDUAL	1	82	13	0	5	0.0197
	2	72	2	1	20	0.0197
	3	70	0	2	20	0.0197
ONE CLASS	1	74	4	0	16	0.1173
	2	72	6	0	18	0.1173
	3	78	2	2	18	0.1173
ALL CLASSES	1	70	4	0	22	0.086
	2	77	14	3	5	0.086
	3	67	20	0	8	0.08

Table 5.4. Experimental results for seed class 22-24.

	Re	Shelled	Not shelled	Partially Shelled	Damaged	Flow rate Kg/min
FEED TYPE						
INDIVIDUAL	1	66	3	1	25	0.0831
	2	67	5	3	20	0.0831
	3	69	3	0	18	0.0831
ONE CLASS	1	76	4	0	18	0.114
	2	69	1	1	25	0.114
	3	71	4	0	21	0.114
ALL CLASSES	1	79	2	0	24	0.1
	2	70	13	2	10	0.1
	3	74	13	0	12	0.1

Table 5.5. Experimental results for seed class 24-26.

	Re	Shelled	Not shelled	Partially Shelled	Damaged	Flow rate Kg/min
FEED TYPE						
INDIVIDUAL	1	71	10	0	12	0.0033
	2	60	4	0	35	0.0033
	3	78	4	1	13	0.0033
ONE CLASS	1	70	5	0	16	0.0119
	2	69	4	3	17	0.0119
	3	66	13	0	18	0.0119
ALL CLASSES	1	70	2	0	22	0.0122
	2	64	12	0	20	0.0122
	3	62	5	4	19	0.0122

The shelled seed responses were not affected significantly by seed sizes and the three different ways to feed the seed. Tables D.1, D.2, D.3, and D.4 (appendix D), where Tukey's statistical analysis is used shows that there was no difference among the three ways to feed the seed.

The unshelled seed responses were not affected significantly by seed sizes and the three different ways to feed the seed. In tables D.5, D.6, D.7, and D.8 (appendix D), using the Tukey's statistical analysis method no statistically difference among the three ways to feed the seed was found.

The partially shelled seed responses were not affected significantly by seed sizes and the three different ways to feed the seed. In tables D.9, D.10, D.11, and D.12

(appendix D), using the Tukey's statistical analysis method it can be observed that there was not difference between the three ways to feed the seed.

The damaged nut responses were not affected significantly by seed sizes and the three different ways to feed the seed. In tables D.13, D.14, D.15, and D.16 (appendix D), using the Tukey's statistical analysis method it can be observed that there was no difference between the three ways to feed the seed.

A correlation was found between seed size and void space. Seeds from the smallest class suffered less damage to the nut. Smallest seeds have more void space as compared to large seeds. The void space between the nut and shell acts as a cushion device when the seed is deformed.

The machine shelling efficiency averaged 70% when averaged over all seed sizes. Averaging damage over all tests showed 16% damage. This 16% of meats classified as damaged can be processed into candies or cakes, where the quality of the nut is related to flavor and not to appearance. Achieving 70% cracking with 84% undamaged seed in a continuous shelling process is a significant improvement over present techniques. In addition the remaining 30% of unshelled seeds can be processed again by collecting the unshelled seeds and dropping them into the next smaller gap. This procedure will likely increase the overall efficiency.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY AND CONCLUSIONS

This research provided basic information on the physical and mechanical properties of pine nuts. This information had not been developed in previous work, but was needed to select engineering principles that could be used in a continuous feed mechanical sheller. Conclusions are summarized below according to the objectives given in chapter 1.

Objective 1

Critical dimensions of pine nut seed, shell, and nuts were established. Seed dimensions ranged from a minimum width of 6.14 mm to a maximum length of 10.27 mm. The respective nut dimensions ranged from 3.88 mm to 7.0 mm. The shell thickness varied according to position. The void space between nut and seed of small sized seeds was 0.92 mm for orientation 1 and 1.24 mm for orientation 2. Medium size seeds have a void space of 0.64 mm and 0.69 mm for orientations 1 and 2 respectively. Large size seeds have a void space of 0.44 mm for orientation 1 and 0.32 mm for orientation 2.

