Effect of Evaporative Cooling, Fat Content and Food Type on Pathogen Survival during Microwave Heating

by

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Abstract

Due to the rapid nature of microwave heating, the microbiological safety of foods prepared in the microwave has been in question for several years. Because foods are heated from the inside out and are strictly governed by their own internal properties such as ionic content, moisture level and specific heat, work must be done to further master control of such properties so microwave cooking can be more predictable, controlled and ensure control pathogens.

This study concentrated on the effect of fat content, evaporative cooling and food type on the rate of food borne pathogen survival rates in microwave heated foods. Foods investigated in this study included fresh, raw broccoli spears; a regular, whole muscle breaded chicken patty and a fat free, breaded, formed chicken patty; and raw ground beef patties at three differing fat percentages. All foods were tested in triplicate. A Sharp® 1000W Light-Duty Commercial Microwave Oven was used to treat inoculated samples according to their recommended cooking times. Two sets of samples were treated, one wrapped with Saran™ Wrap and the other without wrap.

F- values were determined for each product. Raw ground beef patties at fat contents of 30%, 15% and 7%, heated for the same time had F-values ranging from 0.03 to 126.20. The lower the fat content, the lower the lethality. Regular and fat free chicken tenders had similar patterns. F-values for fresh broccoli indicted that vegetative pathogens survived the recommended microwave process.

Covering in Saran™ Wrap had some preventive effect on evaporative cooling depending on the food tested and significantly ($p < 0.05$) increased most F-values.

Inoculated pack studies were performed in triplicate on each food with *Listeria monocytogenes, Salmonella* and *Escherichia coli* O157:H7. Survival was determined by presence or absence of growth of each pathogen after enrichment. *Listeria monocytogenes* survived in all samples except for the 30% fat ground beef patties. The *Salmonella* species had a lower survival rate; however, it was still present in uncovered 15% fat ground beef, covered 7% fat ground beef, uncovered chicken patties (both types) and in all broccoli samples tested. *E. coli* O157:H7 survived in all samples except the 30% fat ground beef samples.

Results indicate that higher fat contents seem to ensure lower rates of pathogen survival. This was especially true for the raw ground beef, which had received no prior processing other than the grinding of the whole muscle. There were fewer survival differences in the preprocessed, frozen chicken patties. Both were shown to support no pathogen survival in covered samples, except the fat free chicken patties. *Listeria monocytogenes* was shown to consistently survive the suggested cooking time in these samples. This is consistent with expectations that fat free food samples would display more survival than regular fat samples.

Overall, covering samples with Saran™ had little effect on pathogen survival rates. There were survival differences in some covered and uncovered samples consistent with expectations that covered samples would show less survival than uncovered, but further work including more samples would be

necessary to ensure that the covered or uncovered variable made the true difference in pathogen survival. Finally, broccoli demonstrated consistent pathogen survival in all categories of testing. This indicates microwave oven prepared vegetables could be a prime source of pathogen transmission to consumers. Further work needs to concentrate on determining the correct processing times and parameters that need to be met to ensure safe food.

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Introduction

Pathogen survival during microwave reheating and cooking has emerged as a growing concern for consumers, the government and the food industry. Prior research at the Virginia Tech Department of Food Science and Technology has indicated that evaporative cooling, a phenomenon where the surface of a microwave treated food is actually cooled by a developing jacket of air around the product, may be a factor in the survival of food borne pathogens on microwave treated food. Another investigation at the University of Nebraska Department of Food Science identified a food's fat content as a potential source of pathogen destruction citing higher fat contents might result in lower pathogen survival rates.

As utilization of the microwave grows in popularity, it is increasingly important to understand the nature of microwave heating and how to ensure safe food cooked under such conditions. There are few homes without a microwave in America. In fact, it is projected that there are roughly 150 million microwaves in US homes resulting in an approximately 95% saturation level (Schiffman, 1997). People are conditioned to having this convenience and will take advantage of it even when microwave preparation may not be a top choice for cooking a certain food. Some people do not read the directions provided on the box of a microwave entrée (Schiffman, 1995). That person prepares all microwave foods the same: cooked on the highest setting for the shortest amount of time, even if a

hold time is recommended for temperature equilibration (Schiffman, 1995). Few people are ever aware of it because they did not even take the time read that section of the box (Schiffman, 1995). A food may be undercooked in some areas, overcooked in other areas and the consumer eats it anyway. Undercooked areas present a possible health risk that health officials are worried about. Those are the areas in which food borne pathogens can survive and even grow if not stored properly after heating (Fields et al., 1986).

Research is necessary to determine how to design microwave foods and microwave processes so that the food will be free of pathogens. It must be recognized that no matter how many warnings are given in the case of microwave foods, people will still have the "it could never happen to me" mentality. Safety needs to be designed into microwave foods, microwave ovens and microwave cookbooks. This research targets the problem of designing safer foods and processes for the microwave. It helps answer more of the standing questions pertaining to the survival of food borne pathogens – whether fat content and moisture loss play a role in this problem. Also, little vegetable tissue research has been conducted regarding pathogen survival during microwave cooking. Inoculated, fresh broccoli spears were used in this project to determine differences between vegetable and muscle food pathogen survival.

Prior research indicates that major factors affecting pathogen survival include hot and cold spots, nonuniform heating, the dielectric properties of a food (fat, salt, protein, moisture content), wattage and power output of the microwave

being used, and the size, shape and orientation of the food once in the microwave cavity (Carter, 1994; Flores, 1994; Schiffman, 1993). The diversity of microwave ovens has also been implicated in the lack of heating uniformity of microwave foods (Fakhouri and Ramaswamy, 1993a). There are no standards for consumers to follow to correct this difference in microwave ovens across the United States and only one set of heating directions provided with most products; therefore many microwave foods are not completely cooked, leaving them vulnerable to any surviving pathogens (Fakhouri and Ramaswamy, 1993a; Schiffman, 1997).

Because of the threat that food borne pathogen survival poses to the young, old and immunocompromised population, research to correct these problems is necessary. The overall objective of this research was to further answer food product development questions on how to make microwave products safer.

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Chapter One: Review of Literature

I. Microwave Cooking vs. Conventional Methods

Cooking food over a flame, on the grill, in an oven or in a pot on the stovetop burner was the consumer's only choices for thousands of years. These methods are all known as conventional heating methods. Since these were the only cooking mechanisms available to people before the twentieth century, there a high time involvement was associated with the preparation of a hot meal (Decareau, 1985).

Today, another method of heating is available to consumers, the microwave oven. Much faster at heating foods than conventional ovens, the microwave oven is ideal for the current busy lifestyles that most Americans face each day. However, though microwave prepared foods take a much shorter time to cook, they seldom heat as uniformly or develop tastes and colors as well as conventional cooking methods (Schiffman, 1993). As long as the product is of high quality, provides an enjoyable eating experience and is liked by the rest of the family, the consumer receives a quiet satisfaction by his/her product choice (Schiffman, 1995). Due to several common problems encountered when heating food in a microwave atmosphere, food quality and consumer satisfaction can be remarkably low as compared to conventionally cooked foods. These problems include heating instructions, the respective food's heating pattern, heating rate (affected by several factors), and the uniformity of its heating (Heddleson and Doores, 1994b).

Also, when considering the dependability of microwave heating instructions for ready-to-eat meat products, it is important to consider the findings of earlier research. In 1993, Fakhouri and Ramaswamy conducted research to determine the reliability of manufacturer heating instructions of microwavable food products. Two products, lasagna and shepherd's pie, from the commercially refrigerated and frozen food categories were selected. The objective of the testing was to assure adequate heating of the foods to assure microbial safety – the minimum requirement being determined as 70- 75^{o}C at the product's cold point (Fakhouri and Ramaswamy, 1993a). A 700W household microwave oven (Model EM-563C; Sanyo Canada, Montreal, PQ) was used for the testing.

The recommended heat treatment was shown to raise temperature of the frozen lasagna at its center to 90^{o}C, which is well within the target of microbial safe temperatures. Alternatively, the given instructions for the frozen shepherd's pie only raised product temperature to 20^{o}C in the center – well below the recommended 70^{o}C for microbial safety. With respect to the refrigerated foods examined, the shepherd's pie reached a temperature of 75^{o}C after a five-minute holding period, but the lasagna did not reach 70^{o}C after a holding period. These results imply that not all specified consumer product instructions are adequate to ensure microbial safety of a food that may be subject to post-process contamination (Fakhouri and Ramaswamy, 1993a). No inoculated pack studies were performed in this study to confirm the given heating data.

A. Heating Pattern

It has long been recognized that microwaves heat food in a different way than a stove or oven heats. The conventional heating process heats a food from the outside layer to the center of the food while microwaves heat a food by causing great friction in the food's dipolar molecules, the most common of which is water (Fakhouri and Ramaswamy, 1993a). Salts, fats and proteins also act as dipolar components within the food and effect heating rates. Thus, regardless of the type of food being heated, uneven heat distribution must be expected (Anantheswaran et al., 1993).

Instead of heating the outside of the food and letting the heat transfer gradually toward the cold point of the food cooking the material along the way as in conventional methodology, microwaves penetrate to the center of a food almost immediately depending on the depth of the food (Goedeken et al., 1997). The food is then heated rapidly from the inside out. Usually the coolest spots on a microwaved food will be near or on the surface of the food. Earlier research dealing with this problem has shown as much as a three-level temperature gradient, the top being the coolest region, the bottom of the food being the intermediate range and the middle showing the hottest temperatures (Schiffman, 1993; Carter, 1994; Ryynänen, 1995; Burfoot et al., 1996). This is not true of fully heated conventionally treated foods. Since conventionally heated foods take longer to cook, heat has more time to evenly disperse and distribute itself throughout the food. It is recognized that when given a stand or hold time after a

product has been heated in a microwave, the food's temperature readings were more uniform (Gundavarapu et al., 1995; Landgraf and Tassinari, 1997).

Another good reason for allowing a product a hold period is the unavoidable phenomenon of microwave hot and cold spots. These are areas in which the microwave magnetron either distributes more or fewer waves than usual (Anantheswaran et al., 1994). Subsequently, there are hot and cold spots in the microwave treated food (Ryynänen, 1995). A time of equilibration would allow these spots to more evenly disperse heat trapped within the food (Sawyer, 1985; Anantheswaran et al., 1994). This works particularly well when liquid foods such as soups are addressed. A hold time in conjunction with stirring of the liquid gave the least amount of pathogen survival (Anantheswaran et al., 1993).

A third problem that results in uneven heating of microwave foods is the lack of standardization of a particular wattage among the microwave ovens existing in the United States (Schiffman, 1997). Further, there are no guidelines a consumer can go by to heat a food when they have a microwave with a lower or higher than recommended wattage for heating a food by the given directions. In the United Kingdom, a government-mandated program requires microwaves to be rated by a standardized testing plan (Schiffman, 1997). Using a 350-gram water load, ovens are performance-rated. The microwave packaging displays the oven's power (measured by the Geneva, Switzerland-based International Electrotechnical Commission's IEC 705 power output test) and heating category,

which is a rating from A to E (Schiffman, 1997). This package also gives heating time in minutes for several common categories and oven wattage. Such standards have dramatically improved microwave food and in-home preparation in the United Kingdom. Yet, in the United States, the government has not taken such control of microwave standards and little progress is expected within the industry when United States manufacturers are not willing to agree on an identical procedure for measuring a microwave's output power (Schiffman, 1997).

Currently, United States microwaves vary in age by almost 20 years in some cases (Schiffman, 1997). Microwave ovens that were purchased in the 1980s are still being used. Wattage in these earlier ovens approximately 700 (Schiffman, 1997). However, with time, age and use, these machines do not operate on 700W today. Thus, they cook food more slowly and many times even less uniformly than today's new microwave ovens. The new machines average about 1000W and many have better technology such as turntables that allow more even heating. Presented with these facts, a microwave food manufacturer must test his product in several carefully calibrated microwaves of different size, type and wattage and find the best set of directions that will land within the window of quality the most often (Schiffman, 1995).

B. Heating Rate

Conventional methods of heating food generally take longer than microwave heating. Most consumers do not realize that this time requirement is what makes the conventional process safe (Fakhouri and Ramaswamy, 1993b).

Because it takes a greater amount of time to reach the desired temperature to fully cook a food, any microorganisms present on or in the food will most likely be killed (Fields et al., 1986).

Microwave heating is rapid but more complicated. The food may be heated in a shorter amount of time, but obvious hot and cold spots exist in the food due to uneven electrical wave distribution in the product during cooking. As a result of these shorter cooking times and the uneven heating of a product, it is a concern that microbial survival is allowed (Aktas and Ozilgen, 1992). Since the late 1970s, research results indicate a higher than expected survival rate of food borne pathogens (Fields et al., 1986; Aktas and Ozilgen, 1992; Landgraf and Tassinari, 1997). The food is not heated for as long to reach the desired internal temperature. Discussion arises on whether or not the food has reached suitable temperatures to kill all microorganisms in all areas of the food (Heddleson and Doores, 1994a). Studies have been conducted that established the minimum cold point temperature between 70^{o}C and 75^{o}C for microbiological safety of microwave prepared food (Aleixo et al., 1985). These numbers vary depending on the study and the foods tested. In 1994, Heddleson and Doores published a study on the survival of *Salmonella* species in milk and beef broth. They reported that at 68^{o}C or higher, no viable cells were detected in milk, but at 66^{0}C, viable salmonellae were recovered (Heddleson and Doores, 1994b). For the beef broth, a temperature of 70^{o}C was discovered to totally eliminate the presence of the salmonellae (Heddleson and Doores, 1994b). Other studies suggest that a post

processing temperature rise (PPTR) is likely in most microwaved foods and should be accounted for in heating instructions (Sawyer, 1985). With this in mind, a post cook holding time would be in order to ensure all areas of a food reach the minimum temperature requirements mentioned above. Such findings signal that changes in microwave food product development and package instruction are necessary because many currently recommended times have resulted in inadequate temperatures for pathogen destruction when tested by scientists (Fakhouri and Ramaswamy, 1993a; Landgraf and Tassinari, 1997).

Also, when comparing conventional methods to microwave heating, it is important to consider the thawing of food as well. Conventional thawing of frozen foods is generally performed by placing the product in refrigerated thawing rooms or in a refrigerator for 24 hours (Jay, 1996). These are slow processes that limit the convenience of using frozen foods (Goedeken et al., 1997). On the other hand, microwave tempering of a product allows accelerated thawing and decreased thawing times (Aktas and Ozilgen, 1992). Microwave tempering differs in microwave heating in the fact that tempering microwave penetration depth is relatively deep and the temperature more uniform (Goedeken et al., 1997). Such practices also help deter "runaway heating" from occurring, a fairly common occurrence when microwave treating frozen foods (Decareau, 1985). This occurs when certain areas of the food thaw quickly, cooking rapidly while other areas of the food are still frozen. Burned edges or interior accompanied by cold regions result when this happens giving lower product quality and

satisfaction (Decareau, 1985). As well as lower quality food, the remaining cold spots leave areas for pathogens to find refuge during the microwave heating cycle (Aktas, 1992).

C. Heating Uniformity

When considering post processing temperature rise (PPTR), the third contrast of microwave heating to conventional heating becomes important – the lack of uniformity of microwave preparation. Conventional methods heat a food from the outside in, layer by layer through the medium of heat transfer; therefore, ensuring uniform cooking through each stage of the foods heating (Schiffman, 1993). Microwave cooking, on the other hand, heats by a dielectric means, using high frequency waves to align and realign the dipolar molecules (especially water or fat) within the food causing friction (Hill, 1994). The distribution of this heat is not uniform because of several individual parameters. These parameters include concentration and direction of microwaves in all areas of the oven; presence and amount of bone, fat, protein and salt; the size and shape of the food piece, the physical state of water in the food, food composition and the wattage of the microwave (Heddleson and Doores, 1994a; Hegenbart, 1991; Schiffman, 1993; Anantheswaran et al., 1994).

Conventional heating generally heats food in a more uniform pattern because it heats from the outside inward causing sequential food layers to cook as a result (Hotchkiss and Potter, 1997). The product is in more direct contact with the heat source producing a temperature gradient that is able to char a food on

the outside without bringing the inside temperature to degree suitable to kill all organisms present (Hotchkiss and Potter, 1997).

Microwaves do not pass heat by conduction but penetrate a product through the coupling of electrical energy from the electromagnetic field in the microwave cavity and its distribution in the respective food product being heated (Decareau, 1985; Schiffman, 1993; Heddleson and Doores, 1994a). Theoretically, heat is generated quickly and uniformly by this process (Potter, 1995), but numerous experiments have proven this theory wrong as more research has been done to improve the quality and safety of microwave foods (Aktas and Ozilgen, 1992; Fakhouri and Ramaswamy, 1993a; Landgraf and Tassinari, 1997). The centralized magnetron that emits the microwaves is unable to distribute them evenly. Waves leave the source and bounce around the microwave cavity until they are absorbed by the food. This is not a very exacting process (Fields et al., 1986; Cole et al., 1991).

II. Food Safety Concerns of Microwave Cooking

No matter the type of cooking method, food safety concerns will always exist. Grilling, which is essentially cooking over an open flame, brings issues of safety whether it is the presence of possible carcinogens or the survival of *Escherichia coli* O157:H7 in ground beef patties. Microwave technology raises even more questions.

The chief question regarding food safety is whether or not the recommended process is adequate to kill any food borne pathogen present on the

food before it is cooked. Food that does not require further processing or heating before consumption is known as ready-to-eat (RTE). Though RTE or reheated foods are not typically suspected to be contaminated with pathogenic bacteria, the possibility does exist. Many foods are mass-produced, stored, transported and distributed giving the opportunity for the introduction of unwanted microbes along the way.

