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thesis entitled

EFFECT OF VACUUM-INDUCED HYDRATION
ON PHYSICAL PROPERTIES OF PROCESSED BEANS

presented by

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has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agricultural Engineering

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Date Feb 25, 1981

EFFECT OF VACUUM-INDUCED HYDRATION ON PHYSICAL PROPERTIES OF PROCESSED BEANS

By

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1981

ABSTRACT

EFFECT OF VACUUM-INDUCED HYDRATION ON PHYSICAL PROPERTIES OF PROCESSED BEANS

By

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Adequate hydration of beans is normally achieved during the conventional overnight method by soaking the beans in water at room temperature for about 16 to 24 hours. The incorporation of vacuum-induced hydration (which is a physical mechanism for removal of gases from bean tissues) into the soaking phase of processing has been found to accelerate water intake by beans thereby reducing the soaking time for adequate hydration to occur at room temperature.

The major objective of this study was to quantify the effect of vacuum-induced hydration on some physical properties of beans (mainly navy, pinto and kidney) during canning (soaking and retorting). Vacuum-induced hydration was obtained by evacuating enameled cans containing beans and water to a desired level in an enclosure attached to a vacuum pump followed by restoring the can and its contents to atmospheric pressure. The physical properties determined were weight gain, moisture content, volume, specific gravity, anatomical dimensions, maximum compressive peak force and compressive work.

Mathematical models were developed from literature, simplified and solved numerically using data on some of the physical properties to obtain estimates of the thermodynamic work needed to establish various levels of vacuum along with two kinetic parameters, known as average effective diffusivity and softening rate constant which represent the rate of water intake and the index of texture respectively. Relationships between any two of these estimates were found to be linear.

Three-way analysis of variance showed that varying the period of time under vacuum did not cause any significant changes in physical properties while the effect of varying the level of vacuum treatment, soaking time or cooking time on the physical properties of processed beans were significant.

The application of a high vacuum for a very short period of time was found to be the most effective treatment in bringing about vacuum-induced hydration of beans. It was also found that pinto beans got the greatest benefit from vacuum-induced hydration, followed in decreasing order by kidney and navy beans.

Approved George S. Merva
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To My mother
A. Oyinlola Oguntunde
and to the cherished memory of my father,
P. Adebayo Oguntunde

ACKNOWLEDGEMENTS

The author wishes to express his deep appreciation to Dr. George E. Merva (Professor, Agricultural Engineering Department) for his guidance and support throughout the course of this project.

A special thanks to Dr. Dennis R. Heldman (Professor, Agricultural Engineering and Food Science and Human Nutrition Departments) for serving on the guidance committees for both M.S. and Ph.D., in addition to his immense contribution in formulating a Food Engineering program for the author during his graduate studies.

Thanks to Dr. Carl M. Cooper (Professor, Chemical Engineering Department) for his interest in this research subject and serving on the guidance committee.

Many thanks to Dr. Mark A. Uebersax (Assistant Professor, Food Science and Human Nutrition Department) for serving on the guidance committee for both the M.S. and Ph.D., in addition to providing valuable suggestions and necessary equipment during the research period.

Gratitude is extended to the Michigan Bean Commission for the assistship awarded the author through the Department of Agricultural Engineering, during the course of this project.

Finally, the author wishes to express his profound gratitude to his wife, Subuola, and daughter, Olufunmilola, for their patience and understanding of his frequent absence from home, in addition to the encouragement and help received from the wife throughout the course of this study.

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LIST OF SYMBOLS

Chapter 2

Symbol	Meaning
A	= Area over which diffusion would occur
C	= Concentration of moisture
D	= Diffusion coefficient
E_a	= Apparent modulus of elasticity
E_d	= Modulus of deformation
e.g.	= for example
LL	= Linear limit load
M	= Volume concentration of water
m	= mass of moisture
t	= diffusion time
X	= Space coordinate for mass transfer

Chapters 3, 4 and 5

Symbol	Meaning
C	= Concentration, Kg/M^3
C_1	= Charles' law constant, $m^3/^0K$
C_2	= Boyle's law constant, N.m
C_a^{++}	= Calcium ion
C_o	= Initial concentration
C_t	= Concentration at any specified time
D	= Diffusion coefficient, m^2/hr

Symbol	Meaning
db	= dry basis
D_{eff}	= Average effective diffusivity, m^2/hr
F	= Rate of mass transfer per unit area of section, Kg/hr
f	= functional relationship
Hg	= Mercury
K	= Softening rate constant, hr^{-1}
K_f	= Softening rate constant for compressive force, hr^{-1}
K_w	= Softening rate constant for compressive work, hr^{-1}
K_1	= Rate constant, hr^{-1}
ℓ	= thickness of each cotyledon, m
ln	= natural logarithm
M_0	= Initial moisture content, %
M_1	= Moisture content of the outer surface of each cotyledon, %
M_2	= Moisture content of the inner surface of each cotyledon, %
M_e	= Equilibrium moisture content of each cotyledon, %
M_t	= Moisture content at any specified time, %
MC	= Moisture content
P	= Pressure, kPa
P_f	= Final pressure, kPa
P_i	= Initial pressure, kPa
ppm	= parts per million
R	= Universal gas constant, N.m/^{0}K
T	= Temperature, ^{0}K or ^{0}C

Symbol	Meaning
V	= Molar volume, m^3
V_f	= Final molar volume, m^3
V_i	= Initial molar volume, m^3
W	= Thermodynamic work, KJ/g-mole
wb	= wet basis
X	= Space coordinate, m

1. INTRODUCTION AND OBJECTIVES

Michigan is a world leader in the production of dry beans. Beans are not only an important agricultural commodity in Michigan, but a valuable source of protein and carbohydrates throughout the world. The processing of dry beans for human consumption can, however, be time consuming and energy intensive and the combination of these factors has placed them at a disadvantage and has also resulted in lower per capita consumption of dry beans than convenience foods developed for the retail market.

Canning of dry beans consists of soaking and retorting phases. Soaking is basically supposed to enhance uniform swelling and tenderization along with increasing the product yield and purifying the beans prior to further processing. Though the canning industry at the present time, employs many soaking methods, research work with uniform lots of beans has indicated that whatever the soaking method used, the quality of the processed product should be similar when the beans had all been soaked to the same moisture content, e.g., 55% $\pm$ 1%.

Inadequate soaking has been found to necessitate increases from 10% to 50% above the normal retorting time for commercial sterility, in order to achieve a desirable level of tenderness in cooked beans. Longer retorting times lead to the use of more energy than necessary in the processing of beans. Inadequate soaking has also been found to yield initial differences in the rates of hydration of beans prior to the retorting phase. These differences create problems in commercial bean-canning practice, one of which is the difficulty in estimating the initial amounts of bean solids and water (or sauce formulations) to fill each of the various sizes of cans. There is a tendency for the under-hydrated beans to continue to absorb moisture and swell in cans while in storage, thereby causing solid packed product of poor quality. A dense, solid packed product has a potential public health hazard due to changes in thermal process parameters.

Chemical additives are presently being used in the bean industry to accelerate the rate of water uptake in some types of beans. Apart from the fact that these additives cause discoloration of the seedcoats of beans, with the latter becoming unattractive, there is also the potential hazard of some undesirable side chemical reactions occurring during subsequent processing of the beans.

Blanching of dried beans with either moist steam at atmospheric pressure or hot water, for various periods of time before soaking, is also currently employed in the bean industry to accelerate wetting of beans. Moist steam has been observed to cause slight discoloration and wrinkling of the seed coats of some types of beans. High temperature soak conditions also result in the generation of substantial waste effluents due to excessive losses in bean solids while undergoing the soaking phase in tanks. Loss of solids reduces available nutrients and contributes significantly to waste water effluent.

Physical mechanisms involving heat and/or vacuum treatments have also been found to increase water intake by beans. This is due to the fact that these mechanisms promote the removal of air and other gases from the pores of the seedcoats along with those adsorbed onto the seedcoat and cotyledon surfaces. These gases have been found to interfere with water movement into beans during soaking.

Vacuum induced hydration of dry beans involves placing weighed proportional amounts of dry beans and water in an appropriate enclosure attached to a vacuum pump. The enclosure is evacuated to any desired vacuum level after which it is then restored to atmospheric pressure. The creation of vacuum causes a pressure gradient which in turn, induces air and other gases inside the beans to diffuse to the exterior. The subsequent release of the vacuum with the beans immersed in water then causes an inverse pressure gradient that enhances the rapid diffusion of water into the interior of the beans.

The major objectives of this research are:

1. To investigate process parameters for maximum utilization of vacuum induced hydration during the soaking of dry beans.
2. To examine the influence of vacuum induced hydration, soaking and cooking time on some physical characteristics and mechanical properties of processed beans.

2. LITERATURE REVIEW

2.1 Definition of Physical Properties

Physical properties of plant and animal materials encompass the combination of physical characteristics, mechanical, thermal, electrical and optical properties. Any study of these physical properties would require some knowledge of the structure of the plant or animal material as well as certain physiological activities influencing these properties (Mohsenin, 1970).

Many researchers have found that the moisture content of agricultural products of plant origin, e.g., seed grains, exerts a profound influence on the physical properties of the products. The moisture content of a seed grain would decrease when subjected to a dehydration process while an increase would occur during rehydration. Crocker and Barton (1953) investigated the water relations of seed grains from which they ascertained that the initial movement of water into a seed is by imbibition. However, under ideal conditions, such as constant temperature, physical and chemical homogeneity of material, and chemical stability of the seed in the presence of water at room temperature, the imbibition would occur with a continually diminishing speed (Shull and Shull, 1932).

2.2 Factors Affecting Water Intake by Beans

Shull and Shull (1932) investigated the rates of moisture absorption by some plant materials, e.g., cotyledons of peas, corn grains and seeds of Xanthium and generally found the rate of water intake by each tissue to be high at first, and then to decrease rapidly with each increment of moisture after some period of time, due to the increasing satisfaction of the forces causing hydration. As saturation was approached in all the materials studied, the rate of water absorption approached zero and finally ceased or became balanced by the outward diffusion of soluble substances from the tissues.

An understanding of moisture equilibrium of foodstuffs has been found necessary in food engineering because equilibrium data are needed for process and design purposes. The equilibration of a water-foodstuff system involves heat and/or mass transfer processes, which can be modeled and treated mathematically to guide the analysis (Husain et al., 1972; Roman et al., 1979; Wang and Hall, 1961; Whitney and Porterfield, 1968). The diffusion process can be mathematically modeled in different ways (Crank, 1975), depending on whether or not the true tissue structure is taken into account. King (1968) however, emphasized the need to incorporate into any analytical solution, the structure of a foodstuff, rather than considering it as a homogenous solid.

Mass transfer can be active or passive, and the general expression which has been found to describe the rate at which moisture will move through a solid (known as Fick's first Law) can be written as:

$$\frac{dm}{dt} = -DA \frac{dC}{dX}$$

where dm/dt represents the mass (moisture) flux rate; D is the diffusion coefficient or moisture-transport constant which has been found to vary with the substance; A is the area over which diffusion would occur; the differential, dC/dX, is the driving force causing the moisture movement with the minus sign indicating that diffusion would occur from a higher to lower concentration.

The diffusion coefficient may take many forms depending on the mechanism of moisture movement. Gorling (1958) described the various mechanisms that result in moisture migration within a product. These included liquid movement by capillary forces, diffusion of liquids, surface diffusion, and water-vapor diffusion. If however, the movement of moisture within a porous solid is mainly due to capillary forces, the transport process would be a function of a moisture content gradient rather than a vapor-pressure gradient, thereby permitting the use of Fick's second law (Becker and Sallans, 1955), in which the volume concentration of water (M) would represent the mass flux in one-dimensional diffusion as follows:

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial X^2}$$

Shull and Shull (1932) remarked, based on observations conducted on rates of moisture absorption by plant materials, that one of the main causes of irregularities in the rate of water intake by seeds and naked cotyledons is the formation of internal cavities during imbibition due to the breaking of the interior of the material by unequal swelling as observed in pea cotyledons and corn grains. Another main cause of deviation from regular absorption rates was observed to be the lack of physical homogeneity in the absorbing material. In many kinds of seeds, the outer part of the seedcoat (testa) may be heavily cutinized (as illustrated in Appendix A), and impervious to water like the so called "hard" seeds of certain of the Leguminosae and Malvaceae families of plants. Some other legumes (navy beans, cowpeas and soybeans), whose seedcoats are not cutinized, even though they might be one or several layers thick, have been found to absorb moisture very rapidly when hydrated, due to the highly permeable nature of their seedcoats to water (Powrie et al., 1960; Sefa-Dedeh et al., 1979b; Smith and Nash, 1961).

White (1908) believed that the cuticular layer over the palisade epidermal cells of the testa determined the impermeability of small leguminous seeds; while for the larger leguminous seeds, the cuticle is combined with a portion of the palisade epidermal cells to give the impervious effect. Watson (1948) also regarded the cuticle as the main impermeable layer in the testa. These workers did not, however, pay attention to the hilum as having any significance in relation to the impermeability of the testa. The importance of the hilum was demonstrated by Miller (1939), when he showed with the aid of X-ray photographs, that the initial absorption of water into lima beans placed in a hydration medium occurred through the vascular bundles of the hilum; from where it migrated to the chalaza and around the seed primarily through the vascular elements of the testa. The seedcoat of the lima bean was found to be impermeable until wetted from beneath.

Corner (1951) furthermore, suggested that the hilar fissure provided a passage for the exchange of gases involved in respiration, during seed development and germination. Hyde (1954) also described the hilum to be a hygroscopically activated valve in the impermeable epidermis of the testa, after he had observed that when the relative humidity was low, the fissure in the hilum of the seedcoat opened, permitting the seed to dry out; but when the relative humidity was high, the fissure closed, obstructing the absorption of moisture. Further work on the function of the hilum during moisture absorption led Hyde (1954) to conclude that in order to close the hilum, there must be a certain minimal difference in moisture tension between the palisade epidermis and the counter palisade which lie inside and outside the impermeable layer of the testa respectively. If this minimum difference is not achieved the hilum would be open, thereby facilitating the entry of water into the seed.

Several investigators have attempted to accelerate water uptake in dry beans. In most of these cases, some type of heat is usually recommended: for example, steaming at atmospheric pressure (Gloyer, 1921); boiling for 2 minutes, then soaking in hot water for 1 hour (Dawson et al., 1952); dipping in boiling water for 1 minute (Morris et al., 1950); and soaking in 122^{o} F (Synder, 1936). Other treatments, such as scarifying the seedcoat (Morris et al., 1950), and dipping in concentrated sulfuric acid (Gloyer, 1921), have been less successful.

Effect of additives in the soak water has also been studied. These included sodium bicarbonate (Greenwood, 1935); salt (Morris et al., 1950); hexametaphosphate, sulfites, oxalic acid, ammonium oxalate, and hydrochloric acid (Reeve, 1947); and ethylene diaminetetraacetic acid (EDTA) (Elbert, 1961). In general, results of these studies have shown that hexametaphosphate, salt, and EDTA soften the seedcoat and increase tenderness of cooked beans.

Hoff and Nelson (1965) suggested that the removal of gases (probably nitrogen, oxygen and carbon dioxide), which fill the interstitial pores along with being adsorbed onto the internal surfaces of both seedcoat and cotyledons, would facilitate the migration of water into the tissues of beans. Generally, adsorbed and trapped gases in porous solids surrounded by a hydration medium can be released by either raising water temperature or reducing the partial pressure of the gases in the surrounding medium. The suggestion by Hoff and Nelson (1965) was authenticated when they observed an increase in the rate of water uptake in dry pea beans, following the removal of absorbed or trapped gases from the surfaces of the beans with the aid of any of these three simple methods for gas release--steam pressure, vacuum, and sonic energy treatments.

The usefulness of the vacuum method was further demonstrated by Rockland and Metzler (1967) with their "Hydravac" process, which was found to facilitate the infusion of a salt solution through the hilum and fissures in the hydrophobic outer layer of the seedcoat of lima beans. When wetted by the solution, the inner membrane of the seedcoat would hydrate rapidly, thereby plasticizing the seedcoat and causing it to expand to its maximum dimensions within a few minutes. The cotyledons, now encapsulated in a uniform bath of hydration medium, would imbibe the tenderizing solution rapidly and expand to fill out the seedcoat. The "Hydravac" process was found to reduce the number of split beans by minimizing the extension of seedcoat fissures which would otherwise, occur during normal, isobaric hydration.

2.3 Significance And Measurement of Some Physical Properties of Beans

The water absorption characteristics of legumes have been found to influence their physical properties. For example, Bourne (1967) observed that the relative density (determined from weight and volume which were obtained by displacement of water) of dry beans decreased as the beans imbibed water during soaking prior to cooking. Bourne (1967) found that pea beans had relative density of 1.31 before soaking and 1.15 after soaking while marrow beans had a relative density of 1.24 before and 1.06 after soaking.

Sefa-Dedeh and Stanley (1979a), also found a reciprocal relationship between the water absorption characteristics and textural changes during processing (soaking and cooking) of five legumes (cow peas, soybeans, white beans, pinto beans and adzuki beans). Textural changes represent a mechanical property of foods which needs to be monitored closely in certain foods for quality control purposes (Kramer and Twigg, 1966). Measurement of food texture has, therefore, been found to play a significant role in the food industry via product development and improvement, control of manufacturing processes, and in the evaluation of the quality of the finished product to be consumed.

According to Finney (1969), texture, or the kinesthetic characteristic of foods is generally considered to relate to those attributes of quality associated with the sense of feel, as experienced either by the fingers, the hand or in the mouth. It includes such sensations as hardness, tenderness, brittleness, mealiness, etc., but excludes the sensations of temperature and pain. The use of taste panels (selected individuals) for judging food characteristics, has often been inconsistent, thereby leading to the development and subsequent improvement in objective methods for food quality evaluation (Kramer and Mahoney, 1940). Objective measurements of food texture are more consistent since they predominantly involve an analysis of the mechanical or rheological behavior of food materials; that is, their deformation, strain, or flow characteristics when subjected to a mechanical force (stress).

Instruments used on solid foods can be divided into cutting, piercing, puncturing, compressing or shearing devices. Generally, emperical texture testing systems are devices which contain four basic elements: 1) a probe containing the food sample; 2) a driving mechanism for imparting motion in a vertical, horizontal or rotational direction; 3) a sensing element for detecting the resistance of the foodstuff to the applied force; and 4) a read-out system for quantifying the resistance of the food sample.

Bourne (1979) observed that most food rheologists have demonstrated an awareness of the complexities involved in calculating true stress and true strain during texture measurements of foods; and consequently, have resorted to measuring force at constant compression rates, on test pieces of standard dimensions. A comparison of values determined by Shelef and Mohsenin (1969), for three mechanical parameters--apparent modulus of elasticity (Ea), modulus of deformation (Ed), and linear limit load (LL), that depict the physical property of the horny and floury endosperms of crack-free corn kernels at different moisture levels, showed LL to exhibit the most consistent trend; thereby, indicating conclusively, that uni-axial compression force could be a good indicator of the mechanical properties of corn kernels.

The deformation of a food under the influence of a compression force has been frequently used as a measure of quality by several researchers. Though Brinton and Bourne (1972) have classified foods that deform to a small extent as "firm," "hard," or "rigid" and foods that deform to a large extent as "soft," "flaccid," or "spongy;" they, however, noted that softness may be associated with good or poor quality depending on the food.

Bourne (1977) also remarked that most foods are strain-rate sensitive; which means that the force required to achieve a given deformation will be greatly influenced by the rate of deformation. Strain-rate sensitivity of foods has been illustrated very well, using the Instron Universal Testing Machine, by Sherman and his co-workers (Boyd and Sherman, 1975; Shama and Sherman, 1973; Culioli and Sherman, 1976; Vernon Carter and Sherman, 1978).

Hardness is a textural characteristic of foods evaluated organoleptically during the first "bite" of the masticatory cycle (Brandt et al., 1963). At this time, the chewing force is applied to the food in an approximately linear manner which can be satisfactorily reproduced instrumentally by compression testing with the Instron Universal Tensile Tester (Shama and Sherman, 1973). The strain-rate sensitivity of foods, however, makes the relationship between force and compression exhibited by this instrument, to depend on the crosshead speed utilized. If instrumental data are to be utilized for predicting the sensory evaluation of hardness, it would then be necessary to closely simulate the mechanical conditions prevailing in the mouth during the initial stage of mastication. A value of 150 cm/min was used by Voisey (1975) as the approximate average deformation speed occurring in the mouth. Voisey also found that agreement between objective and sensory tests was considerably improved when the Instron data, obtained at a range of deformation rates, were extrapolated to the crosshead speed of 150 cm/min. Because of the mechanical and recording limitations of presently available testing machines, such high deformation rates are not feasible, and the extrapolation method would thus appear to be a very useful approximation.

Szczesniak and Kleyn (1963) pointed out that texture is an important component of food quality and, in certain foods, may be even more important than flavor and appearance to the consumer. This remark has been found to be true in the case of canned beans, which receive more thermal processing than is actually required for commercial sterility, in order to achieve an acceptable degree of tenderness. Hoff and Nelson (1965) suggested that if the quality factor (tenderness or softness) could be significantly affected during the soaking phase of canning, then less process time and less retort capacity might be required for canning beans.

Although there have been numerous attempts to measure the texture of cooked beans objectively (Binder and Rockland, 1964; Van Buren, 1968; Voisey and Larmond, 1971; Quast and da Silva, 1977); however, little information is available in the literature, on the texture of raw and soaked beans (Molina et al., 1976; Ige, 1977). This discrepancy may be attributed to the fact that raw beans could be extremely hard with the possibility that several popular texture test cells would not be able to withstand the forces generated during measurements, without damage.

Martinez-Herrera and Lachance (1979) investigated the functional relationship between hardness (measured as peak compression force or peak bioyield point) of cooked corn kernels and the time for the cooking process, and obtained a linear regression equation as the best mathematical model for predicting the hardness of cooked corn kernels as a function of cooking time. Binder and Rockland (1964) observed the maximum shear force obtained on a Lee-Kramer shear press to decrease linearly with cooking time of lima beans at 212^{o} F; while Uebersax (1972) obtained ten-fold decreases between soaked and thermally processed bean firmness for navy beans, by using the Lee-Kramer shear press. The Kramer shear press was also used by Quast and da Silva (1977) to establish an adequate degree of cooking for black beans, brown beans and soybeans of about 2.5 lb force/g. Sefa-Dedeh et al. (1978), found that soaking raw cow peas in water prior to cooking produced softer beans in which the decrease in hardness was proportional to the soaking time; thus enabling the prediction of the texture of the cooked beans from the texture of the corresponding soaked bean. Sefa-Dedeh *et al*. (1978), also found that heating of cowpeas at 212° F for periods of time up to 90 minutes, led to an exponential reduction in the maximum force needed to compress, shear and extrude cowpeas.

Scanning electron microscopy was used by Rockland and Jones (1974) and Sefa-Dedeh *et al*. (1978) to study changes in microstructures of lima beans and cowpeas respectively, during the cooking process. The major effect observed by these researchers was the breakdown of intercellular material within the middle lamella which then permitted the separation of adjacent whole cells whose cell walls remained intact.

3. THEORY

3.1 Introduction

It has been reported by some researchers (Hoff and Nelson, 1965; Rockland and Metzler, 1967) that appreciable amounts of gases were given off when dry beans were submerged in pure water or salt solutions, and then subjected to a vacuum, which was subsequently released. It is believed that the vacuum created yields a decrease in the partial pressures of the gases in the hydration medium with the result that the gases present in the interstitial pores or adsorbed gases on the internal surfaces of both the seedcoat and cotyledons of a bean expand and become released, thereby facilitating the rapid migration of water into the beans when the vacuum is released and pressure equilibration is achieved.

