This is to certify that the

thesis entitled

HEAT TRANSFER PROPERTIES OF
HOME MEAL REPLACEMENT
PRODUCT/PACKAGE SYSTEMS

presented by

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has been accepted towards fulfillment
of the requirements for

M.S. degree in Packaging

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Date January 26, 2001

HEAT TRANSFER PROPERTIES OF HOME MEAL REPLACEMENT PRODUCT/PACKAGE SYSTEMS

By

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A THESIS

Submitted to
Michigan State University
In partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

School of Packaging

2001

ABSTRACT

HEAT TRANSFER PROPERTIES OF HOME MEAL REPLACEMENT PRODUCT/PACKAGE SYSTEM

By

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This study examined the heat loss profile of four different commercially available frozen food dinners (2 sizes of lasagna, corn, and meatloaf) cooked in a conventional oven and microwave. By monitoring the heat loss profile (temperature vs. time) with thermocouples the R-values of several materials suitable for frozen food packaging (foil, paperboard, and PET) were calculated. The R-value of the materials were 0.607 ft^2 - °F - hr / BTU for PET, 0.441 for foil, and 0.490 for paper. Additionally, heat loss profiles were constructed for the cooling of the frozen dinners after heating. There was significant variation in the initial temperatures of the food products after heating. This suggests that there would be difficulty in theoretically modeling the heating and cooling rates. Additionally, while the individual locations tested for temperature versus time displayed irregular behavior, the average of these points when plotted as heat loss versus time data fitted a simple theoretical model very well. After cooking, the center temperature of the foods was generally lower than that of the surrounding mass. In some cases, the center temperature was much lower than the surrounding mass, which brought about a warming trend of the center mass. This research examines the behavior of water and commercially available food as it cools at room temperature in various packaging materials and sizes.

ACKNOWLEDGEMENTS

I am extremely grateful to all the support I have received working on this project as well as my degree in general. To my graduate committee, Dr. Gary Burgess, Dr. Bruce Harte, and Dr. Robert Ofoli: your knowledge, support, and patience was greatly appreciated. To Dr. Diana Twede, Dr. Robb Clarke, and Dr. Robert Lamoroux: your help with providing financial support through assistantships as well as providing me the flexibility to balance work, studies, and research has been a major contribution to my success. To all the graduate students and the PGA, specifically, Matthew Moon, Matthew Thomas, Erik Knudsen, Laura Bix, and Hussain Qurashi: no matter how many miles lie between us in our future, our friendships will not falter. Your support both academically and socially will not be forgotten. To my family, especially my parents: thank you for your encouragement and understanding. Finally, and most importantly, my wife, Colleen: despite my long hours of studying, researching, and working, you maintained your support, encouragement, patience and love.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

INTRODUCTION

With the decrease in time available for traditional home cooking along with an increase in single parent households, dual income households, and an aging population, people are using alternative means for meal preparation. (Larson, 1998) With this demand for faster and more convenient meal preparation comes the increase in use of home meal replacement food and packaging. Since the introduction of the frozen dinner in 1954, consumers were given the freedom to keep food for extended periods of time with little threat of deterioration or microbial growth. Upon demand, the food could then be prepared quickly using a conventional oven or more recently with a microwave oven.

While the low preparation time offered by home meal replacement foods is important, it does little good to the consumer if the food/package system can not maintain the desired serving temperature. Multiple factors can effect the heat loss that occurs from the time the food has completed cooking until the food is ready to eat. The food parameters that effect heat loss include: water activity, density, contact area with the package surface, chemical composition, phase, and viscosity. Some parameters of the package include: insulating capacity of the material (R-value), density, volume, and surface area. Other factors that need to be considered are initial food temperature, external air temperature, and mode of heat loss at the interface between the food and package as well as the package and the environment. When heating a product with high water activity or low viscosity, the product is allowed greater circulation and thus sweeps the heat away from the outside edge of the package and is able to heat faster. Conversely as the product cools, heat is constantly swept to the outside edge for transfer into the surrounding atmosphere and the product would then cool faster. Substances with higher densities will generally conduct heat at a faster rate than those of a lower density, assuming all else equal.

The objectives of this research were:

1. To determine the insulating ability (R-value) of different packaging tray sizes and materials.
2. To determine the relationship between heat loss and time for different sizes and types of frozen foods.
3. To derive thermodynamic data (heat capacity values) for the different foods tested.

LITERATURE REVIEW

THE 1st LAW OF THERMODYNAMICS

The first law of thermodynamics states that in the absence of work, heat energy added to a substance results in a change in internal energy. For simple heating and cooling processes which do not involve phase changes, the internal energy is proportional to the temperature of the substance. In this way, as a food/packaging system is cooled, the internal energy of the system is transferred from the food/package system to the atmosphere. By definition, a British Thermal Unit (BTU) is the amount of energy required to raise 1 lb. of water 1°F. For substances other than water,

$$BTU = W * C * \Delta T \quad (1)$$

W = the gross weight of the system,

C = the heat capacity of the substance

ΔT = the difference in final and initial temperatures of the system.

If the amount of heat (BTU) removed from the system over a given time period can be determined, then the temperature drop ΔT over time can be determined. (Perry, 1984)

MODES OF HEAT TRANSFER

There are three mechanisms of heat energy from one body to another: conduction, convection, and radiation. (Holman, 1986) (Krieth, 1973) Conduction is the means by which heat energy is transferred from one body directly to another by means of immediate contact. In convection, heat energy is transferred from one body to a fluid medium, like air. In radiation, heat energy is emitted from a body by the emission of photons. Any combination of these three modes may be present in a system. (Perry,1984) As foods cool, conduction and convection are the predominate modes of heat transfer and the contribution of radiation heat loss is negligible.

R-VALUE OF AN INSULATING SYSTEM

The R-value is a unit of measurement for the total thermal resistance of a system. It is used here to describe the ability of a package or container to resist the transfer of heat energy from the food inside at an elevated temperature to the surrounding air at a lower temperature. It combines all three modes of heat transfer and allows for a universal description of the net energy transfer from multiple sources and transfer modes.(Burgess, 1999) In terms of heat loss through a package the R-value can be described as the following:

$$\text{R-value} = A * \Delta T / Q \qquad (2)$$

A = surface area of the container,

ΔT = temperature difference between the food inside and the air outside

Q = heat transfer rate in units of BTU/hr

The English system R-value has the units: $h - ft^2 - {}^{o}F / Btu$. The metric system R-value has the units: $m^2 - {}^{o}C / Watts$. (ASHRAE, 1985) (Holman, 1986) (Krieth, 1973)
The R-value for a package should depend only on the construction of the package wall, specifically the thickness and material. The higher the R-value the better the package will insulate its contents. According to Equation 2, assuming the R-value is constant for a packaging material, an increase in the area or temperature difference will result in a higher rate of heat loss from the package and into the area surrounding the package.

NEWTON'S LAW OF COOLING

For any system at an initial temperature of T_i placed in an atmosphere with temperature T_a with $T_i > T_a$, an application of the first law of thermodynamics coupled with the law of convection heat transfer says that: (Holman, 1986) (Krieth, 1973)

$$(1 / R) * A * [T(t) - T_a] = - W * C * dT/dt \qquad (3)$$

R = the system R-value,

A = the container surface area,

T(t) = temperature of the system at time t,

T_a = temperature of the air surrounding the system (assumed constant)

W = gross weight of the system

C = the heat capacity of the system

Rearrangement of this equation yields:

$$dT/dt + \beta * T(t) = \beta * T_a \qquad (4)$$

$$\beta = [A / (R * W * C)]$$

Solving this differential equation yields:

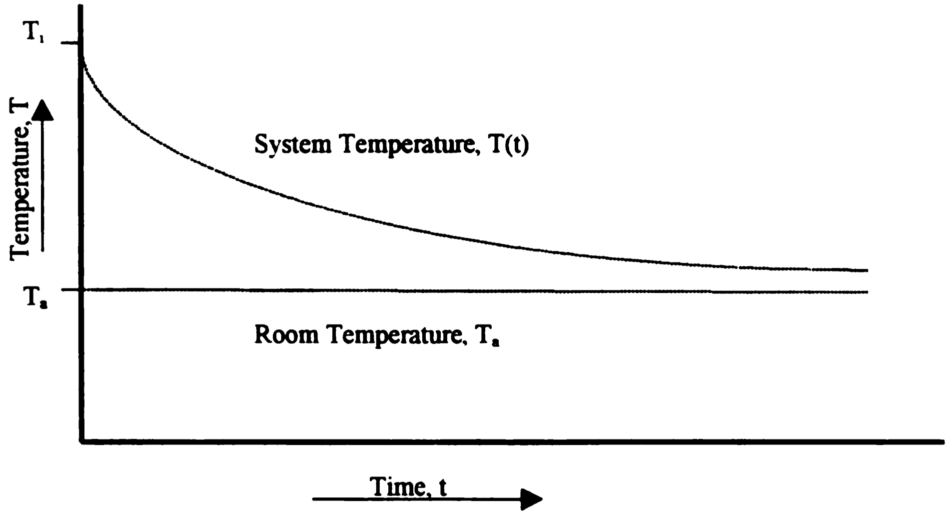
$$T(t) = T_a + k * e^{-\beta t}$$

Where k is some constant to be determined by initial conditions. Forcing the initial temperature of the food immediately after heating to be T_i at t=0 gives $k = T_i - T_a$. The theoretical change in temperature over time then is given by Newton's Law of cooling

$$T(t) = T_a + (T_i - T_a) e^{-\beta t} \qquad (5)$$

This is shown in Figure 1.

Figure 1: Model of Exponential Heat Loss According to Newton's Law of Cooling



Graphs such as this can be constructed for a food product held at a constant temperature provided that T_i, T_a, and β are known. T_i and T_a are easily determined and β is a function of A, R, W, and C. A and W can be easily determined, but R and C can be more difficult. R can be estimated based on package construction, but C is dependent on many variables such as the water content, density, consistency etc... of the food. Filling a food package with water (heat capacity C = 1 BTU / lb. - °F) and fitting the heat loss vs. time to equation 5 allows one to calculate the R-value of the package. This can then be repeated for different packages which allows a comparison of R-values for those packages. It is important to note that equations 3, 4, and 5 apply only to systems which conduct heat internally much more rapidly than they lose heat to the air, which should be the case for cooling foods. This means that the internal temperature is a function of time only, not position. Hence the assumption of a single temperature in equations 3, 4, and 5.

