RELATIONSHIPS BETWEEN ENGINEERING AND TEXTURE PARAMETERS FOR LOW AND INTERMEDIATE MOISTURE FOODS

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ABSTRACT

RELATIONSHIPS BETWEEN ENGINEERING AND
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INTERMEDIATE MOISTURE FOODS

By

Gerard A. Reidy

Both the food engineer and the food technologist are interested in rheological behavior of foods. The engineer is mainly concerned with information for process equipment design whereas the food technologist is primarily interested in rheological responses which give an indication of product texture. No previous attempts have been made to co-ordinate work between these areas although a natural relationship might be expected to exist. The purpose of this research was to use an engineering analysis to predict texture parameters of a pre-cooked freeze-dried food at different water activities and to investigate the possibility that one test might yield sufficient information for both the engineer and the food technologist.

Two mathematical models were proposed to predict the stress-strain function of pre-cooked freeze-dried beef at water activities in the range 0.15 to 0.92, at a temperature of 80°F. The parameter values in the models were estimated from stress relaxation and cyclic deformation tests. The

models were subsequently used to predict both the relaxation and cyclic responses. Accuracy and validity of the models was evaluated by comparing experimental results from independent creep and strain tests with model predictions.

Statistical analysis revealed that, in general, parameter values in both models decreased with increasing water activity. This corresponded to texture changes in the product which exhibited significant decreases in hardness and chewiness values at equilibrium relative humidities greater than 50%.

Experimental results showed that a simple linear visco-elastic model of Kelvin and Maxwell elements in series, was inadequate for general predictions . However, the model satisfactorily predicted creep and relaxation functions. If the model parameters are estimated from relaxation data the prediction of cyclic stresses and texture parameters is not satisfactory.

A mathematical model which assumed nonlinear visco-elastic behavior gave good predictions for all three tests; creep, relaxation and cyclic. In addition to accurately predicting texture, this model illustrated that the cyclic test can also be used to estimate engineering parameters which permit accurate prediction of creep and relaxation responses.

It appears that definite correlations exist between certain parameters in both models and the texture parameters, hardness and chewiness.

Impact experiments were run for the purpose of examining the influence of water activity on the energy absorption properties of the product. However, the quantity of energy absorbed remained relatively constant over the entire equilibrium relative humidity range. It was concluded that energy absorbed could not be used as an index of texture.

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NOMENCLATURE

A	Constant coefficient in Model 2, lbs/in^2.
A_1	Area under force-deformation curve, first compression cycle.
A_2	Area under force-deformation curve, second compression cycle.
B, C	Constant coefficients in Model 2, lbs/in^2.
C_1	Constant coefficients in equation (10), lbs/in^2.
C_2, C_3	Constant coefficients in equation (10), $lbs\text{-}sec/in^2$.
C_4	Constant coefficients in equation (10), $lbs/in^2\text{-}sec$.
C_1, C_2	Also constants defined in equations 16(c), 16(d).
C_3, C_4	Also constants defined in equations 21(a), 21(b).
E	Young's Modulus, lbs/in^2.
G	Shear Modulus, lbs/in^2.
N	Chews per minute, 1/sec.
P	Energy, ft.-lb.
S_s	Shear stress, lbs/in^2.
S_t	Tensile stress, lbs/in^2.
a	Constant coefficient in equation (9).
a_w	Water activity.
p_1	Constant coefficient defined in equation 5(a).
p_2	Constant coefficient defined in equation 5(b).

q_1	Constant coefficient defined in equation 5(c).
q_2	Constant coefficient defined in equation 5(d).
t	Time, seconds.
ϵ	Strain, in/in.
η	Viscosity coefficient, lbs.-sec./in^2
λ	Time constant in Model 2, seconds.
λ_1, λ_2	Coefficients defined in equations 16(a), 16(b).
μ	Poisson's ratio, dimensionless.
σ	Stress, lbs/in^2.

CHAPTER 1

INTRODUCTION AND OBJECTIVES

Although research in the general field of food rheology has been pioneered by Scott-Blair of England forty years ago, it is only within the past two decades that physical properties of food products have been seriously investigated. Even since then, the principal objective of research has been the acquisition of useful data for machine design. Such a trend can only be expected in view of the shift from large labor forces to mechanization which has taken place on the American agricultural scene.

In order to market an agricultural product in good condition, it is essential that mechanical damage by the harvesting device be avoided or minimized. However, this can be carried out only if information is available to the design engineer as to the stresses and strains exerted upon the product to absorb such stresses and strains without undergoing physical and subsequent chemical and microbiological damage.

Typical tests employed by engineers to obtain the required information included simple compression and elongation tests to investigate stresses resulting from various strains, creep and relaxation experiments which yield information on strain and stress behavior with time, and also impact tests to indicate the relative capacities of products to absorb energy under conditions of impact loading. A review of some of the work carried out in this area appears in the literature review.

Since satisfactory level of texture; e.g., tenderness in meat, is a necessary prerequisite for a food to be acceptable to consumers, it is essential that the food technologist also concern himself with the physical characteristics of foods. One would naturally expect that a close relationship should exist between conventional physical properties of a food and its texture. The food technologist has however, all but ignored engineering characteristics of foods when evaluating texture. Instead, he has relied on sensory panels or any of numerous empirical objective methods. Consequently, a situation currently exists where little or no attempt is being made to coordinate the work of the engineer and the food technologist with a view to predicting food texture or to examine the correlation between physical properties and texture of foods.

Figure 1. illustrates the interests of the engineer and the food technologist in a food product, and the various tests used by them to obtain relevant information. The possibility of a relationship between the results obtained from the two different sets of tests seems logical.

It therefore seemed appropriate that the possibility of using an engineering analysis to predict food texture should be investigated, and this was the over-all objective of this

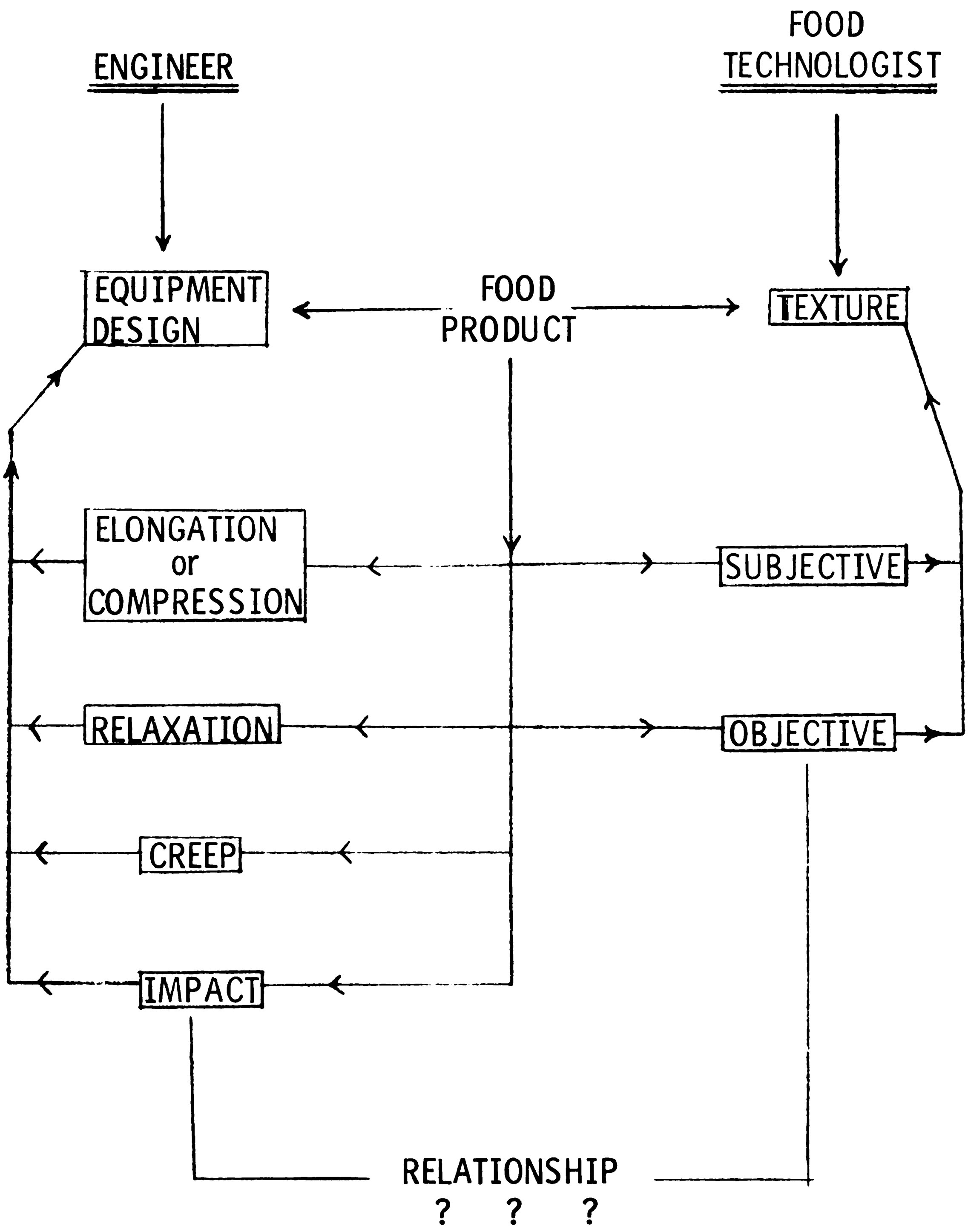


Figure 1. Common interests of the engineer and food technologist in food products.

dissertation.

Pre-cooked freeze-dried beef was chosen as the product to be studied, due to the importance of texture to consumer acceptability of meat products. The influence of different levels of water activity on texture and physical properties was also investigated, due to current interest in the development of new food products in the low to intermediate moisture ranges.

Specifically, the objectives of this research may be summarized as :

(a) to determine a constitutive equation to relate stress and strain for pre-cooked freeze-dried beef at a temperature of $80^{\circ}F$;

(b) as a result of (a), to predict the response on the Instron Testing Machine as used to measure beef texture;

(c) to examine the influence of water activity on engineering characteristics of pre-cooked freeze-dried beef;

(d) to investigate the relationship between mechanical properties and texture parameters.

CHAPTER 11

LITERATURE REVIEW

The exact definition of texture in relation to foodstuffs has been a subject of considerable controversy in the literature. Definitions have varied so much that Matz (1962) and Elder and Smith (1969) appear justified in concluding that texture or rheological properties of foods will have different meanings to individuals, depending on the particular industry of interest e.g. cereal, dairy or confectionary processing.

A dictionary definition of texture is "an identifying quality; the disposition or manner of union of the particles of a body or substance". An alternative definition for texture of food is offered by the Institute of Food Technologists (Kramer, 1959) :

> "The mingled experience deriving from the sensations of the skin in the mouth after ingestion of a food or beverage. It relates to density, viscosity, surface tension and other physical properties of the material being sampled".

However, when referring specifically to meat, Ball *et al.* (1957) state that "texture of cooked meat is the feel of smoothness or fineness of the muscle tissue in the mouth".

The various suggestions for definition of texture found in the literature are thoroughly reviewed by Matz (1962) and Szczesniak (1963), who concluded that the two important elements of texture are :

(1) physical structure of the material (geometry),

(2) the way the material handles and feels in the mouth (surface and mechanical properties).

Szczesniak (1963) suggested a total of eight mechanical characteristics which would completely describe a food; cohesiveness, hardness, adhesiveness, viscosity, elasticity (primary parameters) and brittleness, chewiness, gumminess (secondary parameters). The definitions offered are rather vague and confusing, with some overlapping. Two useful parameters however, which have satisfactorily described freeze-dried beef texture (Reidy and Heldman, 1970); are

Hardness: the force necessary to attain a given deformation on the first bite; and

Chewiness: the energy required to masticate a solid food product to a state ready for swallowing.

Matz (1962) notes that hardness is not considered a fundamental property of solids but a composite property dependent on the elastic moduli and elastic limit.

The Szczesniak (1963) texture profile was critically examined by Sherman (1969) who questioned both the classification of primary and secondary parameters made by Szczesniak and also the significance of the definitions of elasticity, chewiness and gumminess. Sherman suggested a modified texture profile by classifying analytical characteristics elasticity, viscosity, adhesion to palate as secondary characteristics; and masticatory and non-masticatory mechanical properties as tertiary characteristics. The usefulness of such debate is questionable, since it ignores the problem of relating texture of a particular food to meaningful, easily measured rheological characteristics. Both of the profiles offered by Sherman (1969) and Szczesniak (1963) easily distinguish between different foods (e.g. candy, meat and cheese) but are not sensitive to texture differences in the same product (e.g. meat cooked for various time-temperature combinations, or meat of different moisture contents). It is generally accepted that a sensory panel can detect texture differences in the same product, and the ability of a panel to rank meat on a tenderness scale is a typical example.

Despite the fact that no simple satisfactory definition of texture exists however, it may be accepted that consumers have a good concept of texture on a comparative basis when considering specific food items.

The objective methods developed by food technologists to evaluate texture are numerous. Although Metzner (1956) has stated that particle size distribution and rheological tests can be used to describe food texture in a scientific and qualitative way, practically every mechanical device available is empirical. Several reviews appear in the literature which classify and describe texture measuring instrumentation, most notably Pearson (1963) and Schultz (1957) - meat tenderness measurement; Elder and Smith (1969) - non-Newtonian and semi-solid foods; Kramer and Twigg (1959)

- fruits and vegetables; Szczesniak (1963) - general review; and Bourne (1966), who classified the physical methods of texture evaluation into seven groups.

The seven classifications of Bourne (1966) are :

1. Force measuring
2. Distance measuring
3. Time measuring
4. Energy measuring
5. Ratio measuring
6. Multiple measuring instruments; and
7. Multiple variable instruments.

In fact, most methods fall into the force measuring category. There is considerable overlap between the instrumentation and, if anything, Bourne's review only helps to emphasize the empirical approach which exists.

The rheological property which is measured to indicate texture of liquid foods is viscosity - either "true" viscosity for Newtonian fluids or an "apparent" viscosity for non-Newtonian fluids. An apparent viscosity is frequently referred to as "consistency" by food technologists. There are many viscosity measuring instruments available including capillary viscometers, the Bostwick consistometer, the Scott viscometer, the Brabender visco-amylograph, Corn Industries viscometer, Bloom gelometer, the Brookfield, Fann V-G and Rotovisco viscometers. Nearly all of these methods are discussed by Elder and Smith (1969)

The fact that texture is a useful guide to maturity or ripeness of fruits and vegetables has led many people to develop methods for mechanically evaluating the quality of fruits. Over forty years ago, Magness and Taylor (1925) developed a probe pressure tester, which is still widely used today. The force necessary for the plunger to penetrate a given depth into a fruit or vegetable is used as an index of maturity. Martin (1937) developed a tenderometer which proved extremely successful in predicting raw pea quality. Pea samples are compressed and sheared when an upper hinged set of grids engages with a similar stationary bottom set. An instrument which also applies a combination of compression and shear forces is the Kramer shear press (Kramer et al., 1951 and Kramer, 1961), an apparatus which allows the use of a number of different test cells, depending on the product being tested. The force recorded to penetrate the product is used as an index of quality. Penetrometers, such as the Bloom gelometer, indicate the consistency of gels or soft foods e.g. jellies, cheese, bread. A standard weight is allowed to fall onto the product and the resistance to sinking following impact is taken as a guide to consistency (Szczesniak, 1963).

Shearing devices are most frequently utilized in the meat industry (Pearson, 1963; Lowe, 1949; Szczesniak, 1961-64; Deatherage et al., 1952; Bockian et al., 1958). The most popular instrument is undoubtedly the Warner-Bratzler shear (Bratzler, 1932). A cylindrical meat sample is placed in a triangular hole in the center of a 1/32" thick steel blade. The blade is pulled through parallel plates by a gear system powered by a constant speed motor, and the necessary force is measured. Pearson (1963) reported that the correlation between sensory evaluation and Warner-Bratzler shear forces was about 0.75 on average, and suggests that the disappointing results may be due to the fact that the shear force fails to account for the time-load effect. Presumably this might reflect more accurately the work required in chewing. The Warner-Bratzler shear was compared with the Kramer shear press by Burrill et al. (1962) who did not find any significant differences between both instruments when used on cooked beef. Of interest perhaps was their finding that the Warner-Bratzler shear nearly always gave a higher correlation with sensory evaluation than did the Kramer press. Harrington and Pearson (1962) found a high correlation between shear values and chew counts on meat, as suggested by Lowe (1949). In 1956, Miyada and Tappel described a grinding machine which they suggested could predict meat tenderness. However, Bockian et al. (1958) could only find a correlation of the order - 0.6 with taste panel results when working with cooked beef.

Proctor et al. (1955) developed a denture tenderometer at Massachusetts Institute of Technology in an effort to simulate mastication of food in the mouth. The instrument was fitted with a lower (stationary) set of dental plates, while a similar upper set was fitted to allow both vertical and lateral movement. A force-penetration relationship was recorded as the food sample was compressed and allowed to recover. This system was then modified by Friedman et al.

(1963) at General Foods Company who developed the texturometer, while the General Foods Texture Profile was simultaneously developed (Brandt et al., 1963). The basic change from the M.I.T. denture tenderometer was the replacement of the dentures by a plunger and plate. The force-distance diagram which resulted allowed the measurement of a number of texture parameters as follows (see Fig. 2) :

Hardness	=	L_1
Adhesivness	=	A_3
Cohesivness	=	A_2/A_1
Elasticity	=	68.5-B
Chewiness	=	$L_1 \times (A_2/A_1) \times (68.5-B)$
Gumminess	=	$L_1 \times (A_2/A_1)$

The constant 68.5 was the same measurement B made on a completely inelastic material such as clay.

An exhaustive study to examine the suitability of the General Foods texturometer to describe meat texture was carried out for the U.S. Army Natick Laboratories by General Foods (1965). The Kramer shear press and Warner-Bratzler shear were also used. Foods tested included fresh meat, dehydrated pork, turkey and other meats, and pre-cooked freeze-dried beef with emphasis placed on the latter product. The texturometer was found to be highly suitable for measuring meat texture and gave good correlations with taste panel evaluations. However, it was not possible to select any one of the three instruments as being superior, and all three instruments were able to differentiate between the important

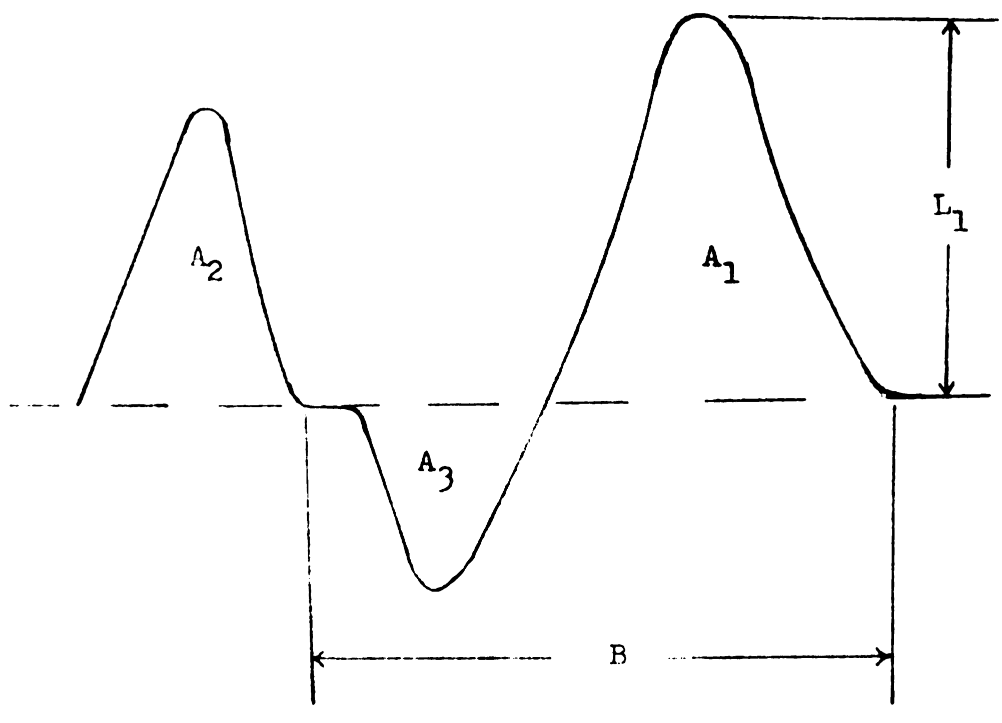


Figure 2. Typical Texturometer curve (Friedman _et al._, 1963).

sample (muscle, animal) and processing (cooking time) variables incorporated into the design. Although General Foods recommended that their Texturometer and Kramer shear press be used for future research on meat texture, they offered little substantiating evidence to justify neglecting the Warner-Bratzler shear.

The tenderometer approach was once again modified by Bourne (1968) for adaption onto the Instron testing machine, which basically is a constant strain rate (vertical motion) apparatus. Bourne points out that with the Instron, the horizontal measurements are exact measurements of penetration - in contrast to the General Foods Texturometer, which has a rotating motion. The following texture parameters can be evaluated on the Instron (Fig. 3) :

$$\text{Hardness} = L_1$$

$$\text{Elasticity} = B_2$$

$$\text{Cohesiveness} = A_2/A_1$$

$$\text{Chewiness} = L_1 \times B_2 \times (A_2/A_1)$$

$$\text{Gumminess} = L_1 \times (A_2 \times A_1)$$

Figure 3. illustrates a typical response on the Instron Testing Machine for pre-cooked freeze-dried beef found by Reidy and Heldman (1970), using Bourne's (1968) approach. Reidy and Heldman(1970) investigated the influence of freeze-dried beef, and found that product texture, as indicated by hardness and chewiness values defined above, was least desirable at water activities of 0.4 to 0.6 and with product

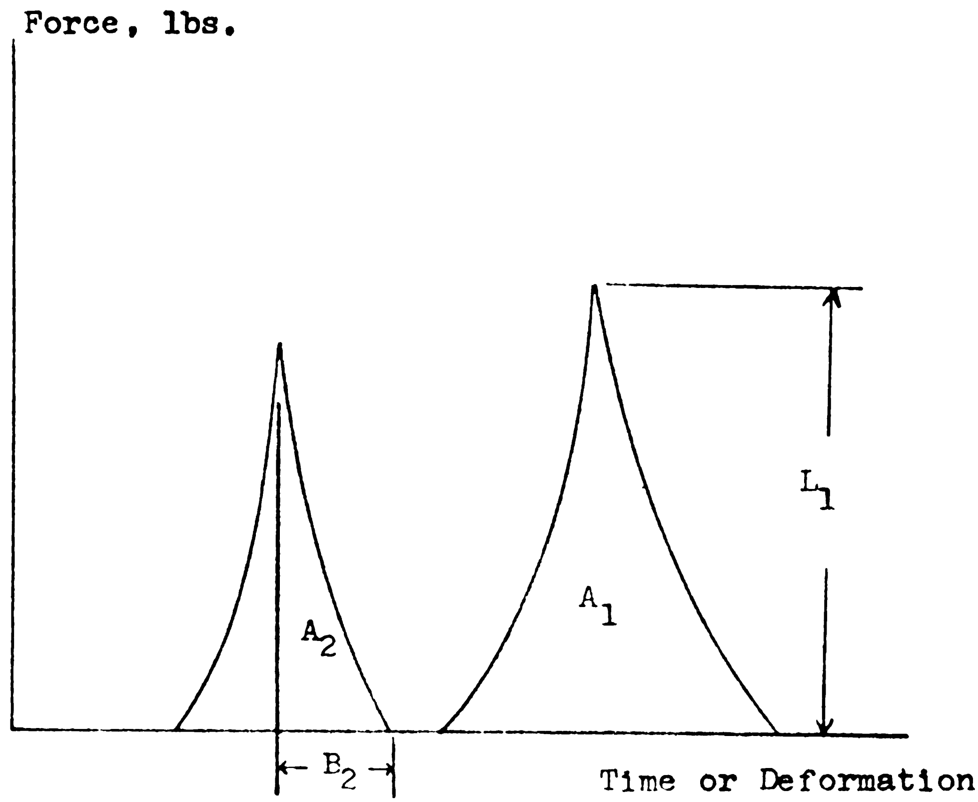


Figure 3. Typical force-deformation response for pre-cooked freeze-dried feef from Instron Testing Machine (Reidy and Heldman, 1970).

freeze-dried at a plate temperature of 105°F.