It is desirable from an engineering point of view, to determine the amount of work needed for the expansion and release of gases from bean tissues during the vacuum treatment for this would allow the development and optimization of a relationship (if any) between the work done in releasing gases, and the rate of moisture uptake in beans during the soaking process.

The rate of moisture uptake in beans during soaking has been shown by many researchers to affect some physical properties of both soaked and cooked beans; but no research has been done before on the relationship that might exist between work done in releasing gases and physical properties of processed beans.

The postulate behind this present research is that, within the practical (or feasible) range of vacuum levels achievable by an experimental vacuum pump, the greater the level of vacuum pulled or work performed, the faster should be the rate of water intake represented by the value of the average effective diffusivity, followed by an increase in the softening rate of processed beans.

3.2 Derivation of Work from the Ideal Gas Law

The simplest thermodynamic system can be assumed to consist of a fixed mass of an isotropic fluid that would not be influenced by either chemical reactions or external fields. Such a system can be described in terms of the three measurable coordinates: pressure, P; volume, V; and temperature, T; and characterized as a PVT system. These three coordinates are not independent of each other; in that, fixing any two of them automatically determines the third. Therefore, an equation of state exists that interrelates the three coordinates for equilibrium states. This equation may be expressed in functional form as:

$$f(P, V, T) = 0$$

If any pair of the three variables is selected as being independent, this functional relationship can then be expressed in three additional alternative forms:

$$P = P(V, T); \quad V = V(P, T); \quad T = T(P, V).$$

Suppose for a constant-composition PVT system,

$$V = V(P, T) \tag{3.2.1}$$

then an exact expression can be written for the total differential of dV as follows:

$$dV = \left(\frac{\partial V}{\partial P}\right)_T dP + \left(\frac{\partial V}{\partial T}\right)_P dT \tag{3.2.2}$$

Charles' law states that, for a gas at low pressures, the volume of the gas is directly proportional to the temperature at constant pressure; while Boyle's law asserts that, for a gas at low pressures, the pressure of the gas is inversely proportional to the volume at constant temperature.

From Charles' law: $V = C_1 T$ at constant P, where C_1 is a constant.

$$\therefore \left(\frac{\partial V}{\partial T}\right)_P = C_1 = \frac{V}{T} \qquad (3.2.3)$$

From Boyle's law: $P = C_2/V$ at constant T, where C_2 is a constant.

$$\therefore \left(\frac{\partial V}{\partial P}\right)_T = \frac{-C_2}{P^2} = \frac{-V}{P} \qquad (3.2.4)$$

Inserting the expressions for $(\partial V/\partial T)_P$ and $(\partial V/\partial P)_T$ in Equations 3.2.3 and 3.2.4 respectively, into Equation 3.2.2 yields a differential equation for V:

$$\frac{dV}{V} = \frac{dT}{T} - \frac{dP}{P} \qquad (3.2.5)$$

Integration of Equation 3.2.5 gives

$$V = \frac{RT}{P} \qquad (3.2.6)$$

Equation 3.2.6 is the Ideal-Gas Law in which R is the universal gas constant and V is the molar volume of the gas.

In engineering thermodynamics, the calculation of work is usually done for idealized processes, because of their tractability to mathematical analysis. The results of calculations for an idealized process are then combined with an appropriate efficiency to give a reasonable approximation of the work for the actual process.

The work done by forces due to pressure, which causes a change in volume of a fluid can be expressed as:

$$\delta W = PdV \tag{3.2.7}$$

From Equation 3.2.6, $P = \frac{RT}{V}$, is substituted into Equation 3.2.7 to give

$$\delta W = RT\ dV/V \tag{3.2.8}$$

Assuming the temperature to be constant, integration of Equation 3.2.8 from the initial to the final molar volume yields

$$W = RT \ln (V_f/V_i) \tag{3.2.9}$$

Since $P_iV_i = P_fV_f$ at constant temperature (Boyle's law), Equation 3.2.9 becomes

$$W = RT \ln (P_i/P_f) \tag{3.2.10}$$

3.3 Evaluation of the Average Effective Diffusivity

Powrie et al. (1960) found from analytical studies that the seedcoats, cotyledons and embryonic axes constituted 7.7%, 90.5% and 1.8% respectively, of the dry weight of mature navy beans. These researchers concluded from their studies that when weight and volume are of primary concern, the two cotyledons represent the most important components of the bean seed.

During the soaking of bean tissue, the mode of water transfer from the hydration medium into the innermost layer of the seedcoat that is in contact with the outer surface of each of the cotyledons depends on the type of beans. Water was observed to migrate rapidly from the hydration medium in one direction through the seedcoat before reaching the cotyledons in the case of navy beans (Powrie et al., 1960); while Miller (1939) reported that water which initially entered through the vascular bundles in the hilum of individual lima beans immersed in a hydration medium wetted the innermost layer of the seedcoat before the rapid migration of water occurred directly through the seedcoat.

Neglecting the resistance to water transport through the seedcoat on a volume basis, the transfer of water across the cotyledons can be modeled as a series of diffusional steps for moisture from the outer to the inner surfaces of each cotyledon. The inner surfaces of the two cotyledons of a bean seed are separated by a shallow depression as illustrated in Figures 3.3.1 and 3.3.2.

Fick's first law of diffusion states that the rate of transfer of a diffusing substance through unit area of a section is proportional to the concentration gradient measured normal to the section, i.e.,

$$F = -D \frac{\partial C}{\partial X} \text{ (for an isotropic medium)} \qquad (3.3.1)$$

where F is the rate of transfer per unit area of section, C is the concentration of diffusing substance, X is the space coordinate measured normal to the section, and D is the diffusion coefficient. In some cases, e.g., diffusion in dilute solutions, D can reasonably be taken as constant, while in others, e.g., diffusion in high polymers, it depends very markedly on concentration.

Assuming the bean tissue undergoing hydration to be homogenous with a constant D value for water, then Fick's second law for one-dimensional mass transfer in which the volume concentration of water (M) represents the mass flux can be expressed as:

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial X^2} \qquad (3.3.2)$$

Crank (1975) described how to obtain the general solutions of the partial differential equation for diffusion given a variety of initial and boundary conditions for various shapes of materials. Crank stated

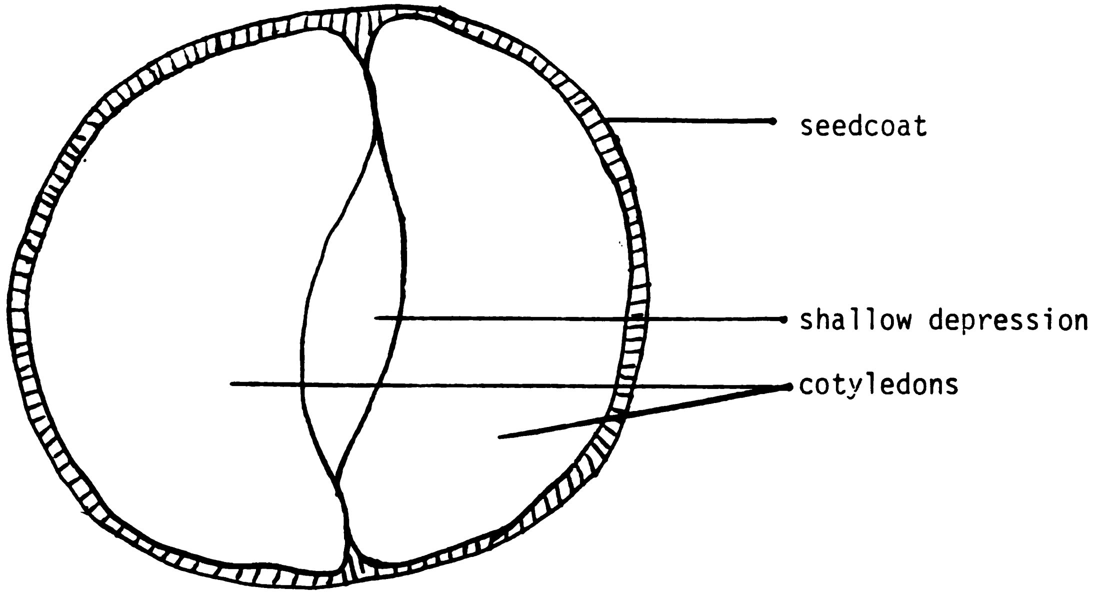


Figure 3.3.1: Transverse section of a bean seed.

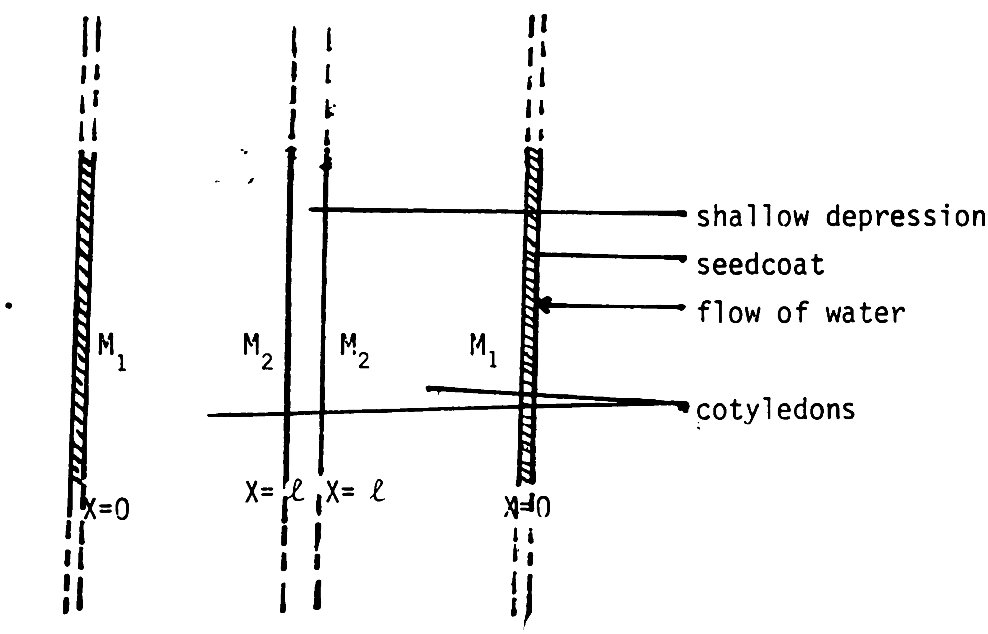


Figure 3.3.2: Longitudinal section of a bean seed.

that there are two standard forms of the solution provided that D is constant. One form consists of a series of error functions or related integrals, which is suitable for numerical evaluations at small times, i.e., during the early stages of diffusion. The second form, derived by using the method of separation of variables, consists of a trigonometrical series, which is suitable for numerical evaluation at moderate and large times. The suitability of each form depends on the ease of convergence with an appropriate optimization technique.

Figure 3.3.2 was used to model the transport of water into dry beans immersed in a soaking medium as a one-dimensional diffusion process in a medium bounded by two parallel planes (the planes at $X = 0$ and $X = \ell$). The longitudinal section of the bean seed was assumed to be so thin that effectively all the diffusing moisture had to enter through the plane faces with a negligible amount through the edges.

Since the soaking times under consideration were not greater than three hours, an initial non-steady state diffusion process was assumed along with a uniform initial distribution of moisture inside the bean seed. The volume concentrations of water at the two surfaces (M_1 and M_2) for each cotyledon at the onset of soaking were regarded as different, with the volume concentration of water at the outer surface or boundary of a cotyledon (M_1) assumed to be constant and equal to the equilibrium moisture content (M_e) which is about 55% wet basis, at constant room temperature of 20° C.

The initial and boundary conditions assumed can be mathematically expressed as

$$M_1 = M_2 = M_o, \quad t = 0 \qquad (3.3.3)$$

$$M_1 = M_e, \quad X = 0, \quad t > 0 \qquad (3.3.4)$$

$$M_t = f(X),\ 0 < X \leq \ell,\ t > 0 \qquad (3.3.5)$$

$$M_1 = M_2 = M_e,\ 0 \leq X \leq \ell,\ t \rightarrow \infty \qquad (3.3.6)$$

Assuming that the average density of the beans during soaking was constant, in addition to the initial and boundary conditions enumerated above, the solution to Equation 3.3.2 for an infinite plane at moderately large times (as determined by Crank, 1975) is the following expression:

$$\frac{M_e-M_t}{M_e-M_o} = \frac{8}{\pi^2}\sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \frac{-D(2n+1)^2\pi^2 t}{4\ell^2} \qquad (3.3.7)$$

where ℓ = thickness of each cotyledon = $\frac{\text{seed thickness or height}}{2}$.

This value of ℓ was assumed to be constant for beans undergoing soaking.

Assuming that the term n=0 is a good approximation to the result, Equation 3.3.7 can be simplified to

$$\frac{M_e-M_t}{M_e-M_o} = \frac{8}{\pi^2} \exp\left(\frac{-D\pi^2 t}{4\ell^2}\right) \qquad (3.3.8)$$

Rearranging Equation 3.3.8 yields

$$\text{Log}\left(\frac{M_e-M_t}{M_e-M_o} \times \frac{\pi^2}{8}\right) = \left(\frac{-D\pi^2}{4\ell^2} \times \frac{1}{2.303}\right)t \qquad (3.3.9)$$

The rate of moisture uptake can then be determined numerically from a semi-logarithmic plot (Figure 3.3.3) in which the x-axis represents time and the y-axis represents the common logarithm of the dry basis value for the dimensionless expression in parenthesis on the left side of Equation 3.3.9. Figure 3.3.3 represents an example plot in which the best line of fit has been drawn through the data points using the least squares method. The slope of the semi-logarithmic plot is equal in value to the expression in parenthesis on the right side of Equation 3.3.9,

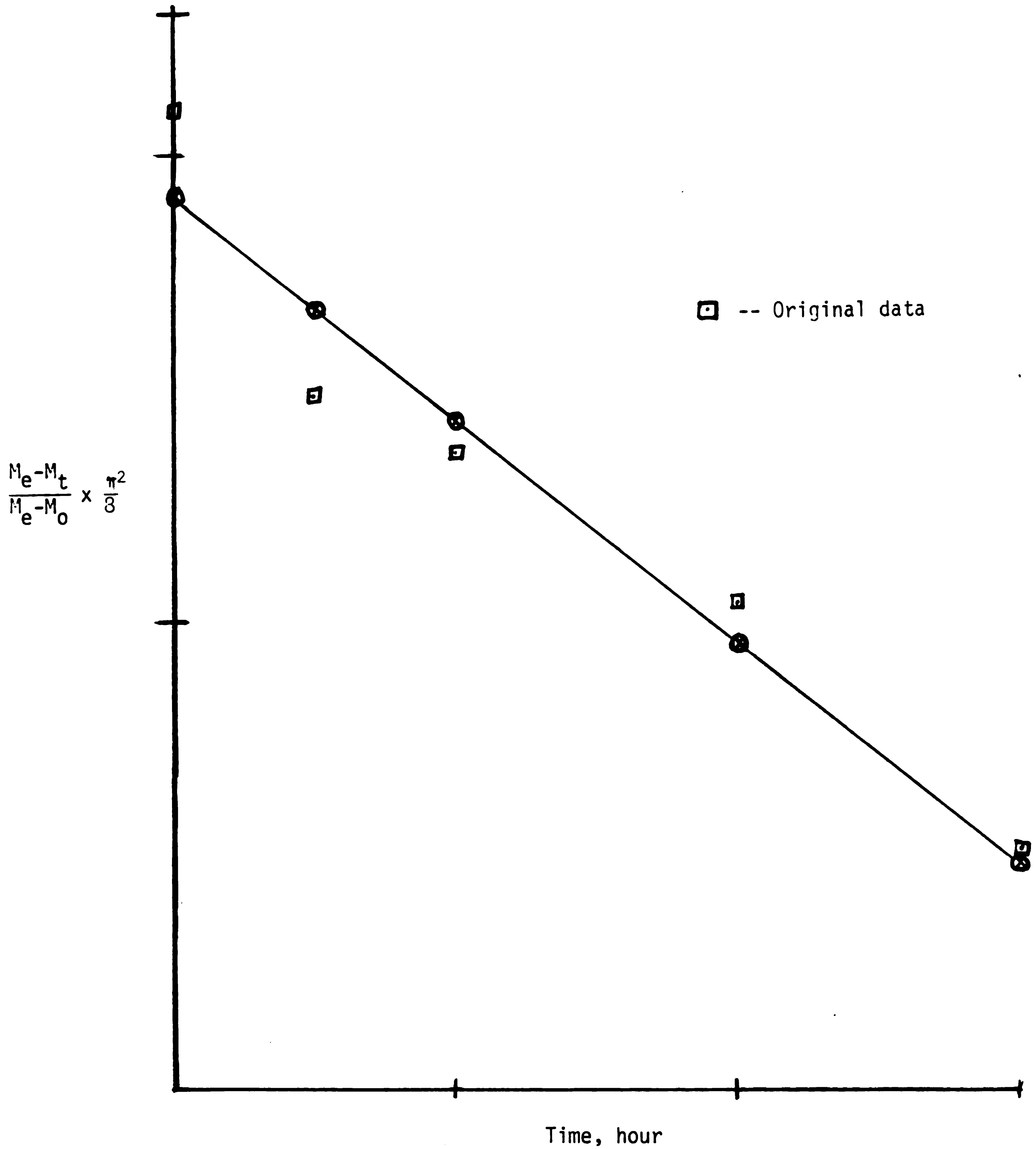


Figure 3.3.3: An example plot of dimensionless parameter in Equation 3.3.9 versus time in hours

i.e., slope (from Figure 3.3.3) $\equiv \left(\frac{-D\pi^2}{4\ell^2} \times \frac{1}{2.303}\right)$ (3.3.10)

Substituting the experimentally determined value of l into Equation 3.3.10 allows the calculation of the value for D which now represents the average effective water diffusivity (D_{eff}) and not the diffusion coefficient, due to the various assumptions made above in the modeling of the moisture uptake by dry beans during soaking at room temperature.

3.4 Evaluation of the Softening Rate of Beans

Kinetics is the study of motion and motion is time dependent. The changes food materials undergo during processing, preparation or storage are the results of a complex of physical changes and chemical reactions. In order to predict quality changes, kinetic studies of essential parameters such as product properties are necessary. Softening of some types of beans was observed by Sefa-Dedeh et al. (1978) to follow first order kinetics.

The general equation for a first order change is:

$$-\frac{dC}{dt} = K_1 C \qquad (3.4.1)$$

where dC/dt = rate of change of a specific parameter; C = concentration of parameter; and K_1 = rate constant, t^{-1}. Separating the variables and integrating Equation 3.4.1 yields

$$-\ln C = K_1 t + \text{constant} \qquad (3.4.2)$$

At t = 0, constant = $-\ln C_o$; and Equation 3.4.2 becomes

$$\ln\left(\frac{C_o}{C_t}\right) = K_1 t \qquad (3.4.3)$$

where C_o = initial concentration of parameter, and C_t = concentration of parameter at time, t. Rearrangement of Equation 3.4.3 yields

$$\frac{C_t}{C_o} = e^{-K_1 t} \qquad (3.4.4)$$

In order to apply Equation 3.4.4 on compression testing of processed (soaked or cooked) beans, the variables are re-defined as follows:

C_o = maximum peak force or work at zero time of process = F_o

C_t = maximum peak force or work at soak or cook time, t = F_t

t = time of soaking or cooking

The desired relationship between these newly defined variables is:

$$\frac{F_t}{F_o} = e^{-Kt} \qquad (3.4.5)$$

in which K represents the index of texture during soaking or cooking and is called the softening rate of beans.

The data on maximum peak force or work were obtained from using the Instron Universal Testing Machine equipped with an Automatic Integrator unit. Figure 3.4.1 represents the general shape of the curve obtained by plotting the force or work ratio (F_t/F_o) on the y - axis against time on the x - axis. This figure indicates that the change in the initial value of the maximum peak force or work with time is an exponential reduction. Values of the force or work ratio and time were subjected to an exponential regression analysis using a calculator program in order to estimate the value of K. When K is derived from the data on peak force it becomes K_f and when it is derived from the data on work it beomce K_w.

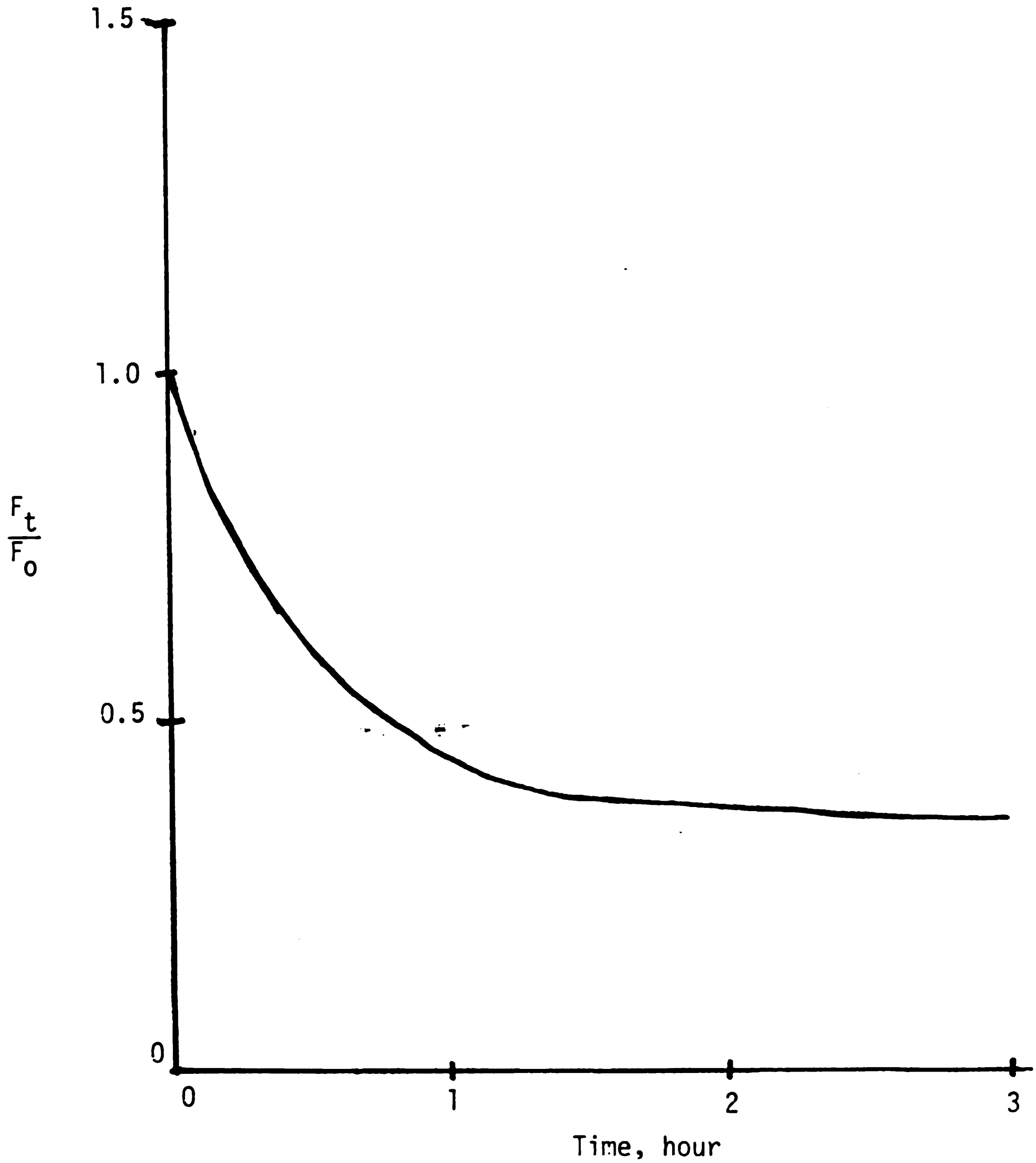


Figure 3.4.1: An example plot of the ratio in Equation 3.4.5 versus time in hours.

