

This is to certify that the

dissertation entitled

MICROWAVE PROCESSING: BACTERIAL SURVIVAL THERMAL
RESPONSES, EVAPORATION LOSS AND HEATING PATTERN
OF MEAT LOAVES AND SIMULATED BENTONITE-BLYCEROL-BHI
BROTH LOAF

presented by

Wen-Syi Lin

has been accepted towards fulfillment
of the requirements for

PhD degree in Foods

Carol A. Sawyer
Major professor

Date November 9, 1989

**PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.**

DATE DUE	DATE DUE	DATE DUE
043		
SEP 06 2022		

MSU Is An Affirmative Action/Equal Opportunity Institution

**MICROWAVE PROCESSING: BACTERIAL SURVIVAL,
THERMAL RESPONSES, EVAPORATION LOSS AND HEATING PATTERN
OF MEAT LOAVES AND
SIMULATED BENTONITE-GLYCEROL-BHI BROTH LOAF**

Volume I

By

Wen-Syi Lin

A DISSERTATION

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

DOCTOR OF PHILOSOPHY

Department of Food Science and Human Nutrition

1989

ABSTRACT

MICROWAVE PROCESSING: BACTERIAL SURVIVAL, THERMAL RESPONSES, EVAPORATION LOSS AND HEATING PATTERN OF MEAT LOAVES AND SIMULATED BENTONITE-GLYCEROL-BHI BROTH LOAF

By

Wen-Syi Lin

That bacteria survive better in microwave processed foods than in conventionally processed foods is well recognized. Hence, the objective of this study was to investigate methods that could be used to improve the microbial quality of foods that had been microwave processed.

Meat loaves (86% ground beef or turkey; 7% dried onion; 6% oatmeal; 0.2% nutmeg; 0.8% salt) and bentonite-glycerol-BHI broth (BGB) loaves (with approximately 10, 20 and 30% fat or glycerol) were inoculated with *Escherichia coli* (O157:H7) and *Staphylococcus aureus* (ATCC 6538), and packed with or without polyvinylidene chloride (PVDC) film into 150, 600 and 1200 g load sizes (n=488 loaves). The loaves were microwave processed at 713 ± 5 or 356 ± 3 watts (2450 MHz) in a domestic-type microwave oven. Each load size was processed using one of four exposed microwave doses (EMD=microwave output power x processing time/load size; 3.57, 4.76, 5.94, and 7.13 watts x min/g) and percent survival of bacteria were assessed. Concurrently, heating pattern and thermal responses, including end-point temperature, microwave processing temperature rise, post processing temperature rise, sum of temperature rise and time of post

processing temperature rise, as well as percent evaporation loss of loaves, were also determined.

Similar bacterial survival in beef and turkey loaves and in the BGB loaf suggested that the BGB loaf has the potential to be a simulation model for bacterial survival of meat loaves (10% fat) after microwave processing. The location of the lowest temperature within a loaf was load-size dependent. Temperature variation within a loaf was improved by wrapping loaves with PVDC film, lowering microwave output power, increasing EMD and reducing load size.

Since EMD was highly correlated to percent survival of bacteria ($R=-0.82$ to -0.83) and the lowest end-point temperature ($R=0.81$) in meat loaves and in BGB models, EMD has the potential to be used to predict bacterial survival in meat products that have been processed by microwave radiation. To optimize microbial quality of beef loaves, the optimal processing conditions suggested by results of the present study were the combined use of: (1) PVDC film; (2) 150 g load size; (3) 20% fat; (4) 50% or less of full microwave output power; and (5) EMD of 5.94 watt x min/g.

Copyright by

Wen-Syi Lin

1989

This work is dedicated to my parents, Dr. and Mrs. Zui-Feng Lin and my wife, Jya-Mei for their love and support, and to my son, Kevin for his cheer.

ACKNOWLEDGEMENTS

The author wishes to thank his graduate committee; Dr. Carol Sawyer, Dr. Alden Booren, Dr. John Gill, Dr. James Pestka and Dr. Mary Zabik for their guidance and assistance. A special thanks to Dr. Sawyer for her professional guidance and assistance throughout my graduate program and to Dr. Pestka for his financial support.

The author wishes to thank the Dow Chemical U.S.A., Midland, Michigan for funding the project. Also thanks to Dr. Michael Doyle of Food Research Institute of University of Wisconsin-Madison and Department of Public Health of State of Michigan for providing the strains of bacteria used in this study.

Lastly, the author wishes to thank Dr. Carl Lee of the Department of Mathematics at Central Michigan University for his statistical advice and valuable time.

TABLE OF CONTENTS

LIST OF TABLES	xvi
LIST OF FIGURES	xviii
KEY TO ABBREVIATIONS AND SYMBOLS	xxiv
I. INTRODUCTION	1
II. LITERATURE REVIEW	3
2.1 Microwave Equipment	4
2.1.1 History of microwave ovens	5
2.1.2 Components of microwave oven	8
2.2 Microwave Processing	11
2.2.1 Theory of microwave heating	12
2.2.2 Thermal responses of a food load that has been microwave processed .	16
2.2.3 Factors affecting microwave heating pattern of food	18
2.2.4 Advantages of microwave processing	21
2.2.5 Disadvantages of microwave processing	24
2.2.6 Temperature measurement in the microwave field	26
2.2.7 Processing loss	28
2.2.8 Applications of microwave processing	29
2.2.8.1 Cooking	29
2.2.8.2 Pasteurization and sterilization	30

2.3 Microbiology of Microwave Processing	31
2.3.1 Enumeration of bacteria	32
2.3.1.1 Injury and resuscitation of bacteria	32
2.3.1.2 Enumeration of injured <i>Escherichia coli</i>	34
2.3.1.3 Enumeration of injured <i>Staphylococcus aureus</i>	35
2.3.1.4 Enumeration of injured aerobic mesophilic bacteria	35
2.3.2 Lethal effect on microorganisms	35
2.3.3 Sublethal (nonthermal) effect on microorganisms	36
2.3.4 Bacterial survival	39
2.3.4.1 Factors which affect bacterial survival	40
2.3.4.2 Bacteria which easily survive microwave processing	48
2.4 Bentonite	50
III. RATIONALE AND HYPOTHESES	54
3.1 Microwave Equipment	54
3.2 Experimental Product	55
3.2.1 Type of loaf	55
3.2.1.1 Meat loaf	55
3.2.1.2 Bentonite-glycerol-BHI broth (BGB) loaf	56
3.2.2 Other variables of experimental products	60
3.2.2.1 Fat content and water content	60
3.2.2.2 Load size	61
3.2.2.3 Shape of container	61
3.3 Microwave processing	62
3.3.1 Polyvinylidene chloride (PVDC) wrapping	62

3.3.2 Microwave output power and processing time	63
3.3.3 Difficulty of temperature measurement	63
3.3.4 Evaporation loss	65
3.4 Microbiology of Microwave Processing	66
3.4.1 Selection of target bacteria	66
3.4.2 Inoculation dose	68
3.4.3 pH and a_w	68
3.5 Strategies to improve microbial quality of microwave processed foods . . .	69
3.5.1 Improve uneven heating pattern	69
3.5.1.1 Wrap food in plastic film	69
3.5.1.2 Regulate load shape	71
3.5.1.3 Use small load size	72
3.5.1.4 Homogenize food load	73
3.5.2 Prolong processing time	74
3.5.2.1 Lower microwave output power	74
3.5.2.2 Extend processing time	75
3.6 Exposed microwave dose	76
IV. MATERIALS AND METHODS	78
4.1 Microwave Equipment	78
4.1.1 Measurement of output wattage in the microwave oven	78
4.2 Experimental Product	79
4.2.1 Actual food loads: beef and turkey loaves	79
4.2.2 Simulated food load: BGB loaf	80

4.2.3 Processing container	80
4.2.4 Load size	80
4.2.5 Time-temperature parameters of handling the experimental product . . .	82
4.2.6 Determination of water content	84
4.2.6.1 Determination of water content in meat loaf	84
4.2.6.2 Determination of water content in BGB loaf	85
4.2.7 Determination of fat content	86
4.2.8 Determination of glycerol content	87
4.2.8.1 Reagents	87
4.2.8.2 Extraction and oxidation of glycerol	87
4.2.8.3 Determination of glycerol	88
4.2.9 Determination of pH	89
4.2.10 Determination of water activity (a_w)	89
4.3 Microwave Processing	91
4.3.1 Microwave output power and processing time	91
4.3.2 Wrapping in PVDC Film	92
4.3.3 Temperature measurement	94
4.3.4 Determination of evaporation loss	94
4.4 Microbiology	96
4.4.1 Inoculation procedure	96
4.4.2 Enumeration method for bacteria	97
4.4.2.1 Sampling and dilution procedure	97
4.4.2.2 Enumeration of <i>Staphylococcus aureus</i>	98
4.4.2.3 Enumeration of <i>Escherichia coli</i>	98

4.4.2.4 Enumeration of aerobic mesophilic bacteria	99
4.5 Experimental Design and Statistical Analyses	100
4.5.1 Analysis of bacterial survival, thermal responses and evaporation loss	101
4.5.1.1 Analysis of main and interaction effects	104
4.5.1.2 Regression model selection	107
4.5.2 Analysis of temperature pattern	109
4.5.2.1 Analysis of temperature distribution	109
4.5.2.2 Analysis of temperature variation	111
V. RESULTS AND DISCUSSION	113
5.1 Beef Loaf	113
5.1.1 Effect of polyvinylidene chloride (PVDC) wrapping	114
5.1.1.1 Bacterial survival	114
5.1.1.2 Thermal responses	119
5.1.1.3 Evaporation loss	129
5.1.2 Effect of load size	131
5.1.2.1 Bacterial survival	131
5.1.2.2 Thermal responses	133
5.1.2.3 Evaporation loss	134
5.1.3 Effect of microwave output power	135
5.1.3.1 Bacterial survival	135
5.1.3.2 Thermal responses	138
5.1.3.3 Evaporation loss	139
5.1.4 Effect of percent fat content	140



5.1.4.1 Bacterial survival	140
5.1.4.2 Thermal responses	141
5.1.4.3 Evaporation loss	144
5.1.5 Effect of percent water content	145
5.1.5.1 Bacterial survival	145
5.1.5.2 Thermal responses	146
5.1.5.3 Evaporation loss	146
5.1.6 Effect of exposed microwave dose	146
5.1.6.1 Bacterial survival	147
5.1.6.2 Thermal responses	149
5.1.6.3 Evaporation loss	150
5.1.6.4 Summary	150
5.2 Turkey Loaves	151
5.2.1 Effect of PVDC wrapping	151
5.2.1.1 Bacterial survival	152
5.2.1.2 Thermal responses	153
5.2.1.3 Evaporation loss	156
5.2.2 Effect of load size	163
5.2.2.1 Bacterial survival	163
5.2.2.2 Thermal responses	164
5.2.2.3 Evaporation loss	164
5.2.3 Effect of microwave output power	165
5.2.3.1 Bacterial survival	165
5.2.3.2 Thermal responses	166

5.2.3.3 Evaporation loss	166
5.2.4 Effect of exposed microwave dose	167
5.2.4.1 Bacterial survival	167
5.2.4.2 Thermal responses	168
5.2.4.3 Evaporation loss	168
5.3 BGB Loaves	169
5.3.1 Effect of percent glycerol content	170
5.3.1.1 Bacterial survival	170
5.3.1.2 Thermal responses	173
5.3.1.3 Evaporation loss	179
5.3.2 Effect of exposed microwave dose	181
5.3.2.1 Bacterial survival	181
5.3.2.2 Thermal responses	181
5.3.2.3 Evaporation loss	182
5.4 Beef Loaves versus Turkey Loaves	183
5.4.1 Effect of type of loaf	183
5.4.1.1 Bacterial survival	184
5.4.1.2 Thermal responses	184
5.4.1.3 Evaporation loss	186
5.4.2 Effect of PVDC wrapping	187
5.4.2.1 Bacterial survival	187
5.4.2.2 Thermal responses	188
5.4.2.3 Evaporation loss	188

5.4.3 Effect of load size	189
5.4.3.1 Bacterial survival	189
5.4.3.2 Thermal responses	190
5.4.3.3 Evaporation loss	190
5.4.4 Effect of microwave output power	191
5.4.4.1 Bacterial survival	191
5.4.4.2 Thermal responses	192
5.4.4.3 Evaporation loss	193
5.4.5 Effect of exposed microwave dose	193
5.4.5.1 Bacterial survival	194
5.4.5.2 Thermal responses	194
5.4.5.3 Evaporation loss	195
5.5 Beef Loaves versus Turkey Loaves versus BGB Loaves	196
5.5.1 Effect of type of loaf	196
5.5.1.1 Bacterial survival	197
5.5.1.2 Thermal responses	197
5.5.1.3 Evaporation loss	199
5.5.2 Effect of load size	200
5.5.2.1 Bacterial survival	200
5.5.2.2 Thermal responses	201
5.5.2.3 Evaporation loss	202
5.5.3 Effect of exposed microwave dose	202
5.5.3.1 Bacterial survival	203
5.5.3.2 Thermal responses	203

5.5.3.3 Evaporation loss	204
5.6 Interactions	205
5.6.1 Effect of interactions on bacterial survival	205
5.6.2 Effect of interactions on thermal responses	213
5.6.2.1 Effect of interactions on microwave processing temperature rise . .	214
5.6.2.2 Effect of interactions on post processing temperature rise	215
5.6.2.3 Effect of interactions on time of post processing temperature rise .	216
5.6.3 Effect of interactions on percent evaporation loss	218
5.6.4 Effect of interactions that related to type of loaf	220
5.6.4.1 Effect of interaction of type of loaf and load size	221
5.6.4.2 Effect of interaction of type of loaf and exposed microwave dose	224
5.6.4.3 Summary	224
5.7. Effect of Other Independent Variables	225
5.7.1 pH	225
5.7.2 Replication	226
5.8 Temperature Pattern	226
5.8.1 Temperature distribution within a loaf	227
5.8.2 Effects of experimental variables on temperature variation within a loaf	238
5.9 Summary of Results	250
5.9.1 Significant levels of main effects of independent variables	251
5.9.2 Significant two-way interactions of independent variables	254
5.9.3 Summary of effects of independent variables	257
5.9.4 Summary of optimal microwave processing conditions	259

VI. CONCLUSIONS AND RECOMMENDATIONS	262
6.1 Conclusions	262
6.2 Recommendations	265
LIST OF REFERENCES	269
APPENDICES	283
Appendix 1. The Fortran subroutines used to rearrange TEMP data set.	283
Appendix 2. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>beef loaves (10, 20 and 30% fat)</u>.	284
Appendix 3. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>turkey loaves (10% fat)</u>.	289
Appendix 4. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>BGB loaves (150 g)</u>.	294
Appendix 5. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>beef loaves (10% fat) and turkey loaves (10% fat)</u>	297
Appendix 6. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol)</u>	302
Appendix 7. The ANOVA results of location of after-processing temperature (APT) computed by the SAS GLM procedure with REPEATED statement for loaves (beef, turkey and BGB).	307
Appendix 8. The ANOVA results of location of end-point temperature (EPT) computed by the SAS GLM procedure with REPEATED statement for loaves (beef, turkey and BGB)	308
Appendix 9. The ANOVA results of temperature variation within a loaf computed by the SAS GLM procedure for a data subset of <u>beef loaves (10, 20 and 30% fat)</u>	309

LIST OF TABLES

Table 1. The dielectric and thermal properties of beef, turkey and bentonite-water dispersions (20:80).	57
Table 2. List of microwave processing treatments used for experimental products.	64
Table 3. Bact Data Set: List of variables used in statistical analysis for bacterial survival, thermal responses and evaporation loss.	102
Table 4. Temp Data Set: List of variables used in statistical analysis for temperature pattern.	103
Table 5. The conditions used in the SAS GLM procedure to analyze the effect of independent variables on bacterial survival, thermal responses, evaporation loss and temperature variation.	105
Table 6. List of full models used in the SAS RSQUARE procedure for optimal subsets selection.	108
Table 7. The main effect of polyvinylidene chloride wrapping (WP) on bacterial survival, thermal responses and evapoartion loss of loaves (beef and turkey) after microwave processing (2450 MHz).	118
Table 8. The main effect of load size (LS) on bacterial, thermal responses and evapoartion loss of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).	132
Table 9. The main effect of microwave output power (MP) on bacterial survival, thermal responses and evapoartion loss of loaves (beef and turkey) after microwave processing (2450 MHz).	137
Table 10. The main effect of percent fat or glycerol content (PFC) on bacterial survival, thermal responses and evapoartion loss of loaves (beef and BGB) after microwave processing (2450 MHz).	142
Table 11. The main effect of exposed microwave dose (EMD) on bacterial survival, thermal responses and percent evapoartion loss of loaves (beef, tukrey and BGB) after microwave processing (2450 MHz).	148

Table 12. The main effect of type of loaf (TL) on bacterial survival, thermal responses and evapoartion loss of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).	185
Table 13. Statsitical results of two-way crosstabulation table of load size (LS) by location of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).	229
Table 14. Statsitical results of two-way crosstabulation tables of type of loaf (TL), polyvinylidene chloride wrapping (PW), microwave output power (MP) and exposed microwave dose (EMD) by location of varied load sizes of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).	230
Table 15. The main effect of polyvinylidene chloride wrapping (PW), microwave output power (MP), percent fat content (PFC) and exposed microwave dose (EMD) on temperature variation of beef loaves after microwave processing (2450 MHz).	244
Table 16. Summary of the significant levels of main effects of polyvinylidene chloride wrapping (WP), load size (LS), microwave output power (MP), percent fat content (PFC), exposed microwave dose (EMD) and type of loaf (TL) on bacterial survival, thermal responses, evaporation loss and temperature variation of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).	252
Table 17. List of significant two-way interactions of independent variables on bacterial survival, thermal responses and evaporation loss of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).	255
Table 18. List of significant two-way interactions of independent variables on temperature variation of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).	256
Table 19. Summary of the effects of polyvinylidene chloride wrapping (WP), load size (LS), microwave output power (MP), percent fat content (PFC), exposed microwave dose (EMD) on bacterial survival, thermal responses, evaporation loss and temperature variation of loaves (beef, turkey and BGB loaves) after microwave processing (2450 MHz).	258
Table 20. Summary of optimal microwave processing conditions for microbial quality, thermal responses, evaporation loss and temperature uniformity of beef loaves.	260

LIST OF FIGURES

Figure 1. Basic components of a microwave oven	9
Figure 2. Microwaves in the electromagnetic spectrum.	13
Figure 3. Doughnut-Shaped Pyrex™ container which held loaves during microwave processing.	81
Figure 4. The plastic packer used to pack loaves into a doughnut-shaped Pyrex™ container.	93
Figure 5. Framework to hold sixteen thermocouples for post processing temperature measurement of loaves processed by microwave radiation. . .	95
Figure 6. Predicted response surface of surviving <i>Escherichia coli</i> in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	115
Figure 7. Predicted response surface of surviving <i>Staphylococcus aureus</i> in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	116
Figure 8. Predicted response surface of surviving aerobic bacteria in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power. . .	117
Figure 9. Predicted response surface of end-point temperature in beef loaf (10% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	120
Figure 10. Predicted response surface of end-point temperature in beef loaf (20% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	121

Figure 11. Predicted response surface of end-point temperature in beef loaf (30% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	122
Figure 12. Predicted response surface of microwave processing temperature rise in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	123
Figure 13. Predicted response surface of sum of temperature rise in beef loaf (10% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	124
Figure 14. Predicted response surface of sum of temperature rise in beef loaf (20% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	125
Figure 15. Predicted response surface of sum of temperature rise in beef loaf (30% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	126
Figure 16. Predicted response surface of post processing temperature rise in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	127
Figure 17. Predicted response surface of time of post processing temperature rise in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	128
Figure 18. Predicted response surface of percent evaporation loss in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).	130
Figure 19. Predicted response surface of surviving Escherichia coli in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).	153
Figure 20. Predicted response surface of surviving Staphylococcus aureus in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).	154

Figure 21. Predicted response surface of surviving aerobic bacteria in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).	155
Figure 22. Predicted response surface of end-point temperature in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power. . .	157
Figure 23. Predicted response surface of microwave processing temperature rise in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	158
Figure 24. Predicted response surface of sum of temperature rise in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	159
Figure 25. Predicted response surface of post processing temperature rise in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	160
Figure 26. Predicted response surface of time of post processing temperature rise in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	161
Figure 27. Predicted response surface of percent evaporation loss in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.	162
Figure 28. Predicted response surface of surviving bacteria in 150 g load size of unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).	171
Figure 29. Predicted response surface of end-point temperature in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).	174
Figure 30. Predicted response surface of microwave processing temperature rise in unwrapped 150 load size of bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).	175

Figure 31. Predicted response surface of sum of temperature rise in unwrapped bentonite-glycerol-BHI broth (BGB) loaf without wrapping after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).	176
Figure 32. Predicted response surface of post processing temperature rise in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).	177
Figure 33. Predicted response surface of time of post processing temperature rise in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W)	178
Figure 34. Predicted response surface of percent evaporation loss in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).	180
Figure 35. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean of percent survival of <i>Escherichia coli</i> in beef loaf after microwave processing (2450 MHz).	206
Figure 36. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean of microwave processing temperature rise (MPTR) in beef loaf after microwave processing (2450 MHz).	207
Figure 37. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean of post processing temperature rise (PPTR) in beef loaf after microwave processing (2450 MHz).	208
Figure 38. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean of time of post processing temperature rise (TPPTR) in beef loaf after microwave processing (2450 MHz).	209
Figure 39. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean of percent evaporation loss (PEL) in beef loaf after microwave processed (2450 MHz).	210

Figure 40. The significant two-way interaction plots of type of loaf (TL) and load size (LS) and exposed microwave dose (EMD) on means of percent survival of <i>E. coli</i> (LEC), microwave processing temperature rise (MPTR), post processing temperature rise (PPTR), time of TTPR (TPPTR) and percent evaporation loss (PEL) in loaves after microwave processing (2450 MHz).	222
Figure 41. The frequency of location distribution for the lowest after-processing temperature (APT) within in a loaf (varied load sizes [LS] of beef, turkey and BGB).	231
Figure 42. The frequency of location distribution for the highest after-processing temperature (APT) within in a loaf (varied load sizes [LS] of beef, turkey and BGB).	232
Figure 43. The frequency of location distribution for the lowest end-point temperature (EPT) within in a loaf (varied load size [LS] of beef, turkey and BGB).	233
Figure 44. The frequency of location distribution for the highest end-point temperature (EPT) within in a loaf (varied load size [LS] of beef, turkey and BGB).	234
Figure 45. The overall means of after-processing temperature (APT) and end-point temperature (EPT) at varied locations within a 150 g load size of loaf (beef, turkey and BGB).	235
Figure 46. The overall means of after-processing temperature (APT) and end-point temperature (EPT) at varied locations within a 600 g load size of loaf (beef, turkey and BGB).	236
Figure 47. The overall means of after-processing temperature (APT) and end-point temperature (EPT) at varied locations within a 1200 g load size of loaf (beef, turkey and BGB).	237
Figure 48. The frequency of location distribution for a group of the four lowest after-processing temperatures (APTs) within a loaf (varied load sizes [LS] of beef, turkey or BGB).	239
Figure 49. The frequency of location distribution for a group of the four highest after-processing temperatures (APTs) within a loaf (varied load sizes [LS] of beef, turkey or BGB).	240
Figure 50. The frequency of location distribution for a group of the four lowest end-point temperatures (EPTs) within a loaf (varied load sizes [LS] of beef, turkey or BGB).	241

Figure 51. The frequency of location distribution for a group of the four highest end-point temperatures (EPTs) within a loaf (varied load sizes [LS] of beef, turkey or BGB).	242
Figure 52. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean log value and range of 16 microwave processing temperature rises (LMPTRs and RMPTRs) within a beef loaf after microwave processing (2450 MHz).	247
Figure 53. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean log value and range of 16 post processing temperature rises (LPPTRs and RPPTRs) within a beef loaf after microwave processing (2450 MHz).	248
Figure 54. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), and exposed microwave dose (EMD) on mean log value and range of 16 post processing temperature rises (LSTRs and RSTRs) within a beef loaf after microwave processing (2450 MHz).	249

L
L
L
L
L
L

KEY TO ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS:

- APT = after-processing temperature (°C), taken at the time when microwave oven was turned off.
- BGB = bentonite-glycerol-brain heart infusion broth.
- EMD = exposed microwave dose (watt x min/g);
$$\text{EMD} = [(713 \times \text{MP}/100) \times (\text{PT}/60)] / \text{LS}.$$
- EPT = end-point temperature (°C), taken at the time when the rise of post processing temperature stop.
- FAB = final aerobic bacteria count.
- FEC = final *E. coli* count.
- FSA = final *S. aureus* count.
- IAB = initial aerobic bacteria count.
- IEC = initial *E. coli* count.
- IPT = initial product temperature (°C).
- ISA = initial *S. aureus* count.
- LAB = log value of percent surviving aerobic bacteria plus 1.
$$\text{LAB} = \log[(100 \times \text{FAB}/\text{IAB}) + 1].$$
- LEC = log value of percent surviving *E. coli* plus 1.
$$\text{LEC} = \log[(100 \times \text{FEC}/\text{IEC}) + 1].$$
- LSA = log value of percent surviving *S. aureus* plus 1.
$$\text{LSA} = \log[(100 \times \text{FSA}/\text{ISA}) + 1].$$
- LMPTR = log value of standard deviation of 16 MPTRs within a loaf (°C).
- LPPTR = log value of standard deviation of 16 PPTRs within a loaf (°C).
- LS = load size (g).
- LSTR = log value of standard deviation of 16 STRs within a loaf (°C).

MP = microwave output power (%).
MPTR = microwave processing temperature rise (°C). $MPTR = APT - IPT$.
PEL = percent evaporation loss (%).
PFC = percent fat or glycerol content (%).
PPTR = post processing temperature rise (°C). $PPTR = EPT - APT$.
PT = processing time (sec).
PW = polyvinylidene chloride film wrapping;
 1= PVDC film wrapped, -1= not wrapped.
PWC = percent water content (%).
RAPT = range of 16 APTs within a loaf (°C).
REP = replication.
REPT = range of 16 EPTs within a loaf (°C).
RMPTR = range of 16 MPTRs within a loaf (°C).
RPPTR = range of 16 PPTRs within a loaf (°C).
RSTR = range of 16 STRs within a loaf (°C).
STR = sum of temperature rise (°C). $STR = EPT - IPT$ or $MPTR + PPTR$.
TL = type of loaf. 1=beef, 2=turkey, 3=BGB.
TPPTR = time of PPTR (sec).

SYMBOLS:

Alfa	α	= Attenuation factor (cm^{-1}), which determines levels of power absorption within the product as a function of depth from the surface.
Delta	δ	= Loss tangent; ϵ''/ϵ', which is related to the product's ability to be penetrated by an electrical field and to dissipate electrical energy as heat.
Epsilon prime	ϵ'	= Dielectric constant, which is related to the amount of electrical energy that can be stored in a product.
Epsilon double prime	ϵ''	= Dielectric loss factor, which is related to the amount of energy a dielectric product can dissipate in the form of heat when the product is exposed to an alternating electrical field.
Eta	η	= intrinsic impedance of product (ohm), which determines whether electrical energy will be absorbed, reflected, or transmitted by product.

CHAPTER I

INTRODUCTION

Although microwave radiation was first used for food processing in the early 1940s, use of microwaves exhibited slow progress during the 20 years that followed [Dcareau, 1985]. Not until the first household microwave oven was introduced into the market in 1967, did the popularity of microwave ovens grow rapidly. By 1989, more than 70% of American households were estimated to have a microwave oven [IFT, 1989]. With increasing demand for microwave ovens, the potential for public health hazards such as food poisoning related to microwave processing also increased.

Microbial quality of foods that have been microwave processed should become a major consumer issue of the 1990's [IFT, 1989]. In the past, microwave processing has been well known for it's uneven heating within and among foods that have been processed [Carlin et al., 1982; Ohlsson and Risman, 1978; Ringle and David, 1975; Sawyer, 1985; Schiffmann, 1981]. Research had shown that high levels of bacterial survival after microwave processing were related to uneven heating [Carlin et at., 1982; IFT, 1989; Rosenburg and Bölg, 1987b; Schiffmann, 1981].

Cousumers follow quidelines for cooking time, power level, and EPT provided by microwave oven manufacturers and food processors. However, these quidelines do not provide enough detailed information to cover wide ranges of variation in microwave ovens, processing and product variables. Further, the use of temperature as an indicator for the end of microwave processing has been questioned (Bryan and Lyon, 1984). Although some microwave ovens are equipped with a thermoprobe, the

accuracy of such thermoprobes is doubtful. Even if consumers are willing to use a thermoprobe, insertion of the probe is no guarantee that the foods will be cooked to completion because no one location for temperature measurement has been shown to be representative of the entire product. The use of temperature to indicate the doneness of food products at the present is inappropriate and microbiologically unsafe. To overcome this problem, indicators other than temperature should be developed to determine the end of microwave processing.

Household applications of destruction of bacteria in a microwave field have been considered unsuccessful when compared to the the success of industrial processes of pasterization and sterilization using microwave energy [Rosenburg and Bölg, 1987b]. Therefore, this study is focused on the household applications to study the effects of microwave processing and product variables on destruction of bacteria.

The purpose of this study was: (1) to understand the main effects of microwave processing and product variables and their interactions on bacterial survival, thermal responses and temperature pattern of experimental products; (2) to determine if bentonite-glycerol-BHI broth (BGB) dispersions could serve as a simulation model for beef and/or turkey loaves that had been processed in microwave ovens; (3) to recommend an alternate indicator for the end of microwave processing; and (4) to recommend optimal microwave processing conditions for meat products based on the results of this study.

CHAPTER II

LITERATURE REVIEW

Microwave radiation was first used for food processing in the early 1940s [Decareau, 1985]. Since then, progress on microwave processing of food products has been slow due to the high cost and lack of advancements in technology [Decareau, 1985]. The first microwave oven, introduced into the household in market in 1967, was considered a luxury item. Twenty years later, microwave ovens had become a standard household appliance [Dziezak, 1987]. With increasing demand for microwave ovens, the potential for public health hazards such as food poisoning due to improper microwave processing will also increase. Microbial quality of microwave processed foods should become a major consumer issue of the 1990s [IFT, 1989].

Compared to other fields, microwave research on food applications has been minimal. Such research is necessary to answer many questions being asked by consumers. Unfortunately, many early research studies were not usable because they lacked indication of and proper control over microwave output [Van Zante, 1973].

This literature review focuses on microwave processing with special attention given to effects of microwave heating on destruction of bacteria. The potential use of bentonite as a simulated food product for microwave processing is also reviewed.

2.1 Microwave Equipment

Microwave ovens may be divided into three general categories based on power output and oven cavity size. Types of microwave ovens include consumer (domestic), commercial, and industrial. Consumer microwave ovens are usually less than 1,000 watts (within the cavity). Those ovens with a power output between 1,000 and 2,000 watts are considered to belong to the commercial group and are commonly used in restaurant type operations [Van Zante, 1973]. Industrial microwave equipment is either batch or conveyor type with one or more magnetrons and can generate multi-kilowatts of power [Decareau, 1985]. The prevalent and commonly accepted wavelength frequency for microwave heating is 2,450 megahertz (10^6 cycles/sec or MHz). A wavelength frequency of 915 MHz also is used in China [Chen, et al., 1982], Japan [Suzuki and Oshima, 1973], the United States [Decareau, 1982; Schiffmann, 1973, 1976a], and Europe [Meisel, 1973].

