MECHANICAL COMPRESSION OF FOOD PRODUCTS DURING FREEZE-DRYING THROUGH FORCE PRODUCED BY SPRINGS

by

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Submitted to the Department of Nutrition and Food Science on January 21, 1976 in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Freeze-drying has been successfully used in preparation of high quality dried foods; however, a major disadvantage is the resulting low product density. This study has investigated the possibility of compressing food materials during freeze-drying to increase their bulk density.

The dependence of degree of compression on compressive force, dry sample moisture contents, and rehydration behavior were determined for a variety of vegetable, fruit, and meat materials. A simple spring driven device was used to supply the compressive force during freeze-drying.

The results indicate that the extent of compression depends on the physical characteristics of the food material

and increases linearly with increasing compressive force.

The compression process does not prevent dehydration of the material to low moisture contents.

Compressed samples rehydrate readily to their pre-compression characteristics (except blueberries) and the extent of rehydration does not depend on the degree of compression (except beef cubes).

Organoleptically compressed samples are not significantly different from non-compressed freeze-dried foods.

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Title: Assistant Professor of Food Engineering

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Although this is an early page of this paper, but is the last and hardest to be written, since I have never been able to express my feelings with words. Nonetheless, I will make an effort to express my thanks to all those who have made this work possible.

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Notation

Rehyd.	Rehydration
Comp. Ratio	Compression Ratio
M.C.	Moisture Content
T.S.	Total Solids
Ave.	Average
wt.	Weight
Ht.	Height
Comp.	Compressed
N.Comp.	Non-Compressed

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1. INTRODUCTION

Freeze-drying has been recognized as the method of dehydration giving dried products having the best quality and retained nutritional value. This technique is now begining to emerge as an important method of dehydration. However, when foods undergo freeze-drying very little change in the physical shape of the material occurs. This results in an open and porous structure which yields a very light and fragile product of low packaging density. The disadvantages related to low packaging density can be summarized as:

- The open structure is very susceptible to oxidation and moisture pickup; and thus special packaging is often required.
- Large package volumes are required to enclose small product weights.
- Readily friable products produce fines during handling and transportation which is essentially wastage of the products.
- Large storage space is required.

A more efficient food system will result by eliminating or minimizing the above mentioned effects. This can be accomplished by compressing the food to remove the void volumes which have been produced by sublimation of ice crystals during the drying process.

To accomplish efficient compression, it is necessary to have the food solids in a plastic state, so when high compression pressures are applied to the product fragmentation can be avoided. This has been achieved either by thermaly plasticizing the dried food, which requires that the food should contain a relatively high sugar content, or by controlled humidification of the dry product to a uniform moisture content in the range of 5-20 percent. Depending on physical characteristics of the food there is an optimum moisture content range for best compression behavior. When the controlled humidification process is used, the added water has to be removed from the compressed wafer or bar to give long-term storage stability.

If it should be possible to remove the sample from the freeze-dryer when a uniform moisture content of the desired level is reached, the initial overdrying and humidification steps of the controlled humidification process can be eliminated. However, with ordinary freeze-drying methods this is not possible since the remaining water is concentrated in the center of the freeze-dried sample as an ice core. By allowing the ice core to melt for redistribution in the sample the region of the core will have an air-dried character and may be hard and discolored. Furthermore different pieces dry at different rates which makes it hard to reach the optimum moisture content in all pieces at the same time. (Hoge and Filsworth, 1973)

Recent studies indicate that with controlled freeze-drying or modified freeze-dryers, it is possible to reach a predetermined uniform moisture content throughout the samples. However, this will have a significant effect on the rate of freeze-drying and the final drying after compression is still required.

Previous investigations of moisture profiles during freeze drying indicate that over a narrow thickness of the dry layer adjacent to the ice interface, high moisture contents exist. (Aguilera and Flink, 1974)

This study is investigating an approach in which it is assumed that the moisture gradients present during the freeze-drying will give sufficient plasticity to allow compression during "normal" freeze drying.

This method for production of compressed freeze-dried foods should be the most efficient, since it does not require either overdrying and humidification or operation at much reduced dry layer temperatures.

1. Investigating the feasibility of simultaneously transmitting compressive force while allowing vapor transport.

2. Determining the effect of compression during freeze drying on the final moisture content.

3. Determining the relationship between compressive force and compression ratio.

4. Determining rehydration behavior of compressed samples (versus non-compressed controls) in terms of time dependence and percent of rehydration in reference to the ratio of:

$$\frac{\text{gr } H_2O}{\text{Total Solids (Rehydrated)}} \Big/ \frac{\text{gr } H_2O}{\text{Total Solids (Fresh)}}$$

5. Evaluations of the acceptability of reconstituted compressed samples (versus non-compressed freeze-dried controls and fresh samples.)

2. LITERATURE SURVEY

Most studies on compression of dehydrated foods to reduce bulk volume have been conducted with freeze-dried product. Since this study investigated continuous compression of food during freeze-drying some basic aspects of the freeze-dehydration technique will be presented before concentrating on a discussion of methods of food compression.

2.1 Freeze-Drying:

Vacuum freeze-drying on a larger than laboratory scale was first developed for the preservation of blood plasma and later penicillin during World War II (Flosdor, 1949). Today this process is widely used for the preservation of a variety of substances including; antibiotics, vaccines, virus cultures, pharmaceuticals, and on the largest scale, food-stuffs.

General descriptions of freeze-drying have been given by many authors (Rowe,1964; Rey, 1964; VanArsdel, 1964; and Cotson and Smith, 1962). Three comprehensive reviews of freeze-drying research have been published. (Harper and Tappel, 1957; Bruke and Decareau, 1964; King, 1971). King (1971) especially concentrates on the pertinent factors which interact to govern rates of freeze-drying.

The principle of freeze-drying is to reduce the temperature of the product to below its eutectic point, a temperature low enough to ensure complete solidification of all constituents, and then to lower the surronding water vapor pressure to below the saturated vapor pressure at this temperature. Under these conditions water vapor will tend to be transported from the food to the "surrondings". To accomplish this sublimation of ice the heat of sublimation (about 1200 BTU/lb of H_2O) must be supplied from a heat source. This can be achieved by radiation to the outer dry layer of a food being freeze-dried, by conduction through the frozen layer or by internal heat generation (microwaves). It is also necessary to remove the water vapor generated by sublimation by having a moisture sink (King, 1971).

Advantages of this technique include the low processing temperature, the relative absence of liquid water and the rapid transition of any local region of the material from a fully hydrated to a nearly completely dehydrated state. This rapid transition minimizes the extent of various degradative reactions which often occur during drying. The low temperatures involved also help to minimize these reactions and to reduce mass transport rates which control the loss of volatile flavor and aroma species. The absence of the liquid state helps to minimize degradative reactions and prevents the transport of soluble species from one region to another within the substance being dried, (i.e. it inhibits surface concentration). (King, 1971) Despite all these advantages, freeze-drying has some drawbacks which include: high initial capital investment, high processing costs, special treatment (cutting, slicing, etc...) of some products prior to drying to improve dehydration, and producing products of very low density. (F. Longmore, 1973)

2.2 The Frozen State and the Ice Front:

The most important change that occurs during freezing is the appearance of at least one new phase (i.e. conversion of water into ice). Other changes include:

1. Dehydration of the insoluble solid material.
2. Coalescence of droplets of immiscible liquids.
3. Crystallization of some solutes.
4. Formation of amorphous precipitates of other solutes.
5. Exclusion of dissolved gases.
6. Formation of concentrated solute glasses.
7. Distruption of molecular complexes (lipoprotein), (MacKenzie, 1965).

Thus the ideal frozen state would show a sharp and discrete dividing surface between a region which consists of ice crystals and a region which consists of concentrated amorphous solution.

During freeze-drying the ice region retreats inwards as the drying proceeds leaving the dried matrix behind.

Most analysis of freeze-drying rates have been made with the postulation of a sharp and discrete dividing surface between a region which is fully hydrated and frozen, and a region which is nearly completely dry. However, there is a considerable amount of contention in recent years regarding the degree of sharpness of this surface when it is retreating as a frozen front during freeze-drying. King (1971) reviews the evidence for a sharp front versus evidence for a diffuse sublimation front. He explains that a very sharp front would result if sublimation occured from a very thin zone near the surface of the frozen region, and if the sublimation removed essentially all of the initial moisture from the remaining solid material immediately after the passage of the frozen front from that region. This is clearly an idealization but has been assumed by most authors to be a good description of the mechanism of freeze drying.

2.2.1 Evidence for a Diffuse Sublimation Front:

Meffert (1963) measured temperature profiles during freeze-drying of rutabaga. From the temperature and thermal conductivities inferred from them he concluded that some 30 percent to 40 percent of the initial water content was left behind by the retreating ice front.

This remaining H_2O had to be removed by secondary drying or desorption.

Brajnikov et al (1969) indicated that the results of some experiments demonstrated the presence of a diffuse sublimation front. In one experiment he took color photographs of cut specimens of beef which had been freeze-dried once, rehydrated with a solution of $CoCl_2$ and then partially freeze-dried again. Divalent cobalt has the property of changing color from pink to blue depending on water activity of its surroundings. Brajnikov's experiments with $CoCl_2$ indicated the presence of a transition zone; however, King (1971) has noted that the cobalt salt can lower the freezing point which could cause the presence of some liquid at the sublimation front, even at -20°C.

Luikov (1969) observed the sublimation behavior of pure ice spheres (80 mm diameter) which were sublimed in a vacuum chamber at -33°C. Luikov observed that ice crystallites of various shapes and lengths (from 0.1 to several mm) formed at the sublimation front near surface irregularities. Their growth was observed visually and it was found that crystallites could oscillate and rotate rapidly at speeds up to 70rpm existing for 20 to 30 revolutions. These oscillations reflect molecular pressure from the escaping vapor. Often the crystallite would break from the ice surface and be entrained in the vapor at velocities of .70 to .36 meter per second. Luikov (1969) and others have pointed out that the very great and sudden expansion of water from the solid to the highly expanded vapor state upon vacuum sublimation can cause strong forces and unusual flow patterns. Local unevenness of temperature along the sublimation front can also cause mechanical stresses which can cause the crystallite to break off and be entrained. Luikov suggests that this entrainment mechanism can have an important effect on the observed rate of sublimation of ice, since this would amount to the removal of moisture without the transfer of an equivalent amount of heat to the sublimation front. Luikov also found that sublimation and ablimation (desublimation from vapor state to solid state) occur simultaneously at the sublimation front of an ice sphere. The occurance of ablimation was confirmed by Luikov in experiments involving vacuum sublimation of water vapor from spherical ice crystals made from water containing red fucin dye. Crystallites formed directly from the solid phase appeared red, but those formed by ablimation were transparent and colorless. The tendency for ablimation to occur depends upon the degree of saturation of surrounding gas phase with water vapor. Ablimation occurs to a greater extent as the surrounding gas became more nearly saturated in water vapor. Ablimation can also occur in a supersaturated zone removed from the ice surface in the vapor phase. King (1971) states that the studies made by Luikov can account for a transition zone with a thickness of perhaps a mm, but not for a zone with a thickness of an inch or more.

2.2.2 Evidence for a Sharp Sublimation Front:

Many investigators have reported cutting open partially freeze-dried specimens and observing a distinct and relatively sharp demarkation between the still frozen zone and dry zone of uniform coloration. These include Hardin (1965) who studied freeze-dried beef, Margaritis and King (1969) who studied freeze-drying turkey meat and Beke (1969) who studied freeze-drying of pork.

Additional evidence was obtained by Hatcher (1964) who used gamma ray attenuation measurements to monitor the profile of moisture content across relatively thick (2 inches) slabs of beef as a function of time during freeze-drying. Hatcher reports that visual inspection of partially dried specimens revealed the ice front to be planner. Since his gamma ray beam diameter was $\frac{3}{16}$ inch he concluded that the ice front was sharper than could be detected by the beam. He also found that the residual moisture in the dry zone was so low that it did not affect the gamma ray count rate.

However, non-uniform retreat of a still sharp ice front has been found by Margaritis and King, and Hatcher (1964) also has reported some preferential drying from the edge of his samples.

MacKenzie (1966) constructed a "freeze-drying microscope" in which he could observe freeze-drying as it occured in various transparent frozen liquid systems. An extremely sharp sublimation front was observed, although the front, while sharp, did not necessarily remain planner. There should be a finite partial pressure of water vapor in the gas within the dry layer, since the water vapor generated by sublimation must escape across the dry layer. One would therefore expect a finite amount of sorbed water to be present in the dry layer corresponding at least to the amount that would be predicted by equilibrium sorption isotherm. Sandall (1966) made calculations for typical conditions of freeze-drying of turkey breast meat using the sorption isotherms for the same material that was measured by King et al (1968). For heating from the outer dry surface he condluded that equilibrium between the dry layer and the escaping water vapor would give an average moisture content within the dry layer equal to 3 percent of the initial water, or about 1.5 percent moisture content on a solid basis. However, this surprisingly low value results from the increasing temperature across the dry layer toward the outer surface as well as from the decreasing water vapor partial pressure. (King, 1971) However, one would expect that the degree of the sharpness of the ice front during freeze-drying mainly reflect the condition(s) of freeze-drying. Important parameters which seem directly to effect broadening of the front are pressure and, temperature difference between local temperature and ice front temperature. Bralsford (1967) postulated the existence of a "diffusion zone" broadening which was due to solute migration which gives more and more ice being melted as the zone recedes into ice core. He felt that at higher chamber pressures more liquid water is present in the ice core which results in some liquid diffusion into the dry layer. Aguilera and Flink (1974) calculated moisture profiles from temperature measurements during freeze-drying. Their calculation was based on the relationship between bound water content (W_B) and temperature difference ($\triangle T_B$) between any position in the dry layer (desorption temperature) and the temperature of ice (sublimation temperature) which was originally postulated by Gentzler and Schmidt (1973) The mathematical expression is based on higher desorption temperatures for bound water as compared with the sublimation temperature for frozen water and can be expressed as:

$$W_B = e^{(a\ T_B + b)}$$

where a and b are constants dependent on each particular product. Aguilera and Flink (1974) based on their experimental results reported that due to above relationship higher moisture contents are to be expected at a given distance from the ice front as drying preceeds. Their results show that at a heater temperature of 128°C. and a surface temperature of 56°, the diffusion zone was about 2 mm when the ice front had retreated 5 mm (after 2.5 hrs), and when the ice had retreated about 15 mm the diffusion zone increased to about 5 mm (after 9 hrs).

Another factor which seems to effect the degree of broadening of the diffusion zone is freezing method. This is discussed in the following section.

2.3 State of Water and of Solutes in Frozen and Freeze-Dried Systems:

The state of water bound to polymers has been investigated using various physical and physicochemical methods of analysis. Karel and Flink (1973) explain that recent Nuclear Magnetic Resonance studies and infrared work indicate that water bound to polymers is less "free" than water in solution, and more "free" than water in ice crystals.

The thermodynamic confirmation of the greater mobility of the non-freezable water in muscle derived foods compared to the water in ice as stated by Karel and Flink (1973) is shown by Riedel who studied the apparent specific heat of frozen beef. The specific heat for bound water (unfreezable water) calculated by Riedel was intermediate between that of ice and pure unfrozen water. Since specific heat reflects molecular mobility, "bound" water is evidently more mobile than water in ice.

A.P. MacKenzie and B.J. Luyet (1967) showed that water binding properties of ox-muscle, expressed in the form of water adsorption isotherms, were markedly dependent upon the manner of initial freezing and at the same time practically independent of the freeze-drying procedure. They concluded that the quantity of water contained in the monolayer is not affected by the manner of freezing or by the freeze-drying treatment; however, the energy with which the monolayer is bound is greatly increased when the initial freezing velocity is raised while not affected by freeze-drying procedure. They also showed that at a given constant relative humidity quickly frozen, dried sample holds more water than slowly frozen dried samples.

Karel and Flink (1973) explained that in slow freezing, the resultant high salt concentration acts on muscle protein long enough to cause dislocation and aggregation. The total number of accessible hydrophylic sites does not change, hence there is no effect of rate of freezing on monolayer value. However, the access to these sites is more difficult and this is thermodynamically equivalent to reducing the energy of water binding site and it similarly explains the requirement for a higher relative humidity for a given amount of water bound by the protein.

The above explanation and the results obtained by MacKenzie and Luyet (1967) could indicate that freezing rate may influence moisture gradients at the ice interface during freeze-drying.

2.4 Methods of Compressing Dehydrated Foodstuff:

The technique of compression was introduced to the industry in the late 30s. The British Ministry of Agriculture, Fisheries and Food, through their experimental factory in Aberdeen experimented with the compression of vegetables, especially carrots, cabbage and fruit bars, (M.M. Hamdy, 1960).

During 1942-1943, M.I.T. carried out a research program on the compression of dehydrated foods. The Agricultural Research Administration of the U.S.D.A. conducted a food compression project in 1943 and 1944, and the Defense Research Medical Laboratories in Canada worked on the development of meat and fruit bars (M.M. Hamdy, 1960). After 1944 the interest in compression of foods faded until

1960 when the U.S. Army Quartermaster Corps initiated new research projects in compressing dehydrated foods. Since then there has been an increasing interest in compressed foods, with most of the research being sponsored by the U.S. Army and reported by Rhaman, Brockman, Henning, Westcott, Schafer and others.

In all methods employed the most important factor necessary for successful compression is that the food has to be in a plastic state. Most dehydrated foods with low moisture contents are very fragile and fragment even under light compressive pressures. In this section the past and present developments of methods for compression of foods are examined. The section is generally subdivided according to the preconditioning techniques that have been employed prior to compression.

2.4.1 Moisture Content:

Moisture content has a pronounced effect on the texture of food materials. It is known that most low moisture foods (generally less than 5 percent) are brittle and fragile. Accordingly they do not yield to compression without destroying the character of food product. Foods of low soluble solid (sugar) contents, are fragile when below 3 percent moisture. Vegetables of all kinds (shredded, diced, etc...) were found to fragment easily at low moisture. Pulverized and powdery dehydrated foods; however, are expected to be less affected by compression at low moisture content (Hamdy, 1960). Nevertheless, moisture content in the range of 5-20 percent has a large plasticizing effect on most foods.

Kapsalis et al (1970a) in a study of mechanical properties of low and intermediate moisture foods found important changes of the textural properties of precooked, freeze-dried beef in the range of a_w, 0.15-0.3, which corresponds to a moisture content range of 5-10% moisture content.

In another study of precooked, freeze-dried beef Kapsalis et al (1970b) reported that the mechanical properties of hardness and cohesiveness (as defined by Szczeniak, 1963) increased with increase in relative humidity from 0-66%, whereas, the mechanical property called the crushability index (as defined by Drake, 1966) and the sensory property "ease of biting" decreased. It is expected that over that moisture content range significant textural changes to occur with other foods as well. During the latter part of World War II at the Aberdeen, Scotland Factory, dehydrated cabbage and carrots were being compressed after conditioning to 8 percent moisture by injecting steam in a heated air stream (Hamdy, 1960).

In the United States, potato and egg powders were compressed after adjusting the moisture content to 15 percent (Hamdy, 1960). In a study on compression of dehydrated food (U.S.D.A, 1948) it was reported that,"usually the surface of the food pieces are at considerably lower moisture levels than the centers and consequently the material will not compress satisfactorily. Uniform distribution of moisture can be obtained by storage at room temperature for several days, and satisfactory homogenity can be brought about in a relatively short time by heating the material in recirculated air under carefully controlled condition of temperature and humidity." They basically used both moisture and heat treatment (described below) as the means of conditioning the product before compression. They report, further, "moisture content often critically affects the compression characteristics of a material. At lower moisture levels, lower bulk densities are usually obtained at a given pressure, and cohesive quality may be considerably lower. The temperature required for satisfactory compression generally decreases as the moisture levels rises. Temperature conditions, especially as they influence breakage and production of fines, become more important as the moisture level falls. At very low moisture contents, many dehydrated foods do not give coherent blocks at any temperature." However, in the majority of cases the procedures adopted in this experimental study were applied to specific comodities at moisture levels conforming to U.S. Quartermaster Corps specifications in force at the time the tests were conducted. Vegetables with low sugar content (i.e. beets, cabbage, carrots, onion, and rutabagas) were compressed satisfactorily at moisture levels of 3.5-5.5%, with the temperatures ranging from 120 to 160°F. and pressure ranging from 200 to 5500 psi. Problems involved with these comodities were usually relaxation of the product after compression, weakness of the bars and difficulty with rehydration. Fruits such as peaches, apricots, and prunes were compressed at moirsture levels of 10.7-18.7% at room temperature with relatively low pressures (100-900 psi). Apple nuggets at moisture contents of 1.3-2.1% at 120-130°F. and 100-400 psi. Cranberries at moisture level of 5.5% at 150°F. at pressures ranging from 400-2000 psi. Potatos, depending on sugar content, at moisture levels of 9-15 at 140-160°F. with pressures ranging from 200-2000 psi. And finally egg powder at moisture content of 2.0 and 5.0%, at temperature of 65-90°F. with 600-1500 psi. Egg powder did not compress well at 2% moisture; however, at 5 percent, satisfactory bars were obtained which were redried to 2 percent to meet the specifications. The increase in density of compressed products in these experiments range from 1.5-7 fold. Hamdy

(1961) generally used low moisture content foods for compression except blanched precooked carrots which had moisture levels of 5.45-6.6 percent. At pressures of 3000-4500 psi a compression ratio of about 4 was achieved He also used heat and sometimes plasticizing agents in his experiments. Results indicated acceptable compressed products. In 1962 Hamdy reported that acceptable compressed freeze-dried spinach could be obtained by increasing the plasticizing moisture content to 9 percent. Ishler (1962) found that successful compressed food can be achieved by spraying freeze-dried cellular food with water to attain 5-13 percent moisture, compression and redrying to less than 3 percent moisture. Lampi has indicated that the moisture level of the food prior to compression may affect rehydration. (Rahman, et al, 1969)

Rahman et al, (1969) used lived steam or water sprays after freeze-drying for preconditioning a variety of vegetable products. The desired equilibrium moisture content for corn was 12 percent before compression. All compressed products were redried in a vacuum oven to moisture levels of approximately 2 percent. Compression pressure of 500-2500 psi was used. Compression ratios obtained were: peas, 4:1; corn, 4:1; sliced onions, 5:1; spinach, 11:1; carrots, 14:1 and green beans 16:1.

