THERMAL DIFFUSIVITY BY FINITE DIFFERENCES AND CORRELATION WITH PHYSICAL PROPERTIES OF HEAT TREATED POTATOES

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ABSTRACT

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Accurate information on the thermal properties of a vegetable is needed to establish the energy requirements of a particular heating or cooling process. In the freezing region of a few vegetables, some of the thermal properties have been determined. In the heating and cooking regions, these properties have not been determined in terms useful for engineering design parameters. Therefore, an investigation was made of the variations in thermal diffusivity of a potato section from the raw state to the cooked state. Physical properties were also evaluated to determine correlations with thermal diffusivity.

In the cooling and freezing region of vegetables, previous investigators have used the guarded hot plate method or the Cenco-Fitch apparatus to determine thermal properties. The guarded hot plate requires considerable time and involves a steady state heat transfer process. The Cenco-Fitch apparatus involves a rapid transient heat process with errors of approximately 5% or larger.

In the procedure used, a heated cylinder of silicone rubber or steel was placed in direct contact with a

cylindrical section of Excel potato (Solanum tuberosum). The temperature history at X = 0 and at X = L of a given length of the potato section was used to calculate the thermal diffusivity by a finite difference method. Thermal diffusivities were determined at the beginning and ending of each heat treatment. After the thermal diffusivity was determined, the calculated and the measured temperatures at X = L differed by a root mean square value of 0.43°F.

Simultaneous recordings of temperatures at X = 0 and X = L permitted a measurement of the temperature-time area between the 160°F line and higher temperatures up to 215°F. The degree-minute area was related to the heat exposure of the potato section and was a parameter of the study. Specific gravity was determined for the raw potato sections. Elastic modulus was determined for both the raw and heat treated potato sections.

The following results were obtained:

1. The thermal diffusivity of the potatoes decreased during a 15-day storage at 40°F.

2. The specific gravity of the raw potato sections was not related to the 15-day storage, thermal diffusivity, or elastic modulus.

3. As heat exposure increased, thermal diffusivity increased up to a maximum and then decreased.

4. The addition of heat to the potato section initially increased the elastic modulus. As cooking progressed,

the elastic modulus decreased rapidly.

5. A rapid decrease in the elastic modulus of the potato sections was accompanied by the maximum increase in the thermal diffusivity.

Approved *Carl W. Hall*
Major Professor
and Department Chairman

Nov. 28, 1966
Date

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By

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Keith

Bruce

Craig

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NOMENCLATURE

Abbreviations

Btu	British thermal units
°F	degrees Fahrenheit
ft	feet
in.	inches
lb_f	pounds force
lb_m	pounds mass
min	minutes
psi	pounds/inch^2
rms	root mean square
sec	seconds

Greek Symbols

α	thermal diffusivity (ft^2/hr)
ρ	density (lb_m/ft^3)
Δ	small increment

Letter Symbols

A	area (ft^2)
c	specific heat (Btu/(lb_m °F))
E	elastic modulus (psi)
F	force (lb_f)
HE	heat exposure (°F-min)

k	thermal conductivity ((Btu ft$_{\parallel}$)/(hr ft$^2_{\perp}$ °F))
M	a dimensionless number defined by equation (3.5)
n	node number
q_m	internal heat generation (Btu/(hr))
T	temperature (°F)
t	time (min or sec)
X	coordinate axis distance (in)
Y	coordinate axis distance (in)
Z	coordinate axis distance (in)

Subscripts

$\parallel$	distance measured parallel to the vector of a quantity
$\perp$	distance measured perpendicular to the vector of a quantity

1. INTRODUCTION

When designing a heating or cooling process for a vegetable, one must make an energy balance of the system and calculate the net energy requirements. An energy balance equates energy losses and consumption to energy input. To determine the net energy requirements, the vegetable can be treated as an engineering material. The thermal properties of the vegetable should be known over the operating range of the process. To calculate net energy requirements, one can estimate the values of thermal properties and also assume that these properties remain constant during the heating or cooling process. With the present development of the science of heat transfer, an engineer should not have to rely on these estimates and assumptions. Hence, the objective of this research was to define and evaluate the engineering parameters that influence the thermal properties of a vegetable.

The thermal properties considered in this research are thermal conductivity, specific heat, density, and thermal diffusivity. The physical properties considered are specific gravity and elastic modulus. Researchers have determined relationships between the specific gravity of potatoes and other physical properties.

The elastic modulus of a heated potato specimen was used as an indication of the degree of cooking or processing. The elastic modulus was used because of its previous use in work on potatoes (Finney, 1963).

Blanching is a heat process used by food processors to inactivate enzymes in vegetables. Food scientists and others have found that enzymes can be inactivated if the vegetable is held for a specified time in a heating medium that is maintained at a given temperature (Tressler and Evers, 1957; Melnick, Hochberg, and Oser, 1944). But to the engineer, these specifications do not describe the energy balance or the heat requirements of the system. The engineer must know the mass rate (lb_m/hr) of vegetables to be blanched, the initial and final temperatures of the vegetables, and the thermal properties of the vegetables. The food researchers have defined an end point in terms not amenable to engineering solutions.

While being heated, the vegetable changes from a raw state to a partially cooked state and the physical properties are changed (Finney, 1963; Personius and Sharp, 1938; Simpson and Halliday, 1941; Weier and Stocking, 1949; Crafts, 1944; Kaczmarzyk, Fennema, and Powrie, 1963). Would not the thermal properties also change under such conditions? A correlation between thermal properties and physical properties would enable an engineer to obtain thermal properties with a minimum of equipment and time. With accurate values of thermal and physical properties of a vegetable, an engineer could apply an energy balance to heating and cooling processes. Thus he could design more efficient equipment and production facilities for the food processing industry. Properly designed facilities would reduce the investment in over-sized equipment and reduce the hazards of inadequate facilities. As the size, complexity, and competition of the food processing industry increases, a carefully engineered production facility becomes imperative.

The change in thermal conductivity of metals with temperature is well known and is described by a simple equation (Schneider, 1955). Because a vegetable undergoes physical and chemical changes during the heat treatments, one might reasonably expect its thermal properties to change not only with temperature but with other factors.

Heating processes for vegetables are usually transient processes. The temperature difference between the vegetable and the heating medium changes with time and theoretically the vegetable does not reach the temperature of the heating medium. Steady state processes are denoted by a constant temperature difference or gradient between the heating medium and the product. Some researchers have used a guarded hot plate, a steady state device, to determine the thermal conductivity of meat (Miller and Sunderland, 1963). Others have used a modified Cenco-Fitch apparatus, a transient state device, to determine the thermal conductivity of meats, fruits, and vegetables (Walters and May, 1963; Bennett, Chace, and Cubbedge, 1962, 1964). The disadvantage of the guarded hot plate is that the transient process found in industrial practice is not duplicated. The modified Cenco-Fitch duplicates the transient process but is subject to errors of approximately 5% (Bennett, Chace, and Cubbedge, 1962; Wing and Monego, 1959). When the thermal and/or physical properties of a vegetable vary with the heat absorbed, one must use other means to determine them.

The research described in this thesis utilized a transient process in which the heat received by the potato was related to heat exposure. The method involved the transfer of heat through a finite length of a semi-infinite cylinder of a potato specimen. The method of finite differences was used to make the thermal diffusivity calculations.

Equally as important as the quantitative results of the research was the development of equipment and procedures for determining the thermal properties of foods in the solid state. The same principles have been used to determine the thermal properties of metals (Beck, 1963). The advantages of this transient process over the methods using the guarded hot plate or the Cenco-Fitch apparatus are discussed.

2. LITERATURE REVIEW

2.1 Thermal Properties

2.1a Thermal Conductivity

Eucken (1940) was probably the first to examine the thermal conductivity of a material composed of several substances. Eucken (1940) applied a formula, derived by Maxwell (1904), that expressed the thermal conductivity of a material as a function of the relative volumes and conductivities of the different particles of which a material is composed.

The following quotations from Long (1955) are descriptions of fish muscle as related to the theoretical equation of Maxwell-Eucken. "Briefly, the major component is water, in which are dissolved various inorganic salts, organic substances such as proteins and fats being dispersed through this medium, either in the form of an emulsion or in a colloidal state, the whole mass being held loosely together by connective tissue." "The fish muscle is considered to be, at any one temperature in the freezing zone, part ice, part salt solution of determinable concentration, and part protein. The thermal conductivity was calculated from the relative proportions of these constituents present at each of a number of temperatures."

Long used a specially designed cylindrical calorimeter with a heat source along the cylinder axis and a heat sink at the radius. Axial guard sections were used to eliminate end-losses; the heat flow was radial from source to sink. No analysis of errors was presented.

Long determined the thermal conductivity of fish muscle from 40°F to -15°F and compared the experimental results with the theoretical equation of Maxwell-Eucken. The resulting theoretical curve was well within the dispersion of the experimental data. The experimental thermal conductivity appeared to be constant between 30°F and 40°F. Below 30°F, the thermal conductivity increased as the temperature decreased.

Kethley, Cown, and Bellinger (1950) estimated the average thermal conductivities of some fruits and vegetables over the range of 80°F to 0°F. These authors were interested in the cooling of fruits and vegetables as a transient heat transfer process. Solid objects of food as well as canned foods were suddenly immersed in a cold constant temperature medium. After measuring the temperature history of the objects, Kethley *et al*. used the graphical method of Gurney and Lurie (1923) to determine the thermal diffusivity of the foods. (These temperature-time charts are now found in most conduction heat transfer textbooks; Eckert and Drake, 1959; Kreith, 1958; and Schneider, 1955.) For the specific heat of a fruit or vegetable, Kethley *et al*.

used an average apparent specific heat which was defined as "the quotient obtained by dividing by 80 the total Btu required to raise the temperature of one pound of the substance from 0°F to 80°F."

For the temperature interval of 80°F to 32°F, Kethley et al. (1950) found that the average thermal conductivities of strawberries, Irish potato flesh, English peas, and peach flesh ranged from 0.61 Btu/(hr ft^2°F)/ft thickness to 0.78 Btu/(hr ft^2°F)/ft thickness. No analysis of errors was given.

Lentz (1961) used a guarded hot plate apparatus to determine the thermal conductivity of several concentrations of gelatin gels from 5°C to -25°C. Gelatin gels were used because models of such material are frequently used in studying the effects of physical factors on cooling and freezing rates of foods. Using the guarded hot plate to determine the thermal conductivity of ice, Lentz obtained results that were reproducible to within ± 1%. The thermal conductivities of ice as determined with the guarded hot plate were about 1% lower than the most reliable values available. In experiments with heat flow both parallel and perpendicular to the grain of meat, Lentz (1961) also determined the thermal conductivities of several meats from 10°C to -25°C. Some of his conclusions were:

1. At temperatures above freezing, the thermal

conductivities of all the meats tested were about equal and about 10% below the established value for water.

2. Thermal conductivity curves for meat were all linear at temperatures below -10°C; the thermal conductivity increased as the temperature was decreased.

3. The thermal conductivity of meat did not appear to be directly related to moisture content or fat content.

4. Heat conduction was 15% to 30% greater along the fibers than across them.

Lentz (1961) also applied the Maxwell-Eucken equation to 6%, 12%, and 20% gelatin gel solutions to obtain a theoretical thermal conductivity. The theoretical and experimental values were in good agreement (-2.4% to +0.4% difference) for the 6% and 12% gel solutions but not for the 20% gel solution (+4.3% to +14.1% difference).

A tabular summary of thermal conductivities of meats and fats from published reports was given by Lentz (1961). Most of the thermal conductivities were from 0°C to -20°C. The increase of thermal conductivity with decrease in temperature was evident in all the results shown.

Bennett, Chace, and Cubbedge (1962) used a modified Cenco-Fitch apparatus to determine the thermal conductivity of samples of Marsh grapefruit rind and samples of Valencia orange rind. The National Bureau of Standards used a guarded hot plate to determine the thermal conductivity of the sample of silastic silicone rubber that Bennett _et al_. used for equipment calibration. The average error of the modified Cenco-Fitch apparatus was approximately 5% with variations from -2% to +13%.

The modified Cenco-Fitch apparatus used by Bennett _et_ _al_. consisted of a sample of orange rind held between a plate and a plug. The plate was maintained at a constant temperature during the test and the plug was initially at a lower uniform temperature. As the test progressed, the temperature of the plug increased due to the heat flow from the plate through the rind sample. Bennett _et_ _al_. (1962) found that the thermal conductivities were significantly lower for plate and plug temperatures of 212°F and 78°F respectively than the thermal conductivities obtained with plate and plug temperatures of 130°F and 78°F respectively. It was stated that the above variations showed the necessity for exercising care in selecting the optimum plate and plug temperatures. These variations could have been due to moisture lost from the sample in contact with the 212°F plate. Voids resulting from the loss of moisture would have an insulating effect and thus a lower value of thermal conductivity. No physical properties of the grapefruit or orange rinds were given in the report. Bennett _et_ _al_. did not consider the initial temperature of the rind samples.

The report of Bennett, Chace, and Cubbedge (1964) was a continuation of the research described in 1962. Bennett _et al_. altered the Cenco-Fitch apparatus to obtain a constant pressure on the samples during testing. Other modifications resulted in an equipment error of 2.68% as contrasted to the previous average of 5%. In addition to the experimental determinations of thermal conductivity of orange and grapefruit rind, Bennett _et al_. (1964) also experimentally determined the thermal conductivity of the juice vesicles of the fruit. By assuming that the rind and the juice vesicles comprised two concentric, hollow spherical shells, the authors derived an equation for the apparent thermal conductivity of the whole fruit. The calculated values of apparent thermal conductivity compared well with values that Bennett _et al_. found in the literature. In the discussion following the paper of Bennett _et al_., the authors noted relationships between specific gravity and thermal conductivity and between moisture content and thermal conductivity.

Miller and Sunderland (1963) used a guarded hot plate to determine the thermal conductivity of beef with heat transfer perpendicular to the grain. The guarded hot plate was calibrated with two materials of known thermal conductivities; agreement was within 0.5% and 1.35% of the known values. An analysis showed that the error in the results was less than ±2.75% and was quite possibly within ±1%. Miller and Sunderland (1963) used mean sample temperatures from 42°F to 2°F. Below 32°F the thermal conductivity of the beef increased as the temperature decreased. Above 32°F the thermal conductivity increased slightly as the temperature was increased. The last statement contradicts the results of Lentz (1961), but Miller and Sunderland used beef that had been previously frozen and whose moisture content was approximately 5.5% less than the beef used by Lentz. The results of Miller and Sunderland showed that the thermal conductivity of beef depended on temperature, moisture content, and direction of heat transfer.

Walters and May (1963) used a Cenco-Fitch apparatus to determine the thermal conductivity of chicken breast muscle and skin. The Cenco-Fitch apparatus was chosen because the test durations of 10 to 20 minutes would have less effect on the moisture content and physical properties of the chicken than the several hours required for each test when using a guarded hot plate. The equipment error of these authors was found to be 11.1% when the equipment was calibrated with a sample of material whose thermal conductivity had been determined by the National Bureau of Standards. Walters and May (1963) found no significant effect on thermal conductivity from variations in percent moisture or percent fat of the muscle and skin. The moisture content varied from 69.1% to 74.9% and the fat content was from none detected to 5.9%.

Charm (1963b) used an equation from Ball and Olson (1957) to derive expressions for determining the thermal conductivity of a finite cylinder of frozen material. The equation in Ball and Olson (1957) was based on heat penetration data. The thermal conductivity values obtained by Charm included the container with the material and were averaged over the range of the heat penetration data. The value of thermal conductivity obtained by such a method failed to reflect the change in thermal conductivity with temperature as had been noted by other authors. Even though the calculated error for thermal conductivity was 9.3%, Charm (1963b) stated that the values of thermal conductivity obtained for frozen codfish were in the range of previous literature values.