4. EXPERIMENTAL PROCEDURES

4.1 Introduction

Five varieties of dry beans (Phaseolus Vulgaris) were used in this study. They can be described as follows: a) the navy bean, a small ovoid white bean; b) the pinto bean, a medium-sized, flattened seed with dark reddish-brown, striped mottling overlying a light tan self color; c) the dark-red kidney bean, a large-sized elongated, ovoid seed; d) the bush cranberry bean, a medium-large variegated seed; and e) the turtle soup bean, a small-seeded black bean.

The experiments carried out during this study can be classified into two main groups:

1. Bench scale experiments on all the five varieties of beans which were obtained from the Michigan State University Research Farm at Tuscola County in the fall season of 1978.
2. Large scale experiments on only navy, pinto and kidney beans. The navy beans were obtained through the Michigan Elevator Exchange, Saginaw, Michigan in early 1980; while the pinto and kidney beans were obtained through the B & W Coop., Beckenbridge, Michigan, in summer, 1980.

In the laboratory, whole undamaged beans were sorted out from the damaged beans and stones, and were stored in laminated paper bags at about 20° C until they were removed for processing.

4.2 Bench Scale Experiments

These consisted of experiments conducted only during the soaking phase of processing beans, as outlined in Figure 4.2.1. The combination of levels for a 2x3x3 dimensional matrix, shown in Figure 4.2.2, was the theoretical basis for the experimental design; with the points in the cube indicating the combination of the variables.

For each combination of variables, duplicates of 25 g dry beans from each of the five varieties, along with 100 ml of water (distilled and demineralized) were placed in a jar attached to a Nalgene hand operated vacuum pump with gauge (Cat. No. 6130-0010) as illustrated in Figure 4.2.3. Three different levels of vacuum (i.e., 15, 20 and 25 inches Hg) were applied on the bean-water mixture for either 5 or 30 minutes and released; after which the beans were left immersed in the soak water for periods of 1, 2 and 3 hours.

A control (normal soaking) which was not subjected to a vacuum treatment was done for each soaking time employed as a variable, in addition to soaking for 24 hours at room temperature.

At the end of each soaking period, the beans were drained and subjected to some tests for physical characteristics as described later in this chapter. Values depicting physical characteristics of the beans were analyzed using 3-way (2x3x3 factorial) analysis of variance with fixed effects and replication that facilitated the study of either the individual or combined variables.

4.3 Large Scale Experiments

These consisted of experiments conducted in duplicates during the soaking phase alone, as outlined in Figure 4.3.1, and also throughout the entire canning process for beans, as outlined in Figure 4.3.2.

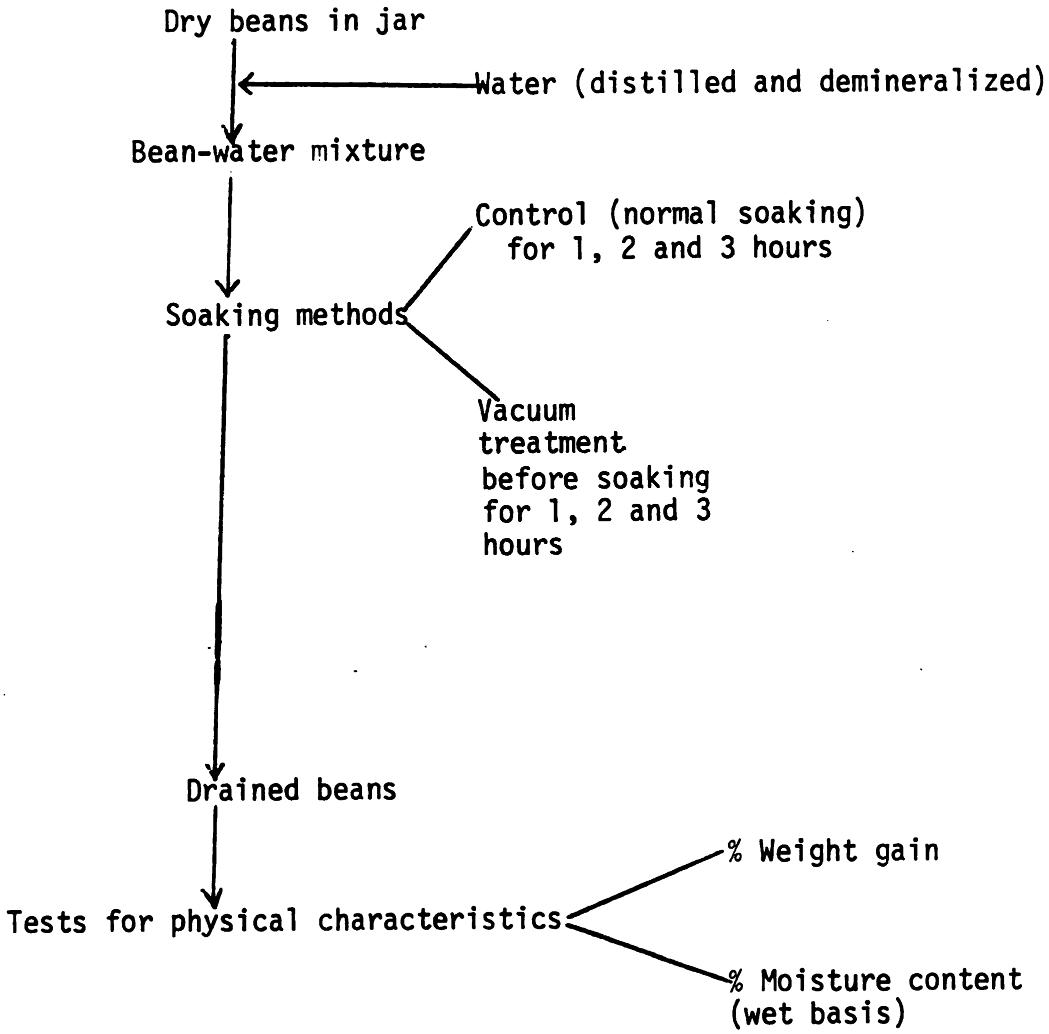


Figure 4.2.1: Outline of procedure for bench scale experiments.

Variable A = Time under vacuum
2 levels — 5 min
— 30 min

Variable B = Soaking time
= 3 levels — 1 hr
— 2 hr
— 3 hr

Variable C = Level of vacuum in inches of Hg
= 3 levels — 15 inches Hg
— 20 incnes Hg
— 25 inches Hg

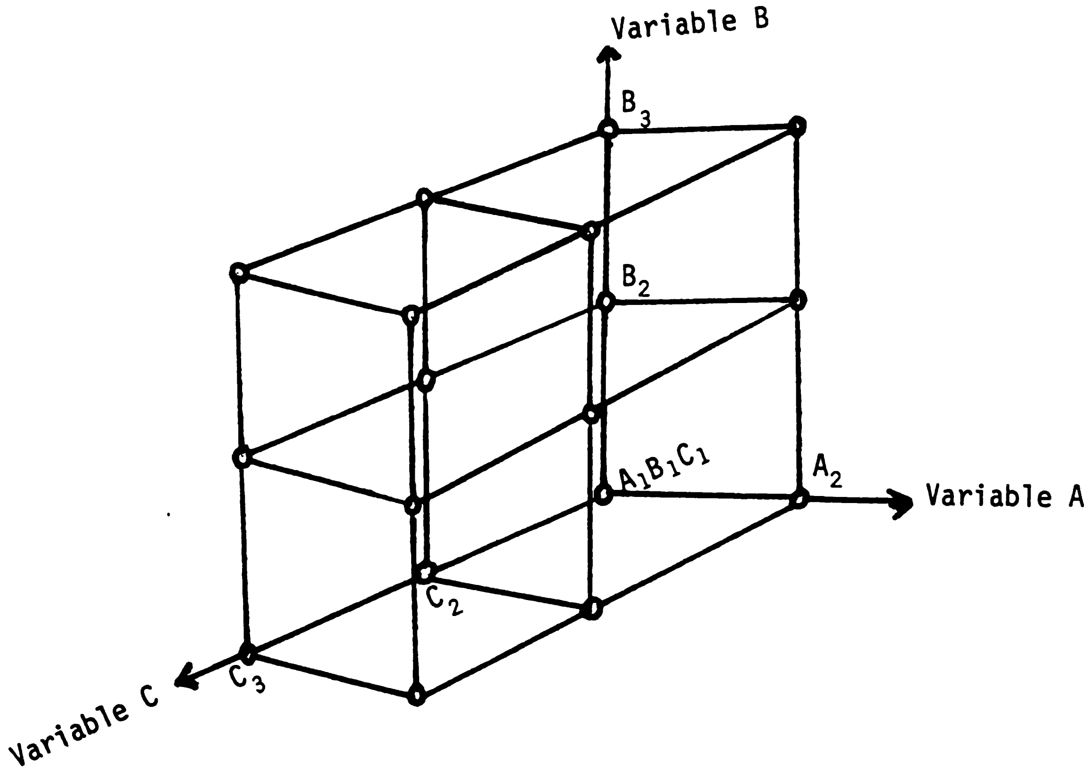


Figure 4.2.2: Theoretical cube for design of the variables involved in vacuum-induced hydration of beans during the bench scale experiments.

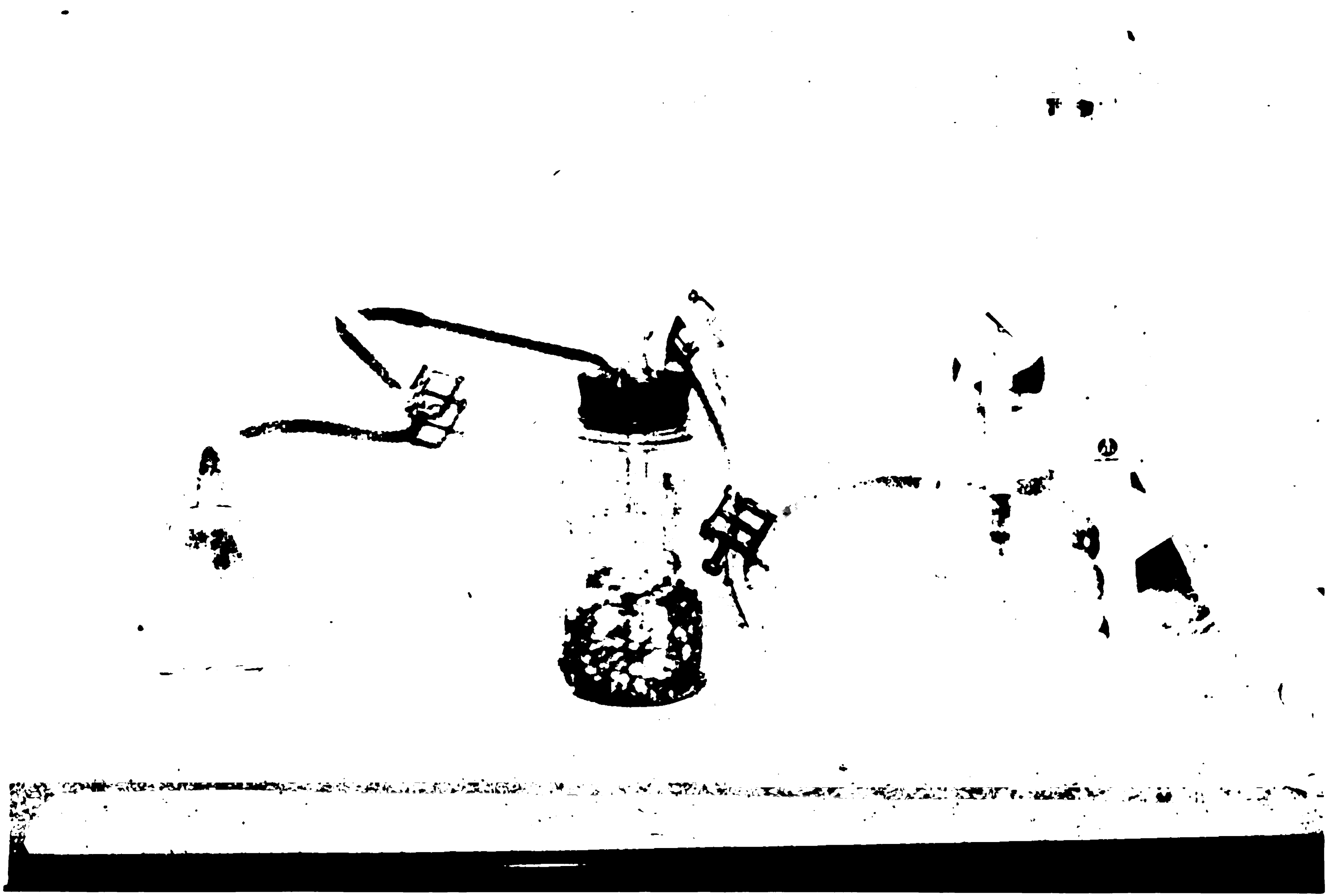
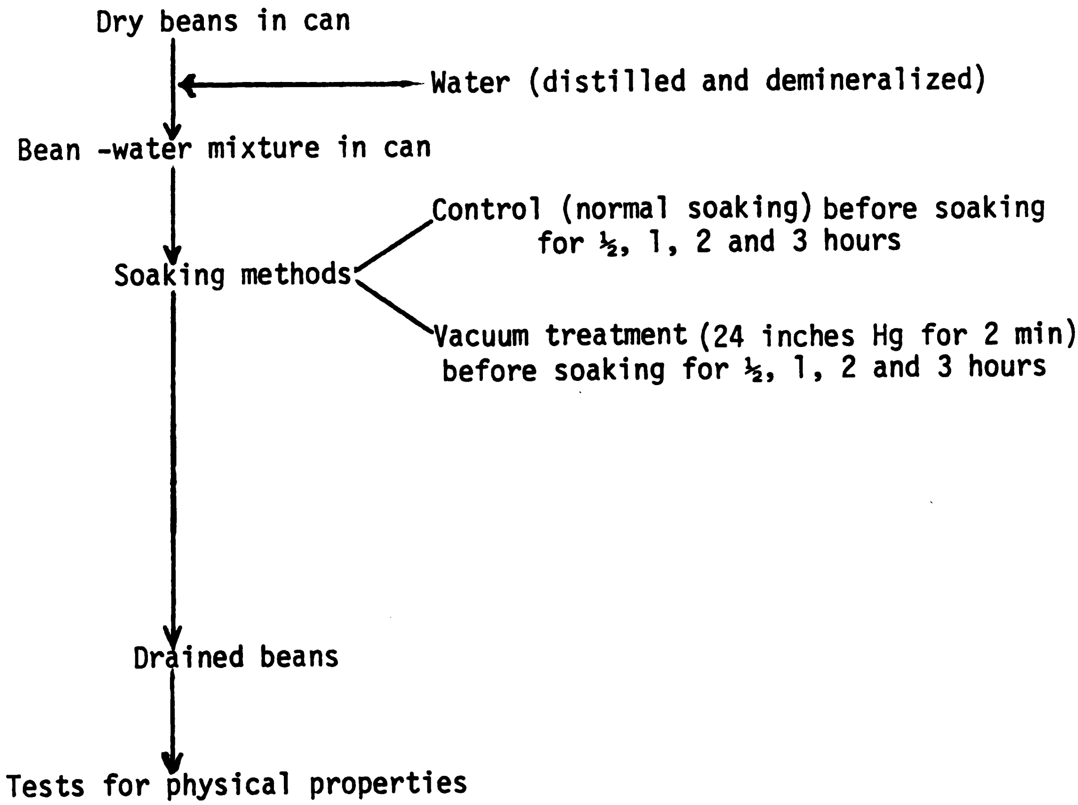


Figure 4.2.3: Laboratory set-up for vacuum treatment during bench scale experiments.



a) % weight gain

b) % moisture content (wet basis)

c) Specific gravity

d) Volume

e) Anatomical characteristics or dimensions (length, width and height)

f) Maximum peak compressive force

g) Compressive work

Figure 4.3.1: Outline of procedure for soaking only during large scale experiments.

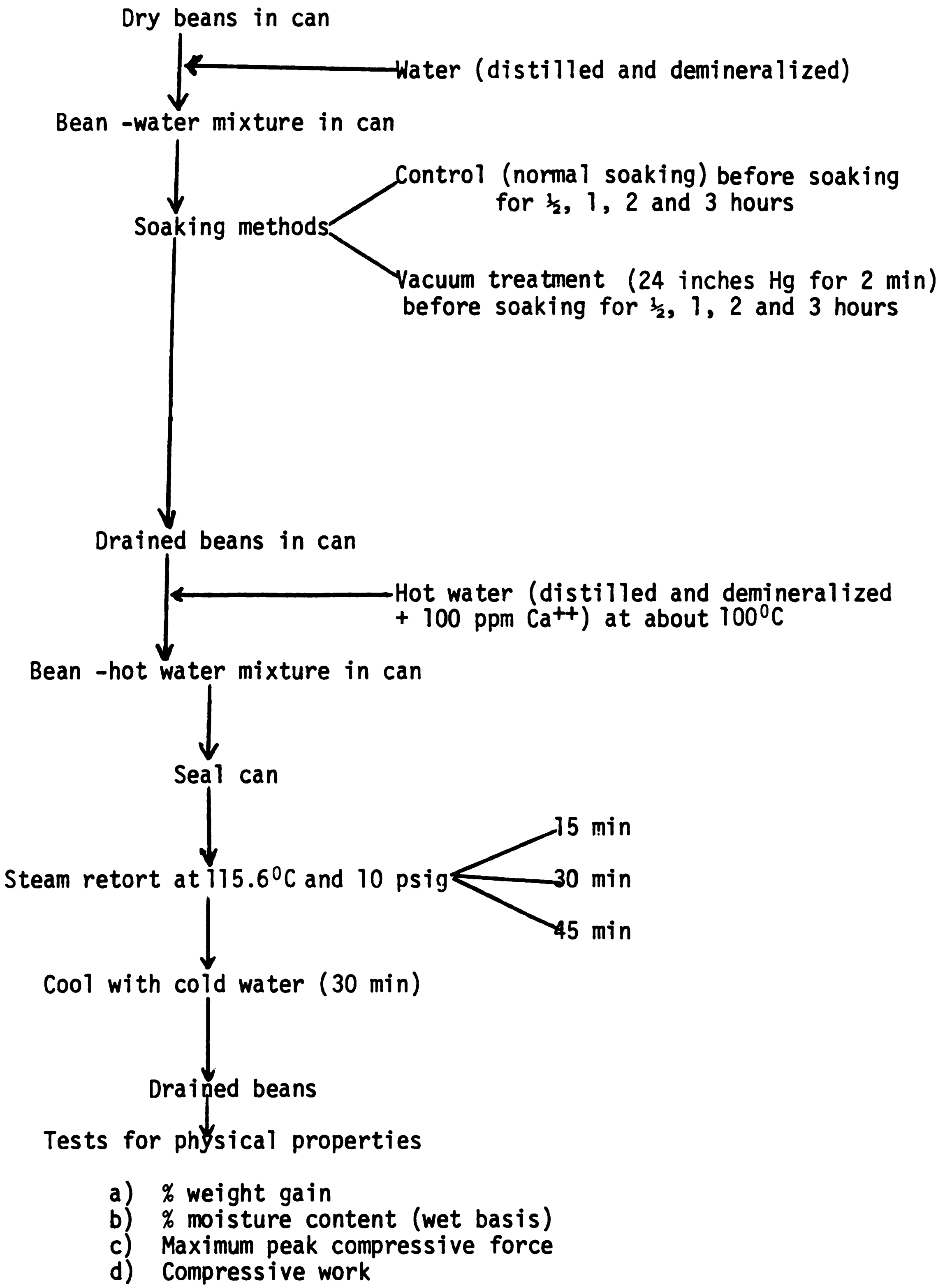


Figure 4.3.2: Outline of procedure for entire canning process during large scale experiments.

Before the soaking phase experiments were conducted, dry beans were removed from storage and subjected to the tests for physical properties (except % weight gain) as outlined in Figure 4.3.1.

The combination of levels for a 3x4x2 dimensional matrix, shown in Figure 4.3.3, was the theoretical basis for the experimental design of the entire canning process outlined in Figure 4.3.2; with the points in the cube indicating the combination of the variables.

For each combination of variables, during the large scale experiments, 300 gm water (distilled and demineralized) at room temperature, were added to a predetermined amount of dry beans (which should contain about 100 gm solids) in a 303x406 enameled can. The can with its contents were subjected to a vacuum of 24 inches Hg in a Rooney Semi-Automatic Vacuum Can Sealer No. 626 (see Figure 4.3.4), for about 2 minutes; after which the vacuum was promptly released and the beans left immersed in the soak water for periods of 1/2, 1, 2 and 3 hours. A control (normal soaking) which was not subjected to a vacuum treatment, was done for each soaking time employed as a variable, in addition to soaking for 24 hours at room temperature. Also, an additional set of experiments, was conducted using navy beans during the soaking phase, in which the cans and contents were subjected to a vacuum of 20" Hg.

At the end of each soaking period for the experiments performed during the soaking phase alone, the beans were drained and subjected to some tests for physical properties as described later in this chapter. The values obtained from these tests were used to determine the rate constants already discussed in the section on theory (Chapter 3). Also at the end of each soaking period for the experiments performed during the entire canning process, the beans were drained and put back into their respective cans. Into each can was then added 300 gm hot water (distilled and

Variable A = Cook time

= 3 levels: 15 min, 30 min, 45 min

Variable B = Soak time

= 4 levels: ½ hr, 1 hr, 2 hr, 3 hr

Variable C = Level of Vacuum

= 2 levels: 0, 24 inches Hg

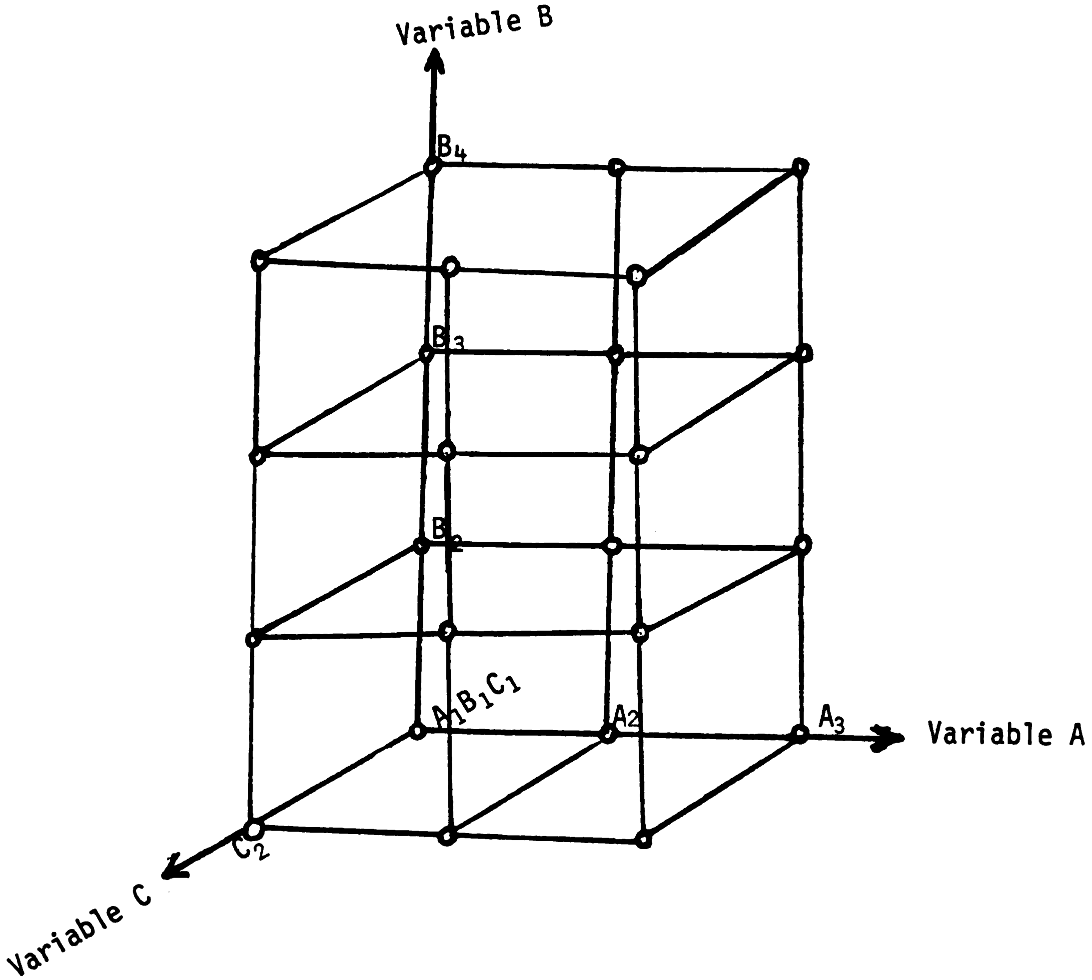


Figure 4.3.3: Theoretical cube for design of the variables involved in vacuum-induced hydration of beans during the canning process in the large scale experiments.