Rahman, et al, (1971a) studied non-reversible compression of intermediate moisture fruit bars where the compressed product is to be eaten "out of hand" rather than rehydrated. To successfully produce compressed fruit bars the moisture content of the fruit ingredients such as dates and figs, maraschino cherries and others was reduced to approximately 8 percent (a range of 7-14% was reported to be applicable). Compressing these fruits with their original moisture (ranging from 15-35%) were unsuccessful due to excessive extrusion of pulp. Approximately 2 percent lecithin was incorporated to the bar to enhance the texture. MacKenzie and Luyet (1969)studied the effect of water on freeze-dried foods, compressed after moisturizing to various relative humidities. They found that freeze-dried carrots and peas compressed after equillibration at 60 percent relative humidity were restored during rehydration to their pre-compression character.

Mackenzie and Luyet (1971) conducted another experimental study where twelve freeze-dried foods, alone and in combinations were brought to certain predetermined water contents by exposure, via the vapor phase, to water at controlled activities. The moist freeze-dried materials were subjected to compression and to further drying, after which they were rehydrated. They reported that processing conditions insuring best rehydration could be defined in terms of water activities to which the foods were adjsusted prior to compression. They also found that composite foods were more likely to respond well to compression where component items wre selected on the bais of compatible water activity dependent behavior.

Their experimental data indicates that the high water activities (0.7-0.8), which corresponds to about 15-35 percent moisture, most foods either collapse (flow) under compression, or compress readily but have very little or no recovery upon rehydration. Also, at low water activity (depending on sugar content) products fragment or crumble upon compression. Fruits which are generally high in sugar content showed best restoration when compressed after resorption to relatively lower water activities. Examples of conditions giving good compression are apples at a water activity close to 0.3 (5% moisture), peaches at water activity of 0.3 (4.5%) and pinapples at water activity of 0.25-0.3 (5%). Vegetables, which have lower sugar content and higher fiber content than fruits, required higher water activites. For example, good compression was achieved with carrots at a water activity of 0.55, cabbage at a water activity of 0.35, and potatos at a water activity of 0.6.

They reported that this difference is mainly due to the sugar content. The freeze-dried plant tissue is viewed as a two-phase, two component system composed of cellulose and sugar. On exposure to water the sugar phase, amorphous after freeze-drying sorbs more water than the cellulose. Given a high enough water activity, the sugar phase softens and flows under the compression force while the cellulosic phase deforms simultaneously presumably with more resistance. Since the sugar rich phase flows only above its glass transition temperature, the sugar: water ratio has to be controlled so that the the glass transition temperature falls near but below the temperature selected for compression. Where the system is moisturized further, the sugar-rich phase may flow too readily, the various internal surfaces being annihilated in the process. The cellulosic component may moreover, lose its ability to retain a strained form at high water activities, with the sugar and the excess water plasticizing an irreversible deformation.

Chicken muscle behaved best when the water activity was increased to about 0.6 (a range of 0.5-0.7) which corresponds to a moisture content of about 10.5% prior to compression.

Tuna showed good compression behavior at moisture levels of 11-22% independent of the way in which the water contents were achieved.

Tuomy (1971) moistened dehydrated products by spraying them with the correct weight of water to give the amount needed for compression. Equilibration was obtained by holding the moistened products under 27 inches of vacuum for 27 hours. He used "The Edisonian Approach" of trial and error in his recipes for best results. The water content of the recipes ranged from 18-35% before compression.

Pilsworth Jr. and Hoge (1973) compressed freeze-dried beef to form bars by plasticizing with water transferred as a vapor. They reported that "freeze-dried beef can be plasticized for compression by partial rehydration in which water is transferred to the beef in the form of vapor to an equilibrated level of 11-12 percent moisture content for satisfactory compression with compression pressures of about 3000 psi."

They also made a test of plasticizing the freeze-dried material by spraying with water until a uniform moisture level of 11.5-12 percent by weight was obtained. The rehumidified products formed satisfactory compressed bars under compression pressure of 5000 psi. Hinnergardt and Sherman (1975) used rehumidification by spraying with water to moisture levels of 8.6-12.9% for compressing freeze-dried foods, such as chili can carne, beef hash, beef with vegetables, chicken with vegetables, chicken with brown rice, beans and franks.

Rahman, et al, (1971b) studied the effect of level of moisture content of peas on compression behavior. They sprayed freeze-dried peas with water to achieve moisture contents of 8, 12, 16, 18, and 20%, and compressed them after equilibration in an over for 10 minutes at 200°F. Three compression pressures (1000, 1500, and 2000 psi) were used to form bars. Their results indicate that the amount of moisture added to peas prior to compression significantly affected the rehydrated product. The rehydration ratio decreased whereas the resistance to shear became greater as the conditioning moisture increased. Pressure did not have an effect on rehydration ratio.

It has been shown that water has a significant influence as a plasticizing agent on the compressibility of food, its texture, reversibility upon rehydration, and stability of the compressed product. However, it is noted that in almost all cases, the products which have been rehumidified prior to compression have been redried to low moisture content so that the microbial and storage stability properties of the dehydrated food are not affected.

2.4.2 Heat Treatment:

Heat treatment alone or together with moisture content also have been used for plasticizing foods prior to compresseion. As mentioned before (2.4.1) the effect of heat is most evident as the moisture content decreases, especially in high sugar content foods which are sensitive to heat treatment. Some combination examples of moisture content and thermal treatment are given in the previous section.

Thermal plasticity at low moisture contents is primarily possible with high sugar content foods such as most fruits.

Problems associated with thermal plasticization are discoloration, burning, and loss of nutritional value of the product.

Rahman, et al, (1970) successfully compressed freeze-dried red tart pitted cherries (RTP) and blueberries at less than 2 percent moisture content by subjecting them to dry heat in an oven at 200^{o}F. for approximately 10 minutes, followed by compression at pressures of 100-1500 psi. The results indicated a significant correlation between compression ratio and compressive pressure. Volume reductions of 8 and 7 fold, respectively, for cherries and blueberries were obtained; when the compressed volume was compared with loose frozen product, a compression ratio of 12 and 13 to 1 was obtained. Pies prepared from compressed products were equivalent in flavor, texture and appearance to those prepared from the non-compressed products. The extent of rehydration was about 30-50 percent of the fresh samples.

In another study Do, et al, (1975) successfully compressed freeze-dried sour cherries with less than 3 percent moisture content by heating for 1 minute at 200°F. under an infrared lamp prior to compression. Compressive pressures of 100-400 psi were used. Their results showed that the texture of compressed sour cherries became softer as the compressive pressure was increased. The rehydration time was less for lower compressive pressure. The freeze-dried cherries were slightly wrinkled prior to compression. The overall quality declined during storage.

Donnelly (1947) developed another method of debulking foods in which he refrigerated flaked, unseasoned mixed vegetables to approximately 20°F. and foods of relatively high fat contents to about 0 to -20°F. and then compressed at pressures around 1000-1500 psi. He reported that depending on fat content and/or sugar content, the moisture level prior to compression can vary from 2-4 percent with high fat content foods and to 6-7 percent with foods of low fat content and with relatively high sugar content.

2.4.3 Binders and other Plasticizing Agents:

A variety of binders and plasticizing agents (other than moisture and heat) have been used (up to permitted levels) in foods with low moisture content (3-4 percent) to improve compressibility, texture, and reversibility of the compressed products.

Gooding, et al, (1958) obtained a better quality of compressed dehydrated cabbage when they scalded the cabbage before dehydration in a solution containing 1-1.5 percent sugar; however, the final product was not acceptable because of sweetness and browning. (Hamdy, 1960)

Berg (1948), in compressing cereals, added 0.5-3 percent of ethylene or propylene glycol, which he claimed improved the firmness of the compressed product. (Hamdy, 1960)

Gooding (1952) sprayed 120 ml of a 5 percent solution of glycerol solution per pound of steam-blanched cabbage, but found that browning occured more readily, especially at high storage temperature. He also obtained the same results when he used 5 percent solution of glycerol mono-leate. Fats have been used as binders in compressing wheat wafers, meat bars, and muttom blocks. (Hamdy, 1960) All methods recommend using high-melting fats such as animal fats or hard-shortenings in order to decrease ex-clusion of fat during compression.

Durst (1967) demonstrated the effectiveness of a bland, high caloric binding material to provide a desi-rable level of cohesion in bars prepared from a large variety of dehydrated components. It was proven earlier that incorporation of predetermined amounts of this binding material provides a basis for compressing a variety of foods into bars of uniform size and equal caloric content. In a related study more than thirty sauces, spreads and relishes in the form of flexible sheets suitable for direct consumption in conjunction with a bland carrier were prepared.

He describes the carriers (Matrices A_3 and B_2) as binders which are easy to handle, have high caloric values (4.9 and 6.3 calorie per gram, respectively) good stability, mild flavor and good rehydration properties. Matrix A_3 which has better binding power than B_2 also has a higher sugar content. The formula for matrices A_3 and B_2 are:

	Protein	Fat	C.H.O.	M.C.	Ash
A_3	23.4	20.0	51.1	31.6	1.1
B_2	16.8	47.7	32.5	2.2	0.8

The protein being sodium casinate, the carbohydrates; sucrose, dextrose, starch and lactose and the fat Durkee 500 oil. Durst used these binders in a wide variety of food recipe with acceptable results. He also used sprayed water in most of his experiments, in combination with the binders mentioned, to achieve moisture of about 4 percent.

Ishler (1962) reported that spraying the dehydrated food with glycerine or propylene glycol before compression produced bars with excellent rehydration characteristics as stated by Rahman, et al, (1969).

Rahman, et al, (1971) reported that incorporation of 2 percent lecithin enhanced the texture of the intermediate moisture food bars.

Konigsbacher, (1974) investigated the applicability of various plasticizing agents and techniques for compression. Use of vanishing plasticizers such as FDA approved freons alone or in combination with oil, or liquefied gases such as carbon dioxide; however, was not successful. He also proposed a process of split stream treatment where fresh food is added to dehydrated food to increase the moisture content of the dried food to give a material in the plastic range. He reported that this process is much more efficient than the classical method of rehumidification by vapor phase equilibration or water spray. He used propylen glycol, glycerol alone or in combination with water, vegetable oil, or combination thereof.

He reported that, "the use of propylene glycol or glycerol as plasticizing agents in combination with a brief steam treatment immediately before compression yielded compressed foods of best Quality." He also reported the use of binders to prevent expansion after compression.

The results indicated that:

- -Minimum expansion was achieved with systems containing gelatin as the binder.
- -Best results were obtained when a mixture of equal parts propylene glycol and steam were applied at the 10 percent level as the plasticizing agent.

Ranadive, et al, (1974) used about 28 different binders in combination with moistening with water (between 10-12 percent) for compressing meat balls and pork sausages. The binders were generally starch, modified starch, corn meal, egg albumin, wheat gluten, soy protein, or locust bean gum, alone or in combination. They reported that the product quality (which includes rehydration properties, flavor, and texture) depended mainly on the type or types of binders used. The best binder for sausages was composed of modified starch (National No. 10), wheat gluten and pregelatinized starch (National No. 711), and for meat balls modified cross linked starch (National No. 10) and wheat gluten.

Pavey (1975) in an study of techniques for controlling flavor intensity in compressed foods used both remoistening and a conditioning/binding agent which minimized the redrying after compression. This agent was prepared by mixing water and glycerine, and then adding gelatin and allowing the gelatin to swell for 5 minutes. This was heated until it melted and then mixed with freeze-dried food products prior to compression. It was reported that this plasticized the meat for compression purposes and allowed the other ingredients to adhere to the wetted meat surfaces.

Schafer, et al, (1975) developed a method to produce compacted and dehydrated food bars which may be easily bitten or chewed without prior rehydration or rapidly rehydrated in bar form in cold water, by incorporating potato particles, which have been freeze-dried to less than 4 percent and thereafter equilibrated with water to a moisture content of from about 5-15 percent. In the food preparation mixture a proportion of about 10-20 percent potato to about 90-80 percent non-potato food bar forming ingredients was used. This mixture can be compressed at a pressure from about 800-1500 psi and then redried to a moisture content below 4 percent. Flavoring agents such as lemon powder are used to mask potato flavor. The potato particles act to allow breakage of the food bar during chewing without prior rehydration or result in the quick rehydration (10 minutes in cold water).

<u>2.4.4 Blanching (Scalding):</u>

Study of the effect of blanching on the final quality of the compressed foods was done by Gooding (1955). He concluded that steam blanching yielded a better quality of dehydrated and compressed cabbage than the quality obtained from water scalded samples. Moreover, he explained that the leaching effect of blanching with water caused increased fragmentation. To overcome this effect, he suggested a 1-1.5 percent solution of soluble solids for water blanching; however, browning was observed with samples treated in this manner. (Hamdy, 1960)

2.4.5 Effect of Freezing Rates on Compression of Freeze-Dried Foods:

MacKenzie and Luyet (1971) who tested four different freezing rates prior to freeze-drying of cooked beef, chicken and carrots, reported that there was no significant difference in the products after compression and restoration. However, they indicated that some trends were evident in the results:

- High freezing rates were more deleterious for compression of beef, though no effect on rehydration was observed.

- Carrots showed less resistance to compression when high freezing rates were used. Also their recovery was low.

- Chicken when frozen with high freezing rates showed less recovery when rehydrated.

They explained that the reason for the observed behavior was mainly due to small ice crystal formation, which presumably decreases the routes available for the re-entry of water.

2.4.6 Continuous Freeze-Drying and Compression:

Konigsbacher, (1974) conducted a test where a constant load was placed on a sample of diced chicken (no plasticizers were used) during freeze-drying. He indicated that the diced chicken had been compressed to about half its original size. The samples rehydrated to their original shape with no changes in their texture or appearance when compared with non-compressed chicken. He further reported that, "this finding opens a new approach to simultaneous freeze-drying and compression. However, this approach represents a concept that needs to be investigated further because of its potential as a one-step process."

He did not further investigate this method which is essentially the approach undertaken in this study.

2.4.7 Limited Freeze-Drying:

Most developmental work to date for compressed freeze-dried foods has utilized full freeze-drying to low moisture contents, followed by remoistening to attain the desired mositure content for compression. Under certain controlled conditions it is possible to carry out the freeze-drying process such that the material is left with a desired uniform moisture content at the "end" of drying, thereby avoiding the remoistening step. The term "Limited Freeze-Drying" was first applied by MacKenzie to this process (MacKenzie and Luyet, 1969). The principle of the method is to carry out freeze-drying in an environment such that the relative humidity at the surface and within the product does not fall belwo some predetermined value, which is high enough to ensure that the moisture content in any region will not drop below the desired value during drying. This is accomplished by separate control of the sample-chamber temperature and condenser temperature each within narrow limits (±.1°C.), which causes the freeze-drying to proceed by simultaneous sublimation of ice and limited desorption of unfrozen water. While the sublimation proceeds to completion, the desorption process stops when the vapor pressure of the water in the product is reduced to that of water vapor in the sample chamber in equilibrium with ice on the condenser. Greater sample chamber-condenser temperature differences result in smaller ultimate water activities in the sample chamber; hence greater desotion from the samples. Generally, the selection of sample chamber temperatures in the range -10 to -40°C. permits the production of materials containing about 25 to 5 $\frac{\text{gram } H_2O}{\text{100 gram dry solids}}$ respectively (MacKenzie and Luyet, 1971).

Accomplishing limited freeze-drying through control of the environmental relative humidity as described above requires that the temperature difference and water-vapor partial pressure difference driving forces for heat and mass transfer be less than in ordinary commercial freeze-driers which necessarily leads to longer drying times. King, et al, (1975) noted that MacKenzie and Luyet had reported that drying times of 25-100 hours were required for 1 cm cubes of beef and various vegetable products. However, King, et al, (1975) reported that the rate of freeze-drying can be accelerated if:

1. The heat transfer coefficient from the heat source to the surface of the product is increased.

2. The temperature of the heat source is raised during the early part of drying so that temperature of the product surface rises toward the point where the surface itself experiences the prescribed relative humidity.

3. Control of environmental relative humidity is accomplished in some other way.

They proposed two alternative methods to accomplish a more efficient limited freeze-drying process. In one method the heating platen temperature is controlled at the desired final surface temperature, instead of a the sample-chamber temperature which was originally used by MacKenzie and Luyet (1969, 1971). They indicated that the piece-surface temperature rises as drying proceeds from an initial value close to the frozen-core temperature to a final value approaching the platen temperature and similarly, the water-vapor partial pressure within the drying chamber may be held at the desired value, with the knowledge that the water-vapor partial pressure at the piece surface will approximate that value and be no lower. Under these conditions, the relative humidity at the piece surface will be no lower than the prescribed value and will be at a higher value during the early stages of the drying process. A major drawback of this method is that small fluctuations of the platen temperature will result in a great change in final moisture content by affecting the local relative humidity. King, et al, (1975) The expected drying times using this procedure are about 3 times longer than for conventional freeze-drying to low moisture contents.

The other method is a self-regulating control of the enviornmental relative humidity by utilizing a water-uptake medium which maintains a particular, predetermined relative humidity independent of temperature or amount of moisture taken up. This relative humidity would be the same as that the surface of the food pieces, provided that food pieces and water-uptake medium are at the same temperature. King, et al, (1975)

In a layered bed with alternating layers of food and hydrating salt desiccant, a circulating low pressure gas is used to transfer heat and mass between the food and desiccant. Since the latent heat of absorption for most desiccants is about equal to the latent heat of sublimation for the same amount of water, the gas will be cooled as it passes through the food layer and then will be dried and reheated as it passes through the desiccant layer. The good mass transfer possible with this configuration permits the use of inert gases at higher total pressures, which reduces the drying time. (Jones and King, 1975)

The hydrating salt desiccantsare good since for any hydrate they have the unique property of maintaining a constant relative humidity over a range of water contents. They also have the additional advantage of maintaining a relative humidity that is independent of small changes in temperature (Jones and King, 1975). With this method the drying times are even shorter than the ones described before; however, they may exceed by about a factor of 2 the drying times of conventional freeze-drying to low moisture contents. Although limited freeze-drying has good promise in food compression processes, it requires longer drying time and the compressed food still must be dried to low moisture contents to preserve stability.

3. MATERIALS AND METHODS

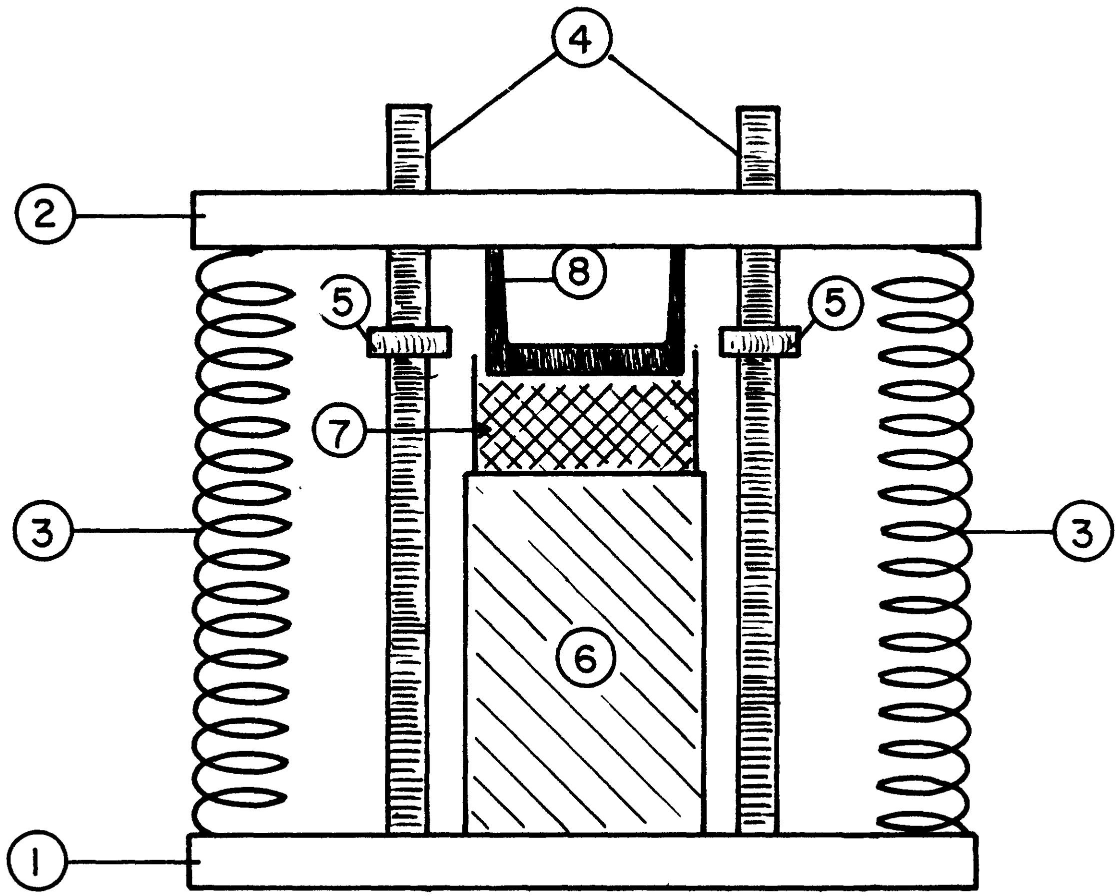
3.1 Equipment:

3.1.1 Freeze-Drier:

A virtis laboratory freeze-drier (Uni-trap Model 10-100) with a custom drying chamber, was used. It was operated with no heat input (except the ambient leakage) chamber pressure, less than 100 microns, and a condensor temperature of $-60^{o}C$.

