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THERMAL SOFTENING KINETICS AND TEXTURAL QUALITY OF THERMALLY
PROCESSED VEGETABLES

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ABSTRACT

Dry Romano beans (*Phaseolus vulgaris*) were soaked and cooked at temperatures ranging from 70 to 100°C for different time intervals. The rate of texture softening associated with each temperature was found to be consistent with two simultaneous pseudo first-order kinetic mechanisms 1 and 2. Approximately 40% of the firmness of Romano beans was lost by the rapid softening mechanism 1. The remaining firmness loss was characterized by mechanism 2 which was found to be much slower (~1/50th of the former). The temperature dependence indicator (z value) of reaction rate constants were 30 and 24 C°, respectively for mechanisms 1 and 2 with associated activation energies of 82 kJ/mole and 103 kJ/mole, respectively.

Turnip (*Brassica napobbrassica*) and beet roots (*B. Vulgaris L.*) were cooked at temperatures ranging from 70 to 100°C for different time intervals. Three textural properties (firmness, springiness, and stiffness) were found to follow the same trend of apparent first order kinetic theory with two substrates. Temperature dependence of softening (z value) was found to be within 27 and 35 C°, with activation energies in the range of 93 and 60 kJ/mole.

Cylindrical turnip, beet root pieces and Romano beans were packed in thin profile plastic containers and cylindrical metal cans and thermally processed in the static and rotational modes. Through heat penetration testing, process times were adjusted to give an equivalent lethality of 10 min for each product. Thin profile packed vegetables, in all cases, were found to have a firmer and stiffer texture. On the other hand, for rotational processing, the result showed no significant improvement in textural properties (firmness, springiness and stiffness) over the still counterparts. It was found that previously determined kinetic data could be used to estimate texture retention.

RESUME

Des haricots romains secs (*Phaseolus vulgaris*) ont été détrempés puis chauffés à des températures allant de 70 à 100 °C. Ils ont été prélevés à différents intervalles de temps. La vitesse à laquelle leur texture se ramollit, associée à chacune des températures, suit effectivement les lois des deux mécanismes cinétiques simultanés 1 et 2, du pseudo premier ordre. Les haricots romains ont perdu approximativement 40 % de leur fermeté suite au premier et rapide mécanisme de ramollissement. La perte de la fermeté résiduelle a été caractérisée par le deuxième mécanisme, qui s'est révélé plus lent (d'un rapport 1/50ième par rapport au premier mécanisme). L'indicateur de dépendance thermique (z) des constantes de vitesse de réaction est de 30 et 24 °C respectivement pour le premier et le deuxième mécanisme. Les énergies d'activation associées sont de 82 et 103 kJ/mol respectivement.

Des navets (*Brassica napobbrassica*) et des betteraves (*B. Vulgaris L.*) ont également été chauffés à des températures allant de 70 à 100 °C et prélevés à différents intervalles de temps. Trois propriétés rhéologiques (la fermeté, l'élasticité et la dureté) ont suivi la même tendance qu'une théorie cinétique apparente du premier ordre à deux substrats. La dépendance thermique du ramollissement (z) se situe entre 27 et 35 °C, avec des énergies d'activation de 93 et 60 kJ/mol.

Des morceaux cylindriques de navets et de betteraves, et des haricots romains ont été placés soit dans des coupelles en plastique de fine épaisseur, soit dans des boîtes de conserve cylindriques. Les produits ont ensuite été chauffés statiquement ou en rotation. Les légumes placés dans les coupelles à l'épaisseur plus fine se sont révélés plus fermes et plus dures dans tout les cas de figure. D'un autre côté, lors du chauffage en mode rotationnel, les résultats n'ont pas montré d'amélioration significative des propriétés rhéologiques (fermeté, élasticité et dureté) par rapport au chauffage en mode statique. On a montré que les données cinétiques précédemment établies pourraient servir à prédire la stabilité de la texture.

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CHAPTER I

INTRODUCTION

Man has invested much time and effort in the preservation of various foods. For centuries, salting, sun drying and fermentation were some of the most popular methods used to protect food from hazardous elements when fresh foods were not available. Due to changing lifestyles, demand for better quality and larger quantities of processed food has increased. This in turn caused great developments in food processing industries by ensuring consumer satisfaction and providing high quality products. Thermally preserving foods (canning) is considered to be one of the most important techniques for producing packaged shelf stable food products.

Obtaining product safety, however is the obvious prerequisite for all the food products and any heating process should be based on inactivation of microorganisms of public health concern to render the products commercially sterile (Fennema, 1975). Nature of food (pH), storage condition, heating behavior of food and container and heating medium, initial load of microorganisms and resistance of microorganisms to the heat energy are the most important factors to bo considered when employing thermal treatment for commercial sterilization.

Thermal processing also results in the loss of quality factors such as texture, color and nutrients. Effect on sensory quality could be either a positive or negative direction. These changes are related to the loss of turgor pressure and to chemical changes in the cell wall and middle lamella in the plant foodstuffs. The uptake or adsorption of water during thermal processing can reduce the cohesiveness of the matrix, soften the cell wall, and decrease the intercellular adhesion (Van Buren, 1979).

Studies by Ball and Olson (1957) and Stumbo (1973) indicated that nutrient and sensory factors are less heat sensitive than hazardous elements and a given increase in temperature causes a larger increase in rate of destruction of microorganisms. This difference in temperature dependence implies that optimization of quality retention in

thermal processed foods is possible. Heat transfer in the food plays an important part in the optimization. High temperature short time (HTST) and ultra high temperature (UHT) processes, aseptic processing, rotary sterilization and thin profile processing promote better quality retention in processed foods. There has also been a considerable amount of scientific work pertaining to the effect of processing on nutritive values and the minimization of quality degradation in thermal processed foods (Teixeira et al., 1969; Tung et al., 1975; Lund, 1982; Gregory, 1983; Leonard et al., 1986; Bender, 1987; Ghazala et al., 1989; Snyder and Henderson, 1989; Ramaswamy and Ghazala, 1990; Ramaswamy et al., 1992; Ramaswamy and Abdelrahim, 1992; Abbatemarco and Ramaswamy, 1993; Jacob John et al., 1993; Ramaswamy et al., 1993;).

Foods are subjected to forces during processing, particularly during size reduction operations and expression (pressing) processes; in addition, packaging material such as can and semi-rigid plastic will undergo stress particularly during heating and cooling, as the contents expand. From the mechanical point of view, equipment should be designed to withstand over-pressures. Also of significance are the mechanical properties of food and their relationship to texture.

In a general fashion, texture refers to the organization of the constituent parts of a structure, normally detected by eye; it has meaning as a quality attribute to people who work with foods. Among all the quality factors, the subject of food texture has received comparatively little serious attention for many decades. Therefore, food texture has come to be regarded as a suitable topic for research in many parts of the world in the last twenty years. A great deal of activity has taken place involving studies of the factors affecting the textural characteristics and correlating the results obtained by sensory methods with those obtained by the use of instruments (Brennan et al., 1975; Bourne, 1980; Olthoff et al., 1986; Seideman and Theer, 1986; Szczesniak, 1987).

As consumers, we are all acutely aware of texture when we eat or drink solids or liquids, and there can be no doubt that texture is an important determinant of food quality. In the mastication process, the forces that a food is subjected to are complex. Chewing breaks the food down and makes it more digestible. During this process, information is transmitted from various sensory receptors in the mouth to specific parts of

the brain, where it is integrated with other incoming information as well as information stored in the memory to give an overall impression of texture. If this does not conform to what we would expect from the particular food, we may well be disappointed with its quality.

Plant materials constitute an important category of foodstuffs in terms of consumption, nutritional contribution and sensory attributes. Their textures cover many intensities of softness/firmness crispiness, mealiness and juiciness to mention a few of the most desirable textural characteristics. Their uses include many plant parts: tubers, roots, leaves, nuts and fruits for soups, salads, appetizers, main courses, side dishes, desserts and snacks. Their morphological structure and chemical composition govern the textural characteristics that they exhibit.

The basic textural properties of plant tissues are provided by the cell wall and are dependent on the structural features of the cellular conglomerate of which it is comprised (Jackman et al., 1992). Cells are bonded together by a layer of pectic substances, referred to collectivity as the middle lamella, which provides the cohesion necessary to hold the conglomerate of cells together as a single structural unit. The plant cell wall bounds cytoplasm, a nucleus, other various organelles and a large central vacuole that may contain as much as 90 % of the cellular fluid. The cell wall in turn consists of cellulose microfibrils randomly oriented and embedded in a flexible, predominantly carbohydrate matrix. They are modified by the cytoplasmic components (carbohydrates, proteins and lipids) in a manner dependent on their amount, chemical and physical properties. The main parameters especially with respect to the carbohydrates, are the molecular weight and the degree of hydration/molecular packing as affected by heat treatment (Lee et al., 1970). Loss of texture in plant tissues as a result of thermal processing, can be expressed in terms of the apparent first order rate constant (k) and its dependence on temperature (E_a) or the corresponding terms employed by bacteriologists, D and z, respectively (Rao et al., 1985).

The kinetics of thermal softening of plant tissues have been reviewed by Rao and Lund (1986) and Bourne (1989) who tabulated the published data on the rate constants and activation energies. These authors also discussed the principal physical tests used to quantify softening which include: puncture, shear, back extrusion and deformation.

The study of the rates at which chemical reactions occur has been a powerful tool for understanding the nature of these reactions. The chemical reactions that occur when vegetable tissue is heated are complex, and a number of different reactions can be occurring simultaneously. In addition, the cell wall and middle lamella are not homogeneous. Further, the linkage between these chemical reactions and firmness is not clear, and is probably nonlinear (Bourne, 1989).

However, it has been found that applying the theories of chemical kinetics to the rate of softening of vegetable tissue can provide useful insights into the softening mechanism and may point the way to developing technologies that produce firmer textured processed products even though the progress of the reaction is measured by a physical test instead of a chemical test.

Objectives

The objectives of this research were to:

1) Evaluate thermal softening behavior of selected vegetables.

2) Evaluate their thermal softening kinetic parameters (k and D) and their temperature dependence.

3) Evaluate texture softening of the vegetables subjected to thermal processing (still and rotary) in thin profile plastic bags and cylindrical metal cans and

4) Predict texture loss/retention in thermo processed vegetables.

CHAPTER II

LITERATURE REVIEW

TEXTURE AS A MAJOR QUALITY FACTOR IN SOLID FOODS

With the advent of the *Journal of Texture Studies* in 1969, the term texture may be considered to have been generally accepted as a major division of sensory quality covering all kinesthetic responses of foods in whatever state they are in (Kramer, 1973). Indeed, the texture of foods is regarded by the processing industry as a key quality parameter in the development and acceptance of new food products and "fabricated" foods, as well as in the grading and quality control of traditional food products. Studies of texture must begin with the identification of words that are major quality descriptors. When such descriptors are found, they can be related to physical parameters, which can then be monitored for quality control. Similarly, combinations of ingredients that generate target values of these physical parameters can yield better food products. This is important because physical properties can be measured quickly and cheaply, while the same is not true for sensory measurements which are often time-consuming and require training of panelists.

Attempts to identify key textural attributes started as soon as texture was recognized to be a complex sensation. The characteristics of perceived "texture" are determined by different physical and physicochemical properties of the food and by the unique and complex features of the human sensory systems. It can be argued, however, that the stimulus in texture perception is predominantly mechanical in nature (Moskowitz and Jacobs, 1987).

Consequently, most, if not all, of the instrumental methods of texture evaluation can also be classified as mechanical tests. To be able to establish the relationship between texture as perceived and the properties of the food, or to interpret the results of instrumental evaluation methods, it is essential to understand the mechanics, or rheology,

of food deformation. This, of course, does not entail that rheology is the sole key to understanding texture, and there is ample evidence that geometrical, chemical, thermal, acoustic, and psychological factors can also play a major role in sensory textural assessment. But, even if we only attempt to deal with the rheological aspects of food texture evaluation, enormous difficulties immediately arise. The reason is not so much the mathematical complexity of the pertinent mechanical theories. It is mainly because in comparison with engineering materials for which these theories were originally developed, most foods and biological materials are at the same time physically unstable.

Anisotropy (as in meat fibers, for example) results in different mechanical properties in different directions, and physicochemical instability produces strong time-dependent properties. The fundamental principals of rheological evaluation of foods are basically the same as those that are applicable to engineering materials, especially polymers. There are differences in the interpretation of the test results. This is because any meaningful interpretation must take into account the specific structural features and the mechanical and biological history of the particular food material in question (Peleg, 1987).

However, the study of food texture is hindered by its discontinuous nature. Although it is a sensory property and, hence, must be ultimately related to a human response, it is often measured by mechanical means that imply the application of engineering principles. The sensory apparatus responds to mechanical properties of food in the mouth (as well as to other stimuli such as auditory and tactile properties); the sensory analyst thus depends on evaluating the reactions of humans, but the food rheologist measures the instrumental behavior of materials in terms of stress, strain, and time effects. It should not be terribly surprising that a major failure in understanding food texture has been the lack of successful integration of these seemingly divergent approaches. This is especially so when one considers that in both cases, the response observed is a result of forces acting on an underlying organized structure. Indeed, perhaps the best approach to defining food texture would be based on how sensory and mechanical responses relate to structural organization.

WHAT IS TEXTURE?

The word "texture" has meaning as a quality attribute to people who work with foods. Many definitions of the term "texture" have been proposed and it is surprising to find there is no completely satisfactory or universally accepted definition of this word as applied to foods. Webster's Dictionary under the term "texture" refers to textiles and weaving in general and then continues, "*it is the manner of structure, interrelation of parts, structural quality*". Examples include textiles, fabrics, artistic composition, music, poetry, bones and plants, and foods are not mentioned.

Brennan (1988) used the definition of British Standards Institution and defined texture as the attribute of a substance resulting from a combination of physical properties and perceived by the senses of touch (including kinaesthesis and mouthfeel), sight and hearing. Physical properties may include size, shape, nature and conformation of constituent structural elements. Texture was clearly defined as a sensory attribute and so only measurable directly by sensory means. Three senses, namely touch, sight and hearing may be involved in sensory assessments.

Bourne (1980) indicated that one problem in the definition of texture is the fact that texture has customarily been considered as a "one point" measurement similar to the measurement of °Brix and pH, whereas, in fact, texture is a group of properties of foods. He, then, continued that, it is time to abandon the word "texture", with its implied association of being a single parameter and turn instead to a term such as "textural properties" which implies a number of parameters. Bourne (1980) put forward the following definition: *"The textural properties of a food are that group of physical characteristics that are sensed by the feeling of touch, are related to the deformation, disintegration and flow of the food under the application of force, and are measured objectively by functions of force, time and distance"*. This definition excludes physical characteristics such as temperature, optical and electrical properties that have nothing to do with texture and restricts the meaning to those properties that can be felt in the mouth or in the hand.

Many attempts have been made to identify, define and classify specific textural terms. Szczeniak (1963), classified textural term in three categories: 1) mechanical

characteristics, which are related to the reaction of food to stress, and subdivided into: primary parameters of hardness, cohesiveness, viscosity, elasticity and adhesiveness, and secondary parameters of brittleness, chewiness and gumminess. 2) geometrical characteristics, those related to the size, shape and orientation of particles within the food, 3) other characteristics which are related to the perception of moisture and fat contents of food. The authors mentioned above and many others (Sherman, 1969; Brennan, 1988) have pointed out the importance of defining terms and adopting some form of classification of such terms when undertaking work involving the assessment of the food texture. However, as yet no one classification has been adopted internationally.

TEXTURE PERCEPTION AND MEASUREMENT

The objective of the rheological analysis of solid foods is usually texture characterization. Therefore, one is generally interested in material performances under strain conditions comparable to those that food undergoes during biting and chewing. An attribute of texture is, also, the result from a combination of physical and chemical properties, and these include the size, shape, number, nature and arrangement of the constituent structural elements (Peleg, 1987).

Textural properties are often a reflection of the structure of a material, and so a structure of a material can often lead to a better understanding of its physical properties and ultimately its textural characteristics. This concept is the basis for most instrumental methods in texture evaluation. The most common principle employed in instrumental texture measurements is to cause a probe to come into contact with the sample. The sample is deformed and the extent of the deformation and/or the resistance offered by the sample is noted and used as an index of the texture of the food. The use and description of many instruments have been reviewed by several authors (Mohsenin, 1970; Szczesniak, 1973; Voisey, 1976; Brennan, 1980; Bourne, 1982; Prentice, 1984).

The use of digital computers in research for data acquisition and analysis is

commonplace. Direct data acquisition by computer is relatively rapid and error-free compared to manual transcription of strip-chart records. Data can also be analyzed by the computer as the experiment proceeds, making the results immediately available at the conclusion of a test. In addition, the computer can be used as a feedback control system to adjust experimental parameters continuously in response to transducer output. Textural studies in which the stress or strain history is controlled are examples of such tests. The analysis technique has been adapted for use with texture measurement systems such as the Instron, the Ottawa Texture Measurement System, Lloyd Instruments material testing system, and the General Foods Texturometer. The technique traditionally consists of analyzing force-time curves produced on an analog strip chart recorder connected to an instrumental texture measuring machine.

The instruments normally provide a force/time plot from which a force/deformation (F/D) plot is derived and from which data are taken. Taking the data from the plots is time consuming, requiring measurement of the various distances, slopes and areas with a ruler and planimeter. If slopes are of interest, determining linear limits and accurately measuring the slopes of short sections of the curve are difficult. In addition, with the use of plots, recorder response speed may be a limiting factor. Computer attachments providing automatic readout of selected force-distance parameters are available. Abbott et al. (1982) described computer-control and data-acquisition systems for the Instron Model TM (table model) Testing Machine. In this study, a control system was constructed in which the "up", "down" and "stop" functions were activated by computer-controlled relays. Stanley et al. (1989) obtained force data from the null-balance potentiometer of the strip-chart recorder circuit; the response time of this system was limited by the dynamics of the potentiometer and recording pen. Abbott et al. (1982) and Buckley et al. (1984) obtained a faster response by acquiring the force data directly from the load cell signal conditioner, the analog output of which was put into machine-readable terms via a low-pass filter, and analog-to-digital (A/D) converter.

The use of a computer makes practical the measurement of large numbers of samples and large numbers of variables. Satisfactory automatic extraction of data depends on thorough examination of sample curves and careful definition of the parameters to be measured. The various features can be defined by appropriate qualifying terms such as change in slope, deformation "windows," maximum and minimum forces, etc. Separate analysis programs will probably be necessary for foods exhibiting extremely different curve shapes.

However, a computerized analysis method has the capability to include several elements which would not be possible without computerization. The amount of data that can be processed can be increased since it is an efficient and automated procedure. The analysis time is deduced by 100-fold and the convenience that comes from using a personal computer makes the program an easily accessible tool.

Instrumental methods of texture measurement have been grouped into four classes (Brennan and Jowitt, 1977). *Empirical methods*, usually involve measurement of the resistance to deformation offered by the sample. Such results are dependent on probe geometry, rate of deformation and sample size. *Imitative methods*, attempt to simulate, to some degree, the forces and deformation that the food is subjected to whilst the food is being consumed. *Fundamental methods*, designed to measure one (or more) well defined physical property of a sample under test and to relate this property to textural characteristics assessed sensorily. *Chemical and microscopic methods*, involve biochemical changes which occur whilst the fruit and vegetables are growing and during subsequent storage which have a direct effect on the texture.

However, each unit of the food and feed materials selected from agricultural products is in itself a biological system which differs from identical mass-produced products. These materials are alive, constantly undergoing changes in shape, size, respiration, and other aspects of life processes. During development and storage, the cells are sensitive to such external influences as humidity, temperature, oxygen, food supply,

energy consumption, as well as the interplay of internal factors which are different to control. In biological bodies, elasticity varies with age and physiological conditions.

As a result of this complex situation, in studying the rheology of a biological system, only an empirical approach is possible. The treatment of the problem usually consists of either a simple description of observed facts or theoretical considerations which often lead to very complicated mathematical formulations containing many variables. Constants, as known by physical experiments, rarely exist.

Despite this apparently hopeless situation, the application of the fundamental principles of mechanics and rheology is a good start for the study of mechanical behavior in biological systems. Until specific laws and principles are derived and established, we can study the relative changes for one definite property by making a rather rough approximation of other variables influencing this one property (Mohsenin, 1986).

The rheological properties of foods obviously play an important role in textural evaluation as well as in the selection of the correct equipment in operation involving the deformation of foods. The more fundamental rheological properties will now be described.

Compressive and Tensile Tests

The tensile or compressive strength of a material is the maximum tensile or compressive stress which a material is capable of sustaining before rupturing. It is calculated from the maximum load during a tensile or compression test and the cross-sectional area of the specimen (Finney, 1973). There are two main types of compression tests:

1) Uniaxial compression in which the sample is compressed in one direction and is unrestrained in the other two dimensions.

2) Biaxial or triaxial compression in which the sample is compressed in three dimensions, usually by means of hydraulic pressure. Figure 1 illustrates the principle of uniaxial and triaxial compression.

Figure 1. Uniaxial compression (a) and triaxial compression (b) compared (Bourne, 1982)

(a)   (b)

Unstressed   *Stressed*   *Unstressed*   *Stressed*
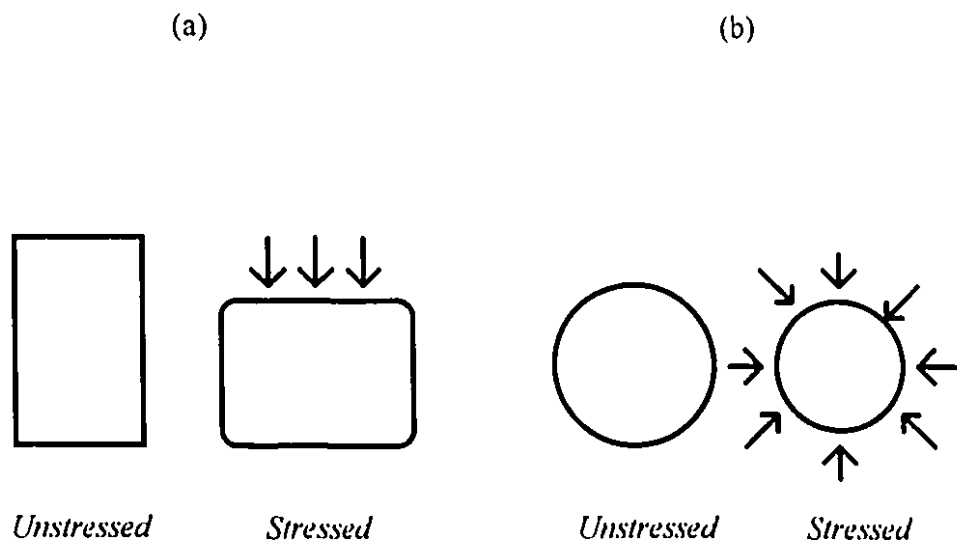
In most uniaxial compressive tests, a food specimen, usually a cylinder or cube, is deformed at a constant deformation rate, as shown schematically in Figure 2. The force that develops is recorded continuously, and the typical relationship between force and time (or absolute deformation) has the shape shown in Figure 3a. The concave upward shape is partly a result of the increasing cross-sectional area and the non linearity of the strain; such "raw curves" convey little information regarding the rheological character of the food in question.

Figure 2. Changes in the specimen dimensions as a result of large deformation. H_0 and A_0 are the original length and diameter, respectively; $H(t)$ and $A(t)$ are the dimensions after time t. (Peleg, 1987)
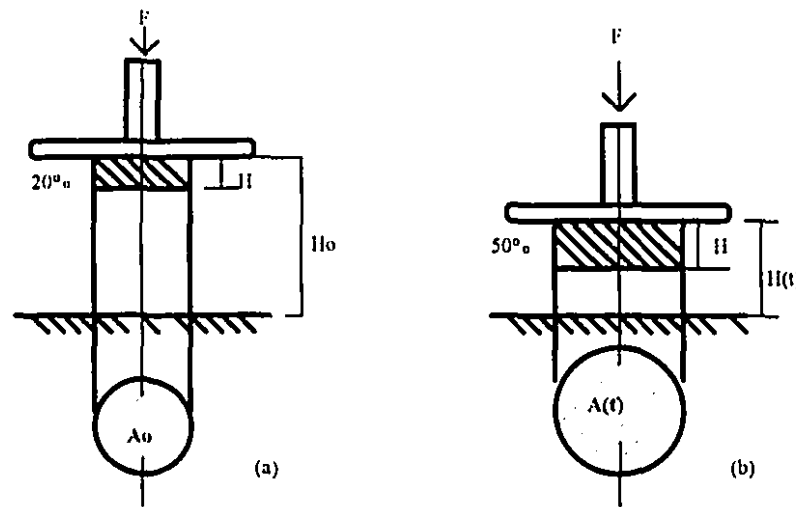
The kind of additional information is demonstrated schematically in Figure 3. The concave upward curve in true coordinates indicates a predominantly compressible material (e.g., bread, sponges). A concave downward curve is an indication of a predominantly yielding material that undergoes considerable structural disintegration as a result of straining. A linear or an approximately linear relationship has two possible interpretations. The first is that the material is predominantly elastic or rubbery. The second is that structural destruction and yielding is compensated by the compaction of the collapsed

structure remnants. It is, of course, also possible that each of the described effects become

dominant at a different strain, thus producing a relationship that has alternating concave

and convex regions.

Figure 3. a, engineering and b, true stress strain relationship (Peleg, 1987)
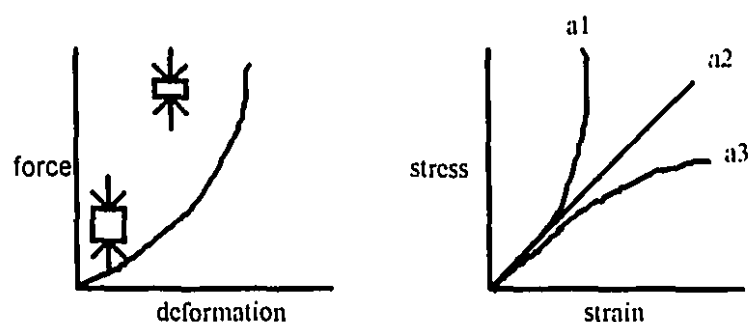
A *puncture* test consists of measuring the force required to push a probe or punch

into a food to a depth that causes irreversible crushing. It imitates the jabbing motion of

the thumb that is wisely used to measure the firmness of products such as apples and

pears. The Magness-Taylor pressure tester, the Chatillon Pressure Tester, and the Effi-Gi

pressure tester are well known and widely used by horticulturists (Bourne, 1980). These

hand-held pressure testers are convenient for the horticulturist because they can be carried

into the field. A comprehensive review of the theory and application of the puncture test in

food texture measurement have been published (Voisey P. W., 1976). The Maturometer is

a multiple punch apparatus widely used in Australia to measure the maturity of fresh green peas.

In *tension*, the situation is reversed with respect to the slope of the force-deformation curve, primarily because the cross-sectional area decreases with the deformation. In true coordinates, the interpretation is similar, with the distinction that strain hardening replaces compressibility or compaction as a means of strength augmentation.

A conventional tensile test assumes that the sample fractures almost instantaneously in a plane that is approximately perpendicular to the plane of the applied tension. The maximum force is the tensile strength of the material. Many foods subjected to tension do not fail suddenly; fracture begins with the small crack that slowly spread across the sample over a comparatively long period of time and the crack may or may not be perpendicular to the plane of the applied force. Several cracks may appear and spread simultaneously. This type of break makes it difficult to obtain a meaningful interpretation of the tensile force measurement.

Another problem with many foods is that of holding the sample so that the break occurs within the sample and not at the jaws that hold the sample. This problem is often solved by cutting out dumbbell-shaped test pieces and holding the sample at the wide ends. The sample is then more likely to break in the narrow center portion of the test piece.

However, as Bourne (1982) pointed out the tensile tests are not widely used with food which is understandable because the process of mastication involves compression, not tension, of the food between the molars. Tensile tests may be used to measure the adhesion of a food to a surface.

Modulus of deformability (stiffness)

A convenient parameter to quantify the stiffness of a material is the slope of the

small, both the true and apparent curves are, for all practical purposes, straight lines (Peleg, 1987).

In such cases, uniaxial compression applied to a Hookean solid of uniform cross-sectional areas a small strain before rupture gives rise to the property known as Young's modulus of elasticity (Bourne, 1982) and its meaning as a mechanical measure of stiffness is unambiguous.

$$Young\ modulus\ of\ elasticity\ E = \frac{compressive - stress}{compressive - strain} = \frac{F}{\Delta L} \frac{A}{L}$$

Where F is the applied force; A, the cross-sectional area; L, the unstressed height; and ΔL, the change in height due to F.

For most food materials, in contrast, the stress-strain relationship is frequently curved, and is also a function of factors such as specimen size and deformation rate. Mohsenin and Mittal (1977) proposed the term "modulus of deformability" for food in place of modulus of elasticity in order to preserve the purity of the meaning of the latter term.

However, when a cylinder of material is compressed uniaxially, its diameter usually increases. Poisson's ratio is defined as the ratio of the fractional increase in diameter (transverse strain) and the fractional decrease in height (axial strain):

$$Poisson's\ ratio\ \mu = \frac{change\ in\ width\ per\ unit\ width}{change\ in\ length\ per\ unit\ length} = \frac{\Delta D / D}{\Delta L / L}$$

Where D is the diameter of unstressed material; ΔD, the change in diameter caused by stress; L, the height of unstressed material; and ΔL, the change in height caused by stress.

