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To the Graduate Council:

I am submitting herewith a dissertation written by Zoe Ann Holmes, entitled "Thermal Conductivity and Related Properties of Heated Ground Pectoral Turkey Muscles." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Food Science.

Ernest E. Goetz
Major Professor

We have read this dissertation
and recommend its acceptance:

Mary J. Hitchcock

Peter W. Cowling

J. L. Collins

Bernadine Meyer

Ada Marie Campbell

Accepted for the Council:

Victor A. Smith
Vice Chancellor for
Graduate Studies and Research

THERMAL CONDUCTIVITY AND RELATED PROPERTIES OF HEATED
GROUND PECTORAL TURKEY MUSCLES

A Dissertation
Presented to
the Graduate Council of
The University of Tennessee

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

by
Zoe Ann Holmes
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ABSTRACT

Thermal conductivity, in association with characteristics of the thermodynamic medium at the food surface, establishes heat flow at the food boundary and reflects the transient properties meat has undergone during temperature change. The purpose of this research was to design and build an apparatus to measure thermal conductivity and to study some of the transient properties of ground pectoral turkey muscles.

Ground turkey pectoral muscles were heated in 9 increments from 77 to 185°F and held at end point temperature for 0 or 15 minutes. Thermal conductivity was calculated directly from data or indirectly by solving for diffusivity and then calculating for thermal conductivity. Water-holding capacity (expressible moisture index, total moisture, cooking loss), protein solubility (protein extractability), and change in pH were studied to determine the possible relation between thermal conductivity and protein denaturation.

The thermal conductivity values were expressed in terms of cal/sec cm °F or Btu/hr ft °F. With both methods of calculation, thermal conductivity values were significantly affected ($P < 0.05$) by end point temperature at the 0 minute but not at the 15 minute holding time even though holding times per se had no significant effect.

Several approaches and modes of calculation of the thermal properties suggested that conductivity values were influenced by a number of factors. Protein denaturation was postulated as a factor

contributing to inconsistencies in thermal values. Significant ($P < 0.01$) effect of temperature upon cooking loss, total moisture, and expressible moisture suggested protein denaturation. The water-holding capacity expressed by these determinations tended to decrease with increasing temperature. These changes were greatest in the end point temperature range of 104 to 158°F. Protein solubility decreased with increase in end point temperature from 77 to 131 to 185°F. A protein fraction extracted with phosphate buffer ($I = 0.05$, pH 7.6) decreased in solubility 30 percent and 60 percent from an initial end point at 77 to 131 to 185° F, respectively. The pH was significantly ($P < 0.01$) affected by temperature. With all parameters, no difference was found between holding times.

It can be postulated that the denaturation phenomenon in the current experiment influenced conductivity values by the changes in structure and composition of the muscle system as well as by the energy consumption involved in conformational changes of the protein. However, specific relationships were not defined.

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CHAPTER I

INTRODUCTION

Present technology has made apparent the necessity of characterization of thermal properties for optimization of development of food processing equipment and procedures and food formulations (Lusk et al., 1964; Saravacoas and Meyer, 1967; Hill et al., 1967; Wadsworth and Spadero, 1969). Current and historic literature indicate an apparent consensus that heat affects the chemical and physical characteristics of a food product. Conclusive definitive information on mode of heat action attributable to thermal properties is difficult to obtain since many of the experiments have been highly individualistic and insufficient detailed sample delineation has been given (Lentz, 1961). Also, the pertinent literature in this area indicates a lack of recognition of the complex dynamic nature of food systems.

Heat curves have been related to heat transfer and other thermal parameters and used to define processing conditions within the food industry (Thompson, 1919; Charm, 1963; Hayakawa, 1969). However, such curves and associated parameters as the coefficients are highly related to the equipment and product formulations and thus the breadth and applicability of the defined parameters are limited. The determination of thermal properties as well as the study of other chemical, biological and physical properties of a food product become increasingly important with modern technology.

The purpose of this research was to design and build an apparatus to measure thermal conductivity and to study some related properties of heated ground pectoral turkey muscles.

CHAPTER II

REVIEW OF LITERATURE

I. THERMAL CHARACTERISTICS AND PROPERTIES

The thermal properties of a food refer to the mode of action of heat distribution in a food product (Dickerson and Read, 1968). Two thermal properties of importance are thermal conductivity and thermal diffusivity. Thermal conductivity is a parameter that indicates the transient processes meat has undergone during temperature change. Conductivity, in association with characteristics of the thermodynamic medium at the food surface, establishes heat flow at the food boundary. Thermal diffusivity is the actual ability of a food to conduct heat to adjacent molecules, serving as a measurement of the quantity of heat absorbed by a food at a given temperature.

Some thermal properties may be expressed in dimensionless parameters. The heat transfer coefficient was reported by Saravacos and Meyer (1967) as a nondimensional expression of heating rate. It was used for calculation of heat balance in fruit products in an agitated kettle. Coefficient methodology was used by Hitchcock (1968) to simulate mathematical models for heat transfer in prepared foods. Earle and Fleming (1967) used a dimensionless temperature ratio to compare cooling rates in various sized lamb and mutton carcasses. Dimensionless parameters were used by Hayakawa (1969) to assist in delineation of thermal properties and calculation of the average temperature in a cylindrical

can during processing. Thermal diffusivity then was determined from these parameters.

Methods and Procedures of Determining Thermal Characteristics and Properties

Thermal properties in foods have been studied by modifications of five principal methods (Woodams and Nowrey, 1968; Qashou et al., 1970): (1) the concentric cylinder method, (2) the concentric sphere method, (3) the parallel plate method, (4) the thermal diffusing method, and (5) the line-source technique. A review of the literature indicates that modifications of the parallel plate method, the thermal diffusing method and the line-source technique are the approaches used most frequently for determination and calculation of thermal conductivity and/or thermal diffusivity in food products.

The principal difficulty with use of the concentric cylinder and concentric sphere methods is the lack of prevention of convection currents and of later applicability to food products. Both of these factors decrease the validity of thermal conductivity values (Woodams and Nowrey, 1968). The plate method, or modification of it, is the one most frequently used for evaluation of thermal conductivity but miscalculation attributable to heat loss from the sample are possible. In using a modified parallel plate method with beef, Melgar (1970) obtained thermal conductivity values 2 to 4 times greater than published literature values. This was postulated as attributable to lack of correct heat input data and equipment factors. Miller and Sunderland (1963), who used a guarded hot plate method, indicated decreased validity in

conductivity values as the temperature differences between the hot and cold plate lessened. The plate method data might become progressively less valid with increasingly complex heat sensitive food systems.

The line-source technique is purported to alleviate some of the disadvantages of the previously cited methods (Qashou et al., 1970). This technique offers advantages in that special dimensions are not required for the meat sample, the transient test time is of short duration, a small temperature change occurs during testing, and data collection enable cross-checking calculation of thermal diffusivity values. The line-source method also has the capability for determination of thermal diffusivity without data on sample density (ρ) and specific heat (C_p) (Nix et al., 1967). Although a uniform temperature throughout the sample is required, Nix et al. (1969) observed that this method is applicable for determination of thermal parameters of samples with amorphous properties. Qashou et al. (1970) defined the basis of the line-source technique as follows: "The temperature rise at any point in an infinite solid containing a suddenly initiated, constant rate, line heat source is a function of spatial position, time, thermal properties of the solid, and source strength."

Although not a definitive method of characterization of thermal properties, differential thermal analysis (DTA) is considered as a relatively precise tool for indication of changes in protein during heating (Steim, 1965). Duckworth (1971) defined DTA as a technique whereby the temperature difference between an inert reference and the test substance is recorded. Usually this is done by constant rate heating or cooling for a given time.

Calculation and Relationship of Thermal Characteristics and Properties

There are numerous mathematical approaches that have possible applicability in a complete detailed delineation of data obtained from the heating of food systems. However, only those calculations important and/or applicable to the research project reported and the capabilities of the investigator are included.

The two properties, conductivity (K) and diffusivity (a), are mathematically related by the following equation:

$$\text{Equation 1: } a = \frac{K}{(\rho)(C_p)}$$

Equation 1 is sometimes called the thermal diffusing method of calculating conductivity (Woodams and Nowrey, 1968). With this method, density (ρ) and specific heat (C_p) are requisite. As early as 1919, Thompson used temperature-time curves and the effect of size and shape of the canned food containers to calculate diffusivity from Equation 1.

Much of the delineation of thermal conductivity under transient and steady-state conditions pertinent to the line-source technique uses probability methods involving intricate mathematical approaches (Leishman, 1968). However, many of the model and problematical approaches are concerned with materials used by industrial and chemical engineers and these have less temperature sensitivity than food.

Several approaches to calculation of thermal properties in food systems have been used (Dickerson and Read, 1968; Qashou et al., 1970;

Cowling, 1972). Dickerson and Read (1968) used a modification of the line-source method developed by Voss (1955) and calculated conductivity using Equation 2. Employment of the equation necessitated knowledge of the amperes (I) and resistance of the heater wire (ohms/ft,Z) as well as two temperatures (V2,V1) and times (T2,T1).

$$\text{Equation 2: } K = \frac{(3.413(I^2)(Z)(\ln(T2/T1)))}{(4.0(\pi)(V2-V1))}$$

Using a thermal conductivity probe, units obtained for the parameter were Btu/hr ft °F.

Qashou et al. (1970) calculated conductivity using Equation 3.

$$\text{Equation 3: } V2 - V1 = q' / (4(K)(\pi)) (\ln((T2-T_0)/(T1-T_0)))$$

Of particular pertinence in this equation is the time correction term of T_0 (initial time) to account for discrepancies from the theory. Line-source strength is designated as q' in Equation 3.

Cowling (1972) used a different approach for calculation of thermal conductivity in a food system. An exact mathematical solution to a line-heat source in an infinitely long cylinder with insulated walls was obtained. When the sample was at a uniform temperature, data were collected to supply the needed temperatures, times, radii, and heat input values. An appropriate FORTRAN program and the IBM 360/65 computer system solved thermal diffusivity and calculated thermal conductivity.

In the three approaches cited for calculation of thermal conductivity from data obtained by the line-source technique, the importance of minimizing temperature error is apparent. The curve-fitted calculated temperatures were used advantageously (Cowling, 1972). By use on the IBM 360/65 computing system of an updated version of the GECAP (V-I, 9-15-71) program, it was possible to print the coefficients for the Nth degree (0 to 10 degree tested) polynomial calculated by the best-fit function (Beadle, 1971).

Thermal conductivity has been expressed in different units by different investigators. For example, Poppendiek et al. (1966) indicated that the thermal conductivity values obtained from use of a modified parallel plate technique on bovine muscle were 0.305 Btu/hr ft °F or $1.261 \text{ cal/cm sec } ^\circ\text{C} \times 10^{-3}$. They used 1 Btu/hr ft °F to equal $4.135 \times 10^{-3} \text{ cal/cm sec } ^\circ\text{C}$. Miller and Sunderland (1963) reported that Btu/hr ft °F were equivalent to units of Btu/hr ft² °F/ft.

Factors Influencing Thermal Characteristics

Characterization of thermal properties in food systems is difficult. A comparison of experimental data from one study to another is confusing and misleading. Often there is a lack of information on experimental conditions as well as on the chemical and/or physicochemical characteristics of the sample itself. A summary of selected thermal conductivity values in the literature may be found in Table 1.

Using the modification of the line-source technique in the form of a probe, Morley (1966) observed that thermal conductivity values of

TABLE 1
INVESTIGATIONS CONCERNING THERMAL CONDUCTIVITY OF MEAT AND WATER

Substance	Temperature °F	K Values	Heat Flow ^a	Method ^b	Moisture %	Reference
Water	68	1.40 cal/cm ² sec °C/cm × 10 ⁻³				Lentz (1961)
Beef, lean	68-77 77-86 86-95 95-104 104-113 113-122 122-131 131-140 140-149 149-158 158-167 167-176 176-185 185-194 194-203	14.40 kcal cm/min cm ² °C × 10 ⁻⁵ 13.54 13.06 12.31 12.32 11.92 11.43 11.28 11.13 11.28 10.89 10.56 10.28 10.12 9.30		Parallel		Melgar (1970) ^c
Beef, lean	low	0.0038 g-cal/sec/cm ²		Parallel		Awbery and Griffiths (1933)
Bovine muscle	75-100	1.261 cal/cm sec °C × 10 ⁻³ 0.305 Btu/hr ft °F		Parallel		Poppendiek et al. (1966)
Beef, ground	42-44 37-38.5	0.2030 Btu/hr ft °F 0.2080		Line-Source	55.28 52.64	Qashou et al. (1970)
Chuck, ground	43-43.3 37-38.7	0.2350 0.2530			67.13 61.63	
Water	41	0.326 Btu/hr ft °F		Parallel		Lentz (1961) ^c
Beef, lean	36.5 32.0 -4.0	0.279 0.284 0.904	1		74.0	
Beef, lean	35.0 32.0 -4.0	0.290 0.284 0.904	2	Parallel	75.0	
Turkey breast	-13.0 5.0 37.0	0.968 0.883 0.302	2		74.0	
Turkey leg	-13.0	0.871				
Beef, lean	8.7 74.4 143.7	0.769 Btu/hr ft °F 0.278 0.281	1	Parallel	78.9	Hill et al. (1967)
Beef, lean	11.1 63.4 141.6	0.806 0.248 0.256	2	Parallel	78.9	
Beef	0-10 15-30 32-40	0.62 Btu/hr ft °F 0.57 0.17	2	Parallel	69.5	Miller and Sunderland (1963) ^c
Broiler muscle	80	2.86 Btu/hr ft ² °F/in	1	Parallel	69-75	Walters and May (1963)
Broiler muscle and skin		2.54				
Hen muscle		3.06				
Hen muscle and skin		2.75				

^aType of heat flow is listed when available by number according to the following key: (1) perpendicular to fiber or grain, and (2) parallel to fiber or grain.

^bType of apparatus is modification of parallel plate or line-source technique.

^cData presentation modified or averaged by this author.

selected muscles were dependent upon temperature. Generally conductivity values increased with a decrease in temperature if data were compared for frozen versus unfrozen meat. Variation among muscle species was accentuated when samples were frozen. Possibly this difference was attributable to a variation in ice crystal formation. This is partially supported by the investigation of the thermodynamic properties of fish (Long, 1955). A sharp increase in thermal conductivity values occurred when temperatures fell below the initial freezing point and the rate of increase diminished as freezing progressed. The thermal conductivity values were approximately 3-1/2 times greater in frozen than unfrozen fish.

Thermal conductivity values have not been extensively investigated for temperature ranges representative of conditions during thermal processing of meat. However, some investigations for temperatures above as well as below the freezing point of meat have been reported. Using a modification of the parallel plate method with beef, pork, veal and lamb at various heat flow patterns, as well as fat and moisture levels, Hill et al. (1967) observed that as temperatures increased above freezing, the conductivity increased slightly; but at temperatures below freezing, conductivity varied inversely with temperature. Miller and Sunderland (1963) also reported similar results. Conversely, Melgar (1970) using a plate method, noted that thermal conductivity values decreased as temperature increased from 20 to 95°C.

Lentz (1961) used a modification of the parallel plate method with slabs of frozen meats, associated fats and model systems to clarify

some of the inconsistencies attributable to heat flow. Models of 6 percent gelatin gel and butter fat were structured to simulate the fat and lean portions of meat. The structures were oriented to have heat flow parallel or perpendicular to the layers. Maximum thermal conductivity values were observed for the heat flow parallel to the layers and were at a minimum when heat flow was perpendicular to the layers. Salmon, codfish, beef (lean sirloin and lean leg), pork (lean leg), and turkey (breast) yielded conductivity values 15 to 30 percent greater when heat flow was parallel than when perpendicular to fibers. This is substantiated in Table 1 (page 9) in which K values from the literature may be found. However some differences have been noted by Lentz (1961). In a study of beef, pork, veal or lamb of identical moisture content, thermal conductivity values were only 8 to 16 percent lower for samples measured perpendicular rather than parallel to the grain. Massey and Sunderland (1967) found thermal conductivity values of freeze-dried beef at 1 Torr pressure and an average interface temperature and surface temperature of 0 and 100°F, respectively, to be 0.0416 Btu/hr ft °F when fiber orientation was parallel to the heat and vapor flow. When heat and vapor flow was not parallel, the conductivity value was 16 percent lower, 0.035 Btu/hr ft °F. Using a modified parallel plate method, Poppendiek et al. (1966) reported only a small percentage difference between heat flow parallel or perpendicular to calf fiber direction in muscle.