Previous investigations into texture of pre-cooked freeze-dried beef were carried out by Kapsalis (1967) and U.S. Army Natick Laboratories (1965). The objective of the latter research was to examine the suitability of the Texturometer, Kramer Press and Warner-Bratzler Tenderometer for meat texture measurement, as previously stated, and did not examine the influence of water activity on product texture as did Kapsalis (1967). Kapsalis (1967) used an instrument called a Masticometer, developed in Sweden, which in fact was a further modification of the Texturometer and gave a response similar to those obtained by the Instron (Fig. 3) and Texturometer (Fig. 2). Dehydrated foods tested included pre-cooked beef and chicken, as well as sandwiches of cheese, chicken and beef. Kapsalis (1967) found that hardness values increased to a maximum at an equilibrium relative humidity of 66% and decreased at relative humidities greater than that. However, since samples had been stored for five and a half months, it is possible that texture changes were emphasized due to storage effects.

On the engineering side, agricultural products have received considerable attention in recent years with regard to their mechanical strength and this may be due to the increasing demand for mechanical harvesters. Certainly the majority of papers publishing data on physical properties of foods make no mention of texture but frequent references to "harvesting machinery", "processing equipment" and "damage by bruising" can be found. The terminology used e.g. "apparent Youngs Modulus" also suggests that the intended application of this data is mostly in machine development. Mohsenin et al. (1963) however, do suggest that loading and unloading curves of fruits and vegetables under compression can reveal certain mechanical properties which "should be of importance in evaluating textural characteristics". They further demonstrated from the relationship between modulus of elasticity and stage of maturation of apples that a greater rate of change and more consistent data can be obtained if measurements can be defined in engineering terms.

Researchers apparently soon realized that the mechanical behavior of biological systems is complicated, and concluded that simple mechanical tests which are easily interpreted would be most meaningful (Finney, 1963). Consequently the literature is composed mainly of simple tension and compression tests to give some idea of mechanical strength, and creep and relaxation tests to indicate behavior with time. Morrow and Mohsenin (1966) reviewed the experimental methods applied to agricultural products to determine parameters. They noted that the fundamental assumption of homogeneity, isotropy and continuity are violated in such tests but recommended that violations could be disregarded by adopting a "black-box" approach i.e. merely examining inputs and outputs. "Apparent" rather than actual parameters therefore could be used.

Although McClelland et al. (1957) treated plants as simple supported beams and concluded that the biological materials tested obeyed the established laws of mechanical behavior, the results of Huff (1967) seem to verify the complexity of biological materials. Huff (1967) investigated the behavior of potato tubers when tested in tension and computed mean values of four mechanical properties. Estimations of tensile strength, strain at failure, failure modulus and unit strain energy at failure varied with the location in the tuber from which the specimens were taken, and length of storage. Properties further varied with strain rate, demonstrating viscoelastic behavior. Potato firmness was also measured by Bourne and Mondy (1967) using the Instron Universal Testing Machine. Standard cylindrical samples and whole potatoes were deformed using a metal punch, and the results compared with sensory panel ratings. A correlation coefficient of 0.8 was found. Earlier interest in mechanical properties of potatoes had been shown by Hansen (1952) who measured the resistance of potatoes to pressure, abrasion and impact loading. The necessary pressure to force a piston a certain depth into the tuber was indicative of resitance to pressure; the torque or energy required for removing the skin indicated abrasion resistance; and a measurement of the depth of bruised tissue resulting from impact by a falling steel ball showed how well the potato could withstand bruising damage.

The simple pressure method of Magness and Taylor (1925) for determining fruit maturity, already described, may possibly be replaced by a sophisticated sonic technique developed by Abbott, Bachman, Childers, Fitzgerald and Matusik (1968). By vibrating cylindrical sections of fruits and vegetables at their natural frequencies, internal friction coefficients and Young's Modulus could be determined. Of more interest is their finding that as a fruit gradually ripens, the "stifness coefficient" (measured by applying sonic energy to the whole fruit) decreased. Mohsenin and Gohlich (1962) determined yield points for apples by applying strains at various rates of loading. They suggested also that the force-deformation relationship was approximately linear. The effect of different chemical solutions on the apparent Young's Modulus of apples, pears and potatoes was demonstrated by Somers (1965). Somers (1965) also did stress relaxation tests and showed how the time for 20% relaxation differed with the chemical treatment. Creep and relaxation tests were performed on McIntosh apples by Morrow and Mohsenin (1966), who simulated the stress-strain response to that of a simple three element model - an elastic spring and Maxwell element arrangement in parallel. Morrow and Mohsenin (1966) point out that the elastic relaxation modulus will not equal the inverse of the elastic creep compliance obtained by instantaneous load application because instantaneous loading and deformation does not truly take place.

Other foods which have been investigated for rheological behavior include marshmallow, caramel and chocolate, cottonseed, butter and grains. Bourne (1967) applied single compression loading to marshmallows. The response obtained could be simulated by a model of several springs of varying heights with different values of Hooke's constant arranged in parallel between two flat plates. The effect of chemical composition of caramels and chocolate on mechanical behavior was demonstrated by Morrow (1969). Samples were subjected to bending and uniaxial compression. The response of butter to static and dynamic testing was investigated by Diener and Heldman (1968). For stresses below the yield point, a model consisting of parallel viscous and Maxwell elements in series with parallel viscous and plastic elements simulated the stress-strain relationship. Clark, Fox and Welsh (1968) performed cyclic stress and cyclic strain tests on cotton-seed and fitted an equation to the experimental data. They also derived entities called "Loss Coefficient" and "Quality Factor" which had been discussed by Lazan (1965) as useful properties of non-linear materials. Zoerb (1958) investigated the energy requirements for shearing grains of different moisture content.

The field of biomechanics i.e. mechanics applied to biology, has also witnessed much activity in recent years. A fairly complete bibliography on the field, with references classified according to subject matter, has been presented by Fung (1968). The emphasis to date has centered around simple elongation tests to collect data on yield stresses and stress-strain relationships at different strain rates, as a basis for the design of artificial limbs or sinews to be used for surgical transplants. Results indicate that in general, tissues exhibit non-linear viscoelastic behavior.

CHAPTER 111

THEORY

The rheological behavior of a system describes the manner in which the system will exhibit flow and/or deformation responses as a result of applied forces. Sometimes it is relatively simple to predict this response if the mechanical properties of the system are known. Due to the complex and heterogeneous nature of biological systems however, it has been difficult to measure mechanical properties which will adequately describe the relationship between stress and strain. Consequently, a somewhat empirical approach has been used. Various combinations of ideal materials have been found to yield constitutive equations which, in effect, will express the influence of external disturbances on the behavior of a material due to its constitution. Frequently the limitations of perfect materials have prevented the formulation of satisfactory constitutive equations and in such instances it has been necessary to propose relationships based purely on experimental results.

Therefore two approaches were used in seeking a model to adequately describe rheological behavior of pre-cooked freeze-dried beef at various water activities :

(a) combining simple elements of ideal materials, which led to Model 1; and

(b) proposing an empirical constitutive equation along guidelines suggested in the literature and on the basis of previous experience with the product, which led to Model 2.

To determine the values of the constants in both models, three different engineering tests were used, a relaxation test which recorded stress as a function of time; a creep test which measured strain changes with time; and a cyclic test in which strain was changed in a cyclic manner at a constant rate and the corresponding stress recorded. Any one of the three tests could be used to cross-check predicted results using the constants as evaluated by a different test. In addition the response from the cyclic test allowed the two texture parameters, hardness and chewiness, to be evaluated.

The theory underlying the above three tests, and the method for calculating the constants in both Model 1 and Model 2 is described in the following sections.

In addition, the necessary equations for a fourth test are presented in which beef cube samples were impacted by a falling weight and the energy absorbed by the samples was measured. The purpose of this experiment was to investigate relationships between the texture parameters and absorbed energy of the beef at various water activities.

The fundamental issue of interest is to determine the engineering parameters in Models 1 and 2, and use these parameters to predict hardness and chewiness values for pre-cooked freeze-dried beef. At that point, the common interests of the engineer and the food technologist in the physical characteristics of a food product will have been integrated.

Ideal Materials

Deformation of a material may be elastic or in-elastic (Mohsenin, 1968). Perfect elasticity is defined by Eirich (1956) as deformation which is independent of loading history, thus forming a conservative system in which all energy absorbed during deformation is reversible. Most materials and particularly foods, however, are not perfectly elastic and do not recover completely to their original shape prior to loading. Mohsenin (1968) suggests a property of biological materials he calls "degree of elasticity", defined as "the ratio of elastic deformation to the sum of elastic and plastic deformation when a material is loaded to a certain load and then unloaded to zero load".

In-elastic deformation can be divided into two categories, viscoelastic and viscoplastic. Viscoelastic behavior is characterized by a stress response dependent not only on the applied strain but also the rate at which strain is applied. The material may be composed of elastic and viscous elements which in combination display viscoelastic properties. A perfectly viscous material is defined by Prager (1956) as one which meets two requirements : (a) the deformation is dependent on the loading history and (b) the stress is proportional to the rate of deformation.

Similarly, a viscoplastic system consists of viscous and plastic materials. Again according to Prager (1956) the plastic material is similar to the viscous material in that deformation is dependent on the loading path, but different in that stress is independent of the rate of deformation. Malvern (1967) further states that the name perfectly-plastic is used for materials which do not show work-hardening properties beyond a yield point. Such materials may deform elastically up to a certain yield-stress point, beyond which the material will continue to deform without further additional stress.

The three classical ideal bodies representing elasticity, viscosity and plasticity are the Hookean body, Newtonian fluid and St. Venant body, respectively. These bodies serve as standards for analyzing stress-strain functions of real systems.

Hooke's law states that stress is directly proportional to strain i.e.

$$\sigma = E\epsilon \qquad (1)$$

where E is Hooke's constant or modulus of elasticity. In a Newtonian fluid, stress is directly proportional to strain rate i.e.

$$\sigma = \eta\dot{\epsilon} \qquad (2)$$

and the constant η is called viscosity. Integration of equation (2) shows that after a certain time period (t) strain will not return to zero when stress is removed, but will remain at the value corresponding to time (t).

A St. Venant body is likened to a block resting on a surface, with a friction factor between the block and surface preventing any movement from taking place. The block will not move until an applied stress ("yield stress") equals or slightly exceeds the static friction, but will then continue to move indefinitely under this stress until some external factor restricts or prevents further movement.

Rheological Models; Model 1

Using the three ideal bodies as building blocks, numerous combinations can be arranged differently to yield an almost infinite variety of models. Such models can, and have been used to satisfactorily represent macroscopic behavior of foods (Finney et al., (1964); Diener and Heldman (1968); Mohsenin et al., (1963); Bourne (1967); Morrow (1965); Shama and Sherman (1966 and 1967).

Some simple models are illustrated on Figure 4. The Hookean body is represented by a spring element and the Newtonian fluid by a viscous dashpot.

Depending not only on the number of elements used but also the manner of arrangement, mathematical equations may be formulated to describe the model. For example, consider the two simplest and most popular models : (a) a spring and dashpot in parallel, called a Kevin solid and (b) a series arrangement, referred to as a Maxwell fluid.

Let the subscripts 1, 2, m refer to the spring, dashpot and model :

$$\sigma_1 = E\epsilon_1$$

$$\sigma_2 = \eta\dot{\epsilon}_2$$

(a)

$$\sigma_m = \sigma_1 + \sigma_2$$

$$\epsilon_m = \epsilon_1 = \epsilon_2$$

$$\dot{\epsilon}_m = \dot{\epsilon}_1 = \dot{\epsilon}_2$$

$$\therefore \quad \sigma_m = E\epsilon_m + \eta\dot{\epsilon}_m \qquad (3)$$

(b)

$$\sigma_m = \sigma_1 = \sigma_2$$

$$\dot{\sigma}_m = \dot{\sigma}_1 = \dot{\sigma}_2$$

$$\epsilon_m = \epsilon_1 + \epsilon_2$$

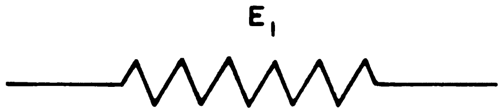
$$\therefore \quad \dot{\epsilon}_m = \dot{\epsilon}_1 + \dot{\epsilon}_2$$

$$= \frac{\dot{\sigma}_1}{E} + \frac{\sigma_2}{\eta}$$

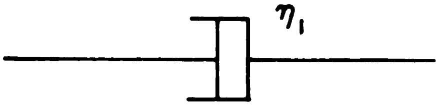
$$= \frac{\dot{\sigma}_m}{E} + \frac{\sigma_m}{\eta} \qquad (4)$$

A similar approach yields equations for any other models chosen. The most frequently used models are the 3-parameter solid, 3-parameter fluid, 4-parameter solid and 4-parameter fluid. Behavior thus becomes a function of the particular arrangement and the relative values of the viscoelastic parameters.

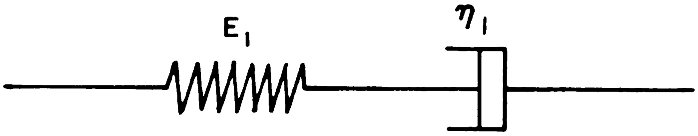
Evidently the advantage of such models is that by inspection it is possible to judge how a material will behave but this is only feasible with a reasonable number of



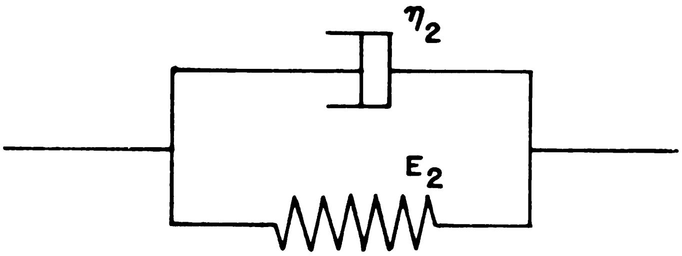
Elastic element $\sigma = E_1 \epsilon$



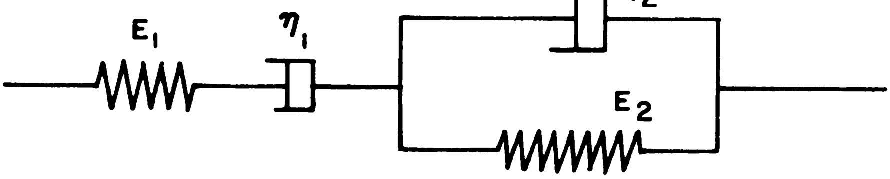
Viscous element $\sigma = \eta_1 \dot{\epsilon}$



Maxwell fluid $\dot{\epsilon} = \dot{\sigma} / E_1 + \sigma / \eta_1$



Kelvin solid $\sigma = E_2 \epsilon + \eta_2 \dot{\epsilon}$



4-element solid $\ddot{\sigma} + \left(\frac{E_1}{\eta_2} + \frac{E_2}{\eta_2} + \frac{E_1}{\eta_1}\right)\dot{\sigma} + \frac{E_1 E_2}{\eta_1 \eta_2}\sigma = E_1 \ddot{\epsilon} + E_1 E_2 \dot{\epsilon}$

Fig.4 Simple viscoelastic models

elements i.e. 3 or 4, beyond which the variety of combinations becomes almost limitless. A further, and more serious limitation, is the assumption that linear viscoelastic behavior occurs, and most biological products probably do not act in this manner.

A model frequently recommended to simulate rheological behavior of foods is the 4-parameter fluid (see Fig. 4). Preliminary relaxation tests confirmed that this model described the behavior of pre-cooked freeze-dried beef better than any other three or four element viscoelastic model, and it was decided to propose this arrangement, a Kelvin solid and Maxwell fluid in series, as Model 1. The model has the advantage of accounting for both solid and fluid response to applied stresses, a factor expected to become apparent especially at the higher water activity levels of the beef samples.

The mathematical equation for this arrangement is :

Model 1

$$\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_1\dot{\epsilon} + q_2\ddot{\epsilon} \qquad (5)$$

where

$$p_1 = \frac{(E_3/E_1 + \eta_3/\eta_1 + 1)}{(E_3/\eta_1)} \qquad (5a)$$

$$p_2 = \frac{\eta_3\ \eta_1}{E_1\ E_3} \qquad (5b)$$

$$q_1 = \eta_1 \qquad (5c)$$

$$q_2 = \frac{\eta_1\ \eta_3}{E_3} \qquad (5d)$$

All four constants E_1, E_3, η_1, η_3 may be calculated from any one of the three mechanical tests - relaxation, creep, cyclic.

<u>Formulation of Constitutive Equations: Model 2</u>

The fundamental problem facing researchers in rheology is the formulation of an equation of state

$$\sigma = f(\epsilon, \dot{\epsilon}, t, T, V, C_1) \qquad (6)$$

that is, the relation between stress and strain, strain rate, time, temperature and physical composition variables (Frisch and Simha, 1956). In equation (6) T represents absolute temperature, V is volume and C_1 is particle concentration.

Bowen (1967) suggests, as a first step, a general set of equations which could describe physical properties of all materials. By imposing restrictions of elastic, plastic and viscous materials on the general equations, he formed more specific equations e.g.

$$\sigma = \sigma \left[T(t), g(t), F(t), \dot{F}(t)\right] \qquad (7)$$

Clark (1968) interprets (7) to state that stress at time (t) is dependent on the temperature, temperature gradient, deformation gradient and the rate of change of the deformation gradient.

Further guidelines towards formulating constitutive equations can possibly be taken from dimensional analysis, which has been found very useful in establishing working formulas in fluid flow and heat and mass transfer. The basic concept of the method is that any mathematical equation which correctly expresses a physical phenomenon must be dimensionally homogeneous i.e. the equation is valid, independent of the system of units used to measure the quantities involved. Charm (1963) attempted to use the dimensional analysis approach in food texture studies and proposed an expression relating the energy (P) required to masticate a food, to Young's modulus (E), a shear modulus (G), shear (S_s) and tensile stress (S_t), and the dimensions of the food sample (L). There is no evidence that any attempt was made to verify the equation suggested,

$$\frac{P}{LNE} = f\left(\frac{G}{E}, \frac{S_t}{E}, \frac{S_s}{E}, \mu\right). \qquad (8)$$

N represents chews per minute, and μ is Poisson's ratio, a dimensionless parameter.

Fung (1968) presented non-linear equations used in biomechanics. He proposed one equation of the form

$$\sigma = C\left[\epsilon\left\{1 - \epsilon + \frac{4}{3}\epsilon^2\right\}\right] e^{a\epsilon} \qquad (9)$$

where C and a were constants. Haut and Little (1969) demonstrated that equation (9) could be used to describe rheological response of canine ligaments extremely well. Clark (1968) suggested an equation for cottonseed of the form

$$\sigma = C_1\epsilon + C_2\dot{\epsilon} + C_3\epsilon\dot{\epsilon} + C_4\int\epsilon\,dt \qquad (10)$$

which satisfactorily predicted stress on the product under cyclic loading.

Adopting a general approach therefore, a second model was postulated on the assumption that food behaves in a non-linear viscoelastic manner and response to stress is a function of deformation or strain, strain rate, time, temperature, processing variables and compositional characteristics of the food i.e. moisture, fat, sugar and protein contents, maturity, past history and physiological traits. This very general functional relationship could be simplified under the circumstances of this study which used samples of pre-cooked freeze-dried beef from only one muscle of one animal, was cooked at one temperature, freeze-dried at one plate temperature and tested mechanically at only one environmental temperature. Further, since moisture was the component whose content was varied over the equilibrium relative humidity range from 15% to 92%, it was assumed that rheological properties would be primarily a function of water activity. Thus a relationship of the form

$$\sigma = f(\epsilon, \dot{\epsilon}, t, \text{w.a.}) \qquad (11)$$

was assumed. Finally, at any one water activity a model exhibiting non-linear behavior was postulated, and proposed as an alternative model :

Model 2

$$\sigma = A\epsilon + B\epsilon e^{-t/\lambda} + C\int_{t_n}^{t} d\epsilon \begin{cases} n=0,2,4\ \ldots;\dot{\epsilon}\geq 0 \\ n=1,3,5\ \ldots;\dot{\epsilon}<0 \end{cases} \qquad (12)$$

The parameters A, B and λ may be evaluated from the relaxation test, leaving the constant C to be determined from either the creep or cyclic test. Alternatively, either the creep or cyclic test may be utilized to evaluate all four parameters.

The subscript n is used to denote whether strain is being increased, kept constant, or decreased. Normally, for only one loading such as relaxation or creep, $n = 0$. For loading in a manner such as the cyclic test however, $n = 0,2,4$ ---- denotes the compression stages whereas $n = 1,3,5$ ---- denotes the stages unloading is taking place. This third term therefore in equation (12) makes a positive contribution to stress as strain increases, but negative as strain decreases.

Relaxation Test

Under relaxation testing conditions, a strain ϵ_o is applied suddenly and kept constant i.e.

$$\epsilon = \epsilon_o H(t) \qquad (13)$$

where H(t) is a step function defined as

$$H(t) = \begin{cases} 0 & -\infty < t < 0 \\ 1 & 0 < t < \infty \end{cases}$$

$$\therefore \quad \dot{\epsilon} = \ddot{\epsilon} = 0 \qquad (14)$$

Constant strain $\epsilon_o H(t)$ for time greater than zero is illustrated on Fig. 6.

Model 1

$$\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_1\dot{\epsilon} + q_2\ddot{\epsilon}$$

$$= 0 \qquad (15)$$

The solution for this reduced homogeneous equation is given by Flügge (1967) as

$$\sigma = \epsilon_o \left[C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} \right] \qquad (16)$$

where

$$\lambda_1 = \frac{1}{2p_2} \left[p_1 - \sqrt{p_1^2 - 4p_2} \right] \qquad (16a)$$

$$\lambda_2 = \frac{1}{2p_2} \left[p_1 + \sqrt{p_1^2 - 4p_2} \right] \qquad (16b)$$

$$C_1 = \frac{(q_1 - \lambda_1 q_2)}{\sqrt{p_1^2 - 4p_2}} \qquad (16c)$$

$$C_2 = \frac{(-q_1 + \lambda_2 q_2)}{\sqrt{p_1^2 - 4p_2}} \qquad (16d)$$

<u>Model 2</u>

$$\sigma = A\epsilon + B\epsilon e^{-t/\lambda} + C \int_{t_n}^{t} d\epsilon$$

$$= \epsilon_o \left(A + Be^{-t/\lambda}\right) \qquad (17)$$

A typical relaxation stress - time relationship for biological materials is shown on Fig. 5.

From experimental curves, the values of C_1, C_2, λ_1 and λ_2 in equation (16) may be estimated and by means of equations (16a) - (16d) and (5a) - (5d) the values of E_1, E_3, η_1, η_3 can be used to predict creep and cyclic behavior for precooked freeze-dried beef and consequently the texture parameters of hardness and chewiness.