Poisson's ratio is 0.5 for materials in which no volume change occurs under compression. The potato has a Poisson's ratio of 0.45 to 0.49, indicating there is a small change in volume as it changes shape. The calculation of Poisson's ratio assumes uniform distribution of stress, and stresses that are below the proportional limit of the material. These conditions usually do not prevail during the testing of food (Bourne, 1982).

Compression-Decompression Tests

From a rheological point of view, three types of deformation are generally recognized; elastic, plastic, and viscous. Even though few materials are either perfectly elastic, plastic, or viscous, theories from elasticity, plasticity, and viscosity have importance in many studies of the rheological behavior of materials. Such concepts also have significance to many of the investigations of textural properties of foods (Finney, 1973).

If an ideal elastic body is subjected to a compression-decompression cycle (Figure 4a), it will always return to its original shape, and all the energy invested in the deformation process will be recovered. In most non ideal elastic materials (e.g., rubber), some energy is always lost mainly due to internal friction. The body, nevertheless, will return to its original shape and will exhibit the same or almost the same properties on being subjected to a subsequent deformation cycle. The energy that dissipates in the process, usually in the form of heat, is represented by the area of the hysteresis loop of the force-deformation curve (Figure 4b).

Most solid food materials are neither ideal elastic nor rubbery. Part of the deformation will, therefore, remain permanent after decompression (plastic deformation). In such materials, a considerable portion of the energy invested in the specimen deformation is irrecoverable due to both internal friction and irreversible structural modifications (Figure 4c).

Figure 4: (a) Linear elasticity in rigid material (steel), (b) non-linear elasticity in semi-rigid material (rubber), (c) inelasticity in plant material (corn).(Mohsenin, 1986)
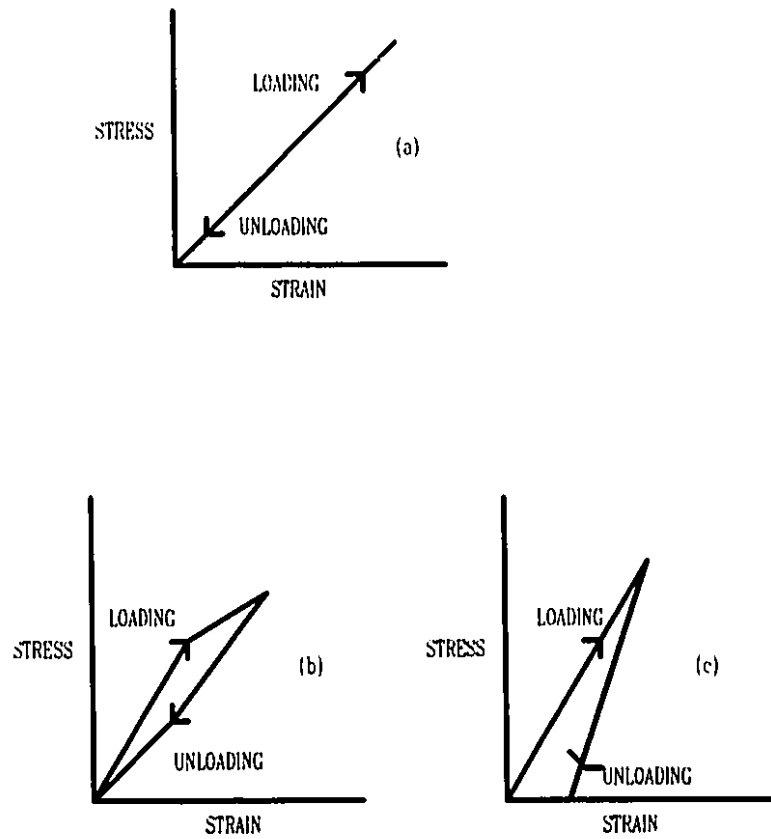
The ratio between the recoverable and the total deformation was suggested as a "degree of elasticity" and, similarly, the ratio between recoverable and irrecoverable work can also be a characteristic of the material. It ought to be remembered, however, that the magnitude of these parameters may strongly depend on the final strain level as well as on other factors (notably the specimen dimensions and the deformation rate). In such cases, the dependency of these parameters on the test conditions (e.g., strain, specimen diameter) themselves can be considered as a rheological fingerprint of the material and be interpreted in terms such as continuous structural disintegration, build-up of hydrostatic pressure, etc.

Mohsenin (1986) indicated that none of the biological materials tested so far show perfect elasticity. Regardless of the level of load there always seems to be some residual deformation remaining after the first loading and unloading cycle. The major part of residual deformation is due to initial setting which may be caused by the presence of pores or air spaces, weak ruptured cells on the surface, microscopic cracks in brittle materials such as grains and dry beans, and other discontinuities which may exist in the structure of the material.

Effect of deformation rate and sample dimensions in objective measurements

Most if not all solid foods are known to be viscoelastic materials. "Viscoelastic" in our context means that their mechanical behavior is neither purely elastic nor purely viscous, but something in between that shares the properties of both. One of the prominent characteristics of viscoelastic materials is that the stress they develop is not only a function on the strain, but also the rate at which it is applied. Generally, the faster the rate, the higher the stress. There is, however, a theoretical limit to the rate effect. The exact nature of the rate dependency is a characteristic of the material. The more solid or elastic it is, the less is the rate effect. Thus, rigid food materials such as unripe fruits and vegetables are less rate-sensitive than are soft foods like some cheeses.

Many food materials, notably plant and animal tissues, are fluid-containing structures. In many cases, the stress level in a deformed specimen taken from such materials is largely a result of hydrostatic pressure build-up. The pressure dissipation rate depends on the total resistance to the fluid outflow toward and through the specimen walls (Figure 5).

Figure 5. Resistance to internal flow in specimens having different diameters.(Peleg, 1987)
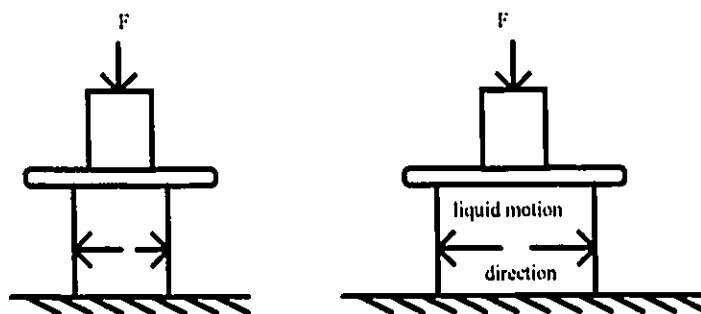
This resistance is primarily determined by the density, porosity, and microstructure of the compressed solid matrix and the total length of materials; a specimen

with a larger diameter exhibits a higher apparent strength (i.e., higher stresses) compared with a "thinner" specimen at the same strain.

Theoretically, the specimen's dimensional effects are also linked to that of the deformations rate's effects. This is because at the same constant deformation rate, a shorter specimen is deformed at a higher true strain rate. The absolute magnitude of the effect, because of its dependency both on experimental conditions (e.g., friction) and inherent structural properties, can vary considerably and, therefore, it is not surprising that there are conflicting reports as to whether the effect is indeed significant. It ought to be mentioned that when the effect is significant, the dependency itself can be considered as a textural property of the given food material.

Other factors which can affect the results obtained in a deformation and fracture test have been pointed out by Luyten et al. (1992), Culiol and Sherman (1976) are:

The shape of the test-piece.

The friction between compression plates and a test piece will be relatively higher for flatter pieces at equal contact area. The homogeneity of the deformation depends on the shape of the test piece. In compression tests, the piece may not be too high, since it otherwise may buckle rather than fracture.

Apparatus.

Stiffness of the apparatus must be taken into account if it is not much higher than the stiffness of the test piece. Range of force and material of the compression plates, in relation to friction are also important.

Other factors.

The way a test-piece is obtained may affect its shape as well as any drying out of the sample before testing. For many food materials, the speed of cutting affects the shape of the test-piece: when cutting slower, test-pieces are often straighter. When performing a test, environmental factors such as temperature and humidity must be considered.

GENERAL CONSIDERATIONS IN TEXTURE OF PLANT FOODSTUFFS

Structural aspects

Typical plants are composed of roots, stems, leaves, flowers, fruits (mature and immature) tubers and seeds. The roots anchor the plant in the soil and absorb water and minerals from it to supply nutrients to the plant. The stem is an above ground organ that supports the leaves, flowers and fruits. The leaves are thin and flat organs with numerous openings (stomata) responsible for photosynthesis. The flowers are sexual organs needed by the plant for sexual propagation.

Plant organs are composed of tissues which are organizations of cells having specific functions. The main tissue types in plants are: epidermis, xylem, phloem, collenchyma, sclerenchma, and parenchyma. A multitude of variations are possible on how plant organs combine the different tissues (Esau, 1966).

The textural properties of a plant organ are determined by the relative proportions of the different tissues. The size and shape of the cells, the ratio of the cytoplasm to the vacuoles, the volume of intercellular spaces, the thickness of the cell wall, the osmotic pressure and the type of solutes present govern the specific textural characteristics exhibited by the parenchyma of fruits and vegetables. Parenchyma is the main plant tissue consumed as food by man and animals, not only because it is the tissue in which the plant has deposited the nutrients, but also because it has the most acceptable texture and is easily broken down, mechanically and chemically, to release the life substances. The cell wall and the middle lamella, their quantity and mechanical properties, are very important in determining how the plant foodstuff will behave under the disintegration action of the forces applied to it during mastication. If the cell wall is stronger than the middle lamella, the tissue will yield between the cells and the cell contents will not be released during mastication. If the cell wall is weaker than the middle lamella, the yielding will occur through the cells and as a result, the liquid contents will be released. In the former case

(eg., raw potatoes), the sensory perception will be that of a dry, chalky granular texture. In the second case (eg., good quality apples), the sensory perception will be that of a juicy product (Ilker and Szczeniak, 1990).

Chemical aspects

Carbohydrates occur in the cytoplasm as dissolved low molecular weight sugars primarily glucose and fructose, but also sucrose and as starch tightly packed in starch grains stored in the plastids. When most carbohydrates are in the form of sugars, the raw tissue is generally tender and succulent. When most carbohydrates are in the form of starch, the raw tissue is firm and hard, and the liquid expressed on mastication may feel 'chalky' due to the presence of suspended starch granules (Lee et al., 1970).

Starch is the principal component of grains, legume, and some root tubers and is a major constituent of foods. It is extracted from the different indigenous sources and used as an ingredient in its own right. Small quantities may not have a pronounced effect, but the large amounts found in some seeds or tubers may characterize texture to a similar extent as do the cell walls. Starch occurs as granules which vary in size and shape according to their origin and contain amylose, a linear polymer, and amylopectin, a branched polymer. Starch granules absorb little water but on heating in an excess of water the granules swell and absorb water; the amylose leaches out of the granule and the collapsed granules containing amylopectin are held in an amylose matrix (Vincent and Lillford, 1991).This in turn causes the starch grain to spew out, unfold and immobilize water in the process of gelatinization. Together with cell separation and in some cases cell rupture, this leads to considerable softening of the tissue, loss of crispness and development of mealiness or pastiness.

With respect to texture, the most important reaction is gelatinization, an enormous swelling of starch molecules when exposed to heat and sufficient water. Gelatinization temperatures vary but typically are between 60 and 70 °C. In raw tubers, rhizomes, and

immature seeds, sufficient water is present within the cells to allow for complete gelatinization (Reeve, 1970).

In mature seeds, judicious addition of water can control the degree of gelatinization and the resulting textural changes (Derby et al., 1975). In addition, the presence of lipids, sugars, acids and salts can modify the degree of gelatinization and the following texture of processed fruit and vegetables.

A known textural defect in potatoes is the conversion of starch to sugars under low temperature storage (Ilker and Szczeniak, 1990). This results in poor texture when such potatoes are boiled, and leads to serious problems in processing when such potatoes are used for making chips or dehydrated mashed potatoes. The conversion of starch to sugars is the mechanism by which plants develop protection from cold injury since, on an equal weight basis, the low molecular weight sugars bind more water and, thus, reduce the temperature at which the water in the cytoplasm will freeze.

Nonenzymatic *proteins* can occur in the plant tissue as part of the cell wall and as storage material in some leucoplasts. This storage material represents most of the protein detected by chemical analysis. Proteins may be categorized into: globular, which are temperature-sensitive such as whey and soya bean; and random-coil, include temperature-insensitive proteins such as casein. The first type can be texturised by heating and the second by spinning methods (Vincent and Lillford, 1991).

Plant tissues high in protein (such as legumes and grains) are generally cooked prior to consumption to make them more acceptable in texture. Proteins unfold, hydrate and denature during cooking, leading to the immobilization of water and general softening of the tissues. As a rule, cooked plant materials high in starch or proteins do not release water on mastication. They may feel moist, but not juicy, in the mouth. The protein content of ripe fruit is usually less than 1% and it is logical to assume that it has a minimal direct effect on texture. However, it may have a very profound indirect effect through its

potential role in maintaining the integrity of the cell membrane. In contrast, the protein content of some nuts is as high as 25-26% and certainly must influence texture as a result of swelling (Ilker and Szczeniak, 1989).

Lipids: Fat present in plant tissue is generally unsaturated. In the case of dry legumes, fatty acids are highly unsaturated (Uebersax and Ruengsakulrach, 1989), however, the exact degree of unsaturation depends on the specific plant. Plant foodstuffs high in fat are usually low in moisture (most nuts, 40-73% fat, 3-5% water; soybeans, 18% fat, 7% water), notable exception being the avocado (26% fat, 65% water) and certain olives about 20% fat, and 73% water (Ilker and Szczesniak, 1989). Lipids provide lubrication properties and depending on the size of the fat granules and the specific structural features of the tissue, may contribute to hardness/crispness (as in nuts) or to softness/mealiness (as in avocado). High levels of fat impart a fatty/oily mouthfeel depending on whether the fat is mostly solid or mostly liquid at consumption temperature.

Cell wall contribution in textural properties of plant tissue

The cell wall probably has the most important bearing on the textural properties of plant tissue. Thus, its chemistry and geometry deserve attention.

Plant cell walls vary greatly in thickness depending partly on the role the specific cells play in the structure of the plant and partly on their age. Studies by Northcote (1958) and Raven et al., (1976) indicated that there are two or three layers in plant cell walls: the intercellular substance (*middle lamella*), which cement together the different cells, and the *primary wall* in addition, many cells deposit a *secondary cell wall*.

The *middle lamella* forms during cell division and is composed predominantly of pectic materials whose nature changes according to the developmental stage of the plant organ. As the tissue matures and the cells expand in size, the middle lamella may connect only proteins of the enlarged cells, thereby creating cellular spaces. These may be filled

with air (apple), CO_2, water vapor (especially in the leaves), and may take the form of channels (lettuce).

The primary cell wall of plant foodstuffs is composed of an organized network of similar percentages of pectic substances, hemicelluloses, cellulose and with protein accounting for about 10% (Van Buren, 1979; Albersheim, 1974). In a very simplified sense, cellulose gives rigidity and resistance to tearing, while pectic substances, extension and hemicelluloses provide plasticity and allow the cell wall to stretch.

The primary cell wall is a highly hydrated structure with water being one of its most variable features. Water is believed to have four major functions in the cell wall; 1) as a structural component of the matrix gel, 2) as a wetting agent hindering direct hydrogen bonding between polymers, 3) as a stabilizer of polymer conformations, and 4) as a solvent (and transport medium) for salts, enzymes and low molecular weight organic compounds. In some cases, as the cell matures and stops growing, a secondary cell wall forms which is a rigid structure composed mainly of cellulose. It is particularly important in specialized cells functioning in conduction and structural strengthening (Ilker and Szczesniak, 1990).

EFFECT OF HEAT PROCESSING ON TEXTURE OF PLANT FOOD CHANGES

Heat treatment of agricultural materials is considered an important process for numerous applications. In heat treatment of living biological materials, obviously the time and temperature of exposure to heat is very critical. Literature in this area shows little evidence of work to find out the location of the microorganism which needs to be eradicated. Knowing this location, the size and thermal conductivity of the fruit, it would be possible to estimate in advance what temperature range and time limits would be most effective. There is considerable amount of literature, however, using the fundamental approach of heat transfer and utilization of thermal and physical properties of the material involved (Mohsenin, 1980).

Studies by Bartolome and Hoff (1972) indicated that controlled heating of a number of fruits and vegetables is accompanied by a modification of pectic substances resulting in strengt'.ening of cell walls and intercellular adhesion and firmer fruit in canned products.

Uebersax and Ruengsakulrach (1989) in a scanning electron microscope (SEM) study of dry beans showed that thermal processing induces the largest alteration in structure ar ! the initiation of diverse chemical reactions among bean constituents. They reported that the scanning electron microscope photograph of soaked/blanched beans illustrates the increase in solubility of protein (loss of indigenous spherical structure) and the relatively unchanged starch granules. During the soak/blanch treatment, native protopectin may also form pectin which will rapidly polymerize. Soluble protein and pectin may leach causing an increase in viscosity of the cooking media. It has been proposed that the differences in pectin composition could be a major factor determining cookability of dry beans. Soaked /blanched beans are subjected to further heating under pressure during retort processing. The absorbed water and heating initiate thermal degradation or inter/intra-cellular and cohesive materials (middle lamella) and thus allows cells to separate and soften.

Results demonstrated (Rockland and Jones, 1974) that in dry and soaked/blanched (30 minutes at 21 °C + 30 minutes at 88 °C) beans, fractures occur across the cell wall; however, in the canned beans, fractures occur in the middle lamella, leaving the cell intact. This cell separation may account for the notable texture differences exhibited.

So far it has been mentioned that chemical studies on the effect of processing on the mechanical properties of the cell wall have been concerned mainly with the changes in pectins. Possible molecular transformation of other cell wall constituents remain largely unknown. Physical studies have involved crystallography, X-ray diffraction, volume and permeability changes, osmotic pressure, and optical and electron microscopy (Willis and Teixeira, 1988).

Cell wall softening is found after heating, freeze-thawing, brining and air drying (Reeve, 1970). Pectin solubilization occurs both at low and high pH. In addition, demethoxylation occurs during heating; pectin methyl esterase is activated between 50-60 deg C. Carboxyl groups may form salt linkages with endogenous ions from the ruptured protoplast, or with Ca, Mg and K added to the medium. Salt linkages may firm up the softened wall to some extent and addition of divalent ions to the canning liquid is used customarily in the processing of some vegetables (Van Buren, 1979; Hoff, 1973)

Kinetic data needed

The initial objective of experimental kinetic studies is the development of a mathematical model to describe the reaction rate as a function of the experimental variables. Various rate expressions can be combined with the basic definition of the reaction rate to yield equations which can be used to predict the composition of the batch system as a function of time (Hill and Grieger-Block, 1980)

A number of chemical changes take place when foods are subjected to a thermal process. Because of the complex chemical composition of foods, it has not been possible to quantify all the changes taking place as a result of heating and to relate, in a quantitative manner, the chemical changes to physical changes such as softening. A simple and useful approach in softening studies has been to express data in terms of either apparent reaction rate constants (Equation 1) or, analogous to microbial death kinetics, in terms of the D-value.

$$-(dC / dt) = k_n C^n \qquad (1)$$

where C is the property used to characterize softening, t is time, k_n is the reaction rate constant, and n is the order of change. The negative sign in Equation 1 indicates that the magnitude of the property at a constant temperature decreases with time.

For materials that soften upon heating, this is true for a quantity such as puncture force but for a parameter such as deformation there will be an increase with time and Equation 1 should be written without the negative sign. If the time dependence of the parameter C is first order (n=1), then it can be expressed as the D-value which is the time in minutes for a one log cycle change of property or decimal reduction time at a constant temperature. The D-value and the first order reaction rate constant are related by the equation :

$$k = \frac{2.303}{D} \tag{2}$$

In addition to describing the change in a property as a function of time at a fixed temperature, one must be able to describe the effect of temperature on the property. Either the Arrhenius relationship can be used to describe the effect of temperature on the reaction rate constant:

$$k = k_o \, e^{-E_a/RT} \tag{3}$$

where E_a is the activation energy (calories / mole) , R is the gas constant , T is the absolute temperature (^{o}K) , and k_o is a constant
or the TDT concept

$$log(\frac{TDT1}{TDT2}) = \frac{(T2-T1)}{z} \tag{4}$$

where TDT1 is the thermal death time at temperature T1, TDT2 is the thermal death time at temperature T2, and z is the temperature range to change the TDT by a factor of ten.

The z-value is used in microbiology to characterize the influence of temperature on the D-value. The z-value and E_a are related (Lund, 1975 b) by:

$$E_a = \frac{2.303 \ R \ T \ T_{ref}}{z} \tag{5}$$

A number of processes that have been studied show a linear relationship between the log of the amount of substance present versus the time. Many of these processes do not arise from simple first-order chemical reactions, or the chemistry of the process may be unclear. Nevertheless, since they empirically fit the model for a first-order chemical reaction, they are commonly called pseudo first order processes. The slope of the log (concentration) versus time plot is called the apparent first order rate constant. The modifying adjective "apparent" is used to signify that the process is not truly first order in the chemical sense, but that the experimental data gives a good fit to the first order chemistry model (Bourne, 1989).

In order to obtain softening data suitable for determining kinetic parameters, a food sample must be subjected to different temperatures for different time periods. It would be preferable to employ at least five different temperatures and at each temperature, at least five different time periods. In general, softening rates of foods are higher than thermal degradation of vitamins; therefore, the time periods for experiments on softening must be relatively short in order to avoid excessive softening. It is important to note that the food must be subjected to conditions similar to those under which the kinetic data will be applied. For example, the heat and mass transport phenomena during the heating of canned black beans are different than when the beans are cooked directly in boiling water. The use of different sizes of a given food also can result in different magnitudes of the kinetic parameters (Rao and Lund, 1986).

Kinetics of thermal softening of vegetables

Vegetables are subjected to sterilization in order to extend their shelf life. During sterilization, quality factors such as firmness, stiffness and springiness are reduced along with the activity of undesirable microorganisms. Huang and Bourne (1983) studied the kinetics of thermal softening of vegetables and postulated that the rate of softening reflects two simultaneous first order mechanisms. Mechanism one is probably due to pectic changes in the interlamellar layer and accounts for 85-97% of the original tissue firmness. Its relative contribution to firmness decreases practically to zero during processing. Mechanism two, whose nature has not been identified, is responsible for the residual firmness of the vegetables after prolonged heating. Figure 6 illustrates the softening of canned diced yellow beets.

Figure 6. Softening of canned diced yellow beets at 220 °F (Huang and Bourne, 1983)
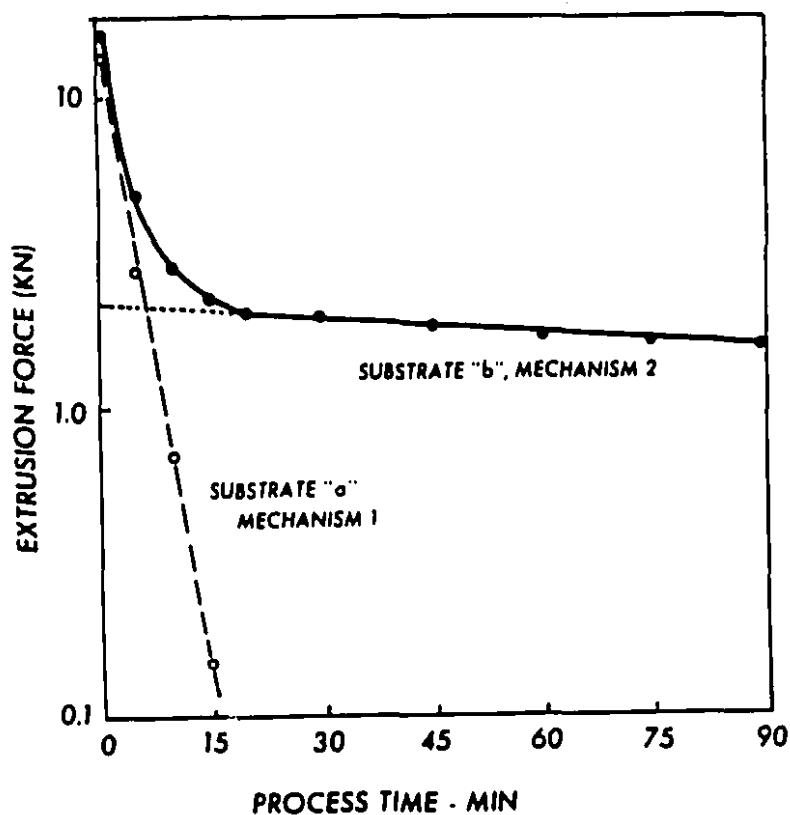
The above seems to confirm the work of Loh and Breene (1981) who found that the first -order kinetic model was a much better predictor of textural changes on heating in tissues having thin cell walls (such as those derived from fruits) than in tissue having thick cell walls (such as those derived from stem and roots).

Loh et al. (1982) used white potato and Chinese water chestnut to study between-species difference in the rate of thermal softening. These plant products were selected as examples of tissues that are, respectively, very susceptible and very resistant to thermal texture destruction in spite of similarities in gross chemical composition. Examination of tissues with the scanning electron microscope (SEM) suggested that the cell wall separation was the main cause of texture loss. However, the microstructure of the resulting plant tissue, as seen in SEM, did not in itself predict thermal texture losses. Loh et al. (1982) suggested that differences in ultra structure and/or in detailed chemical composition may govern textural degradation on heating.

The breakdown of the middle lamella on cooking was also observed by Sefa-Dedeh et al. (1978) in cow peas using SEM. It occurred at 100 $^\circ$C and followed first order kinetics. The thermal softening of the middle lamella, rupture under stress occurs along it in cooked plant tissue and across the cell wall in raw plant tissue.

Similar degradation of the middle lamella at 100 $^\circ$C and separation of individual cells was reported in potatoes (Reeve, 1970) and apples (Sterling, 1955). A mealy texture in cooked potatoes is the result of this phenomenon, whereas adherence of cell walls is linked to sogginess.

While the degradation of the middle lamella appears to be common during cooking, the breakdown of the entire cell wall can also occur. In sweet potato, such a breakdown results in a soggy texture (Sterling , 1963).

The kinetics of thermal softening of plant tissues have been reviewed by Rao and Lund (1986), who tabulated the published data on the rate constants and activation energies and pointed out some of the experimental deficiencies. These authors also

discussed the physical tests used to quantify softening: puncture, shear, back extrusion and deformation. Sefa-Dedeh et al. (1978) used the wire extrusion grid cell with the Ottawa Texture Measuring System and the shear-compression cell with the Texture Test System to quantify the effect of cooking temperature and time on cow pea texture.

A recent study on the role of pectic substances in thermal softening was conducted by Fuchigami (1987) using Japanese radishes as the test material. This researcher found that pectic substances in the cell walls of radishes are insoluble and stable because of calcium bridges, and that pectins linked with insoluble hemicelluloses through covalent bonds are absent. He obtained a good positive correlation between the degree of thermal softening and the amount of pectin extracted with 0.01N HCl at pH 2.0. Tissues containing less of this pectin fraction and more of fractions extractable with sodium acetate buffer or sodium hexametaphosphate (both at pH 4.0) were more difficult to soften on heating.

The cell walls and middle lamella are among several structural components implicated in the hard-to-cook phenomenon in legumes. This topic is of considerable current interest because of the important role that legumes play in supplying much of the world's dietary protein. The hard-to-cook defect occurs in beans that have been exposed to high temperature and high humidity conditions. One hypothesis explains the phenomenon by the insolubility of the middle lamella due to the inability of phytate to remove the Ca and Mg bridges caused by its hydrolysis by phytase potentiated by high humidity. This and other hypotheses have been reviewed by Aguilera and Stanly (1985).

Mirza and Jwell (1976) found that steam blanching resulted in the swelling of the primary walls of carrots and the degradation of the middle lamella. Hot water blanching resulted in extreme swelling and greater softness. Microwave blanching completely disorganized the cell walls so that the tissue became mushy. Microwaves appear to act on the cellulose as well as on the other cell wall fractions.

Thermal processing (canning) of vegetables

Studies have shown that the factors of quality in canned foods such as color, flavor, texture, and vitamin content are most efficiently preserved by the higher temperature -shorter time processes (Clifcorn et al., 1950; Wang et al., 1988; Davis, 1976; Mohr and Kirschstein, 1988; Laing et al., 1978; Lund, 1988). Appert's early attempts at canning involved heating glass bottles of food in water for long periods of time. While low acid canned foods may be sterilized at relatively low temperatures, excessively long times are required which could usually effect the quality of materials. Following the early use of the tin can came higher temperature processes in salt solutions and later the introduction of the pressure retort. As more knowledge developed on the heat resistance of microorganisms in canned foods, it became more imperative to use the pressure retort and temperature of approximately 121 $^\circ$C and higher to insure safe and wholesome canned foods and to retain as much as possible the desirable quality characteristics of the products. In general, as mentioned before, it may be postulated that the destruction of bacteria increases tenfold for each 10 $^\circ$C rise in processing temperature, while the chemical reactions responsible for product deterioration are only doubled. Bacterialogically equivalent processes for shorter times at higher temperatures effect a greater preservation of the natural characteristics of the products being canned. Commercially, such processes may be accomplished through "high temperature short time (HTST), ultra high temperature (UHT), agitating processes, aseptic processing, and thin profile processing.