Parker and Stout (1966) calculated the thermal conductivity of cherry flesh from measurements of density, specific heat, and diffusivity of cherry flesh between 80°F and 40°F. The following equation was obtained by multiple correlation analysis:

$$k_{fl} = -0.275 - 0.0009SS + 0.280\,\rho_{fl} + 0.327c_{fl}$$

where k_{fl} is estimated flesh thermal conductivity (Btu/(hr ft °F))

SS is flesh soluble solids content (%)

ρ_{fl} is flesh density (gm/cc)

c_{fl} is flesh specific heat (Btu/(lb °F))

Standard error of k_{fl} was $\pm$ 0.0025 Btu/(hr ft °F) and the average k_{fl} for 20 samples was 0.298 Btu/(hr ft °F).

With respect to thermal conductivity and the objective of the research in this thesis, the following is concluded from the literature reviewed:

1. Determining the thermal conductivity of food products with the guarded hot plate
   a. does not duplicate the transient process found in industry,
   b. is of such duration that variations due to moisture content are not discernable, and
   c. the apparatus has an error less than 3%.
2. Determining the thermal conductivity of food products with the Cenco-Fitch apparatus
   a. duplicates the transient process,
   b. requires much less time than the guarded hot plate, but
   c. usually has errors larger than 3% and up to 5%.
3. Above freezing, the thermal conductivity of food products may vary with temperature, moisture content, specific gravity, direction of heat transfer, soluble solids, and specific heat.
4. During thermal conductivity tests, food products

should be subjected to constant pressure.

5. The graphical method of Gurney and Lurie (1923) and the method of Charm (1963b) do not account for influences of physical properties on thermal conductivity.
6. Approximately half of the authors did not make an error analysis.
7. Most authors checked the equipment with samples of known thermal conductivity.
8. No information was found on the thermal conductivity of vegetables or food products above 100°F except for the preliminary work of Bennett et al. (1962). Most investigations were concerned with the cooling and freezing range.
9. No one has reported any relationships between thermal conductivity and shear strength, compression strength, or elastic modulus of vegetables or food products.
10. Thermal conductivity as a function of heat exposure of a vegetable or food product has not been reported.

2.1b Specific Heat

The work of Siebel (1892) is the first reported on the specific heat of foods in which he considered food to be composed of water and solids. Above freezing, the specific heat of food was estimated as the percent of water times the specific heat of water plus the percent of solid matter times 0.2.

Short, Woolrich, and Bartlett (1942), using a specially constructed calorimeter, showed specific heat data on five vegetables, two fruits, fresh ham and fresh shrimp. The data covered the range from 70°F to -35°F. Above freezing, the data did not agree with the calculations proposed by Siebel. Most of the data above freezing showed that specific heat increased slightly as temperature increased.

Short and Bartlett (1944) improved the calorimeter and changed the procedure and calculations from that used by Short _et al_. (1942). Essentially, transient state data was averaged to a steady state condition and then used to calculate the specific heat of the fruits and vegetables. Thus, above freezing and up to 70°F, the specific heat was treated as being constant for all fruits and vegetables. The specific heats of various concentrations of sugar solutions were also constant for the same temperature range.

Using similar equipment, in the range of 40°F to -40°F, the findings of Staph (1949) agreed with the results of Short and Bartlett (1944); the specific heats of fruits and vegetables were constant above the freezing point. But from a few preliminary tests above freezing, Staph noted, "indications are that at temperatures above the freezing point the specific heat increases slowly with temperature rise." The author also stated that "data do not follow Siebel's rule since the specific heats of green beans, honeydew melons, and Bartlett pears are nearly the same and yet the water contents vary considerably. Pears have 79% water content, green beans 88%, and melons 93%." One objective of Staph was "to determine a relationship, if any, between heat capacity and water, fat, and water-soluble solids content." The results did not show the existence of a relationship that could be represented by an equation.

Kethley, Cown, and Bellinger (1950) determined an average specific heat or a specific heat factor of some fruits and vegetables. The quantity of heat required to raise one pound of the fruit or vegetable from 0°F to 80°F was determined. This quantity, in Btu, was then divided by 80 to obtain an average specific heat. Because the value for specific heat was an average, no factors were identified that influenced the specific heat of the fruits and vegetables. No comparison was made between the averaged values and the values obtained by other researchers or by other methods.

The work of Staph and Woolrich (1951) was a continuation of the studies reported by Short _et al_. (1942), Short and Bartlett (1944), and Staph (1949). Again, the calorimeter was modified and the results obtained between freezing and 70°F were different than those reported previously. The specific heat of carrots, turnips, green beans, and cauliflower between freezing and 70°F can be expressed with a quotation from Staph and Woolrich. "When the fusion point (of the vegetable) has been reached, the specific heat drops almost instantaneously to values about 1.0 to 0.90 Btu per lb per °F. From this point on (to 70°F) the specific heat decreases slightly with temperature rise, and in some cases begins to increase again with further temperature rise." Staph and Woolrich (1951) determined the water content, fat content, and water soluble solids content of the fruits and vegetables but did not make any correlation between these components and specific heat.

Riedel (1951) devised an elaborate calorimeter to determine the heat content of fruits and vegetables. The accuracy of the calorimeter was stated thusly: "After calibrating the calorimeter by electric heating, check tests made with pure water gave values for the specific heat of water and the latent heat of fusion of ice which agreed within 0.2 percent with the best data given in the literature." Riedel noted that most physical properties of fruit juices do not depend on the kind of fruits but on their dry substance content. The dry substance content of fruit juices was determined by measuring the refractive index of the juice at 20°C. Between 0°C and 20°C, the data of Riedel (1951) showed that the specific heat of juices of fruits and vegetables was a linear function of the dry substance content; the specific heat decreased as the dry substance content increased. The relationship was expressed by the equation

$$c_j = 1.00 - 0.57\, x_o$$

where: c_j is the average specific heat, 0° to 20°C.

x_o is the dry substance content, a decimal.

Riedel expressed the specific heat of a fruit or vegetable as the sum of the specific heat of the juice plus the specific heat of the insoluble dry substance content. From a series of tests, Riedel found that the specific heat of the insoluble dry substance was 0.29 and was sufficiently accurate for any temperature and any kind of fruit or vegetable.

Moline, Sawdye, Short, and Rinfret (1961) were interested in the specific heat of foods between the temperatures of -40°C and -160°C. Using a rather simple calorimeter, beef was simulated by a model composed of 17.6% protein, 18% fat, and 64.4% water. The measured values of the specific heat of the model were compared with the computed values based on the fractional concentration of the components. The computed values of Moline _et al_. were lower than the experimental values by a factor of 1.11 ± 0.03 $\left(= \frac{\text{experimental values}}{\text{computed values}}\right)$.

When natural meats were compared with the model, the computed values were lower than the experimental values by a factor of 1.14 ± 0.06. Thus the data indicated that the specific heat of frozen meat could be predicted with an average error of 4.4% and a maximum error of 10.5%. Based on Siebel's method of water content, the error would have been about 35%.

Charm (1963a) gave the following equation for estimating the specific heat of foods:

$$c_p = 0.5X_f + 0.3X_s + 1X_m$$

where: C_p is the specific heat

X_F is the mass fraction of fat

X_S is the mass fraction of solids

X_m is the mass fraction of moisture

The above equation does not account for the temperature dependence of specific heat as found by Staph (1949). Charm (1963a) did not cite any references for the equation.

To calculate the specific heat of frozen codfish in cans, Charm (1963b) stated that "the specific heat of many materials in the frozen state may be estimated from

$$C_p = 0.49m + 0.6F + 0.33[1-(m + F)]$$

where: C_p is the specific heat

m is fraction moisture in material and

F is fraction fat"

Again, no references were cited for the equation.

The only physical properties noted in the literature with respect to specific heat were water content and dry substance content. No information was found that considered or related shear strength, compression strength, or elastic modulus with the specific heat of foods or vegetables.

In the temperature range of 80°F to 40°F, Parker and Stout (1966) found that the specific heat of cherry flesh was related to soluble solids and flesh weight by the following regression equation:

$$c_{fl} = 0.900 - 0.0051SS + 0.020\, W_{fl}$$

where c_{fl} is estimated flesh specific heat (Btu/lb°F)

SS is soluble solids content of the flesh (%)

W_{fl} is flesh weight of each cherry (gm)

The standard error of c_{fl} was $\pm$ 0.060 Btu/lb°F, and the average c_{fl} was 0.906 Btu/lb°F. The authors noted that the combined effects of both independent variables tended to cancel each other.

With respect to specific heat and the objective of the research in this thesis, the following is concluded from the literature reviewed:

1. Based on today's needs, Siebel's method for the calculation of specific heat is not sufficiently accurate.
2. Between freezing and 70°F, the specific heat

of some vegetables may increase slightly as the temperature is increased.

3. No one has reported the specific heats of vegetables at temperatures above 70°F.
4. No one has reported any relationships between specific heat and shear strength, compression strength, or elastic modulus of vegetables or food products.
5. The specific heat of fruits and vegetables may be a function of the insoluble solids content.
6. Specific heat as a function of heat exposure of a vegetable or food product has not been reported.

2.1c <u>Thermal Diffusivity</u>

Olson and Jackson (1942) used the data from experimental heating curves to derive equations for the thermal diffusivity, α, of various shaped objects: brick, rectangular rod, infinite slab, finite cylinder, infinite cylinder, and sphere. In all the equations, thermal diffusivity was a function of the dimensions of the object and an f-value. The f-value was defined as the time in minutes for the heating curve to traverse one log cycle when the log of the temperature difference between the heating medium and the object was plotted against time of exposure in minutes. The f-value represented the reciprocal of the slope of the heating curve and was a characteristic of the material being heated. No information was given that related f-values to the physical properties of the material.

Kethley, Cown, and Bellinger (1950) recorded the thermal histories of some individual fruits and vegetables. The thermal history data and the graphical method of Gurney and Lurie (1923) were then used to estimate the average thermal diffusivities of the fruits and vegetables for the temperature range of 80°F to 0°F. The authors noted that the estimated diffusivities were of the same order of magnitude as the diffusivity of water in the temperature range of 80°F to 32°F. The diffusivities of the foods for the 80°F to 32°F range were determined and compared with the known values for water. The values for the fruits and vegetables ranged from 5.35×10^{-3} ft^2/hr to 6.15×10^{-3} ft^2/hr. Because average values of thermal diffusivity were estimated, there was no correlation with temperature or other physical properties.

In studies on the processing of beef in cans, Hurwicz and Tischer (1952) found that the temperature of the processing medium and the time at which the temperature measurement was made on the beef were highly significant factors in determining the thermal diffusivity of the beef. The authors noted that the variation in thermal diffusivity was rather small and could be assumed to be constant for practical purposes. The thermal diffusivities shown in Table 2.1 were the experimental values at different locations in the container.

Table 2.1 Thermal diffusivity of beef in cans

Retort Temperature = 225°F	
$\alpha_{30\ min.}$ (cm^2/min)	$\alpha_{90\ min.}$ (cm^2/min)
0.09264	0.10091
0.08734	0.09795
0.08230	0.09581
Retort Temperature = 255°F	
$\alpha_{30\ min.}$ (cm^2/min)	$\alpha_{90\ min.}$ (cm^2/min)
0.09454	0.10849
0.09429	0.10463
0.07196	0.10388

The thermal diffusivity increased as time increased at a given retort temperature. The thermal diffusivity also increased with an increased retort temperature.

In later studies on the processing of beef in cans, Hurwicz and Tischer (1956) found that the thermal diffusivity of beef increased with retort temperatures between 225°F and 261°F. The thermal diffusivity decreased with increased retort temperatures between 279°F and 315°F. The authors noted that "the retort temperature range of 261°F to 279°F may be located in the critical region for processing beef where most of the physical characteristics assume their extremes." The authors also commented that "there were no significant differences in thermal diffusivity due to location in the container" and that "a possibility existed that chemical and moisture changes occurring during processing might have affected the thermal properties of the beef to different extents depending on the distance of the region in the can from the source of heat."

Evans and Board (1954) measured the thermal diffusivity of cans of bean-bentonite mixture and found that the thermal diffusivity increased when the temperature of the heating medium was increased; thermal diffusivity was 1.35×10^{-3} cm^2/sec for a 104°F water-bath temperature and 1.70×10^{-3} cm^2/sec for a 240°F retort temperature. Evans and Board suggested that the increase in thermal diffusivity could have been due to condensation of moisture in the can head space from the bean-bentonite mixture and also could have been due to a small amount of convection heating being superimposed on heating by conduction.

From the reported values for the thermal diffusivity of water, Evans (1958) noted that the thermal diffusivity of water increased by approximately 19% between 68°F and 248°F. Based on theoretical calculations, heating and cooling curves were constructed for water with constant thermal properties and for water with variable thermal properties. The author noted that the slopes of both curves had values near that for constant thermal properties

when using a diffusivity corresponding to the final temperature. Evans cited evidence that the thermal diffusivity of foods is less than that of water. The diffusivities of foods compared with water undergo a smaller variation with temperature. In additional experiments with cans of bean-bentonite mixture and cans of agar gel, Evans found that the thermal diffusivity increased with increased temperatures.

Dyner and Hesselschwerdt (1964) used a mathematical model and specimens of agar-gel to predict temperature-time characteristics during food precooling. Thermal diffusivity was assumed to be constant in order to simplify the mathematical manipulations. The authors noted, however, that thermal diffusivity was a function of temperature, and preliminary test work showed a slight initial decrease in thermal diffusivity as the temperature was reduced. The temperature range was not given. The effect of a varying thermal diffusivity was considered to be minor.

Parker and Stout (1966) determined the thermal properties of tart cherry flesh in the temperature range of approximately 80°F to 40°F. Thermal diffusivity was calculated from temperature history data; the method was not amenable to showing thermal diffusivity variations with temperature. A multiple regression analysis showed that in the temperature range of approximately 80°F to 40°F the thermal diffusivity of cherry flesh was a function of soluble solids; thermal diffusivity decreased as soluble solids content increased. The thermal diffusivity of cherry flesh was given as 5.104×10^{-3} ft^2/hr with a standard error of $\pm 0.416 \times 10^{-3}$ ft^2/hr.

With respect to thermal diffusivity and the objective of the research in this thesis, the following is concluded from the literature reviewed:

1. Thermal diffusivity was a function of the reciprocal of the slope of the heating curve.
2. The reciprocal of the slope of the heating curve has not been related to the physical properties of the food.
3. The thermal diffusivity of canned beef increased as the heating medium temperature increased to 261°F. Thermal diffusivity decreased as the heating medium temperature increased from 279°F to 315°F.
4. The thermal diffusivity of tart cherry flesh was a function of percent soluble solids.
5. Variations of thermal diffusivity with temperature up to 255°F may be small enough to neglect for practical purposes.
6. No one has reported any relationships between thermal diffusivity and shear strength, compression strength, or elastic modulus of vegetables or food products.

2.1d <u>Heat Exposure</u>

For the purpose of this thesis, heat exposure is defined as the area under a heating or cooling curve when the dependent variable temperature is plotted against the independent variable time. Thus if a vegetable were suddenly immersed in a heating medium, time would begin at the instant of immersion and temperature would be that of any selected point at any instant of time. When an immersed object attains the temperature of the heating medium, the transfer of heat ceases (no temperature differential). But when the object remains immersed after attaining the temperature of the heating medium, the thermal and physical properties of the object may be influenced by the total exposure to the heating medium. No direct references to heat exposure were found in the literature. But some of the data tabulated in the references could be examined from the standpoint of heat exposure.