Only three of the constants - A, B and λ - in Model 2 can be found from relaxation experiments since the term containing $d\epsilon$ equals zero under constant strain conditions. Therefore the fourth constant C must be evaluated from one of the other tests used - creep or cyclic.

A computer program using a non-linear estimation method for finding the best estimate of the constants in both models was available, and is briefly described at the end of this chapter.

<u>Creep Test</u>

Deformation is recorded as a function of time due to a suddenly applied stress, σ_o H(t) which is kept constant,

$$\sigma = \sigma_o H(t) \tag{18}$$

$$= \begin{cases} 0 & -\infty < t < 0 \\ \sigma_o & 0 < t < \infty \end{cases}$$

$$\therefore \dot{\sigma} = \ddot{\sigma} = 0 \tag{19}$$

Stress and strain functions with time for the creep test may be seen on Figures 5 and 6.

<u>**Model 1**</u>

$$\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_1\dot{\epsilon} + q_2\ddot{\epsilon}$$

$$\sigma = q_1\dot{\epsilon} + q_2\ddot{\epsilon} \tag{20}$$

The solution to (20) is also presented by Flügge (1967):

$$= \sigma_o \left[C_3 + C_4\, e^{-q_1 t/q_2} + \frac{t}{q_1} \right] \tag{21}$$

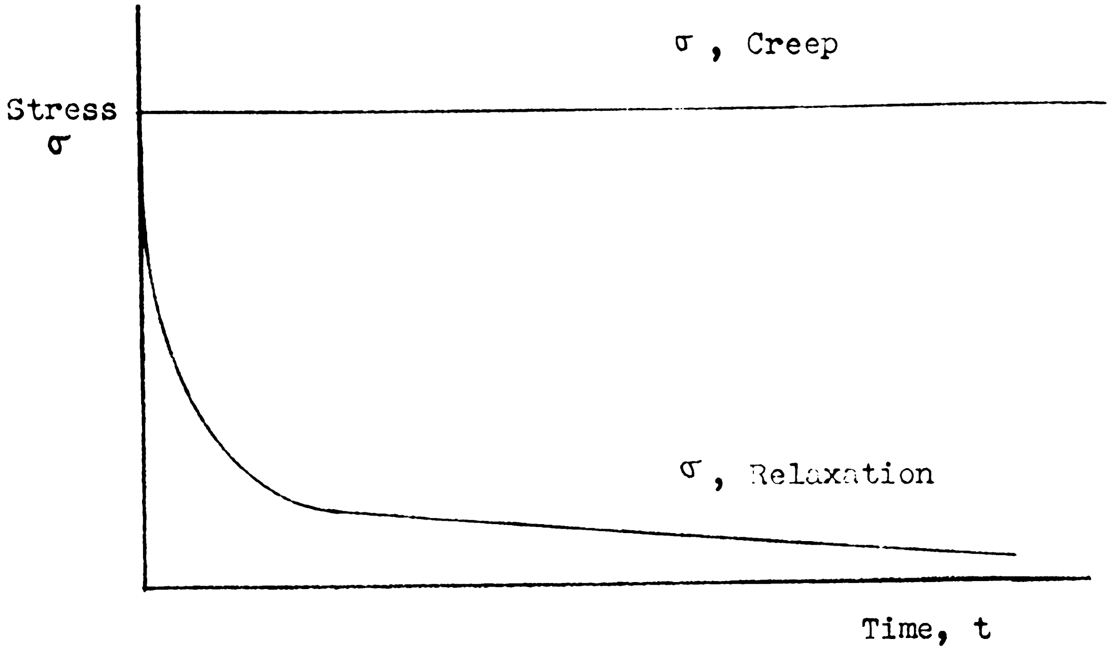


Figure 5. Typical σ- t relationship for creep and relaxation.

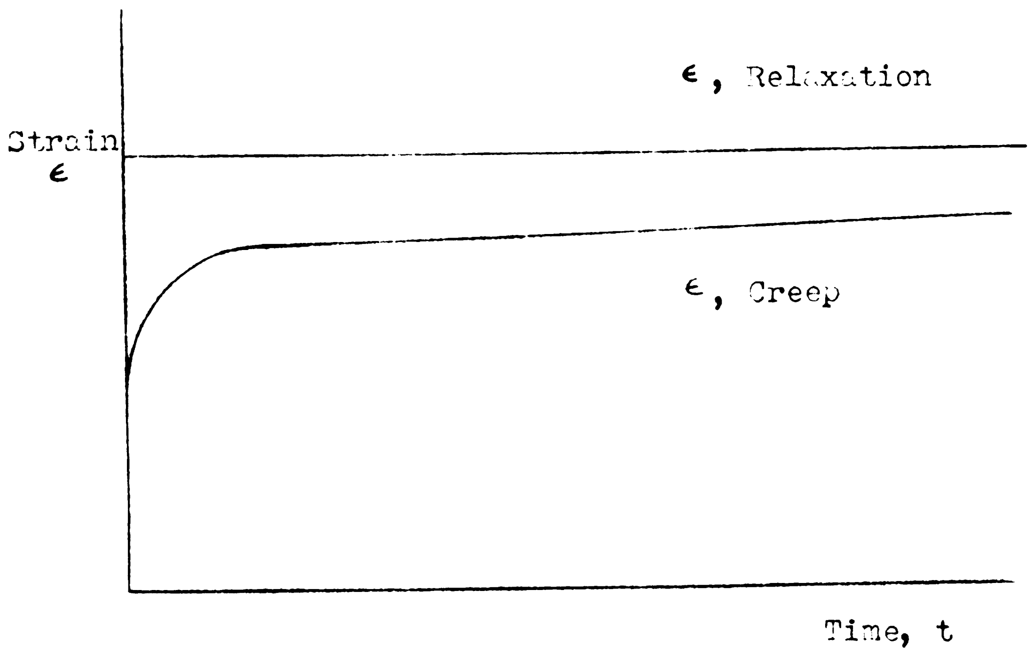


Figure 6. Typical ϵ - t relationship for creep and relaxation.

where

$$C_3 = \frac{p_1}{q_1} - \frac{q_2}{q_1^2} \qquad (21a)$$

$$C_4 = \frac{-1}{E_3} \qquad (21b)$$

Model 2

$$\sigma = A\epsilon + B\epsilon\, e^{-t/\lambda} + C \int_{t_n}^{t} d\epsilon$$

Integration of the last term in Model 2 over time (t) to time (t = zero) yields,

$$C\,(\epsilon_t - \epsilon_o)$$

so that ϵ_t at any time (t) can be easily solved :

$$\epsilon_t = \frac{\sigma_o + C\epsilon_o}{A + Be^{-t/\lambda} + C} \qquad (22)$$

where ϵ_o is given by equation (23) below :

$$\epsilon_o = \frac{\sigma_o}{A + B} \qquad (23)$$

In similar fashion to that outlined for the relaxation tests, the creep experimental data can be used to find C_3, C_4, q_1 and q_2 in equation (21) - which lead to the determination of E_1, E_3, $_1$ and $_3$ in Model 1, - and to find A, B, λ and C for Model 2 from equations (22) and (23).

Cyclic Test

In cyclic tests, deformation takes place at constant rates (see Fig. 7) i.e.

$$\dot{\epsilon} = + C_o \quad 0<t<t_1 \; ; \; t_2<t<t_3 \tag{24}$$

$$\dot{\epsilon} = - C_o \quad t_1<t<t_2 \; ; \; t_3<t<t_4 \tag{25}$$

Model 1.

$$\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_1\dot{\epsilon} + q_2\ddot{\epsilon}$$

$$= \begin{cases} q_1 C_o & 0<t<t_1 \; ; \; t_2<t<t_3 \\ -q_1 C_o & t_1<t<t_2 \; ; \; t_3<t<t_4 \end{cases} \tag{26}$$

a) $0 < t < t_1$

Writing the model in finite difference form, using constant time steps Δt,

$$\sigma(n) + p_1\left[\frac{\sigma(n) - \sigma(n-1)}{\Delta t}\right] + p_2\left[\frac{\sigma(n) - 2\sigma(n-1) + \sigma(n-2)}{\Delta t^2}\right] = q_1 C_o \tag{27}$$

$$\sigma(n) = \frac{q_1 C_o + \dfrac{p_1\sigma(n-1)}{\Delta t} + \dfrac{2p_2\sigma(n-1)}{\Delta t^2} - \dfrac{p_2\sigma(n-2)}{\Delta t^2}}{1 + \dfrac{p_1}{\Delta t} + \dfrac{p_2}{\Delta t^2}} \tag{28}$$

Initial conditions, $\sigma(o) = \sigma(-1) = 0$

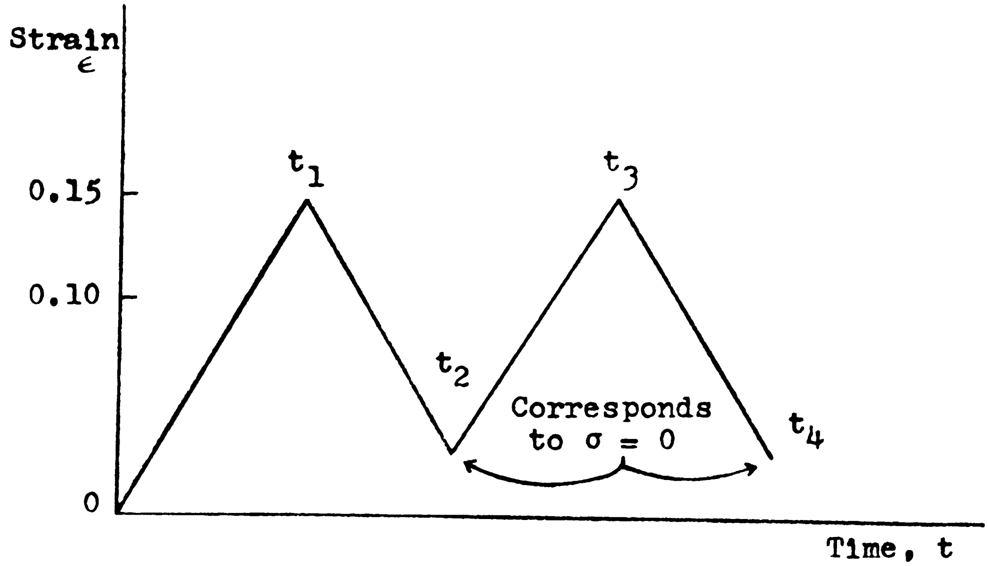


Figure 7. Typical ϵ - t relationship for cyclic test

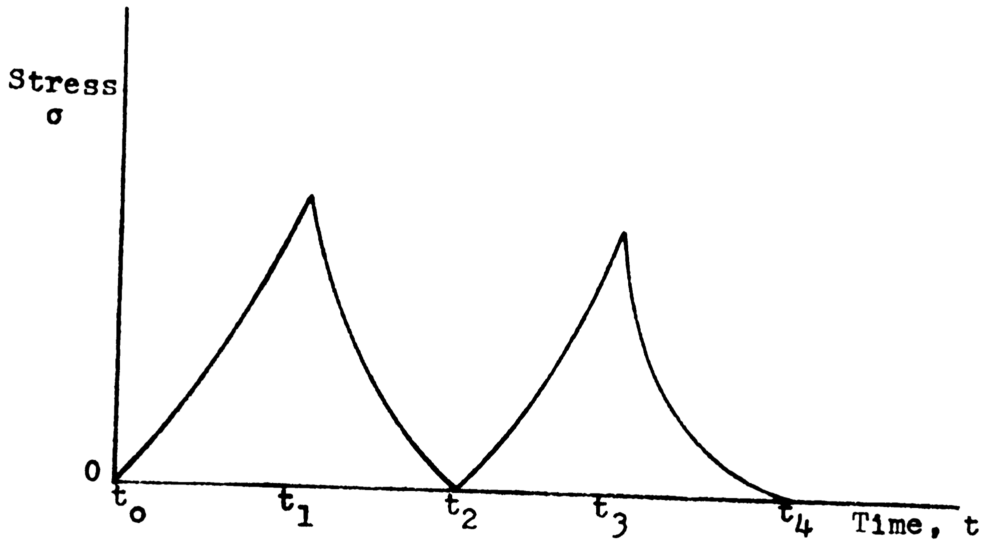


Figure 8. Typical σ - t relationship for cyclic test

b) $t_1 < t < t_2$

Solution is similar to equation (28) except for $-C_o$:

$$\sigma(n) = \frac{-q_1 C_o + \dfrac{p_1 \sigma(n-1)}{\Delta t} + \dfrac{2p_2 \sigma(n-1)}{\Delta t^2} - \dfrac{p_2 \sigma(n-2)}{\Delta t^2}}{1 + \dfrac{p_1}{\Delta t} + \dfrac{p_2}{\Delta t^2}} \qquad (29)$$

Initial conditions :

$\sigma(o) = \sigma_{t_1}$, from (a) above

$\overset{*}{\sigma}(-1) = 2\sigma_{t_1} - \sigma_{t_1 - t}$,

c) $t_2 < t < t_3$

Equation (28) in (a) gives the solution for this part of the cycle.

Initial conditions :

$\sigma(o) = 0$

$\overset{*}{\sigma}(-1) = 2\sigma_{t_2} - \sigma_{t_2 - t}$,

d) $t_3 < t < t_4$

Solution is the same as (29) in (b) above.

Initial conditions :

$\sigma(o) = \sigma_{t_3}$; from (c) above.

$\overset{*}{\sigma}(-1) = 2\sigma_{t_3} - \sigma_{t_3 - t}$

The second initial condition i.e. $\sigma^*(-1)$ for parts (b), (c) and (d) is an approximation. Choice of the actual stress at any of the times $(t_1-\Delta t)$, $(t_2-\Delta t)$, $(t_3-\Delta t)$ as the second initial condition would lead to an unstable solution. The predicted stresses after times t_1 and t_3 would continue to increase, even though strain is being decreased. Such behavior is physically impossible.

Therefore, if the values of E_1, E_3, η_1 and η_3 are previously known from either the relaxation or creep experiments, it is possible to predict the stress-time relationship for cyclic loading conditions, which in fact also gives the texture profile on the Instron machine as used to objectively measure beef texture.

Model 2.

$$\sigma = A\epsilon + B\epsilon e^{-t/\lambda} + C\int_{t_n}^{t} d\epsilon$$

Referring to equations (24) and (25) and integrating the third term in Model 2, the solution for the cyclic test can be written as follows :

e) $0 < t < t_1$

$$\epsilon = C_o t \qquad (30)$$

$$\sigma = \epsilon\,(A + Be^{-t/\lambda} + C) \qquad (31)$$

<u>f)</u> <u>$t_1 < t < t_2$</u>

$$\epsilon = C_o t_1 - C_o(t-t_1) \qquad (32)$$

$$\sigma = \epsilon(A + Be^{-t/\lambda} + C) - CC_o t_1 \qquad (33)$$

<u>g)</u> <u>$t_2 < t < t_3$</u>

$$\epsilon = \epsilon_{t_2} + C_o(t-t_2) \qquad (34)$$

$$\sigma = \epsilon(A + Be^{-t/\lambda} + C) - C\epsilon_{t_2} \qquad (35)$$

<u>h)</u> <u>$t_3 < t < t_4$</u>

$$\epsilon = \epsilon_{t_3} - C_o(t-t_3) \qquad (36)$$

$$\sigma = \epsilon(A + Be^{-t/\lambda} + C) - C\epsilon_{t_3} \qquad (37)$$

Equations (30) through (37) will allow stress to be predicted as a function of strain and time provided A, B, λ and C have been found from relaxation or creep tests. The above equations will also permit the optimum values of A, B, λ and C to be found from cyclic experimental data, using the non-linear estimation method described below.

Impact Test

The purpose of the impact test was to determine the capacity of cubes of pre-cooked freeze-dried beef to absorb energy at different moisture contents and to examine the relationship, if any, existing between energy absorbed and texture parameters.

The calculations involved in determining absorbed energy are relatively simple, once the velocity change in the falling weight, as it impacts the sample, is known. Reference to Figure 9 below will illustrate the change in the velocity of the weight as it makes contact with the cube.

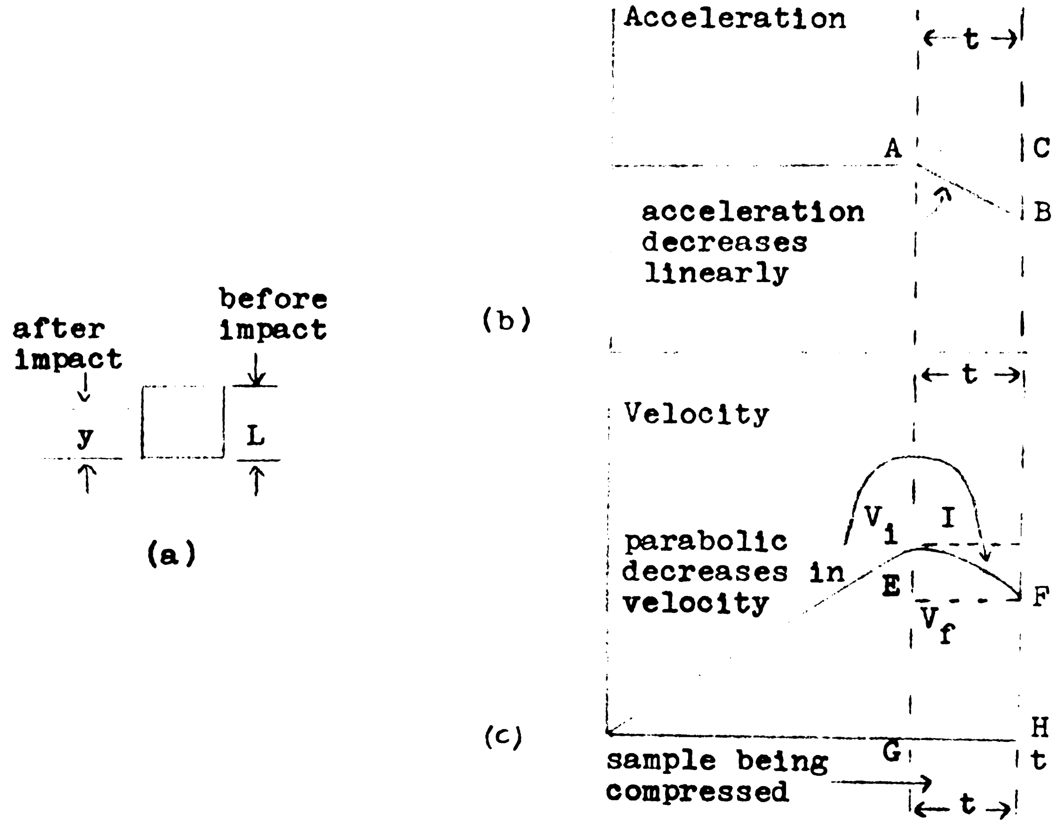


Figure 9. Velocity change in falling weight during impact test.

Let

W = weight (known)

V_1 = initial velocity of weight at impact

V_f = final velocity of weight at impact

ΔV = $V_1 - V_t$

L = original height of cube sample

y = compressed height of cube sample

E_1 = initial total energy of falling weight

E_2 = final total energy of falling weight

E_r = $E_1 - E_2$ = energy loss by weight

= energy absorbed by sample

$$E_1 = \tfrac{1}{2}\frac{W}{g}V_1^2 + WL \qquad (38)$$

$$E_2 = \tfrac{1}{2}\frac{W}{g}V_f^2 + Wy \qquad (39)$$

$$E_r = E_1 - E_2$$

$$= \tfrac{1}{2}\frac{W}{g}(V_1^2 - V_f^2) + W(L - y) \qquad (40)$$

But the height (L-y) is equal to the integration of (weight velocity x time) over the total time in which the weight is impacting the cube i.e. (area EFGH) + (area EFI) in Fig. 9 (c). Assuming a linear fall in acceleration and therefore a parabolic decrease in velocity, height (L-y) may be approximated as

$$(L-y) = t(V_1 - {}^1/_3\,\Delta V) \qquad (41)$$

Therefore,

$$E_r = \frac{W}{g}(V_i^2 - V_f^2) + Wt\,(V_i - {}^1/_3\,\Delta V). \qquad (42)$$

Rewriting

$$(V_i^2 - V_f^2) = (V_i - V_f)(V_i + V_f)$$

$$= \Delta V\,(2V_i - \Delta V)\,,$$

equation (42) can be re-arranged as :

$$E_r = \frac{W}{2g}\Delta V\,(2V_i - \Delta V) + Wt\,(V_i - {}^1/_3\,\Delta V). \qquad (43)$$

The two values V_i, ΔV may be found from experimental data (see Figure 17) and the weight W is known.

Non-linear Estimation of Parameters: GAUSHAUS Program

The GAUSHAUS computer program (Meeter, 1964) for parameter estimation in non-linear models is one of several methods available (Hohner, 1970) and was used here mainly because of the supplementary statistics made available which gives the user valuable information as to the accuracy of the estimates. Basically, it is necessary to supply to the program first estimates of the required parameters, the theoretical model for calculating predicted results, and the experimental data. A comparison is made between the theoretical predictions from the model and the experimental data, and GAUSHAUS then continues to improve the parameter estimates until relative changes in the sums of squares between theoretical and experimental results have been minimized.

Output from the GAUSHAUS routine includes :

(a) optimum parameter estimates, with 95 per cent confidence limits.

(b) final predicted values of the model, also with 95 per cent confidence limits.

(c) sums of squares between theoretical and experimental values.

(d) correlation matrix of the parameters being estimated.

In summary, two models have been proposed to relate stress to strain for pre-cooked freeze-dried beef. Both models include four parameters which can be estimated from engineering tests. All four parameters in Model 1 can be determined from the relaxation, creep or cyclic test. However, one of the parameters (C) in Model 2 can only be determined from either a creep or cyclic experiment. When the values of the parameters are known the models can be used to predict the response for all three tests, and also give estimates of the two texture indices, hardness and chewiness. In addition, certain coefficients in both models should relate closely with texture parameters.

CHAPTER IV

EXPERIMENTAL PROCEDURES

The experimental procedures followed can be divided into three main steps; i.e., product preparation, sample equilibration, and mechanical testing of samples, as outlined on Figure 10.

Product Preparation

Two sides of longissimus dorsi muscle from one animal were each cut into five approximately equal sections, in a direction from front to rear, and cooked at an oven temperature of 325°F until the center of the sections reached 160°F. A sensing element monitored the center temperature and automatically shut off the oven at the pre-set temperature of 160°F, simultaneously informing the operator that cooking was complete. The cooked roasts were then sealed in heavy duty aluminum foil and labelled 1L, 2L, 2R, etc., to identify the location in the muscle from which the particular roast was cut. The numbers 1 through 5 indicated positions from the front to the rear of the muscle, respectively, while L and R denoted the left or right side. All ten roasts were then frozen by storing at -20°F for a minimum of 48 hours.

A high speed band saw (Toledo, Model 5200-0-002) was used to cut the frozen beef into approximately 1/2" cubes.