The scientific determination of processes for canned foods involves the correlation of the thermal death times of the most resistant bacteria which may cause spoilage of the food with the rate of heat penetration in the canned food when heated at some specific temperature. In still processes, liquid and semi-liquid products are heated mainly by convection. Increase in viscosity and the presence of discrete particles retard the rate of heating by convection (Abbatemarco and Ramaswamy, 1993). Many semi-liquid products

are heated by both convection and conduction and processes are necessarily long due to the slow rate to transfer of heat to the ''cold-spot'' of the can contents. Movement of the contents along the walls of the cans as such is slow and overcooking or scorching of the product often takes place. In the larger can sizes, this problem increases to the extent that many somewhat viscous semi-liquid products and some of the more heat sensitive vegetable products cannot be satisfactorily sterilized due to serious overcooking and accompanying undesirable color and flavor changes. An efficient method for agitation of such products to produce the greatest mobility of the can's contents with the least product damage has been greatly needed by the industry (Abbatemarco and Ramaswamy, 1993).

In order to calculate the effectiveness of a thermal process, two items of information are needed: (1) the thermal resistance characteristics of the microorganism used as the basis of the process (z and F value) and (2) the temperature history of the product. Thermal processing of food is accomplished in one of two ways. Either the food is heated to accomplish commercial sterility and then placed in a sterile container and sealed, or the food is placed in a container, sealed and then heated. The first method is referred to as aseptic processing, whereas the second corresponds to conventional canning. It should be noted, however, that the principles apply equally well for aseptic processing (Lund., 1975 a)

If a container of product at low temperature is placed in a vessel and the vessel is filled with steam at high temperature, the steam condenses on the container and the latent heat of condensation is transferred through the wall of the container and into the product. The process involves unsteady-state heat transfer since there is no point in the container where the temperature is constant. In this situation, the temperature at any point in the container is a function of (1) the surface heat-transfer coefficient, (2) the physical properties of the product and container, (3) the difference between the steam temperature and the initial of product, and (4) the size of the container. For thermal processing in condensing steam, it is reasonable to assume that the surface heat-transfer coefficient is

very large compared to the thermal conductivity of the product and, therefore, the only resistance to heat transfer is the product.

The rate of heat penetration into the container is dependent on the mechanism of heat transfer within the product. Some food products are relatively non viscous or contain small particles in brine. These products exhibit relatively rapid heat penetration because natural convection currents occur in the container. The natural convection currents can be aided by rotating or agitating the can, thus increasing the heating rate. This approach is used in continuous retorts.

Extremely viscous or solid food products heat primarily by conduction. For these products, the charts developed for unsteady-state heat transfer can be used to predict the temperature-time heating curve. Examples include cream-style corn, pumpkin, most thick pureed vegetables, potato salad, baked beans, and most intact food tissues.

Finally, there are products in which the mode of heat transfer changes from convection to conduction during heating. Since convection heating is much faster than conduction heating, these products exhibit a change in the rate of heating, and a plot of temperature vs heating time shows an abrupt change in temperature rise. This is referred to as a broken heating curve. Foods containing significant quantities of starch that gel upon heating exhibit this behavior. Examples of products exhibiting broken heating curves are cream-style corn (when the starch has not been gelatinized prior to initiating the thermal process), soups, and noodle products (Lund, 1975 b).

Heat penetration test

The temperature history during heat treatment was previously measured by mercury thermometers. This measuring device could only be used in open water and oil vats (Eisner, 1988). However, with this system, it is not possible to determine the sterilizing effect on the product and thermocouple props are in wide range use today. The use of thermocouples was introduced in 1917 by the National Canners Association, now the

National Food Processors Association, to measure temperatures during heating and cooling of foods in sealed containers (Lopez, 1987). This lead to the graphic mathematical and computerized procedures that are employed to estimate the minimum heat required to produce "commercially sterile" food without excessive damage to their eating quality or nutritional value.

Thermal processing of food could be accomplished in two ways: (1) aseptic processing, whereas the food is heated to obtain commercial sterility and then placed in a sterile container and sealed, (2) conventional canning, whereas the food is placed in a container, sealed, and then heated (Lund, 1975b). If the food is a liquid (juice) or contains a liquid of low viscosity (brine peas), the heat is distributed via convection. If it is a solid (meat, fish) or highly viscous (bean in sauce), it can be heated only via conduction. As a result, it is not surprising that the greater portion of the contents must be severely over-processed on order to sterilize the small volume occupying the geometric center.

Hence, increasing interest is being devoted to prevent the food from over-processing as well as quality degradation and reducing energy usage. Thin profile containers and rotary autoclaves offer a superior product quality due to rapid heat penetration. Aseptic canning, a special application of high-temperature-short time (HTST) processing is now rather commonplace and is particularly useful in processing foods that are easily damaged by heat (Ramaswamy and Tung, 1988; Govaris and Scholefield, 1984; Abbatemarco and Ramaswamy, 1993) .

Each of these technological and engineering improvements, in turn, opens up new possibilities in the variety of foods that can be preserved through heat processing. On the other hand, each imposes upon the processor the necessity for more stringent and sophisticated procedures to assure adequate control. Furthermore, the newer heat processing methods are being employed for the production of high quality formulated foods that were not possible to produce using conventional heating, which, in itself, imposes the need for the processor to exercise greater stringency in order to assure product sterility.

Commercial sterility in canned foods

As indicated, the very basis for the preservation of foods by canning is the use of heat to destroy bacteria which are generally capable of spoiling the product. Food poisoning bacteria are readily destroyed by heat. As a practical example of this fact, the pasteurization temperature for milk is about 143°F for 30 minutes, or 161°F for 15 seconds. The usual process or heat treatment given low acid canned foods of pH 4.6 or higher is equivalent to at least 3 minutes at 250°F. This heat treatment is more than sufficient to destroy any food poisoning bacteria. It is also equivalent to more than 6 hours at 212°F and frequently affords much more lethality.

Acid foods of pH 4.6 or below will not support the growth of food poisoning bacteria. Tests have shown that not only are the food poisoning bacteria incapable of reproducing in acid foods but that large numbers deliberately added to such acid foods actually die in relatively short periods of time. Acid foods are not subjected to as much heat as low acid foods. However, they are heated sufficiently to destroy all vegetative bacterial cells, yeast, and molds which could, if not destroyed, cause spoilage.

· For all practical purposes, it may be considered that when a food is hermetically sealed in a container there will be included microorganisms which, unless they are subsequently destroyed, will thrive under the environmental conditions afforded and cause spoilage of the food. The destruction by heat of the organisms naturally present in the sealed container is the fundamental operation of food preservation by canning. The operation is known as processing to commercial sterility. The time and temperature combination at which the product is heated is known as the process. The process is determined from a study of the rate of heat penetration for the product and from a study of the heat resistance of significant spores. A theoretical process is then calculated and tested by inoculation of product with a known spore load.

An example is the determination of a process for canned corn. Since it is known that flat sour and sulfide thermophiles as well as putrefactive anaerobic mesophiles cause spoilage of corn, it is necessary to study the condition under which these agents are destroyed. After preparing a spore crop of each test organism, a heat resistance determination is made. By using thermocouples, the rate of heat penetration into canned

corn is determined. Employing a mathematical correlation between heat resistance and heat penetration, we arrive at what is known as a "theoretical process," and then incubate to determine the spoilage levels.

The inoculated pack technique is valuable especially for products, such as spinach, which exhibit rather gross variations in their rate of heat penetration. If the inoculated pack results confirm the mathematically derived theoretical process, the mathematical methods can usually be applied to the product in a variety of can sizes, thus precluding the need for studying the effects of the process on experimental packs in each can size. The process so determined will produce a commercially sterile canned food product with the greatest retention of quality.

A thermal process that produces commercial sterility in low-acid canned foods may be defined as "that process by which all *Clostridium botulinum* spores and all other pathogenic bacteria have been destroyed, as well as more heat resistance organisms which, if present, could produce spoilage under normal conditions of non-refrigerated canned food storage and distribution." If the number of organisms in the product is excessive, recommended processes may not be adequate to prevent spoilage. Therefore, it is essential to exercise strict principles of sanitation while the agricultural commodities are prepared for canning.

There are some thermophilic or heat-loving bacteria (*eg: Clostridium thermosaccharolyticum and Bacillus stearothermophilus*) which produce spores of such high resistance to heat that they cannot be destroyed in some products without processing to such a degree that the canned product would be unmarketable.

Fortunately, the thermophilic bacteria are not infectious or poisonous and are therefore of no significance with respect to public health, since we know that large numbers are ingested in coffee sweetened with table sugar. When such thermophilic spores survive the process in canned foods, they are unable to germinate and cause spoilage at storage temperatures of 100°F or lower. Prompt cooling of processed cans to an average temperature of 100°F and avoidance of high temperature storage safeguards against spoilage by thermophilic bacteria. Incubation of low acid canned foods at 131°F will quite obviously allow germination with recovery of vegetative cells.

Microbial decomposition of canned foods may result from lack of commercially sterile conditions, or from contamination of can contents after processing.

Continuous rotary pressure sterilizers

Still retorts were prevalent for low-acid foods until about 1950. Since then the continuous agitating type of retort has become more common in the industry, resulting in considerably reduced processing times made possible by the higher rate of heat penetration into the food, and by the higher temperatures used (Lopez, 1987). Advantages of agitational processing are cited on reduction of process time. Also production costs are reduced through savings in labor as well as in steam. Higher quality and improved nutrient retention could be acheived due to the higher temperature-shorter processing times. Can damage and product loss are also reduced.

Retortable flexible containers

Shelf-stable foods are now available in a new and unique array of retortable plastic containers. One of the first containers marketed in the U.S. was the "plastic can" - a semi-rigid, one piece, cylindrical container with a double-seamed metal lid. This style container can be processed with only minor modification to existing canning facilities. The plastic is normally a multilayered construction, consisting of 5 or 7 layers, with an oxygen barrier material of either ethylene vinyl alcohol (EVOH) or polyvinylidene chloride (PVDC) at the center. These containers may be formed by either extruding or blow-molding. Foods packaged in these containers have shelf lives of up to 2 years.

Semi-rigid containers-filling and sealing

While the technology of the high barrier plastic materials has been evolving, so have the adaptations or design of equipment for filling and sealing. Like aseptic filling and sealing lines, it is necessary to minimize residual head space and provide a hermetic seal. Unlike aseptic containers, semi-rigid retortable containers use heavier materials which require higher temperatures and pressures for sealing, may or may not be filled hot to creat vacuum but need to survive retort processing at elevated temperatures.

Laboratory testing has been conducted on one-up heat sealing units. Each of these units seals in a vacuum chamber. The heat sealing unit is easily converted to accept a variety of container shapes. Sealing speeds are 1-2 containers per minute depending upon the product handling (Lopez 1987).

For experimental production, such as pilot plant operations, equipment are intermittent motion fill and seal machines operating between 15 and 25 units per minute depending upon the food product. Sealing and air removal takes place in a vacuum chamber.

Advantages and disadvantages of retortable flexible containers

Retort pouches combine the advantages of the metal can and of the frozen boil-in-the bag. The attributes of flexible containers offer benefits for the consumer, retailers, and manufacturer, as follows.

(a) The thin profile of the pouch or container provides rapid heat transfer for both preparation and for sterilization during processing. A 30% - 40% reduction in processing time is possible, with savings of energy.

(b) Reduced heat exposure results in improvements in taste, color and flavor; there are also less nutrient losses.

(c) Preparation of products which need to be heated to serving temperature can be accomplished in three to five minutes by immersing the pouch in boiling water, or placing the plastic container in a microwave oven; there are no pans to clean up in the kitchen.

(d) Food can be consumed directly from the semi-rigid container.

(e) Storage space of the retort pouch or container in a paperboard carton is no larger than that for cans; disposal space is less.

(f) Shelf life of retort pouch products is at least equal to that of foods in metal cans; refrigeration or freezing is not required by packers, retailers, or consumers. Shelf life of products in higher barrier plastic containers is one year.

(g) Pouches and containers do not corrode externally and there is a minimum of product-container interaction.

(h) Opening the pouch requires only tearing the pouch across the top at the notch in

the side seam, or by using scissors. The container lid may be peeled open or cut with a knife.

(i) The flexible container is safer in that the consumer would not cut himself or herself as on a metal can or be faced with broken glass as with glass jars.

(j) The flexible container lends itself to portion control and thus has a marketing advantage for single people and the elderly.

(k) Package size flexibility is another advantage. It is difficult for a canner to switch from 6 to an 8 or a 9 ounce rigid package. With the pouch system, size changes are comparatively easy. Furthermore, many products fit the pouch more logically than a can. For example, sliced meats, meat loaf, etc.

(l) Empty retort pouches and nesting containers offer processors a reduction in storage space and lighter weight compared with empty cans, an equal number of retort pouches use 85% less space; one thousand 4.5 x 7 inch pouches weigh 9.4 pound compared with one thousand 211 x 304 metal cans weighing 112.5 pounds; a 45-foot trailer holds less than 200,000 eight-ounce empty metal cans, whereas on the same trailer over 2.3 million empty pre-formed pouches can be shipped.

(m) Dented cans, according to the US. Department of Agriculture market service reports, are the single largest spoilage factor in the supermarkets today, representing 49% of the total. Adoption of flexible containers could potentially eliminate or at least greatly reduce this problem for both the retailer and the manufacturer.

(n) Advantages for the retailer include savings in shelf space. For example, a carton carrying two-8-ounce pouches provides a 10% saving in shelf space when compared to two 8-ounce metal cans. Also, the carton shape makes it easier for the retailer to handle and display the product.

(o) The use of a flat carton as an overwrap to hold one or two pouches provides for better product identification on the shelf than cans do. The pouch also offers the opportunity to market multipacks, e.g., entrée in one pouch and accompaniment such as rice in another.

(p) The individual container costs to the canner likely will be less than the conventional rigid type containers presently in use. However, with the protective

overwrap the cost could be about the same as that of metal cans.

(q) The energy requirements for container construction are less than for cans.

The disadvantages of flexible containers are as follows:

(1) Major capital investment would have to be made in new filling and closing equipment for the particular container and modifications made in some thermal processing systems.

(2) Filling is slower and more complex. Retort pouch filling lines currently run from 30-60 pouches a minute, compared with some 400 per minute for canned and frozen foods and up to 1,200 per minute for glass containers. Semi-rigid container lines may run at 120 per minute.

(3) Thermal processing of flexible containers is more complex and processes have to be established for each product in the particular type and size of container.

(4) There are limitations as to the size of the containers which can be reasonably handled and processed.

(5) Retort pouches at present require overwrapping such as a carton and may be required for semi-rigid containers.

(6) Since the pouch is a flexible container, the detection of leakage is more difficult than with a conventional type of container.

(7) Pouches and semi-rigid containers may be punctured.

(8) Marketing studies indicate very positive acceptance of foods packed in retort pouches. Nevertheless, considerable advertising expenditures may be needed to educate the retail consumer, although the institutional market may allow for easier entry into market.

QUALITY PROPERTIES OF FOODS

As discussed earlier, quality or degree of excellence is a relative term, and as applied to foods it is interpreted as "those attributes which render the food agreeable to the person who eats it" (Ramaswamy et al., 1992). Some quality factors of foods are crucial in determining their safety and acceptability. Some quality loss occurs due to the processing operations while additional loss may occur during storage. The shelf life of a food is the

time period up to which a product can be expected to maintain a predetermined level of certain quality factors under specified processing or storage conditions. The shelf life end point is also a complex qualitative parameter involving a multitude of factors involving the gradual loss of flavor, development of off-flavors, and visual, color, and textural changes. Quality has been described as a combination of several factors: appearance (shape, size, form, color, gloss, defects), texture (firmness, crispness, succulence, mealiness, toughness, etc), flavor (sweetness, sourness, astringency, bitterness, aroma, off-flavor), nutritive value (carbohydrates, proteins, fat, minerals, vitamins), and safety (naturally occurring toxins, contaminants, mycotoxins, microbial contamination).

Effect of thermal processing on food quality

As noted before, the application of food-processing techniques that extend the availability of perishable foods also limits the availability of some of the essential nutrients. Maximizing the nutrient retention during thermal processing has been a considerable challenge for the food industry in recent years. The losses of nutrients as a result of processing have been divided into three categories; intentional, accidental, and inevitable (Ramaswamy et al., 1992) Some unwanted parts of the food are intentionally removed, for example, meat is deboned, grains are milled and polished, and vegetables and fruit are peeled. The accidental or avoidable losses occur as a result of inadequate control and handling of the food materials. The major concern from a food processing point of view is the inevitable losses that represent the loss of heat-labile nutritional elements destroyed to some degree by heat. The extent of these losses depends on the nature of the thermal process (blanching, pasteurization, and sterilization), the raw materials, and processing preparation, because operations such as size reduction (dicing and slicing) result in increasing losses through increasing the surface-to-volume ratio. All water-soluble proteins and carbohydrates may be susceptible to losses. The major emphasis in food processing operations is to reduce these inevitable losses through the adoption of the proper time-temperature processing conditions as well as appropriate environmental factors (concentration, pH, etc.) in relation to the specific food product and its target essential nutrient.

An optimal thermal process may be defined as the minimum heat treatment required to achieve commercial sterility because heating cost and product quality losses increase if the process time is prolonged. However, as noted earlier, the commercial sterility is dependent on several factors: nature of the food (pH, a_w); heat resistance of the microorganism or enzyme, heat-transfer characteristics of the food, the processing system, the initial load of microorganisms and the concentration of the heat-resistant enzyme.

There are situations where the heat treatment is sufficient for the destruction of microorganisms, but not for the enzymes naturally present in the food system. Consequently, the thermal process must be optimized by increasing or decreasing the temperature, so that the destruction rate of the heat-resistant enzyme is equal to the destruction rate of the microorganism used as the basis of the process.

HTST or UHT approaches are not always beneficial for conduction heating food products that heat relatively slowly and exhibit large temperature gradients between the surface and center of the container. Optimized conditions for these might occur at intermediate temperatures. Container agitation and the use of thin profile packages are other approaches employed to promote better quality in these products by improving the overall rate of heat transfer to the packaged food. The sterility at the slowest heating zone in the largest particulate in the processing system must be ensured, but there are concerns in relation to the overprocessing of the carrier liquid medium. Vast data exist in the literature on the loss of nutrients and other quality factors in foods as a consequence of processing and storage. Research efforts in recent years have been focused on the improvement and optimization of quality factors, a driving force for the changing technology to meet consumer demands. Basic research related to the mechanisms of microbial and nutrient destruction, food-package-process interactions, and the mathematics related to the transfer of heat into packaged food has led to the developing of new processing and packaging technologies that promote the ultimate objective of obtaining high-quality shelf-stable foods.

CHAPTER III

THERMAL KINETICS OF TEXTURE SOFTENING
OF ROMANO BEANS

ABSTRACT

Dry Romano beans (*Phaseolus vulgaris*) were soaked in distilled water and cooked at temperatures ranging from 70 to 100 oC for different time intervals. Hydrated and cooked samples were subjected to a single cycle compression test using a computer interfaced Universal Testing Machine with the force-to-deformation ratio indicating sample firmness. The rate of texture softening associated with each temperature was found to be consistent with two simultaneous pseudo first order kinetic mechanisms 1 and 2. Approximately 40% of the firmness of hydrated Romano beans was lost by the rapid softening mechanism 1. The remaining firmness loss was characterized by mechanism 2 which was found to be much slower (~1/50th of the former). Heat penetration to the center of the Romano bean to correct for thermal lag result in changes of kinetic data and their temperature dependence for, only, the rapid mechanism. The temperature dependence indicator (z value) of reaction rate constants were 30 and 24 Co, respectively for mechanisms 1 and 2 with associated activation energies of 82 kJ/mole and 103 kJ/mole, respectively.

INTRODUCTION

The quality of processed dry beans depends on several physical and chemical properties of raw beans and their dependence on processing conditions. The dry bean seed structure is comprised of a seed coat, cell wall, middle lamella and other cellular membranes which greatly influence textural characteristics (Uebersax and Ruengsakulrach, 1989). The texture of dry beans is derived primarily from the cell wall and middle lamella. Most of the interior volume of the cell is comprised of aqueous solutions of sugar and salt which does not impart structural strength to the tissue, especially for succulent vegetables although may not be true for vegetables that have a high starch contant (Bourne, 1989). However, the cell wall itself contributes to the rigidity of the cotyledon tissue. The middle lamella is composed primarily of pectic substances which provide adhesion to adjacent cells resulting in the integrity of the total tissue. In addition, pectic substances allow divalent cation cross-linking and, thus, form intercellular polyelectrolytes which significantly contribute to the textural quality (Jen, 1989). In heat processed products, chemical composition, and size of the cell wall and middle lamella determine the textural quality. Texture of processed products result from changes in the chemistry of hydrophilic polymeric material that affect the physical properties (Lee et al., 1979; Van Buren, 1979).

Thermal processes inevitably cause some destruction of food quality. Nutritional value, texture, color and flavor are usually damaged to some extent. There have been numerous studies on the degradation kinetics of nutrients (Van Buren et al., 1962; Hahn et al., 1977; Quast and da Silva, 1977; Kon, 1979; Lenz and Lund, 1980; Rao et al., 1981; Wang et al., 1988; Jen, 1989; Morris, 1990) but fewer studies have been conducted on the kinetics of thermal softening even though texture is one of the major components of quality in most foods and the excessive softening caused during thermal processing renders some foods unmerchantable (Jelen and Chan, 1981; Bourne, 1982; Kaletunc et al., 1992; Andersson et al., 1994).

Most of the experimental data found in the literature on thermal softening show apparent first-order kinetics. Huang and Bourne (1983) measured softening of green peas, green beans, dry white beans, beet and carrot by the back extrusion cell mounted in the Instron Universal Testing Machine and found the rate of thermal softening of all commodities to be consistent with two simultaneous first-order kinetic mechanisms acting on two substrates and that the apparent rate constants for mechanism 1 were 20 times or more higher than for mechanism 2. Bourne (1987) measured thermal softening of diced carrots and cut green beans and found that the intercept of the substrate contributed in mechanism 2 on the ordinate measured the amount of participant substrate at zero process time.

The objectives of this study were to investigate the effect of cooking temperature on kinetics of thermal softening of hydrated Romano beans to determine:

1- Whether cooking of Romano beans for different time-temperature combinations yield two simultaneous first-order kinetic behaviors as has been reported for other legumes, and

2- To evaluate kinetic parameters (reaction rate constant and activation energy) for thermal softening of Romano beans to be used for predicting the loss of texture in canned Romano beans.

MATERIALS AND METHODS

Raw material

Dry Romano beans were obtained from a local store. Beans were sealed in polyethylene bags (200 g for each bag) to minimize moisture changes (Aguilera and Ballivian, 1987) and stored at room temperature until use.

Soaking and destoning procedure

For each temperature treatment, a bag of dry beans was soaked for 14 hours in three volumes of distilled water at room temperature. Distilled water was used to secure a satisfactory product from the standpoint of textural properties (Hincks and Stanley, 1986). The beans are usually run over a water riffle in order to remove the stones (Lopez, 1987), however, in these experiments the beans were hand sorted and kept in an ice bath prior to cooking (blanching).

Cooking

Test samples of hydrated beans in approximately 100 g batches were placed in a small perforated basket and cooked in a water bath (THERMOMIX 1480) for selected times (1-30 min) and temperatures (70-80-85-90-95-100 oC $\pm$0.7 °C,). Each temperature treatment was performed during one day, and in total 6 days.

Texture evaluation

A Universal Testing machine (Lloyd Model LRX - 2500 N; Lloyd Instruments Ltd., Fareham, Hans, UK) was used in this study. A circular plate (50 mm diameter) was made to descend vertically at a constant speed of 2.5 mm min^{-1} on an individual bean. The firmness was derived from the force deformation curve as indicator of physical propertie.

Since a 50 N load cell was used in the study, deformation tests were stopped when the applied force reached 40 N. The ratio of this maximum force to the corresponding deformation produced was taken as firmness and expressed in N/mm (Figure 7). Five beans for each time temperature were tested and their mean values were used as indicators of textural properties of beans.

Kinetic method

Perforated cans containing sufficient sample for analysis were placed in a water bath and cooked at different time-temperature combinations. The raw data consisted of textural properties versus cooking condition (temperature/time combination). The kinetic model for softening was assumed to be first order. A first-order reaction is one in which the rate of the reaction at any time is directly proportional to the concentration of the reactant present at that time. It is described by the well known equation:

$$-dC/dt = k.C \tag{6}$$

where C is the concentration of the reactant, t is the time, and k is the rate constant. Integrating and transposing yields:

$$\ln C = \ln C_o - k.t \tag{7}$$

where C_0 is the concentration of that reactant at zero time. A plot of the ln C versus time will be linear for a first order reaction. The slope of the line gives the rate constant k, and the intercept on the ordinate at time zero gives ln C_0.

D-value is the time required at a particular temperature to reduce the firmness, one-tenth (D) was calculated using Eq.(8):

$$D = \frac{2.303}{k} \qquad\qquad (8)$$

The temperature dependence of a first order rate constant is given by the:

1-Arrhenius equation:

$$\ln k = \ln A - Ea/RT \qquad\qquad (9)$$

where k is the rate constant, A is a constant, E_a is the activation energy, R is the gas constant and T is the absolute temperature. A plot of ln k vs 1/T is rectilinear. The value of E_a can be calculated since the slope of the line is Ea/R, and the value of R is known.

2- TDT concept: (generally used in the food industry):

$$\log (D_1/D_2) = (T_2-T_1) / z \qquad\qquad (10)$$

where D_1 and D_2 are the decimal reduction times at temperatures T_1 and T_2, respectively and z is the temperature range required to change the D values by a factor of 10. The value of z was obtained as the negative reciprocal slope of the log D vs T curve.

A number of researchers who studied the rate of thermal softening of vegetables tissue have found a good fit of their empirical data to the first order kinetic model because a plot of log firmness versus time is rectilinear. Nagel and Vaughn (1954), Nicholas and Pflug (1962) found that pickles soften by a pseudo first order process. Many of the processes do not arise from simple first-order chemical reactions, or the chemistry of the process may be unclear. Nevertheless, since they empirically fit the model for a first-order

chemical reaction, they are commonly called pseudo first order processes.

Generally, the slope of the log (concentration) versus time plot is called the apparent first order rate constant. The modifying adjective "apparent" is used to signify that the process is not truly first order in the chemical sense, but that the experimental data give a good fit to the first order chemistry model.

From analogy with kinetic theory for two apparent first order processes, it can be postulated that the texture of vegetable tissue is composed of two substrates, "a" and "b", and that substrate "a" softens rapidly by mechanism 1 while substrate "b" softens slowly by a different mechanism 2. Based on the assumption that the faster mechanism ceases to be significant after a reasonably long time, the rate constant for mechanism 2 can be obtained from the latter portion of the curve. Then the linear portion of mechanism 2 is extrapolated back to zero cooking time and this extrapolated line is subtracted from the line above it to get a second line. The derived line represents mechanism 1 and the slope is its apparent rate constant. The linear portion of the shallow line represents mechanism 2 and the slope is its apparent rate constant.

The chemical kinetics theory for two simultaneous first order processes as was assumed by Bourne (1987) is followed by two substrates, "a" and "b":

$$-da/dt = k_1.a \qquad \text{and} \qquad -db/dt = k_2.b \qquad (11)$$

where "a" is the firmness contributed by the first component and "b" the firmness contributed by the second component; t is the time, k_1 is the apparent rate constant for substrate "a" and k_2 is for substrate "b". $k_1 > k_2$ since substrate "a" decays more rapidly than substrate "b" when the tissue is heated.

Integration and transposing in the usual manner gives:

$$\ln a = \ln a_o - k_a.t \qquad \text{and} \qquad \ln b = \ln b_o - k_b.t \qquad (12)$$

where a_o and b_o are the amount of substrate "a" and "b" respectively at zero cooking time. At any cooking time, the total firmness = (a+b) and this value can be calculated when a_o, k_a, b_o and k_b are known. Since "a" has a high softening rate, its contribution to firmness becomes inconsequential after a long heating time.

Correction for thermal lag

During the kinetic experiments, the time temperature profile at the center of prepared vegetable pieces was measured using copper constantan thermocouples in order to evaluate the effectiveness of the come-up period. Come-up time (CUT) effectiveness has been traditionally taken to be 42% of CUT as originally suggested by Ball (1923) for thermal process calculations. Procedures for obtaining the effective portion of the come-up period and for correcting the kinetic data have been reported in the literature (Nath and Ranganna, 1977; Awuah et al., 1993). When the heating times are higher than CUT, a single correction factor accommodating the effective portion of CUT will suffice, and the total heating times are reduced by the ineffective portion of CUT. However, when the heating times involved are less than CUT, the full-CUT effectiveness may lead to overestimation of effective time. Consistent with thermal processing concepts, the effective time can be computed in a manner similar to the computation of thermal time or process lethality:

$$t_{\text{effective}} = \int_0^t 10^{(T-T_{ref})/z} dt \qquad (13)$$

The z value calculated from the uncorrected log D vs T data is initially used to get the first estimates of effective time. New D values and subsequently a new z are then computed. The procedure is repeated several times for convergence of the z value.