A. Proper Package Heating Instruction

Since questions about the safety of microwave heated food first arose, scientists have been testing both food products currently on the market and other potentially marketable foods as well (Heddleson and Doores, 1994a). One such study by Landgraf and Tassinari in 1997 employed the modeling of microbial inactivation kinetics and heat transfer of microwave reheating three food types. The two tested foods inoculated with 10^4 CFU/g *S. typhimurium* for destruction during microwave heating. Thirty samples of commercial baby food with separate formulations, 30 samples of homemade mashed potatoes and 30 samples of homemade beef stroganoff were tested. Each sample was placed in a circular glass container with a 13-cm inferior diameter, 15-cm superior diameter and 6 cm in height. The container was then covered with wax paper and heated using two separate turntable microwave ovens, one a 750W machine and a the other a 700W machine with a preset program (based on final temperature of product). Samples were tested for temperature, time of process to inactivate *S. typhimurium* and for pathogen destruction at each time interval.

Results indicated that both microwave ovens allowed survival of the microorganism though survival in the higher wattage oven allowed only half the survival that the preset program oven allowed (Landgraf and Tassinari, 1997). Time and temperature values played a direct role in microwave destruction effects of *S. typhimurium.* Mashed potato and beef stroganoff samples were heated for 75 seconds as opposed to 50 seconds for baby food and demonstrated a survival rate of 20%, 40% and 83.3%, respectively (Landgraf and Tassinari, 1997). All samples were also stirred after treatment to further ensure uniform temperature of the product from interior to surface. Less survival of *S. typhimurium* in mashed potatoes and beef stroganoff in the 750W oven was attributed to the longer heating times required by the apparatus. On the other hand, baby food samples showed the lowest rate of survival in the preset microwave (80%), which required shorter times (Landgraf and Tassinari, 1997). Their final result were in harmony with those of several other researchers in that food reheated in microwave ovens can sustain substantial pathogen survival when not closely monitored for adequate temperatures throughout the product (Carter, 1994; Flores, 1994; Heddleson and Doores, 1994a; Lund, 1994; Landgraf and Tassinari, 1997).

Research dealing with microwaved ground beef loaves agreed with these results and also cited a link to fat content of a food with the amount of pathogen survival (Flores, 1994). Meat with lower fat content tended to have a higher rate of pathogen survival, which was expected (Spite, 1984; Flores, 1994). The higher

the amount of fat present in a food, the lower its specific heat. A low specific heat value causes a food to heat quickly in a microwave oven (Schiffman, 1993). Reasons for this will be further discussed in a later section.

B. Post Process Contamination

There are several concerns among food industry processors about the safety of packaged food products designed for cooking or reheating in the microwave. One of the primary considerations is post process contamination of a product that may have received an adequate heating process but was mishandled after its heat treatment. Post process contamination occurs when a food comes in contact with unsanitary objects after it has gone through its cooking process. This can occur through the unclean hands of plant workers, dirty conveyer belts or machinery, contaminated packaging or even during transport in the case of a product like pasteurized, liquid eggs (Neergaard, 1998). Additionally, there are some foods that do not receive a heating process before consumption.

Because of this, proper methods of microwave cooking are required – methods that would ensure adequate kill of any threatening food pathogen (Heddleson and Doores, 1994a). Scientists are working to improve these methods, discovering which foods are getting the right treatment and which ones are not. In 1994, research at the Virginia Tech Food Science and Technology Department concluded that one brand each of the chicken breasts, spicy wings and drumsticks being studied only reached F-values of zero or very close to zero after being heated in the microwave (Carter, 1994). At the same time, whole

chickens, one brand of thighs heated at the minimum suggested time and one brand of the half chickens reheated at the maximum recommended time in the study did receive ample heating at the surface while approximate cold spot areas received inadequate heating (Carter, 1994). The study recommended increased reheating times for those products with zero or close to zero F-values recognizing that the suggested heating times for these products were too low (Carter, 1994). Research by Flores at the University of Nebraska, reported that sections on the outside of internally inoculated ground beef loaves generally reached significantly higher temperatures than sections in the middle (Flores, 1994). This interaction of the heating differential of the ends and middle of the sample showed linear affects on the overall temperature of the ground beef samples and the resulting microbial counts (Flores, 1994). Findings like these show that proper microwave heating methods are not yet in place for all foods, and pathogen survival is possible as long as that is true.

C. Cooking and reheating

The main reason the majority of Americans heat their food is to improve its palatability. Heating the food will also inactivate any microorganisms present within the food (Jay, 1996). For the first three-quarters of the 20th century, conventional heating methods were the commonality in the American home. However, with the new technology and increasing availability of microwave ovens for the home, conventional heating methods have become less popular

because of increased heating time and less consumer convenience (Schiffman, 1997).

With the rise in popularity of the microwave oven, the safety of this cooking method will continued to be questioned by government, industry and consumers (Fields et al., 1986; Heddleson and Doores, 1994a). Since microwave heating times are much shorter than that of the conventional oven and its nonuniform heating results in obvious cold spots in most foods, it is difficult to pinpoint where to start fixing the problem. Some food companies are attempting to correct some of the problems by product formulation while others feel that a government-mandated program for rating of microwave ovens should be in place as in the United Kingdom (Schiffman, 1997).

As safety issues are addressed by researchers, one fact is clear: it is critical that definite and proven package directions be developed for all microwave foods and in-home processes (Fakhouri and Ramaswamy, 1993a). Directions must be determined by the technologists designing the food or the person authoring a microwave cookbook. Extensive tests need to be run on these foods using several reliable microwave units under both normal and abusive testing conditions (Schiffman, 1995). Normal testing involves following the product label instructions, and performing all variations included with those instructions. These are the methods a manufacturer would expect a consumer to follow to heat the food. On the other hand, abusive testing is trying to duplicate any outlandish blunders consumers could make when preparing the food (Schiffman, 1995).

Such error could include not adhering to manufacturer directions; not stirring, covering, opening or removing a lid, severely over or under heating, or incorrectly reheating a product after it has been heated once in the microwave (Schiffman, 1995). Tests such as these help a manufacturer understand what problems might occur with the product once it is the consumer's hand. Necessary changes in the directions can then be made before the food is marketed to avoid the worst of such cases. When microwave foods were first introduced to the public, it was not a common practice to do such testing with most product development projects dealing with microwave foods (Schiffman, 1997). Many companies simply released their regular product to the public with microwave directions and waited for complaints fixing them as they arose (Schiffman, 1997). This was a bad policy considering food safety, product quality and public perception. Now companies do a more thorough job of testing their products before releasing them (Schiffman, 1997). Standards of testing need to be instated to further ensure the safety and restore public confidence in these microwave products.

Additionally, it would be helpful to aid consumers in understanding the purpose for a hold time when it is included on a product's direction panel because this step helps alleviate temperature gradients that would otherwise exist in the heated food (Sawyer, 1984; Heddleson and Doores, 1994b; Landgraf and Tassinari, 1997). Many consumers do not realize that the food temperature and quality characteristics could still go through even more change directly after the

heating process has finished. Process completion needs to be emphasized to the consumer in this situation to ensure better, safer results of the cooking process.

D. Storage Abuse

A final factor that should be addressed is food storage abuse of a microwavable product. Storage abuse is a common problem for processors and distributors. When food is not stored at adequately low temperatures to warrant its maximum shelf life, it is considered to be temperature abused, which is a form of storage abuse. Higher temperatures encourage the growth of any microorganisms – pathogens or spoilage flora – present in a food (Jay, 1996). Higher numbers of pathogens or spoilage flora may cause a suggested microwave heating time to be inadequate. Additionally, a food that is damaged during shipping by rough handling is classified to have experienced storage abuse. Because the damage may puncture the package and allow microbial contamination, it may present a problem to consumers.

Storage abuse can occur at many points during a food's production and shipment. If packers and warehouse employees do not handle food in a careful manner, food packaging can become ruptured before it leaves the processing facility. Again, this may allow microbial contamination or interfere with any modified atmosphere packaging methods used in the product's containment (Potter, 1995).

Another source of storage abuse is during a product's display time in a grocery store's storage case. In many stores the case's temperature is not well

monitored and the food is stored at a higher than recommended temperature (Price, 1998). These instances give organisms naturally present on some meats, like *Campylobacter jejuni* or *Salmonella enteriditis* on chicken carcasses, the chance to slowly grow and increase in number (Jay, 1996; Lee, 1997). With adequate cooking and proper handling procedures, these organisms should be eliminated from the meat. Yet, if one does not have a reliable heat process to follow, especially in a varying unit like the microwave oven, this microbial elimination may not occur.

III. Microwave Mechanism of Microbial Destruction

Because of the number of existing differences between microwave cooking and all other heating processes, it is important to note that microwaves also have their own singular method of microbial destruction. It is now generally accepted that mainly thermal effects cause the death of microorganisms in microwave heated food (Goldblith and Wang, 1967; Lund et al., 1994; Heddleson and Doores, 1994a). No conclusive evidence exists from the numerous studies on athermal effects of microwave microbial death that lead scientists to a theory that can be agreed upon (Culkin and Fung, 1975; Fung and Cunningham, 1980; Lund et al., 1994; Heddleson and Doores, 1994a). Questions arise as to whether or not all microorganisms die by thermal action because of the differences in microwave heating compared with traditional, conventional methods (Dreyfuss and Chipley, 1980; Khalil and Villota, 1988; Coote et al., 1991). Most cells appear to die by heat

alone on the outer surface and edges of a food that receives the recommended heating treatment, especially those present in foods with a significant salt content.

NaCl has been shown to create a large temperature gradient in such foods because the surface heats first due to a depression of the dielectric constant (Anantheswaran et al., 1993; Heddleson and Doores, 1994b). This occurs as the microwaves strike the salt particles and are stopped from further penetrating the product. Due to this lowering of the dielectric constant, penetration depth is decreased (Anantheswaran et al., 1993; Heddleson and Doores, 1994a).

A. Electromagnetic radiation

Many doubt that electromagnetic radiation plays a role in microbial destruction because the quantum energy levels required to break chemical bonds and prompt reactions that could result in toxic compounds in a food are too low (Mudgett, 1989). Microwaves operate at low frequencies. The lower the wave frequency the lower the photon energy level that is emitted from the wave source (Elgun, 2000). Due to these very low photon energy levels, it is impossible to change the atomic or molecular structure of the cells being heated (Elgun, 2000). However, some reports do sight it as a possible cause of microbial destruction (Fung and Cunningham, 1980; Fu et al., 1995). A review by Fung and Cunningham highlighted a study where *Escherichia coli* and *Salmonella typhimurium* were inoculated into three different soups and heated in a 915MHz microwave oven (Fung and Culkin, 1975; Fung and Cunningham, 1980 Heddleson and Doores, 1994b). Using temperature-sensitive paper strips, it was

determined after heating of the soups in a cylinder, that the fewest viable cells existed at the top of the container, the region where the temperature was the coolest (Fung and Culkin, 1975; Fung and Cunningham, 1980; Heddleson and Doores, 1994b). This could have only happened through athermal effects of the microwaves as they passed through the soup, but several valid reasons have been given since that time that such conclusions may have been based on faulty reasoning (Fung and Culkin, 1975; Fung and Cunningham, 1980; Heddleson and Doores, 1994a). Another investigation by Dreyfuss and Chipley (1980) examined the enzyme activity of *Staphylococcus aureus* when heated in both a microwave oven and a conventional, electric oven (Dreyfuss and Chipley, 1980; Heddleson and Doores, 1994a). Results demonstrated that microwaves acted on enzymes activity levels in a very different way than the conventional heating process (Dreyfuss and Chipley, 1980). Yet, in defense of the separate mechanisms, it has been suggested that the two process were not equal and that the conventional process calculated was too low, therefore giving invalid results (Dreyfuss and Chipley, 1980; Heddleson and Doores, 1994a). Of the other studies performed, results and doubts about those results were similar. Additionally, fluoroptic thermometry was not yet in existence and precise temperature data was not accessible (Heddleson and Doores, 1994a).

B. Dipolar rotation

Two main interaction mechanisms are responsible for microwave heating, the first of these being dipolar rotation (Schiffman, 1993). Dipolar rotation is

responsible for almost 80 percent of all heating inside a microwave oven operating at the common frequency of 2450 MHz (Charm Bioengineering, 1999). Schiffman cited the perfect example of this dipolar rotation as being water. The more water in a food, the more polar its composition and the more effectively the food is heated in a microwave oven. Because water is a prevalent ingredient in most food systems and present in high concentrations, it tends to dominate the frictional heating of a food that takes place in a microwave (Schiffman, 1993).

C. Ionic Conduction

The second mechanism responsible for microwave heating is ionic conduction. It accounts for the majority of the remaining percentage of heat in the microwave cavity (Charm Bioengineering, 1999). Ionic conduction is a type of resistance heating that is controlled by the acceleration of ions through a given food or liquid and the subsequent billiard-ball-like collisions (Schiffman, 1993). If a food has a high concentration of interfering ions, such as the ions sodium and chloride, the food may heat very quickly and unevenly depending on the resulting penetration depth of the microwaves (Schiffman, 1993). This is where the dielectric properties of a food come into play.

IV. Relevant food characteristics

Successful microwave heating of a food depends on many characteristics such as moisture content, free ionic salt content, fat, protein and solids content (including bone) (Heddleson and Doores, 1994a). Because water makes up 50 to 90 percent of most foods, understanding its effect on dielectric activity is vital

(Heddleson and Doores, 1994a). Higher moisture content usually lowers the dielectric loss factor of a food; thus, causing it to heat more efficiently (Heddleson and Doores, 1994a). Still, other components such as high salt content may lower a microwave's wave penetration depth. The primary factors that control heating include the dielectric properties of the food (salt, fat, protein), its thermal conductivity, the size, shape, and orientation of the food relative to the oven, the molecular state of the water in the product, the presence of bone in a product, and its moisture content (Carter, 1992; Lund et al., 1994; Berek and Wickersheim, 1990).

A. Dielectric properties of food

When a food is to be heated by microwaves or is to be designed for use in a microwave oven, several factors must be accounted for in calculation of the products' time and power setting in the microwave oven. First, the dielectric properties of the food – the amount of free water, salt, fat and protein content (Heddleson and Doores, 1994a), must be accounted for. The more of these dielectric elements present in a food, the more microwaves will be absorbed or reflected. For instance, high levels of sodium lower the dielectric constant of a food causing it to heat more quickly (Anantheswaran et al., 1993). This is also true of a component like fat (Flores, 1994). Research conducted on low fat ground beef concluded that the lower the fat content of the meat being cooked the lower the temperature attained over a fixed cooking time (Flores, 1994). Furthermore, a large amount of free water in a food, as in a vegetable like broccoli, encourages

faster heating (Schiffman, 1993).

Because microwaves cook mainly by dielectric heating (the rapid rotation of polar molecules), the dielectric properties of a food must be accounted for. For instance, a food system rich in polar molecules, such as salts, contributes to accelerated rates of heating by increasing the dielectric constant of the food (Schiffman, 1993). As the dielectric constant is depressed, there is a rapid temperature increase at the surface of the aqueous, ionic food and an accompanying decrease in microwave penetration depth (Anatheswaran et al., 1993). This occurrence is welcome in a thin, sliced food but not in a thicker product such as a whole turkey or ham shank. In these foods, irregular heating results due to uneven distribution of the polar molecules throughout the product (Heddleson and Doores, 1994a; Berek and Wickersheim, 1990; Mudgett, 1989). Such foods either need to be reformulated or resized to better distribute the ionic materials that effect heating or should be cut into thinner pieces (Schiffman, 1993). These actions will alter the penetration depth of the microwaves into the food (Schiffman, 1993).

Increased sodium and fat contents have been shown to correlate with a decrease in wave penetration depth in microwave foods (Heddleson and Doores, 1994a). Sodium and lipid ions reflect the electric waves that are responsible for microwave heating causing ionic polarization (Hill, 1994). However, before reflecting these waves from penetrating deeper into the food, these ions are heated and reflect this heat into the organic material directly surrounding

themselves (Schiffman, 1993; Heddleson and Doores, 1994a). The areas directly in contact with these ions then heat quickly. Yet, by reflecting the electrical waves, sodium lowers the effectiveness of microwave heating and allows the possibility of greater pathogen survival rates (Heddleson and Doores, 1994b).

B. Specific Heat

Though food's thermal conductivity levels are less important in microwave cooking than in conventional methods because of the much shorter heating times, a related factor of this parameter is very important to microwave heating (Schiffman, 1993). This factor is a food's specific heat (Burfoot et al., 1996; Berek and Wickersheim, 1990; Mudgett, 1989). A proper definition of specific heat is "the physical property that denotes the ease with which heat is transferred through a homogenized substance" (Merkel, 1974). The greater the thermal conductivity of the food, the quicker it will heat. A high thermal conductivity corresponds to a lower specific heat, which results in faster heating in a shorter time (Schiffman, 1993). Because microwave heating is fast, controlling specific heat is a major factor in ensuring correct heating of a food. Specific heat can be raised by increasing the solids content of a system by adding components like lipids, salts and proteins (Schiffman, 1993). This begins to explain why Flores found ground beef with lower fat contents achieved lower temperatures overall than higher fat ground beef cooked for the same amount of time (Flores, 1994).

Variables such as this determine the magnitude of a local temperature rise in a food given its dielectric constant. In a food system where system components

are not evenly distributed, these parameters will all vary within the product and result in different heating rates and different equilibrium temperatures throughout the food (Berek and Wickersheim, 1990; Burfoot et al., 1996). The temperature of a product with low thermal conductivity will not equilibrate thereby making "hot" and "cold" spots in a food more noticeable. A product with high thermal conductivity will equilibrate (Carter, 1994). Furthermore, a food with high thermal conductivity will benefit from stirring an/or a post-heating holding time to allow conduction heating to occur throughout the product (Sawyer, 1984; Heddleson and Doores, 1994b).

C. Shape and size

Size, shape, and orientation of a product relative to the microwave oven all contribute to its heating rate (Heddleson and Doores, 1994a). The size of a product affects its heating rate due to the depth of microwave penetration. Microwave penetration is affected by many other factors other than size, though the size of a product is a rather basic and obvious concern (Heddleson and Doores, 1994a; Berek and Wickersheim, 1990; Mudgett, 1989). Small products will heat faster than larger products because the microwaves are able to penetrate the entire product at a higher rate. However, smaller products are also more susceptible to oven pattern variations or "hot" and "cold" spots, which exist in the oven and are not generated within the food.

