Outbreaks of disease caused by *Escherichia coli* O157:H7 associated with the consumption of undercooked ground beef patties have raised interest in improving the cooking process. The inability to accurately measure temperature, using temperature probes and the complex nature of the beef patty structure makes end point temperature prediction difficult. X-ray computer aided tomography (CAT) scanning was used to characterize the internal structure of ground beef patties. Images captured by the CAT scanner showed the porous structure of the patty. Air pores were randomly distributed, as were lipid and muscle tissues after cooking. A crust layer was visualized on the cooked surfaces of the beef patty. Cross sectional images illustrated an inconsistent thickness across the patty, indicating that constant contact with the grill was not maintained. Locations of thermal probes inserted into the patty were verified using the x-ray CAT scanning. Temperatures corresponding to verified locations demonstrated temperature differences across the thickness of the patty.

Finite element modeling using digital images illustrated the effect that a non-homogenous structure has on conductive heating. Homogeneous model images resulted in uniform heating, while images of ground beef patties with pores, crust, and an inconsistent cooking surface resulted in a heating pattern that is disrupted. The cook time was delayed by increasing patty thickness, crust development, and porosity.

X-ray CAT scanning and FEM modeling demonstrated the effect of internal structure on conductive heat transfer in ground beef patties.
INDEX WORDS: Ground Beef Patty, X-ray CAT scan, Finite Element Modeling, Crust, Meat, Conductive Heat Transfer
FINITE ELEMENT MODELING OF THE COOKING PROCESS IN GROUND BEEF PATTIES

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DEDICATION

This dissertation is dedicated to my parents, Justo and Julie, and my wife, Shirley.
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I am thankful for all the support, training and encouragement that Dr. Joseph Frank, my major advisor, has given me through the years.

Captain Dowd you are a true friend and without you this project most certainly would not have been completed. Now we’ll have time to enjoy the bicycles more.

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Revis, you are the life of the lab and one of my dearest friends.
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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW
Introduction

Food pathogens that pose significant health risks to humans continue to find their way into consumer’s homes, despite efforts by government and health organizations to impose guidelines and regulations. Since these contaminants may reach the consumer undetected, the person preparing the meal becomes the last barrier to safe food consumption.

*Escherichia coli, Salmonella, Listeria, Campylobacter, etc.* are just a few of the many microorganisms that have caused illness and even death. Eliminating them from food is difficult. Eliminating them from the environment is impossible. Manufacturers and market handlers can only minimize the growth and spread of these organisms. Their quality assurance can only test a limited quantity of product before it becomes too costly for them. However, proper thermal processing will destroy all human pathogenic organisms in food products.

Beef, and particularly ground beef, is quite popular in the American diet. Because of its wide spread popularity, many people could be exposed to contaminated material. Ground beef patties, when undercooked, have been implicated in numerous disease outbreaks. Because of its structure, ground beef patties provide a large surface area for bacteria to grow on. During grinding, microorganisms become internalized, where they are better protected from surface heat. They are also a nutrient rich medium for microorganisms to proliferate, if the raw materials are not stored at a low enough temperature to slow this activity.

The manufacture of ground beef patties can vary quite drastically. Commercial patties’ can show a high level of uniformity; however, this cannot be said of homemade
patties, which can vary in size, shape, formula and handling methods. These subtle differences can affect the time it takes to cook the beef and attain the minimum safe temperature of 71°C.

Methods to determine doneness, such as meat color and enzyme testing, have had limited success. Internal temperature is the most reliable method of determining end point temperature. However, monitoring internal temperatures by thermometers are only as reliable as the instrument and the location that is being probed.

It is the purpose of this dissertation to describe the non-uniform heating patterns of ground beef patties that result from their heterogeneous structure. By employing medical techniques to ascertain the internal arrangement of food structures and using finite element modeling, we can better understand the complexities of cooking and why it is difficult to find a common end point temperature within the same object.

Using x-ray computer aided tomography (CAT) scanning, structures within the ground beef patties that affect the internal heat patterns were identified. Placements of thermal couples were verified using CAT scanning. Structural and composition changes of the beef patties were collected over time and used to develop thermal properties. Computer programs were created to translate the captured images from the scanner; generate the finite element mesh and assign the thermal properties to each image pixel; and, lastly, demonstrate thermal patterns that develop during cooking. Thermal properties were calculated using several existing models and implemented in the finite element program. Unusual structures were given unique thermal property assignments. Models demonstrating isothermal patterns representing sample cross sections were generated. Lastly, an image coordinate temperature plotter demonstrated how each pixel
in the image cross-section changes over time. These plots and models describe non-uniform heating caused by the structures within the patty.

**Literature review**

Outbreaks of *Escherichia coli* O157:H7 linked to contaminated ground beef had a devastating effect on the public and its trust in the way food establishments were handling food. In addition to outbreaks, a large number of sporadic cases were widely distributed across the United States (Remis et al., 1984). Because of the deaths associated with those outbreaks, *E. coli* O157:H7 has drawn a great deal of attention to ground beef. It called into question the handling of meat products, the cooking process, and the proper determination of doneness.

From the time of slaughter to the final packaged product, there are many points where pathogenic microorganisms can proliferate. Practices such as steam vacuuming, steam pasteurization, hot water washing, acid washing and antimicrobial washing of carcasses have been used to reduce contamination, and have some efficacy in lowering the bacterial load in ground beef. (Brackett, et al., 1994; Dorsa et al., 1996, 1997, 1998; Sage and Ingham, 1998; Kochevar et al., 1997; Nutsch et al., 1997; Phebus et al., 1997). Even further, Kim and Slavik (1994) found that trisodium phosphate (TSP) was effective in removing *E. coli* O157:H7 and *S. typhimurium* from fascia and fat tissue surfaces. Bacterial load plays an important role as Cutter et al. (1997) found that bacterial level significantly affects the efficacy of the spray washing, while temperature of the wash had no measurable effect on its removal.
Ground beef hamburgers are one of the most popular food items on the consumer market. The average American will consume approximately 28 pounds of ground beef a year, totaling 7.5 billion pounds of ground beef (Anon1., 2001). Most ground beef that is brought into U.S. supermarkets can come from more than one source. The beef can come in a coarse grind and be reground and repacked at the store (Anon1., 2001). Often the ground beef can be mixed with beef trimmings and re-ground and re-packed to form the final product. By now, the ground beef could have been in contact with many employees and possibly many sources of contamination. The task of eliminating microbial contamination from meat products is multi-faceted, and it appears to be difficult to guarantee zero tolerance of pathogens in such products.

Efforts to describe thorough cooking of ground beef have been focused on final color and temperatures. Because of the various problems with determining proper color, most of the effort has been to cook the beef patties to 71°C (USDA, 1995; USDA, 1997). Because of its thickness and non-uniform structure it is difficult to take temperatures of the patty. Often what are found are different temperatures, even though the thermal couples or probes are apparently in the same place. Complicating matters is the fact that most consumers and institutions do not have accurate temperature measuring devices (Hague et al., 1994).

The ground beef patty is a heterogeneous mixture of fat, protein and water. Because of the non-uniform distribution of these components, rates of heat and mass transfer are non-uniform (Singh et al. 1997). Because of these non-uniform structures and heating patterns, it is difficult to determine where the cold spots will be in the product. From a heat transfer point of view, changes such as shrinkage, porosity and
bulk movement within the patty will affect cooking rates and, ultimately, the cooking temperature and time relationship. Little is known about the dimensional changes that also occur during the cooking process or how they affect heat transfer (Singh et al. 1997). It is clear that to effectively kill pathogenic organisms by heat, the heating pattern within a non-homogenous product must be understood.

*Escherichia coli Contamination In meat*

There are many microorganisms that are associated with meats. Most are harmless and are associated with spoilage, but it is the pathogenic type that concerns most consumers. Pseudomonads, *Enterobacteriaceae*, and lactic bacteria were identified as the primary microorganisms that cause spoilage of refrigerated ground beef (Gill, 1986; Lambert et al., 1991). Organisms of health concern found in refrigerated meat include *Escherichia coli*, *Salmonella* spp., *Campylobacter jejuni*, and *Listeria* spp.

Coliforms are gram-negative, rod-shaped, facultatively anaerobic bacteria. They can ferment sugar such as glucose and produce acid and gas from lactose. The coliform group includes species from the genera *Escherichia*, *Klebsiella*, *Enterobacter*, and *Citrobacter*, and includes *Escherichia coli O157:H7*. Coliforms are commonly used as indicator microorganisms to serve as a measure of fecal contamination. Some coliforms are found in the intestinal tract of man, but most are found throughout the environment and have little to do with sanitation (Greenberg and Hunt, 1985).

*Escherichia coli* exists in the intestinal tract of humans and other warm-blooded animals naturally. Most forms of the bacteria are not pathogenic and serve useful functions in the intestine; however, pathogenic *Escherichia coli* food infection causes
abdominal cramping, watery or bloody diarrhea, fever, nausea and vomiting (Ward et al., 1997). Five classes of *E. coli* that cause diarrheal diseases are recognized. Enterovirulent *Escherichia coli* (EEC) include the following subgroups: Enterohemorrhagic *Escherichia coli* (EHEC), which produce six verotoxins and causes hemorrhagic colitis and hemolytic uremic syndrome; Enteroinvasive *Escherichia coli* (EIEC), which causes a diarrheal illness similar to shigellosis; Enterotoxigenic *Escherichia coli* (ETEC), which is a major cause of travelers’ diarrhea due to heat stable and labile toxins; Enteropathogenic *Escherichia coli* (EPEC), which causes infant diarrhea; and Enteroadherent (EAEC) (Reed, 1994).

Outbreaks associated with enterohemorrhagic *Escherichia coli* O157:H7 have been linked to contaminated food with devastating effects including death. With cattle being a major reservoir for this pathogen, undercooked ground beef and raw milk have been the foods most often associated with disease outbreaks (Padyhe and Doyle, 1991, 1992; Ahmed et al., 1995). Of the 16 documented outbreaks of *Escherichia coli* O157:H7 prior to 1993, six have been traced to ground beef (Mermelstein, 1993). The outbreak that occurred from 1992 to 1993 was associated with a fast food establishment serving undercooked hamburgers.

*Escherichia coli* O157:H7 was also isolated in retail poultry products (Doyle and Shoeni, 1987) and several other outbreaks have been associated with contaminated poultry (Ryan et al., 1986; Carter et al, 1987). *Escherichia coli* O157:H7 readily colonizes the ceca of chickens and is shed in feces for several months after initial infection. An intense study by the USDA of 6000 ready to cook poultry samples produced zero positives for *Escherichia coli* O157:H7. These studies indicate that poultry
could be another reservoir of *Escherichia coli* O157:H7 and poultry products could be cross-contaminated by further processing, handling or distribution (Ahmed et al., 1995).

Seafood also has been implicated in *Escherichia coli* O157:H7 outbreaks, but because the products were fully cooked, the contamination was more likely due to post-process handling (Padyhe and Doyle, 1991, 1992; Ahmed et al., 1995).