A major deficiency with many studies has been the absence of corrections for thermal lag, which is necessary for the following reasons:

- Test samples take different time intervals to come to the test temperature (CUT). For example, when we measure the firmness of an individual bean after a 15 s exposure to 100 $^{\circ}$C, the heat may affect only the surface of the sample and not the whole body. Therefore;

- It is necessary to determine the effective portion of CUT and;

- Correction for CUT permits the use of effective heating times at the test temperature.

Furthermore, very often significant softening occurs by the time the food sample reaches the test temperature. In general, the measured property (i.e., compression force) will be an average value for the entire sample and the non-uniform softening during a test must be considered mathematically.

RESULTS AND DISCUSSION

A typical force-deformation curve for hydrated beans is shown in Figure 7. Plots for other heat treated samples were similar except for the fact that the associated deformations were much larger indicating lower firmness values. Typical firmness data obtained for a test sample is shown in Table 1. The variability associated with the firmness was about 15% (calculated as coefficient of variation, 100 x mean / standard deviation, as can be expected for biological materials.

Figure 7. Typical response curve of soaked Romano beans and measured parameter

$$\text{Firmness} = \frac{\text{Maximum Force}}{\text{Total Deformation}}$$

Total Deformation

Maximum Force

Force (N)
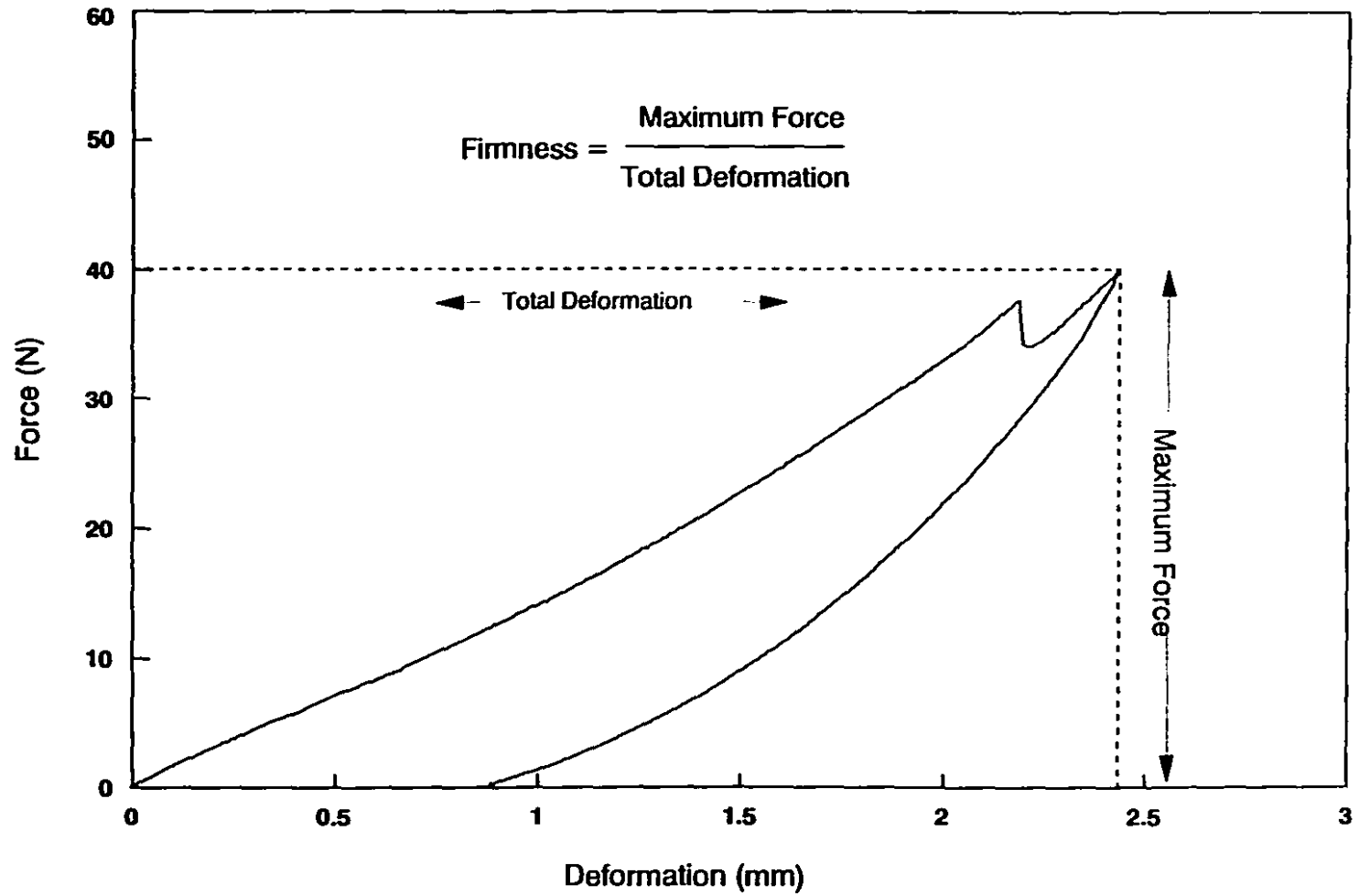
Deformation (mm)

Table 1. Typical data derived from force-deformation curves for hydrated Romano beans after soaking for 14 h in cold water

Sample#	Bbtch1	Firmness (N/mm) Bbtch2	Bbtch3
1	15.44	15.95	17.25
2	15.69	17.33	18.65
3	16.40	15.88	16.93
4	21.98	18.99	15.22
5	16.88	16.56	17.54
Mean	17.28	16.94	17.19
Standard Deviation	2.69	1.29	1.24
Coefficient of Variation	15.6	7.6	7.2

The thermal softening of Romano beans is shown as log mean values of firmness vs heating time at selected temperatures in Figure 8 which indicated it to be characterized by two pseudo first order reactions, one thermally more sensitive than the other. All plots showed a rapid softening at the start of cooking after which the rate of softening slowed. Based on the analyses of such behavior with other legumes by Huang and Bourne (1983) and Bourne (1987, 1989), the kinetic data were resolved to indicate softening by two different mechanisms.

For this purpose, the rate constant for the second or slower softening mechanism (typically involving long heating times) was first evaluated as the negative slope of the linear portion of the curve. This linear portion was then extrapolated backwards to zero cooking time and the values from the extrapolated line were subtracted from the experimental data above it. The result was a derived line with much steeper slope which gave the apparent rate constant for the first or rapid softening mechanism (Figure 9).

Heat penetration rate into the particle during come-up time was plotted as shown in Figure 10. Correction for thermal lag was determined for each test and kinetic parameters were recalculated using corrected thermal times. In fact, the only fraction affected by correction for thermal lag was the heat sensitive fraction or substrate "a" which contributed to mechanism 2. The results indicate that the substrate "b" contributing to mechanism 2 remained intact. It must be emphasized that the thermal lag effect will depend not only on the size of the particle but also on the food under investigation. For these reasons, correction for thermal lag must be determined for each test. The effectiveness increases with the time up to CUT. After the come-up, a single correction will be sufficient.

Corrected rate constants obtained from slopes of the linear portion of the softening curves for both rapid and slow softening mechanisms are presented in Table 2. The results generally confirm the first order nature for both softening mechanisms as indicated by their associated high R^2 values (0.86-0.99).

Figure 8. Thermal softening curves for the heat resistant fraction of
hydrated Romano beans at selected temperatures
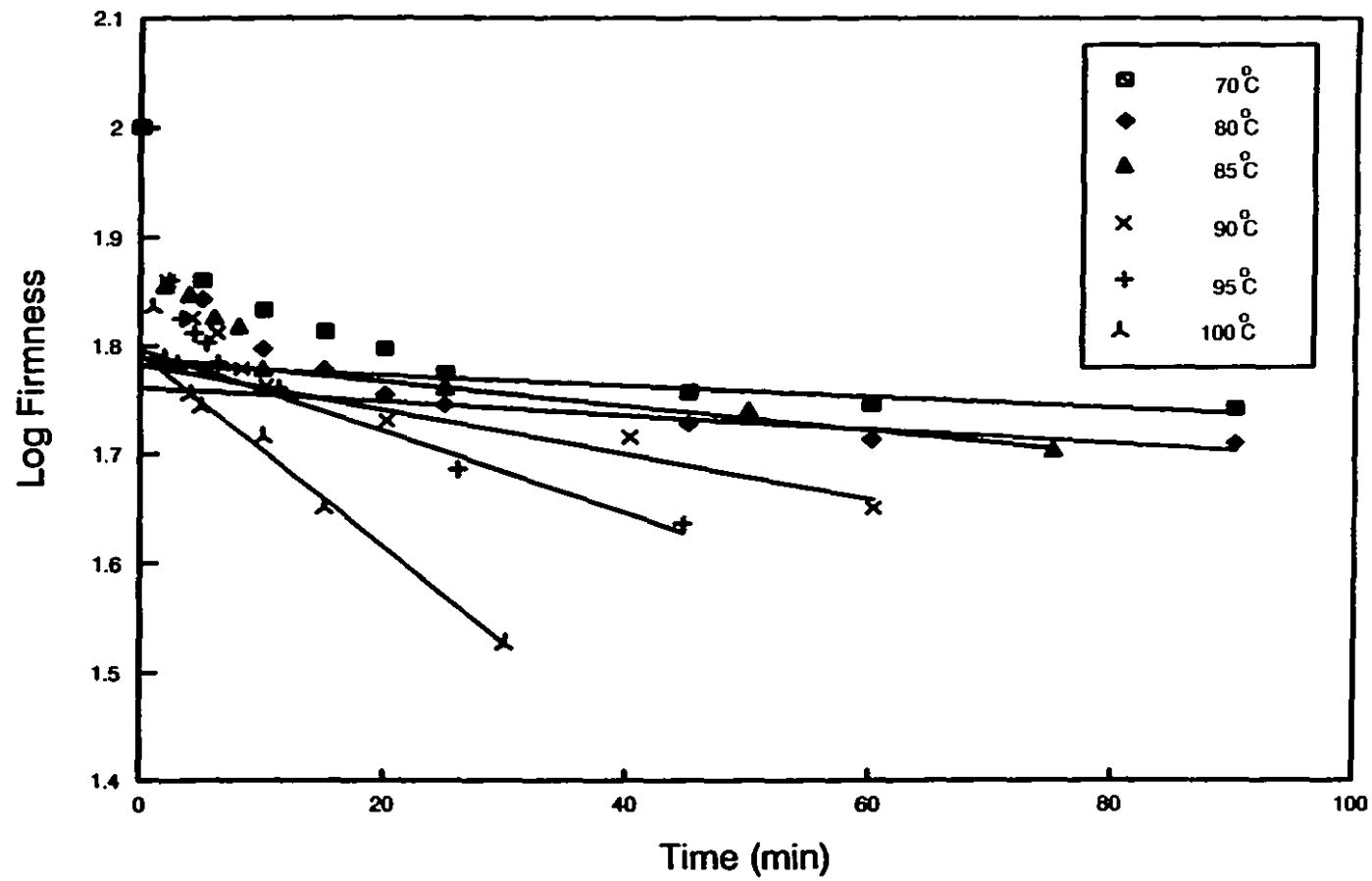
Figure 9. Thermal softening curves for the heat sensitive fraction of hydrated Romano beans at selected temperatures.
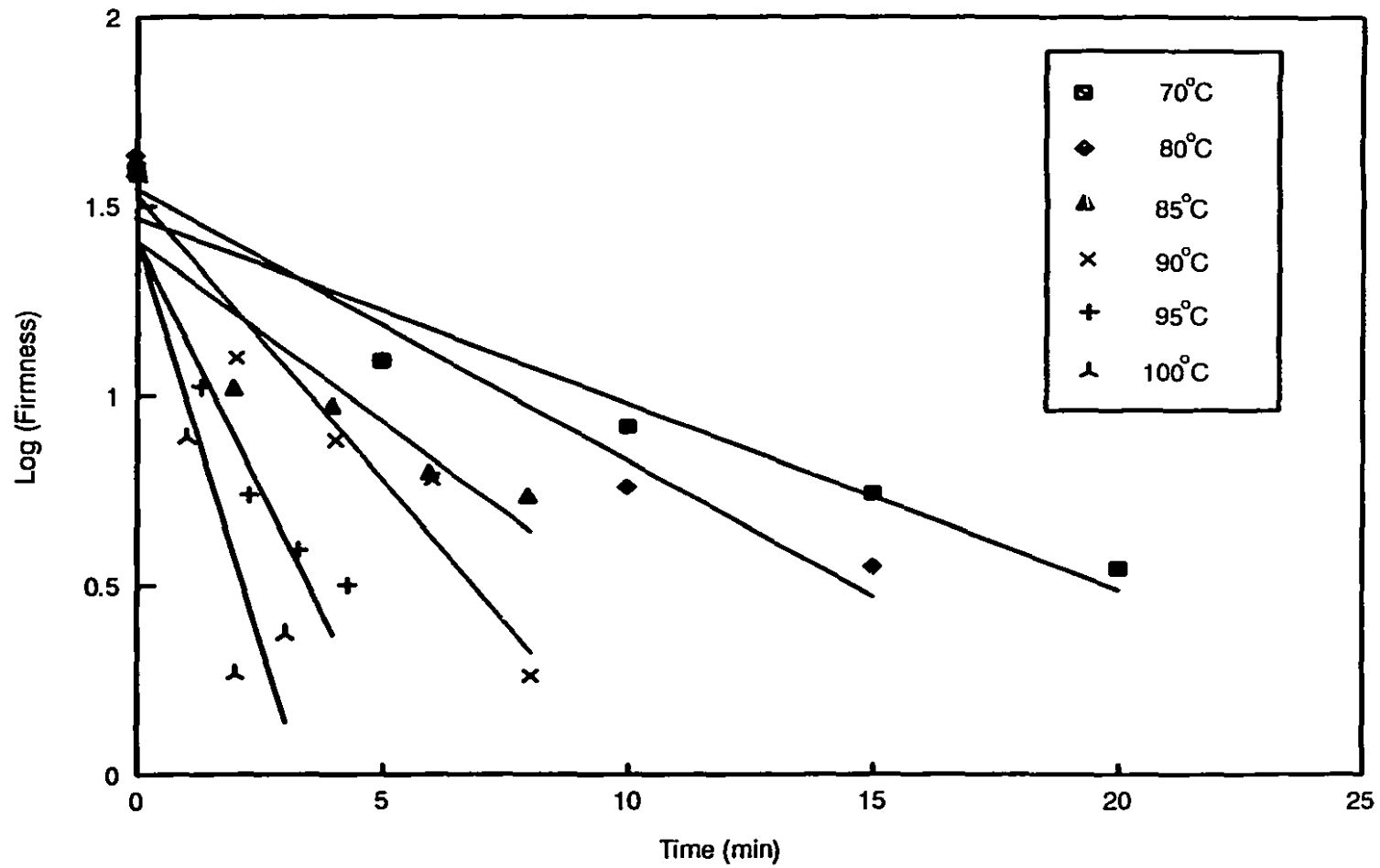
Figure 10. Heat penetration curve for Romano beans at 100°C during come-up time

Effectiveness =

$$\frac{\text{Area under ABCA}}{\text{Area under ADBCA}}$$
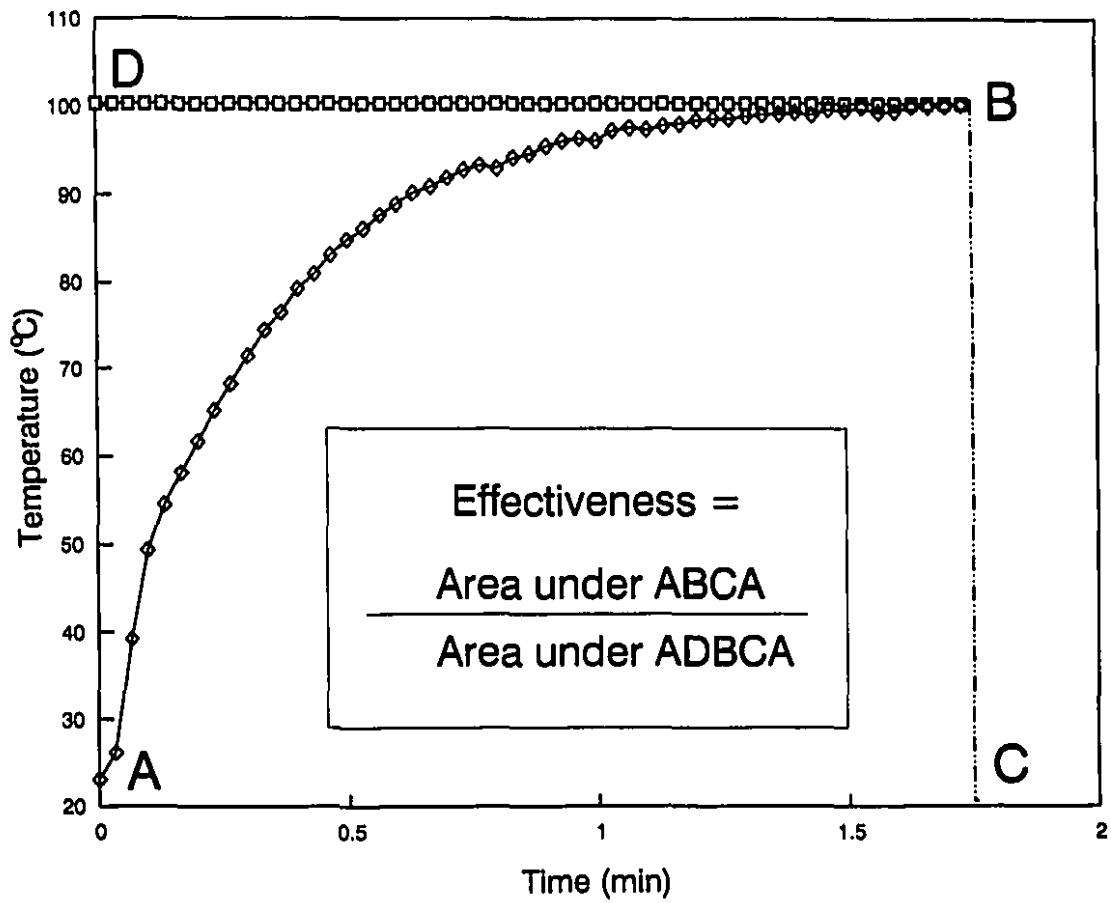
Table 2. Kinetic parameters for thermal softening of hydrated Romano beans (values in parenthesis indicated the uncorrected data)							
Temperature	Decimal Reduction Time				Apparent rate constants		
	Mechanism 1		Mechanism 2		Mechanism 1		Mechanism 2	
(oC)	(min)	R^2	(min)	R^2	(min-1)	R^2	(min1)	R^2
70	20.1 (20.4)	0.94 (0.94)	2036	0.86	0.114 (0.113)	0.94 (0.94)	0.0011	0.86
80	13.5 (13.9)	0.96 (0.95)	1543	0.88	0.170 (0.165)	0.96 (0.95)	0.0014	0.88
85	9.99 (10.5)	0.80 (0.80)	895	0.98	0.231 (0.219)	0.80 (0.80)	0.0026	0.98
90	6.24 (6.67)	0.95 (0.94)	487	0.94	0.369 (0.345)	0.95 (0.94)	0.0047	0.94
95	3.87 (3.55)	0.89 (0.77)	269	0.97	0.595 (0.649)	0.89 (0.77)	0.0085	0.97
100	1.99 (2.35)	0.83 (0.83)	112	0.99	1.154 (0.977)	0.83 (0.83)	0.0248	0.99

D values associated with the slow mechanism which varied between 2036 and 112 min in the temperature range 70-100°C were nearly 50 to 100 times larger than the range of values for the rapid mechanism. The values of reaction rate constant (k) showed similar trends with higher values associated with the rapid mechanism than the slower one (obvious because k is reciprocally related to D). The results, therefore, indicated that the softening by the rapid mechanism 1 is approximately 50 times faster than the slower mechanism 2. Results from Table 2 also show that when cooking times involved exceed an equivalent of 5 min at 100°C, the substrate responsible for the rapid mechanism 1 would probably disappear (more than 99% destruction) leaving the softening by the slower mechanism 2 to play a more important role with respect to the texture of the cooked product.

The intercept of the extrapolated line of the second or slower mechanism was reported (Huang and Bourne, 1983) to represent a measure of uncooked materials. In fact, since after a long heating time most of the contributed substrate to mechanism "1" is destroyed, the dominant factor that determines residual firmness in canned Romano beans depends on the amount of substrate present for mechanism "2". The intercept of the extrapolated mechanism "2" line on the ordinate was taken as a measure of the amount of residual firmness at zero time for mechanism "2". This point which was considered to be a good indicator of the firmness of vegetable after canning, was named the "thermal firmness value" (Bourne, 1987). The log mean thermal firmness value found in this study was 1.75-1.80. Compared with the initial value of 2.0 (100%) initial activity on logarithmic scale), this represents a residual texture value, 56-63% of the initial starting material. Thus, the rapid softening mechanism accounts for about 40% loss in texture value of the product. Huang and Bourne (1983) theorized that mechanism "1" is probably due to pectic changes in the interlamellar based on similar studies by Van Buren (1979). There are, also, many chemical reactions involved in mechanism "2" which need further examination. Figure 11 illustrates the TDT and Arrhenius plots for Romano beans before and after correction for thermal lag.The value of z is obtained as the negative reciprocal slope of the log D vs T curve.

Figure 11. Changes in z values (a) and activation energies (b) of

Romano beans before and after correction for thermal lag
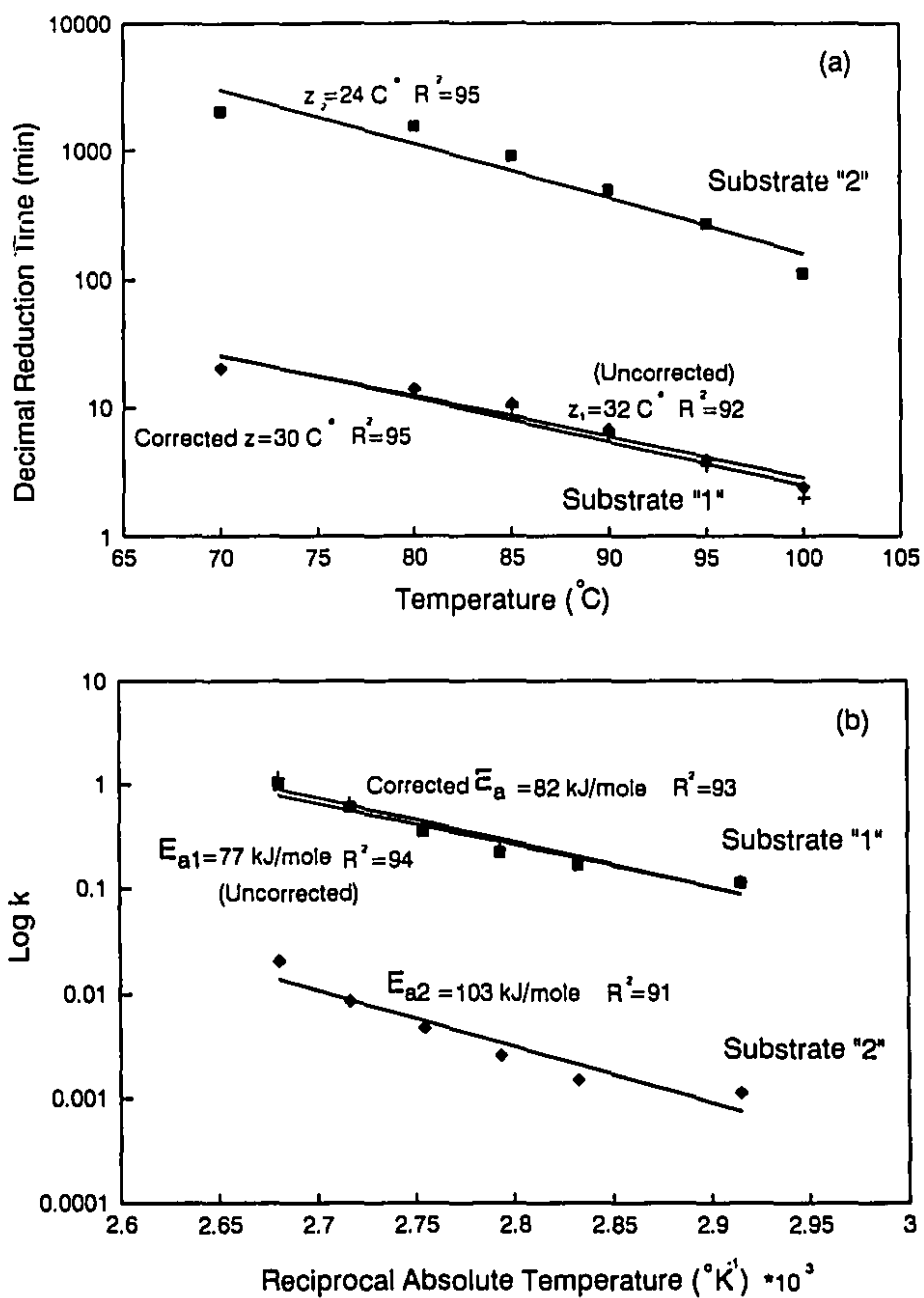
The z value calculated from regression (R^2 = 0.92-0.95) was 30 C^o for the rapid mechanism and 24 C^o for the slower mechanism. E_a is obtained as the product of R and the negative slope of ln k vs 1/T curve. The associated activation energies obtained from regression (R^2 = 0.90-0.93) were found to be 82 kJ/mole for mechanism "1" and 103 kJ/mole for mechanism "2".

CONCLUSION

The results of this study indicate that kinetic parameters for the loss of texture can be determined from compression tests involving individual beans subjected to a selected thermal treatment. The softening process follows two simultaneous pseudo first rate softening mechanisms, one more rapid than the other. The dominant factor that determines residual firmness in thermally treated Romano beans is the slower mechanism since the substrate responsible for the rapid mechanism could be lost during a short exposure to 100^oC. It was also found that correction for thermal lag affected only the rapid softening mechanism 1.

CHAPTER IV

EFFECT OF HEAT TREATMENT ON THE QUALITY OF ROOT VEGETABLES: KINETICS OF TEXTURAL CHARACTERISTICS

ABSTRACT

Turnip (*Brassica napobbrassica*) and beet roots (*B. Vulgaris L*) were cooked at temperatures ranging from 70 to 100 °C for different time intervals. Texture values of cooked products were evaluated by a computer interfaced Universal Testing Machine using a single cycle deformation test. The force-to-deformation ratio was used to indicate the sample firmness, the ratio of recoverable part-to-total deformation to represent the springiness and stress-to-strain ratio as a measure of the modulus of deformability (stiffness) in treated samples.

All three textural properties were found to follow the same trend of apparent first-order kinetic theory with two substrates. Softening rate for both samples ranged from 1.26 min up to 20.3 min for the first substrate and 67 min up to 1830 min for the second substrate at 100 and 70 °C, respectively. Temperature dependence of softening rate (z-value) was found to be within 27 and 35 C° degrees, with the activation energies of 93 and 60 kJ/mole. The softening rate of turnip was found to be almost twice that of beet root.

INTRODUCTION

Vegetables are subjected to thermal processing in order to destroy microorganisms that cause spoilage so that they can be consumed long after they have been harvested.

Thermal processing also results in the loss of quality factors such as texture, color and nutrients. Thermal effect on sensory quality could be in both a positive and negative direction. These changes are related to the loss of turgor pressure and to chemical changes in the cell wall and middle lamella in the plant foodstuffs. The uptake or adsorption of water during thermal processing can reduce the cohesiveness of the matrix, soften the cell wall, and decrease the intercellular adhesion (Van Buren, 1979).

Plant roots constitute an important category of foodstuffs in terms of consumption, nutritional contribution and sensory attributes. The Swedish or Russian turnip, a large elongated yellowish root with a cylindrical pod and tipped with a conical beak is native of Europe, Asia and Africa. This type of turnip which is common in North America, is called regular turnip and is usually cooked with other vegetables and served as soup. A limiting factor in the cooking of vegetables is the softening that is caused in the tissue. The morphological structure and chemical composition govern the textural characteristics of vegetables. Cell wall softening is found after heating, freeze-thawing, brining and air drying (Reeve, 1970; Silva et al., 1981).

Saguy and Karel (1980) suggested that improvement of quality factors have been made possible by the increase in knowledge of kinetics of food deterioration, by advanced analytical methods, and by availability of numerical methods and powerful computers that can simulate the behavior of complex systems. The analytical approach to food quality deterioration allows a wider scope of investigation which may provide alternative processes, different conditions, or more efficient operation, to minimize undesired changes and optimize quality retention. It also provides a deeper understanding of the mechanisms controlling the processes studied.

A number of chemical changes take place when foods are subjected to a thermal process. Because of the complex chemical composition of foods, it has not been possible to quantify all the changes taking place as a result of heating and to relate, in a quantitative manner, the chemical changes to physical changes such as softening. A simple and useful

approach in softening studies has been to express data in terms of either apparent reaction rate constants or, analogous to microbial death kinetics, in terms of D-value.

For an optimization of the sensory quality in thermal processing, the temperature dependence of the sensory quality in various foods should be known with fair accuracy (Ohlsson, 1980). The chemical reactions in foods have a temperature dependence that can be described by a z-value of 33 C^0 (Lund, 1977). The z value corresponds to the temperature shift needed for a tenfold change in the rate of a chemical reaction or biological inactivation. The inactivation of bacterial spores, with a z-value of around 10 C^0 is, however generally the basis for the duration of the sterilization (Ohlsson, 1980). The differences in temperature dependence will mean that if a product is sterilized at two different temperatures but to the same bacteriological inactivation level, mostly negative changes in the quality will be smaller for the product sterilized at the higher temperature.