As cited previously, Hurwicz and Tischer (1952) found that the temperature of the processing medium and the time at which the temperature measurement was made on the beef were highly significant factors in determining the thermal diffusivity of the beef. The data given in Table 2.1 shows that thermal diffusivity appears to be a function of the temperature-time exposure of the product.

The report of Evans and Board (1954) did not give heating curves or degree-minute data but the tabulations showed a larger thermal diffusivity for cans of bean-bentonite mixture heated in a 240°F retort as compared to heating in a 104°F water-bath. The area under a heating curve from an initial temperature of 75°F to a 240°F retort temperature was probably larger than the area under a heating curve from an initial temperature of 32°F to a 104°F water-bath temperature. Thus a possibility exists for a relationship between the heat exposure and thermal diffusivity.

Nicholas and Pflug (1961) processed fresh cucumber pickles at several combinations of temperature and time: 150°F to 204.5°F and 7 min to 166 min. The pickles became softer as the area under the heating curve was increased.

Blanching temperature, blanching time, and green bean firmness data was given by Kaczmarzyk, Fennema, and Powrie (1963), but the relationships among the three variables were too erratic to consider firmness as a function of some temperature-time area. Firmness was related to temperature intervals and not directly to time and/or temperature.

The effect of cooking temperature and time on the tenderness of beef was reported by Tuomy, Lechnir, and Miller (1963). Shear values measured with a Kramer shear press indicated the tenderness of the beef. From a plot of lines of constant meat temperature on a graph of shear press values vs. time, the authors noted that the "curves show that the initial effect of heat in the meat was a toughening and, as the temperature was increased, the degree of toughening increased. After the initial toughening, which occurred very rapidly, the resulting tenderness depended upon temperature and time. If the temperature was below 180°F, time resulted in little or no tenderizing. If the temperature was 180°F or above, the meat became tender at a rate and to a degree dependent on both time and temperature." Thus the heat exposure had an effect on the physical properties of the beef.

Zaehringer, Cunningham, Le Tourneau, and Hofstrand (1963) cooked potato slices in boiling water (98°C, high altitude) for periods of 5 min to 25 min. The potato slices gained weight during the first 5 min interval of cooking, and maintained that weight during the second 5 min interval of cooking. After 10 min of cooking, the potato slices lost weight and the tissue progressively disintegrated with time. Thus, the heat exposure may have affected the physical properties of the product.

No information was found on the comparative effects of short time and high temperature versus long time and low temperature.

With respect to the heat exposure and the objective of the research in this thesis, the following is concluded from the literature reviewed:

1. The extent of heat exposure of a vegetable

affects the physical properties and thus may affect the thermal properties.

2. No reports were found that were directly concerned with heat exposure and its influence on the thermal and physical properties of a biological product.

2.2 Physical Properties

2.2a Specific Gravity

Researchers have correlated specific gravity with various physical and chemical properties of potatoes. A chart for converting specific gravity readings to percentage total solids and starch content is used by the United States Department of Agriculture, Finney (1963).

Whittenberger and Nutting (1950) noted that potato tissues of highest specific gravity occurred on both sides of the vascular ring. Tissues of lowest specific gravity were in the central section.

Sharma, Isleib, and Dexter (1958) determined the specific gravity for each of the three concentric zones within a potato. Zone one was defined as extending from the tuber surface approximately to the vascular ring. Zone two was considered to be bounded peripherally by the vascular ring and extended slightly less than halfway toward the center of the potato. Zone three comprised the remainder of the tuber. A two-year study of nineteen varieties showed that zone two had the highest specific gravity, followed by zone one and then three. Sharma et al. (1958) concluded that "there was generally little difference in specific gravity between zones one and two. Specific gravity of zone three was relatively uniform between varieties."

Sharma, Isleib, and Dexter (1959) investigated the influence of specific gravity and chemical composition on hardness of potatoes after cooking. The authors concluded that "tubers or parts of tubers with high specific gravity are firmer after cooking than are those with a low specific gravity."

An investigation of several rupture parameters of potatoes by Finney (1963) showed that no linear relationship existed between the parameters and specific gravity. Finney concluded that "specific gravity and tuber strength are not linearly related."

Lujan and Smith (1964) used a shear press, (Kramer and Twigg (1962)), on raw potatoes cut into cubes to determine that the correlation of shear force values with specific gravity was negative and significant at the 1% level.

Porter, Fitzpatrick, and Talley (1964) determined regression equations for the relationship of specific gravity to total solids of potatoes.

With respect to specific gravity and the objective of the research in this thesis, the following is concluded from the literature reviewed:

1. A known relationship exists between specific gravity of potatoes and their total solids and starch content.
2. Specific gravity of a potato may be related to firmness after cooking.
3. Specific gravity of a potato varies with location within the potato.
4. Specific gravity and tuber strength are not linearly related.
5. Specific gravity has been correlated to the shear force of raw potato.

2.2b Elastic Modulus

Finney (1963) made an extensive study of the design parameters of five varieties of potatoes. Raw potato cylinders of various cross-sectional areas and 1 in. long were subjected to a uniaxial compression test between parallel plates. The elastic modulus was calculated from the stress and deformation data. The mean elastic modulus for Russet Rural potatoes was 543 psi with a 7.9% coefficient of variation.

Finney also determined the elastic modulus on cylindrical sections of Arenac potatoes. The whole potatoes were kept in various constant temperature chambers prior to testing. "Below 60°F, however, and above 105°F the elastic modulus varied inversely with temperature from a maximum of 545 psi at 40°F to a minimum of 355 psi at 135°F. This decrease in elastic modulus with rising temperature was in agreement with results reported for other materials." "Within the 60 to 105°F range, the elastic modulus was unaffected by temperature variations." The elastic modulus was approximately 490 psi in the 60°F to 105°F range.

With respect to elastic modulus and the objective of the research in this thesis, the following is concluded from the literature reviewed:

1. An increase in the temperature of a potato can cause a decrease in the stiffness or elastic modulus of the potato.

3. THEORETICAL CONSIDERATIONS

3.1 Heat Conduction Equations

The general heat conduction equation that results from an energy balance on a small volume of material is given in heat transfer texts (Schneider, 1955) (Carslaw and Jaeger, 1959) as:

$$\frac{\partial}{\partial X}\left(k_m \frac{\partial T}{\partial X}\right) + \frac{\partial}{\partial Y}\left(k_m \frac{\partial T}{\partial Y}\right) + \frac{\partial}{\partial Z}\left(k_m \frac{\partial T}{\partial Z}\right) + \frac{q_m}{V} = c\rho\frac{\partial T}{\partial t} \quad (3.1)$$

where: k_m = thermal conductivity of the material $\left(\frac{\text{Btu ft}_{\parallel}}{\text{hr ft}_{\perp}^{2}\ {}^\circ\text{F}}\right)$

T = temperature (°F)

q_m = internal heat generation $\left(\frac{\text{Btu}}{\text{hr}}\right)$

V = volume (ft^3)

c = specific heat $\left(\frac{\text{Btu}}{\text{lb}_m\ {}^\circ\text{F}}\right)$

ρ = density of the material $\frac{\text{lb}_m}{\text{ft}^3}$

t = time (hr)

Considering a body with the following characteristics,

1. k_m independent of position and temperature,
2. one dimensional heat flow in the X direction, and
3. no internal heat generation,

equation (3.1) reduces to:

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \tag{3.2}$$

where: α = thermal diffusivity

$$= \frac{k_m}{\rho c} \ (ft^2)/hr$$

A body subjected to a heat transfer process may be divided into nodal points that are a distance ΔX apart. About any node an energy balance can be written and expressed in finite difference form (Schneider, 1955). Temperatures in the body can be expressed with respect to position and time by means of subscripts and superscripts n and t respectively, Figure 3.1. For one dimensional heat flow in the X-direction in a finite body, nodes are located at X = 0, X = X, and X = L. Temperature boundary conditions may be specified at X = 0 and at X = L.

	$\vert\leftarrow \Delta X \rightarrow\vert$		
t+1	0	0	0
t	0	0	0
	n-1	n	n+1

Fig. 3.1. Node notations for position and time

In finite difference form, equation (3.2) becomes:

$$\alpha \frac{T_{n-1}^{t+1} - T_n^{t+1} + T_{n+1}^{t} - T_n^{m}}{(\Delta X)^2} = \frac{T_n^{t+1} - T_n^{t}}{\Delta t} \tag{3.3}$$

Equation (3.3) can be solved for the temperature at node n for time t = t+1.

$$T_n^{t+1} = \frac{T_{n-1}^{m+1} + T_{n+1}^{m} + T_n^{m}(M-1)}{M+1} \qquad (3.4)$$

where:

$$M = \frac{(\Delta X)^2}{\alpha \Delta t} \quad \text{a dimensionless number} \qquad (3.5)$$

3.2 Thermal Diffusivity by Finite Differences

A computer program using finite differences and based on the method of Beck (1963) was used to calculate thermal diffusivity from temperature measurements. The basic operations of the program were:

1. The magnitude of ΔX was determined.
2. At the first and last node, a programmed time step was used to calculate temperatures with respect to time;

   T^t, T^{t+1}, ... T^{t+i}

   where: $(t+1) - t$ = programmed time step

   $(t+i) - t$ = time interval of data
3. The finite difference equation (3.4) was used with an assumed α to calculate temperatures at each node. Calculations were made in two "passes"; an "odd pass" proceeding from first to last node and an "even pass" proceeding from last to first node.
4. The method of least squares was used to minimize with respect to α the difference between the calculated and measured temperatures.

5. The change in diffusivity was calculated and added to the assumed α to obtain a new value of α.

6. The new value of α was used in an iteration procedure to determine a more accurate value for α.

The above program was based on the following assumptions:

1. Initial and boundary conditions of the body were:

   a. $T\ (X,0) = 0$

   b. $T\ (0,t) = T_1$

   c. $T\ (\infty,t) = 0$

2. One dimensional heat transfer.

3. Constant α with respect to time and temperature.

4. The last node was at $X = \infty$.

The complete program is shown in Appendix A.

4. EXPERIMENTAL EQUIPMENT AND PROCEDURES

4.1 Objectives

The objectives of the research were:

A. To determine the thermal diffusivity of an internal section of a potato after the section had received

   1. a small heat treatment,
   2. sufficient heat treatment to change some of the physical properties of the section, and
   3. sufficient heat treatment to nearly cook the section.

B. To investigate the correlation between thermal and physical properties of the potato section for the parameters of

   1. thermal diffusivity,
   2. heat exposure,
   3. specific gravity, and
   4. elastic modulus.

The first objective was accomplished by holding a cylindrical heat source in direct thermal contact with a cylindrical section of potato. Temperature histories of the semi-infinite potato cylinder were recorded at X=0 (interface of heat source and potato), X=L, and X=infinity. Temperature histories were used to calculate the thermal diffusivity of the potato section at X=L.

The heat exposure of the potato section was obtained as the area between the temperature histories at X=0 and X=L for the duration of the experiment. Specific gravity was a routine test and the elastic modulus was determined from data of the force applied to a potato section and the resulting deformation of the potato section.

4.2 Equipment

The major pieces of equipment consisted of the following:

A. Specimen holder for transient heat transfer experiments. See Figure 4.1.

B. Leeds and Northrup Precision Potentiometer
   Model 8686, Serial No. 1581952
   Accuracy $\pm$ 0.03% of reading + 3 microvolts without reference junction

C. Leeds and Northrup Recording Potentiometer, two pens
   Model G, Serial No. B66-752270-1-1
   Range 60°F to 260°F, Copper-Constantan Thermocouples
   Accuracy $\pm$ 0.3% of full scale

Figure 4.1. Specimen holder with electric heating unit and black glass foam insert

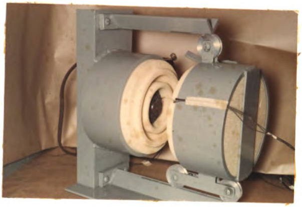


Figure 4.2. Specimen holder with red silicone rubber heat source and microswitch (black)

Figure 4.3. Equipment during a test. From left to right: recording potentiometer, specimen holder, autotransformer, and recording potentiometer

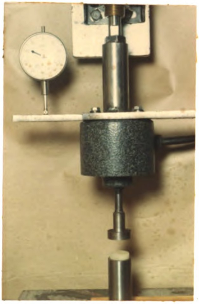


Figure 4.4. Elastic modulus test equipment. From top to bottom: dial gauge, load cell (below horizontal bar), and parallel plates with potato section in place

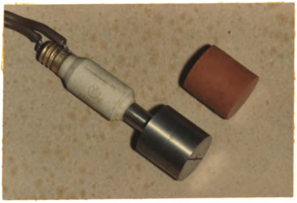


Figure 4.5. Heat sources: electric heating element with steel cylinder and silicone rubber cylinder

D. Honeywell Recording Potentiometer, two pens
Model Electronik 17, Serial No. F5731475001
Range 0°F to 250°F, Copper-Constantan Thermocouples
Accuracy ± 0.25% of full scale

E. Mettler Analytical Balance
Type A, Serial No. 34021
Range 0 to 200 gms.

F. Testing Machine for applying and sensing force on potato sections (Finney, 1963). See Figure 4.4.

G. Universal Amplifier
Model RD 5612 00

H. Moseley Autograf X-Y Recorder
Model 135, Serial No. 2138

The specimen holder was designed to hold a heat source and a potato section in intimate and uniform contact with each other for the duration of an experiment, Figure 4.2. Each half of the specimen holder was made from a 3 in. length of standard 6 in. diameter steel pipe. The stationary half of the holder was welded to channel iron. A flat base plate and angle iron rails were also welded to the channel iron. V-grooved wheels mated with the angle iron rails maintained accurate alignment in all planes between the movable and stationary halves. The longitudinal displacement of the V-grooved wheels from each other facilitated the rapid installation of the movable half onto the rails. During the experiments a constant pressure was maintained at the heat source-potato section interface by rotating the specimen holder 90° and supporting the holder by the channel iron, Figure 4.3.

A microswitch and its trip lever were fastened to the stationary half and movable half respectively, Figure 4.2. When the halves of the specimen holder were brought together for an experiment, the microswitch completed a circuit for an electric interval timer and for an indexing pen on each recording potentiometer. The microswitch was adjusted to close the circuit when the heat source and potato section made contact. A separate series circuit consisting of a dry cell, light, and metal plates (to simulate the heat source and potato surfaces) were used to adjust the microswitch. Adjustment was correct when the light and indexing pens operated simultaneously.

The insulation for the specimen holder was a polyurethane type (Dow Chemical Co., QX-3851.1) with a thermal conductivity of approximately 0.16 Btu. in./(hr. ft^2 °F). A 4 in. length of insulation was machined to a snug fit in the bore of each half of the holder. Mating grooves were machined into the halves of insulation to minimize any air currents and convection heat losses. A hole, 31/32 in. diameter and 1 in. deep, was machined into the face of the insulation of the movable half of the specimen holder; the potato sections were installed in the hole for the experiments. A hole of the same dimensions was machined into the face of the insulation for the stationary half of the specimen holder; a silicone rubber heat source was installed in the hole for the experiments, Figure 4.2. When an electric heating element was used for the heat source, the temperatures were too high for the stability of the polyurethane insulation; a glass foam insert was made to go between the heating element and the polyurethane insulation, Figure 4.1.

For some of the lower temperature experiments, a heated cylinder of silicone rubber was used as a heat source, Figure 4.5. Cylinders of silicone rubber 61/64 in. diameter and 1 1/32 in. long were cut from a cured slab of silicone rubber; General Electric Co., SE-3604U. When not in experimental use, the cylinders were kept at the desired temperature in an oven.