The most favorable condition for microwave heating food exists when a high frequency of microwave (contains high energy) is applied the food load and the dielectric absorption factor (the ability of a material to absorb dielectric energy) of the food load is maximum; these conditions assure that a large amount of microwave energy is converted efficiently to heat within the food [Copson, 1975b]. Theoretically, to obtain uniform heating, low frequency is preferable, but in practice a frequency between 900 MHz and 3,000 MHz is a good compromise between maximum heating and uniformity of heating. This is one reason 915 MHz and 2,450 MHz have predominately been chosen for use with microwave ovens [Garrick, 1966].

Other reasons for the choice of 915 MHz and 2,450 MHz as microwave frequencies are related to federal regulation in the U.S.. The frequencies for microwave heating are regulated by the Federal Communications Commission (F.C.C.) which provides certain frequencies for industrial, scientific, and medical (I.S.M.) uses to avoid interfering with microwave communications. The frequencies permitted by F.C.C for I.S.M. uses are [Decareau 1985]:

13.56	MHz	±	6.68	KHz
27.12	MHz	±	160	KHz
40.68	MHz	±	20	KHz
915	MHz	±	25	MHz
2,450	MHz	±	50	MHz
5,800	MHz	±	75	MHz
22,125	MHz	±	125	MHz

Of these, only 915 and 2,450 Mhz frequency are practical in commercial and domestic food preparation because both frequencies can generate heat efficiently with a relatively reason uniform heating pattern [Copson, 1975b].

2.1.1 History of microwave ovens

In 1832, Michael Faraday postulated the electromagnetic field (the field of force associated with electric charge in motion, having both electric and magnetic components and containing a definite amount of electromagnetic energy) hypothesis. Scientists did not pursue this hypothesis area until James Clerk Maxwell mathematically predicted the existence and behavior of radio waves 41 years later [Decareau, 1985]. Herinrich Hertz verified Maxwell's theory by experiment in 1885.

After that, Jacques Arsène d'Arsonval used Hertz's first high-frequency oscillator to experiment on the effects of high frequency (500,000 - 1,500,000 Hz), low-voltage alternating current on animals. d'Arsonval noted, as had Hertz, that the only effect was the production of heat. This discovery led to the first high-frequency heat therapy unit under d'Arsonval's direction in 1895 at the Hôtel Dieu Hospital in Paris [Decareau 1985].

The potential application microwave energy to food heat processing appears not to have been recognized until the early 1940s. Sherman (1946) described "electronic heat", how it was produced, and its potential applications to the food industry. During the period of 1944 to 1947, several workers [Marcum 1944; Lund 1945; Wenger 1945; Cathcart 1946a, 1946b; Cathcart and Parker 1946; Kinn 1947; Marcum and Kinn 1947; Morse and Revercomb 1947; Moyer and Stotz 1945, 1947] studied the potential use of radio frequency energy (< 100 MHz) over a broad range of possible food subjects.

In 1946, announcements began to appear in the food trade press of a new device for cooking foods that involved the use of high-frequency energy in the microwave region. The first such announcement was a device made by General Electric Co., in which frankfurters, cheese sandwiches, or hamburgers could be heated [Anonymous, 1946a]. Announcement of Raytheon Co.'s first Radarange appeared in the trade literature in November 1946 [Anonymous, 1946b]. In this unit the magnetron and horn feed assembly for directing energy were located above the cooking zone, essentially beaming energy directly onto the food being cooked. This unit had a relatively small oven cavity to hold food. By June 1947, a second-generation Radarange microwave oven had been developed [Anonymous,

1947a] with a larger oven capacity. A later announcement in 1947 [Anonymous, 1947b] told of the Radarange being used in a large fine restaurant chain in Boston for thawing and heating frozen main courses that had been prepared in a central kitchen, thus proclaiming thawing as one of the more important applications of radio frequency energy. The same unit was used by Proctor and Goldblith (1948) to study the use of microwave energy for cooking and blanching food products and its effect on the vitamin content of the food.

The high cost (\$ 2,500/kW) of microwave ovens in the 1940s-1950s precluded the use of microwave ovens in the home and limited their use to restaurants [Decareau, 1985]. Moreover, "runaway" heating in the defrosting of frozen foods (to be discussed in Section 2.2.4), also remained a problem. Thus, microwave heating was confined to restaurant kitchens and to the laboratory. Not until the early 1960s was a practical continuous radio frequency applicator system devised [Decareau, 1985].

The market for microwave ovens remained small until the mid-1960s, primarily because the ovens available then were large, cumbersome, complex, costly and unreliable. The price of the early ovens was \$3,000-5,000, but dropped to the \$1,500-2,500 range by 1964 [Moore, 1966]. The commercial market for microwave ovens suddenly expanded in 1965 when a small, compact 1 kW unit operating on 110 V with a list price under \$1,000, a full 1-year warranty, and a style specifically designed for the vending trade was introduced by Litton Industries [Moore, 1966]. In 1970, it was estimated that the non-industrial market for small 1 to 2 kW microwave ovens might approach a total of 100,000 units (exclusive of industrial processors) installed [Weizeorick, 1972]. As the popularity of microwave ovens

increased, the price went down sharply ($\leq \$ 500 /kW$). Six million microwave ovens were shipped during 1983 [Anonymous, 1984] and 12.4 million units were shipped in 1986 . In 1987, 55% of American households had a microwave oven, making the microwave oven the most popular household appliance in the U.S. [Dziezak, 1987]. The popularity of microwave ovens continued to grow; in 1989, more than 70% of American households were estimated to have a microwave oven. [IFT, 1989].

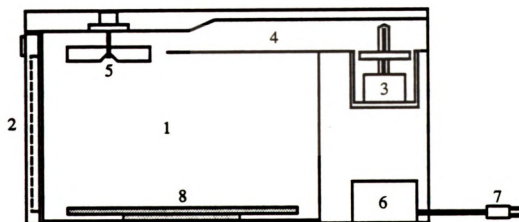
For the future, the growth of microwave oven market will probably have a major impact on the number of new food products developed for microwave use as well as on the processes used in producing many of the food products for that market. Developments that have occurred in plastic packaging materials with good barrier properties can be expected to result in the introduction of containers that will compete with the metal can and to function as serving dishes. Sterilized foods in portion-size quantities, packaged in a microwavable container, could be sold "hot" to consumers directly from a vending machine which contained a microwave oven [Decareau, 1985].

2.1.2 Components of microwave oven

The typical microwave oven can be divided into the eight major components (Figure 1; Sawyer, 1983; Schiffmann, 1976b; Van Zante, 1973):

1. A box-like cavity (radio frequency or RF cavity) which encloses the food within sealed metallic walls so that the distributed energy absorbed by the food is received directly from the microwave source or reflected from the walls.

Figure 1. Basic components of a microwave oven.



- | | |
|---------------|-----------------|
| 1. CAVITY | 5. MODE STIRRER |
| 2. DOOR | 6. POWER SUPPLY |
| 3. MAGNETRON | 7. POWER CORD |
| 4. WAVE GUIDE | 8. ROTATOR |

Figure 1.

w

po

loc

bo

lea

"m

mic

whi

is a

soun

a va

cylin

elect

surre

colle

radia

The r

oven.

4

a feed

2. A door at the front of the cavity with energy sealing or trapping devices which retain the microwaves within the oven. For safety reasons, the door has a power-on lock device to prevent the door from being opened during operation. The locks and interlocks of the door do not allow microwaves to escape and harm the body. The gasket on the door provides extra safety for preventing microwave leakage.

3. The microwave generator or power tube, usually known as the "magnetron", is an oscillator capable of converting electrical power into microwaves. The magnetron is a cylindrical diode with a ring of resonant cavities which act as the anode (positively charged electrode) structure. A cavity in this case is a space in the tube which becomes resonant or excited in a way that makes it a source for the oscillation of microwave energy. The resonant cavities are enclosed in a vacuum chamber and a magnetic field is imposed in the a direction parallel to the cylinder axis. When the proper voltage is reached across the diode, an interaction of electrons and magnetic field results in the oscillation of the magnetron. Electrons surrender energy to the microwave field and microwave energy is generated and collected by a magnetic coupling to the resonant cavities. The collected energy is radiated from an antenna which is enclosed in the vacuum envelope of the tube. The radiation is then propagated down a wave guide and directly injected into the oven.

4. The transmission and coupling section, which includes the wave guide and a feed box, is used to transfer the generated microwaves to the oven.

5. A rotating disc or stirrer, is usually located at the bottom of the feed box at the top of the oven. The stirrer distributes the microwaves into the oven and also disturbs standing wave patterns that may tend to form.

6. The power supply which draws electrical current from the line and converts it to the form required by the microwave generator. The power supply usually consists of a high-voltage transformer and steps up sixty cycles per second (60 Hz) alternating current to an A.C. plate voltage usually in the range of 4,000 to 5,000 volts. Microwave ovens may be used on either 100 to 120 volts or 220 to 240 volts A.C. at 60 Hz.

7. Power cord which connects power supply to the electrical plug.

8. Rotator provides rotation movement for food during microwave heating. While food is rotating during microwave heating, the microwave energy can be more evenly distributed onto the food. Thus food can be heated more evenly.

2.2 Microwave Processing

To understand how microwave energy is transformed into thermal energy, and how products being processed respond to microwave energy, one must consider microwave equipment, the environment, and the food load as one system and study the interactions among them [Schiffmann, 1986]. In this section, the theory of microwave heating, the thermal responses of food load that has been microwave processed, factors affecting microwave heating patterns of food, advantages and disadvantages of microwave processing, temperature measurement in the microwave field, processing losses and application of microwave processing are introduced.

is
n
hy
o
n
P
i
S
is

2.2.1 Theory of microwave heating

In conventional heat processing, food may be heated by conduction, convection, and/or radiation. During conduction and convection processing, thermal energy is transferred from product surfaces toward their center 10 to 20 times slower than during microwave heating.

Microwave is a non-cumulative non-ionization radiation which is characterized by a rise in temperature [Mohsenin, 1983c]. Microwave ovens use a monochromatic form of electromagnetic waves that concentrate all energy at a single frequency. The waves are of a single length, larger than those used in conventional radiation, but smaller than the common radio wave (Figure 2). This is the reason for the term "microwave" [Van Zante, 1973]. Its frequency ranges from 300 to 3,000 MHz with centers of positive and negative charge that change direction billions of times each second.

Microwave energy penetrates to a considerable depth into the product which is being heated [Copson, 1975b; Decareau, 1985; IFT, 1989; Mudgett, 1982, 1986; Schiffmann, 1986] . Penetration and heating of foods by microwave energy are instantaneous. As the microwaves enter the product, they react with regions of positive and negative charges on water molecules (electrical dipoles) that rotate the molecules in the electrical field by forces of attraction and repulsion between oppositely charged regions of the field and dipoles. This results in the disruption of hydrogen bonds between neighboring water molecules and generates heat by "molecular friction". The heat generated within a product by the microwave energy is then transferred throughout the product by conventional thermal conduction.

Figure 2. Microwaves in the electromagnetic spectrum.

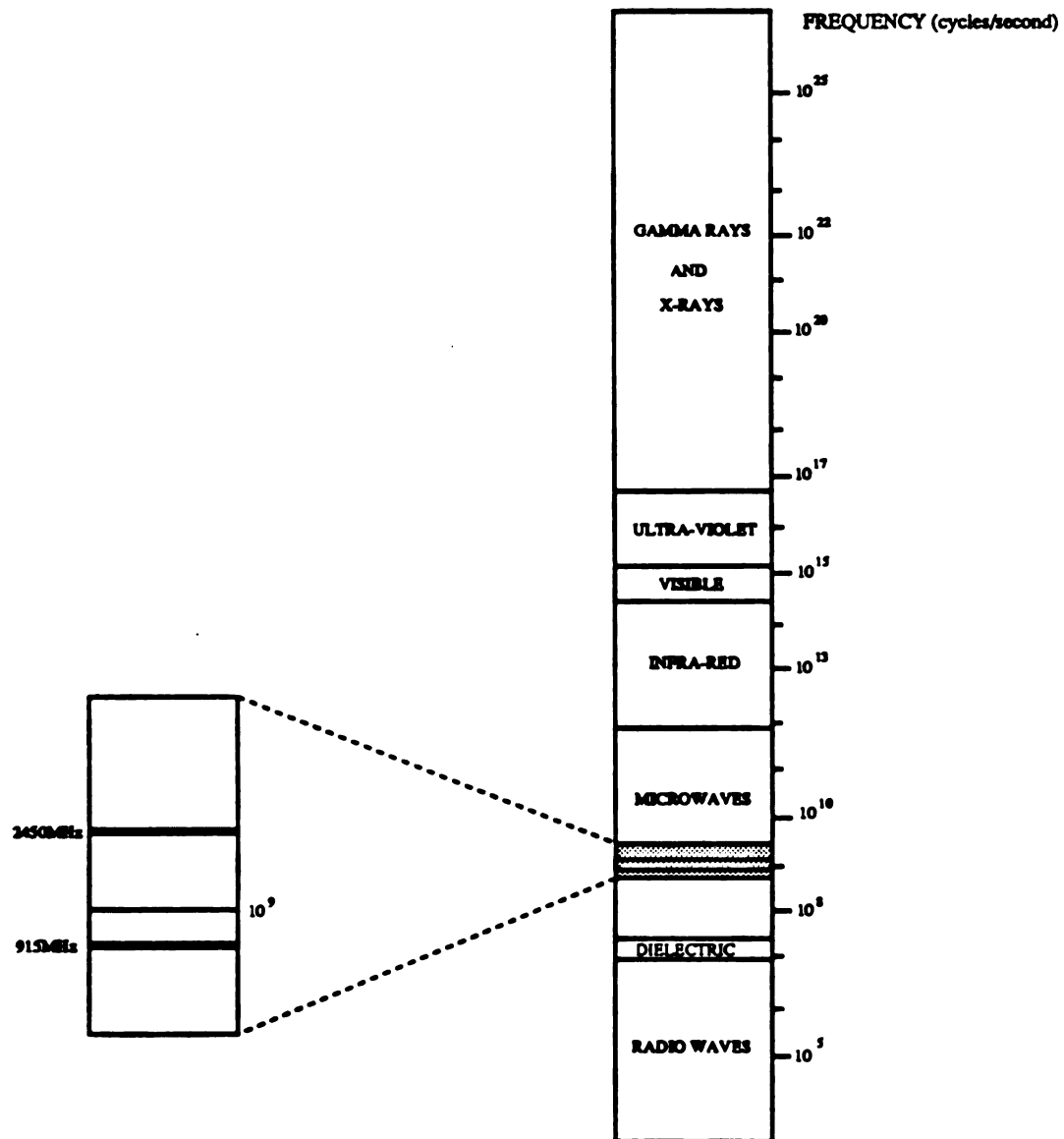


Figure 2.

The electrical and physical properties of foods which determine microwave penetration depth, conventional heat transfer, and overall heating rate are electrical: the dielectric constant (ϵ'), dielectric loss factor (ϵ''), loss tangent (δ) and physical: thermal conductivity, heat capacity (specific heat), and density [Decareau, 1985; Mudgett, 1982; 1986; Schiffmann, 1986].

The dielectric constant (ϵ') is related to the amount of electrical energy that can be stored in a product [Mohsenin, 1983c]. The value of ϵ' is microwave frequency and temperature dependent (changes while frequency or temperature varies). The higher value of ϵ' , the more microwave energy can be stored in a food load. The range of ϵ' of foods can be as high as that of water (78; 245 MHz at 25 °C; Schiffmann, 1986) to as low as fat (2.49; 2450 MHz at 25 °C; Kent, 1987). Raw beef and turkey has high value of ϵ' (52.8; 2450 Mhz at 5 °C; Mudgett et al., 1974) are considered to be "lossy" (have better dielectric properties).

The dielectric loss factor (ϵ'') is related to the amount of energy a dielectric product can dissipate (to reduce by conversion) in the form of heat when the product is exposed to alternating electrical field [Mohsenin, 1983c]. The value of ϵ'' is also microwave frequency and temperature dependent. The higher value of ϵ'' , the more microwave energy can be converted into heat. The range of ϵ'' of foods can be as high as that of cooked ham (25.2; 2450 MHz at 20 °C; Schiffmann, 1976) to as low as ice (0.0029; 2450 MHz at 25 °C; Schiffmann, 1986). The values of ϵ'' of beef and turkey are 19.8 and 21.4 respectively (2450 MHz at 5 °C; Mudgett et al., 1974).

The ratio of the dielectric loss factor to the dielectric constant (ϵ''/ϵ'), defined as the loss tangent (δ), is related to the product's ability to be penetrated by an

electrical field and to dissipate electrical energy as heat [Mudgett, 1986]. The range of δ can be as high as cooked ham (0.56; 2450 MHz at 20 °C; Schiffmann, 1976) and as low as ice (0.0009; 2450 MHz at 25 °C; Schiffmann, 1986). The calculated values of δ of beef and turkey are 0.375 and 0.405 (2450 Mhz at 5 °C; Mudgett et al., 1974).

Dielectric properties of food are primarily determined by their moisture and salt contents [Swami and Mudgett, 1981]. Generally, the greater the content of moisture and salt, the shallower the microwave penetration depth and the less uniform the heating rate throughout the product.

The depth of microwave penetration depends on the transparency and density of the product, the microwave frequency, dielectric properties of the product and product temperature. In general, penetration depth decreases as product density, microwave frequencies, dielectric constant and loss tangent increase [Mohsenin, 1983a, 1983b, 1983c]. The effect of temperature on penetration depth is varied and depends upon the product [Mohsenin, 1983c]. Moisture content and temperature of product also affect rates of conventional heat transfer (internal conduction and surface convection) which are determined by thermal diffusivity (ratio of thermal conductivity to heat capacity and density). Heat is also lost from the product to the microwave oven as a result of surface cooling by moisture evaporation.

In conclusion, the basic dielectric properties of foods (dielectric constant [ϵ'], dielectric loss factor [ϵ''] and loss tangent [δ]) are related to their chemical composition, and can be modified to some extent by physical structure, which is highly frequency and temperature dependent.

2.2.2 Thermal responses of a food load that has been microwave processed

Foods vary in their composition of moisture, fat, protein, carbohydrate, and mineral. Food composition as well as dielectric properties change during microwave processing due to processing losses and temperature change. There may also be a change of state of the food product (i.e., solid to liquid; liquid to vapor).

The thermal responses of a food that have been microwave processed are different based on the stages of processing. Microwave processing can be divided into two stages (1) microwave power on and (2) microwave power off. In the first stage when microwave power is turned on, heat is generated in the food load. The amount of heat generated is affected by the dielectric properties of the particular food such as dielectric constant, dielectric loss factor, loss tangent, intrinsic impedances, and attenuation factor, and physical properties such as heat capacity, physical states (solid or liquid), initial temperature (should either be controlled or known), size and shape, density of food products, and the microwave equipment such as frequency, free space between food product and cavity, microwave power and rate of heating [Decareau, 1985; IFT, 1989; Mudgett, 1982; 1986; Schiffmann, 1986]. As a result of the heat generated, the temperature in the food product rises.

In the second stage when microwave power is turned off, conventional thermal transfer (conduction, convection, and radiation) takes place in the food load. At this stage, the physical properties such as product temperature, thermal conductivity, heat capacity, density, size of the product, and the moisture and temperature of the environment affect the thermal transfers within a product and between the product and the surrounding environment [Heldman, 1981; Mudgett 1986; 1981; Schiffmann,

1986]. The higher the temperature and moisture potential (difference) between product and environment, the faster the vapor and temperature loss to the environment becomes. The rates of conventional heat transfer (internal conduction and surface convection) are determined by thermal diffusivity (ratio of thermal conductivity to heat capacity and density; Heldman, 1981). Heat is also lost from the product to the environment as a result of surface cooling by moisture evaporation.

Larger food loads appear to have a larger post processing temperature rise (PPTR) when compared to smaller loads [Sawyer, 1985; Zimmermann and Beach, 1982]. Extent of PPTR and contribution to temperature patterns in food loads of varying sizes should be noted when research on thermal effects of microwave radiation is considered [Sawyer, 1985]. Time of thermal processing for food in microwave ovens has been reported as shorter in microwave ovens than in conventional hot air ovens because the internal temperature in the food rises more rapidly [Decareau, 1985; Mudgett, 1986; Schiffmann, 1986]. After microwave power was turned off, thermal conduction still took place inside the food while heat exchange between food and environment was also going on. Thermal equilibrium was reached only after microwave power was turned off [Mudgett, 1982]. Final reports of internal product temperature after microwave processing should include temperature change after microwave processing [Sawyer, 1985].

2.2.3 Factors affecting microwave heating pattern of food

Microwave energy absorption and transmission in foods are determined by mutual interactions between the microwave power source and the food load. Several factors which affect microwave heating patterns of food are described below.

(1) **Microwave frequency.** The frequency of microwave radiation affects the depth of microwave penetration into a material. For example, the half-power penetration depth (the depth at which half of the incident energy is absorbed) for water is approximately 2.3 cm at 2450 MHz and 20.0 cm at 915 MHz [Schiffmann, 1986].

The heating patterns and heat generated by different microwave frequencies are varied. For example, the heating pattern of 2,450 MHz was described as "peripheral" heating and the heating pattern of 915 MHz was described as "core" heating [Copson, 1965b]. These two heating patterns used in unison could compliment each other [Copson, 1975b]. The microwave ovens built with dual frequencies (915 and 2450 Mhz) will have significant advantages to improve heating pattern and time required for heating. A similar idea (multi-frequency technique) had been used successfully to ontinuously pasteurized milk prodcut [Rosenburg and Bögl, 1987].

(2) **Microwave power and speed of heating.** One problem which can arise from the high speed of microwave heating is nonuniform temperature distribution. This occurs probably partially because the heating may be so fast as to prevent the effective thermal conductivity of heat from the hotter to the cooler portions of the food [Schiffmann, 1986]. This is particularly a problem with unusually shaped pieces or pieces with sharp corners because the area around sharp edges and corners

are usually hotter than other areas. A general rule to be followed in microwave processing is "fast, but as slow as possible". [Schiffmann, 1986].

(3) **Mass and density.** There are two considerations concerning mass and density: (1) the total mass being heated at one time, and (2) the mass of an individual piece. The latter will be discussed under size and shape in Section 2.2.3. As for the total mass, if products needed to be heated to desired temperature, the amount of microwave energy must be adjusted proportionally to the increasing total mass of product to achieve the same target temperature [Schiffmann, 1986].

The density of a product has an effect on its dielectric constant. As a product's density increases, so does its dielectric constant, often in an almost linear fashion. For example, the dielectric constant of air is 1.0 and air is completely transparent at the microwave heating frequencies (915 and 2,450 MHz). Thus, air inclusions will reduce a material's dielectric constant. The more air inclusions in the material, the smaller dielectric constant of that material will be [Schiffmann, 1986].

(4) **Size and shape.** If the size of each individual piece of food is very large in comparison to the wavelength of microwave being applied, and more importantly to the depth of penetration (the larger size means increased thickness per piece with a corresponding shallower depth of microwave penetration), the heating will not be uniform. On the other hand, if the size is close to the wavelength, the temperature of the piece of food may be the highest in the center [Schiffmann, 1986].

To be able to select the appropriate frequency of microwave may be helpful. For example, the penetration depth at 915 MHz may compensate for a larger size of individual pieces. When it is possible, product size should be kept small and similar

to the size of the wavelength (i.e. 12.2 cm for 2450 MHz or 32.8 cm for 915 MHz; Copson, 1975b).

The more regular the shape in the food load, the more uniform the heating. Sharp edges and corners should be avoided, since these will tend to be overheated [Schiffmann, 1986]. If the shape of a product is irregular, such as a chicken leg, there is a strong possibility of overheating the thinner portions such as those near the ankle and undercooking the large muscle portions such as the thigh. In conclusion, size and shape of product can be used to help control the heating pattern of microwave processing.

(5) **Other anomalous effects.** Other dielectric properties of basic interest in microwave heating are:

a. the product's intrinsic impedance (η ; ohm) relative to free space, which affects levels of power transmission and reflection at product surfaces [Mudgett, 1986]. The impedance (the factor to decide whether energy will be absorbed, reflected or transmitted) mismatch between a microwave processed product and free space in the microwave cavity may create standing wave patterns of nodes and antinodes (minimum and maximum amplitude). These standing wave patterns cause high and low incident power levels in the microwave oven cavity that result in uneven energy distribution at the surface of the product and hot spots within the product. Basically, this is a problem related to the design of the oven feed system and can be minimized by mode stirring.

b. the attenuation factor (α ; cm⁻¹) which determines levels of power absorption within the product as a function of depth from the surface [Mudgett, 1986]. It is possible that energy transmitted to the product from one surface and lightly

attenuated within the product may reach the opposite surface and be reflected back to the surface of incidence. This could lead to standing wave patterns within a product, caused by interaction between the internally transmitted and reflected waves, which create internal hot spots. This possibility seems likely for material with very low dielectric loss factors (ϵ'') such as low-moisture solids or dry solids.

2.2.4 Advantages of microwave processing

The major advantages of microwave heating for food processing are [Schiffmann, 1986; Mudgett, 1982]:

(1) **Speed.** Microwave processing offers advantages over conventional cooking/heating methods in terms of rapid heating and convenience. This has been reflected in the growing consumer demand for commercial and domestic models of microwave ovens [IFT, 1989; Dziezak, 1987; Anonymous, 1985].

(2) **Uniformity of heating.** Since the generation of heat by microwave energy occurs from inside as well as beneath the surface of food load, temperature distribution is more uniform than did that of conventional heating. Unlike conventional heating where heat transfer starts from the outside and moves toward the inside, The overheating on the surface of the food load (case hardening) is rare for microwave processing but is quite common for conventional heating [Schiffmann, 1986; Mudgett, 1982]. Therefore, the way of microwave heating is usually more uniform (temperature gradient between the surface and inside of the foos is smaller) than conventional heating. However, other factors may reduce this uniformity, as explained in Section 2.2.3.

(3) Product quality. Qualities such as texture, quantity of toxicants formed, nutrition and flavor can be improved by microwave processing. For example, the case hardening (formation of dry, hard layer) could be avoided during microwave dehydration process since the surface temperature of microwave processed foods does not have to be as high as that of conventional processing [Schiffmann, 1986]. Fewer nitrosamines were formed when bacon was microwave processed because bacon was heated for a shorter time [Hoffman and Zabik, 1985b]. The retention of heat-labile nutrients such as thiamin, riboflavin, pyridoxine, folacin, and ascorbic acid were equal or better than conventional methods because the time of microwave processing was shorter than that conventional methods [IFT, 1989; Hoffman and Zabik, 1985b; Cospon, 1975b].

Studies have been done on lipid oxidation during microwave heating/reheating. Researchers indicated that microwave heating resulted in reduced levels of lipid oxidation of foods when compared to foods that were conventionally heated [Hsieh and Baldwin, 1984; Penner and Bowers, 1973; Pikul et al., 1985; Pikul et al., 1984]. Sensory quality of microwave processed foods is at least acceptable, sometimes even better than that of conventionally processed foods [Cipra and Bowers, 1971; Hoffman and Zabik, 1985b]. This was especially true when fats and oils were present as a major ingredients in the products such as meat [Hassoun, 1981].

(4) Selective heating. Microwaves are absorbed selectively into food loads because the different components of a given food load have varied dielectric properties. Selective heat is beneficial especially for high moisture content of foods because water tended to be heated well in the microwave field. To take the advantage of selective heating of microwave, a serving product such as ice cream

that had hot fudge cover the cold base became possible because fudge was selectively heated by a specially designed package [Hoffmann and Zabik, 1985b]. although selective heating can lead to great heating efficiency, it can also cause undesired temperature profiles in multicomponent food systems such as pizza which is a layered product [Schiffmann, 1986].

(5) **Cost.** Edgar (1986) showed favorable cost advantages for tempering frozen foods and recooking meats in a modular processing system. The following advantages: reduced product loss, increased production, energy savings and increased product quality were resulted from the microwave processing. A recent study by Amana Refrigeration Inc., compared energy consumption of conventional and microwave ovens. Researchers suggested a median energy savings of 63% (range from 50 to 73%) in 57 of 77 home-microwave-cooked food items [Schiffmannm 1988].

While the above are advantages of microwave heating, they also present a potential problems to food product developer such as uneven heating. Uneven heat was known to be caused by speedy and selective heating. However, by designing product carefully (choose food cpmponents with similar dielectric properties for product formulaion), the uneven heating can be reduced to the minimum, hence, the advantages of microwave processing can be retained.

2.2.5 Disadvantages of microwave processing

The major disadvantages of microwave processing are:

(1) Uneven heating. One of the major disadvantages of microwave processing is uneven heating. Processing food by microwave radiation is characterized by uneven heating [Carlin et al., 1982; Schiffmann, 1981; Ringle and David, 1975]. Uneven heating has resulted in wide ranges of temperature within and among food products processed by microwave radiation. Carlin et al. (1982) reported 5 to 19% of product underdone and 3 to 16% of product overdone in beef-pork loaves that had been microwave cooked. Fruin and Guthertz (1982) reported temperature ranges of 63-81 °C, 65-87 °C, and 56-86 °C for meat loaves processed by microwave, conventional, and slow cookery methods respectively. Dahl et al. (1980c) reported a temperature range of 47-75 °C for beef loaf microwave reheated (1408 W, at 2540 MHz) for 50 sec. and 42-83 °C for rehydrated mashed potatoes reheated 65 sec. Such temperature ranges within and among food items receiving identical microwave processing have strong implications for the microbial quality of these items.

(2) Runaway heating. Runway heating is a serious problem for frozen foods being thawed or tempered in microwave ovens. The result of runaway heating is unevenly heated foods with poor quality [Decareau, 1985; IFT, 1989; Mudgett, 1982; Schiffmann, 1986]. Tempering, the process of raising the temperature of solidly frozen foods to a temperature just below the freezing point of water, is often done instead of complete thawing to avoid runaway heating. A disadvantage of using microwave energy for tempering is that at temperature ranges slightly below 0

°C, the outer layer of the food load may absorb significant amounts of microwave energy and cause "runaway heating".

Runaway heating in the defrosting of frozen food by microwave energy was first described by Ede and Haddow (1951). This phenomenon was recognized as a serious overheating of portions of foods before the remaining frozen portions were thawed, and was attributed to variations in electrical conductivity arising from differences in temperature in the food load. The difference in temperatures among varied portions of the food load was enhanced further when the temperature gaps increased [Decareau, 1975].