The differences in the temperature dependence between bacteriological inactivation and chemical and sensory quality changes, imply that an optimization of the quality retention is possible (Ball and Olson, 1957). However, knowledge of the time and temperature relationship for the changes during thermal processing is necessary. In addition, the sensory quality is evaluated as a volume averaged value, whereas the spore inactivation is considered only at its minimum value.

The objectives of this study were to investigate:

1. The effects of cooking on the textural properties (firmness, springiness and stiffness) of turnip and beet root for the purpose of gathering the data to be used in predicting texture loss of roots subjected to thermal processing.

2. Whether cooking of these root vegetables yield two simultaneous first-order kinetic reactions for the above textural characteristics as have been observed with the thermal softening behavior of Romano beans in Chapter III.

MATERIALS AND METHODS

Sample preparation:

During a period covering six harvest dates, a total of 80 kg regular turnip and red beet roots of medium diameter (8-10 cm) were obtained from an orchard located on Ile Perrot, Quebec, Canada. Turnip and beet roots were packaged in vented, polyethylene bags (5 kg) to maintain high humidity and stored at 4 °C until use (Peirce, 1987; Parkin and Im, 1990). For each temperature treatment, a 5 kg bag of turnips or beets was used and textural properties were measured the same day. Turnips and beets were first sliced (turnips 20 mm and beets 10 mm thick) using an electrical slicer. Later, each slice was punched out by two cork borers to provide cylindrical pieces of turnips (20 mm thick x 18 mm diameter) and beets (10 mm thick x 9 mm diameter). Cylindrical specimens were placed in the sealable polyethylene bags to prevent moisture loss prior to further experiments. Figure 12 illustrates the sample preparation of these root vegetables.

Figure 12. Steps in sample preparation of root vegetables

Root	*Sliced*	*Cylindrical piece*
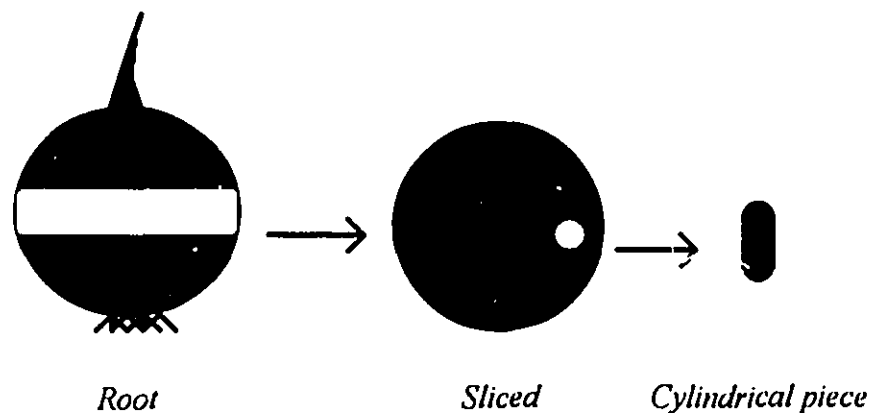
Cooking

Two perforated cans were filled with cylindrical pieces of each sample and immersed in a water bath (THERMOMIX 1480) at selected times (1-80 minutes). Five heating temperatures (70, 80, 90, 95 and 100 $^{\circ}$C $\pm$ 0.7 $^{\circ}$C) as suggested by Lenz and Lund (1980) were employed to heat treat the samples. After cooking, samples were drained for two minutes and cooled to room temperature and then placed in polyethylene sealable bags to prevent moisture loss during texture measurement. Each temperature treatment and texture measurement was performed on the same day. All experiments for both root vegetables required a total of ten days.

Texture evaluation

Evaluation of textural properties was performed using a Universal Testing Machine (Lloyd Model LRX - 2500 N; Lloyd Instruments Ltd., Fareham, Hans, UK). The cylindrical pieces of turnip and beet root were compressed under a constant force of 30 N in a unique cycle compression-decompression test, using a 50 N load cell and a 50 mm diameter circular probe with 10 mm min^{-1} as a rate of deformation. Several parameters were derived from the deformation curves as indicators of physical properties based on the following definition :

$$\textit{Firmness} = \frac{\text{Maximum Force}}{\text{Maximum Deformation}} = \frac{MF}{MD} \qquad (14)$$

$$\textit{Stiffness} = \frac{\text{Stress}}{\text{Strain}} = \frac{\text{Force / cross sectional area}}{\text{Deformation / initial length}} = \frac{F/A_0}{D/L} = \frac{(F/D)}{(A_0/L)} \qquad (15)$$

whre: F/D is the slope of the linear section.

$$\textit{Springiness} = \frac{\text{recoverable work}}{\text{total deformation part}} \qquad (16)$$

Figure 13. Typical plot of force-deformation for cooked turnip
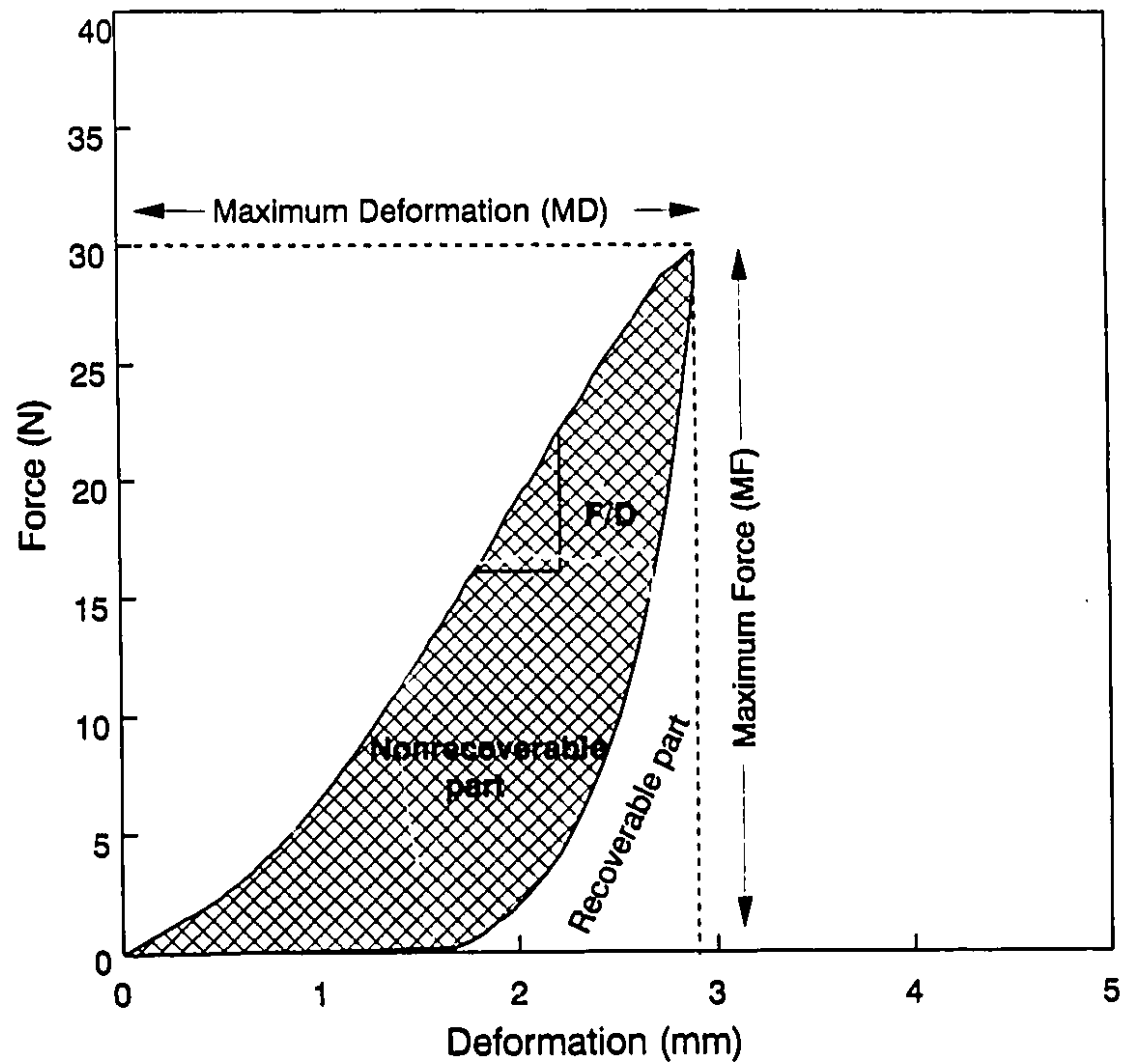
Firmness was expressed in N/mm. Modulus of deformability (stiffness) was expressed as stress to strain ratio in N/mm^2 and percent recovery (springiness) was determined as the percentage ratio of recoverable part to the total deformation. Each test was replicated five times and their mean values were used as indicators of the textural properties of these selected vegetables.

Kinetic method and correction for thermal lag

The kinetic method and correction for thermal lag used in this study is outlined in Chapter III. (Pages 50-54)

RESULTS AND DISCUSSION

A typical plot of force-deformation for cooked turnip at 100 °C is shown in Figure 13. Plots for other heat treated samples were similar except for the fact that the associated deformations were smaller indicating higher texture values. Figure 14 illustrates the influence of heat treatment on softening of beet and turnip at 100 °C. The graphs of cooked samples show a larger deformation which is associated with lower texture values, also raw beet has a lower texture value as compared with raw turnip. This is due to the fact that the dimensions of turnip's cylindrical pieces were two times bigger (hight and diameter) than those of the beets. The differences arising from small dimensional variations generally get normalized when texture values are calculated in the form of firmness, stiffness or springiness.

Figure 14. Force-deformation curves for raw and cooked sample of turnip and beet

Raw turnip

Cooked turnip

11 min   100 $^{\circ}$C

Raw beet

Cooked beet

25 min   100 $^{\circ}$C
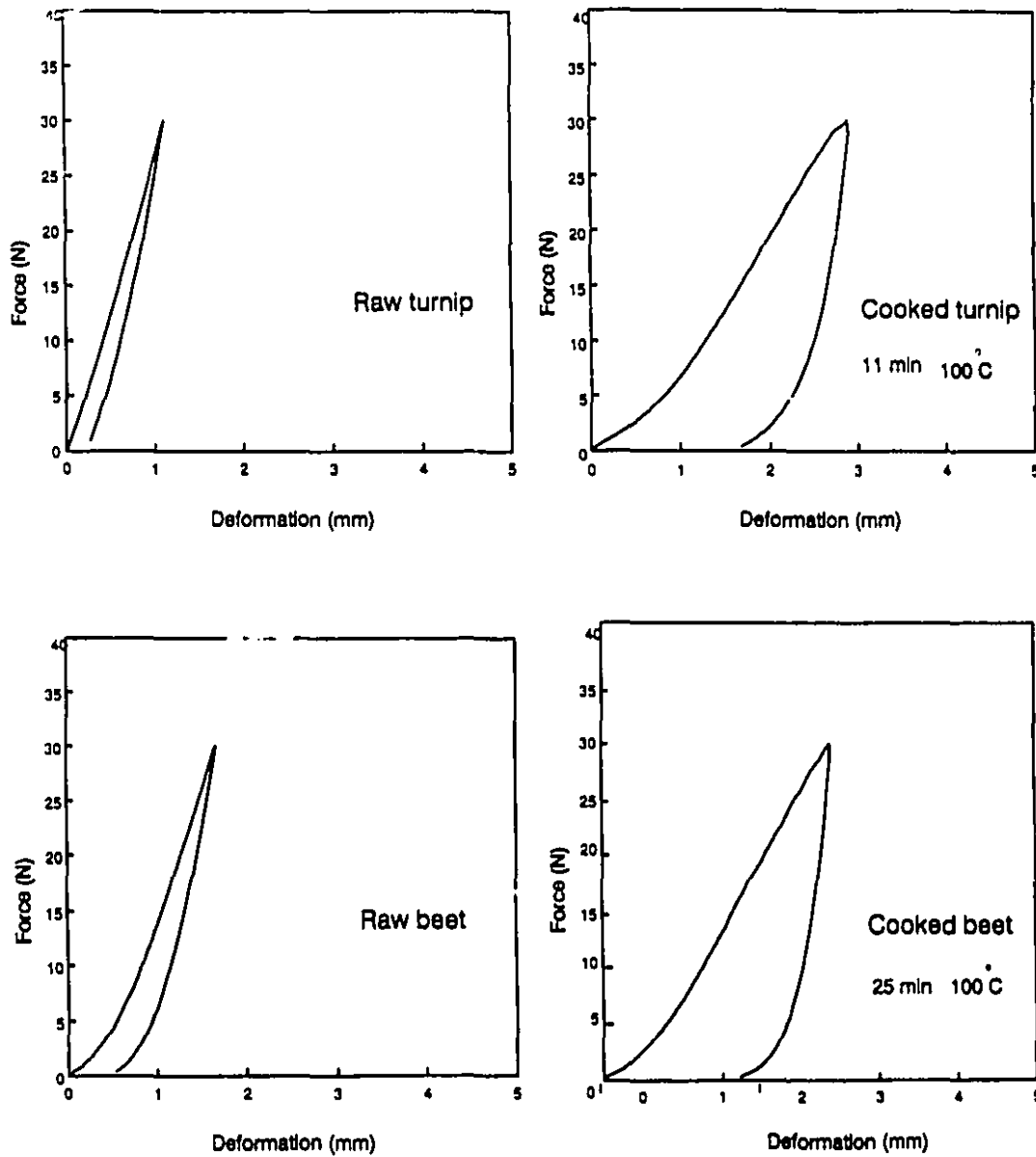
The study of rate of thermal softening of root vegetables showed a similar pattern in the softening curve for every product. Figure 15 (a) and (b) is a plot of log firmness versus cooking time for beet and turnip cooked at 70 to 100 $^\circ$C. The softening curve is characterized by an initial rapid decrease in firmness. This is consistent with the findings of the apparent first order softening kinetics in the other studies (Huang and Bourne, 1983). But then, rate of texture loss decreases; the firmness curves off into a second straight line with a shallow slope at longer process times. Since a first order process is represented by a rectilinear plot on a semilogarithmic scale, it is quite clear that simple apparent first order kinetics cannot apply to lengthy cooking times. The general shape of this curve is typical for both root vegetables that were studied. The striking features of Figure 15 are the initial linear relationship with a steep slope and the later linear relationship with a shallow slope. Although inconsistent with a simple apparent first order process, this relationship is entirely consistent with two pseudo first order processes with different rate constants occurring simultaneously. One process is rapid and the other process is slow.

Heat penetration rate into the particle during come-up time was plotted as shown in Figure 16 (a) and (b). Correction for thermal lag was determined for each test and kinetic parameters were recalculated using corrected thermal times. In fact, the only fraction affected by correction for thermal lag was the heat sensitive fraction or substrate "a" which contributed to mechanism 2. The results for all vegetables were the same ana substrate "b" contributing to mechanism 2 remained intact. It must be emphasized that the thermal lag effect will depend not only on the size of the particle but also on the food under investigation. For these reasons, correction for thermal lag must be determined for each test. A short heating time of 3 min at 95 $^\circ$C for a cylindrical piece of turnip yielded an effective heating time of 1.28 min with a 42% CUT effectiveness approach; but in reality its effectiveness will be far less. The effectiveness increases with the time up to CUT. After the come-up, a single correction will be sufficient.

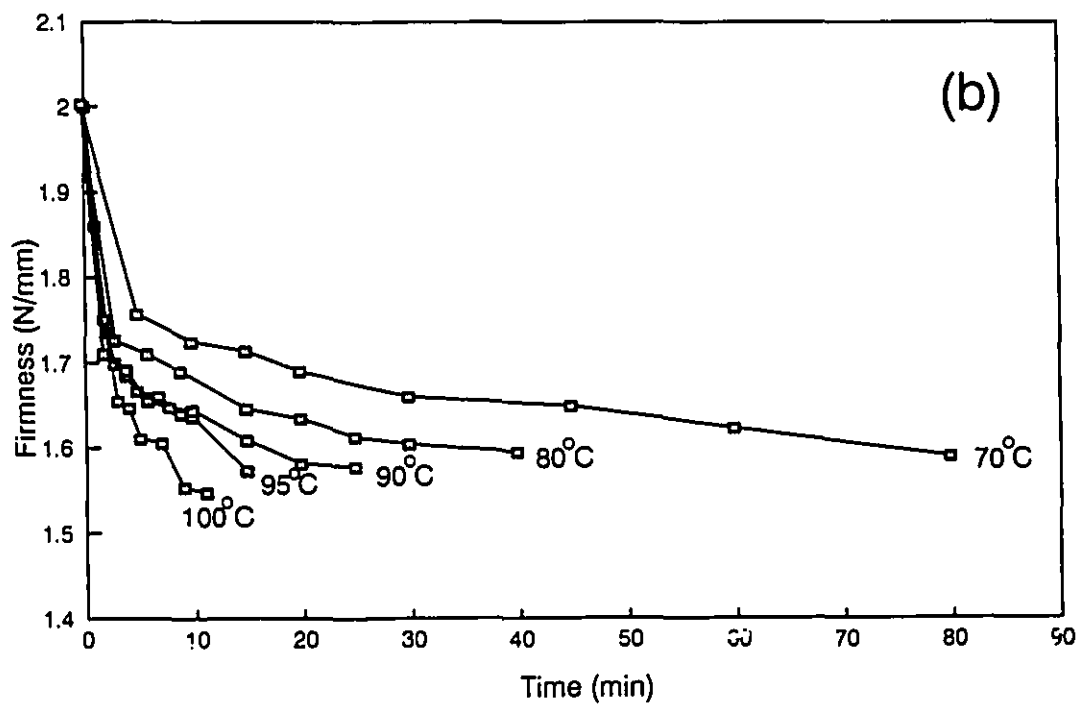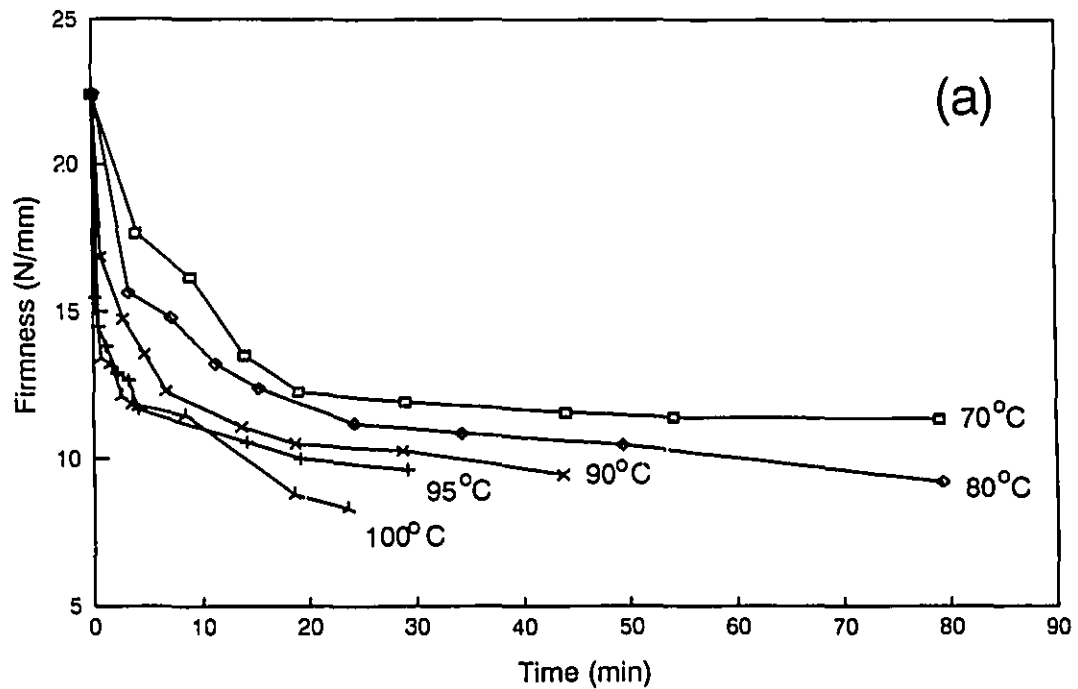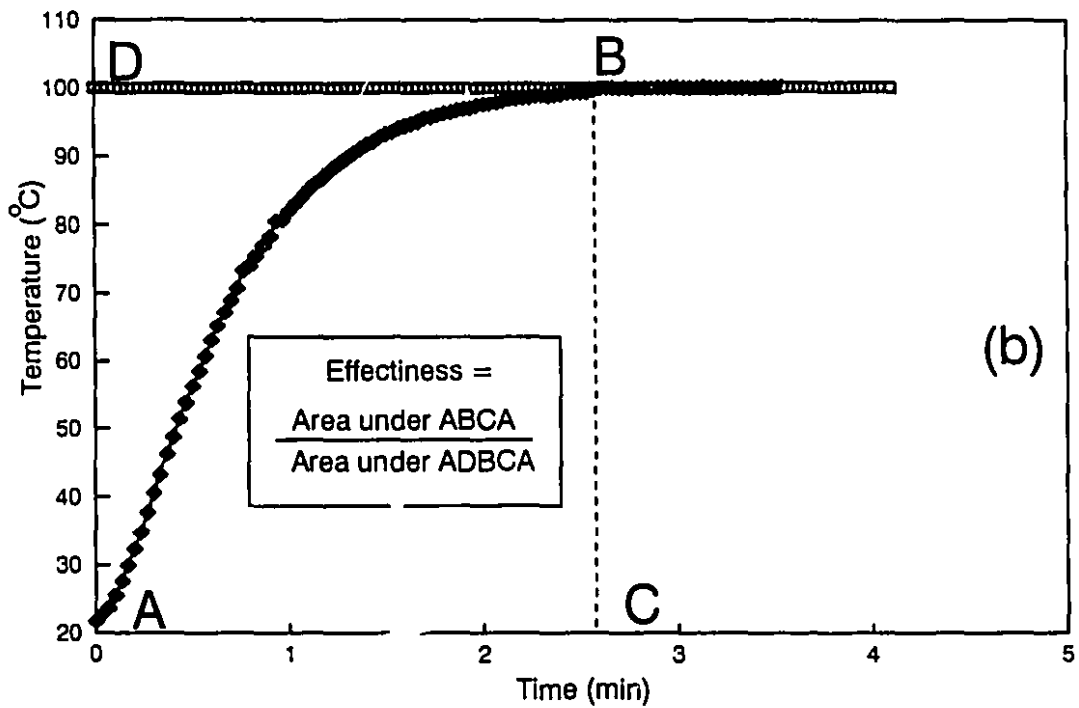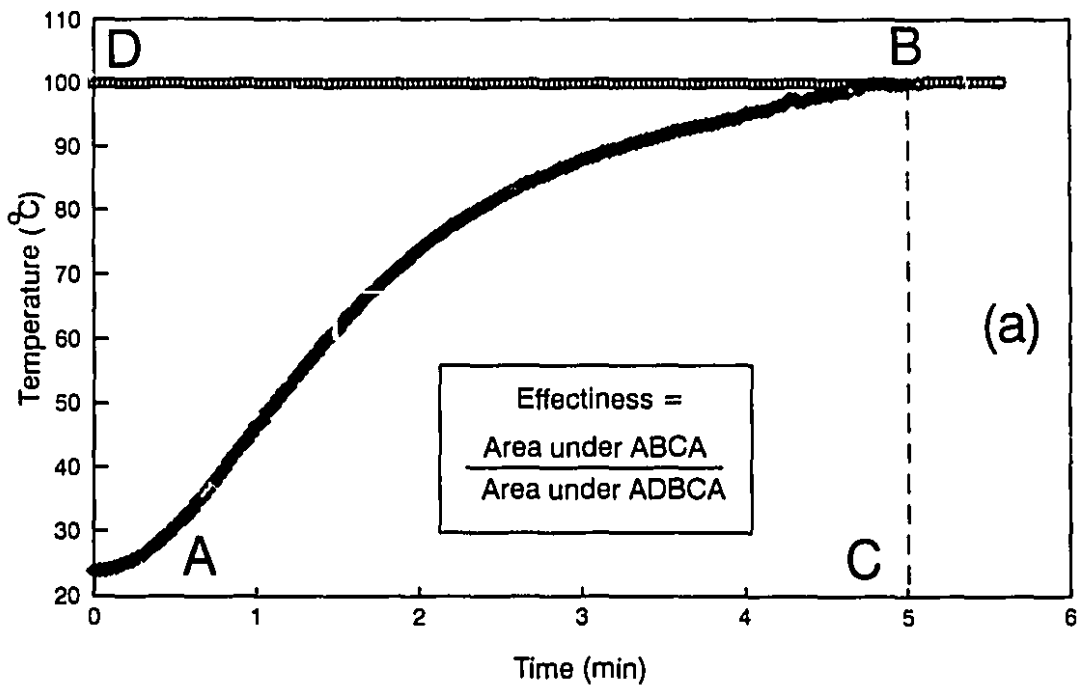# Figure 15. Softening curves for beet (a) and turnip (b) at different time temperature intervals

Figure 16.Heat penetraton curve for turnip (a) and beet (b) at 100 °C during come-up time

The result showed no effect of corrected time for kinetic values and their dependence on temperature (z and E_a) for the heat resistant fraction. Therefore, searching for a way to slow the apparent rate constant k_1 (rapid mechanism) can only provide a small gain since k_1 is so fast that even reducing it by 50% will have little net effect on texture after a commercial process.

A plot of three measured parameters, firmness, stiffness (modulus of deformability) and springiness for beet root are shown in Figure 17. All measured textural properties were found to decrease with an increase in exposure to heat. Loading and unloading of biological materials for several cycles has shown the reduction of residual deformation and strain hardening phenomena. When the slope of the unloading curves for the first and the subsequent cycles were compared, no change in slope was detected (Mohsenin, 1986). For calculation of stiffness and firmness, force and the corresponding elastic deformation, F/D, was obtained from the single loading and unloading cycle. Each point on the curves represents the mean of five measurements in a single cycle loading and unloading test. A comparison between three textural characteristics of thermal softening of beet root at 80 °C indicates a good relationship for two softening indicators, firmness and stiffness while this is not shown for springiness in both vegetables. Such behavior as has been pointed out by Mohsenin (1986) may be due to some residual deformation after the first loading and unloading cycle. None of the biological materials tested so far show perfect springiness. The major part of the residual deformation is due to initial setting which may be caused by the presence of pores or air spaces, weak ruptured cells on the surface, microscopic cracks in brittle materials, and other discontinuities which may exist in the structure of the material.

Following correction for thermal lag, the rate constant for the second or slower softening mechanism was first evaluated as the negative slope of the linear portion of the curve. This linear portion was then extrapolated backwards to zero cooking time and the values from the extrapolated line were subtracted from the experimental data above it (Figure 18).The result was a derived line with much steeper slope which gave the apparent rate constant for the first or rapid softening mechanism (Figure 19).