3.1.2 Design of a Static Loading Cell:

As the size of the chamber of the Virtis freeze-drier used is relatively small (30 cm height, 25 cm diameter), there is not enough space for a large static load (such as lead) having appreciable compressive force to be placed on the sample during freeze-drying. However, it is possible to use the resultant force from extension of springs to attain compressive pressures high enough to compress the food. Figure 1 shows the cell loading system. This system is not truly, a static system since the length of the extended springs decrease as the height of the food bed is reduced due to being compressed. This causes the force produced by the springs to decrease as the food is compressed. This change in force during compression can



1 Base Plate

2 Top Plate

3 Matched Set of Springs (Extension Type)

4 Threaded Guide Rods

5 Nuts for Raising Top Plate

6 Sample Cell Stand

7 Sample Holder

8 Compression Plate

Fig. 1. Load Cell.

be minimized by selecting springs which have a large initial tension (force required to initiate extension) and a relatively small relationship of modulus to initial tension (i.e. $\triangle$ F due to $\triangle$ L is small compared to F) so that the main part of the force is due to the initial tension and only a small fraction of the force is due to extension. Ideally this means that after the force required to initiate extension is achieved no more force is necessary to further extend the springs. Since this is not possible, it is desirable to use long springs so that $\triangle$ $L/_L$ is small for a given sample thickness.

Different sets were used in order to widen the range of compressive force. All springs were tested for linear response of force with extension. The extension of the spring versus force was graphed for all springs of each set. Table 1 represents the properties of the springs selected for this study. Cell configurations using either 2, 4, or 6 springs have been constructed, allowing three levels of compressive force from each spring set.

3.1.3 Sample Holder:

The sample holder is constructed of aluminum and stainless steel mesh to allow application of the compressive force without significantly impending the flow of vapor from the drying surface. Its dimensions are

TABLE 1: Properties of Springs (as measured)

Spring Set Number	Rest Length cm***	Initial Tension Kg	Modulus Kg/cm	Max. Force Kg	ΔF for 1 cm Compression	$\frac{\Delta F}{F\ max.}$
C-259*	7.8	11	8.89	56.2	8.89	0.16
27**	10.0	1.8	2.34	12.5	2.34	0.19
28**	20.2	5.0	3.86	24.6	3.86	0.16
36**	20.0	10.0	4.41	36.9	4.41	0.12
44**	20.3	38.6	16.0	113.3	16.0	0.14

*; Centry Spring Corp., Los Angeles, Cal.

**; Hardware Products Company Inc. Boston, Mass.

***; Based on Average of 4 Springs

approximately 2x3x2 inches. Figure 2 shows the detail of the sample holder.

In practice, the cell is assembled without the sample holder. A small scissors jack is used to raise the top plate (2, in Figure 1) and extend the springs. The nuts (5) are raised until they are just under the top plate. The jack is removed so that the frozen material in the sample holder (7) can be placed on the loading cell stand (6) while the nuts (5) maintain the springs under tension. The compression plate (8) is inserted and the nuts (5) are lowered permitting the top plate (2) to contact the compression plate which is on the bed of food. The nuts are lowered sufficiently so that the top plate (2) can move down the guide rods (4) without contacting the nuts before the end of compression.

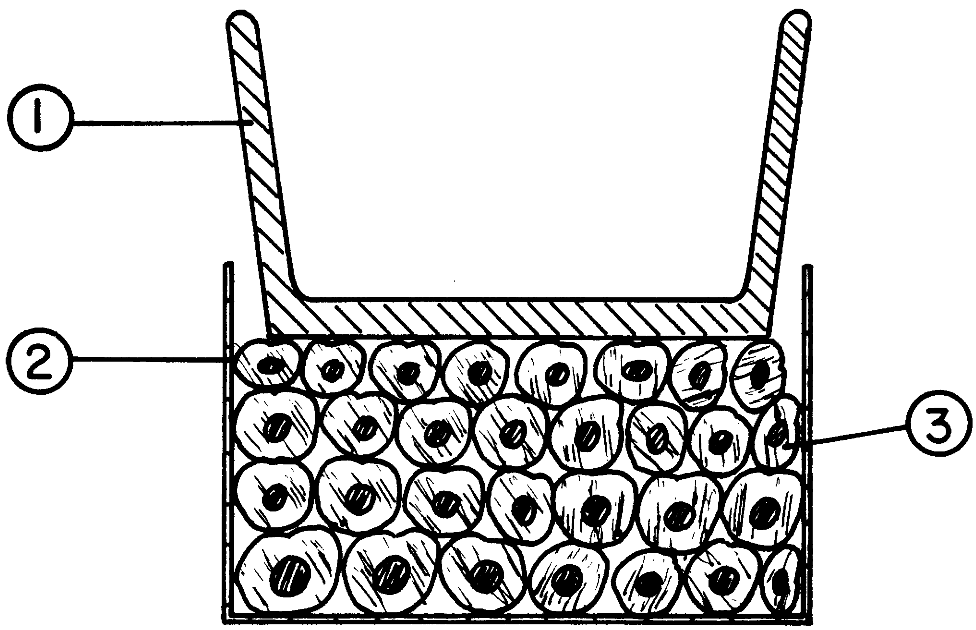
3.2 Experimental Procedure:

Figure 3 shows the principle steps used for each experiment.

3.2.1 Sample Preparation:

Table 2 lists the food materials used.

All samples except for cherries and blueberries were kept in a freezer at -20°C.



(1) Compression Plate

(2) Sample Holder (wire mesh)

(3) Green Beans (sample)

Fig. 2. Sample Holder.

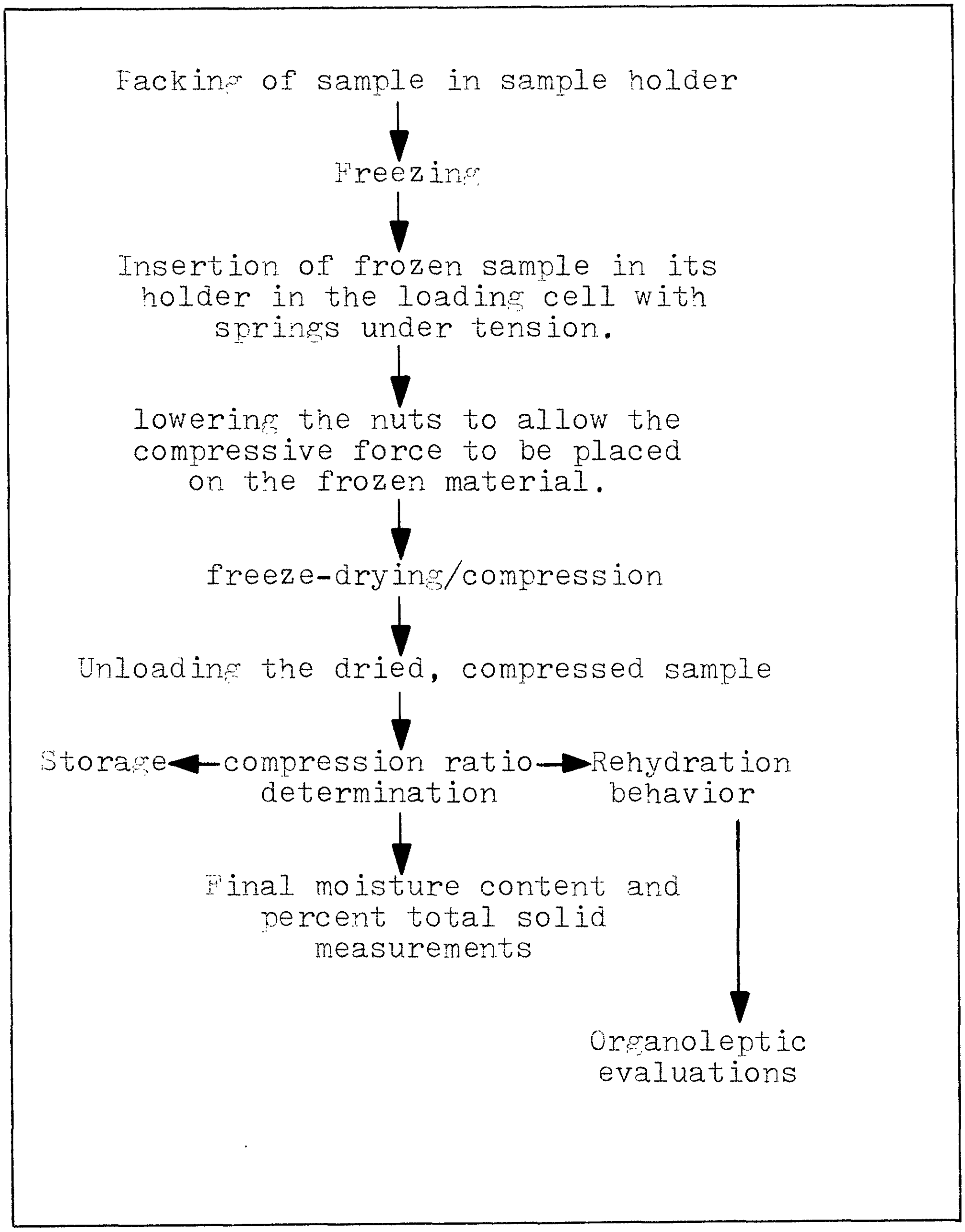


Fig. 3. Principle steps for each experiment.

System	Material	Comments
Vegetables	*green beans	cut frozen packed
	**carrots	diced frozen packed, cubes approximately 6 mm on each side
	***peas	frozen packed
	*corn	frozen packed, kernels
Fruits	***blueberries	fresh
	***black cherries	fresh, pitted and halved
Meat	***ground beef	fresh, 18 percent fat
	***bottom round steak	fresh

*Purchased from a local supermarket as frozen packed, in large quantities (5-6 large packages) to minimize variability within the samples.

**Purchased as mixed frozen peas and diced carrots, they were separated by hand and stored.

***Purchased fresh from a local supermarket (cherries and blueberries were purchased in quantities sufficient for one or two experiments since the quality and texture would change upon storage.)

TABLE 2: Materials used.

The frozen vegetables were first thawed by placing them in water at room temperature for several seconds. The excess water was then removed by an absorbent paper towel. The reason for this procedure is that the frozen vegetable usually had a shell of ice around it which would decrease the measured total solid percent of the material.

All samples were hand packed in the sample holder with minimum void volume between pieces. When the frozen sample was initially subjected to the force (before freeze-drying) some breakage was produced in the frozen sample. To reduce this cracking layers of cheese cloth were placed in the sample holder under and over the bed of food to provide some cushioning.

Uniform sized cut green beans were selected for compression. They were aligned uniformly next to each other as rows and layers in the sample holder (Figure 4), with the force perpendicular to the grain.

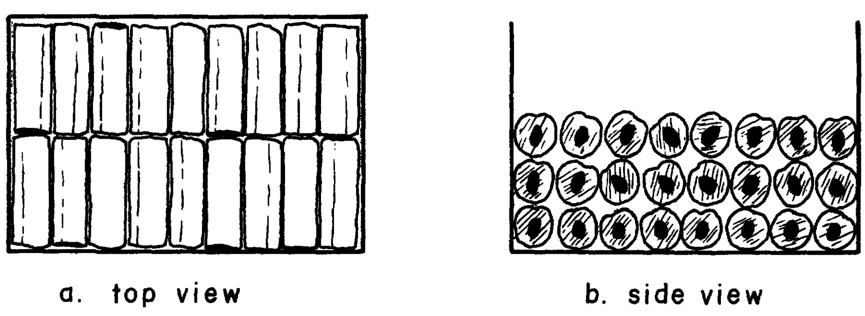


Fig. 4. Configuration of beans in the sample holder.

Diced carrots were placed into the sample holder such that all cubes formed an orderly array of rows and layers. No effort was made to separate dices according to presence or absence of carrot core material. Blueberries, peas and corn were placed in the sample holder fully packed.

Cherries were pitted first and then put into the sample holder either whole, or halved. Ground beef was gently "packed" into the sample holder so that void volume was avoided while "pre-compression" on the fresh sample was minimized. The steak was trimmed of fat and cut into cubes approximately 1 cm on a side. The cubes were then packed as rows and layers into the sample holder with grain perpendicular to the direction of force. (as beans) A few tests were conducted with the grain parallel to the direction of force.

All samples were weighted and final weights were obtained by difference of the sample holder with and without the sample. In all experiments one or two samples were freeze-dried without compression as control. One control, approximately the same weight as the sample being compressed, was freeze-dried in a 250 ml glass beaker randomly filled. The other control was usually a 10-12 grams sample in a 50 ml beaker. The first control was used for moisture, rehydration and organoleptic comparisons with the compressed sample while the second control gave a second value of percent moisture content and percent total solids of the raw material.

3.2.2 Freezing:

In most cases the samples in the holder were frozen in a freezer at -20°C. Prior to the experiment they were further cooled down by a stream of liquid nitrogen. (In some cases when there was not time for slow freezing the thawed samples were quickly frozen by the aid of liquid nitrogen.)

3.2.3 Loading of the Cell:

After freezing, the sample holder was quickly placed into the loading cell with the springs extended. The force was placed on the frozen sample by lowering the nuts. The length of the springs were recorded, and then the system was immediately placed in the freeze-drier and the process started.

The lengths of the springs were recorded again after freeze-drying/compression so that the force on the sample during compression could be calculated.

3.2.4 Compression Ratio:

The term compression ratio is defined as the ratio of the initial volume of the sample prior to compression to the final sample volume following compression and drying. However the numerical value of the compression ratio can vary depending on the method of measuring or defining volume. In this study compression ratios are given by three different methods.

a- <u>Compression ratio by displacement</u>:

The lowest numerical value of compression ratio is obtained by taking the initial and final density (on a dry basis). This can be done by a displacement technique for determining volume using lead shots similar to that used for bread volume measurements using rapeseed. In this measure, no void volume for the bulk sample is included, hence it approaches closest to the "real" volume changes of the sample. Lead shots were used due to the fact that their diameter was much smaller than rapeseeds. Also, since small quantities of sample were used, lead shots which have a very high density respond much better to small displacements. To calculate the density (dry basis) the following equation is used.

$$\frac{\text{vol.}}{\text{t.s.}} = \frac{1}{\rho} = \frac{\dfrac{\text{wt.(cont.+L.S.)} - \text{wt.(s+cont.+L.S.)}}{\rho_{\text{L.S.}}}}{\text{gr t.s.}}$$

where:

vol.	volume
t.s.	total solids
ρ	density of the sample

$\rho_{L.S.}$	density of the lead shots
wt.	weight
cont.	container
L.S.	lead shots
s	sample

It was not feasible to measure the volume of the wet, initial sample since lead shots would stick to surface. In this case the ratio of the densities of the freeze-dried non-compressed to the freeze-dried compressed samples was used assuming that the change in volume of the freeze-dried samples (non-compressed) is not significant.

b- Compact compression ratio (by height) and random compression ratio:

Compact compression ratio is obtained by taking the volume of the food as occupied in the sample holder before and after compression. Since the compression area remains unchanged and that compression is uni-directional (i.e. only the thickness decreases), measuring the bed height before and after the compression can be good indication of compression ratio.

This compression ratio gives lower values than normally reported in literature, since these values use a random fill of the initial material as base rather than the aligned fill used in this study. To make values of compression ratio reported here comparable to those in the literature a volume ratio of random to aligned packing was determined for each sample. This is done by measuring the volume that each food with the given piece size occupies randomly, and measuring the corresponding weight of the sample. The same quantity of food occupies a much smaller volume if packed orderly. (as measured in the sample holder). The ratio of these two different volumes gives a correction factor for each food product with a given piece size. By multiplying the correction factor to the compression ratio by height, a good measure of random compression ratio for each sample can be calculated, as long as they have a relatively uniform piece size.

3.2.5 Moisture Content, Total Solid Determination:

Immediately after freeze-drying the weights of the compressed and non-compressed samples were recorded and a random portion of each used to determine moisture content. From this the percent total solid in the fresh (or frozen) samples was calculated.

The moisture content was determined on 1-2 gram of sample by drying under the IR lamp to a constant weight. The percent moisture content left after freeze-drying is used to calculate the grams of water left in the dried sample, and subtracting this from total dried weight, the grams of total solid is measured. Then:

$$\%T.S. = \frac{\text{grams total solid x 100}}{\text{initial wet weight}}$$

3.2.6 Rehydration:

Rehydration behavior of the samples was examined at different water temperature, namely cold (about, 40°F.), warm (about, 90-100°F.), and hot (about, 130-160°F.). Individual pieces were rehydrated and their weights measured at 1, 2, 5, 15, 30 minutes or 2, 7, 15, and 30 minutes after the initial immersion. In most cases 30 minutes or less was enough for full rehydration. In a few cases rehydration was carried out for up to 1 hour. In most rehydration tests the samples were immersed under water and held submerged with a screen; except when weights recorded. To test for air entrapment in the void volumes produced by sublimation of ice (specially in non-compressed samples) vacuum was used initially in order to release any entrapped air. In one test the samples were evacuated for 5 minutes, the vacuum was released with air and then the samples were rehydrated. In other method the vacuum was released with water instead of air and the rehydration was carried out.

The results of rehydration tests were calculated as,

$$\frac{\text{grams } H_2O \text{ up-take}}{\text{grams total solid}}$$.

the,

$$\frac{\text{gram } H_2O \text{ in fresh (frozen sample)}}{\text{gram total solid}}$$ was used as a reference

in order to calculate the percentage of the rehydration.

3.2.7 Organoleptic Test:

In a few cases rehydrated cooked or fried (steak only) samples were evaluated organoleptically. In each test three samples were compared: compressed, non-compressed, and fresh (frozen), all prepared the same way. A taste panel of 8-15 people used for each test. Two preference evaluations were conducted simultaneously for each test, one based on a 1-9 (dislike extremely - like extremely) hedonic scale, and a ranking test. (Larmond, 1970)

3.2.8 Storage Stability:

All samples were stored in darkness in desiccators with no vacuum. Rehydration tests were conducted on a few samples in order to see if there was any change in rehydration behavior after storage, and also to see if there was any relaxation of the compressed sample with time.

Carrot samples stored showed a sizable disappearance of the color pigments (carotinoids). Portions of compressed and non-compressed samples from the same experiment were stored in dark under vacuum over desiccant and in dark over desiccant but without vacuum.

3.3 Data Treatment:

For each food, the compression ratio as a function of pressure used during compression was determined. The rehydration behavior of freeze-dried compressed and non-compressed samples examined in relation to the fresh (or frozen) foods. The rehydration behavior of compressed samples was also examined with respect to compression ratio. Organoleptic tests were used to investigate acceptability of compressed samples with respect to non-compressed and fresh samples.

4. RESULTS AND DISCUSSION

The primary aim of this study was to investigate feasibility of compressing foods during freeze-drying to produce easily reversible compressed foods or food bars with high compression ratios that are highly acceptable, upon rehydration.

4.1 Presentation of Results:

The experimental results have been divided into 3 major sections:

1. Vegetables
2. Fruits
3. Meat

Subdivisions of these sections cover experimental results obtained for each particular type of food. Detailed experimental results for each subdivision are tabulated in Appendicies. At the end of this section a general discussion covering all food materials tested is presented.

4.2 Vegetables:

The data for this section is tabulated in Appendix A.

4.2.1 Beans:

Table 3 shows the summarized results for green beans.

BEANS

Experiments 1-9

Ave. Pressure (psi)	Comp. Ratio Displacement	Comp. Ratio Ht.	Comp. Ratio Random	Final M.C. % wt. Comp.	Final M.C. % wt. N.Comp.	% T.S. (wet basis) Comp.	% T.S. (wet basis) N.Comp.	*Extent of rehyd. after 30 min. (% fresh) Comp.	*Extent of rehyd. after 30 min. (% fresh) N.Comp.
15.5	-	2.0	3.3	1.6	1.3	6.3	8.5	56	69
17.6	-	2.3	3.8	2.6	2.2	8.3	8.4	93	68
33.0	-	3.0	5.0	1.8	2.8	8.1	8.9	-	-
31.5	1.5	3.0	5.0	2.6	2.5	7.8	8.4	72	72
41.8	1.7	3.3	5.6	2.6	2.5	8.7	8.2	87	63
61.0	2.0	3.6	6.1	4.1	4.3	8.9	9.4	64	50
70.0	2.6	4.5	7.5	3.9	4.7	9.3	9.8	84	55
98.3	3.1	5.5	9.2	3.6	2.6	8.9	8.6	91	59
130.0	3.3	7.0	11.8	2.7	2.6	8.7	8.3	72	64

TABLE 3 : Experimental results for Green Beans.

*Rehydration in cold water with no vacuum.