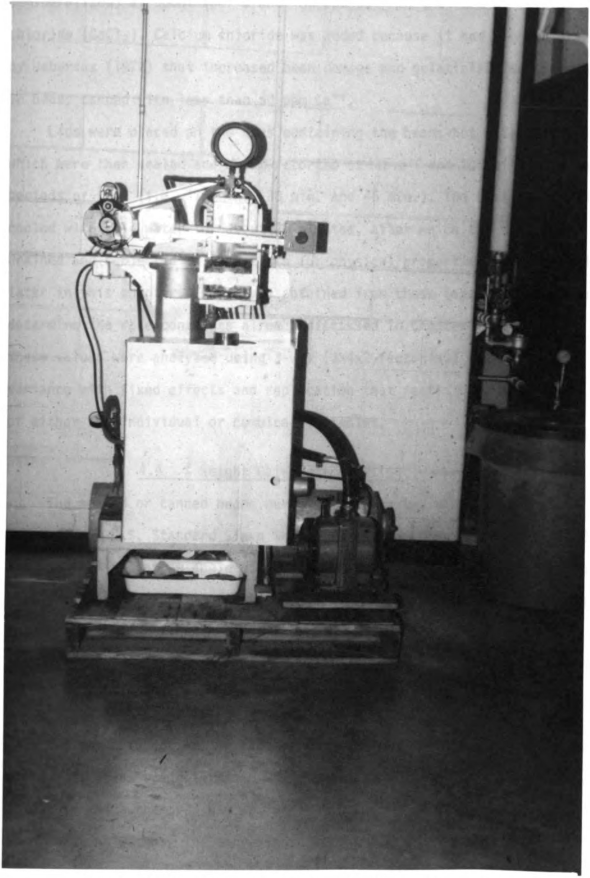


Figure 4.3.4: Rooney Semi-Automatic Vacuum Can Sealer.

demineralized) at about 100° C and 100 ppm Ca^{++} in the form of calcium chloride ($CaCl_2$). Calcium chloride was added because it had been observed by Uebersax (1972) that increased bean damage and gelatinization occurred in beans canned with less than 50 ppm Ca^{++}.

Lids were placed on the cans containing the beans-hot water mixtures, which were then sealed and steam-retorted at 115.6°C and 10 psig for various periods of time (i.e., 15 min., 30 min. and 45 min.). The cans were then cooled with cold water for about 30 minutes, after which the beans were drained and subjected to some tests for physical properties as described later in this chapter. The values obtained from these tests were used to determine the rate constants already discussed in Chapter 3. Also these values were analyzed using 3-way (3x4x2 factorial) analysis of variance with fixed effects and replication that facilitated the study of either the individual or combined variables.

4.4 % Weight Gain Determination

The soaked or canned beans were drained for two minutes on a sieve No. 8 of the U.S. Standard Sieve Series which had a pore opening of 2.38 mm, and was inclined at an angle of 45° to the horizontal. The drained beans were then weighed and the increase in weight of the beans determined. The increase in weight over the initial weight of the beans multiplied by 100% was reported as the % weight gain for a specified period of time.

4.5 % Moisture Content Determination

The moisture content of each of the dry and hydrated (either soaked or canned) beans was determined using the standard oven method (A.O.A.C., 1970); in which the oven was set at 100° C ± 5° C and each sample dried to a constant weight. The decrease in weight over the initial weight of the beans multiplied by 100% was reported as the % moisture content (M.C.) wet basis. This value was further converted to the % M.C. dry basis (as outlined in Appendix B), which was used in calculations to obtain the rate constants discussed in Chapter 3.

4.6 Determination of Specific Gravity and Volume

The experimental procedure followed the steps outlined by Mohsenin (1970). Figure 4.6.1 illustrates the experimental set-up in which the pycnometer (a specific gravity bottle) has been hooked to a Nalgene hand-operated vacuum pump with gauge (Cat. No. 6130-0010).

The detailed steps followed in obtaining the values for the specific gravity and volume of beans are outlined in Appendix C.

4.7 Anatomical Characteristics Tests

Ten beans were randomly selected from each of the dry and soaked beans samples and the length, width and height of an individual bean (as illustrated in Figure 4.7.1, were measured with a calipers. The mean and standard deviations of the resulting values were then recorded.

4.8 Compression Tests

The dry and hydrated (either soaked or canned) beans were subjected to compression in the Instron Universal Testing Machine, Model TTBM, Serial No. 1950, produced by Instron Corporation, Canton, Massachusetts (see Figure 4.8.1). This Instron machine was equipped with an automatic dual strip chart recorder and was connected to an automatic integrator. The strip chart recorder (operating as an automatic null-balancing potentiometer), plotted force versus deformation directly on a scale, which was calibrated prior to taking readings for individual sets of experiments.

Figure 4.6.1: Pycnometer set-up for specific Gravity determination.

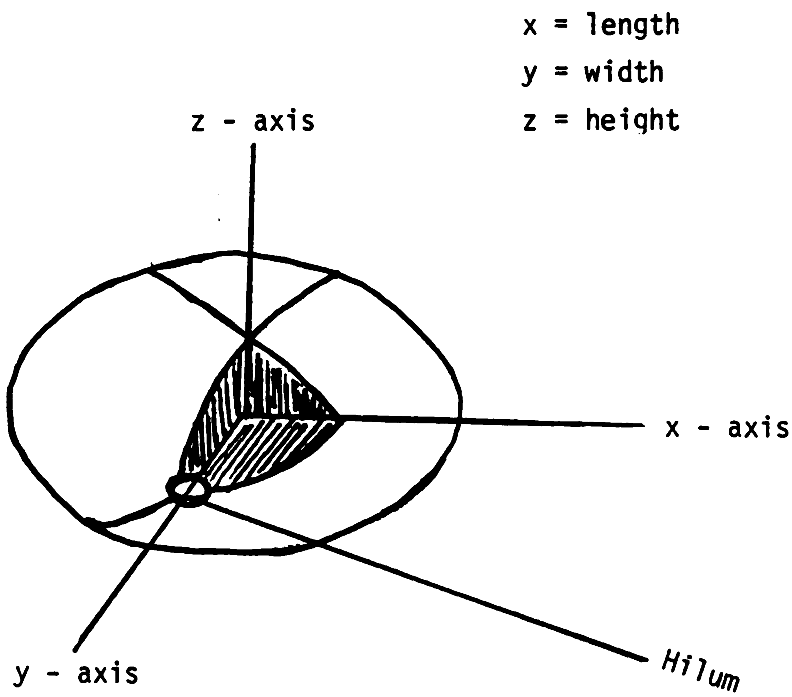


Figure 4.7.1: Anatomical dimensions of a bean

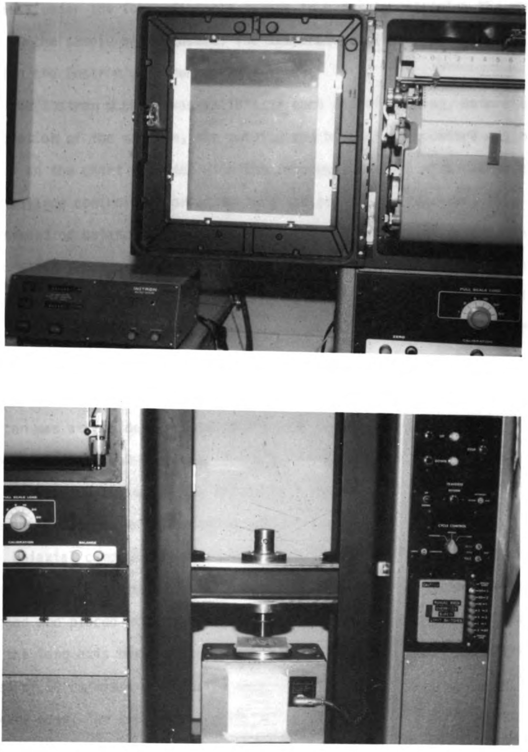


Figure 4.8.1: Instron Universal Testing Machine

The integrator (an accessory to the Instron machine), integrated directly the area under the force-distance curves in order to determine the work done on the sample being tested. The temperature of the laboratory housing the Instron machine was 23 ± 1° C.

The Instron machine was calibrated each day of testing. Before the calibration of the machine, the zeroing and balancing procedure was performed on the chart recorder with the zero button along with coarse and fine balance controls in order to zero the pen of the recorder. This adjustment of balance served to standardize the instrument system. The calibration procedure involved placing the Load-Selector switch on the Instron machine to the lowest position (i.e., 1); followed by attaching or placing a 1-kilogram weight (the appropriate calibrating weight of the load cell for the machine model used) on the compression table. The calibrating control knob was then unlocked and rotated until the recording pen was at the desired division on the strip chart; after which the knob was locked back in place. The 1-kilogram weight was removed from the compression table and the appropriate load scale for each set of experiments was selected prior to taking readings.

Uniaxial compression force was applied to whole beans (ten of navy beans; three of pinto beans; or two of kidney beans) which had been weighed and placed with the hilum of the individual beans on the side and the long axis horizontal as illustrated in Figure 4.8.2. A cross-head speed of 50 cm/min and a round compression cell (probe) of diameter 5.5 cm were used. The cross-head speed of 50 cm/min was chosen in order to deform the beans about 90% within 0.5 sec, which represents the time that corresponds to the duration of the downstroke (compression) in the first masticatory cycle in human mouths, for relatively hard foods.

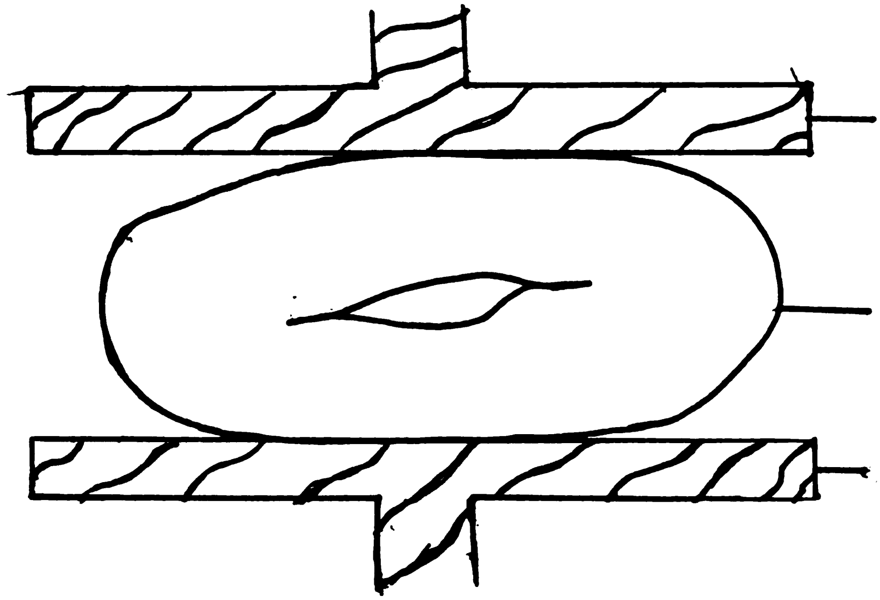


Figure 4.8.2: Orientation of the beans for compression tests.

A chart speed of 20 cm/min was also selected after preliminary tests to determine readable records.

Figure 4.8.3 illustrates the typical force-displacement curve obtained for beans which had been compressed at 50 cm/min. The maximum peak compression force (which corresponds to the maximum bioyield point) was recorded as force in Newtons; while the work done (rupture energy) was resolved by the automatic integrator and recorded as work in Joules. These two parameters were divided by the respective weights of beans used and reported as Newtons per gm and Joules per gm; in order to limit the amount of variation, normally inherent in biological materials (A.S.A.E., 1979).

Calculations for determining the means and standard deviations were done with a TI Programmable 59, manufactured by Texas Instruments, Inc., Dallas, Texas. The three-way analysis of variance of the results was calculated using the Canon Computer System (situated in the Department of Animal Husbandry) manufactured by Canon U.S.A., Inc., Long Island, New York; while the F-values for significance tests were obtained from Steel and Torrie (1960).

The design and computational formulae developed by Canon Inc., for the three-way analysis of variance is in Appendix D.

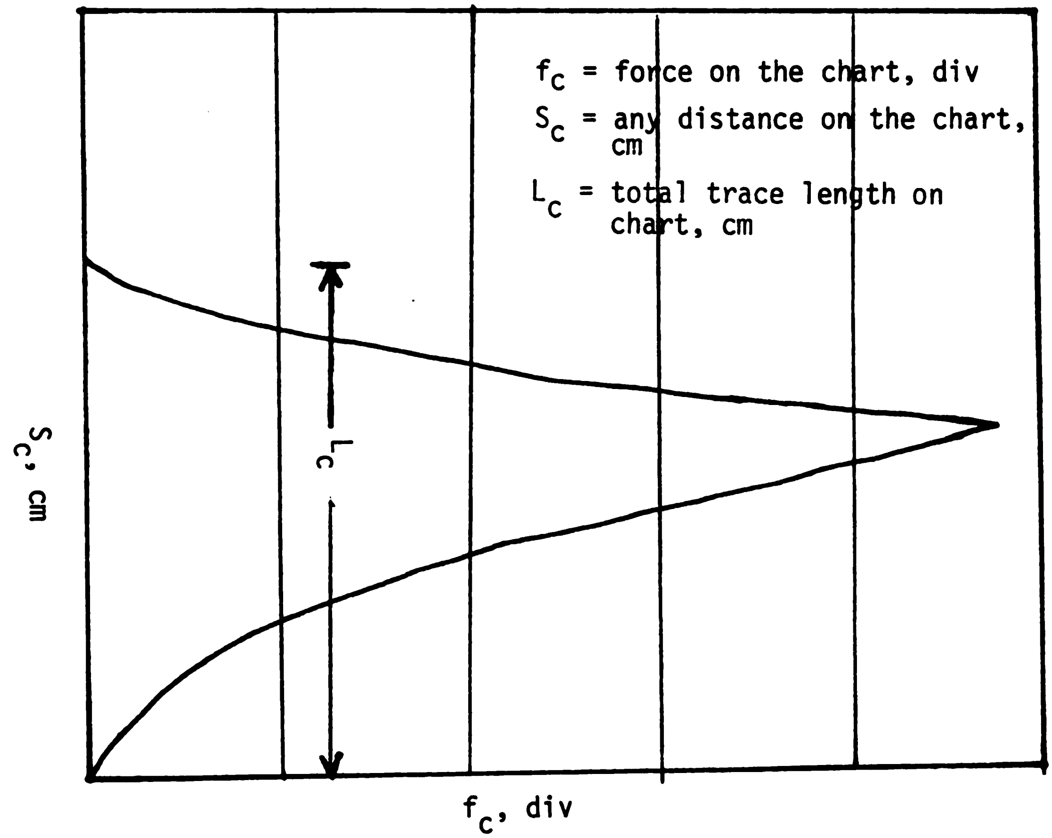


Figure 4.8.3: Typical Force - displacement curve of beans compressed at 50 cm/min with the Instron.

5. RESULTS AND DISCUSSION

5.1 Introduction

The process parameters that favored maximum utilization of vacuum-induced hydration were found after analysis of data from the bench scale experiments while the effect of vacuum-induced hydration on physical properties of processed beans was found from the large scale experiments. It was observed from random samples in both sets of experiments that vacuum-induced hydration did not cause any appreciable increase in the percent splits (represented by the percent ratio of split beans to the initial number of dried beans) after the soaking phase.

5.2 Effect of Experimental Variables During Soaking Phase on Water Intake and Softening of Beans

The hydration curves obtained by plotting the moisture content (decimal dry basis) of beans against soaking time are illustrated by Figures 5.2.1 through 5.2.5 for the bench scale experiments. It can be seen from each of these figures that increasing the level of vacuum treatment imposed on any type of beans prior to soaking in water led to a steepening of the hydration curve due to a statistically significant increase in the amount of moisture absorbed over the same period of time. Due to some operational limitations on the part of each of the experimental vacuum pumps used in this study, the highest

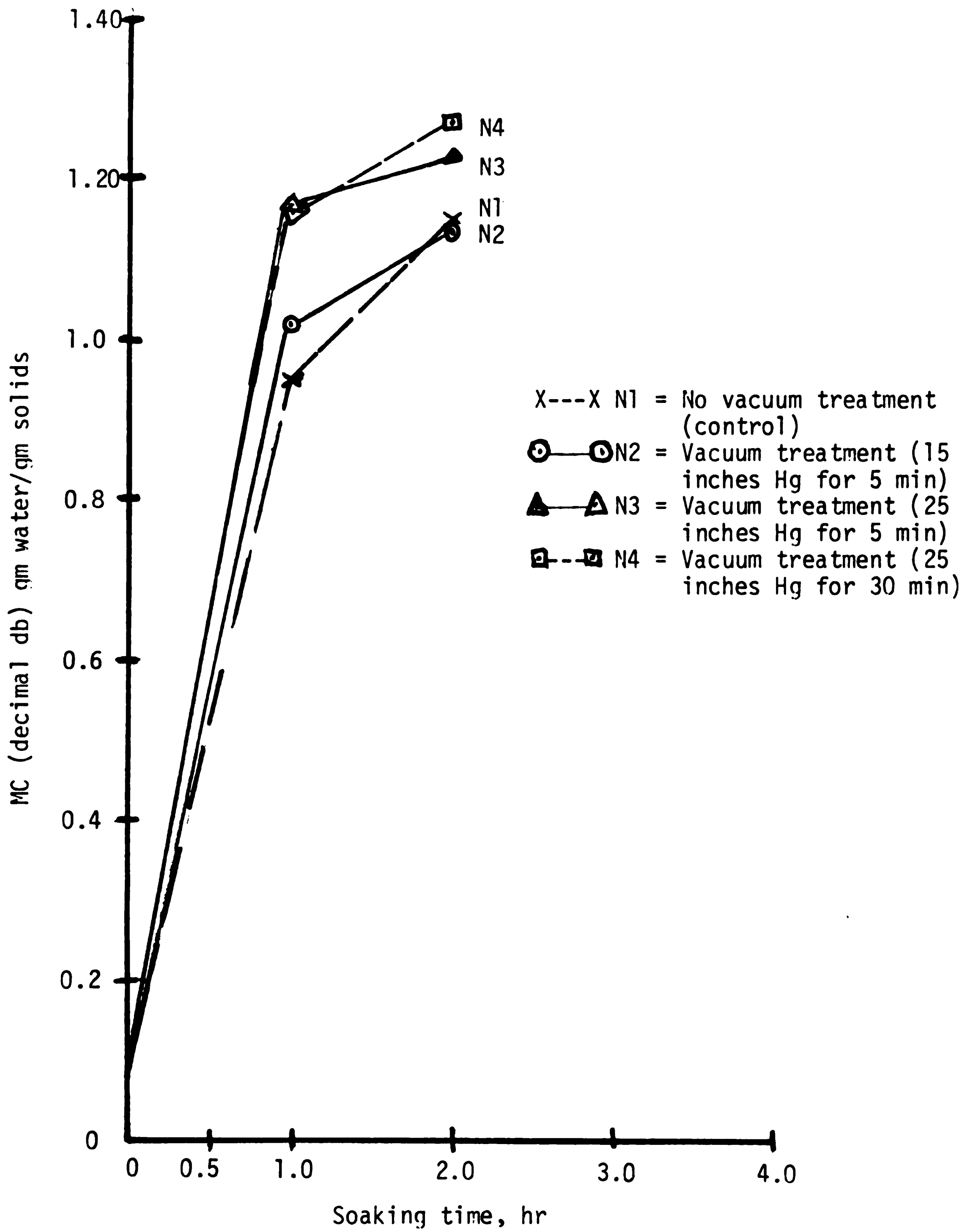


Figure 5.2.1: Hydration curves of navy beans subjected to vacuum treatments and control during the soaking phase of bench scale experiments.

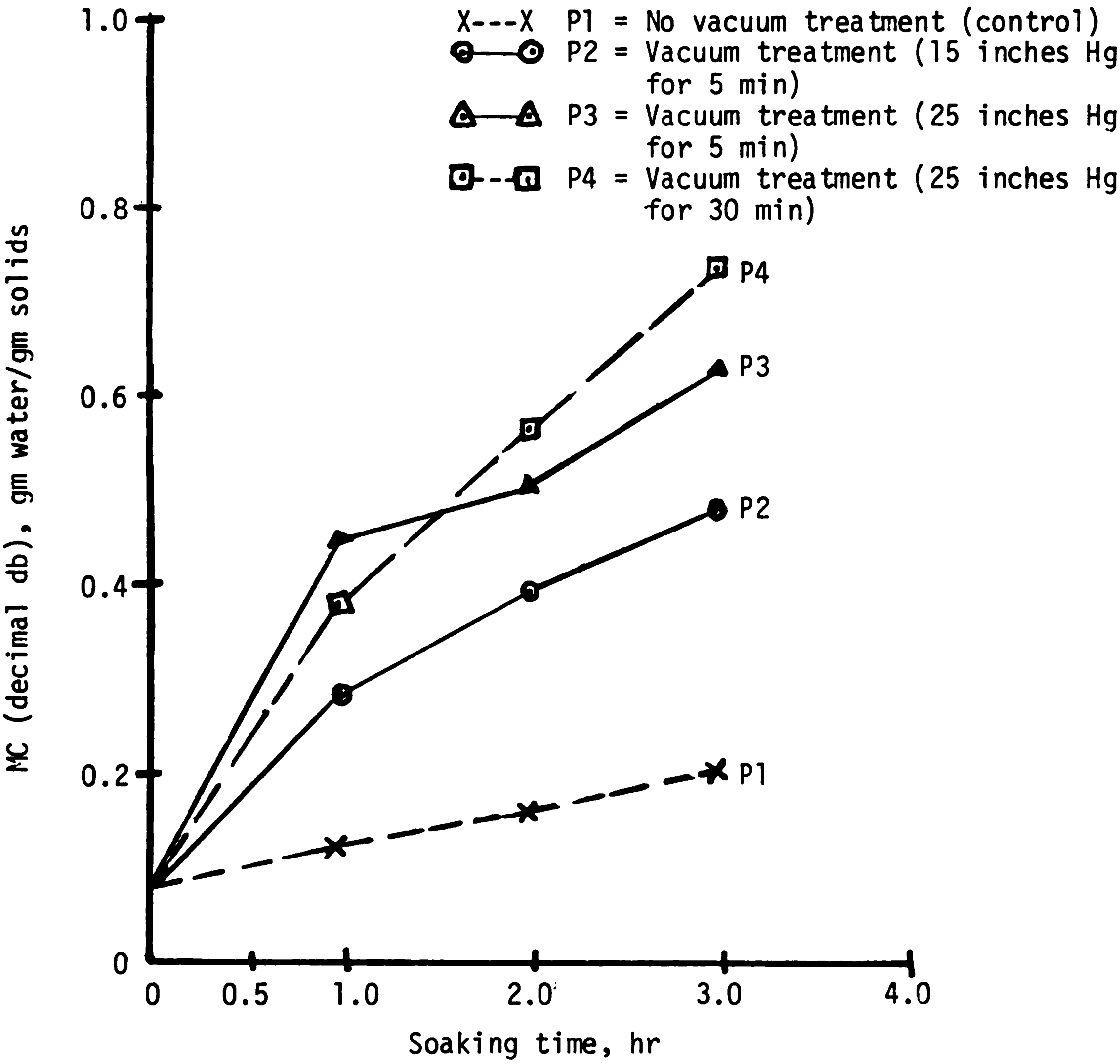


Figure 5.2.2: Hydration curves of pinto beans subjected to vacuum treatments and control during the soaking phase of bench scale experiments.