The values for roundness for three sizes are about 0.54 which is much less than the value of 1.0 for a round nut. Observation show that shape transitions are smooth, but the low roundness value shows that the seeds will seek a unique orientation when placed on a flat surface. The values for sphericity are also well below 1.0 verifying a more ellipsoidal shape. This shape and smooth surface is adaptable to continuous feeding nuts in mechanical shelling.

Objective 2

Soaking seeds to increase shell moisture content reduced rupture forces and increased deformations for all three seed size classifications evaluated. When exposed to moisture the seed first absorbs water into the shell and after a period of time the water is absorbed by the nut. However, increased moisture content reduced nut quality and reduced shattering of shells at rupture. Soaking the seeds is not a good procedure to crack pine nuts. Use of unsoaked seeds is essential for shell nut separation even though force is approximately 63% grater than for soaked seeds.

The deformation required to rupture the large sized seeds is greater than for small sized seeds in natural rest position. This indicates the need to cause different levels of deformation for fracturing pine nuts of different sizes, so sizing is an important part of the process.

The values of deformation, forces, and energy for unsoaked seeds are important in establishing design criteria (objective 4) for a mechanical sheller.

Objective 3

Force was unaffected by the range of loading rates of the texture analyzer used for compression testing. The speed of the counter rotating rollers was much higher and was observed within the range of 244 mm/s to 957 mm/s. It was found that low speeds near 244 mm/s caused damage to the nut, while the highest speed of 957 mm/s resulted in incomplete rupture of the shell. A compromise speed of 600 mm/s was found to give the best results in terms of seed breakage with acceptable levels of damage.

Objective 4

Based on the study of the physical and mechanical properties of the pine nut, criteria for mechanical shelling with numerical values are listed below.

1. Cracking non soaked pine nuts with about 8.9 % moisture content enhances shattering of shells at rupture.
2. Deformations ranging from 0.82 mm to 1.14 is required to fracturing pine nuts of different sizes.
3. Void spaces allow deformation of shell without contacting the nut, but void spaces differ according to nut size, so grouping seeds in uniform size classifications is needed to minimize nut damage.
4. Compression forces to crack seeds in different size classification range from 160 N to 305 N.
5. A continuous feed process to crack seeds is needed to obtain adequate capacity because of the small seed size.
6. Pine nut shells ruptured and shattered at low loading rates so impact loading is not necessary for the shelling process.

Objective 5

Results from tests with an experimental device to rupture pine nut seeds showed that principals using counter rotating rollers can be adapted for continuous feed shelling of pine nuts. Approximately 70 % of the nuts of all sizes were adequately cracked to allow for separation of shells from endosperm. Evaluation of the endosperm separated from shells showed that for large sized seeds, 20 % were damaged. For small sizes only 10 % were damaged. Void space was shown to vary inversely with size, so the larger void space of small seeds allow more deformation of shell without contacting the endosperm. Large seeds which have less void space suffered more damage to the endosperm. Achieving 70% cracking with 84% undamaged seed in a continuous shelling process is a significant improvement over present techniques. In addition the remaining 30% of unshelled seeds can be process again by collecting the unshelled seeds and dropping them into the next smaller gap. This procedure will likely increase the overall efficiency.

RECOMMENDATIONS

This work provided significant advances toward developing an efficient, effective mechanical pine nut sheller. However, additional work is needed to provide a complete mechanical process. The following work is needed:

1. Develop techniques to separate nuts from shells, and cracked nuts from uncracked or damaged. These techniques will be based on other pine nut properties such as shell friction coefficient, shearing, and aerodynamic properties.

2. Evaluate alternative methods of sizing such as diverging rollers to provide increased accuracy in selecting size ranges for the counter rotating rollers.
3. Evaluate effect of roller diameter, roller surface finish, and groove design on cracking efficiency.