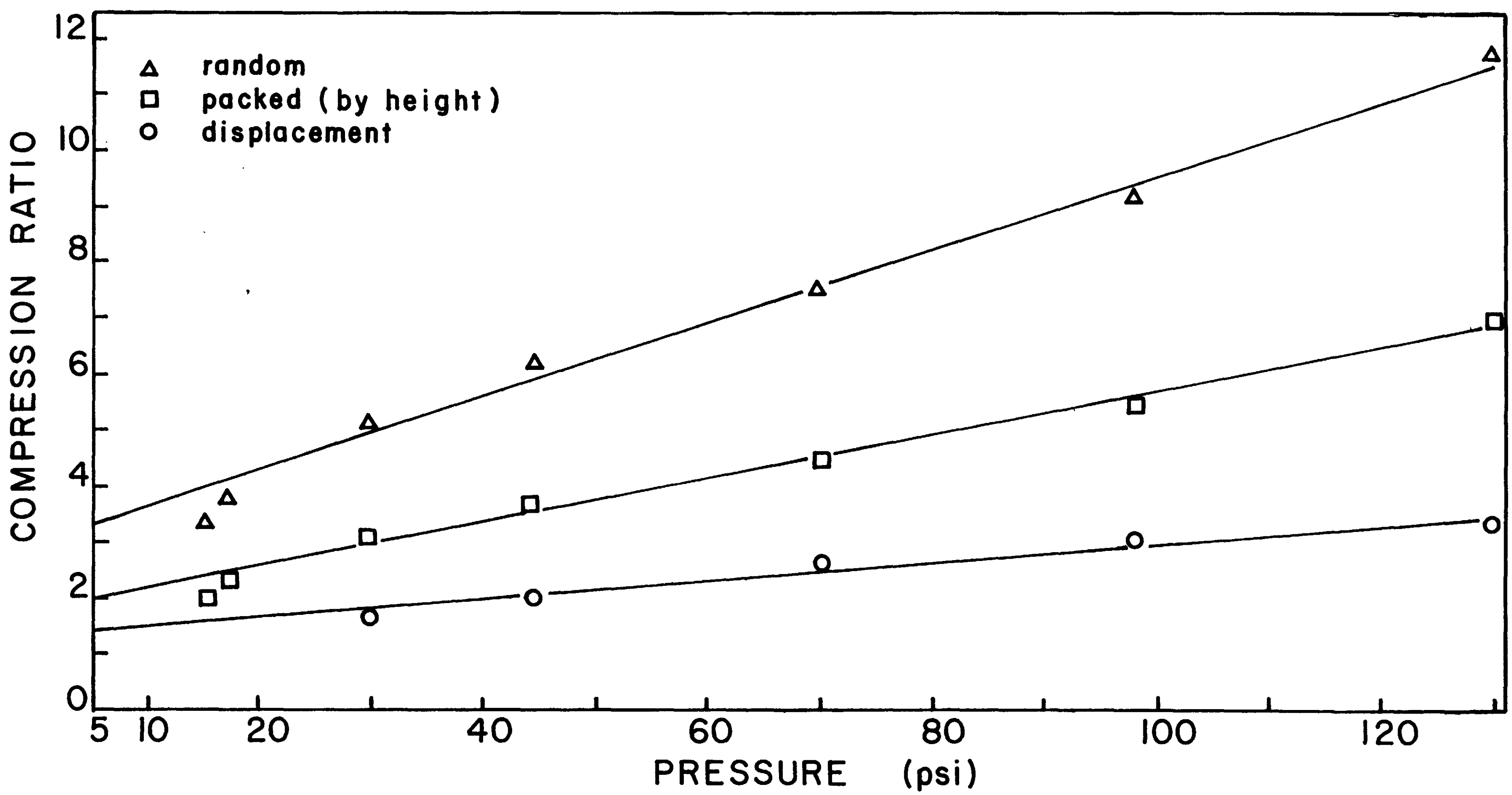
4.2.1.1 Compression Ratio:

Beans did not produced bars upon compression; however, they gave the highest compression ratios compared to other samples. As seen in table 3 the range of pressures used was from 15 psi-130 psi which gave random compression ratio ranging from 3:1 to 12:1. The increase in compression ratios with pressure was linear over the range experimented. (Figure 5) The correction factor to calculate the random compression ratio is 1.7. Over 12 months the compressed beans did not seem to relax and increase their volume.

4.2.1.2 Moisture Content:

The final moisture content of freeze-dried compressed beans were always similar to the non-compressed products which were dried at the same time (Table 3). This indicates that compression during freeze-drying does not produce a surface layer of lower permeability sufficient to prevent complete drying. The percent moisture range obtained after 48 hours drying was between 1.35-4.7%. The percentage of total solid calculated were very close and agreed well with values in the Table of Composition of Foods, U.S.D.A, Handbook number 8. The observed range was from 6.4 to 11.8% solids, while the literature value is about 8 percent.

Fig. 5. Effect of pressure on compression ratio of beans.



4.2.1.3 Rehydration:

Initial studies of rehydration were conducted at 3 temperatures. Figure 6 shows the time dependence of rehydration for a typical experiment. It was noted in these studies that rehydration was most complete when cold water was used, and that compressed beans rehydrated more completely than non-compressed. In later experiments only cold water was used for rehydration. The rehydration essentially reached equilibrium after 15 minutes under conditions where beans were placed in the water and held below the surface with a screen. The original sample volume was recovered after rehydration. To investigate if the difference of rehydration between compressed and non-compressed freeze-dried samples was due to air entrapped in the non-compressed samples, vacuum was used prior to rehydration, (see section 3.2.5). Figure 7 is a typical example. Little effect was noted for compressed beans, while the non-compressed samples showed a marked increase in rehydration when vacuum was used. Vacuum rehydration increased the extent of rehydration of non-compressed beans to that of compressed. This suggests that there has been some changes in bean structure during compression which affects the ability of air to escape from the non-compressed cells. The compression ratios

Fig. 6. Rehydration of compressed and non-compressed beans at different temperatures.

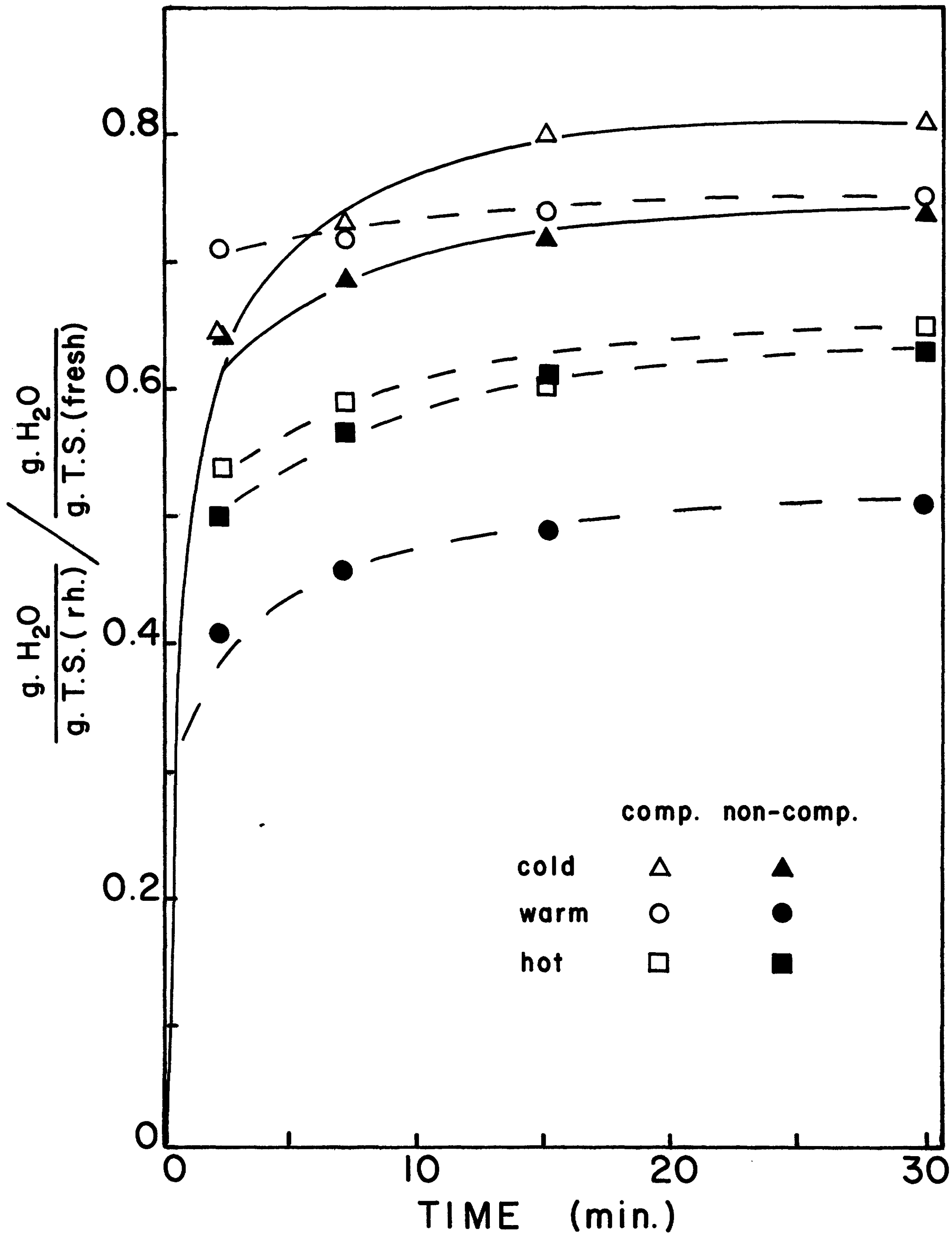
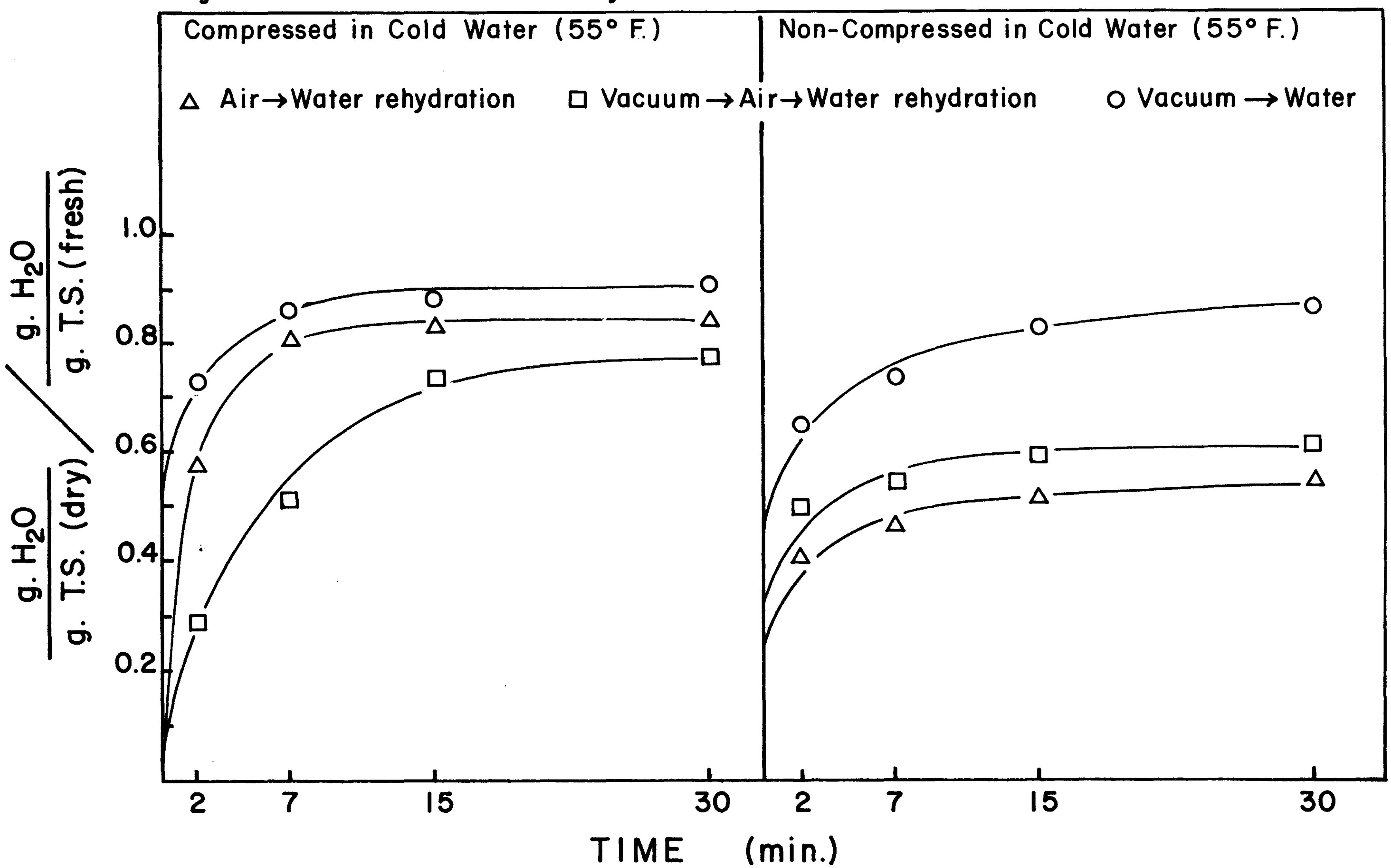


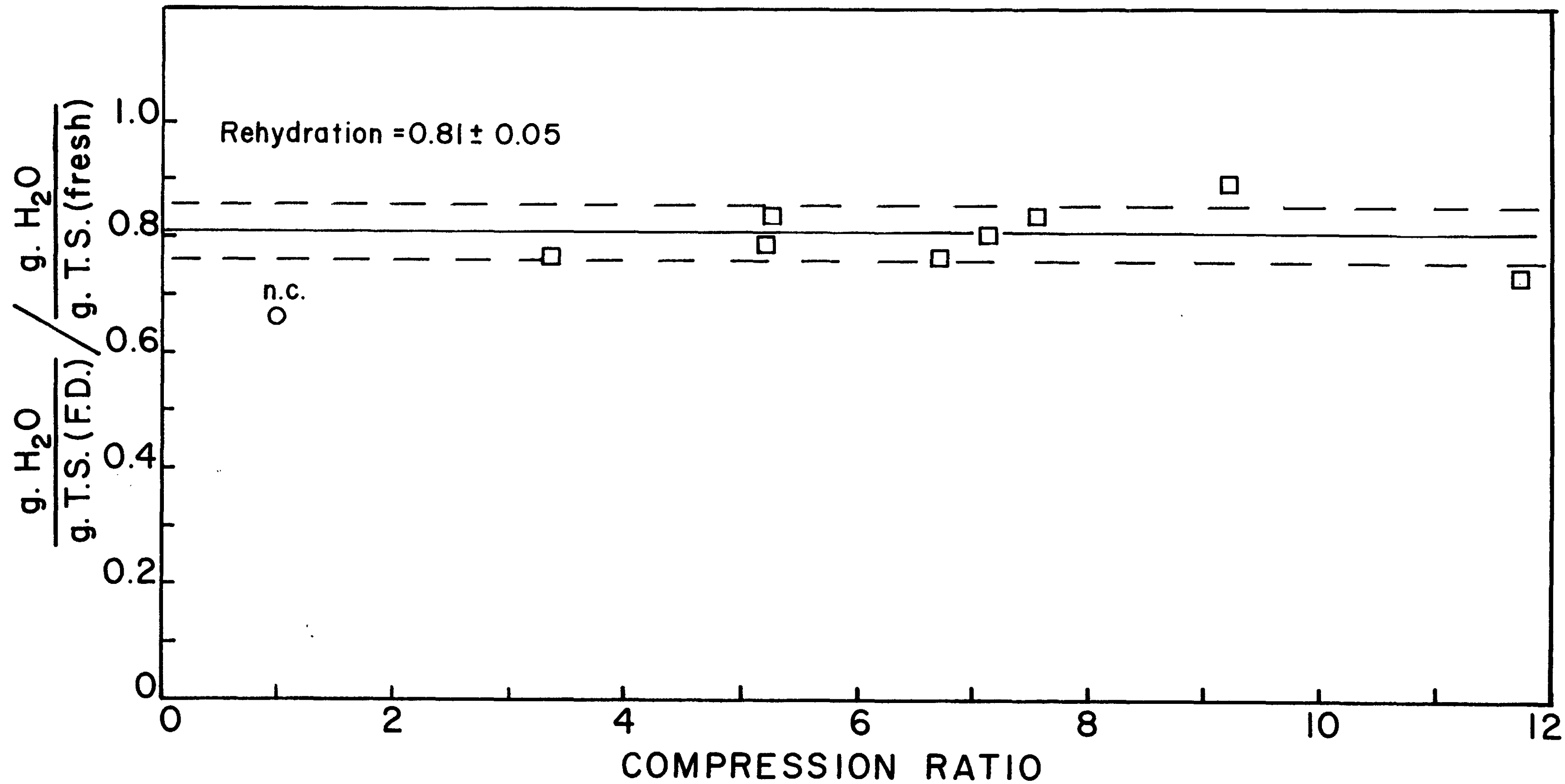
Fig. 7. Effect of vacuum on rehydration of beans.



attained did not appear to affect the extent of rehydration of green beans. (Figure 9) More detailed results of rehydration of beans are given in Appendix A-1. When the rehydration of compressed and non-compressed freeze-dried beans stored for 2 months was tested, no change in rehydration behavior was observed, with the same general pattern of rehydration being obtained. (Appendix A-1)

When no protective cheese cloth was used in the sample holder the surface of beans that were in contact with the mesh (the sample holder) showed some destruction of the tissue when compressed at high pressures ($>$90 psi). Upon rehydration the texture of these beans was in general soft and mushy, and in some cases they fractured extensively after rehydration. However, when layers of cheese cloth were used under and over the bed of sample, the destruction was greatly reduced, due apparently to a cushioning effect of the cheese cloth. The texture of the compressed rehydrated samples (as felt by hand)showed no difference from that of non-compressed. Compression (with cheese cloth) did not affect the physical appearance of the rehydrated sample and the compressed beans showed a more desirable green color than non-compressed, which were pale.

Fig. 8. Effect of compression ratio on rehydration of beans.



4.2.2 Carrots:

Table 4 shows the summarized results for carrot dice.

4.2.2.1 Compression Ratio:

Carrot dices were compressed at pressures from 65-132 psi. Figure 9 shows that all three compression ratios (displacement, height, and random increase linearly with increasing compression pressure, over the range of pressures tested. The random compression ratios for the pressure range tested varied from 2.7-7.7. The correction factor to calculate random compression ratio of diced carrots was 1.76. No visual expansion of volume of compressed carrots was observed during 3 months of storage.

4.2.2.2. Moisture Content:

As seen from Table 4 in many cases the moisture content of non-compressed samples is much higher than the corresponding moisture content of compressed samples. This could be an indication of a faster rate of drying with the compression process. Possibly due to better heat transfer in the packed sample holder. It should be noted that the comparisons in tables are made with non-compressed controls which weighed approximately the same as the compressed sample, while the small quantity non-compressed control (10-12 grams) dried to final moisture contents which were equal to or lower than the compressed samples. With the exception of two experiments

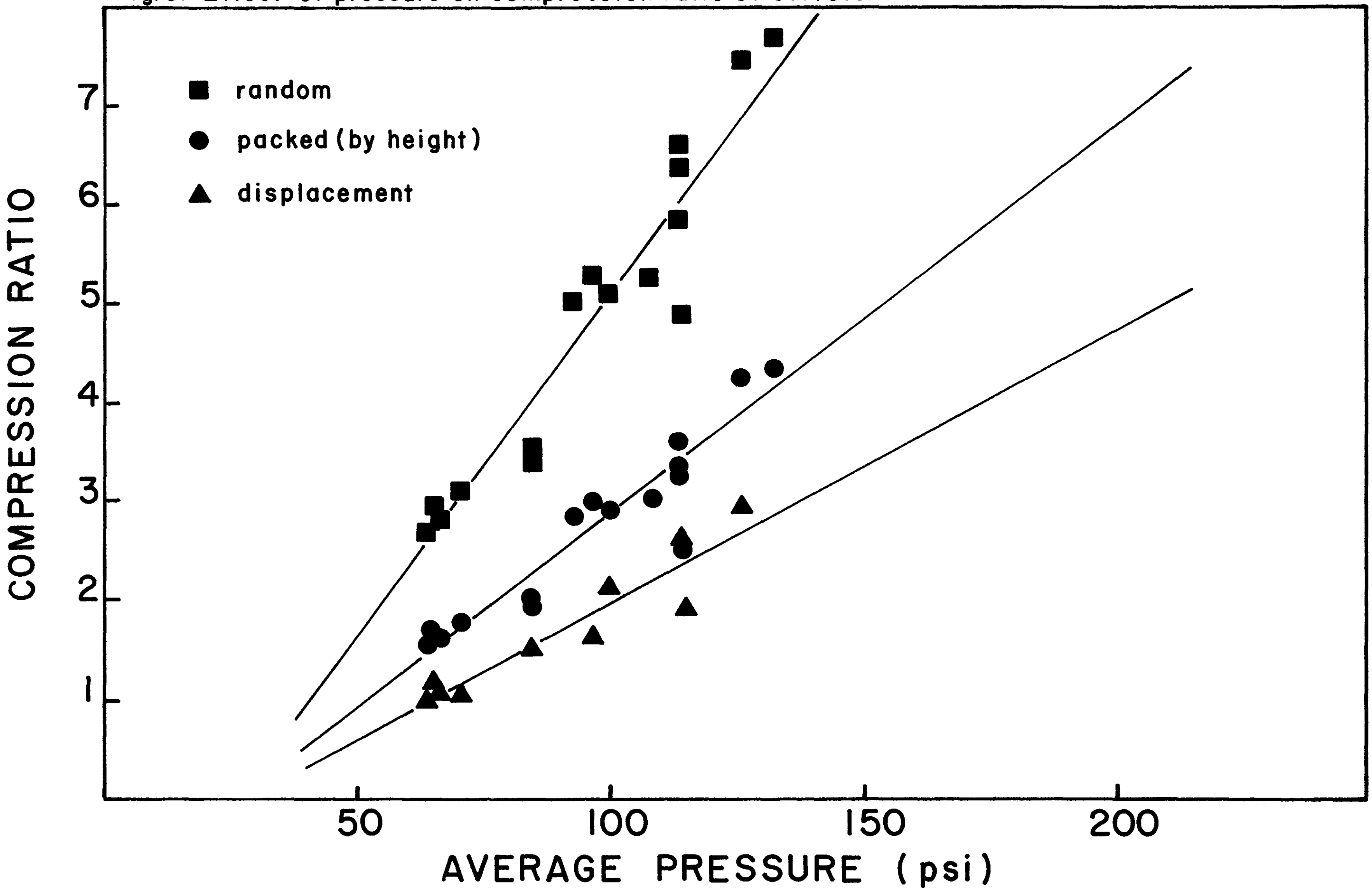
CARROTS
Experiments 1-16

Ave. Pressure (psi)	Comp. Ratio			Final M.C. % wt.		% T.S. (wet basis)		*Extent of rehyd. after 30 min. (% fresh)	
	Displacement	Ht.	Random	Comp.	N.Comp.	Comp.	N.Comp.	Comp.	N.Comp.
64.3	1.0	1.5	2.7	3.4	2.2	9.8	9.9	77	80
65.5	1.1	1.7	2.9	3.4	3.4	9.9	9.8	90	94
66.3	1.1	1.6	2.8	2.9	7.5	10.0	9.5	89	55
70.9	1.1	1.8	3.1	4.4	7.6	9.6	9.9	57	37
85.2	1.4	1.9	3.4	3.0	23.9	11.7	11.2	64	56
85.2	1.5	2.0	3.5	2.9	2.9	11.6	11.3	80	53
92.8	-	2.9	5.0	1.5	1.3	11.4	11.5	89	65
97.0	1.6	3.0	5.3	2.8	1.8	10.4	10.2	85	66
100.0	2.1	2.9	5.1	3.1	3.1	9.4	8.8	75	77
108.5	-	3.0	5.3	2.2	2.3	11.6	11.4	86	93
113.5	2.6	3.6	6.3	4.5	5.1	9.9	9.8	80	80
113.9	1.3	3.7	6.6	3.3	3.7	9.9	9.6	84	51
113.9	2.4	3.3	5.9	3.6	2.9	11.5	11.8	81	75
114.5	1.9	2.5	4.4	3.7	10.0	11.6	12.5	80	59
126.5	2.9	4.2	7.5	3.8	5.4	9.8	9.7	72	87
132.5	1.6	4.4	7.7	6.0	7.0	9.6	9.7	80	44

TABLE 4: Experimental results for Carrots.