(3) **Lack of browning effects.** Another disadvantage of microwave processing has been lack of browning effects. Microwave processed foods lack the attractive browning appearance, flavors and crispy texture of conventionally processed foods [Copson, 1975a; Van Zante, 1973]. The browning reactions occurred during conventional processing are nonenzymatic browning reactions such as caramelization, and Maillard reactions [Whistler and Daniel, 1985]. These browning reactions required the existence of browning reagents such as carbohydrates, proteins or amino acids and water. The browning reaction only takes place under favorable conditions such as high temperature which is usually absent in microwave processing [Van Zante, 1973]. To overcome this disadvantage, several improvements have been successfully tried. Browning and crisping agents such as soy sauce or brown gravy mix have been added to products for microwave processing to produce higher acceptability [IFT, 1989; Van Zante, 1973]. Combination ovens which combine microwave and conventional heat sources in a single oven have both a magnetron and a browning element (usually a infra-red source). Microwaves are used to

achieve internal heating, and the conventional heat source is used to produce the desired surface browning or crispness as well as reduction of microbial counts at product surfaces [IFT, 1989; Copson, 1975a; Van Zante, 1973]. A recent development in packaging technology allowed microwavable product surfaces to be heated up to 260 °C when wrapped in heat susceptors (materials such as polyester film that laminated with ferrite or aluminum particle film) which intensify localized heating in packaged food products [Borodinsky, 1988]. Although browning and crispness can be achieved, the question of migration of packaging materials to products under extreme high temperature conditions is of great concern [IFT, 1988; Anonymous, 1988].

2.2.6 Temperature measurement in the microwave field

Measurements of temperature within a product during microwave processing with conventional temperature sensors (i.e thermistors or thermocouples) are not accurate. They interact with the magnetic components of the field and result in spurious signals, electrical discharges, and fused thermocouples [Decareau, 1985]. Some commercial systems are available for temperature measurement in the microwave field, such as fiber optic probes [Luxtron Inc., Mountain View, CA; Technology Dynamics Inc., Woodinville, WA], a high resistant lead thermistor manufactured by Vitek, Inc. [van de Voort, et al., 1987] or glass thermometers containing fluids with low thermal expansion coefficients [Decareau, 1985]. These devices either are expensive or awkward since accurate time-temperature profiles

require a large number of sensors at close space intervals to give a reasonable analysis of temperature distributions within the product at discrete time intervals.

An inexpensive thermocouple capable of temperature measurement in the microwave field was developed and tested successfully [van de Voort et al., 1987]. This copper constantan thermocouple was shielded with nickel plated copper braid and used aluminum tubing to form the probe portion of the sensor. The unit, which shield by aluminum foil, worked effectively to prevent the microwave energy from interfering with the voltage differential generated at the junction. Temperatures of up to 340 °C were successfully recorded within 1 °C accuracy.

An interesting post-processing method employed by Ohlsson and Risman (1978) involved infrared thermographic measurements of section samples to obtain semiquantitative time-temperature profiles for products of cylindrical and spherical geometry. This method is valuable to show the temperature pattern, but not accurate enough for temperature measurement. Heating patterns can also be observed by using heat sensitive papers (Recording Chart No. 651-52, Graphic Controls Canada Ltd.; Kashyap and Wyslouzil, 1977) or papers coated with liquid crystals that change color with temperature [Decareau, 1985].

The procedure to measure time-temperature profiles following microwave processing for discrete time periods by inserting temperature probes at various positions within the product are reasonably accurate, since the time constants for conventional heat transfer are relatively long compared to the time required for temperature measurements [Decareau, 1985].

It would be the best to use one temperature measurement devices to monitor time-temperature profiles continuously from the beginning of processing until the

end of temperature equilibrium. Such a device, should have multiple microwave proof thermo-sensors with high accuracy and be monitored by computer which has a time-sharing function. Such device has not been commercialized.

2.2.7 Processing loss

Weight losses after processing include evaporation and drip losses [Carlin et al., 1982; Dale and Matthews, 1980; Van Zante, 1973]. Processing weight loss affects qualities of food products such as texture and nutrient value as well as production cost. The amount of processing loss is affected by; the composition of the food product such as moisture and fat content; processing conditions such as temperature and time; and the processing environment such as air temperature and water vapor pressure.

Losses by weight after microwave processing seem to vary, depending on experimental controls. In general there seems to be a slightly larger loss after microwave processing than after conventional processing. Vadehra (1970) compared total weight loss of microwave cooked whole chicken and conventionally cooked whole chicken and found no significant difference, although more drip loss was found with microwave cooked whole chicken. Van Zante (1973) compared microwave and conventional cooking methods for moisture loss and showed that microwave cooking losses of moisture were frequently greater. This, however, was often due to excessive microwave heating. If excessive heating was controlled and reduced, no difference in moisture loss would be found between the two cooking methods [Van Zante, 1973].

2.2.8 Applications of microwave processing

Depending on the application, the frequency of microwave processing can be varied but must be within the F.C.C. regulated range (13.56 KHz - 22,125 MHz). While microwave processing have been applied to several areas such as cooking, reheating, dehydration, freeze-drying, blanching, enzyme inactivation, baking, tempering, pasteurization and sterilization [Baba et al., 1987; Baldwin et al., 1986; Chiu et al., 1984; Crespo and Ockerman, 1977; Decareau, 1985; Kotula, et al., 1982; Rosenberg and Bögl, 1987a, 1987b, 1987c; Sanborn et al., 1982; Wang and Toledo, 1987], only applications related to the present study will be discussed.

2.2.8.1 Cooking

Microwave ovens are widely used in foodservice systems. Eighty percent (80%) of microwave ovens used in foodservice are used for reheating, while 10% are used for primary cooking [Hoffman and Zabik, 1985a]. The basic requirement of cooking is to heat treat raw materials and transform them into edible products (with different degrees of doneness). Some unsatisfactory qualities, such as unattractive appearance, and poor organoleptic characteristics after microwave cooking might be a partial explanation for the minimal use of microwave cooking in foodservice operations thus far.

Because microwave cooking of food is very product dependent, not all foods are suitable for microwave cooking. Currently, improvements in microwave oven design and technology, new microwavable products and packages are being

developed or marketed. For example, combination convection-conduction-microwave ovens can achieve improved sensory quality of food as the result of browning and crispy texture. Improvements in the design for future microwave ovens are expected for control of heating rates and product "doneness" [Masi, 1988]. Future microwave ovens will have the feedback systems and computerized algorithms or "cookbooks" that can automatically set power levels and processing times by product weight and moisture and by oven cavity environmental conditions (gas, humidity, temperature, infrared and electromagnetic conditions) measured by field sensors [IFT, 1989].

Microwavable product development has been emphasized in new food formulas and packaging techniques. One can expect an increase in microwave cooking in the future. As for reheating food, continuous improvement in uniformity of temperature patterns is expected as more information related to the interactions between products' dielectric and physical properties and microwave equipment is gathered, as well as improved formulations for microwavable food products [IFT, 1989].

2.2.8.2 Pasteurization and sterilization

Microbial reduction by microwaves (pasteurization and sterilization) has been reported in the literature using a large variety of foods and bacteria under various conditions. More detailed information can be obtained from the review literature [Fung and Cunningham, 1980; Rosenberg and Bögl 1987b].

Household applications of destruction of bacteria have been considered to be unsuccessful relative to the success of Industrial pasteurization and sterilization. When compare to industrial applications, the bacterial survival after household

microwave processing was usually observed in food load, while did not observed for industrial processing. The low destruction of bacteria after household microwave processing was probably due to uneven heating caused by the nonhomogeneous field distribution in microwave ovens.

Continuous microwave equipment designed for industrial use has provided more effective and consistent destruction of bacteria. Industrial pasteurization or sterilization permits the products to pass through microwave fields (one magnetron or more; or multi-frequency) on a conveyor belt [Decareau, 1985]. These techniques enable the throughput, time, and output to be varied. Microwave treatment to sterilize or pasteurize milk and milk products, fruit and vegetable products such as fruit juice, jam, or oranges in syrup, as well as solid vegetable or meat has been just as successful as the treatment of sliced bread or beer [Rosenberg and Bögl, 1987b]. These researchers reviewed these studies and concluded that microwave energy is very well suited for pasteurization and sterilization in the food industry.

2.3 Microbiology of Microwave Processing

When considering microorganisms of public health significance in relation to meat and poultry, the primary concern is food poisoning or food intoxication. A significant potential health hazard exists because bacteria which survive after microwave processing could infect or intoxicate human beings after eating [Rosenberg and Bögl, 1987b].

2.3.1 Enumeration of bacteria

Enumeration of injured bacteria is extremely important in any microbial assesment of a food. This is especially applicable to microwave processing because bacteria have a better chance to survive than conventional methods. To determine the microbial quality of microwave processed foods, enumeration should include counting injured bacteria which have been permitted to recover and grow after microwave processing.

The major effect of microwave energy on bacteria has been suggested to be thermal denaturation of proteins and nucleic acids [IFT, 1989]. After microwave processing, injured bacteria need the proper environment and adequate time to resuscitate or an incomplete enumeration of bacteria in experimental products would be expected [Sawyer and Pestka, 1985]. The background of injury and resuscitation of bacteria and the enumeration methods of bacteria used in this study are reviewed below in this section 2.3.1.1 to 2.3.1.4.

2.3.1.1 Injury and resuscitation of bacteria

Microwave processing may damage as well as kill bacteria [Sawyer and Pestka, 1985]. If processing is inadequate to kill, the surviving bacteria may be injured or stressed. Important characteristics of injured bacteria include: loss of resistance to selective chemical agents such as surface-active agent, organic acids, salts, dyes; a prolonged lag phase; damage to permeability barrier; and an increase in nutritional requirements [ICMSF, 1980]. For injured bacteria to resuscitate and be enumerated

correctly, media which contain selective agents are no longer appropriate because injured bacteria are sensitive to these agents. If selective media are used, injured bacteria will not fully resuscitate and multiply; consequently they remain undetected.

Injured bacteria exhibit altered growth characteristics. Special conditions are required to allow injured bacteria to return to their normal state [Sawyer and Pestka, 1985]. Such injured bacteria have been reported to be able to repair under nonselective conditions [ICMSF, 1980]. A complete medium which contains all the necessary nutrients for bacteria to grow but without selective agents has been recommended. When selective media are necessary for the enumeration of injured bacteria, the bacteria should first be resuscitated in a nonselective medium before being exposed to selective agents. Depending on the purpose, liquid or solid systems can be used for resuscitation of injured bacteria [Sawyer and Pestka, 1985; ICMSF, 1980].

In liquid repair systems, injured bacteria are resuscitated in nonselective broth for an appropriate period of time and then transferred to an acceptable selective medium [ICMSF, 1980]. Liquid repair is very useful for detection of the presence of pathogens; however, liquid repair may not be useful when an actual count of a desired specie of bacteria is expected. When using liquid repair systems, the bacterial count might increase due to multiplication of uninjured cells as well as of injured cells during the resuscitation period [Sawyer and Pestka, 1985].

Solid repair systems, on the other hand, can provide actual bacterial counts in a more direct and rapid way and is recommended for quantitaion purposes because each colony on a solid plate represents a single cell [Sawyer and Pestka, 1985].

In conclusion, to avoid undercounting the surviving bacteria in foods after heat processing, the injured bacteria should be allowed to resuscitate in complete media and return to their normal state. Should a quantitative detection be needed, a solid repair system is recommended for the injured bacteria.

2.3.1.2 Enumeration of injured *Escherichia coli*

Escherichia coli (*E. coli*) are most commonly enumerated by the most probable number (MPN) technique but if the liquid medium contains bile salts and certain dyes, injured *E. coli* may not be resuscitated [ICMSF, 1980]. Several techniques have been described to resuscitate injured cells of *E. coli* prior to selective plating: (1) a short resuscitation period in liquid media such as nutrient broth before plating out [Mossel and Ratto, 1970; Warseck et al., 1973]; (2) a replica plating technique in which the cells were first grown on a nutrient agar and then transferred by the method of Lederberg to the selective agar [Lederberg and Lederberg, 1952]; and (3) a double agar technique in which the cells were grown on Tryptone Soy Agar (TSA) for a short period of time then the selective agar (violet red bile agar) was carefully poured over the nonselective agar [Speck et al., 1975; Hartman et al., 1975]. Among these three techniques, the first technique might give misleading results because uninjured cells of *E. coli* might multiply in liquid media. The second and third techniques are more appropriate because solid media are used.

2.3.1.3 Enumeration of injured *Staphylococcus aureus*

Several surveys have shown that Baird-Parker agar was suitable for the direct enumeration of injured *Staphylococci* [Baird-Parker and Davenport, 1965]. Similar findings by other researchers have led to the adoption of this medium in the official methods of A.O.A.C. [Baer et al., 1975], and other standard methods such as ICMSF (1978) and F.D.A (1978). The success of the Baird-Parker agar is due to its salt-free, pyruvate content. Flower et al. (1977) showed that injured cells were more sensitive to H_2O_2 than were uninjured cells. Pyruvate not only degrades H_2O_2 but also improves the medium normally not suitable for counting injured bacteria by the inclusion of catalase [ICMSF, 1980].

2.3.1.4 Enumeration of injured aerobic mesophilic bacteria

The enumeration procedure for aerobic mesophilic bacteria are similar among three standard methods [F.D.A., 1978, ICMSF, 1978; Baer et al., 1975]. TSA or nutrient agar (complete, nonselective media) are used for injured aerobic mesophilic bacteria. No other media or modification is needed because no specific bacterium but rather a group of bacteria were enumerated.

2.3.2 Lethal effect on microorganisms

A great deal of controversy surrounds the effects of microwave radiation on bacteria. Most researchers agree that traditional thermal injury plays a major part in

the observed effects of microwave radiation to bacteria. The question, whether microorganisms subjected to microwave treatment may be expected to show other changes than the purely thermal effects of microwave energy, is still a matter of debate. Rosenberg and Bögl (1987b), based on the energy balance theory, made a conclusion that no nonthermal effects were expected alone. Rosén (1972) used the quantum energy concept to explode the possibility of nonthermal effects on bacteria. Based on the fact that the quantum energy of microwaves fell short by several orders of magnitude to break chemical bonds, Rosén concluded that nonthermal effects did not exist. Microbial inactivation by microwave radiation depends on the same time/temperature relationships as does conventional processing [Mudgett, 1986]. The rates of inactivation can be evaluated from kinetic parameters available in the literature [Lund, 1977; Stumbo, 1973]. The temperature level has been considered the most important factor responsible for the lethal effects [Haines, 1987; Rosenberg and Bögl, 1987b; Stumb, 1973].

2.3.3 Sublethal (nonthermal) effect on microorganisms

Thermal injury plays a major part in the observed effects of microwave radiation on bacteria. Questions related to non-thermal effects of microwave radiation have aroused disagreement among some researchers. Hossain and Dutta (1982), Dreyfuss and Chipley (1980), Mezykowski et al., (1980), Cope (1976) and Culkin and Fung (1975) postulated that factors other than thermal effects might be involved. Vela and Wu (1979), Correlli et al. (1977), Hamrick and Butler (1973)

and Goldblith and Wang (1967) however, claimed that non-thermal effects of microwave radiation were not likely to damage bacteria.

Kazbekov and Vyacheslavov (1987) failed to detect any nonthermal effects of microwaves on some membrane-related processes in bacteria. They performed a series of experiments on intact cells or the spheroplast of *E. coli* and *Bacillus subtilis*. They failed to find any nonthermal effect induced by continuous microwave irradiation of a low power density (at wave length range from 6.0 to 7.8 mm). Data showed that thymidine and thymine uptake, leakage of potassium and hydrogen ions, as well as the uptake of transforming DNA by the component cells of *B. subtilis* were affected in a way typical of that due to heating of a sample. No specific dependence on the effects observed from wavelength was found.

Strong evidence supports the hypothesis that microwave radiation has nonthermal effects on bacteria. Two mechanisms for nonthermal effects proposed by Barnes and Hu (1977) suggested that both shifts in ion concentrations across a membrane and the orientation of long chain molecules were possible in microwave and radio-frequency fields. Further, evidence provided by Saeed and Gilbert (1981) indicated that the cell envelope was a primary target for long-time exposure to low dose microwave radiation. Growth of microorganisms in the presence of microwave energy produced minor structural changes in their cell envelopes, this in turn resulted in an alteration of preservative (2-phenoxyethanol, chlorhexidine diacetate, benzalkonium chloride) sensitivity. Such changes were not great enough to result in any alteration of specific growth rates during continuous microwave exposure, nor were motility or cellular morphology affected. This work suggested that permanent structural or compositional changes had occurred in the cells during growth under

microwave radiation, and this led to an alteration of bacterial responses towards the drugs.

Dreyfuss and Chipley (1980) conducted a study to characterize some of the effects of sublethal microwave radiation on cells of *S. aureus*. Results showed that various enzymatic activities were affected by microwave radiation. Increased levels of thermonuclease activity were observed when cells were exposed to microwave radiation for 10 or 20 seconds. Data indicated that microwave radiation affected *S. aureus* in a manner which could not be explained by thermal effects.

A comparative study was done by Khalil and Villota (1988) on *S. aureus* recently. *S. aureus* was exposed to a sublethal temperature of 50 °C for 30 min in 0.1 M phosphate buffer using either microwave energy or a conventional heating source. The results showed that microwave-heated cells had greater membrane damage and a slower rate to regain enterotoxin production than conventionally-heated cells.

Webb and Dodds (1968), Webb and Booth (1968) stated that *E. coli* exposed to microwave radiation (136 GHz) at a constant temperature of 25 °C did not divide, but no lethality occurred (as measured by plate counts) after 4 hours of incubation. They concluded that radiation injured the cells, slowing down their rate of division and specifically inhibiting some undetermined metabolic processes in the early stages of growth of the cell.

Another study examined the effects of microwave radiation to determine whether any genetic mutation could be induced in *E. coli* mutants deficient in excision and recombination repair mechanisms. Berteaud et al. (1975) exposed cells to 70-75 GHz of radiation for 15 minutes. No new mutants resulting from radiation

or lesions were seen in DNA accessible to the known repair mechanisms. In conclusion, the cell envelope and metabolic activities of bacteria may be affected by microwave radiation. The effect of microwave radiation at the genetic level remains unexplained.

Sublethal effects are believed to result from selective absorption of microwave energy by bacterial cells of high intracellular conductivity which favor microwave absorption in culture media of low conductivity [IFT, 1989]. Because different frequencies of microwave radiation were applied to various species of bacteria under different experimental conditions, and most of all, since the internal temperature of a bacterial cell can not yet be measured, it is impossible to prove or disprove such claims [IFT, 1989].

2.3.4 Bacterial survival

Microbial survival and thermal denaturation of heat-labile constituents such as proteins and nucleic acids in microwave processing are governed by the same time/temperature relationships as those in conventional heating [IFT, 1989]. Other factors such as water, fat, salt and protein content of food products as well as pH, and initial numbers of bacteria can also affect bacterial survival [Jay, 1986].

Microbial death tends to follow first-order chemical inactivation. By plotting the logarithm of survivors against time, plots are generally linear, but several exceptions, including "shoulder" and "tailing" effects, may result. Troller and Christian (1978b) described the basis for survivor curves and have explained that cell clumps or chains, cell injury, physiological age, and heterogeneity of cell populations may

influence the nonlinearity of the survivor curve. Survivor curves are used to describe the effects of processing, freezing, heating and dehydration on viable microbial populations. These treatments, in combination with water activity (a_w), affect the survival of microorganisms [Rockland and Beuchat, 1987].

2.3.4.1 Factors which affect bacterial survival

A total of eleven factors (water, oil and fat, salts, carbohydrates, pH, protein, inhibitory compounds, cell concentration, age, temperature and other growth conditions as well as other protective compounds) related to microorganisms and their environment have been studied to determine their effects on heat destruction [Hansen and Reimann, 1963]. Five factors which related to this study and reported by Hansen and Reimann (1963) plus other four additional factors mentioned by Schiffmann (1986) and Spite (1984) are presented below. The factors are: (1) time and temperature; (2) water; (3) fat; (4) pH; (5) proteins; (6) microwave frequency; (7) microwave power and speed of heating; (8) mass and density of food load; (9) size and shape of food load; (10) homogeneity of food load.

1. **Time and temperature.** Temperature, which is a measure of the heat energy level, is the most important variable in the heat destruction of microorganisms; the action of temperature is a function of time [Hansen and Reimann, 1963; ICMSF, 1980]. One would expect that the longer the time of processing, the greater the killing effect on bacteria. A more dependable rule is that the higher the processing temperature, the greater is the killing effect to bacteria. As temperature increases, time necessary to achieve the same killing effect decreases. It is generally accepted

that the exponential death rate of heated bacteria is due to heat denaturation of cell proteins, because studies with pure proteins have shown that their inactivation followed first-order kinetics [Haines, 1987]. Rosenberg et al. (1971) found a numerical correlation between the thermodynamic parameters of protein denaturation and the observed death rate of various organisms and suggested that protein denaturation was a likely cause of cell death in mesophilic organisms. Another factor involved in the heat inactivation of bacterial cells is membrane destruction and inactivation. The cell membrane is vulnerable to heat because of its protein and lipid contents. Cell membrane requires a certain range of temperature to keep the lipids in a liquid-crystalline state to participate in transport and other metabolic activities [Haines, 1987]. Several basic concepts such as thermal death time (TDT), D value, z value, F value, and thermal destruction curves are used to describe the status of thermal resistance of bacteria [Stumb, 1973]. Not all of these concepts are appropriate for microwave processing. For example, D value, the time required at a specific temperature to destroy 90% of the spores or vegetative cells of a given organism, or TDT, the time needed to destroy a given number of spores or vegetative cells of a given organism at a specific temperature are not appropriate for microwave application. In actual microwave processing, temperature will not be a constant throughout the processing, therefore, the value of D value and TDT which determined at constant temperature are not applicable. Modification on these concepts are needed to meet the unique situation of microwave processing. One should also remember that during microwave processing, the dielectric loss factor (ϵ'') of the material may increase or decrease with temperature, depending upon the material [Mudgett, 1986]. This means that the conversion of microwave energy into heat is

temperature dependent. The change in temperature and moisture levels of product during microwave processing, may have a substantial effect on the final product temperature and bacterial survival.

2. **Water.** Like growth, microbial survival is affected by the presence of water in an available form in the environment. The most useful measurement of the availability of water is a_w . The a_w of a food or solution is the ratio of water vapor of the food to that of pure water at the same temperature. The relationship between water content of a food and its a_w is expressed by the water sorption isotherm [Troller and Christian, 1978a]. In general, a food with higher water content will have higher a_w . The heat resistance of microbial cells increases with decreasing humidity or moisture (lower a_w) of the environment. Evidence is well established that protein denaturation occurs at a faster rate when heated in water than in air. This phenomenon has been suggested that protein denaturation is either the mechanism of death by heat or is closely associated with it [Jay, 1986]. The heating of wet proteins causes the formation of free-SH groups with a consequent increase in the water-binding capacity of proteins. The presence of water allows for thermal breaking of peptide bonds, a process that requires more energy in the absence of water and consequently provides a greater refractivity to heat.

In microwave processing, one would expect bacteria to survive less well in foods of higher water content than foods of lower water content. Besides higher a_w , foods of higher water content have a higher dielectric loss factor and dielectric constant; hence, higher temperatures could be reached in foods of higher water content [Schiffmann, 1986]. Spite (1984) claimed increased moisture generally enhanced bacterial survival during microwave heating. When carefully reviewing

Spite's data, none of the four species of bacteria Spite tested actually demonstrated better survival in mashed potatoes with higher water content (30% more).

Bacterial survival also can be affected by the interaction of a_w with intrinsic and extrinsic factors [Rockland and Beuchat, 1987]. The intrinsic factors include water-binding properties, nutritive potential, pH, E_a , and the presence of antimicrobial compounds. The influences exerted by these factors interact with a_w both singularly or in combination. Extrinsic factors such as temperature, oxygen, chemical treatments and irradiation are important in terms of food processing operations. The complexity of these interaction will not be discussed; detailed information can be reviewed in the book of Rockland and Beuchat (1987).

3. Fat. In the presence of fats, there is a general increase in the heat resistance of *E. coli* [Jay, 1986] and other microorganisms. This is referred to as fat protection and is presumed to increase heat resistance by directly affecting cell moisture. Sugiyama (1951) demonstrated the protective effect of long-chain fatty acids on *Clostridium botulinum* when heated. It appeared that the long-chain fatty acids were better protectors than short-chain fatty acids. Spite (1984) demonstrated *C. perfringens* survived better in food with high lipid content than in food with low lipid content after microwave processing. However, three other species of bacteria, including *S. aureus*, had the opposite results. The end-point temperature of food in the study by Spite with high lipid content was 13 °C higher than food with low lipid content.

In conclusion, the protective effect of fat on bacterial survival has varied depending on the species of bacteria. During microwave processing, food with a higher fat content will heat at a faster rate to a higher temperature than food with a

lower fat content because of the lower specific heat of fat [Schiffmann, 1986, Spite, 1984]. Foods with high fat content do not always mean better protection for all bacteria after microwave processing.

4. **pH.** Bacteria are most resistant to heat at their optimal pH of growth, which is generally about 7.0. As pH is lowered or raised from this optimal value, there is a consequent increase in heat sensitivity. Although there are variations among individual organisms, resistance is at a maximum in the pH range 6.0 to 8.0. [Pflug and Holcomb, 1983].

The effect of pH on bacteria has been investigated by several researchers [Freese et al. 1973; Hunter and Segel, 1973; Neal et al. 1970; Kashket and Wong, 1969]. Evidence has shown that internal pH of bacteria was affected by the pH of the menstruum (environment around bacteria). A variety of weak acids such as sorbate, benzoate, and propionate, at or below their pK_a values (the pH at which 50% of the total acid is undissociated) affected bacterial survival [ICMSF, 1980]. Hunter and Segel (1973) reported that the undissociated form of weak acids might diffuse freely through the cell interior. Freese et al. (1973) concluded that it was the rate of proton leakage into the cell relative to the proton-rejection capacity of the cell that determined the extent to which an environment was inhibitory. The same pH effect can apply to microwave processing.

5. **Proteins.** It is well known that proteins in the heating menstruum have a protective effect on microorganisms. Consequently, foods with high protein content must be heat processed to a greater degree than foods with low protein content in order to achieve the same bacterial survival [Jay, 1986].

Spite (1984) demonstrated *C. perfringens* survived better in food with higher protein content (30% more) than food with lower protein content after microwave processing. However, three other species of bacteria, including *S. aureus*, had a lower percent survival in food with lower (30% less) protein content than in food with higher protein content. The end-point temperature of food with high protein content was 5 °C higher than food with low protein content.

In conclusion, the protective effect of proteins has varied depending on the species of bacteria. During microwave processing, food with a higher protein content will heat to a higher temperature than food with a lower protein content [Spite, 1984]. Food with high protein content does not always result in better protection for bacteria that have been microwave processed.

6. Microwave frequency. The frequency of microwaves affects the depth of microwave penetration into a material [Schiffmann, 1986] and the heating pattern [Copson, 1975b]. Obviously, the microwave frequency chosen for heat processing has an important impact on the survival of bacteria. When bacteria are equally heated with different microwave frequencies (915 vs. 2,450 MHz), end-point temperature and the distribution of heat in food load will be different (Copson, 1975b). Since bacterial survival is related to the temperature, one can expect bacterial survival will also be different.

7. Microwave power and speed of heating. Mudgett (1986) studied microbial lethality models and found that at full power level, second-order (nonlinear) inactivation kinetics were observed, suggesting the possibility of selective energy absorption by the test bacteria due to the concentration of salts from the suspending medium.

At 20% of full power, first-order (linear) inactivation kinetics were observed, suggesting the possibility of thermal equilibrium during the off period of the duty cycle. The results indicated that by using varied microwave output power during microwave processing, the destruction kinetics of bacteria might have followed different mechanisms. Hence, bacterial survival may be dependent on the level of microwave output power.

The speed of microwave heating is usually controlled by varying the output power. The higher the output power, the faster the heating for a given mass. As mentioned before, the heat destruction of bacteria follows first-order inactivation kinetics [Mudgett, 1986]. It is possible that microwave processing may heat too rapidly to provide the same cumulative time-temperature relationship necessary for the destruction of bacteria as do conventional methods [Fruin and Guthertz, 1982].

Another problem which can arise from excess speed of heating is nonuniform temperature distribution. Heating may occur so fast that the normal effectiveness of thermal conductivity in transferring heat to the cooler portion is prevented [Schiffmann, 1986]. Therefore, bacteria may survive in the cold areas where the required lethal temperature were never reached throughout the entire microwave process.

8. Mass and density of food load. To destroy bacteria efficiently, the amount of microwave energy must be adjusted to the total mass of product to achieve the desired temperature [Schiffmann, 1986]. The density of a product has an effect on its dielectric constant. As the density of a product increases, so does its dielectric constant; the product with a higher density will be heated to higher temperature. Hence, bacteria may survive less well in a higher density product than in a lower

density of that product when exposed to the same amount of microwave energy per gram of food load. As mentioned in Section 2.2.3, air is completely transparent to microwave heating frequencies. Thus, air inclusions in a product will reduce a product's dielectric constant. To reduce the chance for bacteria to survive microwave processing, a product should be of the highest possible density and air-free.

9. **Size and shape of food load.** As mentioned previously in Section 2.2.3, if the size of each individual piece of the food load is very large in comparison to the wavelength of microwave being applied, the heating will not be uniform [Schiffmann, 1986]. When it is possible, product size should be kept small and similar to the wavelength i.e. 12.2 cm for 2450 MHz or 32.8 cm for 915 MHz [Copson, 1975b]. The microwave ovens built with dual frequencies (915 and 2450 Mhz) will have significant advantages to improve heating pattern and time required for heating. Hence, bacterial survival can also be reduced.

The more regular the shape of the food product, the more uniform will be the heating in a food that has been microwave processed. Sharp edges and corners for foods/containers should be avoided since these will tend to be overheated [Schiffmann, 1986]. In summary, the heating pattern of microwave processed food can be controlled by size and shape; hence, bacterial survival can probably also be affected as a result of such manipulation.

10. **Homogeneity of food load.** Spite (1984) studied the effect of homogeneity of food on bacterial survival after microwave processing and found that bacterial survival significantly increased as homogeneity of the food decreased. Spite suggested that cooler micropackets were formed during microwave processing which allowed bacteria to survive better.

The difficulty of dealing with heterogeneous foods during microwave processing has been identified by Sawyer (1985) and Mudgett (1982). The wider range of end-point temperatures within a heterogeneous product than that of a homogeneous product was reported by Sawyer (1985). The uniformity of end-point temperatures within the product decreased as heterogeneity of the product increased [Sawyer, 1985]. Hence, the chance for bacteria to survive in cooler areas of the product increased.

2.3.4.2 Bacteria which easily survive microwave processing

Several researchers (Rosenburg and Bölg 1987b; Wright-Rudolph et al. 1986; Aleixo et al. 1985; Spite 1984; Baker et al. 1983; Fruin and Guthertz 1982; NRA 1981; Fung and Cunningham 1980; Crespo et al. 1977; Stack 1974; Lacey and Winner 1965) have reported that bacteria survive better in foods that had been processed by microwave radiation than by conventional methods.

The reasons that might have contributed to better survival of bacteria and other microorganisms in foods after microwave processing have been cited by Carlin et al. (1982) and Schiffmann, (1981) and are given below. The theories behind these reasons have previously been discussed in Section 2.3.4.1.