Shape and size of the food in question must also be known when cooking food in a microwave oven. Both determine how the food will heat and at what

rate (Landgraf and Tassinari, 1993). If the food piece is too thick, the microwaves will be unable to effectively permeate it since the penetration of most microwaves is usually only about 10 – 15 mm from each side (Hill, 1994). It is also important to note that a food of a spherical or cylindrical form with a diameter of 20 – 60 mm will heat unevenly, the center heating more swiftly than the surface (Hill, 1994). This phenomenon is known as the concentration effect (i.e. heat is focused toward the center of the round) (Hill, 1994).

In irregularly shaped products such as chicken legs, wings, and thighs, nonuniform heating rates exist due, in part, to these differences in product thickness (Robertson, 1993; Mudgett, 1989). Microwave penetration depth is the most prevalent factor in determining whether cylindrically and spherically shaped products are preferentially heated on the surface, uniformly throughout, or develop "hot" spots internally due to "focusing" (Schiffman, 1993). In rectangular or square products, slab geometrics basically determine heating rates throughout the product (Decareau, 1985; Mudget, 1989). These effects are basically independent of microwave penetration depth (Buffler, 1993).

It is important to note that the geometry of the food as well as the shape of the container it is contained in must be considered before treating food in a microwave oven (Hill, 1994). It has been observed that food shapes with corners tend to display localized heating in those areas of the sample because of the multi-directional distribution of the electrical energy from the microwave (Heddleson and Doores, 1994a). Conversely, cylindrical or spherical foods reduce

edge and corner heating but are subject to center heating or focusing effects (Copson et al., 1962; Heddleson and Doores, 1994a). This causes heating of the product to be mainly at its center. Therefore, in regard to the shape of the heating container, it is important to avoid sharp edges and corners as this may also effect the foods reheating pattern (Hill, 1994). The shape of the container will often dictate the shape of the food portion in contains.

The size of the portion being heated is another factor that affects the rate at which a food cooks or reheats. The larger a food portion, the less efficiently it heats in the microwave atmosphere and vice versa (Decareau, 1985; Schiffman, 1993). Because of a phenomenon known as "coupling," larger objects are able to absorb more energy than smaller foods (Heddleson and Doores, 1994a). Ironically, these foods tend to heat slower though due to the fact that more time is required to allow the temperature gradient of the food to equilibrate and decrease (Heddleson and Doores, 1994a). This is because, as mentioned before, microwaves' penetration ability is limited to 10 to 15 millimeters from each side in most foods (Hill, 1994). Thus very thin foods may receive too much heat while thicker foods are cooked only on the outside layers (Hill, 1994).

D. Orientation

Orientation of the food product is another factor of concern (Heddleson and Doores, 1994a). The orientation of the product in the oven affects its heating rate because of oven pattern variations. As the microwave source emits radio waves, they bounce off the walls of the microwave until striking and being

absorbed into the food. How the product is placed in the oven will determine how these microwaves hit, absorb and heat each area of the product. Adding to this variation is the presence of "hot and cold spots" in the oven where food consistently heats less efficiently (as in a back corner) (Fields et al., 1986; Calzada et al., 1995). These result from uneven distribution of the waves inside the oven cavity. These temperature variations can be lessened by a wave stirrer but may still present a problem, especially for small products (Mudgett, 1989; Buffler, 1993).

E. Molecular State of Water

The molecular state of water in a food product can also affect its rate of heating. Water in its liquid state has a much higher dielectric constant than that of ice. Therefore, if dealing with a frozen product, any thawed areas in the product will heat much more quickly than the still frozen sections of the product, resulting in the thawed areas being overcooked and frozen areas being undercooked (Mudgett, 1989; Goedeken et al., 1997). Molecular state of water in a food is an important point of calculation because it determines how the food will absorb the microwaves (Schiffman, 1993). The more ionic components (i.e., free water, fat, salt, protein) in the food, the quicker it will heat (Decareau, 1985; Schiffman, 1993; Heddleson and Doores, 1994a). Liquid water more readily absorbs microwaves than ice; therefore, wide temperature gradients are able to occur within a frozen product causing a phenomenon known as run-away heating (Goedeken et al., 1997). "Run-away" heating causes quality defects in a

frozen or partially frozen product such as thermal degradation and excessive water loss (Decareau, 1985; Goedeken et al., 1997). The thermal conductivity of the food is increased when the amount of free water is increased and is only countered by the presence of other dielectric elements such a salt, fats and proteins (Fakhouri and Ramaswamy, 1993b).

The moisture content of a product greatly affects its dielectric properties and consequently affects microwave penetration depth (Hill, 1994). Nonuniform heating rates are seen in high moisture foods because of low microwave penetration depth; however, low moisture foods have more uniform heating rates because of the higher microwave penetration depth and their low heat capacities (Mudgett, 1989; Heddleson and Doores, 1994a). The moisture content of a food can also affect the rate of conventional heat transfer through conduction (Hotchkiss and Potter, 1997). Another problem with high moisture foods is that heat can be lost through surface cooling as a result of evaporation (Berek and Wickersheim, 1990). As temperature continues to increase though, moisture will start being lost by this evaporative action, thereby decreasing the moisture content of the product (Heddleson and Doores, 1994a). Additionally, the molecular state of water

F. Presence of Bone

A final consideration is the presence of bone in meat products in addition to their irregular shape. Bone in a product affects the uniformity of microwave heating in that calcium and other minerals present in the bone reflect the

microwaves as sodium ions do (Carter, 1994). Consequently, the rate of heating in the meat surrounding the bone is greater than that in other areas of the meat because the reflected microwaves spend most of their energy in the area immediately surrounding the bone (Heddleson and Doores, 1994a; Mudgett, 1989).

G. Presence of Fat

When considering the presence of fat in a microwave food, it is especially important to consider what percentage of that product is fat and how it is distributed to better understand how the food will cook (Schiffman, 1993; Heddleson and Doores, 1994a). Fat is a dielectric component of a food system, so it can both absorb heat and reflect it (Heddleson and Doores, 1994a). If this fat is distributed evenly and the food sample is not too thick, the sample will cook faster because it will absorb the microwaves, be heated by dipolar rotation and transfer that heat to the food directly surrounding it (Schiffman, 1993; Heddleson and Doores, 1994a). However, if the food is too thick, the fat particles will heat the food directly surrounding itself but reflect other microwaves from reaching the center of the food (Schiffman, 1993). Flores illustrated this using low fat ground beef loaves (Flores, 1994). Samples with lower fat contents generally showed lower temperatures over the set microwave cooking time than did higher fat products (Flores, 1994).

V. Microorganisms of Concern

Three food pathogens tend to stand out as a concern to public health in prior studies dealing with microwavable foods. *Listeria monocytogenes*, several *Salmonella* species and *E. coli* O157:H7 are becoming more and more recognized because of their prevalence as sources of causing human illness and further concern for food companies, government agencies, consumer activist groups and consumers themselves (Heddleson and Doores, 1994a). Therefore researchers have often concentrated their efforts in these areas.

A. *Listeria monocytogenes*

Four areas of concern regarding foods prepared only by microwave means before consumption are: the survival of *L. monocytogenes* resulting from inadequate processing or post process contamination of pre-cooked refrigerated foods (Cole et al., 1994); uneven heating and reheating throughout a food (Anantheswaran et al., 1994; Landgraf and Tassinari, 1997); inadequate manufacturer directions (Fakhouri and Ramaswamy, 1993a; Anantheswaran et al., 1994); and the difference between surface and internal temperatures (Sawyer, 1984; Fields et al., 1986).

Problems with *L. monocytogenes* are not uncommon in the food processing industry. It is a hardy organism that can survive process temperatures that eliminate many other microbes (Jay, 1996). Once it survives a process, there are little or no other competitors; thus, it can grow easily from refrigeration temperatures up to room temperature. In December of 1984, an Oklahoma

woman with cancer was hospitalized due to a sepsis caused by Listeriosis (<Mmwrq@cdc.gov>, 1989). *Listeria monocytogenes* was afterward isolated from a partially used package of Plantation Brand turkey franks (<Mmwrq@cdc.gov>, 1989). The patient said she had eaten the turkey franks after heating them in a microwave oven (<Mmwrq@cdc.gov>, 1989). Cultures of *L. monocytogenes* were then isolated from two unopened packages of the Plantation Brand turkey franks at a nearby store (< Mmwrq@cdc.gov>, 1989). *Listeria monocytogenes* strains from the patients refrigerator and the unopened packs were confirmed at the Centers for Disease Control and Prevention as serotype 1/2a with the same electrophoretic enzyme type (< Mmwrq@cdc.gov>, 1989). The incident eventually led to a voluntary recall by the manufacturing plant and an investigation by the United States Department of Agriculture (<Mmwrq@cdc.gov>, 1989). This was one of the first well-known indicators to government, industry and public that microwave heating and reheating could hold serious health implications if not adequate heating was not achieved.

In 1994, Carter employed the use of *L. monocytogenes* in inoculated pack studies to illustrate that the reheating times for some chicken products, such as chicken breast, spicy chicken wings and drumsticks resulted in F-values of zero or very close to zero (Carter, 1994). The same study indicated that similar whole muscle chicken products, such as whole birds and thighs, received heat treatments adequate to give the desired 4D process during reheating (Carter, 1994). These mixed results brought the researcher to the conclusion that some

suggested times are indeed adequate to kill *L. monocytogenes* during microwave heating, but some of these times required reevaluation to ensure correct processing temperatures during reheating (Carter, 1994).

A study conducted by Cole et al. (1994) showed that *L. monocytogenes* was able to increase its thermotolerance during slower, milder heating processes. This increased thermotolerance increases the risk of its survival on food ready for human consumption (Cole et al., 1994). Results such as these could help strengthen the safety of microwave cooking due to the speed which it heats.

Galuska et al. (1988) conducted an early investigation of *L. monocytogenes* in microwave ovens examining the thermotolerance of strains Scott A and V7 in a nonfat dry milk suspension. Both strains were heated in a microwave, with calculated D-values at five temperatures between 60°C and 88.2°C, and in a water bath (Galuskla et al., 1988; Heddleson and Doores, 1994a). Resulting heating data were compared. The D-values were shown to be highest in the microwaved sample, and microwave treatment above 71.1°C concluded a 4 – 5 $\log_{10}$ reduction in levels of *L. monocytogenes* within 15 seconds at 71.1°C (Galuska et al., 1988). It was concluded that at conventional pasteurization processing temperatures, microwaves would be equally as effective as conventional heating in destroying *L. monocytogenes* in food products (Galuskla et al., 1988; Heddleson and Doores, 1994a).

Another study that should be mentioned was conducted by Unilever Research in 1994. Researchers showed that cultures of *L. monocytogenes* heated at

rates of 5.0°C min^{-1} displayed no increase in thermotolerance of the cells while heating at rates of less than 0.7°Cmin^{-1} induced maximum thermotolerance in the cell cultures (Cole et al., 1994). Levels of thermotolerance then increased proportionally as heating rates were decreased from 5.0°C min^{-1} to 0.7°C min^{-1} (Cole et al., 1994). These findings show that the quickness of microwave heating may be a plus in pathogen reduction.

B. *Salmonella* species

Salmonella species contaminate the surface of several common foods, poultry and fresh vegetables being the most notable. Poultry naturally have *Salmonella* spp. as part of their normal gut microflora, which is often transferred to the chicken carcass from feces or during the kill process (Dawson, 1999), so it is always important to thoroughly cook such meat to a full degree of doneness throughout. Otherwise, areas that did not receive full heat may harbor injured cells that may prove to be more harmful than the original live cells. The reason for this is that no one is expecting *Salmonella* spp. to be present and might store the product improperly or eat the product after those cells have had time to repair without cooking it.

In 1986, research was conducted to determine whether or not internal temperatures were an adequate guide for controlling death of *S. typhimurium* in microwave heated food. Whole chickens were halved and inoculated with 5×10^5 *S. typhimurium* (Fields et al., 1986). Comparison temperatures were obtained by cooking one half of the chickens in an electric, conventional oven while the other

halves of each bird were separately treated in a 2450 MHz microwave oven (Fields et al., 1986). After testing, it was concluded that internal temperatures could not be used as a satisfactory means of determining the death of pathogens in a microwave ovens because of the high survival rate of *S. typhimurium* in microwave samples as compared to conventionally prepared samples (Fields et al., 1986).

Another study conducted by Heddleson and Doores to determine the differences in heat gradients between high and low sodium contents in liquid food systems (Heddleson and Doores, 1994b). Milk was used as the low sodium solution and beef broth as the high sodium liquid food. Results showed that sodium content and other dielectric components of the system did indeed play a primary role in affecting the thermotolerance of bacteria present within the food systems as well as the temperatures that could be achieved in each food (Heddleson and Doores, 1994b). Sodium content proved to decrease the microwave penetration depth of each liquid in turn increasing surface heating rates and giving lower temperatures at greater depths (Heddleson and Doores, 1994b). Despite these findings, the study did site that sodium content alone could not be an exact indication of the heating pattern of a food (Mudgett, 1989; Heddleson and Doores, 1994b). Other factors like the colloidal content and complexed salts in a given food system may cause it to heat differently than a food with a higher amount of free salts that serve to speed heating rates (Mudgett, 1989; Heddleson and Doores, 1994b).

Another 1994 investigation explored the destruction of *Salmonella* species and its relationship with container shape, post-heating holding, covering of container and the effects of product mass (Anantheswaran et al., 1994). Milk was used as a model system. Variations in treatment of the inoculated system included heating four microwaves of different wattage, six separate time-temperature combinations, rectangular and circular containers and covering with Styrofoam ™ (Dow Chemical Co.) caps or no covering of the sample (Anantheswaran et al., 1994). Results indicated that the turntable microwave consistently emitted a power output equal to or greater than the other three microwaves while the top feed model substantially reduced greater numbers of bacteria than the turntable and Capri models (Anantheswaran et al., 1994). Milk treated at low power setting showed significantly more survival of *Salmonella* spp. milk treated at high power settings; a 2.0 minute holding time showed a considerably higher bacterial destruction rate than samples with no holding times or holding times of less than a minute; and no differences were noted into bacterial destruction for covered and uncovered milk samples given a holding time of two to eight minutes (Anantheswaran et al., 1994). Conclusions stated that no significant difference was recorded between containers of differing shapes and volumes, covered or uncovered. The study cited that heating to end-point temperatures was a better means to effect concordant bacterial destruction than the more familiar application of heating to a designated time (Anantheswaran et al., 1994).

Other studies on S*almonella* spp. have served to verify recommended USDA processing schedules, ensure the safety of manufacture's reheating instructions, and to compare the difference in bacterial destruction between microwave, convection microwave and conventional electric ovens (Heddleson and Doores, 1994a; Cherry-Merritt et al., 1997; Landgraf and Tassinari, 1997).

C. Escherichia coli O157:H7

Escherichia coli O157:H7 is a threat to almost everyone, but especially the old, young and immunocompromised. Any small amount of it can be a threat to such consumers. For instance, if a patty of ground beef is cooked or reheated in a microwave but never reaches the proper internal temperature throughout, *E. coli* will most likely survive and infect the person who eats the patty – unless they are of good health. If good health is the case, this person may never know they ate a burger contaminated with viable *E. coli*, but a person with a weaker immune system would in all probability become very ill, become dehydrated from continual diarrhea and possibly be afflicted with hemolytic uremic syndrome (HUS). Considerations such as this make *E. coli* O157:H7 a concern in every operation that it might be introduced.

An early study on *E. coli* and *Bacillus subtilis* focused on determining the effect of microwaves on the membrane transport process. Though microwave frequencies used in the analysis were not common to the food industry, information did result to help understand the death mechanism of microwaves on bacterial cells (Heddleson and Doores, 1994a). No notable effects on uptake of

thymine or thymidine were recognized after microwave heating, and potassium ion leakage was noted to have increased (Heddleson and Doores, 1994a). All data led the researchers to the conclusion that all bacterial reduction was due to thermal effects of heating alone (Heddleson and Doores, 1994a).

Escherichia coli destruction in relation to nutrient loss was the subject of an examination by Aktas and Ozilgen. Thermal death and injury models of *E. coli* during pasteurization were contrasted with the degradation kinetics of riboflavin to acquire more data on the effect of microwaves on pathogen destruction (Aktas and Ozilgen, 1992). Results showed that 15 to 25 percent of surviving *E. coli* cells were injured after a pasteurization process with microwaves in a tubular flow reactor (Aktas and Ozilgen, 1992). The researchers noted that these injured cells might possibly be dangerous in a microwave pasteurization process because they would not be detected in immediate microbiological tests (Aktas and Ozilgen, 1992). In relation to riboflavin, acceptable levels of microbial destruction were recorded with degradation of 35 to 40% of initial riboflavin amounts (Aktas and Ozilgen, 1992).

In 1994, Flores conducted research to determine whether or not low-fat ground beef loaves inoculated with *E. coli* O157:H7 survived in a microwave oven when cooked to a predetermined time. Using ground beef samples at 4, 6, 12, and 22 percent fat, inoculated samples were heating to the suggested heating time in a 900W rotating microwave (Flores, 1994). Heating data revealed a significant linear effect of leanness on temperature of the samples (Flores, 1994). The greater

the difference between the fat percentages (i.e., 4% fat and 22% fat), the greater the degree of pathogen destruction (Flores, 1994). It was also cited that the lower temperatures reached in the 4 and 10 percent fat products may have been a result of the presence of sodium in the meat, which demonstrated a blocking effect on the microwaves (Flores, 1994). Further conclusions recognized microwave heating to be a safe means of cooking as long as the food was cooked to adequate temperatures throughout the entire product (Flores, 1994).