II. MUSCLE COMPOSITION

Muscle is a component of meat of considerable importance and interest to the food scientists and technologists. In this report meat will refer specifically to the system under discussion, whether composed of the muscle tissue only or of muscle and fat. Lean muscle is about 75 percent water, 18 percent protein, 3 percent fat, 1.6 percent non-protein nitrogenous compounds, 1.2 percent carbohydrate and its metabolites, 0.7 percent inorganic salts, plus traces of vitamins and other compounds (Paul and Palmer, 1972). The major classification of organic matter in meat on a waterfree basis is protein (Bodwell and McClain, 1970). Muscle proteins are classified as myofibrillar (10 percent), sarcoplasmic (6 percent) or connective tissue proteins. Other specialized proteins of relatively lesser amounts are present in other tissues in meat.

Sarcoplasmic proteins are contained within the sarcoplasm and subcellular organelles of the muscle fiber (Paul and Palmer, 1972). This class of proteins probably consists of over 50 enzymes important to the oxidation-reduction reactions in the live animal tissue. In addition, nucleoproteins, lysosomal protein, and myoglobin also are sarcoplasmic proteins.

Myofibrillar proteins are those which compose the contractile structures of the muscle. Thus, they function to translate chemical energy into the mechanical energy of the muscle. The primary types of proteins designated in this class are myosin (50-55 percent), actin

(20-25 percent), tropomyosin (10-15 percent) and a number of miscellaneous proteins (5-10 percent). Connective tissue proteins consist of collagen, elastin, reticulin and ground substance.

III. PROTEIN DENATURATION

Phenomenon of Protein Denaturation

Problems in definition of denaturation are apparent from the literature. In 1944 Neurath et al. defined the phenomenon by writing "Denaturation is any nonproteolytic modification of the unique structure of a native protein giving rise to definite changes in chemical, physical, or biological properties." The multifold manifestations of these changes indicate the inadequacy of this definition. In 1965, Joly presented a general definition to indicate denaturation as "any modification of the secondary, tertiary and quaternary structure of the protein molecule, excluding any breaking of covalent bond." Thus in this study, denaturation will refer to the process, or sequence of processes whereby the protein molecule undergoes intramolecular change or rearrangement (Kauzmann, 1959; Putnam, 1953).

Denaturants. Change in the protein molecule may be brought about by the physical, chemical and/or biological action of denaturants. In the production of meat products, the action of heat and chemical denaturation are of main importance. The denaturant of immediate concern in this study was heat. Chemical denaturation will be discussed as it pertains to the results of thermal action even though it is recognized

that pH and temperature are interdependent denaturants and separation of the two is difficult (Joly, 1965).

Heat denaturation. Heat denaturation of protein has been studied in both intact and model systems. During the thermal transition of the protein there is the denaturation as defined by Joly (1965). That is, there is a conformational change, a modification of the original native protein. These changes occur throughout the protein molecule within a narrow range of temperatures (Tanford, 1968). Although exceptions have been found, generally a loss of solubility attributable to protein coagulation occurs during heating. Using moderate temperatures, heat denaturation brings about beadlike aggregates of protein molecules (Joly, 1965). If pH and protein concentration remain constant, the beadlike aggregates increase in length with increasing temperature and/or heating time. Aggregation of the protein molecules into a gel may occur if concentration and temperature are favorable. Other factors also may be operational in their effect on denaturation.

Hamm (1966) reviewed and discussed the effect of heat upon muscle protein. Applicability of basic knowledge to a muscle on the effect of heating upon isolated muscle proteins is suspect. For instance, the heat gelling properties of myosin, actin and actomyosin in model saline systems do not depict the interactions occurring in muscle systems (Samejima et al., 1969). In the ground meat, the interaction of stroma proteins contribute to the heat gelling phenomenon. In addition, further differences between the two possible situations can

be attributed to probable higher protein concentrations in tissue, a protective nature of some of the tissue proteins, and a special steric position of each protein in the intact muscle tissue (Hamm, 1966).

Physical and chemical changes in muscle during heating were summarized as follows (Hamm, 1966). At 20-30°C ATP activity of myosin decreases. At 30°C small fragments of myosin begin to be split off the molecule. At 30-50°C the peptide chains of the myofibrillar proteins begin to unfold and relatively unstable cross-linkages begin to form. Denaturation of sarcoplasmic proteins also begins during this temperature span. At 50-55°C rearrangement of myofibrillar proteins continues with increasing stability of the initial cross-links. Further denaturation of sarcoplasmic proteins occurs. At 55-65°C most of the globular and myofibrillar muscle proteins are denatured to the point of coagulation. Bendall (1964) concurred that sarcoplasmic and myofibrillar proteins denatured at 62°C. Thus, the helical portions of these proteins would be unfolded and unraveled and the resulting less organized chains would form hydrogen and/or ionic bonds as relatively stable cross-links. Changes in the collagen begin to occur above 65°C (Hamm, 1966). Above 70°C formation of the disulfide cross-bonds from actomyosin occurs.

Measurable Properties of Protein Denaturation

Denaturation of protein often is defined and described in terms of measurable properties. Each change in a measurable property of protein reflects a change in protein structure and is considered as denaturation (Kauzmann, 1959). Putnam (1953) indicated that solubility

determination is an important quantitative method for evaluation of protein denaturation and the associative kinetics of the process. Changes in water-holding capacity and pH indicate alteration in the type and nature of intra- and intermolecular bonding in a protein system.

Solubility. Change in solubility when protein is acted upon by a denaturing agent is considered by some investigators as a criterion of denaturation. A decrease in protein extractability occurs with increased protein denaturation (Hargus et al., 1970). However, gross changes in solubility are not always reflective of the extent of denaturation.

Solubility of the fibrillar proteins is decreased by heating the muscle (Hamm, 1966). This decrease increased from 20 to 60°C with the greatest occurring in the 40 to 60°C range. Almost complete insolubility of fibrillar proteins is evidenced above 60°C. The sarcoplasmic proteins, although not as readily denatured are completely insoluble above 80°C. Landes et al. (1971) reported that precipitation of denatured sarcoplasmic proteins upon native myofibrillar proteins accompanied a decreased myofibrillar protein extractability. Huber et al. (1970b) postulated that this probably accounts for greater total soluble fibrillar protein nitrogen in muscles of anesthetized than those of nonanesthetized turkeys, Huber et al. (1970a, 1970b) used protein solubility in two different phosphate buffer systems (pH 7.4, I = 1.0; 0.03 M buffer) to characterize the decrease in protein solubility of chicken and turkey muscle heated to 85°C end point temperature.

Many buffers and chemicals have been used to extract protein and determine the effect of a wide range of treatments, situations and environments. Methods and procedures are oriented to the fractionation of the protein components as previously discussed. Phosphate buffers and other solutions of varying pH and ionic strength frequently have been used by investigators for protein fractionation and solubility differentiation (Hegarty et al., 1963; Landes et al., 1971; Huber and Stadelman, 1970a). Ovine samples have been fractionated into myofibrillar and sarcoplasmic proteins by use of a phosphate buffer. Sarcoplasmic protein was extracted with potassium phosphate buffer of 0.01 M, pH 7.4. Myofibrillar proteins were extracted with the identical buffer containing additional 1.1 M potassium iodide (McLoughlin, 1968). Chaudhry et al. (1969) used a potassium phosphate buffer containing (0.03 M, pH 7.4) to extract sarcoplasmic protein and a phosphate buffer containing either KCl or KI (0.5 M KCl, 0.1 M K-phosphate buffer, pH 7.4; 1.1 M KI, 0.1 M K-phosphate buffer, pH 7.4) to extract myofibrillar protein from rabbit and bovine muscle. A frequently cited procedure by Hegarty et al. (1963) used a potassium phosphate buffer (pH 7.6, $I = 0.05$) to extract and fractionate sarcoplasmic protein and a high ionic strength solution, Weber-Edsall buffer, to extract fibrillar protein from beef muscle. It was suggested that with this method, mechanical damage during freezing could bring about an overestimation of sarcoplasmic proteins because of greater solubility of actin and myosin.

Care must be taken in applying extraction results from meat other than poultry to chicken or turkey protein fractionation procedures.

In postmortem extraction of chicken, beef and pork muscles in KCl buffer (0.6 M) a difference was noted among the three meats (McIntosh, 1967). A 0.03 potassium phosphate buffer and a 0.1 M potassium phosphate 0.5 M potassium chloride buffer at pH 7.4 were used to remove turkey sarco-plasmic and turkey myofibrillar proteins, respectively (Maxon and Marion, 1969). Huber et al. (1970b) used two phosphate buffers to extract total soluble proteins (0.049 M $\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$, 0.0045 M NaH_2PO_4 , KCl, $I = 1.0$, pH 7.3) and sarcoplasmic proteins (0.03 M potassium phosphate buffer, pH 7.4) from turkey pectoralis muscles.

Water-holding capacity. The degree to which water is held in the meat is sometimes expressed by the term water-holding capacity (WHC). Hamm (1960) defined water-holding capacity as "the ability of meat to hold fast to its own or added water during application of any force." This definition will be applicable throughout the subsequent report. If the water from a meat sample is liberated by force, this is termed "loose water"; whereas, that retained by the tissue is occasionally defined by use of a quantitative press method. The pressed "loose water" from the sample was reported as an expressible moisture index (Rogers et al., 1967). Also, total moisture in a meat sample has been determined by warm air drying (Ruff, 1970). A third parameter which indicates a change in water-holding capacity is percent cooking loss.

Water is held by meat through capillary condensation, absorption on the hydrophilic groups of the protein chains, and by condensation of randomly oriented water molecules in the hydrated surface (Wierbicki and

Deatherage, 1958). A considerable portion of the polar water molecules is held due to the hydrophilic characteristics of the muscle protein. The hydrophilic groups to which water is attracted are the ionizable basic and acidic groups such as in the amino acid residues arginine, lysine and histidine. Similarly the nonionic amino acid residues of the muscle protein such as cystine, cysteine, tyrosine, serine and tryptophan assist in holding the water in a meat sample.

Changes in water-holding capacity have been shown to occur concurrently with changes in muscle protein during heating. In reporting the biochemistry of meat hydration, Hamm (1959) indicated that the steric effect of the muscle proteins serves a role in hydration. Water-holding capacity tends to change with a change in the protein molecule conformation. Generally, a decrease in WHC is initiated at 30°C with the possible unfolding of the protein molecule and formation of a tighter closer structure through new cross-linkages (Hamm, 1960). The greatest rate of decrease occurs between 40 and 50°C. Reduction in water-holding capacity increases at a slower rate up to the highest temperature of 80°C. Conjunctional with these temperature changes is a decrease in the hydrophilic acidic groups. The marked change in hydration of the meat might be attributable to a decrease in carboxyl groups rather than new stable cross-linkages. The decreased hydration from 45 to 60°C indicates that thermal action has decreased the available polar groups and possibly caused formation of new relatively stable cross-linkages. With a slight decrease in WHC from 60 to 80°C there was a further decrease in polar groups.

Reports of moisture loss during heating of a muscle and/or muscle system are plentiful. Sanderson and Vail (1963) observed that end point temperatures of 140 , 158 and 170°F yielded highly significant lower mean percent press fluid values of 54.0, 45.2 and 36.4 (percent of cooked muscle) respectively, for oven-cooked beef. Tube-cooked beef had mean press fluid values of 58.0, 41.6, and 33.0 for the end point temperatures of 140 , 158 and 176°F. In a study of broiled rib pork chops, percent total moisture decreased and cooking loss increased as end point increased from 155 to 170 to 185°F (Holmes et al., 1966). These results were indicative of decreased water-holding capacity with increased end point temperatures. Rogers et al. (1967) determined that total moisture and expressible moisture indexes decreased for both the pectoral major and semimembranosus turkey muscles with increasing temperatures from 25 to 65°C. Another study indicated a significant change in total moisture content of pectoralis major muscle in turkey occurred with increase in end point temperature from 165 to 175°F (Hoke et al., 1968). No change in moisture occurred with additional heating to 185°F. Total moisture decreased significantly with each increase in end point temperature to which the gluteus primus turkey muscle was heated. Similar results were found in this same study with press fluid yields.

pH. Discussion of pH as a separate entity is difficult in that this parameter has been related to other measurable properties of protein denaturation. For example, pH has been shown to enhance the rate

and/or amount of thermal denaturation (Bendall, 1964). In turn, thermal denaturation has been shown to affect the ultimate pH. A general increase in pH of meat to which heat has been applied is primarily a reflection of changes which have occurred in the muscle protein molecule.

The pH changes that occur are attributable to either charge changes on the amino acid residues or to conformational changes of the myofibrillar proteins and/or intra- and intermolecular cross-bonding (Hamm, 1966). Concurrently, muscle protein shows increased dissociation of acidic groups and decreased dissociation of basic groups. Consequently, this protein change shifts the isoelectric point to a higher pH value. This effect varies with the type of meat (Hamm, 1960). In beef the pH sharply increased between 40 and 50°C. At 50-55°C new formation of cross-links caused a small decrease in pH. Subsequent elevation occurred with heating from 55 to 80°C.

Several studies have shown that pH of meat increases during heating. Pork rib, loin and shoulder chops tended to show increased pH with elevation of end point temperatures (Holmes et al., 1966). Increase of pH with accession in temperature was observed during the heating of pectoralis major and semimembranosus turkey muscle (Rogers et al., 1967). Through heat action, each of the 10° increments from 25 to 65°C evidenced an increase of 0.11 pH units and 0.26 pH units, respectively, for the light and dark muscles. Using ground pectoralis major muscles, Williams (1970) observed that as samples were heated from an initial temperature of 7-9°C to an end point of 61-64°C, pH increased about 0.08 unit.

Sample Characteristics and Thermal Properties

It generally is agreed that thermal properties are affected by the composition of the meat (Awbery and Griffiths, 1933; Poppendiek et al., 1966; Hill et al., 1967; Qashou et al., 1970). However, there is not agreement as to the nature of the effect.

Qashou et al. (1970), using the line-source technique, noted that ground beef with a higher moisture and lower fat content had higher conductivity than a conversely composed sample (see Table 1, page 9). Comparison of ground beef versus ground chuck indicated that chuck had slightly higher conductivity values than beef. This was attributed to the lower fat and higher moisture content of the ground chuck. These seemingly contradictory results likely are attributable to experiment variation. Increased moisture content in beef samples correspond with increased thermal conductivity values in a study reported by Hill et al. (1967). Using a Cenco-Fitch apparatus, Walters and May (1963) determined that thermal conductivity values for pectoralis major muscles for broilers or hens were not affected by the percent fat, percent moisture, or weight. Equations 4 and 5 presented by Earle (1966) emphasize the probable relationship between total moisture content (percent) (TM) and thermal conductivity. Earle reported that the

$$\text{Equation 4: } K = 0.32 \text{ TM}/100 + 0.15(100 - \text{TM})/100 \text{ Btu/ft hr } ^\circ\text{F}$$

$$\text{Equation 5: } K = 0.48 \text{ TM}/100 + 0.22(100 - \text{TM})/100 \text{ kcal/m hr } ^\circ\text{C}$$

above represents considerable oversimplification and should be used with caution.

Conversely, Poppendiek et al. (1966) noted that it was not always possible to correlate water content and conductivity. The degree of correlation apparently was influenced by the type of tissue. Conductivity values were not linearly correlated with moisture when bovine muscle, kidney, brain, liver, lung, fat and chicken skin were analyzed using a modified parallel plate method. Chicken skin at 0.206 Btu/hr ft °F and bovine lung at 0.163 Btu/hr ft °F, particularly were unrelated to moisture content.

A difference in source of meat and resulting conductivity values was supported by work reported by Lentz (1961). Using a modified parallel plate method, a difference in conductivity values among turkey, pork, codfish and beef was noted at temperatures below -15°C. Walters and May (1963) reported a significant difference ($P < 0.01$) between thermal conductivity values of the pectoralis major muscle of broilers and of hens.

The effect of changes in the sample during evaluation of thermal properties particularly during increased temperatures has not been extensively investigated. Thermal conductivity values were shown to be influenced by weight loss in meat cooked within the 80 to 150°F range (Hill et al., 1967). The weight loss was due to decreases in moisture and fat. Using a modified plate method, Melgar (1970) observed an increase in liberation of meat juices and a decrease in thermal conductivity from 20 to 95°C. Therefore as moisture content decreased, thermal conductivity also decreased. However, the effect of moisture content upon a muscle system that has undergone some protein denaturation is not necessarily analogous to that in a system where the protein is

in a native state. Additionally, the temperature and physical state of water also affect conductivity values (Powell, 1958). Miller and Sunderland (1963) postulated that freezing of beef tissue altered the structural characteristics of the sample and thus affected the conductivity values.