Figure 17. Softening of beet root at 80°C
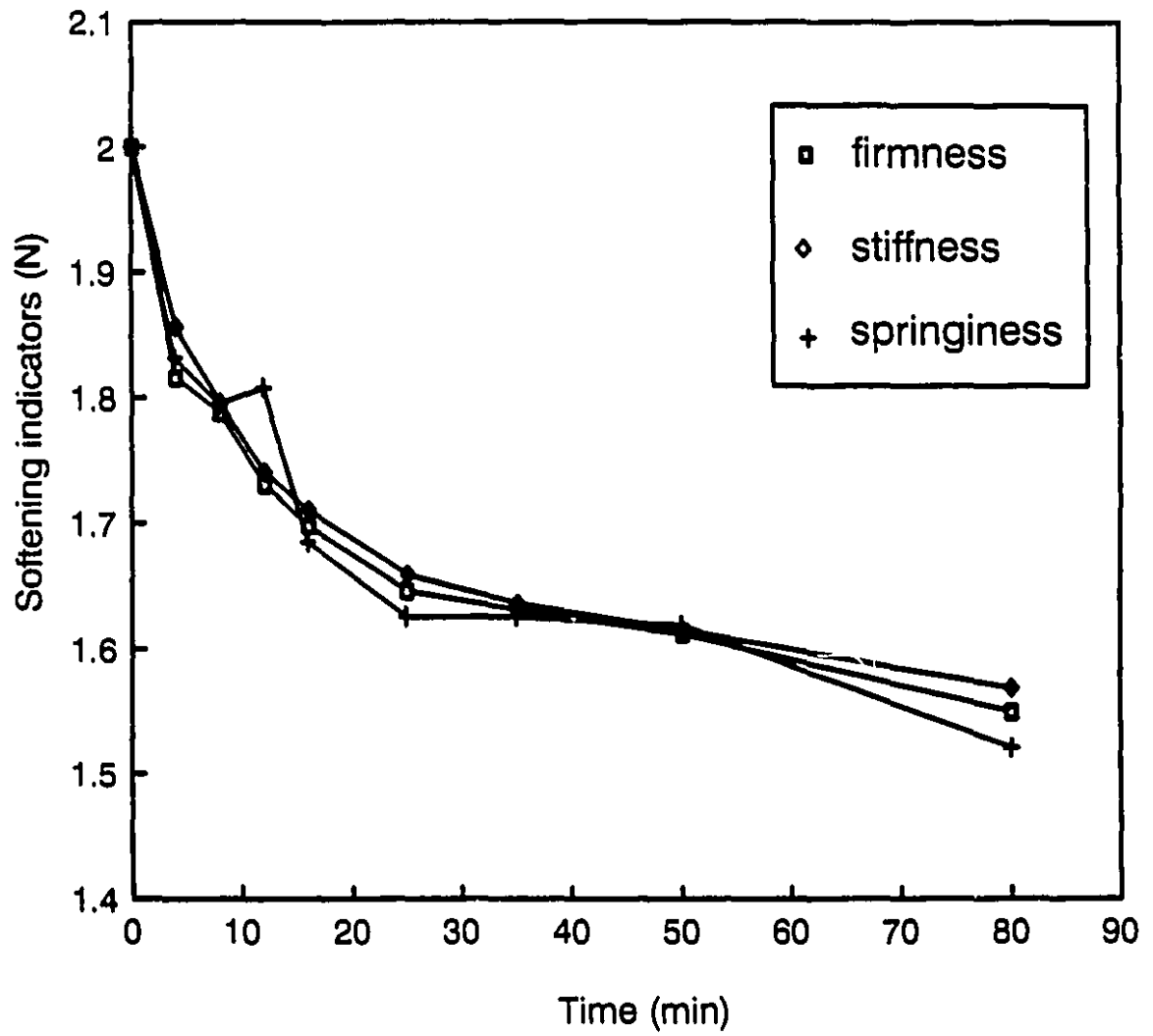for different time intervals

Figure 18. Firmness of beet at selected temperatures

(Regression lines indicate softening kinetics of the heat resistant fraction)
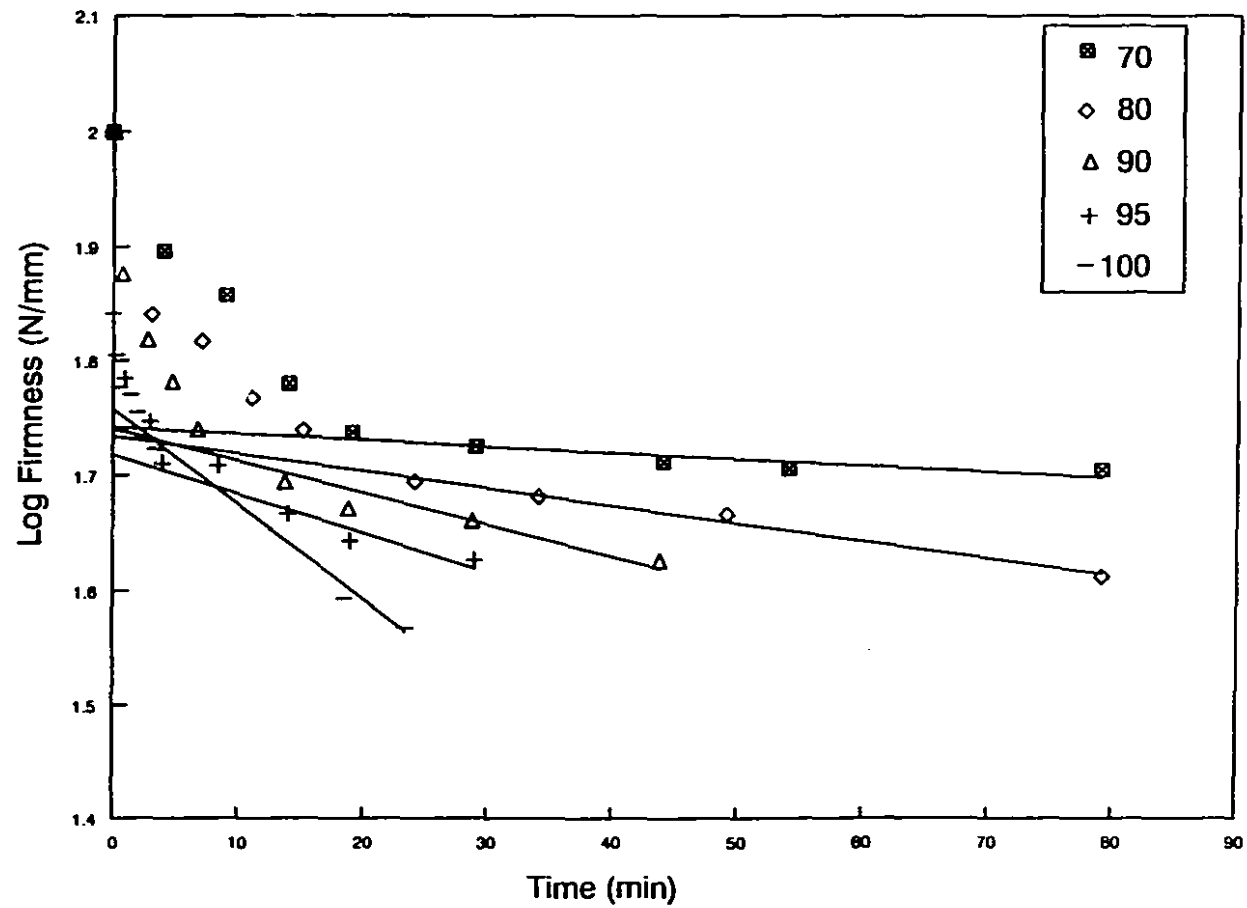
Figure 19. Firmness of beets at selected temperatures

(Regression lines indicate softening kinetics of the heat sensitive fraction)
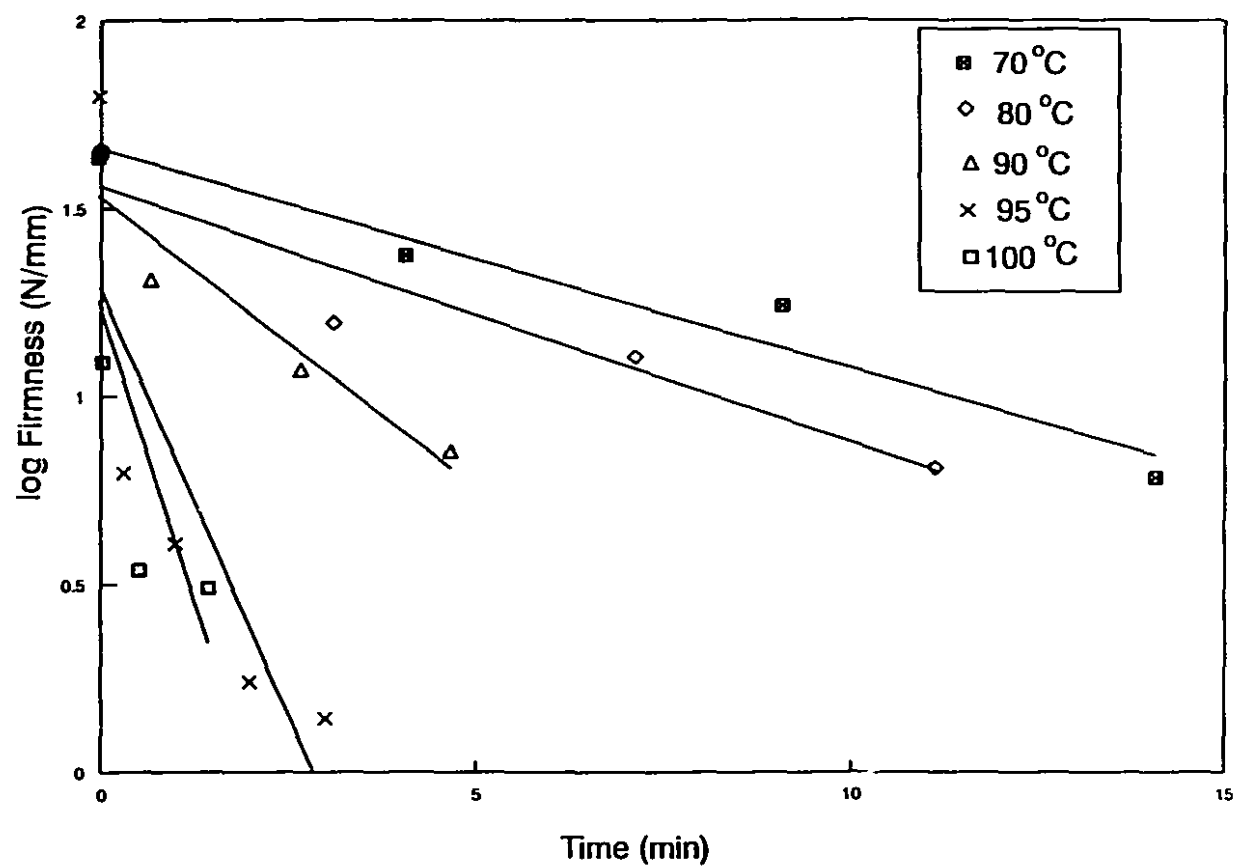
Corrected values for the apparent first order rate constants and associated softening rates for two mechanisms and three textural characteristics are given in Tables 3-8. Figures 20 and 21 illustrate the Arrhenius and TDT plots for turnip and beet before and after correction for thermal lag. The results generally confirm the first order nature for both softening mechanisms as indicated by their associated high R^2 values (0.82-0.99) in selected vegetables and the textural characteristics. Springiness in turnip and beet is the only one which indicates a lower R^2 in comparison with the other properties. This difference could be attributed to the residual deformation in biological materials as was previously indicated. D values associated with the slow mechanism which varied between 1830 to 1.26 min for turnip and beet in the temperature range 70-100°C were nearly 50 to 100 times larger than the range of values for the rapid mechanism. The values of reaction rate constant (k) showed similar trends with higher values associated with the rapid mechanism than the slower one (obvious since k is reciprocally related to D). The results, agin, indicated that softening by the rapid mechanism 1 is 50 times or more faster than the slower mechanism 2. These are followed by Arrhenius and TDT plots (Figure 22-25). Both apparent rate constant, k_1 (mechanism 1) and k_2 (mechanism 2) in all the cases give an excellent fit to the Arrhenius temperature relationship. A comparison between rate of softening of turnip and beet at any selected temperature obviously indicates that cooking causes softening of turnip's tissue much faster than that of beet root.

The z values and activation energies (E_a) calculated from regression for both mechanisms of softening properties in turnip and beet are presented in Table 9. These data show that temperature dependence of softening rates (z values) for first mechanism in turnip are larger than that of second mechanism while they are the inverse in beet root. This may be attributed to structural or compositional differences between these two biological materials. The intercept of extrapolated back of second mechanism (Thermal Firmness Value) obtained for turnip and beet are shown in Table 10.

Table 3. Kinetic parameters for thermal softening (firmness) of beet root

Temperature	Mechanism 1			Mechanism 2		
°C	K (min^{-1})	D (min)	R^2	K (min^{-1})	D (min)	R^2
70	0.134	17.2	0.95	0.00126	1826	0.82
80	0.157	14.6	0.95	0.00348	662	0.99
90	0.355	6.48	0.91	0.00638	360	0.90
95	0.621	3.71	0.76	0.00784	293	0.95
100	1.42	1.61	0.75	0.0190	120	0.97

Table 4. Kinetic parameters for thermal softening (stiffness) of beet root.

Temperature	Mechanism 1			Mechanism 2		
°C	K (min^{-1})	D (min)	R^2	K (min^{-1})	D (min)	R^2
70	0.114	20.0	0.92	0.00168	1373	0.84
80	0.150	15.3	0.99	0.00316	728	0.99
90	0.374	6.15	0.92	0.00557	413	0.95
95	0.615	3.74	0.75	0.00746	308	0.93
100	1.77	1.29	0.75	0.0228	101	0.98

Table 5. Kinetic parameters for thermal softening (springiness) of beet roots.

Temperature	Mechanism 1			Mechanism 2		
°C	K (min^{-1})	D (min)	R^2	K (min^{-1})	D (min)	R^2
70	0.142	16.1	0.98	0.00255	902	0.75
80	0.157	14.6	0.78	0.00459	501	0.86
90	0.399	5.76	0.98	0.0154	149	0.82
95	0.908	2.54	0.75	0.0167	137	0.96
100	1.86	1.23	0.87	0.0343	67	0.91

Table 6. Kinetic parameters for thermal softening (firmness) of turnip

Temperature	Mechanism 1			Mechanism 2		
°C	K (min⁻¹)	D (min)	R^2	K (min⁻¹)	D (min)	R^2
70	0.17	13.28	0.83	0.00333	692	0.98
80	0.29	7.94	0.75	0.00486	474	0.91
90	1.23	1.87	0.76	0.01049	219	0.95
95	3.10	0.74	0.83	0.2203	104	0.97
100	11.70	0.20	0.93	0.0321	71	0.91

Table 7. Kinetic parameters for thermal softening (stiffness) of turnip.

Temperature	Mechanism 1			Mechanism 2		
°C	K (min⁻¹)	D (min)	R^2	K (min⁻¹)	D (min)	R^2
70	0.169	13.6	0.81	0.00332	693	0.98
80	0.288	7.99	0.77	0.00480	479	0.91
90	1.25	1.84	0.75	0.01048	219	0.96
95	2.25	1.02	0.92	0.0226	102	0.98
100	10.87	0.212	0.80	0.0322	71	0.91

Table 8. Kinetic parameters for thermal softening (springiness) of turnip.

Temperature	Mechanism 1			Mechanism 2		
°C	K (min⁻¹)	D (min)	R^2	K (min⁻¹)	D (min)	R^2
70	0.136	16.9	0.78	0.00395	582	0.84
80	0.330	6.97	0.75	0.00841	273	0.90
90	1.17	1.95	0.88	0.01407	163	0.75
95	2.42	0.953	0.93	0.1719	133	0.94
100	25.9	0.088	0.83	0.03065	75	0.99

Figure 20. Arrhenius and TDT plots for turnip before and after correction for thermal lag
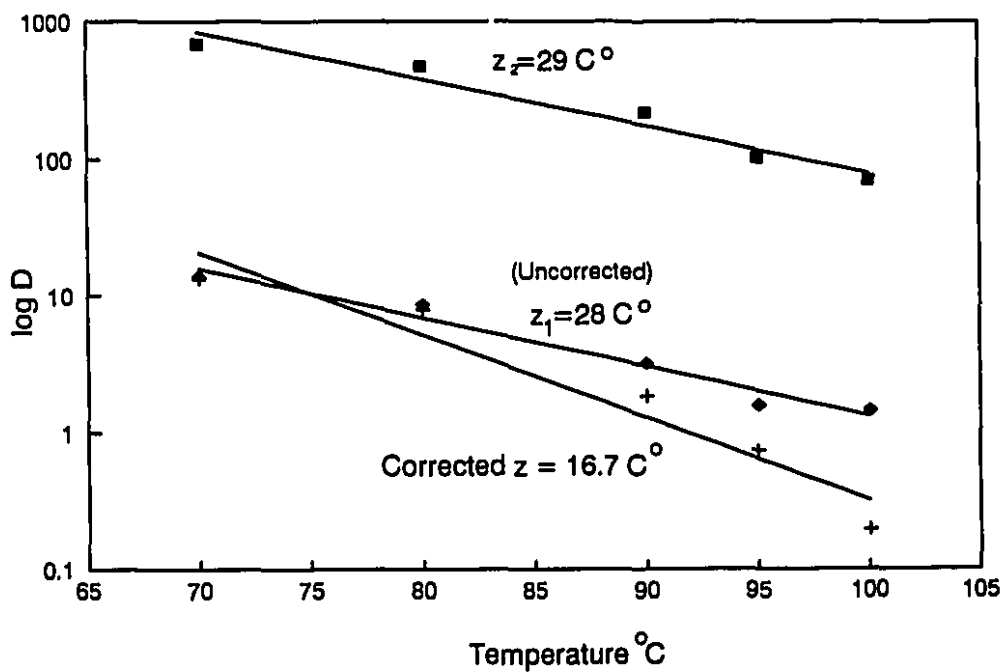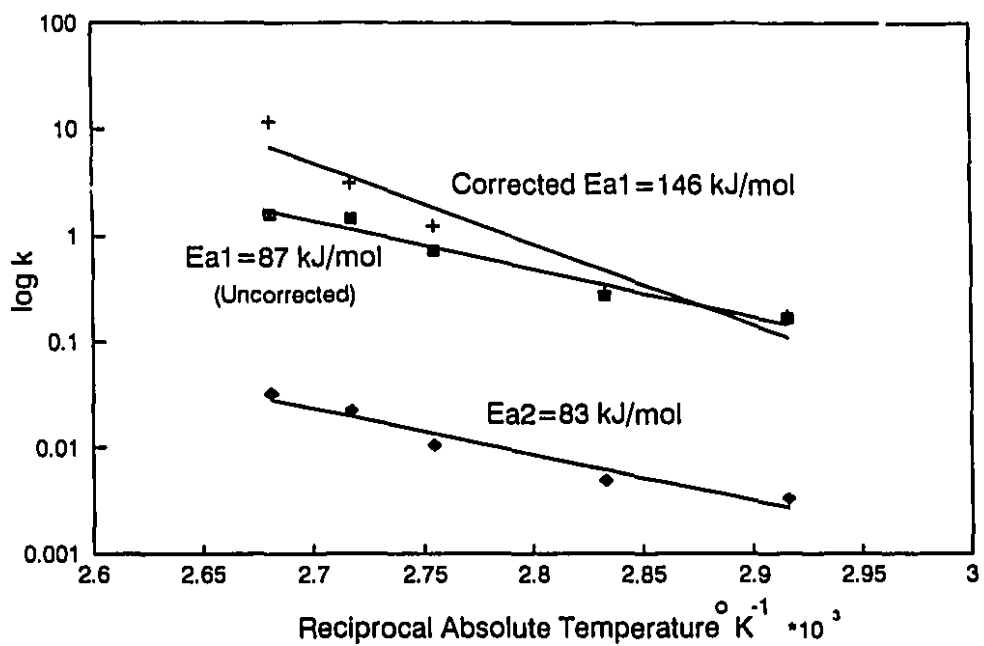
Figure 21. Arrhenius and TDT plots for beet before and after correction for thermal lag
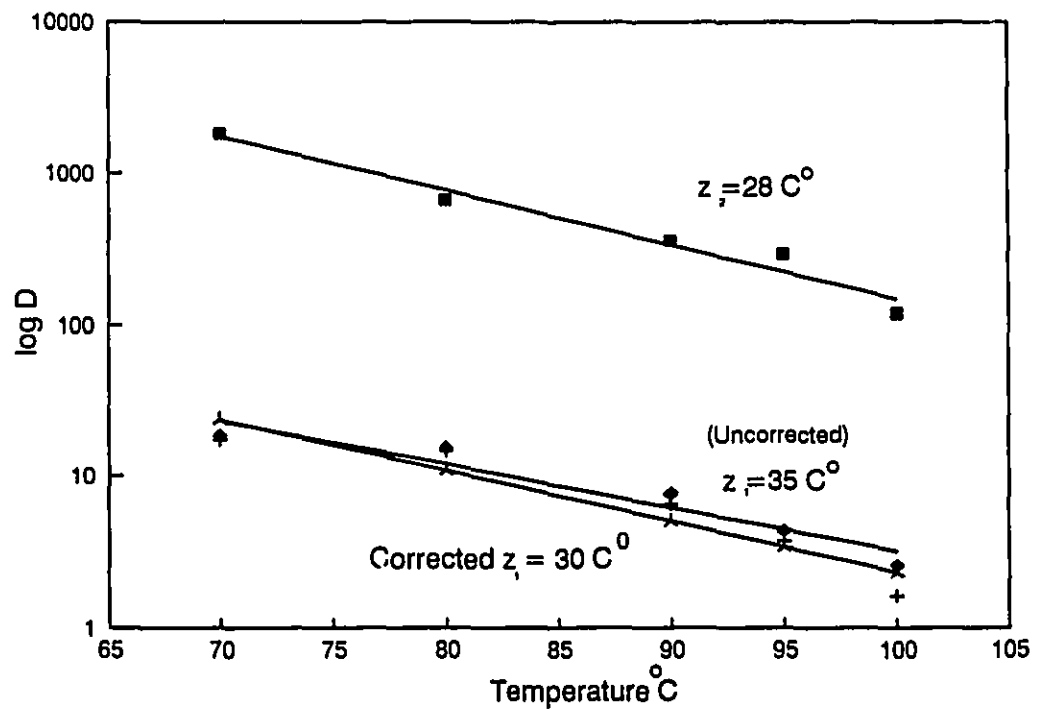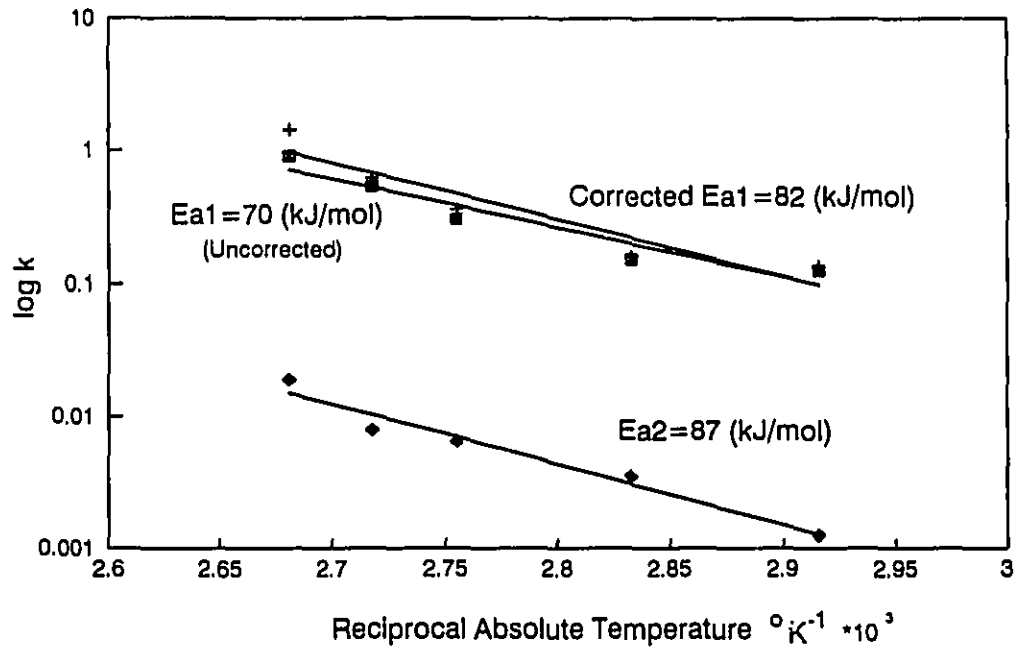
Figure 22. Arrhenius plots for softening properties of turnip
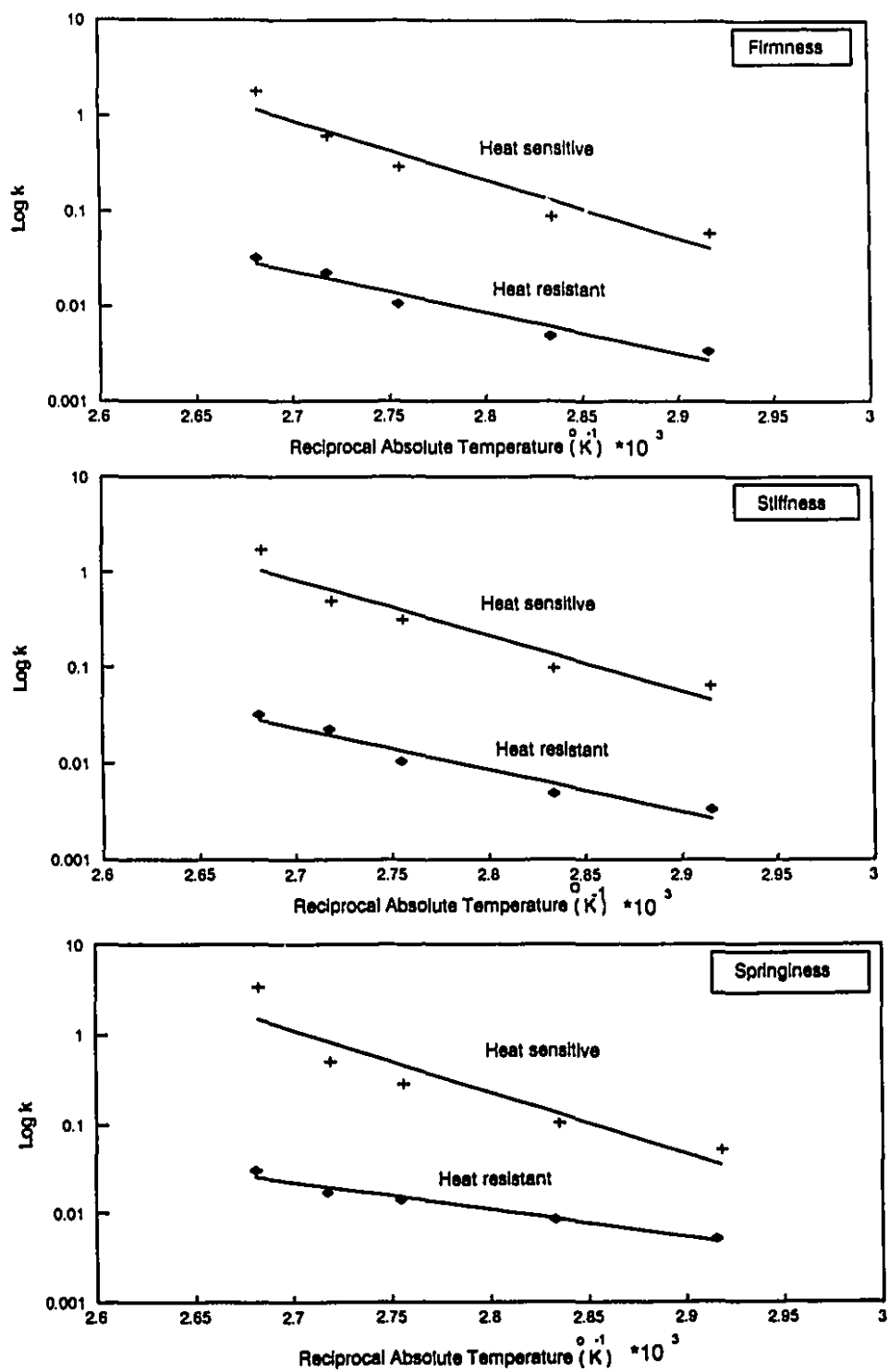
Figure 23. Arrhenius plots for softening properties of beet
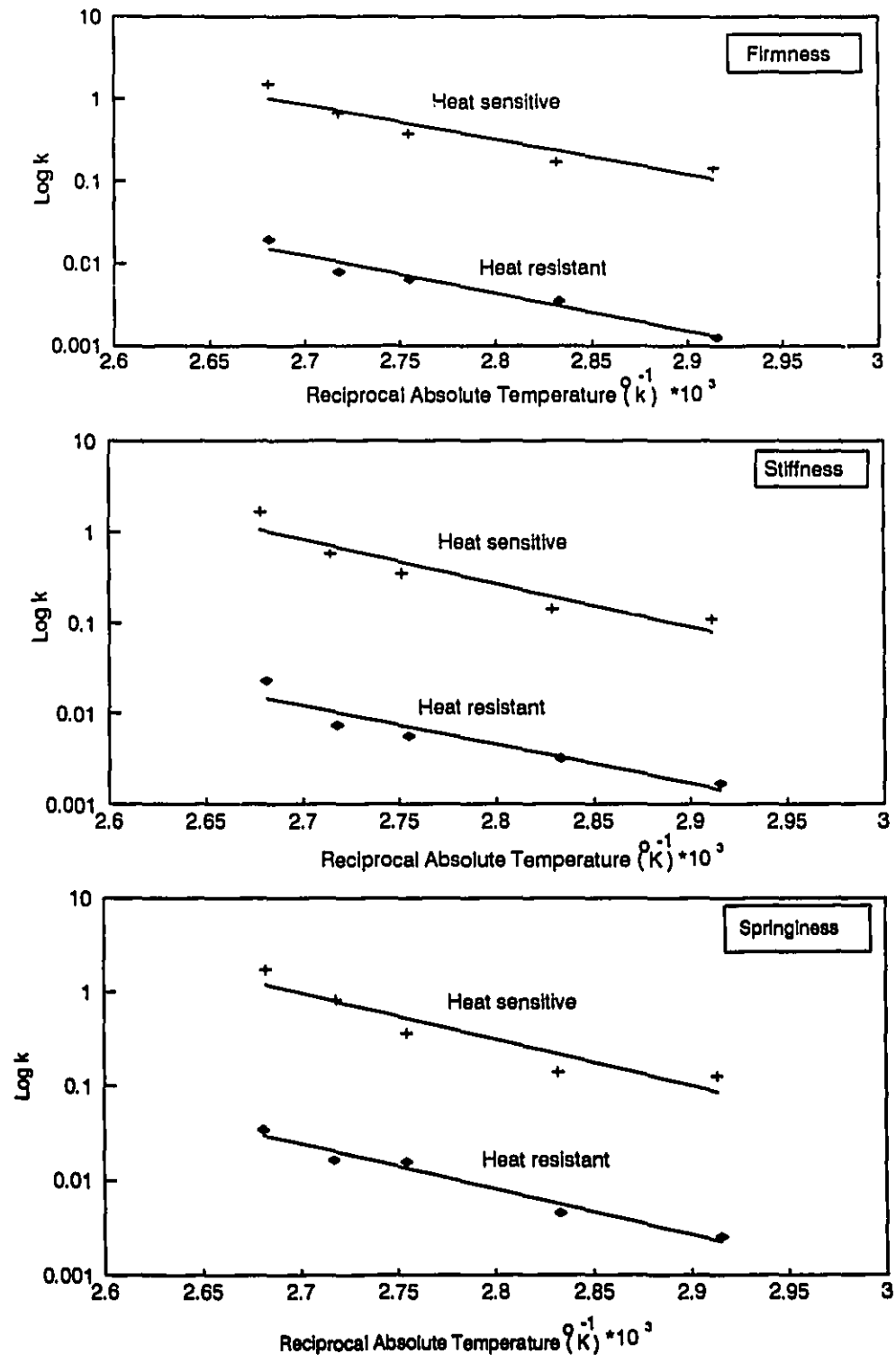
Figure 24. TDT plots for softening properties of turnip
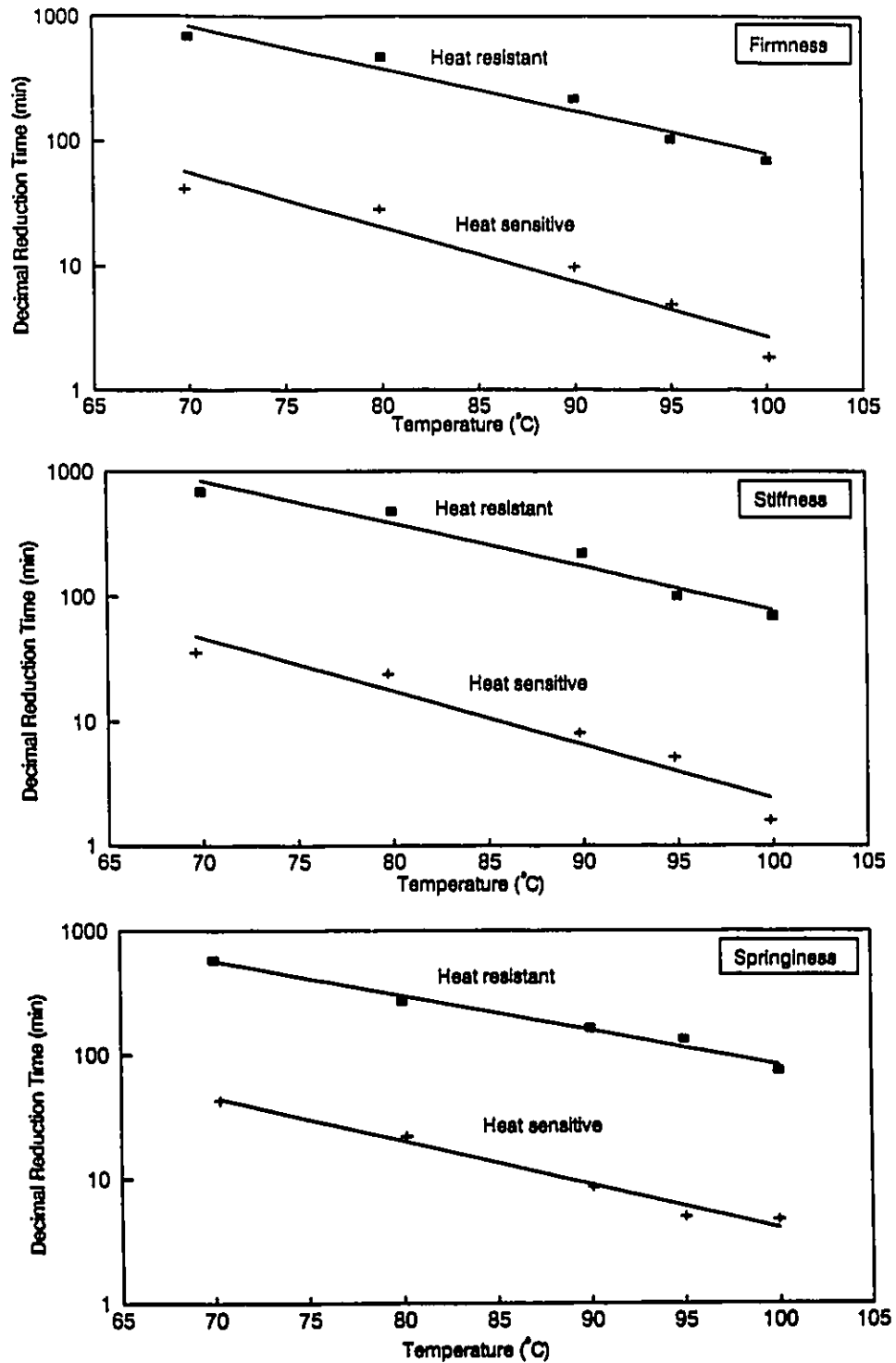
Figure 25. TDT plots for softening properties of beet
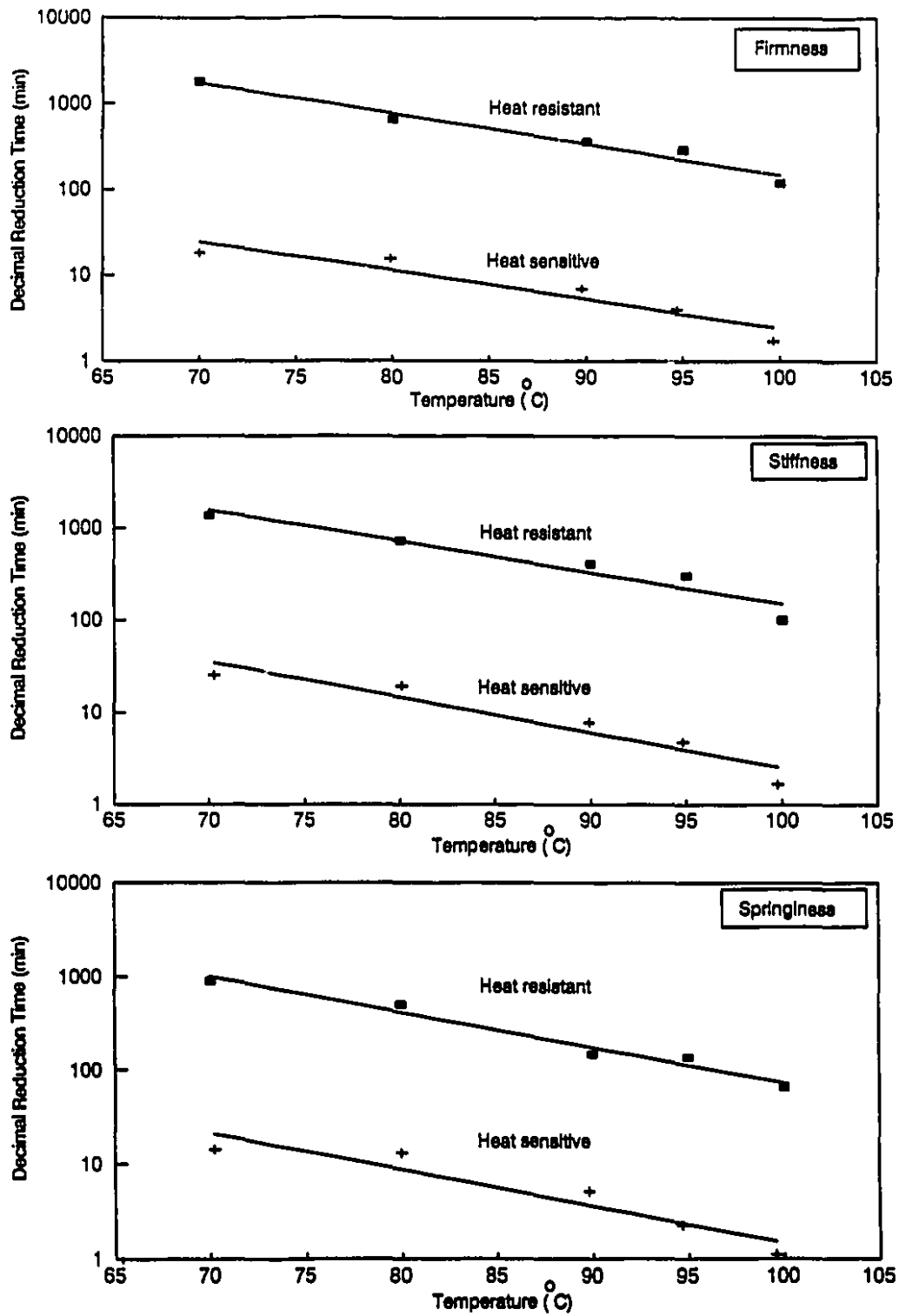
Table 9. Calculated activation energies (E_a) and temperature dependence of softening rate (z value) in turnip and beet root.