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APPENDIX A

DATA FROM TEST 1 EFFECT OF FIVE SEED MOISTURE CONTENT AND TWO COMPRESSION LOAD ORIENTATIONS

Table A1. Experimental data obtained from test 1: The effect that seed moisture content and the orientation has on the force, deformation, and energy up to the shell rupture. For five moisture content and two compression load orientations.

TREAT	MC % WB	ORIENTA TION	REP	FORCE N	DEF mm	ENERGY Nm
			1	229.78	1.16	0.1582
			2	282.30	1.20	0.1784
			3	364.64	1.32	0.2671
			4	279.64	1.31	0.2070
1	8.9	1	5	234.21	1.13	0.1541
			6	211.98	1.05	0.1307
			7	180.95	0.71	0.0728
			8	310.41	1.39	0.2468
			9	175.83	0.66	0.6640
			10	310.63	1.39	0.2464
			1	271.83	1.12	0.1672
			2	213.63	1.11	0.1225
			3	253.37	1.74	0.1492
			4	316.42	1.29	0.2134
2	8.9	2	5	269.46	1.03	0.1477
			6	274.70	1.35	0.1906
			7	244.06	1.42	0.1452
			8	230.50	1.18	0.1366
			9	185.72	0.80	0.0896
			10	236..80	1.00	0.1261

Table A1. Continued.

TREAT	MC % WB	ORIENTATION	REP	FORCE N	DEF mm	ENERGY Nm
			1	160.88	0.96	0.0943
			2	175.51	0.88	0.0904
			3	258.10	1.02	0.1526
			4	148.66	0.87	0.0780
			5	84.09	0.35	0.0190
3	17.66	1	6	185.27	1.00	0.1064
			7	159.60	0.88	0.0854
			8	190.66	0.99	0.1133
			9	70.51	0.26	0.0119
			10	157.315	0.84	0.0800
			1	136.20	1.19	0.0649
			2	110.24	0.80	0.0459
			3	76.85	1.99	0.0263
			4	103.06	1.86	0.0350
4	17.66	2	5	136.89	1.34	0.0887
			6	84.43	1.34	0.0298
			7	94.25	0.41	0.0242
			8	128.53	0.61	0.0440
			9	134.49	0.92	0.0734
			10	206.65	1.47	0.0179

Table A1. Continued.

TREAT	MC % WB	ORIENTA TION	REP	FORCE N	DEF mm	ENERGY Nm
			1	110.41	0.61	0.0420
			2	140.40	0.85	0.0729
			3	111.98	0.75	0.0506
			4	65.99	0.24	0.0104
5	19.95	1	5	131.54	0.81	0.0633
			6	101.67	0.65	0.0420
			7	119.77	0.87	0.0647
			8	257.37	1.35	0.1945
			9	263.92	1.43	0.2285
			10	138.30	0.90	0.0729
			1	212.29	1.12	0.1230
			2	147.03	0.85	0.0740
			3	184.43	1.01	0.0850
			4	153.97	0.81	0.0680
6	19.95	2	5	145.49	0.85	0.0770
			6	229.03	1.15	0.1580
			7	100.69	0.64	0.0410
			8	107.38	0.65	0.0420
			9	177.07	1.30	0.2120
			10	123.46	0.61	0.0430

Table A1. Continued.

TREAT	MC % WB	ORIENTATION	REP	FORCE N	DEF mm	ENERGY Nm
			1	176.83	1.05	0.0118
			2	142.04	0.89	0.0753
			3	126.46	0.63	0.0494
			4	109.38	0.64	0.0405
7	20.73	1	5	123.17	0.63	0.0475
			6	132.78	0.84	0.0694
			7	188.17	1.35	0.1386
			8	154.90	0.75	0.0680
			9	92.08	0.40	0.0228
			10	190.06	0.97	0.1082
			1	63.43	1.46	0.0158
			2	213.69	1.03	0.1301
			3	81.66	0.49	0.0242
			4	87.33	0.43	0.2321
8	20.73	2	5	124.30	1.25	0.5153
			6	124.30	1.25	0.8689
			7	205.34	1.20	0.1400
			8	101.87	0.95	0.0614
			9	118.64	0.84	0.0599
			10	119.03	0.70	0.0499

Table A1. Continued.