MATERIALS AND METHODS

A. Materials

1. Food / Packaging Materials: Commercial food products were used, according to procedure, in evaluating the heat loss profile of the given product/package system.

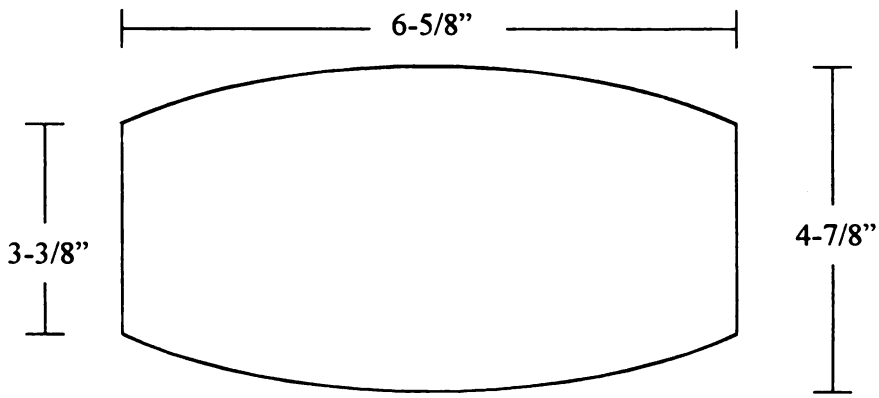
   a. 10.5 oz. (297g) Stouffers Lasagna With Meat Sauce in a 15.8-mil rectangular PET thermoform tray with a 0.488-mil PET heat sealed film covering. The tray had an internal volume of 24.0 in^3. and the dimensions length = 4" to 4.75", width = 3" to 3.75", and depth = 1.75". The range of length and width dimensions represent the difference between the dimensions at the top and bottom of the nestable tray. The surface area of the container was 40 in^2 and the surface area of the lid was 14.77 in^2. The suface area and volumes listed were estimated using the mean average of the dimensional ranges. In this study this product is referred to as "Small Lasagna." This product was selected because it is available in multiple sizes and comparisons of size versus heat loss per unit of time can be established. Also, the food has a large surface contact area with the package as well as a low product surface area compared with particulate foods such as corn.

   b. 21 oz. (595g) Stouffers Lasagna With Meat Sauce in a 20.3-mil rectangular PET thermoform tray with a 0.52-mil PET heat sealed film covering. The tray had an internal volume of 42.9 in^3. and had the dimensions length = 5.44" to 6.13", W = 4.13" to5", and D = 1.63". The range of length and width dimensions represents the difference between the dimensions at the top and bottom of the nestable tray. The surface area of the container was 60 in^2 and the surface area of the lid was 26.38 in^2. The suface area and volumes listed were estimated using the mean average of the dimensional ranges. This is referred to as "Medium Lasagna." This product was selected because it is available in multiple sizes and comparisons of size versus heat loss per unit of time can be established. Also, the food has a large surface contact area with the package as well as a low product surface area compared with particulate foods such as corn. This empty package was also used to calculate the R-value of a PET tray with a PET film covering. This package is referred to as "PET". This package was selected because it represents a highly utilized microwaveable / ovenable convenience packaging material.

c. 10 oz. (283g) Boston Market Sweet Corn in Herb Sauce in a 21.85 mil rectangular PET thermoform tray with a 0.59 mil PET heat sealed film covering. The tray had an internal volume of 30.35 in^3. and had the dimensions L = 5.0625 to 5.75, W = 3.5 to 4.3125, and D = 1.4375". The range of length and width dimensions represent the difference between the dimensions at the top and bottom of the nestable tray. The surface area of the container was 47.89 in^2 and the surface area of the lid was 21.12 in^2. The suface area and volumes listed were estimated using the mean average of the dimensional ranges. This is referred to as "Corn." This product was selected because it represents food that has multiple contact surfaces with the packaging material and the food has a large overall surface area compared to non-particulate food.

d. 9 oz. (255g) Boston Market Meatloaf With Gravy in a 16.34 mil semi-rectangular PET thermoform tray with a 0.54-mil PET heat sealed film covering. The tray had an internal volume of 34.84 in^3. and dimensions as illustrated in figure 2, with a depth of 1.1875". The surface area of the container was 52.20 in^2 and the surface area of the lid was 29.34 in^2. The volume was determined by filling the container with water and measuring the volume with a graduated cylinder. The surface area of the top and bottom of the package was estimated by dividing the volume by the depth. The surface area of the sides were estimating by multipling the circumference by the depth This is referred to as "Meatloaf." This product was selected because it represents food that has a large contact surface with the packaging material and the food has a low overall product surface area compared to particulate food such as corn.

Figure 2: Meatloaf Tray Dimensions



e. 3.46 mil rectangular aluminum foil tray with 15.66 mil foil coated paperboard covering. The tray had an internal volume of 50.03 in^3 and had the dimensions L = 5.875" to 6.5", W = 3.875" to 4.75", and D = 1.875". The range of the length and width dimensions represent the difference between the dimensions at the top and bottom of the nestable tray. The surface area of the container was 66.06 in^2 and the surface area of the lid was 26.68 in^2. The surface area and volumes listed were estimated using the mean average of the dimensional ranges. This is referred to as "Foil." This product was selected because it is an alternative to PET for ovenable food packaging.

f. Empty 18.84 mil rectangular PET coated paper tray with 17.13 mil PET coated paper covering. The tray had an internal volume of 35.89 in^3 and the dimensions L = 6" to 6.25", W = 4.375" to 5", and D = 1.25". The range of the length and width dimensions represent the difference between the dimensions at the top and bottom of the nestable tray. The surface area of the container was 55.74 in^2 and the surface area of the lid was 28.71 in^2. The surface area and volumes listed were estimated by using the mean average of the dimensional ranges. This is referred to as "Paperboard." This product was selected because it is an alternative to PET for ovenable food packaging.

2. Equipment

   a. Oven: GE model JBS27AY2AA – 4.5 cubic foot conventional oven was used for all samples referred to as "oven." This oven was selected because it represents an oven "typically" used in a home environment.

   b. Microwave Oven: Goldstar model MA-963M – 0.7 cubic foot – 850 Watt microwave oven with automatic turntable.

3. Instrumentation

   a. Thermocouples: Omega precision fine wire thermocouples with glass insulation. Type: T. Thermocouple data was recorded with an Omega OM-

5000 datalogger with 40 channel capacity recording temperature readings every 30 seconds

B. Methods:

1. Determining the R-value of packaging materials

The package to be tested was positioned on a piece of ½ inch thick plywood. The same piece of plywood was used for all studies to normalize the differences between countertops at different testing locations. The package was fitted with a thermocouple that would, when filled and sealed, rest with the sensor in the geometric center of the container. A second thermocouple was placed near the package to monitor room temperature but, placed far enough away from the package as to avoid recording heat given off by the package. The package was then filled with hot (near boiling) water and sealed. The paperboard packages had to be lined with 0.5-mil PET film to prevent the water from melting the coating and leaking out. The datalogger was turned on and the temperature vs. time was recorded until such time that the internal temperature of the package was below 120°F. The data was then downloaded into a Microsoft Excel Spreadsheet and plotted as $T(t) - T_a$ vs. t. (See Appendix 1.) A best-fit to the theoretical result $T(t) - T_a = k\ e^{-\beta t}$ using standard regression software was then done and the correlation coefficient R^2 value was determined.

The system R-value was then calculated using the fitted value for β as follows:

$$R = A / (\beta W C) \tag{6}$$

A = the system surface area

β = the fitted value

W = gross weight of the system

C = the heat capacity of the system

2. Determining the heat/loss vs. time

Three samples of each product were cooked according to directions in both microwave and oven. Cooking times as listed on the package label were given as range. An average of that range was used for the experimental cooking time. (Table 1.)

Table 1: Cooking Times & Temperatures Used

Heating Conditions				
Cooking Method	Product	Temperature / Power Setting	Package Directions Time (min)	Experiment Time (min)
Oven	Small Lasagna	350 °F	45-50	47.5
	Medium Lasagna	350 °F	53-55	54
	Corn	350 °F	40	40
	Meatloaf	350 °F	40	40
Microwave	Small Lasagna	HIGH	6-8	7
	Medium Lasagna	HIGH	12-15	13.5
	Corn	HIGH	4-6 (Stir after 3)	5 (Stir after 3)
	Meatloaf	HIGH	4.5	4.5

After cooking was completed, the product was placed on a piece of ½ inch thick plywood. The same piece of plywood was used for all samples to normalize the differences between countertops at different testing locations. The package was fitted with three thermocouples and one thermocouple was placed near the package to monitor room temperature but placed far enough away from the package as to avoid recording heat given off by the package. For both sizes of lasagnas and the corn the thermocouples were placed as follows.

- Channel 1 was placed in the center of the product mass (center of length, width, and depth) labeled as "center".
- Channel 2 was placed at length = ¼, width = ½, and depth = ½ labeled "side".
- Channel 3 was placed at length = ¾, width = ½ and placed just barely below the surface of the food labeled "surface".

For the meatloaf, which came prepared as two separate ½" patties the thermocouples were placed as follows.

- Channel 1 and 2 were each placed in the center of a patty labeled patty 1 and patty 2 respectively.
- Channel 3 was placed in the geometric center of the container which would coincide with the edge of one of the patties.

The datalogger was then turned on and the temperature vs. time was recorded until such time that all thermocouples inside the package read below 120°F. The data was then downloaded into a Microsoft Excel Spreadsheet and plotted as ΔT (°F) vs. time (min). An exponential best-fit line with equation and R^2 value was then constructed to determine β. (See Apendix 2)

RESULTS AND DISCUSSION

Relationship between ΔT and Time

According to Newton's Law of Cooling (Equation 5) the relationship between ΔT, the difference between the food temperature and the room temperature, and time should be an exponential decay. The results of this study showed that when an average of the three thermocouples readings were taken the relationship holds true for water in the various trays. Appendix 1 gives the results of the experiment. Table 2 shows the T_i, β, & R^2 value for the fit of these averages. An R^2 of 1 indicates a perfect fit where the theoretical results predicts the experimental data exactly. The fact that all R^2 in Table 2 are nearly 1 means that the fit is near perfect.