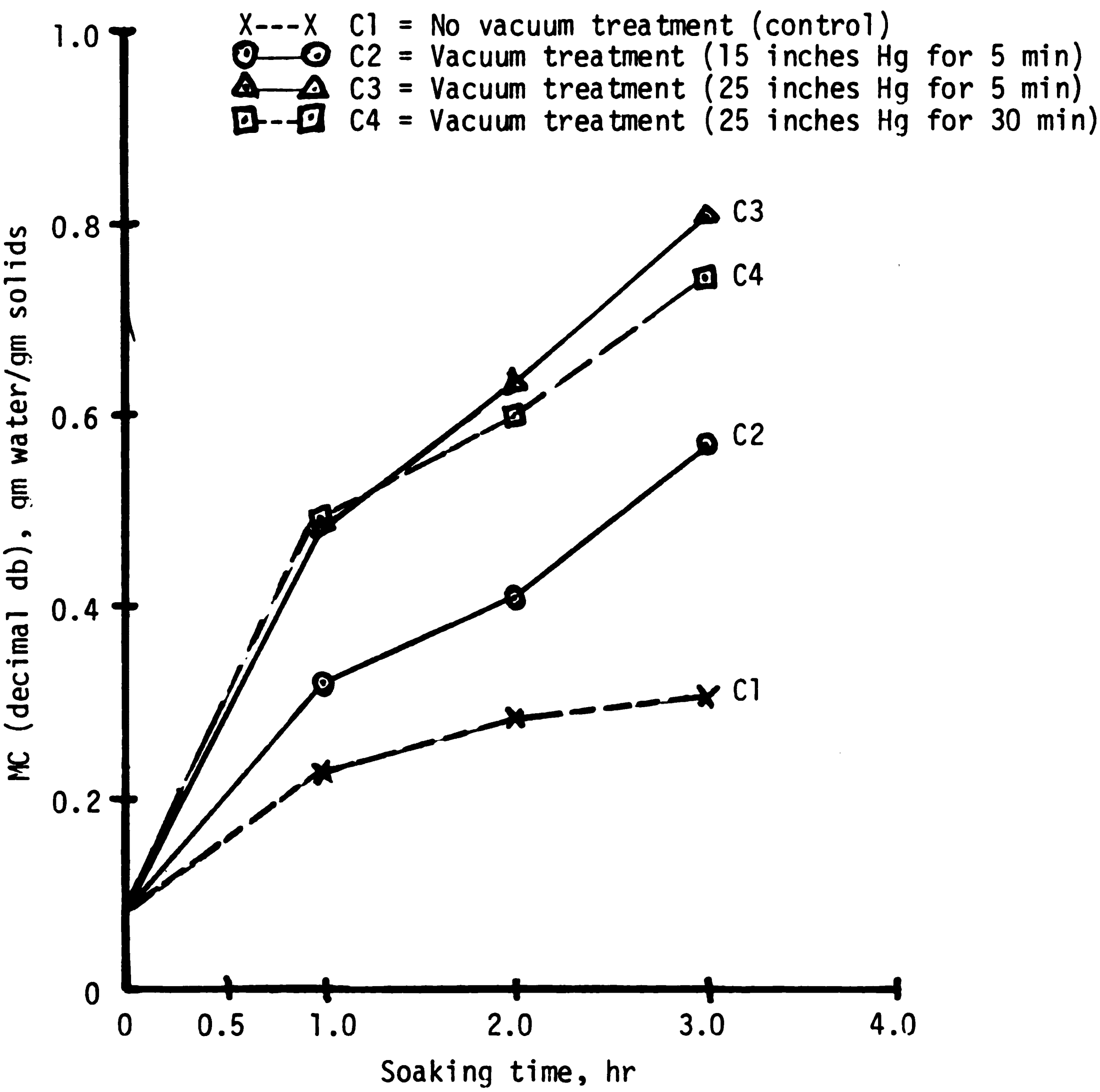


Figure 5.2.3: Hydration curves of cranberry beans subjected to vacuum treatments and control during the soaking phase of bench scale experiments.

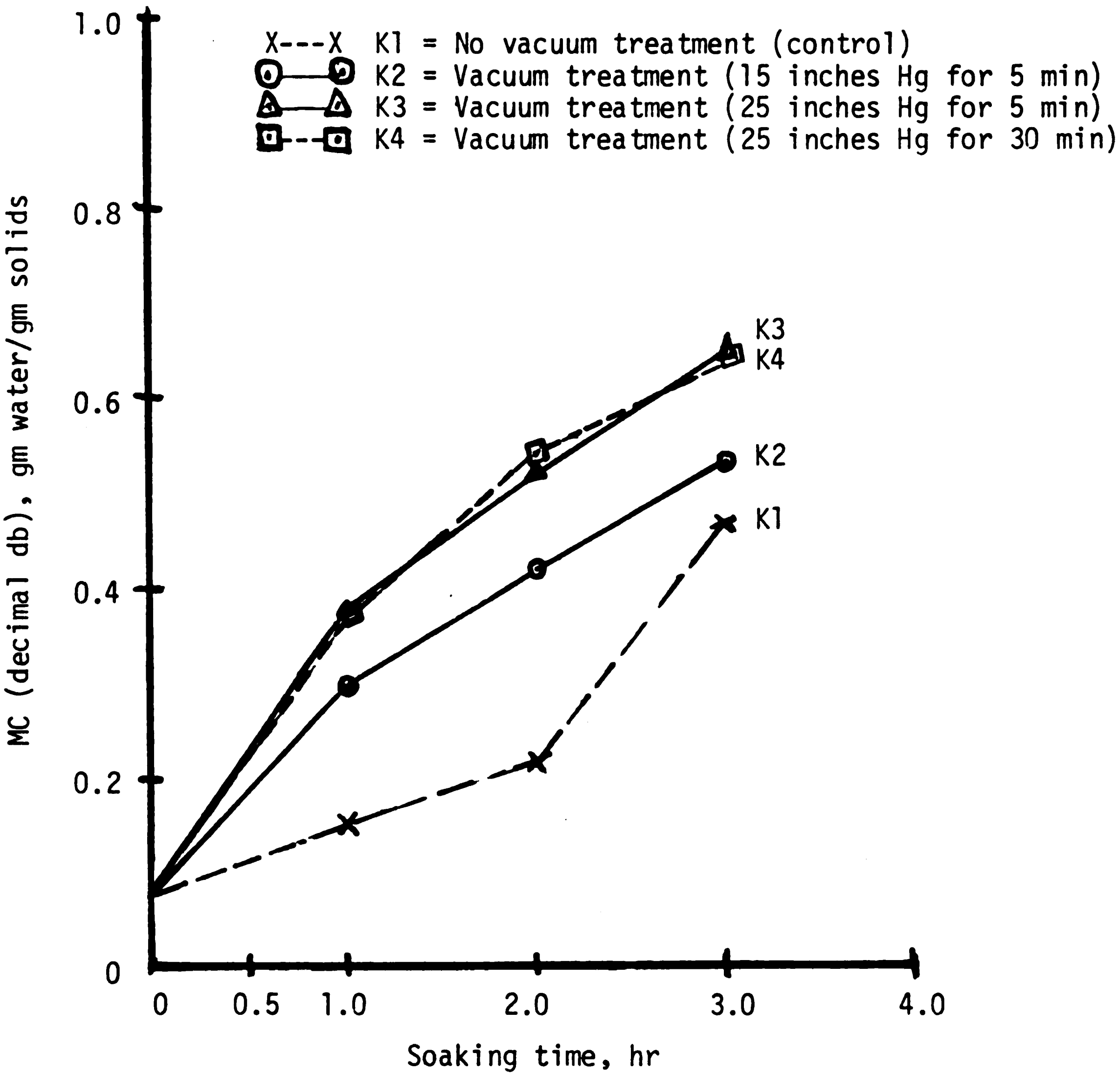


Figure 5.2.4: Hydration curves of kidney beans subjected to vacuum treatments and control during the soaking phase of bench scale experiments.

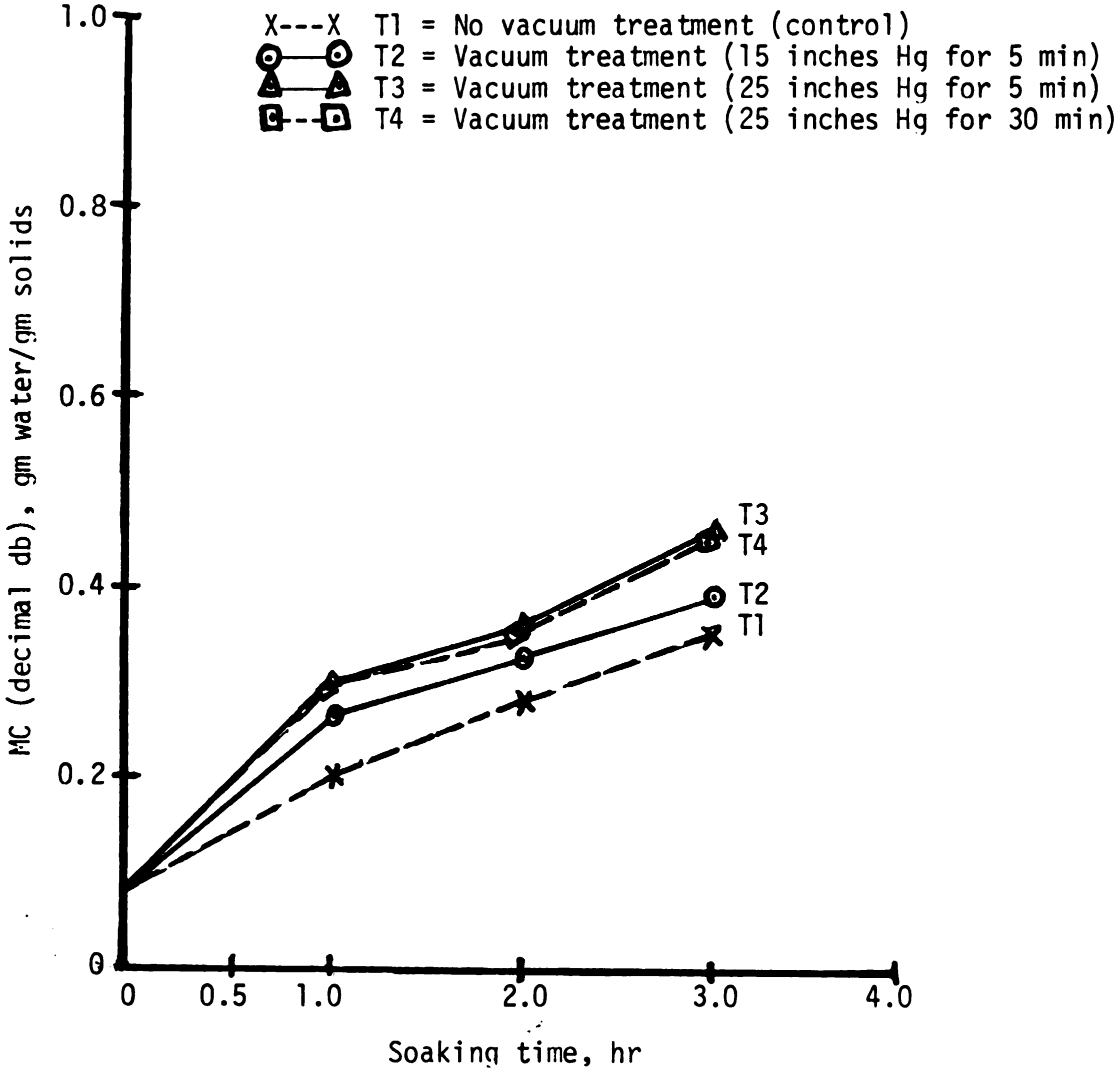


Figure 5.2.5: Hydration curves of black turtle soup beans subjected to vacuum treatments and control during the soaking phase of bench scale experiments.

levels of vacuum treatment imposed on the beans were 25 inches Hg (84.42 kPa) and 24 inches Hg (81.04 kPa) during the bench scale and large scale experiments respectively.

Table 5.2.1 similarly shows that increasing the level of vacuum treatment (represented by work done) imposed on beans during the bench scale experiments led to an increase in the rate of water intake as represented by the average effective diffusivity (D_{eff}) which was determined using the procedure outlined in Section 3.3. The predictive equations in Table 5.2.2 for describing the relationship between the two parameters (work done and D_{eff}) were derived by linear regression analysis. It can be seen from these predictive equations that the dependence of D_{eff} on work is greatest for navy beans, followed in decreasing order by cranberry, pinto, kidney and turtle soup beans. The values of D_{eff} for navy beans in Table 5.2.1 are also considerably higher than any corresponding value for the other types of beans. This difference could be attributed to the method used in drying the harvested bean seeds for there were more visible cracks observed in the navy bean samples prior to experimentation, than in any of the other four types of bean samples. The drying and subsequent hydration of the navy beans might have led to the formation of internal cavities which then caused the irregularities or high rates of water intake as previously observed by Shull and Shull (1932) for peas and corn grains.

Varying the period of time that beans were kept under different levels of vacuum did not cause any statistically significant changes in the physical characteristics (% weight gain and % moisture content). This fact is also evident in Figures 5.2.1 through 5.2.5 for the bench scale experiments, from where it can be seen that the hydration curves

Table 5.2.1: Effect of level of vacuum or work done during the vacuum treatment on the moisture content (decimal db) and effective diffusivity (D_{eff}), for the soaking phase of beans in the bench scale experiments.

Type of Beans	Level of Vacuum (inches of Hg.)	Work (kJ/g-mole)	M.C. (decimal db), gm. water/gm. solids after soaking					D_{eff} (m^2/hr) x 10^6
			No soak	1 hr soak	2 hr soak	3 hr soak	24 hr soak	
Navy	0	0	0.08	0.95	1.15	--	1.24	4.09
	15	1.72	0.08	1.04	1.17	--	1.24	4.53
	20	2.72	0.08	1.11	1.18	--	1.24	4.78
	25	4.44	0.08	1.17	1.25	--	1.24	7.67
Pinto	0	0	0.08	0.12	0.16	0.20	1.24	0.12
	15	1.72	0.08	0.30	0.38	0.50	1.24	0.50
	20	2.72	0.08	0.35	0.46	0.53	1.24	0.56
	25	4.44	0.08	0.41	0.54	0.68	1.24	0.81
Cranberry	0	0	0.08	0.23	0.28	0.31	1.22	0.27
	15	1.72	0.08	0.36	0.45	0.57	1.22	0.68
	20	2.72	0.08	0.41	0.56	0.63	1.22	0.81
	25	4.44	0.08	0.48	0.61	0.78	1.22	1.13
Kidney	0	0	0.08	0.16	0.22	0.47	1.36	0.50
	15	1.72	0.08	0.30	0.42	0.51	1.36	0.59
	20	2.72	0.08	0.33	0.51	0.59	1.36	0.75
	25	4.44	0.08	0.38	0.53	0.65	1.36	0.84
Turtle Soup	0	0	0.08	0.21	0.28	0.35	1.24	0.29
	15	1.72	0.08	0.27	0.31	0.39	1.24	0.33
	20	2.72	0.08	0.29	0.34	0.41	1.24	0.37
	25	4.44	0.08	0.30	0.36	0.46	1.24	0.43

Table 5.2.2: Mathematical expressions relating effective diffusivity (D_{eff}) to work done during vacuum-induced hydration of various beans in bench scale experiments.

Type of beans	Predictive equation
Navy	$D_{eff} = (3.54 + 0.78W) \times 10^{-6}$
Pinto	$D_{eff} = (0.16 + 0.15W) \times 10^{-6}$
Cranberry	$D_{eff} = (0.30 + 0.19W) \times 10^{-6}$
Kidney	$D_{eff} = (0.49 + 0.08W) \times 10^{-6}$
Turtle soup	$D_{eff} = (0.28 + 0.03W) \times 10^{-6}$

for vacuum treatment of 25 inches Hg for both 5 minutes and 30 minutes duration are sometimes indistinguishable from each other, thereby signifying no clear-cut differences in the rates of water intake by beans, between small and large periods of time for vacuum treatment.

The above-mentioned results clearly show the effectiveness of subjecting dry beans soaked in water to very high levels of vacuum for short periods of time (i.e., high vacuum short time treatment) in accelerating the rate of water intake by beans. This optimized procedure would greatly reduce the soaking time for dry beans. This procedure would also represent an improvement over the low vacuum levels that were applied for considerably longer times by some previous workers (Hoff and Nelson, 1965; Rockland and Metzler, 1967). These workers had reported that vacuum treatment aided the removal of gases from either the pores or surfaces of bean tissues, thereby leading to greater imbibition of water by these tissues followed by an increase in the rate of water entry through the hilum and testa into the interior of seeds.

The values of D_{eff} for various types of beans which were obtained from data on the soaking phase of the large scale experiments can be found in Table 5.2.3. These values are not greatly different from each other, unlike the values in Table 5.2.1 which were obtained during the bench scale experiments; and this closeness in values may be due to the fact that the beans used during the large scale experiments were commercially dried in elevators and had less visible cracks than beans used during the bench scale experiments. Table 5.2.4 contains predictive equations derived by linear regression analysis for describing the relationship between work done during vacuum-induced hydration and

Table 5.2.3: Effect of level of vacuum or work done during the vacuum treatment on the moisture content (decimal db), effective diffusivity (D_{eff}) and softening rate constants for the soaking phase of beans in the large scale experiments.

Parameter determined		Type of beans and level of vacuum						
		Navy			Pinto		Kidney	
		0" Hg	20" Hg	24" Hg	0" Hg	24" Hg	0" Hg	24"Hg
Work done (kJ/g-mole)		0	2.72	3.99	0	3.99	0	3.99
M.C. (decimal db), gm. water gm. solids	0 hr soak	0.12	0.12	0.12	0.16	0.16	0.16	0.16
	½ hr soak	0.76	0.82	0.90	0.35	1.05	0.43	0.67
	1 hr soak	0.92	0.93	1.04	0.39	1.11	0.68	1.04
	2 hr soak	1.04	1.05	1.09	0.66	1.23	0.99	1.19
	3 hr soak	1.10	1.13	1.14	0.93	1.30	1.20	1.32
	24 hr soak	1.25	1.25	1.25	1.33	1.33	1.35	1.35
$D_{eff}(m^2/hr)x10^6$		1.98	2.14	2.15	1.18	3.75	2.93	5.18
Softening rate constant for compressive force (K_f, hr^{-1})		0.350	0.370	0.371	0.268	0.282	0.337	0.360
Softening rate constant for compressive work (K_w, hr^{-1})		0.259	0.273	0.287	0.171	0.195	0.190	0.204

Table 5.2.4: Mathematical expressions relating effective diffusivity (D_{eff}) to work done during vacuum-induced hydration of various beans in large scale experiments.

Type of beans	Predictive equation
Navy	$D_{eff} = (1.99 + 0.05W) \times 10^{-6}$
Pinto	$D_{eff} = (1.18 + 0.64W) \times 10^{-6}$
Kidney	$D_{eff} = (2.93 + 0.56W) \times 10^{-6}$

Table 5.2.5: Mathematical expressions relating softening rate constants to work done and effective diffusivity (D_{eff}) during vacuum-induced hydration in large scale experiments.

Type of beans	Predictive equations	
Navy	$K_f = 0.351 + 0.006W$;	$K_f = 0.110 + 0.039\ D_{eff}$
	$K_w = 0.258 + 0.007W$;	$K_w = 0.006 + 0.041\ D_{eff}$
Pinto	$K_f = 0.268 + 0.004W$;	$K_f = 0.261 + 0.002\ D_{eff}$
	$K_w = 0.171 + 0.006W$;	$K_w = 0.160 + 0.003\ D_{eff}$
Kidney	$K_f = 0.337 + 0.006W$;	$K_f = 0.307 + 0.010\ D_{eff}$
	$K_w = 0.190 + 0.004W$;	$K_w = 0.170 + 0.003\ D_{eff}$

D_{eff}. It can be seen from these predictive equations that the dependence of D_{eff} on work is greatest for pinto beans, followed in decreasing order by kidney and navy beans. This trend in Table 5.2.4 is different from that found in Table 5.2.2, and this difference may be due to inherent variation in the efficiencies of the vacuum pumps used in this study coupled with the methods for drying the harvested beans prior to experimentation.

Table 5.2.3 also contains the values of the two softening rate constants (K_f and K_w) which were determined using the procedure outlined in Section 3.4. K_f and K_w represent the softening rate constants derived from the mechanical properties denoted by maximum peak compressive force and compressive work respectively. Table 5.2.5 contains the predictive equations derived by linear regression analysis for describing the relationships between K_f or K_w and each of D_{eff} and work done during vacuum-induced hydration. It can be seen from these mathematical expressions that increase in either the work done during vacuum treatment or D_{eff} leads to an increase in each of K_f and K_w. Since an increase in work done during vacuum treatment also leads to an increase in D_{eff} as discussed above in this section, then the postulate suggested in Section 3.1 which states that the greater the level of vacuum pulled during vacuum-induced hydration, the faster should be the rate of water intake followed by an increase in the softening rate of processed beans is really true.

5.3 Changes From Normal Physical Properties of Soaked Beans Due To Vacuum-Induced Hydration

The percent changes in the different physical properties of beans soaked in water under normal conditions (no vacuum treatment) that are caused by the incorporation of the highest vacuum treatment studied (i.e., 81.04 kPa) into the soaking phase during the large scale experiments can be found in Tables 5.3.1 and 5.3.2. These changes which consist of increases in % weight gain, % MC (wet basis), volume and anatomical dimensions (length, width and thickness) along with decreases in specific gravity and compressive force or work, diminish in magnitude with increase in soaking time.

Similarly, Figure 5.3.1 illustrates that the percent differences between the hydration curves for some beans (subjected to no vacuum treatment and vacuum treatment at 81.04 kPa) which are greatest at a soaking time of 30 minutes, generally decrease with increase in soaking time. This trend of decrease in percent change of moisture content with increase in soaking time may be due to the increasing satisfaction of the forces causing hydration of the bean tissue as the soaking phase progresses.

The changes over the values of D_{eff} (from Table 5.2.3) for normally soaked beans due to vacuum-induced hydration at 81.04 kPa are increases of 9%, 218% and 77% for navy, pinto and kidney beans respectively; thereby indicating that pinto beans benefit the most from vacuum-induced hydration, followed by kidney and navy beans in decreasing order.

5.4 Changes From Normal Physical Properties of Canned Beans Due To Vacuum-Induced Hydration During Soaking Phase of Large Scale Experiments

The percent changes in some physical properties of canned beans (that had undergone normal soaking) due to the incorporation of the highest vacuum treatment studied (i.e., 81.04 kPa) into the soaking

Table 5.3.1: Percent deviations from normal physical properties of soaked beans attributable to vacuum-induced hydration at 24 inches Hg (81.04 KPa) during large scale experiments.