Another investigation conducted at Michigan State University served to compare the thermal inactivation rates of *E. coli* O157:H7 and *S. senftenberg* to those six earlier identified endogenous muscle proteins (Cherry-Merritt et al., 1997). Control and inoculated sample of ground beef were microwaved at four temperatures for preset periods of time in Thermal-death-time studies (Cherry-Merritt et al., 1997). The six proteins used in the study were acid phosphatase (AP), peroxidase (PO), phosphoglycerate mutase (PGAM), glyceraldehyde-3-phosphate dehydrogenase (GAPDH), triose phosphate isomerase (TPI) and lactate dehydrogenase (LDH) (Cherry-Merritt et al., 1997). All were identified as potential endpoint temperature indicators in ground beef (Collins et al., 1991; Wang et al., 1995; Wang et al., 1996). When thermal death time (TDT) curves were plotted for each pathogen, it was obvious they closely paralleled the processing requirements of hamburger patties (Cherry-Merritt et al., 1997). All *E. coli* or *E. coli*-like microbes were recovered after aseptic collection of beef (Cherry-Merritt et al., 1997). The protein TPI had a temperature dependence close to both

pathogens studies, therefore it was cited as the most probable endogenous muscle protein for use in indicating adequacy of processing for *E. coli* O157:H7 and *S. senftenberg* (Cherry-Merritt et al., 1997). Further studies were recommended by the researchers to ensure the protein in time-temperature processing use. Information such as this could lead process engineers to safer processing time and temperatures when employing microwave pasteurization techniques in industry.

VI. Objectives

Objectives for this research were to determine the effects of evaporative cooling variations in fat content of foods on pathogen survival and to ascertain the differences in heating between a vegetable and a muscle food product during microwave heating.

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Chapter Two

The Effect of Fat Content, evaporative Cooling and Food Type on Pathogen Survival During Microwave Cooking

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Key words: Microwave, food borne pathogens

Abstract

The survival of food borne pathogens *Listeria monocytogenes*, *Salmonella* species and *Escherichia coli* O157:H7 in relation to food fat content, evaporative cooling and food type was investigated. Regular, 19% fat and nonfat ready-to-eat chicken patties and raw ground beef patties with fat contents of 7%, 15% and 30% were heated in a Sharp® 1,000Watt - Light Duty Commercial Microwave Oven, Model R-21HT, employing the suggested heating times for each. Microbiological analyses were run on each sample post heating to determine the effectiveness of each microwave heat treatment. Pathogens were consistently killed in the 30% fat ground beef patties showing only 17% survival. Survival rates in the 7% and 15% fat ground beef patties were higher at 56% and 67%, respectively. Chicken patties had less difference in pathogen survival with the 19% fat chicken patties resulting in a survival rate of 42% and nonfat patties 50%. Pathogen survival due to evaporative cooling was also investigated. Samples were either covered with Saran™ Wrap or left with no covering. Samples were weighed before and after heating to determine whether or not covering the food made a significant difference in pathogen survival in each food. No significant difference was observed between survival rates in the covered and uncovered samples though post cook weights were generally higher in the covered samples. Broccoli survival rates were tested in conjunction with the meat samples. Survival rates were 94% in broccoli compared to 46% for all meat samples combined. This is an indication that due to the absence of fat, protein and salt in the vegetable system,

such foods may require more rigorous heating than is presently recommended. The highest survival rates in meat samples were recorded in the 15% fat ground beef patties at 67%. The 7% fat ground beef samples had a slightly lower survival rate at 56%. Of the food borne pathogens tested, *Listeria monocytogenes* demonstrated the highest pathogen survival rates while *Salmonella* species had the lowest pathogen survival.

Introduction

Historically, foods have been heated conventionally. Heating occurred by heat transfer from one warmed layer to the next deeper layer until finally reaching the center of the food (Decareau, 1985). Today, another method of heating is available to consumers, the microwave oven. Much faster at heating foods than conventional ovens, the microwave oven is ideal for the current busy lifestyles that most Americans. However, though microwave prepared foods take a much shorter time to cook, they seldom heat as uniformly or develop tastes and colors as well as conventional cooking methods (Schiffman, 1993). Due to several common problems encountered when heating food in a microwave atmosphere, food quality and consumer satisfaction can be remarkably low as compared to conventionally cooked foods. These problems include heating instructions, the respective food's heating pattern, heating rate (affected by several factors), and the uniformity of its heating (Heddleson and Doores, 1994a).

In 1993, Fakhouri and Ramaswamy conducted research to determine the reliability of manufacturer heating instructions of microwavable food products (Fakhouri and Ramaswamy a, 1992). Two products, lasagna and shepherd's pie, from the commercially refrigerated and frozen food categories were selected. The objective of the testing was to assure adequate heating of the foods to assure microbial safety – the minimum requirement being determined as 70- 75^{o}C at the product's cold point (Fakhouri and Ramaswamy a, 1992). A 700W household microwave oven (Model EM-563C; Sanyo Canada, Montreal, PQ) was used for

the testing.

The recommended heat treatment was shown to raise temperature of the frozen lasagna at its center to 90°C, which is well within the target of microbial safe temperatures. Alternatively, the given instructions for the frozen shepherd's pie only raised product temperature to 20°C in the center – well below the recommended 70°C for microbial safety. With respect to the refrigerated foods examined, the shepherd's pie reached a temperature of 75°C after a five-minute holding period, but the lasagna did not reach 70°C after a holding period. These results imply that not all specified consumer product instructions are adequate to ensure microbial safety of a food that may be subject to post-process contamination (Fakhouri and Ramaswamy a, 1992). No inoculated pack studies were performed in this study to confirm the given heating data.

It has long been recognized that microwaves heat food in a different way than a stove or oven heats. The conventional heating process heats a food from the outside layer to the center of the food while microwaves heat a food by causing great friction in the food's dipolar molecules, the most common of which is water (Fakhouri and Ramaswamy, 1993b). Salts, fats and proteins also act as dipolar components within the food and effect heating rates. Thus, regardless of the type of food being heated, uneven heat distribution must be expected (Anantheswaran et al., 1993).

Microwave cooking heats by a dielectric means, using high frequency waves to align and realign the dipolar molecules (especially water or fat) within

the food causing friction (Hill, 1994). The distribution of this heat is not uniform because of several individual parameters. These parameters include concentration and direction of microwaves in all areas of the oven; presence and amount of bone, fat, protein and salt; the size and shape of the food piece, the physical state of water in the food, food composition and the wattage of the microwave (Heddleson and Doores, 1994a; Hegenbart, 1992; Schiffman, 1993; Anantheswaran et al., 1994).

The chief question regarding food safety is whether or not the recommended process is adequate to kill any food borne pathogen present on the food before it is cooked. Food that does not require further processing or heating before consumption is known as ready-to-eat (RTE). Though RTE or reheated foods are not typically suspected to be contaminated with pathogenic bacteria, the possibility does exist. Many foods are mass-produced, stored, transported and distributed giving the opportunity for the introduction of unwanted microbes along the way.

Since questions about the safety of microwave heated food first arose, scientists have been testing both food products currently on the market and other potentially marketable foods as well (Heddleson and Doores, 1994a). One such study by Landgraf and Tassinari in 1997 employed the modeling of microbial inactivation kinetics and heat transfer of microwave reheating three food types. The two tested foods inoculated with 10^4 CFU/g *Salmonella typhimurium* for destruction during microwave heating. Thirty samples of commercial baby food

with separate formulations, 30 samples of homemade mashed potatoes and 30 samples of homemade beef stroganoff were tested. Each sample was placed in a circular glass container with a 13-cm inferior diameter, 15-cm superior diameter and 6 cm in height. The container was then covered with wax paper and heated using two separate turntable microwave ovens, one a 750W machine and a the other a 700W machine with a preset program (based on final temperature of product). Samples were tested for temperature, time of process to inactivate *S. typhimurium* and for pathogen destruction at each time interval. Results indicated that both microwave ovens allowed survival of the microorganism though survival in the higher wattage oven allowed only half the survival that the preset program oven allowed (Landgraf and Tassinari, 1997). Time and temperature values played a direct role in microwave destruction effects of *S. typhimurium.*

Because of the number of existing differences between microwave cooking and all other heating processes, it is important to note that microwaves also have their own singular method of microbial destruction. It is now generally accepted that mainly thermal effects cause the death of microorganisms in microwave heated food (Goldblith and Wang, 1967; Lund et al., 1994; Heddleson and Doores, 1994a). No conclusive evidence exists from the numerous studies on athermal effects of microwave microbial death that lead scientists to a theory that can be agreed upon (Culkin and Fung, 1975; Fung and Cunningham, 1980; Lund et al., 1994; Heddleson and Doores, 1994a). Questions arise as to whether or not all microorganisms die by thermal action because of the differences in microwave

heating compared with traditional, conventional methods (Dreyfuss and Chipley, 1980; Khalil and Villota, 1989; Coote et al., 1991). Most cells appear to die by heat alone on the outer surface and edges of a food that receives the recommended heating treatment, especially those present in foods with a significant salt content.

When a food is to be heated by microwaves or is to be designed for use in a microwave oven, several factors must be accounted for in calculation of the products' time and power setting in the microwave oven. First, the dielectric properties of the food – the amount of free water, salt, fat and protein content (Heddleson and Doores, 1994a), must be accounted for. The more of these dielectric elements present in a food, the more microwaves will be absorbed or reflected. For instance, high levels of sodium lower the dielectric constant of a food causing it to heat more quickly (Anantheswaran et al., 1993). This is also true of a component like fat (Flores, 1994). Research conducted on low fat ground beef concluded that the lower the fat content of the meat being cooked the lower the temperature attained over a fixed cooking time (Flores, 1994). Furthermore, a large amount of free water in a food, as in a vegetable like broccoli, encourages faster heating (Schiffman, 1993).

When considering the presence of fat in a microwave food, it is especially important to consider what percentage of that product is fat and how it is distributed to better understand how the food will cook (Schiffman, 1993; Heddleson and Doores, 1994a). Fat is a dielectric component of a food system, so it can both absorb heat and reflect it (Heddleson and Doores, 1994a). If this fat is

distributed evenly and the food sample is not too thick, the sample will cook faster because it will absorb the microwaves, be heated by dipolar rotation and transfer that heat to the food directly surrounding it (Schiffman, 1993; Heddleson and Doores, 1994a). However, if the food is too thick, the fat particles will heat the food directly surrounding itself but reflect other microwaves from reaching the center of the food (Schiffman, 1993). Flores illustrated this using low fat ground beef loaves (Flores, 1994). Samples with lower fat contents generally showed lower temperatures over the set microwave cooking time than did higher fat products (Flores, 1994).

Three food pathogens tend to stand out as a concern to public health in prior studies dealing with microwavable foods. *Listeria monocytogenes*, several *Salmonella* species and *E. coli* O157:H7 are becoming more and more recognized because of their prevalence as sources of causing human illness and further concern for food companies, government agencies, consumer activist groups and consumers themselves (Heddleson and Doores, 1994a).

In 1986, research was conducted to determine whether or not internal temperatures were an adequate guide for controlling death of *S. typhimurium* in microwave heated food. Whole chickens were halved and inoculated with 5×10^5 *S. typhimurium* (Fields et al., 1986). Comparison temperatures were obtained by cooking one half of the chickens in an electric, conventional oven while the other halves of each bird were separately treated in a 2450 MHz microwave oven (Fields et al., 1986). After testing, it was concluded that internal temperatures

could not be used as a satisfactory means of determining the death of pathogens in a microwave ovens because of the high survival rate of *S. typhimurium* in microwave samples as compared to conventionally prepared samples (Fields et al., 1986). Another 1994 investigation by Heddleson, Doores and Anantheswaran explored the destruction of *Salmonella* species and its relationship with container shape, post-heating holding, covering of container and the effects of product mass. Milk was used as a model system. Variations in treatment of the inoculated system included heating four microwaves of different wattage, six separate time-temperature combinations, rectangular and circular containers and covering with Styrofoam ™ (Dow Chemical Co.) caps or no covering of the sample (Anantheswaran et al., 1994). Results indicated that the turntable microwave consistently emitted a power output equal indicated that the turntable microwave consistently emitted a power output equal to or greater than the other three microwaves while the top feed model substantially reduced greater numbers of bacteria than the turntable and Capri models (Anantheswaran et al., 1994). Conclusions stated that no significant difference was recorded between containers of differing shapes and volumes, covered or uncovered. The study cited that heating to end-point temperatures was a better means to effect concordant bacterial destruction than the more familiar application of heating to a designated time (Anantheswaran et al., 1994).

An early study on *E. coli* and *Bacillus subtilis* focused on determining the effect of microwaves on the membrane transport process (Goldblith and Wang,

1967). Though microwave frequencies used in the analysis were not common to the food industry, information did result to help understand the death mechanism of microwaves on bacterial cells (Goldblith and Wang, 1967; Heddleson and Doores, 1994a). No notable effects on uptake of thymine or thymidine were recognized after microwave heating, and potassium ion leakage was noted to have increased (Heddleson and Doores, 1994a). All data led the researchers to the conclusion that all bacterial reduction was due to thermal effects of heating alone (Heddleson and Doores, 1994a).

In 1994, Flores conducted research to determine whether or not low-fat ground beef loaves inoculated with *E. coli* O157:H7 survived in a microwave oven when cooked to a predetermined time. Using ground beef samples at 4, 6, 12, and 22 percent fat, inoculated samples were heating to the suggested heating time in a 900W rotating microwave (Flores, 1994). Heating data revealed a significant linear effect of leanness on temperature of the samples (Flores, 1994). The greater the difference between the fat percentages (i.e., 4% fat and 22% fat), the greater the degree of pathogen destruction (Flores, 1994). It was also cited that the lower temperatures reached in the 4 and 10 percent fat products may have been a result of the presence of sodium in the meat, which demonstrated a blocking effect on the microwaves (Flores, 1994). Further conclusions recognized microwave heating to be a safe means of cooking as long as the food was cooked to adequate temperatures throughout the entire product (Flores, 1994).

Objectives for this research were to determine the effects of evaporative cooling variations and food fat content on pathogen survival and to ascertain the differences in heating between a vegetable and a muscle food product during microwave heating.

III. Materials and Methods

A. Source, Type and Classification of Products

Food samples included fresh broccoli spears, frozen ready-to-eat 19% fat (regular variety) and nonfat chicken nuggets with reheating instructions, and ground beef with fat levels at 30%, 15% and 7%. Foods were obtained from a local grocery store and stored refrigerated or frozen as directed at the Virginia Tech Food Science and Technology Department. The fat content of the breaded, formed chicken patties and all ground beef samples were tested using a Foss-let fat analyzer. All samples were tested in triplicate for the maximum suggested reheating time.

B. Heating curves

One surface and three internal fluoroptic temperature probes were used to measure the internal and surface temperatures of the products once inside the microwave oven. The oven used was a Sharp® 1,000Watts - Light Duty Commercial Microwave Oven, Model R-21HT. Cavity dimensions of this machine were 13 7/8" (W) by 14 5/8" (D) by 8 1/8 " (H). Listed output power was 1,000W and oven frequency was 2450MHz. An 8mm hole was drilled in the top of the microwave so the fluoroptic probes could be inserted into the

microwave cavity. Temperature probes were monitored by a Luxtron Model 755 Fluoroptic™ Thermometer that recorded internal food temperatures at four individual points every 20 seconds. Probes were inserted into food samples at the center, each end of the food slab and at the surface. The data obtained from these tests was collected by an WIN 386 PC then converted from simple temperatures to F values using an F value program written within the Virginia Tech Food Science and Technology Department based on the F value method of Stumbo. F values were then used to compare differences in food heating patterns in the cooking cycle and during the holding time.

C. Inoculated Pack Studies

1. Inoculum Preparation

a. Listeria monocytogenes

A suspension of four strains of Listeria monocytogenes was prepared by individually enumerating each of the strains on tryptic soy agar (TSA) slants. The four strains used were Scott A serotype 4b, V7 serotype 1, LCDC and D43. Strain Scott A serotype 4b was received from Dr. R.E. Brackett at the University of Georgia. It was an isolate from a 1985 pasteurized milk outbreak in Massachusetts. The strain LCDC was acquired from the Centers for Disease Control and was isolated from the Mexican-style cheese outbreak in California in 1985. Strain V7 serotype 1 was obtained from and strain D43 were obtained from the Virginia Tech Food Science and Technology Culture Collection. Each strain was grown individually for 48 hours at 30^{o}C. Inoculum was serially prepared by

covering the TSA slant with a Phosphate Buffered Saline (PBS) solution and gently scraping with a sterile, glass rod. Each PBS solution with its respective strain was then transferred into a common test tube and thoroughly mixed to give a homogenous solution of L. monocytogenes of approximately 10^7 CFU/ml.

b. *Salmonella* species

Five *Salmonella* cultures were obtained from the University of Nebraska-Lincoln Department of Food Science. All the strains were from the National Veterinary Services Lab (NVSL) in Ames, Iowa and had been isolated from chickens. Species included *Salmonella enteriditis* PHAGE 13 (15855-96 NVSL), *Salmonella blockley* (3698-95 NVSL), *Salmonella typhimurium* (6904-96 NVSL), *Salmonella oranienburg* (12608-96 NVSL) and *Salmonella heidelberg* (3347-1 Sheldon). Each strain was grown on TSA slants overnight at 35°C. Inoculum was then prepared as previously stated for *L. monocytogenes*.

c. *Escherichia coli* O157:H7

Five *E. coli* O157:H7 strains were obtained from the University of Nebraska-Lincoln Department of Food Science. Strains included human isolate N4042/932 (Doyle), 1982 (CDC/FSIS/USDA), beef isolates MF1847 (FSIS/USDA) and N4044/933 (Doyle), and the acid resistant strain H933 (Doyle). All strains were grown on separate TSA slants overnight at 35°C. Inoculum was then prepared as previously stated for *L. monocytogenes*.

2. Study Design

For inoculated pack studies, each of the six foods were tested in triplicate at their maximum suggested heating times either covered with a Saran™ plastic wrap or left without covering. The inoculum level was 1 x 10^7 cells per sample. This number represented a worst case scenario number of pathogens per product. If suggested heating times were correct, all pathogens should have been eliminated from the food samples.