Property → Product ↓	Firmness E_a (kJ/mole) (k_{100})	R^2	z (C°) (D_{100})	R^2	Stiffness E_a (kJ/mole) (k_{100})	R^2	z (C°) (D_{100})	R^2	Springiness E_a (kJ/mole) (k_{100})	R^2	z (C°) (D_{100})	R^2
Turnip Mech. 1	146 (1.6862)	0.92	17 (1.33)	0.93	141 (1.6916)	0.91	17 (1.32)	0.92	167 (1.6829)	0.87	22 (1.26)	0.98
Turnip Mech. 2	83 (0.0279)	0.95	29 (80)	0.96	83 (0.0281)	0.95	29 (79)	0.95	60 (0.0256)	0.97	36 (84)	0.98
Beet Mech. 1	81.7 (0.7088)	0.88	30 (3.16)	0.92	92 (0.8225)	0.89	30 (2.71)	0.93	92 (0.8279)	0.88	26 (2.70)	0.89
Beet Mech. 2	87 (0.0150)	0.96	28 (148)	0.96	82 (0.0146)	0.90	29.6 (152)	0.91	92 (0.0301)	0.97	27 (74)	0.97

The numbers in parentheses indicate the D and k values at 100 °C on the slope of TDT and Arrhenius plots

Table 10. The log mean thermal firmness values for root vegetables.

Temperature °C	Turnip			Beet		
	Firmness	Stiffness	Springiness	Firmness	Stiffness	Springiness
70	1.70	1.70	1.86	1.74	1.75	1.70
80	1.67	1.67	1.85	1.73	1.73	1.69
90	1.68	1.68	1.85	1.74	1.71	1.74
95	1.72	1.72	1.84	1.72	1.72	1.73
100	1.69	1.69	1.80	1.77	1.75	1.71

The results generally indicate the amount of 46-58% residual firmness and stiffness and 49-72% residual springiness for turnip and beet. The bigger amount of springiness as was discussed before may refer to residual firmness after loading of the sample. The result, however, showed no difference between thermal firmness values obtained from cooking at different temperatures.

CONCLUSIONS

The kinetic evidence given above pointing to two softening mechanisms indicates that any attempt to specify the textural quality of vegetables cannot employ simple first-order kinetics, except for very short heating times. Of practical interest is the fact that an extension of heating past a certain time causes little further deterioration of textural properties. The softening process follows two simultaneous pseudo first order rate softening mechanisms, one more rapid than the other. The dominant factor which determines residual firmness in thermally treated samples is the slower mechanism since the substrate responsible for the rapid mechanism could be lost during a short exposure to 100°C. These results confirm and expand the findings of the Huang and Bourne (1983) as the slower mechanism remained intact.

CHAPTER V

EFFECT OF THIN PROFILE AND ROTATIONAL PROCESSING ON TEXTURE OF VEGETABLES

ABSTRACT

Considerable thermal degradation of vegetable products may occur during the canning process. Thin profile and rotational processing allow the use of shorter process times and cause more uniformity of temperature distribution, which may result in a product of superior quality. The purpose of this study was to examine the influence of these processes on the texture of canned Romano beans (*Phaseolus vulgaris*), beet root (*B. Vulgaris L.*) and regular turnip root (*Brassica apobrassica*).

Cylindrical turnip and beet root pieces and hydrated Romano beans were packed in thin profile plastic containers (140 mm   100 mm   27 mm) and conventional metal cans (211 x 400). After conducting a heat penetration test and processing to equivalent lethality, textural properties of samples were evaluated using an instrumental method. In a single-cycle deformation test, force-to-deformation ratio was used as the indicator of firmness for all three products. The ratio of recoverable part to total deformation and stress-to-strain ratio represented the springiness and stiffness for turnip and beet roots, respectively. Thin profile packed vegetables, in all cases, were found to have a firmer and stiffer texture. On the other hand, for rotational processing, although less variation of texture values was found within the containers, the result showed no significant improvement in textural properties over the still counterparts. It was found that previously determined kinetic data could be used to estimate texture retention.

INTRODUCTION

Thermal processing (canning) of agricultural materials is considered an important process for extending the shelf life of foods. During heat treatment of living biological materials, obviously, the time and temperature of exposure to heat is very critical. The process is determined from a study of the rate of heat penetration for the product and from heat resistance of microbial spores of public health or spoilage concern. The quality of canned vegetables is affected by several factors, such as cultivars, production environment, process methodology and storage condition (Shattuck et al., 1991; Saldana et al., 1979; Perkins-Veazie and Collins, 1991; Junek et al., 1980; Nordstrom and Sistrunk, 1979; Hosfield et al., 1984). In order to maximize the quality retention, the process times should be kept at the minimal level required to assure commercial sterility in the product.

The food industry has experienced tremendous technological advances in the last 50 years. In the 1980s, the U.S. food processing industry began to develop more heat-sensitive, formulated food products requiring the use of more creative processing techniques. The selection of a rotary processing system for some products and container types over still batch steam or water processing was initially simple: a faster rate of heat penetration and product cooling could be accomplished with end-over-end continuous container motion (Park et al., 1990).The integrity of the ingredients used in the product remains intact for the most part. This becomes very notable in products containing coarsely chopped and diced ingredients, which do not lose their shape. Breakdown of the muscle fiber, a common problem with static high temperature sterilization, is totally eliminated by the rotary process (Eisner, 1988). In a recent study, Abbatemarco and Ramaswamy (1994) demonstrated that firmer vegetable products could be obtained following rotational processing. Because of the smaller thermal gradients in the can, the

danger of either over or understerilization is greatly reduced. The food processing industry also saw new opportunities to introduce formulated shelf-stable foods in flexible and semi-rigid containers which required system over pressure during heating and cooling phases of the process. One of the advantages of thin-profile containers over tinplate cylindrical cans is the fact that its shape provides greater surface area per unit mass. This permits more rapid heat transfer and thus reduces the process time necessary for commercial sterility (Ramaswamy and Tung, 1986). With reduced heat exposure, improved food quality (both sensory and nutritional) may be expected, as compared to similar products in conventional cans. The benefits of thin-profile pouches were reviewed by Mermelstein (1978), Gomez et al. (1980) and Snyder and Henderson (1989).

Despite the envisaged advantages of rotational and thin profile processing, vegetables are mainly canned in the traditional fashion, notwithstanding poor acceptance. Little has been published on improving the textural quality of these products as affected by packaging and processing.

The objectives of this study were: (1) to verify the commonly stated advantage of reduced process time in both rotational and thin profile processing (2) to investigate the effect of these thermal processing methods on the textural properties of selected vegetables. Three products were used in the study: turnips, beets and Romano beans. The metal cans and semi-rigid containers used in this study contained equal fill weights.

MATERIALS AND METHODS

Thermal processing

Romano beans, obtained from a local store, were hand sorted and soaked for 14 hours in three volumes of distilled water at room temperature prior to processing. Turnip and red beet roots of medium diameter (8-10 cm) were obtained from a local farm and prepared as cylindrical pieces: first by slicing using an electric slicing machine and then by

punching out a cylinder using a cork borer. The dimensions for turnips were 20 mm thick × 18 mm diameter and for beets 10 mm thick × 9 mm diameter.

The thin profile containers used in this study were semi-rigid plastic trays with the following dimensions (160 mm   115 mm   33 mm) and food volume of 300 mL. The cylindrical (metal) cans were 211   400, (100 mm hight and 65 mm diameter) picnic type, with enameled body and ends and a 300 mL volume. Each container was filled with 180 grams of solid and 60 grams of liquid (water was used as liquid to fill up the spaces between the particles) allowing for the industry standard of 1/4 inch headspace.

The location of the thermocouple when carrying out a heat penetration test is an important decision. The temperature in a container of food is not uniform during a sterilization process. The point of measurement should be the slowest heating zone of the product to ensure that the process determined with the results of the data will be adequate for all points in the container (Snyder and Henderson, 1989). A semi-rigid CNS copper-constantan thermocouple (Ecklund-Harrison Technologies, Cape Coral. FL) was placed through a compatible Omega packing gland attached to the bottom corner of the semi-rigid container and center point of the vertical axis of the metal can. A cylindrical piece of root vegetable or a single hydrated Romano bean was placed on the semi-rigid thermocouple so that the thermocouple tip would approximately reach the particle center. In order to prevent the removal of the particle during the experimental runs, vegetable pieces were fixed on one side with a rubber washer and a small piece of wood on the other side (Figure 26a). In order to verify the stability of particles at the desired location, containers were opened and inspected after each experimental run. All vegetable particles fitted in all containers remained at the original position (Figure 26b). For both semi-rigid containers and cans containing the turnips or beets or hydrated Romano beans in water which were to receive either an agitated or still cook, the thermocouple tips were placed in the container's geometric center. Several thermocouple probes were also placed throughout the retort in order to verify that uniform heat distribution had been achieved.

Figure 26. Samples at the cold spot of the containers (a) before and (b) after processing

(a)
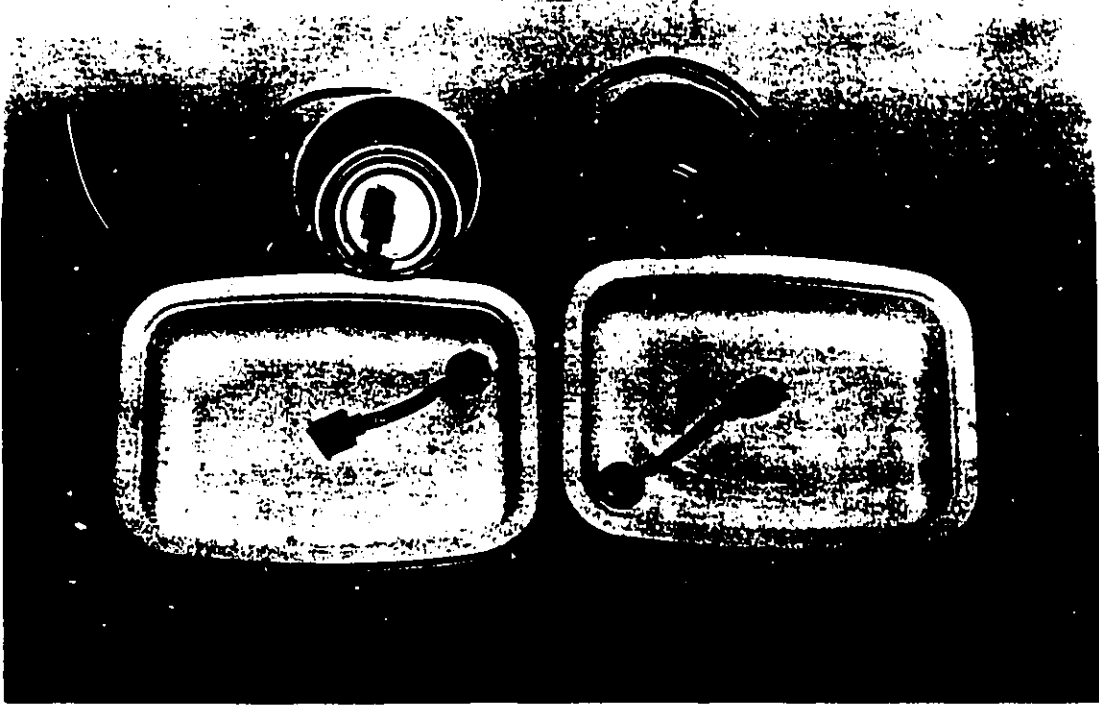
(b)
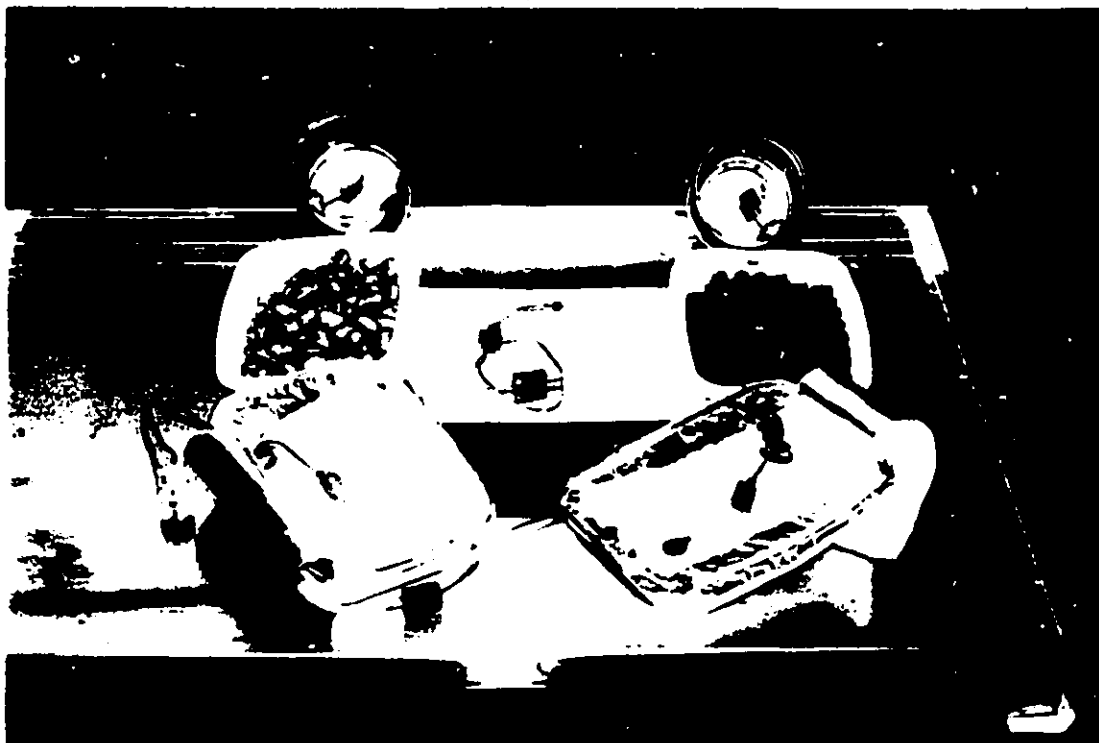
A pilot scale vacuum sealer model REYCON [R] 103, (Reynolds Metals Co., Richmond, VA.) sealed the aluminum lid over the semi-rigid container and cans were seamed in a semi-automatic sealer machine (Double Seamer, Type W-200, Continental Can Co., New York).

A pilot scale rotary, single cage, full-water immersion retort (STOCK-ROTOMAT-PR 900; HERMANN STOCK MASCHINENFABRICK, GERMANY) was used in either end-over-end rotation and static mode to commercially sterilize the selected products The sterilization trays used for this study were designed for semi-rigid (plastic) containers with a maximum thickness of 3/4 inch, with 12 containers per tray. Figure 27 shows the processing vessel of the Rotomat.

A common air over-pressure of 70 kPa was used for all test runs with the Rotomat. The retort was set at 121.1 ^{o}C (250 ^{o}F) with an overriding pressure to give a total pressure of 175 kPa, which was maintained during the cooling period to prevent package damage. Tap water at approximately 15°C was used for cooling all containers. Operating conditions were still (0 rpm) and rotational sterilization (10 rpm) for beets, turnips and Romano beans in both cans and semi-rigid containers. Thus, a total of 12 experimental runs were carried out.

Temperature readings were computer recorded at 15 s intervals via a data logger (Dash-8, Meta-Byte Corp., Tauton, MA) as containers were subjected to static or end-over-end rotational processing. Temperature data was acquired using the LabTech Notebook Software.

Figure 27. Loading of samples in the processing vessel
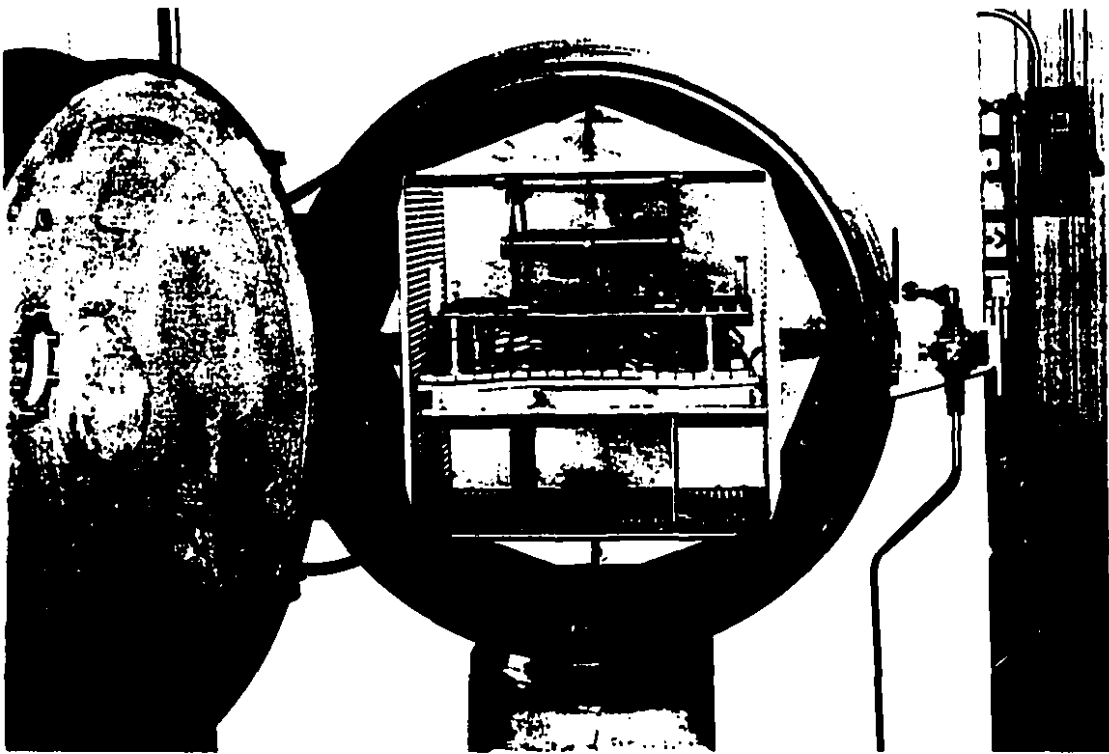
Heat penetration tests and data processing

Preliminary experiments which consisted of initial heat penetration tests were carried out with both cans and trays processed together. All containers were overprocessed during a period of approximately 40 minutes (including come-up time and holding time periods) in order to determine appropriate process times for an equivalent lethality of 6 minutes. Time-temperature plots were obtained using a Lotus worksheet and the accumulated process lethality (F_0 during the entire process) was calculated for each of the preliminary runs by numerical integration of the time-temperature data ($z = 10^\circ C$):

$$F_0 = \int_0^t 10^{(T-121.1)/z} dt \qquad (17)$$

The heating time (come-up time and holding period) required to obtain an F_0 value (heating) of approximately 5 minutes was evaluated from the above. The time during cooling contributed the remaining lethality for a total of approximately 6 minutes. Consequently, the total process time for each combination varied so as to accommodate the required equivalent lethality.

Texture measurements

The textural properties of processed vegetables were evaluated with a Universal Testing Machine (Lloyd Model LRX - 2500 N; Lloyd Instruments Ltd., Fareham, Hans, UK). The Lloyd Instrument was interfaced to a computer and the force/deformation curves were recorded at an interval of 0.06 sec (Figure 28). A circular plate (50 mm diameter) was made to descend vertically at a constant speed of 10 mm min^{-1} on the processed cylindrical pieces of turnips or beets or individual Romano beans under a constant force for all the commodities. A 50 N load cell was used in the study.