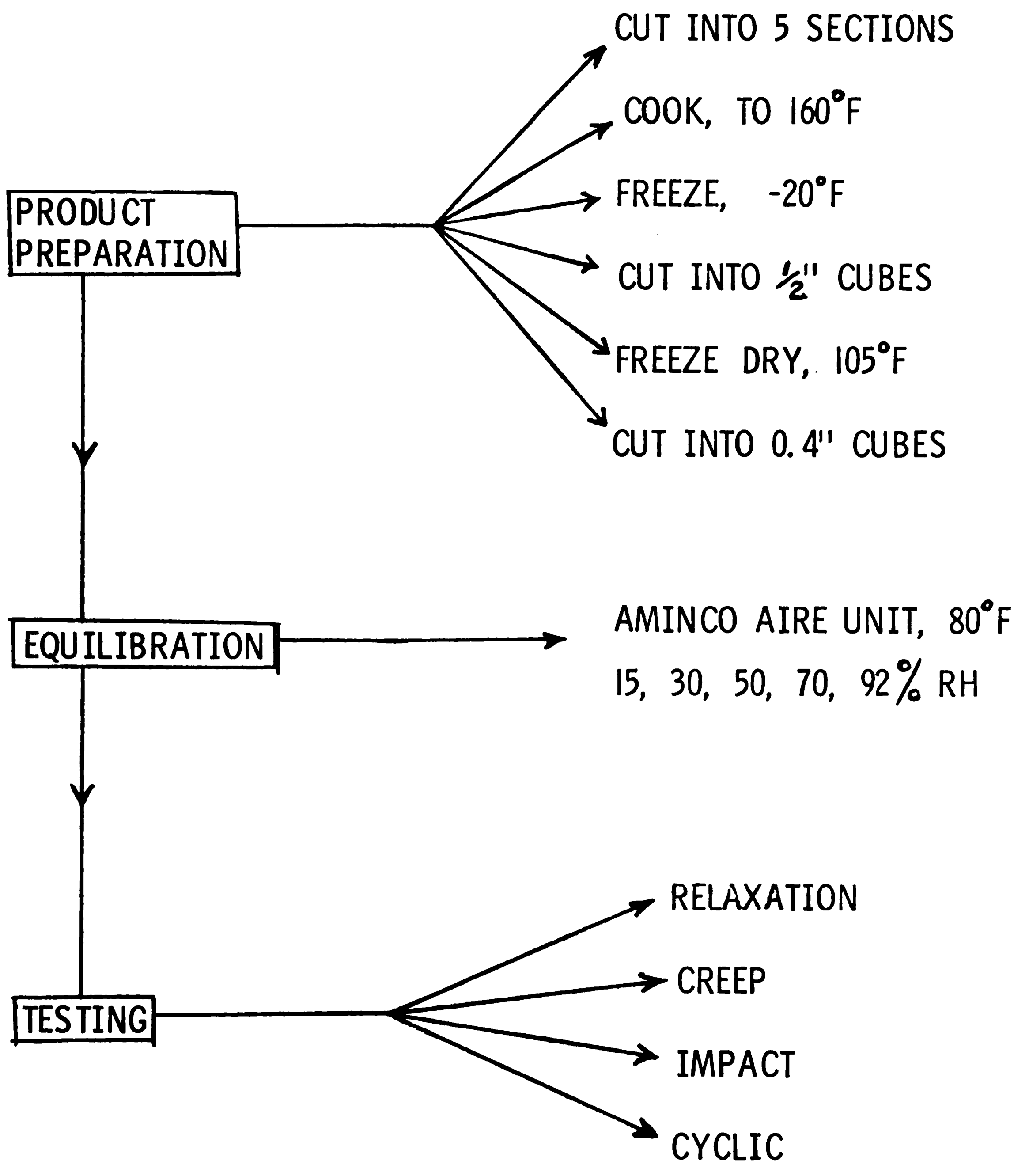


Figure 10. Outline of experimental procedure

Cubes were cut so that fiber direction was as nearly perpendicular to a particular face as possible, to ensure that samples were similar in physical characteristics.

The cubes were placed in aluminum trays, which in turn were sealed with heavy duty aluminum foil, and placed in the cold room at -20°F for another period of 48 hours to insure that any samples which may have partially thawed during cutting would be re-frozen prior to drying.

Drying was carried out in a freeze-dryer (Virtis-Rep, Model 42) with a plate temperature setting of 105°F. Product temperature was measured by utilizing thermocouple junctions placed at the center of a number of cubes and a continuous recording potentiometer (Leeds-Northrup, Speedomax W Model). When the product temperature reached plate temperature, drying was assumed to be complete. The samples were subsequently stored in a desiccator at -20°F until equilibrating and mechanical testing.

After several preliminary tests it was evident that a wide variation existed between results from samples similarly equilibrated, and it was felt that this could largely be attributed to non-homogeneities within the samples and to some irregularities in dimensions of samples. To overcome these problems, a small timber jig was assembled. By holding a cubed sample in the jig, which was clamped to the miter gage head on the table of a Craftsman 18" band saw (Craftsman, Model 112.23580), it was possible to cut off obvious non-homogeneities lying near the surface of the cubes and simultaneously reduce the cubes in size to a uniform dimension of 0.4 inch. The results reported refer to experiments using 0.4 inch cubes.

Sample Equilibration

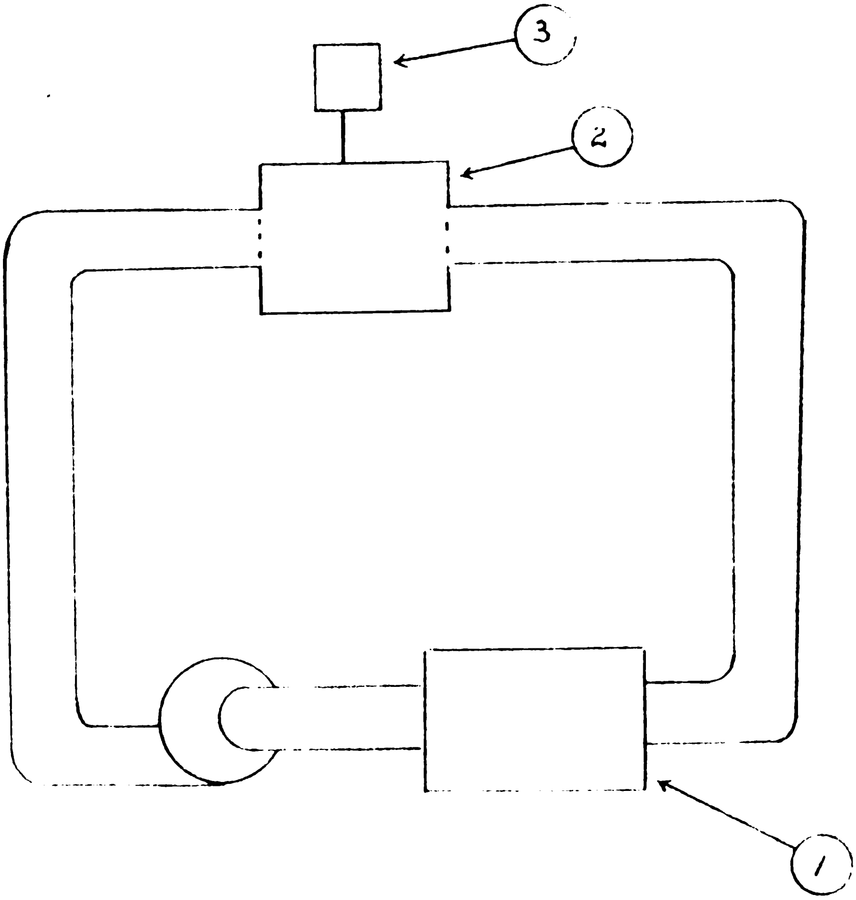
The cubes from corresponding sections on both sides of the muscle were grouped together (i.e., 1R with 1L, 2R with 2L, etc.), and from each of these five lots one sample was randomly selected for mechanical testing. Thus for every test, five replications were run, as illustrated on Fig. 11.

An Aminco Aire air-conditioning unit, capable of circulating air with controlled temperature and relative humidity (R.H.), was used to equilibrate the beef samples. Samples were placed in an insulated chamber (2 on Fig. 12) and equilibrated to moisture contents corresponding to 30, 50, 70, and 92% R.H. at a temperature of 80°F. Room temperature was 80°F, and room R.H. was 15%. The Aminco unit was incapable of circulating air at 15% R.H., so the samples at this low R.H. were allowed to equilibrate at room conditions.

Moisture content of the beef cubes equilibrated at 80°F, 15% R.H. was determined to be 3.1% (dry basis) using a hot air mechanical convection oven at 100°C for 18 hours. The dry weight corresponding to this moisture content was then used to calculate the moisture content at the higher relative humidities. The equilibrium condition was determined by weighing the sample cubes at 10-minute intervals until

	(front)				(rear)	
POSITION	1	2	3	4	5	
RH %						
15	X	X	X	X	X	n=5
30	X	X	X	X	X	
50	X	X	X	X	X	
70	X	X	X	X	X	
92	X	X	X	X	X	
	n=5					

Figure 11. Experimental design for statistical analysis



1. Air conditioning (Aminco) unit.

2. Equilibration chamber.

3. Temperature and R.H. measurement unit.

Figure 12. Apparatus used for equilibration of pre-cooked freeze-dried beef cubes.

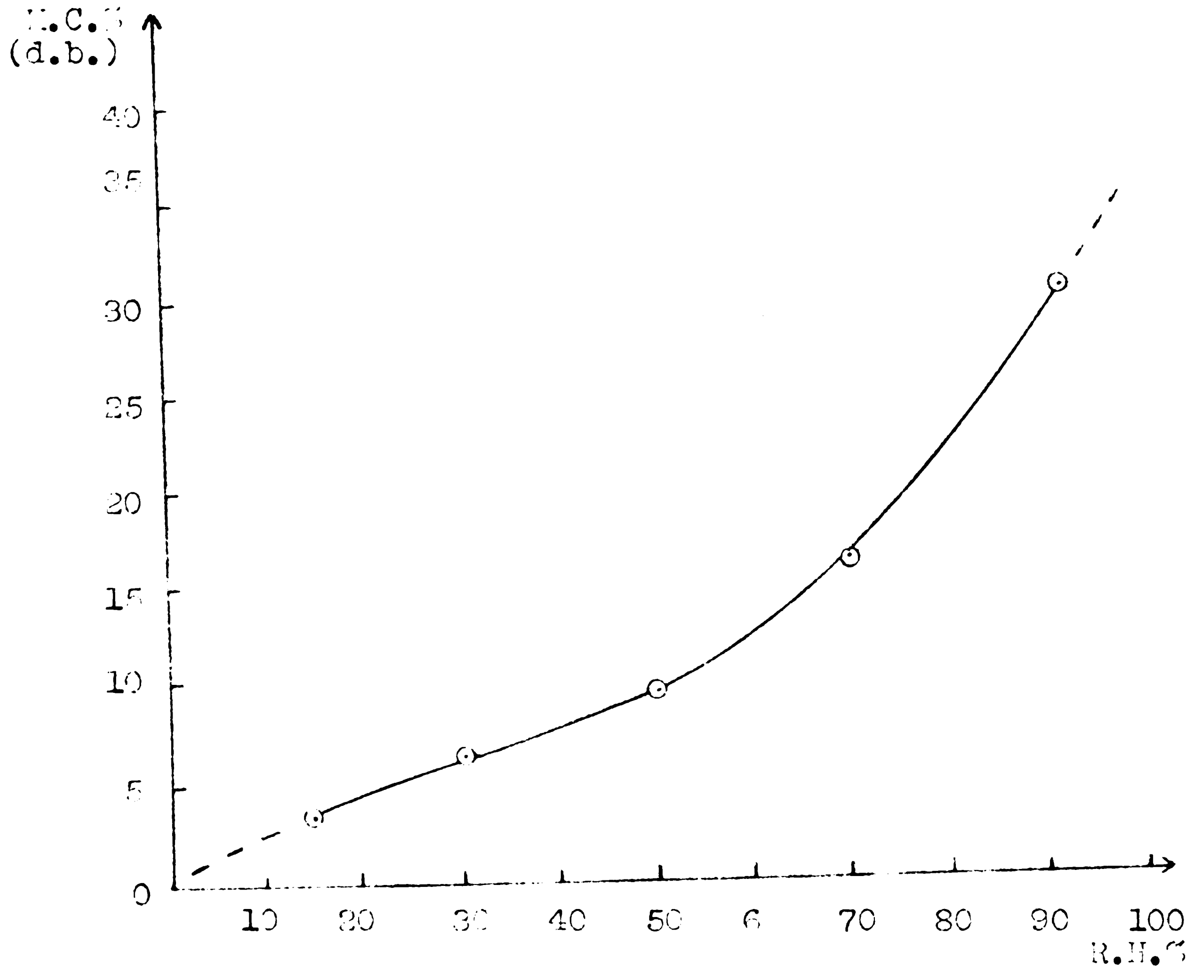


Figure 13. Absorption isotherm for pre-cooked freeze-dried beef at 80 F.

three successive readings indicated that a constant weight had been achieved. For the various tests carried out, the cubed beef samples were removed from the chamber of the Aminco Aire unit, one at a time. Figure 13 shows the resulting equilibrium moisture contents at 15, 30, 50, 70, and 92% R.H. to be approximately 3, 6, 10, 16 and 30% (dry basis), respectively.

Relaxation Tests

An Instron Universal Testing Machine, table Model TM, 200 kilograms capacity, with standard crosshead speeds of 0.2 to 50 inches/minute was used to study relaxation behavior of pre-cooked freeze-dried beef. This experimental set-up is shown on Figure 14.

The crosshead was set to deform the 0.4 inch cubes through 0.06 inch, or the equivalent of 0.15 strain. Ideally, a relaxation test involves instantaneous deformation. The crosshead speed used was 20 inch/minute, which applied the required deformation in 0.18 seconds. Any faster speed would have resulted in the crosshead slightly over-running the set stop-point and thus excessively deforming the samples.

Since short time behavior was of prime interest, the change in stress (force divided by the cross-sectional area of the sample, 0.16 sq. in.) over a time of 100 seconds was recorded. Mean behavior was evaluated by calculating the mean stress at every 1.2 second intervals up to 24 seconds, and at each 6 second interval thereafter.

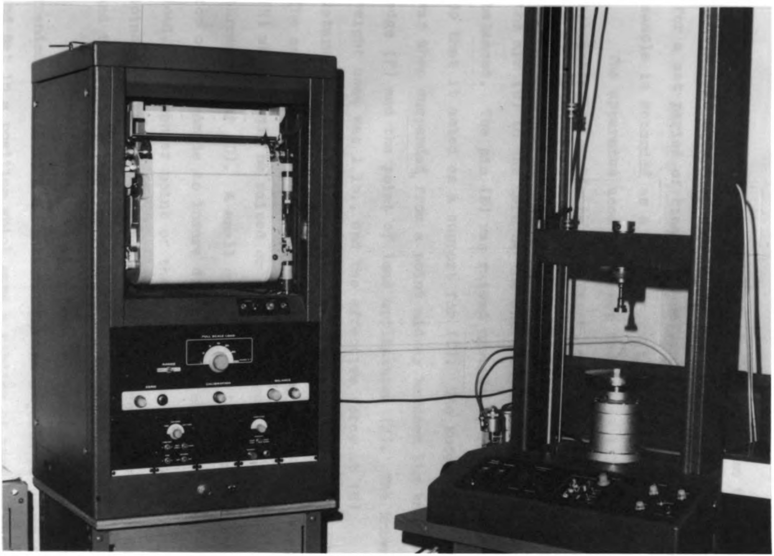


Figure 14. Instron testing machine used for relaxation and cyclic tests.

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Creep Tests

A creep test is the opposite to a relaxation test in that a sudden load is applied to the sample and held constant for a set period of time. The deformation or strain on the sample is recorded as a function of time.

The apparatus used for creep testing is illustrated schematically on Figure 15. First, the balance weight was positioned along the threaded arm (E) such that the part of the arm (C) to the left of the knife-edge (F) was exactly balanced. The pin (B) was raised upwards by the switch (A) so that it acted as a support for (C). The known weight (M) was then suspended from a point midway between the knife-edge (F) and the point of load application (H). The known weight used was 1 lb., and the effective force at (H) determined by calibration with a load cell, was 0.48 lb. The sample was inserted between (H) and a supporting stand (K) which could be raised or lowered by rotation of the threaded gear (D). A small glass plate (L) was placed on top of the sample to insure distribution of the applied load. The center point of the glass plate was placed to coincide with the center of the top surface area of the sample and the load application point.

The displacement rod of the linear variable displacement trandsducer (LVDT) was contacted by the adjustable screw (G) and set in a position which gave a reading of zero on the transducer-amplifier indicator (Daytronic 200D). At this

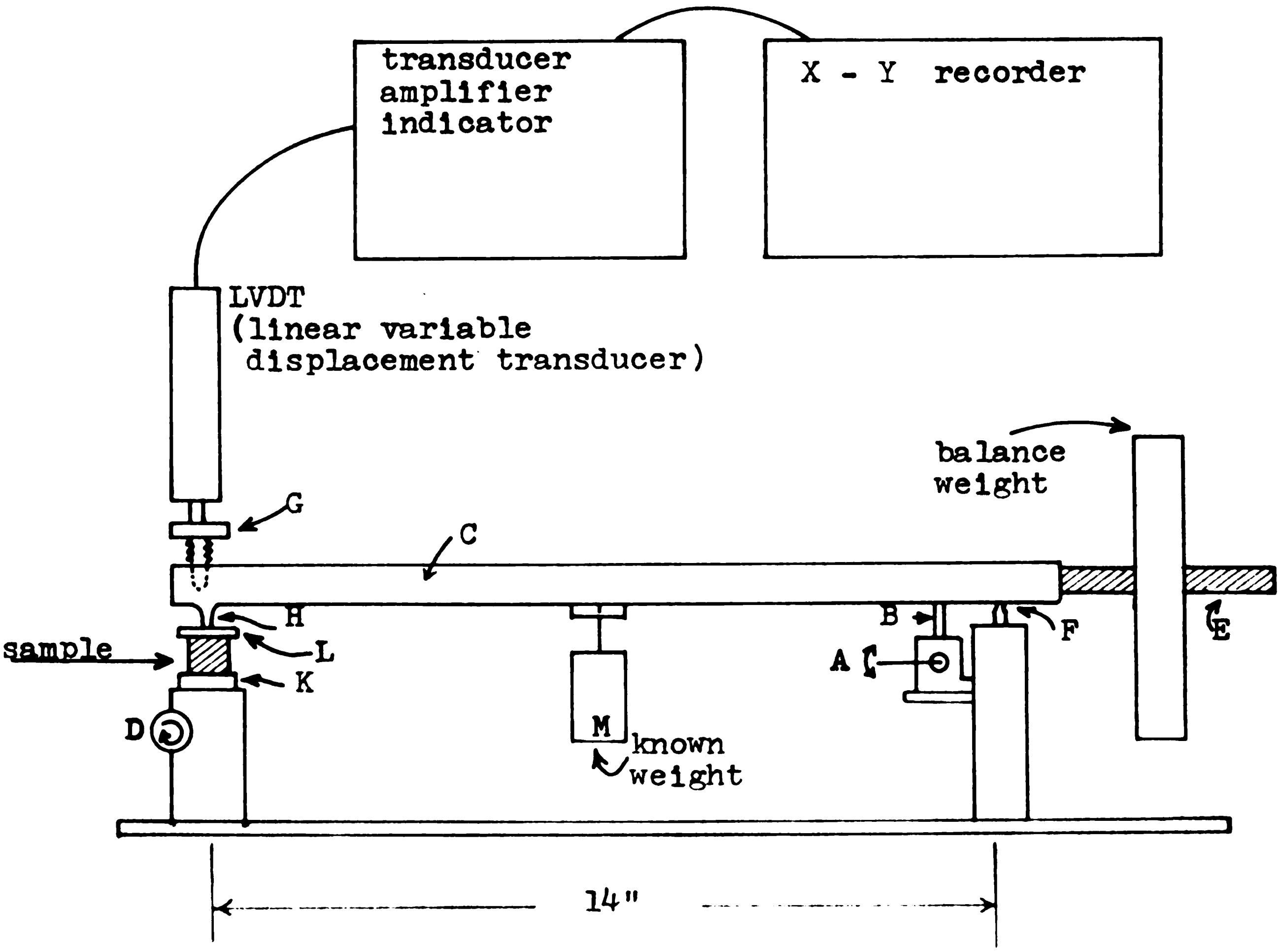


Figure 15. Schematic diagram of creep test apparatus

stage the recording pen on the X-Y recorder (Moseley 7035A) was adjusted to the origin of the X-Y axes.

Creep testing was accomplished by releasing the switch (a) and allowing the supporting pin (B) to fall. Deformation of the sample was recorded through the LVDT by the X-Y recorder over a time period of 100 seconds.

Impact Tests

The capacity of the beef cubes to absorb energy under impact loading conditions was measured using the drop tester and auxiliary equipment arranged as indicated on Figure 16.

The load was applied to the sample by the probe attached to the two-inch long drop weight. The probe, drop weight and accelerometer attached together weighted 2.0 lb. The drop weight was raised by the electro-magnet which was powered by 6 v D.C. obtained from an Erco transistorized D.C. power supply. The magnet-weight system was raised by turning the reel at the lower right of the tester stand to the required drop height as read from the scale along the drop tube. By turning the power supply off, the drop weight was released and, guided by the drop tube, it fell onto the product located on the load plate.

A Sigma Model 8L3 light source and Model 8P8 photo relay were located, one on each of the vertical supports. When the light beam of the relay system was interrupted, a pair of contacts in the photo relay closed, linking a

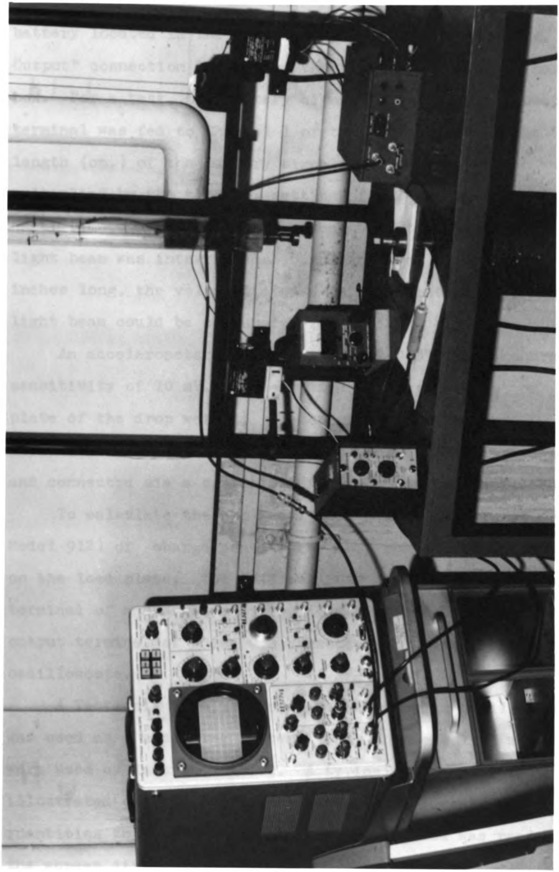


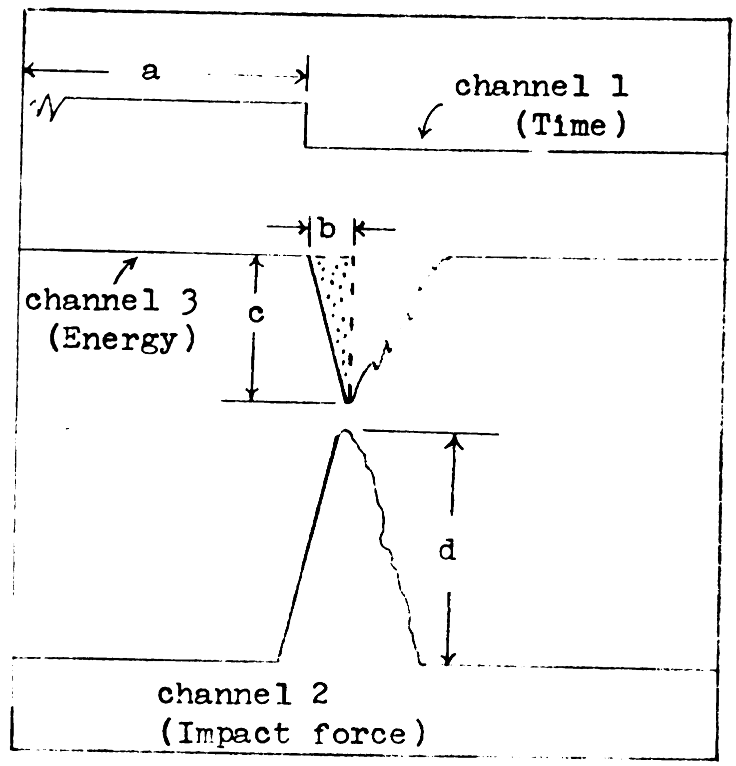
Figure 16. Apparatus used for impact tests.

battery located in the trigger control box to the "Trig. Output" connection located on the right-hand side of that box. For a test, the battery signal from the "Trig. Output" terminal was fed to Channel 1 of the oscilloscope. The length (cm.) of the battery signal trace on the screen was multiplied by the time/cm. setting of the oscilloscope sweep time control to give the length of time that the light beam was interrupted. Since the drop weight was two inches long, the velocity at the point it interrupted the light beam could be computed.