Most of the experiments were performed with a steel cylinder and an electric heating element as the heat source, Figure 4.5. The 1 in. diameter and 1 in. long steel cylinder was continuously heated by a 37.5 watt soldering iron heating element. Power to the heating element was controlled by an autotransformer. A thermocouple was silver soldered to the face of the steel cylinder.

The Leeds and Northrup Model 8686 Precision Potentiometer was used to check the calibration of the two recording potentiometers. The recording potentiometers were calibrated within the manufacturers' tolerance. The instruments were within the manufacturers' tolerance at the completion of the experiments. The precision potentiometer was also used to calibrate the thermocouples.

The recording potentiometers were used to record simultaneously the temperatures at the following locations:

1. heat source contact surface,
2. potato section contact surface,
3. X=L of the potato section, and at
4. X= infinity of the potato.

The analytical balance was used to weigh the potato sections before and after heat treatment. For specific gravity determinations, a suspension system was used on the scales to obtain the weight of the potato section in water; see Figures 4.6 and 4.7.

For elastic modulus determinations, the testing machine consisted of:

1. air motor
2. load cell, BLH Type U-1B, 50 lb. capacity

   Accuracy $\pm$ 0.25% with a maximum nonlinearity of $\pm$ 0.10% valid for both tension and compression
3. parallel plates

The double-acting pneumatically driven air motor had a 4 in. stroke and a hydraulically controlled piston

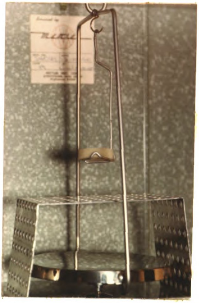


Figure 4.6. Weighing potato section in air

Figure 4.7. Weighing potato section in water

speed in both up and down directions. The speed of the loading piston was independent of the applied force (or constant) within the force range from 0 to 150 lbs. The load cell sensed the force applied to a potato section located between the 1 1/8 in. diameter parallel plates, Figure 4.4.

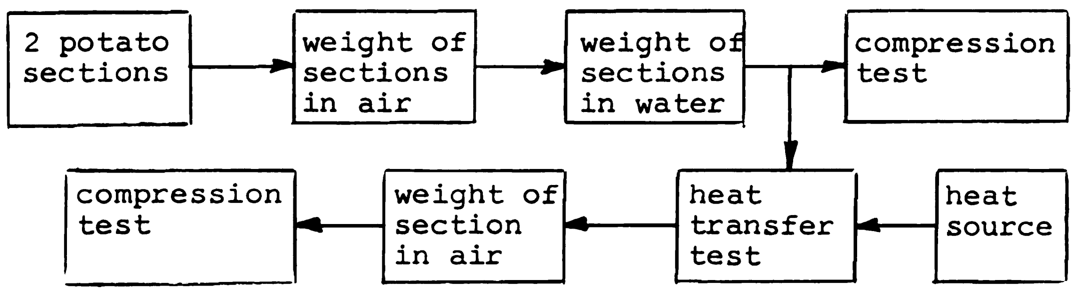
The force signal from the load cell was amplified and fed into the Y-axis of the X-Y recorder. A constant pen travel time of 2.09 sec./in. was fed into the X-axis of the X-Y recorder. Thus the compression of a potato section was recorded as force (lb./in. of chart) vs. pen speed (sec./in. of chart). The force scale of the X-Y recorder was calibrated before each series of tests with a weight of 10.050 lbs. suspended from the upper parallel plate. The gain of the amplifier was adjusted to give a pen deflection of 1 in. on the graph paper.

A dial gauge, Figure 4.4, accurate to $\pm$ 0.001 in., was used to determine the downward speed of the air motor piston. Just prior to the compression of a potato section between the parallel plates, a stop watch was used to measure the time required for the piston to travel 1 inch.

Thermocouples were made from No. 30 gauge copper-constantan wire. The junctions were silver soldered after the wires had been cleaned of insulation and had been twisted together. The junctions were trimmed to a length of 1/16 in. or less. Distilled water was used to calibrate the thermocouples at temperatures of melting ice, 74°F, 157°F, and boiling water. The maximum average error of any thermocouple was less than 0.75% of the known temperature.

4.3 Experimental Procedure

4.3a Flow Chart of Experimental Procedure



4.3b Heat Sources

1. Silicone Rubber

   a. The cylindrical section of rubber was heated and kept in a controlled temperature oven.

   b. When preparing for a heat transfer and thermal properties test, the rubber cylinder was placed in insulation at room temperature and transported 8 ft. to test room and specimen holder. (Insulation for transporting rubber cylinder was machined to mate the insulation of the specimen holder.)

   c. The rubber cylinder was dropped into the specimen holder with a minimum exposure to the ambient air.

d. The thermocouple was inserted into exposed end of the rubber cylinder.

e. After each test, the rubber cylinder was returned to the oven.

f. No rubber cylinder was used more than once in an 8 hr. period as a heat source for the potato section.

2. Steel Cylinder

a. The power to the heating element was turned on a few hours prior to any experiments.

b. The power level was adjusted with the auto-transformer to maintain the desired temperature of the steel cylinder.

c. After each experiment the steel cylinder was allowed to equilibrate to the desired temperature.

4.3c <u>Potato Sections</u>

1. A 0.953 in. diameter cylindrical section was removed from a potato. The cylinder was cut perpendicular to the least curved surface of the potato, Figure 4.8.

2. An aluminum ring and single-edged razor blade were used to remove a section from the potato cylinder.

a. The section was removed from the central area and just below the vascular ring.

Figure 4.8. Potatoes and cutting equipment. From left to right: aluminum ring assembly 1 1/32 in. long, potato cylinder and ring for cutting potato section to proper length, and boring tool for removing cylindrical section from potato

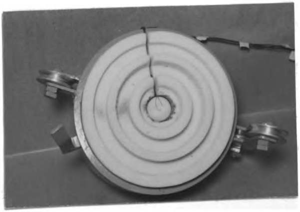


Figure 4.9. Semi-infinite portion of potato in specimen holder with thermocouple at X = L

b. The 0.953 in. inside diameter aluminum ring was 0.238 in. thick (length to diameter ratio of 1 to 6).

3. Excess surface moisture was removed from the potato section with a clean paper towel.
4. The potato section was weighed in air and in distilled water, Figures 4.6 and 4.7.
5. Excess surface moisture was removed from the potato section with a clean paper towel.
6. The potato section was used immediately for elastic modulus determinations.
7. The remaining potato cylinder was placed in a welded aluminum ring assembly and trimmed to a length of 1 1/32 in., Figure 4.8.
8. Another potato section adjacent to the first was removed from the 1 1/32 in. potato cylinder. The aluminum ring of 2b above was used.
9. Excess surface moisture was removed from the potato section and cylinder with a clean paper towel.
10. The potato cylinder was placed in the movable half of the specimen holder. The potato cylinder became the semi-infinite portion of the potato, Figure 4.9.
11. The $X = L$ thermocouple was placed on top of the semi-infinite portion of the potato.

12. The potato section was weighed in air and in distilled water.
13. Excess surface moisture was removed from potato section with a clean paper towel.
14. The thickness of potato section was measured with calipers.
15. The potato section was placed on top of the $X = L$ thermocouple in the movable half of the specimen holder.
16. The $X = 0$ thermocouple was placed into the potato section.
17. After the heat transfer test, the potato section and semi-infinite portion were placed together in a plastic bag and sealed.
18. The plastic bag was placed in front of the room air conditioner for rapid cooling to room conditions.
19. After the potato section and semi-infinite portion had equilibrated to room conditions for a few hours, the pieces were replaced in the specimen holder for an additional 3 min. heat treatment at a maximum temperature of 160°F at $X = 0$ of the potato.
20. The potato section was reweighed in air.
21. The thickness of the potato section was remeasured.

22. The diameter of the potato section was measured at the X = 0 surface.
23. The potato section was placed between the parallel plates of the testing machine with the X = 0 surface next to the upper parallel plate.

4.3d Elastic Modulus Determinations

1. The amplifier was turned on at least one hour prior to calibration and use.
2. The X-Y recorder was turned on approximately 15 min. prior to calibration and use.
3. The calibration of the load cell, amplifier, and X-Y recorder was checked at the beginning and end of each day.
4. To minimize any horizontal components of shear, a film of light oil was placed on the parallel plates of the testing machine.
5. The air motor was energized to force downward the piston, load cell, and upper parallel plate.
6. A stop watch was started when the dial gauge indicated 0.000 in.
7. When the dial gauge indicated 1.000 in. the stop watch was stopped and time recorded as sec/in.
8. The X-Y recorder pen was energized just before the upper parallel plate contacted the potato section.

9. The air motor and X-Y recorder pen were turned off when the load cell reached its limit or when the potato section ruptured.
10. For each experiment the elastic modulus curve for both the raw and heat treated potato sections were recorded on the same sheet of X-Y recorder paper.

4.3e <u>Heat Transfer and Thermal Diffusivity Tests</u>

1. As soon as the thermocouple was inserted in the rubber cylinder, the two halves of the specimen holder were pushed into contact. As the surface of the rubber cylinder contacted the potato section, the microswitch completed the electrical circuit to the interval timer and to the indexing pen on each recording potentiometer. The specimen holder was rotated 90° so that the potato section was above the rubber cylinder and the axis of the cylinders was in the vertical plane, Figure 4.3.
2. Thermal contact at constant pressure between the rubber cylinder or steel cylinder and potato section was maintained for the desired length of test.

4.4 Discussion of Experimental Techniques

4.4a Potatoes

Excel potatoes grown on the Michigan State University Farm, Lake City, Michigan, were used for the tests. The Excel variety is known to have consistent cooking qualities. The potatoes were harvested in 1965 and stored at 40°F until the tests were performed in July, 1966. Stored potatoes are normally more uniform in physical characteristics than freshly harvested potatoes.

The potatoes were removed from storage approximately 24 hr before use and equilibrated to the testing room temperature of 76°F. The equilibration of the potatoes to the testing room temperature and the performance of all procedures in the constant temperature testing room insured an initial condition of uniform temperature distribution in the potato specimen as required for the thermal diffusivity tests.

Only firm potatoes without defects were used for the tests. Cylinders cut from soft potatoes were not uniform in diameter and the diameter was less than the 0.953 in. specified for the tests. The elastic modulus of a raw specimen from a soft potato was found to be approximately 100 psi higher than the elastic modulus of a raw specimen from a firm potato. Ten replications were made at each test condition.

4.4b Heat Transfer and Thermal Diffusivity Tests

To minimize thermocouple conduction errors, the lead wires were placed across the face of the heat source and wound partly around the circumference of the heat source before entering the insulation of the specimen holder (Figure 4.1). The same method was used for placing thermocouple leads at $X = 0$, $X = L$, and at $X = \infty$ (Figure 4.9). The thermocouple at $X = \infty$ was silver soldered to a thin copper wafer which held the thermocouple in proper position at all times.

One of the boundary conditions required the temperature at $X = \infty$ to be constant during the interval of determining thermal diffusivity. The recorded temperatures at $X = \infty$ showed that the boundary conditions prevailed for at least 2 1/2 min. for every test. Therefore, a data time of 100 sec. or less was chosen for all tests.

To satisfy the conditions of one dimensional heat transfer, a potato section length equal to 1/6 of the section diameter was chosen. This was a compromise between edge heat losses and convenient size potato sections.

To attain one of the objectives of the research, the thermal diffusivity had to be determined for a potato section before and after heat treatment. The boundary conditions restricted thermal diffusivity data to the first one hundred seconds of each test, which was satisfactory for determinations on a raw potato section.

Because thermal diffusivity data could not be taken at the end of a heat treatment, the heat treated section and its semi-infinite portion were removed from the specimen holder, stored in a sealed plastic bag, and equilibrated to the testing room temperature. After attaining the desired initial condition of uniform temperature distribution, the potato section and its semi-infinite portion were replaced in the specimen holder and given a 3 minute heat treatment with a maximum temperature of 160°F at $X = 0$. The first one hundred seconds of data from the second heat treatment was used to compute the thermal diffusivity of the heat treated potato section.

When silicone rubber cylinders were used for a heat source, a thermocouple junction approximately 1/32 in. long was bent perpendicular to the lead wires and was placed in a small slit in the surface of the rubber. Thus the longitudinal axis of the junction coincided with the longitudinal axis of the cylinder. The same technique was used for the placement of a thermocouple at $X = 0$ of the potato section. The average temperature of the two thermocouples was used as the temperature at $X = 0$.

A thermocouple was silver soldered in a small depression in the surface of the steel cylinder. Lead wires were laid in the groove across the face of the cylinder. The thermocouple junction was soldered in the plane of the surface of the cylinder and made direct contact with the

X = 0 surface of the potato section. Therefore, a separate thermocouple at X = 0 in the potato section was eliminated and the thermocouple on the steel cylinder measured the temperature at X = 0.

A length of 1 in. was chosen for the steel cylinder to insure uniform heating at the surface in contact with the potato section. To check for variations in surface temperature, a thermocouple was placed at several positions on the surface of the steel cylinder. No variations in temperature were found.

4.4c Specific Gravity Tests

When a section was cut from a potato, moisture accumulated on the surfaces. Prior to any weighing operations the excess moisture was removed with a paper towel. The potato sections were weighed in grams accurate to the third decimal place. Removal of moisture other than excess surface moisture may have introduced some error in the specific gravity determinations. But the ten replications for each test condition should have averaged out any such random errors.

4.4d Elastic Modulus Tests

The velocity of the air motor and piston on the testing machine was not uniform from one operation to the next. An error in the velocity of the piston would cause a large error in the calculated strain and the resulting elastic modulus of the potato section. By determining the velocity of the piston for a one inch displacement preceding the contact of the upper parallel plate with the potato section for each individual test, this error was minimized to $\pm$ 1%.

5. RESULTS AND DISCUSSION

Finite difference methods have been adapted to computer use for solving heat transfer equations. The magnitude of the errors introduced by the estimation process are frequently less than the magnitude of the errors in the data. This is shown in Table 5.1 where many of the root mean square values are less than 0.5°F. The recording potentiometers had a permissible error of 0.6°F.

All data calculations were done by the Control Data Corporation 3600 Computer at Michigan State University. All curve fittings were done with a least squares computer program identified as E2 UTEX LSCFWOP.

The heat transfer methods used in the experiments combined with the finite difference method of data analysis had the advantages of speed, simplicity, ease of application to other products and accuracy. Depending upon test duration, approximately four heat treatments could be completed in an hour. No difficult laboratory preparations or techniques were involved. Other biological products could be adapted to the specimen holder and large masses were not required. Random errors were cancelled by the finite difference method, but a continuous error of +1°F in temperature measurement was found to cause an error of

Table 5.1. Comparison of root mean square values of temperatures resulting from thermal diffusivities calculated after 50 seconds and 100 seconds

			Root Mean Square Values			
			Raw Potato		Heated Potato	
Test Series No.	Length of Test (min)	Maximum Temp. at X = 0 (°F)	t = 100 sec (°F)	t = 50 sec (°F)	t = 100 sec (°F)	t = 50 sec (°F)
709	10	162	0.409	0.220	0.452	0.313
711	10	179	0.547	0.317	0.507	0.393
721	10	195	1.220	0.561	0.997	0.601
724	15	195	1.181	0.530	0.827	0.521
717	4	212	0.789	0.355	0.334	0.249
714	10	210	1.177	0.499	0.303	0.252
719	15	212	1.535	0.646	0.863	0.599
		Averages	0.980	0.447	0.612	0.418

-0.5% or less in the value of the thermal diffusivity. As indicated in the literature reviewed, errors of 5% were not uncommon in the determination of thermal properties.