Table 2: T_i, β, & R^2-Values for Heat Loss Vs. Time Graphs

Product	Sample	T_i (oF)	β	R^2-value
Small Oven Lasagna	A	156.15	0.0052	0.9854
	B	159.42	0.0054	0.9969
	C	143.3	0.0039	0.9753
Small Microwave Lasagna	A	165.05	0.0087	0.9983
	B	153.29	0.0069	0.9420
	C	144.08	0.005	0.9512
Medium Oven Lasagna	A	124.71	0.0017	0.8466
	B	131.04	0.0022	0.9165
	C	133.93	0.0023	0.9075
Medium Microwave Lasagna	A	171.44	0.0073	0.9786
	B	171.14	0.0062	0.9985
	C	166.95	0.0077	0.9982
Oven Corn	A	125.87	0.0057	0.8988
	B	135.16	0.0065	0.9946
	C	149.24	0.0077	0.9981
Microwave Corn	A	172.7	0.0111	0.9440
	B	171.61	0.0098	0.9879
	C	170.12	0.0118	0.9813
Oven Meatloaf	A	173.86	0.0153	0.9676
	B	178.57	0.0169	0.9646
	C	172.45	0.0151	0.9629
Microwave Meatloaf	A	176.41	0.018	0.9832
	B	173.47	0.0159	0.9821
	C	170.6	0.0174	0.9872

Initial Temperatures of Foods

Despite cooking all products according to instructions and under near identical conditions, there was little regularity in initial temperatures at any of the thermocouple points in the food product. In many cases the difference between the highest initial temperature and the lowest initial temperature of the 3 samples, referred to as the range, were high. The initial temperature ranges are listed Appendix 3.

Only 3 thermocouple points (out of the 24 total points for all food) were within a 10°F range for all trials of the particular food. These data points and there respective ranges are listed below:

1. Surface of Oven Corn (9.1°F range)
2. Side of Microwave Corn (5.5°F range)
3. Patty 2 of Oven Meatloaf (3.2°F range)

In contrast the 3 worst ranges were:

1. Side of Small Oven Lasagna (42.9°F range)
2. Surface of Small Microwave Lasagna (47.1°F range)
3. Center of Medium Microwave Lasagna (58.8°F range)

None of the cooking methods consistently had a higher or lower range than another. From the total of all thermocouple readings, half of the microwave locations had a wider range of initial temperature and half had a narrower initial range than that of the oven.

There was no regularity in temperature after heating between samples cooked in the oven versus samples cooked in a microwave. The difference between average initial temperature for all samples was greater than 10°F. The microwave samples tended to have a higher initial temperature for the medium lasagnas and corn. The meatloaf had a higher average initial temperature in all three locations for the samples cooked in the oven. The small lasagna had no definitive trend with two points being hotter for microwave and one point being higher for the oven. (Appendix 3)

R-value of Packaging Material

Newton's law of cooling allows us to find the R-value of a particular package (Equation 5,6). Using the values listed in the materials section (pages 7-10) and the β values from fitting the experimental data in Table 2 (page 15) to Newton's law of cooling the R-values were determined. The values calculated are listed in Table 3.

Example: Water in PET B

$$R = A / (\beta W C) \qquad (6)$$

$\beta = 0.0155 \text{ min}^{-1} = 0.930 \text{ hr}^{-1}$

$A = 86.38 \text{ in}^2 = 0.5999 \text{ ft}^2$

$W = 567.99 \text{ g} = 1.2511 \text{ lb}$

$C = 1 \text{ BTU / lb. - } ^\circ\text{F}$

$R = 0.5999 \text{ ft}^2 / [0.930 \text{ hr}^{-1} * 1.2511 \text{ lb.} * (1 \text{ BTU / lb.} - ^\circ\text{F})$

$R = 0.516 \text{ ft}^2 - ^\circ\text{F} - \text{hr / BTU}$

Table 3: Experimental R-Values of Packaging Materials Determined From Equation 6

R-Values of Packaging Materials*			
Sample	PET	Paper	Foil
A	0.672	0.5143	0.398
B	0.516	0.4553	0.416
C	0.634	0.4992	0.509
AVG	0.607	0.490	0.441
STD DEV	0.081	0.031	0.060
* $(\text{ft}^2 - ^\circ\text{F - hr}) / \text{BTU}$			

It is clear from the chart that the PET tray is the superior package in terms of maintaining food temperature. Foil is the worst food insulator and paper is in between.

Heat Capacity of a Selected Food

Using the average R-value calculated for the PET tray ($0.607\ ft^2 - {}^\circ F - hr / BTU$) the heat capacity of the Medium lasagna was calculated. See Table 4. Rearranging equation 6 to solve for C instead of R yields:

$$C = A / (\beta * R * W) \qquad (7)$$

Example: Medium Microwave Lasagna A

$A = 86.38\ in^2 = 0.5999\ ft^2$

$\beta = 0.0201\ min^{-1} = 01.21\ hr^{-1}$

$R = 0.607\ ft^2 - {}^\circ F - hr / BTU$

$W = 557.12g = 1.22lb$

$C = 0.5999\ ft^2 / [1.21\ hr^{-1} * (0.607\ ft^2 - {}^\circ F - hr / BTU) * 1.22\ lb]$

$C = 0.6650\ BTU / lb - {}^\circ F$

Table 4: Heat Capacity of Medium Microwave Lasagna Average.

Heat Capacity of Medium Microwave Lasagna*	
A	0.6650
B	0.9348
C	0.7817
AVG	0.7938
STD DEV	0.1353
*Units = BTU / (lb.-°F)	

Since the heat capacity of the Medium Microwave Lasagna is less than 1 BTU / lb-°F, less energy is needed to increase the temperature of Lasagna than is needed for the same weight of water. This result agrees with the theoretical prediction that higher density matter transfers heat more efficiently than lower density matter. It also agrees with heat capacity values obtained by other means and listed in published references.(Frozen Food Roundtable, 1981)

In the instances where multiple types of food are present in a single package, the heat capacity (C) for each individual item will be independent of each other causing different initial temperatures (T_i) for each food when heating is completed. In instances where C varies greatly, consumers will potentially have a low quality perception of the cooked foods. For example, if two foods, Food-A and Food-B are placed in a single package and Food-A has a lower C than Food-B, Food-A has the potential to overcook if the cooking directions target the optimum serving temperature for Food B. Likewise, Food-B has the potential to be undercooked if the cooking directions target the optimum serving temperature for Food-A.

Internal Temperature Behavior of Samples

In at least one sample of every product/cooking method, with the exception of the Oven Meatloaf, the behavior of the center temperature varied from the theoretical behavior expected from a cooling product. In Newton's Law of Cooling, it is assumed that, after a body of mass is heated and placed in an atmosphere at a lower temperature, a unidirectional heat flow away from the mass into the surrounding atmosphere will occur (figure 3). In several samples an increase in temperature at the center was noted after heating of the product was completed. This irregularity is caused by a large temperature difference between the center of the food mass and the surrounding food mass. This large temperature difference created a second thermal gradient directed towards the center of the food mass (the slowest heating point). This second thermal gradient caused the center mass to continue to increase in temperature, or at least plateau until such time that the temperature difference was low enough to negate the second gradient. (Figure 4) The reason for this irregular behavior is due to the thickness of the food products. With thick samples, such as the lasagnas, and corn (all greater than 1" thick), the surrounding mass (Figure 4) prevents the heat energy from reaching the center mass. Since the center mass does not receive the same amount of energy as the surrounding mass the center mass will have a lower initial temperature than the surrounding mass. In thick samples, the difference between the initial temperature of the center mass and surrounding mass is large enough to establish the second heat gradient. This rationale explains why the meatloaf patties, which ranged from ½" to ¾" thick, did not exhibit the irregular behavior. This finding negates the assumption behind equations 3,4, and 5 which were used to find R-values and heat capacities (C). The values obtained for these quantities are therefore suspect from a theoretical point of view. The fact that they agree with expected values however says that they have experimental merit. Specifically, the C values represent averages over position within the food when the food is subjected to convection cooling. Likewise, R should also be taken as an "insitu" value.

When water cooled in the individual packages the center-heating phenomena did not occur. The contents began cooling as predicted by the model. (Figure 1,3, Appendix 1) The major reason for this difference, compared to foods, is that with water being a fluid, it is allowed to circulate thus creating heat gradients within the package so small they are negligible.

Figure 3: Heat Flow in a Body Having a Uniform Temperature

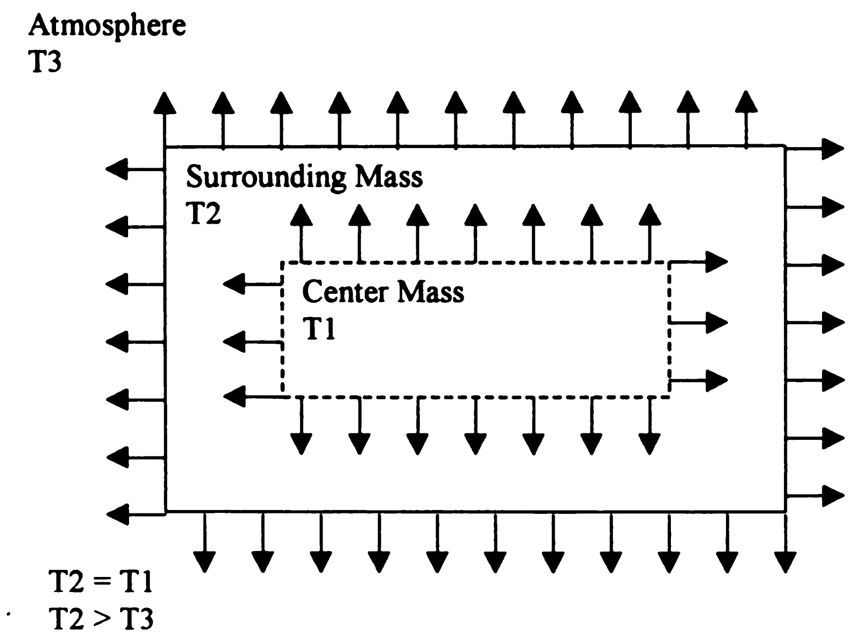
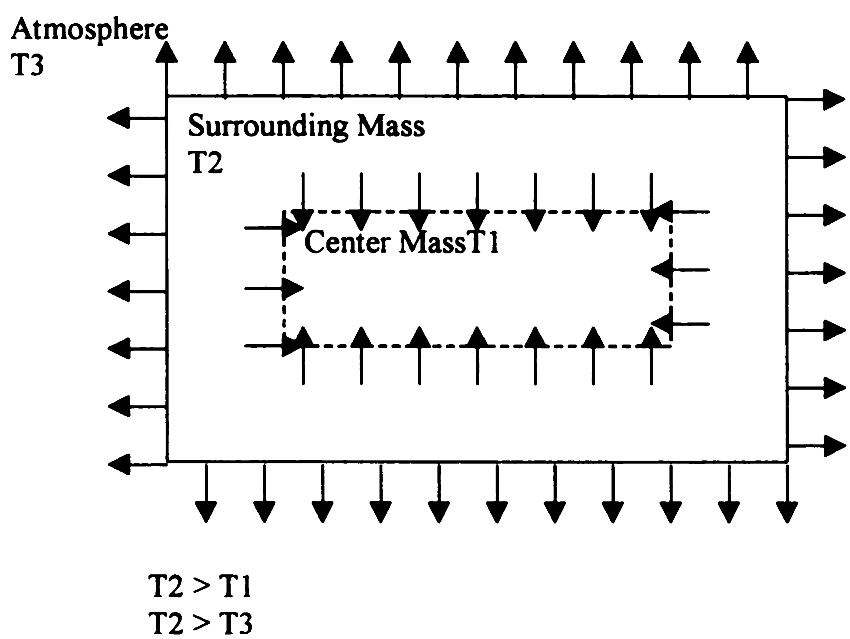