**Escherichia coli O157:H7 and extrinsic resistances**

Undercooking of food products or survival of *Escherichia coli* O157:H7 during cooking has been a contributing factor in most outbreaks (Mermelstein, 1993). While *Escherichia coli* O157:H7 does not show any unusual heat resistances, with D-values at 57-64°C ranging from 270-9.6 seconds (Padhye and Doyle, 1992; Line et al., 1991; Shipp et al. 1992), some extrinsic factors, such as increased product fat levels, can raise D-values (Ahmed, 1995).

*Escherichia coli* O157:H7 survives the freeze thaw cycle to the extent that it does not decrease appreciably to levels where one can ignore the proper cooking of ground beef patties. Sage and Ingham, (1998) were able to demonstrate variation in survivability between different strains of *Escherichia coli* O157:H7 and also that microwave thawing does not seem to destroy any more cells than slow thawing in a refrigerator at 4°C. This tells us that strain characteristics play an important part in sensitivity to environmental stresses.

Ahmed et al. (1995) demonstrated that composition of the meat product will influence the lethality of heat against *Escherichia coli* O157:H7. The higher the fat level
the greater the D-values. The lower fat levels in the meat products increase the moisture which increase the effect of heat on the microbial cells (Ahmed et al., 1995).

The initial conditions of the beef patties seem to have an influence on the efficacy of heat in killing *Escherichia coli O157:H7*. Jackson et al. (1996) demonstrated increased heat resistance in *Escherichia coli O157:H7* in frozen patties and increased sensitivity to heat in patties that have been held at 21 or 30ºC prior to cooking. They did not, however, demonstrate a reason for this phenomenon, but they do suggest susceptibility to heat during the growth phase.

In the fall of 1991, an outbreak of diarrhea and hemolytic uremic syndrome (HUS) was linked to the consumption of apple cider, and *Escherichia coli O157:H7* was identified as the causative agent (Besser et al., 1993). *Escherichia coli O157:H7* survives in low pH foods such as apple juice. These pH values can go as low as 2 according to Miller and Kaspar (1994), and the pathogen can still be detected after 24 hours. On the other extreme, they found that *Escherichia coli O157:H7* no longer survives as pH increases to 11 and 12, however.

Some *Escherichia coli O157: H7*’s acid tolerance does not appear to influence heat tolerance. Splittstoesser et al. (1996) found an increased sensitivity to heat at pH’s 4.4 to 3.6. However, no unusual heat tolerances were found in these acid tolerant strains of *Escherichia coli O157:H7*. The FDA asked that juice producers pasteurize their products, but made the practice voluntary. Heat treatments at pasteurization temperatures of 71ºC are sufficient to eliminate *Escherichia coli O157:H7* in apple juice and other food products.
With respect to shelf life, freezing and irradiation are viable means to stop or reduce microbial growth. By storing ground beef patties at -18ºC, the shelf life can be extended out to 42 days with no increase in microbial growth. If treated with gamma radiation, shelf life can be extended to 42 days from 7 days when meat is stored at 4ºC (Roberts and Weese, 1998). In 1994, Isomedix Inc. in New Jersey had petitioned the FDA to have non-frozen red meat treated with 4.5 kilograys (kGy) of radiation and 7.0 kGy for frozen red meat to control pathogens (Morrison et al., 1997). Doses of 2.5 to 3.0 kGy are sufficient enough to control or reduce pathogens such as *Salmonella*, *E. coli* O157:H7, and *Vibrio vulnificus* that maybe found on meat, poultry and seafood. Higher doses are needed to control or reduce viruses or spore forming species such as *Clostridium botulinum* (Morrison et al., 1997). Irradiation does not sterilize nor make products shelf stable. Proper handling and refrigeration are still required to maintain quality.

**Cooking Ground Beef Patties**

Because taking temperatures in thin products such as ground beef patties is difficult, consumers have been advised to use the absence of pink color as an indication of thorough cooking (Berry, 1998). Using color to determine endpoint however can be deceptive. For instance premature browning can be an indication of spoilage and a potential food safety concern (Hague et al., 1994; van Laack et al., 1996a,b). On the other hand beef that remains pink or red after it has been cooked to 71ºC can become very hard and undesirable when cooked even further (van Laack et al., 1996a,b, 1997).
When relying on color of the beef alone as an indicator, determining endpoint can be complicated by numerous factors. For instance, beef patties that are cooked from a frozen state tend to appear pinker than patties cooked from a thawed state (van Laack et al., 1996b). Ingredients that can be added to the ground beef formulation can affect the cooked patty color (Hague et al., 1994; van Laack et al., 1996a,b, 1997). Denaturation of myoglobin, by cooking is inhibited by high pH in muscle and can lead to an occurrence of pink or red color in beef patties (van Laack et al., 1996a, 1997).

Cooking to higher internal temperatures has been shown to increase internal brown color. Even though Lavelle et al. (1995) found that browning can be visually and instrumentally shown to increase over cook time, Hague et al. (1994) observed no color changes from 66°C to 71°C. Liu and Berry (1996) found variability in internal color in patties cooked to 68°C and 71°C. Patties that have pigment in the metmyoglobin state have similar color at 55°C to patties with pigment in the deoxymyoglobin cooked to 75°C (Hunt et al., 1995; Warren et al., 1996b). Patties, which are predisposed to a pink/red color at 71°C, required a final internal temperature of 80°C to eliminate the undercooked appearance (van Laack et al., 1996a,b). Because it so difficult to determine if ground beef is fully cooked by looking at the internal color, it has been strongly suggested that temperature be used to gauge cooking thoroughness (USDA, 1997).

Another potential means of determining doneness are enzymes that are in inactivated by heating the muscle tissue. Orta-Ramirez et al. (1997) examined acid phosphatase (AP), peroxidase (PO), phosphoglycerate mutase (PGAM), glyceraldehydes-3-phosphate dehydrogenase (GAPDH), triose phosphate isomerase (TPI), and lactate dehydrogenase (LDH) as potential endpoint temperature indicators in ground beef. They
found that TPI temperature inactivation was similar to those of *E. coli* O157:H7 and *S. senftenberg* and could be used as an endogenous time-temperature indicator in beef products.

Thermal death time is affected by product composition, storage conditions, intrinsic and extrinsic factors, so it is difficult if not impossible to determine the outcome of using color or enzymes as an indicator of doneness. Ultimately, adequate cooking by gauging temperature still remains the most effective method to eliminate microorganisms from ground beef.

*Thermal properties of beef*

Ground beef patties consist of fat, water, protein and trace amounts of carbohydrates and ash. Many studies have been performed to ascertain the thermal properties of whole muscle beef and ground beef. In parallel, studies of heat, mass transfer, yield, sensory, composition and quality have increased our knowledge of how cooking is achieved in beef products. Collectively, the information has allowed us to understand cooking on a macroscopic level, but may not explain heating on a microscopic level. The complications of verifying temperatures become evident when handling non-homogenous materials such as ground beef.

Currently there is very little consistent information regarding the basic thermodynamic properties of food items. What is known of thermal properties of meat can vary greatly due to the nature of the product. Thermal properties of meat products vary with type and variety (Morley, 1972), muscle fiber orientation (Lentz, 1961), and
processing conditions (Baghe-Khandan and Okos, 1981). These include information regarding specific heat, thermal conductivity, and density.

What complicates matter even more is the dynamic movement of materials within the product that occurs which, in turn, affects the internal conductive heating patterns as well as the development of models to explain the thermal dynamic properties. As temperatures climb myosin begins to denature at 54-58°C and sarcoplasmic protein and collagen at 65-56°C (Stabursvik and Martens, 1980; Findlay et al., 1986). The denaturation is observed as shrinkage or even expansion if the sample is not contained or compressed.

The following is known of the compositional changes of ground beef during cooking. Moisture is driven off as temperatures rise. The percentage of protein increases, as moisture is lost. Very little lipid is lost during cooking. Ash and carbohydrate remain the same. (Singh, 1982).

Changes in density can vary greatly, but generally as the moisture is driven off and protein starts to denature density decreases (Tsai et al., 1998). The decrease could also be due to air pockets within the product created by the loss of water (Perez and Calvelo, 1984). On the other hand if the patties are under compression or cooked to a higher temperature the density can increase. The reported densities of restructured meat product vary with the moisture levels. Moisture levels of restructured beef with binders can range from 51 to 74% and have a corresponding density range of 1017 to 1053 kg/m$^3$ (Tsai et al., 1998; Mahadeo et al., 1992; Perez and Calvelo, 1984).

Specific heat values do not change drastically through out cooking for restructured beef with or without binders (Tsai et al., 1998). Values range from 3.33 to
3.81 kJ/kg°C and appear to vary based on the initial moisture levels (Tsai et al., 1998; McProud and Lund, 1983).

Baghe-Khandan and Okos (1981) have determined thermal conductivity values range from 0.45 to 0.47 W/m°C for ground beef. Tsai et al. (1998) also confirms these values. When the meat product is heated though, several authors reported conflicting results. Tsai et al. (1998) reports no decrease in conductivity as products were heated from 35°C to 65°C. McProud and Lund (1983) on the other hand, reported increasing thermal conductivity, as the product was heat processed. Banghe-Khandan and Okos (1981) found thermal conductivity to decrease as moisture content decreased. Perez and Calvelo (1984) reported that density and conductivity were dependent on moisture content and independent of final product temperature. Singh (1982) demonstrated that thermal diffusivity, which is a function of thermal conductivity, density and specific heat, was affected by moisture content and temperature. As these discoveries were encountered, it was necessary to try to model the changes to these thermal properties.

**Thermal Property Model development**

Because cooking is a transient activity thermal property models were constructed to help explain how they change over time. To take into account the many different compositions and changes in states, several models have been created to best describe how they affect the conductivity.

Because of this thermal conductivity values can vary greatly. Deriving the model equations necessary to estimate thermal conductivity over a range of temperatures forced researchers to make some assumptions. Most of the mathematical models for thermal
conductivity have followed one of the following assumptions: (1) substances are uniformly distributed; and (2) the constituent of the substance are positioned in parallel or perpendicular to the heat flow (Baghe-Khandan et al. 1982). Long (1955) had used equations, developed by Maxwell (1904), that take into account the solid or liquid phase of the substance, but do not handle temperatures that are much above the freezing point as the equations were developed for freezing of cod fish.

Koppelman (1961) developed equations for fibrous foods, which predicted conductivity either parallel or perpendicular to the fibers of the food. Poppendick et al. (1966) developed similar models to Koppelman based on material components, water, protein and fat, where water and protein worked in parallel and fat was considered to work perpendicular to conduction. Sweat (1972) developed equations based on data collected from various food materials with their water contents and temperature profiles. The equations however, did not include data of products at cooking temperatures or the effects of product densities.