3. Inoculation of Product

Each inoculum was individually plated to verify pathogen counts. Using standard enumeration methods, *L. monocytogenes* was grown on modified oxford (MOX) agar plates, *Salmonella* species were grown on Bismuth Sulfite (BS) agar and Xylose Lysine Deoxycolate (XLD) agar plates, and *E. coli* O157:H7 was grown on Sorbitol MacConkey (SMAC) agar plates. Dilutions were prepared to impart a 0.1 ml inoculum containing 1 x 10^7 cells. Each broccoli and breaded, formed chicken patty sample was inoculated drop wise with a separate, sterile 0.1 ml syringe at random locations on all sides of the product surface. For each ground beef sample, 0.1 ml of inoculum was added to the sample and massaged into the ground meat, which was contained in a Zip-Loc® Freezer Bag. Each ground beef sample was inoculated and prepared separately, to ensure inoculum numbers per sample. All inoculated samples were allowed to sit for 1 hour at 0°C (frozen foods) or 4°C (refrigerated foods) to allow inoculum time to soak into the samples (Landgraf and Tassinari, 1997). The four temperature probes were then inserted

into each sample in the center, on each slab end and on the surface. Samples were then heated to their suggested reheating times and subjected to a hold time before opening the microwave oven. Temperatures were recorded on the adjacent computer from beginning of heating until the end of the hold period.

4. Pathogen recovery

a. *Listeria monocytogenes*

Post heating, the food sample was aseptically weighed then added to a Stomacher™ bag with the proper amount of Modified Listeria broth (Fisher Scientific, Pittsburgh, PA) to result in a 1:10 dilution and mixed for 2 minutes. The bag was then securely folded, taped and incubated at 30°C for 22 ± 2 hours. A positive, unheated and uninoculated control was tested with each set of samples. For secondary enrichment, 0.1 ml of the Modified Listeria broth enrichment culture was added to a tube (10 ml) of Fraser broth (Fisher Scientific, Pittsburgh, PA) and incubated at 35°C for 27 ± 1 hours. All Fraser broth enrichment cultures were streaked onto modified Oxford (MOX) agar (Fisher Scientific, Pittsburgh, PA) plates and incubated at 35°C for 24 and 48 hours. After 24 hours of incubation, plates were inspected for black, 1 – 2 mm round colonies surrounded by zones of esculin hydrolysis. If no colonies matching this description were detected, a second plate was streaked from the 48 hour Fraser broth enrichment sample onto MOX agar and incubated for another 24 hours at 35°C (USDA/FSIS Microbiology Lab. Guidebook, 3rd edition, 1998).

b. *Salmonella* species

Post heating, the corresponding food sample was aseptically weighed and transferred into a sterile Stomacher™ bag with the proper amount of Lactose enrichment broth (Fisher Scientific, Pittsburgh, PA) to result in a 1:10 dilution. Sample was mixed for 2 minutes and incubated at 35 ±1°C for 20 – 24 hours. A positive, unheated and uninoculated control was tested with each set of samples. Following incubation, 0.5 ml of broth was added to 10 ml Tetrathionate (TT) broth (Fisher Scientific, Pittsburgh, PA) and incubated at 35 ±1°C for 20 – 24 hours. Next, 1 ml of the TT broth was added into 10 ml Rappaport-Vassiliadis (RV) broth (Fisher Scientific, Pittsburgh, PA). The RV broth was then incubated at 42 ±0.5°C for 22 – 24 hours. After incubation, the RV broth was streaked onto Bismuth Sulfite (BS) agar (Fisher Scientific, Pittsburgh, PA) and Xylose Lysine Deoxycolate (XLD) agar (Fisher Scientific, Pittsburgh, PA) plates. Plates were then incubated at 35±1°C for 22 – 24 hours. Plates with no growth were incubated for an extra day (USDA/FSIS Microbiology Lab. Guidebook, 3rd edition, 1998).

3. *E. coli* O157: H7

Post heating, the respective food sample was placed into a sterile Stomacher™ bag with the proper amount of modified E. coli plus novobiocin (mEC+n) broth (Fisher Scientific, Pittsburgh, PA) to result in a 1:10 dilution. The sample was blended for 2 min. and incubated at 35± 2 °C for 20 – 24 hours. A positive, negative and uninoculated medium control was included for each set of samples tested at one time. From the enrichment cultures, a Biocontrol® brand

visual immunoprecipitate (V.I.P.) assay test for *E. coli* O157:H7 (Biocontrol, Bellevue, WA) was inoculated following the manufacturer's directions. Positive samples were reported as potential positives. Isolation and confirmation were initiated from the enrichment cultures on Sorbitol MacConkey (Fisher Scientific, Pittsburgh, PA) agar.

D. Pathogen survival curve determination

F value determination involved employing the temperature information from the Luxtron® in conjunction with a program that would convert those temperatures into F-values. This DOS-based program required the entry of a reference temperature, a Z-value for each microorganism, the number of probes used and the name of the PRN file recorded through the Luxtron® onto the computer. Based on the F-value formula method of Stumbo, $F = T - T_{ref} / Z$ (Stumbo, 1973), the program showed the approximate F value at each temperature point throughout the heat and hold process (Carter, 1994). Z-value data were set at 6.8 for *L. monocytogenes*, 7.7 for *S. enteriditis* and at 5.8 for *E. coli* O157: H7 (Carter, 1994; Jay, 1996).

VI. Results and Discussion

A. Survival of *Listeria monocytogenes*

Of the three food borne pathogens examined, *Listeria monocytogenes* demonstrated the greatest overall survival rates followed by *Escherichia coli* O157:H7. Because *L. monocytogenes* is a highly thermotolerant microorganism, this result was not surprising. It was eliminated only from the covered 19% fat

chicken patties, the uncovered nonfat chicken patties and all samples of the 30% fat ground beef. Because of the higher fat content, it was expected that *L. monocytogenes* in the 19% fat chicken patties and 30% fat ground beef would be destroyed. Further, the covering was expected to increase the chance of *L. monocytogenes* destruction. This was true for the covered, 19% fat chicken patties. However, destruction was not expected to be consistent in the uncovered nonfat chicken patties as results showed.

$F_{100}^{7.7}$ values in the *L. monocytogenes* testing category varied widely among each sample type. In all samples tested, computer data indicated that $F_{100}^{7.7}$ values were generally lowest on the surface and in the center of each product and were consistently highest on the outer edges. Final $F_{100}^{7.7}$ values in broccoli ranged from 0.01 to 105.10 on Probe 4 (right of center) alone showing that readings were seldom consistent in each heating region even with protocols in place to reduce heating variation (Figure 1). This may have been due to power fluctuation, probe location, varying dielectric properties in each food tested, sample placement within the microwave cavity or probe error.

Survival occurred in all broccoli samples after heating to recommended times and allowing each sample a two-minute hold time (Appendix E). The hold time was enacted to allow each sample time for temperature equilibration, which was expected to decrease pathogen survival rates in all samples. Temperature data showed that the coolest points on the samples did not reach 70°C for at least two minutes or *L. monocytogenes* would have been eliminated, or for high $F_{100}^{7.7}$

values, uneven heating resulted in cold spots that could not be brought to an adequate time and temperature for pathogen destruction (Cole et al., 1994).

$F_{100}^{7.7}$ values in both 19% fat and nonfat chicken patties varied greatly as well (Figures 2 and 3). Destruction occurred in both covered 19% fat chicken patties and uncovered nonfat chicken patties. Greater *L. monocytogenes* destruction rates probably occurred in these samples as compared to broccoli due to the protein, salt and other dielectric constituents of each food. These compounds aid the microwaves in heating the food faster, especially in the case of the 19% fat chicken patties. The fat in this product helps depress the food's dielectric constant allowing the food to heat faster (Anantheswaran et al., 1993). Additionally, all patties were of a uniform size and shape due to their factory-processed origin, whereas fresh broccoli spears have natural variation in shape. *Listeria monocytogenes* destruction results varied as much as the $F_{100}^{7.7}$ values for breaded, formed chicken patty samples (Figures 2 and 3). As illustrated in Appendix E, the majority of covered, 19% fat chicken patty samples showed complete *L. monocytogenes* destruction as did the majority of uncovered nonfat chicken patties. The first results were expected. However, uncovered, nonfat chicken patties were expected to have the highest survival rates instead of the majority samples resulting in complete destruction.

All ground beef showed consistent survival of *L. monocytogenes*, except 30% fat ground beef samples both covered and uncovered (Appendix E, Figure 4, Figure 5). Little difference in destruction occurred in the 7% and 15% fat ground

beef samples, though $F_{100}^{7.7}$ values tended to be slightly higher for the 15% fat ground beef. This was probably because of the depression of the dielectric constant by the higher amount of fat.

For all food types tested, there was no significant difference in *L. monocytogenes* destruction rates for covered samples in comparison to uncovered samples, though $F_{100}^{7.7}$ values did tend to be somewhat higher in covered samples.

B. Survival of *Salmonella* species

Salmonella species showed the lowest survival rates after microwave cooking. *Salmonella* species were killed in all 30% fat ground beef samples, all 7% fat ground beef samples, covered 15% fat ground beef, and in all covered breaded, formed chicken patty samples (Appendix E).

Survival occurred in all but one broccoli sample, covered and uncovered. This survival may have been caused by several factors. Early research by Baldwin et al. (1971) concluded that uneven wave distribution within the microwave cavity caused inconsistant internal temperatures thus increasing the survival of *Salmonella spp*. (Baldwin et al., 1971). Studies by Chen et al. (1973) and Baker et al. (1983) concluded that differing combinations of higher temperatures and extended cooking times would help in reducing the survival of *Salmonella* species after conducting separate microwave heating trials of poultry products (Chen et al. 1973; Baker et al., 1983).

Again, $F_{100}^{6.8}$ values in broccoli samples were broad ranging from a low of 0.00 to a high 58.41 (Figure 6). The one sample that showed complete destruction

had lower $F_{100}^{6.8}$ values than other samples that showed survival of *Salmonella* species. Therefore, it is difficult to draw any conclusive results as to whether higher $F_{100}^{6.8}$ values ensure pathogen destruction in the microwave oven heating atmosphere. This further supports results of Langraf and Tassinari's 1993 study showing that that highest number of positive food samples for *Salmonella* also achieved the highest temperatures during microwave heating (Landgraf and Tassinari, 1997).

All breaded, formed chicken patty results demonstrated expected results for *Salmonella* species. All covered samples demonstrated complete pathogen destruction, though there was no difference in the 19% fat and nonfat sample survival rates (Appendix E, Figures 7 and 8). This may have been due to added salts and preservatives in the nonfat breaded, formed chicken patty that were able to compensate for any dielectric properties that were absent as a result of no fat in the food system. Additionally, manufactured samples had the additional advantage of uniform shape and dimension that hand-prepared broccoli and ground beef samples did not. It is also possible that the additional hold times were of importance in the high amount of destruction illustrated here. A 1994 study by Heddleson and Doores concluded that an additional holding period after heating food in a microwave oven was necessary in helping to reduce large temperature gradients that develop in foods with high ionic salt contents (Heddleson and Doores, 1994b). Because chicken patties are processed and packaged, their ionic salt contents are higher than unprocessed foods. This may

help explain the huge $F_{100}^{6.8}$ values in chicken patties as well as explain some of the pathogen destruction in all microwave-heated foods.

Ground beef samples showed consistent destruction of *Salmonella* species with the exception of uncovered, 15% fat ground beef samples (Appendix E, Figures 9 and 10). However, with more repetitions of the 15% fat ground beef samples, it is possible that this group would also give a majority of samples with *Salmonella* destruction. Additionally, of the samples tested, it was expected that the 7% fat ground beef would show survival rather than the higher fat samples. More testing would allow the discovery of the level of fat required to increase and/or ensure pathogen survival in microwave-prepared ground beef. Again, pathogen survival did not seem to be significantly affected by covering the sample.

C. Survival of *Escherichia coli* O157:H7

Escherichia coli O157:H7 was only consistently destroyed in 30% ground beef samples and uncovered 7% fat ground beef samples (Appendix D, Figures 12 and 13). The 30% fat samples were expected to show this high level of pathogen destruction based on results of a 1994 study by Flores. Injection of raw ground beef meat loaves with *E. coli* O157:H7 revealed that samples with the lower amount of fat had the greatest amount of pathogen survival (Flores, 1994). Further, $F_{100}^{5.8}$ values increased as fat content of the ground beef increased (Flores, 1994). However, the lowest pathogen destruction in ground beef would have been expected for the uncovered, 7% fat ground beef. It is difficult to say why

this destruction may have occurred, especially as compared to the covered 7% fat ground beef and all 15% ground beef. Also, $F_{100}^{5.8}$ values in the 15% fat ground beef patties were higher than the 7% fat samples (Figure12, Figure 13) so less survival would be expected in the 15% fat ground beef samples. Fluctuations in the microwaves heating output or varied homogeneity of the samples could be possible reasons for some of the difference in pathogen survival (Schiffman, 1993; Heddleson and Doores, 1994a).

Escherichia coli O157:H7 survived well in broccoli samples. The intricate nature of the broccoli head probably allowed the pathogen to survive despite its heat treatment. $F_{100}^{5.8}$ values were much lower for broccoli spears than those for all meat samples. This in itself indicates that the same heat is not being generated in the vegetable material as in the meat; therefore, higher pathogen survival would be expected. Because of the very different natures of muscle food and vegetative material composition, higher time and temperature allowances would once again most likely help ensure a greater amount of pathogen destruction in vegetables.

D. Comparison of High Fat/Low Fat Survival Rates

Survival rates were consistently lower in ground beef samples with a 30% fat content (Appendix D, E, F). These findings were consistent with those of a 1994 study by Flores of *Escherichia coli* O157:H7 in ground beef loaves (Flores, 1994). There was a statistically significant ($P<0.05$) rise in temperature within higher fat meat loaves and at least a 10% change on fat content was required to raise or lower temperatures on the meat (Flores, 1994). Outcomes of this research

agreed with such results in that little difference was obvious between survival rates for 7% fat and 15% fat ground beef indicating that a jump in fat content of greater than 10% may be required to show a difference in pathogen survival rates. F values were usually higher in 30% fat ground beef samples as well, though there were a few exceptions where 15% fat ground beef sample gave higher cumulative F values (Figures 4, 5, 9, 10, 12 and 13). These exceptions may have occurred due to power fluctuation, probe location, varying dielectric properties in each food tested, sample placement within the microwave cavity or probe error.

Chicken patty samples showed no significant difference in pathogen survival due to differing fat contents. The 19% fat patties showed as much fluctuation in survival and F values as did the nonfat patties. Because these were processed samples produced at a factory, uniform shape and specific microwave formulations to account for differences in dielectric constants probably helped to deter great fluctuations in heating and survival rates in these samples. For instance, a higher salt, moisture or solids content level in the nonfat chicken patties could have helped account for the missing fat in the product (Anantheswaran et al., 1993). These are recognized as some of the most temperature enhancing constituents of food heated in a microwave oven because of their affect on the dielectric properties of food (Anantheswaran et al., 1993).

E. Comparison of Covered/Uncovered Survival Rates

Covered samples showed no appreciable increase in pathogen destruction than uncovered foods. A 1994 examination by Carter of *L. monocytogenes* in

chicken products showed some evidence that wrapping products could help reduce the effect of the evaporative cooling phenomenon allowing less pathogen survival (Carter, 1994). Conversely, results of this study showed that only in the *Salmonella* samples did there seem to be any pattern of covering in increasing pathogen destruction (Figures 6, 7, 8, 9 and 10). This may have been due to coincidence because it was the only organism that showed consistent pathogen destruction in covered samples. However, wrapping products did raise F values and surface temperatures in broccoli and all ground beef samples. Thus, wrapping a product as opposed to leaving it uncovered may increase chances of pathogen destruction. Further testing would be required to determine the exact impacts of covering a sample while heating in a microwave ovens and whether or not the action encourages pathogen destruction.

F. Implications Against Evaporative Cooling

Evaporative cooling effects were tested by weighing the sample before and after heating as well as covering with Saran™ Wrap to attempt to create a jacket of steam around the respective food samples to reduce any effects surface cooling might impart. It is suspected that surface cooling allows cooler temperature on the surface of a food than in its center, therefore allowing pathogens on the food surface to survive. Additionally, thermal pictures of each food were utilized in identifying surface heating differences between covered and uncovered samples.

Samples of each of the six foods were prepared as for typical microwave heating. Each food was treated in each of four variations: covered with a hold

time, uncovered with a hold time, covered without a hold time and uncovered without a hold time. As expected, the highest, most evenly distributed temperatures resulted from samples that were covered and allowed a hold time after heating. Chicken patties, both 19% fat and nonfat, showed the highest recorded temperatures when covered and allowed a hold time or immediately removed from the microwave cavity and photographed. The only breaded, formed chicken patty exceptions were those that were left uncovered and given a hold time. Thermal photography revealed much lower temperatures for these two samples, although the 19% fat sample did indicate warmer temperatures overall. This was most likely due to an insulating effect caused by the fat present in this sample.

Ground beef samples showed highest surface temperatures in the 30% fat samples covered and immediately photographed after heating. Uncovered samples of the same type had peak surface temperatures approximately 63^{o}C. The second highest ground beef temperatures resulted from the 30% fat covered sample given a hold time. Temperatures were more uniform in this sample than the one given no hold time with the greater part of the surface registering temperatures of at least 64^{o}C after a five minute hold time. Uncovered, the highest temperatures on the surface of the 30% fat sample were only about 56^{o}C after a five-minute hold time. This obvious surface temperature difference indicates that covering food heated in microwave ovens would decrease chances of pathogen survival all other factors being equal.

Covering only seemed to affect broccoli surface temperature if a holding time was instated. After a two-minute hold time, covered broccoli samples showed surface temperatures as high as 67.5°C while uncovered samples displayed peak temperatures of 60°C. Broccoli samples immediately photographed after heating showed less temperature difference recording 65°C for covered sample and 62°C for uncovered. Once again, this shows how covering food during microwave heating does tend to raise surface temperature by some method.

Cook loss differences were generally lower for covered samples than uncovered samples, though it seemed to have no effect on pathogen destruction (Figures 14, 15, 16). Reducing cooking loss may be important in the view that holding more moisture in the food will keep free water in the food system, allowing the food to heat more efficiently due to the dielectric nature of water (Schiffman, 1993).

V. Conclusions

Results of this study indicate that higher fat content does improve the heating characteristics of foods heated in microwave ovens. This is probably by means of depression of the dielectric constant with the higher fat content and insulation of the food from heat loss once heated. Further, when, fat is taken out of a food it can be compensated for by adding other dielectrically active constituents to the system such as salts, proteins and more free water.