Physical Property		Type of Beans		
		Navy	Pinto	Kidney
% increase in % weight gain	0.5 hr soak	20.58	349.27	98.67
	1 hr soak	9.31	272.89	54.26
	2 hr soak	6.75	96.68	25.62
	3 hr soak	5.34	51.54	14.20
% increase in % MC (wet basis).	0.5 hr soak	10.16	99.10	34.24
	1 hr soak	5.83	87.00	25.71
	2 hr soak	2.27	38.67	11.20
	3 hr soak	1.66	17.46	4.27
% decrease in specific gravity.	0.5 hr soak	0.42	7.91	1.88
	1 hr soak	1.52	7.98	5.59
	2 hr soak	1.19	4.12	2.70
	3 hr soak	0.52	1.86	0.43
% decrease in maximum peak compressive force per gm of beans.	0.5 hr soak	5.22	14.65	16.88
	1 hr soak	8.12	16.21	17.81
	2 hr soak	10.54	9.28	3.27
	3 hr soak	6.25	8.61	2.99

Table 5.3.2: Percent deviations from normal physical properties of soaked beans attributable to vacuum-induced hydration at 24* inches Hg (81.04 kPa) during large scale experiments.

Physical property		Type of beans		
		Navy	Pinto	Kidney
% increase in volume	0.5 hr soak	6.18	64.92	23.51
	1 hr soak	4.55	62.44	23.50
	2 hr soak	1.94	27.64	9.80
	3 hr soak	0.90	20.66	5.34
% increase in length	0.5 hr soak	1.08	10.68	5.23
	1 hr soak	1.29	16.74	8.35
	2 hr soak	1.92	19.06	6.84
	3 hr soak	2.27	2.03	5.57
% increase in width	0.5 hr soak	0.56	10.21	3.60
	1 hr soak	2.84	11.71	8.52
	2 hr soak	2.67	10.79	7.26
	3 hr soak	2.12	3.79	1.86
% increase in thickness	0.5 hr soak	0.30	17.33	10.12
	1 hr soak	1.15	19.83	17.22
	2 hr soak	3.07	17.52	8.53
	3 hr soak	1.43	9.89	2.99

*Vacuum-induced hydration for navy beans was at 20 inches Hg (67.54 kPa).

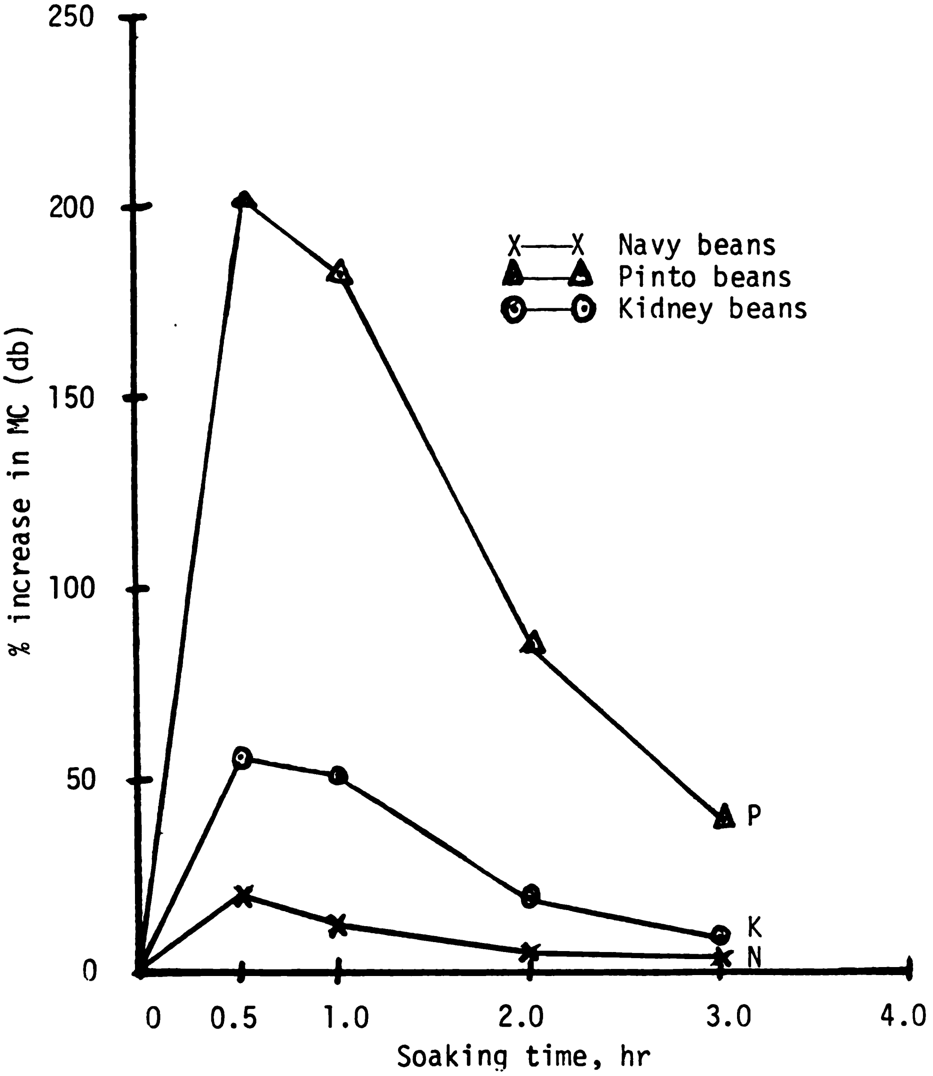


Figure 5.3.1: Variation of % increase in MC (db) of soaked beans attributable to vacuum-induced hydration at 24 inches Hg (81.04 kPa) with soaking time during the soaking phase of large scale experiments

phase of the large scale experiments can be found in Tables 5.4.1, 5.4.2 and 5.4.3. These changes consist of increases in % weight gain and % MC (wet basis), and decreases in mechanical properties represented by maximum peak compressive force and compressive work. It can also be seen from these three tables that in general, when the soak time is kept constant, the percent changes in physical properties diminish in magnitude with increase in cooking time.

Similarly, Figure 5.4.1 illustrates that the percent differences between the hydration curves for some canned beans (subjected to no vacuum treatment and vacuum treatment at 81.04 kPa) with a 30-minute soak period, diminish very rapidly within the first 15 minutes of cooking and gradually between 15 and 45 minutes of cooking. It can also be seen from the figure that 45 minutes of cooking time would cause no difference between the hydration curves for normal hydration and vacuum-induced hydration in the case of navy beans, and a very slight difference in the case of kidney beans while the difference would still be substantial in the case of pinto beans.

An inspection of the values in Tables 5.3.1 through 5.4.3 and Figure 5.4.1 reveals that greater changes in physical properties which are due to vacuum-induced hydration occur during the soaking phase than during the retorting phase of canning beans.

5.5 Elimination of the Use of Soaking Tanks

The experimental set-up developed in this study for the incorporation of vacuum-induced hydration into the soaking phase allowed the entire canning process (consisting of soaking and retorting phases) in cans; thereby eliminating the use of soaking tanks that are presently used in the food industry for soaking dry beans prior to retorting.

Table 5.4.1: Percent deviations from normal physical properties of canned navy beans attributable to vacuum-induced hydration at 24 inches Hg (81.04 kPa) during the large scale experiments.

Physical property		Soak time 0.5 hr	1 hr	2 hr	3 hr
% increase in % weight gain	15 min cook	5.06	1.99	0.82	2.24
	30 min cook	1.60	0.79	0.68	0.25
	45 min cook	1.41	0.06	0.29	0.00
% increase in % MC (wb)	15 min cook	1.08	0.32	0.34	1.05
	30 min cook	1.17	0.63	0.10	0.96
	45 min cook	0.10	0.00	0.31	0.46
% decrease in maximum peak compressive force per gm of beans	15 min cook	2.27	3.17	3.21	0.75
	30 min cook	1.59	2.65	1.66	1.39
	45 min cook	0.17	0.73	2.41	1.15
% decrease in compressive work per gm of beans	15 min cook	1.59	1.63	2.23	2.31
	30 min cook	1.61	1.68	2.29	2.37
	45 min cook	1.32	2.09	2.25	1.83

Table 5.4.2: Percent deviations from normal physical properties of canned pinto beans attributable to vacuum-induced hydration at 24 inches Hg (81.04 kPa) during the large scale experiments.

Physical property		Soak time 0.5 hr	1 hr	2 hr	3 hr
% increase in % weight gain	15 min cook	7.28	8.56	7.12	5.68
	30 min cook	5.41	5.60	6.69	6.44
	45 min cook	2.93	3.81	3.84	3.07
% increase in % MC (wb)	15 min cook	3.75	3.57	3.23	2.09
	30 min cook	2.06	2.58	2.44	1.92
	45 min cook	1.34	1.18	1.15	1.04
% decrease in maximum peak compressive force per gm of beans	15 min cook	3.71	4.51	7.05	3.53
	30 min cook	2.12	1.55	3.61	3.01
	45 min cook	0.99	1.39	2.49	2.09
% decrease in compressive work per gm of beans	15 min cook	1.21	4.41	5.21	4.50
	30 min cook	4.65	7.93	7.27	3.65
	45 min cook	1.03	4.50	2.47	1.82

Table 5.4.3: Percent deviations from normal physical properties of canned kidney beans attributable to vacuum-induced hydration at 24 inches Hg (81.04 kPa) during the large scale experiments.

Physical property		Soak time			
		0.5 hr	1 hr	2 hr	3 hr
% increase in % weight gain	15 min cook	2.96	2.23	3.86	3.68
	30 min cook	4.01	3.49	4.09	4.36
	45 min cook	3.36	2.12	2.13	1.42
% increase in % MC (wb)	15 min cook	1.64	1.31	1.91	1.93
	30 min cook	0.37	0.92	1.55	0.69
	45 min cook	0.34	0.23	0.67	0.33
% decrease in maximum peak compressive force per gm of beans	15 min cook	1.31	5.70	4.24	5.13
	30 min cook	1.71	5.29	4.56	0.74
	45 min cook	0.68	5.76	1.62	1.20
% decrease in compressive work per gm of beans	15 min cook	3.70	5.22	1.51	1.52
	30 min cook	2.68	3.48	1.05	0.63
	45 min cook	0.73	2.16	1.49	1.09

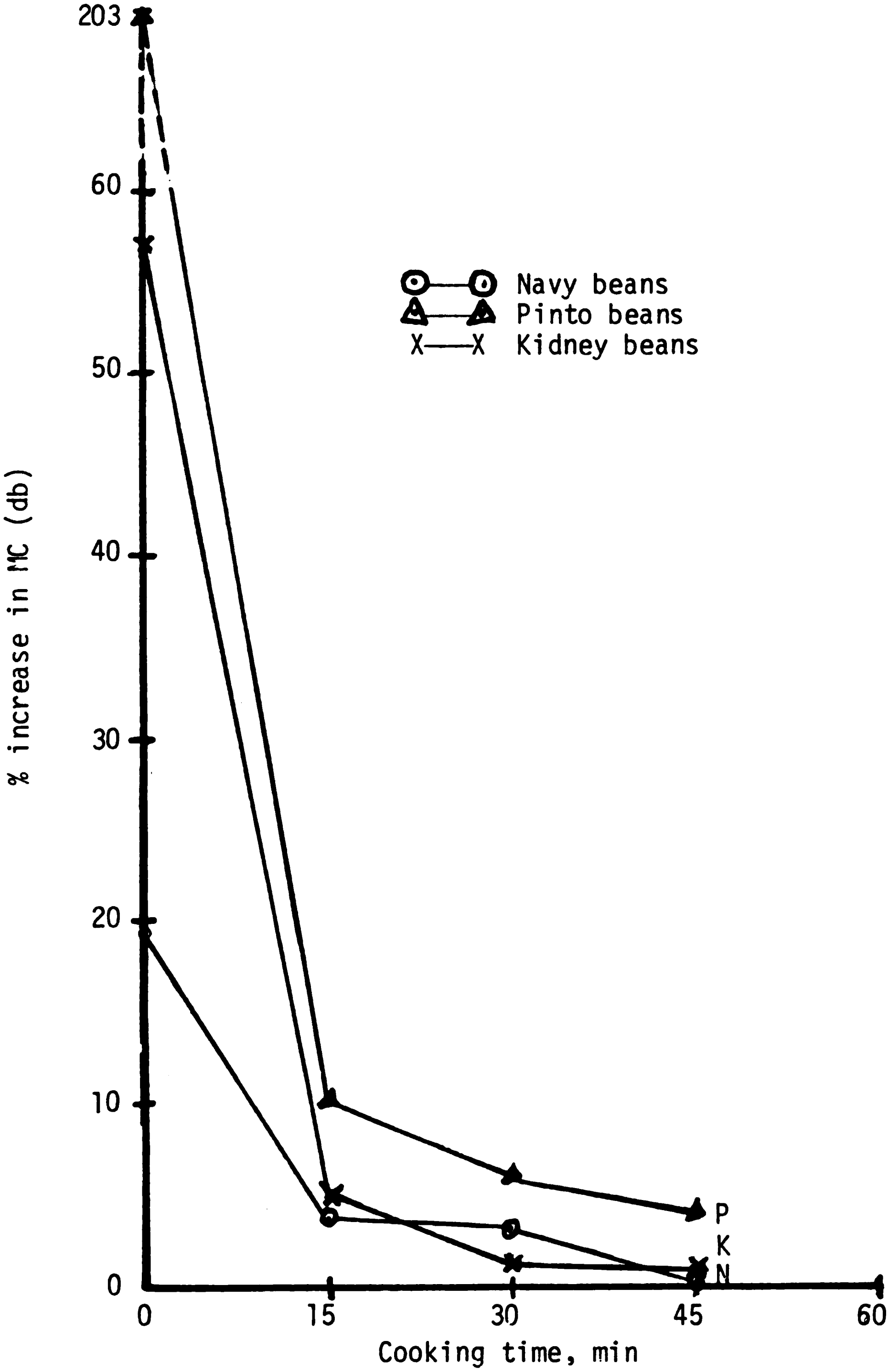


Figure 5.4.1: Variation of % increase in MC (db) of cooked beans attributable to vacuum-induced hydration (81.04 kPa and 30 minute soak-period) with cooking time during the retorting phase of large scale experiments.

Soaking in cans could lead to a short, continuous process that would help to reduce labor cost and increase industrial plant flexibility because less extensive equipment and valuable floor space will be required for the entire canning operation.

6. CONCLUSIONS

The following conclusions have been drawn from this study:

1. Increasing the level of vacuum (represented by work done) on beans during vacuum-induced hydration at constant temperature leads to a significant increase in the rate of water intake (represented by the average effective diffusivity) followed by an increase in the index of texture (represented by any of the two softening rate constants).
2. The dependence of the average effective diffusivity on work done during vacuum-induced hydration in the large scale experiments is greatest for pinto beans, followed in decreasing order by kidney and navy beans.
3. Varying the period of time for keeping beans under different levels of vacuum does not cause any significant change either in the % weight gain or % moisture content of the soaked beans.
4. The application of a high vacuum for a very short period of time is the most effective treatment in bringing about vacuum-induced hydration of beans.
5. Vacuum-induced hydration causes increases in % weight gain, % moisture content, volume and anatomical dimensions along with decreases in specific gravity and compressive force or work over values for normally soaked beans; these changes however, diminish in magnitude with increase in soaking time.

6. Vacuum-induced hydration causes increases in % weight gain and % moisture content along with decreases in compressive force or work over normally soaked and retorted beans; these changes at a constant soak time however, diminish in magnitude with increase in cooking time.
7. The magnitude of the changes in physical properties of processed beans due to vacuum-induced hydration are greater during the soaking phase than during the retorting phase of canning beans.
8. Beans can be subjected to the vacuum treatment and also left to soak directly in enameled cans, thereby eliminating the use of soaking tanks.

7. RECOMMENDATIONS FOR FURTHER STUDIES

1. It would be desirable to evaluate, in depth, basic thermal processing parameters needed to ensure a commercially sterile product, when vacuum induced hydration is utilized during the soaking phase of canning beans.
2. A computer program for parameter estimation would be needed to obtain and subsequently evaluate the accuracy of estimates of the thermal processing parameters mentioned in Number 1 above.
3. Results from objective and subjective methods for analysis of food texture should be compared with each other.

APPENDICES

APPENDIX A

ANATOMY OF A LEGUMINOUS SEED

APPENDIX A

According to Corner (1951), the leguminous seed is generally of medium or large size, more or less compressed and exalbuminous, with a large inner embryo and an outer hard, dry and smooth testa (or seedcoat).

The testa consists of three layers: the outer epidermis; the hypodermis; and the inner mesophyll. The epidermis consists of closely packed palisade cells, whose long axes are perpendicular to the surface of the seed. There is a layer of cuticle on the outer wall of the palisade cells. The hypodermis consists of sclerenchyma and "hour glass" or "pillar" cells, while the mesophyll consists of thin-walled and flattened parenchyma cells.

The seedcoat is marked by a distinct scar, known as the hilum, which also has a tiny hole, known as micropyle, at one of its ends. Figure A-1 illustrates the anatomy of the seedcoat in the region of the hilum. In contact with the cuticle of the epidermis is the counter-palisade layer, which is also composed of cells elongated in the direction perpendicular to the surface of the seed. Overlying the counter-palisade layer is parenchyma with large intercellular spaces. Both palisade and counter-palisade are interrupted along the mid-line by a very fine groove (the median or hilar groove). The groove is an air-passage in the ripe seed. The groove leads to the tracheid bar, which in the sub-hilum, is a rod of short tracheids extending the length of the hilum, from raphe almost to micropyle (see Figure A-2).

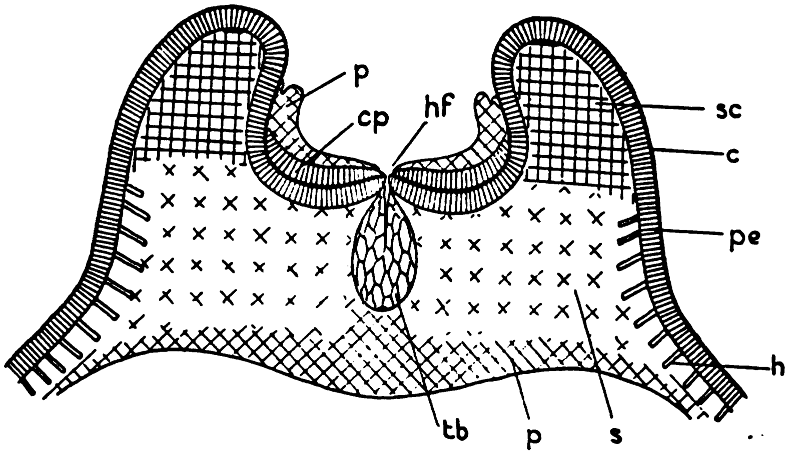


Figure A-1: Transmedian longitudinal section of the hilum and adjacent tissues in the seed-coat of a leguminous seed. *p*, parenchyma; *cp*, counter-palisade; *hf*, hilar fissure; *sc*, sclerenchyma; *c*, cuticle; *pe*, palisade epidermis; *h*, sub-epidermal layer of 'hour glass' or 'pillar' cells; *s*, stellate cells; *tb*, tracheid bar.

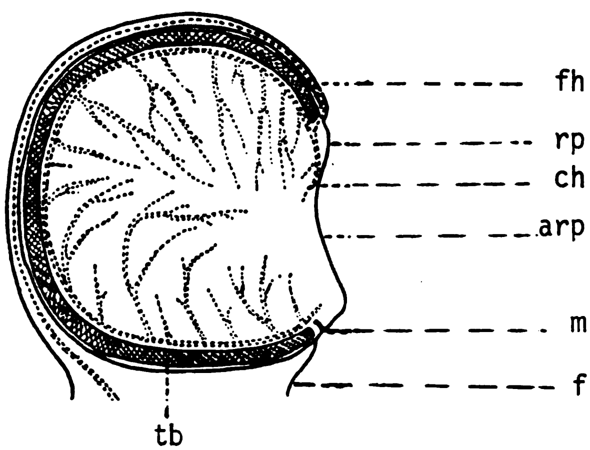


Figure A-2: Longitudinal section of the leguminous seed to show the elongate hilum with long tracheid bar (hatched) and the vascular supply to one side of the seed from the recurrent vascular bundle. *arp*, antiraphe; *ch*, chalaza; *f*, funicle; *fh*, funicle-head; *m*, micropyle; *rp*, raphe; *tb*, tracheid bar.

The embryo consists of two large fleshy cotyledons, a plumule with two well-developed primary leaves, and a hypocotyl radicle axis that rests in a shallow depression formed by the cotyledons.

Analytically, the legume seed may be considered as a composite body, consisting of a central spherical core of two hemispheres (the cotyledons), surrounded by an outer concentric shell, the seedcoat.

APPENDIX B

RELATIONSHIP BETWEEN MOISTURE CONTENT'S WET AND DRY BASIS VALUES

APPENDIX B

MOISTURE CONTENT

Two different ways of expressing the moisture content of foods are: 1) moisture content, wet basis ≡ M_{wb} and 2) moisture content, dry basis ≡ m_{db}.

M_{wb} moisture content, wet basis, is more commonly encountered than moisture content, dry basis. As a percentage it is sometimes called the "commercial" or "as is" basis.

M_{db} moisture content, dry basis, is widely used in theoretical or applied studies of keeping quality as a function of moisture content and in applied or theoretical studies of drying rates.

The conversion formulae from one form to the other are as follows:

$$M_{wb} = m_{db}/(1+m_{db}) \quad (B.1)$$

$$m_{db} = M_{wb}/(1-M_{wb}) \quad (B.2)$$

Note: a) Equations are entered with fractions, not percentage.

b) As a number, $M_{wb} \leq m_{db}$.

APPENDIX C

EXPERIMENTAL PROCEDURE FOR DETERMINATION OF SPECIFIC GRAVITY AND VOLUME OF BEANS

APPENDIX C

EXPERIMENTAL DETERMINATION OF SPECIFIC GRAVITY (S.G.) AND VOLUME OF BEANS

1. a) Weigh pycnometer when empty [W_1]

   b) Weigh pycnometer when filled with i) distilled water [W_2] and ii) toluene [W_3] at 20° C.

2. Weigh [W_4] about ten gms [W_4-W_1] of beans and place them in pycnometer with sufficient toluene to cover them.

3. Gradually exhaust the air from the pycnometer with a vacuum pump to promote the escape of the air trapped under the surface hairs and in the creases of the seeds or kernels.

4. When the air bubbles cease to be given off after several cycles of vacuuming and releasing the vacuum, fill the pycnometer with toluene and allow the temperature to reach 20° C.

5. Weigh [W_5] the pycnometer with its contents.

6. Calculate the specific gravity of the beans as follows:

$$\text{Specific gravity of bean} = \frac{\text{specific gravity of toluene} \times \text{wt of beans}}{\text{weight of toluene displaced by the beans}}$$

   The weight of toluene displaced by the beans is found by subtracting the difference in bottle weights when filled with toluene and when containing the beans, from the weight of the beans' sample.