One of the earliest attempts to characterize the thermal conductivity of ground beef by Qashou et al. (1970) resulted in the following equation [1]:

$$K = 0.0324 + 0.3294W$$  \[1\]

Where: $K$ = thermal conductivity, $W$ = Weight fraction of water. Qashou et al. (1970) clearly demonstrated a relationship between moisture content and thermal conductivity.

Baghe-Khandan, Okos, and Sweat (1982) determined the thermal conductivities of beef samples containing varying levels of moisture, fat and protein levels. They used the information to develop a correlation between beef thermal conductivity and product
composition over the temperature range of 30 to 120 °C (Baghe-Khandan and Okos, 1981).

Thermal conductivity is a property that is dependent on the material’s composition and temperature as Baghe-Khandan and Okos (1981) describes in the following formula [2]:

\[ K = K_W X_W + K_F X_F + K_P X_P \]  

[2]

Where: \( K \) = thermal conductivity, \( X \)= fraction of composition; subscripts: \( w \) = water, \( f \) = fat, and \( p \) = protein. The total conductivity is the sum of conductivities for each component water, fat, and protein. To test the formula [2] Baghe-Khandan and Okos (1981) needed formulas to describe each component. The thermal conductivity for water was determined from Eckert’s (1950) formula [3].

\[ K_W = 5.94 \times 10^{-1} + 9.57 \times 10^{-4} T \]  

[3]

Baghe-Khandan, et al. (1982) were able to determine the temperature conductivity relationship for fat described in formula [4]

\[ K_F = 1.79 \times 10^{-1} - 2.23 \times 10^{-4} T \]  

[4]

They then used Poppendick et al.’s (1966) formula for protein

\[ K_P = 1.72 \times 10^{-1} + 2.81 \times 10^{-4} T \]  

[5]


\[ K = 10^{-3}(400-4.49 F_o + 0.147 W_o + 1.74 T) \]  

[6]
Baghe-Khandan, et al. (1982) noted that density, moisture and fat levels for ground muscle samples changed at a different rate than whole muscle samples. These differences directly affected the conductivities. In ground products the distribution of fat, protein and moisture can be random and it possible to develop regions within the product that is more one component than the other.

Even though spatial development of pores occurs due to moisture loss, Unklesbay et al. (1982) were able to determine that thermal conductivity was affected by a change in density. The process to produce beef patties could affect the densities and shape of the product. Density changes across the profile of the patty will affect the diffusion of heat into the product. The thickness of the patty affects the rate heating and the temperature in the center of the product. Patties with non-uniform thickness will produce non-uniform heating patterns. Contact with a cooking surface will affect the efficacy of the heating. Should the patty undergo compression during cooking in a dual sided cooker density could be affected. Should an air pocket develop, direct conductive heating is lost, and convective heating with its surroundings will predominate.

Beef patties are typically frozen before use, and develop a dry crust on the surface as they are cooked that is drastically different from the moist interior. Surface temperatures of cooking ground beef patties can rapidly exceed temperatures of 100 °C and form a crust (Dagerskog and Bengtsson, 1974). This layer of dry protein can disrupt heating patterns, as it does not form in a uniform manner. Skjöldebrand and Olsson (1980) studied crust formation during convection oven cooking of meat loaves. They defined crust as parts of the product, which have reached 100°C. A linear regression was
used to demonstrate the development of a 100°C evaporation zone with respect to time. With an air temperature of 225°F and air velocity of 5 m/s the linear relationship is as follows:

\[ Y = -27 \times 10^{-2} + 0.12 \times 10^{-2} X \]  \[8\]

Where: \( Y \) = thickness of the crust and \( X \) = time in seconds.

While this is not applicable to a direct contact model, it does demonstrate that the longer the surface is heated, the thicker the crust layer becomes.

In similar work with frying, Ateba and Mittal (1994) found that crust color changed and mass loss increased with frying time and pan temperature. The reduced moisture on the surface reduces the heat transfer rate at the surface and internally. Holtz et al. (1984) observed surface temperatures of baked meat products and discovered that surface temperatures increased more rapidly in products containing more fat and less moisture. As water evaporation decreases in the crust, a majority of energy is used to increase the temperature of the surface and the crust. Holtz et al. (1984) were able to correlate mass loss to supplied energy. Dagerskog and Bengtsson (1974) found a well-defined relationship among crust color formation, yield, pan temperature, heating for a specific formulation, sample thickness and contact pressure imparted by a dual sided cooker.

The thermal properties not only have to be determined for the internal portions of the beef, but must also be considered at the cooking surfaces. The formation, and cooking conditions, must be considered as they can affect density and surface heating respectively.
**Finite element modeling**

The finite method is a numerical procedure for solving differential equations. It is commonly used in the areas of structural analysis, continuum mechanics, fluid flow and heat transfer (Segerlind, 1984).

To predict doneness of food finite element analysis of heat transfer can be performed on the cooking process and the heating within the food product. The thermal properties of materials can vary drastically from one product to another. Formulation will have an effect on product moisture content and solids composition. Mechanical formation of the product also affects its density and shape. On a microscopic level the materials can be broken down into their different parts and analyzed separately as elements. The cooking process can affect the effectiveness of how heat is delivered to the product. The cooking process defines the boundary conditions, which are to be used for the FEM analysis. If the numerical method can make accurate predictions of the heat propagation through the cooking product, the numerical result can be used to predict the time of cook and how to minimize the probability of under processing.

For direct heating of the ground beef patties using a clamshell grill, heat conduction analysis can be performed, taking into account latent heat effects and allowing for the variation in the thermal properties of the materials with temperature. Since ground beef is porous, a coupled heat and mass transfer analysis is required (Lewis et al., 1996). Mathematical models can accurately predict the movement of moisture and heat in porous materials and help obtain a better insight into the physical process of cooking.
Exact analytical solutions of the governing equations of heat transfer, are usually obtained by restricting or simplifying assumptions, with respect to geometry, material properties and boundary conditions (Lewis et al., 1996). The finite element method is an ideal approach because of its flexibility in dealing with complex geometries.

Initially the differential equations governing heat conduction are derived and the boundary conditions are determined, which is needed for the finite element method. The finite element method generates a system of simultaneous equations, which have to be solved to obtain the approximation of temperature field in the body of interest. Finite difference methods are employed when time dependent problems are encountered. As thermal properties vary over time, separate algorithms are introduced to handle non-linear equations. Phase changes and convection heat transfer issues can be handled in a similar manner. As mentioned before, these changing conditions can also be handled as pre-requisites for the next calculation of temperatures.

The following are five basic steps of the finite element method as summarized by Segerlind (1984) are:

1. Discretize the region. This includes locating and numbering the node points, as well as specifying their coordinate values.
2. Specify the approximation equation. The order of the approximation, linear or quadratic, must be specified and the equations must be written in terms of the unknown nodal. An equation is written for each element.
3. Develop the system of equations. When using Galerkin’s method, the weighting function for each unknown nodal value is defined and the weighted
residual integral is evaluated. This generates one equation for each unknown nodal value.

4. Solve the system of equations.

5. Calculate quantities of interest. These quantities are usually related to the derivative of the parameter and include the stress components as well as heat flow and fluid velocities.

The finite element method is not without its problems. They can arise when short time intervals or complex equations are used. The result can be an answer that makes no sense and is erratic. Stability of the time stepping algorithm can be affected by any error introduced in the approximation of the time step. Instability of an algorithm is characterized by non-physical oscillations in the numerical solution, which increase in amplitude, swamping out the true solution. A possible solution would be to increase the time intervals and simplify the equations such that the calculated residuals have less of an impact on the results (Segerlind, 1984).

**Computer Modeling of ground beef cooking**

Several mathematical methods have been employed to describe the thermal heating of food products. These methods include finite difference and finite element modeling. While FEM has been widely accepted as a method to model thermal processes related to mechanical engineering, it has had limited applications in cooking, baking, microwave processing, and food textural properties (Ikediala et al., 1996).

Ikediala et al. (1996) modeled the frying of meat patties and validated the models using experimental data. Some of the cooking parameters they looked at included single
sided frying as well as the effects of turnover frequency on temperature distribution, cooking time to doneness, and crust formation. Unlike DeBaerdemaeker et al. (1997), Ikediala et al. (1996) accounted for changing material properties by accounting for moisture loss during the process. They did, however choose to ignore factors such as shrinkage/swelling, denaturation, and fat melting, to simplify the analysis.

**X-ray Imaging and Computer Aided Tomography**

Computed tomography (CT) has allowed medical radiologists to examine the human body in three spatial dimensions, where typical x-ray exams are viewed in two. By taking sequential images through an object the examiner can step through each image and reconstruct objects and formations within a body (Berland, 1987). X-ray computer aided tomography (CAT) scanning is a tool to help us understand complex shapes, internal structures, and their orientations.

CT uses a computer to reconstruct images collected from x-ray beams, which pass through a target. The images are cross sections of the target. The thickness of each CT slice of the target is referred to as the Z-axis. The operator is able to adjust the thickness of the z-axis. Thin slices concentrate the x-ray beam to specified thickness and reduce scatter radiation and superimposition by other structures (Romans, 1995).
Figure 1.1. The gray disk represents a cross-sectional slice. A pixel is two-dimensional square. A voxel incorporates the thickness of the slice, and is a three-dimensional cube. Adapted from Romans (1995)
Differing levels of gray represent structures in a CT images. Depending on the density of the structure, x-ray energy is allowed to pass through or is stopped by the structure. This is referred to as beam attenuation (Romans, 1995). Beams, which are stopped completely, appear as white and those that go unimpeded show up as black. For example, bone would show up on the computer as a white image and air would be black. All other intermediate attenuations would show up in the gray levels. (Romans, 1995)

There are some advantages and disadvantages of CT over conventional x-ray. Aside from the previously mentioned scanning of image sequences, CT is highly sensitive to small differences in X-ray attenuation. This is achieved by avoiding superimposed structures, which contribute to image noise. Scattered x-rays can also reduced due to the configuration of the emitter and detection assembly in the CT unit (Berland, 1987).

Disadvantages over conventional x-rays include a reduced spatial resolution and long exposure time on the target (Berland, 1987). Small objects that lie in between pixels or border larger objects may get averaged into the pixels representing the adjacent object; therefore two separate objects may appear as one. Movement of material in the target or by the target, during the scanning phase, can produce false images due to the time required to capture an image. Because objects can appear the same, knowledge of existing structures within the target allows the examiner to determine whether or not something unusual exists (Berland, 1987).
Visualizing internal structures of Food by x-ray CAT scanning

Using x-ray imaging allows for the nondestructive examination of most materials. X-ray usages for medical purposes are widely known, but x-ray technology for food applications have primarily been focused on the detection of foreign material such as stones, bones, metal and other objects. Just like analytical purposes for medical examinations, x-ray computer tomography can be useful for examining the internal structures of foods as well as changes that might occur over time.

According to Kak and Slaney (1987), tomography refers to the “cross sectional imaging of an object from either transmission or reflection data collected by illuminating the object from many different directions”.