An accelerometer (Piezotron, Model 918) with a charge sensitivity of 10 mV./g. was bolted to the inner bottom plate of the drop weight. The output cable from the accelerometer was brought out of the top of the drop weight and connected via a coupler to Channel 3 of the oscilloscope.

To calculate the applied force, a load cell (Kistler, Model 912) of charge sensitivity 48.8 pcb./lb., was located on the load plate. The load cell was connected to the input terminal of a charge amplifier (Kistler, Model 503M15), the output terminal of which was connected to Channel 2 of the oscilloscope.

A Tectronik Type 549 Four-Channel-Storage oscilloscope was used as a recording system. Only Channels 1, 2 and 3 were used as described above. A typical test trace is illustrated on Figure 17 with accompanying definitions of quantities to be measured. All pertinent data was read off the screen directly.



Note :

$$V_i \propto a$$

$$V \propto bc$$

$$t \propto b$$

Figure 17. Typical test trace on oscilloscope for impact loading of pre-cooked freeze-dried beef samples.

Cyclic Tests

The table model Instron Machine was used for cyclic testing as well as for relaxation testing previously described.

Automatic controls on the Instron allowed the cubed samples to be deformed at constant rates between two set points - one corresponding to a strain of 0.15, the other corresponding to zero stress (Figure 7). For example, initial deformation of the sample began at zero stress and continued at a constant rate until the setting corresponding to 0.15 strain was reached. At this point, the crosshead began to return towards its original setting at the same constant rate. However, when the point of zero stress on the sample was reached (when the probe was just losing contact with the beef cube) the crosshead once more began to descend. This type of loading continued in a cyclic manner.

Three deformation rates were used, 0.5, 1.0, and 2.0 inch/minute; and as in the other tests, five samples from different muscle locations were used. Data was collected on each sample from only two cycles since this response provided the necessary information for evaluating the texture parameters required. These parameters, hardness and chewiness, were measured as described above in Chapter 11 (page 13, Figure 3).

Thus, four different types of experiments were run;

(a) an impact test, which investigated the relationship between water activity and energy absorbed;

(b) a relaxation test, which was used for parameter estimation of both Models 1 and 2, which were then used to predict creep and cyclic responses;

(c) cyclic tests, used to estimate parameters for Model 2 which was subsequently used to predict creep and relaxation functions. The cyclic tests were also used for evaluating hardness and chewiness, the texture parameters of the product;

(d) finally, the creep test was carried out and the predicted strain from the models compared with experimental results. It was decided to employ the creep test results for the sole purpose of checking the validity of the models whose parameters were determined from one or both of the cyclic and relaxation tests.

In addition, possible relationships between model and texture parameters were investigated.

CHAPTER V

RESULTS AND DISCUSSION

The results and discussion are divided into four main parts; (a) the impact tests, (b) the accuracy of the models, (c) the influence of water activity on model parameters and (d) ability of the models or engineering parameters to predict the required texture values. The use of any one test to yield all the necessary information for both the food technologist and the food engineer is also discussed.

Impact Tests

The mean energy absorption values at various equilibrium relative humidities (E.R.H.) are presented in Table 1 and illustrated on Figure 18.

Table 1 Mean energy absorbed in impact tests.

E.R.H. %	15	30	50	70	92
Energy Absorbed, ft.-lb.	0.152	0.216	0.236	0.215	0.187

The results reveal relatively little effect of water activity on the capability of the cube samples to absorb energy. An analysis of variance also failed to detect a significant effect of water activity (Table A-1).

The quantity of energy absorbed increased to a maximum

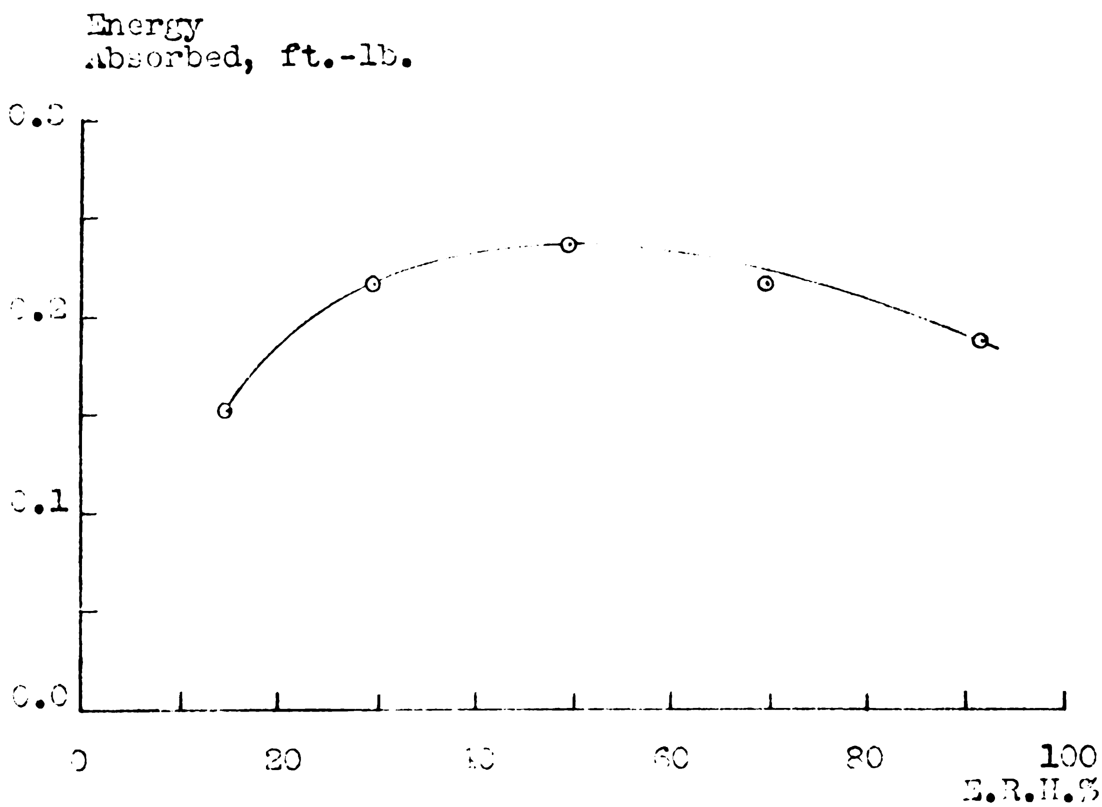


Figure 1[illegible]. Energy absorbed (under impact loading) by 0.4 inch cubes of pre-cooked, freeze-dried beef, at different equilibrium relative humidities.

at a water activity of 0.5, and decreased at water activities greater than that. Although the maximum value of energy absorbed was 50% greater than the minimum value it is difficult to justify drawing any conclusions regarding a definite relationship between equilibrium relative humidity and energy absorbed. For example, a quadratic type of function would seem adequate for describing the curve on Figure 18, but this could not be supported by statistical analysis. Further, it may be worthwhile to note that the one value of 0.54 ft.-lb. at 15% E.R.H. (Table A-8) is an isolated instance and probably due to inhomogeneities in that particular sample. It has the effect of decreasing the value for energy absorbed at $a_w = 0.15$ to a level which is probably not typical. This one value could also be the cause for finding differences in energy absorbed due to the location in the muscle from which the sample was taken, a conclusion that can barely be drawn at the 95% confidence level (Table A-1).

It is evident from Figure 19 that energy absorbed cannot be taken as a good guide for predicting water activity, and consequently texture parameters. These results tend to illustrate that energy absorbed is insensitive to changes in the hardness index. It may be concluded therefore that the impact test does not appear to offer information which could lead to predicting texture indices.

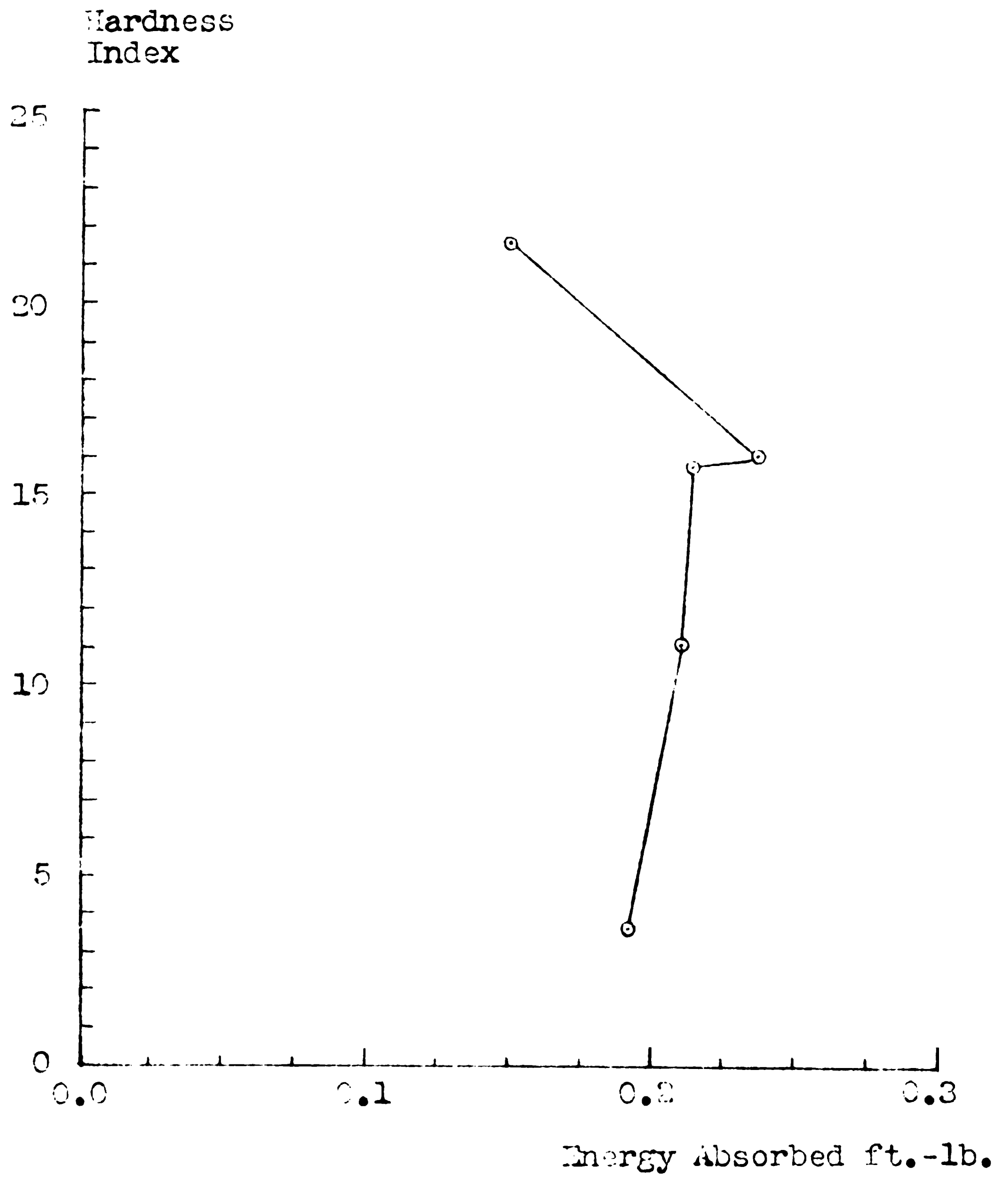


Figure 19. Relationship of energy absorbed under impact loading to Hardness Index for pre-cooked freeze-dried beef.

Accuracy of the Models

Three different approaches were adopted for estimating the parameters in both models. Accuracy of the models was checked not only by the experimental data of the test used for parameter estimation but also by independent tests. The concept underlying this approach is illustrated on Figure 20.

Figure 20 illustrates that the relaxation test data allowed all four parameters E_1, E_3, η_1, η_3 to be estimated for Model 1, which was then used to predict cyclic and creep functions. Similarly, the cyclic tests were used to estimate A, B, λ and C in Model 2(b), and the equation for that model subsequently predicted both creep and relaxation responses. The third approach used both the relaxation and cyclic tests to determine the coefficients in Model 2(a). The creep test results were employed for comparison purposes between Models 1, 2(a) and 2(b).

As will be discussed below, except for the failure of Model 1 to predict the cyclic response, the models appear to give satisfactory predictions. Since all of the parameters in Model 1, and three of the four in Model 2(a) were evaluated from relaxation tests, these models should give close agreement with the experimental relaxation data. Once the equation for a model gives a solution whose function is **similar** to the experimental pattern, then it only remains to calculate the optimum values of the constants in the model which give best

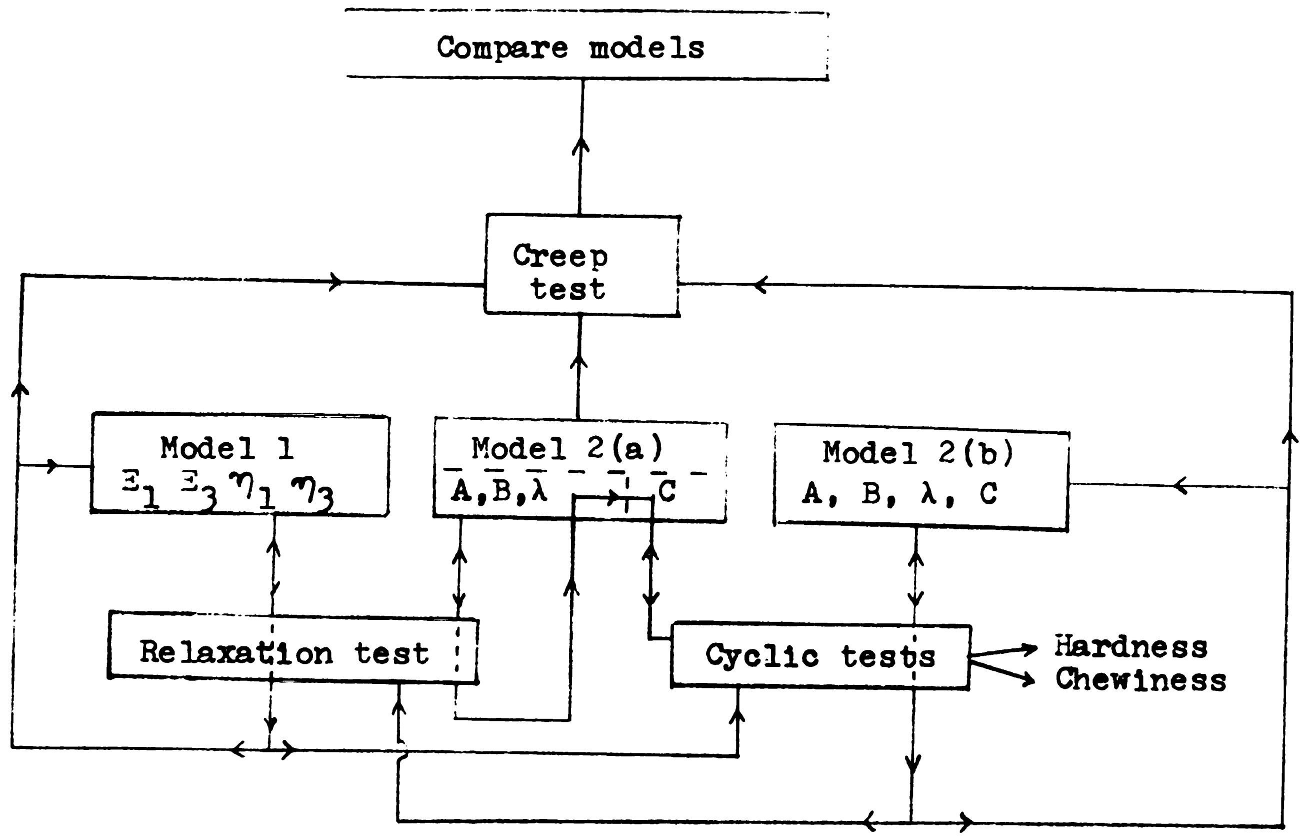


Figure 20. **Parameter estimation, function predictions, and model comparison at each water activity.**

agreement with experimental results. This optimization procedure was accomplished by using the GAUSHAUS non-linear estimation method.

Figures 21-25 illustrate a comparison between the models and experimental data for the relaxation tests. The differences which may exist between Model 1 and Model 2 as time approaches infinity may not be obvious. Reference to equations (16) and (17) will show that stress (σ) for Model 1 reduces to zero after an infinite time, whereas, in Model 2, the stress will approach a constant value; $\sigma(t=\infty) = A\epsilon_o$. Within the time periods considered in the present experiments however, large differences between both models were not apparent.

The relaxation function suggested by the model whose parameters were estimated without using relaxation data i.e. Model 2(b), agrees exceptionally well with experimental results at equilibrium relative humidities of 70% and 92%. For the lower water activities the predicted stresses are higher than the experimental values for about the first five seconds, and approximately 25% too low for times greater than that. One possible explanation for this lack of agreement may be related to the fact that the parameters in Model 2(b) were determined from the cyclic tests, which gave results somewhat inconsistent from what the relaxation data indicate. For example, a strain of 0.15 is applied instantaneously to the sample in a relaxation test but in a cyclic test the application is gradual e.g. over 7.2 seconds when the

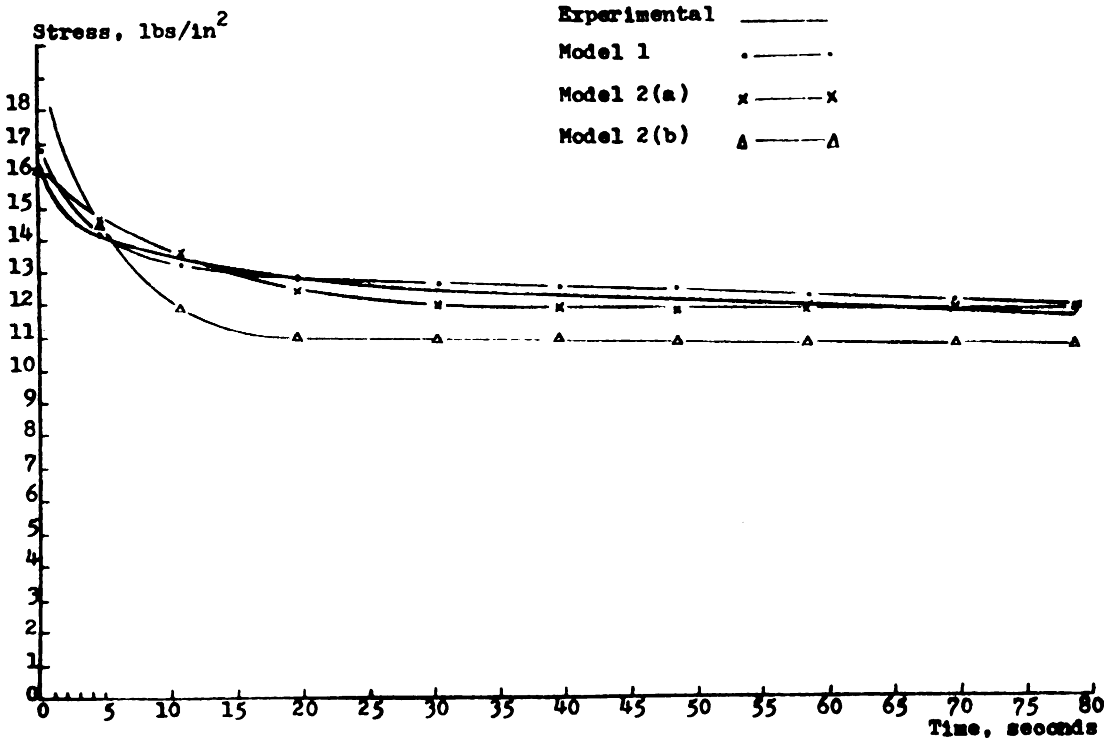


Figure 21. Experimental results and theoretical predictions for relaxation test - 80°F., 15% R.H.

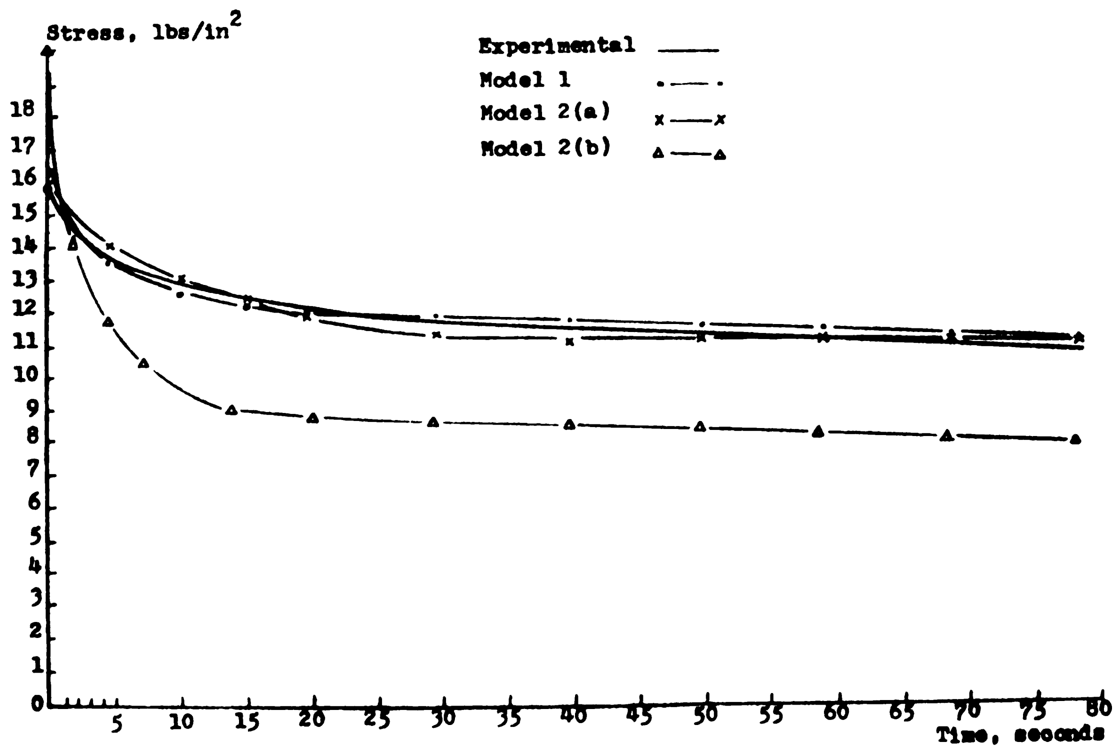


Figure 22. Experimental results and theoretical predictions for relaxation test - 80°F., 30% R.H.