7. $$\text{Volume of sample} = \frac{\text{wt of beans}}{\text{S.G. of beans}}$$

From above:

$$\text{S.G. toluene} = \frac{W_3-W_1}{W_2-W_1} \quad (C.1)$$

$$\text{S.G. beans} = \frac{\text{S.G. toluene} \times (W_4-W_1)}{[(W_4-W_1) - (W_5-W_3)]} \quad (C.2)$$

$$\text{Volume of beans} = \frac{W_4-W_1}{\text{S.G. beans}} \quad (C.3)$$

APPENDIX D

DESIGN AND COMPUTATIONAL FORMULAE FOR THREE WAY ANALYSIS OF VARIANCE

APPENDIX D

Table D-1: .Design for three-factor experiments (n observations per group).

	c_1				c_r		
	b_1	b_j	b_q	.....	b_1	b_j	b_q
	X_{1111}	X_{1j11}	X_{1q11}	.....	X_{11r1}	X_{1jr1}	X_{1qr1}
	⋮	⋮	⋮		⋮	⋮	⋮
a_1	X_{111m}	X_{1j1m}	X_{1q1m}	.....	X_{11rm}	X_{1jrm}	X_{1qrm}
	⋮	⋮	⋮		⋮	⋮	⋮
	X_{111n}	X_{1j1n}	X_{1q1n}	.....	X_{11rn}	X_{1jrn}	X_{1qrn}
	X_{1111}	X_{ij11}	X_{iq11}	.....	X_{i1r1}	X_{ijr1}	X_{iqr1}
	⋮	⋮	⋮		⋮	⋮	⋮
a_i	X_{i11m}	X_{ij1m}	X_{iq1m}	.....	X_{i1rm}	X_{ijrm}	X_{iqrm}
	⋮	⋮	⋮		⋮	⋮	⋮
	X_{i11n}	X_{ij1m}	X_{iq1n}	.....	X_{i1rn}	X_{kjrn}	X_{iqrn}
	X_{p111}	X_{pj11}	X_{pq11}	.....	X_{p1r1}	X_{prj1}	X_{pqr1}
	⋮	⋮	⋮		⋮	⋮	⋮
a_p	X_{p11m}	X_{pj1m}	X_{pq1m}	.....	X_{p1rm}	X_{pjrm}	X_{pqrm}
	⋮	⋮	⋮		⋮	⋮	⋮
	X_{p11n}	X_{pj1n}	X_{pq1n}	.....	X_{p1rn}	X_{pjrn}	X_{pqrn}

Where

1. X_{ijkm} represents an observation on subject m under treatment combination $a_i b_j c_k$ in group G_{ijk}.
   $i = 1,2,\ldots,p$; $j = 1,2,\ldots,q$
   $k = 1,2,\ldots,r$; $m = 1,2,\ldots,n$

2. Each group G_{ijk} contains n observations.

3. Each of the subjects in G_{ijk} is observed under q_r different treatment combinations, all these treatment combinations involving factor A at level a_i.

The Canon program printed out:

1. All the input data

2. The number of the data memories which were needed to run the program

3. Analysis of Variance table

4. F ratios together with degrees of freedom of denominator (df_2) to be used in making statistical tests on the hypotheses.

The following table contains most of the computational formulae used in the program:

Table D-2: Analysis of variance table for the effect of three-variables.

Source of variation	Sum of squares (SS)	Degree of freedom (df)
A	(c)-(a)	p-1
B	(d)-(n)=(j)	q-1
C	(e)-(a)=(k)	r-1
AB	(f)-(c)-(j)	(p-1)(q-1)
AC	(g)-(c)-(k)	(p-1)(r-1)
BC	(h)-(d)-(k)	(q-1)(r-1)
ABC	(i)-(f)-(g)+(c)-(1)	(p-1)(q-1)(r-1)
Experimental error	(b)-(i)	pqr(n-1)
Total	(b)-(a)	pqrn-1

Where

$$(a) = [\sum_{ijkm}\Sigma\Sigma\Sigma X_{ijkm}]^2/npqr \qquad (D.1)$$

$$(b) = \sum_{ijkm}\Sigma\Sigma\Sigma X^2_{ijkm} \qquad (D.2)$$

$$(c) = [\sum_{i}(\sum_{jkm}\Sigma\Sigma X_{ijkm})^2]/nqr \qquad (D.3)$$

$$(d) = [\sum_{j}(\sum\sum\sum_{ikm} X_{ijkm})^2]/npr \quad (D.4)$$

$$(e) = [\sum_{k}(\sum\sum\sum_{ijm} X_{ijkm})^2]/npq \quad (D.5)$$

$$(f) = [\sum\sum_{ij}(\sum\sum_{km} X_{ijkm})^2]/nr \quad (D.6)$$

$$(g) = [\sum\sum_{ik}(\sum\sum_{jm} X_{ijkm})^2]/nq \quad (D.7)$$

$$(h) = [\sum\sum_{jk}(\sum\sum_{im} X_{ijkm})^2]/np \quad (D.8)$$

$$(i) = [\sum\sum\sum_{ijk}(\sum_{m} X_{ijkm})^2]/n \quad (D.9)$$

The remaining formulae used were the following:

$$\text{Mean squares for each factor (MS)} = \frac{\text{Sum of squares (SS)}}{\text{degrees of freedom}}$$

$$\text{F-ratio} = \frac{\text{MS factor (s)}}{\text{MS experimental error}}$$

APPENDIX E

STATISTICAL ANALYSIS FOR EFFECT OF SOAK METHOD ON PHYSICAL CHARACTERISTICS OF VARIOUS BEANS DURING BENCH SCALE EXPERIMENTS

Table E.1: Effect of various levels of vacuum treatment and control on physical characteristics of soaked navy beans (initial MC = 7.48% wb) during the bench scale experiments.

Soak Procedure		% Wt. Gain		% MC (wb)	
		1 hr soak	2 hr soak	1 hr soak	2 hr soak
Normal Soaking* (control)		79.98 ±0.93	99.85 ±0.35	48.67 ±0.44	53.59 ±0.37
Vacuum Hydration at 15" Hg	5 min	91.99 ±1.87	102.22 ±0.59	50.58 ±0.47	53.21 ±0.08
	30 min	92.37 ±1.20	103.58 ±2.30	51.29 ±0.49	54.72 ±0.50
Vacuum Hydration at 20" Hg	5 min	97.19 ±2.45	103.75 ±1.86	52.59 ±0.16	54.23 ±0.23
	30 min	96.45 ±0.23	103.51 ±1.09	52.49 ±0.25	54.18 ±1.65
Vacuum Hydration at 25" Hg	5 min	98.72 ±2.39	103.71 ±0.95	53.94 ±0.82	55.18 ±0.50
	30 min	99.70 ±0.08	107.72 ±0.47	53.92 ±0.13	56.08 ±0.09

* Wt. gain after 24-hr normal soaking = 107.90 ± 1.73%.
MC gain after 24-hr normal soaking = 55.40 ± 0.64% wb.

Table E.2: 3-way analysis of variance of the main effects and interactions on % weight gain values for soaked navy beans in Table E.1.

Source of Variation	df	SS	MS	F-ratio
Total	23	557.89		
Time under vacuum (A)	1	5.52	5.52	1.95
Soaking time (B)	1	385.04	385.04	136.24**
Vacuum level (C)	2	97.14	48.57	17.19**
A x B	1	3.39	3.39	1.20
A x C	2	8.94	4.47	1.58
B x C	2	22.11	11.05	3.91*
A x B x C	2	1.81	0.91	0.32
Experimental error	12	33.91	2.83	

* Significant at 5% level.
** Significant at 1% level.

Table E.3: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) values for soaked navy beans in Table E.1.

Source of Variation	df	SS	MS	F-ratio
Total	23	60.32		
Time under vacuum (A)	1	1.45	1.45	3.49
Soaking time (B)	1	27.25	27.25	65.53**
Vacuum level (C)	2	22.02	11.01	26.48**
A x B	1	0.52	0.52	1.25
A x C	2	1.41	0.71	1.71
B x C	2	2.42	1.21	2.91
A x B x C	2	0.22	0.11	0.26
Experimental error	12	4.99	0.42	

** Significant at 1% level.

Table E.4: Effect of various levels of vacuum treatment and control on physical characteristics of soaked pinto beans (initial MC = 7.10% wb) during the bench scale experiments.

Soak Procedure		% Wt. Gain			% MC (wb)		
		1 hr soak	2 hr soak	3 hr soak	1 hr soak	2 hr soak	3 hr soak
Normal Soaking* (control)		3.46 ±0.18	7.90 ±1.34	11.24 ±1.76	10.84 ±0.10	13.48 ±0.74	16.43 ±0.92
Vacuum Hydration at 15" Hg	5 min	20.73 ±0.89	29.74 ±3.13	37.49 ±1.65	22.24 ±0.33	27.98 ±1.52	32.38 ±0.64
	30 min	22.30 ±0.48	28.89 ±1.47	41.58 ±2.94	23.88 ±0.13	27.37 ±1.51	34.08 ±2.12
Vacuum Hydration at 20" Hg	5 min	25.00 ±0.05	32.70 ±1.10	40.79 ±3.56	24.99 ±1.01	29.92 ±0.06	33.84 ±1.96
	30 min	25.30 ±3.68	38.15 ±4.88	44.45 ±1.35	26.35 ±2.83	32.75 ±2.05	35.65 ±0.21
Vacuum Hydration at 25" Hg	5 min	34.22 ±4.36	41.50 ±4.70	50.02 ±2.23	30.92 ±3.35	33.81 ±2.86	38.62 ±1.02
	30 min	28.57 ±0.37	43.89 ±4.21	59.79 ±5.01	27.53 ±0.47	36.11 ±3.07	42.40 ±2.09

* Wt. gain after 24-hr normal soaking = 58.50 ± 2.47%.
MC gain after 24-hr normal soaking = 55.40 ± 0.99% wb.

Table E.5: 3-way analysis of variance of the main effects and interactions on % weight gain values for soaked pinto beans in Table E.4.

Source of Variation	df	SS	MS	F-ratio
Total	35	3856.75	110.19	
Time under vacuum (A)	1	47.74	47.74	3.41
Soaking time (B)	2	2320.68	1160.34	82.79**
Vacuum level (C)	2	1032.23	516.11	36.82**
A x B	2	75.62	37.81	2.70
A x C	2	3.60	1.80	0.13
B x C	4	55.38	13.84	0.99
A x B x C	4	69.22	17.30	1.23
Experimental error	18	252.26	14.01	

** Significant at 1% level.

Table E.6: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) for soaked pinto beans in Table E.4.

Source of Variation	df	SS	MS	F-ratio
Total	35	1078.73		
Time under vacuum (A)	1	14.49	14.49	2.46
Soaking time (B)	2	621.88	310.94	52.86**
Vacuum level (C)	2	292.40	146.20	24.85**
A x B	2	10.08	5.04	0.86
A x C	2	2.41	1.20	0.20
B x C	4	8.39	2.09	0.36
A x B x C	4	23.18	5.79	0.98
Experimental error	18	105.89	5.88	

** Significant at 1% level.

Table E.7: Effect of various levels of vacuum treatment and control on physical characteristics of soaked cranberry beans (initial MC = 7.48% wb) during the bench scale experiments.

Soak Procedure		% wt. Gain			% MC (wb)		
		1 hr soak	2 hr soak	3 hr soak	1 hr soak	2 hr soak	3 hr soak
Normal Soaking* (control)		13.37 1.30	19.73 0.74	23.30 0.09	18.54 1.28	21.95 0.29	23.54 0.97
Vacuum Hydration at 15" Hg	5 min	23.61 ±4.36	31.43 ±5.81	46.08 ±6.83	24.37 ±3.34	29.20 ±2.95	36.11 ±3.78
	30 min	28.30 ±1.04	36.96 ±1.48	44.92 ±2.48	28.47 ±2.14	32.83 ±0.81	36.27 ±0.74
Vacuum Hydration at 20" Hg	5 min	31.23 ±1.80	42.50 ±2.43	53.85 ±1.65	28.71 ±0.56	34.92 ±1.34	39.06 ±0.66
	30 min	30.65 ±1.48	41.40 ±1.56	49.75 ±3.82	28.97 ±1.26	36.85 ±1.34	38.00 ±1.41
Vacuum Hydration at 25" Hg	5 min	36.25 ±3.17	47.21 ±1.49	66.73 ±8.34	32.63 ±1.47	38.46 ±0.45	44.72 ±3.11
	30 min	37.68 ±4.16	45.62 ±2.27	58.18 ±0.68	32.65 ±2.41	37.34 ±0.85	42.75 ±0.70

* Wt. gain after 24-hr normal soaking = 114.34 ± 1.18%.
MC gain after 24-hr normal soaking = 55.0 ± 0.51% wb.

Table E.8: 3-way analysis of variance of the main effects and interactions on % weight gain values for soaked cranberry beans in Table E.7.

Source of Variation	df	SS	MS	F-ratio
Total	35	4585.44		
Time under vacuum (A)	1	3.28	3.28	0.15
Soaking time (B)	2	2910.80	1455.40	67.51**
Vacuum level (C)	2	1077.54	538.77	24.99**
A x B	2	73.22	36.61	1.70
A x C	2	60.51	30.25	1.40
B x C	4	59.08	14.77	0.68
A x B x C	4	12.95	3.24	0.15
Experimental error	18	388.06	21.56	

** Significant at 1% level.

Table E.9: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) values for soaked cranberry beans in Table E.7.

Source of Variation	df	SS	MS	F-ratio
Total	35	1053.12		
Time under vacuum (A)	1	3.93	3.93	0.79
Soaking time (B)	2	624.75	312.37	62.40**
Vacuum level (C)	2	284.71	142.36	28.44**
A x B	2	11.78	5.89	1.18
A x C	2	20.38	10.19	2.04
B x C	4	13.50	3.38	0.67
A x B x C	4	3.96	0.99	0.20
Experimental error	18	90.10	5.01	

** Significant at 1% level.

Table E.10: Effect of various levels of vacuum treatment and control on physical characteristics of soaked kidney beans (initial MC = 7.0% wb) during the bench scale experiments.

Soak Procedure		% Wt. Gain			% MC (wb)		
		1 hr soak	2 hr soak	3 hr soak	1 hr soak	2 hr soak	3 hr soak
Normal Soaking* (control		7.71 ±4.92	13.80 ±3.32	38.25 ±1.20	13.45 ±3.44	17.90 ±1.84	32.15 ±0.78
Vacuum Hydration at 15" Hg	5 min	20.75 ±1.77	34.35 ±0.71	44.70 ±4.31	22.95 ±1.41	29.80 ±0.14	35.00 ±1.91
	30 min	21.57 ±6.64	32.03 ±3.35	39.54 ±2.50	23.29 ±4.84	29.70 ±2.55	32.66 ±0.89
Vacuum Hydration at 20" Hg	5 min	24.65 ±4.45	40.80 ±4.88	45.35 ±5.02	25.50 ±3.32	33.90 ±2.69	37.15 ±4.29
	30 min	23.78 ±1.63	42.20 ±4.79	43.40 ±4.87	24.65 ±0.64	33.80 ±3.11	37.33 ±4.91
Vacuum Hydration at 25" Hg	5 min	25.06 ±5.98	44.73 ±0.38	52.52 ±0.13	27.59 ±0.18	34.38 ±0.69	39.46 ±0.24
	30 min	27.53 ±1.95	45.01 ±2.06	52.22 ±3.30	27.55 ±1.87	35.21 ±0.52	39.33 ±1.32

* Wt. gain after 24-hr normal soaking = 125.70 ± 0.86%
MC gain after 24-hr normal soaking = 57.60 ± 0.47% wb.

Table E.11: 3-way analysis of variance of the main effects and interactions on % weight gain values for soaked kidney beans in Table E.10.

Source of Variation	df	SS	MS	F-ratio
Total	35	4184.18		
Time under vacuum (A)	1	3.53	3.53	0.17
Soaking time (B)	2	3191.69	1595.84	77.12**
Vacuum level (C)	2	488.35	244.17	11.80**
A x B	2	16.86	8.43	0.41
A x C	2	13.94	6.97	0.34
B x C	4	86.22	21.56	1.04
A x B x C	4	11.14	2.79	0.13
Experimental error	18	372.45	20.69	

** Significant at 1% level.

Table E.12: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) values for soaked kidney beans in Table E.10.

Source of Variation	df	SS	MS	F-ratio
Total	35	1154.95		
Time under vacuum (A)	1	0.54	0.54	0.06
Soaking time (B)	2	827.51	413.75	46.54**
Vacuum level (C)	2	154.53	77.26	8.69**
A x B	2	1.44	0.72	0.08
A x C	2	1.27	0.64	0.07
B x C	4	5.80	1.45	0.16
A x B x C	4	3.82	0.96	0.11
Experimental error	18	160.04	8.89	

** Significant at 1% level.

Table E.13: Effect of various levels of vacuum treatment and control on physical characteristics of soaked black turtle soup beans (initial MC = 7.50% wb) during the bench scale experiments.

Soak Procedure		% Wt. Gain			% MC (wb)		
		1 hr soak	2 hr soak	3 hr soak	1 hr soak	2 hr soak	3 hr soak
Normal Soaking* (control)		12.55 ±0.08	19.40 ±1.41	27.90 ±4.23	17.45 ±0.64	22.05 ±0.49	26.10 ±1.11
Vacuum Hydration at 15" Hg	5 min	16.15 ±1.34	24.50 ±2.12	27.75 ±1.34	21.00 ±1.41	24.70 ±1.42	28.15 ±0.21
	30 min	19.11 ±3.96	21.33 ±0.88	26.38 ±0.47	21.35 ±2.43	22.50 ±0.48	27.56 ±0.54
Vacuum Hydration at 20" Hg	5 min	19.40 ±3.11	24.97 ±1.85	28.37 ±2.05	22.26 ±1.77	26.15 ±2.76	29.30 ±0.85
	30 min	19.20 ±0.85	24.32 ±0.78	29.10 ±0.57	22.17 ±0.21	25.10 ±0.99	29.29 ±0.14
Vacuum Hydration at 25" Hg	5 min	21.92 ±0.11	30.81 ±2.06	36.30 ±2.31	23.15 ±0.31	26.51 ±1.90	31.50 ±2.07
	30 min	20.75 ±4.72	30.45 ±3.51	36.10 ±2.05	23.02 ±3.22	26.38 ±2.85	31.30 ±0.18

* Wt. gain after 24-hr normal soaking = 59.80 ± 2.20%.
MC gain after 24-hr normal soaking = 55.30 ± 0.83% wb.

Table E.14: 3-way analysis of variance of the main effects and interactions on % weight gain values for soaked black turtle soup beans in Table E.13.

Source of Variation	df	SS	MS	F-ratio
Total	35	1271.40		
Time under vacuum (A)	1	1.31	1.31	0.18
Soaking time (B)	2	767.01	383.50	51.81**
Vacuum level (C)	2	305.78	152.89	20.66**
A x B	2	5.59	2.80	0.38
A x C	2	0.53	0.26	0.04
B x C	4	42.16	10.54	1.42
A x B x C	4	15.79	3.95	0.53
Experimental error	18	133.23	7.40	

** Significant at 1% level.

Table E.15: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) values for soaked black turtle soup beans in Table E.13.

Source of Variation	df	SS	MS	F-ratio
Total	35	452.16		
Time under vacuum (A)	1	1.82	1.82	0.48
Soaking time (B)	2	327.89	163.94	43.48**
Vacuum level (C)	2	46.04	23.02	6.10**
A x B	2	2.20	1.10	0.29
A x C	2	0.67	0.34	0.09
B x C	4	3.86	0.97	0.26
A x B x C	4	1.79	0.45	0.12
Experimental error	18	67.88	3.77	

** Significant at 1% level.

APPENDIX F

STATISTICAL ANALYSIS FOR EFFECT OF SOAK METHOD ON PHYSICAL PROPERTIES OF VARIOUS BEANS DURING LARGE SCALE EXPERIMENTS

Table F.1: Data on physical properties of dry and soaked navy beans during the large scale experiments.

Parameter Observed	Dry (Untreated) Beans	24-hour soak	No Vacuum (Control) 0.5 hr soak	No Vacuum (Control) 1 hr soak	No Vacuum (Control) 2 hr soak	No Vacuum (Control) 3 hr soak
Weight Gain	0 0	99.93 ± 0.11	51.71 ± 3.23	68.66 ± 4.51	77.07 ± 0.49	81.78 ± 0.82
Moisture Content	10.51 ± 0.01	55.55 ± 0.07	43.10 ± 0.63	48.19 ± 0.30	51.05 ± 0.11	52.30 ± 0.01
Specific Gravity	1.381 ± 0.004	1.160 ± 0.001	1.191 ± 0.005	1.188 ± 0.021	1.174 ± 0.009	1.163 ± 0.006
Average Volume (cc) of Single Beans After Each Treatment	0.165 ± 0.001	0.365 ± 0.001	0.259 ± 0.001	0.286 ± 0.005	0.309 ± 0.002	0.332 ± 0.002
Anatomical Characteristics of Single Beans						
Length (cm)	0.873 ± 0.082	1.164 ± 0.075	1.017 ± 0.028	1.094 ± 0.046	1.095 ± 0.049	1.102 ± 0.063
Width (cm)	0.645 ± 0.052	0.795 ± 0.038	0.714 ± 0.031	0.740 ± 0.041	0.743 ± 0.041	0.754 ± 0.034
Height (cm)	0.562 ± 0.054	0.649 ± 0.049	0.608 ± 0.020	0.610 ± 0.024	0.613 ± 0.031	0.630 ± 0.031
Maximum Peak Force (Nx10⁴) per gm of Beans Compressed at 50 cm/min	19.470 ± 0.086	3.825 ± 0.157	5.208 ± 0.076	4.975 ± 0.077	4.726 ± 0.201	4.466 ± 0.055
Work done (Jx10⁶) per gm of Beans Compressed at 50 cm/min	13.215 ± 0.629	3.531 ± 0.054	8.128 ± 0.123	7.809 ± 0.192	6.094 ± 0.319	4.951 ± 0.363

Parameter Observed	Vacuum Treatment (67.54 KPa) 0.5 hr soak	Vacuum Treatment (67.54 KPa) 1 hr soak	Vacuum Treatment (67.54 KPa) 2 hr soak	Vacuum Treatment (67.54 KPa) 3 hr soak
Weight Gain	60.00 ± 0.30 62.35 ± 0.53*	72.23 ± 0.69 75.05 ± 0.45*	80.22 ± 0.08 82.27 ± 0.16*	83.67 ± 0.47 89.42 ± 0.40*
Moisture Content	44.92 ± 0.24 47.48 ± 0.33*	48.25 ± 0.05 51.00 ± 0.13*	51.16 ± 0.01 52.21 ± 0.01*	53.10 ± 0.04 53.17 ± 0.09*
Specific Gravity	1.186 ± 0.005	1.170 ± 0.007	1.160 ± 0.001	1.157 ± 0.001
Average Volume (cc) of Single Beans After Each Treatment	0.275 ± 0.001	0.299 ± 0.002	0.315 ± 0.001	0.335 ± 0.001
Anatomical Characteristics of Single Beans				
Length (cm)	1.028 ± 0.056	1.095 ± 0.051	1.116 ± 0.061	1.127 ± 0.048
Width (cm)	0.718 ± 0.023	0.761 ± 0.035	0.769 ± 0.049	0.770 ± 0.039
Height (cm)	0.594 ± 0.036	0.617 ± 0.025	0.638 ± 0.034	0.639 ± 0.030
Maximum Peak Force (Nx10⁴) per gm of Beans Compressed at 50 cm/min	5.142 ± 0.046 4.936 ± 0.044*	4.830 ± 0.054 4.571 ± 0.039*	4.414 ± 0.041 4.228 ± 0.028*	4.250 ± 0.030 4.187 ± 0.021*
Work done (Jx10⁶) per gm of Beans Compressed at 50 cm/min	7.177 ± 0.064 6.125 ± 0.208*	6.865 ± 0.133 5.628 ± 0.211*	5.917 ± 0.059 5.129 ± 0.162*	4.854 ± 0.138 4.830 ± 0.044*

*Vacuum treatment was done at 81.04 KPa.

Table F.2: Data on physical properties of dry and soaked pinto beans during the large scale experiments.