Vegetable material does not appear to heat as efficiently or reach the high F values of meats prepared in microwave. Because of this, extra precaution needs to be taken when heating vegetables in the microwave. Covering the food to ensure higher surface temperature, allowing the food at least a two minute hold time to allow for internal temperature equilibration and increasing the recommended heating time would all help ensure vegetables are safe from pathogens after being treated in the microwave. Further studies need to be performed to determine the correct time in different wattage microwave ovens required ensuring complete pathogen destruction.

Finally, evaporative cooling does have an effect on F values achieved during microwave cooking though survival rates do not appear to be as effected. Covering foods helps to keep the generated heat close to the food surface, thus generating higher F values. Further work is recommended to ascertain the exact effects of evaporative cooling on pathogen survival.

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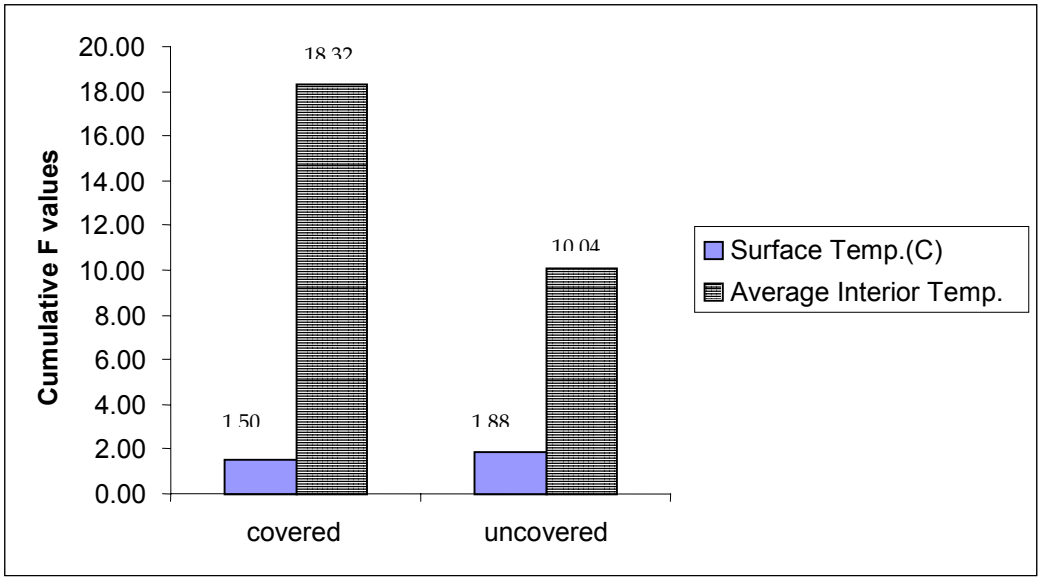

Figure 1. Cumulative *L. monocytogenes* Broccoli Covered vs. Uncovered Final $F_{100}^{7.7}$ values

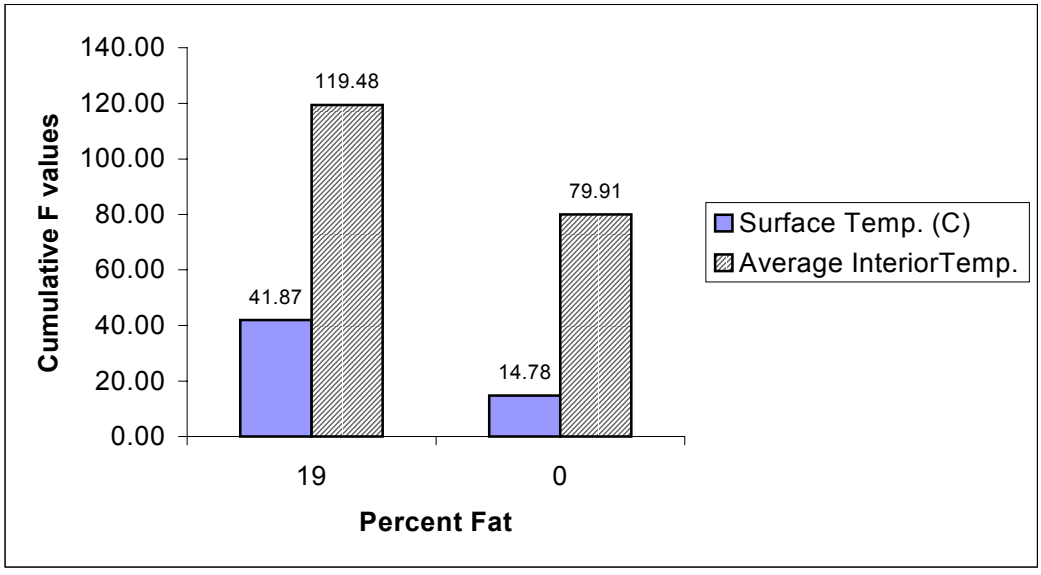

Figure 2. Cumulative *L. monocytogenes* Chicken Patty Covered Final $F_{100}^{7.7}$ values

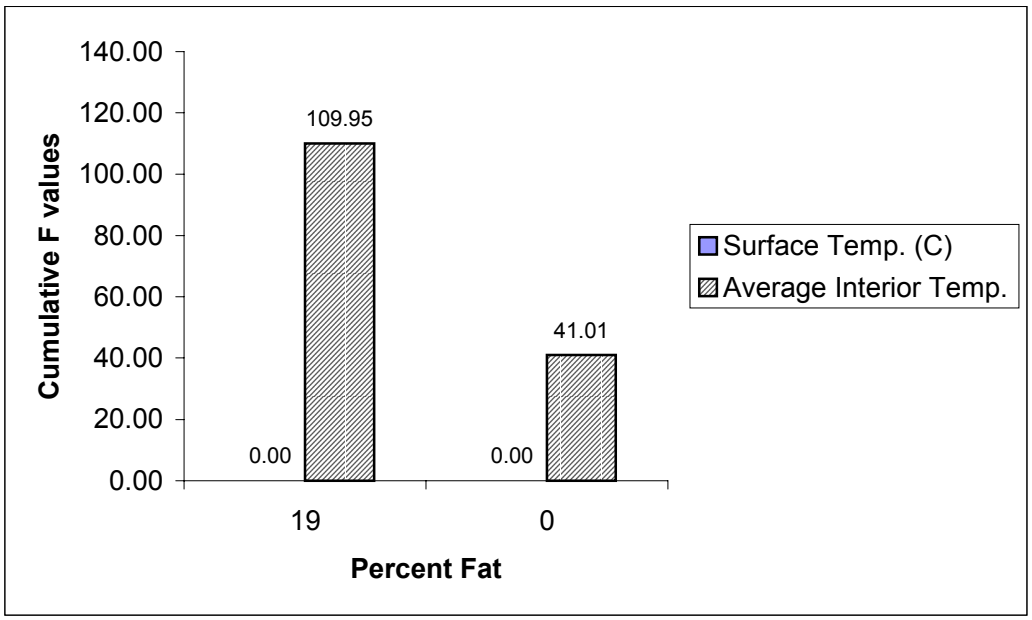

Figure 3. Cumulative *L. monocytogenes* Chicken Patties Uncovered Final $F_{100}^{7.7}$ values

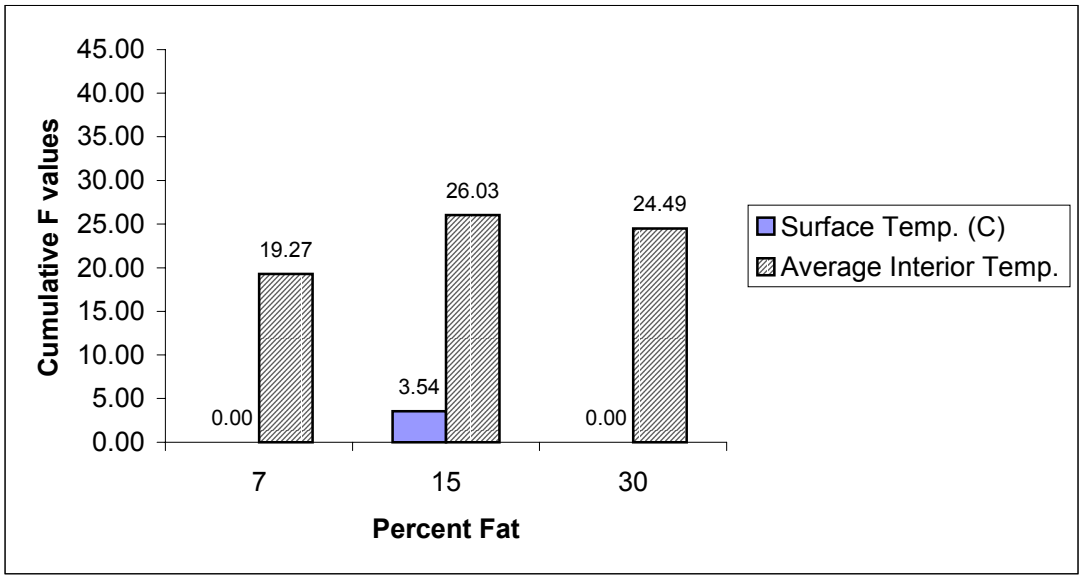

Figure 4. Cumulative *L. monocytogenes* Ground Beef Covered Final $F_{100}^{7.7}$ values

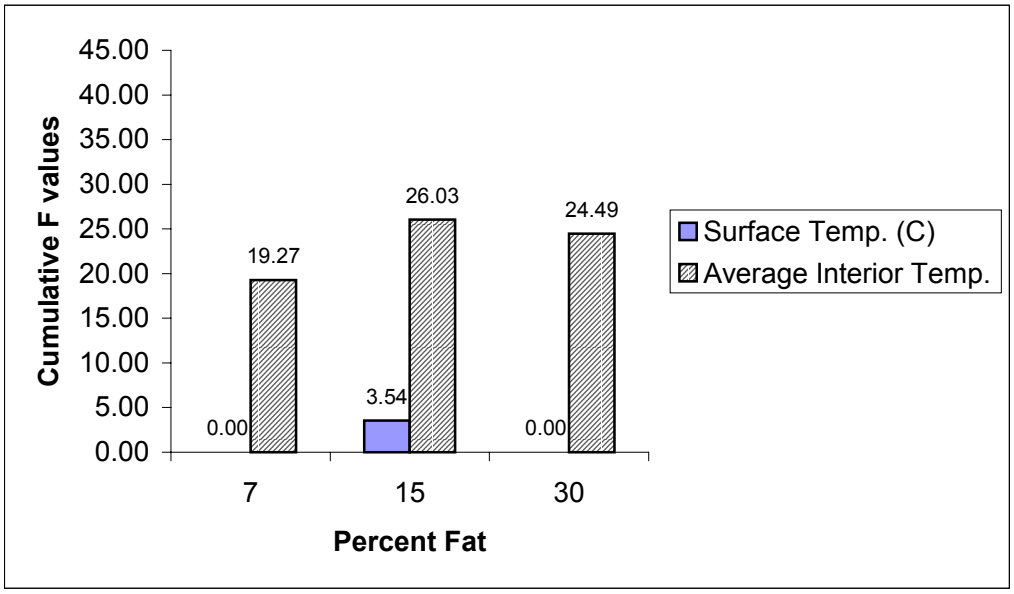

Figure 5. Cumulative *L. monocytogenes* Ground Beef Uncovered Final $F_{100}^{7.7}$ values

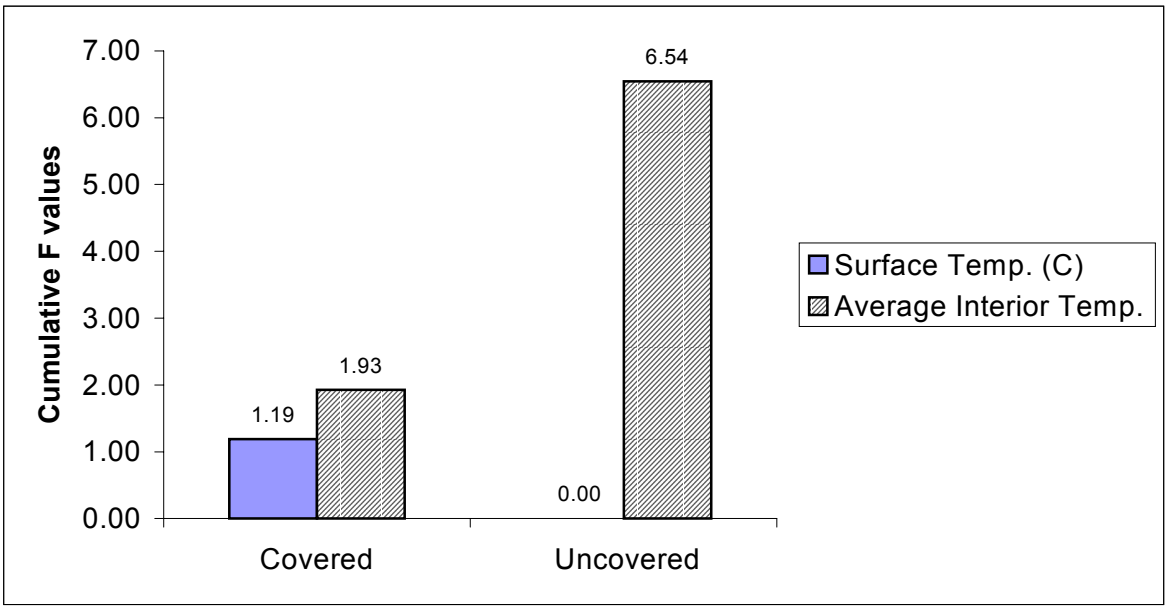

Figure 6.Cumulative *Salmonella* spp. Broccoli Covered vs. Uncovered Final $F_{100}^{6.8}$ values

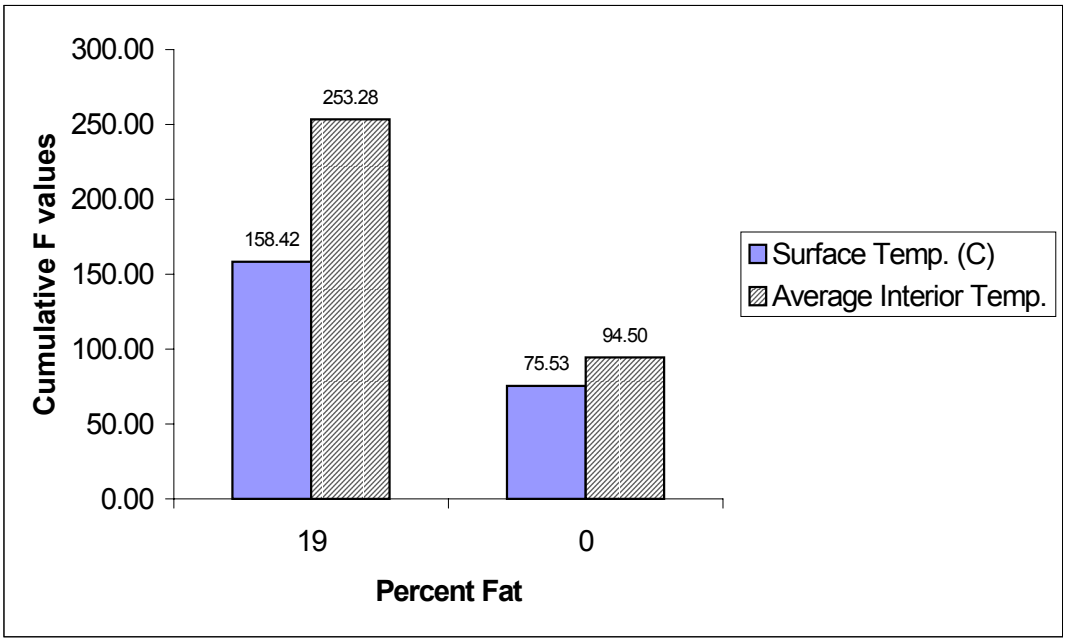

Figure 7.Cumulative *Salmonella* spp. Chicken Patties Covered $F_{100}^{6.8}$ values

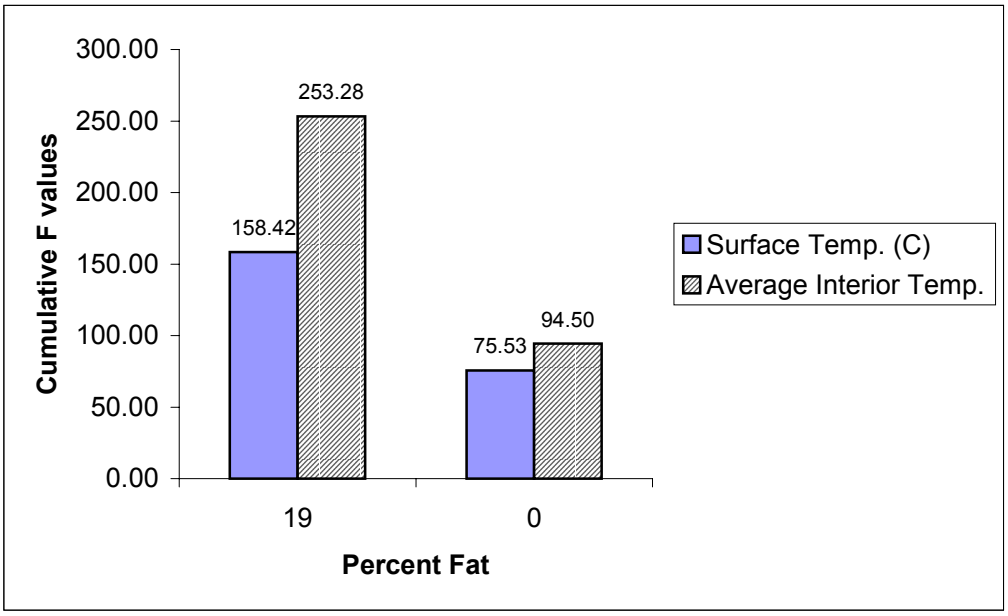

Figure 8. Cumulative *Salmonella* spp. Chicken Patties Uncovered Final $F_{100}^{6.8}$ values