A review of various differential thermal analysis studies yields some indication of possible effects of change in the thermal properties of the sample during heating. A comparison of thermograms obtained by differential thermal analysis indicated that each of six proteins compared had an endotherm with a characteristic shape (Steim, 1965). The study indicated that heat denaturation of protein and the effect of a number of factors can be critically investigated by differential thermal analysis (DTA). Karmas and DiMarco (1970) used DTA to show the effect of heat upon the protein in both model and intact protein containing food systems. Berg and Egunov (1970) postulated that peak areas obtained by DTA were affected by the thermal conductivity of the sample.

CHAPTER III

PROCEDURE

Turkey pectoral muscles were used to study the relationship of thermal conductivity and associated properties. Ground pectoralis major and minor muscles were heated to end point temperatures at 9° intervals between 77 and 185°F with two holding times (0 or 15 minutes). Using a completely random block experimental design with 2 replications for all combinations of the two variables (end point temperature, holding time), data were collected for calculation of thermal conductivity, the expressible moisture index, total moisture, cooking loss, protein extractability, and pH as affected by the applied treatment. Several of these determinations were used to indicate changes in water-holding capacity (cooking loss, total moisture, expressible moisture index) or protein solubility (protein extractability). Uniformity between lots was determined by analysis of representative raw samples from each lot for determination of total moisture, lipid content, protein content and solubility, and pH.

I. SAMPLE

Thirty fresh grade A Nicholas tom turkeys (25 weeks old) of known history and similar background were obtained from Wampler Foods, Inc., Hinton, Virginia. Turkeys were slaughtered and dressed by commercial methods. The birds (24 to 26 pounds) were aged 12 to 16 hours in

chipped ice at 37°F or less, placed in plastic bags which then were placed in wooden crates containing chipped ice. The turkeys were transported to Knoxville, Tennessee, in approximately 8 hours. The turkeys were stored in chipped ice (35° to $\pm$ 4°F) for an additional 12 to 20 hours before muscles were dissected and ground.

Ten turkeys were randomly assigned to each of three lots. The pectoralis major and minor muscles were removed and fat and connective tissue for each muscle were minimized. The muscles were cut into one-inch chunks and mixed for homogeneity within each lot. Muscle temperatures during dissection, lot mixing, and grinding were approximately 50°F. Each lot of pectoralis major and minor muscle chunks was ground through a Hobart Grinder (Model 4722) at low speed using four grinding plates (1 cm, 0.5 cm, 0.25 cm and 0.25 cm consecutively). During the final grind, the turkey was packaged (0.0007 gauge aluminum foil) alternately in approximately 60 or 180 gram samples. Packaged samples were frozen in institution freezers (0°F). When frozen, packages were grouped as to lot in plastic bags and stored (0°F) for approximately four to six months prior to use.

II. LINE-SOURCE APPARATUS AND PROCEDURE

The apparatus design and associated equipment shown in Figure 1 are a modification of the transient line-source technique reported by Qashou et al. (1970). The collection of data for calculation of thermal properties was done using water-jacketed infinite cylinders and necessary associated wiring (Figures 2 and 3). The pyrex cylinder was 2.8 cm in

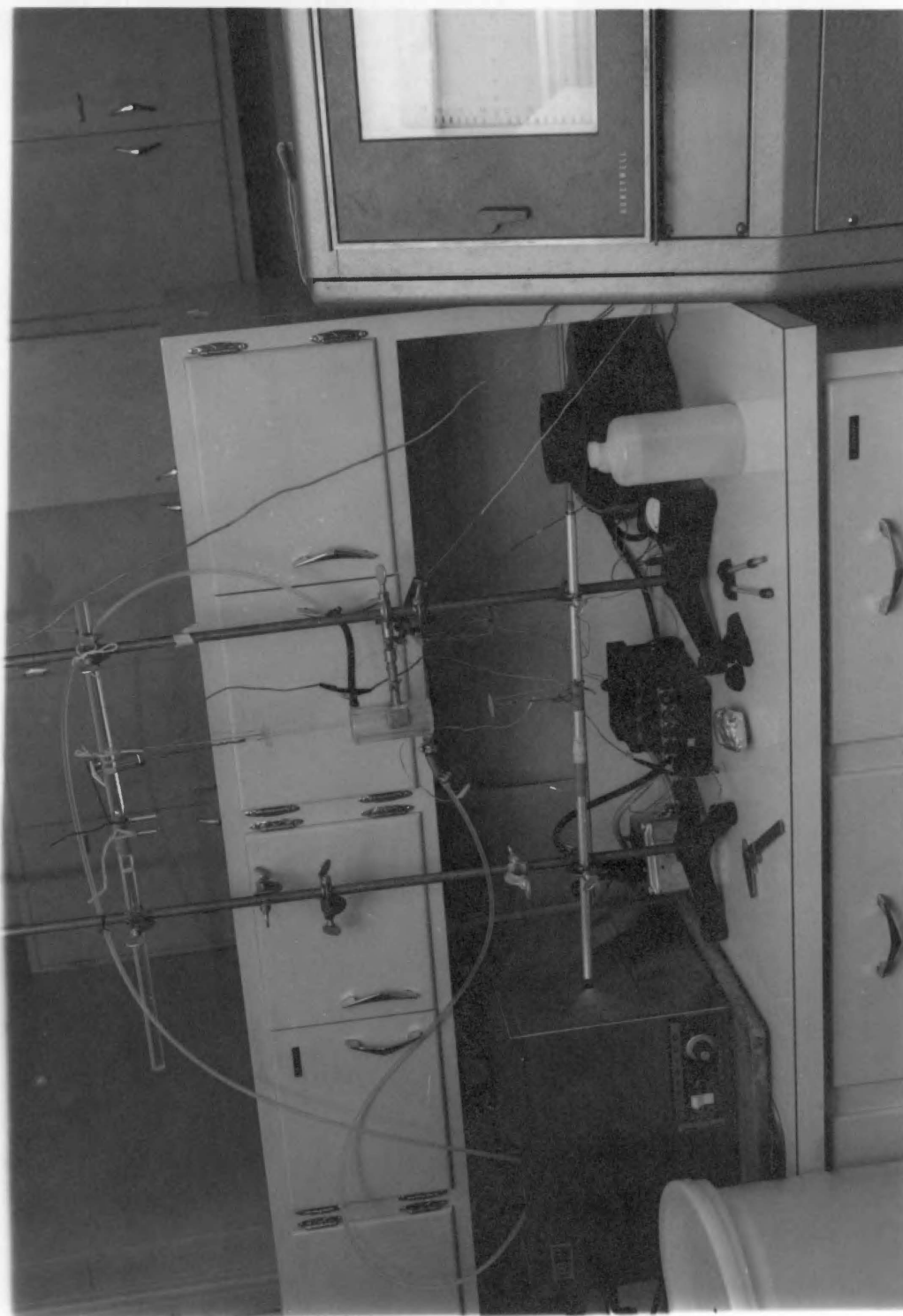


Figure 1. Thermal conductivity apparatus and accessories.

Parts list in Appendix, Table 13, page 80.

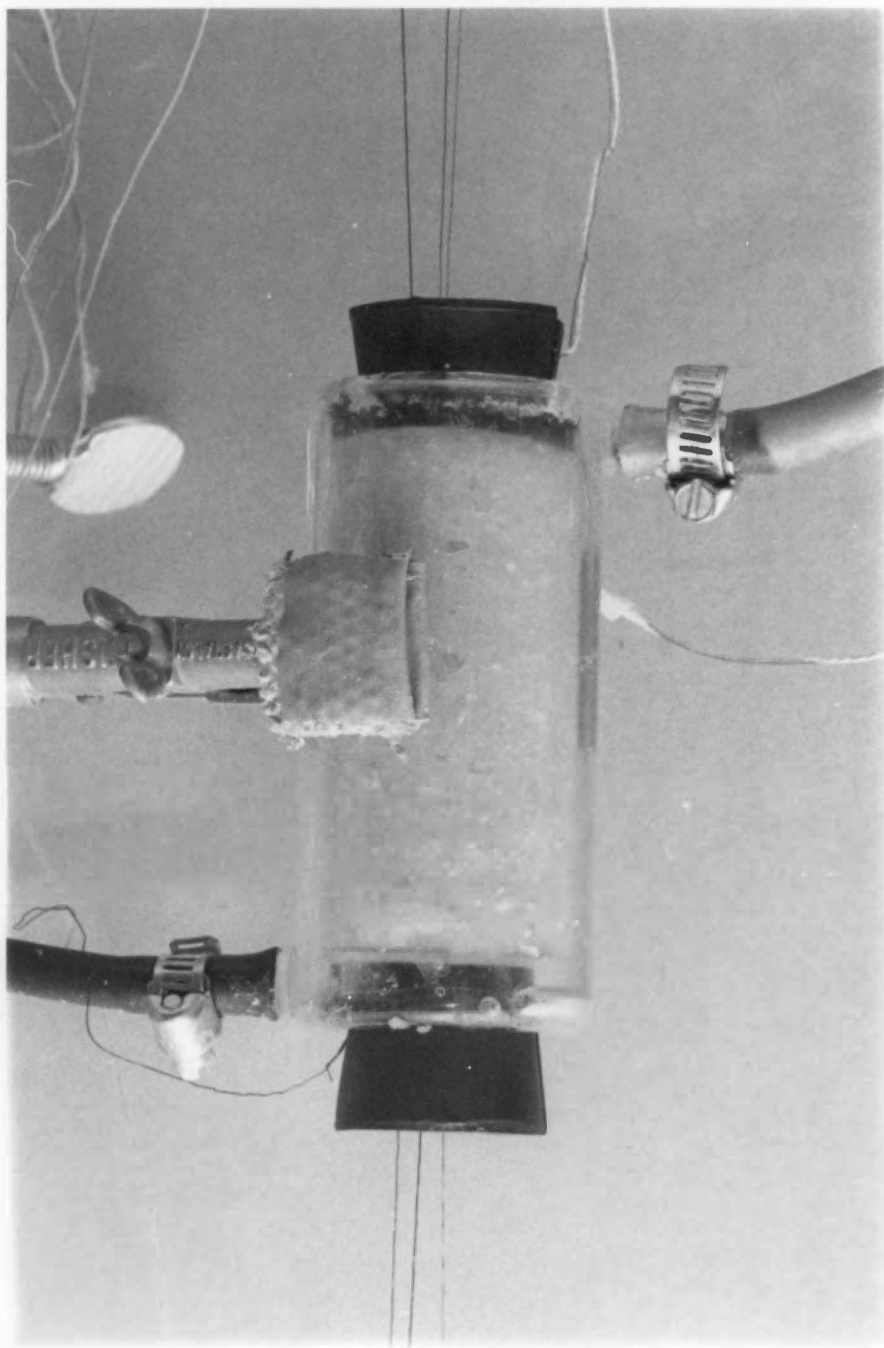


Figure 2. Heat cylinder.

Parts list in Appendix, Table 13, page 80.

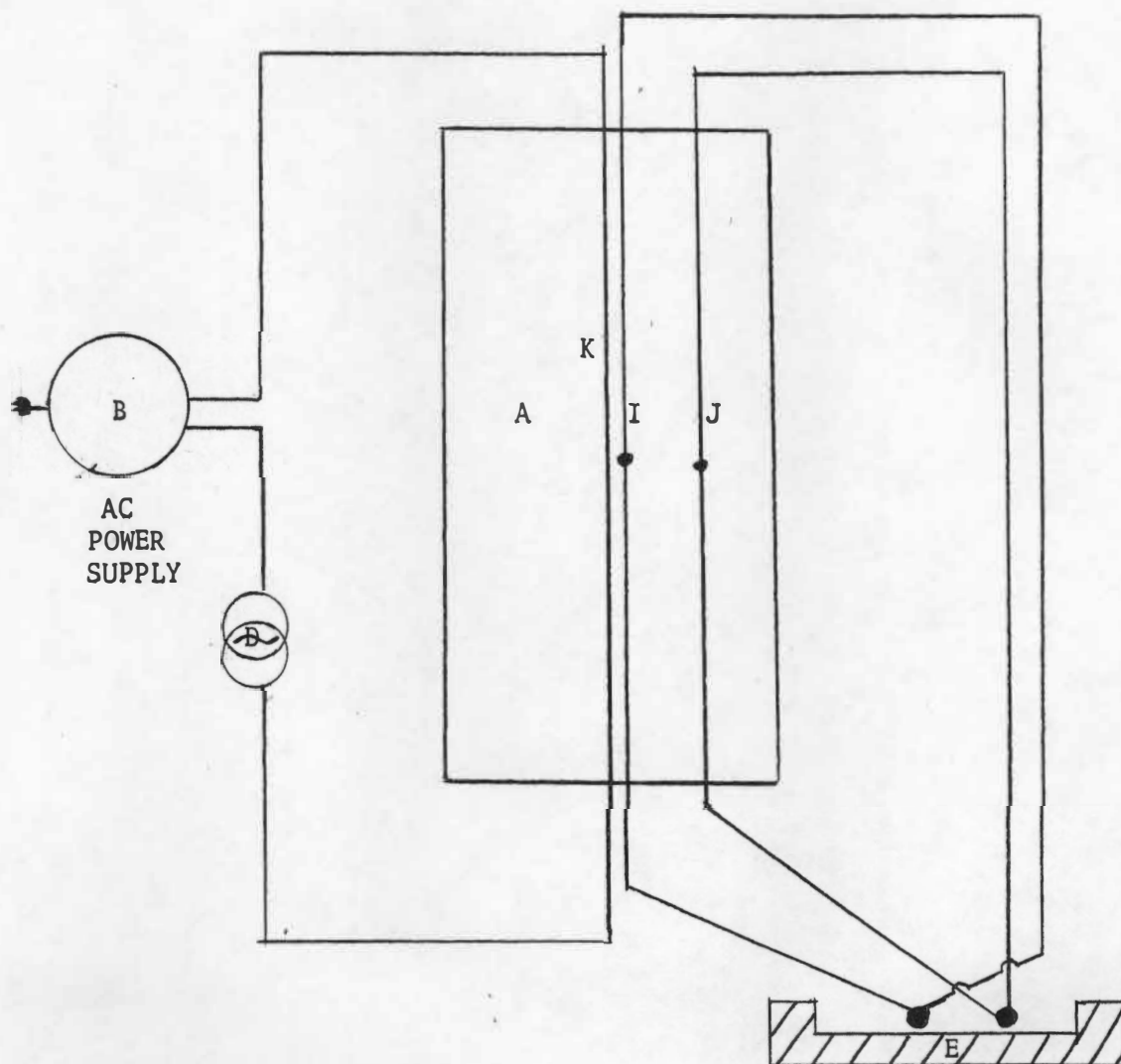


Figure 3. Electrical schematic of thermal conductivity apparatus.
Parts List in Appendix, Table 13, page 80).

diameter with the length greater than twice this diameter. Each end of the cylinder contained a plastic fitted disk through which the two thermocouples and one resistance wire were strung. The wires were maintained under tension during operation by use of springs and a jury rig set up. A closed system was completed by stoppering the cylinder with tight fitting vertically split black rubber stoppers.

Thermocouple wires were made of 30 gauge copper and constantan wire joined and soldered (high resin solder: 60 percent tin, 40 percent lead) as a vertical junction. Thermocouples were calibrated before installation by use of boiling water and then recalibrated against a known standard after installation. A 24 point Honeywell Elektronik 16 recording potentiometer was used on selected junctions to chart the temperature of meat samples at designated intervals. Voltage and amperes (I) of the chromel-C resistance wire (ohms: 6.54 per foot) were determined with a Simpson Model 157 voltmeter (0-25 AC volts) and a General Electric AC ammeter (2/5/10/20 amperes), respectively. Total voltage along the resistance wire was controlled and maintained with a rheostat. An electrical schematic of apparatus and wiring is shown in Figure 3.

Water at the selected experiment temperatures ($\pm 0.5^{\circ}\text{C}$) was pumped through the cylinder using a Sears Submersible Pump (Model 27711; approximately 140 gallons per hour). Water bath temperatures identical to the predetermined end point temperatures in meat samples were maintained with a Model 83 Precision Scientific Products water bath.