(1) **Unevenness of heating pattern.** One of the well recognized characteristics of microwave heating has been wide ranges of temperature within and among food products that received identical microwave processing treatments (time and output power). Bacteria located in areas of a food load that received minimal microwave radiation (cooler areas) survived in greater numbers [Spite, 1984]. Bryan and Lyon

(1984) recommended that microwave reheating no longer be considered a critical control point in hospital foodservice operations because of the sporadic nature of end-point temperature in foods. These authors were also unable to make recommendations to sanitarians on where temperature of the food should be taken, because of the unpredictable nature of temperature patterns in foods that had been microwave processed. The two factors noted in the literature that probably contributed to the uneven heating pattern are below.

a. Large load size and irregular shape. Decareau (1975) suggested that the larger the food load, the greater the potential for wider ranges of temperature within a food, and hence the wider range of surviving cells per gram of product. The same conclusion was reached by Schiffmann (1986). Schiffmann further recommended that when it is possible, product size should be kept small and related comparable to the wavelength of microwave being used. Overheating on the edges and corners of irregular shaped products was observed because the incidence of microwaves occurred at more than one surface [Mudgett, 1986].

b. Composition of food load. The nature of composite or heterogeneous food products especially those with different phase properties (liquid vs. solid) such as soups and jelly doughnuts have ingredients that have different dielectrical properties. These products are more difficult to deal with in microwave processing since they may absorb energy by mechanisms which result in several differential heating rates within the same product [Sawyer, 1985; Mudgett, 1982]. Therefore, the greater the variety of ingredients in a food product, the better the chance for bacteria to survive. In general, foods composed of ingredients that vary in dielectric properties may protect bacteria in those foods from being destroyed by microwave energy. The

heterogeneous composition of food probably contributes to the net uneven distribution of temperatures and possibly creates areas of protective environment for bacteria to survive microwave processing.

(2) **Rapid processing time.** The larger number of microorganisms which have been shown to survive in a microwave field compared to a conventional oven was due to the increased speed of temperature rise during microwave processing [Fruin and Guthertz, 1982; Zimmermann, 1983]. The shorter processing time affected the number of bacteria killed since quantity of bacteria killed is a function of both time and temperature [Jay, 1986].

It is important to recognize that the microwave killing effect on bacteria may vary considerably with the temperature, chemical composition, and physical state of the food load.

2.4 Bentonite

Depending upon origin, bentonites vary in their chemical composition.

Bentonite is composed of silica and alumina sheet-like units arranged in such a way that **smectites** are essentially books of sheets or laths, or bundles of needles. The **primary components** of bentonite are: SiO_2 ; Al_2O_3 ; Fe_2O_3 ; CaO ; and MgO . The **properties** of bentonites are contingent upon their chemical composition, atomic structure, and morphology (structure of earth features). The individual sheets or **laths or needles** are loosely tied together. These unique structures allowed water to **enter between the sheets, laths, or needles** separating them. As a consequence,

smectite clays are readily dispersed in water into extremely small particles and still remain physiochemically stable [Grim and Guven, 1978].

The major constituent of bentonite is montmorillonite [Marshall, 1937; Hauser and Reed, 1937], described as expanding lattice clays. Montmorillonite clays differ from other clays because of their large ion-exchange capacity and large swelling capacity [Krauskopf, 1979].

Bentonites have a wide variety of uses in many different industries. In the food industry, bentonite has been used in small amounts (1-5%) as a bonding agent in pelletizing animal feed, and as a suspending agent in wet-mash type of feeds [Grim and Guven, 1978]. Holden (1948) claimed that the addition of 0.25-1.25% by weight of the total cereal content of flour reduced staling in bread and other baked products.

Because of the remarkable dispersion property mentioned above, bentonite, an adsorptive, colloidal and homogeneous clay, was used to study heat transfer mechanisms for the canning industry [Jackson and Olson, 1953]. Yamano et al. (1975) used both 25% and 40% bentonite-water dispersion cakes packaged with film pouches (150 x 200 mm) to simulate conduction heating in flexible food package. Bentonite cakes were formed into slabs 20 mm thick, 200 g per pouch. The Japanese found that the thermal diffusivity for the 40% bentonite-water dispersion was nearly equal to published values for fish and meat, and recommended use of bentonite because wide variations in water content could be used and the mixtures were physiochemically stable. Darsch et al. (1979) used a mixture of 5.0% bentonite, 47.5% glycerin (glycerol) and 47.5% water to simulate solid foods and a

1% bentonite, 49.5% glycerin and 49.5% water mixture to simulate soups or beverages when testing a food delivery cart.

A bentonite, glycerin and water combination, unlike water alone, has heat characteristics similar to many foods [Jackson and Olson, 1953]. This mixture was used as the testing media, during both heating and chilling, to avoid introducing variations inherent in food composition.

Unklesby et al. (1980) used a bentonite-water (ratio of bentonite to water ranging from 60-78.5%) to simulate ten menu items for energy consumption, evaporation loss and product yield studies. Unklesbay et al. (1980) concluded that bentonite-water dispersion had the potential use for the study of energy consumption for foodservice heating equipment. Unklesbay et al. (1981) used bentonite-water (18.2% to 81.8% by weight) to simulate energy consumption of sausage patties during convective heat processing and reported no significance difference between sausage and bentonite patties for the energy consumption. Peterson and Adams (1983) performed research on retort pouches containing 10% bentonite-water dispersions and determined their thermal properties.

Niekamp et al. (1983) used bentonite-water dispersions to simulate quiche and found no significant difference in energy consumption on a per pie basis between the quiche and the bentonite model during convective heat processing. Niekamp et al. (1984) determined thermal properties of bentonite-water dispersions with varied water content. Noh et al. (1985) had no problem using 1% bentonite-water suspension to simulated fruit juices for aluminum canning by flame pasteurization. McGinnis (1986) used 10% bentonite-water paste to study heat transfer in flexible retort pouches and found no significant difference between bentonite model and

beef. Unklesbay et al. (1988) used bentonite-glycerol-water (20%, 10%, 70% by weight) dispersion to simulate turkey rolls for energy consumption during convective heating. No significant differences were found between turkey rolls and the bentonite model. Researchers have concluded that bentonite dispersions were effective food models for energy and thermal processing studies.

CHAPTER III

RATIONALE AND HYPOTHESES

The rationale for selection of microwave equipment, experimental products, microwave processing variables and bacteria are given in this chapter. Strategies to improve microbial quality of microwave processed food: (1) wrap food in plastic film; (2) regulate load shape; (3) use small load size; (4) homogenize food load; (5) lower microwave output power; (6) extend processing time and the concept of exposed microwave dose are also discussed.

3.1 Microwave Equipment

A single microwave oven was planned for use in processing experimental products throughout this study. The use of one oven in the present study is in contrast to most other microwave research studies which used two or more ovens [Zimmermann, 1983; Aleixo, et al., 1982; Carlin, et al., 1982].

In other studies when two or more microwave ovens were used for food research, the data were more representative of field results than when a single microwave oven was used. However when basic microwave processing research has been carried out, using a single microwave oven has an advantage over multiple microwave ovens because variation among the heating patterns of microwave ovens has been eliminated. Thus, results should be unbiased without complications arising from variation resulting from multiple ovens. Based on the above reason, a single microwave oven was proposed for use in this study.

3.2 Experimental Product

Actual meat (beef and turkey) and simulated meat (bentonite-glycerol-brain heart infusion broth or BGB) loaves were planned for use as experimental products. The rationale for choosing type of loaf and other variables such as fat content and water content, product shape and size are given below.

3.2.1 Type of loaf

The rationale for choosing beef, turkey and BGB loaves as experimental products are presented. Also the thermal and dielectric properties of beef, turkey and bentonite are discussed in this section.

3.2.1.1 Meat loaf

Beef loaf was planned for use as the main experimental product because of its homogeneous composition compared to other meat products and because other researchers who studied microwave processing used a similar product [Berry and Lebby, 1984; Sawyer et al., 1984, 1983; Dale et al., 1980a, 1980b, 1980c; Crespo et al., 1977]. Foods differ widely in their thermal responses to microwave radiation due to variations in their specific heat and their dielectric properties [Sawyer, 1983]. To study the effect of variety of food products on bacterial survival and thermal responses after microwave processing, turkey loaf was planned for use as an experimental product. Turkey loaf would be compared with beef loaf at one of three

fat content levels. The reason to choose turkey as a second meat product in the present study were: (1) ground turkey is available in the market and is gaining popularity among consumers because of the low fat content; (2) like beef, turkey also has been used in microwave processing studies [Aleixo et al., 1985; Cipra and Bowers, 1971]; and (3) turkey meat products have been compared to bentonite models [Unklesbay et al., 1988] which was also planned for use as an experimental product (Section 3.2.1.2).

Because of the similarity of the thermal and dielectric properties of beef and turkey (Table 1), one could expect that the thermal responses of beef loaf and turkey loaf would be similar. Relatedly, the bacterial survival of microwave processed beef and turkey loaves would also be expected to be similar. Based on the assumption above, the following hypothesis may be stated:

H₀₁: Bacterial survival in beef loaves and in turkey loaves are similar.

3.2.1.2 Bentonite-glycerol-BHI broth (BGB) loaf

When foods have been microwave heated, temperatures in the foods after heating have shown wide ranges (see Section 2.3.4.2). This has been partially attributed to the lack of homogeneity in food [Mudgett, 1982]. Most food items such as meat, even when ground and formed into a loaf, are still not as homogeneous as is water. Therefore, even beef loaf was not considered to be an ideal product to study microwave processing.

Table 1. The dielectric and thermal properties of beef , turkey and bentonite-water dispersions (20:80).

Factor	Beef	Turkey	Bentonite-water
Dielectric constant (ϵ') 2450 MHz at 5 °C	52.8 ^A	52.8 ^A	-
Dielectric loss factor (ϵ'') 2450 MHz at 5 °C	19.8 ^A	21.4 ^A	-
Thermal conductivity (W/m °K)	0.43-0.49 ^B	0.50-0.52 ^B	-
(W/cm °C)	0.40 ^C	-	0.666 x 10 ⁻² ^D
(Btu/Hr. Ft. °F)	0.266 ^E	0.290 ^E	-
Heat capacity (KJ/Kg °F)	3.404 ^B	3.284 ^F	3.222 ^D

^A Mudgett et. al. (1974).

^B Heldman (1981).

^C McProud and Lund (1983).

^D Nickamp et. al. (1984).

^E Woodams and Nowrey (1968).

^F calculated from Charm's formula (1978) based on the experimental data.

When food products are processed in a microwave field, the heterogeneity within any given food can create unexpected variations in results such as temperature and microbial plate counts. To obtain information about temperature pattern and microbiological data with smaller variations, a simple homogeneous system was needed so conclusions would be drawn without complications arising from heterogeneity of most food loads. Bentonite has been reported to be a homogeneous product [Darsch et al., 1979]. Therefore, the following hypothesis may be stated:

Ho2: Bentonite can improve temperature uniformity when compares to meat loaves.

Bentonite was considered for use in this study as a food model for three reasons: (1) bentonite is quite homogeneous so that the effect of variations inherent in food composition could be eliminated [Darsch et al., 1979]; (2) bentonite could be mixed with various quantities of water to form liquid or solid phases, and the mixture would be expected to remain physiochemically stable [Yamano et al., 1975]; and (3) bentonite has similar thermal characteristics to many food products including beef and turkey which were chosen for use in the present study [Unklesbay, et al., 1988, 1984, 1981, 1980; Noh, et al., 1985; Nickamp, et al., 1983; Darsch, et al., 1979].

In a previous study, bentonite, water and glycerol, a fat substitute, were used to simulate beef steak [Darsch et al, 1979] and turkey roll [Unklesbay et al, 1988]. No

research has been done on using a bentonite model to study microwave processing and microbial survival.

To use bentonite as a research model for bacterial survival, a modification of a formulation of Unklesbay et al. (1988) was planned; a portion of the water would be replaced with brain heart infusion (BHI) broth, a nutrient for bacteria. The purpose of the addition of BHI nutrients would be to provide a better environment for adjustment of bacteria in BGB loaf.

The heat capacity of bentonite-water dispersions is similar to those of beef and turkey. However, the thermal conductivity of a bentonite-water dispersion is much smaller than that of beef and turkey (Table 1). The difference in thermal conductivity between bentonite-water dispersions and meat suggested that the post processing temperature change of a microwave processed bentonite dispersion could be quite different from that of meat.

The modified (bentonite-glycerol-BHI broth, or BGB) model might have potential as a food model for studying bacterial survival in foods after microwave processing. Therefore, the conclusion was made that a BGB model could be used to study bacterial survival in a microwave field. Results of the BGB model would be compared to those of beef loaf and turkey loaf. Based on the conclusion made above, the following hypothesis may be stated:

Ho3: BGB (10% glycerol) can simulate bacterial survival in a microwave field for meat loaves (10% fat).

3.2.2 Other variables of experimental products

In addition to the variables of type of meat (beef vs. turkey) and homogeneity (meat vs. BGB), other experimental product variables which have been reported to affect microwave processing were fat content, water content, and load size. Thus, experimental products of this study also were planned to vary in type of loaf, percent fat content, percent water content, and load size.

3.2.2.1 Fat content and water content

Fat, a major component of beef, has a specific heat of 2.0 KJ/kg·°C compared to water which has a specific heat of 4.2 KJ/kg·°C. [Schiffmann, 1986]. Thus, fat could be expected to heat twice as fast as water in a microwave field. If the micro-environment in a food system affects bacterial survival, contents of the food load to be microwave processed such as percent of fat and water must be determined. A protective effect of fat on bacteria has been suggested [Jay, 1986]. Whether this protective effect of fat on bacteria exists after microwave processing requires investigation. Based on the assumption that fat could protect bacteria in a microwave field, the following hypothesis may be stated:

Ho4: Bacterial survival can be enhanced by increasing fat content of food load after microwave processing.

Three levels of fat content (10, 20 and 30%) were planned for use in beef loaves used in this study to evaluate the effect of fat content on bacterial survival in beef loaves after microwave processing.

The choice of these percents of fat content are similar to the diet lean (5-8% fat), lean (15-18% fat) and regular (25-27% fat) ground beef sold on the consumer market [local communication with retail food stores]. Only one level of fat content (10%) was proposed for use with turkey loaf because 10% fat content represented the ground turkey sold on the consumer market and could be used to compare to the result of beef loaf with 10% fat. Three levels of glycerol content (10, 20 and 30% fat) were planned for BGB loaves in this study to compare to three levels of fat in beef loaves.

3.2.2.2 Load size

Some researchers have suggested that temperature uniformity in a food load could be improved by reducing the size of the food load [Decareau, 1975]. Thus, three load sizes (150, 600 and 1200 g; Section 3.5.1.3) were planned for use in this study to evaluate the effect of load size on improving uniformity of temperature distribution and bacterial survival in loaves after microwave processing.

3.2.2.3 Shape of container

The loaves used for this study were to be formed in doughnut-shaped containers. Doughnut-shaped containers were planned for use for microwave

processing because the shape had been shown to improve uniformity of temperature distribution within a food load [Schiffmann, 1986; Hoffman and Zabik, 1985a]. This improvement occurred because the central cold spot was eliminated and overheated corners caused by microwave concentration were avoided [IFT, 1989; Schiffmann, 1986; Starrack, 1980; Copson, 1975b].

3.3 Microwave processing

Rationale for choice of the microwave processing variables used in this study, wrapping in plastic film, microwave output power and processing time are discussed below. The difficulty to obtain expected minimum temperature of a food load after microwave processing is also briefly described. Reason to consider evaporation loss as a dependent variable is included.

3.3.1 Polyvinylidene chloride (PVDC) wrapping

Wrapping foods in plastic film has been recommended by several researchers to improve microbial quality of foods after microwave processing [Sawyer and Biglari, 1984; Sawyer et al., 1984; Baldwin, 1982; Fung and Cunningham, 1980; Ruyack and Paul, 1972]. In this study, polyvinylidene chloride (PVDC) film (Saran Wrap®, Dow Chemical U.S.A., Midland, MI) was chosen because PVDC is heat durable, microwave transparent and water proof [Brydson, 1982].

3.3.2 Microwave output power and processing time

As mentioned in Section 2.3.4.3., increasing the microwave processing time could improve microbial quality of foods. Therefore, two levels of output power (50 or 100%) were planned for use in this study. To assure that the same amount of microwave radiation per gram was received by experimental products at 50% output power and at 100% output power, time of microwave processing at 50% output power would be doubled.

At each output power level, four different processing times would be chosen so loaves could receive sublethal or lethal doses of microwave energy; hence, survival patterns of bacteria could be established (Table 2). Experimental products to be processed at the second longest processing time for each output power were expected to reach the target temperature of 74 °C which is recommended by USDHEW (1978) for safe processing of beef.

3.3.3 Difficulty of temperature measurement

Because of reports of inconsistent temperature pattern among and within food loads that had been processed in a microwave oven, accurate location and measurement of the point of lowest end-point temperature (EPT) in a food load was considered not possible. In the present study, sixteen thermocouples were to be used to measure EPT. The lowest temperature measurement among the 16 locations was to be considered the minimum EPT for the food load subjected to a particular treatment.

Table 2. List of microwave processing treatments used for experimental products.

Loaves	Microwave output power (%) of 713 watts	Load size (g)	Processing times[*]				(unit)
Meat[#]	100	150	45,	60,	75,	90	sec
Meat	100	600	3,	4,	5,	6	min
Meat	100	1200	6,	8,	10,	12	min
Meat	50	150	90,	120,	150,	180	sec
Meat	50	600	6,	8,	10,	12	min
Meat	50	1200	12,	16,	20,	24	min
BGB[†]	100	150	45,	60,	75,	90	sec
BGB	100	600	3,	4,	5,	6	min
BGB	100	1200	6,	8,	10,	12	min
BGB	50	150	90,	120,	150,	180	sec
BGB	50	600	6,	8,	10,	12	min
BGB	50	1200	12,	16,	20,	24	min

Footnotes:

^{*} Each load size was exposed to four identical levels of microwave energy per gram of loaf.

[#] Beef (10, 20, or 30% fat), or turkey (10% fat).

[†] Bentonite-glycerol-BHI broth (three load sizes for 10% glycerol; 150 g load size for 20 and 30% glycerol).

In this study, the temperature rise which occurred during microwave processing was defined as the microwave processing temperature rise (MPTR) and would be distinguished from the temperature rise after microwave processing which was defined as post processing temperature rise (PPTR; Sawyer, 1985). The length of time of PPTR would begin at the time of microwave power was turned off and would end when temperature rise was no longer observed [Sawyer, 1985].

3.3.4 Evaporation loss

Weight losses during microwave processing have usually been attributed to evaporation of water and the drip loss of fat and water into the container (Carlin et al., 1982; Dale and Matthews, 1980). Extensive weight loss in a food could result in poor eating quality, nutrient loss and high production cost [Trout and Schmidt, 1987]. Weight loss due to microwave processing has been related to food composition such as water, fat content and processing conditions such as processing time and temperature. In this study, weight loss of products after processing would be considered to be evaporation loss. Drip loss that would be retained in the processing container would be considered as part of product weight after processing. Evaporation loss would be measured and correlated to the fat content and water content of experimental product as well as other processing variables.

3.4 Microbiology of Microwave Processing

The criteria for choice of inoculants and the rational for inoculation levels of bacteria into experimental products are given below. The probable effects of pH and water activity (a_w) on bacterial survival are also considered.

3.4.1 Selection of target bacteria

Target bacteria were selected from among pathogens related to meat and poultry products. Bacteria species were also chosen to serve as indicator organisms and therefore should have characteristics common to other food pathogens. Therefore, the results of the destruction of indicator bacteria in a microwave field are likely to be applied to the group of pathogens that indicator bacteria represented. In this study, aerobic mesophilic bacteria were chosen because they have very high contamination rate in meat and poultry products and most pathogens are mesophiles [ICMSF, 1978].

Staphylococcus aureus was considered for use in the present study. The presence of *S. aureus* in a food has usually been considered an indication of contamination from food handling workers or inadequately cleaned equipment [Brown, 1982]. The presence of large numbers of *S. aureus* has been a good indication that sanitation and temperature control have not been adequate. *S. aureus* has been found more frequently in poultry products than in any other meat products [Brown, 1982]. The Center for Disease Control reported that in some years *Staphylococci* accounted for more outbreaks of foodborne disease in the U.S.A. than

did any other bacterium [CDC, 1979]. Based on the reasons mentioned above, *S. aureus* (ATCC 6538), as recommended by the Department of Public Health of State of Michigan, was chosen as one of the target bacteria for this study.

Escherichia coli was considered for use in the present study. The native habitat for *E. coli* is the enteric tract of man and other warm-blooded animals. Presence of this organism has been generally considered an indication of pollution of direct or indirect faecal origin. Hence, *E. coli* has become the classical indicator of the presence of enteric pathogens and has a high frequency of documental contamination in meat products [Brown, 1982]. A rare *E. coli* serotype, O157:H7, which affected at least 47 people with hemorrhagic colitis in Oregon and Michigan in February through March and May through June, 1982 [Riley, et al. 1983], was chosen as one of the two target bacteria for this study.

Most foods (except fermented products) are regarded as unwholesome when they have a large population of microorganisms [ICMSF, 1978]. High viable counts often indicate contaminated raw materials, unsatisfactory sanitation, or unsuitable time/temperature conditions during production or storage. If the organisms which contaminate foods are mesophiles, this means conditions may have existed which might favor the occurrence of pathogens in large numbers since most pathogens are mesophiles. In addition, high microorganism counts foretell the likelihood of spoilage, because most foods contains 10^6 and 10^8 microorganisms per gram at the time when decomposition becomes evident. Also various common bacteria (e.g., faecal streptococci, *Proteus*, pseudomonads) not usually regarded as pathogens have been suspected of causing poisoning when excessive numbers of living cells were present in food. Because the pathogenic and suspect species are almost all

mesophilic bacteria, attention is concentrated on this type of organism [ICMSF, 1978]. With respect to above reasons, aerobic mesophilic bacteria can generally be regarded as indicator organisms and are chosen for use in this study.

Based on their ability to serve as an indicator organism and the frequency of bacterial contamination in meat products, *Staphylococcus aureus* (Gram positive) and *Escherichia coli* (Gram negative) were planned for inoculation into the experimental products to observe bacterial survival patterns under various conditions of microwave processing [ICMSF, 1978].

3.4.2 Inoculation dose

To assure that the inoculated *E. coli* and *S. aureus* can survive and be enumerated after microwave processing, high inoculation dose is recommended. The inoculation dose would be 10^6 to 10^7 cells/gram of loaf which was about 10,000 times higher than initial bacterial counts (10^2 to 10^3 cells/gram of loaf) of unprocessed loaves before inoculation [Brown, 1982].

3.4.3 pH and a_w

The pH in a food load to be heat processed affected bacterial survival [Jay, 1986]. Therefore, the pH changes of loaves were planned for measurement before and after microwave processing to determine if pH was related to bacterial survival.

The a_w in fresh meats is greater than 0.98 and has not been considered to have any protective effect on bacteria [ICMSF, 1980]. However, the a_w of BGB loaves

was unknown. To assure that BGB loaves had a formulation that produced an a_w similar to that of meat loaf, measurements of a_w in BGB loaves were to be taken before BGB loaves were processed.

3.5 Strategies to improve microbial quality of microwave processed foods

Strategies, that have been recommended in the literature to improve microbial quality of foods after microwave processing, can be categorized into two groups: (1) improve uneven heating pattern and (2) prolong processing time. These strategies, planned for use in this study, are summarized below:

3.5.1 Improve uneven heating pattern

The wide ranges of temperature within a food can be reduced by: (1) wrapping foods in plastic film [Sawyer et al., 1984]; (2) regulating shape of loaf [Schiffmann, 1986]; (3) using a small load size [Decareau, 1975] and (4) improving the homogeneity of food [Mudgett, 1982]. The discussion of these strategies follows.

3.5.1.1 Wrap food in plastic film

Wrapping loaves in PVDC film was considered for use in the present study. Several researchers [Sawyer et al. 1984; Baldwin 1982; Fung and Cunningham 1980] have suggested that food should be wrapped in plastic film for reduction of bacterial survival in foods after microwave processing. If food loads were wrapped

in plastic film, convective heat and water vapor transferred to the environment could be reduced by forming a heat sink which would retain heat generated by microwave radiation [Mudgett, 1986]. The higher temperature (more destructive to bacteria) in food resulted when more heat was retained by wrapping. Hence wrapping foods in plastic film can probably improve heat distribution within a food.

Vinylidene chloride, a thermally unstable polymer, is unable to withstand melt processing. However, by copolymerizing the vinylidene chloride with 10-15% of vinyl chloride, processable polymers (PVDC) may be obtained which are used in the manufacture of filaments and films [Brydson, 1982]. These copolymers have been marketed by the Dow Company since 1940 under the trade name Saran Wrap®. The properties of vinylidene chloride-vinyl chloride copolymers are greatly dependent on crystallization and orientation during processing. Saran Wrap®, a biaxially-stretched copolymer film, is a useful packaging material. Its unique properties such as exceptional clarity, brilliance, toughness and water and gas impermeability, plus its microwave transparency, and heat resistance [Brydson, 1982] make it a good wrapping film for microwave processing. Therefore, PVDC film was chosen as the wrapping material for this study. The effect of PVDC wrapping on bacterial survival will be evaluated by comparing the bacterial survival between PVDC wrapped meat loaves and unwrapped ones. Based on the assumption that PVDC could retain heat generated by microwave energy, the following hypothesis may be stated:

**Ho5: Wrapping foods with PVDC film can reduce bacterial survival,
improve product yield and temperature uniformity.**

In the pre-study of beef loaves, the second highest processing time (Table 2; Section 3.3.2) was lethal to *E. coli* and *S. aureus* when meat loaves were wrapped with PVDC film. Since bentonite would be used for the first time to study bacterial survival for microwave processing, it would be better not to wrap BGB loaves with PVDC film. Hence, the surviving curves of bacteria can cover wider range of sublethal and lethal conditions if BGB loaves are not wrapped.

3.5.1.2 Regulate load shape

The more regular (less sharp edges and corners) the shape of the food load, the more uniform will be the heating after microwave processing. Sharp edges and corners should be avoided since these will tend to be overheated [Schiffmann, 1986]. If the shape of a product is irregular, it is most likely that one portion will be overheated and the other portions will be underheated. In this study, doughnut-shaped containers which did not have sharp edges or corners, were used to eliminate the "cold spot" in the center [Copson, 1975b] and to improve heating uniformity [Hoffman and Zabik, 1985a; Starrack, 1980]. Based on the assumption above, the following hypothesis may be stated:

Ho6: The center "cold spot" of a food load can be eliminated by using doughnut-shaped containers.

3.5.1.3 Use small load size

Decareau (1975) concluded that a large food load size created greater unevenness of temperature and suggested that load sizes be reduced to increase temperature uniformity and, hence, to improve microbial quality. Schiffmann (1986) made a similar suggestion about choice of load size and avoiding irregular shapes for food. As load size is reduced, the thickness of the food load also is usually reduced. It is very important that product thickness be limited to power penetration depth, i.e., the depth at which about 67% of transmitted power is absorbed, to obtain uniform heating [IFT, 1989].

Three sizes of beef loaf were chosen: 150 g which represented a single portion of the food item at point of service; 600 g which represented four portions as may be used by a family; and 1200 g which represented eight portions as may be used in a small foodservice facility. In the present study, the effect of load size will be evaluated by comparing bacterial survival, thermal responses, evaporation loss and temperature patterns among three load sizes for loaves that received identical microwave treatments. Based on the suggestion by Decareau (1975) and Schiffmann (1986), the following hypothesis may be stated:

Ho7: Reducing load size can improve temperature uniformity and reduce bacterial survival.

The three load sizes were planned for use in this study for beef, turkey and BGB (10% glycerol) experiemntal products. Only the 150 g load size were planned

for use for the BGB loaf with 10, 20, and 30% glycerol because in the pre-study of beef loaves, the bacterial survival and thermal responses of 150 g load sizes showed more obvious changes to varied microwave processing conditions than larger load sizes. Therefore, only the 150 g load size would be chosen for BGB loaf to study the effect of glycerol content on bacterial survival, thermal responses and evaporation loss.

3.5.1.4 Homogenize food load

Heterogeneity of a food load could result in a wide range of temperature within the product because of different dielectric properties (relative dielectric constant [ϵ'], loss tangent [δ] and loss factor [ϵ'']) of ingredients [Mudgett, 1982]. Since food components such as fat, water, salt have different thermal conductivity and specific heat [Schiffmann, 1986], one could expect that each food component would be heated differently in a microwave field and hence a wide range of temperature would assure. To achieve a homogeneous system using actual food ingredients is extremely difficulty. However, when feasible, microwavable foods should be designed to be as homogeneous as possible. In this study, the temperature variation within a loaf between meat loaves and BGB loaves would be compared to determine if temperature uniformity can be improved by the introduction of homogeneity into the foods.

3.5.2 Prolong processing time

To achieve the same microbial quality, the end-point temperature of microwave processed foods should be higher than that of conventional methods [Baker, et al., 1983]. The F.D.A Unicode 2-401.18 [F.D.A., 1988] recommended that when foods are cooked in microwave ovens, an additional 13.9 °C be added to the target temperature to compensate for the shorter cooking time (compared to conventional methods). Prolonging processing time can be done either by extending the processing time while maintaining the same microwave output power or by lowering the microwave output power and increasing processing time proportionally so an equal amount of microwave energy can be received by foods. However, microwave processing time should only be prolonged to the extent that the nutrients in food and the advantage of "fast" processing are still retained. In the present study, prolong processing time was planned to be achieved by lowering microwave output power or by extending processing time.

3.5.2.1 Lower microwave output power

In the past, microwave ovens were not capable of varying the heating rate [Fruin and Guthertz, 1982]. However, many modern microwave ovens have settings which can be used to choose output power ranging from 10% to 100%. By lowering output power with prolonged processing time, a slower heating rate can be achieved. Zimmermann (1983) and Fruin and Guthertz (1982) suggested minimizing the

microwave output power with prolonged processing time so that the slow heating rate could destroy microorganisms more efficiently.

In the present study, two levels of microwave output power (50% vs. 100% of 713 watts) were planned for use to study the effect of level of microwave output power on bacterial survival. Loaves that received equal amount of microwave energy per gram but vary in microwave output power would be used for comparison of bacterial survival to see if the lower microwave output power can improve microbial quality of foods. Based on the suggestion of Fruin and Guthertz (1982) and Zimmermann (1093), the following hypothesis may be stated:

Ho8: Microbial quality of meat loaves can be improved by lowering microwave output power.

3.5.2.2 Extend processing time

Baker et al. (1983) observed that longer processing and higher end-point temperatures were needed for microwave processing to achieve microbial quality of foods equal to that which had been processed by conventional methods. F.D.A. (1988) also recommended that foods which were processed by microwave ovens should be cooked to higher temperatures by extending the cooking time. Therefore, extending processing time to achieve a higher end-point temperature to destroy bacteria in loaves was planned in the present study.

In this study, four different processing times (Table 2; Section 3.3.2) were

planned for use so loaves could receive sublethal or lethal doses of microwave energy. Hence, survival patterns of bacteria could be established and be compared to evaluate the effect of extension of processing time on bacterial survival in loaves.

3.6 Exposed microwave dose

As discussed in Section 2.2.3, the temperature patterns of foods at the end of microwave processing show wide ranges of temperature which make it impossible to measure representative product temperature [Sawyer, 1985; Bryan and Lyon, 1984; Bakanowski and Zoller, 1984]. Dahl et al. (1980b) investigated the EPT of selected foods after microwave heating and concluded that criteria other than EPT should be developed to determine the end of microwave processing. The use of end-point temperature (EPT) to indicate the doneness of food products thus is theoretically inappropriate and microbiologically unsafe.