Figure 4: Heat Flow in a Partially Heated Body



CONCLUSIONS

This study provided a basis for comparing and selecting appropriate food/package systems. Specifically this study provided a method for determining R-values of packaging materials as well as heat capacities of foods using Newton's Law of Cooling. It was concluded that the R-value of PET is higher than that of Foil and Paper and therefore is a superior insulator of food products. Generally speaking, the initial center temperature of the selected foods was lower than that of the surface and remained lower for the entire cooling process. Although the individual points within a meal did not always follow the predicted behavior according to Newton's Law of Cooling, when an average of the points were taken the behavior closely resembled the theoretical predictions. While results of individual average cooling behavior followed theoretical outcome closely, the initial temperatures of identical food/package systems prepared under identical conditions contained high variability. Furthermore, initial temperatures of microwave and conventional oven were dissimilar with respect to all points tested. Therefore, modeling of required cooking time for desired heat level may not be completely dependable.

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Appendix 1

Heat Loss vs. Time Data to Determine R-Value of Packaging Materials

Note: The following images in this thesis were originally published in color.

In the following graphs, for the best-fit lines, Y = temperature and X = time.

Figure 5: Heat Loss Vs. Time for Water in PET A

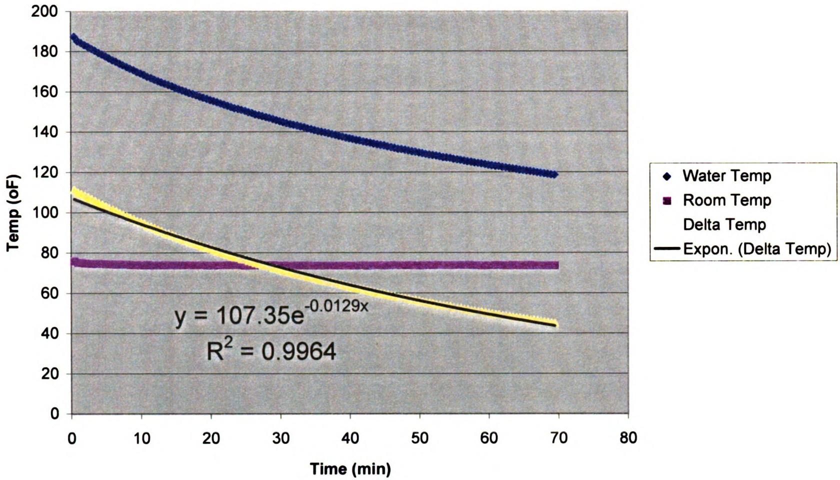


Figure 6: Heat Loss Vs. Time for Water in PET B

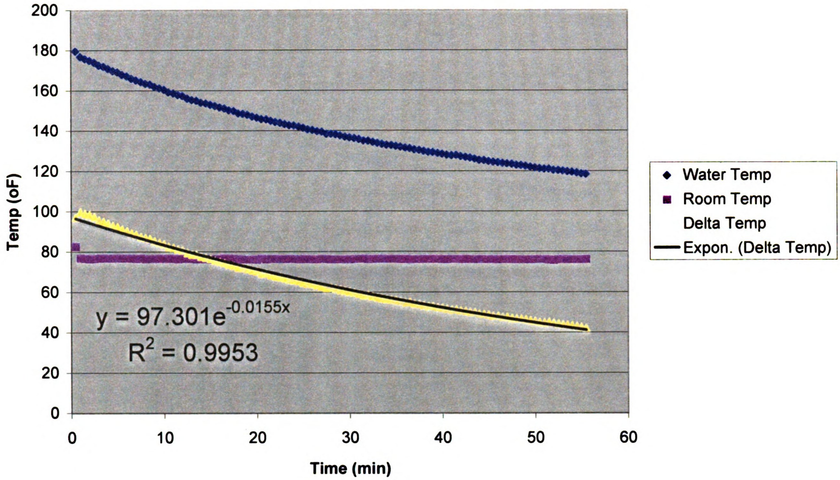


Figure 7: Heat Loss Vs. Time for Water in PET C

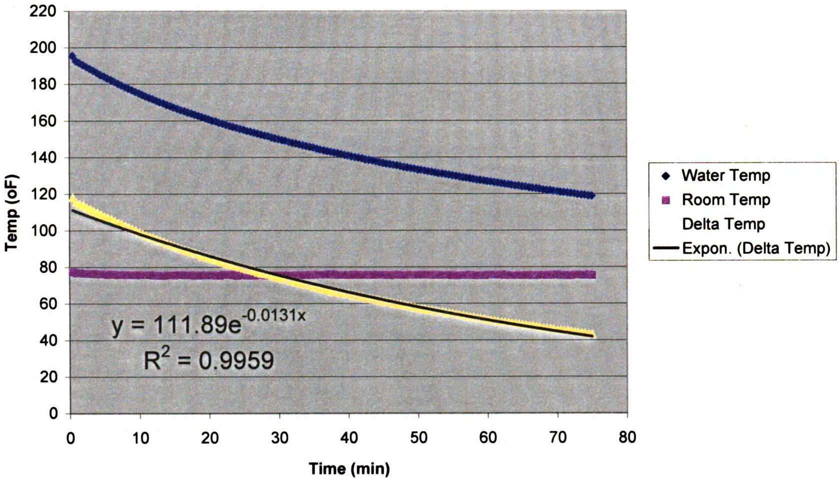


Figure 8: Heat Loss Vs. Time for Water in Paper A

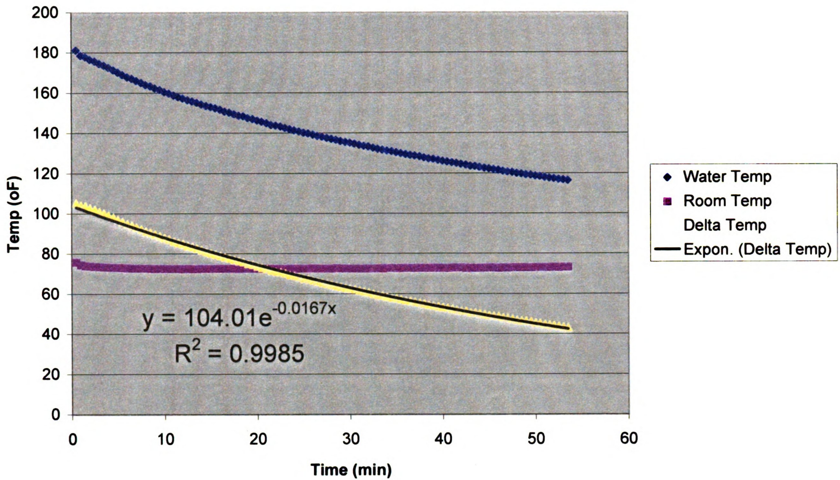


Figure 9: Heat Loss Vs. Time for Water in Paper B

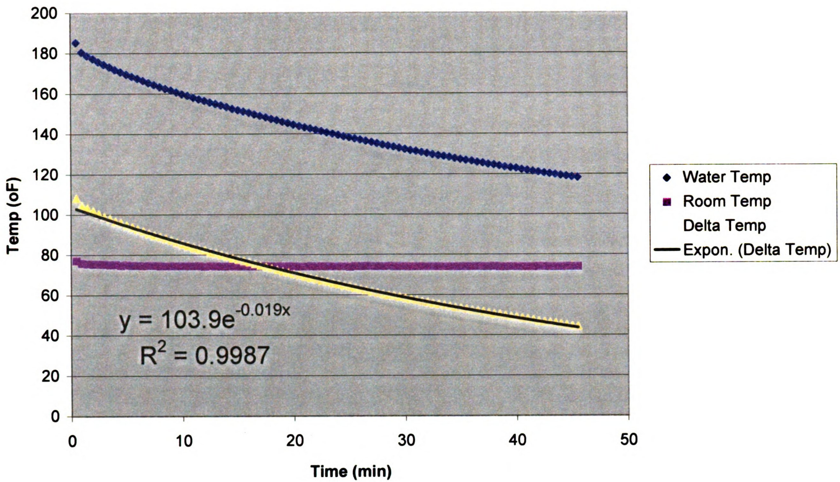


Figure 10: Heat Loss Vs. Time for Water in Paper C

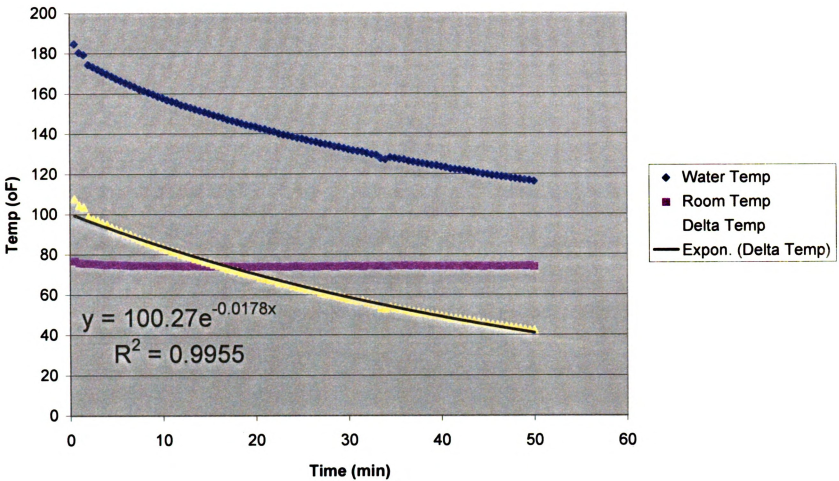


Figure 11: Heat Loss Vs. Time for Water in Foil A

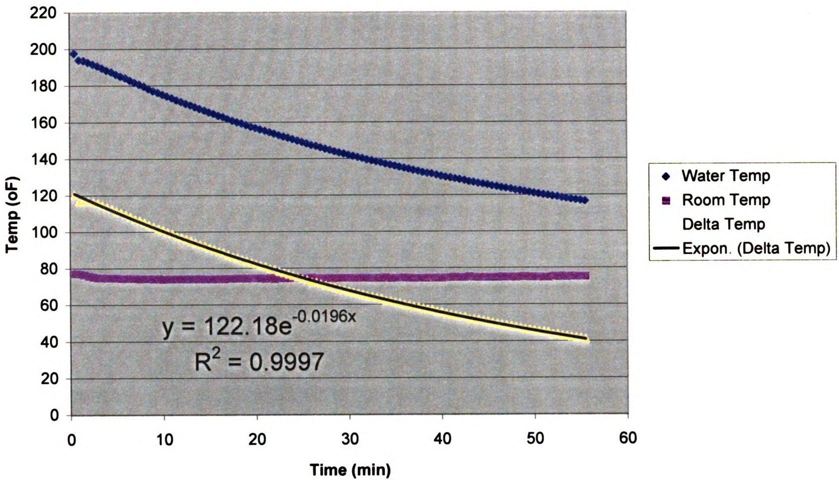


Figure 12: Heat Loss Vs. Time for Water in Foil B

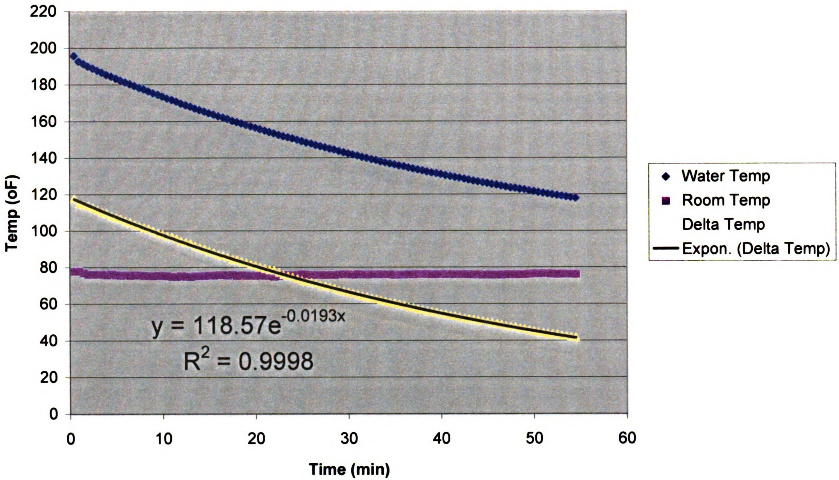
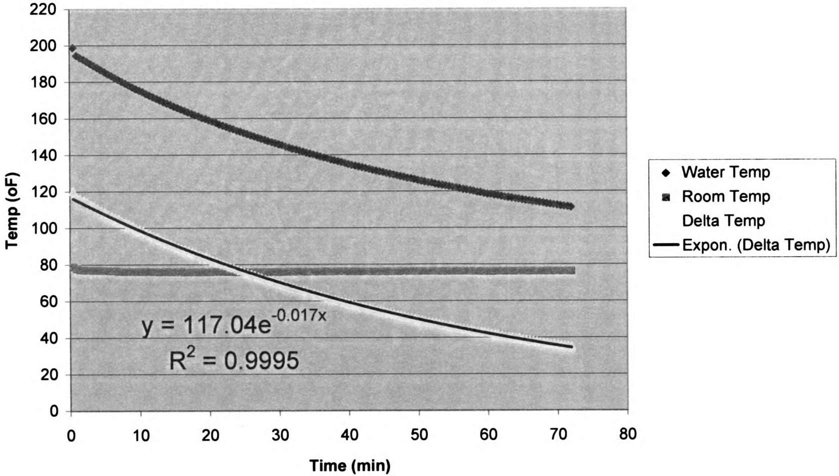


Figure 13: Heat Loss Vs. Time for Water in Foil C



Apendix 2

Heat loss vs. Time Data of Food/Package Systems

Note: The following images in this thesis were originally published in color.

In the following graphs, for the best-fit lines, Y = temperature and X = time.