TREAT	MC % WB	ORIENTATION	REP	FORCE N	DEF mm	ENERGY Nm
			1	130.95	0.81	0.0645
			2	254.57	1.11	0.1670
			3	157.27	0.82	0.0757
			4	284.50	1.03	0.0164
9	23.16	1	5	120.16	0.63	0.0457
			6	208.60	1.16	0.1383
			7	133.30	0.90	0.0694
			8	162.33	0.75	0.0762
			9	85.90	0.33	0.0178
			10	123.23	0.45	0.0336
			1	226.73	1.03	0.1365
			2	206.79	1.01	0.1146
			3	239.49	0.92	0.1274
			4	115.10	0.94	0.0483
10	23.16	2	5	138.97	0.80	0.0630
			6	121.70	0.86	0.0647
			7	53.65	0.23	0.0083
			8	97.63	0.60	0.0277
			9	207.45	1.78	0.1192
			10	204.66	1.20	0.1393

Table A.2. Results of the LSD test. Testing the effect of 5 moisture content levels in position 1 on the force.

Source	df	Mean square
Model	4	22909.54
Error	45	3199.34
Total	49	

Table A.3. Results of the LSD test. Testing the effect of 5 moisture content levels in position 2 on the force.

Source	df	Mean square
Model	4	27078.90
Error	45	2121.70
Total	49	

Table A.4. Results of the LSD test. Testing the effect of 5 moisture content levels in position 1 on the seed deformation.

Source	df	Mean square
Model	4	0.2026
Error	45	0.0812
Total	49	

Table A.5. Results of the LSD test. Testing the effect of 5 moisture content levels in position 2 on the seed deformation.

Source	df	Mean square
Model	4	0.2412
Error	45	0.1302
Total	49	

Table A.6. Results of the LSD test. Testing the effect of 5 moisture content levels in position 1 on the energy.

Source	df	Mean square
Model	4	0.0120
Error	45	0.0033
Total	49	

Table A.7 Results of the LSD test. Testing the effect of 5 moisture content levels in position 2 on the energy.

Source	df	Mean square
Model	4	0.0124
Error	45	0.0019
Total	49	

APPENDIX B

DATA FROM TEST 2 EFFECT OF SEED SIZE AND TWO LOAD ORIENTATIONS

Table B1. Experimental data obtained from test 2: The effect that seed size and two load orientations has on the force, deformation, and energy up to the shell rupture.

TREAT	NUT SIZE	ORIENTA TION	REP	FORCE N	DEF mm	ENERGY Nm
			1	210.06	1.03	0.1203
			2	184.21	0.72	0.0795
			3	228.71	0.95	0.1241
			4	237.58	1.11	0.1544
1	SMALL	1	5	223.67	1.06	0.1379
			6	215.46	0.86	0.1029
			7	221.84	1.18	0.1585
			8	254.309	0.95	0.1364
			9	246.164	1.14	0.1556
			10	211.89	0.75	0.8782
			1	140.10	1.24	0.0586
			2	148.85	0.67	0.0578
			3	158.13	0.76	0.0691
			4	141.38	1.29	0.0539
2	SMALL	2	5	132.63	0.51	0.0404
			6	178.48	0.70	0.0722
			7	178.44	0.86	0.0913
			8	165.16	0.74	0.0689
			9	149.99	0.56	0.4943
			10	203.52	0.86	0.1003

Table B1. Continued.