Parameter Observed	Dry (Untreated) Beans	24-hour Soak	No Vacuum (Control) 0.5 hr soak	No Vacuum (Control) 1 hr soak	No Vacuum (Control) 2 hr soak	No Vacuum (Control) 3 hr soak	Vacuum Treatment (81.04 KPa) 0.5 hr soak	Vacuum Treatment (81.04 KPa) 1 hr soak	Vacuum Treatment (81.04 KPa) 2 hr soak	Vacuum Treatment (81.04 KPa) 3 hr soak
Weight Gain	0 0	99.03 ± 0.22	15.83 ± 0.40	20.77 ± 0.41	45.82 ± 0.62	65.05 ± 0.82	71.12 ± 0.83	77.45 ± 2.05	90.12 ± 2.66	98.58 ± 1.23
Moisture Content	14.03 ± 0.04	57.08 ± 0.43	25.69 ± 0.62	28.07 ± 1.21	39.72 ± 2.92	40.05 ± 0.15	51.15 ± 0.16	52.49 ± 1.57	55.08 ± 0.91	56.44 ± 0.63
Specific Gravity	1.313 ± 0.028	1.140 ± 0.001	1.289 ± 0.005	1.278 ± 0.019	1.215 ± 0.015	1.135 ± 0.007	1.187 ± 0.004	1.176 ± 0.001	1.165 ± 0.001	1.163 ± 0.001
Average Volume (cc) of Single Beans After Each Treatment	0.285 ± 0.006	0.705 ± 0.001	0.382 ± 0.001	0.402 ± 0.006	0.550 ± 0.007	0.610 ± 0.004	0.630 ± 0.002	0.653 ± 0.001	0.702 ± 0.001	0.736 ± 0.001
Anatomical Characteristics of Single Beans										
Length (cm)	1.279 ± 0.066	1.602 ± 0.147	1.330 ± 0.083	1.338 ± 0.075	1.385 ± 0.036	1.622 ± 0.092	1.472 ± 0.156	1.562 ± 0.143	1.649 ± 0.121	1.655 ± 0.073
Width (cm)	0.832 ± 0.034	0.972 ± 0.037	0.842 ± 0.035	0.871 ± 0.065	0.903 ± 0.049	0.977 ± 0.045	0.928 ± 0.035	0.973 ± 0.047	1.006 ± 0.033	1.014 ± 0.055
Height (cm)	0.573 ± 0.051	0.728 ± 0.049	0.577 ± 0.040	0.600 ± 0.049	0.662 ± 0.096	0.708 ± 0.038	0.677 ± 0.071	0.719 ± 0.082	0.778 ± 0.061	0.778 ± 0.066
Maximum Peak Force ($N \times 10^3$) per gm of Beans Compressed at 50 cm/min	17.839 ± 0.349	5.703 ± 0.034	8.539 ± 0.294	8.006 ± 0.275	6.857 ± 0.151	6.495 ± 0.181	7.288 ± 0.276	6.708 ± 0.371	6.221 ± 0.089	5.806 ± 0.091
Work done ($J \times 10^6$) per gm of Beans Compressed at 50 cm/min	13.833 ± 0.354	6.000 ± 0.059	7.309 ± 0.093	7.087 ± 0.054	6.976 ± 0.044	6.743 ± 0.167	7.014 ± 0.059	7.003 ± 0.015	6.524 ± 0.123	6.236 ± 0.118

Table F.3: Data on physical properties of dry and soaked red kidney beans during the large scale experiments.

Parameter Observed	Dry (Untreated) Beans	24-hour soak	No Vacuum (Control)				Vacuum Treatment (81.04 KPa)			
			0.5 hr soak	1 hr soak	2 hr soak	3 hr soak	0.5 hr soak	1 hr soak	2 hr soak	3 hr soak
% Weight Gain	0 0	99.97 ± 0.28	23.34 ± 1.60	46.22 ± 3.65	73.33 ± 2.58	85.96 ± 2.31	46.37 ± 0.87	71.30 ± 1.08	92.12 ± 0.76	98.17 ± 0.74
% Moisture Content	13.99 ± 0.01	57.37 ± 0.69	29.82 ± 1.88	40.49 ± 2.55	49.84 ± 2.95	54.55 ± 0.64	40.03 ± 0.23	50.90 ± 1.53	54.31 ± 0.50	56.88 ± 0.48
Specific Gravity	1.325 ± 0.008	1.146 ± 0.001	1.277 ± 0.002	1.234 ± 0.005	1.185 ± 0.036	1.152 ± 0.003	1.253 ± 0.002	1.165 ± 0.002	1.153 ± 0.003	1.147 ± 0.003
Average Volume (cc) of Single Beans After Each Treatment	0.511 ± 0.003	1.371 ± 0.002	0.740 ± 0.001	0.932 ± 0.004	1.143 ± 0.035	1.236 ± 0.003	0.914 ± 0.001	1.151 ± 0.002	1.255 ± 0.003	1.302 ± 0.004
Anatomical Characteristics of Single Beans										
Length (cm)	1.741 ± 0.032	2.467 ± 0.123	1.913 ± 0.085	2.029 ± 0.086	2.150 ± 0.099	2.243 ± 0.086	2.013 ± 0.183	2.239 ± 0.177	2.254 ± 0.157	2.368 ± 0.098
Width (cm)	0.892 ± 0.054	1.120 ± 0.054	0.945 ± 0.055	0.986 ± 0.058	1.019 ± 0.054	1.074 ± 0.053	0.979 ± 0.067	1.070 ± 0.063	1.093 ± 0.098	1.094 ± 0.064
Height (cm)	0.658 ± 0.051	0.876 ± 0.041	0.682 ± 0.036	0.691 ± 0.029	0.774 ± 0.040	0.835 ± 0.045	0.751 ± 0.058	0.810 ± 0.080	0.840 ± 0.065	0.860 ± 0.062
Maximum Peak Force (Nx10^{3}) per gm of Beans Compressed at 50 cm/min	20.097 ± 1.267	4.537 ± 0.019	7.122 ± 0.087	6.498 ± 0.042	5.352 ± 0.040	5.114 ± 0.059	5.920 ± 0.056	5.341 ± 0.050	5.177 ± 0.024	4.961 ± 0.011
Work done (Jx10^{1}) per gm of Beans Compressed at 50 cm/min	14.566 ± 1.193	6.375 ± 0.020	9.785 ± 0.324	8.910 ± 0.265	7.941 ± 0.054	7.431 ± 0.157	9.010 ± 0.084	7.392 ± 0.182	7.194 ± 0.029	6.882 ± 0.020

Table F.4: Date on physical properties of navy beans subjected to different soak treatments before cooking at 115.6^{0}C for various periods of time during the large scale experiments.

Parameter Observed		No Vacuum				Vacuum Treatment (81.04 KPa)			
		0.5 hr soak	1 hr soak	2 hr soak	3 hr soak	0.5 hr soak	1 hr soak	2 hr soak	3 hr soak
% Weight Gain	15 min cook	140.21 ± 0.42	149.66 ± 1.46	154.96 ± 0.11	156.32 ± 4.20	147.30 ± 1.10	152.64 ± 0.47	156.23 ± 0.52	159.82 ± 0.74
	30 min cook	163.46 ± 0.73	167.55 ± 0.66	169.80 ± 0.57	171.04 ± 0.68	164.44 ± 0.03	168.88 ± 1.61	170.95 ± 0.76	171.47 ± 1.08
	45 min cook	174.70 ± 1.95	177.20 ± 0.94	177.97 ± 2.23	178.98 ± 1.61	177.16 ± 0.24	177.30 ± 2.01	178.49 ± 1.54	178.98 ± 1.67
% MC (Wet Basis)	15 min cook	64.63 ± 0.13	66.33 ± 0.28	66.67 ± 0.22	66.83 ± 0.31	65.33 ± 0.08	66.54 ± 0.03	66.90 ± 0.82	67.53 ± 0.45
	30 min cook	67.67 ± 0.36	68.59 ± 0.08	69.62 ± 0.15	69.72 ± 0.76	68.46 ± 0.54	69.02 ± 0.33	69.41 ± 0.25	70.39 ± 0.81
	45 min cook	69.66 ± 0.52	69.69 ± 0.22	70.24 ± 0.72	70.30 ± 0.64	69.73 ± 0.42	69.61 ± 0.74	70.46 ± 0.62	70.62 ± 0.49
Maximum Peak Force ($N \times 10^3$) per gm of Beans Compressed at 50 cm/min	15 min cook	4.847 ± 0.133	4.518 ± 0.072	4.294 ± 0.048	4.140 ± 0.031	4.737 ± 0.330	4.375 ± 0.260	4.156 ± 0.106	4.109 ± 0.033
	30 min cook	4.208 ± 0.145	4.113 ± 0.177	3.982 ± 0.154	3.882 ± 0.015	4.141 ± 0.111	4.004 ± 0.134	3.916 ± 0.068	3.828 ± 0.037
	45 min cook	4.029 ± 0.223	3.968 ± 0.124	3.949 ± 0.028	3.736 ± 0.029	4.022 ± 0.092	3.939 ± 0.061	3.854 ± 0.027	3.693 ± 0.115
Work Done ($J \times 10^6$) per gm of Beans Compressed at 50 cm/min	15 min cook	5.215 ± 0.206	5.090 ± 0.151	4.979 ± 0.092	4.799 ± 0.072	5.132 ± 0.080	5.007 ± 0.074	4.868 ± 0.089	4.688 ± 0.093
	30 min cook	3.847 ± 0.255	3.757 ± 0.187	3.674 ± 0.176	3.542 ± 0.165	3.785 ± 0.154	3.694 ± 0.143	3.590 ± 0.137	3.458 ± 0.128
	45 min cook	3.705 ± 0.398	3.639 ± 0.138	3.559 ± 0.074	3.438 ± 0.226	3.656 ± 0.457	3.563 ± 0.295	3.479 ± 0.147	3.375 ± 0.118

Table F.5: 3-way analysis of variance of the main effects and interactions on % weight gain values of processed navy beans in Table F.4.

Source of Variation	df	SS	MS	F-ratio
Total	47	6081.52		
Cooking time (A)	2	5321.28	2660.64	1164.84**
Soaking time (B)	3	469.99	156.66	68.59**
Vacuum level (C)	1	16.97	16.97	7.42*
A x B	6	151.87	25.31	11.08**
A x C	2	39.37	19.68	8.62**
B x C	3	2.69	0.90	0.39
A x B x C	6	24.53	4.09	1.79
Experimental error	24	54.81	2.28	

* Significant at 5% level.
** Significant at 1% level.

Table F.6: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) values of processed navy beans in Table F.4.

Source of Variation	df	SS	MS	F-ratio
Total	47	149.88		
Cooking time (A)	2	119.93	59.97	258.40**
Soaking time (B)	3	18.62	6.21	26.76**
Vacuum level (C)	1	1.58	1.58	6.81*
A x B	6	3.17	0.53	2.28
A x C	2	0.15	0.07	0.30
B x C	3	0.44	0.15	0.65
A x B x C	6	0.40	0.07	0.30
Experimental error	24	5.57	0.23	

* Significant at 5% level.
** Significant at 1% level.

Table F.7: 3-way analysis of variance of the main effects and interactions on maximum peak compressive force (N) per gm values of processed navy beans in Table F.4.

Source of Variation	df	SS	MS	F-ratio
Total	47	4.19		
Cooking time (A)	2	2.19	1.10	62.54**
Soaking time (B)	3	1.22	0.41	23.40**
Vacuum level (C)	1	0.07	0.07	3.79
A x B	6	0.26	0.04	2.49
A x C	2	0.01	0.00	0.22
B x C	3	0.01	0.00	0.12
A x B x C	6	0.01	0.00	0.07
Experimental error	24	0.42	0.02	

** Significant at 1% level.

Table F.8: 3-way analysis of variance of the main effects and interactions on compressive work (J) per gm values of processed navy beans in Table F.4.

Source of Variation	df	SS	MS	F-ratio
Total	47	21.67		
Cooking time (A)	2	19.90	9.95	265.10**
Soaking time (B)	3	0.76	0.25	6.75**
Vacuum level (C)	1	0.07	0.07	1.99
A x B	6	0.03	0.01	0.13
A x C	2	0.00	0.00	0.03
B x C	3	0.00	0.00	0.01
A x B x C	6	0.00	0.00	0.00
Experimental error	24	0.90	0.04	

** Significant at 1% level.

Table F.9: Data on physical properties of pinto beans subjected to different soak treatments before cooking at 115.6^{0}C for various periods of time during the large scale experiments.

Parameter Observed		No Vacuum				Vacuum Treatment (81.04 KPa)			
		0.5 hr soak	1 hr soak	2 hr soak	3 hr soak	0.5 hr soak	1 hr soak	2 hr soak	3 hr soak
% Weight Gain	15 min cook	115.65 ± 1.83	115.83 ± 1.12	120.16 ± 0.79	124.16 ± 0.91	124.07 ± 1.00	125.75 ± 0.72	128.71 ± 0.64	131.21 ± 0.33
	30 min cook	135.93 ± 0.17	136.28 ± 0.96	137.08 ± 0.55	138.23 ± 0.46	143.29 ± 0.57	143.91 ± 0.71	146.25 ± 0.44	147.13 ± 0.34
	45 min cook	142.94 ± 0.17	144.74 ± 1.05	145.95 ± 0.67	147.35 ± 0.44	150.13 ± 0.95	150.25 ± 0.98	151.56 ± 0.03	151.87 ± 0.22
% MC (Wet Basis)	15 min cook	61.03 ± 0.55	61.33 ± 0.48	62.60 ± 0.45	63.45 ± 0.22	63.32 ± 0.10	63.52 ± 0.09	64.62 ± 0.22	64.67 ± 0.04
	30 min cook	65.13 ± 0.19	65.22 ± 0.81	65.45 ± 0.48	65.70 ± 0.30	66.47 ± 0.47	66.90 ± 0.38	67.05 ± 0.28	67.07 ± 0.21
	45 min cook	66.50 ± 0.21	66.73 ± 0.20	66.91 ± 0.40	67.21 ± 0.76	67.39 ± 0.35	67.52 ± 0.08	67.68 ± 0.11	68.15 ± 0.14
Maximum Peak Force ($Nx10^3$) per gm of Beans Compressed at 50 cm/min	15 min cook	7.003 ± 0.052	6.719 ± 0.111	6.485 ± 0.164	5.865 ± 0.084	6.743 ± 0.082	6.416 ± 0.121	6.028 ± 0.075	5.658 ± 0.075
	30 min cook	6.000 ± 0.050	5.736 ± 0.111	5.679 ± 0.081	5.551 ± 0.035	5.873 ± 0.037	5.647 ± 0.024	5.474 ± 0.035	5.384 ± 0.022
	45 min cook	5.139 ± 0.101	5.034 ± 0.129	4.821 ± 0.037	4.747 ± 0.098	5.088 ± 0.068	4.813 ± 0.067	4.701 ± 0.030	4.648 ± 0.021
Work Done ($Jx10^6$) per gm of Beans Compressed at 50 cm/min	15 min cook	6.965 ± 0.206	6.778 ± 0.324	6.549 ± 0.638	6.174 ± 0.599	6.881 ± 0.422	6.479 ± 0.481	6.208 ± 0.707	5.896 ± 0.410
	30 min cook	6.671 ± 0.216	6.306 ± 0.206	6.028 ± 0.150	5.694 ± 0.133	6.361 ± 0.169	5.806 ± 0.156	5.590 ± 0.140	5.486 ± 0.125
	45 min cook	5.361 ± 0.173	5.250 ± 0.165	5.027 ± 0.120	4.951 ± 0.106	5.306 ± 0.135	5.014 ± 0.125	4.903 ± 0.112	4.861 ± 0.101

Table F.10: 3-way analysis of variance of the main effects and interactions on % weight gain values of processed pinto beans in Table F.9.

Source of Variation	df	SS	MS	F-ratio
Total	47	6152.59		
Cooking time (A)	2	5202.09	2601.05	4128.65**
Soaking time (B)	3	156.18	52.06	82.63**
Vacuum level (C)	1	707.25	707.25	1122.62**
A x B	6	45.08	7.51	11.92**
A x C	2	13.13	6.57	10.43**
B x C	3	4.01	1.34	2.13
A x B x C	6	9.81	1.63	2.59
Experimental error	24	15.04	0.63	

** Significant at 1% level.

Table F.11: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) values of processed pinto beans in Table F.9.

Source of Variation	df	SS	MS	F-ratio
Total	47	189.72		
Cooking time (A)	2	143.56	71.78	422.24**
Soaking time (B)	3	8.10	2.70	15.88**
Vacuum level (C)	1	27.33	27.33	160.76**
A x B	6	4.05	0.68	4.00**
A x C	2	1.38	0.69	4.06*
B x C	3	0.64	0.21	1.24
A x B x C	6	0.48	0.08	0.47
Experimental error	24	4.17	0.17	

* Significant at 5% level.

** Significant at 1% level.

Table F.12: 3-way analysis of variance of the main effects and interactions on maximum peak compressive force (N) per gm values of processed pinto beans in Table F.9.

Source of Variation	df	SS	MS	F-ratio
Total	47	22.13		
Cooking time (A)	2	17.78	8.89	1366.36**
Soaking time (B)	3	2.89	0.96	148.22**
Vacuum level (C)	1	0.44	0.44	68.45**
A x B	6	0.71	0.12	18.19**
A x C	2	0.08	0.04	6.28**
B x C	3	0.03	0.01	1.31
A x B x C	6	0.03	0.01	0.87
Experimental error	24	0.16	0.01	

** Significant at 1% level.

Table F.13: 3-way analysis of variance of the main effects and interactions on compressive work (J) per gm values of processed pinto beans in Table F.9.

Source of Variation	df	SS	MS	F-ratio
Total	47	23.69		
Cooking time (A)	2	16.29	8.14	81.03**
Soaking time (B)	3	3.68	1.23	12.20**
Vacuum level (C)	1	0.73	0.73	7.26*
A x B	6	0.35	0.06	0.60
A x C	2	0.11	0.06	0.55
B x C	3	0.08	0.03	0.24
A x B x C	6	0.03	0.01	0.06
Experimental error	24	2.41	0.10	

* Significant at 5% level.
** Significant at 1% level.

Table F.14: Data on physical properties of kidney beans subjected to different soak treatments before cooking at 115.6 C for various periods of time during the large scale experiments.

Parameter Observed		No Vacuum				Vacuum Treatment (81.04 KPa)			
		0.5 hr soak	1 hr soak	2 hr soak	3 hr soak	0.5 hr soak	1 hr soak	2 hr soak	3 hr soak
% Weight Gain	15 min cook	144.08 ± 0.85	148.01 ± 0.11	148.21 ± 0.62	149.36 ± 2.16	148.35 ± 2.10	148.63 ± 0.21	153.93 ± 0.64	154.85 ± 0.01
	30 min cook	155.00 ± 0.40	156.02 ± 0.46	159.51 ± 0.47	160.74 ± 2.12	161.21 ± 0.26	161.46 ± 0.57	166.04 ± 0.82	167.75 ± 1.12
	45 min cook	161.73 ± 0.86	164.46 ± 1.44	164.81 ± 1.62	166.73 ± 2.14	167.17 ± 0.04	167.95 ± 0.69	168.32 ± 1.54	169.09 ± 0.54
% MC (Wet Basis)	15 min cook	65.71 ± 0.46	66.20 ± 0.22	66.32 ± 0.15	66.49 ± 0.27	66.79 ± 0.52	66.81 ± 0.25	67.59 ± 0.37	67.77 ± 0.04
	30 min cook	67.99 ± 0.45	68.18 ± 0.81	68.34 ± 0.20	68.93 ± 0.49	68.24 ± 0.47	68.34 ± 0.14	68.80 ± 0.26	69.16 ± 0.58
	45 min cook	68.08 ± 0.60	68.81 ± 0.75	68.87 ± 0.62	69.62 ± 1.07	69.13 ± 0.18	69.71 ± 0.62	69.94 ± 0.30	70.10 ± 0.18
Maximum Peak Force ($Nx10^3$) per gm of Beans Compressed at 50 cm/min	15 min cook	5.434 ± 0.089	5.390 ± 0.141	5.071 ± 0.145	4.870 ± 0.037	5.363 ± 0.075	5.083 ± 0.088	4.856 ± 0.015	4.620 ± 0.032
	30 min cook	5.157 ± 0.072	5.139 ± 0.113	4.846 ± 0.118	4.604 ± 0.036	5.069 ± 0.069	4.867 ± 0.079	4.625 ± 0.042	4.570 ± 0.032
	45 min cook	4.864 ± 0.064	4.847 ± 0.102	4.631 ± 0.095	4.572 ± 0.033	4.831 ± 0.062	4.568 ± 0.05	4.556 ± 0.038	4.517 ± 0.029
Work Done ($Jx10^6$) per gm of Beans Compressed at 50 cm/min	15 min cook	7.240 ± 0.753	7.107 ± 0.525	6.667 ± 0.525	6.583 ± 0.079	6.972 ± 0.511	6.736 ± 0.275	6.566 ± 0.594	6.483 ± 0.427
	30 min cook	6.865 ± 0.705	6.813 ± 0.394	6.545 ± 0.565	6.458 ± 0.128	6.681 ± 0.295	6.576 ± 0.334	6.476 ± 0.093	6.417 ± 0.074
	45 min cook	6.576 ± 0.226	6.559 ± 0.162	6.500 ± 0.098	6.424 ± 0.059	6.528 ± 0.029	6.417 ± 0.177	6.403 ± 0.049	6.354 ± 0.029

Table F.15: 3-way analysis of variance of the main effects and interactions on % weight gain values of processed kidney beans in Table F.14.

Source of Variation	df	SS	MS	F-ratio
Total	47	2926.73		
Cooking time (A)	2	2375.68	1187.84	914.07**
Soaking time (B)	3	194.13	64.71	49.79**
Vacuum level (C)	1	262.22	262.22	201.78**
A x B	6	24.61	4.10	3.16*
A x C	2	15.99	8.00	6.15**
B x C	3	9.11	3.04	2.34
A x B x C	6	13.80	2.30	1.76
Experimental error	24	31.19	1.30	

* Significant at 5% level.
** Significant at 1% level.

Table F.16: 3-way analysis of variance of the main effects and interactions on % M.C. (w.b.) values of processed kidney beans in Table F.14.

Source of Variation	df	SS	MS	F-ratio
Total	47	76.94		
Cooking time (A)	2	55.67	27.84	119.20**
Soaking time (B)	3	6.57	2.19	9.38**
Vacuum level (C)	1	6.49	6.49	27.79**
A x B	6	0.63	0.11	0.45
A x C	2	1.36	0.68	2.90
B x C	3	0.17	0.06	0.25
A x B x C	6	0.45	0.07	0.32
Experimental error	24	5.60	0.23	

** Significant at 1% level.

Table F.17: 3-way analysis of variance of the main effects and interactions on maximum peak compressive force (N) per gm values of processed kidney beans in Table F.14.

Source of Variation	df	SS	MS	F-ratio
Total	47	4.08		
Cooking time (A)	2	1.37	0.68	45.75**
Soaking time (B)	3	1.75	0.58	39.08**
Vacuum level (C)	1	0.30	0.30	20.18**
A x B	6	0.17	0.03	1.91
A x C	2	0.02	0.01	0.67
B x C	3	0.08	0.03	1.83
A x B x C	6	0.02	0.00	0.26
Experimental error	24	0.36	0.01	

** Significant at 1% level.

Table F.18: 3-way analysis of variance of the main effects and interactions on compressive work (J) per gm values of processed kidney beans in Table F.14.

Source of Variation	df	SS	MS	F-ratio
Total	47	7.46		
Cooking time (A)	2	0.77	0.39	1.85
Soaking time (B)	3	1.02	0.34	1.63
Vacuum level (C)	1	0.22	0.22	1.04
A x B	6	0.30	0.05	0.24
A x C	2	0.01	0.01	0.03
B x C	3	0.08	0.03	0.12
A x B x C	6	0.05	0.01	0.04
Experimental error	24	5.01	0.21	

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