X-ray computed tomography has been used to examine damage to produce such as apples, peaches, and lettuce (Tollner et al., 1992; Suzuki et al., 1994; Barcelon et al. 1999). Barcelon et al (1999) have related the CT number to pH, moisture content, soluble solids, and density changes as well as titratable acidity. Peiris et al. (1998) were able to very easily differentiate section drying, an internal disorder in tangerines. Lower tissue densities as well as changes in the tangerine’s vesicles allowed them to identify healthy and damaged fruits. Being able to track moisture content can be helpful in tracking the thermal conductivity in food products as moisture changes. Density changes are also critical in calculating thermal diffusivity, as density changes quite a bit during the cooking process of beef patties.

X-ray computer aided tomography can also be used in conjunction with external software packages to estimate areas and shapes, and also to differentiate between tissue types. Einen et al. (1998) used x-ray computer tomography to examine Atlantic salmon
for weight loss, body shape changes, and visual fat deposits. They were able to discern height, width, and areas of the fillets. Estimates of protein and fatty tissue were readily determined from the x-ray scans. Particle size and distribution of samples can be determined as demonstrated by Tollner et al. (1998) who were able to measure the size distribution of soil aggregates with x-ray CT. With porous material such as foam, Brown et al. (1987) were able to observe the spatial distribution of water and content in porous material. Changes in moisture content and location were visualized over a 16 hour drainage period for various porous phenolic foam materials.

During the cooking of hamburgers, shrinkage, moisture displacement, and fat melting all occur within the formed patty. No one has quantified these changes or its effects on the thermal heating pattern (Singh et al., 1997). Being able to determine the translocation of materials and their spatial orientation could allow for a better description of internal heating patterns within the beef patty.
References


North Carolina Sea Grant, Raleigh, NC.

CHAPTER 2

CHANGES IN INTERNAL STRUCTURE OF GROUND BEEF PATTIES DURING COOKING AS VIEWED BY X-RAY COMPUTER AIDED TOMOGRAPHY

\[1\]

\[\text{Wong Liong, J.W., Frank, J.F. and E.W. Tollner to be submitted to Food Engineering.}\]
ABSTRACT

To eliminate food borne pathogens in ground beef patties they must be cooked to a minimum internal temperature of 71°C. Structural changes during cooking make temperature assessment difficult and doneness hard to predict. This investigation used x-ray computer aided tomography (CAT) to observe structural changes in ground beef patties during the cooking process and investigate how the changes can influence the internal heating pattern. Ground beef patties, of various lean beef content, in frozen, thawed and cooked states were scanned using CAT. Patties formed from a 3/16” grind head and commercially available patties produced from a 5/64” grind head exhibited structural changes after the cooking process. CAT scan images showed a redistribution of materials within beef patties during cooking. Drippings flowing through the patty were visualized as an increase in electron density, which was indicated as a progressive increase in image brightness and a broadening of the gray level spectrum. Increases in porosity and shrinkage reduced cross-sectional area measurements from 16% to 30% depending on the formulation. Displaced fat, moisture and protein were not easily distinguishable from each other, whereas the development of air pores and cracks during cooking were readily apparent. Cross-sectional area data obtained from x-ray CAT scans revealed reductions.

Beef patty tissues closest to the upper cooking surface appeared denser than tissues in the geometric center. Denser tissue varied in thickness from 1 to 4 mm. The increase in density is related to the development of a crust. Tissues closest to the lower cooking surface also increase in density, but it is not clear from the x-ray image if this is
only due to crust development or also to the accumulation of moisture and lipid. Surface irregularities, fissures, cracks, and pore development were detected by x-ray CAT scans.

X-ray computer aided tomography was used to scan ground beef patties during cooking to verify temperature probe placement. Thermal probe placement was examined in relationship to internal beef patty structures using simultaneous scanning and temperature monitoring. Ground beef patties containing 70 % lean beef manufactured with a 3/16” grind head were cooked in a miniature clamshell cooker modified for use in an x-ray CAT scanner. A small difference in placement relative to either cooking surface yielded temperature recording with differences up to 10 degrees in spite of attempts to place probes in the geometric center. Probes inserted to a radial distance of 5 cm from the edge, and verified at depths of 1, 2, and 4 mm from the cooking surface, showed steady increases in time lag before cooking progressed from one depth to the next. A 175 % increase in time lag was noted between the 2 mm and 4 mm depths.

Dynamic imaging and thermal probe placement and their relationships between structural changes and temperature propagation could be used to construct effective heat transfer models to predict cooking of ground beef patties.
INTRODUCTION

*Escherichia coli* O157:H7 infections and deaths associated with consumption of undercooked hamburgers have raised interest in determining safe methods for cooking ground beef patties. Among some of the difficulties are the numerous cooking devices, beef patty shape and formulation, and problems determining the cold spot for thermal probes or thermometer placement. During cooking, beef patties can be subjected to external conditions such as flipping or compression, which can have an affect of reducing or increasing the amount of necessary cook time. Mass action must also be considered, as moisture and fat loss will change the thermal properties of the sample over time.

Thermal properties, which directly affect the time required for a safe cooking, change as a beef patty is cooked. Water is a strong conductor of heat and, as it evaporates from the product, its contribution to the overall thermal conductivity is reduced. The same is true for fat as it leaves the meat matrix. However, if there are changes in density, the diffusion of heat through the product will also be affected. Air, unlike other food materials, often acts as an insulator. The internal structures of proteins, water, fat particles, and trapped air make up the food matrix. Their spatial arrangement and differing quantities will influence the amount of thermal energy that must be applied to provide a safe cook.

The use of x-ray computer aided tomography (CAT) allows for the non-destructive imaging of internal structures in many objects. Computer aided tomography has found use in a broad range of fields. X-ray CAT scans are used extensively in the medical field for examinations of bone structure and internal organs. Likewise x-ray
scanning is used to sort foreign material such as bones in food products (Tollner et al., 1992; Tao and Ibarra, 2000) and for sorting of injured fruit (Diener et al., 1970). CAT scans of building materials are used to determine the strength as well as identify any internal defects of support structures used in many construction sites (Jacobs, 1995). In food systems, x-ray CAT scans were evaluated for non-destructive examination of fruits (Suzuki, 1994). Sonego (1995) used x-ray CAT scan to examine nectarines that have undergone textural changes due to woolly breakdown. In addition, Tollner et al. (1992) were able to relate x-ray absorption to bulk density and water content in apples.

Pure beef patties have a complex structure. When the beef is ground, blended and formed into a patty, the structure may include air pores, water, muscle tissue, and fat particles. Physical properties of complex substance can be quantified by correlation with x-ray absorption (Tollner et al., 1992). X-ray absorption patterns may provide information on the spatial distribution of beef patty components based on the different electron densities of these components. X-ray computer aided tomography can be combined with image analysis to reveal the structural changes in the cooking ground beef patties that occur over time.

The objectives of this study are to examine the internal structural features of ground beef patties, identify structural components produced at different patty compositions, observe structural changes in ground beef patties as a result of cooking, and demonstrate the effect of structural changes on thermal probe position.
MATERIALS AND METHODS

Beef patties x-ray CAT scan samples

Ground beef patties were made using beef trimmings obtained from the University of Georgia abattoir. Lean and fatty beef were ground together using a Hobart model number 4046 (Troy, OH) equipped with a 3/16” head to produce product containing 50%, 70%, 80% and 90% lean. Patties were formed using a Hollymatic Super 54 Food Portioning Machine (Hollymatic Corp., Countryside, IL.). The cylindrical patties of 114.3 mm in diameter, 10 mm in thickness and 114 grams, were separated from one another by wax paper. For comparison purposes, ground beef patties manufactured using a 5/64” grind head were obtained from a commercial source.

While the patties were still soft, 1 mm x 76 mm stainless steel spikes were inserted at the mid-line of the patties’ edges and pushed towards the center of the patties’ diameter to bore a path for the temperature probes. Once the patties were frozen individual patties were packed in waterproof plastic bags to prevent moisture loss, and stored at –80ºC until they were used. Prior to x-ray CAT scanning, patties were stored in a -10ºC freezer until used. The five different patty types were examined in their frozen, thawed, and cooked states.

To obtain an x-ray histogram of lipid material, fat was obtained by melting beef tallow and filtering the liquid fat through Whatman paper to remove large protein solids. The liquid fat was allowed to cool and reform in petri plates at 22ºC.

Moisture and fat content of the patties were determined by AOAC (1990) methods.
Bulk density of meat sections was determined by sectioning nitrogen frozen 8x8x8 mm cubes and weighing them on a Mettler- Toledo Inc model AG245 (Columbus, Ohio).

**Cooking Equipment**

**Dual sided cooker for x-ray CAT scanning**

A clamshell cooker was made by using two Cole-Parmer silicon-heating pads, part number E-03125-50, (Cole-Parmer Instrument Company, Vernon Hill, IL), bonded to two 1/16” thick aluminum plates. Power was supplied to the pads by two Cole-Parmer power converters, part number 02604-00 (Cole-Parmer Instrument Company, Vernon Hill, IL). To prevent interference from metal pieces, the heating plates were clamped together using nylon screws and springs to hold the patty in a vertical plane to the CAT scanner. Each plate was heated to 400°F prior to use and temperature verified using a Raytek Infrared thermal probe model ST20 (Raytek, Santa Cruz, CA). Figure 2.1 illustrates the upright cooker and its arrangement. Samples using this cooker were oriented on their sides and cross-sectional images are of the x-y plane. An illustration of the three-dimensional planes in Figure 2.2 shows the scanning orientation.
Figure 2.1. Side view of a miniature cooker used for upright cooking in x-ray CAT scanner. Dotted line represents the path of the x-rays, which passes through the patty and the nylon all thread.
**Figure 2.2.** The x-y-z planes describe the 3-D orientation of the ground beef and how they were scanned by the x-ray CAT scanner. Adapted from Romans (1995).

**Dual sided cooker for x-ray CAT scanning for probe verification and crust development**

Samples were fried for cross section imaging in the x-z plane using a Taylor Freezer Inc (Rockton, IL) model QS24-23 dual sided electric grill. Each plate was pre-heated to 400°F, prior to cooking and temperature was verified using a Raytek Infrared thermal probe model ST20 (Santa Cruz, CA). The height of the top platen was set to 8 mm to slightly compress the 10 mm patties and maintain constant contact. Pressure from the weight of the platen was not measured. Corn oil was spread on the surface to prevent the patties from sticking. Each patty was cooked to an internal temperature of 71°C, and
immediately placed into a plastic bag and submerged into a nitrogen bath to freeze. Patties were then stored in a –80°F freezer until analyses were performed.

**X-Ray Computer Aided Tomography**

Each patty type was examined in frozen and cooked state using a CATSCAN Neurological CT scanner model TCT-20A (Toshiba, JPN) for 9 sec at 120 kV / 230 mA in 2 mm thick sections. Six scans were obtained for each frozen patty type, and three scans were obtained for each cooked patty.