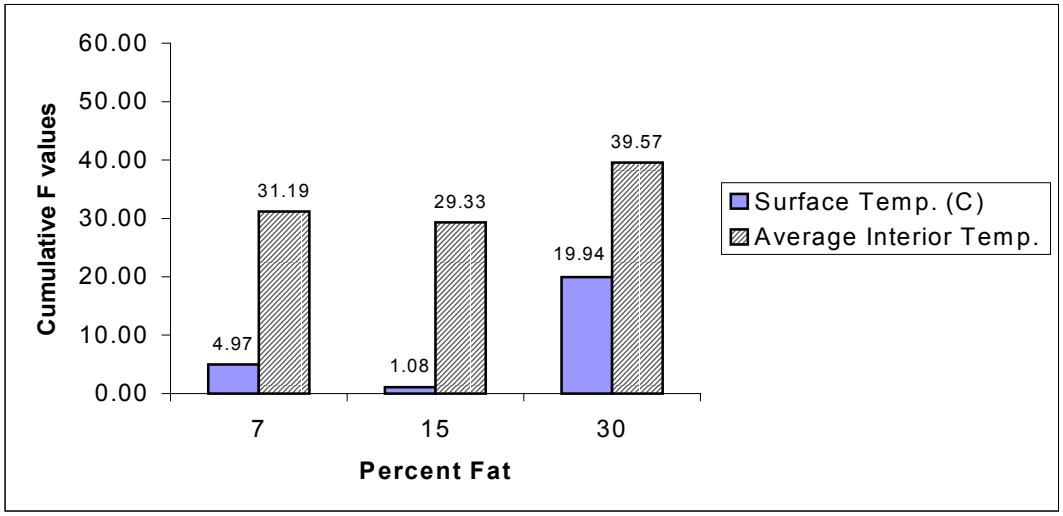

Figure 9. Cumulative *Salmonella* spp. Ground Beef Covered Final $F_{100}^{6.8}$ values

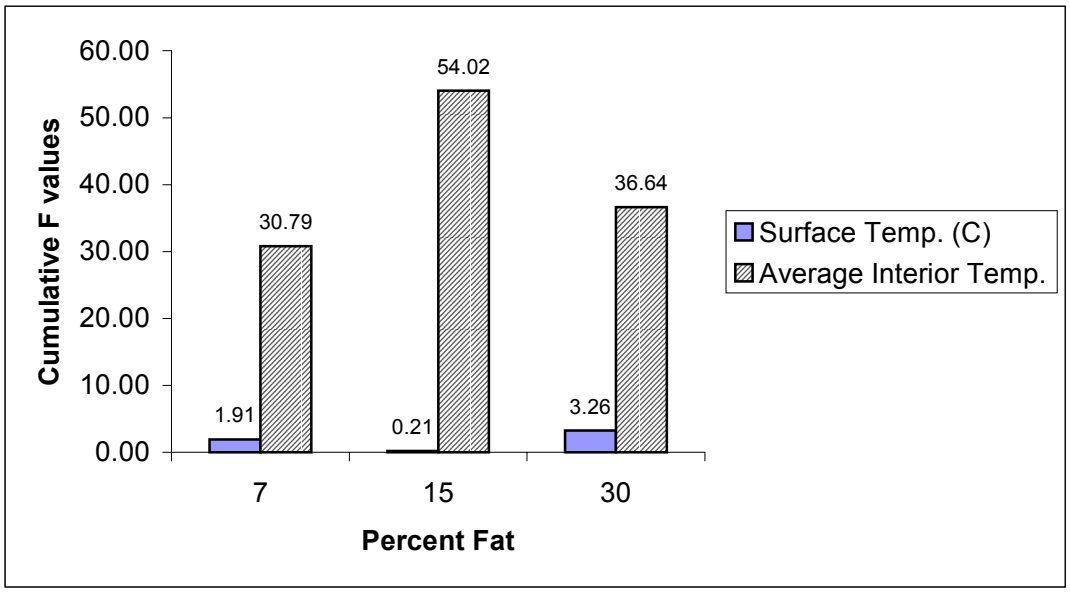

Figure 10. Cumulative *Salmonella* spp. Ground Uncovered Beef Final $F_{100}^{6.8}$ values

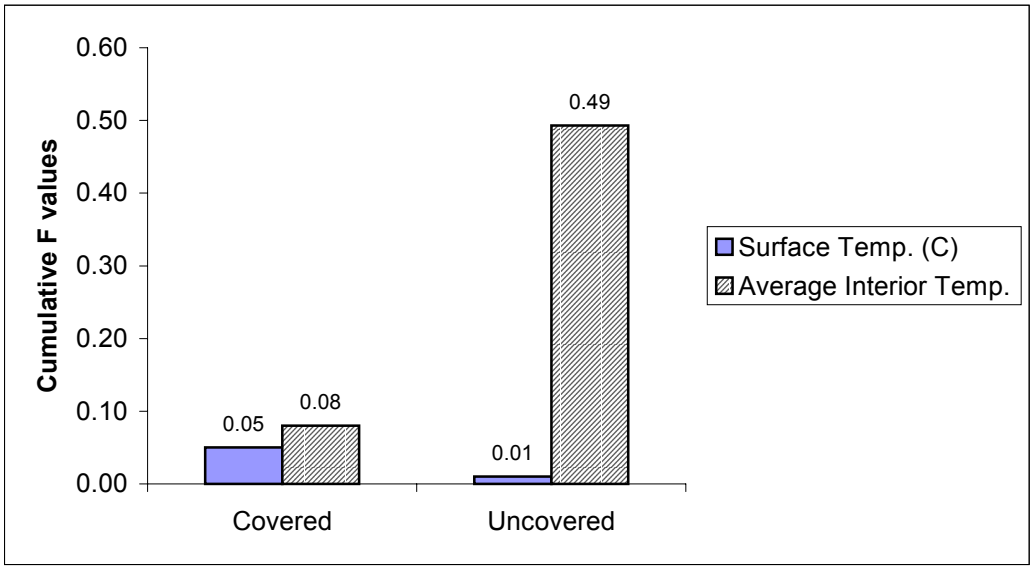

Figure 11. Cumulative *E coli O157:H7* Broccoli Covered vs. Uncovered Final $F_{100}^{5.8}$ values

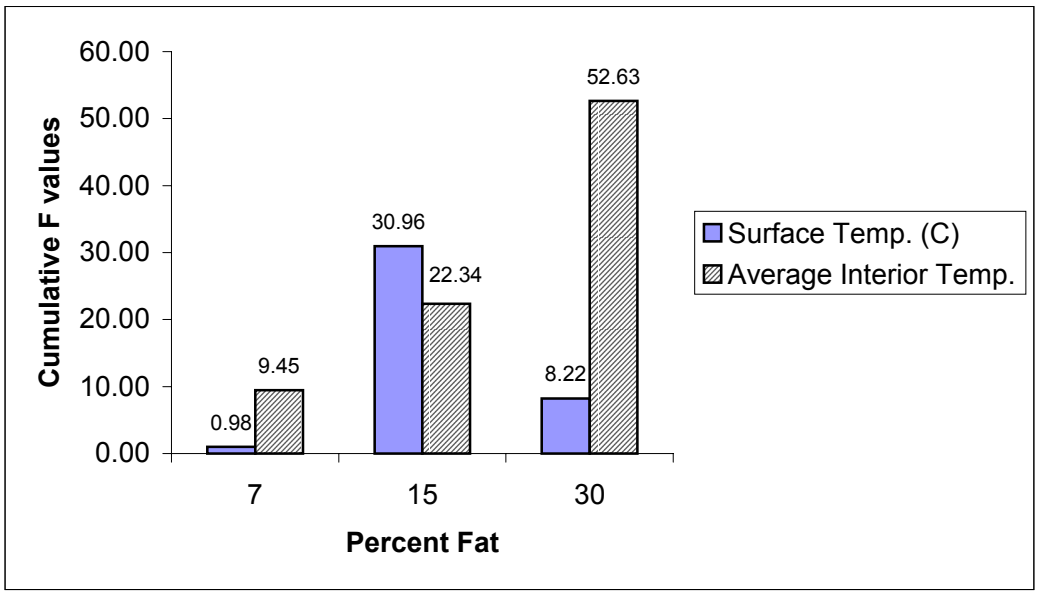

Figure 12. Cumulative *E coli* O157:H7 Ground Beef Covered Final $F_{100}^{5.8}$ values

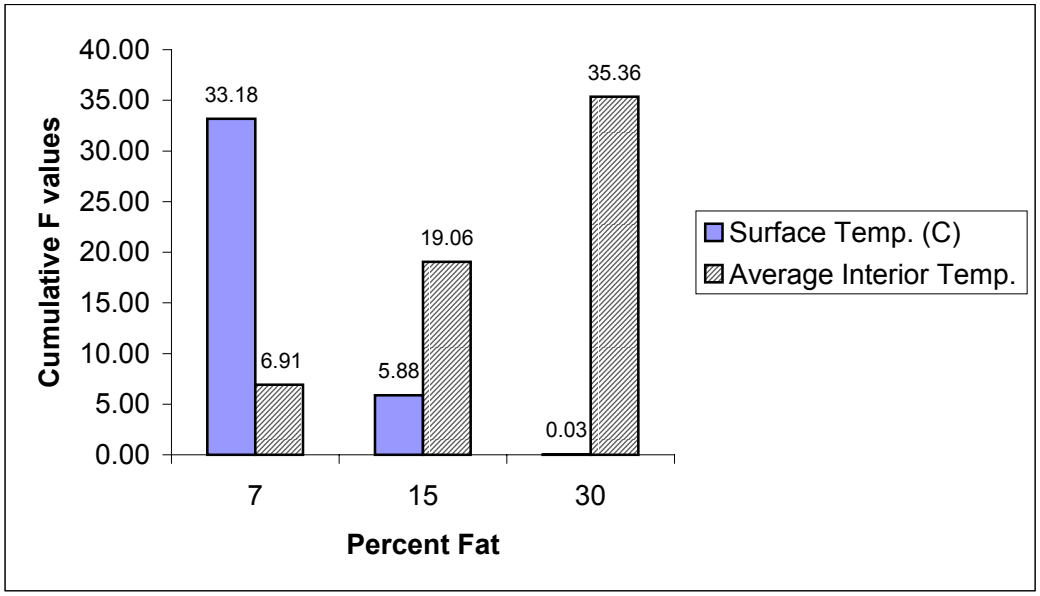

Figure 13. Cumulative *E coli* O157:H7 Ground Beef Uncovered Final $F_{100}^{5.8}$ values

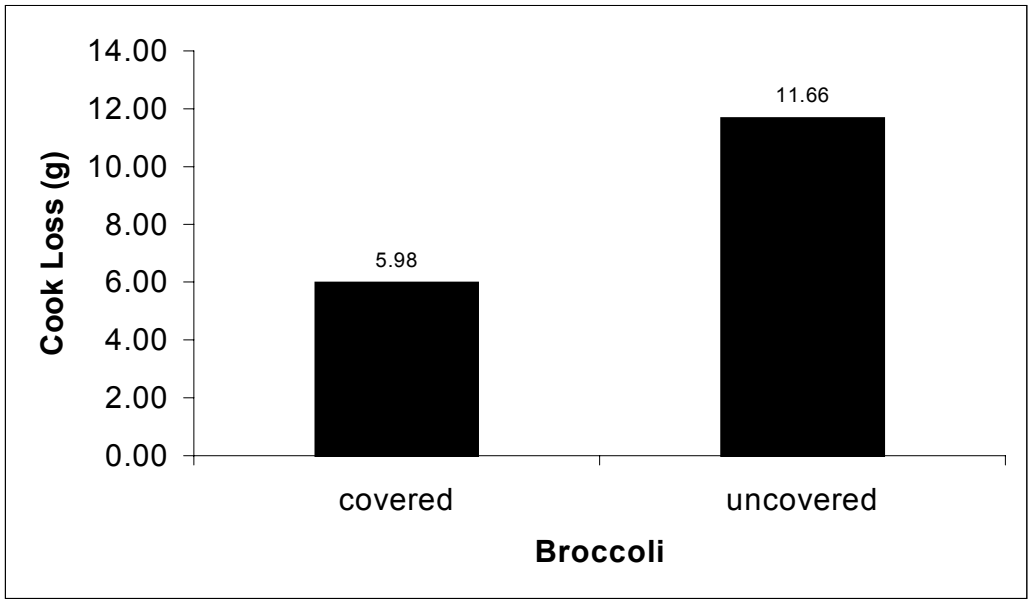

Figure 14. Cumulative Broccoli Covered vs. Uncovered Cook Loss Differences

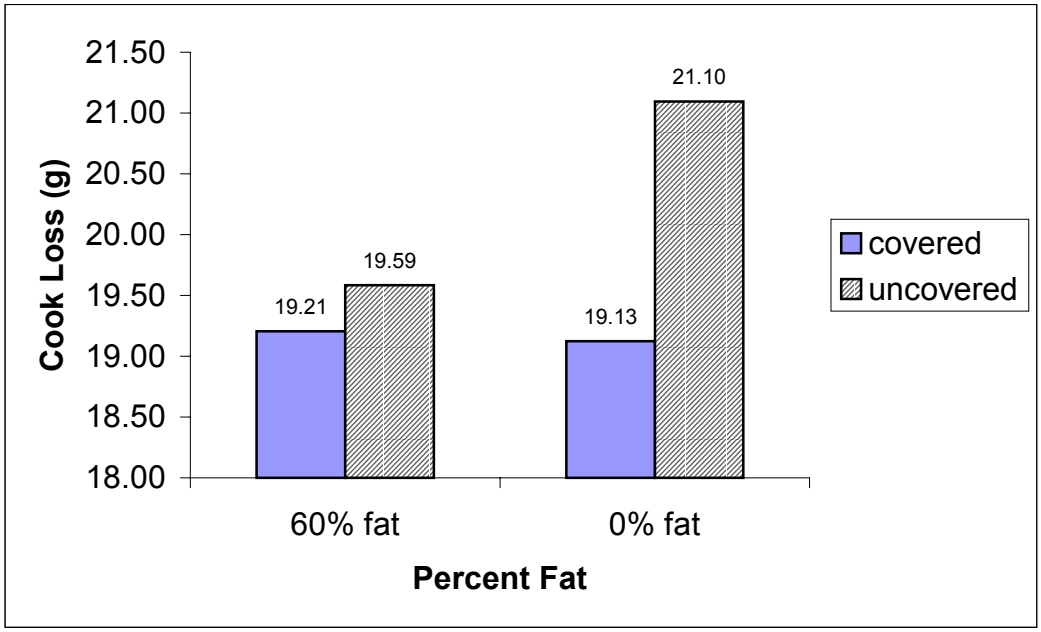

Figure 15. Cumulative Chicken Patty Cook Loss Differences

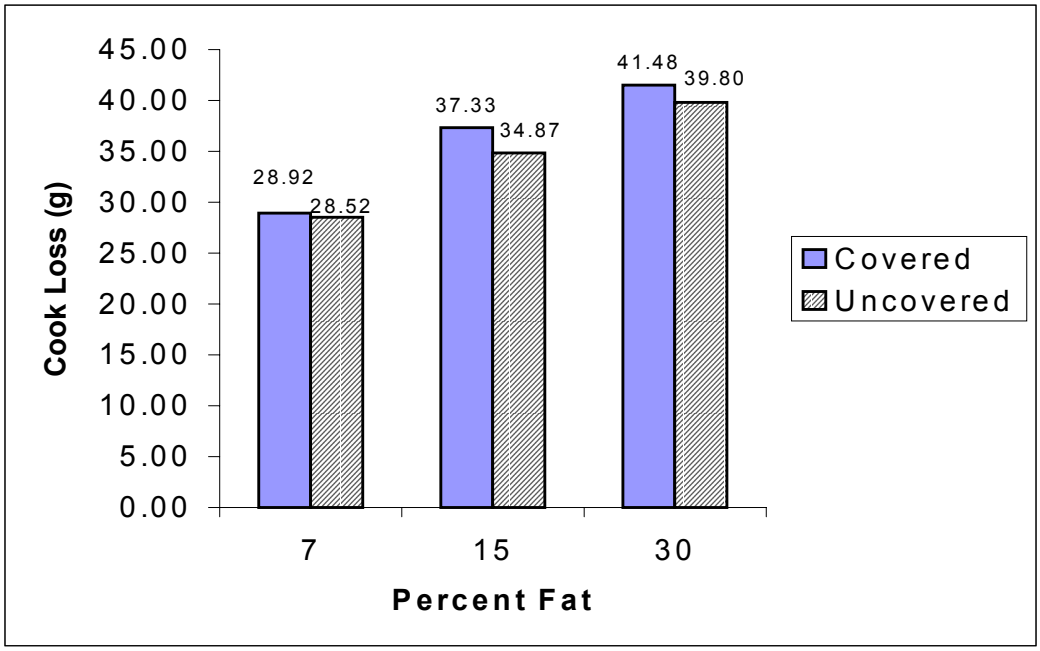

Figure 16. Cumulative Ground Beef Cook Loss Differences

Appendix A:
Weight Loss – *Escherichia coli* O157:H7

Food Type	*Cooking Time (sec)*	*Cover / Uncovered*	*Cooking Time (sec)*	*Hold Time (sec)*	*Pre Cook Weight (g)*	*Post Cook Weight (g)*	*Average Post Cook Weight (g)*	*Average Cook Loss*	*Percent Weight Loss*
Broccoli	40	Covered	40	180	100.8	94.95			
Broccoli	40	Covered	40	180	100.8	96.92	96.90	4.71	4.7%
Broccoli	40	Covered	40	180	100.8	96.91			
Broccoli	40	Uncovered	40	180	100.8	88.24			
Broccoli	40	Uncovered	40	180	100.8	91.66	91.35	9.45	9.4%
Broccoli	40	Uncovered	40	180	100.8	94.16			
7% Ground Beef	75	Covered	120	300	113.4	94			
7% Ground Beef	75	Covered	120	300	113.4	83.38	86.93	26.47	23.3%
7% Ground Beef	75	Covered	120	300	113.4	83.4			
7% Ground Beef	75	Uncovered	120	300	113.4	82.8			
7% Ground Beef	75	Uncovered	120	300	113.4	82.6	82.27	31.13	27.4%
7% Ground Beef	75	Uncovered	120	300	113.4	81.4			
15% Ground Beef	75	Covered	120	300	113.4	80.94			
15% Ground Beef	75	Covered	120	300	113.4	74.66	77.37	36.03	31.8%
15% Ground Beef	75	Covered	120	300	113.4	76.5			
15% Ground Beef	75	Uncovered	120	300	113.4	80.29			
15% Ground Beef	75	Uncovered	120	300	113.4	74.96	78.82	34.98	30.8%
15% Ground Beef	75	Uncovered	120	300	113.4	80			
30% Ground Beef	75	Covered	105	300	113.4	67.73			
30% Ground Beef	75	Covered	105	300	113.4	72.68	70.21	43.20	38.1%
30% Ground Beef	75	Covered	105	300	113.4				
30% Ground Beef	75	Uncovered	105	300	113.4	71.94			
30% Ground Beef	75	Uncovered	105	300	113.4	72.11	72.52	40.88	36.0%
30% Ground Beef	75	Uncovered	105	300	113.4	73.5			