The concept of exposed microwave dose (defined as Watts x minutes processed/grams of food or EMD) was to be introduced in the present study to describe the relationship between wattage output, time of microwave processing and load size. This new derived variable - $[(713 \times MP/100) \times (PT/60)/LS]$, was planned for use to replace processing time (PT) in all statistical analyses because it would be expected to describe bacterial survival, thermal responses and evaporation loss better than did processing time. Based on the assumption above, the following hypothesis may be stated:

Ho9: EMD can be used to predict bacterial survival, thermal responses and evaporation loss of foods that have been microwave processed.

CHAPTER IV

MATERIALS AND METHODS

Detailed descriptions of experimental equipment, products, and procedures are given in this chapter. Also experimental design and statistical analyses of experimental data are briefly presented.

4.1 Microwave Equipment

One domestic-sized microwave oven [2450 MHz, model PR-9TA, Amana Refrigeration Inc., Amana, Iowa] was used throughout this study. A 0.1 cm diameter hole was drilled on the left upper side of the microwave oven to allow a Fiber Optic thermoprobe [GSA-2, Luxtron, Mountain View, CA] to be inserted into the oven chamber to monitor temperature changes during microwave processing. Electric power for the microwave oven was regulated by a Power Stat Variable Auto-transformer [Type 116B-1159, Superior Electric Co., Bristol, CT.] which set the line voltage at 115 volts throughout the study. The output power of this microwave oven was measured (Section 4.1.1) before the study began and was checked about once a month thereafter until the study was completed (n=28 months).

4.1.1 Measurement of output wattage in the microwave oven

Wattage output power of the microwave oven was calculated using 1000 ml of distilled water heated 120 sec according to the method recommended by Copson

(1975a). As determined in a prestudy, the output wattages measured at 100% power and 50% power were 713 ± 5 watts and 356 ± 3 watts respectively ($n=3$). The output wattage was rechecked once a month for a period of 28 months. During this period of time, the measured wattages of microwave output power fluctuated, but were within 95% confidence interval of prestudy's values (± 9.19 and ± 5.51 W for 100% and 50% output powers respectively).

4.2 Experimental Product

Actual (beef and turkey loaf) and simulated (BGB loaf) food loads were used as experimental products in this study. Details about formulations for loaves, processing containers, load sizes, time-temperature parameters of handling the experiment product and procedures to measure water content, fat/glycerol content, pH and water activity follow.

4.2.1 Actual food loads: beef and turkey loaves

Ground beef (with 10%, 20%, and 30% fat content) or ground turkey (with 10% fat content) were used as actual food products (section 3.2.2.1). Meat loaf was formulated with ground beef or turkey, 86%; dried onion [Basic American Foods, San Francisco, CA], 7%; oatmeal [Quick Oats™, Ralston Purina Co., St. Louis, MO], 6%; nutmeg [Seasonings & Ingredients INC., Bedford Park, IL], 0.2%; and salt [Morton Thiokol INC., Chicago, IL], 0.8%.

4.2.2 Simulated food load: BGB loaf

BGB loaves were formulated to simulate beef loaf with 10, 20, and 30% fat content or turkey loaf with 10% fat content. Ingredients were bentonite, 20% [Sigma Chemical Co., St. Louis, MO]; glycerol, 10, 20 or 30% [Sigma Chemical Co., St. Louis, MO] and buffered BHI broth, 70, 60 or 50% [Difco Laboratories, Detroit, MI].

4.2.3 Processing container

Three sizes of doughnut-shaped Pyrex glass containers, made in the glass shop of the Chemistry Department, Michigan State University, were used to hold the meat loaves (wrapped or unwrapped with PVDC film) and BGB loaves (unwrapped) during microwave processing (Figure 3). The doughnut-shaped containers were designed with a center stem to eliminate the "cold spot". [Starrack, 1980; Copson, 1975b].

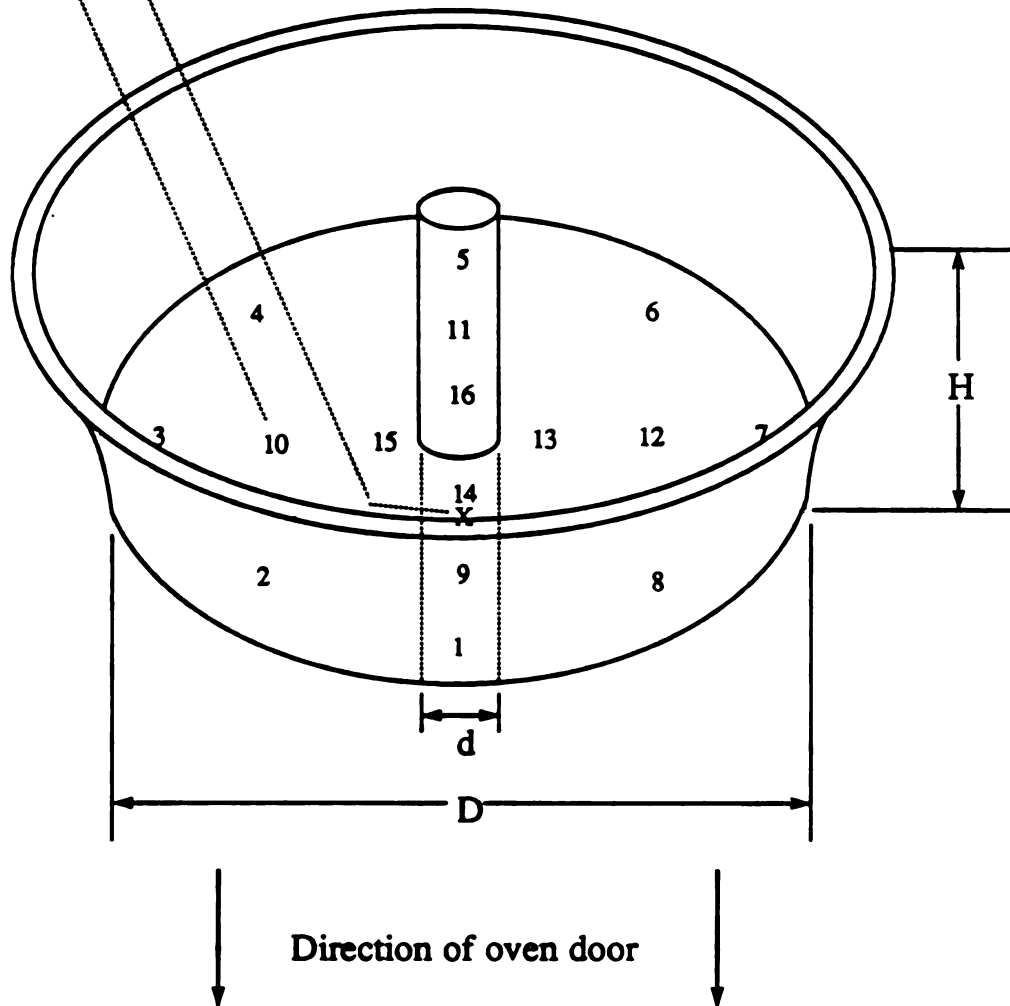
4.2.4 Load size

Three sizes of beef loaf were used: 150 g represented a single portion at point of service; 600 g represented four portions as might be used by a family; and 1200 g represented eight portions as might be used in a small foodservice facility. The three sizes of loaf (150 g, 600 g and 1200 g) were used for beef, turkey and

Figure 3. Doughnut-Shaped Pyrex™ container which held loaves during microwave processing.

Temperature measuring locations for 16 thermocouples

Temperature measuring location for Luxtron thermoprobe



Load Size	D (cm)	d (cm)	H (cm)
150 g	12.5	1.27	5.6
600 g	15.0	1.59	6.5
1200 g	19.0	1.91	8.8

Figure 3.

BGB (10% glycerol) experimental products. Only the 150 g size was used for the BGB loaf with 10, 20, and 30 % glycerol.

4.2.5 Time-temperature parameters of handling the experimental product

Four batches (82 kg/batch) of ground beef (with 10%, 20%, and 30% fat content) and ground turkey (with 10% fat content) were purchased through Michigan State University Food Stores and handled according to methods described in the Hazard Analysis Critical Control Point (HACCP) Model for foodservice systems [Bryan and Lyon, 1984; Baird-Parker et al., 1982; Bobeng and David, 1978a, 1978b] to minimize bacterial growth. After receiving ground meat ($\leq 10^{\circ}\text{C}$) from Food Stores, meat loaves were mixed using a Butcher Boy meat mixer [model 250F, Lasar MFG. Co., Inc., Los Angeles CA] and stored within one hour. Meat loaves were weighed into 250, 700, and 1300 gram loaves (the extra 100 g for each load sizes was taken into account for handling waste and samples needed for water/fat determination and microbial enumeration). Thirty two (32) loaves for each load size were individually packaged into Ziploc® freezer bags (17.8 cm x 0.3 cm x 2.7 mil for 250 g loaves; 26.8 cm x 27.9 cm x 2.7 mil for 700 and 1300 g loaves; Dow Chemical U.S.A., Midland, MI), frozen and held in a walk-in freezer (-30 to -25°C) for four months or less. One day before microwave processing, meat loaves were thawed in a walk-in refrigerator ($\leq 10^{\circ}\text{C}$) for 24 hr. *S. aureus* (ATCC 6538; American Type Culture Collection, Rockville, MD) and *E. coli* (O157:H7) were manually inoculated into meat loaves [Riley et al, 1983]. Inoculated meat loaves were thoroughly hand mixed and the appropriate weight of meat loaves were

packed into the appropriate processing containers. Loaves were then placed into the refrigerator for 1-4 hr to assure the initial temperature of experimental products were within refrigeration temperatures (1-10 °C) before microwave processing.

To produce 20 kg of BGB dispersions (10% glycerol) using a Hobart mixer [Model 6000, Hobart Manufacturing Co., Troy, OH], BHI broth was first prepared by dissolving 518 g of BHI medium into 14 liters of 0.1 M KH_2PO_4 -NaOH buffer solution (pH =5.7). Exactly 14 kg of buffered BHI broth was poured into the mixer and 2 kg of glycerol was added and mixed; then 4 kgs of bentonite were added gradually. The mixing was continued mechanically for another 2 hr after bentonite was completely dispersed into the liquid [Unklesbay et al., 1988]. The BGB dispersion was covered with 3 layers of polyethylene film and tightened with a string to prevent moisture loss, then stored in a walk-in refrigerator (≤ 10 °C) overnight.

Four batches (3 kg/batch; 2 batches for each different % glycerol) of BGB dispersions (20 and 30% glycerol) were prepared using a Kitchen Aid Mixer [Model K5-A, Hobart Manufacturing Co., Troy, OH]. The preparation procedure was the same as for the BGB dispersions with 10% glycerol. For the BGB dispersions with 20% glycerol (by weight: 20% bentonite, 20% glycerol, 60% buffered BHI broth,) and the BGB dispersions with 30% glycerol (by weight: 20% bentonite, 30% glycerol, 50% buffered BHI broth), only 250 g loaves were individually packaged into Ziploc® freezer bags 24 hr after mixing. The BGB dispersions with 10% glycerol were mixed and weighed into 250, 700, and 1300 g loaves and individually packaged into Ziploc® freezer bags, frozen and held in a walk-in freezer (-30 to -25 °C).

One day before microwave processing, BGB loaves were thawed in a walk-in refrigerator ($\leq 10\text{ }^{\circ}\text{C}$) for 24 hr before being internally inoculated with bacteria. Loaves were then weighed and manually packed into the appropriate processing containers. The inoculated, packed products were stored in a refrigerator ($\leq 10\text{ }^{\circ}\text{C}$) for an additional 2 hr before microwave processing to assure temperature equilibration.

4.2.6 Determination of water content

Due to the varied physical properties of meat and BGB loaves, two different methods were used to determine water content in experimental products. The Section below describes the method used to determine water content in meat and BGB loaves.

4.2.6.1 Determination of water content in meat loaf

The procedure for determination of water content of meat loaf followed the A.O.A.C. 24.003 (1984) standard method. Aluminum moisture dishes were numbered with a sharp pencil point on dish tabs, then dried at least 1 hr at $100\text{ }^{\circ}\text{C}$ in an air convection oven [Stabil-Therm Laboratory Oven, Blue M Electronic Co., Blue Island, IL]. Handling of dishes was done with tongs to avoid fat and moisture contamination from the hand onto the dried aluminum dishes. Two replicates were run per sample ($n=768$ dishes). Dried dishes were cooled in a Pyrex™ glass desiccator [250 x 326 mm (I.D. x Height)] and weighed by using a Mettler

analytical balance [model B5, Mettler Instruments Co., Highstown, NJ] precisely to 4 decimal places.

Random sampling of the inoculated unprocessed loaf mixture was done immediately after inoculation. Approximately 4 g samples were weighed into tared dried dishes and the exact weight of the sample plus the dish was recorded to 4 decimal places. Samples were dried in an air convection oven [Stabil-Therm laboratory oven, Blue M Electric Co., Blue Island, IL] at 100 °C for 18 hr. Samples were cooled in a desiccator and final weights determined to 4 decimal places and recorded.

4.2.6.2 Determination of water content in BGB loaf

The procedure for determination of water content of BGB loaves followed the A.O.A.C. 7.003 (1984) standard method. The sample handling procedure was the same as for meat loaf described in Section 4.2.6.1 above. BGB samples were dried in a vacuum oven (Model 19, Precision Scientific, Chicago, IL) at 70 °C and pressure ≤ 50 mm Hg to a constant weight (20 hr). The percent water content of loaves was calculated using Formula 1 below:

Formula 1. Formula used to calculate percent water content.

$$\% \text{ water content} = 100\% - \left[\frac{\text{dried sample weight in g}}{\text{fresh sample weight in g}} \times 100\% \right]$$

4.2.7 Determination of fat content

The procedure for determination of fat followed the A.O.A.C. 24.005 (1984) standard method using diethyl ether extraction with a Goldfisch apparatus [model 350011, Lab. Con. CO., Kansas City, MO].

Goldfisch beakers were numbered and dried in a convection oven for at least 1 hr at 100 °C, then cooled in a desiccator. The weight of the beaker was recorded to 4 decimal places. Dried loaf samples (after water content determination) were used for fat determination. Dried samples in aluminum dishes were taken out from the desiccator and rolled to fit into the porous thimbles. About 30 ml of anhydrous diethyl ether was poured into each tared and dried beaker and boiled from 4 to 6 hr, depending on the amount of fat in the sample. After thimbles were replaced by reclaimed tubes, ether was heated again and collected in reclaimed tubes. The remaining ether in the beakers were driven off in a convection oven for 1 hr and cooled in a desiccator. The weight of beaker plus extracted fat was recorded to 4 decimal places. The percent fat was calculated using Formula 2 below:

Formula 2. Formula used to calculate percent fat content.

$$\% \text{ fat} = \frac{\text{ether extract weight in g}}{\text{fresh sample weight in g}} \times 100\%$$

4.2.8 Determination of glycerol content

The procedure for determination of glycerol followed the A.O.A.C. 35.081-083 standard method. Glycerol was first extracted and then oxidized by periodate. The quantity of consumed periodate during oxidation was determined and converted to the amount of glycerol present in BGB loaves (see Section 4.2.8.3).

4.2.8.1 Reagents

All inorganic chemicals and organic solvents were of reagent grade or better. Sources were: KIO_4 (Fisher Scientific Co., Fair Lawn, N.J.); NaOH, bromocresol purple, CHCl_3 , NaHCO_3 , KI (J.T. Baker Chemical Co., Phillipsburg, N.J.); propylene glycerol (Sigma Chemical CO., St. Louis, MO); H_2SO_4 (MCB Manufacturing Chemists Inc., Cinicinnati, OH); and As_2O_3 (U.S. Dept. of Commerce, National Bureau of Standard, Washington D.C.).

4.2.8.2 Extraction and oxidation of glycerol

Two (2) to 10 g of BGB samples were placed in a separator, then 25 to 50 ml of distilled water were added and acidified slightly with H_2SO_4 (10 g/100 ml). The acidified BGB solution was then extracted with 5 successive portions (35 ml/portion) of CHCl_3 to remove CHCl_3 -soluble substances. The combined CHCl_3 extract was washed with 10 ml of distilled water. The aqueous solution and wash water were filtered through a cotton plug to remove droplets of CHCl_3 , and the

filtrate was collected in a 250 ml volume flask. Three drops of bromocresol purple indicator (0.1 g/100 ml alcohol) were added to the filtrate, neutralized with CO₂-free alkali (0.1 N NaOH), and finally adjusted with 0.02 N NaOH. The neutralized solution was diluted almost to 250 ml with distilled water, and if necessary, more alkali was added to keep the solution a light but definite purple. The dilution was then completed to the final volume of 250 ml and mixed.

The aliquot neutralized solution, preferably containing 30 to 40 mg glycerol, was transferred to a 100 ml volume flask, and 50 ml of 0.02 M KIO₄ solution was added. The solution was then diluted to 100 ml with distilled water and stood about 1 hr to allow oxidation to take place. Excess periodate, which must be present in the oxidized mixture was tested by adding NaHCO₃ and KI to the test portion.

4.2.8.3 Determination of glycerol

Twenty ml of the aliquot oxidized mixture was transferred to a titration flask and diluted with 50 ml of distilled water. One gram of NaHCO₃, 0.5 g of KI, and 5 ml starch indicator were then added. The mixture was titrated immediately with 0.02 N As₂O₃ solution until the blue color disappeared. Ten ml of 0.02 M KIO₄ (blank) was similarly titrated. The different volume of As₂O₃ solution between the two titrations represented the amount of periodate reduced in the 20 ml aliquot being tested. The percent of glycerol content in BGB loaves was calculated using Formula 3 below.

Formula 3. Formula used to calculate percent glycerol content.

$$\% \text{ glycerol} = \frac{\text{difference in ml of As}_2\text{O}_3 \times 0.4605}{\text{fresh BGB loaf weight}} \times 100$$

4.2.9 Determination of pH

The pH was measured directly by inserting the pH electrode of a Fisher pH meter [model 230A, Fisher Scientific Co., Pittsburgh, PA] into the loaf without any sample preparation. Unprocessed loaf mixture and processed loaves were at room temperature when pH was measured. For the unprocessed loaf mixture, pH was measured by inserting a pH electrode into the loaf twice at random locations. The pH of processed loaves was measured by inserting the electrode into the hole where the sample was taken for microbial enumeration.

4.2.10 Determination of water activity (a_w)

The measurement of a_w used psychrometry methodology [Troller and Christian, 1978; Campbell and Gardner, 1971]. A thermocouple psychrometer sample changer [SC-10A, Decagon Devices Inc. Pullman, WA] connected to a nanovoltmeter [NT-3, Decagon Devices, Inc. Pullman, WA]. was used to measure a_w . The sample changer equipped with a 0.025 mm diameter chromel and constantan thermocouple wires which enable wet-bulb temperature reading were connected to large copper reference junctions in the thermocouple assembly of the SC-10A. The copper lead wires of the SC-10A passed through an aluminum heat sink and then connected to

the copper reference junctions and eventually connected to the NT-3. The sample or standard solution used for calibration (see below) was placed in a sample cup and rotated into a sealed isothermal chamber where the thermocouple was located. The prewetted thermocouple then measured relative humidity by measuring wet-bulb depression as well as temperature at the point of vapor equilibration [Decagon Manual, 1981].

The procedures for calibration and sample measurement of a_w follow:

1. **Calibration.** Three saturated salt solutions with known a_w : (NaCl, $a_w=0.755$; KCl, $a_w=0.851$; KNO_3 , $a_w=0.946$; all chemicals were analytical grade, J.T. Baker Chemical, Philisburg, N.J.) were prepared and stood for 3 days for equilibration before using for calibration. To determine the psychrometer constant, KNO_3 , which was near the range of the a_w of BGB loaves, was chosen for calibration. The average of psychrometer constants obtained by four repeated measurements of the KNO_3 saturated solution was used to determine a_w for the BGB loaves.

2. **Sample measurement.** BGB loaves (with 10, 20, and 30% glycerol) and double-distilled water were placed into sample cups. The microvolt output of each sample was measured and the chamber temperature was recorded. The microvolt output and temperature data collected from standard solutions, samples, and double-distilled water were then fed into a computer calculation program provided by the manufacturer to compute the a_w of BGB loaves.

4.3 Microwave Processing

The microwave oven was turned on to warm up the magnetron for 10 min at 100% output power before each day's processing [Sawyer, 1983; Culkin and Fung; 1975]. A Pyrex™ glass dish containing approximately 1000 ml of cold distilled water was put into the microwave oven during the warm up period to absorb energy and moisturize the chamber atmosphere. Before processing, the microwave oven was set at the desired output power (50% or 100%) and processing time (Table 2, Section 3.3.2). A processing container was put at the geometric center of the oven chamber (37.8 cm x 37.8 cm x 26.3 cm) during processing throughout the entire study.

4.3.1 Microwave output power and processing time

Processing times were calculated using microwave output power and load size so that each load size was exposed to four identical microwave doses. For example, an 150 g load size processed for 45 sec at 100% (713 watts) output power would receive the identical exposed microwave dose as would a 600 g load size processed for 6 min at 50% (356 watts) output power or 1200 g load size processed for 6 min at 100% output power ($713 \text{ watts} \times 1 \times 45/60 \text{ min}/150 \text{ g} = 713 \text{ watts} \times 0.5 \times 6 \text{ min}/600 \text{ g} = 713 \text{ watts} \times 1 \times 6 \text{ min}/1200 \text{ g}$). The definition and formula of exposed microwave dose was given Section 3.1.5.

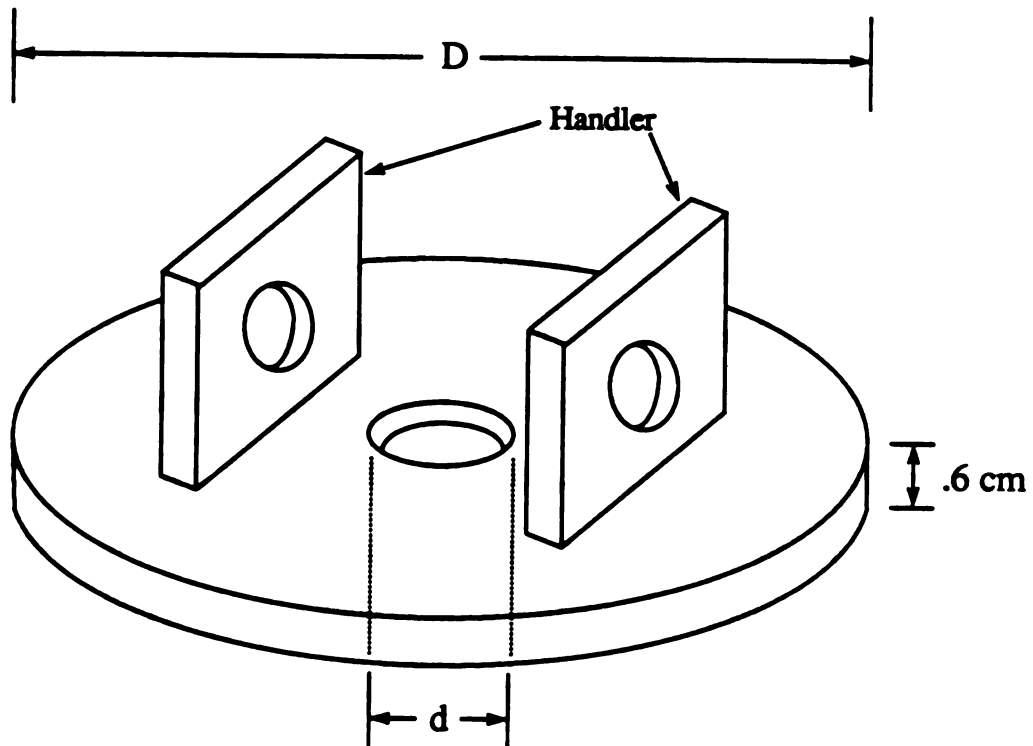
Microwave processing times and microwave output powers were calculated based on the various sizes of loaves. Table 2 shows processing times and output powers used for loaves in this study.

4.3.2 Wrapping in PVDC Film

The PVDC film completely enclosed the meat loaf being tested. When PVDC film was used to wrap a meat loaf, one piece of film (29 x 45 cm for 150 g load, 29 x 60 cm for 600 g load, 29 x 90 cm for 1200 g load) was cut. The piece of film was placed so that the bottom and sides of the Pyrex container were completely lined. The appropriate amount of meat loaf was then placed into the lined container, and the PVDC film was manually closed over the loaf. To provide as uniform a density as possible for both wrapped and unwrapped loaves, an appropriate size of plastic packer (Figure 4) was pressed on the top of the loaf by hand to achieve consistent volume and air-bubble free package. The BGB loaf was not wrapped with PVDC film in the study for reasons explained in Section 3.3.1.

Figure 4. The plastic packer used to pack loaves into a doughnut-shaped Pyrex™ container.

93a



Load Size	D (cm)	d (cm)
150 g	12.4	1.26
600 g	14.9	1.58
1200 g	18.9	1.90

Figure 4.

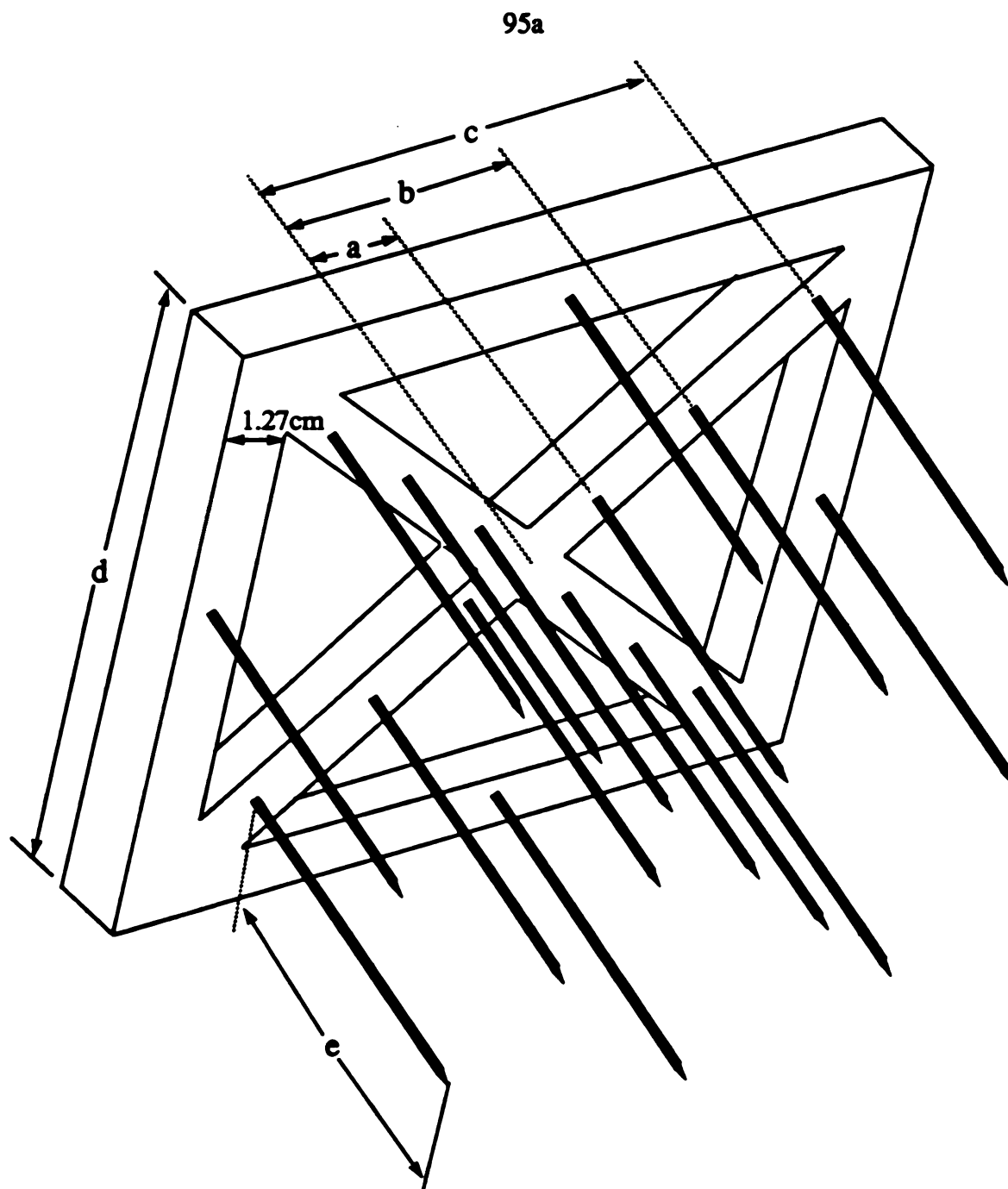
4.3.3 Temperature measurement

During microwave processing, the temperatures of a loaf were measured and recorded using a Fluoroptic Thermometer [model 1000A, Luxtron, Mountain View, CA] and a single connecting optical fiber thermoprobe [GSA-2, Luxtron, Mountain view, CA] placed in the approximate geometric center of the loaf (Figure 3). Immediately after microwave processing, the loaf was removed from the oven and the optical fiber thermoprobe was disconnected. Post processing temperature rise (PPTR) and time were monitored using a potentiometer connected to 16 iron-constantan thermocouples [model Electronik 16, Honeywell Industrial Products Group, Philadelphia, PA]. The thermocouples, attached to a bamboo frame by a small piece of teflon tubing (Figure 5) were then inserted into the loaf. The 16 thermocouples were placed approximately half-depth into the loaf in an attempt to identify and monitor the lowest internal temperature from which microbial sample would be taken. Temperature readings were continuously printed out every 20 sec until PPTR was no longer observed [Sawyer, 1985].

4.3.4 Determination of evaporation loss

The loaves were weighed with container before and after microwave processing using a Sartorius balance [type 2204, Sartorius Balances, Westburg, NY]. Percent evaporation loss of product was calculated using Formula 4 below:

Figure 5. Framework to hold sixteen thermocouples for post processing temperature measurement of loaves processed by microwave radiation.



Load Size	a (cm)	b (cm)	c (cm)	d (cm)	e (cm)
150 g	0.95	2.60	4.30	9.70	6.60
600 g	1.10	3.20	5.30	11.50	7.50
1200 g	1.25	4.00	6.70	14.30	9.80

Figure 5.

Formula 4. Formula to calculate percent evaporation loss of loaf after microwave processing.

$$\% \text{ evaporation loss} = 100\% - \left[\frac{\text{loaf weight after processing in g}}{\text{loaf weight before processing in g}} \times 100\% \right]$$

4.4 Microbiology

Experimental products were inoculated with bacteria before microwave processing. *S. aureus* and *E. coli* plus aerobic mesophilic bacteria in loaves were enumerated before and after microwave processing. Section 4.4.1 below describes the inoculation and enumeration procedures for bacteria used in this study.

4.4.1 Inoculation procedure

S. aureus (ATCC 6538) and *E. coli* (O157:H), transferred separately from day-old culture into fresh Brain Heart Infusion (BHI) medium [Difco Laboratories, Detroit, MI], were incubated [Lenco forced circulation incubator, Central Scientific Co., Chicago, IL] at 37 °C for 20 hr before inoculation. Two and one half ml of each inoculant per 100 g of loaf were hand mixed with thawed meat or BGB loaf while the researcher wore sterile Latex surgeon's gloves [TRIFLEX™, Travelnol Lab. Inc., Deerfield, IL] for about 2 min to ensure inoculants and loaf ingredients were well mixed. The goal of inoculation was a concentration of 10⁶ to 10⁷ cells/gram of loaf.