Patties were either suspended in the miniature cooker in the upright position for cooking or contained and taped into position in 6-inch petri plates. For verification of thermal probe placement and patty thickness, patties were laid flat onto a wood board and scanned. All patties were measured with Vernier calipers prior to scanning. These measurements are used to set the image analysis measurement scales.

**Temperature measurement**

Temperature data was collected on a Luxtron 755 multi-channel Fluoroptic Thermometer using fiber optic probes (Santa Clara, California) to avoid magnetic interference from the scanner and cookers. Two Luxtron SEL-02 (Santa Clara, California) surface contact temperature probes were used to monitor cooking grill temperatures, and two Luxtron SFF-02 (Santa Clara, California) fast response probes were used to monitor patty temperatures.

**Image and Statistical analysis**

Images were obtained by scanning across the x-y plane and were analyzed using a 400mm² square region selection tool. Images scanned in the x-z plane were analyzed with a smaller 64mm² square.
All experiments were performed in triplicate. Images were subjected to analysis from three different regions. Using three locations within each sample, nine data points were given for each test. Histograms were generated by NIH image program (U.S. National Institutes of Health, available http://rsb.info.nih.gov/nih-image/). Images analysis was based on a gray scale of 0 to 255, with zero being absolute black and 255 being white. It was determined that gray values of 1 to 6 represented air and values of 7 to 255 represented the ground beef.

RESULTS AND DISCUSSION

The pre- and post-cooked compositions of each group of ground beef patties are described in Table 2.1. Levels of fat prior to cooking indicate that the patties contained more lean beef than manufacturing indicates. The four types of laboratory patties used, initially contained 68%, 82%, 87%, and 92% lean beef. The commercially patty consisted of 77% lean beef. After cooking, moisture and fat is driven off and protein becomes the predominate component. This was true of all lean patty types.

Attempts to visualize individual components of fat and protein failed. From Table 2.1 a majority of the material lost is moisture and fat, but this is not evident from the captured images. Because the gray levels of these components overlap in their image densities, they cannot be distinguished from one another. Shifts in image brightness indicating a change in electron density of the scanned region are apparent. These changes can be due to factors such as compression, shrinkage, and hydration changes. Brienne et al. (2001) correlated dual X-ray absorption to determine the fat content of 3 types of
meat. They acknowledged, however, that this technique had to be employed prior to the
grinding of the meat. Also noted by Brienne et al. (2001), the muscle tissue being
examined had to be clearly defined for a correlation between fat and absorption to be
successful. For example, the shape and thickness of the samples needed to be well
defined for the meat samples. Ground beef patties, while uniform in shape, are a
blending of muscles tissues. After the ground beef is mixed, none of the tissues are well
defined. Attempts to correlate fat particles with the development of pores failed because
fat particles were not clearly defined in the images.

The CAT scan images could provide information on shifts in image density,
shrinkage in the x-y and x-z planes, porosity increases and crust development. This
information could be useful in the definition of thermal properties and how they could be
localized within the cooking patty.

**Shifts in image gray levels**

Patties in frozen, thawed and cooked states exhibit different x-ray attenuations.
Figure 2.3 shows the same 82 percent lean beef patty in each of these states. As the patty
thaws and water returns to its liquid form, the image becomes brighter. A commercial
patty in Figure 2.4 shows a similar pattern of changes in the different states, but the
distribution and shades of gray are more consistent in the commercial patty. While the 82
percent lean patty contains a slightly higher percentage of moisture and protein, the only
difference between it and the commercial patty is the production grind head. This
indicates that manufacturing technique influences the density of ground beef patties.

In Table 2.2, the mean gray level increases as the patty goes from –10°C and
stabilizes at 27°C at each level of patty leanness. The shift in brightness is greater in the
leaner patties; however, the higher number of voids in the 68% lean beef patties lowered the mean gray level.

Ground beef patties shifted in x-ray attenuation during cooking. As the patties are cooked, moisture and fat are driven off, and the mean gray levels decrease to levels similar to the frozen state. In all cases, the standard deviations and ranges broadened when the patties were cooked. The images in Figure 2.5 are histogramic representations of the gray levels for patties in Figure 2.4, and show a right shift toward white pixels over time. This indicates a denser scanned region as the water changes state. As the patty is cooked, the data in Figure 2.5(C) is skewed toward the left, indicating areas that are less dense in the image. The histogram in Figure 2.5(A) is narrow when compared to the cooked patty in Figure 2.5(C). More area representing voids was encountered when sampling the cooked patty than when frozen. The graph in Figure 2.6 shows how rapidly the image gray levels change early in the cooking process. Fast cooking methods similar to the dual sided cooker used, have shown similar rapid changes in hamburger such as protein denaturation, melting of fat, evaporation, and loss of water (Singh et al., 1997). After the initial change however, the gray levels increase steadily over time indicating that the tissue being scanned is denser. Bulk density measurements however do not follow this trend indicating that higher mean reading is not a good indicator of bulk density, rather the sampling is taking in account a wider range of pixel intensities that are moving the average up in value. Density measurements would have just taken in account the tissues alone rather than air possibly trapped in them. Sectioning samples inclusive of only solid tissues could have improved or shown a relationship between the x-ray images and patty density.
Movement of materials could be visualized by the x-ray CAT scanner indicating a potential to obtain temporal information. Figure 2.7 provides a side-by-side visualization of a cooking patty. Figure 2.7 (A) is a patty that has been exposed to 5 seconds of heat. The cooking patty in Figure 2.7(B) was taken when the temperature had reached approximately 60°C. Because of the orientation of the cooker, cook drippings emptied through the bottom edge of the patties. Note the brighter pixels at the bottom of the patty in Figure 2.7(B). Cooking a patty laying flat on a cooking surface would have made detecting this movement difficult. This kind of information can be used to assess the movement of fluids through porous material while cooking or even how well water binding ingredients performs in muscle foods.

**Porosity and Shrinkage**

Air is trapped in the patties when they are formed. Pockets of trapped air in frozen patties can seen in Figures 2.3(A) and 2.4(A). As the patties cook additional voids are created as tissues shrink and fat and moisture are expelled. Pores in the patties increased in number and size, and appear to randomly distributed. The number of pores and percentage of area occupied by pores show a significant increase as the patties are cooked (Table 2.3). Initial fat content appears to have an effect on the percentage of area (Figure 2.8) that is considered a pore or void. The ground beef patties in Figures 2.8(A), (B), (C) and (D) contained 68, 83, 92 and 78 percent lean beef respectively. The fully cooked patties vary size and porosity. Large areas of dark pixels appear in the 68% lean patty and occupy a large percentage of area in the cross section, while the 92% lean patty in Figure 2.8(C) appears relatively solid through the center of the patty. The commercially produced patty in Figure 2.8(D) was produced using a 5/64” final grind head. The finer
cut when compared to a patty of similar composition in Figure 2.8(B) provided a more even distribution of pores and smaller in total area in this cross section.

Porosity plays an important part in thermal conductivity in food products. Rahman (1992) developed several mathematical models based on apparent and true densities. The images collected in this study indicate that density and porosity in ground beef can vary from one small area to another. Developing models based on non-differentiating densities may be difficult.

The total area that the patty occupies is reduced as tissues shrink after cooking (Table 2.3). A greater portion of pore and fissure development occurs in patties where higher levels of fat are used as demonstrated in Figure 2.8 and Table 2.3. From Table 2.3 the amount of porous area increases from 1 to 2 percent to well over 30% as in the case of the 68% percent lean ground beef patties. The distribution of porous area is finer in Figure 2.8(C) and Figure 2.8(D) when compared to the larger pores in the Figure 2.8 (A) and (B). These large pockets could act as insulation points where the diffusion of heat could be limited or they could be areas where moisture accumulated and pockets of steam were generated.

Side profiles of pre- and post- cooked patties clearly show shrinkage of the patty. D’sa et al. (2000) reported an increase in height of the product at reaching a final internal temperature of 71.2°C using a double sided grilling-broiling system and 20 mm patties. Image analysis of our 10mm patties show a shrinkage using a similar system. The conflicting data indicates that how a patty is cooked or formed can influence the final physical dimensions. This information becomes important, as thickness is an important
factor in heat transfer. If the patty changes thickness during cooking then predictive models may need to take this factor into account.

**Probe position verification**

Using stainless steel spikes allowed the location of the anticipated probe position to be verified. The highlighted lines in Figure 2.9 (A) show the relative location of the probes when they are to be inserted prior to cooking. The ends of the thermal probes are shown in Figure 2.9 (B) in an x-z scan of the patty laying flat on the scanner bed. The intent of inserting the probes along the mid-line of the ground beef patties was to ensure temperature recording at the geometric center. As the image demonstrates, exact placement was never achieved. The temperature/time profiles of four verified probes in Figure 2.10 show large differences in come up time. For the probe near the surface (2.1 mm from surface) of the patty exhibited a dip in the temperature profile. This dip could be attributed to the sudden cooling effect of moisture migrating towards the surfaces of the patty as the ice melts and the patty cooks. Not enough samples were tested to determine if these differences were significant.

**Crust development**

Patty crust is defined as a hard brown layer upon the surface of the cooked meat partially created by Maillard reactions and protein denaturation (Skjöldebrand and Olsson, 1980; Ateba and Mittal, 1994; Dagerskog, 1979). Skjöldebrand and Olsson, (1980) further defines the crust as a layer that has reached a 100ºC and moves from the edge toward the center of the heated product. Patties scanned while laying flat reveal bright edges along the bottom and top. These surfaces were closest to the cooking surfaces and were hard when examined manually. This layer was 1mm to 4mm thick. The
bottom and top layers differ from each other, as the bottom layer remains relatively uniform with respect to a hard brown crust layer. Visual inspection of the upper surface indicated that it developed crust in spots. The upper surface is uneven and wavy when viewed by x-ray and manual handling. Shrinkage of the patty and pressure from the cooker’s plates could explain some of the deformation. Measurements less than 8mm may be due to shrinkage or from pressure displacement by the upper cooking plate of the cooker.

Crust formation can affect the heat transfer rate at the surface of meat products. Understanding the time it takes to develop and how thick it can become can help in the development of thermal models.

**Conclusions**

X-ray CAT scanning and image analysis can be used to detect internal structures of ground beef patties and quantify changes that occur over time. Manufacturing differences and formulation differences were readily detected by x-ray CAT scanning. Captured data confirms the appearance of pores in the patties. The pores are more apparent in the x-y view than the x-z side view. Their appearance is random, but their size can tell us how fine a grind was used. The size of grind and differing percentages of fat produced different image densities and tissue distributions.

The location of dehydrated tissue and their thickness were visualized along the edges and cooking surfaces. Their relative thickness and placement indicates that moisture rapidly evaporates from these locations. Random shrinkage of the muscle tissue is visualized by the variability in thickness profiles and also distribution of tissues after cooking.
Developing a universal model for heat transfer in ground beef patties may be complicated by the numerous parameters visualized by CAT scanning. Defining a heat transfer model will have to come from a defined ground beef patty.