*Rehydration in cold water with no vacuum.

Fig. 9. Effect of pressure on compression ratio of carrots.



where non-compressed samples showed a very high moisture content after drying which might have been due to accidental exposure to high humidity or incomplete drying, the range of moisture contents left after drying is between 1.5-7.7 percent. (Table 4) Drying times were between 48-60 hours. Percent total solid based on measured moisture contents were in the range of 9-12% which again closely agree with the literature value of 11.5%.

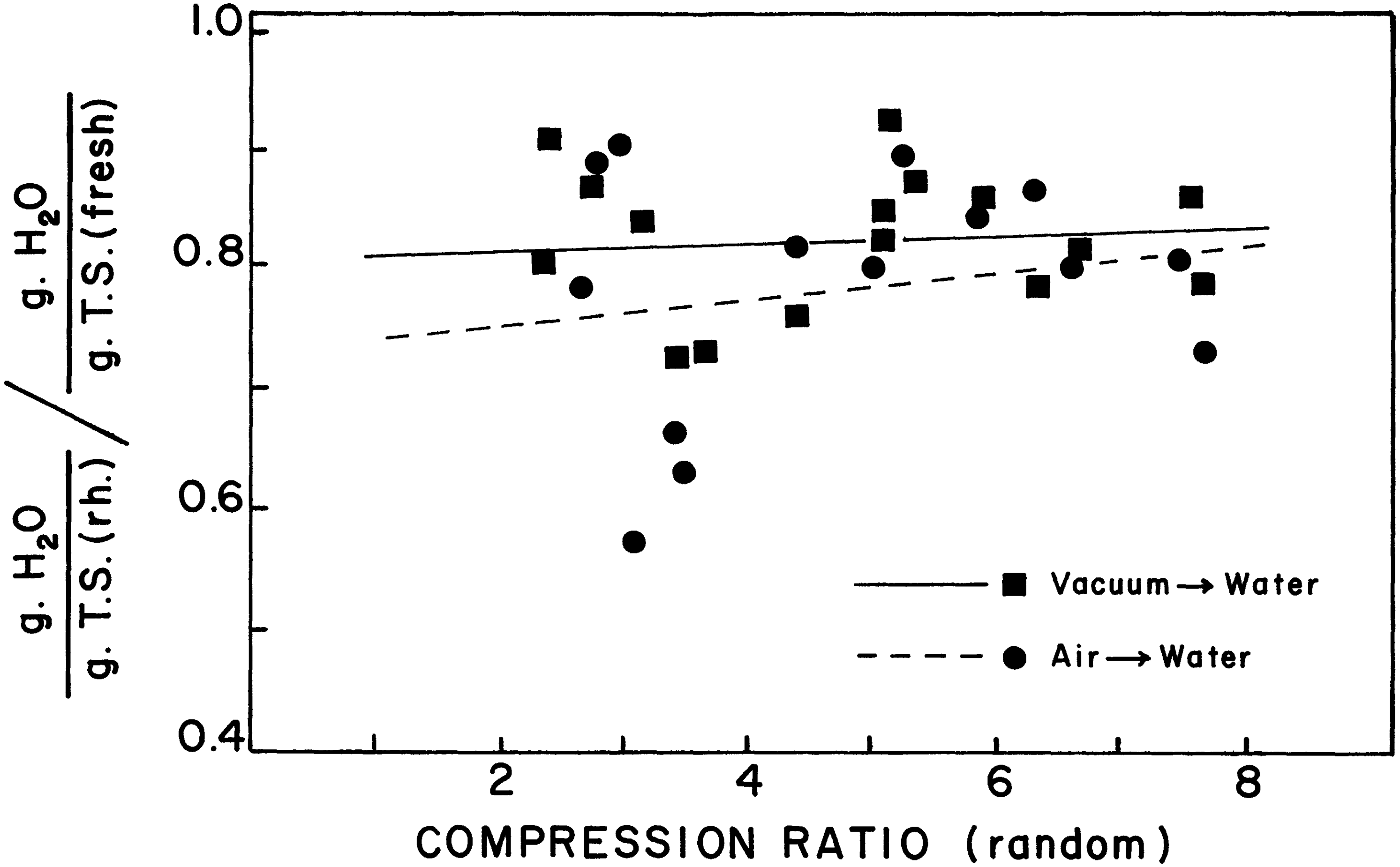
4.2.2.3 Rehydration:

Tests on the effect of water temperature, rehydration time, and sample evacuation on the carrots rehydration were similar to those of beans. When samples rehydrated without prior evacuation, compressed samples showed higher extent of rehydration in cold water (70°F.) than hot water (140°F.) or warm water (90°F.). Only one experiment was conducted at 3 different temperatures and thereafter cold water was used in later rehydration tests. Hydration was rapid generally reaching near to equilibrium in 15 minutes. Vacuum rehydration had a little effect on compressed samples whereas non-compressed samples showed an increase in rehydration to a level equal to that of compressed. (Appendix A-2) The effect of vacuum on rehydration of carrots suggests some structural changes during compression which effects the amount of air entrapped in the cells or ease of its removal with water influx. Figure 10 shows that there is little effect of compression ratio (random) on extent of rehydration. Rehydrated compressed carrots did not differ from non-compressed samples in physical appearnace. They returned to their original volume upon reconstitution. By hand feel the texture of compressed rehydrated samples were slightly softer than that of non-compressed.

A test of rehydration behavior of stored samples showed no changes (Appendix A-2); however, when storing compressed and non-compressed samples from earlier studies it became appparent that air-storage at 0% RH even in absence of light (i.e. in a cabinet) resulted in a bleaching of the pigments in carrot dices and loss of desirable flavor (as indicated from organoleptic tests).

An experiment was conducted where compressed and non-compressed carrots were stored in the absence and presence of air in the absence of light. After 2 months, carrots which were stored in presence of air were completely bleached and became almost pale yellow in color; the samples stored in absence of air did not visually seem to have lost any pigments. It is concluded that bleaching and the loss of flavor detected in organoleptic tests is due to air oxidation of dried carrots. More detailed results of rehydration

Fig. 10. Effect of compression ratio on rehydration of carrots.



tests for carrots are presented in Appendis A-2.

4.2.2.4 Organoleptic Evaluation:

Two organoleptic tests were conducted to evaluate acceptability of compressed carrots versus non-compressed and frozen. Carrots were boiled for 5 minutes prior to testing. In the first test frozen carrots were rated significantly better than compressed and non-compressed, while compressed was rated slightly higher than non-compressed. Comments indicated a large loss of color and flavor in both dried samples. The carrots used in the above organoleptic test had been stored for over a month in an unevacuated light free desiccator. A second organoleptic test was conducted on dried samples which were not stored. This significantly improved the organoleptic evaluations of the dried samples. Although, frozen carrots still were rated best there was no signigicant difference observed in taste and texture. The compressed ranked second while the non-compressed remained last. Results of organoleptic tests for carrots are given in Appendix A-2.

4.2.3 Peas:

Table 5 gives the summarized results for peas.

4.2.3.1. Compression Ratio:

Compression pressures used for peas were between

PEAS
Experiments 1-10

Ave. Pressure (psi)	Comp. Ratio			Final M.C. % wt.		% T.S. (wet basis)		*Extent of rehyd. after 30 min. (% fresh)	
	Displacement	Ht.	Random	Comp.	N.Comp.	Comp.	N.Comp.	Comp.	N.Comp.
39.5	1.2	2.0	2.7	1.6	2.3	22.1	21.7	73	95
40.5	1.4	2.4	3.2	0.9	1.6	22.7	20.6	90	94
42.3	1.9	2.7	3.6	4.2	3.2	22.3	21.8	87	54
42.5	2.0	2.7	3.6	6.9	3.5	21.6	21.8	60	36
42.7	1.5	2.5	3.3	1.4	2.1	20.7	19.5	73	43
45.1	-	3.0	4.0	6.1	3.8	21.5	22.1	81	55
45.1	2.0	2.5	3.3	4.6	4.0	21.3	21.7	67	54
55.4	1.5	2.8	3.7	2.3	2.6	21.3	21.5	85	85
59.1	1.1	3.2	4.2	1.7	2.1	21.8	22.4	91	107
97.3	1.3	4.2	5.6	1.7	1.6	19.8	19.8	90	66

TABLE 5: Experimental results for Peas.

*Rehydration in cold water with no vacuum. Non-compressed values correspond to peas with split skin.

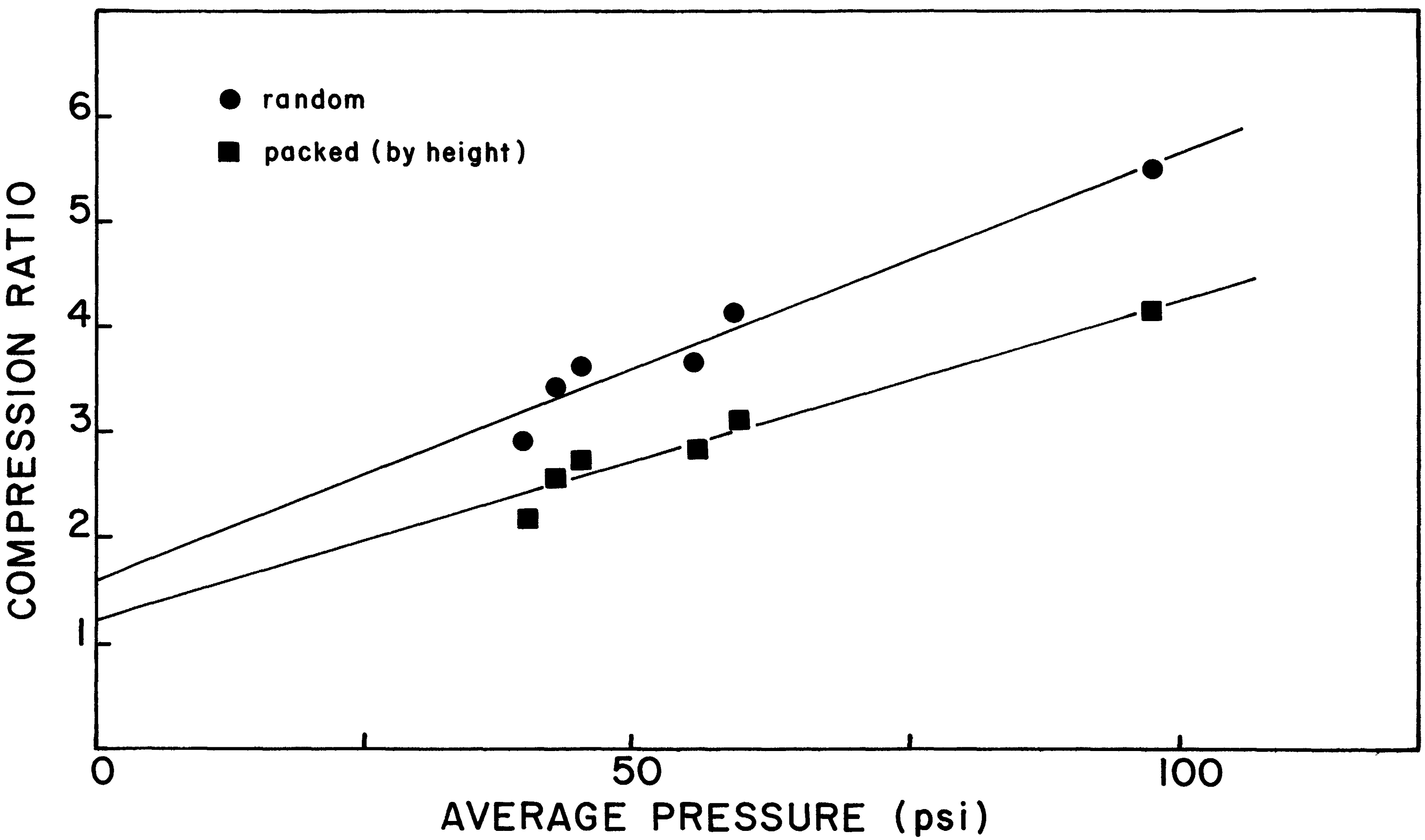
39-97 psi giving random compression ratios of 2.9 to 5.5. Figure 11 shows the different compression ratios as a function of compression pressure. It is seen that compression ratio increases linearly with increasing pressure. A correction factor of 1.33 was determined to obtain random compression ratios from the measured compression ratios based on height. No change in volume of compressed peas was observed over 12 months of storage.

4.2.3.2 Moisture Content:

Drying times of 48-60 hours were used for peas. As seen from table 5, final moisture content of compressed samples are very close to those of non-compressed (control number 1).

This suggests that the process of compression during freeze-drying of peas does not impede the flow of vapor to the extent that drying to low moisture contents would not be possible. It can be noted that the final moisture content of control number 2 which was freeze-dried in smaller quantities were always lower or equal to that of the compressed samples. The range of final moisture contents in the compressed samples were from 0.9-7.0%. The percent total solids calculated from percent moisture content was between 19.8-22.7 which is quite close to reported literature values of 19.3 (U.S.D.A., Handbook No. 8).

Fig. 11. Effect of pressure on the compression ratio of peas.



4.2.3.3 Rehydration:

Rehydration of dried compressed peas was quick and went to equilibrium in about 15 minutes in cold water. The original volume was recovered. In general compressed peas rehydrated better than non-compressed, which is similar to beans and carrots. Vacuum rehydration with vacuum release with water improved rehydration of peas to a large extent. However, it was still noted that some non-compressed peas rehydrated very slowly and to low extents. (Appendix A-3)

Further investigation showed that most compressed peas had a hole or crack in their outer skin which apparently was produced during compression. On the other hand the skin of many non-compressed peas (40 percent) remained intact. The unbroken skin slows down the extent of rehydration to a great degree. The effect of vacuum on rehydration of non-compressed peas and the influence of the skin are noted in Appendix A-3. It is seen that vacuum and broken skin faciliate the extent of rehydration in the case of non-compressed peas. Little influence of vacuum was observed for compressed peas. In later experiments, only non-compressed peas which were cracked were tested for rehydration. The color and texture of rehydrated compressed peas were very good and did not seem to have been affected by compression. Figure 12 shows the effect of compression ratio on the extent of rehydration after 30 minutes. It is seen that compression does not affect the rehydration behavior of the dried sample. Appendix A-3 gives more detailed experimental results of rehydration behavior of peas.

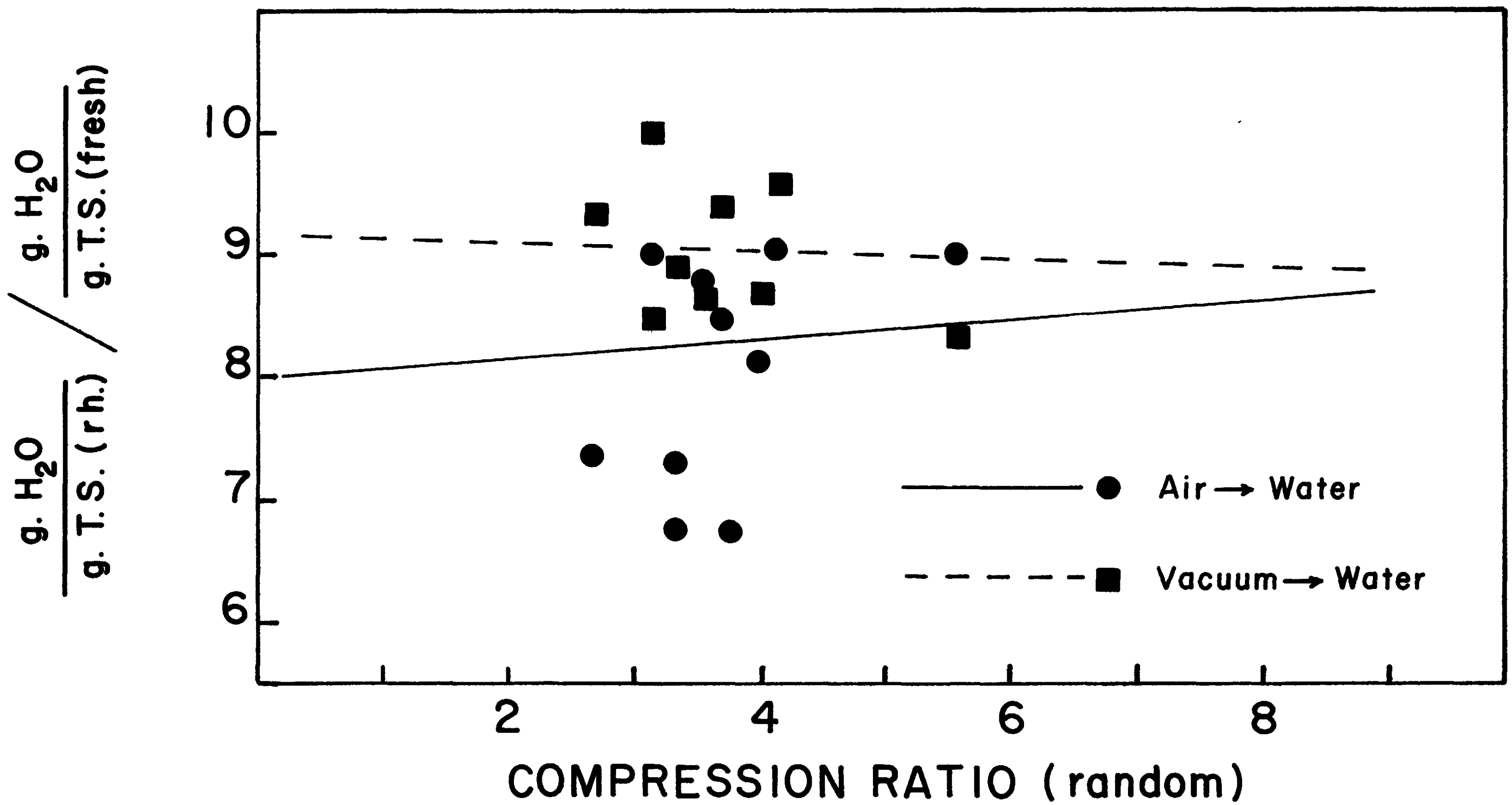
4.2.3.4 Organoleptic Evaluation:

Frozen, non-compressed rehydrated and compressed rehydrated samples were boiled for 5 minutes and served with a touch of salt and butter. Although all samples showed insignificant statistical difference, the compressed and fresh were rated very close in terms of their texture and taste. Ranking test showed again that compressed and frozen were very close, with the frozen rated first, compressed next, and non-compressed rated last. The results of organoleptic evaluations for peas are given in Appendix A-3.

4.2.4 Corn:

Only 2 experiments were conducted on cut corn kernels. At pressures of 43 and 47.5 psi, the corresponding random compression ratios were 2.8 and 2.9, respectively. The final moisture content of both compressed and non-compressed dried products was very low, being between 1.5-2.9%, indicating that the compression process did not affect drying

Fig. 12. Effect of compression ratio on rehydration of peas.



to low moisture contents. Rupture or fracture of the outer kernel skin of compressed products produced some fines. Upon rehydration the whole kernels re-attained their original volume. Vacuum did not seem to affect rehydration and both compressed and non-compressed rehydrated to nearly the same extent (up to 70%). Appendix A-4 gives more detailed results of rehydration with time.

4.3 Fruits:

The data for this section is given in Appendix B.

4.3.1 Blueberries:

Table 6 shows the summarized results.

4.3.1.1 Compression Ratio:

Fresh blueberries were slowly frozen and compressed/freeze-dried at pressures from 3.9-30 psi. Out of 19 experiments, 5 were classified as having significantly collapsed product and 2 as having completely collapsed product. (A collapsed sample was identified by exuded juice which had run out through the sample holder mesh and which usually were puffed during drying.) Collapse phenomena was probably due to high sugar content of blueberries. Also due to the short season that fresh blueberries are available, the textural variation in the raw material is relatively high. It was noted that toward the end of the season the texture of blueberries became softer and they were more prone to

BLUEBERRIES
Experiments 1-12

Ave. Pressure (psi)	Comp. Ratio Displacement	Comp. Ratio Ht.	Comp. Ratio Random	Final M.C. % wt. Comp.	Final M.C. % wt. N.Comp.	% T.S. (wet basis) Comp.	% T.S. (wet basis) N.Comp.	*Extent of rehyd. after 30 min. (% fresh) Comp.	*Extent of rehyd. after 30 min. (% fresh) N.Comp.
3.9	-	2.1	2.8	3.9	2.3	15.0	15.7	25	45
6.2	1.5	2.6	2.3	1.4	3.1	15.0	15.3	33	67
8.1	-	3.4	4.5	4.5	4.6	14.4	16.2	20	31
14.0	1.7	3.9	5.0	5.0	4.1	13.6	14.6	23	19
14.3	1.5	3.9	5.2	6.2	8.6	14.2	14.1	15	39
15.0	1.5	2.8	3.7	1.9	3.0	14.2	14.6	26	50
18.7	1.7	6.2	8.1	2.8	2.9	17.2	15.6	21	47
18.9	1.5	5.1	6.6	3.0	2.2	16.0	16.9	12	51
19.1	1.1	5.3	7.0	4.7	4.6	17.4	17.2	22	32
20.1	1.3	2.5	3.3	3.0	2.3	16.8	16.9	20	49
26.4	-	4.3	5.6	3.6	4.1	13.9	14.5	13	77
27.4	-	6.5	8.5	3.3	2.5	14.2	14.2	46	46

TABLE 6: Experimental results for Blueberries.