Some of the terms used in the tabulations and in the discussions to follow are clarified. The value for the diffusivity of a "raw" potato section was determined from data taken during the first fifty seconds of heat treatment. (Data were originally taken for one hundred seconds but changed to fifty seconds for reasons explained in the next section.) "Heated potato" sections received a specified heat treatment, were cooled to desirable initial thermal conditions, and were reheated for a short time at a low temperature. The only purpose of the reheat was to obtain data for an additional fifty second interval to determine the diffusivity of the potato section after the desired heat treatment. Thus an assumption was made that the reheat had no effect on the thermal or physical properties of the heat treated potato section. The same reheat treatment was given to all heat treated potato sections.

Complete data on all tests and replications is in Appendix B. The tabulations and graphs in "Results and Discussion" contain the averages of ten replications for each test.

5.1 Thermal Diffusivity

Temperatures of the potato sections at $X = 0$, $X = L$, and $X = \infty$ were read from the recorded charts in 10 sec intervals from time $t = 0$ to $t = 100$ sec. An assumption was made that the thermal properties of the raw potato section were constant during the first one hundred seconds of any heat treatment and would not influence the value of thermal diffusivity. This assumption was investigated by computing the thermal diffusivities at $t = 50$ sec and at $t = 100$ sec. An inspection of Table 5.1 shows that for all raw potato diffusivities, the average root mean square value of the difference between the calculated temperatures and the measured temperatures was higher for the $t = 100$ sec determinations than for the $t = 50$ sec determinations. The average values were 0.980°F for $t = 100$ sec and 0.447°F for $t = 50$ sec. In contrast, small differences occurred between the rms values at $t = 100$ sec and $t = 50$ sec for the heat treated sections of potato.

As the severity of the heat treatment was increased, with maximum temperatures of 195°F and above at $X = 0$, the rms values for raw potato sections increased to above 1°F for $t = 100$ sec. This was not true for the raw potato sections for $t = 50$ sec. The agreement in rms values for both raw and heat treated sections at $t = 50$ sec was good and the averages were nearly the same. There were no consistent trends of individual values.

Thus the larger errors in the $t = 100$ sec data were due to the changing properties within the potato. Starch begins to gelatinize in the range of 147°F to 160°F (Talburt and Smith, 1959), with moisture movement and evaporation occurring. The higher temperatures accelerated the changes. This also accounts for small increases in the rms values at the higher temperatures after only 50 sec. On this basis, the t = 50 sec diffusivity data were used for all subsequent correlations between parameters.

The plot of thermal diffusivity in Figures 5.2 and 5.3 shows the data of the 714 test series to be much higher than any of the other points. The data was rechecked but no errors or inconsistencies were found. The rms values for the thermal diffusivity temperatures of the 714 test series were comparable to the rms values of other tests. The 714 test series data were evaluated in two ways: assuming the data to be in error, and assuming the data to be indicative of some unusual change. To give credence to the 714 test series data, other tests should be performed with slightly different times and temperatures.

The thermal diffusivity of the raw potato sections was found to be of the same order of magnitude as some other fruits and vegetables. Parker and Stout (1963) determined the thermal diffusivity of tart cherry flesh; 5.00 x 10^{-3} ft^2/hr to 5.20 x 10^{-3} ft^2/hr. Kethley, Cown, and Bellinger (1950) gave values for fruits and vegetables that ranged from 5.35 x 10^{-3} ft^2/hr to 6.15 x 10^{-3} ft^2/hr.

Hurwicz and Tischer (1956) experienced increasing and decreasing values of thermal diffusivity for different combinations of time and temperature when processing canned beef. A maximum critical point was also noted.

5.2 Elastic Modulus

Data for elastic modulus determinations was obtained from the X-Y recorder charts by constructing a tangent to the first linear portion of the curve following the initial deformation of the potato section, Figures 5.7, 5.8, and 5.9. The slope of the tangent was used in the calculation of the elastic modulus.

Because the methods of obtaining data for elastic modulus determinations involved a destructive test, two sections were removed from each cylinder cut from a potato. The section next to the vascular ring was used for raw potato elastic modulus determinations. The heat treatment of the other potato section was followed by the elastic modulus determination. Thus an assumption was made that the elastic moduli of the two raw sections were equal. No information was found that invalidated the assumption.

After the elastic modulus was computed for all tests and replications, the results showed more variation in elastic modulus between the raw potato replications (a minimum of 51 psi) than between the averages of the tests (a maximum variation of 39 psi). Thus the elastic moduli of the heated potato sections were used for the correlations and the assumption that the elastic moduli of the two raw sections were equal became unnecessary.

5.3 Specific Gravity

Specific gravity was determined on both raw potato sections; one used for raw elastic modulus tests and the one used for heat treatment tests. The standard equation (5.1) was used. The temperature was maintained at 76°F for all tests.

$$\text{Specific Gravity} = \frac{\text{weight in air}}{\text{weight in air} - \text{weight in water}} \qquad (5.1)$$

The potato section used for the elastic modulus test was located nearer the vascular ring than the section used for the heat treatment tests. For all tests and replications, the specific gravity for the outer section averaged 0.976% higher than the specific gravity of the inner section. These results agreed with the findings of Whittenberger and Nutting (1950) and Sharma *et al*. (1958).

Correlations between specific gravity and the other parameters were attempted but none were found to exist. Also, the specific gravity did not show any pattern of change over the 15-day testing period.

5.4 Heat Exposure

When using a temperature-time relationship in this study, the area under the heating curves was considered a parameter and correlated with thermal diffusivity and elastic modulus. For the purposes of this research, such an area was denoted as heat exposure with units of °F-min.

No information was found in the literature as to the individual effects of temperature and time on biological products. One intuitively assumes that exposure to a 1°F temperature difference for 1 min at 200°F would have more influence on a biological product than an exposure of 1°F temperature difference for 1 min at 100°F. In the absence of any precedent on the subject, a base of 160°F was chosen; only temperatures above 160°F were used in the measurement of the area under the heating curve. The area was measured with a planimeter. A base temperature of 160°F was chosen for the following reasons:

1. Starch begins to gelatinize in the range of 147°F to 160°F.
2. The maximum temperature of the second heat treatment on each potato section was 160°F or less and therefore did not contribute to the area.

In the correlations of the parameters, the heat exposure with units of °F-min was used as the independent variable.

5.5 Correlation of Parameters

5.5a Thermal Diffusivity and Storage Time

The thermal diffusivity tests were conducted during a 15-day interval from July 9, 1966, to July 24, 1966. An unexpected variation of thermal diffusivity with the storage interval was found. Figure 5.1 is a plot of the thermal diffusivity of the raw potato sections against the

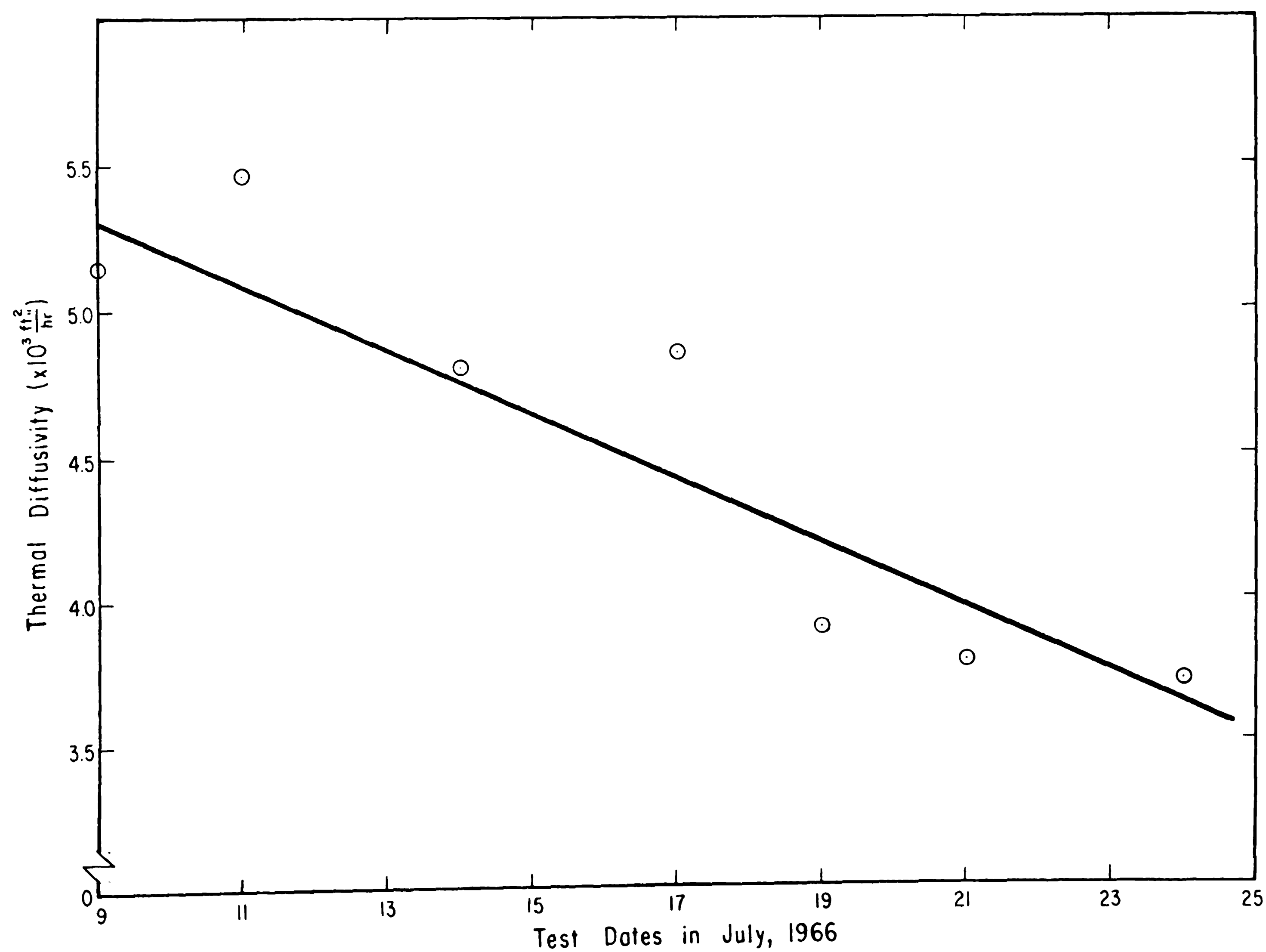


Figure 5.1. Relationship between thermal diffusivity and date of test

test dates. The diffusivity decreased linearily with time according to the relation

$$\alpha = 6.327 \times 10^{-3} - (1.126 \times 10^{-4} \times \text{test date}) \quad (5.1)$$

The root mean square value of the relation was 4.08×10^{-4} ft^2/hr. Specific gravity and elastic modulus did not show any correlations with the storage interval. Why the thermal diffusivity decreased with storage interval is not known. One can surmise that the change was due to small physiological changes that are not detectable with the usual macrophysical tests.

The variation in thermal diffusivity due to the storage interval was larger than the variations caused by heat treatments. Thus for subsequent correlations, the change in diffusivity from the raw section to the heat treated section was used for the parameter.

5.5b Thermal Diffusivity and Heat Exposure

Data from Table 5.2 was used to plot the upper curve in Figure 5.2. As noted in Section 5.5a, the ordinate for the curve is the change in diffusivity from the raw section to the heat treated section. Assuming the 714 test series point to be valid, it may have been a critical point or a point of maximum influence of heat exposure on thermal diffusivity. Also, the point may have been due to the rupture of the cell walls and other physical changes that were not complete or uniform throughout the section. The extent of cooking is indicated in Figure 5.4 by the depth of the black

Table 5.2. Date and description of tests tabulated with average values of thermal diffusivity and heat exposure

Date	Test Series No.	Length of Test (min)	Maximum Temp. at X = 0 (°F)	Diffusivity Raw Potato ($X10^{-3} ft^2/hr$)	Diffusivity Heated Potato ($X10^{-3} ft^2/hr$)	Heat Exposure (°F - min)
7-9-66	709	10	162	5.163	5.311	36.63
7-11-66	711	10	179	5.468	5.765	186.73
7-21-66	721	10	195	3.778	4.120	315.30
7-24-66	724	15	195	3.722	4.044	505.76
7-17-66	717	4	212	4.846	5.173	198.70
7-14-66	714	10	210	4.800	5.593	457.29
7-19-66	719	15	212	3.904	4.040	674.87

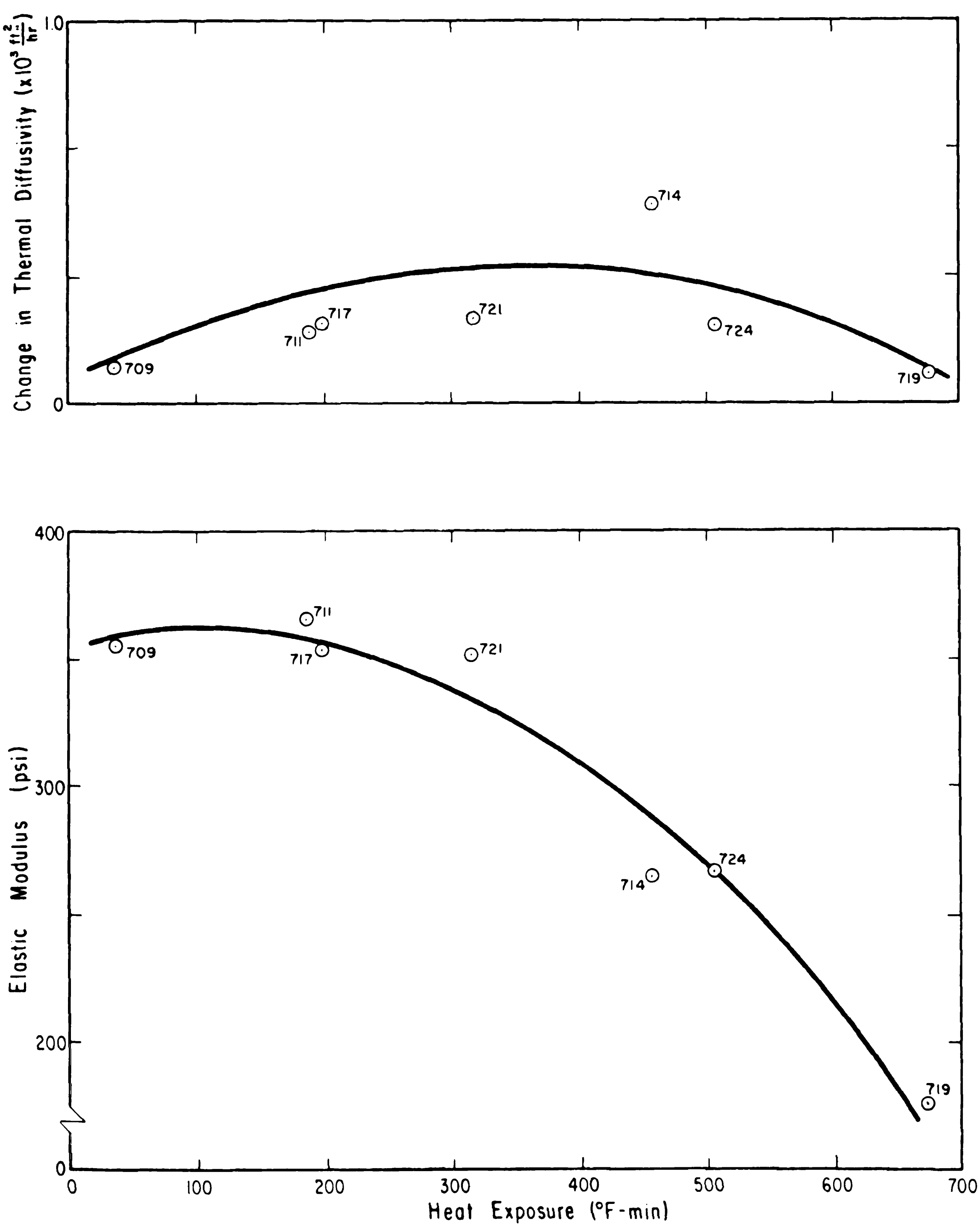


Figure 5.2. Parameters of thermal diffusivity and elastic modulus versus heat exposure

ring (associated with enzyme activity) below the X = 0 surface; the depth of the ring increased with cooking. The heat treated sections of the 714 test series were soft at X = 0 and firm at X = L. The heat treated sections of the 719 test series were soft at both surfaces and appeared more uniform in physical appearance. Note that the 719 test series had the most severe heat exposure and the lowest thermal diffusivity.