Figure 14: Heat Loss Vs. Time for Small Microwave Lasagna A

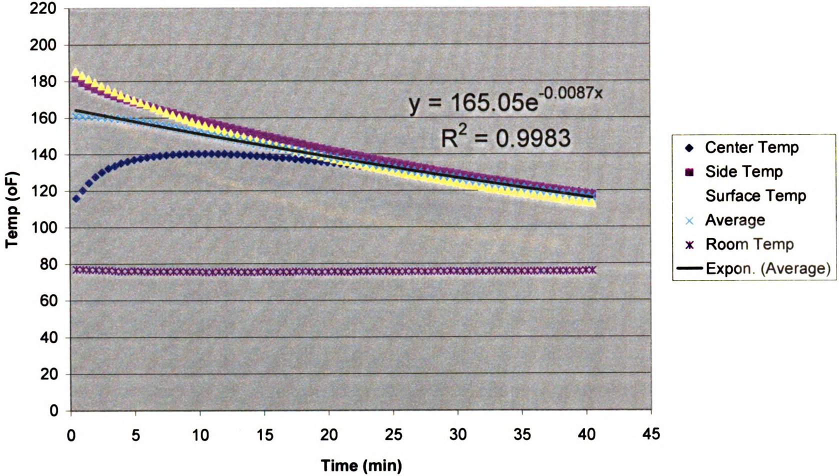


Figure 15: Heat Loss Vs. Time for Small Microwave Lasagna B

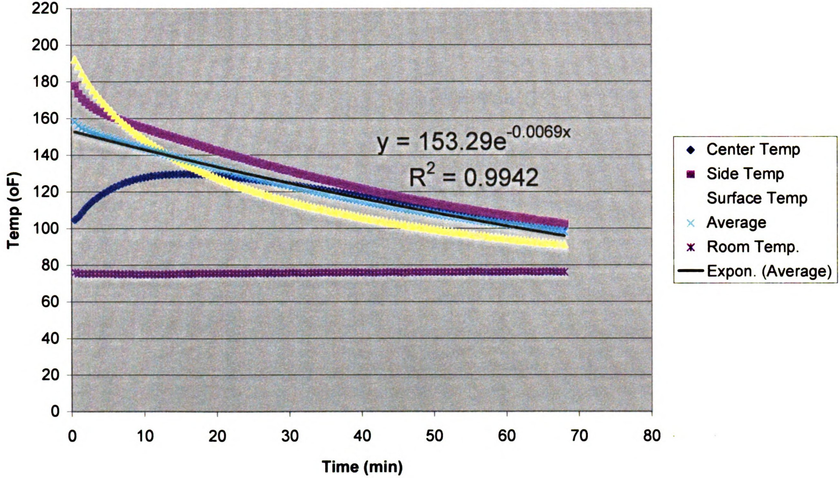


Figure 16: Heat Loss Vs. Time for Small Microwave Lasagna C

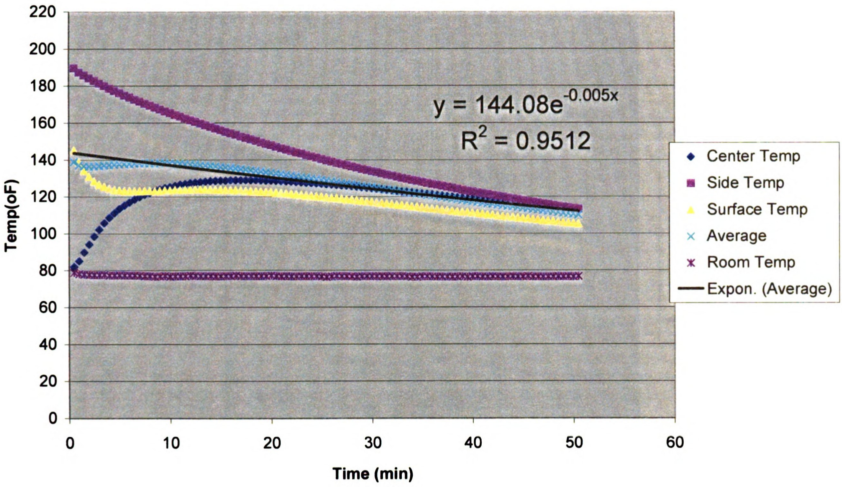


Figure 17: Heat Loss Vs. Time for Medium Microwave Lasagna A

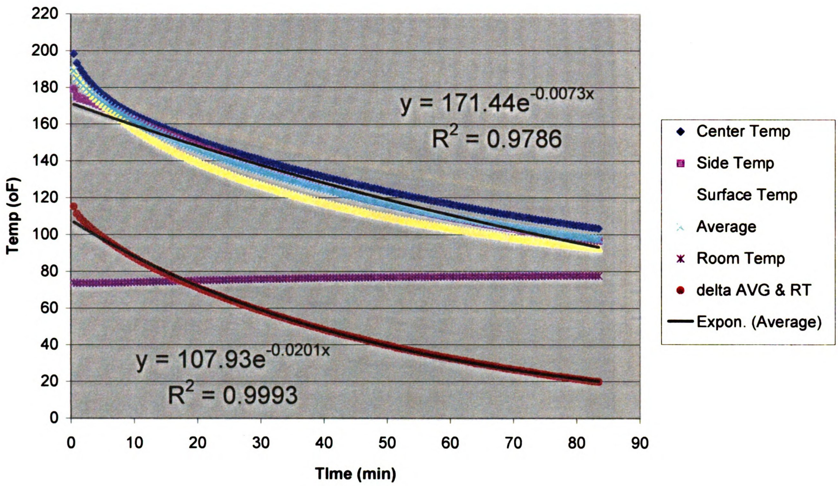


Figure 18: Heat Loss Vs. Time for Medium Microwave Lasagna B

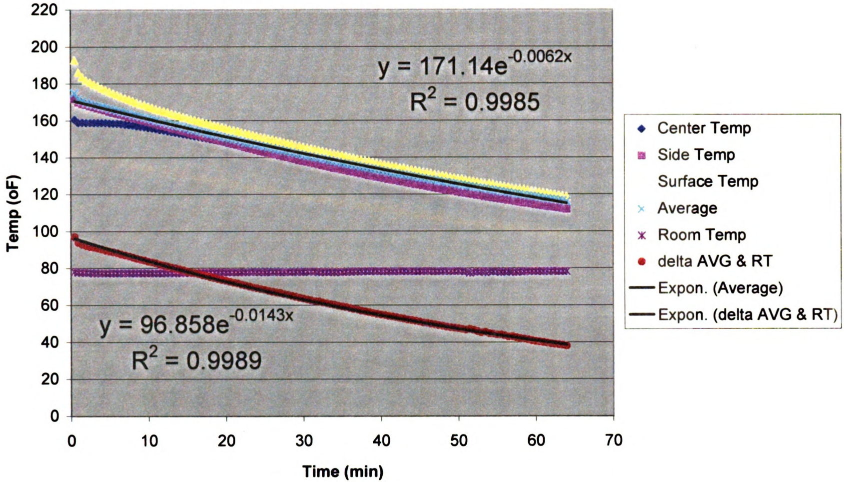


Figure 19: Heat Loss Vs. Time for Medium Microwave Lasagna C

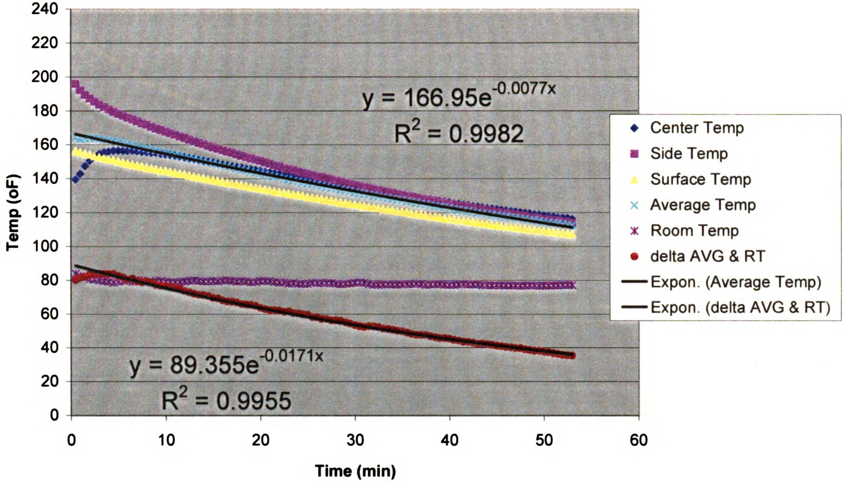


Figure 20: Heat Loss Vs. Time for Microwave Corn A

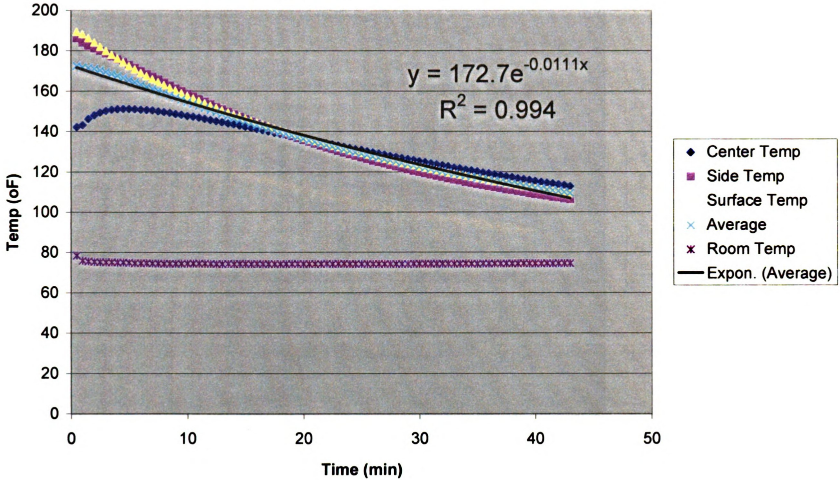


Figure 21: Heat Loss Vs. Time for Microwave Corn B

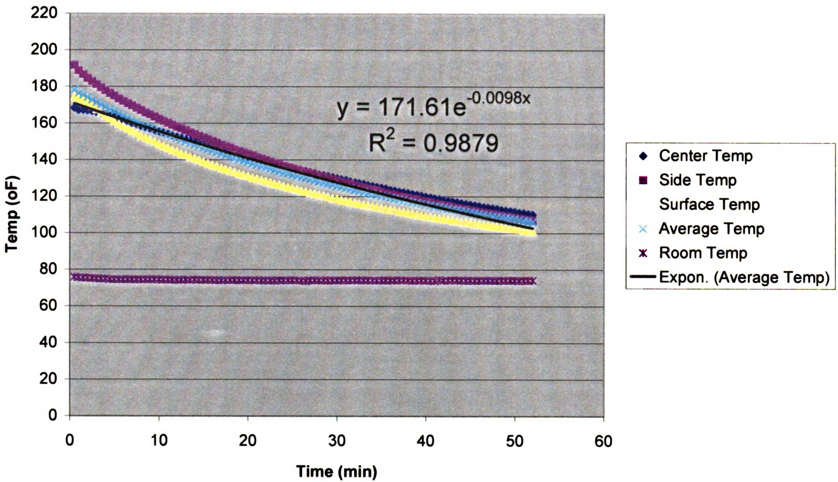


Figure 22: Heat Loss Vs. Time for Microwave Corn C

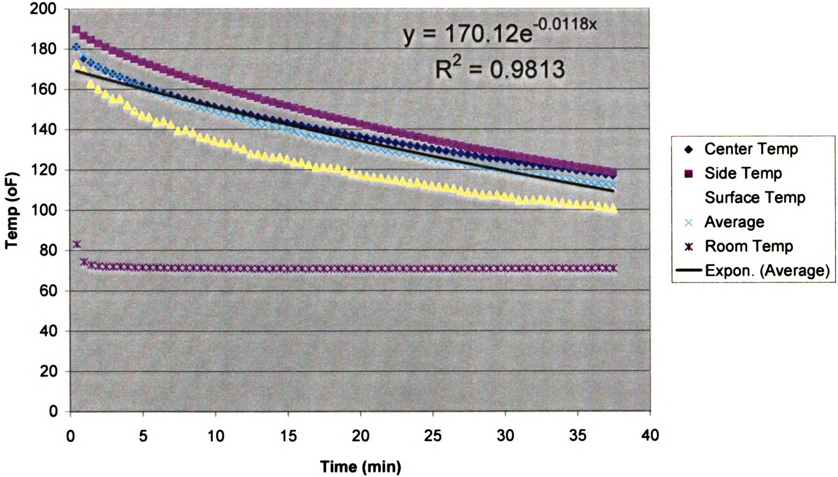