4.4.2 Enumeration method for bacteria

The enumeration procedures for *S. aureus*, and aerobic mesophilic bacteria followed standard ICMSF (1978) procedures. A modified double agar procedure [Speck et al. 1975] was used for *E. coli* enumeration. Two incubators [Lenco forced circulation incubator, Central Scientific Co., Chicago, IL] one set at 32 °C was used for aerobic bacteria incubation. The other one set at 37 °C was used for *E. coli* and *S. aureus* incubation.

4.4.2.1 Sampling and dilution procedure

Based on the assumption that bacteria survive best in a loaf at the location of the lowest internal temperature [Jay, 1986], samples for microbiological analysis (5 g for 150 g load, 10 g for 600 and 1200 g loads) were taken using a sterile stainless steel cheese trier. A vertical cylinder of product was taken at the location of lowest, monitored, internal temperature in each processed loaf at the end of post processing temperature rise. Twenty five grams (25 g) of unprocessed inoculated loaf were also taken for initial bacterial counts before processing. All samples for microbial enumeration were weighed to 0.1 g accuracy using a Sartorius balance [type 2204, Sartorius Balances, Westburg, NY] placed in sterile Stomacher ethylene bags (100 mm x 152 mm x 65 µ).

Forty-five milliliter (45 ml; for 5 g sample) or 90 ml (for 10 g sample) of sterile 0.1% peptone water were added into the Stomacher bags and blended in a Stomacher Lab Blender [Model 400, Tekmar Co., Cincinnati OH] for 3 min. The

mixture was allowed to stand 15 min at room temperature to permit resuscitation of the microorganisms [ICMSF, 1978]. After contents were blended, 1 ml of homogenate was aseptically pipetted into a tube containing 9 ml of sterile dilution peptone water and mixed with a Vortex mixer [Lasar MFG. Co. Inc., Los Angeles, CA]. One milliliter (1 ml) of dilution was then transferred with a fresh pipette to another dilution tube and mixed. The procedure was repeated until the required dilution was made. Each successive dilution decreased the concentration ten-fold. Duplicate plates for each dilution were prepared.

4.4.2.2 Enumeration of *Staphylococcus aureus*

Enumeration of *S. aureus* was completed using Baird-Parker Agar [Oxoid Limited, Basingstoke Hants, England] and the spread plate technique [ICMSF, 1978]. Plates were incubated at 37 °C for 48 hr. The black colonies with clear zones around were assumed to be *S. aureus* [ICMSF, 1978]. Petri dishes (90 x 15 mm) containing 30 to 300 colonies were counted using a Darkfield Quebec colony counter [model 3330, American Optical Co., Buffalo, NY] and the number of *S. aureus* per gram of loaf was computed.

4.4.2.3 Enumeration of *Escherichia coli*

The method of Speck et al. (1975) was adopted for injured *E. coli*. Recovery time was lengthened to 4 hr at 37 °C before 10 ml of melted (kept at 45 °C) Violet Red Bile Agar [Difco Laboratories, Detroit, MI] was overlaid on the top of Tryptic

Soy Agar. Petri dishes were inverted and incubated for another 20 hr after Violet Red Bile Agar was solidified. The red colonies which appeared on petri dishes containing 30 to 300 colonies were counted as *E. coli* and the number of *E. coli* per gram of loaf was computed.

4.4.2.4 Enumeration of aerobic mesophilic bacteria

Enumeration of aerobic mesophilic bacteria was completed using Tryptic Soy Agar [Difco Lab., Detroit, MI] and the pour plate technique [ICMSF, 1978]. The solidified agar plates were inverted and incubated at 32 °C for 24 hr [ICMSF, 1978]. Petri dishes containing 30 to 300 colonies were counted as aerobic mesophilic bacteria and the number of aerobic mesophilic bacteria per gram of loaf was computered. Percent survival of each bacteria was calculated using Formula 5 below.

Formula 5. Formula used to calculate percent survival of *S. aureus*, *E. coli* and aerobic mesophilic bacteria.

$$\% \text{ survival of bacteria} = \frac{\text{no. of surviving bacteria/g}}{\text{no. of initial bacteria/g}} \times 100\%$$

4.5 Experimental Design and Statistical Analyses

A $2 \times 2 \times 3 \times 4 \times 4$ (wrapped or unwrapped $\times$ 2 power levels $\times$ 3 load sizes $\times$ 4 processing times $\times$ 4 batches, 3 levels of fat content of beef plus turkey) factorial design was used for the present study of beef and turkey loaves. Each treatment was duplicated once; a total of 384 meat loaves were processed.

A 3×4 (3 load sizes $\times$ 4 processing times) factorial design was used for the BGB loaf (20% glycerol) study. Each treatment was duplicated once; 24 BGB loaves were processed.

To study the effect of glycerol content, a 3×4 (3 glycerol contents $\times$ 4 processing times) factorial design was used for the 150 g load size of BGB loaf. Each treatment was repeated 4 times. Because 8 treatments of the 150 g load size were identical between 2 factorial designs for the BGB study, only 40 BGB loaves were processed. In total, 448 loaves (288 beef loaves; 96 turkey loaves ; 64 BGB loaves) were processed.

Two sets of data were used for statistical analyses. The first data set (BACT, $n=448$ loaves), containing data from bacterial survival, thermal responses and percent evaporation, was collected from the lowest temperature point out of 16 locations. The second data set (TEMP, $n=448$ loaves), containing all 16 after-processing temperatures (APTs) and end-point temperatures (EPTs), was collected from 16 locations of temperature measurement within a loaf. The first data set (BACT) was used for bacterial survival, thermal response and percent evaporation loss analysis. The second data set (TEMP) was used for temperature pattern analysis.

Experimental data were analyzed by using SAS (SAS, 1985) and SPSSX (SPSSX, 1988) statistical computer packages on the IBM 3090 mainframe computer located at the Computer Center of Michigan State University.

The variables used for statistical analyses are shown in Table 3 and Table 4. A derived variable, EMD, which was derived from three original experimental variables (microwave output power or MP; processing time or PT; load size or LS) was used in all analyses to replace PT. Percent fat or glycerol content or PFC, a continuous covariate in experimental data, was redefined into three levels (10, 20, 30) in SAS DATA procedure to analyze the effect of PFC on dependent variables when SAS GLM procedure was performed. The log value of percent surviving bacteria was adopted to better normalize the data of bacterial survival. To avoid the log value becoming meaningless when zero percent of bacteria survived, one (1) was added to the percent surviving bacteria before taking the log value.

4.5.1 Analysis of bacterial survival, thermal responses and evaporation loss

Two different statistical approaches were used to understand the effects of independent variables (Table 3) on bacterial survival, thermal responses and evaporation loss. Initially, the SAS GLM procedure was performed to explore the main and interaction effects on bacterial survival, thermal responses and evaporation loss. Secondly, based on the GLM results, the SAS RSQUARE and SAS REG procedures were performed to establish regression models for bacterial survival and thermal responses.

Table 3. Bact Data Set: List of variables used in statistical analysis for bacterial survival, thermal responses and evaporation loss.

Independent variables	Description
EMD*	exposed microwave dose (watt x min/g). $EMD = [(713 \times MP/100) \times (PT/60)] / LS$.
LS	load size (g).
MP	microwave output power (%).
PFC	percent fat or glycerol content (%).
PT	processing time (sec).
PW	1=PVDC film wrapped, -1=not wrapped.
PWC	percent water content (%).
REP	replication.
TL	type of loaf. 1=beef, 2=turkey, 3=BGB.
Dependent variables	Description
APT	after-processing temperature (°C).
EPT	end-point temperature (°C).
FAB	final aerobic bacteria count.
FEC	final <i>E. coli</i> count.
FPH	final pH.
FSA	final <i>S. aureus</i> count.
IAB	initial aerobic bacteria count.
IEC	initial <i>E. coli</i> count.
IPH	initial pH.
IPT	initial product temperature (°C).
ISA	initial <i>S. aureus</i> count.
LAB*	log value of 1 plus percent surviving aerobic bacteria. $LAB = \log(1 + 100 \times FAB/IAB)$.
LEC*	log value of 1 plus percent surviving <i>E. coli</i> . $LEC = \log(1 + 100 \times FEC/IEC)$.
LSA*	log value of 1 plus percent surviving <i>S. aureus</i> . $LSA = \log(1 + 100 \times FSA/ISA)$.
MPTR*	microwave processing temperature rise (°C). $MPTR = APT - IPT$.
PEL	percent evaporation loss (%).
PHC*	pH change of product.
PPTR*	post processing temperature rise (°C). $PPTR = EPT - APT$.
STR*	sum of temperature rise (°C). $STR = EPT - IPT$ or $MPTR + PPTR$.
TPPTR	time of PPTR (sec).

* transformed variables.

° derived variables.

Table 4. Temp Data Set: List of variables used in statistical analysis for temperature pattern.

Independent variables	Description
EMD*	exposed microwave dose (watt x min/g). $EMD = [(713 \times MP/100) \times (PT/60)]/LS$.
LS	load size (g).
MP	microwave output power (%).
PFC	percent fat or glycerol content (%).
PT	processing time (sec).
PW	1=PVDC film wrapped, -1=not wrapped.
PWC	percent water content (%).
REP	replication.
TL	type of loaf. 1=beef, 2=turkey, 3=BGB.
Dependent variables	Description
APT	after-processing temperature (°C).
EPT	end-point temperature (°C).
IPT	initial product temperature (°C).
LAPT*	log value of standard deviation of 16 APTs within a loaf (°C).
LEPT*	log value of standard deviation of 16 EPTs within a loaf (°C).
LMPTR	log value of standard deviation of 16 MPTRs within a loaf (°C).
LPPTR*	log value of standard deviation of 16 PPTRs within a loaf (°C).
LSTR*	log value of standard deviation of 16 STRs within a loaf (°C).
MPTR*	microwave processing temperature rise (°C). $MPTR = APT - IPT$.
PPTR*	post processing temperature rise (°C). $PPTR = EPT - APT$.
RAPT*	range of 16 APTs within a loaf (°C).
REPT*	range of 16 EPTs within a loaf (°C).
RMPTR*	range of 16 MPTRs within a loaf (°C).
RPPTR*	range of 16 PPTRs within a loaf (°C).
RSTR*	range of 16 STRs within a loaf (°C).
STR*	sum of temperature rise (°C). $STR = EPT - IPT$ or $MPTR + PPTR$.
TPPTR	time of PPTR (sec).

* transformed variables.

° derived variables.

The first data set, BACT (n=448 loaves), was used for analysis of bacterial survival, thermal responses and percent evaporation loss. The variables used to analyze bacterial survival, thermal responses and percent evaporation loss are shown in Table 3. In general, only cases with identical treatment were selected for balanced data analysis (except missing values). For different types of loaf, combinations of treatment were not identical. For example, beef loaf had 3 levels of PFC, but turkey only had 1 level; meat loaf had 2 levels of PW and MP, but BGB loaves had only 1 level. This was the reason why multiple analyses were required in the present study.

Based on the different purposes, the approach for statistical analyses on bacterial survival, thermal responses and evaporation loss are summarized in Table 5. This table was also applicable to the analyses of temperature variation. Since PFC was redefined into three levels (10, 20, 30) for the SAS GLM procedure analysis, it was considered as a independent factor, but not a covariate as in the regression analysis.

4.5.1.1 Analysis of main and interaction effects

To analyze the effect of independent variables (Table 3) and their possible interactions on bacterial survival, thermal responses and percent evaporation loss, the SAS GLM procedure was used with Tukey's test [SAS, 1985; Gill, 1978]. Three transformed variables, log value of percent survival of bacteria plus 1 (LSA, LEC, LAB) derived from the first data set (BACT), were used for analysis of bacterial

Table 5. The conditions used in the SAS GLM procedure to analyze the effect of independent variables on bacterial survival, thermal responses, evaporation loss and temperature variation.

Sub data sets	Sample size (n)	Independent variables selected
Beef (10, 20 and 30% fat)	288	PW, PFC, MP, LS, EMD, REP
Turkey (10% fat)	96	PW, MP, LS, EMD, REP
BGB (150 g load size)	48	PFC, EMD, REP
Beef & turkey (10% fat)	192	TL, PW, MP, LS, EMD, REP
Beef (10, 20 and 30% fat) & turkey (10% fat)	384	MP
Beef & turkey (10% fat) & BGB (10% glycerol)	72	TL, LS, EMD, REP
Beef (10, 20 and 30% fat) & turkey (10% fat) & BGB (10, 20 and 30% glycerol)	448	REP

Key:

BGB = bentonite-glycerol-BHI broth.
EMD = exposed microwave dose (watt x min/g).
LS = load size (g).
MP = microwave output power (%).
PFC = percent fat content (%).
PW = polyvinylidene chloride (PVDC) wrapping.
REP = replication.
TL = type of loaf.

survival. Other temperature variables in the first data set (BACT) such as IPT, APT, EPT, were used to generate three new temperature variables (MPTR, PPTR, and STR). These three new temperature variables plus TPPTR were used for analysis of thermal responses.

PEL was used for analysis of percent evaporation loss. Seven models, including selected independent variables (Table 5) and their two-way interactions were tested by the SAS GLM procedure. Type III sum of squares was used to determine if there were any significant interaction effects on dependent variables. The means of multiple classes that belonged to the main effect were compared by using Tukey's test at the 0.95 significance level.

The SAS GLM results of main effects were valid only if main effects were not involved in any significant interaction ($p \leq 0.1$). Only significant 2-way interactions were further analyzed by using SAS GLM procedure with a "BY" to obtain separate analyses on observations in groups defined by the BY variables.

Regardless of any involvement in other interactions, the means for each class of the first factor involved in a 2-way significant interaction were computed for each class of the second factor, but averaged over the rest of factors which were not involved in the interaction in question. For a given factor, such means were compared by using Tukey's test at the 0.95 significance level. Interactions that had two identical factors (regardless of their positions in the interaction) were considered to be the same and were only computed once.

4.5.1.2 Regression model selection

To establish regression models for bacterial survival (LSA, LEC, and LAB), thermal responses (MPTR, PPTR, STR, TPPTR) and percent evaporation loss (PEL), the SAS RSQUARE and SAS REG procedures were used [SAS, 1985].

Based on preliminary ANOVA results of calculations using SAS GLM procedure, the interaction of independent variables had significant effects on bacterial survival, thermal responses and percent evaporation, and therefore should be included in the regression model. Since each type of loaf had different treatment combinations, regression model selection was done separately for each type of loaf. SAS RSQUARE procedure was used to select optimal subsets of independent variables from a full model which included 1st, 2nd, and 3rd degree of independent variables, two covariate, i.e. PWC and PFC, and their two-way interactions (Table 6).

The selection criteria for optimal subsets of independent variables were mainly based on Hocking's method (1972) and procedures suggested by Myers (1986). R^2 and Mallows' C_p were used as criteria to determine the fitness of the regression model. To be good subsets, R^2 should be high and Mallows' C_p should be relatively close to p (the number of variables in that subset including intercept), if any. After screening, the candidate subsets were further analyzed by the SAS REG procedure to check each regression coefficient in that particular subset. The partial t-test value

Table 6. List of full models used in SAS RSQUARE procedure for optimal subsets selection.

Type of loaf	Dependent variables	Candidate variables in full model
Beef [*]	LSA LEC LAB	PW, EMD, EMD ² , EMD ³ , LS, MP, PFC, PWC, PW*EMD, PW*LS, PW*PWC, EMD*LS, EMD ² *LS, EMD ² *PFC, EMD ² *PWC, MP*EMD, MP*LS. (K [†] =17).
Beef [*]	MPTR PPTR STR EPT TPPTR PEL	PW, EMD, EMD ² , EMD ³ , LS, LS ² , MP, PFC, PWC, PW*EMD, PW*LS, PW*PWC, EMD*LS, EMD ² *LS, EMD ² *PFC, EMD ² *PWC, LS*PFC, LS*PWC, MP*EMD, MP*LS. (k=20).
Turkey	LSA LEC LAB MPTR PPTR STR EPT TPPTR PEL	PW, EMD, EMD ² , EMD ³ , LS, LS ² , MP, PW*EMD, PW*LS, EMD*LS, EMD ² *LS, MP*EMD, MP*LS. (k=13).
BGB	LSA LEC LAB MPTR PPTR STR EPT TPPTR PEL	EMD, EMD ² , EMD ³ , LS, LS ² , PWC, EMD*LS, EMD ² *LS, EMD ² *PWC, LS*PWC. (k=10).

Key: EMD = exposed microwave dose (watt x min/g).

LS = load size (g).

MP = microwave output power (%).

PFC = percent fat content (%).

PW = polyvinylidene chloride (PVDC) wrapping.

PWC = percent water content (%).

Footnote: [†] k = number of candidate variables in a full model.

* for bacterial survival.

* for thermal responses and evaporation loss.

of each regression coefficient should be greater or equal to the 0.95 significance level. If more than two subsets were qualified, the one with the smallest prediction error sum of square (PRESS) would be selected as the best regression model.

4.5.2 Analysis of temperature pattern

The second data set, (TEMP), used for the analysis of temperature pattern, was collected from 16 locations of temperature (APTs and EPTs) measured within a loaf (n=448 loaves). The variables used to analyze temperature pattern are shown in Table 4.

To analyze the distribution of locations of lowest and highest temperature(s), SPSSX FREQUENCIES and CROSSTABS procedures were used [SPSSX, 1988]. To analyze temperature variation within/among loaves, the means of range and log value of standard deviation of 16 temperatures within a loaf (Table 4) were compared by using the SAS GLM procedure with REPEATED option and Tukey's test at the 0.95 significance level [SAS, 1985].

4.5.2.1 Analysis of temperature distribution

The SPSSX FREQUENCIES and CROSSTABS procedures were used to describe the distribution of the locations of lowest and highest temperature within a

loaf. Experimental data (TEMP, n=448 loaves) was first rearranged by using a fortran subroutine (Appendix 1) before FREQUENCIES or CROSSTABS procedures were performed. Temperature data (APTs and EPTs) were rearranged in ascending order (Lowest to highest) in two different ways. One data set (NEW1) had 16 groups (1 temperature per group, n=448) after rearrangement. The other rearranged data set (NEW2) had 4 groups (4 temperatures per group, n=1792). As a result, the first group in the first new data set (NEW1) had the lowest temperature, and the first group in the second new data set (NEW2) had four temperatures (lowest, second lowest, third lowest, and fourth lowest). The corresponding location number of each temperature was also rearranged to the order of temperature just described. The rearranged location numbers were used for frequency and crosstabulation analyses.

For the first new data set (NEW1), the whole data set was used (n=448 loaves) for both frequency and crosstabulation analyses. The same analyses were also performed by breaking down the data set by load size (LS; n=176 for 150 g load, n=136 for 600 and 1200 g loads) to describe temperature distribution vs varied LS.

For the second new data set (NEW2), both frequency and crosstabulation analyses were performed by breaking down the data set by LS (n=704 for 150 g load, n=554 for 600 and 1200 g loads). Under each LS, data sets were further broken down by type of loaf (TL), PW, MP, and EMD for the same analyses. One-way frequency tables and two-way crosstabulation tables were computed. The likelihood-ratio chi square value obtained by CROSSTABS procedure was used to

determine if the temperature distribution was affected by these independent variables mentioned above. The significance level was set at 0.95 for the chi square test.

Since FREQUENCIES and CROSSTABS procedures would not be able to analyze the possible interaction effects on temperature distribution, the SAS GLM procedure with REPEATED option and F test was performed to analyze for main effects and possible interaction effects on temperature distribution among/within loaves. A model including all independent variables except PWC and PT (Table 4) and their two-way interactions was tested by using the raw data set (TEMP, n=448 loaves).

4.5.2.2 Analysis of temperature variation

The temperature data set (TEMP) was used to analyze the temperature variation within/among loaves. Range, and log value of standard deviation of 16 temperatures (APT, EPT, MPTR, PPTR, STR) within a loaf were computed. Direct analysis for standard deviation was not available in SAS and SPSSX because standard deviation is not normally distributed. The solution to this problem was to take the log value of the standard deviation. Transformed log values should be more normally distributed and were analyzed by the SAS GLM procedure.

Seven different models, including selected independent variables (Table 5) and their two-way interactions were tested by using the SAS GLM procedure with means compared by Turkey's test at the 0.95 significance level. The reason for

multiple analyses of the data is mentioned in Section 4.5.1. The effects of selected independent variables and their interactions on the means of range, and log value of 16 temperatures (APT, EPT, MPTR, PPTR, STR) within a loaf were analyzed following the guidelines in Section 4.5.1.1.

CHAPTER V

RESULTS AND DISCUSSION

The data showing main effects and possible interactions of independent variables (Table 3) on bacterial survival, thermal responses and evaporation loss of meat loaves (beef and turkey) and bentonite-glycerol-BHI broth (BGB) loaves as well as temperature pattern of experimental products are presented and discussed in this chapter. Discussion of main effects of independent variables, based on the type of loaf (Section 5.1 to 5.3) are followed by comparing the main effects of independent variables among types of loaf (Section 5.4 to 5.5). The results of significant 2-way interactions of independent variables are presented (Section 5.6). The effect of other independent variables (pH and replication) are also mentioned briefly (Section 5.7). The main effects and interactions of independent variables on the temperature pattern of experimental products are discussed (Section 5.8). Finally, the chapter concludes with a summary of results (Section 5.9).

5.1 Beef Loaf

Beef loaf was the major experimental product used in this study. The study of beef loaf involved six independent variables with a total of one hundred and forty four (144) treatment combinations (Table 5). The data subset from processing 288 beef loaves (10, 20 and 30% fat) was statistically analyzed. The results of the ANOVA showed that significant main and possible interactions of independent

variables on bacterial survival, thermal responses and percent evaporation loss existed (Appendix 2). More detailed results are discussed below.

5.1.1 Effect of polyvinylidene chloride (PVDC) wrapping

Wrapping with PVDC film was one of the strategies cited in Section 3.5.1.1 to improve microbial quality of microwave processed foods. The purpose of wrapping beef loaves with PVDC film before microwave processing was to determine if PVDC wrapping (PW) had an effect on bacterial survival, thermal responses and evaporation loss of beef loaves. The results and discussion of the effect of PW on bacterial survival, thermal responses and evaporation loss of beef loaves are presented below.

5.1.1.1 Bacterial survival

The result of the ANOVA indicated that the main effect of PW on bacterial survival was significant ($p \leq 0.0001$; Appendix 2) for beef loaves. The predicted survival curves of *E. coli*, *S. aureus*, and aerobic bacteria after microwave processing, derived from multiple regression analyses, are shown in Figures 6-8. Percent survival of three types of bacteria were significantly lower ($p \leq 0.05$) in beef loaves that had been wrapped in PVDC film than in loaves that had not been wrapped (Table 7 and Figures 6-8: A vs. C, B vs. D, E vs. G, F vs. H, I vs. K, J vs. L). Neither *E. coli* nor *S. aureus* survived in beef loaves that had been wrapped in PVDC film after the longest processing time (highest exposed microwave dose;

Figure 6. Predicted response surface of surviving *Escherichia coli** in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 6-A: LS= 150, PW= 1, MP=100.

Fig. 6-B: LS= 150, PW= 1, MP= 50.

Fig. 6-C: LS= 150, PW=-1, MP=100.

Fig. 6-D: LS= 150, PW=-1, MP= 50.

Fig. 6-E: LS= 600, PW= 1, MP=100.

Fig. 6-F: LS= 600, PW= 1, MP= 50.

Fig. 6-G: LS= 600, PW=-1, MP=100.

Fig. 6-H: LS= 600, PW=-1, MP= 50.

Fig. 6-I: LS=1200, PW= 1, MP=100.

Fig. 6-J: LS=1200, PW= 1, MP= 50.

Fig. 6-K: LS=1200, PW=-1, MP=100.

Fig. 6-L: LS=1200, PW=-1, MP= 50.

Footnotes:

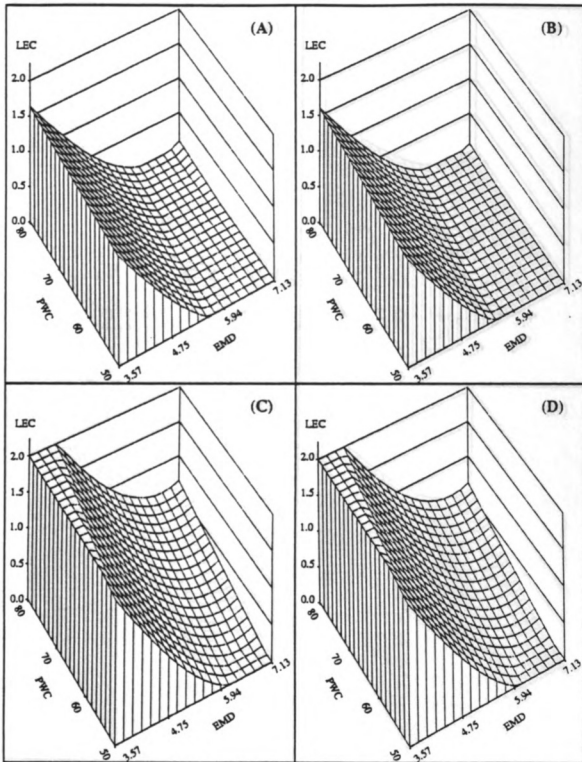
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

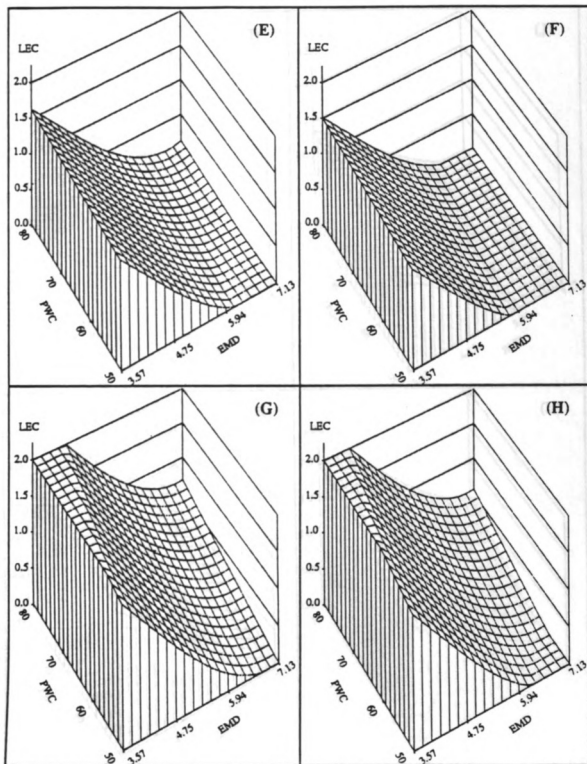
* Plotted from multiple regression equation ($R^2=0.80$, $C_p=9.30$):

$$\begin{aligned} \text{LEC} = & 3.39099391 - 0.30116815 \cdot \text{EMD}^2 \\ & + 0.03060959 \cdot \text{EMD}^3 \\ & - 0.003691605 \cdot \text{LS} \\ & + 0.01456068 \cdot \text{PWC} \\ & + 0.05553556 \cdot \text{PW} \cdot \text{EMD} \\ & - 0.008497843 \cdot \text{PW} \cdot \text{PWC} \\ & + 0.0000041374 \cdot \text{MP} \cdot \text{LS} \\ & + 0.001359444 \cdot \text{LS} \cdot \text{EMD} \\ & - 0.000124441 \cdot \text{LS} \cdot \text{EMD}^2 \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.
 PWC = PERCENT WATER CONTENT (%).
 LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

Figure 6.

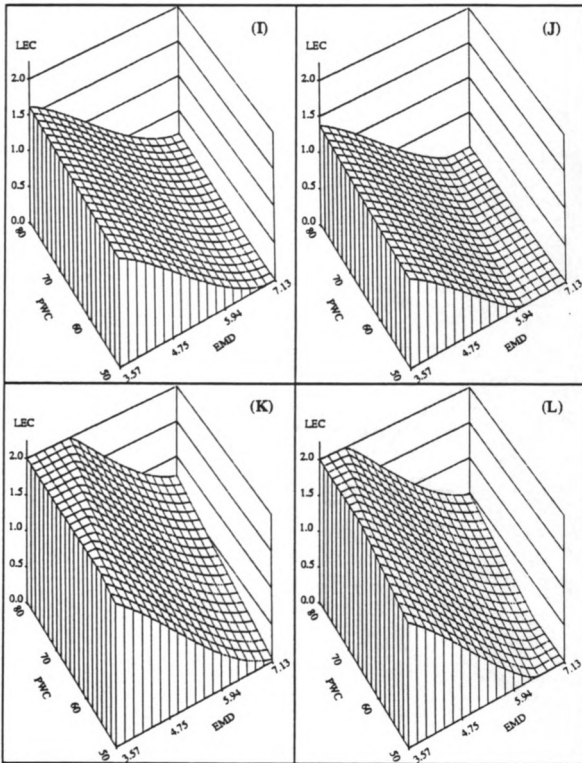


EMD = EXPOSED MICROWAVE DOSE(WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

Figure 6 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

Figure 6 (cont'd).

Figure 7. Predicted response surface of surviving *Staphylococcus aureus*^a in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

- Fig. 7-A: LS= 150, PW= 1, MP=100.
 Fig. 7-B: LS= 150, PW= 1, MP= 50.
 Fig. 7-C: LS= 150, PW=-1, MP=100.
 Fig. 7-D: LS= 150, PW=-1, MP= 50.
 Fig. 7-E: LS= 600, PW= 1, MP=100.
 Fig. 7-F: LS= 600, PW= 1, MP= 50.
 Fig. 7-G: LS= 600, PW=-1, MP=100.
 Fig. 7-H: LS= 600, PW=-1, MP= 50.
 Fig. 7-I: LS=1200, PW= 1, MP=100.
 Fig. 7-J: LS=1200, PW= 1, MP= 50.
 Fig. 7-K: LS=1200, PW=-1, MP=100.
 Fig. 7-L: LS=1200, PW=-1, MP= 50.