Appendix B:
Weight Loss – *Salmonella spp.*

Food Type	*Cooking Time (sec)*	*Cover / Uncovered*	*Cooking Time (sec)*	*Hold Time (sec)*	*Pre Cook Weight (g)*	*Post Cook Weight (g)*	*Average Post Cook Weight (g)*	*Average Cook Loss*	*Percent Weight Loss*
Broccoli	40	Covered	40	180	100.8	95			
Broccoli	40	Covered	40	180	100.8	95.13	94.76	6.04	5.9%
Broccoli	40	Covered	40	180	100.8	96.16			
Broccoli	40	Uncovered	40	180	100.8	94.75			
Broccoli	40	Uncovered	40	180	100.8	95.12	94.29	6.51	6.4%
Broccoli	40	Uncovered	40	180	100.8	92.99			
FF Chicken Patty	12	Covered	120	300	73	51.95			
FF Chicken Patty	120	Covered	120	300	73	55.45	54.61	18.39	25.5%
FF Chicken Patty	120	Covered	120	300	73	56.44			
FF Chicken Patty	120	Uncovered	120	300	73	54.78			
FF Chicken Patty	120	Uncovered	120	300	73	56.75	55.32	17.68	24.2%
FF Chicken Patty	120	Uncovered	120	300	73	54.43			
Reg. Chicken Patty	120	Covered	120	300	74	49.56			
Reg. Chicken Patty	120	Covered	120	300	74	49.01	50.28	23.72	32.1%
Reg. Chicken Patty	120	Covered	120	300	74	52.27			
Reg. Chicken Patty	120	Uncovered	120	300	74	50.3			
Reg. Chicken Patty	120	Uncovered	120	300	74	48.98	49.40	24.60	33.2%
Reg. Chicken Patty	120	Uncovered	120	300	74	48.91			
7% Ground Beef	75	Covered	105	300	113.4	81.86			
7% Ground Beef	75	Covered	105	300	113.4	82.68	84.13	29.27	25.8%
7% Ground Beef	75	Covered	105	300	113.4	87.86			
7% Ground Beef	75	Uncovered	105	300	113.4	85.24			
7% Ground Beef	75	Uncovered	105	300	113.4	91.21	87.93	25.47	22.5%
7% Ground Beef	75	Uncovered	105	300	113.4	87.35			
15% Ground Beef	75	Covered	105	300	113.4	78.26			
15% Ground Beef	75	Covered	105	300	113.4	76.38	76.83	36.57	32.2%
15% Ground Beef	75	Covered	105	300	113.4	78.61			
15% Ground Beef	75	Uncovered	105	300	113.4	81.55	79.60	33.80	29.8%

15% Ground Beef	75	Uncovered	105	300	113.4	78.63			
15% Ground Beef	75	Uncovered	105	300	113.4	78.61			
30% Ground Beef	75	Covered	105	300	113.4	71.99			
30% Ground Beef	75	Covered	105	300	113.4	72.86	73.07	40.33	35.6%
30% Ground Beef	75	Covered	105	300	113.4	74.36			
30% Ground Beef	75	Uncovered	105	300	113.4	73.38			
30% Ground Beef	75	Uncovered	105	300	113.4	75.73	74.15	39.25	34.6%
30% Ground Beef	75	Uncovered	105	300	113.4	73.34			

Appendix C:
Weight Loss – *Listeria monocytogenes.*

Food Type	*Cooking Time (sec)*	*Cover / Uncovered*	*Cooking Time (sec)*	*Hold Time (sec)*	*Pre Cook Weight (g)*	*Post Cook Weight (g)*	*Average Post Cook Weight (g)*	*Average Cook Loss*	*Percent Weight Loss*
Broccoli	40	Covered	40	180	93	80.75			
Broccoli	40	Covered	40	180	93	88	85.82	7.18	8.37
Broccoli	40	Covered	40	180	93	88.71			
Broccoli	40	Uncovered	40	180	93	84.26			
Broccoli	40	Uncovered	40	180	93	63.42	73.99	19.01	25.69
Broccoli	40	Uncovered	40	180	93	74.29			
FF Chicken Patty	120	Covered	120	300	73	53.39			
FF Chicken Patty	120	Covered	120	300	73	52.38	52.98	20.02	37.79
FF Chicken Patty	120	Covered	120	300	73	53.17			
FF Chicken Patty	120	Uncovered	120	300	73	50.56			
FF Chicken Patty	120	Uncovered	120	300	73	57	52.43	20.57	39.24
FF Chicken Patty	120	Uncovered	120	300	73	49.72			
Reg. Chicken Patty	120	Covered	120	300	74	60.4			
Reg. Chicken Patty	120	Covered	120	300	74	59.81	58.55	15.45	26.39
Reg. Chicken Patty	120	Covered	120	300	74	55.44			
Reg. Chicken Patty	120	Uncovered	120	300	74	55.12			
Reg. Chicken Patty	120	Uncovered	120	300	74	52.88	56.41	17.59	31.17
Reg. Chicken Patty	120	Uncovered	120	300	74	61.24			
7% Ground Beef	75	Covered	105	300	113.4				
7% Ground Beef	75	Covered	105	300	113.4	82.54	82.38	31.02	37.65
7% Ground Beef	75	Covered	105	300	113.4	82.22			
7% Ground Beef	75	Uncovered	105	300	113.4				
7% Ground Beef	75	Uncovered	105	300	113.4	86.4	84.46	28.95	34.27
7% Ground Beef	75	Uncovered	105	300	113.4	82.51			
15% Ground Beef	75	Covered	105	300	113.4	72.68			
15% Ground Beef	75	Covered	105	300	113.4	72.73	74.00	39.40	53.24
15% Ground Beef	75	Covered	105	300	113.4	76.59			
15% Ground Beef	75	Uncovered	105	300	113.4	77.23			46.17

15% Ground Beef	75	Uncovered	105	300	113.4	77.59	77.58	35.82	
15% Ground Beef	75	Uncovered	105	300	113.4	77.93			
30% Ground Beef	75	Covered	105	300	113.4	72.42			
30% Ground Beef	75	Covered	105	300	113.4	71.57	72.48	40.92	56.46
30% Ground Beef	75	Covered	105	300	113.4	73.45			
30% Ground Beef	75	Uncovered	105	300	113.4	72.45			
30% Ground Beef	75	Uncovered	105	300	113.4	74.76	74.12	39.28	53.00
30% Ground Beef	75	Uncovered	105	300	113.4	75.14			

Appendix D
F-Values Escherichia coli O157:H7

Food Type	*Covered/ Uncovered*	*$F_{100}^{5.8}$ Values*				*Survival*
		Probe 1[a]	*Probe 2*[b]	*Probe 3*[c]	*Probe 4*[d]	
Broccoli	Covered	0.00	0.00	0.00	0.68	
Broccoli	Covered	0.12	0.00	0.01	0.05	
Broccoli	Covered	0.03	0.00	0.00	0.00	
Average		0.05	0.00	0.00	0.24	3/3
Broccoli	Uncovered	0.01	0.01	0.01	4.09	
Broccoli	Uncovered	0.01	0.08	0.23	0.00	
Broccoli	Uncovered	0.00	0.00	0.00	0.00	
Average		0.01	0.03	0.08	1.37	3/3
7% Ground Beef	Covered	0.00	3.98	0.00	0.00	
7% Ground Beef	Covered	0.02	4.21	0.00	21.39	
7% Ground Beef	Covered	2.91	37.97	0.00	17.48	
Average		0.98	15.39	0.00	12.96	3/3
7% Ground Beef	Uncovered	28.93	1.47	0.00	8.76	
7% Ground Beef	Uncovered	43.55	34.08	0.16	14.41	
7% Ground Beef	Uncovered	27.06	0.05	0.01	3.23	
Average		33.18	11.87	0.06	8.80	0/3
15% Ground Beef	Covered	71.10	26.96	0.66	21.01	
15% Ground Beef	Covered	0.09	42.30	0.23	26.65	
15% Ground Beef	Covered	21.69	37.05	0.03	46.17	
Average		30.96	35.44	0.30	31.27	3/3
15% Ground Beef	Uncovered	0.15	11.25	0.01	32.43	
15% Ground Beef	Uncovered	4.65	41.79	0.01	13.82	
15% Ground Beef	Uncovered	12.84	43.86	0.05	28.35	
Average		5.88	32.30	0.02	24.87	2/3
30% Ground Beef	Covered	2.47	74.56	0.72	86.49	
30% Ground Beef	Covered	22.19	58.94	0.00	78.45	
30% Ground Beef	Covered	0.00	54.13	0.00	120.44	
Average		8.22	62.54	0.24	95.12	0/3
30% Ground Beef	Uncovered	0.04	67.43	0.09	11.38	
30% Ground Beef	Uncovered	0.04	46.32	0.00	111.12	
30% Ground Beef	Uncovered	0.02	1.81	0.00	80.05	
Average		0.03	38.52	0.03	67.52	1/3

[a] Probe 1 = Surface
[b] Probe 2 = Right of Center
[c] Probe 3 = Center
[d] Probe 4 = Left of center

Appendix E
F-Values *Salmonella spp.*

Food Type	*Covered/ Uncovered*	*$F_{100}^{6.8}$ Values*				*Survival*
		Probe 1[a]	*Probe 2[b]*	*Probe 3[c]*	*Probe 4[d]*	
Broccoli	Covered	3.35	0.25	0.01	0.15	
Broccoli	Covered	0.19	0.94	0.05	14.76	
Broccoli	Covered	0.03	1.10	0.00	0.10	
Average		1.19	0.76	0.02	5.00	3/3
Broccoli	Uncovered	0.00	0.04	0.00	58.41	
Broccoli	Uncovered	0.00	0.08	0.03	0.03	
Broccoli	Uncovered		0.31	0.00	0.01	
Average		0.00	0.14	0.01	19.48	2/3
Reg. Chicken Patty	Covered	195.66	79.35	116.42	132.86	
Reg. Chicken Patty	Covered	358.90	105.95	111.97		
Reg. Chicken Patty	Covered	180.89	255.12	96.94	462.33	
Average		160.98	169.86	84.50	231.06	0/3
Reg. Chicken Patty	Uncovered	152.42		77.97	600.90	
Reg. Chicken Patty	Uncovered	185.97	167.31	90.91	259.35	
Reg. Chicken Patty	Uncovered	136.86	540.04	99.34	90.05	
Average		158.42	353.68	89.41	316.76	2/3
FF Chicken Patty	Covered	77.37	85.74	58.03	90.60	
FF Chicken Patty	Covered	69.42	67.02	62.96	95.45	
FF Chicken Patty	Covered	91.35	58.36	46.00	116.92	
Average		79.38	70.37	55.66	100.99	0/3
FF Chicken Patty	Uncovered	89.05	51.33	5.44	52.20	
FF Chicken Patty	Uncovered	84.08	55.49	39.95	339.30	
FF Chicken Patty	Uncovered	53.46	97.73	58.33	150.70	
Average		75.53	68.19	34.57	180.73	2/3
7% Ground Beef	Covered	0.00	0.00	0.08	42.36	
7% Ground Beef	Covered	13.77	44.76	0.02	55.21	
7% Ground Beef	Covered	1.15	64.71	0.50	73.05	
Average		4.97	36.49	0.20	56.87	1/3
7% Ground Beef	Uncovered	5.38	27.57	0.01	41.69	
7% Ground Beef	Uncovered	0.32	52.81	0.02	62.62	
7% Ground Beef	Uncovered	0.04	51.73	0.06	40.54	
Average		1.91	44.04	0.03	48.29	0/3
15% Ground Beef	Covered	0.00	0.00	0.27	140.31	

15% Ground Beef	Covered	0.51	18.46	13.84	29.47	
15% Ground Beef	Covered	1.65	53.26	0.15	60.79	
Average		1.08	35.86	7.00	45.13	0/3
15% Ground Beef	Uncovered	0.35	34.40	0.02	49.72	
15% Ground Beef	Uncovered	0.15	23.09	0.69	49.05	
15% Ground Beef	Uncovered	0.14	48.97	0.45	279.84	
Average		0.21	35.49	0.38	126.20	2/3
30% Ground Beef	Covered	0.51	98.67	0.18	41.90	
30% Ground Beef	Covered	58.96	20.75	0.58	64.92	
30% Ground Beef	Covered	0.34	61.67	0.17	67.26	
Average		19.94	60.36	0.31	58.03	0/3
30% Ground Beef	Uncovered	8.71	61.20	0.03	52.83	
30% Ground Beef	Uncovered	0.04	57.87	0.18	43.34	
30% Ground Beef	Uncovered	1.05	67.12	0.38	46.83	
Average		3.26	62.06	0.20	47.67	0/3

[a] Probe 1 = Surface
[b] Probe 2 = Right of Center
[c] Probe 3 = Center
[d] Probe 4 = Left of center

Appendix F
F-Values *Listeria monocytogenes.*

Food Type	*Covered/ Uncovered*	*$F_{100}^{7.7}$ Values*				*Survival*
		Probe 1[a]	*Probe 2[b]*	*Probe 3[c]*	*Probe 4[d]*	
Broccoli	Covered	2.55	28.28	16.65	105.10	
Broccoli	Covered	0.92	0.28	0.00	14.39	
Broccoli	Covered	1.04	0.01	0.01	0.16	
Average		1.50	9.52	5.55	39.88	3/3
Broccoli	Uncovered	0.06	5.97	0.00	0.01	
Broccoli	Uncovered	4.28	25.55	9.20	24.61	
Broccoli	Uncovered	1.30	1.28	0.02	23.73	
Average		1.88	10.94	3.07	16.12	3/3
Reg. Chicken Patty	Covered	51.84	157.77	44.72	109.93	
Reg. Chicken Patty	Covered	73.75	353.96	76.30	157.08	
Reg. Chicken Patty	Covered	0.00	0.00	47.44	128.10	
Average		41.87	170.58	56.15	131.71	1/3
Reg. Chicken Patty	Uncovered	0.00	163.17	36.82	107.87	
Reg. Chicken Patty	Uncovered	0.00	110.40	40.39	152.09	
Reg. Chicken Patty	Uncovered	0.00	123.88	56.93	198.03	
Average		0.00	132.48	44.71	152.66	2/3
FF Chicken Patty	Covered	15.22	95.52	0.96	11.32	
FF Chicken Patty	Covered	19.12	98.74	1.21	87.41	
FF Chicken Patty	Covered	9.99	101.45	3.87	113.01	
Average		14.78	98.57	2.01	70.58	3/3
FF Chicken Patty	Uncovered	0.00	75.01	0.18	54.66	
FF Chicken Patty	Uncovered	0.00	63.82	1.44	76.87	
FF Chicken Patty	Uncovered	0.00	40.81	20.69	35.63	
Average		0.00	59.88	7.43	55.72	1/3
7% Ground Beef	Covered	0.08	1.23	13.79	23.76	
7% Ground Beef	Covered	0.00	39.28	1.27	56.95	
7% Ground Beef	Covered	10.56	31.86	0.15	62.56	
Average		3.55	24.12	5.07	47.75	3/3
7% Ground Beef	Uncovered	0.00	10.17	0.33	36.88	
7% Ground Beef	Uncovered	0.00	45.03	0.03	4.89	
7% Ground Beef	Uncovered	0.00	37.08	1.70	37.31	
Average		0.00	30.76	0.69	26.36	3/3
15% Ground Beef	Covered	0.79	54.39	4.08	46.75	
15% Ground Beef	Covered	0.26	67.32	1.84	36.46	
15% Ground Beef	Covered	3.10	59.08	1.31	40.48	

Average		1.39	60.26	2.41	41.23	3/3
15% Ground Beef	Uncovered	1.69	64.77	4.26	36.01	
15% Ground Beef	Uncovered	8.92	23.80	1.43	17.54	
15% Ground Beef	Uncovered	0.00	75.81	1.00	9.69	
Average		3.54	54.79	2.23	21.08	2/3
30% Ground Beef	Covered	0.26	116.60	11.91	54.08	
30% Ground Beef	Covered	0.00	0.00	0.08	65.95	
30% Ground Beef	Covered	4.19	46.00	1.78	69.89	
Average		1.48	54.20	4.59	63.31	1/3
30% Ground Beef	Uncovered	0.00	85.33	1.66	49.57	
30% Ground Beef	Uncovered	0.00	18.46	0.13	6.12	
30% Ground Beef	Uncovered	0.00	14.58	1.16	43.41	
Average		0.00	39.45	0.98	33.03	1/3

[a] Probe 1 = Surface
[b] Probe 2 = Right of Center
[c] Probe 3 = Center
[d] Probe 4 = Left of center

Vita

April Hix was born on the 24th of January, 1975, the daughter of Alan and Rita Hix of Harmony, North Carolina. In 1993, she graduated from North Iredell High School in Olin, NC. She then entered North Carolina State University where she received her Bachelors of Science degree in Food Science and Technology in December of 1997. After an eight-month internship in Product Development at the Kellogg's Company in Battle Creek, Michigan, she entered Virginia Polytechnic Institute and State University to work toward her Masters of Science in Food Science and Technology in August of 1998. She completed her degree in August of 2000.