Figure 23: Heat Loss Vs. Time for Microwave Meatloaf A

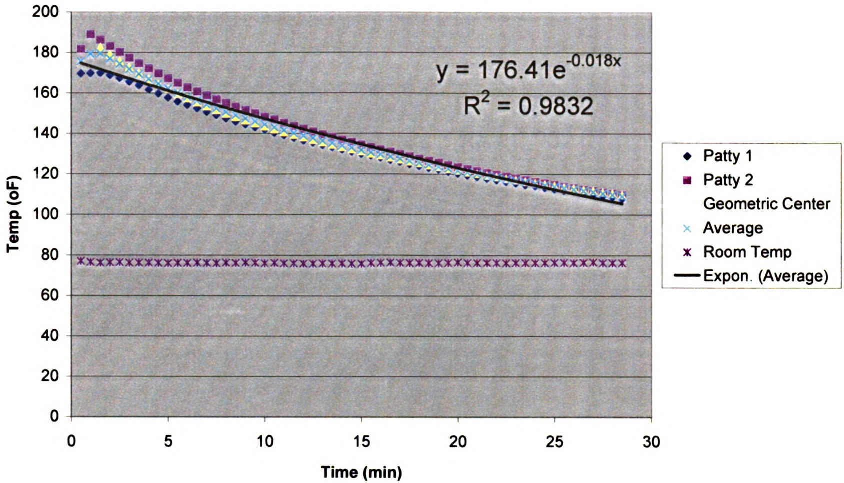


Figure 24: Heat Loss Vs. Time for Microwave Meatloaf B

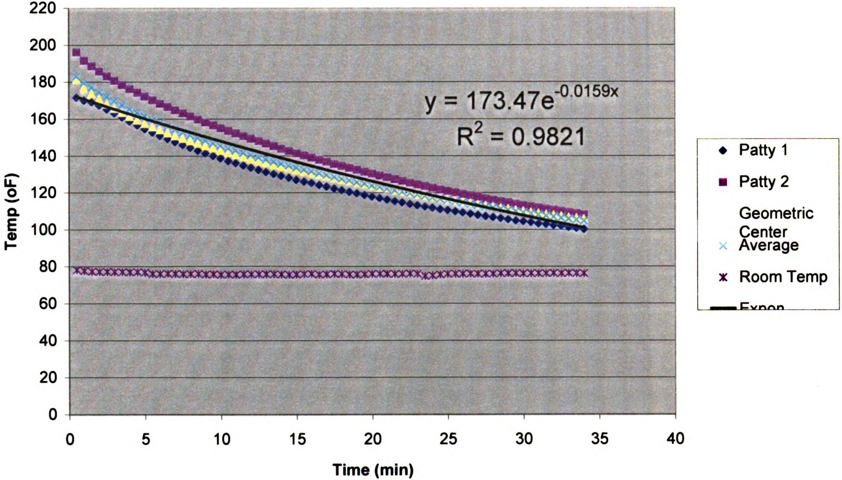


Figure 25: Heat Loss Vs. Time for Microwave Meatloaf C

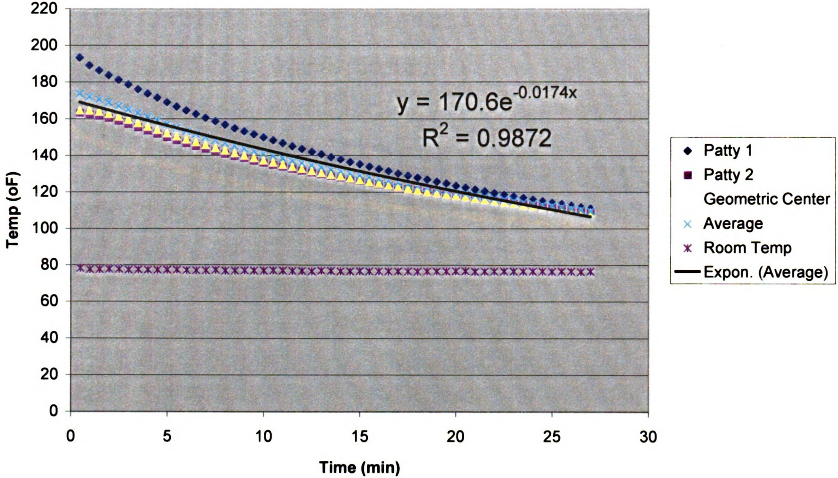


Figure 26: Heat Loss Vs. Time for Small Oven Lasagna A

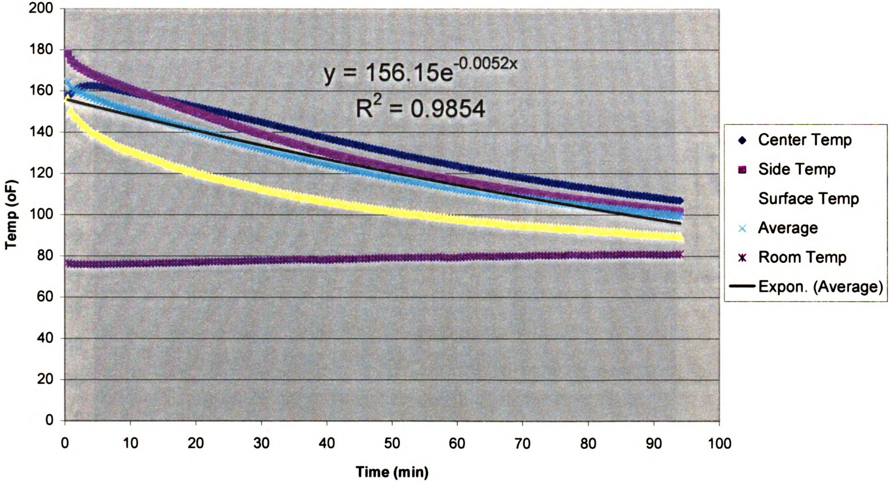


Figure 27: Heat Loss Vs. Time for Small Oven Lasagna B

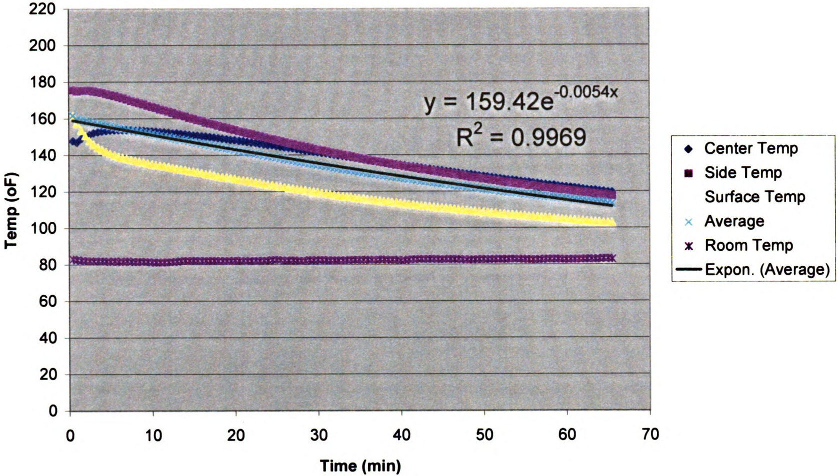


Figure 28: Heat Loss Vs. Time for Small Oven Lasagna C

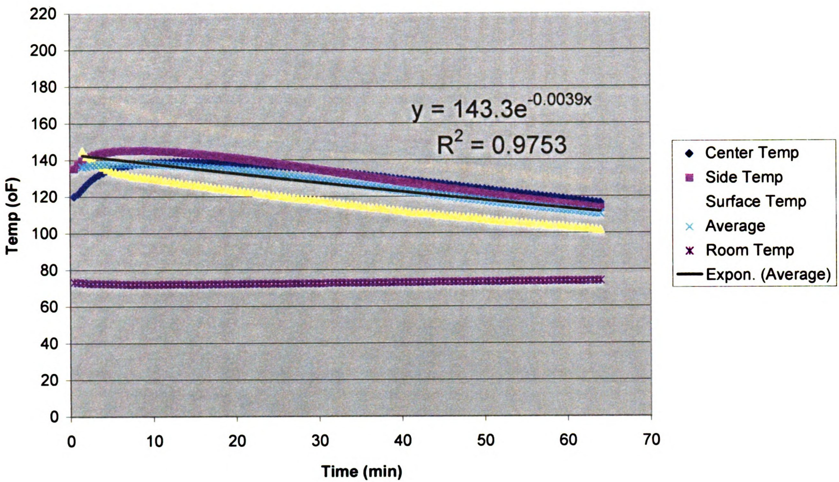


Figure 29: Heat Loss Vs. Time for Medium Oven Lasagna A

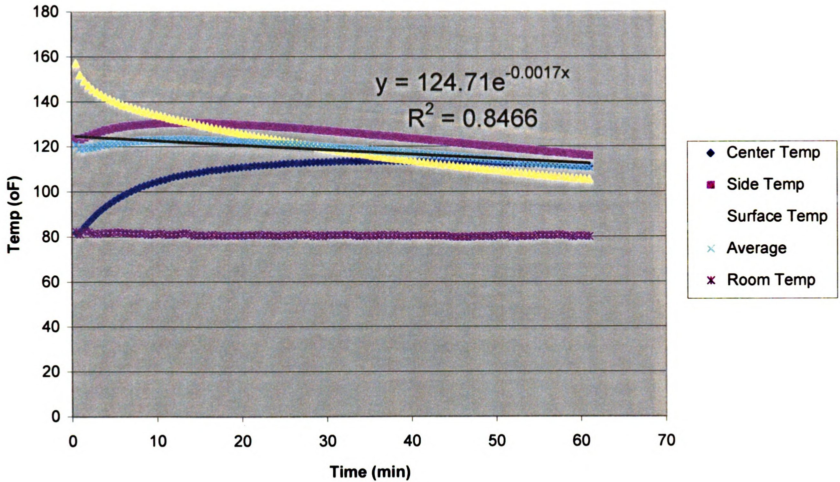


Figure 30: Heat Loss Vs. Time for Medium Oven Lasagna B

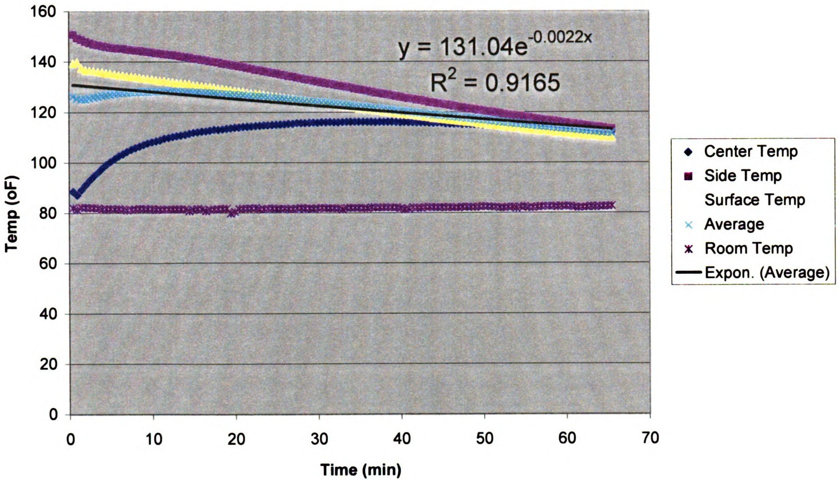


Figure 31: Heat Loss Vs. Time for Medium Oven Lasagna C