Footnotes:

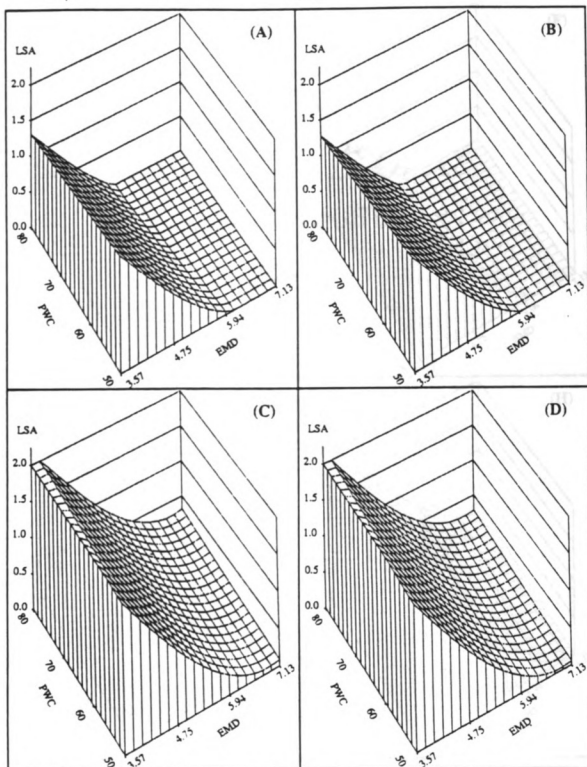
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.79$, $C_p=11.91$):

$$\begin{aligned} \text{LSA} = & 3.85859767 - 0.25930056 \cdot \text{EMD}^2 \\ & + 0.02573243 \cdot \text{EMD}^3 \\ & - 0.002859356 \cdot \text{LS} \\ & + 0.04441180 \cdot \text{PW} \cdot \text{EMD} \\ & - 0.007544880 \cdot \text{PW} \cdot \text{PWC} \\ & + 0.00000411921 \cdot \text{MP} \cdot \text{LS} \\ & + 0.001083808 \cdot \text{EMD} \cdot \text{LS} \\ & - 0.000101955 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$

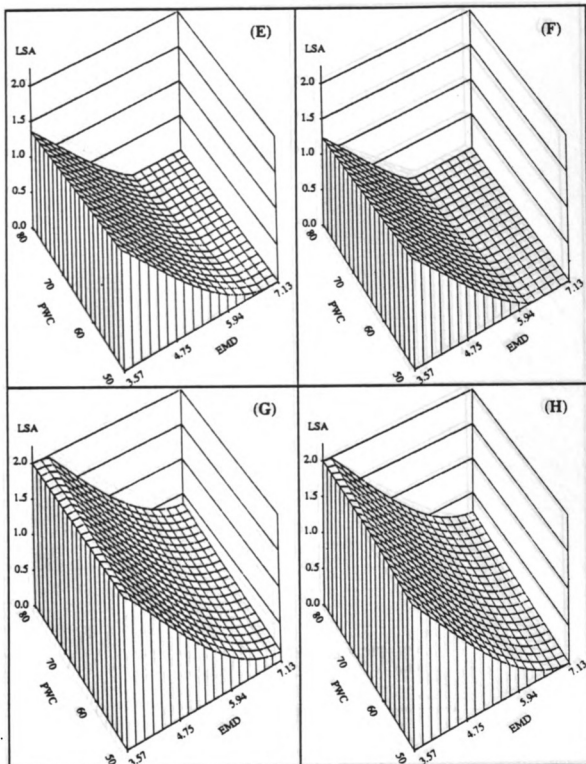


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LSA = LOG VALUE OF (% SURVIVING *Staphylococcus aureus*+1).

Figure 7.

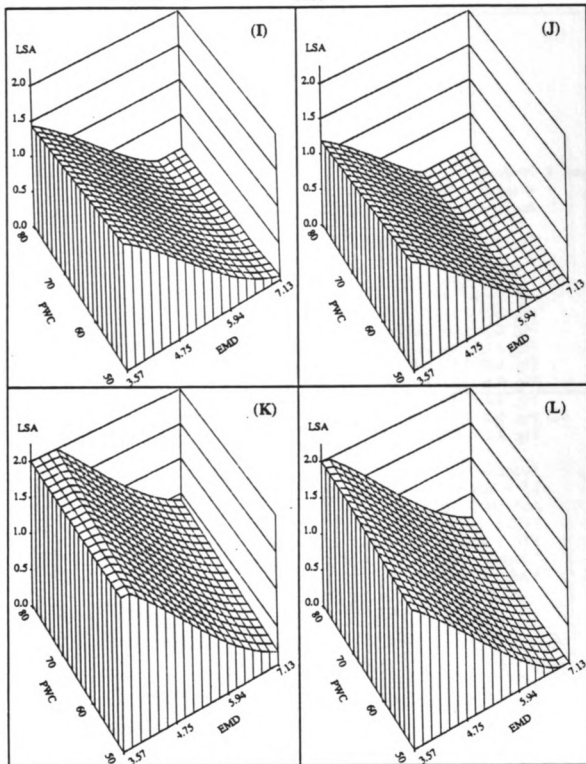


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LSA = LOG VALUE OF (% SURVIVING *Staphylococcus aureus*+1).

Figure 7 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LSA = LOG VALUE OF (% SURVIVING *Staphylococcus aureus* + 1).

Figure 7 (cont'd).

Figure 8. Predicted response surface of surviving aerobic bacteria* in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 8-A: LS= 150, PW= 1, MP=100.

Fig. 8-B: LS= 150, PW= 1, MP= 50.

Fig. 8-C: LS= 150, PW=-1, MP=100.

Fig. 8-D: LS= 150, PW=-1, MP= 50.

Fig. 8-E: LS= 600, PW= 1, MP=100.

Fig. 8-F: LS= 600, PW= 1, MP= 50.

Fig. 8-G: LS= 600, PW=-1, MP=100.

Fig. 8-H: LS= 600, PW=-1, MP= 50.

Fig. 8-I: LS=1200, PW= 1, MP=100.

Fig. 8-J: LS=1200, PW= 1, MP= 50.

Fig. 8-K: LS=1200, PW=-1, MP=100.

Fig. 8-L: LS=1200, PW=-1, MP= 50.

Footnotes:

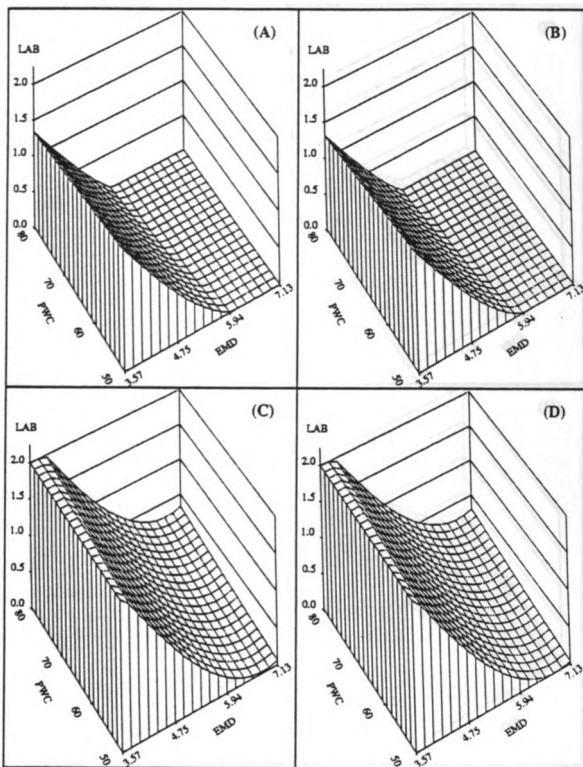
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.80$, $C_p=10.88$):

$$\begin{aligned} \text{LAB} = & 4.24305837 - 0.29391136 \cdot \text{EMD}^2 \\ & + 0.02953728 \cdot \text{EMD}^3 \\ & - 0.003737050 \cdot \text{LS} \\ & + 0.05670727 \cdot \text{PW} \cdot \text{EMD} \\ & - 0.008788937 \cdot \text{PW} \cdot \text{PWC} \\ & + 0.0000032651 \cdot \text{MP} \cdot \text{LS} \\ & + 0.001376930 \cdot \text{EMD} \cdot \text{LS} \\ & - 0.000124626 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$

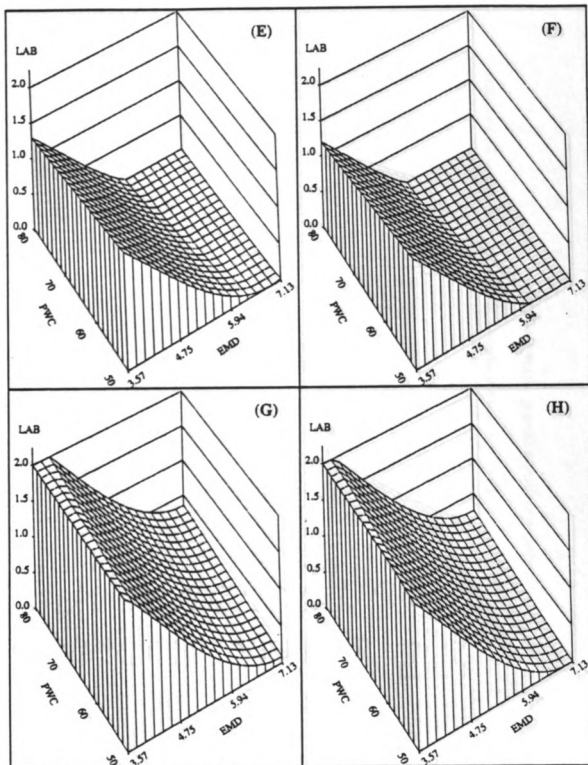


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LAB = LOG VALUE OF (% SURVIVING AEROBIC BACTERIA+1).

Figure 8.

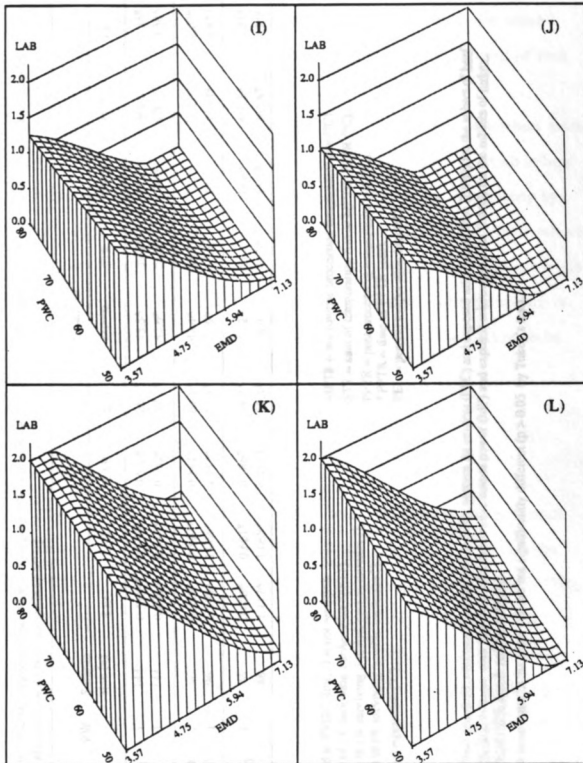


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LAB = LOG VALUE OF (% SURVIVING AEROBIC BACTERIA+1).

Figure 8 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.
 PWC = PERCENT WATER CONTENT (%).
 LAB = LOG VALUE OF (% SURVIVING AEROBIC BACTERIA+1).

Figure 8 (cont'd).

Table 7. The main effect of polyvinylidene chloride wrapping (PW) on bacterial survival, thermal responses and evaporation loss of loaves (beef and turkey) after microwave processing (2450 MHz).

Subset	PW	Sample size (n)	Mean ^a of									
			LEC	LSA	LAB	EPT	MPTR	STR	PPTR	TPPTR	PEL	
Beef (10, 20 and 30% fat)	1	144	0.516 ^{ab}	0.550 ^b	0.526 ^b	65.7 ^a	45.5 ^a	59.7 ^a	14.2 ^a	544.0 ^a	2.33 ^b	
	-1	144	0.896 ^a	0.943 ^a	0.932 ^a	57.1 ^b	42.6 ^b	51.5 ^b	8.9 ^b	426.7 ^b	3.38 ^a	
Beef (10% fat) & Turkey (10% fat)	1	96	0.555 ^b	0.549 ^b	0.541 ^b	62.1 ^a	42.4 ^a	58.1 ^a	15.7 ^a	522.5 ^a	2.07 ^b	
	-1	96	1.108 ^a	1.066 ^a	1.115 ^a	53.3 ^b	39.9 ^b	50.3 ^b	10.4 ^b	395.4 ^b	3.45 ^a	
Turkey (10% fat)	1	48	0.606 ^b	0.601 ^b	0.586 ^b	58.7 ^a	40.2 ^a	57.1 ^a	16.8 ^a	486.5 ^a	1.83 ^b	
	-1	48	1.117 ^a	1.068 ^a	1.153 ^a	51.3 ^b	38.7 ^a	49.9 ^b	11.1 ^b	361.8 ^b	3.25 ^a	

Key:

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec).

PEL = percent evaporation loss (%).

Footnote:

* Average over load size (LS), microwave output power (MP), percent fat content (PFC) and exposed microwave dose (EMD) for the subset of beef (10, 20 and 30% fat); average over load size (LS), microwave output power (MP) and exposed microwave dose (EMD) for the subsets of turkey (10% fat) and beef (10% fat) & turkey (10% fat).

Means with the same letter in the same cell are not significantly different ($p > 0.05$ by Tukey's test).

Figures 6-7:A, B, E, F, I, J). PVDC film probably formed a heat sink which retained heat generated in the product by microwave radiation (approval of Ho5; Section 3.5.1.1).

Similar results were reported by Aleixo et al. (1985). These researchers placed whole turkeys in brown-in-bags and found that cooking turkeys in brown-in-bags increased the destruction of *C. perfringens* and *S. typhimurium*. In the study by Sawyer et al. (1984), PVDC wrapping had no statistical effect on bacterial survival when chicken drumsticks, ham slices and pork slices were tested. However, in the study by Sawyer et al. (1984), bacteria were inoculated only onto the surface of food products and were probably exposed to a sufficient microwave dose to be killed regardless of wrapped or unwrapped condition.

5.1.1.2 Thermal responses

The result of the ANOVA indicated the main effect of PW on the thermal responses, end-point temperature (EPT), microwave processing temperature rise (MPTR), sum of temperature rise (STR), post processing temperature rise (PPTR), and time of PPTR (TPPTR), was significant ($p \leq 0.0001$; Appendix 2). The predicted response surfaces of thermal responses of beef loaf after microwave processing, derived from multiple regression analyses, are shown in Figures 9-17. Beef loaves wrapped in PVDC film had higher EPT, MPTR, STR, PPTR and TPPTR (Table 7 and Figures 9-15:A vs. C, B vs. D, E vs. G, F vs. H, I vs. K, J vs. L; Figures 16-17:A vs. C, B vs. D) than did unwrapped loaves. Higher EPT,

Figure 9. Predicted response surface of end-point temperature* in beef loaf (10% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

- Fig. 9-A: LS= 150, PW= 1, MP=100.
 Fig. 9-B: LS= 150, PW= 1, MP= 50.
 Fig. 9-C: LS= 150, PW=-1, MP=100.
 Fig. 9-D: LS= 150, PW=-1, MP= 50.
 Fig. 9-E: LS= 600, PW= 1, MP=100.
 Fig. 9-F: LS= 600, PW= 1, MP= 50.
 Fig. 9-G: LS= 600, PW=-1, MP=100.
 Fig. 9-H: LS= 600, PW=-1, MP= 50.
 Fig. 9-I: LS=1200, PW= 1, MP=100.
 Fig. 9-J: LS=1200, PW= 1, MP= 50.
 Fig. 9-K: LS=1200, PW=-1, MP=100.
 Fig. 9-L: LS=1200, PW=-1, MP= 50.

Footnotes:

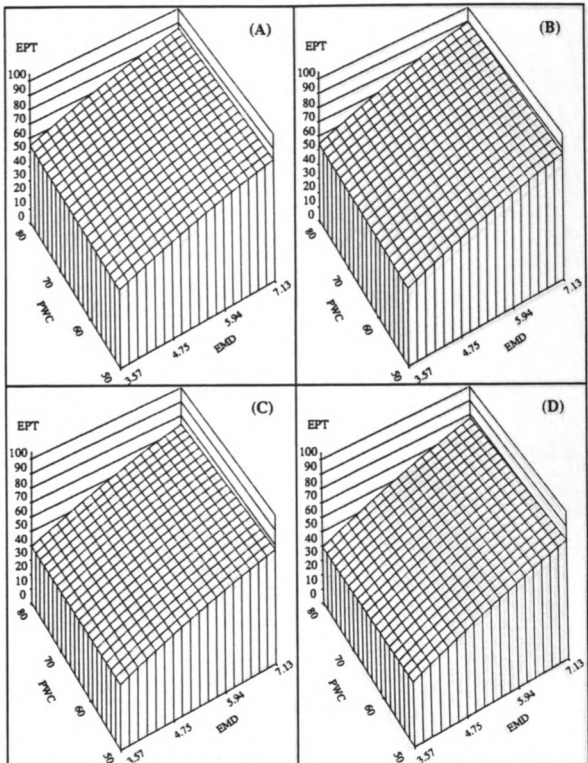
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.90$, $C_p=13.71$):

$$\begin{aligned} \text{EPT} = & -11.02637165 + 19.37310109 \cdot \text{EMD} \\ & - 0.72369088 \cdot \text{EMD}^2 \\ & + 0.00000400001 \cdot \text{LS}^2 \\ & - 0.18575203 \cdot \text{PFC} \\ & + 0.09478620 \cdot \text{MP} \\ & - 0.02172536 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.000067209 \cdot \text{MP} \cdot \text{LS} \\ & - 0.40212869 \cdot \text{PW} \cdot \text{EMD} \\ & + 0.11204693 \cdot \text{PW} \cdot \text{PFC} \\ & + 0.000431463 \cdot \text{LS} \cdot \text{PFC} \\ & - 0.002417919 \cdot \text{EMD} \cdot \text{LS} \end{aligned}$$

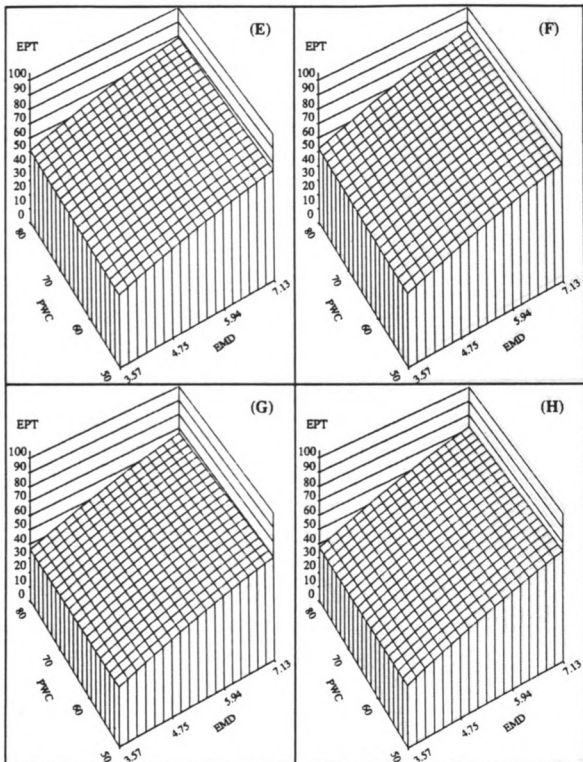


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

Figure 9.

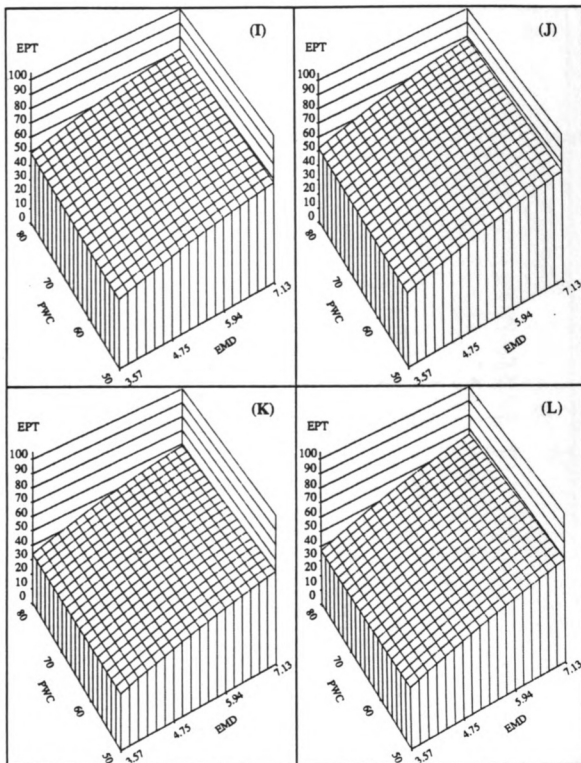


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

Figure 9 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

Figure 9 (cont'd).

Figure 10. Predicted response surface of end-point temperature* in beef loaf (20% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 10-A: LS= 150, PW= 1, MP=100.

Fig. 10-B: LS= 150, PW= 1, MP= 50.

Fig. 10-C: LS= 150, PW=-1, MP=100.

Fig. 10-D: LS= 150, PW=-1, MP= 50.

Fig. 10-E: LS= 600, PW= 1, MP=100.

Fig. 10-F: LS= 600, PW= 1, MP= 50.

Fig. 10-G: LS= 600, PW=-1, MP=100.

Fig. 10-H: LS= 600, PW=-1, MP= 50.

Fig. 10-I: LS=1200, PW= 1, MP=100.

Fig. 10-J: LS=1200, PW= 1, MP= 50.

Fig. 10-K: LS=1200, PW=-1, MP=100.

Fig. 10-L: LS=1200, PW=-1, MP= 50.

Footnotes:

LS = load size in gram.

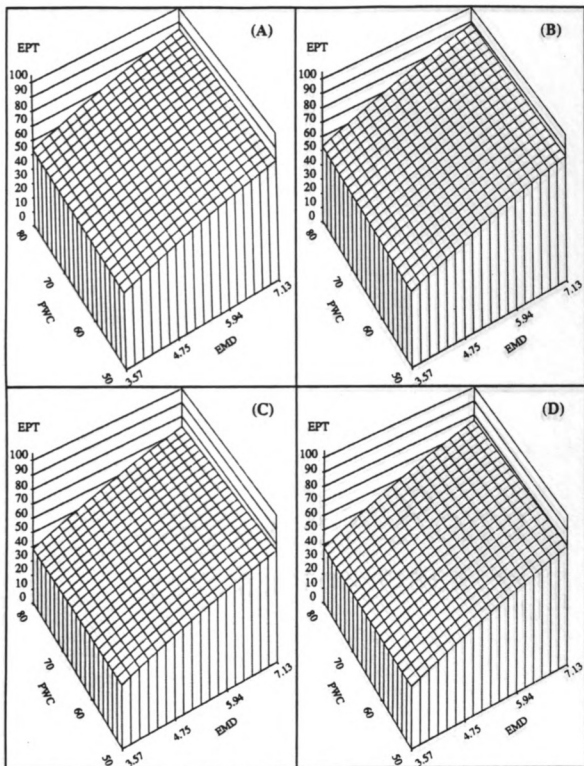
MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.90$, $C_p=13.71$):

$$\begin{aligned} \text{EPT} = & -11.02637165 + 19.37310109 \cdot \text{EMD} \\ & - 0.72369088 \cdot \text{EMD}^2 \\ & + 0.00000400001 \cdot \text{LS}^2 \\ & - 0.18575203 \cdot \text{PFC} \\ & + 0.09478620 \cdot \text{MP} \\ & - 0.02172536 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.000067209 \cdot \text{MP} \cdot \text{LS} \\ & - 0.40212869 \cdot \text{PW} \cdot \text{EMD} \\ & + 0.11204693 \cdot \text{PW} \cdot \text{PFC} \\ & + 0.000431463 \cdot \text{LS} \cdot \text{PFC} \\ & - 0.002417919 \cdot \text{EMD} \cdot \text{LS} \end{aligned}$$

121a

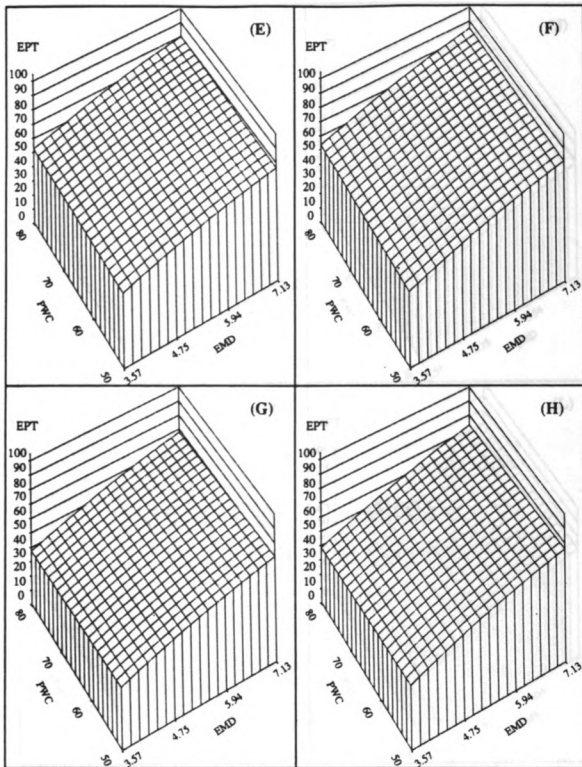


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

Figure 10.

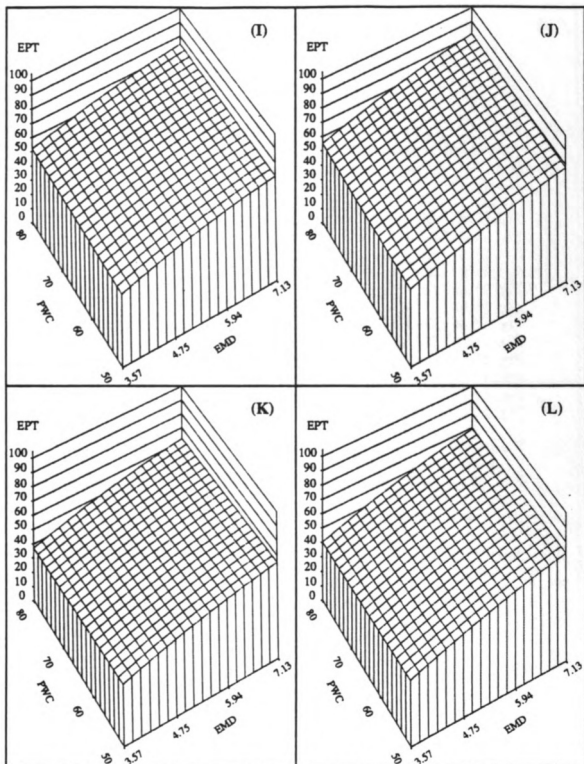


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

Figure 10 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

Figure 10 (cont'd).

Figure 11. Predicted response surface of end-point temperature^a in beef loaf (30% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 11-A: LS= 150, PW= 1, MP=100.
 Fig. 11-B: LS= 150, PW= 1, MP= 50.
 Fig. 11-C: LS= 150, PW=-1, MP=100.
 Fig. 11-D: LS= 150, PW=-1, MP= 50.
 Fig. 11-E: LS= 600, PW= 1, MP=100.
 Fig. 11-F: LS= 600, PW= 1, MP= 50.
 Fig. 11-G: LS= 600, PW=-1, MP=100.
 Fig. 11-H: LS= 600, PW=-1, MP= 50.
 Fig. 11-I: LS=1200, PW= 1, MP=100.
 Fig. 11-J: LS=1200, PW= 1, MP= 50.
 Fig. 11-K: LS=1200, PW=-1, MP=100.
 Fig. 11-L: LS=1200, PW=-1, MP= 50.

Footnotes:

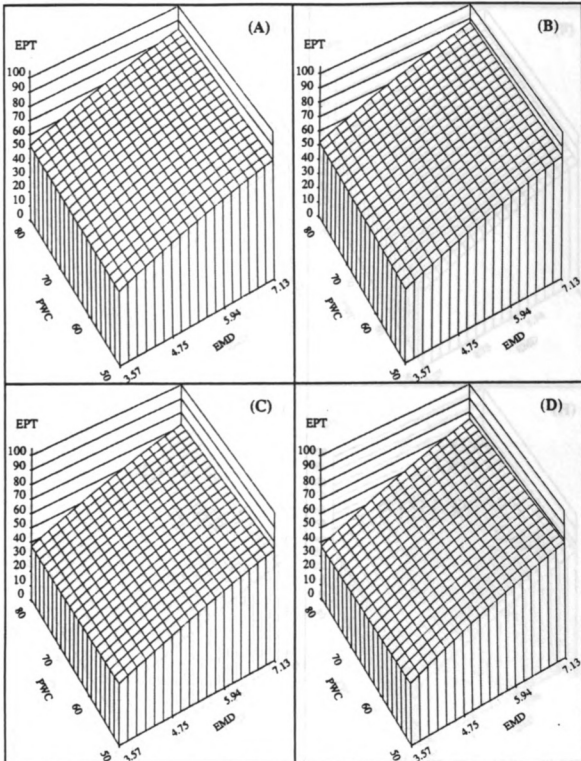
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.90$, $C_p=13.71$):

$$\begin{aligned} \text{EPT} = & -11.02637165 + 19.37310109 \cdot \text{EMD} \\ & - 0.72369088 \cdot \text{EMD}^2 \\ & + 0.00000400001 \cdot \text{LS}^2 \\ & - 0.18575203 \cdot \text{PFC} \\ & + 0.09478620 \cdot \text{MP} \\ & - 0.02172536 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.000067209 \cdot \text{MP} \cdot \text{LS} \\ & - 0.40212869 \cdot \text{PW} \cdot \text{EMD} \\ & + 0.11204693 \cdot \text{PW} \cdot \text{PWC} \\ & + 0.000431463 \cdot \text{LS} \cdot \text{PFC} \\ & - 0.002417919 \cdot \text{EMD} \cdot \text{LS} \end{aligned}$$

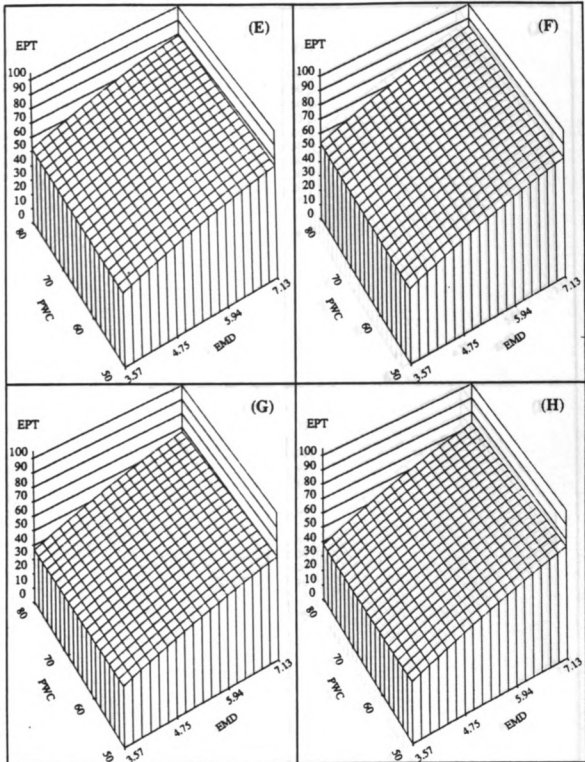


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

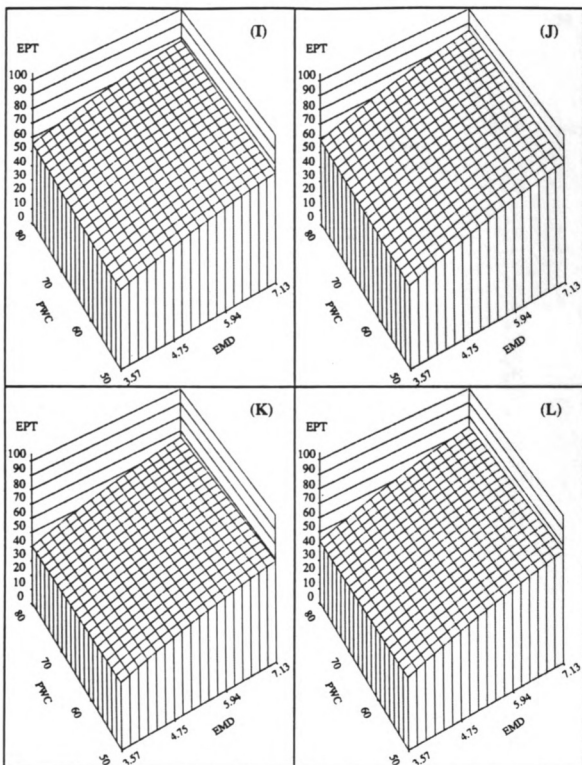
EPT = END-POINT TEMPERATURE (°C).