TREAT	NUT SIZE	ORIENTA TION	REP	FORCE N	DEF mm	ENERGY Nm
			1	234.72	1.02	0.1382
			2	176.36	0.70	0.0739
			3	250.55	1.15	0.1597
			4	238.03	1.15	0.1601
			5	181.05	0.67	0.0695
3	MEDIUM	1	6	199.21	0.62	0.6982
			7	310.06	1.23	0.2167
			8	365.78	1.38	0.2771
			9	258.74	1.07	0.1600
			10	290.09	1.77	0.2447
			1	207.97	1.68	0.1119
			2	181.20	0.77	0.0758
			3	215.73	0.74	0.0886
			4	250.29	1.17	0.1376
4	MEDIUM	2	5	254.46	1.18	0.1614
			6	297.29	1.23	0.1979
			7	309.89	1.57	0.1825
			8	349.12	1.21	0.2293
			9	184.54	0.83	0.0855
			10	161.88	0.79	0.0766

Table B1. Continued.

TREAT	NUT SIZE	ORIENTA TION	REP	FORCE N	DEF mm	ENERGY Nm
			1	355.82	1.20	0.2260
			2	237.82	1.24	0.1805
			3	311.80	1.56	0.2795
			4	329.08	1.55	0.2885
5	LARGE	1	5	251.50	1.17	0.1470
			6	322.49	1.28	0.2247
			7	280.34	1.47	0.2386
			8	240.84	0.83	0.1138
			9	385.84	1.63	0.3455
			10	334.41	1.44	0.2673
			1	239.46	1.22	0.1472
			2	309.55	1.41	0.1978
			3	244.14	1.15	0.1603
			4	230.84	0.85	0.1108
6	LARGE	2	5	223.40	1.01	0.1248
			6	266.14	1.25	0.1694
			7	354.37	1.09	0.2163
			8	205.69	0.75	0.0812
			9	289.80	0.91	0.1464
			10	262.55	1.07	0.1504

Table B.2. Results of the LSD test. Testing the effect of 3 seed sizes in position 1 on the force.

Source	df	Mean square
Model	2	16696.07
Error	27	2486.34
Total	29	

Table B.3. Results of the LSD test. Testing the effect of 3 seed sizes in position 2 on the force.

Source	df	Mean square
Model	2	25933.45
Error	27	1822.10
Total	29	

Table B.4. Results of the LSD test. Testing the effect of 3 seed sizes in position 1 on the seed deformation.

Source	df	Mean square
Model	2	0.5298
Error	27	0.0736
Total	29	

Table B.5. Results of the LSD test. Testing the effect of 3 seed sizes in position 2 on the seed deformation.

Source	df	Mean square
Model	2	0.3116
Error	27	0.0898
Total	29	

Table B.6. Results of the LSD test. Testing the effect of 3 seed sizes in position 1 on the energy.

Source	df	Mean square
Model	2	0.0133
Error	27	0.0492
Total	29	

Table B.7. Results of the LSD test. Testing the effect of 3 seed sizes in position 2 on the energy.

Source	df	Mean square
Model	4	0.0124
Error	45	0.0019
Total	49	

APPENDIX C

DATA FROM TEST 3 EFFECT OF LOADING RATE ON THE FORCE

Table C1. Experimental data obtained from test 3: The effect that the loading rate has on the force up to the shell rupture for one moisture content and one load orientation.

TREAT.	MC % WB	ORIENTA TION	VELOCITY mm/s	REP	FORCE N
				1	194.55
				2	210.58
1	8.9	1	0.1	3	206.80
				4	324.68
				5	185.82
				1	191.77
				2	240.02
2	8.9	1	0.5	3	261.95
				4	171.65
				5	241.83
				1	230.47
				2	183.79
3	8.9	1	1	3	236.32
				4	255.60
				5	217.07
				1	192.98
				2	292.37
4	8.9	1	5	3	226.17
				4	209.77
				5	204.18
				1	282.65
				2	233.03
5	8.9	1	10	3	271.33
				4	274.27
				5	341.56

Table C.2. Statistical analysis (LSD) comparing the mean force values for five cell velocities when it is compressed in one orientation.