Energy and mass transfer depends on knowledge of mass, composition and area. The x-ray CAT scan was useful in demonstrating cross sectional shrinkage as well as development of crusts and pores. Data could be collected to determine the rate at which these events occur. These rate equations can be implemented into a dynamic thermo-physical model eliminating the need to assume homogeneity of the cooking product.
Figure 2.3. X-ray CAT scan images of laboratory produced 82% lean ground beef patty in its three different states. The image of a frozen patty (A) is darker than the thawed patty (B), but much lighter than the cooked patty (C).
Figure 2.4. X-ray CAT scans of commercially produced ground beef patties in three different states. There are very few voids in the frozen patty (A). As the patty thaws (B) the image becomes brighter as the ice turns to water. Pores and cracks are visualized in the cooked patty (C).
Figure 2.5. Gray value histograms obtained from CAT scan data from commercially produced ground beef patties in frozen, thawed and cooked states. (A) Frozen patties exhibit a narrow band of gray pixels. (B) Thawed patties shift towards white or brighter pixel intensities. (C) Cooked patties shift leftward as more pores appear showing more black and dark regions in the images. The histograms get wider, showing a broader spectrum of gray peaks indicating shifting image densities.
**Figure 2.6.** Mean gray values from histogram analysis of CAT scan data from ground beef patty during cooking.
Figure 2.8. X-ray CAT scan images demonstrating how the amount of area occupied by tissues differs with lean beef content after cooking. Image (A) is ground beef patty formed with 68% lean beef. Images (B) and (C) contain 82% and 92% lean ground beef and the commercial (D) patty is approximately 71% lean ground beef.
Figure 2.7. Side by side images of a ground beef patty obtained during cooking. (A) A patty with two thermal probes in place shows very little change after 5 seconds of heating. (B) The patty starts to drip juices and the image becomes brighter along the bottom edge after temperature reaches 60°C internally. Bar = 10 mm.
Figure 2.9. Stainless steel spikes used to bore holes for the thermal probes highlight the relative locations where the probes were inserted.
Figure 2.10. Temperature versus time plots of ground beef patties during cooking. Probe locations were verified by X-ray CAT scanning.
Table 2.1. Composition of pre and post cooked ground beef patties used in x-ray CAT

scan examinations. *

<table>
<thead>
<tr>
<th>% Lean beef</th>
<th>Pre-cook</th>
<th>Post-cook</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Moisture %</td>
<td>Fat %</td>
</tr>
<tr>
<td>50</td>
<td>50.48</td>
<td>31.97</td>
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<tr>
<td>70</td>
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<tr>
<td>90</td>
<td>67.24</td>
<td>8.07</td>
</tr>
<tr>
<td>Commercial</td>
<td>58.51</td>
<td>22.51</td>
</tr>
</tbody>
</table>

* Determined by AOAC methods.
Table 2.2. Statistical data derived from gray level histograms of ground beef patties in frozen, thawed and cooked states.

<table>
<thead>
<tr>
<th>Beef Patty</th>
<th>Mean Gray Level Raw</th>
<th>Standard deviation</th>
<th>Gray level range raw</th>
<th>Mean Gray Level thawed</th>
<th>Standard deviation</th>
<th>Gray level range thawed</th>
<th>Mean Gray Level cooked</th>
<th>Standard deviation</th>
<th>Gray level range cooked</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
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* The gray level scale is based on 0 to 255 levels. A 0 reading is for absolute black and 255 is white.
Table 2.3. Percentage of tissue before and after cooking showing a decrease in overall cross-sectional area and an increase in pore/void area after cooking.

<table>
<thead>
<tr>
<th>Patty type</th>
<th>Average cross-sectional area before cook (mm²)</th>
<th>Average cross-sectional area after Cook (mm²)</th>
<th>Percentage of cross-sectional area retained</th>
<th>Percentage solid tissue area before cook</th>
<th>Percentage solid tissue area after cook</th>
<th>Percentage Pores/void after cook</th>
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REFERENCES


CHAPTER 3

FINITE ELEMENT MODELING OF CONDUCTIVE HEAT TRANSFER IN GROUND BEEF PATTIES USING DIGITAL IMAGES CAPTURED BY X-RAY COMPUTER AIDED TOMOGRAPHY

ABSTRACT

Ground beef patties must be cooked to a minimum internal temperature of 71.1°C to be free of pathogens. Cooking ground beef patties is a dynamic process with many internal changes that include evaporation, fat melting and protein denaturation. Structural changes cause the thermal properties of a patty to change over time. Knowing the placement of temperature probes within the patty structure can help develop an improved heat transfer model by assigning the appropriate thermal properties to those locations. Our objectives were to mathematically model heat transfer in ground beef patties using finite element modeling (FEM) and information obtained from x-ray computer aided tomography (CAT) images. Moisture loss, density changes, and fat loss rates were functions of internal temperatures and time. Crust thickness was estimated from x-ray cat scanned images and incorporated into the FEM program with an independent set of thermal properties from the rest of the beef patty. X-ray CAT scan images where discretized using pixel information from the image with each element representing a single pixel. Using gray levels from 0 to 255, thermal properties were assigned to each pixel based on a particular gray level range. Pixels representing crust were automatically detected in the program, and set to a fixed thickness from the surface towards the mid-line of the patty. Pores, crust, and muscle tissues were assigned three separate thermal properties in the FEM program. An artificially created homogenous image without pores, cracks, or crust; was able to generate straight uniform isotherms. CAT scanned image of ground beef patties with cracks, pores and surfaces not touching the grill, showed non-uniform heating. Coordinate plots show that the temperature at the geometric center of
the patty is influenced by patty thickness, crust thickness, porosity, and surface contact. Direct x-ray image input and FEM can be useful in heat transfer analysis of food products.

INTRODUCTION

Food borne illnesses related to Escherichia coli O157:H7 emphasize the need for thorough cooking of ground beef patties. Proper heat treatment of food products kills pathogenic microorganisms. An internal temperature of 71.1°C is required by the USDA (1973) for a product to be labeled “fully cooked” or “ready to eat”. However, it is difficult to ensure this heat treatment because of problems in monitoring internal temperature due to the non-homogeneous nature of the patties. The result is patties that are either overcooked, which presents a quality loss, or under processed which compromises food safety. An understanding of the cooking process will help in the development of more precise better cooking specifications and better ensure food safety and quality (Singh et al., 1997).

Beef patties, frozen or refrigerated can be cooked various ways, which include single sided frying, broiling, and double sided grilling. Direct surface contact is the most efficient method of delivering heat. With these methods, factors such as flipping, distance from heat source, and pressure, as in the case of a double grill, are important, as these factors influence heat transfer coefficients.

During the cooking process, the beef patty undergoes a number of physical and chemical changes. Ice and fat melt, water drains, fat expulses, and proteins denature.
Because of the heterogeneous nature of beef patties, the distribution of these materials, as well as the heat and mass transfer rates are non-uniform (Singh et al., 1997).

Physical and thermal properties of a cooking beef patty are transient and because of this heat and mass transfer processes are complex (Singh et al., 1997). To ensure food safety and quality through mathematical modeling, an understanding of the structural and chemical changes and how they affect heat transfer is necessary.

**Thermal properties**

Numerous thermal properties have been derived to describe heat transfer in whole beef and ground beef. Qashou et al. (1970) determined the thermal conductivity values for ground chuck and beef in a temperature range of 37 to 44ºF but recognized that these values needed to be expanded for cooking products. Dagerskog (1979a) reported relationships for thermal conductivity, density and specific heat capacity as functions of meat patty temperature, moisture and fat content. Baghe-Khandan et al. (1982) modeled thermal conductivities of several beef cuts and ground beef. Perez and Calvelo (1984) obtained thermal conductivity values of cooked meat products at elevated temperatures. All have acknowledged the difficulties of obtaining thermal property values as structural changes occur within the product. A quantitative description of change in the thermal properties of beef patties from sub-freezing temperatures to the end-point temperature is lacking (Singh et al., 1997).

**Dimensional changes**

As the beef patties are cooked, shrinkage occurs and the ability of the patty to hold water is reduced. Dagerskog and Bengtsson (1974) noted that moisture loss was dependent on formulation. The higher the fat level the higher the moisture loss. These
losses are exacerbated when pressure from the upper cooking surface of a double-sided grill is used (Dagerskog, 1979b). Conflicting information with respect to dimensional changes exist. Trout et al. (1992) reported decreases in diameter and thickness, others, D’sa et al, (2000) and Housová and Topinka, (1985) reported an increase in thickness. Thickness affects the time needed for penetration of heat to the center of the patty. As thickness changes, the rate of heating is also affected.

Porosity affects the density of ground beef, and consequently, its thermal properties. Perez and Calvelo (1984) found agreement with existing thermal conductivity equations when beef samples are treated as a continuous matrix of dry fiber, water, and air. They also found that air occupies up to 10% of the volume in a beef patty sample. As shrinkage of protein occurs, air partially replaces evaporating water. The effect of air, which has a very low thermal conductivity, is difficult to assess independently from the rest of the structural matrix.

Protein denaturation that leads to crust development is important for sensory and flavor acceptance of ground beef patties. The crust has an equally important influence on the heat transfer that occurs at the surface of the beef product. Dagerskog and Bengtsson (1974) were able determine an activation energy at the point when crust development occurs, but recognized the activation energy was significantly lower than those normally associated with Maillard reactions. Surface irregularities and evaporative cooling could explain the discrepancies (Dagerskog and Bengtsson, 1974). Skjöldebrand and Olsson (1980) developed a staining method to determine the thickness of the crust layer and determined a time/temperature relationship of an evaporation zone within minced meat. The thermal conductivity of this layer was low when compared to fully hydrated tissues.
Perez and Calvelo (1984) reported thermal conductivity values of 0.472 W/mºK for fresh meat consisting of 70% moisture and a conductivity value of 0.142 W/mºK for crust with a moisture content of 10%. Thermal properties incorporated into heat penetration models for cooking ground beef patties need to be handled in multiple phases based on moisture content, temperature and time; and these need to be handled based on differing locations within the cooking patty.

**Model development**

Several heat and mass transfer models for ground beef patties have been developed. Dagerskog (1979b) developed a single direction heat transfer model based on water loss and meat temperature-dependent drip and pan temperature-dependent evaporation loss. Ikediala et al., (1996) demonstrated a water loss relationship with heated surface temperature. These have included convection oven cooking as well as single and double sided pan frying (Holtz and Skjöldebrand, 1986; Dagerskog, 1979 a,b; Housová, and Topinka. 1985). Vijayan et al. (1997) developed a model to predict temperature and *E. coli* O157:H7 lethality in beef patties during dual-sided cooking. Dimensional changes in these models were ignored to simplify the solution.