The correlation curve shows that the thermal diffusivity increased as heat exposure was increased up to 350 °F-min. Above a heat exposure of 350 °F-min diffusivity decreased. The correlation was given by

$$\alpha = 1.031 \times 10^{-4} + (2.528 \times 10^{-6} \times HE) - [3.628 \times 10^{-9} \times HE^2] \qquad (5.2)$$

where: HE = heat exposure (°F - min)

The correlation had a rms value of 4.91×10^{-4} ft²/hr.

5.5c <u>Thermal Diffusivity and Maximum Temperature at X = L</u>

Because the thermal diffusivity of the potato sections was determined at X = L, a correlation with the maximum temperature at X = L was made. The correlation was given by

$$\alpha = -1.962 \times 10^{-2} + (2.617 \times 10^{-4} \times T) - (8.500 \times 10^{-7} \times T^2) \qquad (5.3)$$

where: T = maximum temperature at X = L (°F)

The rms value of the correlation was 5.00×10^{-4} ft²/hr.

The curve in Figure 5.3 is similar in shape to the thermal diffusivity vs. heat exposure curve in Figure 5.2. According to the correlation curve, thermal diffusivity was a maximum for a temperature of 155°F at X = L. But as in the previous correlation, the 714 test series had the maximum values for the curve at an average temperature of 165°F at X = L. Having the maximum diffusivity occur in the 155°F to 165°F range suggests that the maximum diffusivity was related to the starch gelatinization of the potato. A maximum physical and/or chemical change in the potato may have contributed to the maximum value of thermal diffusivity. Talburt and Smith (1959) did not discuss the factors that may influence the temperature at which gelatinization occurs.

An examination of Table 5.3 and Figure 5.3 shows that the maximum temperatures at X = L differed by only 4°F for the 717 and the 711 test series. Correspondingly, the diffusivities changed very little; 0.327 ft^2/hr and 0.297 ft^2/hr, respectively. This reaction may be compared to the differences of 2°F between the 724 and the 714 test series. The diffusivities changed from 0.322 ft^2/hr to 0.792 ft^2/hr. This analysis indicates that the 165°F temperature may be the critical point for reactions within the potato section.

The results of the correlation between thermal diffusivity and maximum temperature at X = L show the following:

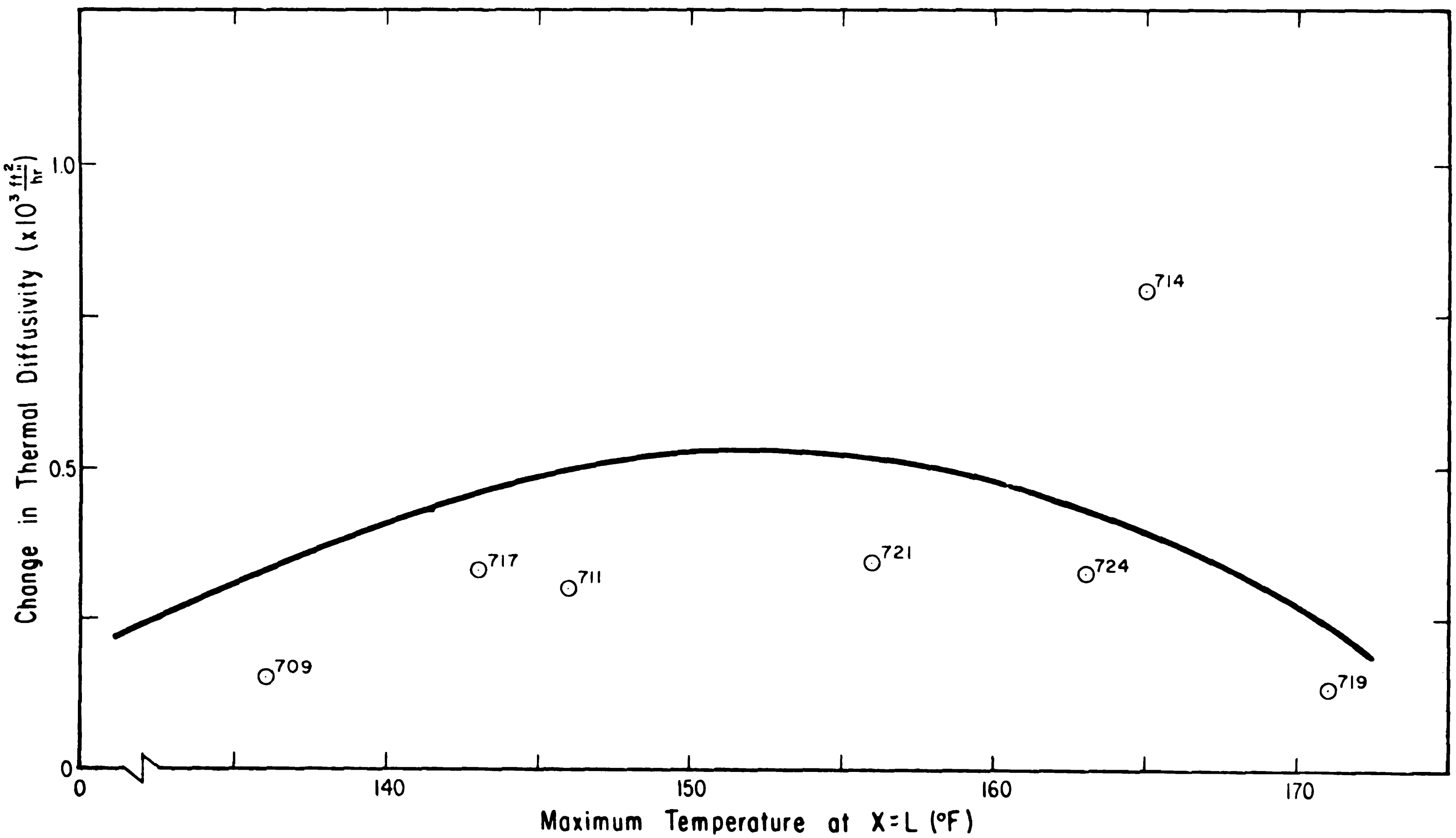


Figure 5.3. Relationship between the change in thermal diffusivity and the maximum temperature at X = L

Table 5.3. Date and description of tests tabulated with average values of the parameters

Test Series No.	Length of Test (min)	Maximum Temp. at X = 0 (°F)	Maximum Temp. at X = L (°F)	Change in Diffusivity ($X10^{-3}$ ft^2/hr)	Heat Exposure (°F - min)	Elastic Modulus Heated Potato (psi)	Specific Gravity Heated Potato
709	10	162	135	0.148	36.63	355.11	1.0375
711	10	179	146	0.297	186.73	366.43	1.0514
721	10	195	155	0.342	315.30	351.75	1.0477
724	15	195	163	0.322	505.76	266.66	1.0489
717	4	212	142	0.327	198.70	253.65	1.0517
714	10	210	165	0.792	457.29	264.50	1.0457
719	15	212	171	0.136	674.87	176.33	1.0483

1. Thermal diffusivity increased as the maximum temperature was increased to 155°F.
2. Thermal diffusivity decreased for temperatures above 155°F.
3. The lowest and highest temperatures changed the thermal diffusivity by the same amount.

5.5d Elastic Modulus and Heat Exposure

The lower curve in Figure 5.2 shows that the initial influence of heat exposure was to increase the elastic modulus or to make the potato section less stiff and more "rubbery." Additional heat exposure made the potato sections softer. These results are comparable to the findings of Tuomy _et al_. (1963) with respect to the influence of heat on meat; as heat treatment increased the toughening increased. Tenderness was shown to be dependent on both time and temperature.

The decrease in elastic modulus with increasing heat exposure began in the area of the 711 and the 717 test series. A comparison of the data in Table 5.3 for these tests shows that a long time and low temperature (10 min and 179°F) had the same influence on elastic modulus as a higher temperature and short time (4 min and 212°F). Note that the heat exposures are similar, being 186.73 °F-min and 198.70 °F-min, respectively. Similar comparisons can be made for the 714 and the 724 test series; the temperatures and times were different but the heat exposures and the resulting elastic moduli were equivalent.

The relationships between elastic modulus and heat exposure are shown more vividly in Figures 5.5 and 5.6. The rupture of a 719 test series potato between the parallel plates is shown in Figure 5.5. Heat exposure increased from left to right on the potato sections in Figure 5.6. Elastic modulus tests on the potato sections in Figures 5.4 and 5.6 resulted in the plots shown in Figures 5.7, 5.8, and 5.9. In the latter figures, the first break in the slope of the force-time line coincided with the initial rupture of the potato section. Approximately half of the heat treated potato sections of the 721 test series exhibited broken force-time curves. All of the heat-treated potato sections of the 714, 719, and 724 test series exhibited broken force-time curves. In general, the break occurred with decreasing values of force as the heat exposure was increased.

The correlation between the elastic modulus and heat exposure was given by:

$$E = 3.568\text{x}10^{2} + (1.144\text{x}10^{-1} \times HE) - (5.786\text{x}10^{-4} \times HE^{2}) \qquad (5.4)$$

where: E = elastic modulus (psi)

HE = heat exposure (°F-min)

The rms value of the correlation was 36.53 psi.

Figure 5.4. Representative heat treated potato sections and corresponding semi-infinite cylinders. Test series numbers are, from left to right, 717, 714, and 719.

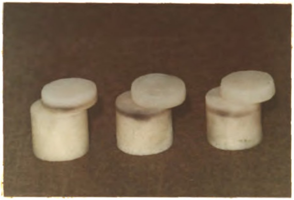
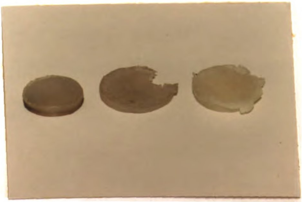


Figure 5.5. Rupture of heat treated potato section representative of test series number 719

Figure 5.6. Representative ruptured heat treated potato sections. Test series numbers are, from left to right, 717, 714, and 719.