Each packaged turkey sample was defrosted at approximately 5°C for 36 hours. Upon packing the sample into the cylinder, sample weight and height were recorded. This packed sample, whether heated or not, will henceforth be termed "heat cylinder". From an initial temperature of 77° ± 1.5°F, samples were heated to the selected end point temperatures. When the end point temperature became constant throughout the sample and had been held for the appropriate holding time, the preset voltage of approximately 5 volts was applied to the resistance wire. Temperature increase, voltage, and amperes were recorded for 2 minutes. At the end of the 2 minute data collection period, voltage was switched off and the cooling vat used to supply circulating water in order to return the sample to the initial temperature of 77°F. During heating and cooling of the sample appropriate temperatures and times were also recorded. Detailed procedure for operation of line-source apparatus is reported in the Appendix (page 81). Representative turkey samples for each treatment and replication were removed from the heated cylinder for determination of protein solubility, expressible moisture index, total moisture, and pH (see Figure 4).

III. DATA ANALYSIS BY MATHEMATICAL AND STATISTICAL METHODS

Two curves, the heating curve and the TC heat curve, were recorded per replication. The heating curve designates the temperatures during the time period from the initial temperature of 77°F through to the appropriate end point temperature exclusive of the holding time. The term "TC heat curve" designates the temperature change from the

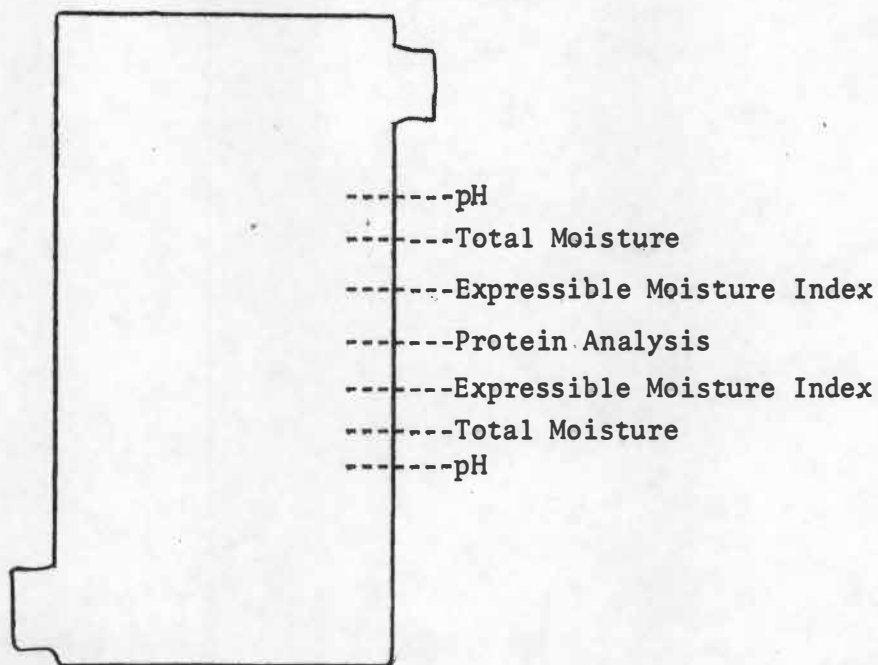


Figure 4. Sampling scheme for protein denaturation determination.

appropriate end point temperature throughout the operation of the data collection time. Temperature rise was standardized by using the difference of temperature rise subtracted from the initial temperature (time equals 0.0) for each curve. The curves were defined in terms of degree and best-fit polynomial (Beadle, 1971). An updated version of the GECAP (V-I, 9-15-71) program by the IBM 360/65 computer system calculated both degree and coefficient of the polynomial.

Three methods were used to calculate thermal conductivity. Two methods involved use of the line-source technique. These methods are designated as the Cowling method and the Dickerson method. Data obtained from temperature-time curves recorded during operation of the line-source apparatus were used. Thermal conductivity values also were calculated from percent total moisture. The calculated best-fit temperatures were used with the Cowling and Dickerson methods. The GECAP program was used for the temperature data of the TC heat curve from 0.0 to 2.0 minutes and from 0.0 to 1.5 minutes for all replications. Selected end point temperatures and holding times were used to define polynomial degree when analyzed on temperatures conjunctional with times from 0.0 to 1.0 or 0.0 to 0.75 minutes. In this report the curves from which calculated temperatures were obtained will be defined by the absolute value of number of minutes, i.e., 0.0 to 1.5.

The IBM 360/65 computer system was used to solve for diffusivity and calculate conductivity for the Cowling method (Cowling, 1972). The detailed FORTRAN program is represented in the Appendix (page 74). Data input consisted of calculated curve-fitted temperatures and associated

times, radius (R) from heat source to inner thermocouple, and heat output (Q). Heat input values were calculated according to Equation 6. In this report, unless otherwise indicated calculated temperatures (V2/V1) conjunctional to 15 and 90 (T2/T1) seconds were used for

$$\text{Equation 6: } Q = \frac{\left(\frac{I^2 \times 3.413 \times 252}{30.5} \right)}{3600} \text{ cal/cm/sec}$$

calculation in both the Cowling and the Dickerson methods. Thermal conductivity was expressed in terms of cal/sec cm °F in the Cowling method. The Dickerson method was used to calculate thermal conductivity according to Equation 2 (refer to page 7) (Dickerson and Read, 1968). Mathematical manipulations were done by use of the Olivetti Programma 101. Conductivity values were expressed in terms of Btu/hr ft °F. Thermal conductivity values on the basis of total moistures (Earle, 1966) were calculated according to Equation 4 (refer to page 22) and was expressed in terms of Btu/hr ft °F. Average total moisture (percent) values for each end point temperature and holding time combination were used.

Analysis of variance and the t-test for paired comparisons were calculated on selected data (Steel and Torrie, 1960). An Olivetti Programma 101 was used for the appropriate mathematical manipulations.

IV. DETERMINATION OF MEASURABLE PROPERTIES

Protein fractions were extracted by modification of the procedure by Hegarty et al. (1963). A detailed schematic (Figure 5, page 87) and discussion of procedure used may be found in the Appendix.

For pH determination two 1 g samples of meat were obtained from the ground pectoral muscle (Figure 4, page 32). After maceration of the 2 g sample in 25 ml water using the VirTis 45 homogenizer, the pH was determined with IL pH meter.

For determination of percent total moisture, duplicate 6 ± 0.5 g turkey samples from the approximate center of the interior of the heat cylinder were weighed into preweighed aluminum foil pans and dried uncovered to constant weight in an air oven at 100°C (Ruff, 1970). Weighed pans were cooled for 30 minutes in a desiccator containing a dessicant and reweighed. Total moisture was calculated by Equation 7.

$$\text{Equation 7: Total moisture} = \frac{\text{initial weight} - \text{final weight}}{\text{initial weight}} \times 100$$

For determination of the expressible moisture index, triplicate 300 ± 20 mg portions of turkey were weighed into polyethylene sample containers. The three samples for each replication were from an area in close proximity to the thermocouple junction that recorded TC heat curve during heating and cooling (see Figure 4). After the triplicate samples were weighed, each was placed in the center of a piece of Whatman No. 1 filter paper (7.0 cm) (Rogers et al., 1967). The filter paper and first sample was placed on a Plexiglas plate, and covered with a second Plexiglas plate. The second sample was placed on filter paper and plate similarly. The process was repeated for the third sample until a stack contained 3 samples and filter paper and 4 Plexiglas plates. On a Harco hydraulic press 15 psig (unit pressure = $\frac{\text{total force}}{\text{unit area}}$ = $\frac{5500 \text{ lb}}{36 \text{ sq in}}$) using a 5 minute schedule was applied to the previously

described stack. Upon completion of the 5 minute schedule, pressure was removed and the pressed meat and expressed juice boundaries were traced. The meat sample area and meat plus juice area were determined with a compensating polar planimeter. Equation 8 was used to calculate the expressible moisture index (EMI).

$$\text{Equation 8: EMI} = \frac{\text{meat area, cm}^2}{\text{meat + juice area, cm}^2 - \text{meat area, cm}^2}$$

Initial weight of sample placed in the heat cylinder was obtained and recorded. Upon completion of each experimental test period for all end point temperature and holding time combinations, samples were drained for approximately 5 minutes. The resulting sample weight (final weight) was determined. Equation 9 was used to calculate percent cooking loss for each replication.

$$\text{Equation 9: Cooking loss} = \frac{\text{initial weight} - \text{final weight}}{\text{initial weight}} \times 100$$

Quantitative lipid analyses were done on raw ground muscle samples from each lot (Ostrander and Dugan, 1961).

CHAPTER IV

RESULTS AND DISCUSSION

The line-source technique offers advantages of short duration of transient test time, small temperature change, no test specimen dimension requirements, and concurrent determination of thermal diffusivity (Qashou et al., 1970). Apparatus, method of operation, method of mathematical calculations and sample behavior influence the precision with which thermal characteristics can be defined by use of the modified line-source technique. The need to develop either a procedure or an apparatus to minimize meat sample phase change or to develop a mathematical model to accurately account for this phase change are evidenced from this study. Accuracy, sensitivity and precision of the various recording instruments must be maximized.

I. THERMAL CONDUCTIVITY VALUES

Thermal conductivity values were calculated according to the Cowling and the Dickerson methods with two different sets of curve-fitted data for each holding time and end point temperature combination. The results of these variables are presented in Table 2 and tend to indicate the influence of method of calculation of K, mode of calculation of curve-fitted TC heat curve data (0.0 to 2.0 or 0.0 to 1.5) and holding time.

TABLE 2
THERMAL CONDUCTIVITY VALUES FOR HEAT TREATED GROUND TURKEY PECTORAL MUSCLES^{a,b}

End Point °F	Cowling, cal/sec cm °F ^c				Dickerson, Btu/hr ft °F			
	Curve-Fitted							
	0.0 to 2.0		0.0 to 1.5		0.0 to 2.0		0.0 to 1.5	
	Holding Time, Min.							
	0	15	0	15	0	15	0	15
77	1.2080 1.2844	1.4489 1.3823	1.5610 1.3415	1.6476 1.5988	0.3960 0.3040	0.3047 0.3086	0.3535 0.2857	0.2792 0.2788
86	0.4468 1.1766	0.6524 0.5444	0.4858 1.3890	0.5545 0.5624	0.2593 0.2740	0.2725 0.3414	0.2653 0.2418	0.3285 0.3297
95	0.7944 0.9151	0.7135 0.6258	1.0728 1.2658	0.5635 0.6835	0.3521 0.3422	0.2609 0.3466	0.2969 0.2915	0.2805 0.3641
104	0.5820 0.6752	1.8342 0.6349	0.6578 0.5980	2.1322 0.7018	0.3178 0.2685	0.3385 0.3350	0.3142 0.3049	0.3065 0.3364
113	0.7632 1.1243	1.1856 0.8935	0.7204 1.2746	2.1577 1.1619	0.3601 0.3351	0.3500 0.3586	0.3680 0.2947	0.2871 0.2990
122	0.6140 0.4740	0.9531 0.6982	0.7830 0.3856	1.2860 0.8684	0.3166 0.2987	0.4364 0.3437	0.2580 0.3283	0.3651 0.2846
131	0.8381 1.0270	0.8506 1.0463	0.9114 0.9910	1.0972 1.5144	0.3401 0.3572	0.3663 0.3674	0.3479 0.3632	0.3169 0.3134
140	2.3295 1.5456	0.8505 1.0324	2.8297 3.7612	0.6387 0.8484	0.3324 0.3747	0.3241 0.3140	0.3068 0.3061	0.3504 0.3331
149	1.3366 1.7968	0.7003 1.0667	1.3709 2.2684	0.6341 0.8752	0.2906 0.3386	0.3899 0.2892	0.2768 0.2997	0.3588 0.2876
158	1.0174 0.9347	0.9940 1.1441	1.8581 1.1556	0.8566 0.9633	0.3583 0.3666	0.3123 0.3036	0.2824 0.3136	0.3536 0.3436
167	0.7474 0.7756	1.5635 0.9977	0.8285 0.8285	2.4514 0.8996	0.3535 0.3521	0.4008 0.3694	0.3645 0.3700	0.3646 0.4079
176	1.2709 1.4111	0.9511 1.3520	1.4229 1.3345	1.2923 1.7852	0.2964 0.3347	0.3184 0.3469	0.2668 0.3363	0.2678 0.2905
185	1.7061 0.9397	1.1708 0.9570	1.6860 0.9877	1.6654 1.3076	0.3552 0.4142	0.4447 0.3774	0.3572 0.4385	0.3688 0.3087

^aValues for each replication are shown for each treatment.

^bSignificant ($P < 0.05$) effect of temperature on thermal conductivity values at 0 minute but not 15 minute holding time for all methods of calculation.

^c $K \times 10^{-3}$.

The effect of end point temperature and holding time was similar for the Cowling and Dickerson methods. Thermal conductivity values were affected ($P < 0.05$) by end point temperature at the 0 minute holding time but not at the 15 minute holding time. Comparison of the holding time once the sample had reached end point temperature indicated no effect ($P < 0.05$) of the two times (0 and 15 minutes) upon conductivity values. Thermal conductivity values calculated according to both the Cowling and the Dickerson methods in the current study are within the same range of values reported by Poppendiek et al. (1966). This conclusion is relatively easy to arrive at as calculations of Poppendiek et al. were expressed in terms of Btu/hr ft °F and cal/cm sec °F $\times 10^{-3}$. For example, the average conductivity of bovine muscle over a range of 75°-100°F was 0.305 Btu/hr ft °F or 1.261 cal/cm sec °C $\times 10^{-3}$. Thermal conductivity values for turkey breast and leg muscles reported by Lentz (1961) are different from those calculated by the Dickerson method in this study. In addition to investigating muscle type and temperature, Lentz also investigated heat flow patterns. Depending upon the patterns, conductivity values at 39°F were 0.290 to 0.302 and at 23°F were 0.641 to 0.798 Btu/hr ft °F. However, comparison of these values with those determined in the current study is difficult in that the temperatures are considerably lower and thus sample characteristics are not similar.

Few studies report conductivity values of compositionally defined meat samples at end point temperatures comparable to those used in this study. Fewer studies yet use the line-source technique to obtain these values. However, Qashou et al. (1970) used the line-source technique

at temperatures ranging from 37 to 43°F to determine K values of ground beef and chuck. Conductivity values calculated by the Dickerson method in the present study were 50 to 100 percent higher than those reported by Qashou et al. (1970). The meat used had approximately 5 percent less moisture and 11 percent higher fat than the turkey meat used in this study. Method of calculation of conductivity also was dissimilar in the Qashou et al. (1970) investigation. Other comparisons of thermal conductivity in this study with values reported in the literature becomes increasingly difficult. Results shown in Table 1 (page 9) indicate that variations occur in the samples used as well as in the techniques for collection and calculation of data and the terms in which they are expressed. Thus, any true comparison is almost impossible.

The method of manipulation and calculation of data influences the conductivity values. A comparison of thermal properties in Table 2 (page 38) illustrates the effect of the curve-fitted approach for 0.0 to 2.0 minutes and for 0.0 to 1.5 minutes. In all cases, data collected for the TC heat curve was for 2.0 minutes which included the recording of 9 temperatures. However, the application of recorded times and temperatures to the Generalized Curve-fitting and Plotting Program (GECAP) (Beadle, 1971) was varied and included 2.0, 1.5, 1.0 and 0.75 minutes with 9, 7, 5, and 4 temperatures, respectively.

The increase in temperature during the collection of TC heat curve data was not only dependent on time but also on other unknown factors as shown by best-fit calculated temperatures. These factors likely caused variation in the ease of heat transfer and thus deviation from

the assumption used for this transient method of determining thermal conductivity. A basic requisite for the methods used in calculation of thermal conductivity is that no phase change occurs during data collection.