Finite element modeling is a numerical method commonly used in engineering applications. Its use to describe cooking is limited, but this would be a good application because of the complex nature of cooking heterogeneous foods (Puri and Anantheswaran, 1993). Ikediala et al. (1996) used the finite element method to develop a predictive model for heating of ground beef patties. The discretized area they used relied on a uniform, non-shrinking cross section of the patty. They did take into account crust development and treated it separately from the rest of the interior of the patty.
It is the purpose of this study to use x-ray CAT scan imaging and the finite element method to model the internal heat patterns of a non-uniform structure taking into account changing densities, moisture, fat and crust thickness.

**MATERIALS AND METHODS**

**Assumptions governing theoretical heat transfer model development.**

The following assumptions were made in deriving the governing equations for heat transfer in the meat patty. Heat transfer inside the patty was assumed to be conductive with no generation of heat. The grill temperature was assumed to be constant. The beef patties were treated as heterogeneous mixtures with three thermal property assignments. Air pockets, internal protein tissues, and crust were assigned their own thermal conductivity and diffusivity equations. The heat of reaction requirements due to phase changes of water and fat were ignored as their densities, thermal conductivities, and specific heats were incorporated into thermo-physical equations used in the FEM program. Beef patty shrinkage and swelling were neglected, as was pressure applied by the upper cooking platen of the dual-sided grill. Surface heat transfer was also assumed to constant with free convection and radiation being ignored. Heat transfer along a vertical z-plane was considered with heating from two surfaces. Radial directions were ignored for this study. Initial moisture content, densities were measured and assumed to be the same throughout the patty. Unique properties were assigned to crust and air pores. Steam generation with in the pores was ignored.
The following governing equation was used to model a two-dimensional transient heat conduction:

\[
\frac{\partial}{\partial x} k(T) \frac{\partial T}{\partial x} + \frac{\partial}{\partial z} k(T) \frac{\partial T}{\partial z} + Q = \nabla \cdot \mathbf{J} \cdot \frac{\partial T}{\partial t}
\]  

(1)

Equation (1) is subject to the following initial and boundary conditions:

**Initial and Boundary conditions**

The entire patty was assumed to be at the same initial temperature.

\[
T(x,z,t = 0) = T_0
\]

(2)

Temperature set for the upper surface of the patty was 400°F and 300°F for the lower surface to simulate cooking conditions. The circumferential surfaces were ignored.

**Implementation procedure**

X-ray CAT scanned images of ground beef patties were discretized into elements and nodes using image data. A modified node subroutine in Istok’s (1989) FEM program was used to assign elements and nodes corresponding to the number of pixels inputted by the user. Each square element represented approximately a 1mm x 1mm pixel. This represents the smallest amount of visible area scanned. An example of a discretized image is in Figure 3.1.

This program sets the initial and boundary conditions for the FEM. The program asks for the actual measured dimensions of width and height and also the number of pixels that represent widths and height. This ensures that each pixel element represents a 1mm x 1mm area.

The data file from the mesh generator is then read into a modified FEM program of Istok (1989). The program assigns one of two sets of thermal properties to elements, with a pre-determined pixel gray level in the mesh-generating program. For gray levels
between 0 and 5 thermal properties for air were assigned to these pixels. Pixels with gray levels from 5 to 255 were assigned thermal properties for beef. A third thermal property set is exclusive to the crust layers of the beef patty, which can be set to any thickness. The crust thickness sets both top and bottom surfaces simultaneously. The program searches for a non-air pixel and assigns crust properties should there be an air pocket between the cooking surface and the patty. It continues towards the mid-line of the patty until it reaches the designated thickness. With the initiating equations assigned to pixels the program approximates the solution for temperature.

**Thermal properties assignment**

Thermal properties were derived for individual areas identified in the x-ray CAT scanned images. These include areas of beef tissue, air pores and a crust layer.

Properties assigned for air pores were for temperatures 273ºK to 477.594ºK

\[
k_a = 7 \times 10^{-05} \cdot T_0 + 0.0046
\]

(5) for thermal conductivity of air

\[
C_{pa} = 0.0004 \cdot T^2 - 0.1755 \cdot T + 1025.4
\]

(6) for specific heat

\[
\rho = -0.0033 \cdot T_0 + 2.1469
\]

(7) for density (Kreith and Bohn, 1997).

Properties assigned for beef tissues were for temperatures 273ºK to 477.594ºK.

\[
k_a = 7 \times 10^{-05} \cdot T_0 + 0.0046
\]

(8) for thermal conductivity of tissue.

\[
C_{pa} = 0.0004 \cdot T^2 - 0.1755 \cdot T + 1025.4
\]

(9) for specific heat.
\[ \Box = -0.0033 \cdot T_0 + 2.1469 \]  \hspace{1cm} (10)

for density.

The crust was handled in two steps. For temperatures 273°K to 373°K, properties associated with beef were used. For temperatures above 373°K where moisture is reduced, the following properties were used.

\[ k_c = -(0.0003) \cdot T^2 + (0.0067) \cdot T + 0.2724 \]  \hspace{1cm} (11)

for conductivity

\[ C_{pc} = 6.1398 \cdot T + 2154.4 \]  \hspace{1cm} (12)

for specific heat

\[ \Box_c = -4.9371 \cdot T + 1276.4 \]  \hspace{1cm} (13)

for density.

Thermal conductivity, density, and specific heat values were calculated based on temperature and used to calculate thermal diffusivity for each of the identified beef patty structures.

\[ \Box = \frac{k}{C_p} \]  \hspace{1cm} (14)

The governing equation (1) in conjunction with initial and boundary conditions (Eq. 2 to 14), were solved using the FEM.

**Finite element transformation**

The weighted residual method based on Galerkin approximation was used (Istok, 1989). Galerkin approximations were used too approximate solution, \( T \). The FEM transformation reduces the set of equations to a matrix form, a system of \( n \) equations in \( n \) unknowns for numerical implementation, stated below:
\[ M \frac{dT}{dt} + KT = f \quad (\text{Lewis et al., 1996}). \quad (15) \]

\([M]\) contains the specific heat capacity and density of the beef patty. \([K]\) contains the thermal conductivity. Transformation yielded the matrix forms:

\[ M_{ij} = \int CN_i N_j dxdz \]

\[ K_{ij} = \int k_i(T) \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + k_i(T) \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} dxdz + \int N_i N_j dxdz \]

\[ f_i = \int \nabla Q dxdz \int \nabla N d\Omega + \int \nabla N \frac{\partial T}{\partial x} d\Omega. \]

The differential equations are non-linear because the thermal properties are a function of the state variable temperature. In general this problem can be solved by iteration using the thermal properties from the previous iteration step (Lewis, 1996).

\[ M \frac{dT^n}{dt} + K(T^n)T^n = f^n \quad (\text{Lewis et al., 1996}) \quad (17) \]

For this problem we used the thermal properties from the previous time step without iteration. This is functionally equivalent to linearizing the differential equations at each time step. Iterations with a short time step were found to be unnecessary.

**Sample preparation**

Ground beef patties were made using beef trimmings obtained from the University of Georgia abattoir. Lean and fatty beef were ground together using a Hobart model number 4046 (Troy, OH) equipped with a 3/16” head to produce product containing 83% lean. Patties were formed using a Hollymatic Super 54 Food Portioning Machine (Hollymatic Corp., Countryside, IL.). The cylindrical patties of 114.3 mm in
diameter, 10 mm in thickness and 114 grams, were separated from one another by wax paper.

While the patties were still soft, 1 mm x 76 mm stainless steel spikes were inserted at the mid-line of the patties’ edges and pushed towards the center of the patties’ diameter. Once the patties were frozen individual patties were packed in waterproof plastic bags to prevent moisture loss, and stored at –80°C until they were used. Prior to x-ray CAT scanning, patties were stored in a -10°C freezer.

Moisture and fat content of the patties were determined by AOAC (1990) methods.

Bulk density of meat sections, was determined by sectioning nitrogen frozen 8x8x8 mm cubes and weighing them on a Mettler- Toledo Inc model AG245 (Columbus, Ohio).

**Frying equipment**

Samples were fried for cross section imaging in the x-z plane using a Taylor Freezer Inc (Rockton, IL) model QS24-23 dual sided electric grill. The upper plate was pre-heated to 400°F and the lower grill surface heated to 300°F prior to cooking, and temperature was verified using a Raytek Infrared thermal probe model ST20 (Santa Cruz, CA). The height of the top platen was set to 8 mm to slightly compress the 10 mm patties and maintain constant contact. Pressure from the weight of the platen was not measured. Corn oil was spread on the surface to prevent the patties from sticking. Each patty was cooked to an internal temperature of 71°C and immediately placed into a plastic bag and submerged into nitrogen bath to freeze. Patties were then stored in a –80°F freezer until analyses were performed.
**X-Ray Computer Aided Tomography**

Each patty type was examined in frozen and cooked state using a CATSCAN Neurological CT scanner model TCT-20A (Toshiba, JPN) for 9 sec at 120 kV / 230 mA in 2 mm thick sections. Scans were obtained for each frozen patty and for each cooked patty.

Patties were laid flat onto a wood board and scanned. All patties were measured with Vernier calipers prior to scanning. These measurements are used to set the image analysis measurement scales.

**Temperature measurement**

Temperature data was collected on a Luxtron 755 multi-channel Fluoroptic Thermometer using fiber optic probes (Santa Clara, California) to avoid magnetic interference from the scanner and cookers. Two probes Luxtron SEL-02 (Santa Clara, California) surface contact temperature probes were used to monitor cooking grill temperatures, and two Luxtron SFF-02 (Santa Clara, California) fast response probes were used to monitor patty temperatures.

**Model validation**

The simulation models were compared to actual temperature where the thermal couple placement was verified using x-ray CAT scanning. These temperatures were plotted against the simulated FEM temperature profiles.

**Image analysis**

Images scanned in the x-z plane were analyzed to determine thickness and width using NIH image program (U.S. National Institutes of Health, available http://rsb.info.nih.gov/nih-image/).
Images analysis was based on a gray scale of 0 to 255, with zero being absolute black and 255 being white. Scanning samples of beef fat, it was determined that gray values of 1 to 6 represented air and values of 7 to 255 represented non-air material.

Artificial images representing ideal homogeneous beef patties were created using Adobe Photoshop® (Adobe Systems Inc., San Jose, Ca).

RESULTS AND DISCUSSION

Structural homogeneity

Separating thermal properties by type of material influences the predicted internal temperatures. The isothermal map in the model of a homogenous patty in Figure 3.2, without pores, cracks and full contact with the cooking surfaces illustrates how uniform heating can be achieved within a uniform beef patty.

The actual non-homogeneous beef patty illustrated in Figures 3.3 & 3.4 has irregular surfaces, internal pores, and cracks that disrupt the heating pattern. Comparing calculated temperatures at the geometric center of a non-homogenous and homogeneous patty in Figure 3.5 shows the increased time needed to achieve the same temperature.