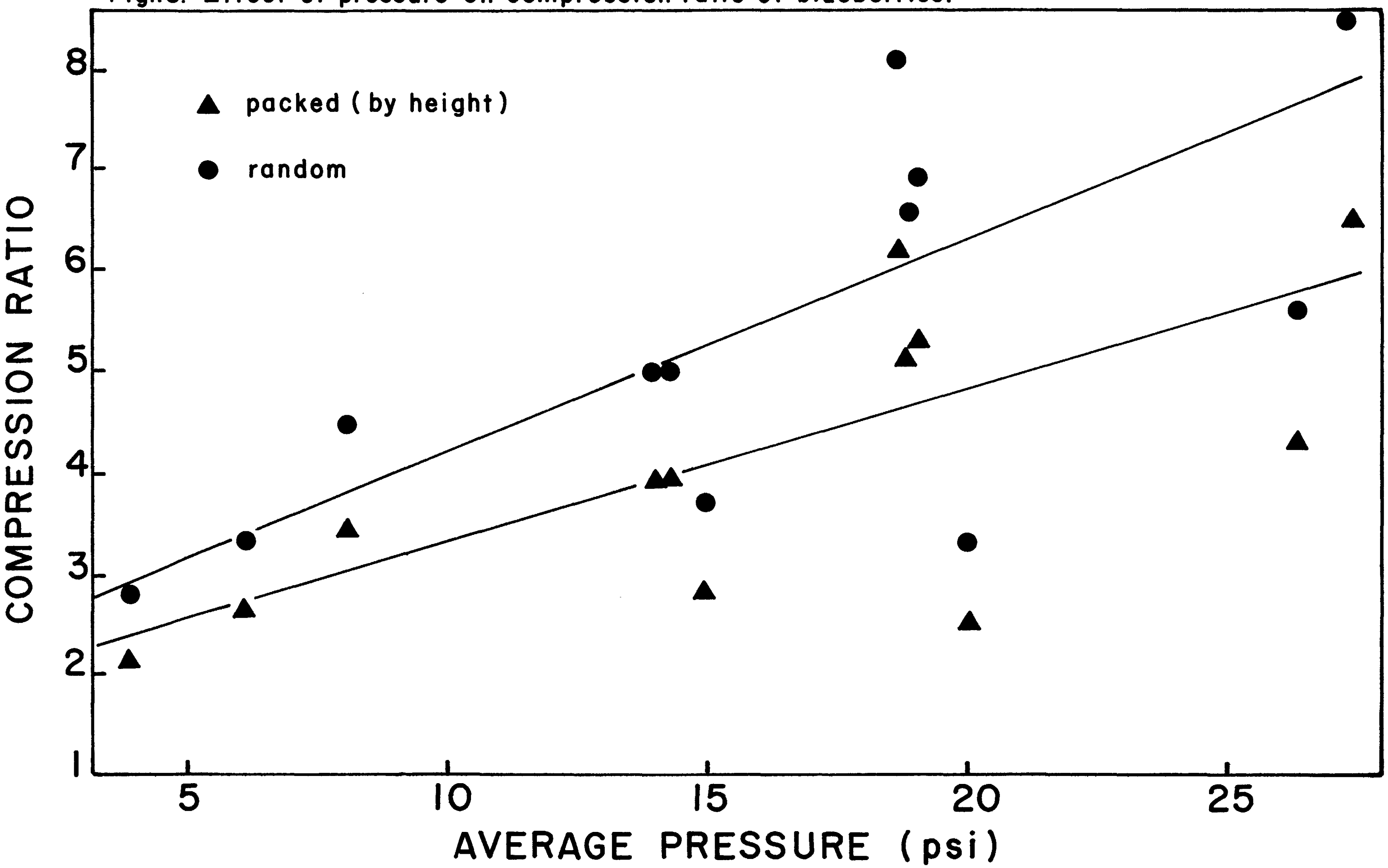
*Rehydration in cold water.

collapse. The experimental data given for blueberries is based on the 12 experiments where little or no collapse was observed. Figure 13 shows the relationship between compression ratios and pressure. It is seen that the correlation is not very good which is probably due to the variation in the texture of different blueberry batches used. A correction factor of 1.3 was calculated to convert compression ratios by height to random compression ratio. Compressive forces required to compress blueberries were much lower than that needed for vegetables for given compression ratios. For the compressed samples the skin was usually broken or cracked; however, the berry itself remained whole. No relaxation of compressed samples was observed over time. Non-compressed dried controls shrank somewhat after freeze-drying and their skin became quite wrinkled.

4.3.1.2 Moisture Content:

Final moisture contents for blueberries which were successfully compressed during freeze-drying were generally between 2.0-4.5 percent. The drying cycle was lengthened to 60 hours, since the samples were not completely dry in 48 hours. This is probably due to the tough skin which cause the drying rate to be reduced. A range for total solids was obtained (13.6-17.4), which compares well with

Fig.13. Effect of pressure on compression ratio of blueberries.



the reported value of 16.8 (U.S.D.A, Handbook No. 8).

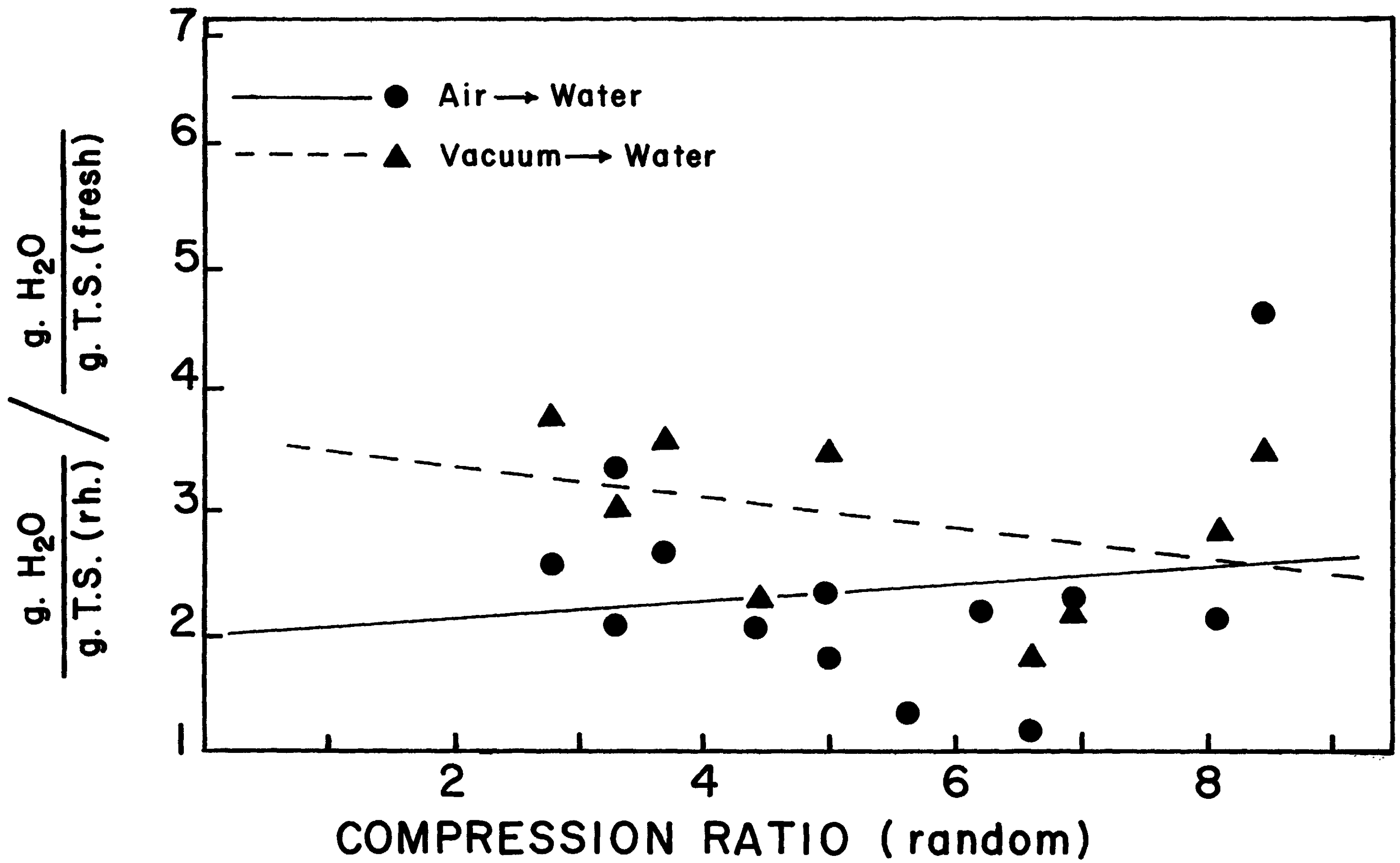
4.3.1 3 Rehydration:

The extent of rehydration of both compressed and non-compressed blueberries was generally poor. Rehydration at different water temperature indicates that blueberries rehydrate best in hot water. (Appendix B-1) Vacuum prior to rehydration generally gave some improvement for both compressed and non-compressed (Appendix B-1) samples. A comparison of the extent of rehydration of compressed and non-compressed samples showed that the non-compressed samples rehydrated about 2 times that of compressed samples. The original volume was not recovered after rehydration and compressed samples remained flat, even though there was some water pickup and the product softened somewhat. The rehydrated samples were not as soft as fresh. Some leaching of the color pigments was also noted during rehydration of compressed samples. For compressed samples, there did not seem to be any particular relationship between compression ratio and rehydration (Figure 14).

4.3.1.4 Organoleptic Evaluation:

A number of organoleptic tests were conducted with blueberry products, one with blueberry pie filling and three with blueberry muffins. Recipes were taken from Sutherland, et al, (1973).

Fig. 14. Effect of compression ratio on rehydration of blueberries.



The Hedonic preference test with pie filling showed significant differences between the texture of fresh or non-compressed samples with compressed. No significant difference was observed between the texture of fresh and non-compressed. No significant difference in taste was observed between any samples. In the ranking test fresh and non-compressed blueberries were rated the same and significantly higher than the compressed sample. The pie filling made from compressed sample was too "thin" since compressed blueberries rehydrate very poorly and thus there was too much water in the pie filling.

In later experiments with muffins, the dried blueberries (compressed and non-compressed) were either held over steam until they were soft, or only very little water was added to just soften the samples. The panelists were asked to evaluate the taste and texture of only the blueberries in the muffin and not the muffin itself. They were to be ranked based only on the blueberries. In the first test both the texture and taste of compressed blueberries (in muffins) were preferred over fresh (not significant) and non-compressed, (significantly different). In the second test fresh and compressed samples were rated equal in terms of taste and texture, with non-compressed rated last; however, no significant difference was observed between all samples. In the third experiment all samples were rated very close to each other and no significant difference was observed. Appendix B-1 gives the results of organoleptic evaluation for blueberries.

4.3.2 Cherries:

Fresh cherries were pitted and used as whole or halves. Almost all drying experiments conducted were unsuccessful, in that the product underwent collapse. Compresseion pressures as low as 11 psi resulted in collapse. Two experiments gave product that seemed to be uncollapsed, though the physical appearance was poor. The sample had browned and was cracked and wrinkled. They showed compression ratios of 2.9 and 3.0 (random) with compression pressure of 41 and 43 psi, respectively. The moisture contents were about 4 percent. Non-compressed cherries which also had a poor appearance (browned and wrinkled) had final moisture contents of 2.5-3 percent. In another experiment in which the cherries appeared to be uncollapsed the final moisture content was 2.4 percent. In this case the compression pressure of 17 psi gave a compression ratio of 14.3. The percent total solids calculated from the final moisture content ranged from 17.1-20.5% which agrees with the reported value of 20.6%

(U.S.D.A., Handbook No. 8).

The dried samples had good taste but a rather chewy texture. Upon reconstitution the compressed samples fractured extensively and browned further, while the non-compressed samples, though cracked, remained whole, and became browner.

The results with cherries do not seem to be reliable and it seems that cherries are not very suitable for compression during freeze-drying, at least with the loading cell used in these experiments. It should be noted that the drying apparatus was always operated at chamber pressures below 100 millitorr.

4.4 Meat:

The detailed experimental data for this section is given in Appendix C.

4.4.1 Ground Beef:

Two experiments were carried out with 18% fat ground beef. Average compression pressures of 44.7 and 66.3 psi were applied during freeze drying giving compression ratios (height) 1.2 and 1.8, respectively. The final moisture content of both compressed and non-compressed samples were relatively low in the range of 1.7-2.5% after 48 hours of drying.

The percent total solids calculated from the final moisture content were between 32.6-34.7%.

Rehydration of both compressed and non-compressed samples in cold water was very fast, generally reaching more than 80 percent relative to fresh after 2 minutes and more than 90 percent after 30 minutes. Vacuum did not seem to affect rehydration. (Appendix C-1)

4.4.2 Bottom Round Steak:

Table 7 shows the summarized results.

4.4.2.1 Compression Ratio:

Fresh bottom round steak trimmed of fat was used as cubes approximately 1 cm on each side. Frozen cubes were packed in the sample holder so that the direction of force would be perpendicular to the grain. A few tests were conducted with grain parallel to the direction of compression. The influence of compression pressure on compression ratio is shown in Figure 15. The compression ratio based on height is given since the random compression ratio will depend on the size of the beef cubes. With 1 cm beef cubes, the correction factor to calculate the random compression ratio from the height values is approximately 2. It can be noted from Figure 15 that the degree of compression is linearly related to the compression pressure; however, compression is much less responsive to increase in pressure than the fruits and vegetables tested.

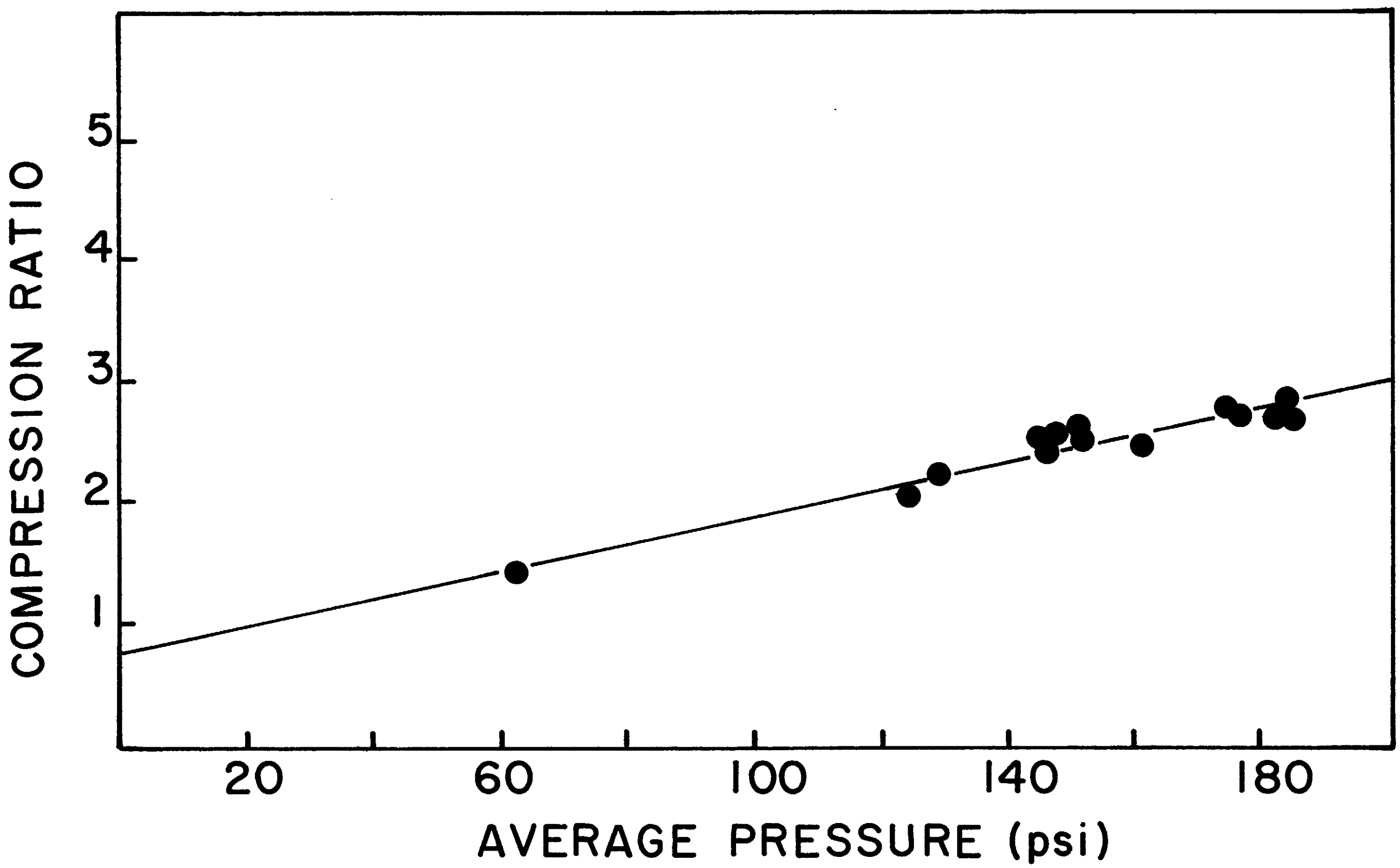
BEEF CUBES
Experiments 1-14

Ave. Pressure (psi)	Comp. Ratio Displacement	Comp. Ratio Ht.	Comp. Ratio Random	Final M.C. % wt. Comp.	Final M.C. % wt. N.Comp.	% T.S (wet basis Comp.	% T.S (wet basis N.Comp.	*Extent of rehyd. after 30 min. (% fresh) Comp.	*Extent of rehyd. after 30 min. (% fresh) N.Comp.
63.2	1.2	1.4	-	2.6	2.4	28.3	29.1	82	90
125.3	1.2	2.0	-	1.1	1.1	26.2	27.1	84	94
129.5	-	2.2	-	-	-	-	-	-	-
144.7	1.4	2.5	-	0.9	1.4	26.3	26.9	70	84
146.7	1.7	2.4	-	1.3	0.8	27.2	27.1	60	78
147.7	1.5	2.5	-	0.4	0.5	25.7	27.2	89	98
151.4	1.3	2.6	-	1.2	1.0	25.2	27.6	62	84
151.8	1.4	2.5	-	1.2	1.2	25.8	26.8	68	72
162.0	1.4	2.4	-	1.4	1.7	26.2	27.2	87	95
175.2	1.5	2.7	-	1.1	1.5	28.8	29.6	68	80
177.1	1.8	2.7	-	1.1	0.9	27.4	28.3	57	81
182.0	1.3	2.7	-	1.1	0.9	26.9	26.7	56	88
184.8	1.6	2.8	-	1.1	9.3	26.3	25.7	53	81
184.8	1.6	2.7	-	1.o	1.0	26.6	27.1	68	92

TABLE 7: Experimental results for Beef Cubes.

*Rehydration in cold water with no vacuum.

Fig.15. Effect of pressure on compression ratio (by height) of beef.



The compression ratios of the samples having the grain perpendicular to the direction of force were not different from those having the grain parallel. Maximum compression ratio (height) obtained for beef cubes was 2.9 at a pressure of 185 psi. No expansion of volume of compressed beef was observed over 8 months of storage.

4.4.2.2 Moisture Content:

Final moisture contents of both compressed and non-compressed dried beef cubes were quite low, in the range of 0.4-2.6%. As seen from table 7 after 48 hours of freeze-drying the final moisture contents of compressed samples are very close to non-compressed, and in many cases less. This indicates that compression of beef during freeze-drying does not prevent achieving low moisture contents. Percent total solids in fresh samples were calculated from values of final moisture content and ranged from 25-29.5% which compares well with the reported literature value of 27.3% (U.S.D.A., Handbook No. 8) for lean, raw round beef.

4.4.2.3 Rehydration:

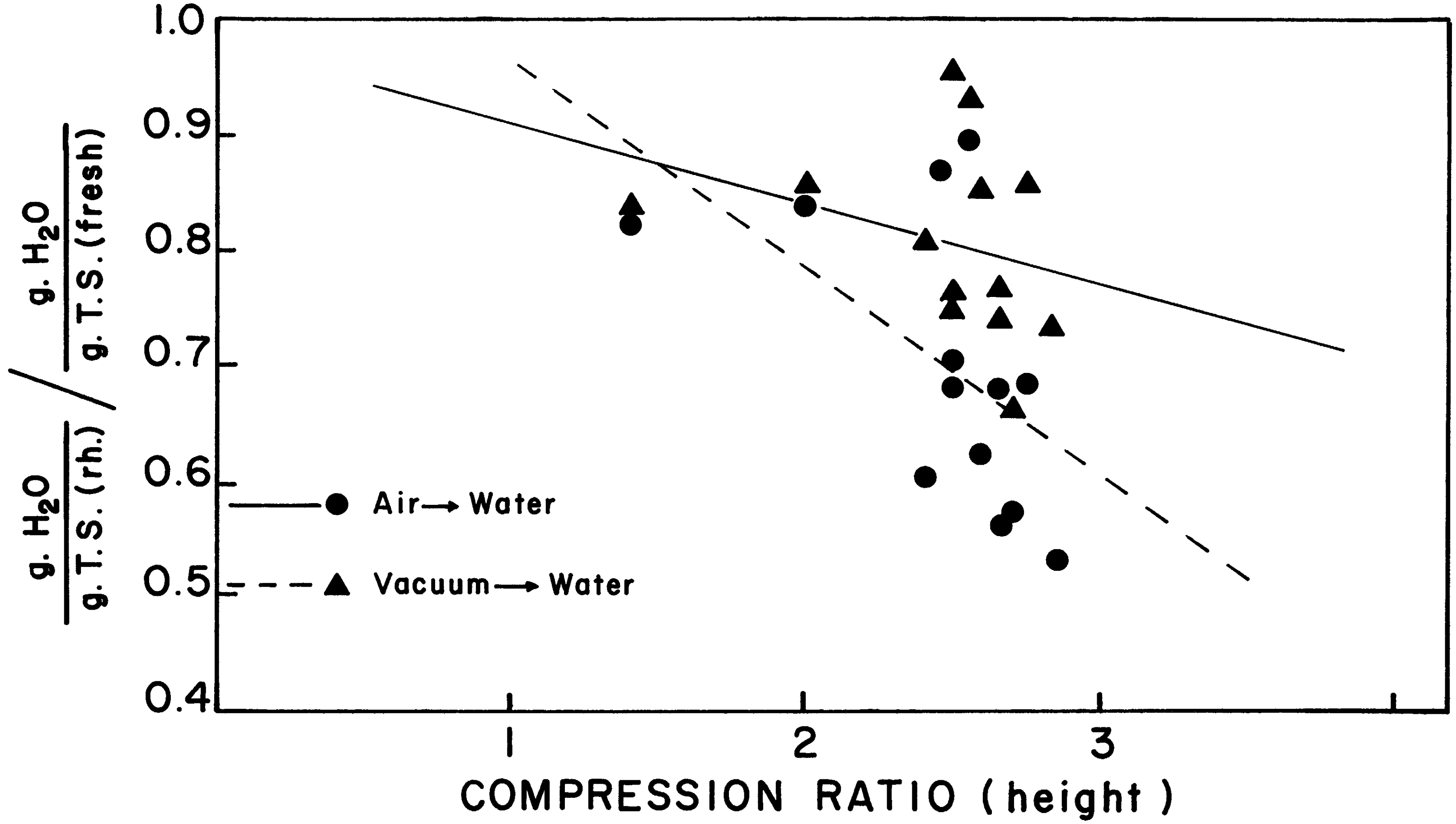
Examination of rehydration behavior of freeze-dried beef cubes showed that in all cases non-compressed samples rehydrated better than compressed (Appendix C-2). There was little influence of prior evacuation on rehydration of either compressed or non-compressed samples (Appendix C-2). In one test on the effect of water temperature on the extent of rehydration, it was noted that warm water (100°F.) gave better rehydration than either cold or hot water (Appendix C-2). Cold water rehydration gave the best color, since warm or hot water rehydration resulted in samples with a darkened, greyish-brown color, and a cooked appearance. The rate of water uptake by compressed samples was much slower than that of non-compressed. Rehydration of non-compressed samples was fast and went to equilibrium in about 2 minutes. In most cases compressed samples still had a hard core after 30 minutes of rehydration and more than one hour was required for complete penetration of water (Appendix C-2). Compression samples recovered almost full volume after rehydration.