Comparison of the mean K values of the end point temperatures and holding time indicates that data curve-fitted at 0.0 to 2.0 minutes were about 6 percent lower than those curve-fitted at 0.0 to 1.5 minutes in the Dickerson method and about 19 percent higher in the Cowling method. Analogous results were shown with thermal diffusivity values (Appendix, Table 14, page 83). However, there is considerable fluctuation in effect of the curve-fitted temperatures used in the calculations. A comparison of K values (Table 2, page 38) from the 0.0 to 2.0 and 0.0 to 1.5 curve-fitted calculations with the Cowling method indicates that at 77°F, 0 minutes holding time, for the first replication the K values were about 23 percent higher when values from the 0.0 to 1.5 curve-fitted temperatures were used; whereas, with the second replication the elevation was only about 4 percent. K values for the two replications at 0 minutes holding time and 77°F determined according to the Dickerson method were about 8 percent higher for the 0.0 to 1.5 than for the 0.0 to 2.0 curve-fitted temperatures. Using the identical treatment it was determined that further shortening of the span of temperatures, that is, to 0.0 to 1.0 or 0.0 to 0.75 minutes did not follow the previously cited trend. For instance, for replication 1 and 2 at the 77°F end point temperature and 0 minutes holding time (Table 3) the Dickerson method indicated that a difference of about 9 percent and 0 percent occurred;

TABLE 3
EFFECT OF VARIATION WITHIN METHOD OF CALCULATION UPON THERMAL CONDUCTIVITY VALUES

Variation	End Point, °F	Holding Time, min	Replication	Method	Curve-Fitted Thermal Conductivity	
Removal of Selected Times, min.					0.0 to 1.5	
0.0	86	0	1	Dickerson	0.0 to 1.5	0.1558 Btu/hr ft °F
0.25, 1.50	86	0	1	Dickerson	0.0 to 1.5	0.2708 Btu/hr ft °F
0.25, 0.75, 1.50	86	0	1	Dickerson	0.0 to 1.5	0.2708 Btu/hr ft °F
0.0	86	0	2	Dickerson	0.0 to 1.5	0.1566 Btu/hr ft °F
0.25, 1.50	86	0	2	Dickerson	0.0 to 1.5	0.1836 Btu/hr ft °F
0.25, 0.75, 1.50	86	0	2	Dickerson	0.0 to 1.5	0.2136 Btu/hr ft °F
Variation in Curve-Fit ^a	77	0	1	Dickerson	0.0 to 1.5	0.5418 Btu/hr ft °F
				Cowling		1.5609 cal/sec cm °F × 10 ⁻³
	77	0	1	Dickerson	0.0 to 1.0	0.5975 Btu/hr ft °F
				Cowling		0.8349 cal/sec cm °F × 10 ⁻³
	77	0	1	Dickerson	0.0 to 0.75	0.5975 Btu/hr ft °F
				Cowling		0.9883 cal/sec cm °F × 10 ⁻³
	77	0	2	Dickerson	0.0 to 1.5	0.4379 Btu/hr ft °F
				Cowling		1.3415 cal/sec cm °F × 10 ⁻³
	77	0	2	Dickerson	0.0 to 1.0	0.4379 Btu/hr ft °F
				Cowling		0.9966 cal/sec cm °F × 10 ⁻³
	77	0	2	Dickerson	0.0 to 0.75	0.4378 Btu/hr ft °F
				Cowling		0.9966 cal/sec cm °F × 10 ⁻³
	77	15	1	Dickerson	0.0 to 1.5	0.4279 Btu/hr ft °F
				Cowling		1.6476 cal/sec cm °F × 10 ⁻³
	77	15	1	Dickerson	0.0 to 1.0	0.3704 Btu/hr ft °F
				Cowling		1.4043 cal/sec cm °F × 10 ⁻³
	77	15	1	Dickerson	0.0 to 0.75	0.3704 Btu/hr ft °F
				Cowling		2.7006 cal/sec cm °F × 10 ⁻³
	77	15	2	Dickerson	0.0 to 1.5	0.4274 Btu/hr ft °F
				Cowling		1.5988 cal/sec cm °F × 10 ⁻³
	77	15	2	Dickerson	0.0 to 1.0	0.3608 Btu/hr ft °F
				Cowling		2.9283 cal/sec cm °F × 10 ⁻³
	77	15	2	Dickerson	0.0 to 0.75	0.3608 Btu/hr ft °F
				Cowling		1.4043 cal/sec cm °F × 10 ⁻³
Change in Temperature ^b						
Increase 0.25	77	0	1	Dickerson	0.0 to 1.5	0.3052 Btu/hr ft °F
Decrease 0.25	77	0	1	Dickerson	0.0 to 1.5	0.3052 Btu/hr ft °F
Increase 0.25	77	0	2	Dickerson	0.0 to 1.5	0.2823 Btu/hr ft °F
Decrease 0.25	77	0	2	Dickerson	0.0 to 1.5	0.3699 Btu/hr ft °F
Input ^c						
0.25, 1.50	77	0	1	Dickerson	0.0 to 1.5	0.3535 Btu/hr ft °F
				Cowling		1.5610 cal/sec cm °F × 10 ⁻³
0.75, 1.25	77	0	1	Dickerson	0.0 to 1.5	0.2499 Btu/hr ft °F
				Cowling		1.1314 cal/sec cm °F × 10 ⁻³
0.25, 1.00	77	0	1	Dickerson	0.0 to 1.5	0.4559 Btu/hr ft °F
				Cowling		1.6535 cal/sec cm °F × 10 ⁻³
Change in Heat Input						
Increase Q 10%	77	0	1	Cowling	0.0 to 2.0	1.7171 cal/sec cm °F × 10 ⁻³
Decrease Q 10%	77	0	1	Cowling	0.0 to 2.0	1.423 cal/sec cm °F × 10 ⁻³

^aCurve-fitted temperatures associated with 15 and 45 seconds were used in each method.

^bCurve-fitted temperatures associated with 30 and 90 seconds were used in each method.

^cCurve-fitted temperatures associated with time given were used in each method.

whereas, at the 15 minutes holding time an average difference of about 15 percent occurred for the 2 replications with the 5 or 4 curve-fitted temperatures. Sources and reasons for the variations can only be conjecture. The results point the way to the need for more work.

Neither method for calculation of K completely accounts for adjustments related to use of temperature rise as a function of thermal conductivity in the line-source technique with ground turkey. If both heat cylinder and heater wire and thermocouples remained unchanged, it would be necessary to obtain and use representative temperatures in a manner different from the curve-fit approaches. The variation in type of curves, the polynomial coefficients of the curves, and best-fit calculated temperatures tends to indicate that there would be considerable advantage in using more temperatures within a shorter time period. This postulation may be further supported by data (Table 3) at the 86°F end point which showed variability in K ranging from 2 to 42 percent with removal of 2 or 3 of the 7 temperatures in a typical 0.0 to 1.5 curve-fitted calculation of values by the Dickerson method.

Comparison of the two methods, such as shown in Table 2 (page 38) would tend to indicate greater sensitivity to experimental data is inherent in the Cowling method of calculation of thermal properties. The ideal method of calculation would incorporate terms to account for experimental fluctuations. Concurrence with Kopelman and Pflug (1968) by this writer is underscored. Kopelman and Pflug (1968) indicated that any equation that uses data in which a change of phase or temperature dependent thermal properties are involved, causes difficulties in

solving the differential equation with no exact solution possible. Alles and Cowell (1971) determined calculations whereby data for a heating curve could be used to form a straight line. The use of slopes or shape coefficients in the calculation of thermal properties of food systems has been reported (Charm, 1963). However, it is considered that their use would not have solved calculation problems in this study as the slopes and shape are not likely a simple function of heat input and inherent conductivity. In order to develop the necessary equations for the system used, further basic knowledge must be obtained as to the changes which occur during the heating of meat.

Instrument and Recording Problems

The sensing and recording of temperatures also contributed to possible discrepancies in thermal conductivity. The Honeywell Electronic 16 temperature recorder used in this study has a resolution of $\pm 1^{\circ}\text{F}$. Some difficulty also was encountered in reading temperatures on the recording chart for use on the computer data sheets. It is possible for a misjudgment of temperature to cause some change in K from the original value (Table 3, page 42). Possible error attributable to incorrect alignment of paper on the recorder was minimized in that temperature differences rather than actual temperatures were used in the calculations by the Cowling and the Dickerson method.

Amperes (I) used for calculation (Table 4) of each of the thermal conductivity values fluctuated approximately 0.1 units during one TC heat curve determination. Since the resistance wire length and voltage were identical and unchanged during the study, this ampere

TABLE 4
 AMPERES AND DENSITY OF HEAT TREATED GROUND
 TURKEY PECTORAL MUSCLES

End Point °F	Amperes		Density g/cm ^{3a}	
	Holding Time, Min			
	0	15	0	15
77	0.700	0.689	1.054	1.078
	0.670	0.680	1.089	1.050
86	0.702	0.715	1.080	1.137
	0.720	0.715	1.075	1.046
95	0.680	0.720	1.134	1.088
	0.684	0.680	1.082	1.075
104	0.720	0.705	1.081	1.115
	0.722	0.700	1.070	1.068
113	0.720	0.680	1.083	1.077
	0.724	0.700	1.061	1.078
122	0.715	0.682	1.105	1.061
	0.700	0.716	1.075	1.086
131	0.700	0.698	1.073	1.098
	0.695	0.700	1.087	1.087
140	0.690	0.735	1.064	1.058
	0.686	0.698	1.073	1.077
149	0.680	0.710	1.089	1.095
	0.680	0.710	1.080	1.047
158	0.722	0.680	1.065	1.045
	0.735	0.730	1.068	1.056
167	0.680	0.685	1.068	1.064
	0.680	0.685	1.084	1.075
176	0.730	0.735	1.049	1.091
	0.705	0.730	1.066	1.065
185	0.697	0.710	1.052	1.077
	0.705	0.682	1.050	1.071

^aNo significant ($P < 0.05$) effect of temperature or holding time on density values.

variation is attributable to the instrumentation and the fluctuations in current. Variation in amperes could cause some discrepancies in the K values. A 10 percent increase or decrease in heat input (Q) could cause a similar elevation or depression of around 8 percent when conductivity was calculated according to the Cowling method.

Heat loss in this experiment was considered to be minimal. Insertion of thermocouples into the inflow and outflow tubes of the heat cylinder indicated no decrease in temperature. Heat loss due to wiring also was minimal and well within instrument sensitivity. However, in use of 30-gauge thermocouples (copper-constantan), Lusk et al. (1964) indicated that there was considerable conduction error when these wires were used in association with a plate method. With a stretched heater wire, there is purported to be little error attributable to loss of heat (Powell, 1958).

Sample Influences

Sample variation as a contributing factor to discrepancies was minimized in this project; however, it is postulated that error due to any nonhomogeneity of sample is maximized by the line-source method. Expressible moisture index, total moisture (percent), protein analyses, pH and lipid values did not significantly ($P < 0.05$) differ among lots before treatment (Appendix, Table 15, page 84).

It has been well established that directional flow will influence heat flow (Lentz, 1961). For example, Triebes and King (1966) observed in a study of freeze-dried turkey, conductivity parallel to the grain

showed greater values than those obtained normal to the grain. It is possible that there was directional heat flow in this study since the heat cylinder was packed sectionally. However, such directional flow would have had a random effect. Lentz (1961) indicated that it is important to eliminate air spaces since "such spaces may cause serious error." Fortunately, packing evidently was uniform and air spaces were not a problem. Density values (Table 4, page 45) shown did not vary significantly.

II. PHASE CHANGE AND CONDUCTIVITY VALUES

As previously discussed, the mathematical approaches used in the calculation of thermal conductivity were not completely appropriate during all heat treatments of the ground pectoral turkey muscle. At all times before initiation of the heat input and the recording of the TC heat curve, the sample was of uniform temperature. This uniformity of temperature is a basic requisite of the line-source technique for calculation of thermal properties. Although the sample was considered as thermally homogeneous, it is likely that, at critical temperatures for protein change, it was not consistent and homogeneous in composition. Heat input does not only bring about heat rise but calories may be absorbed because of phase change, i.e., primarily protein denaturation. Lack of consistency of K values and the characteristics of the measurable properties indicate that protein may cause difficulty in the calculation of thermal characteristics in a system analogous to that used by the food industry for heating meat products.

Although not analyzed or even greatly recognized by other workers, phase change problems are evidently a source of error in K values determined. In relating phase change and conductivity it becomes evident that protein denaturation can be minimized only by using as low a heat input from the heater wire over as short a time period as possible. Lentz (1961) alluded to the possible problem of phase change. Using a modification of the plate method, he indicated that at below-freezing temperatures, a relatively small temperature difference was maintained between cold and hot plates in order to minimize changes in the composition of the sample due to differences in temperature.

The five determinations used to characterize protein denaturation in this study were the expressible moisture index, cooking losses (percent), total moisture (percent), protein extractability and pH. When the measurable properties indicating protein denaturation were studied in relation to the TC heat curves and conductivity values at each of the end point temperatures, there was evidence that phase change attributable to treatment and to line-source technique occurred. Curve-fitted temperatures determined using the original TC heat curves were an attempt to minimize randomness, but this possibility may have introduced further variability in conductivity values. Although small, TC heat curves had an initial temperature rise from 0.0 to 0.25 minutes which tended to skew the curves when fitted to the polynomial. Elimination of this temperature jump would result in different curve-fitted temperatures and thus different thermal conductivity values. With beef sample, Qashou et al. (1970) observed a sharp increase in the initial portion

of the curve. It may be postulated from data in this study that phase change occurred during initial heat input and this caused a "case hardened insulation" around the wire. This increase might have been greater at temperatures at which protein denaturation most readily occurs. For example, when the slope of the first two temperatures within each replication was calculated a sharper increase was shown at 86°F than at 77 or 95°F. Of possible further need for investigation would be a correlation of magnitude of this initial jump with the type of TC heat curve. This initial slope for replication 2 at 86°F and 0 minutes holding time was unlike those of the other 3 time and temperature combinations at 86°F. The type of curve with both the curve-fitted approaches using 7 or 9 TC heat curve temperatures indicated an analogous fluctuation.

The occurrence of phase change in the ground turkey is substantiated by study of factors related to protein denaturation. This study indicated that conformational changes in the protein molecule altered protein solubility and the water-holding capacity of the system. Water-holding capacity (WHC) measured primarily the decrease in "loose" water. Denaturation of protein is mainly concerned with "loose" water rather than "bound" water. Thus, a decrease in WHC indicated that denaturation occurred with sample heating. Protein solubility was measured primarily by a decrease in amount of nitrogen extractable in a buffer of low-ionic strength. A decrease in protein solubility has been one prime criteria in indicating protein denaturation (Joly, 1965). Cooking losses, total moisture, expressible moisture index, pH and protein extractability

tended to indicate increased denaturation with elevation of end point temperatures (Tables 5, 6, and 7). Although there tended to be some difference in results with holding time (0 vs. 15 minutes) these were not significant for any of the 5 parameters studied.

Water-holding capacity of ground turkey pectoral muscles decreased with increased end point temperature with the greatest change occurring in the temperature range of 104 to 158°F. This tended to show possible rate and extent of protein denaturation. Cooking losses were affected significantly ($P < 0.01$) by progressively higher end points with the greatest increase after 140°F. Although not significantly influenced by holding time, the cooking losses at 15 minutes ($\bar{X} = 7.3$ percent) were slightly higher than at 0 minutes ($\bar{X} = 5.7$ percent) holding time. Using whole turkey, Hoke et al. (1968) observed a significant ($P < 0.01$) increase in cooking losses with increase in end point temperature from 165 to 175 to 185°F. Total moisture (percent) shown in Table 3 (page 42) was significantly ($P < 0.01$) affected by temperature. WHC expressed by total moisture in this study gradually decreased from 149 to 185°F end point temperature. The gradual decrease in total moisture found in this experiment also was noted in the investigation by Rogers et al. (1967). Total moisture of pectoralis major muscle was significantly ($P < 0.01$) affected by elevated end points (165 to 175 to 185°F) of cooked whole turkey carcass (Hoke et al., 1968).

Study of data in Table 4, page 45, emphasizes that decreasing expressible moisture index and loss of water-holding capacity occurred

TABLE 5
TOTAL MOISTURE AND COOKING LOSS FOR HEAT TREATED
GROUND TURKEY PECTORAL MUSCLES

End Point °F	Total Moisture, % ^a		Cooking Loss, % ^b	
	Holding Time, Min			
	0	15	0	15
77	73.86	73.96	2.50	1.77
	73.94	73.69	2.86	1.41
86	74.18	73.95	3.63	6.41
	74.04	74.17	2.00	4.51
95	73.82	73.71	4.90	2.53
	74.10	74.10	1.32	1.53
104	73.69	74.20	3.10	3.17
	73.91	73.74	2.22	3.12
113	73.41	73.72	3.49	1.69
	73.57	73.60	2.50	2.91
122	73.41	73.30	3.77	4.00
	73.53	73.72	2.27	3.96
131	73.61	73.22	4.46	4.86
	73.10	73.35	4.48	4.00
140	73.63	74.01	3.17	3.92
	74.08	73.38	3.49	3.55
149	73.54	74.25	4.08	7.06
	73.51	73.10	5.40	16.40
158	73.54	72.14	6.30	8.63
	74.15	72.93	4.41	8.37
167	72.60	71.63	9.45	12.00
	71.50	70.85	12.31	14.50
176	71.21	69.60	15.25	16.98
	73.31	70.39	9.26	17.48
185	70.09	71.35	16.62	17.39
	69.39	71.13	15.66	17.58

^aTotal moisture significantly ($P < 0.01$) affected by temperature at both holding times.