FORCE FOR ORIENTATION 1

(LSD)

α=0.05 df=16

Critical value of T=2.12

Least Significant Difference=59.53

Means same letter are not significantly diff

T Grouping	Mean	N	Velocity mm/s
A	280.57	5	10.0
A			
A	225.10	5	5.0
A			
A	224.65	5	1.0
A			
A	224.49	5	0.1
A			
A	221.44	5	0.5

APPENDIX D

STATISTICAL ANALYSIS OF THE SHELLER EXPERIMENTAL DEVICE PERFORMANCE

Table D.1. Statistical analysis Tukey's test for shelled seeds size 18-20 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

SHELLED SEEDS 18-20

α=0.05 df=6 MSE= 38

Minimum Significant Difference= 15.44

Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	72.66	3	One seed
A			
A	69.33	3	One class
A			
A	69.33	3	Four classes

Table D.2. Statistical analysis Tukey's test for shelled seeds size 20-22 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

SHELLED SEEDS 20-22

α=0.05 df=6 MSE= 25.66

Minimum Significant Difference= 12.69

Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	74.66	3	One seed
A			
A	74.66	3	One class
A			
A	71.33	3	Four classes

Table D.3. Statistical analysis Tukey's test for shelled seeds size 22-24 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

SHELLED SEEDS 22-24

α=0.05 df=6 MSE= 11.88
Minimum Significant Difference= 8.63
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	74.33	3	One seed
A			
A	72.00	3	One class
A			
A	67.33	3	Four classes

Table D.4. Statistical analysis Tukey's test for shelled seeds size 24-26 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

SHELLED SEEDS 24-26

α=0.05 df=6 MSE= 34.66
Minimum Significant Difference= 14.75
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	69.66	3	One seed
A			
A	68.33	3	One class
A			
A	65.33	3	Four classes

Table D.5. Statistical analysis Tukey's test for non shelled seeds size 18-20 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

NON SHELLED SEEDS 18-20

α=0.05 df=6 MSE= 88.22

Minimum Significant Difference= 23.53

Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	17.66	3	One seed
A			
A	15.00	3	One class
A			
A	9.33	3	Four classes

Table D.6. Statistical analysis Tukey's test for non shelled seeds size 20-22 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

NON SHELLED SEEDS 20-22

α=0.05 df=6 MSE= 39.44

Minimum Significant Difference= 15.73

Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	12.66	3	One seed
A			
A	5.00	3	One class
A			
A	4.00	3	Four classes

Table D.7. Statistical analysis Tukey's test for non shelled seeds size 22-24 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

NON SHELLED SEEDS 22-24

α=0.05 df=6 MSE= 14.88
Minimum Significant Difference= 9.66
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	9.33	3	One seed
A			
A	3.66	3	One size
A			
A	3.00	3	Four sizes

Table D.8. Statistical analysis Tukey's test for non shelled seeds size 24-26 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

NON SHELLED SEEDS 24-26

α=0.05 df=6 MSE= 20.88
Minimum Significant Difference= 11.45
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	7.33	3	One seed
A			
A	6.33	3	One size
A			
A	6.00	3	Four sizes

Table D.9. Statistical analysis Tukey's test for partially shelled seeds size 18-20 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

PARTIALLY SHELLED SEEDS 18-20

α=0.05 df=6 MSE= 0.55
Minimum Significant Difference= 1.86
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	0.666	3	One seed
A			
A	0.666	3	One class
A			
A	0.00	3	Four classes

Table D.10. Statistical analysis Tukey's test for partially shelled seeds size 20-22 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

PARTIALLY SHELLED SEEDS 20-22

α=0.05 df=6 MSE= 1.77
Minimum Significant Difference= 3.34
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	1.00	3	One seed
A			
A	1.00	3	One class
A			
A	0.66	3	Four classes

Table D.11. Statistical analysis Tukey's test for partially shelled seeds size 22-24 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