Figure 28. Lloyd Instrument Universal Testing Machine
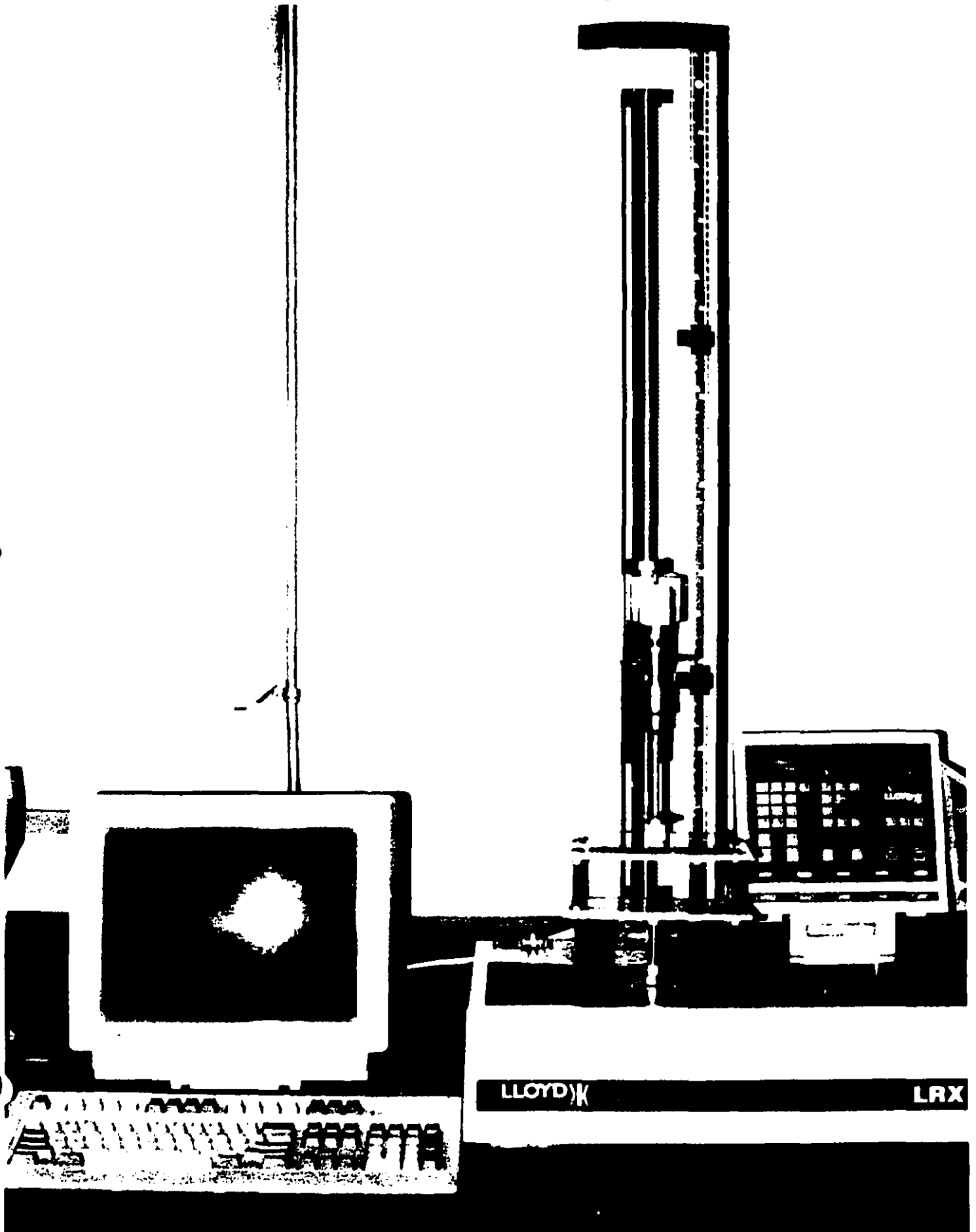
The ratio of the maximum force to the corresponding deformation produced was taken as firmness and expressed in N/mm. Each test was replicated 10 times and the mean values were used as indicators of textural properties of processed products.

The stiffness and springiness of turnip and beet root were derived based on the following calculations (as was indicated in chapter IV):

$$Firmness = \frac{\text{Maximum Force}}{\text{Maximum Deformation}} = \frac{MF}{MD}$$

$$Stiffness = \frac{\text{Stress}}{\text{Strain}} = \frac{\text{Force / cross sectional area}}{\text{Deformation / initial length}} = \frac{F/A_0}{D/L} = \frac{(F/D)}{(A_0/L)}$$

whre: F/D is the slope of the linear section.

$$Springiness = \frac{\text{recoverable work}}{\text{total deformation part}}$$

Prediction of texture loss in thermal processing

This part is a practical look at the exposure of food particles to heat during processing, to attempt to quantify degradation of texture by a method that can be applied for optimizing processes for a particular food product (vegetables). This may also serve as a tool in evaluating the application of the heat and the resulting thermal degradation in an existing processing system. The procedure point out differences between processing methods and highlights the steps taken in a process where undesired thermal degradation and waste of energy occur.

The prediction or optimization of a thermal process for nutrient and sensory quality retention requires specific kinetic parameters for the basis of the process (i.e., *C. botulinum* spores or other pathogenic organisms) as well as quality factors. The temperature dependence of reaction rates for loss of texture in three selected vegetables

were tabulated in Chapter III and IV. Two parameters were given for each class of constituent. First is the Arrhenius activation energy (E_a) which characterizes the temperature dependence of the reaction. Second is z-value resulting from the TDT curve which represents the ten-fold change in D-value.

Upon heating, a heat-labile constituent such as sensory quality, will change into products that are stable under the given conditions. The first approximation as was mentioned before is to treat this loss as a first-order chemical reaction and the rate of loss of the texture of the labile constituent can be expressed as in Equation 18 in which $-dc/dt$ is the rate, the change in concentration of the constituent (dc) in a time interval (dt).

$$-dC/dt = k.C \qquad (18)$$

This equation may also be expressed by using the D-value concept , commonly used in thermal process calculations to characterize microbial destruction rates:

$$d \log C/dt = -1/D \qquad (19)$$

$D = 2.303/k$ is analogous to the decimal (90%) reduction value in the thermal destruction of bacteria. D is a function of temperature, approximated empirically by

$$D_T = D_{Tref} 10^{(Tref - T)/z} \qquad (20)$$

Obviously, D_T is an exponential function of temperature (T) relative to a reference temperature (T_{ref}) and the corresponding D_{Tref} value characteristic of a constituent in equation. The z-value is a constant, analogous to the z-value of the thermal destruction of bacteria, and characteristic for each chemical reaction of a particular constituent (texture) involved in thermal degradation. The sterilizing values were calculated, using the

temperature history of the canned products and the D_O was obtained through the slope of the TDT curve.

During thermal processing, microorganisms are destroyed progressively and more rapidly as the temperature rises in the container. Thus, the value of thermal destruction imparted during processing can be integrated over the time, by the following equation:

$$\text{Sterilizing value} = Fz_{Tref} = D_{Tref} (\log a - \log b) = \int_0^t 10(Tref-T)/z \, dt \qquad (21)$$

where a is the original texture value and b is the texture value at time t, D_{Tref} = D-value for the constituent at reference temperature (T_{ref}), z = a value that characterizes the constituent response to change in temperature (Leonard et al., 1986). The residual texture value (b) following a process is back calculated using Equation (23).

Statistical analysis

Statistical analysis was performed using Statgraphics Statistical Software (STATISTICAL GRAPHICS CORPORATION, USA STSC Inc., 1987). The general linear model ANOVA procedure were employed to determine a one way analysis of variance. Where applicable, means were tested by Duncan's multiple range test (Steel and Torrie, 1960).

RESULTS AND DISCUSSION

Process times

Process times for each experimental run equivalent to a lethality of 6 minutes are shown in Table 11. It is evident from this data that for almost all combinations, a reduction in process time was observed for agitated cans and semi-rigid containers as compared to their still counterparts.

Table 11. Comparison of processing times for different containers and processing methods

PRODUCT	CAN/SRC	RPM	F_OH	F_O TOTAL	PROCESS TIME (MIN)
BEET	Can	0	5.05	6.11	21
BEET	Can	10	5.30	6.09	16
BEET	SRC	0	5.06	6.14	14
BEET	SRC	10	5.47	6.01	14.25
TURNIP	Can	0	5.00	6.25	25
TURNIP	Can	10	5.35	6.05	15.25
TURNIP	SRC	0	5.03	6.01	17
TURNIP	SRC	10	5.31	6.10	14.75
BEAN	Can	0	5.25	6.07	20.75
BEAN	Can	10	5.45	6.02	15.50
BEAN	SRC	0	5.0	6.30	13.75
BEAN	SRC	10	5.24	6.04	13.75

With the only exceptions of beets and beans in semi-rigid containers, reductions in process times for all rotated products ranged from 13% to 39%. With respect to still processes only, semi-rigid containers offered a clear advantage as compared to the cans. Process time reductions for these conditions were found to average 33% for all products. For processes which were subjected to rotation only, reductions for semi-rigid containers as compared to cans were smaller and ranged from 3.3% to 11.3%. Figure 29 is a graphic illustration of the process times included in Table 11. It is evident from the graph that processing advantages for semi-rigid containers as opposed to cans are more effective and noticeable in still processes than rotational processes. This was found to be true for all products in this study. On the other hand, results indicated that for rotational processes, differences in process times for the two types of containers were not considerable.

Heat penetration

Figure 30 shows a typical time-temperature plot of thin-profile and canned beets and turnips processed in the still mode. As expected, the products packaged in thin profile containers were found to exhibit faster heat penetration. The main reason for this behavior is the thinner profile of the semi-rigid container which allows faster heat transfer to the slowest heating or critical point. Thin profile processing permits the required amount of heat during sterilization to reach that critical point with minimal overcooking near the peripheral container area. Studies have shown that flexible films offer little resistance to heat conductivity into the packages and that variance among tested materials, 1.25-3 mils in thickness, were nil (Lopez, 1987). Heating times are more nearly a function of the shape of the container and the conductivity of the food. Consequently, it was found in Figure 28 that this faster rate of heat penetration into the thin profile containers resulted in a considerable difference in the heating profile between the beets and turnips, whereas the heating profiles for the canned beets and turnips were found to be quite similar. This may be attributed to the different thermal conductivities of these two products.

Figure 29. PROCESS TIME COMPARISON FOR THE EQUIVALENT STERILIZING VALUE $F_o=6$ (min)
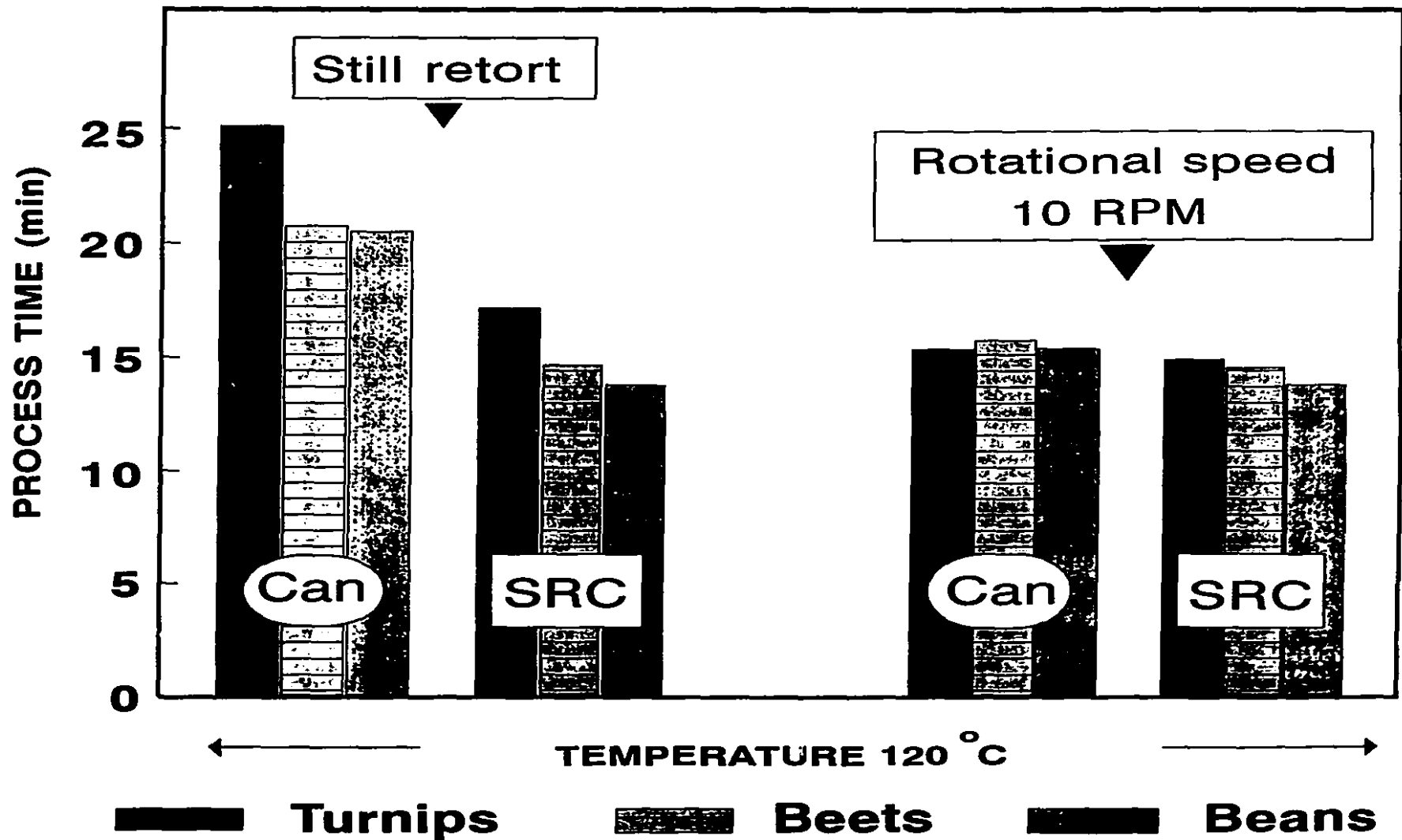
FIGURE 30. TEMPERATURE HISTORY DURING STILL PROCESSING OF VEGETABLES

THIN PROFILE (PLASTIC) vs CYLINDRICAL (METAL) CONTAINERS
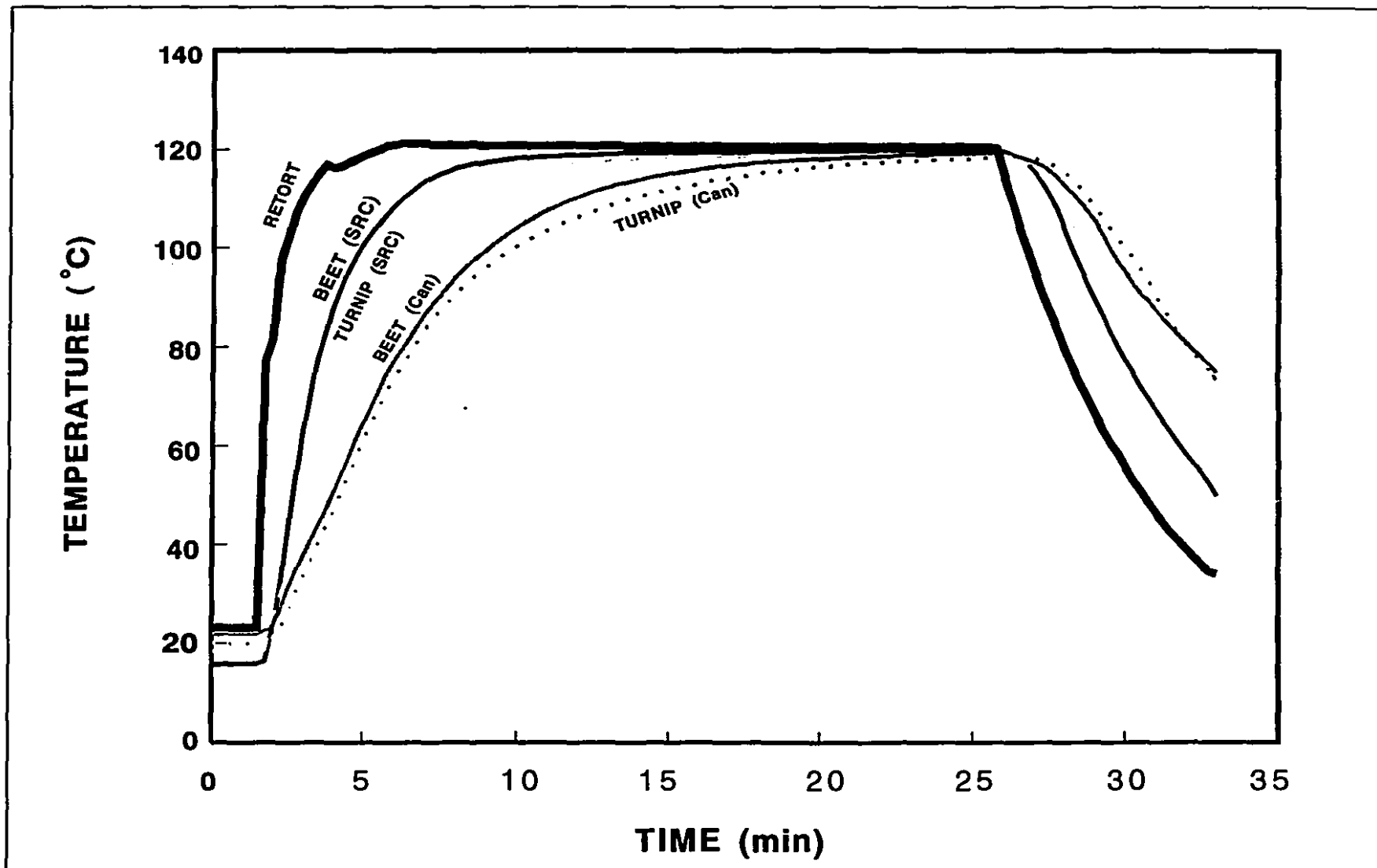
Time-temperature profiles of beets and beans during rotational processing are shown in Figure 31. As expected, the products in the thin-profile containers exhibited faster heat penetration as compared to their canned counterparts. Even though the products are not the same for both conditions (0 and 10 rpm), the differences in heat penetration between canned and thin-profile containers for rotational processing are not as considerable as those of still processing.

Texture

The firmness of much produce is sensed by squeezing it in the hand. This is a subjective measurement of the softness of many commodities (Bourne, 1980). Preliminary tactile examination of the processed products showed that the thin-profile packaged products were firmer to the touch and firmer to squeeze than the canned products. Table 12 shows the firmness values of the beets, turnips and Romano beans after still processing for an equivalent sterilizing value (F_0 = 6 min) in both semi-rigid and conventional containers. Each value in this table is the mean of ten replicates which have been measured under the same condition of applied force and deformation rate. With rotational processes, it is well recognized that each product particle receives more or less the same amount of heat during the process due to forced innermixing. With still processes, the particles on the outer package edge will be exposed to considerably more heat than those sheltered particles in the container center. For sampling purposes, it was important to obtain at least 10 samples from a mixture of still-processed particles in order to be assured of obtaining a representative sample in terms of heat exposure. The results from a multiple range test clearly indicate that for all three products processed in the still mode, firmness was found to be significantly higher (p<0.05) for those packaged in semi-rigid containers as compared to cans. All products in the semi-rigid containers showed an improvement in textural quality, however, Romano beans were subjected to the least damage and retained more than twice their firmness as compared to those in cans. it is noteworthy that the coefficient of variation is about three time higher for the can than for SRC, which confirm a superior quality (uniformity) of product packed in semi-rigid containers.

FIGURE 31. TEMPERATURE HISTORY DURING ROTATIONAL PROCESSING THIN PROFILE (PLASTIC) vs CYLINDRICAL (METAL) CONTAINERS
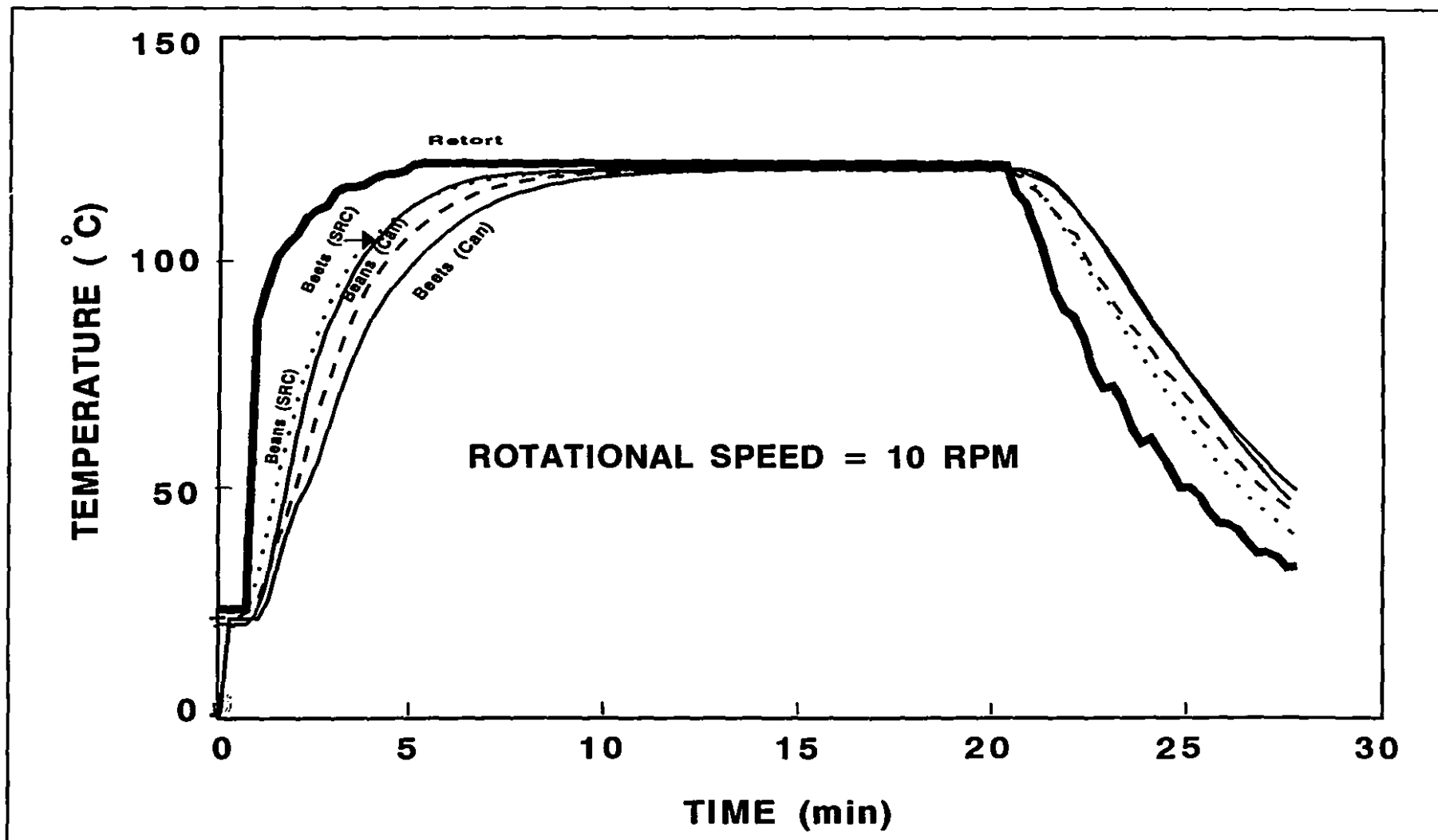
Table 12.Firmness of still processed products in thin profile and cylindrical containers.

PRODUCT	CAN /SRC	FIRMNESS (N/MM)	STANDARD DEVIATION	COEFFICIENT OF VARIATION
BEET	Can	3.25 a	0.65	0.20
BEET	SRC	4.59 b	0.32	0.07
TURNIP	Can	1.92 a	0.53	0.28
TURNIP	SRC	3.35 b	0.35	0.10
BEAN	Can	1.97 a	0.53	0.27
BEAN	SRC	4.71 b	0.43	0.09

For each commodity (beet, turnip and bean), means in the same column refering to the Can and semi-rigid container (SRC) followed by a different letter are significantly different at the 0.05 level.

Factors influencing texture loss in processed vegetables are of two types. These are destruction or damage to the semipermeable cell membranes and disruption of the intercellular structures resulting in cell separation (Hall and Pither, 1991). The effects of these types of tissue damage are a loss in cell turgor and cellular adhesion which give rise to loss of crispness and softening. Decreasing the processing time through increased heat transfer rates (as in the case of semi-rigid containers) may result in less structural damage and an increase in firmness, as noted in Table 12. These results are in agreement with those of Lyon and Klose (1981) and Durance and Collins (1991) who reported that processing in thin profile containers yields firmer products as compared to conventional canned products.

Table 13 shows the firmness values of test samples processed in the rotational mode and packaged in thin profile and cylindrical containers. A multiple range test indicated that with the exception of turnips, the beets and beans packaged in the semi-rigid containers were significantly firmer than those packed in conventional cans. It is interesting to note, however, that this general increase in firmness for the rotational mode is not as high as compared to the still mode; the change for Romano beans in the rotational mode is less than that previously reported for the still mode. As expected, less variation in texture values occurred during rotational processing than still processing. This was most likely due to the effect of innermixing.

Table 14 shows how the stiffness and springiness of turnips and beets differ as a function of the various processing methods. In general, results indicate that semi-rigid packed products retain more of their textural properties related to stiffness and springiness.

Predicted values for texture retention

The thermal degradation of texture in the vegetables in this study was determined using experimental data, listed in Chapter IV, and obtained kinetic data presented in Chapter III. Table 15 compares the experimental and calculated values for percent texture retention. The results indicate that the calculated values are in close agreement with experimental values. With the exception of beets, the predictions tend to underestimate the actual values.

Examination of these data bring two important points into focus. First, sensory quality are up to six orders of magnitude more resistant to thermal destruction than spores and vegetative cells. This is very important because frequently processes are designed for reducing microbial or spore populations by factors of 10^5 to 10^{12} and if sensory quality were not significantly more resistant, the food would be rendered unmerchantable after thermal processing.

The second important observation is that sensory quality shows a markedly different temperature dependence than vegetative cell and spores. For enzymes, the range of activation energy is unusually broad because there are heat-resistant and heat-labile enzymes and isozymes. Most heat-resistant enzymes of the type used as the basis of blanching operations have thermal resistance characteristics similar to those of nutrients and quality factors. With the given data, it is possible to examine each thermal process for an opportunity to maximize sensory quality retention.

Table 13. Firmness of rotational processed products in thin profile and cylindrical

containers.

PRODUCT	CAN /SRC	RPM	FIRMNESS (N/MM)	STANDARD DEVIATION
BEET	Can	10	3.00 a	0.42
BEET	SRC	10	3.87 b	0.23
TURNIP	Can	10	1.85 a	0.32
TURNIP	SRC	10	1.90 a	0.21
BEAN	Can	10	1.94 a	0.12
BEAN	SRC	10	3.82 b	0.32

For each commodity (beet, turnip and bean), means in the same column refering to the Can and semi-rigid container (SRC) followed by a different letter are significantly different at the 0.05 level

Table 14. Effect of thin profile and rotational processing on textural properties of vegetables.

PRODUCT	CAN SRC	RPM	STIFFNESS (N/mm^2)	STANDARD DEVIATION (N/mm^2)	SPRINGINESS %	STANDARD DEVIATION %
BEET	Can	0	3.71	0.54	33.90	5.73
BEET	Can	10	3.31	0.41	37.40	4.80
BEET	SRC	0	4.90	0.23	34.97	4.23
BEET	SRC	10	4.33	0.13	31.64	4.10
TURNIP	Can	0	1.33	0.37	25.18	7.84
TURNIP	Can	10	1.13	0.29	27.45	6.51
TURNIP	SRC	0	2.18	0.32	46.47	6.99
TURNIP	SRC	10	1.24	0.17	32.57	7.13

Table 15. Experimental and calculated values for texture retention.

Product	Sterilizing value (F_{Tref}^z)	% Retention	
		Experimental value	Calculated value
Beet	10.94	37.87	40.67
Turnip	11.04	24.47	21.1
Bean	9.67	46.13	37.98

Conclusion

The results of this study demonstrate that the still processing of turnip, beet roots and Romano beans to an equivalent lethality in semi-rigid containers, yielded, on average, a 33% reduction in process time as compared to the conventional can. For rotational processes, the process time reductions for the semi-rigid containers were significantly less and ranged from 3.3% to 11.3%. Thus, in this study, process time reductions for thin-profile containers seem to be more of an advantage during still processes than during rotary processes. Although process times were considerably reduced for the rotational process, the results showed no improvement in firmness values for products in thin-profiles and cans. Obtained kinetic data may be used to estimate retention textural properties in the resulting products. Alternatives for reducing the degradation in these operations become a matter of economic and practical consideration.

CHAPTER VI

OVERALL CONCLUSION

The thermal softening kinetics of dry bean and root vegetables were evaluated in this study for application in thermal processing. The result showed that the softening was well characterized by two pesudo-first order mechanisms, with the first one taking place at a faster rate than the second one. It was found that properties such as firmness, stiffness and springiness could be effectivelly used to evaluate the softening kinetics. The effect of temperature on kinetic parameter was well described by both Arhenius and TDT-type relationship. It was emphasized that studies must take into consideration the effects of thermal lag while computing kinetic parameters.

In order to adequately evaluate the thermal effects on the texture of canned vegetables, one has to consider the two substrate - two pesudo first order softening mechnisms. Searching for a way to slow the apparent rate constant k_a (rate constant for the first mechnism) can provide only small gains, because k_a is generally so high that even reducing it by 50% will have little effect on the overall firmness after a commercial process. The real gains in firmness in commercially canned vegetables will be found by studying the factors that affect the second substrate (k_b) and the thermal firmness value as obtained from the extrapolation of the kinetic curve mechanism 2 to the origin.

The study shows that the softening kinetic could be successfully coupled with heat penetration data obtained under thermal processing conditions, to predict/evaluate the texture value of the resulting product. Such a concept has been used in this study to compare the effectiveness of two processing and two packaging techniques. Extention of such a work would easily lend itself to process optimization with the objective of providing canned foods with best possible texture. Literature lacks data on the thermal softening of many foods (cereals and grains and many other vegetables and meats). Studies are needed on understanding the effect of heat on the tissue structure of foods. In this respect, techniques such as scanning electron microscopy can provide valuable information. Since texture of plant foods is related to their structure, research aimed at elucidating the structure/texture relationship can make important contributions to our ability to understand and control the textural characteristics of these products.

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