^bCooking loss significantly ($P < 0.01$) affected by temperature at both holding times.

TABLE 6

EXPRESSIBLE MOISTURE INDEX AND pH OF HEAT TREATED GROUND
TURKEY PECTORAL MUSCLES

End Point °F	Expressible Moisture Index ^a		pH ^b	
	Holding Time, Min			
	0	15	0	15
77	1.1478	0.8498	5.7366	5.6866
	0.7335	0.9897	5.6566	5.6900
86	1.0775	0.9203	5.6833	5.7000
	0.8225	0.7087	5.7033	5.6900
95	1.0775	0.9058	5.6666	5.6500
	0.9569	0.7594	5.7000	5.6933
104	0.7711	0.8369	5.7166	5.6833
	1.0155	0.9803	5.7000	5.7066
113	0.5550	0.6221	5.7366	5.7200
	0.5511	0.5645	5.6900	5.6933
122	0.3286	0.2597	5.7400	5.7733
	0.4149	0.3354	5.7266	5.7600
131	0.3023	0.2870	5.7966	5.7633
	0.2357	0.2423	5.8066	5.7566
140	0.2374	0.2038	5.7800	5.9500
	0.2696	0.2043	5.8366	5.8433
149	0.2014	0.2013	5.7733	5.8333
	0.1861	0.1808	5.8866	5.8133
158	0.1682	0.2002	5.8300	5.8766
	0.1574	0.2072	5.9800	5.8433
167	0.1550	0.1483	5.9266	5.8266
	0.1815	0.1720	5.8733	5.8766
176	0.2012	0.1770	5.8000	5.8333
	0.1575	0.2501	5.8400	5.9400
185	0.1878	0.2035	5.7933	5.6366
	0.2230	0.2270	5.8533	5.8933

^aExpressible moisture index significantly ($P < 0.01$) affected by temperature at both holding times.

^bpH significantly ($P < 0.01$) affected by temperature at both holding times.

TABLE 7

NITROGEN COMPOSITION OF TOTAL AND EXTRACTED PROTEIN
IN GROUND TURKEY PECTORAL MUSCLES AT 3
SELECTED END POINT TEMPERATURES^a

End Point °F	Holding Time Min	Low-Ionic Strength Fraction ^b	Nonprotein Fraction ^c	Total Protein ^c
77	0	55.36	21.11	150.71
		63.26	21.20	144.47
	15	57.82	29.67	156.86
		39.00	18.19	150.57
131	0	40.90	28.64	157.67
		37.11	23.54	141.53
	15	41.38	19.75	152.65
		37.27	23.81	146.59
185	0	16.97	22.28	152.03
		19.85	18.82	137.09
	15	19.75	19.16	145.72
		20.46	20.25	155.41

^amg N/g tissue (dry weight basis).

^bLow-ionic strength fraction significantly ($P < 0.01$) affected by temperature at both holding times.

^cNo significant ($P < 0.05$) effect of temperature or holding time on nonprotein fraction or total protein values.

with increasing temperature. The significant ($P < 0.01$) effect of temperature was most pronounced between approximately 95 and 131°F. Somewhat similar results were reported by Hamm and Deatherage (1960). They determined that decreased WHC begins at 95° and was greatest between 104 and 122°F. The effect of varying end point temperature has been noted. Rogers et al. (1967) noted that expressible moisture index decreased significantly ($P = 0.05$) with each 10°C increment in temperature from 50 to 95°F in both the pectoralis major and semimembranosus turkey muscle.

Changes in protein extractability (Table 7, page 53) indicate the effect of heat upon the primary and tertiary structure of the sarcoplasmic and myofibrillar proteins. The method used in this study determined the difference at 3 end point temperatures (77, 131, and 185°F) in amount of protein and nonprotein nitrogen extractable by a potassium phosphate buffer system of low-ionic strength (pH 7.6, $I = 0.05$). Conversion of nitrogen to amount of protein is an approximation and thus values are discussed and expressed as mg N/g of tissue (dry weight). Nitrogen content of tissue on a dry weight basis is used to study the relationship between protein solubility and temperature. Although no significant effect of holding time was noted, a comparison of means indicates that the samples held 15 minutes tended to have slightly less protein extractable at low ionic strength. A comparison of the means with the initial end point temperature (77°F) indicates that protein extracted at low ionic strength was about 30 percent less at 131°F and 60 percent less at 185°F end point temperature. No

significant effect of change in temperature was determined with total protein or the nonprotein fraction. Regression calculated on protein extractability in pork muscle was determined by Penny (1969) to account for 82.4 percent of the total variation in water-holding capacity. In the present experiment, water-holding capacity and protein extractability were noted to decrease with increase in temperature. Hegarty et al. (1963) extracted a low strength fraction with a phosphate buffer ($I = 0.05$, $pH = 7.6$) and calculated sarcoplasmic protein by subtraction of the nonprotein nitrogen from the total nitrogen fractionated from the muscle. Thus, values obtained in this study may be indicative of changes occurring in the sarcoplasmic protein. Cooking of chicken muscle to an internal temperature of $185^{\circ}F$ decreased protein solubility about 10 percent in comparison with that for the raw tissue in one investigation (Huber et al., 1970b).

In this study pH values (Table 6, page 52) were significantly ($P < 0.01$) influenced by temperature and tended to increase up to $176^{\circ}F$ and then decrease slightly. Williams (1970) determined an increase in pH when ground turkey was heated from an initial temperature of 7 to $8^{\circ}C$ to $62^{\circ}C$. In intact pectoralis major turkey muscle, Rogers et al. (1967) noted an increase of approximately 0.11 unit with increase in temperature from 10 to $65^{\circ}C$.

Thermal conductivity and the specific effect of the measurable properties indicating protein denaturation is elusive and difficult to define. The 5 properties in this experiment can only be related to conductivity as a possible indication of extent of protein denaturation.

It can be postulated that the denaturation phenomena in the current experiment influenced conductivity values both by the changes in structure and composition of the muscle system as well as by the energy consumption involved in conformational changes of the protein.

Structural changes in the heated ground pectoral muscles were observed both by subjective and objective evaluations. It was noted that the protein appeared to become coagulated as temperature increased. This coagulation became extensive at approximately 167°F and a shrinkage and extrusion of liquid within the sample was noted. Support of this change in structure is given by the progressive increase in cooking losses, particularly above 158°F and decrease in expressible moisture index, total moisture and protein solubility. The manner in which these changes influence thermal conductivity is difficult to assess. Other workers have indicated that loss of moisture with application of heat influenced thermal conductivity measurements (Hill et al., 1967). Melgar (1970) reported that conductivity of beef round decreased with increased temperature from 20 to 95°C with the concurrent liberation of juices. These workers used an open system where juices and fat were drained. The current experiment had a closed system.

Denaturation of protein is primarily an endothermic reaction (Scheraga et al., 1962; Joly, 1965). Change in protein conformation through the breaking of hydrogen bonds and/or the formation of hydrophobic bonds requires energy input. In the current study it can be postulated that the protein conformational changes were influenced by endothermic reactions and consumption of energy. If energy was

consumed, the temperature rise attributed to "simple" ease of heat transfer would not occur. For example, at 86°F for 0 minutes of holding time, the K decreased in value. Possibly a sudden initiated heat input along the wire caused an acceleration in fragmentation and conformational changes of the fibrillar proteins. The sensitivity of the meat sample to denaturation around 86°F is supported by decreased water-holding capacity indicated by the expressible moisture index. A second general decrease in thermal conductivity occurred at 122°F for 0 holding time. Possibly, this could be related to an observation by Hamm (1966) that the greatest changes in protein denaturation occurred between 104° and 140°F.

Generally, it may be postulated that holding the sample for 15 minutes tended to level the protein denaturing effect of heat input. The denaturation that occurred near the selected end point temperature had time for the reaction to be completed. However, it is of interest that decrease in conductivity values occurred with both 0 and 15 minute holding time at the 176°F end point temperature (Table 2, page 38). Possibly this was due to heat input and the formation of disulfide bonds.

The probable relationship (refer to Equation 4, page 22) between total moisture and thermal conductivity has been reported by Earle (1966). Therefore, the calculation of K on a basis of this measurable property indicating protein denaturation, total moisture, was done. The results shown in Table 8 were not significantly ($P < 0.05$) affected by the end point temperatures investigated. Comparison of the conductivity values to those obtained with the Dickerson method in this study

TABLE 8

THERMAL CONDUCTIVITY (Btu/hr ft °F) CALCULATED ON A BASIS
OF PERCENT TOTAL MOISTURE OF HEAT TREATED
GROUND TURKEY PECTORAL MUSCLES^{a,b}

End Point °F	Holding Time, Min	
	0	15
77	0.2756	0.2755
86	0.2760	0.2759
95	0.2098	0.2756
104	0.2755	0.2758
113	0.2749	0.2752
122	0.2749	0.2750
131	0.2747	0.2746
140	0.2756	0.2753
149	0.2750	0.2753
158	0.2755	0.2733
167	0.2725	0.2711
176	0.2728	0.2690
185	0.2686	0.2711

^a Average total moisture values used for each end point.

^b No significant ($P < 0.05$) effect of temperature on holding time on thermal conductivity values.

indicated the two approaches were not identical ($P < 0.05$). It cannot be discerned whether the results shown are attributable to experimental design and effect of the variables or the method of calculating thermal conductivity on a basis of total moisture.

It must be stressed that relating the endothermic reactions of protein denaturation to the fluctuations and variations in the current experiment can only be conjecture. Little related work can be found in the literature. In use of the line-source technique, Qashou et al. (1970) indicated that larger than expected variations in K values of ground beef occurred. Possibly these workers were experiencing some of the difficulties of phase change. Differential thermal analysis suggested endothermic reactions with proteins did cause a variation in temperature differentials. Calculations in this experiment assumed that the rise in temperature, which occurred during data collection for the TC heat curve, was a direct function of thermal conductivity. Steim (1965) indicated that DTA supported the presence of and traced the conformational changes that occurred during protein denaturation. Some of the TC heat curves in this study (see Appendix, Tables 10 and 11, pages 72 and 73) were determined to be sigmoid shaped. Sigmoid DTA curves have been determined for thermal denaturation of pepsin and ovalbumin (Hoyer, 1967). The sigmoid curves were reported as indicative of activation energies of 39 kcal/mole and 79 kcal/mole during thermal denaturation of pepsin and ovalbumin solutions, respectively. The possible relationship of the study by Hoyer (1967) and the line-source technique can only be conjecture. From the results obtained in the current

experiment, it could be postulated that thermal conductivity in a dynamic food system may be determined by a modification and incorporation of both the line-source technique and differential thermal analysis.

CHAPTER V

SUMMARY

Thermal conductivity and related properties of the ground turkey pectoral muscles heated in 9° increments from 77 to 185°F were studied. After an end point temperature was obtained, the sample was held for 0 or 15 minutes. The line-source technique was the basis for development of the apparatus and procedure. Thermal conductivity was calculated directly from data or indirectly by solving for diffusivity and then calculating for thermal conductivity. Water-holding capacity (expressible moisture index, total moisture, cooking loss), protein solubility (protein extractability), and change in pH were studied to determine the possible relation between thermal conductivity and protein denaturation.

The thermal conductivity values were expressed in terms of cal/sec cm °F or Btu/hr ft °F. With both methods of calculation, thermal conductivity values were significantly affected ($P < 0.05$) by end point temperature at the 0 minute but not at the 15 minute holding time even though holding times per se had no significant effect.

Several approaches and modes of calculation of the thermal properties suggested that conductivity values were influenced by a number of factors. Protein denaturation was postulated as a factor contributing to inconsistencies in thermal values. Significant ($P < 0.01$) effect of temperature upon cooking loss, total moisture, and

expressible moisture suggested protein denaturation. The water-holding capacity expressed by these determinations tended to decrease with increasing temperature. These changes were greatest in the end point temperature range of 104 to 158°F. Protein solubility decreased with increase in end point temperature from 77 to 131 to 185°F. A protein fraction extracted with phosphate buffer (I = 0.05, pH 7.6) decreased 30 percent and 60 percent from an initial end point at 77 to 131 to 185°F, respectively. The pH was significantly ($P < 0.01$) affected by temperature. With all parameters, no difference was found between holding times.

It can be postulated that the denaturation phenomenon in the current experiment influenced conductivity values both by the changes in structure and composition of the muscle system and by the energy consumption involved in conformational changes of the protein. However, specific relationships were not defined.

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APPENDIX

TABLE 9
DEGREE AND BEST-FIT COEFFICIENTS FOR POLYNOMIALS USING CASES CONSISTING OF DATA
FROM HEATING PHASE OF GROUND TURKEY

Treatment	Degree	Coefficients for Polynomial
77/0/1	1	0.0
77/0/2	1	0.0
77/15/1	1	0.0
77/15/2	1	$0.0 + 0.5000T$
86/0/1	1	$-0.7636 + 0.9786T$
86/0/2	1	$-0.3857 + 0.9149T$
86/15/1	1	$0.5956 + 1.0071T$
86/15/2	1	$-0.4118 + 0.7110T$
95/0/1	3	$-1.0769 + 1.9630T + 0.0459T^2 - 0.0066T^3$
95/0/2	3	$-1.1426 + 1.5448T + 0.1081T^2 - 0.0089T^3$
95/15/1	2	$-1.6910 + 2.6722T - 0.0848T^2$
95/15/2	5	$0.1175 - 0.7554T + 1.0720T^2 - 0.1471T^3 + 0.0078T^4 - 0.0001T^5$
104/0.1	2	$-3.3255 + 3.5535T - 0.1093T^2$
104/0/2	2	$-2.8965 + 3.3498T - 0.1083T^2$
104/15/1	2	$-2.7782 + 3.8322T - 0.1261T^2$
104/15/2	2	$-2.9088 + 3.7130T - 0.1169T^2$
113/0/1	2	$-4.0980 + 4.7526T - 0.1446T^2$
113/0/2	2	$-3.8820 + 5.1296T - 0.1705T^2$
113/15/1	2	$-3.1210 + 5.0395T - 0.1614T^2$
113/15/2	2	$-3.7071 + 4.6955T - 0.1433T^2$
122/0/1	4	$-1.2718 + 0.9803T + 0.8313T^2 - 0.0726T^3 + 0.0017T^4$
122/0/2	2	$-4.5756 + 5.8739T - 0.1809T^2$
122/15/1	2	$-2.6893 + 6.1917T - 0.1641T^2$
122/15/2	2	$-3.0913 + 5.3322T - 0.1451T^2$
131/0/1	2	$-5.3875 + 7.2719T - 0.2220T^2$
131/0/2	2	$-5.0726 + 7.4850T - 0.2261T^2$
131/15/1	2	$-6.3731 + 7.0807T - 0.2114T^2$
131/15/2	2	$-5.9733 + 7.9279T - 0.2624T^2$
140/0/1	2	$-4.0122 + 7.4364T - 0.2028T^2$
140/0/2	2	$-5.2338 + 7.7022T - 0.2170T^2$
140/15/1	2	$-3.0356 + 7.2560T - 0.1926T^2$
140/15/2	2	$-3.6956 + 7.0402T - 0.1875T^2$
149/0/1	2	$-7.8358 + 9.8689T - 0.3253T^2$
149/0/2	2	$-4.9085 + 8.1772T - 0.2205T^2$
149/15/1	2	$-3.7076 + 8.5389T - 0.2430T^2$
149/15/2	2	$-5.6748 + 8.4308T - 0.2346T^2$
158/0/1	2	$-3.0402 + 8.7284T - 0.2336T^2$
158/0/2	2	$-5.3989 + 9.7865T - 0.2788T^2$
158/15/1	2	$-5.7642 + 9.0732T - 0.2390T^2$
158/15/2	2	$-10.9908 + 10.8226T - 0.3516T^2$
167/0/1	2	$-8.0989 + 11.2458T - 0.3402T^2$
167/0/2	2	$-5.1981 + 10.9911T - 0.3382T^2$
167/15/1	2	$-13.0508 + 13.4813T - 0.5068T^2$
167/15/2	2	$-6.6438 + 10.9668T - 0.3150T^2$
176/0/1	2	$-9.3226 + 12.5408T - 0.3706T^2$
176/0/2	2	$-7.1137 + 11.8046T - 0.3383T^2$
176/15/1	2	$-8.2927 + 11.8126T - 0.3309T^2$
176/15/2	2	$-7.3194 + 11.8504T - 0.3311T^2$
185/0/1	2	$-8.7670 + 13.6912T - 0.4025T^2$
185/0/2	2	$-12.4056 + 15.0817T - 0.4885T^2$
185/15/1	2	$-7.0168 + 12.3923T - 0.3338T^2$
185/15/2	2	$-4.4683 + 12.5176T - 0.3482T^2$