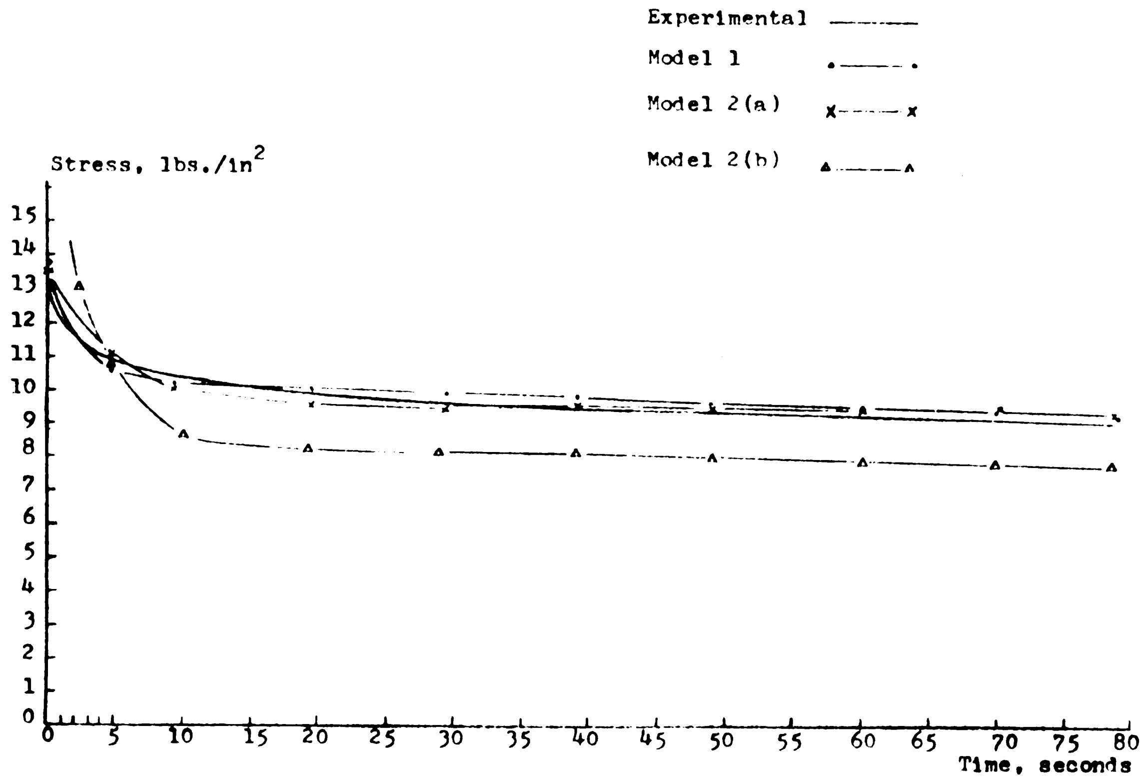


Figure 23. Experimental results and theoretical predictions for relaxation test - 80°F., 50% R.H.

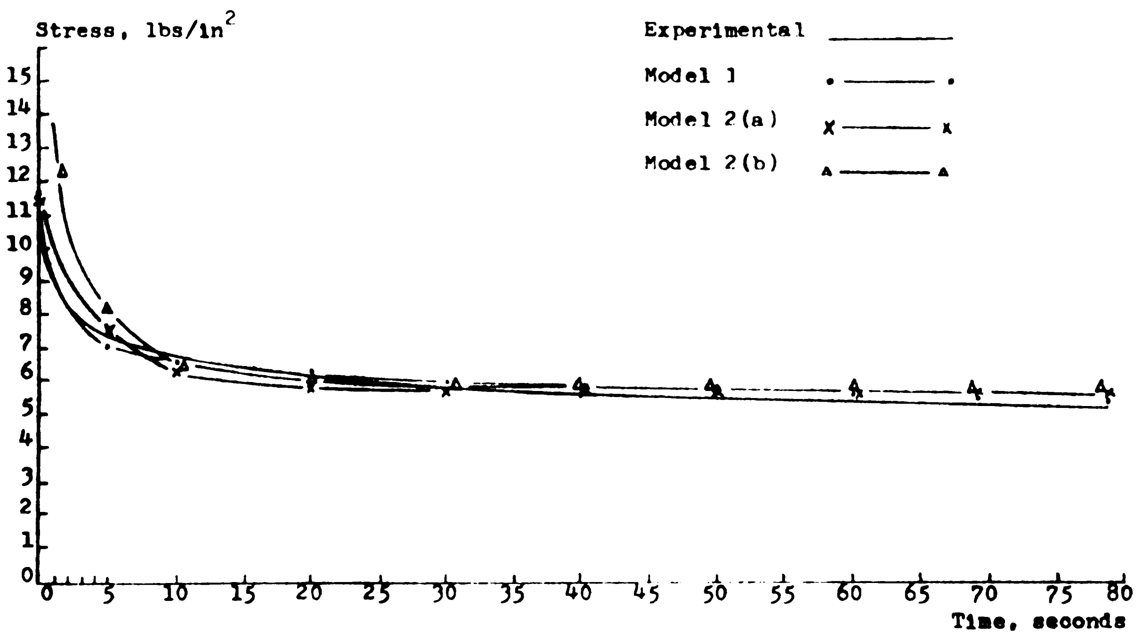


Figure 24. Experimental results and theoretical predictions for relaxation test - 80°F., 70% R.H.

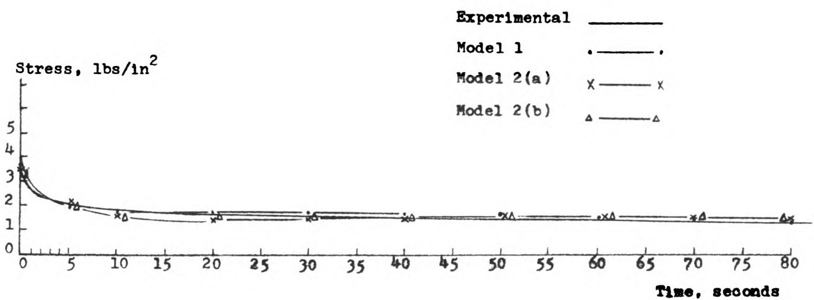


Figure 25. Experimental results and theoretical predictions for relaxation test - 80°F., 92% R.H.

deformation rate is 0.5 inch/min. Some stress should have "relaxed" during this time period. Therefore the cyclic stress when strain reaches 0.15 should be lower than the relaxation stress for the same strain at time, t = 0. But the experimental results at the lower water activities showed that the maximum stress for a cyclic test was greater than the maximum stress for a relaxation test.

The very high relaxation stresses predicted by Model 2(b) for times less than five seconds substantiate the above explanation. Indeed, this same apparently inconsistent behavior eliminates the possibility that Model 1, with parameters estimated from the relaxation experiments, could accurately predict cyclic stress behavior.

Such discrepancies between initial stress, σ_o, during relaxation loading and maximum stress, σ_{max}, under cyclic load application can perhaps be attributed to at least four possibilities : (a) differences in the samples tested; (b) the effect of sudden loading in a relaxation test; (c) a possible work-hardening effect during gradual compression in cyclic tests, or (d) changes in the product at different water activities.

Random errors due to sample differences is a strong possibility for the relaxation results, since only five replications were run at each equilibrium relative humidity. However, fifteen cyclic tests at each water activity should have been sufficient to account for product differences. Further, the trends for both types of experimental results are the same - it is the relative magnitude of the stress values which is surprising.

It is conceivable that the sample structure would be more susceptible to fracture or yielding under sudden impacting than under more gradual force application. Also, at lower moisture contents the product structure seemed more brittle than at higher moisture levels. The fact that Model 2(b) predicts relaxation much better at higher moisture contents, when presumably the product is less brittle, would support the contention that manner of loading combined with changes in the product structure at increased moisture levels is the most acceptable explanation for the apparent inconsistancies.

The fourth possible reason mentioned was a work-hardening effect. This behavior is exhibited by many engineering materials and it could also be true of low moisture foods i.e. the product becomes more resistant to compression as deformation is increased.

The use of the relaxation data to estimate parameters would lead to predictions of cyclic stresses which would be too low, as already discussed. However, the failure of Model 1 to predict cyclic response with any degree of accuracy must lead to the conclusion that a simple linear viscoelastic model is inadequate to describe the general stress-strain relationship for pre-cooked freeze-dried beef. Nevertheless, such models may be very suitable for specific tests such as creep or relaxations.

For example, the four element model proposed gives the best fit of all the three models to relaxation curves, and also gives suitable predictions for creep at 0.15, 0.30 and 0.50 water activities (Figures 26 - 28). At the higher water activities, creep predictions indicate that all four coefficients, E_1, E_3, η_1 and η_3, are too low (Figure 29, 30). Specifically, increasing the values of η_1 and E_1 would decrease the rate of change of strain, and also the magnitude of strain. These changes would also have the effect of increasing the predicted cyclic stress to a value nearer the experimental value. Unfortunately, such changes would lead to inaccurate predictions of the relaxation function.

Model 2(b), whose coefficients were calculated from cyclic test data, describes cyclic behavior excellently. It can also satisfactorily predict creep strain at all water activities (Figures 26 - 30). The fact that relaxation stresses predicted are too high for times below five seconds, and too low for times greater than that, is due to the exponential term ($B\varepsilon\, e^{-t/\lambda}$) being determined to satisfy cyclic results. The inconsistencies between cyclic and relaxation data discussed above meant that this term, for times near $t = 0$, would make too high a contribution to predicted relaxation stress. Nevertheless, even allowing for this inaccuracy, the predicted relaxation stresses are reasonable estimates of the experimental results.

The combination of cyclic and relaxation data utilized to determine the constant parameters in Model 2(a) overcomes

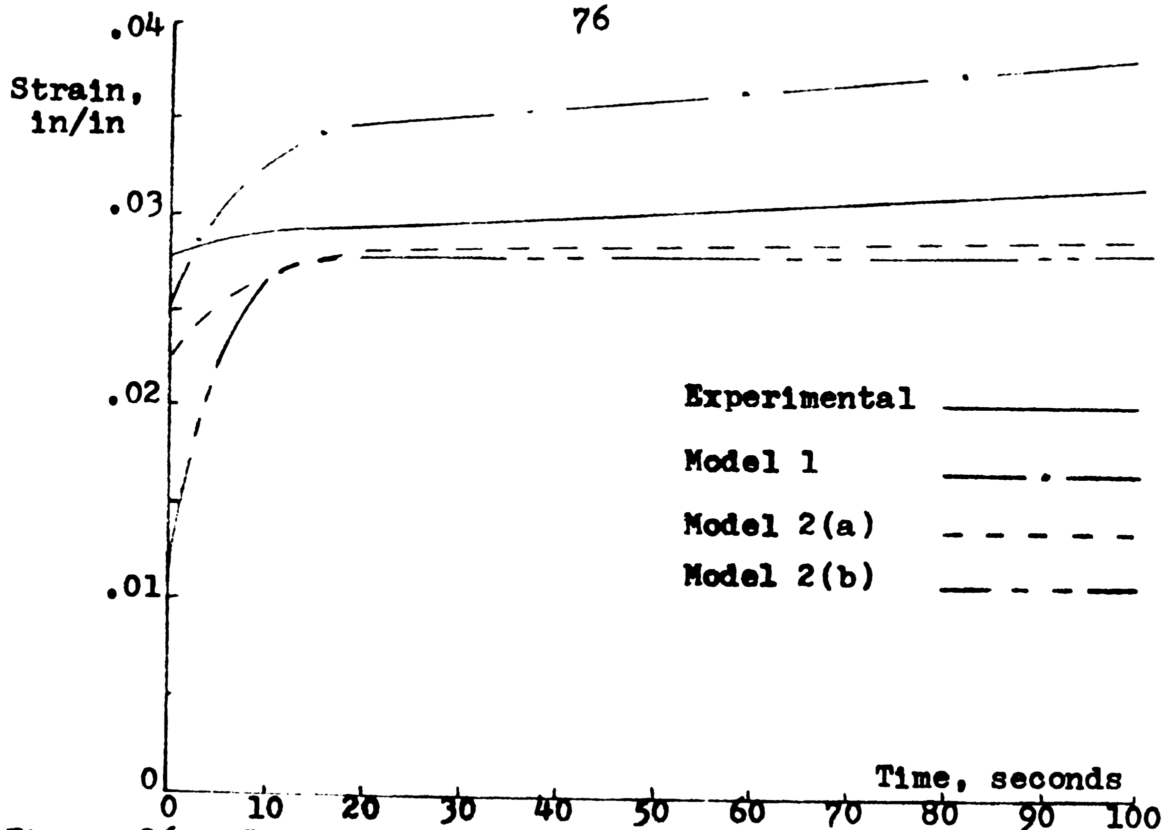


Figure 26. Creep experimental results and theoretical predictions - 80°F., 15% R.H.

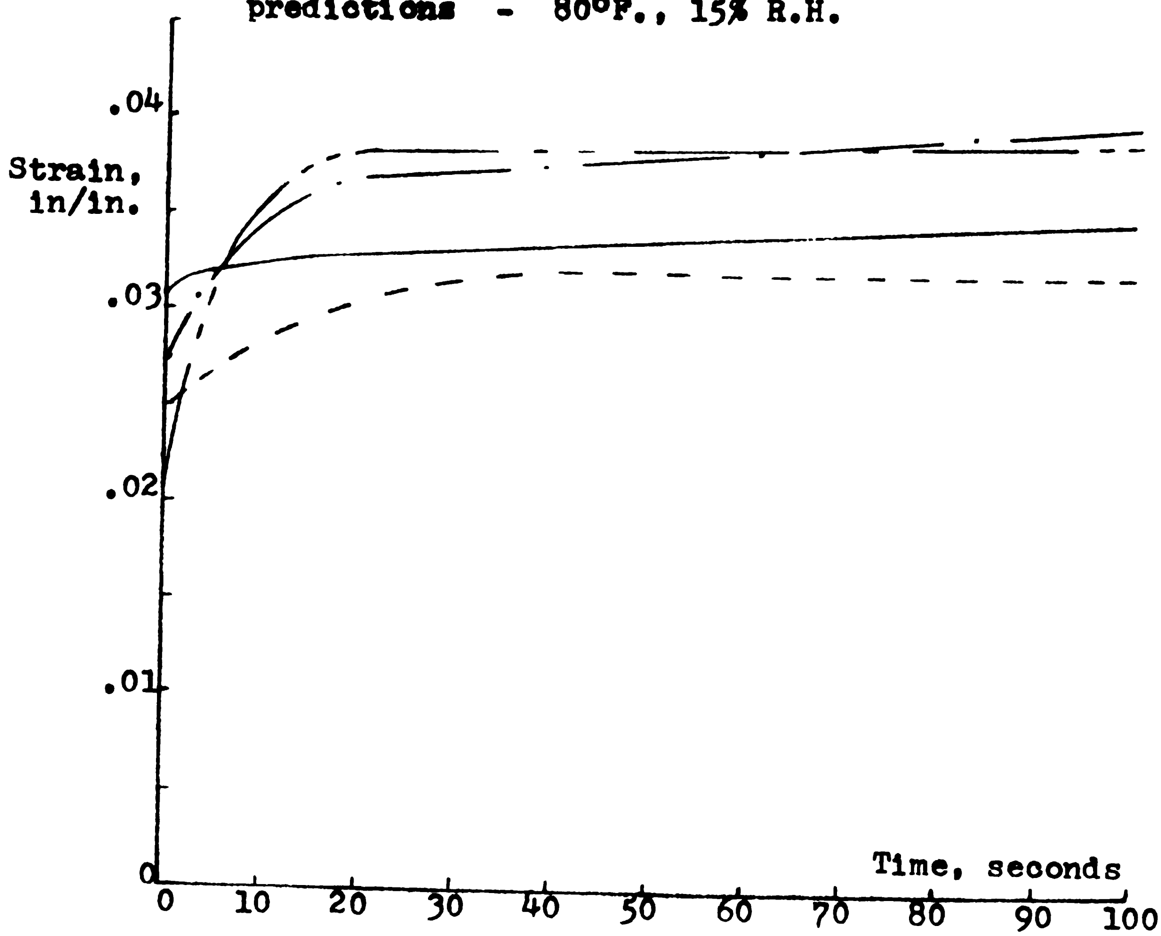


Figure 27. Creep experimental results and theoretical predictions - 80°F., 30% R.H.

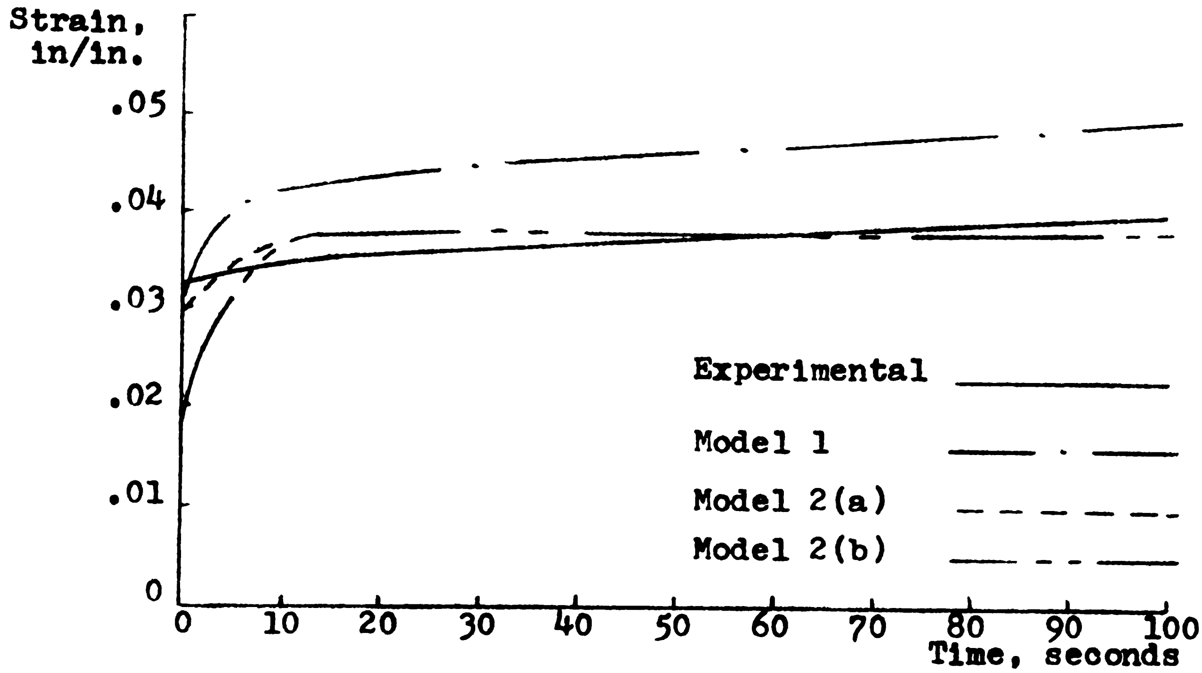


Figure 28. Creep experimental results and theoretical predictions - 80°F., 50% R.H.

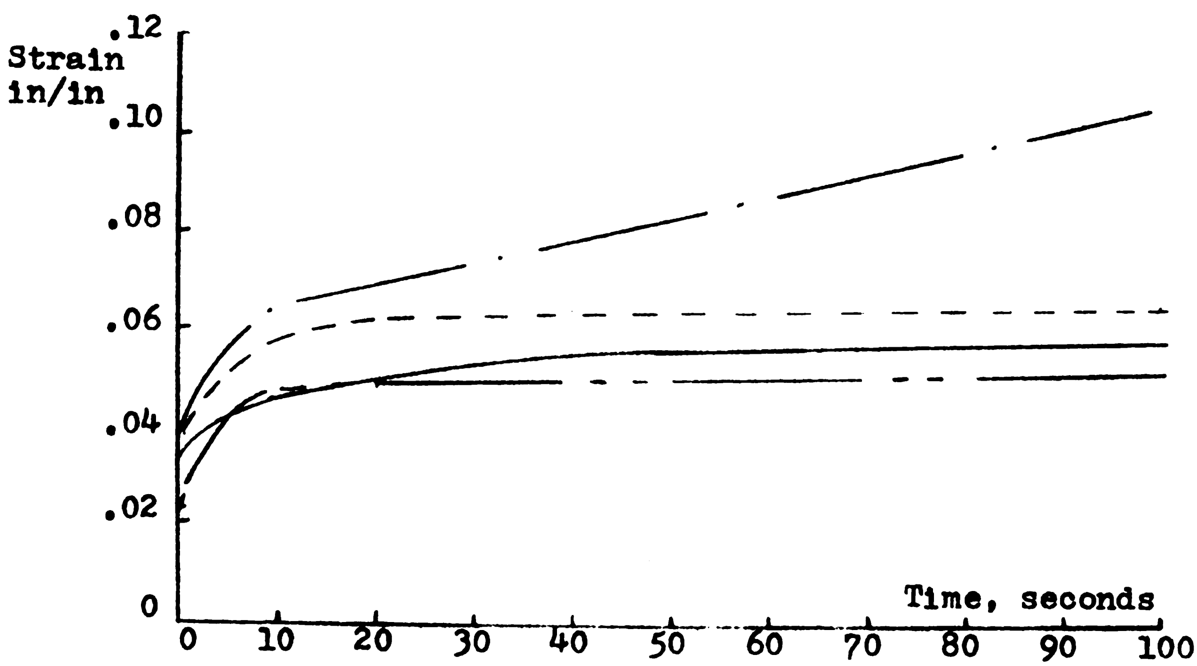


Figure 29. Creep experimental results and theoretical predictions - 80°F., 70% R.H.