The influence of compression ratio on rehydration is shown in Figure 16. Some scatter of the data points is noted, perhaps due in part to the narrow range of compression ratios (compared to other products tested). Fitting a straight line to the data does indicate a trend toward a decrease in rehydration with increasing compression.

4.4.2.4 Organoleptic Evaluation:

Fresh, non-compressed rehydrated and compressed rehydrated beef cubes were fried in butter and served

Fig.16. Effect of compression ratio on rehydration of beef cubes.



immediately for organoleptic evaluation. The results showed that both compressed and non-compressed samples were very close in taste and texture. Fresh samples were rated first, non-compressed next, and compressed last. However, no significant difference was noticed between all samples at 1 percent level of significance. Appendix C-2 gives the results of organoleptic test evaluation of fried beef cubes.

4.5 General Discussion:

All samples tested showed good compressibility, except for cherries and in some cases, blueberries. These products underwent collapse at the pressures applied. It is likely, that the collapse which occured with these products is mainly due to mass transfer limitations which give rise in sample temperature and the high sugar contents.

The packed configuration in the mesh container and the thick skin of these samples can contribute significant mass transfer resistances. Also, compression of the dry layer during freeze-drying reduces the channals and pathways by which vapor escapes. These effects can increase the temperature of the frozen layer. On the other hand as mentioned in section 2.4 MacKenzie and Luyet (1971) explained that increase in sugar content and/or water: sugar ratio can significantly decrease glass-transition temperature of sugars. When the temperature of the boundary layer passes this glass-transition temperature, the sugar phase then flows under pressure with simultaneous and irreversible deformation of cellulosic phase which seems to be the case with blueberries and cherries. It should be noted that examination of non-compressed samples which had been freeze-dried at pressures well below 100 microns with only ambient leakage heat input showed poor physical appearance, and in some instances even partial collapse.

Compressed samples generally did not form bars unless handled carefully. This was due to the difficulties in releasing the compressed sample from the holder. This problem should be eliminated by design of the sample holder with sufficient lubrication and possibly by use of binders in the product.

Examination of products before completion of compression/freeze-drying showed that compression proceeded with the retreat of the ice front which indicates that compression took place at the ice-dry layer interface. This supports the concept that at the ice-dry layer interface, the high moisture content present gives a material having plastic properties.

The compressive pressures used in this study (4-185 psi) are significantly lower than those required for compression of foods with the other methods currently employed (100-5000 psi) to obtain corresponding compression ratios. Besides differences in plasticity this may be due to the difference in the thicknesses of the samples to be compressed.

In general a bed height of several centimeters is used for techniques involving compression after complete dehydration. Studies on moisture profiles during freeze-drying have shown that the "diffusion zone" at the interface where high moisture contents exist, has a thickness of a few millimeters (Aguilera, and Flink, 1974). As mentioned above the only place which is continuously compressed during freeze-drying is this narrow layer where enough plasticity exists due to the high moisture content present. Therefore, the pressures to compress this narrow layer should be much less than the pressures required to compress samples with a thickness of several centimeters.

Compression ratios obtained were linearly related to compressive pressure and increased with increasing pressure over the range tested. It is expected that the compression ratio would reach a maximum value at some compressive pressure so that no increase in compression occurs with further increase in pressure. It should be noted that during compression process two types of void volumes are being eliminated. One is the void volume between individual pieces in the sample holder and the other is the voids that are produced by sublimation of ice, which reflect the true change in the volume of individual pieces. This reduction in volume is directly related to the initial water content of the fresh material and its maximum value approximately equals the volume originally occupied by water in the fresh sample. This is clear in experiments with beef. Lean beef has approximately 65% water when fresh. The maximum values of compression ratios obtained in this study or reported elsewhere for this product is approximately 3 which corresponds to about 65% reduction in volume. Also that, when the compressive pressure was increased from 175 to 185 psi (Table 7) no increase in compression ratio was observed. This could probably indicate the maximum compression ratio obtainable by this technique is attained at pressures around 180 psi.

If food is considered as a plastic material with a constant resistance to deformation, when stress is applied there will be a minimal (residual) force required to initiate compression (yield stress). This was estimated to be (not shown in graphs) relatively high for peas, carrots, and beef cubes (around 50 psi), but very low for blueberries and beans ($<$10 psi) which indicates that the force required to initiate compression depends on the particular food. If this resistance remains constant during compression process then, the net force which causes deformation can be expressed as:

$$F_1 = F_2 = \Delta F = Ma$$

$$= M \frac{d^2s}{dt^2}$$

$$\text{or: } \frac{d(\frac{ds}{dt})}{dt} = \frac{\Delta F}{M}$$

$$= d(\frac{ds}{dt}) = \frac{\Delta F}{M} dt$$

By integrating the above equation:

$$\frac{ds}{dt} = \frac{\Delta F}{M}(t - t_o) \quad \text{where: } t_o = 0$$

$$\text{then: } ds = \frac{\Delta F}{M} \cdot tdt$$

Second integration results:

$$s = \frac{\Delta F}{M} \cdot \frac{t^2}{2}$$

If the drying rate is constant then:

$$\frac{t^2}{2M} = K_1$$

$$\text{and: } s = K_1 \Delta F$$

$$\text{since: } F_2 = \text{Constant}$$

$$\text{then: } s = K_1(F_1) - K_2$$

where:

F_1	force applied (springs)
F_2	resistance force (food)
M	mass of element being compressed
t	time element is plastic enough
s	distance that element moves in time = t

From the above equation it can be seen that the extent of deformation which is related to the degree of compression is directly related to the force applied, inversely, to the mass at the interface (which is related to the thickness of diffusion zone), physical characteristics of the material and time. As mentioned before the bigger the diffusion zone the higher force will be required for compression or in other words with constant compressive pressure the degree of compression of the boundary layer depends on the thickness of the boundary layer and increase in thickness of this layer results in decrease in degree of compression.

Final moisture contents of both compressed and non-compressed samples were always similar and in most cases about 1.5-4.5%. This shows that compression process during freeze-drying does not prevent the dehydration of the samples to low moisture contents. There were some indications that the heat transfer might be improved due to compression; however, further investigations of drying rates during compression are necessary to evaluate drying times.

Rehydration of samples was quick and in most cases went to equilibrium within 15 minutes. All samples except blueberries re-attained their pre-compressed volume after rehydration. Non-compressed vegetables rehydrated to lesser extents than compressed. Vacuum rehydration revealed that the cause for lower uptake of water by non-compressed vegetables was due to air entrapped in the cells. Higher rehydration of compressed samples than non-compressed (when no vacuum was used) indicates some structural changes (distruptions) caused by compression either faciliate water uptake or removal of entrapped air. It is known that cell distruption as produced by slow freezing (Logan, 1973) or cooking (Rahman, 1972) faciliates water uptake. Curry, et al, (1976) showed that soaking pre-cooked carrots in water or low concentrations of NaCl (0.1-0.2 Molar) before freeze-drying markedly improved rehydration. They suggested that soaking in water for relatively long times (24 hrs) causes cells to become turgid with maximum water uptake which in turn cause more distruption of cells during freeze-drying resulting in better rehydration.

NaCl solutions do the same thing; however, it has also been suggested that after freeze-drying, NaCl crystals deposited on the cells may attract water molecules (polar effect) to faciliate flow inside the cells which causes even higher rehydration than soaking in plain water. Nevertheless compression or vacuum rehydration seem to improve rehydration of carrots to the same extent.

The percent rehydration (relative to fresh sample) did not seem to be affected by the degree of compression (except for beef cubes).

Organoleptic evaluations of prepared non-compressed, compressed, and fresh samples indicated that compressed were always rated equal to or higher than the non-compressed. The fresh samples usually were rated higher than either the compressed and non-compressed freeze-dried product. However in most cases the differences noted were not significant at the 1% level.

5. CONCLUSIONS

1. Compression during freeze-drying can be successfully accomplished.

2. High compression ratios are attainable with application of relatively low compressive forces.

3. This process allows effective drying to low moisture contents of compressed foods.

4. During freeze-drying the ice-dry layer interface has enough plasticity to allow compression. This supports the existance of a non-linear moisture gradient having high values near the ice interface or a "diffusion zone," though may be narrow at the ice interface.

5. Most dehydrated foods which can be plasticized for compression through remoistening should be compressible during freeze-drying using the procedure described.

6. The degree of compression obtainable depends on physical characteristics of the food material and the compressive pressure applied.

7. Rehydration of compressed samples obtained by this procedure is rapid and generally not affected by the extent of compression.

8. Products prepared from compressed samples are as acceptable as non-compressed samples.

9. Compression during freeze-drying is advantageous

and more efficient than the methods currently used in compression, in that:

a. It provides samples having a considerable decrease in volume, which are below moisture contents allowed, and which rehydrate rapidly.

b. It does not require an initial over-drying step to low moisture contents prior to compression.

c. It does not require a conditioning step prior to compression.

d. It does not require a final drying step after compression.

6. SUGGESTIONS FOR FUTURE RESEARCH

6.1 Dependence of Compression Ratio on Sample Thinckness:

In the course of this study the time was insufficient to perform a thorough investigation on the effect of sample thickness on compression ratio. However, in some cases when the same force was applied to different thicknesses of the same product different compression ratios were obtained. Therefore, is assumed that compression ratio also is dependent on the sample thickness. However, further studies are required for a more precise measurement of the effect and determination of the best sample thickness to be used for compression of particular samples.

6.2 Effect of Compression during Freeze-Drying on Drying Rate:

There is little doubt that compression during freeze-drying will affect the subsequent rate of drying since the volume decrease is being achieved at the expense of void volume which normally serves as pathways for vapor escape. Reduction of the dimension of the vapor pathways will increase with increasing compression ratio, and furthermore, as drying proceeds these reduced vapor pathways will increase in length. From another view point compression of the dry layer will result in improved heat transfer in the dry layer. The combination of these effects will result in complex changes in drying behavior, and it is necessary to consider them.

6.3 Effects of Sample Temperature (Frozen Layer and Dry Layer) on Compression Behavior:

While moisture content is an important parameter influencing plasticity, the temperature of the matrix is also an important factor in determining the existing plasticity. The temperature gradients present should interact with the resultant moisture gradients, to produce the thickness of the layer which is capable of being compressed. Also, the frozen layer temperature seems to be critical, since the higher moisture content regions of the matrix should have a temperature very close to that of the frozen layer. The effect of this is most evident when collapse occurs.

6.4 Dependence of Compression Ratio on Sample Loading:

To some degree this has been investigated with the system used in this study. However, there was no control of the compression force during freeze-drying. If compressive force is transmitted by a hydraulic pressure system, the pressure on the sample at any time can be controlled to produce improved final compression ratio and also minimize the physical damage to the sample.

With the technique used in this study, it was necessary to subject the frozen sample to pressure prior to the start of freeze-drying. This in many cases caused cracking of the sample, since initially the frozen sample is quite rigid and no plastic layer has yet been produced. This cracking effect was minimized by use of cheese-cloth to give a cushion effect. However, with use of a hydralic system it is possible to start the freeze-drying first and after the plastic layer is formed to apply the pressure for compression.

6.5 Use of Binders and Plasticizing Agents:

As mentioned earlier, binders and plasticizing agents have been added to dehydrated food prior to compression. This can have a tremendous effect on compressibility of the product and the final character of the compressed bar. However, for compression during freeze-drying it is necessary to add these agents in the wet state, that is prior to freeze-drying. The effect has to be evaluated. For instance, when Shipman, et al, (1972) used glycerol to improve the texture of celery, the glycerolated samples underwent low temperature evaporative drying rather than true freeze-drying as glycerol preventsfreezing in most cases. Nevertheless, use of binders may improve the cohessiveness of the food pieces and result in an improved compressed food bar.

6.6 Design of a Sample Holder for "Easy Removal" of Compressed Bars:

As mentioned, unless careful handling is exercized in most cases the compressed samples separated into individual pieces during removal. A better design of the sample holder with smooth and lubricated walls should reduce this problem.

6.7 Freeze-Drying/Compression with Other Food Materials:

For more completeness other food materials than the ones already tested could be considered.

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APPENDICIES

TABULATED RESULTS OF
REHYDRATION TESTS AND ORGANOLEPTIC EVALUATIONS

EXPLANATION OF REHYDRATION TESTS:

Notations

a — % Rehydration

$$= \frac{\text{gr } H_2O}{\text{gr T.S. (rehydrated)}} \Big/ \frac{\text{gr } H_2O}{\text{gr T.S. (fresh)}}$$

b — Sample codes:

Comp.	Compressed
N.Comp.	Non-compressed

c — Indicates if vacuum applied prior to water content (see section 3.2.5)

No	No vacuum
Vac.-air	Vacuum released with air
Vac.-H_2O	Vacuum released with water

d — Water temperature

Cold	(40-70°F.)
Warm	(90-100°F.)
Hot	(130-160°F.)

EXPLANATION OF ORGANOLEPTIC EVALUATION:

Notations:

a	Mean Score (9 point hedonic scale) 1: Extremely dislike to 9: Extremely like	
b	Ranking test: Scale of +0.85 to -0.85 used	
c	Sample codes:	
	Comp.	Compressed
	N.Comp.	Non-compressed
	F.	Non-dried material (fresh or frozen thawed)
@, #	Indicate if there is any statistical difference. Diffenret symbols indicate significant difference (at 1% level).	

APPENDIX A

TABULATED RESULTS OF REHYDRATION TESTS AND ORGANOLEPTIC EVALUATION FOR VEGETABLES

Appendix A-1 Green Beans

TABLE 8: Rehydration Results for Green Beans

Sample Code[b]	Vacuum[c]	Water Temperature[d]	% Rehydration[a] Time in minutes						
			0	1	2	5	10	20	30
		Experiment 1							
Comp.	No	Cold	0.01	29	33	45	48	53	56
N. Comp.	No	Cold	0.01	32	44	52	57	62	69
Comp.	No	Warm	0.01	34	41	51	56	58	59
N. Comp.	No	Warm	0.01	41	48	52	64	66	69
Comp.	No	Hot	0.01	28	35	42	45	50	52
N. Comp.	No	Hot	0.01	39	46	55	60	65	67
		Experiment 2							
Comp.	No	Cold	0.03	42	62	74	82	90	93
N. Comp.	No	Cold	0.02	38	44	52	62	67	68
Comp.	No	Warm	0.03	58	70	81	85	91	94
N. Comp.	No	Warm	0.02	47	57	68	75	84	90
Comp.	No	Hot	0.03	66	77	83	85	89	88
N. Comp.	No	Hot	0.02	57	63	75	75	77	80

TABLE 8 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 3					
Comp.	No	Cold	0.02	63	69	70	72
N.Comp.	No	Cold	0.02	58	62	65	73
Comp.	No	Warm	0.02	82	84	89	89
N.Comp.	No	Warm	0.02	56	60	65	66
Comp.	No	Hot	0.02	80	83	84	85
N.Comp.	No	Hot	0.02	44	51	54	58
		Experiment 4					
Comp.	No	Cold	0.02	61	77	78	79
N.Comp.	No	Cold	0.02	52	60	62	63
Comp.	No	Warm	0.02	69	74	75	75
N.Comp.	No	Warm	0.02	54	56	61	61
Comp.	No	Hot	0.02	60	65	63	63
N.Comp.	No	Hot	0.02	53	59	62	63

TABLE 8 continued

			Time in minutes				
			0	2	7	15	30
			Experiment 5				
Comp.	No	Cold	0.02	66	73	80	82
N.Comp.	No	Cold	0.02	64	69	72	73
Comp.	No	Warm	0.02	71	73	74	75
N.Comp.	No	Warm	0.02	41	46	49	51
Comp.	No	Hot	0.02	55	59	60	65
N.Comp.	No	Hot	0.02	50	57	60	62
			Experiment 6				
Comp.	No	Cold	0.03	47	76	85	87
N.Comp.	No	Cold	0.02	55	63	66	63
Comp.	No	Warm	0.03	64	68	70	73
N.Comp.	No	Warm	0.02	40	46	48	51
Comp.	No	Hot	0.03	68	76	75	75
N.Comp.	No	Hot	0.02	42	53	57	59

TABLE 8 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 7					
Comp.	No	Cold	0.06	15	21	43	45
N.Comp.	No	Cold	0.05	29	33	38	54
Comp.	No	Warm	0.06	27	41	50	54
N.Comp.	No	Warm	0.05	24	39	46	52
Comp.	No	Hot	0.06	16	29	36	47
N.Comp.	No	Hot	0.05	23	30	42	46
		Experiment 8					
Comp.	No	Cold	0.03	35	52	70	73
N.Comp.	No	Cold	0.02	51	57	62	64
Comp.	No	Warm	0.03	-	-	-	-
N.Comp.	No	Warm	0.02	51	60	63	66

TABLE 8 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 9					
Comp.	No	Cold	0.04	56	80	87	91
N.Comp.	No	Cold	0.02	47	50	55	59
Comp.	Vac.-Air	Cold	0.04	54	72	77	79
N.Comp.	Vac.-Air	Cold	0.02	57	63	70	72
Comp.	Vac.-H_2O	Cold	0.04	52	71	73	77
N.Comp.	Vac.-H_2O	Cold	0.02	65	75	77	78
		Experiment 10					
Comp.	No	Cold	0.04	58	81	83	84
N.Comp.	No	Cold	0.05	41	48	52	55
Comp.	Vac.-Air	Cold	0.04	23	41	73	76
N.Comp.	Vac.-Air	Cold	0.05	44	47	51	52
Comp.	Vac.-H_2O	Cold	0.04	73	86	88	91
N.Comp.	Vac.-H_2O	Cold	0.05	69	71	74	79

TABLE 8 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 11					
Comp.	No	Cold	0.03	51	61	67	70
N.Comp.	No	Cold	0.03	31	37	43	46
		Experiment 12					
Comp.	No	Cold	0.04	57	62	63	64
N.Comp.	No	Cold	0.05	40	45	46	50
Comp.	Vac.-Air	Cold	0.04	64	67	68	69
N.Comp.	Vac.-Air	Cold	0.05	45	51	57	61
Comp.	Vac.-H_2O	Cold	0.04	74	83	87	89
N.Compl	Vac.-H_2O	Cold	0.05	56	63	65	66

Appendix A-2 Carrots

TABLE 9: Rehydration Results for Carrots

Sample Code[b]	Vacuum[c]	Water Temperature[d]	% Rehydration[a] Time in minutes				
			0	2	7	15	30
		Experiment 1					
Comp.	No	Cold	0.04	71	80	84	90
N.Comp.	No	Cold	0.04	81	86	90	94
Comp.	Vac.-Air	Cold	0.04	82	95	100	102
N.Comp.	Vac.-Air	Cold	0.04	94	97	98	98
Comp.	Vac.-H_2O	Cold	0.04	82	89	90	91
N.Comp.	Vac.-H_2O	Cold	0.04	91	95	96	97
		Experiment 2					
Comp.	No	Cold	0.04	29	46	68	80
N.Comp.	No	Cold	0.06	73	82	86	87
Comp.	Vac.-H_2O	Cold	0.04	30	48	70	86
N.Comp.	Vac.-H_2O	Cold	0.06	75	82	91	96

TABLE 9 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 3					
Comp.	No	Cold	0.05	41	65	75	86
N.Comp.	No	Cold	0.06	65	76	81	80
Comp.	Vac.-H_2O	Cold	0.05	31	51	65	78
N.Comp.	Vac.-H_2O	Cold	0.06	81	84	87	88
		Experiment 4					
Comp.	No	Cold	0.04	73	75	76	78
N.Comp.	No	Cold	0.03	62	73	76	80
Comp.	Vac.-H_2O	Cold	0.04	80	84	86	86
N.Comp.	Vac.-H_2O	Cold	0.03	72	78	83	85
		Experiment 5					
Comp.	No	Cold	0.03	83	86	88	89
N.Comp.	No	Cold	0.09	46	52	53	54
Comp.	Vac.-H_2O	Cold	0.03	76	78	79	81
N.Comp.	Vac.-H_2O	Cold	0.09	49	57	62	65