TABLE 10
DEGREE AND BEST-FIT COEFFICIENTS FOR POLYNOMIALS USING HEAT TREATED
GROUND TURKEY CONSISTING OF DATA FROM TC HEAT CURVES
(0.0 TO 2.0 MIN)^a

Treatment	Degree	Coefficients for Polynomial
77/0/1	1	$0.900 + 3.1500T$
77/0/2	2	$0.2564 + 6.1839T - 1.3853T^2$
77/15/1	2	$0.1873 + 6.4846T - 1.4390T^2$
77/15/2	2	$0.1339 + 6.6498T - 1.6199T^2$
86/0/1	3	$0.1707 + 16.5159T - 10.5780T^2 + 3.5428T^3$
86/0/2	2	$0.0064 + 9.3910T - 2.6139T^2$
86/15/1	2	$0.7958 + 9.1822T - 2.5177T^2$
86/15/2	4	$0.0434 + 14.7825T - 12.5980T^2 + 5.5812T^3 - 0.9697T^4$
95/0/1	1	$1.2900 + 3.3433T$
95/0/2	1	$1.1756 + 3.4800T$
95/15/1	2	$0.5094 + 10.2735T - 2.9801T^2$
95/15/2	1	$1.6367 + 3.3967T$
104/0/1	3	$-0.0748 + 14.6473T - 9.4551T^2 + 2.2518T^3$
104/0/2	2	$0.6661 + 9.8573T - 2.8087T^2$
104/15/1	2	$-0.0546 + 6.8013T - 1.7506T^2$
104/15/2	3	$0.0788 + 12.0340T - 7.5784T^2 + 1.8424T^3$
113/0/1	3	$0.0944 + 10.8790T - 6.4098T^2 + 1.4896T^3$
113/0/2	2	$0.1548 + 8.0772T - 2.3403T^2$
113/15/1	1	$0.8644 + 3.3633T$
113/15/2	3	$-0.0061 + 9.6030T - 5.2121T^2 + 1.1152T^3$
122/0/1	3	$0.1545 + 12.6231T - 7.4459T^2 + 1.6808T^3$
122/0/2	3	$0.2662 + 14.4879T - 9.4378T^2 + 2.3084T^3$
122/15/1	3	$-0.0384 + 8.5503T - 5.7885T^2 + 1.5973T^3$
122/15/2	3	$0.1515 + 11.1914T - 6.2606T^2 + 1.3252T^3$
131/0/1	3	$-0.0283 + 10.3938T - 6.0566T^2 + 1.4411T^3$
131/0/2	3	$0.0667 + 8.4539T - 4.6380T^2 + 1.1555T^3$
131/15/1	3	$0.0490 + 9.5431T - 5.7812T^2 + 1.4411T^3$
131/15/2	1	$1.0391 + 3.3953T$
140/0/1	2	$0.0033 + 5.7467T - 1.2000T^2$
140/0/2	1	$0.6778 + 3.1833T$
140/15/1	2	$0.4799 + 8.5743T - 2.4751T^2$
140/15/2	2	$0.1897 + 7.9410T - 2.2805T^2$
149/0/1	1	$0.7667 + 4.0500T$
149/0/2	2	$-0.0737 + 6.4825T - 1.7176T^2$
149/15/1	2	$0.8576 + 7.5669T - 2.0251T^2$
149/15/2	2	$0.2703 + 8.1299T - 2.1100T^2$
158/0/1	1	$1.1711 + 3.7040T$
158/0/2	3	$0.0494 + 9.8903T - 5.1061T^2 + 1.0480T^3$
158/15/1	2	$0.2273 + 7.5208T - 2.1437T^2$
158/15/2	2	$0.1221 + 8.7484T - 2.4459T^2$
167/0/1	3	$-0.1107 + 10.9319T - 7.1579T^2 + 1.8322T^3$
167/0/2	3	$-0.0914 + 10.5166T - 6.4777T^2 + 1.5488T^3$
167/15/1	1	$0.6700 + 2.9800T$
167/15/2	2	$0.4000 + 6.2666T - 1.7333T^2$
176/0/1	2	$0.0639 + 8.6460T - 2.3247T^2$
176/0/2	4	$0.0066 + 7.0357T - 0.1068T^2 - 2.1808T^3 + 0.6900T^4$
176/15/1	3	$-0.1126 + 11.1832T - 5.8170T^2 + 1.2337T^3$
176/15/2	2	$-0.0561 + 8.2774T - 2.4951T^2$
185/0/1	2	$0.0176 + 6.3426T - 1.6346T^2$
185/0/2	3	$0.0227 + 8.9136T - 5.3212T^2 + 1.2848T^3$
185/15/1	1	$0.9673 + 2.8860T$
185/15/2	3	$-0.0672 + 9.5053T - 5.8187T^2 + 1.4195T^3$

^aOriginal data may be obtained by contacting: FSIA, College of Home Economics, The University of Tennessee, Knoxville.

TABLE 11

DEGREE AND BEST-FIT COEFFICIENTS FOR POLYNOMIALS USING HEAT TREATED
GROUND TURKEY CONSISTING OF DATA FROM TC HEAT CURVES
(0.0 TO 1.5 MIN)^a

Treatment	Degree	Coefficients for Polynomial
77/0/1	1	$0.696425 + 3.528569T$
77/0/2	1	$0.742858 + 3.999997T$
77/15/1	1	$0.639386 + 4.328571T$
77/15/2	1	$0.641072 + 4.221426T$
86/0/1	2	$0.417858 + 13.37856T - 4.942850T^2$
86/0/2	1	$0.835713 + 5.457139T$
86/15/1	2	$0.338097 + 11.928561T - 4.552375T^2$
86/15/2	3	$0.059526 + 14.180982T - 10.352423T^2 + 2.933351T^3$
95/0/1	1	$0.955352 + 3.964287T$
95/0/2	1	$0.849998 + 4.085716T$
95/15/1	3	$0.009524 + 15.471439T - 11.066669T^2 + 3.200000T^3$
95/15/2	2	$0.348810 + 8.599989T - 3.066689T^2$
104/0/1	2	$0.135711 + 11.800003T - 4.345827T^2$
104/0/2	2	$0.369046 + 11.685724T - 4.190486T^2$
104/15/1	1	$0.517859 + 4.128567T$
104/15/2	2	$0.248799 + 9.774391T - 3.466784T^2$
113/0/1	3	$0.032141 + 11.752349T - 7.942787T^2 + 2.133298T^3$
113/0/2	1	$0.910716 + 4.528567T$
113/15/1	1	$0.474997 + 4.100000T$
113/15/2	1	$0.935714 + 4.171427T$
122/0/1	1	$1.446425 + 5.042860T$
122/0/2	6	$-0.000000 + 20.35003T - 26.38897T^2 + 25.19953T^3 - 25.42095T^4$ $+ 19.19893T^5 - 5.68860T^6$
122/15/1	1	$0.80358 + 3.24285T$
122/15/2	1	$1.31072 + 4.58572T$
131/0/1	2	$0.08928 + 8.73570T - 2.94285T^2$
131/0/2	3	$0.04286 + 8.75233T - 5.11420T^2 + 1.33330T^3$
131/15/1	1	$0.98571 + 3.91428T$
131/15/2	1	$0.71786 + 3.98000T$
140/0/1	1	$0.37321 + 3.95000T$
140/0/2	1	$0.27857 + 3.91428T$
140/15/1	3	$-0.03357 + 14.21368T - 11.55817T^2 + 3.69781T^3$
140/15/2	3	$-0.07976 + 10.59605T - 6.24766T^2 + 1.51113T^3$
149/0/1	3	$0.00476 + 8.41902T - 5.24758T^2 + 1.86665T^3$
149/0/2	1	$0.45178 + 3.92715T$
149/15/1	2	$0.61309 + 9.04287T - 3.12382T^2$
149/15/2	3	$0.03572 + 11.30078T - 7.86666T^2 + 2.57778T^3$
158/0/1	1	$0.64464 + 4.69857T$
158/0/2	1	$1.03643 + 4.38571T$
158/15/1	2	$-0.00357 + 8.92855T - 3.19999T^2$
158/15/2	1	$-0.1298 + 10.3143T - 3.6381T^2$
167/0/1	2	$0.00833 + 8.96287T - 3.27620T^2$
167/0/2	2	$-0.00238 + 8.96430T - 3.30478T^2$
167/15/1	2	$-0.04762 + 5.49285T - 1.26666T^2$
167/15/2	2	$0.25357 + 7.17857T - 2.42858T^2$
176/0/1	1	$0.83214 + 5.07143T$
176/0/2	2	$-0.01191 + 7.67857T - 2.23810T^2$
176/15/1	1	$0.92678 + 5.13572T$
176/15/2	1	$0.66608 + 4.67000T$
185/0/1	2	$-0.0083 + 6.4786T - 1.7238T^2$
185/0/2	2	$0.10000 + 7.63571T - 2.71429T^2$
185/15/1	6	$-0.0000 + 8.2167T - 18.7356T^2 + 62.0002T^3 - 89.9559T^4$ $+ 53.3335T^5 - 10.8089T^6$
185/15/2	1	$0.86607 + 3.83571T$

^aOriginal data may be obtained by contacting: FSIA, College of Home Economics, The University of Tennessee, Knoxville.

TABLE 12

FORTRAN PROGRAM USED FOR CALCULATION OF THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY ACCORDING TO THE COWLING METHOD^a

Statement	Program
	Dimension A(40)
900	F(Y)=.32*Y*(T1/V1-T2/V2)+(R**2/12.5-.75-ALOG(R/2.5))*(1./V1-1./V2)-(.8417*BX1*(EXP(-2.35*Y*T1(1)/V1-EXP(-2.35*Y*T2)/V2))
901	FP(Y)=.32*(T1/V1-T2/V2)-(.8417*BX1*(EXP(-2.35*Y*T1)/V1**2.35*T1)-(EXP(-2.35*Y*T2)/V2*DE)))
	READ 12,N
12	FORMAT (I10)
	DO 300 J=1,N
	READ I1,R,Q,V1,T1,V2,T2
11	FORMAT (6F10.4)
	DE=2.35*T2
	DX=7.873*T2
	DY=16.56*T2
	X1=1.5326*R
	X2=2.806*R
	X3=4.0695*R
	PROD=1.
	BX1=1.
	BX2=1.
	BX3=1.
	DO 20 I=1,20
	A(I)=2*I
	PROD=PROD*A(I)
	PBX1=(-1)**I*(XI**A(I))/(PROD**2)
	PBX2=(-1)**I*(X2**A(I))/(PROD**2)
	PBX3=(-1)**I*(X3**A(I))/(PROD**2)
	BX1=BX1+PBX1
	BX2=BX2+PBX2
	BX3=BX3+PBX3
20	CONTINUE
	PRINT 70
70	FORMAT(1H,27X,4H BX1,17X,4H BX2,13X,4H BX3)
	PRINT 80,BX1,BX2,BX3
80	FORMAT(1H0,20X,3(SX,E15,7))
902	Y=0.4
	Z=F(Y)
	PRINT 140,Y,Z
140	FORMAT(1HC,20X,3H I,17X,4H Y1,17X,7H F(Y1)/20X,4H 0,2(8X,F15.6))
	DO 110 I=1,50
	Y1=Y-F(Y)/FP(Y)
	Z=F(Y1)
	PRINT 120,I,Y1,Z
120	FORMAT(20X,14,2(8X,E15.6))
	Y=Y1
	IF (ABS(Z).LT.1.E-5) GO TO 30
110	CONTINUE
30	S1=Q/(6.2832*V1)*(.32*Y*T1+(R**2/12.5)-.75-ALOG(R/2.5)-(.8417*1BX1*EXP(-2.35*Y*T1))
	1-(.4524*BX2*EXP(-7.873*Y*T1))- (.3106*BX3*1EXP(-16.56*Y*T1)))
	S2=Q/(6.2832*V2)*(.32*Y*T2+(R**2/12.5)-.75-ALOG(R/2.5)-(.8417*1BX1*EXP(-2.35*Y*T2))
	1-(.4524*BX2*EXP(-7.873*Y*T2))- (.3106*BX3*1EXP(-16.56*Y*T2)))
	PRINT 40,S1,S2,Y
40	FORMAT(///20X,3E15.6)
300	CONTINUE
	CALL EXIT
	END

^aStatements 900 and 901 were in the original program as follows:

```

900      F(Y)=.32*Y*(T1/V1-T2/V2)+(R**2/12.5-.75-ALOG(R/2.5))*(1./V1-1./V2)1-(.8417*BX1*(EXP
1(-2.35*Y*T1)/V1-EXP(-2.35*Y*T2)/V2))- (.3106*BX3*1EXP(-16.56*Y*T1)/V1-EXP(-16.56*Y*T2)
1/V2))- (.4524*BX2*(EXP(-7.873 1*Y*T1)/V1EXP(-7.873*Y*T2)/V2))
901      FP(Y)=.32*(T1/V1-T2/V2)- (.8417*BX1*(EXP(-2.35*Y*T1)/V1*(-2.35*T1)-(EXP(-2.35*Y*T2)/V2*DE)))
1-(.4524*BX2*(EXP(-7.873*Y*T1)/V1*(-7.873*T1)-(EXP(-7.873*Y*T2)/V2*DX)))- (.3106(BX3*(EXP
1(-16.56*Y*T1)/V1*(16.56*T1)-(EXP(-16.56*Y*T2)/V2*DY)))
902      Y=.0007068

```

DERIVATION OF EQUATION TO FIND THERMAL CONDUCTIVITY
AND THERMAL DIFFUSIVITY

The governing Laplace transformed differential equation is given by Carslaw and Jaeger (1959):

$$\frac{\partial^2 \bar{V}}{\partial r^2} + \frac{1}{r} \frac{\partial \bar{V}}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \bar{V}}{\partial \theta^2} - q^2 \bar{V} = 0 \quad 0 \leq r \leq a$$

with insulated boundary $\frac{\partial \bar{V}}{\partial r} = 0.0$, $r = a$

$$\text{and } \lim_{R \rightarrow 0} R \frac{\partial \bar{V}}{\partial R} = - \frac{Q}{2\pi K \rho}$$

$$\text{where } R = \sqrt{r^2 + r'^2 - 2 r r' \cos \theta}$$

The complete solution is given by

$$V = \frac{Q}{2\pi K} \left\{ \frac{2kt}{a^2} + \frac{r^2 + r'^2}{2a^2} - \frac{3}{4} - \frac{1}{2} \ln \left(1 - \frac{rr'}{a^2} \cos \theta + \frac{r^2 r'^2}{4a^4} \right) - \frac{1}{2} \ln \left(\frac{r'^2}{a^2} - \frac{rr'}{a^2} \cos \theta + \frac{r^2}{a^2} \right) \right\} - \frac{Q}{\pi K} \sum_{n=0}^{\infty} \epsilon_n \cos n\theta \sum_{m=1}^{\infty} e^{-k\alpha_{n,m}^2 t}$$

$$\frac{J_n(r \alpha_{n,m}) J_n(r' \alpha_{n,m})}{(a^2 \alpha_{n,m}^2 - n^2) J_n^2(a \alpha_{n,m})}$$

For a heat source at the center of the cylinder, let $r' = 0.0$, $\theta = 0.0$, and $v \neq f(\theta)$, then $n = 0$, $\theta = 1$.

$$V = \frac{Q}{2\pi K} \left\{ \frac{2kt}{a^2} + \frac{r^2}{2a^2} - \frac{3}{4} - \ln \frac{r}{a} \right\} - \frac{Q}{\pi K} e^{-k\alpha_m^2 t} \sum_{m=1}^{\infty} \frac{J_0(r\alpha_m)}{a^2 \alpha_m^2 J_0(a\alpha_m)}$$

where α_m are the positive roots of $J'_0(a\alpha) = 0.0$.