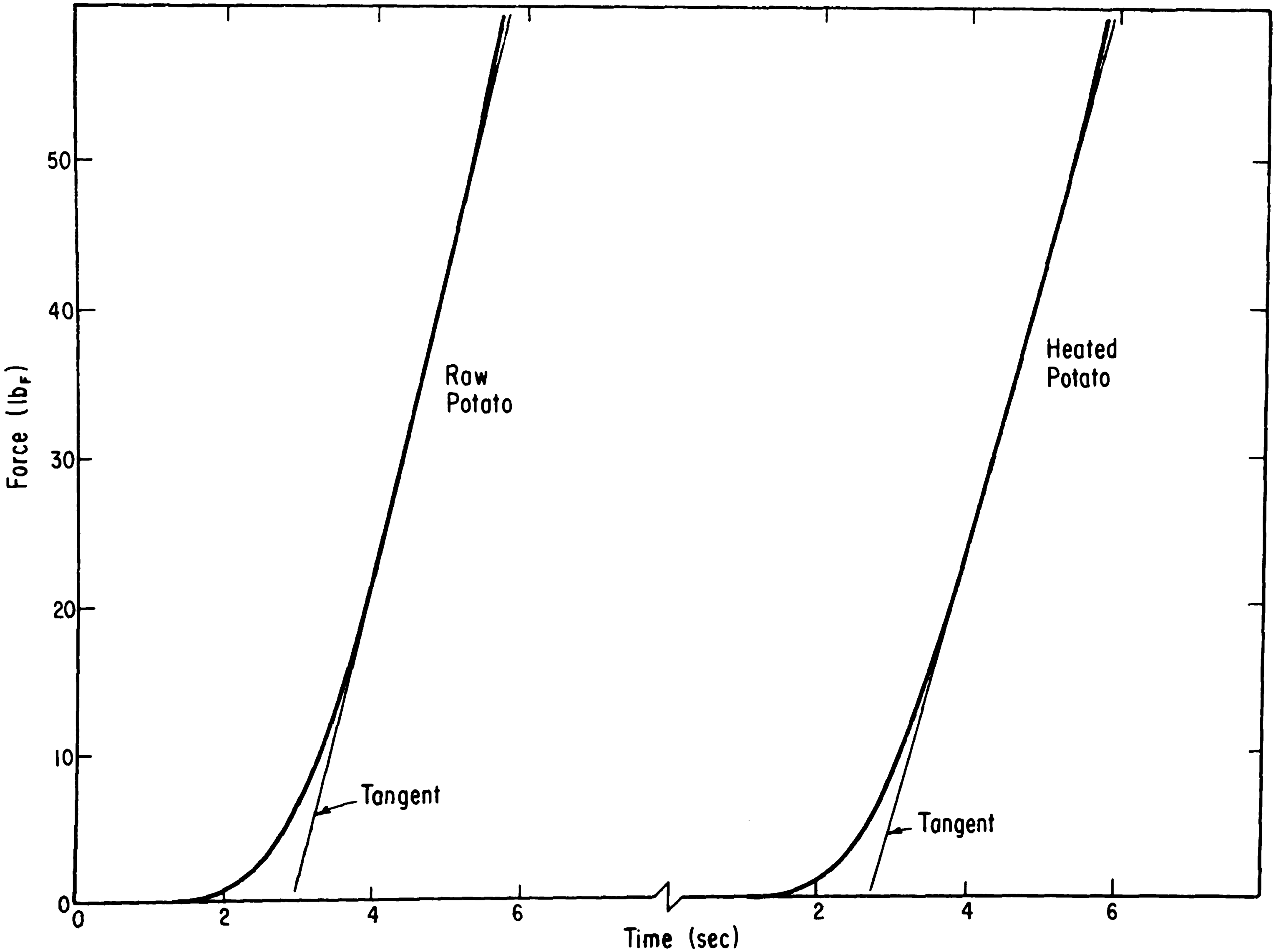


Figure 5.7. Representative force-time curves of 717 test series

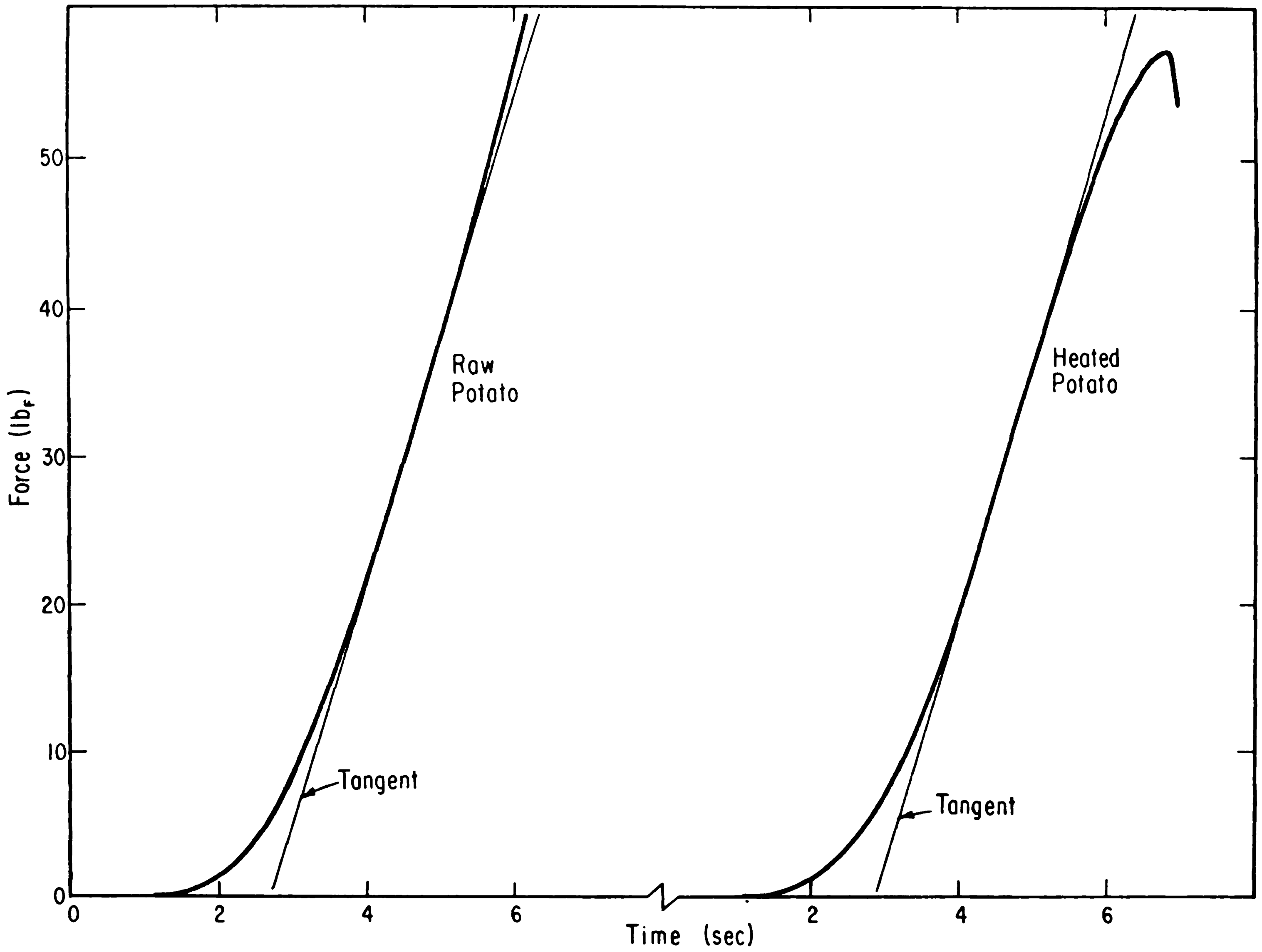


Figure 5.8. Representative force-time curves of 714 test series

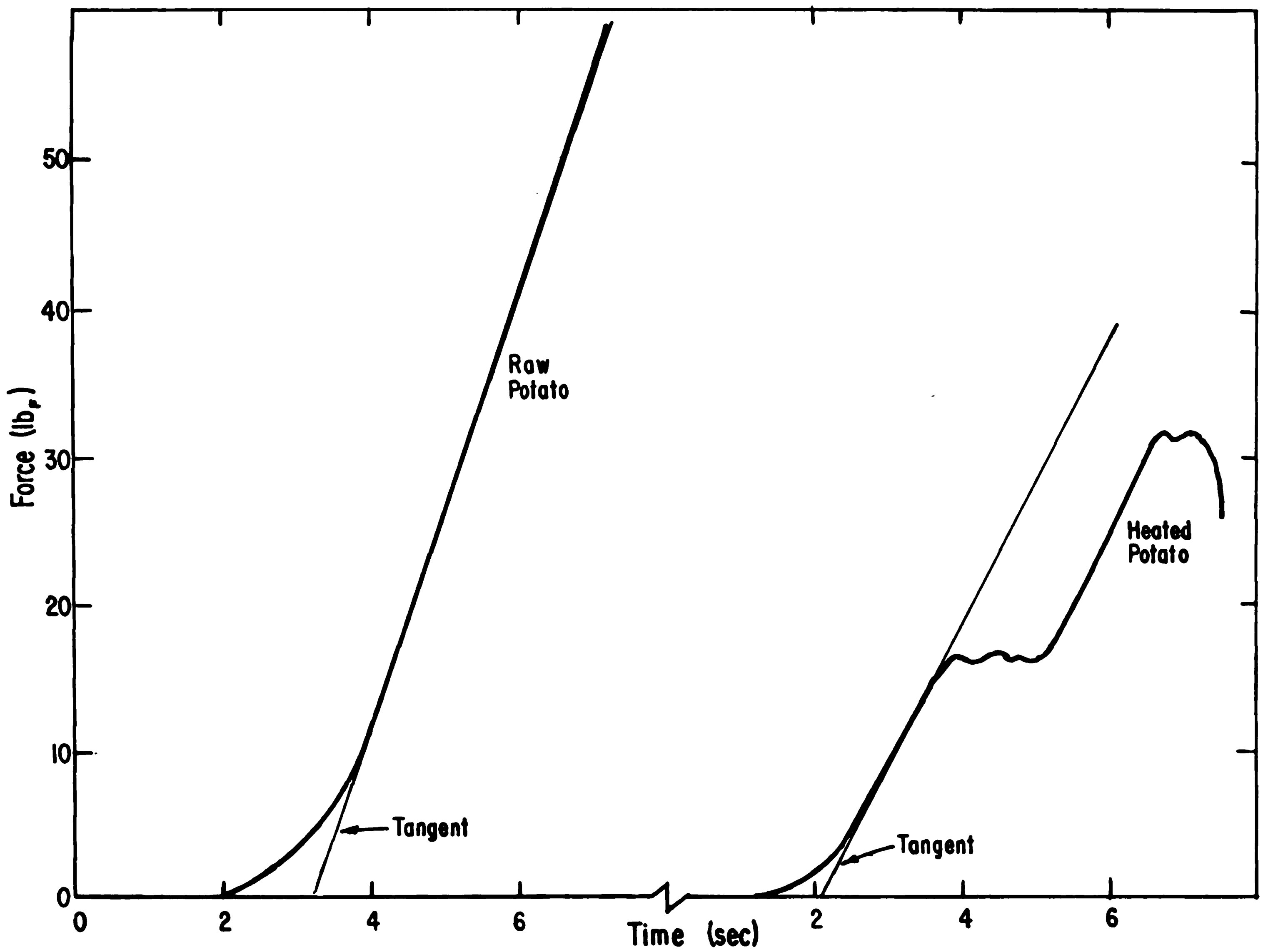


Figure 5.9. Representative force-time curves of 719 test series

5.5e Thermal Diffusivity and Elastic Modulus

The plot of thermal diffusivity and elastic modulus against a common parameter of heat exposure in Figure 5.2 indicates that diffusivity and elastic modulus have similar behaviors with respect to heat exposure. As heat exposure was increased, diffusivity and elastic modulus increased a small amount and then decreased. The initial rapid decrease in the elastic moduli of the potato sections was accompanied by the maximum increase in thermal diffusivity.

5.6 Application of Results

The thermal diffusivity and the elastic moduli of the heat treated potato sections are plotted in Figure 5.2 to indicate a unique application of physical and thermal properties. Elastic modulus was a measure of the degree of cooking or heat treatment of the potato. Therefore, a potato processor could specify a desirable elastic modulus for his product. An engineer could use the curves in Figure 5.2 to select the required heat exposure for the product. A value for heat exposure would permit an engineer to select the most desirable combination of temperature and time with respect to such factors as energy sources, equipment capacity, production rates, and costs of operation.

From the chosen point on the elastic modulus curve, a vertical line would be extended to the thermal diffusivity curve. Predetermined values of density and specific heat of the potato would be used with the value of thermal diffusivity to calculate the thermal conductivity of the potato. Fourier's heat conduction equation

$$q = - k A \frac{dT}{dX} \tag{5.5}$$

where: q = heat requirements (Btu/hr)

would be used to determine the energy requirements of the process. The advantages of determining the energy requirements of the process were discussed in chapter one.

6. CONCLUSIONS

1. The finite difference method of calculating the thermal diffusivity from temperature history data provided less variability than the guarded hot plate method and the Cenco-Fitch apparatus used by other researchers.

2. The thermal diffusivities calculated for the potato sections at time equal to 50 seconds had lower root mean square values than the values calculated at time equal to 100 seconds.

3. The thermal diffusivity of Excel potatoes decreased during a 15-day storage at 40°F. The 15-day storage had no influence on other parameters.

4. The specific gravity of the raw potato sections was not related to any of the determined thermal or physical property parameters.

5. The thermal diffusivity of the potato sections was related to the maximum temperature at X = L. As temperature increased, the thermal diffusivity increased up to a maximum and then decreased with higher temperatures.

6. The thermal diffusivity of the potato sections was related to heat exposure. As heating increased, thermal diffusivity increased up to a maximum and then decreased with additional heating.

7. The heating of the potato section initially increased the elastic modulus. As cooking progressed, the elastic modulus decreased rapidly.

8. A sudden decrease in elastic modulus of the potato sections was accompanied by the maximum increase in thermal diffusivity.

9. The maximum thermal diffusivity was associated with the starch gelatinization of the potato section.

7. RECOMMENDATIONS FOR FUTURE WORK

The results of this research have indicated an exigency to investigate the following areas:

1. Determine the relationships between time and temperature for the heat exposure of food products. Derive a standard definition for heat exposure that would have universal application and acceptance.

2. Determine the individual contributions of thermal conductivity, density, and specific heat to the variations of thermal diffusivity with respect to processing food products from the raw state to the cooked state.

3. Investigate the existence of critical points or points of maximum change in the thermal properties of food products.

4. Define the cooked state of food products in terms of elastic modulus or by standard engineering tests.

5. Determine whether or not meats, fruits, and vegetables have similar curves for relationships between thermal properties and physical properties.

6. With respect to vegetables, investigate the variation of thermal diffusivity with time in storage and relate the variation to some defined parameter.

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APPENDIX A

Thermal Diffusivity Computer Program

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FTN5.11                                                                   08/17/66

          PROGRAM HORNIK
C         FIND THERMAL DIFFUSIVITY IN A FINITE WALL OF A SEMI-INFINITE POTATO WHERE
C         NTIM = NO. OF INPUTS, TIM = TIMES OF INPUTS, TZER = TEMP AT X = 0
C         TXL = TEMP AT X = L, TXINF = TEMP AT X = INFINITY, DT = TIME STEP,
C         YMAX = LENGTH OF CALCULATION, ALP = ASSUMED ALPHA, SMINFL = SEMI-INFINITE
C         LENGTH, TBEG = INITIAL TEMP, MN = NO. OF NODES, JL = THERMOCOUPLE
C         POSITION AT X = L, INDEX = COUNTER, TT = STARTING TIME, TMOV = TIME JUMP
C         BETWEEN TWO MEASURED TEMPS, MAXC = COUNTER, PL = LENGTH OF POTATO SLICE
C         AT X = L, JJ = MIDDLE NODE, TX = TIME STEP, T = CALCULATED TEMP,
C         X = CALCULATED DISTANCE
C         N= NUMBER OF TESTS IN THE PROGRAM
          DIMENSION T(50), TZER(300), TXL(300), TXINF(50), TIM(50), X(50), T
         1ESTNO(50), PL(50), TBEG(50)
          READ 98, NTIM,MN,JL,DT,YMAX,ALP,N
       98 FORMAT (3I10,3F10.2,I10)
          PRINT 10
       10 FORMAT (//(10HNO. INPUTS,5X,9HNO. NODES,5X,8HX=L NODE,5X,2HDT,5X,4H
         1YMAX,5X,5HALPHA,5X,12HNO. OF TESTS))
          PRINT 99, NTIM,MN,JL,DT,YMAX,ALP,N
       99 FORMAT (5X,I2,12X,I2,10X,I2,7X,F5.2,4X,F4.0,5X,F5.3,8X,I3)
          READ 110, (TIM(IA), IA=1,NTIM)
      110 FORMAT (8F10.1)
          PRINT 11
       11 FORMAT (//(8X,15HTIMES OF INPUTS))
          PRINT 310, (TIM(IA), IA=1,NTIM)
      310 FORMAT (8F10.2)
      101 DO 6 I=1,N
      103 FORMAT (/, F10.3, 10F10.3)
      100 FORMAT (F10.3,1X,10F10.3)
      102 FORMAT (I10,F15.2,2F15.3,2F15.2)
          ITER=1
          ALP=0.005
          READ 20, TESTNO(I),PL(I),TXINF(I)
       20 FORMAT (3F10.3)
          IF (TESTNO(I)) 6,6,23
       23 PRINT 21, TESTNO(I)
       21 FORMAT (//(8HTEST NO.,F8.3))
          PRINT 22, PL(I)
       22 FORMAT (//(5X,24HPOTATO LENGTH AT X=L IS ,F8.3,1X,6HINCHES))
          READ 111, (TZER (IB), IB=1, NTIM)
      111 FORMAT (8F10.2)
          PRINT 12
       12 FORMAT (//(8X,19HTEMPERATURES AT X=0))
          PRINT 311, (TZER(IB), IB=1, NTIM)
      311 FORMAT (8F10.2)
          READ 115, (TXL(IH), IH=1,NTIM)
      115 FORMAT (8F10.2)
          PRINT 16
       16 FORMAT (//(8X,19HTEMPERATURES AT X=L))
          PRINT 316, (TXL(IH), IH=1,NTIM)
      316 FORMAT (8F10.2)
          PRINT 14, TXINF(I)
       14 FORMAT (//(8X,23HTEMPERATURE AT X=INFINITY IS,F7.2))
          TBEG(I)=TXINF(I)
        5 PRINT 15
       15 FORMAT (///(5X,9HITERATION,4X,11HDIFFUSIVITY))
```

FTN5.11 08/17/66