TABLE 9 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 6					
Comp.	No	Cold	0.05	52	54	56	57
N.Comp.	No	Cold	0.09	31	33	35	37
Comp.	Vac.-H_2O	Cold	0.05	52	72	80	84
N.Comp.	Vac.-H_2O	Cold	0.09	42	56	64	67
		Experiment 7					
Comp.	No	Cold	0.07	37	52	63	72
N.Comp.	No	Cold	0.08	37	39	41	44
Comp.	Vac.-H_2O	Cold	0.07	57	70	78	79
N.Comp.	Vac.-H_2O	Cold	0.08	46	50	55	57

TABLE 9 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 8					
Comp.	No	Cold	0.04	72	76	78	80
N.Comp.	No	Cold	0.04	47	50	51	51
Comp.	No	Cold	0.04	75	79	80	81
N.Comp.	No	Cold	0.04	54	60	63	65
Comp.	No	Warm	0.04	54	67	69	71
N.Comp.	No	Warm	0.04	39	43	45	46
Comp.	No	Hot	0.04	59	71	73	73
N.Comp.	No	Hot	0.04	24	34	42	45
		Experiment 9					
Comp.	No	Cold	0.05	59	75	80	81
N.Comp.	No	Cold	0.16	52	54	56	59
Comp.	Vac.-H_2O	Cold	0.05	70	74	75	76
N.Comp.	Vac.-H_2O	Cold	0.16	60	74	85	86

TABLE 9 continued

			Time in minutes				
			0	2	7	15	30
			Experiment 10				
Comp.	No	Cold	0.05	28	54	70	84
N.Comp.	No	Cold	0.04	65	68	72	76
Comp.	Vac.-H_2O	Cold	0.05	28	59	74	86
N.Comp.	Vac.-H_2O	Cold	0.04	82	85	88	88
			Experiment 11				
Comp.	No	Cold	0.03	50	77	80	89
N.Comp.	No	Cold	0.02	62	63	64	66
Comp.	Vac.-H_2O	Cold	0.03	68	85	86	87
N.Comp.	Vac.-H_2O	Cold	0.02	47	69	88	96
			Experiment 12				
Comp.	No	Cold	0.03	60	77	81	85
N.Comp.	No	Cold	0.03	72	74	76	77
Comp.	Vac.-H_2O	Cold	0.03	83	89	91	93
N.Comp.	Vac.-H_2O	Cold	0.03	76	89	95	96

TABLE 9 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 13					
Comp.	No	Cold	0.04	46	59	63	66
N.Comp.	No	Cold	0.39	39	48	52	56
Comp.	Vac.-H_2O	Cold	0.04	39	50	62	72
N.Comp.	Vac.-H_2O	Cold	0.39	38	56	71	78
		Experiment 14					
Comp.	No	Cold	0.04	36	50	59	63
N.Comp.	No	Cold	0.04	48	51	53	53
Comp.	Vac.-H_2O	Cold	0.04	60	65	70	72
N.Comp.	Vac.-H_2O	Cold	0.04	54	66	76	80
		Experiment 15					
Comp.	No	Cold	0.02	43	66	73	79
N.Comp.	No	Cold	0.02	58	61	64	65
Comp.	Vac.-H_2O	Cold	0.02	51	71	78	82
N.Comp.	Vac.-H_2O	Cold	0.02	44	60	73	85

TABLE 9 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 16					
Comp.	No	Cold	0.03	42	61	75	80
N.Comp.	No	Cold	0.03	41	93	93	93
Comp.	Vac.-H_2O	Cold	0.03	80	89	91	92
N.Comp.	Vac.-H_2O	Cold	0.03	90	99	100	108
		Experiment 16 (stored under vacuum for 2 months)					
Comp.	No	Cold	0.03	26	43	59	64
N.Comp.	No	Cold	0.03	96	99	104	107
Comp.	Vac.-H_2O	Cold	0.03	40	78	83	86
N.Comp.	Vac.-H_2O	Cold	0.03	99	102	105	106
		Experiment 16 (stored in air for 2 months)					
Comp.	No	Cold	0.03	41	58	67	81
N.Comp.	No	Cold	0.03	97	102	104	105
Comp.	Vac.-H_2O	Cold	0.03	71	81	82	82
N.Comp.	Vac.-H_2O	Cold	0.03	100	104	108	109

TABLE 10: Organoleptic Evaluation of Carrots

	Sample[c]	Mean Score[a]		Ranking[b]
		Texture	Taste	
Test 1	Comp. (Stored)	5.1 @	4.5 @	-0.15 @
	N.Comp. (Stored)	5.2 @	3.5 @	-0.54 @
	F.	7.4 #	7.2 #	+0.70 #
Test 2	Comp.	6.1 @	6.1 @	+0.085@
	N.Comp.	5.8 @	4.7 @	-0.17 #
	F.	6.3 @	5.7 @	+0.085@

Note: Different symbols (@, #) indicate significant difference (at 1% level)

Appendix 3 Peas

TABLE 11: Rehydration Results for Peas

Sample Code[b]	Vacuum[c]	Water Temperature[d]	% Rehydration[a] Time in minutes 0	2	7	15	30
		Experiment 1					
Comp.	No	Cold	0.21	12	26	49	58
N.Comp.	No	Cold	0.01	16	20	23	25
Comp.	Vac.-Air	Cold	0.21	6	35	49	60
N.Comp.	Vac.-Air	Cold	0.01	20	27	33	36
Comp.	Vac.-H_2O	Cold	0.21	18	39	55	67
N.Comp.	Vac.-H_2O	Cold	0.01	51	54	56	58
		Experiment 2					
Comp.	No	Cold	0.14	18	79	89	92
N.Comp.	No	Cold	0.01	16	25	28	34
Comp.	Vac.-H_2O	Cold	0.14	40	64	73	83
N.Comp.	Vac.-H_2O	Cold	0.01	28	42	51	64

TABLE 11 continued

			Time in minutes 0	2	7	15	30
			Experiment 3				
Comp.	No	Cold	0.18	22	63	75	81
N.Comp.	No	Cold	0.11	39	48	53	55
Comp.	Vac.-H_2O	Cold	0.18	30	64	78	87
N.Comp.	Vac.-H_2O	Cold	0.11	54	60	66	67
			Experiment 3 (effect of skin on rehydration)				
N.Comp. *B.	No	Cold	0.11	61	69	74	84
N.Comp. ** N.B.	No	Cold	0.11	19	24	31	36
N.Comp. *B.	Vac.-H_2O	Cold	0.11	89	99	105	107
N.Comp. **N.B.	Vac.-H_2O	Cold	0.11	29	41	50	52
			Experiment 4				
Comp.	No	Cold	0.12	23	71	82	88
N.Comp.	No	Cold	0.09	42	48	51	54
Comp.	Vac.-H_2O	Cold	0.12	31	59	60	86
N.Comp.	Vac.-H_2O	Cold	0.09	52	59	63	68

*Broken skin
**Non-broken skin

TABLE 11 continued

			Time in minutes				
			0	2	7	15	30
			Experiment 5				
Comp.	No	Cold	0.13	17	44	63	68
N.Comp.	No	Cold	0.11	35	44	48	54
Comp.	Vac.-H_2O	Cold	0.13	37	71	81	89
N.Comp.	Vac.-H_2O	Cold	0.11	52	61	66	70
			Experiment 6				
Comp.	No	Cold	0.05	72	85	89	91
N.Comp.	No	Cold	0.06	89	98	103	107
Comp.	Vac.-H_2O	Cold	0.05	75	82	88	96
N.Comp.	Vac.-H_2O	Cold	0.06	97	102	104	104
			Experiment 7				
Comp.	No	Cold	0.07	75	81	83	85
N.Comp.	No	Cold	0.07	72	75	85	85
Comp.	Vac.-H_2O	Cold	0.07	85	92	93	94
N.Comp.	Vac.-H_2O	Cold	0.07	80	91	93	94

TABLE 11 continued

			Time in minutes				
			0	2	7	15	30
			Experiment 8				
Comp.	No	Cold	0.05	40	65	73	74
N.Comp.	No	Cold	0.06	75	86	92	95
Comp.	Vac.-H_2O	Cold	0.05	62	85	92	95
N.Comp.	Vac.-H_2O	Cold	0.06	105	106	106	106
			Experiment 9				
Comp.	No	Cold	0.03	88	96	91	90
N.Comp.	No	Cold	0.04	89	93	93	94
Comp.	Vac.-H_2O	Cold	0.03	79	96	98	100
N.Comp.	Vac.-H_2O	Cold	0.04	90	98	98	98

TABLE 11 continued

				Time in minutes			
			0	2	7	15	30
		Experiment 10					
Comp.	No	Cold	0.04	60	67	71	73
N.Comp.	No	Cold	0.05	36	40	42	43
Comp.	Vac.-H_2O	Cold	0.04	76	83	84	85
N.Comp.	Vac.-H_2O	Cold	0.05	80	89	90	90
		Experiment 11					
Comp.	No	Cold	0.04	69	82	87	90
N.Comp.	No	Cold	0.04	45	56	62	66
Comp.	Vac.-H_2O	Cold	0.04	74	80	82	83
N.Comp.	Vac.-H_2O	Cold	0.04	79	89	93	93

TABLE 12: Organoleptic Evaluation of Peas

	Sample[c]	Mean Score[a]		Ranking[b]
		Texture	Taste	
Test 1	Comp.	6.8 @#	6.8 @	+0.28 @
	N.Comp.	6.8 @	5.6 @	-0.47 @
	F.	6.6 #	6.9 @	+0.19 @

Note: Different symbols (@, #) indicate significant difference (at 1% level)

Appendix A-4 Corn

TABLE 13: Rehydration Results for Corn

Sample Code[b]	Vacuum[c]	Water temperature[d]	%Rehydration[a] Time in minutes 0	2	7	15	30
		Experiment 1					
Comp.	No	Cold	0.09	44	52	55	58
N.Comp.	No	Cold	0.08	48	56	57	58
Comp.	Vac.-Air	Cold	0.09	47	51	56	61
N.Comp.	Vac.-Air	Cold	0.08	43	48	52	55
Comp.	Vac.-H_2O	Cold	0.09	47	57	62	66
N.Comp.	Vac.-H_2O	Cold	0.08	52	58	63	67
		Experiment 2					
Comp.	No	Cold	0.05	31	38	43	46
N.Comp.	No	Cold	0.04	31	36	42	46
Comp.	Vac.-H_2O	Cold	0.05	57	62	69	71
N.Comp.	Vac.-H_2O	Cold	0.04	50	55	61	63

APPENDIX B

TABULATED RESULTS OF REHYDRATION TESTS AND ORGANOLEPTIC EVALUATION FOR FRUITS

Appendix B-1 Blueberries

TABLE 14: Rehydration Results for Blueberries

Sample Code[b]	Vacuum[c]	Water Temperature[d]	% Rehydration[a] Time in minutes				
			0	2	7	15	30
Experiment 1							
Comp.	No	Cold	0.06	10	12	13	13
N.Comp.	No	Cold	0.07	75	76	76	77
Experiment 2							
Comp.	No	Cold	0.08	14	19	21	23
N.Comp.	No	Cold	0.07	8	15	17	19
Comp.	Vac.-H_2O	Cold	0.08	29	31	33	34
N.Comp.	Vac.-H_2O	Cold	0.07	36	40	40	41
Experiment 3							
Comp.	No	Cold	0.06	38	41	44	46
N.Comp.	No	Cold	0.04	43	44	45	46
Comp.	Vac.-H_2O	Cold	0.06	30	32	34	35
N.Comp.	Vac.-H_2O	Cold	0.04	43	47	50	51

TABLE 14 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 4					
Comp.	No	Cold	0.11	9	13	17	22
N.Comp.	No	Cold	0.01	12	18	26	32
Comp.	Vac.-H_2O	Cold	0.11	13	15	18	21
N.Comp.	Vac.-H_2O	Cold	0.01	20	24	28	33
		Experiment 5					
Comp.	No	Cold	0.06	13	15	18	20
N.Comp.	No	Cold	0.05	38	41	45	49
Comp.	Vac.-H_2O	Cold	0.06	22	26	29	34
N.Comp.	Vac.-H_2O	Cold	0.05	39	45	50	57
		Experiment 6					
Comp.	No	Cold	0.11	7	9	11	15
N.Comp.	No	Cold	0.15	24	33	37	39
Comp.	Vac.-H_2O	Cold	0.11	10	11	13	17
N.Comp.	Vac.-H_2O	Cold	0.15	21	27	32	38

TABLE 14 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 7					
Comp.	No	Cold	0.03	14	18	27	26
N. Comp.	No	Cold	0.05	45	47	48	50
Comp.	Vac.-H_2O	Cold	0.03	21	26	31	36
N. Comp.	Vac.-H_2O	Cold	0.05	44	48	51	55
		Experiment 8					
Comp.	No	Cold	0.06	11	14	17	21
N. Comp.	No	Cold	0.06	38	42	45	47
Comp.	Vac.-H_2O	Cold	0.06	12	16	21	28
N. Comp.	Vac.-H_2O	Cold	0.06	50	56	63	67
		Experiment 9					
Comp.	No	Cold	0.06	4	7	8	12
N. Comp.	No	Cold	0.05	42	45	47	51
Comp.	Vac.-H_2O	Cold	0.06	10	11	14	18
N. Comp.	Vac.-H_2O	Cold	0.05	43	49	55	59

TABLE 14 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 10					
Comp.	No	Cold	0.08	7	13	17	20
N.Comp.	No	Cold	16	28	30	31	31
Comp.	Vac.-H_2O	Cold	0.08	12	16	20	23
N.Comp.	Vac.-H_2O	Cold	16	30	34	36	37
		Experiment 11					
Comp.	No	Cold	0.32	6	8	9	9
N.Comp.	No	Cold	0.63	14	21	26	29
Comp.	Vac.-H_2O	Cold	0.32	22	27	30	33
N.Comp.	Vac.-H_2O	Cold	0.63	31	39	45	47
		Experiment 12					
Comp.	No	Cold	1.12	16	21	23	25
N.Comp.	No	Cold	0.55	36	41	43	45
Comp.	Vac.-H_2O	Cold	1.12	25	31	35	38
N.Comp.	Vac.-H_2O	Cold	0.55	36	42	45	48

TABLE 14 continued

			Time in minutes				
			0	2	7	15	30
			Experiment 13				
Comp.	No	Cold	0.24	5	7	8	8
N.Comp.	No	Cold	0.87	15	22	25	27
Comp.	Vac.-H_2O	Cold	0.24	11	13	15	16
N.Comp.	Vac.-H_2O	Cold	0.87	18	29	36	40
Comp.	No	Warm	0.24	4	7	8	8
N.Comp.	No	Warm	0.87	12	15	18	21
Comp.	No	Hot	0.24	7	14	21	25
N.Comp.	No	Hot	0.87	14	23	28	33

TABLE 15: Organoleptic Evaluation of Blueberries

	Sample[c]	Mean Score[a]		Ranking[b]
		Texture	Taste	
Test 1 Pie Filling	Comp.	3.7 #	5.1 @	-0.76 #
	N.Comp.	5.9 @	6.4 @	+0.42 @
	F.	6.1 @	6.6 @	+0.34 @
Test 2 Muffin	Comp.	7.9 @	7.5 @	+0.42 @
	N.Comp.	5.2 #	5.4 #	-0.78 #
	F.	7.5 @	6.8 @#	+0.35 @#
Test 3 Muffin	Comp.	7.4 @	7.3 @	+0.14 @
	N.Comp.	5.8 @	6.2 @	-0.28 @
	F.	7.2 @	7.4 @	+0.14 @
Test 4	Comp.	5.9 @	6.1 @	-0.25 @
	N.Comp.	5.9 @	5.9 @	-0.25 @
	F.	6.4 @	6.9 @	+0.51 #

Note: Different symbols (@, #) indicate significant difference (at 1% level)

APPENDIX C

TABULATED RESULTS OF REHYDRATION TESTS AND ORGANOLEPTIC EVALUATION FOR MEAT

Appendix C-1 Ground Beef

TABLE 16: Rehydration Results for Ground Beef

Sample Code[b]	Vacuum[c]	Water Temperature[d]	% Rehydration[a] Time in minutes 0	2	7	15	30
		Experiment 1					
Comp.	No	Cold	0.14	90	95	97	99
N.Comp	No	Cold	0.09	63	71	77	81
Comp.	Vac.-Air	Cold	0.14	90	93	95	97
N.Comp.	Vac.-Air	Cold	0.09	77	86	93	99
Comp.	Vac.-H_2O	Cold	0.14	90	95	98	99
N.Comp.	Vac.-H_2O	Cold	0.09	93	100	104	107
		Experiment 2					
Comp.	No	Cold	0.13	85	89	90	91
N.Comp.	No	Cold	0.12	84	87	88	90
Comp.	Vac.-H_2O	Cold	0.13	83	88	89	92
N.Comp.	Vac.-H_2O	Cold	0.12	81	85	86	88

Appendix C-2 Beef Cubes

TABLE 17: Rehydration Results for Beef Cubes

Sample Code[b]	Vacuum[c]	Water Temperature[d]	% Rehydration[a] Time in minutes 0	2	7	15	30	45	60	70	85
			Experiment 1								
Comp.	No	Cold	0.11	74	79	81	82				
N.Comp.	No	Cold	0.10	81	86	88	90				
Comp.	Vac.-Air	Cold	0.11	80	81	83	84				
N.Comp.	Vac.-Air	Cold	0.10	72	80	83	86				
Comp.	Vac.-H_2O	Cold	0.11	80	84	85	84				
N.Comp.	Vac.-H_2O	Cold	0.10	91	97	99	99				
			Experiment 2								
Comp.	No	Cold	0.05	43	49	53	60	65	68	72	
N.Comp.	No	Cold	0.03	74	78	78	78	76			
Comp.	Vac.-H_2O	Cold	0.05	77	80	81	81				
N.Comp.	Vac.-H_2O	Cold	0.03	76	80	81	78				

TABLE 17 continued

			Time in minutes								
			0	2	7	15	30	45	60	70	85
			Experiment 3								
Comp.	No	Cold	0.04	53	68	72	72				
N.Comp.	No	Cold	0.04	83	87	87	88				
Comp.	Vac.-H_2O	Cold	0.04	66	72	75	75				
N.Comp.	Vac.-H_2O	Cold	0.04	83	84	85	86				
			Experiment 4								
Comp.	No	Cold	0.04	40	47	51	57				
N.Comp.	No	Cold	0.04	78	80	81	81				
Comp.	Vac.-H_2O	Cold	0.04	48	63	65	66				
N.Comp.	Vac.-H_2O	Cold	0.04	71	75	76	75				
			Experiment 5								
Comp.	No	Cold	0.04	33	40	46	52	-	64	68	77
N.Comp.	No	Cold	0.36	83	82	81	81				
Comp.	Vac.-H_2O	Cold	0.04	58	72	73	73				
N.Comp.	Vac.-H_2O	Cold	0.36	84	87	85	84				

TABLE 17 continued

			Time in minutes						
			0	2	7	15	30	45	60
		Experiment 6							
Comp.	No	Cold	0.05	46	52	57	68	77	80
N.Comp.	No	Cold	0.06	71	75	78	80		
Comp.	Vac.-H_2O	Cold	0.05	74	83	85	86		
N.Comp.	Vac.-H_2O	Cold	0.06	86	90	92	93		
		Experiment 7							
Comp.	No	Cold	0.04	43	49	55	56		
N.Comp.	No	Cold	0.03	81	87	89	88		
Comp.	No	Warm	0.04	59	70	72	74		
N.Comp.	No	Warm	0.03	70	74	75	75		
Comp.	No	Hot	0.04	45	50	51	53		
N.Comp.	No	Hot	0.03	66	67	69	70		

TABLE 17 continued

			Time in minutes 0	2	7	15	30
			Experiment 8				
Comp.	No	Cold	0.04	57	64	66	68
N.Comp.	No	Cold	0.04	84	86	87	92
Comp.	Vac.-H_2O	Cold	0.04	54	68	73	77
N.Comp.	Vac.-H_2O	Cold	0.04	85	91	91	92
			Experiment 9				
Comp.	No	Cold	0.03	54	61	66	70
N.Comp.	No	Cold	0.05	79	82	83	84
Comp.	Vac.-H_2O	Cold	0.03	71	75	76	76
N.Comp.	Vac.-H_2O	Cold	0.05	76	79	81	82
			Experiment 10				
Comp.	No	Cold	0.05	74	82	85	87
N.Comp.	No	Cold	0.07	89	93	95	95
Comp.	Vac.-H_2O	Cold	0.05	83	94	95	96
N.Comp.	Vac.-H_2O	Cold	0.07	86	97	97	97

TABLE 17 continued

			Time in minutes				
			0	2	7	15	30
		Experiment 11					
Comp.	No	Cold	0.01	66	76	83	89
N.Comp.	No	Cold	0.02	88	98	98	98
Comp.	Vac.-H_2O	Cold	0.01	86	92	93	93
N.Comp.	Vac.-H_2O	Cold	0.02	101	103	102	102
		Experiment 12					
Comp.	No	Cold	0.04	52	57	60	62
N.Comp.	No	Cold	0.04	79	84	84	84
Comp.	Vac.-H_2O	Cold	0.04	67	79	82	85
N.Comp.	Vac.-H_2O	Cold	0.04	88	89	89	90
		Experiment 13					
Comp.	No	Cold	0.04	72	77	83	84
N.Comp.	No	Cold	0.04	91	94	94	94
Comp.	Vac.-H_2O	Cold	0.04	81	82	85	86
N.Comp.	Vac.-H_2O	Cold	0.04	76	79	81	81

TABLE 18: Organoleptic Evaluation of Beef Cubes

	Sample[c]	Mean Score[a]		Ranking[b]
		Texture	Taste	
Test 1	Comp.	5.9 #	6.7 @	-0.11 @
	N.Comp.	6.1 @#	6.6 @	-0.23 @
	F.	7.3 @	7.1 @	+0.34 @

Note: Different symbols (@, #) indicate significant difference (at 1% level)