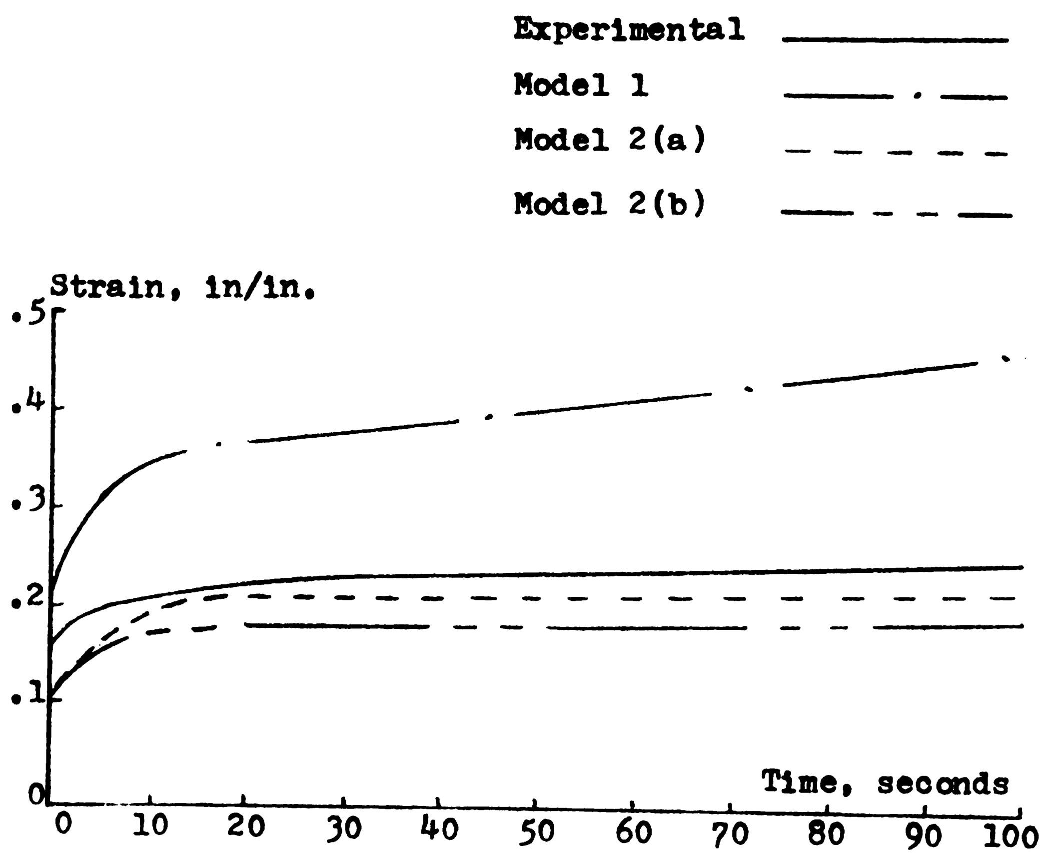


Figure 30. Creep experimental results and theoretical predictions - 80°F., 92% R.H.

the irregularities in results between both tests. Only one part of Model 2 is applicable under relaxation conditions;

$$A\epsilon + B\epsilon e^{-t/\lambda}$$

and this can be satisfactorily fitted to the experimental data for the relatively short time periods being considered. Using this part of the model to predict cyclic response (i.e. omitting the term $C \int_{t_n}^{t} d\epsilon$), it was found that for the loading parts of the cycle ($0 < t < t_1$ and $t_2 < t < t_3$) predicted stresses were too low, whereas the opposite was the case during unloading. Thus the term $C \int_{t_n}^{t} d\epsilon$ plays an important role, since it increases the predicted stress for loading conditions, but decreases it when strain - and therefore stress - is being decreased. The result is very good predictions, as illustrated on Figures 31 - 35. In addition, when comparing the predictions by models with results of creep experiments, the predictions by Model 2(a) were in closer agreement than either Model 1 or Model 2(b). The approach used to evaluate the parameters of Model 2(a) would therefore seem to give the most acceptable general model.

To avoid confusion, the cyclic curves resulting from the solution of Model 1 have not been included in Figures 31 - 35. The maximum theoretical stresses were only one-fourth to one-third the values of the experimental stresses, as illustrated by the results presented in Table 5.

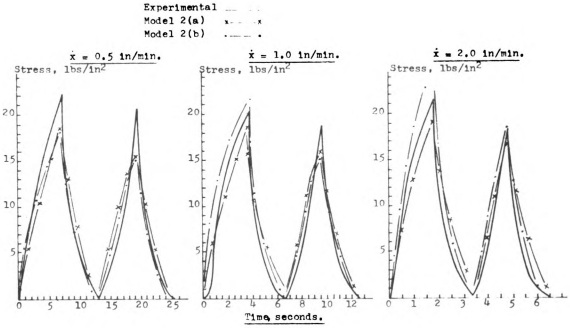


Figure 31. Experimental results and theoretical predictions for cyclic tests - 80°F., 15% R.H.

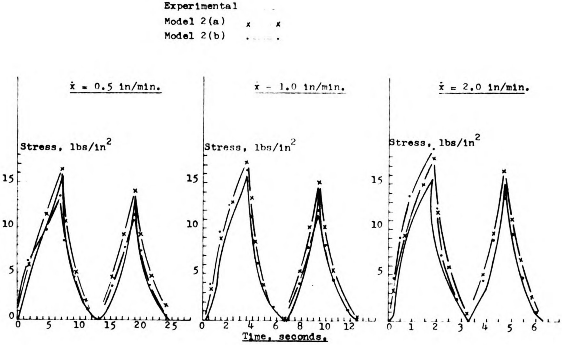


Figure 32. Experimental results and theoretical predictions for cyclic tests - 80°F., 30% R.H.

Experimental
Model 2(a)
Model 2(b)

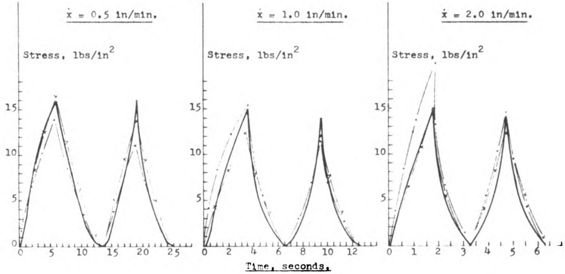


Figure 33. **Experimental results and theoretical predictions for cyclic tests** - 80°F., 50% R.H.

Experimental
Model 2(a)
Model 2(b)

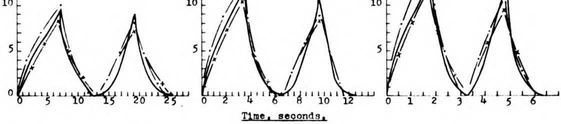


Figure 34. **Experimental results and theoretical predictions for cyclic tests** - 80°F., 70% R.H.

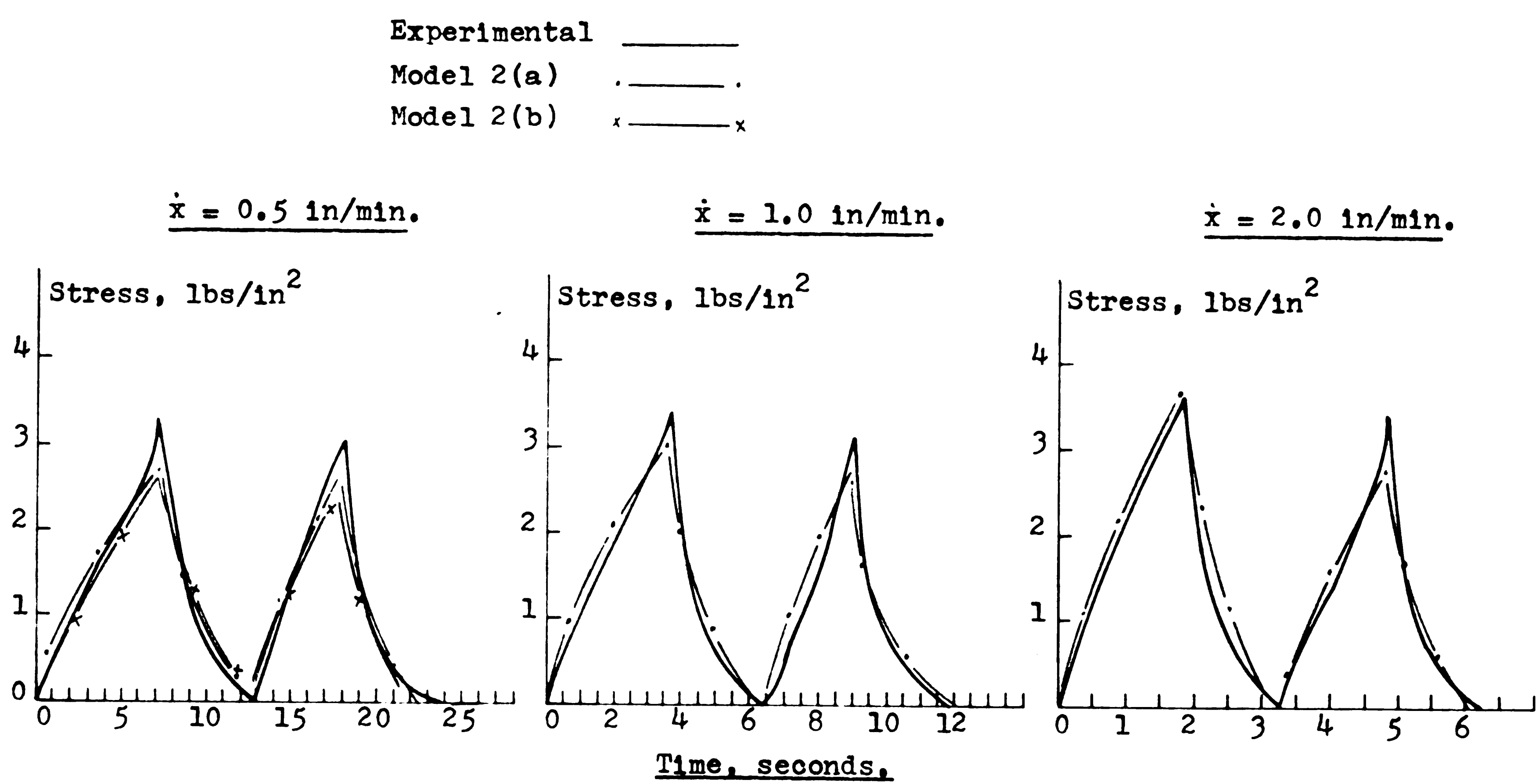


Figure 35. Experimental results and theoretical predictions for cyclic tests - 80°F., 92% R.H.

Influence of Water Activity on Model Parameters

Two different methods were used for calculating mean parameters. One approach used for the parameters estimated from relaxation data involved the determination of a mean relaxation response at each water activity. From the mean curve thus obtained, optimum mean parameter values were estimated using the GAUSHAUS non-linear estimation procedure. Parameter estimates were also made from each individual curve. The coefficients estimated in this manner included E_1, E_3, τ_1 and τ_3 in Model 1, and A, B and λ in Model 2(a).

The second approach merely estimated the arithmetic mean of fifteen values for each parameter at every water activity, using experimental cyclic results. In addition to C in Model 2(a), all four parameter means in Model 2(b) were calculated by this method.

Analysis of variance tests revealed that water activity levels had a significant effect, at the 99% confidence level, on every parameter except λ in Model 2(b), (Tables A-2, A-4, A-6). This conclusion could be anticipated from the large decrease in parameter values at the higher equilibrium relative humidities, particularly at 92%.

Mean parameter values for the various models are presented in Tables 2, 3 and 4; all parameter estimates are presented in the Appendix (Tables A-9, A-10 and A-11).

The general trend is one of decreasing parameter values with increasing moisture content. At the lower water

TABLE 2. Model 1 : Parameter values estimated from mean relaxation data.

R.H.	15%	30%	50%	70%	92%
E_1	112.6	109.1	94.2	81.3	25.0
E_3	402.6	351.0	249.3	132.3	13.2
η_1	64760	55474	55052	6375	2494
η_3	1819.6	2023.2	672.9	412.1	37.8

TABLE 3. Model 2(a) : Mean parameter values; A, B, λ, estimated from relaxation data; C from cyclic test data.

R.H.	15%	30%	50%	70%	92%
A	79.2	73.9	63.5	38.3	9.7
B	28.5	31.0	27.0	38.9	13.3
λ	10.63	11.36	4.85	4.09	4.53
C	37.5	16.9	30.0	23.2	6.9

TABLE 4. Model a(b) : Mean parameter values estimated from cyclic test data.

R.H.	15%	30%	50%	70%	92%
A	72.8	55.0	53.9	41.0	13.2
B	164.0	91.0	107.9	87.0	10.8
λ	2.52	3.53	2.69	2.65	3.72
C	34.0	22.9	25.6	20.0	4.9

activities relatively little change is evident, but any statistically significant differences between means indicate that the parameter value at the lower equilibrium relative humidity is higher than the corresponding parameter value at the next highest a_w. Dunnett's supplementary test was applied to all means to determine statistically significant differences. The results of this analysis are also presented in the Appendix (Tables A-3, A-5, A-7).

The main inconsistent difference of statistical significance was C at 0.30 in Model 2(a). The explanation for the low value in this instance is that A, B and λ had been previously computed from the relaxation tests. An examination of and comparison between the relaxation and cyclic test results at 0.30 and 0.50 water activities will show that the relaxation response for 0.50 is 10% to 15% lower than that at 0.30. Statistical analysis confirmed significant differences between both of these responses (Table A-5). Yet the cyclic results at these water activities were quite similar.

Use of A, B, and λ calculated from the relaxation experiment to determine C in Model 2(a) from cyclic data meant that the relaxation differences must be compensated for when fitting the model to the cyclic results. Accordingly, since B at 0.30 estimated from relaxation was much higher than B at 0.50, the corresponding values for C estimated from cyclic results should differ in the opposite direction. Again, this was the case and was supported by statistical analysis. Dunnett's supplementary test confirmed the similarity between cyclic results at 0.30 and 0.50 water activity, there being no significant difference between Model 2(b) constants at these two levels.

The trends noted in the results up to 0.50 water activity are not in complete agreement with Kapsalis (1967) or Reidy and Heldman (1970) who both found that for pre-cooked freeze-dried beef, hardness increased slightly with water activity level up to 0.5 - 0.6. At higher water activities, the values decreased significantly. The latter trend is definitely confirmed by the results which also suggest that further research concentrated at water activities of 0.5 - 1.0 is warranted, to more precisely define the magnitude of change occurring in hardness of the product at different intervals in this water activity range. Similarly, further research should also be carried out to confirm texture changes which occur in the a_w range of 0.0 - 0.5. Kapsalis (1967) and Reidy and Heldman (1970) did not illustrate that statistically significant differences existed between individual means at the lower equilibrium relative humidities, but based their conclusions on the trend of the means. The increase in toughness found by Kapsalis (1967) was only very slight from one level to another, whereas the results of Reidy and Heldman (1970) show considerable deviation between samples at any one water activity. It would appear therefore that the results included in this report neither confirm or contradict previous work at lower water activities. They might more appropriately lead to the conclusion that toughness of pre-cooked freeze-dried beef is affected very little by increasing equilibrium relative humidity up to 50% but decreases significantly for water activities greater than that.

The smaller stresses required to deform the samples at higher moisture contents could be due to the adsorbed moisture being less tightly bound. Being relatively loose, this moisture might bring about a lubricating effect on the product components when subjected to externally applied stresses. Kapsalis' (1967) suggestion that cross-linking, which occurs to a greater extent above 20% R.H., has a toughening effect on meat could possibly explain the relatively stable values of hardness and chewiness found at 30% and 50% R.H.

It is interesting to note from Figure 36 that the changes which occur in hardness of the product as equilibrium relative humidity increases, are almost inversely related to the isotherm especially at a_w greater than 0.50. This would suggest that textural changes in the product may be closely related to water binding properties. As previously suggested however, further research is required to establish precisely the textural changes occurring at moisture contents below the monomolecular layer level i.e. corresponding to 20% - 25% equilibrium relative humidity.

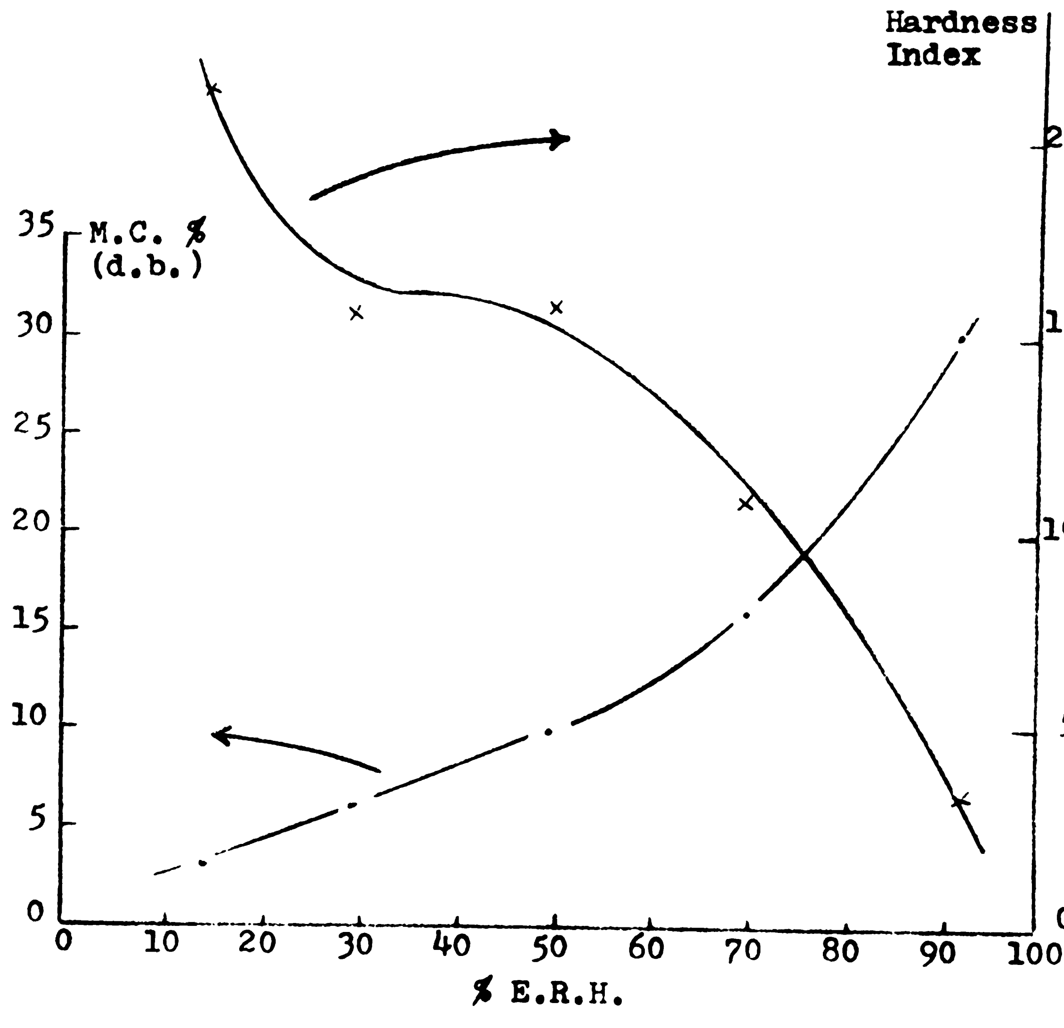


Figure 36. Moisture content and Hardness Index vs. Equilibrium Relative Humidity for pre-cooked freeze-dried beef at 80°F.

Use of the Models to Predict Texture Parameters

As previously discussed, Model 1 failed to predict stress-strain behavior for cyclic loading conditions and consequently was inadequate for predicting texture. The poor comparison between actual and predicted texture indices is evident from Figures 37 and 38.

However, an accurate linear relationship appears to exist between chewiness and hardness :

$$C = (0.59)H + 3.61 \qquad (44)$$

where C represents chewiness and H hardness. Therefore if a correlation exists between any model parameter value and hardness, it would be possible to arrive at reasonable estimates for both texture parameters.

For example, use of the free spring element (E_1) in Model 1, to predict hardness gives values of 16.9, 16.4, 14.1, 12.2 and 3.8 compared to 21.3, 15.6, 15.8, 10.9 and 3.4 respectively, (Figure 39). None of the other parameters (E_3, η_1, η_3) in Model 1 show a consistent relationship with either chewiness or hardness. The values of η_1 change in a relatively similar manner to hardness values between 15% and 50% E.R.H. but at higher relative humidities the large decrease in magnitude is not consistent with changes in texture.

Model 2 satisfactorily predicts cyclic response and therefore the texture profile from which hardness and chewiness are estimated. Any of the other texture parameters

Table 5. Mean experimental and predicted values for texture paramaters, hardness and chewiness.

R.H.		Hardness	Chewiness
15%	Model 1	5.1	4.7
	Model 2(a)	18.5	19.4
	Model 2(b)	22.5	19.6
	Experimental	21.3	18.7
30%	Model 1	4.2	3.8
	Model 2(a)	17.3	15.6
	Model 2(b)	16.3	13.6
	Experimental	15.6	13.1
50%	Model 1	5.5	5.3
	Model 2(a)	13.7	12.0
	Model 2(b)	16.5	13.4
	Experimental	15.8	13.8
70%	Model 1	4.0	3.9
	Model 2(a)	9.8	8.3
	Model 2(b)	12.8	11.7
	Experimental	10.9	9.1
92%	Model 1	1.2	1.0
	Model 2(a)	3.1	2.6
	Model 2(b)	3.1	2.8
	Experimental	3.4	2.9

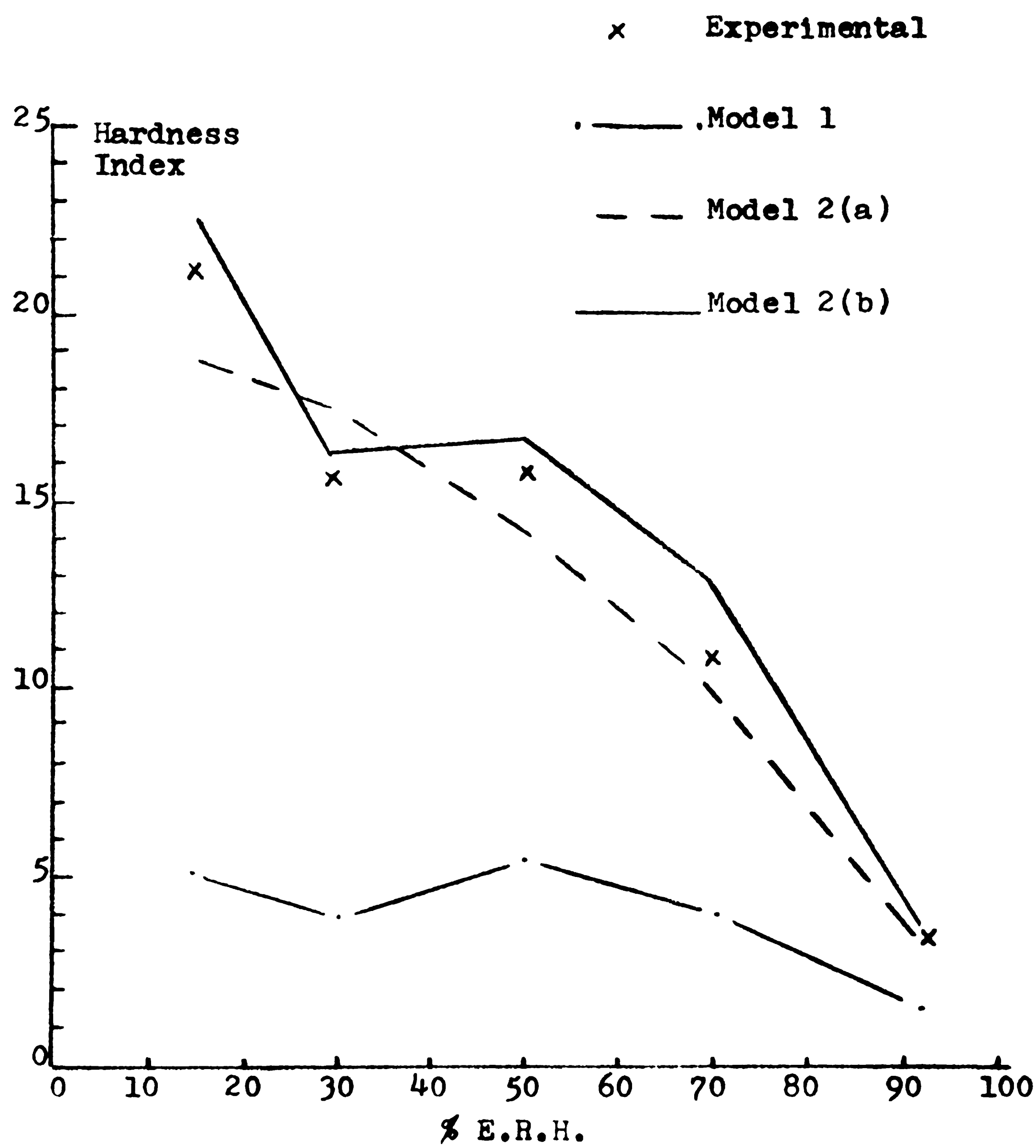


Figure 37. Mean experimental and predicted values of texture - Hardness Index.