PARTIALLY SHELLED SEEDS 22-24

α=0.05 df=6 MSE= 1.33
Minimum Significant Difference= 2.89
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	1.33	3	One seed
A			
A	0.66	3	One class
A			
A	0.33	3	Four classes

Table D.12. Statistical analysis Tukey's test for partially shelled seeds size 24-26 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

PARTIALLY SHELLED SEEDS 24-26

α=0.05 df=6 MSE= 2.88
Minimum Significant Difference= 4.25
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	1.33	3	One seed
A			
A	1.00	3	One class
A			
A	0.33	3	Four classes

Table D.13. Statistical analysis Tukey's test for damaged seeds size 18-20 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

DAMAGED NUTS 18-20

α=0.05 df=6 MSE= 22.66
Minimum Significant Difference= 11.92
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	13.66	3	One seed
A			
A	10.33	3	One class
A			
A	7. 66	3	Four classes

Table D.14. Statistical analysis Tukey's test for damaged seeds size 20-22 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

DAMAGED NUTS 20-22

α=0.05 df=6 MSE= 52.88
Minimum Significant Difference= 18.21
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	17.33	3	One seed
A			
A	15.0	3	One class
A			
A	11. 66	3	Four classes

Table D.15. Statistical analysis Tukey's test for damaged seeds size 22-24 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

DAMAGED NUTS 22-24

α=0.05 df=6 MSE= 27.55
Minimum Significant Difference= 13.15
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	21.33	3	One seed
A			
A	21.00	3	One class
A			
A	15.33	3	Four classes

Table D.16. Statistical analysis Tukey's test for damaged seeds size 24-26 comparing the three different ways to feed the machine. One seed at a time for each class, one class at a time, and the four classes at the same time.

DAMAGED NUTS 24-26

α=0.05 df=6 MSE= 57.44
Minimum Significant Difference= 18.98
Means same letter are not significantly different

Tukey Grouping	Mean	N	Feed Type
A	20.33	3	One seed
A			
A	20.00	3	One class
A			
A	17.00	3	Four classes

APPENDIX E

ROUNDNESS AND SPHERICITY CALCULATIONS

<u>Roundness</u>

Small:

$$A_p = \frac{\pi}{4} * (11.75\ mm) * (6.14\ mm) = 56.66\ mm^2 \qquad (E.1)$$

$$A_c = \pi * (5.87\ mm)^2 = 108.4$$

$$R = \frac{56.660\ mm}{108.43\ mm} = 0.52$$

Medium:

$$A_p = \frac{\pi}{4} * (13.87\ mm) * (7.49\ mm) = 81.59\ mm^2 \qquad (E.2)$$

$$A_c = \pi * (6.93\ mm)^2 = 151.09\ mm^2$$

$$R = \frac{56.660\ mm}{108.43\ mm} = 0.54$$

Large:

$$A_p = \frac{\pi}{4} * (16.36\ mm) * (9.04\ mm) = 116.15\ mm^2 \qquad (E.3)$$

$$A_c = \pi * (5.87\ mm)^2 = 210.21\ mm^2$$

$$R = \frac{56.660\ mm}{108.43\ mm} = 0.52$$

Sphericity

Small:

$$di = 6.14 \text{ mm} \quad (E.4)$$

$$d_c = 11.75 \text{ mm}$$

$$S = \frac{6.140 \text{ mm}}{11.75 \text{ mm}} = 0.52$$

Medium:

$$di = 7.49 \text{ mm} \quad (E.5)$$

$$d_c = 13.87 \text{ mm}$$

$$S = \frac{7.490 \text{ mm}}{13.87 \text{ mm}} = 0.54$$

Large:

$$di = 7.49 \text{ mm} \quad (E.6)$$

$$d_c = 13.87 \text{ mm}$$

$$S = \frac{7.490 \text{ mm}}{13.87 \text{ mm}} = 0.54$$

APPENDIX F

MATERIALS OF THE SHELLER EXPERIMENTAL DEVICE

LIST OF MATERIALS

The materials presented in table below are shown in figures F.1, F.2, and F.3.