```
      PRINT 314, ITER,ALP
  314 FORMAT (6X,I2,5X,F15.8)
      INDEX=1
      TT= TIM(INDEX+1)
      INDEX=INDEX+1
      TMOV= TIM(INDEX)-TIM(INDEX-1)
      TMOVM=TMOV-.0001
      MAXC= 10.0
      SLT= 0.0
      RM=0.0
      SCLT= 0.0
      DO 200 K=1,50
      X(K)=TREG(I)
  200 T(K)=TREG(I)
      XMN=MN
      SMINFL=5*PL(I)
      DX=SMINFL/XMN
      XM=(DX*DX/(ALP*DT))*25.0
      XMM= XM-1.0
      XMP= XM+1.0
      MNP= MN+1
      ALPM= (ALP*0.0001)
      ALPE= ALP+ (0.0001*ALP)
      XME=(DX*DX/(ALPE*DT))*25.0
      HRM= XME-1.0
      HRP= XME+1.0
C                  BEGIN ODD PASS
  201 TX=0.0
      GO TO 212
  228 TX= TX+0.5
  212 T(1)=(TX/TMOV)*(TZER(INDEX)-TZER(INDEX-1))+TZER(INDEX-1)
      T(MNP)=(TX/TMOV)*(TXINF(INDEX)-TXINF(INDEX-1))+TXINF(INDEX-1)
  202 DO 203 KK=2,MN
      T(KK)= (T(KK-1)+T(KK+1)+XMM*T(KK))/XMP
  203 CONTINUE
      X(1)= T(1)
      X(MNP)= T(MNP)
      DO 303 KK=2,MN
      X(KK)=(X(KK-1)+X(KK+1)+HRM*X(KK))/HRP
  303 CONTINUE
C                 FIND  SUMMATION
      IF(TX-TMOVM) 226,222,222
  222 ELT=(X(JL)-T(JL))/ALPM
      CLT=TXL(INDEX)-T(JL)
      RM= RM+(CLT**2)
      SCLT= SCLT+(CLT*ELT)
      SLT= SLT+(ELT*ELT)
      PRINT 105, TT,(T(ID),ID=1,9)
      PRINT 106,TT,(X(ID), ID=1,9)
      PRINT 102, JL,TXL(INDEX),ELT,CLT,SCLT,SLT
      INDEX= INDEX+1
      TMOV= TIM(INDEX)-TIM(INDEX-1)
      TMOVM= TMOV-.0001
      TT= TT+ ABSF(TMOV)
      IF(TT-YMAX)206,206,205
C                  BEGIN EVEN PASS
```

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```
  206 TX= 0.0
      GO TO 214
  226 TX= TX+0.5
  214 T(1)=(TX/TMOV)*(TZER(INDEX)-TZER(INDEX-1))+TZER(INDEX-1)
      T(MNP)=(TX/TMOV)*(TXINF(INDEX)-TXINF(INDEX-1))+TXINF(INDEX-1)
      DO 204 K2=2,MN
      K3=MN-K2+2
      T(K3)= (T(K3-1)+T(K3+1)+XMM*T(K3)) / XMP
  204 CONTINUE
      X(1)= T(1)
      X(MNP)= T(MNP)
      DO 304 K2=2,MN
      K3=MN-K2+2
      X(K3)= (X(K3-1)+X(K3+1)+HRM*X(K3))/HRP
  304 CONTINUE
      IF(TX-TMOVN) 226,230,230
C                     FIND  SUMMATION
  230 ELT=(X(JL)-T(JL))/ALPM
      CLT=TXI(INDEX)-T(JL)
      RM= RM+(CLT**2)
      SCLT= SCLT+(CLT*ELT)
      SLT= SLT+(ELT*ELT)
      PRINT 103, TT,(T(ID),ID=1,9)
      PRINT 105,TT,(X(ID), ID=1,9)
      PRINT 102, JL,TAL(INDEX),ELT,CLT,SCLT,SLT
      INDEX= INDEX+1
      TMOV= TIM(INDEX)-TIM(INDEX-1)
      TMOVN= TMOV-.0001
      TT= TT+ ABSF(TMOV)
      IF(TT-XMAX) 201,201,205
  205 CONTINUE
C                     FIND DA
      DA= SCLT/SLT
      RALP= DA/ALP
      RMS= SQRTF(RM/(INDEX  ))
      PRINT 25
   25 FORMAT (//(8HMODE NO.,1X,11HDIFFUSIVITY,2X,11HDELTA ALPHA,3X,13HDEL
     1TA A/ALPHA,5X,9HRMS VALUE))
      PRINT 207, JL,ALP,DA,RALP,RMS
  207 FORMAT (I15,4E15.8)
      IF (ITER-MAXC) 208,208,211
  208 IF (ABSF(RALP)-.00005) 211,211,210
  210 ALP= ALP+DA
      ITER=ITER+1
      GO TO 5
  211 GO TO 101
    6 CONTINUE
      END
```

Although this program has been used by the author, no warranty, expressed or implied, is made as to the accuracy and functioning of the program.

APPENDIX B

Table B.1a. Summary of data and results

Test No.	Length of Test (min)	Max. Temp. at X = O (°F)	Max. Temp. at X = L (°F)	Thermal Diffusivity Raw Potato (ft^2/hr)	Thermal Diffusivity Heated Potato (ft^2/hr)	RMS Values of Difference Between Experimental and Calculated Temperatures Resulting from Thermal Diffusivity Iterations Raw Potato (°F)	RMS Values ... Heated Potato (°F)	Elastic Modulus Raw Potato (psi)	Elastic Modulus Heated Potato (psi)	Specific Gravity of Raw Potatoes Used for E.M. Test	Specific Gravity of Raw Potatoes Used for Heating	Heat Exposure (°F – min)
709-2	10	164.75	134.5	5.281×10^{-3}	5.046×10^{-3}	0.33[illegible]	0.314	357.[illegible]	334.34	1.0330	1.0218	41.[illegible]
709-3	10	153.63	135.5	5.086	5.215	0.142	0.341	342.06	397.26	1.0221	1.0193	55.47
709-4	10	162.12	133.75	4.807	5.157	0.130	0.257	306.44	328.33	1.0314	1.0257	43.16
709-5	10	160.37	132.5	5.358	5.638	0.107	0.132	32[illegible].70	365.67	1.0324	1.0296	13.68
710-1	10	164.25	135.25	[illegible].718	4.875	0.31[illegible]	0.402	345.25	381.62	1.0451	1.0349	47.43
710-2	10	161.5	135.5	5.412	4.807	0.375	0.429	325.34	333.32	1.0551	1.0512	24.62
710-3	10	161.62	137	5.349	5.143	0.173	0.402	344.66	348.[illegible]	1.0630	1.0528	25.53
710-4	10	163.37	136.5	5.293	[illegible]	0.158	0.22[illegible]	345.73	[illegible]	1.0462	1.0434	[illegible]
710-5	10	163.28	135.75	4.999	5.802	0.187	0.1[illegible]	346.18	[illegible]	1.0519	1.0452	52.39
710-6	10	155.25	131	4.329	5.072	0.232	0.322	317.72	331.83	1.0641	1.0517	5.47
711-1	10	182.37	147	5.137	5.078	0.237	[illegible]	353.75	[illegible]	1.0655	1.0522	239.54
711-2	10	182.12	148	5.038	5.839	0.335	0.465	317.42	365.81	1.0660	1.0526	201.55
711-3	10	186.75	146.25	4.704	5.[illegible]13	0.117	0.345	328.17	387.34	1.0535	1.0469	1[illegible]0.54
711-4	10	179.0	147	4.535	6.068	0.336	0.44[illegible]	290.73	416.33	1.0[illegible]34	1.0457	175.15
711-6	10	177.25	144	5.699	5.491	0.312	0.398	346.40	[illegible]	1.0654	1.0634	1[illegible]8.44
711-7	10	177.87	146	5.724	5.728	0.345	0.362	344.87	4[illegible].14	1.046	1.0441	1[illegible]2.[illegible]
711-8	10	175.5	143.75	5.019	5.479	0.402	0.331	2[illegible]3.84	358.43	1.0641	1.0516	170.23
711-9	10	177.5	145.75	4.831	5.976	0.414	0.302	327.65	361.62	1.0487	1.0459	166.8[illegible]
711-10	10	175.0	143	4.638	6.135	0.312	0.257	313.93	348.34	1.05[illegible]	1.0525	154.16
711-12	10	177.25	146.5	5.351	6.143	0.360	0.277	306.[illegible]	345.89	1.0701	1.0562	153.2[illegible]
714-1	10	209.5	163.5	4.895	4.993	1.051	0.376	313.94	211.01	1.0661	1.0578	449.3[illegible]
714-2	10	210.25	167	5.245	4.591	0.474	0.341	351.47	273.26	1.0551	1.0474	453.25
714-3	10	20[illegible].5	166.25	5.008	5.988	0.631	0.149	367.51	2[illegible]6.[illegible]8	[illegible]	1.0376	4[illegible]4.43
714-4	10	209.5	165	4.768	5.542	0.393	0.492	370.72	28[illegible].65	1.0596	1.0449	43[illegible].6
714-5	10	210	164	5.021	6.063	0.401	0.147	331.68	239.23	1.0564	[illegible]	[illegible]
714-7	10	212.5	165	4.620	5.560	0.256	0.176	330.21	215.84	1.0595	1.046[illegible]	473.[illegible]2
714-9	10	210.5	166.25	4.367	5.884	0.[illegible]51	0.184	366.45	2[illegible]3.15	1.0538	1.0456	46[illegible].32
714-11	10	211	165	4.746	4.992	0.509	0.110	368.13	240.58	1.0497	1.0412	469.36
714-12	10	210.5	164.25	4.873	6.144	0.419	0.363	335.12	255.65	1.0572	1.0516	4[illegible].62
714-13	10	210.5	167	4.382	6.109	0.399	0.135	383.43	263.85	1.0483	1.0377	465.10
717-1	4	213	143	5.103	5.245	0.247	0.298	456.42	388.74	1.0615	1.0497	204.26
717-2	4	211	144.5	5.738	5.614	0.720	0.208	351.73	386.80	1.0652	1.0514	188.17
717-3	4	211	143	5.046	5.516	0.546	0.288	363.79	342.56	1.0[illegible]87	1.055[illegible]	19[illegible].37
717-4	4	212	141	4.846	5.040	0.312	0.223	341.80	354.11	1.0546	1.0509	201.54
717-5	4	213	139.5	4.141	4.931	0.153	0.067	352.23	354.12	1.0763	1.0576	195.81
717-6	4	211	139	5.165	5.104	0.295	0.439	354.76	327.72	1.0571	1.0494	19[illegible]
717-7	4	212	144	4.747	5.326	0.388	0.311	334.37	306.89	1.0712	1.0571	202.15
717-9	4	212	145	5.156	5.326	0.263	0.236	324.11	380.78	1.0592	1.0373	196.12
717-10	4	212	143	4.256	4.634	0.349	0.210	347.22	352.62	1.0663	1.0509	200.38
717-11	4	212	142.5	4.259	4.998	0.274	0.210	362.95	342.60	1.0723	1.0568	202.48
719-1	15	213.5	170	3.702	3.702	0.631	0.341	329.39	195.66	1.0727	1.0582	705.50
719-2	15	211.5	172.75	3.599	4.124	0.680	0.735	344.42	195.48	1.0531	1.0438	652.18
719-3	15	213	174.25	4.321	3.923	0.497	0.533	354.23	209.68	1.0489	1.0334	685.04
719-4	15	211	169.5	3.635	4.248	0.557	0.423	330.60	191.35	1.0621	1.0519	683.18
719-5	15	212.25	167.75	3.927	3.770	0.769	0.876	313.83	228.63	1.0631	1.0543	639.78
719-6	15	210	172	3.712	3.860	0.588	0.390	31[illegible].01	145.27	1.0596	1.0481	659.62

For engineering purposes, the test results have an estimated accuracy of ± 10%.

Table B.1b. Summary of data and results

Test No.	Length of Test (min)	Max. Temp. at X = O (°F)	Max. Temp. at X = L (°F)	Thermal Diffusivity Raw Potato (ft^2/hr)	Thermal Diffusivity Heated Potato (ft^2/hr)	RMS Values of Difference Between Experimental and Calculated Temperatures Resulting from Thermal Diffusivity Iterations Raw Potato (°F)	RMS Values … Heated Potato (°F)	Elastic Modulus Raw Potato (psi)	Elastic Modulus Heated Potato (psi)	Specific Gravity of Raw Potatoes Used for E.M. Test	Specific Gravity of Raw Potatoes Used for Heating	Heat exposure (°F - min)
719-7	15	214.5	172.25	4.033×10^{-3}	3.801×10^{-3}	0.578	0.684	303.13	136.73	1.0603	1.0506	689.39
719-8	15	210.5	172	3.882	4.158	0.636	0.623	340.26	168.60	1.0534	1.0438	657.14
719-9	15	211.5	174	4.226	4.636	0.699	0.839	318.50	137.65	1.0497	1.0350	655.38
719-10	15	214.25	169.75	4.004	4.174	0.825	0.547	330.70	154.25	1.0725	1.0624	718.52
721-1	10	194.25	150	3.405	3.599	0.311	0.433	336.61	354.96	1.0569	1.0432	295.72
721-2	10	196	152	2.978	3.621	0.305	0.511	337.66	353.59	1.0628	1.0385	316.79
721-5	10	196.5	154.5	3.888	4.567	0.596	0.717	342.37	316.15	1.0638	1.0527	309.35
721-6	10	195.75	151.5	3.737	4.280	0.637	0.608	290.66	307.52	1.0659	1.0542	306.87
721-7	10	195.25	155	3.820	4.371	0.604	0.754	290.12	390.49	1.0570	1.0452	321.13
721-8	10	195	156.5	3.955	3.849	0.744	0.603	324.97	379.18	1.0603	1.0471	309.97
721-9	10	195	156	3.982	3.914	0.563	0.619	332.85	398.13	1.0591	1.0399	322.37
721-10	10	195.75	155.5	3.800	4.256	0.524	0.580	302.21	293.56	1.0666	1.0558	318.65
721-11	10	195.75	156.5	4.014	4.468	0.651	0.638	324.11	335.68	1.0607	1.0520	322.99
721-12	10	194.75	157.5	4.109	4.275	0.676	0.545	310.17	388.04	1.0589	1.0482	329.19
724-1	15	195.25	163	3.784	3.899	0.499	0.670	293.29	279.18	1.0407	1.0315	484.18
724-2	15	195.25	160.75	3.746	4.097	0.525	0.353	330.96	255.39	1.0639	1.0529	499.06
724-3	15	195.5	163	3.629	4.007	0.397	0.486	[illegible]	287.75	1.0455	1.0440	530.92
724-4	15	196	164	3.821	3.585	0.501	0.416	345.85	340.86	1.0554	[illegible]	[illegible]
724-5	15	196.5	163	3.299	4.153	0.488	0.577	272.24	132.44	1.0763	1.0625	532.54
724-6	15	194.5	161.25	3.275	3.948	0.327	0.542	323.30	371.27	1.0686	1.0485	[illegible]
724-7	15	195.5	165	4.212	4.187	0.385	0.569	268.66	243.48	1.0577	1.0491	520.14
724-8	15	195	162.5	4.103	4.202	0.634	0.639	305.14	263.17	1.0699	1.0551	[illegible]
724-9	15	194.25	164.75	3.796	4.197	0.588	0.525	346.44	214.50	1.0604	1.0545	[illegible]
724-10	15	195.75	164.5	3.555	4.174	0.952	0.432	309.75	[illegible]	1.0716	1.0582	511.46

For engineering purposes, the test results have an estimated accuracy of ± 10%.

Table B.2. Summary of average values of data and results

Date	Test Series No.	Length of Test (min)	Max. Temp. at X = 0 (°F)	Max. Temp. at X = L (°F)	Thermal Diffusivity Raw Potato (ft^2/hr)	Thermal Diffusivity Heated Potato (ft^2/hr)	RMS Values of Difference Between Experimental and Calculated Temperatures Resulting from Thermal Diffusivity Iterations Raw Potato (°F)	RMS Values of Difference Between Experimental and Calculated Temperatures Resulting from Thermal Diffusivity Iterations Heated Potato (°F)	Change in Thermal Diffusivity (ft^2/hr)	Elastic Modulus (psi)	Specific Gravity	Change in Heat Exposure (°F - min)
7-9-66	709	10	162	135	5.163×10^{-3}	5.311×10^{-3}	0.220	0.313	0.148×10^{-3}	355.11	1.0375	36.63
7-11-66	711	10	179	146	5.468	5.765	0.317	0.393	0.297	366.43	1.0514	186.73
7-21-66	721	10	195	155	3.778	4.120	0.561	0.601	0.342	351.75	1.0477	315.30
7-24-66	724	15	195	163	3.722	4.044	0.530	0.521	0.322	[illegible]	1.0489	505.76
7-17-66	717	4	212	142	4.846	5.173	0.355	0.249	0.327	253.65	1.0517	[illegible]
7-14-66	714	10	210	165	4.800	5.593	0.49	0.252	[illegible]	264.50	[illegible]	[illegible]
7-19-66	719	15	212	171	3.904	4.040	0.646	0.599	0.136	[illegible]	[illegible]	674.87

For engineering purposes, the test results have an estimated accuracy of ± 10%.

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