The non-homogeneous model in Figure 3.3 illustrates cold spots within the patty. A probe could unknowingly be place in a cold spot. If a probe were placed in a pore, temperatures can differ greatly from other probes that were placed in solid meat matrix. Materials such as water, water vapor, or fat could pass through the porous regions, causing fluctuations in temperature readings.
When using an image input, it is assumed that the structure doesn’t change from the initial dimensions. When the patty melts, air pores decrease, and the denser patty will exhibit a different internal heating pattern. The FEM program could be further developed to handle a shrinking patty and one that is under compressive forces, as in the case of a clamshell cooker. The thermal properties used in this study take into account the changing densities, but not the disappearance of the pores should they become filled with water steam or compressed.

**Influence of crust layer**

A crust layer develops on the surface of the cooking patty and progresses towards the center as the tissues become dehydrated (Ateba and Mittal. 1994; Dagerskog and Bengtsson. 1974). How thick this layer becomes is dependent on the amount of moisture migrating to the surface (Ateba and Mittal. 1994). Moisture is strong conductor of heat when compared to protein and fat tissues. The conductivity of these dehydrated regions is reduced and can slow the progression of heat towards the center of the patty. For the graph in Figure 3.7, simulated 114mm x 10 mm patty images were created to minimize the influence from cracks and pores. Only the crust was changed to show differences. In Figure 7, increasing thickness of the crust increased the time needed to reach similar temperatures.

The FEM program applied a uniform crust to the top layer of the patty, but Ateba and Mittal (1994) has indicated that this is not always the case. Figure 3.8 illustrates high spots on the patty surface. The amount of contact is random, and shrinkage is never uniform (Singh et al., 1997)
Influence of patty thickness

Thicker materials require greater heat to obtain an acceptable cook at the geometric centers. This principle is illustrated in Figure 3.6 for ground beef patties. Homologated patties with 1mm of crust and various thicknesses were used to minimize the influences of pores and cracks for data presented in this figure. A simulated patty of 6 mm thickness cooks rapidly from its frozen state and achieves 71°C under 20 seconds. Patties of 10 and 15 mm achieve 71°C at 63 and 110 seconds respectively.

FEM Model Verification and thermal properties

Actual patties that were 114 mm in diameter and 10 mm in thickness required 82 seconds cooked to a temperature of 71°C as shown in Figures 3.5 and 3.6. The simulation underestimated cook time. In Figure 3.5, the actual patty temperature profile was plotted against a non-homogeneous and homogeneous model. Both models initially required more time to heat, but at 20 seconds, the actual patty plateaus and the two models climb rapidly in temperature. The same phenomenon is seen in Figure 3.6 when compared to patties of various thicknesses. This data indicates that initial assumptions regarding the thermal properties of the patties may need to be modified. Unlike the models, the actual beef patty undergoes compression and shrinkage, which are not directly accounted for in the thermal properties in the FEM program. Pores within the patty, for instance, were treated as air only. Fat, moisture and steam could have passed through these areas, reducing or increasing the transference of heat. Density measurements taken and applied to the thermal diffusivity equation could have taken into account the compression, but changes during the cooking process could have not been accounted for that post-cook analysis will miss. Energy required for phase changes were also ignored, and these
changes could have easily increased cook times to what was actually seen in real samples. A significantly higher amount of energy is required for a phase change than simply raising the temperature a degree. Surface boundary conditions were assumed to be constant with no consideration of surface heat transfer coefficients. These coefficients could have improved the model and increased cook times similar to those in actual samples.

**Conclusions**

Previous predictive modeling for ground beef patties included relationships between density, thermal conductivity and specific heat capacities as functions of meat patty temperatures, moisture and fat contents (Dagerskog, 1979a,b; Housova and Topinka, 1985; Ikediala et al., 1996). Ikediala et al. (1996) utilized FEM to model single-sided frying of beef patties and successfully validated this model, which included surface heat transfer and moisture loss rate. These studies assumed a homogenous meat block in their models. They also acknowledge an inability to verify temperature position during their sampling.

This study shows that X-ray CAT scan images can be used for finite element modeling. X-ray CAT scan also verified temperature probe position, which ensures accurate model verification. With well-defined boundaries, the combined techniques are useful in predicting heat transfer in foods.

Erratic patterns in the FEM model show that the non-homogeneous nature of ground beef patties influences the time-temperature of a cooking beef patty. Air treated as
a low thermal conductive point causes the thermal patterns to change within the patty and explains why there are temperature differences when probing a beef patty.

Crust development is important for sensory purposes, but heating is slowed as the crust thickens. Additional research is needed to define the rate of crust thickening.

Thickness of the patty has a large influence on the cooking time. A thin patty heats rapidly and reaches cook temperature much sooner than thick patties. However, due to the crust layer development and dehydration the thicker patty may be desirable from a sensory perspective.

Improved thermal properties, incorporating phase changes, and material migration need to be studied to improve modeling of localized heating within the ground beef patty.

**Nomenclature**

\[ T, T_o = \text{Temperature, Initial temperature} \]

\[ x, z = \text{Coordinate direction} \]

\[ f = \text{Force vector temperature component of the element force vector} \]

\[ \rho = \text{Density} \]

\[ t = \text{Time} \]

\[ Q = \text{Plastic potentials} \]

\[ K = \text{Conductance matrix} \]

\[ k_a, k_c, k_x, k_z = \text{Thermal conductivity} \]

\[ \Gamma = \text{Boundary} \]

\[ C_p, c = \text{Specific heat} \]

\[ \kappa = \text{Thermal diffusivity} \]

\[ M = \text{Mass heat capacity matrix} \]
\( n \) \hspace{1cm} = \text{Iteration number}

\( N \) \hspace{1cm} = \text{Shape function}
Figure 3.1. The discretized mesh section of a beef patty with height of 11mm and a width of 117 mm. Each square element represents a single pixel that measures approximately 1mm x 1mm.
Figure 3.2. Homogeneous meat block with no crust or pores results in straight isotherms across the profile of the patty. The Y-axis is the height of the patty in mm and the X-axis is width in mm. The temperatures in color-coordinated legend are in degrees Kelvin.
Figure 3.3. A non-homogeneous cross section with pores and crust causes the isotherms to bend and appear disrupted. The Y-axis is the height of the patty in mm and the X-axis is width in mm. The temperatures in color-coordinated legend are in degrees Kelvin.
Non-Homogeneous Beef Patty
Isothermal Patterns
Figure 3.4. Image (A) is 114 mm in width and 10 mm in height. The pores and cracks at the surface cause the erratic isothermal patterns in image (B). The isothermal model was captured at 30 seconds of cooking.
Figure 3.5. Non-homogeneous beef patties that have cracks and pores heat less rapidly than homogenous meat blocks. The simulated non-homogenous and homogeneous patties cook more rapidly. The actual patty sample has a stepped heating pattern and takes longer to reach 71.1°C.
Figure 3.6. Thickness of the ground beef patty influences the amount of time needed to reach 71°C. Thicker patties take longer to heat than thin ones.
Figure 3.7. Influence of crust layer thickness on geometric center temperature. The thicker the crust the longer it takes to reach equivalent temperatures.
Figure 3.8. Chalk impression shows that surface contact is not uniform across the face of a beef patty. Bar = 10 mm
Reference


Sonego, L., Ben-Arie, R., Raynal, J., and Pech, J.C. 1995. Biochemical and physical evaluation of textural characteristics of nectarines exhibiting woolly breakdown:


CHAPTER 4
SUMMARY AND CONCLUSIONS
Food safety is paramount in a society that is relying more on ready-to-eat foods. As food preparation and consumption moves away from the home, food establishments become liable for the well being of their customers. As home users prepare ground beef for the family, they need to be aware of the potential food hazards that can be eliminated with proper and adequate thermal treatment.

X-ray CAT scanning allows for non-destructive examination of ground beef patties. Internal structures were visualized and changes were quantified using image analysis software. Pores, cracks, and shrinkage were observed and found to vary with beef leanness and manufacturing method. CAT scans during the cooking process shows dripping of fat and moisture flowing through the product. The loss of materials and tissue shrinkage corresponded with the appearance of a more porous structure. Volumetric changes to the patty were observed in three dimensions, and the development of a crust was observed.

Finite element modeling of the conductive heat transfer in ground beef patties showed a disrupted pattern in a cross sectional isothermal map. Using homologated images in comparison to actual non-homogeneous images demonstrated the effect of patty thickness, crust development, and porosity. As thickness increases, the time required to cook the patty increases. Crust, which has low thermal conductivity compared to fresh beef, slows heating as it develops. The thicker the crust on the surface of the patty, the longer it takes for heat to progress towards the geometric center. The porous/non-homogeneous nature of the ground beef patty causes the cooking to slow when compared to a homogenous model. Collectively, the structure that is set during the
manufacturing of the beef patty and changes that occur during the cooking process slows cooking by reducing the heat transfer rate.

When the models were compared to actual cooking data, a plateau and longer cook time indicated that additional factors needed to be included in the thermal properties used in the FEM program. Further research is needed to include the effects of compression, surface boundaries, shrinkage and phase changes; which affect heat transfer. These changes were visualized using x-ray CAT scanning, but need to be included in future research.
Thermal Property Equations

Air thermal properties (Kreith and Bohn, 1997)

Thermal conductivity

\[ k_a = 7 \times 10^{-05} \cdot T_0 + 0.0046 \]

Specific heat

\[ C_{pa} = 0.0004 \cdot T^2 - 0.1755 \cdot T + 1025.4 \]

Density

\[ \rho = -0.0033 \cdot T_0 + 2.1469 \]

Ground beef thermal properties

Thermal conductivity based on composition for beef and crust (Baghe-Khandan and Okos, 1981)

\[ k = k_w + k_f + k_p \]

\[ k_w = 5.94 \times 10^{-1} + 9.57 \times 10^{-4} \cdot T \]

\[ k_f = 1.79 \times 10^{-1} - 2.23 \times 10^{-4} \cdot T \]

\[ k_p = 1.72 \times 10^{-1} + 2.81 \times 10^{-4} \cdot T \]

Specific heat for products of known composition (Singh and Heldman, 1993)

\[ C_p = 1.549M_p + 1.675M_f + 4.187M_w \]

Thermal property equations derived from actual time and temperature data used for beef hydrated tissue

Thermal conductivity

\[ k_a = 7 \times 10^{-05} \cdot T_0 + 0.0046 \]

Specific heat

\[ C_{pa} = 0.0004 \cdot T^2 - 0.1755 \cdot T + 1025.4 \]
Density
\[ \rho = -0.0033 \cdot T_0 + 2.1469 \]

**Thermal properties for dehydrated beef described as crust**

Conductivity
\[ k_c = -0.0003T^2 + 0.0067T + 0.2724 \]

Density
\[ \rho = -4.9371T + 1276.4 \]

Specific Heat
\[ C_p = 6.1398T + 2154.4 \]

**Nomenclature**

- \( C_p \) = Specific Heat
- \( k \) = Thermal conductivity
- \( k_a, k_f, k_w, k_c \) = Thermal conductivity of air, fat, water, crust.
- \( \rho \) = Density
- \( T \) = Temperature

**References**