PART No.	DESCRIPTION	QUANTITY
1	Feeder hopper	1
2	Cold rolled shaft (3/4" Dia. X 26")	1
2A	Shaft coupling (2 1/2" L. X 3/4 Bore Dia.)	1
3	Guard	2
4	Drive system	1
5	Variable speed motor	1
5A	Variable sheave	1
5B	Gear reducer	1
6	Main frame (45" X 22" X 35")	1
7	Basket	1
8	Gap adjusters	2
9	Rollers (18" X 4" Dia.)	2
10	Drive spur gear (5 1/2" Pitch Dia. X 3/16)	1
11	Drive chain	1
12	Tensioner	1
13	Driven spur gear (5 1/2" Pitch Dia. X 3/16)	1
14	Universal joint	2
15	Mounted bearings (5" X 1 1/2" X 2 3/4",3/4 Bore Dia)	8

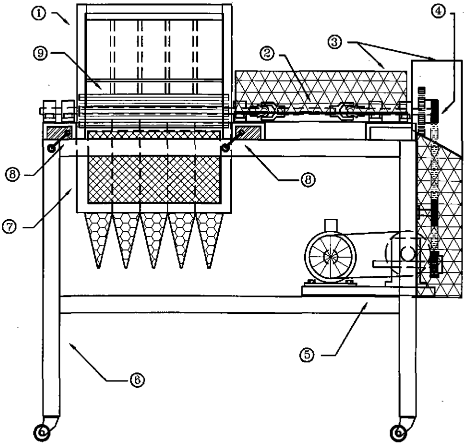

Figure F.1. Front view of the device.

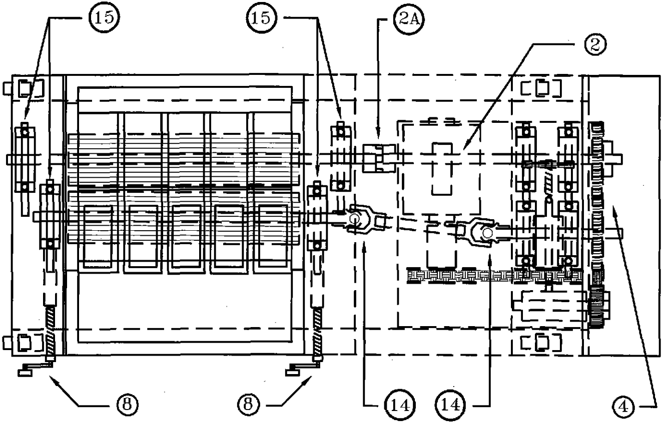

Figure F.2. Top view.

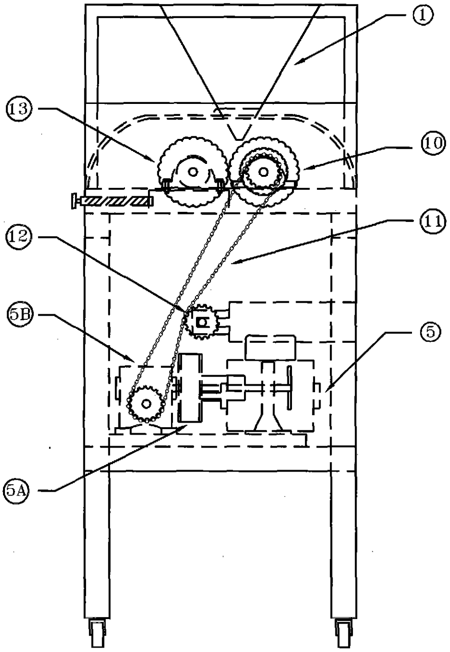

Figure F.3. Side view.

VITA

Jesús Menchaca Lara was born in Saltillo, Coahuila, México on August 27, 1969.

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