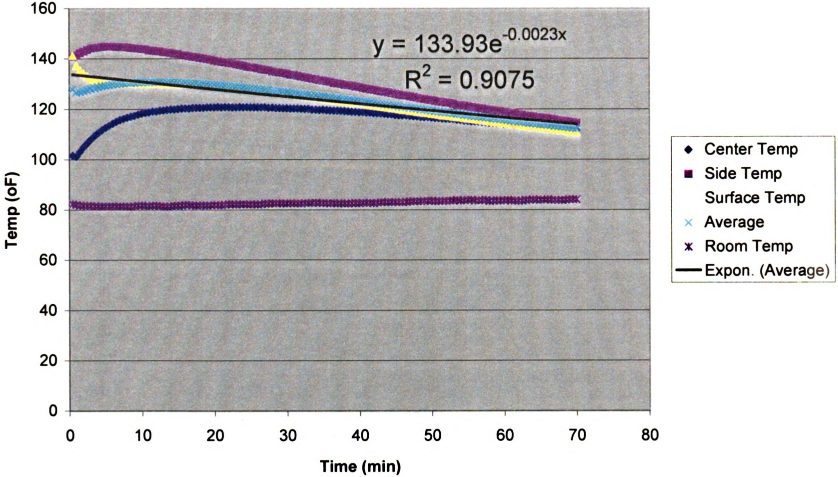


Figure 32: Heat Loss Vs. Time for Oven Corn A

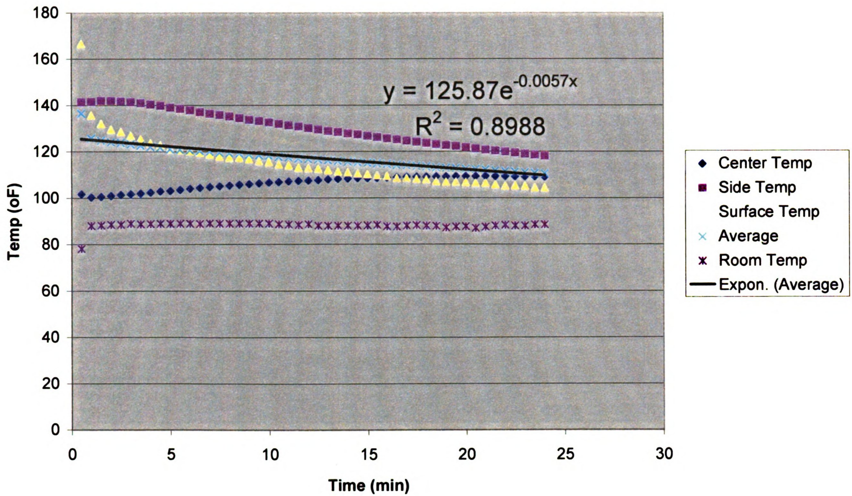


Figure 33: Heat Loss Vs. Time for Oven Corn B

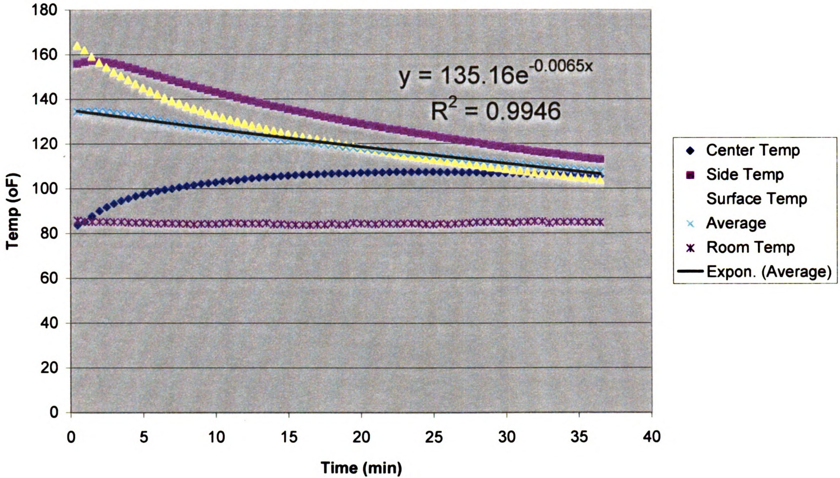


Figure 34: Heat Loss Vs. Time for Oven Corn C

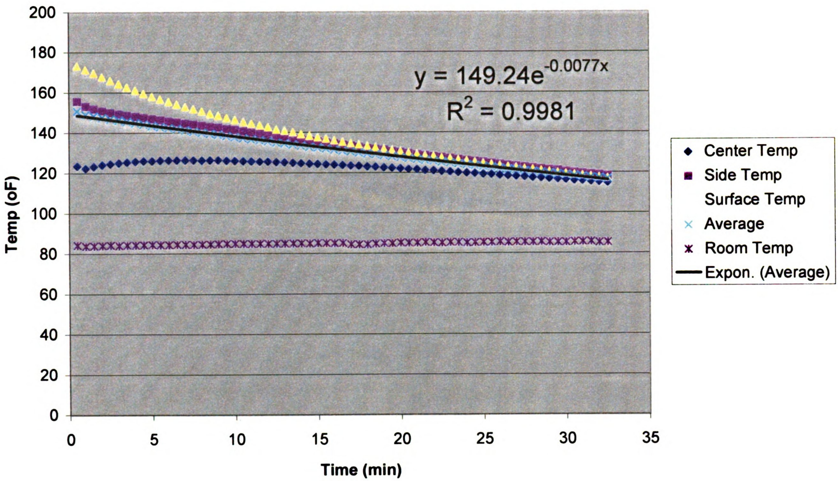


Figure 35: Heat Loss Vs. Time for Oven Meatloaf A

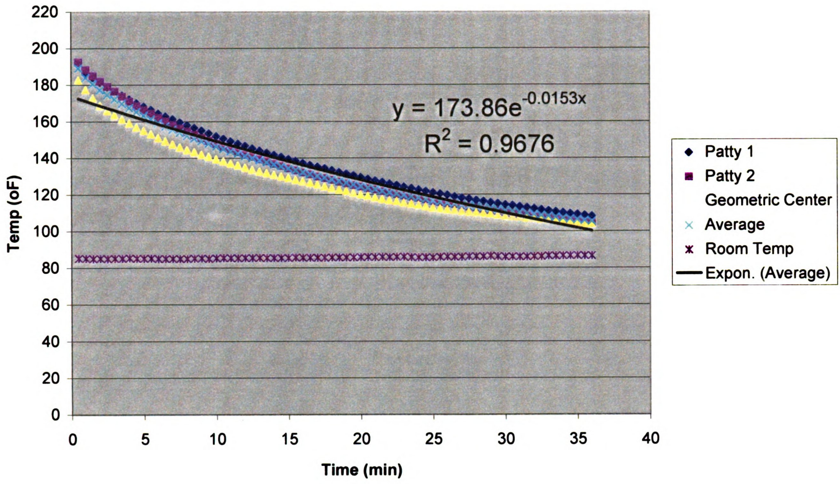


Figure 36: Heat Loss Vs. Time for Oven Meatloaf B

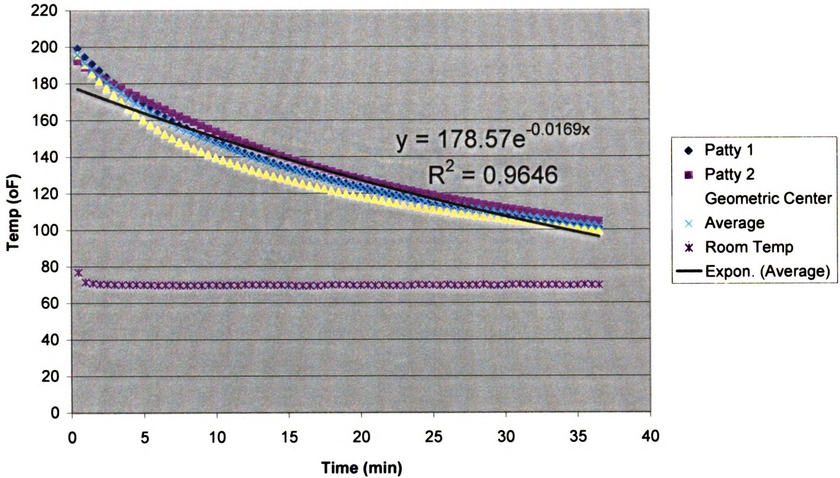
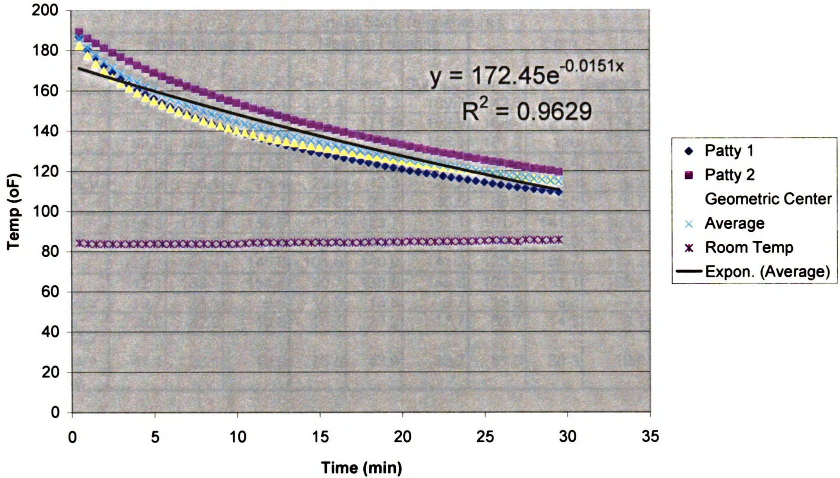


Figure 37: Heat Loss Vs. Time for Oven Meatloaf C



Appendix 3
Initial Temperature Readings of Foods

		Initial Start Temperatures											
		Small Lasagna			Medium Lasagna			Corn			Meatloaf		
		Center	Side	Surface	Center	Side	Surface	Center	Side	Surface	Patty 1	Patty 2	Geometic Center
Microwave	A	116.0	181.9	185.4	198.4	179.3	189.7	142.3	186.3	189.4	169.8	181.9	182.8