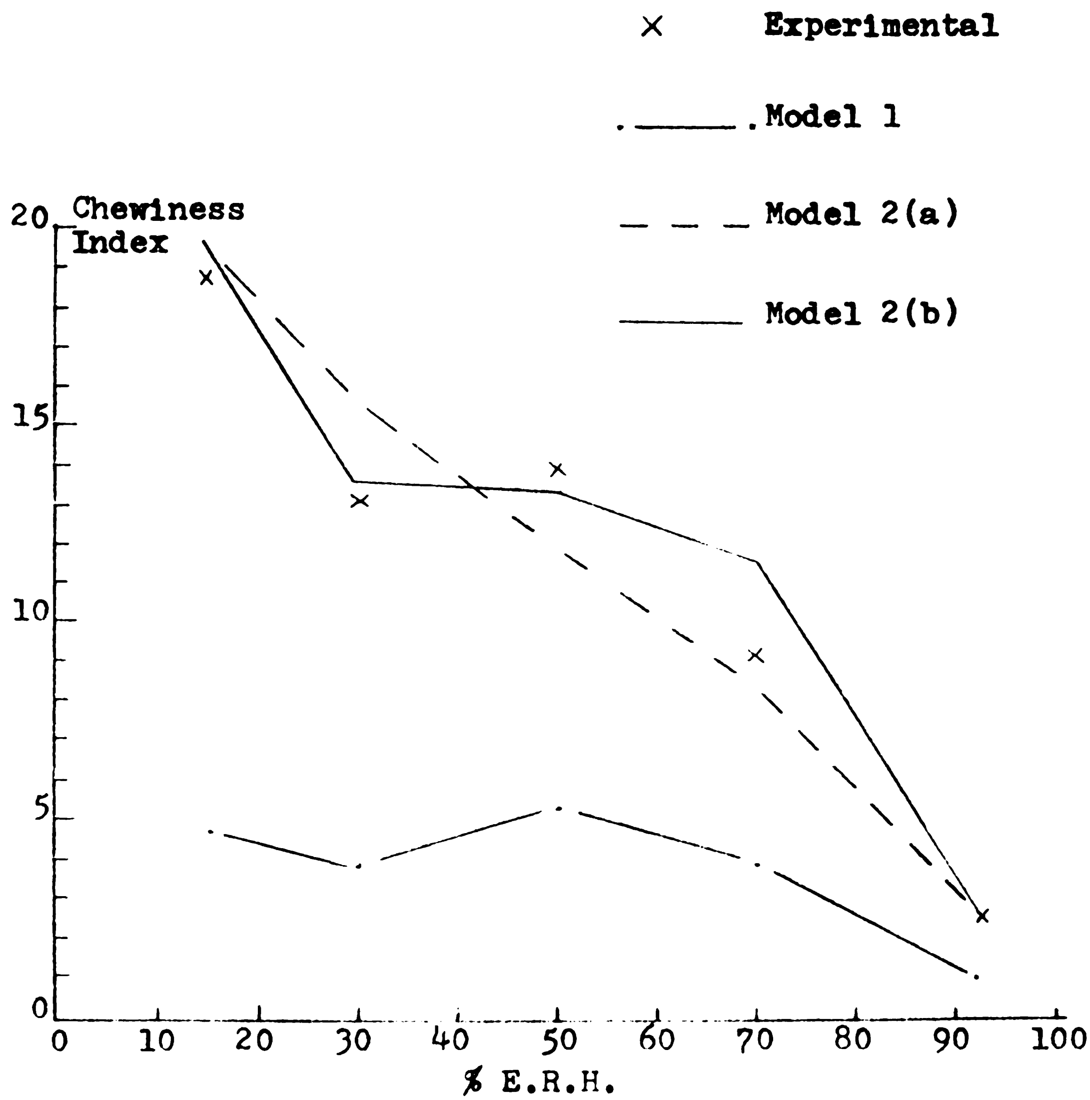


Figure 38. Mean experimental and predicted values for texture - Chewiness Index.

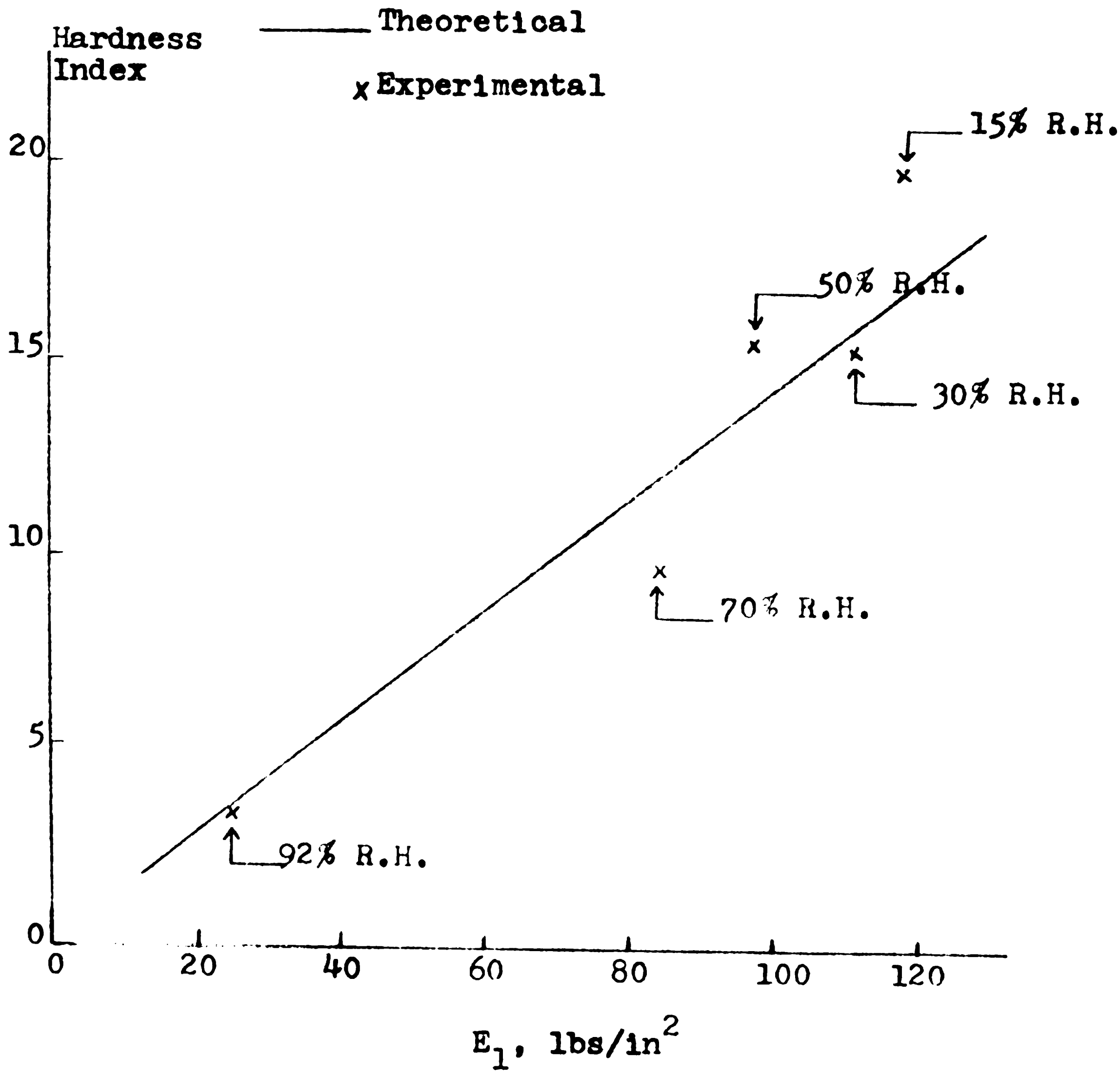


Figure 39. Comparison of experimental values of the Hardness Index with theoretical values predicted by the free spring (E_1) in Model 1.

suggested by Szczesniak, et al (1963) can also be found from the profile predicted by Model 2. The better predictions of Model 2(b) compared to 2(a) (Figures 37 and 38) can be attributed to the fact that all of the model constants in 2(b) were evaluated from cyclic data. The fact that this model - 2(b) - can also give satisfactory predictions for three different tests, yet utilizes only one of them for parameter estimation, makes it particularly attractive.

The parameter A in Model 2(a) could possibly be used to give an approximation of hardness since the relative ratios at various water activities are similar to hardness ratios. The value predicted for hardness at 30% E.R.H. would be too high, again on account of the poor agreement between the relaxation and cyclic behavior frequently referred to. None of the other parameters in Model 2(a), used individually, could be used to indicate texture.

To predict textural parameters using Model 1 and Model 2 it is necessary to consider the total equations (5) and (12), and not merely any one or two terms. The magnitude of some terms, however, have more influence on hardness and chewiness than others. In Model 1, a relatively weak free spring i.e. a low value for E_1, will result in very low hardness values because most of the strain will occur in this element. Little energy will be absorbed and therefore the stress response for the second compression cycle will be very similar to that for the first cycle.

Should the free spring be strong, however, the strain will occur in either the dashpot or the Kelvin part of the model, depending on the relative strength of these elements. For example, if the viscosity value, η_1, of the dashpot is low, then more deformation will occur through this element. Since the dashpot absorbs energy, the stress in the second and subsequent compression cycles will be much lower than for the first cycle, and consequently the chewiness index will be lower than if the model had a stronger free dashpot.

In Model 2, both A and C are the parameters most influencing hardness. The term $(B \epsilon e^{-t/\lambda})$ will largely determine the quantity of energy absorbed. The magnitude of (λ) will determine how fast the energy in this whole term is absorbed, and therefore will seriously affect chewiness values.

It should be emphasized however, that no single parameter in either model can independently predict either the hardness or chewiness indices.

CHAPTER VI

CONCLUSIONS

1. A four element linear viscoelastic model (Model 1) of Kelvin and Maxwell bodies in series, successfully predicted relaxation functions of the freeze-dried product. Using parameter values estimated from relaxation data, the model gave satisfactory predictions of creep strain at water activities of 0.15, 0.30 and 0.50. Use of the same parameter estimates failed to satisfactorily predict cyclic behavior. Therefore the model is inadequate for predicting product texture.

2. An empirical constitutive equation (Model 2) which contained a probable non-linear term satisfactorily predicted responses to relaxation, creep and cyclic tests. This model accurately predicted the texture indices of hardness and chewiness.

3. The cyclic test as used on the Instron testing machine to objectively evaluate food texture can also be used to estimate engineering coefficients which allow accurate relaxation and creep functions for the food to be predicted.

4. The most accurate overall predictions of stress-strain behavior was achieved by using both relaxation and

cyclic test data to estimate parameter values of Model 2.

5. Mean relaxation stresses decreased consistently with increasing water activity.

6. Resultant stresses from cyclic deformation experiments decreased from 0.15 to 0.30 water activity; remained relatively constant at water activities of 0.30 and 0.50, and decreased at water activities greater than 0.50.

7. Statistical analysis revealed that water activity has most influence on the stress-strain behavior of pre-cooked freeze-dried beef at water activities above 0.50. Resistance to deformation decreases at higher moisture contents.

8. Location in the muscle from which samples were taken had no influence on the parameter values in Model 1 and Model 2.

9. The use of impact tests failed to establish any relationship between energy absorbed and water activity or texture of pre-cooked freeze-dried beef at 80°F.

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APPENDIX

TABLE A-1. Analysis of vaiance in energy absorbed.

Source	d.f.	SS	MS	F-ratio
Water activity	4	0.0092	0.0023	1.53
Muscle location	4	0.0200	0.0050	3.34*
Experimental Error	16	0.0243	0.0015	

*F(.95,4,16) = 3.01

TABLE A-2. Analysis of variance in parameter estimates of Model 1.

	Source	D.F.	SS	MS	F-ratio
E_1	Water activity	4	23197.5	5799.4	21.29**
	Muscle location	4	1086.6	271.7	1.00
	Experimental Error	16	4357.7	272.4	
E_3	Water activity	4	674872.1	168718.0	13.17**
	Muscle location	4	43843.7	10961.9	0.86
	Experimental Error	16	205049.2	12815.6	
η_1	Water activity	4	8188×10^6	2047×10^6	53.98**
	Muscle location	4	410×10^6	102×10^6	2.70
	Experimental Error	16	607×10^6	37.9×10^6	
η_3	Water activity	4	119×10^5	29.8×10^5	9.44**
	Muscle location	4	107×10^4	26.7×10^4	0.84
	Experimental Error	16	5.1×10^6	3.2×10^5	

**F(.99,4,16) = 4.77

TABLE A-3. Summary of Dunnett's test Model 1.

E_1

E.R.H. Means				
15%				
	-			
		*		
30%				
	-		*	
		*		*
50%				
	-		*	
		*		
70%				
	*			
92%				

E_3

15%				
	-			
30%		-		
	-		*	
50%		*		*
	*		*	
70%		*		
	-			
92%				

η_1

15%				
	-			
30%		-		
	-		*	
50%		*		*
	*		*	
70%		*		
	*			
92%				

η_3

30%				
	-			
15%		-		
	-		*	*
50%		*		
	-		*	
70%		*		
	-			
92%				

Note

* = 95%, significant difference.

TABLE A-4. Analysis of variance in parameter estimates of Model 2(a).

	Source	d.f.	SS	MS	F-ratio
B	Water activity	4	1415	354	10.14**
	Muscle location	4	127	32	0.91
	Experimental Error	16	558	35	
A	Water activity	4	16,459	4115	26.79**
	Muscle location	4	529	132	0.86
	Experimental Error	16	2,457	154	
λ	Water activity	4	200	50	24.52**
	Muscle location	4	8.8	2.2	1.08
	Experimental Error	16	33	2	
C	Water activity	4	8,780	2195	23.55**
	Muscle location	4	925	231	2.48
	Experimental Error	66	6,151	93	

**F(.99,4,66) = 3.63

**F(.99,4,16) = 4.77

TABLE A-5. Summary of Dunnett's test Model 2(a).

A

E.R.H. Means				
15%				
	-			
30%		-		
	-		*	
50%		*		*
	*		*	
70%		*		
	*			
92%				

B

70%				
	-			
30%		-		
	-		*	
15%		*		*
	-		*	
50%		*		
	*			
92%				

λ

30%				
	-			
15%		*		
	*		*	
50%		*		*
	*		*	
70%		*		
	-			
92%				

C

15%				
	*			
50%		*		
	-		*	
70%		*		*
	-		*	
30%		*		
	*			
92%				

Note

* = 95%, significant difference.

TABLE A-6. Analysis of variance in parameter estimates of Model 2(b).

	Source	d.f.	SS	MS	F-ratio
A	Water activity	4	29,760	7,440	84.25**
	Muscle location	4	491	123	1.39
	Experimental Error	66	5,829	88	
B	Water activity	4	179,636	44,909	11.05**
	Muscle location	4	17,072	4,268	1.05
	Experimental Error	66	268,246	4,064	
λ	Water activity	4	18.6	4.64	1.26
	Muscle location	4	5.5	1.37	0.37
	Experimental Error	66	242	3.7	
C	Water activity	4	6,795	1,699	82.17**
	Muscle location	4	169	42.3	2.05
	Experimental Error	66	1,365	20.7	

$^{**}F(.99,4,66) = 3.63$

$^{*}F(.95,4,66) = 2.52$

TABLE A-7. Summary of Dunnett's test Model 2(b).

A

E.R.H. Means				
15%				
	*			
30%		*		
	-		*	
50%		*		*
	*		*	
70%		*		
	*			
92%				

B

15%				
	*			
50%		*		
	-		*	
30%		-		*
	-		*	
70%		*		
	*			
92%				

λ

92%				
	-			
30%		-		
	-		-	
50%		-		-
	-		-	
70%		-		
	-			
15%				

C

15%				
	*			
50%		*		
	-		*	
30%		*		*
	-		*	
70%		*		
	*			
92%				

Note

* = 95%, significant difference.

TABLE A-8. Impact test results : energy absorbed, ft.-lb.

Muscle Location

E.R.H. %	1	2	3	4	5
15	.102	.207	.188	.054	.206
30	.194	.234	.165	.254	.234
50	.222	.278	.212	.237	.233
70	.201	.239	.167	.246	.221
92	.168	.185	.184	.213	.183

TABLE A-9. Parameter values of Model 1.

Muscle Location		E.R.H. % 15	30	50	70	92
E_1	1	102.42	101.74	88.39	56.95	22.42
	2	89.69	126.36	69.80	-	28.83
	3	140.00	97.92	66.64	75.42	39.56
	4	124.36	120.37	103.02	104.73	18.62
	5	98.36	100.27	112.35	85.76	25.65
E_3	1	355.36	314.16	322.11	86.38	20.82
	2	284.29	474.70	266.82	-	28.80
	3	814.33	315.22	249.33	110.57	46.03
	4	499.05	463.52	494.69	143.19	20.40
	5	346.34	339.14	368.43	112.86	26.59
η_1	1	40446.3	36790.1	51614.97	8549.2	1826.3
	2	36180.2	50644.2	35559.1	-	2547.7
	3	33240.1	36543.5	35478.7	13689.5	3857.9
	4	59143.7	50786.1	52564.1	16862.4	1928.4
	5	41749.0	40061.7	51896.5	13332.5	2297.8
η_3	1	1363.6	1594.7	1031.1	318.9	72.0
	2	676.1	2193.6	1069.0	-	97.7
	3	3611.2	1495.3	1007.4	430.6	116.9
	4	1699.8	2325.8	1497.7	469.9	45.6
	5	957.3	1648.7	1036.1	354.6	67.9

TABLE A-10. Parameter values of Model 2(a).

	Muscle Location	E.R.H. % 15	30	50	70	92
A	1	69.7	66.6	64.1	26.9	8.1
	2	60.7	86.7	49.9	39.5	10.8
	3	109.2	64.9	47.8	37.4	12.0
	4	88.9	83.5	72.5	50.2	7.7
	5	67.9	67.8	77.9	40.5	9.8
B	1	27.7	31.0	21.2	25.4	12.8
	2	23.4	34.2	17.1	25.2	15.8
	3	37.7	29.0	16.4	33.9	14.5
	4	29.5	32.2	25.8	48.4	9.9
	5	24.7	28.5	29.1	40.3	13.7
λ	1	10.57	10.69	6.89	7.26	4.03
	2	8.06	12.22	9.66	1.65	4.63
	3	12.78	10.84	9.01	5.55	6.14
	4	10.51	12.26	8.44	4.71	3.14
	5	9.65	10.73	7.19	4.42	4.19
C (0.5"/min)	1	41.5	13.5	39.4	10.6	6.2
	2	39.7	15.7	38.1	21.0	8.8
	3	33.7	1.8	19.7	10.0	7.9
	4	46.1	38.4	35.9	14.1	6.0
	5	61.8	18.0	50.0	23.8	6.0

TABLE A-10. (continued).

	Muscle Location	E.R.H. % 15	30	50	70	92
C (1.0"/min)	1	27.1	16.7	14.0	25.6	4.4
	2	39.5	4.2	29.7	35.5	9.5
	3	20.2	1.8	30.8	10.0	1.1
	4	27.1	44.2	19.5	24.7	4.3
	5	43.8	7.8	22.2	23.1	12.3
C (2.0"/min)	1	46.9	41.1	31.0	25.3	7.2
	2	36.0	11.5	41.2	32.3	0.4
	3	39.6	6.5	25.5	12.8	3.2
	4	36.6	21.9	18.1	19.8	6.6
	5	22.6	3.0	17.5	19.1	1.0

TABLE A-11. Parameter values of Model 2(b).

	Muscle Location	E.R.H. % 15	30	50	70	92
A (0.5"/min)	1	80.7	50.1	62.9	27.2	12.5
	2	59.8	62.8	64.6	33.6	14.7
	3	74.4	44.0	49.7	26.4	12.7
	4	80.4	70.9	52.3	33.8	11.0
	5	84.3	42.6	64.5	39.1	11.0
A (1.0"/min)	1	58.7	57.6	47.7	41.3	9.2
	2	71.8	47.2	55.1	49.9	14.9
	3	55.1	58.1	55.0	29.9	8.1
	4	77.1	51.9	48.8	44.9	8.1
	5	81.9	33.0	44.4	28.1	18.2
A (2.0"/min)	1	91.4	73.1	60.0	43.3	15.3
	2	62.9	43.6	75.9	56.8	15.5
	3	64.3	59.3	50.1	39.9	16.5
	4	85.1	73.3	43.0	45.0	17.7
	5	63.6	55.0	46.6	49.9	-
B (0.5"/min)	1	222.1	18.5	93.5	44.6	-
	2	108.2	26.3	227.0	79.2	-
	3	189.1	114.2	30.3	62.6	9.6
	4	204.0	175.9	166.2	49.7	16.6
	5	401.7	27.8	263.2	84.2	7.8

TABLE A-11. (continued).

	Muscle Location	E.R.H. % 15	30	50	70	92
B (1.0"/min)	1	53.4	122.7	24.8	159.4	11.0
	2	130.5	25.1	80.7	110.8	18.4
	3	36.1	59.2	81.0	77.2	10.1
	4	213.1	40.3	68.7	87.9	6.8
	5	156.6	127.0	114.7	77.2	10.2
B (2.0"/min)	1	117.5	294.4	59.3	80.2	7.8
	2	166.5	53.4	175.2	132.4	7.8
	3	236.9	18.1	69.5	36.0	16.8
	4	67.1	47.3	121.0	91.6	17.7
	5	157.8	136.1	43.2	137.4	-
λ (0.5"/min)	1	3.25	8.01	4.95	3.78	-
	2	5.27	3.16	3.26	3.98	-
	3	3.54	4.06	6.16	3.28	3.50
	4	3.96	4.11	3.98	3.71	3.40
	5	3.05	7.95	3.75	11.02	4.49
λ (1.0"/min)	1	4.29	3.64	3.40	1.47	2.32
	2	2.63	3.52	2.71	1.81	2.27
	3	3.20	3.57	2.52	1.67	1.66
	4	1.86	3.87	2.24	1.74	5.72
	5	2.07	2.20	2.17	2.32	2.45

TABLE A-11. (continued).

Muscle	Location	E.R.H. % 15	30	50	70	92
A (2.0"/min)	1	1.26	0.79	1.51	1.52	4.84
	2	1.25	2.54	0.67	0.77	2.46
	3	1.28	1.48	1.09	1.00	7.05
	4	0.06	1.08	0.96	0.79	4.50
	5	0.90	2.92	0.99	0.88	-
C (0.5"/min)	1	32.6	25.2	32.5	14.5	6.6
	2	39.9	16.9	26.3	19.4	8.3
	3	27.6	21.9	23.5	13.6	7.6
	4	34.5	30.7	29.1	15.2	5.7
	5	42.7	23.7	32.6	17.9	6.1
C (1.0"/min)	1	30.8	25.8	21.0	22.3	6.0
	2	34.9	18.2	28.3	29.6	8.0
	3	31.4	15.3	30.1	14.3	3.7
	4	35.5	22.5	23.1	22.7	6.1
	5	37.0	18.8	23.5	17.3	10.4
C (2.0"/min)	1	38.6	33.3	24.8	22.4	0.0
	2	30.3	21.8	29.0	27.2	0.0
	3	27.6	18.8	24.1	18.3	0.0
	4	41.1	27.5	16.2	21.1	0.0
	5	25.4	23.3	20.2	24.5	-