A computer will be used to find k and K from the above equation by measuring radius, r , heat source strength, Q , temperature, V , at r , and time, T . We use Newton's iteration method to solve the equation as follows:

$$\text{if } J'_0(a\alpha) = 0.0 \text{ i.e. } J_1(a\alpha) = 0.0$$

for the basis of discussion assume outside radius, $a = 2.5$ cm

$$a\alpha_1 = 3.8317 \qquad \alpha_1 = \frac{3.8317}{a} = \frac{3.8317}{2.5} = 1.5326$$

$$a\alpha_2 = 7.0156 \qquad \alpha_2 = \frac{7.0156}{a} = \frac{7.0156}{2.5} = 2.806$$

$$a\alpha_3 = 10.1735 \qquad \alpha_3 = \frac{10.1735}{a} = \frac{10.1735}{2.5} = 4.0695$$

$$J_0(a\alpha_1) = J_0(3.8317) = -0.4023$$

$$J_0(a\alpha_2) = J_0(7.0156) = 0.2997$$

$$J_0(a\alpha_3) = J_0(10.1735) = -0.2494$$

Let $S = K$, $Y = K$, $BX1 = J_0(r\alpha_1)$, $BX2 = J_0(r\alpha_2)$, $BX3 = J_0(r\alpha_3)$.

Substitute in the equation we get

$$S_1 = \frac{Q}{6.2832 V_1} \left\{ 0.32 Y_{T1} + \frac{r^2}{12.5} - 0.75 - \ln \frac{r}{2.5} - 0.8417 BX1 e^{-2.35 Y_{T1}} \right. \\ \left. - 0.4524 BX2 e^{-7.873 Y_{T1}} - 0.3106 BX3 e^{-16.56 Y_{T1}} \right\}$$

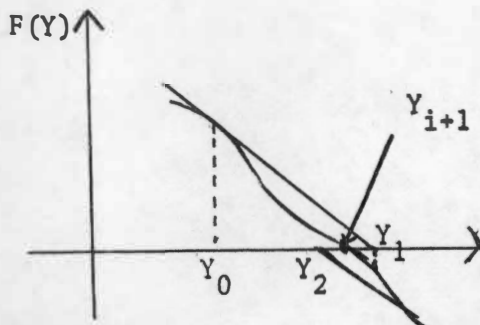
$$S_2 = \frac{Q}{6.2832 V_2} \left\{ 0.32 Y_{T2} + \frac{r^2}{12.5} - 0.75 - \ln \frac{r}{2.5} - 0.8417 BX1 e^{-2.35 Y_{T2}} \right. \\ \left. - 0.4524 BX2 e^{-7.873 Y_{T2}} - 0.3106 BX3 e^{-16.56 Y_{T2}} \right\}$$

$$\text{Let } F(Y) = S_1 - S_2 = 0$$

$$0.32Y \left(\frac{T_1}{V_1} - \frac{T_2}{V_2} \right) + \left(\frac{r^2}{12.5} - 0.75 - \ln \frac{r}{2.5} \right) \left(\frac{T_1}{V_1} - \frac{T_2}{V_2} \right) \\ - 0.8417 BX1 (e^{-2.35 Y_{T1}/V_1} - e^{-2.35 Y_{T2}/V_2}) \\ - 0.4524 BX2 (e^{-7.873 Y_{T1}/V_1} - e^{-7.873 Y_{T2}/V_2}) \\ - 0.3106 BX3 (e^{-16.56 Y_{T1}/V_1} - e^{-16.56 Y_{T2}/V_2})$$

$$\begin{aligned}
 F'(Y) = & 0.32 \left(\frac{T_1}{V_1} - \frac{T_2}{V_2} \right) - 0.8417 \text{ BX1} \left(e^{-2.35 Y T_1} \frac{-2.35 T_1}{V_1} - \right. \\
 & \left. e^{-2.35 Y T_2} \frac{-2.35 T_2}{V_2} \right) - 0.4524 \text{ BX2} \left(e^{-7.873 Y T_1} \frac{-7.873 T_1}{V_1} - \right. \\
 & \left. - e^{-7.873 Y T_2} \frac{-7.873 T_2}{V_2} \right) - 0.3106 \text{ BX3} \left(e^{-16.56 Y T_1} \frac{-16.56 Y T_1}{V_1} - \right. \\
 & \left. - e^{-16.56 Y T_2} \frac{-16.56 Y T_2}{V_2} \right)
 \end{aligned}$$

For Newton's method



$$\text{Slope} = F'(Y_0) = \frac{F(Y_0) - 0}{Y_0 - Y_1}$$

$$Y_1 = Y_0 - \frac{f(Y_0)}{F'(Y_0)}$$

$$\text{Slope} = F'(Y_1) = \frac{f(Y_1) - 0}{Y_1 - Y_2}$$

$$Y_2 = Y_1 - \frac{f(Y_1)}{F'(Y_1)}$$

$$Y_{i+1} = Y_i - \frac{F(Y_2)}{F'(Y_2)}$$

Assuming Y_0 then we can use computer with Newton's iteration method to solve the equation

$$Y_{i+1} = Y_i - \frac{f(Y_i)}{f'(Y_i)}$$

thermal conductivity and thermal diffusivity values may be calculated.

Source: Cowling, P. 1972. Private Communication. Dept. of Mechanical and Aerospace Engineering. The University of Tennessee, Knoxville.

TABLE 13
PARTS LIST OF THERMAL CONDUCTIVITY APPARATUS
AND ACCESSORIES

Part	Description
A	Heated cylinder
B	Rheostat
C	Voltmeter, Simpson Model 157
D	Ammeter, General Electric AC
E	Potentiometer, Honeywell Electronik 16
F	Water bath, Precision Scientific Products
G	Pump, Sears Submersible
H	Cooling vat
I	Inner thermocouple, cooper-constantan
J	Outer thermocouple, copper-constantan
K	Resistance-heater wire, chromel-C
L	Vernier caliper
M	Sample

OPERATION OF THERMAL CONDUCTIVITY APPARATUS
AND ACCESSORIES

Adjust waterbath to selected end point temperature.

Check voltage to 5 volts.

Check accuracy of thermocouples.

Adjust cooling vat to 77°F.

Weigh initial package sample weight.

Pack sample in heat cylinder using the sample packer.

Record final weight of sample package.

Measure and record sample height using Vernier calipers.

Stabilize initial sample temperature at 77°F using circulating water
from cooling vat.

Place pump in waterbath at selected end point temperature.

Turn on pump and record initial temperature of the inner thermocouple
simultaneously.

Continue recording during the heating phase until a steady-state condition at the selected end point temperature is reached, i.e., the inner and outer thermocouple record temperatures identical to inflow temperature of the waterbath medium.

Initiate procedure to record data for calculation of thermal conductivity.

Select only record of the inner thermocouple, i.e., the
thermocouple closest to the heat source.

Move up the potentiometer chart paper slightly.

Simultaneously as the inner thermocouple begins to record
turn on voltage.

Check voltage and amperes. Record volts and amperes.

Record temperature rise for a 2 minute period.

As last record for the 2 minutes is completed

Turn off pump and switch to cooling vat. Turn off voltage.

Move up chart

Select temperature record for both inner and outer
thermocouples

Turn on pump to circulate water from cooling vat.

Cool sample until a temperature of 77°F is obtained.

Remove top and bottom stoppers and plastic disks from the ends of heat
cylinder.

Place sample in preweighed plastic container and cover.

Wash heat cylinder.

TABLE 14

THERMAL DIFFUSIVITY VALUES CALCULATED FROM TWO TC HEAT CURVES^a

End Point °F	Curve-Fitted			
	0.0 to 2.0		0.0 to 1.5	
	Holding Time, Min			
	0	15	0	15
77	0.3243	0.5056	0.4694	0.6274
	0.4489	0.4767	0.4988	0.6101
86	0.1813	0.2543	0.1927	0.1792
	0.4524	0.1692	0.6050	0.1811
95	0.2401	0.2881	0.3844	0.2116
	0.2743	0.1921	0.4454	0.1998
104	0.1929	0.5753	0.2205	0.7387
	0.2663	0.2014	0.2077	0.2217
113	0.2232	0.3605	0.2062	0.7997
	0.3573	0.2649	0.4607	0.4130
122	0.2064	0.2158	0.3230	0.3739
	0.1686	0.2158	0.1244	0.3242
131	0.2620	0.2404	0.2785	0.3679
	0.3045	0.3028	0.2889	0.5136
140	0.7453	0.2792	0.9806	0.1939
	0.4352	0.3503	1.3021	0.2713
149	0.4893	0.2305	0.5270	0.1855
	0.5647	0.3873	0.8053	0.3195
158	0.2915	0.3387	0.6754	0.2577
	0.2713	0.3983	0.3921	0.2963
167	0.2250	0.4121	0.2419	0.7103
	0.2344	0.2853	0.2382	0.2330
176	0.4533	0.3178	0.5638	0.5134
	0.4476	0.4120	0.4212	0.6496
185	0.5116	0.2764	0.5027	0.4742
	0.2408	0.2456	0.2392	0.4103

^aCalculated by the Cowling method in terms of cm/sec.

TABLE 15
SAMPLE COMPARISON OF DATA OBTAINED FROM TURKEY
PECTORAL MUSCLES

Parameters	Lot		
	A	B	C
Total moisture, %	74.13	74.17	73.80
	74.11	73.88	73.53
Lipid, %	1.60	1.68	1.58
pH	5.73	5.69	5.71
	5.74	5.74	5.69
Expressible moisture index	1.03	1.23	1.31
	1.23	1.15	1.27
Protein, mg N/g ^a			
Low-ionic strength fraction	14.36	17.92	17.72
Nonprotein fraction	4.63	6.28	5.08
Total	39.72	41.20	35.34
	30.47	43.77	31.04

^aWet tissue basis.

PROTEIN ANALYSIS

Low-Ionic Strength Fraction

Remove two-gram sample from heat cylinder (Figure 4, page 32) and place in 35 ml potassium phosphate buffer (K_2HPO_4 , KH_2PO_4 ; $I = 0.05$, pH 7.6) at approximately 37°F.

Homogenize in VirTis 45 Homogenizer and place in 50 ml polyethylene centrifuge tube.

Rinse flask with 15 ml buffer.

Stand one hour, agitate every 15 minutes.

After one hour, centrifuge homogenate 20 minutes at $27,000 \times G$ (37°F).

Filter supernatant through Whatman No. 1 filter paper.

Resuspend residue in centrifuge with 25 ml phosphate buffer.

Agitate every 15 minutes for one hour and centrifuge and filter as before.

Record total volume.

Determine mg N/g tissue on two 5 ml samples of supernatant according to the AOAC (1970) micro-Kjeldahl method. Calculate using Equation 10.

Nonprotein Nitrogen

Add 5 ml of 10 percent trichloroacetic acid to 15 ml low-ionic strength fraction supernatant.

After 30 minutes filter through Whatman No. 1 paper.

Determine mg N/g tissue on two 15 ml samples of filtrate according to the AOAC (1970) micro-Kjeldahl method. Calculate using Equation 11.

Total Protein

Using approximately 0.200 g of sample (Figure 4, page 32) determine mg N/g tissue according to the AOAC (1970) micro-Kjeldahl method. Calculate using Equation 12.

Equations for Calculation of mg N/g Tissue

$$\text{Equation 10: mg N/g tissue} = \frac{(A - B) \times C \times N \times 14.01}{D \times E}$$

$$\text{Equation 11: mg N/g tissue} = \frac{(A - B) \times C \times N \times 14.01 \times 1.33}{D \times E}$$

$$\text{Equation 12: mg N/g tissue} = \frac{(A - B) \times N \times 14.01}{D}$$

A represents ml HCl used to titrate sample.

B represents ml HCl used to titrate blank.

C represents volume of supernatant.

D represents grams of sample used in determination.

E represents volume of filtrate analyzed.

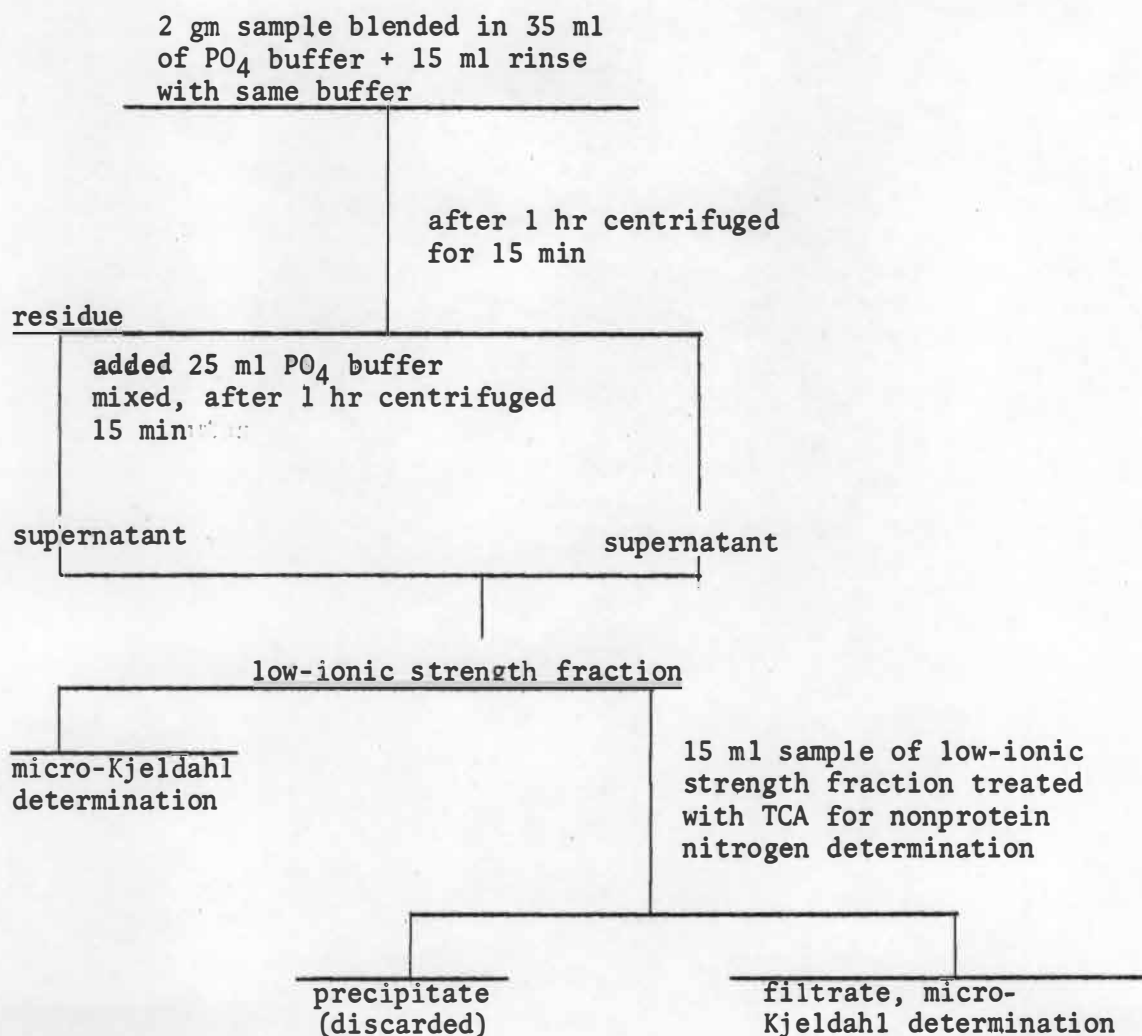


Figure 5. Scheme for determination of protein extractable in phosphate buffer.

VITA

Zoe Ann Holmes was born in Pittsburg, Kansas, on February 28, 1942. She graduated from high school in 1960. She received a Bachelor of Science degree in Home Economics with an option in Foods and Nutrition Research in 1964, at Kansas State University, Manhattan. In 1965, she completed work for a Master of Science degree with a major in Foods and Nutrition at Kansas State University, Manhattan.

Upon completion of her Master's degree, she taught at Oregon State University from September 1965 until June 1969. She is a member of Sigma Xi, the Institute of Food Technologists, the American Home Economics Association and Omicron Nu.

She entered the Graduate School at The University of Tennessee, Knoxville, in September 1969, and received the Doctor of Philosophy degree with a major in Food Science in August 1972.