	B	104.9	177.9	192.3	160.7	171.9	192.8	168.4	191.8	174.3	171.7	196.3	181.5
	C	82.2	189.8	145.2	139.6	196.0	156.3	181.2	190	172.7	193.4	163.4	164.7
	AVG	101.0	183.2	174.3	166.2	182.4	179.6	164.0	189.4	178.8	178.3	180.5	176.3
	STD DEV	17.2	6.1	25.4	29.8	12.3	20.2	19.8	2.8	9.2	13.1	16.5	10.1
	Range	33.8	11.9	47.1	58.8	24.1	36.5	38.9	5.5	16.7	23.6	32.9	18.1
Oven	A	158.3	178.3	156.5	81.9	123.7	157.1	101.7	141.5	166.7	192.4	192.6	182.8
	B	147.9	175.7	161.6	88.6	150.9	139.4	83.8	156.0	164.1	199.4	192.5	195.8
	C	120.1	135.4	145.0	101.6	140.9	141.3	123.5	155.7	173.2	187	189.4	182.4
	AVG	142.1	163.1	154.4	90.7	138.5	145.9	103.0	151.1	168.0	192.9	191.5	187.0
	STD DEV	19.7	24.1	8.5	10.0	13.8	9.7	19.9	8.3	4.7	6.2	1.8	7.6
	Range	38.2	42.9	16.6	19.7	27.2	17.7	39.7	14.5	9.1	12.4	3.2	13.4
Average Oven Vs. Microwave Difference		-41.1	20.1	19.9	75.5	43.9	33.7	61.0	38.3	10.8	-14.6	-11.0	-10.7