Figure 11.



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.
 PWC = PERCENT WATER CONTENT (%).
 EPT = END-POINT TEMPERATURE (°C).

Figure 11 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

Figure 11 (cont'd).

Figure 12. Predicted response surface of microwave processing temperature rise* in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 12-A: LS= 150, PW= 1, MP=100.

Fig. 12-B: LS= 150, PW= 1, MP= 50.

Fig. 12-C: LS= 150, PW=-1, MP=100.

Fig. 12-D: LS= 150, PW=-1, MP= 50.

Fig. 12-E: LS= 600, PW= 1, MP=100.

Fig. 12-F: LS= 600, PW= 1, MP= 50.

Fig. 12-G: LS= 600, PW=-1, MP=100.

Fig. 12-H: LS= 600, PW=-1, MP= 50.

Fig. 12-I: LS=1200, PW= 1, MP=100.

Fig. 12-J: LS=1200, PW= 1, MP= 50.

Fig. 12-K: LS=1200, PW=-1, MP=100.

Fig. 12-L: LS=1200, PW=-1, MP= 50.

Footnotes:

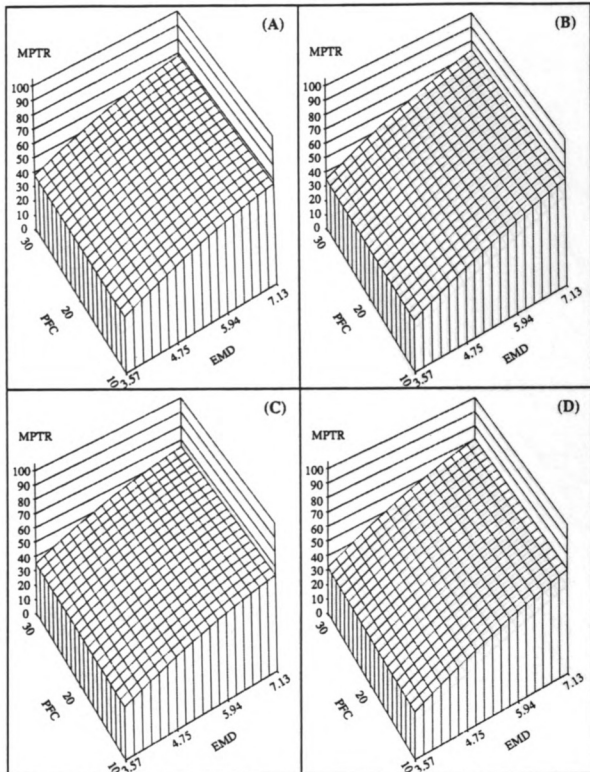
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.89$, $C_p=11.11$):

$$\begin{aligned} \text{MPTR} = & -50.20171795 + 1.44695815 \cdot \text{PW} \\ & + 27.80060812 \cdot \text{EMD} \\ & - 1.34604734 \cdot \text{EMD}^2 \\ & + 0.03192895 \cdot \text{LS} \\ & + 0.000012812 \cdot \text{LS}^2 \\ & + 0.24941277 \cdot \text{MP} \\ & - 0.04597823 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.000166748 \cdot \text{MP} \cdot \text{LS} \\ & + 0.000167668 \cdot \text{LS} \cdot \text{PFC} \\ & - 0.01917655 \cdot \text{EMD} \cdot \text{LS} \\ & + 0.001543915 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$

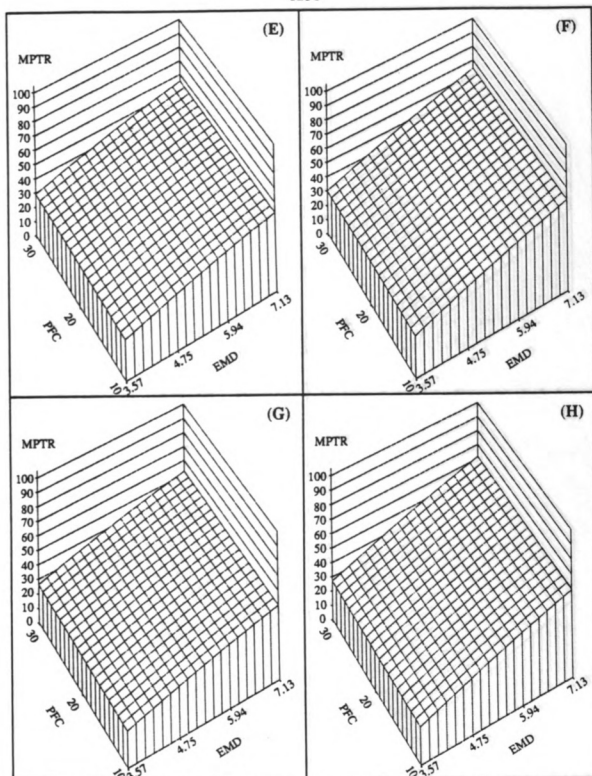


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PFC = PERCENT FAT CONTENT (%).

MPTR = MICROWAVE PROCESSING TEMPERATURE RISE (°C).

Figure 12.

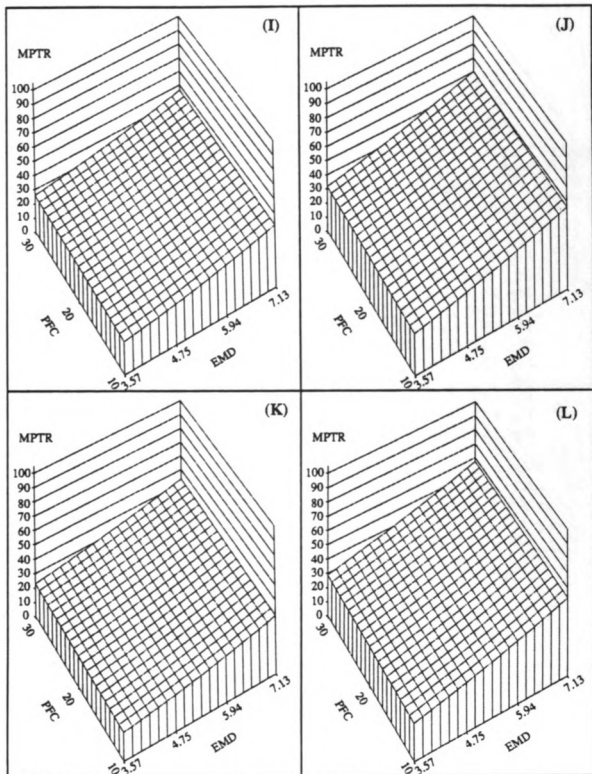


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PFC = PERCENT FAT CONTENT (%).

MPTR = MICROWAVE PROCESSING TEMPERATURE RISE (°C).

Figure 12 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PFC = PERCENT FAT CONTENT (%).

MPTR = MICROWAVE PROCESSING TEMPERATURE RISE (°C).

Figure 12 (cont'd).

Figure 13. Predicted response surface of sum of temperature rise^a in beef loaf (10% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 13-A: LS= 150, PW= 1, MP=100.

Fig. 13-B: LS= 150, PW= 1, MP= 50.

Fig. 13-C: LS= 150, PW=-1, MP=100.

Fig. 13-D: LS= 150, PW=-1, MP= 50.

Fig. 13-E: LS= 600, PW= 1, MP=100.

Fig. 13-F: LS= 600, PW= 1, MP= 50.

Fig. 13-G: LS= 600, PW=-1, MP=100.

Fig. 13-H: LS= 600, PW=-1, MP= 50.

Fig. 13-I: LS=1200, PW= 1, MP=100.

Fig. 13-J: LS=1200, PW= 1, MP= 50.

Fig. 13-K: LS=1200, PW=-1, MP=100.

Fig. 13-L: LS=1200, PW=-1, MP= 50.

Footnotes:

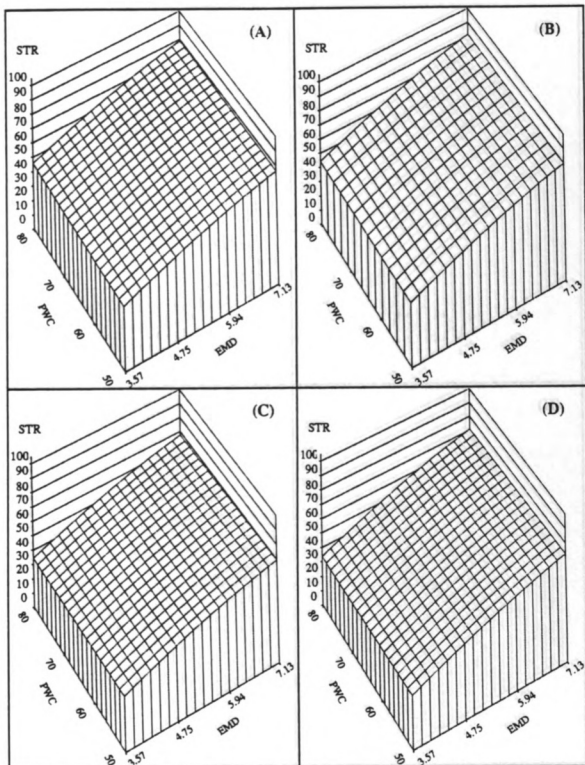
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW,1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.90$, $C_p=11.14$):

$$\begin{aligned} \text{STR} = & -18.18250972 + 16.48072440 \cdot \text{EMD} \\ & - 0.05280283 \cdot \text{EMD}^3 \\ & + 0.01179239 \cdot \text{LS} \\ & + 0.10389723 \cdot \text{MP} \\ & - 0.02208500 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.000078908 \cdot \text{MP} \cdot \text{LS} \\ & + 0.07107716 \cdot \text{PW} \cdot \text{PWC} \\ & + 0.000123370 \cdot \text{LS} \cdot \text{PFC} \\ & - 0.002577925 \cdot \text{EMD} \cdot \text{LS} \end{aligned}$$

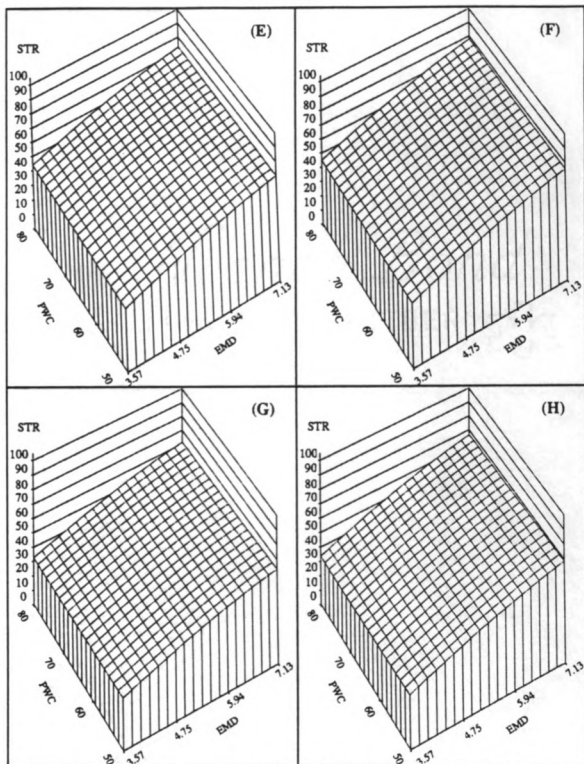


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 13.

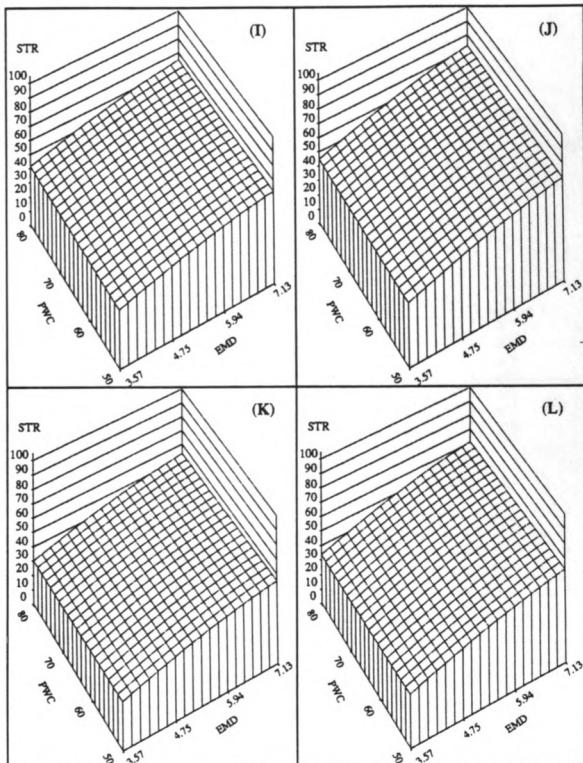


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 13 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 13 (cont'd).

Figure 14. Predicted response surface of sum of temperature rise^a in beef loaf (20% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 14-A: LS= 150, PW= 1, MP=100.

Fig. 14-B: LS= 150, PW= 1, MP= 50.

Fig. 14-C: LS= 150, PW=-1, MP=100.

Fig. 14-D: LS= 150, PW=-1, MP= 50.

Fig. 14-E: LS= 600, PW= 1, MP=100.

Fig. 14-F: LS= 600, PW= 1, MP= 50.

Fig. 14-G: LS= 600, PW=-1, MP=100.

Fig. 14-H: LS= 600, PW=-1, MP= 50.

Fig. 14-I: LS=1200, PW= 1, MP=100.

Fig. 14-J: LS=1200, PW= 1, MP= 50.

Fig. 14-K: LS=1200, PW=-1, MP=100.

Fig. 14-L: LS=1200, PW=-1, MP= 50.

Footnotes:

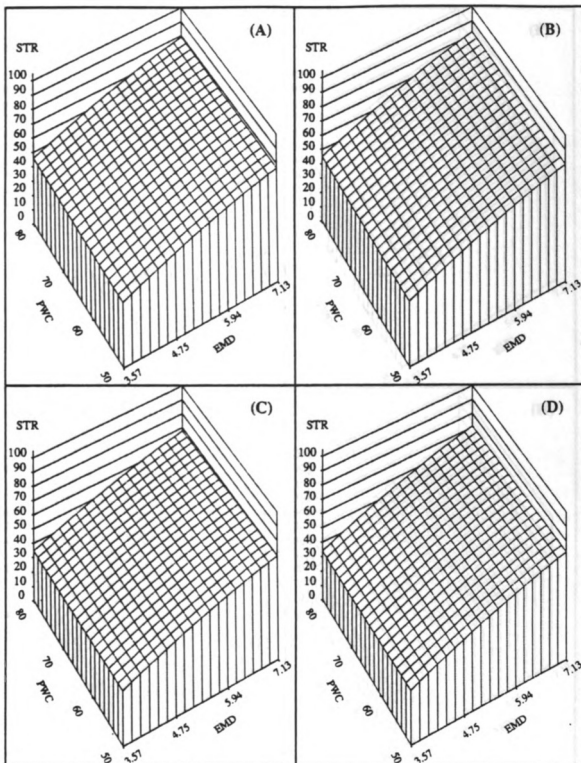
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film, -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.90$, $C_p=11.14$):

$$\begin{aligned} \text{STR} = & -18.18250972 + 16.48072440 \cdot \text{EMD} \\ & - 0.05280283 \cdot \text{EMD}^3 \\ & + 0.01179239 \cdot \text{LS} \\ & + 0.10389723 \cdot \text{MP} \\ & - 0.02208500 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.000078908 \cdot \text{MP} \cdot \text{LS} \\ & + 0.07107716 \cdot \text{PW} \cdot \text{PWC} \\ & + 0.000123370 \cdot \text{LS} \cdot \text{PFC} \\ & - 0.002577925 \cdot \text{EMD} \cdot \text{LS} \end{aligned}$$

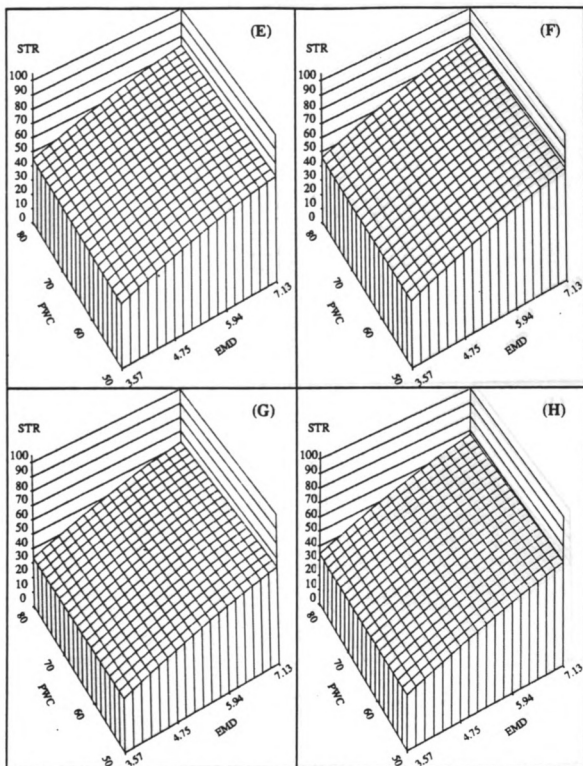


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 14.

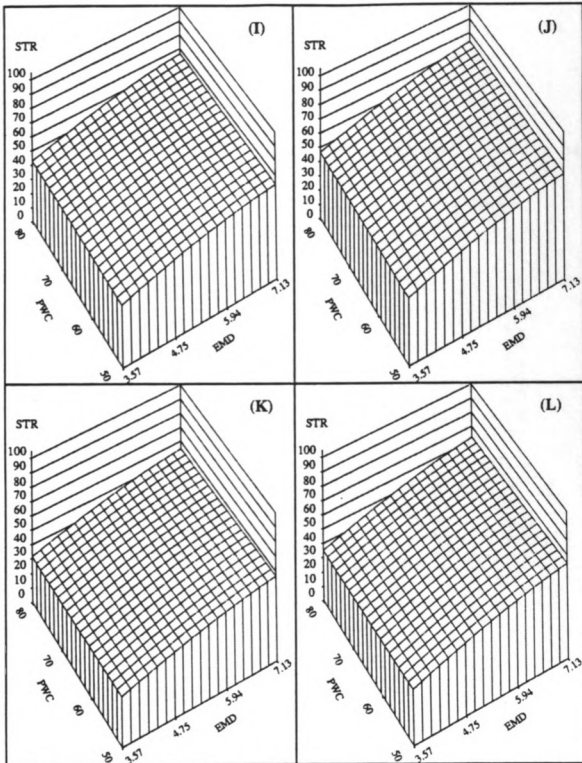


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 14 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 14 (cont'd).

Figure 15. Predicted response surface of sum of temperature rise^a in beef loaf (30% fat content) wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 15-A: LS= 150, PW= 1, MP=100.

Fig. 15-B: LS= 150, PW= 1, MP= 50.

Fig. 15-C: LS= 150, PW=-1, MP=100.

Fig. 15-D: LS= 150, PW=-1, MP= 50.

Fig. 15-E: LS= 600, PW= 1, MP=100.

Fig. 15-F: LS= 600, PW= 1, MP= 50.

Fig. 15-G: LS= 600, PW=-1, MP=100.

Fig. 15-H: LS= 600, PW=-1, MP= 50.

Fig. 15-I: LS=1200, PW= 1, MP=100.

Fig. 15-J: LS=1200, PW= 1, MP= 50.

Fig. 15-K: LS=1200, PW=-1, MP=100.

Fig. 15-L: LS=1200, PW=-1, MP= 50.

Footnotes:

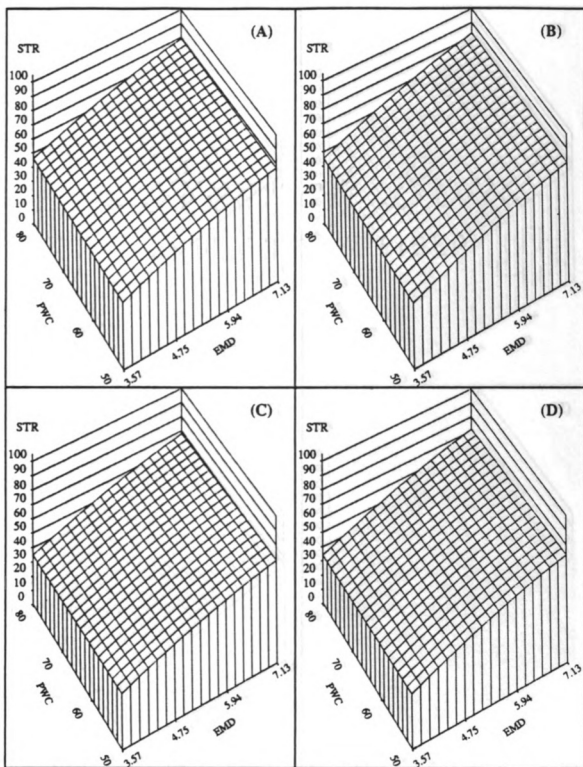
LS = load size in gram.

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.90$, $C_p=11.14$):

$$\begin{aligned} \text{STR} = & -18.18250972 + 16.48072440 \cdot \text{EMD} \\ & - 0.05280283 \cdot \text{EMD}^3 \\ & + 0.01179239 \cdot \text{LS} \\ & + 0.10389723 \cdot \text{MP} \\ & - 0.02208500 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.000078908 \cdot \text{MP} \cdot \text{LS} \\ & + 0.07107716 \cdot \text{PW} \cdot \text{PWC} \\ & + 0.000123370 \cdot \text{LS} \cdot \text{PFC} \\ & - 0.002577925 \cdot \text{EMD} \cdot \text{LS} \end{aligned}$$

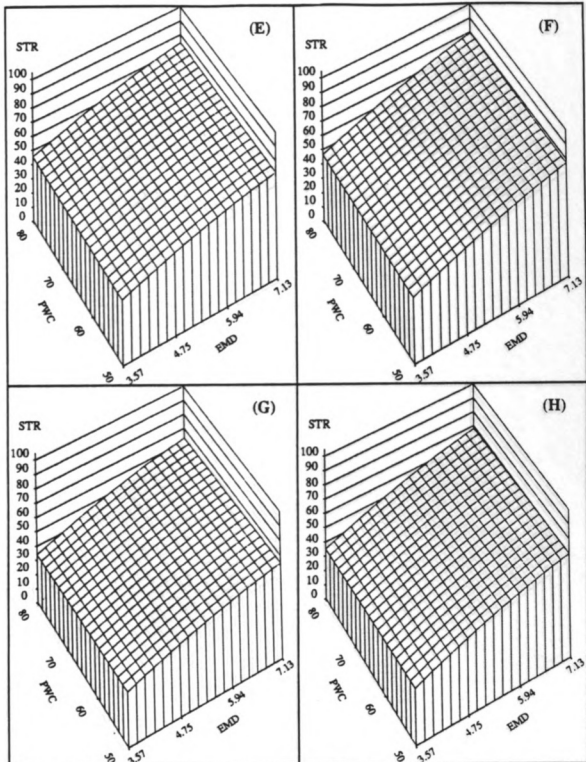


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 15.

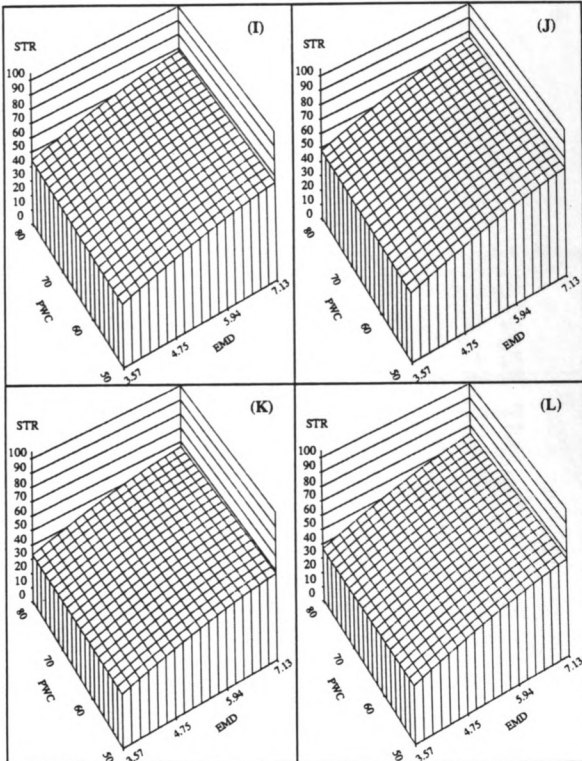


EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 15 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 15 (cont'd).

Figure 16. Predicted response surface of post processing temperature rise* in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 16-A: PW= 1, MP=100.

Fig. 16-B: PW= 1, MP= 50.

Fig. 16-C: PW=-1, MP=100.

Fig. 16-D: PW=-1, MP= 50.

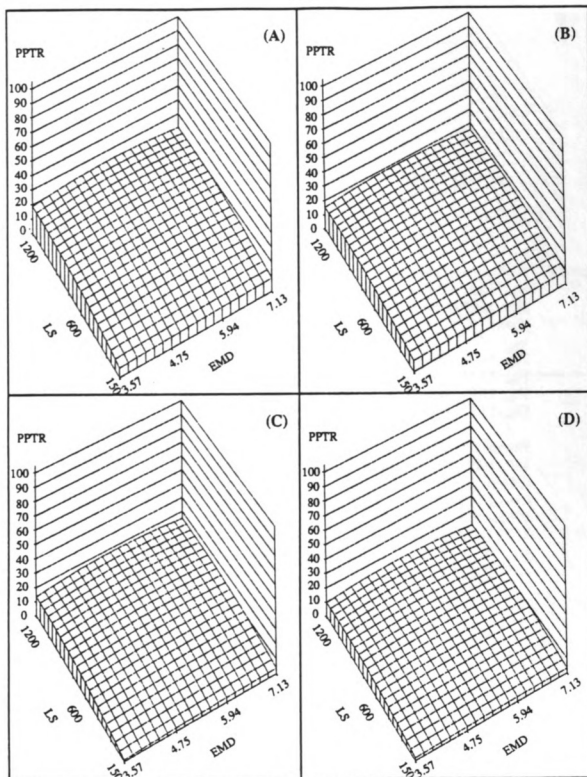
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.64, C_p=7.05$):

$$\begin{aligned} \text{PPTR} = & 2.90215443 + 2.66493056 \cdot \text{PW} \\ & - 0.06126239 \cdot \text{MP} \\ & + 0.007966663 \cdot \text{MP} \cdot \text{EMD} \\ & + 0.000089499 \cdot \text{MP} \cdot \text{LS} \\ & - 0.000012634 \cdot \text{LS}^2 \\ & + 0.008592526 \cdot \text{EMD} \cdot \text{LS} \\ & - 0.000835027 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

LS = LOAD SIZE (G).

PPTR = POST PROCESSING TEMPERATURE RISE (°C).

Figure 16.

Figure 17. Predicted response surface of time of post processing temperature rise^a in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 17-A: PW= 1, MP=100.

Fig. 17-B: PW= 1, MP= 50.

Fig. 17-C: PW=-1, MP=100.

Fig. 17-D: PW=-1, MP= 50.

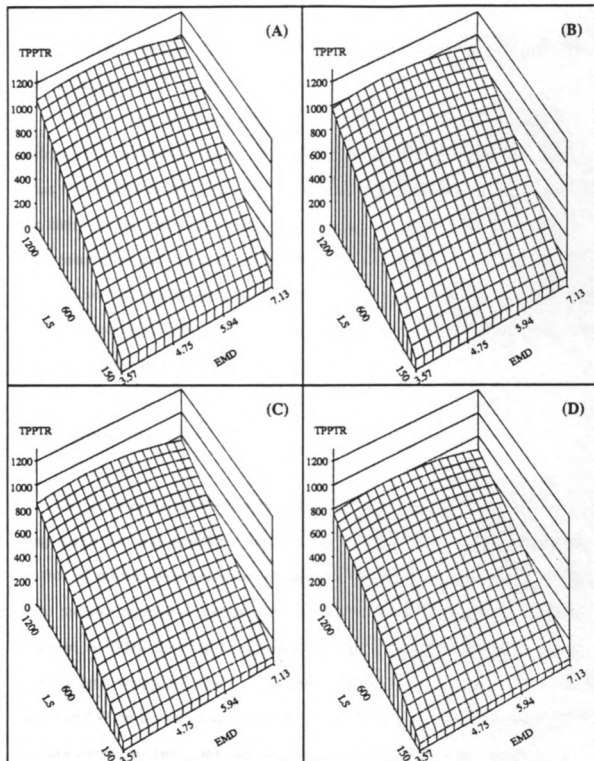
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film, -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.90, C_p=8.66$):

$$\begin{aligned} \text{TPPTR} = & -75.89583333 + 0.49345739*LS \\ & - 0.000176620*LS^2 \\ & + 0.08965278*PW*LS \\ & + 0.001310391*MP*LS \\ & + 0.19507313*EMD*LS \\ & - 0.01997249*EMD^2*LS \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.
 LS = LOAD SIZE (G).
 TPPTR = TIME OF POST PROCESSING TEMPERATURE RISE (SEC).

Figure 17.

MPTR, PPTR, STR, and TPPTR resulted because more heat was retained by beef loaves wrapped in PVDC film.

The effect of PVDC wrapping on EPT of three food products reported by Sawyer et al. (1984) was not significant. In that report, EPT taken from only one point of temperature measured in each sample was very likely not representative of the entire product temperature range. In this study, 16 temperature measurements were taken from each loaf and the lowest temperature location was chosen to study bacterial survival and thermal responses after microwave processing. The temperature measurements of the product in the present study were more representative than the result of Sawyer et al. (1984).

5.1.1.3 Evaporation loss

The result of the ANOVA indicated the main effect of PW on percent evaporation loss was significant ($p \leq 0.0001$; Appendix 2). The predicted response surface of percent evaporation loss of beef loaf after microwave processing derived from multiple regression analysis is shown in Figure 18. Beef loaves that had been wrapped in PVDC film had a lower percent evaporation loss than beef loaves that had not been wrapped (Table 7 and Figure 18:A vs. D, B vs. E, C vs. F). A similar effect of PW on percent evaporation loss of microwave cooked foods was reported by Sawyer and Biglari (1984) and Ruyack and Paul (1972). Lower percent evaporation loss resulted because more evaporated substances (mainly water) and drip loss were retained by beef loaves wrapped in PVDC film.

Figure 18. Predicted response surface of percent evaporation loss^a in beef loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).

Fig. 18-A: LS= 150, PW= 1.

Fig. 18-B: LS= 600, PW= 1.

Fig. 18-C: LS=1200, PW= 1.

Fig. 18-D: LS= 150, PW=-1.

Fig. 18-E: LS= 600, PW=-1.

Fig. 18-F: LS=1200, PW=-1.

Footnotes:

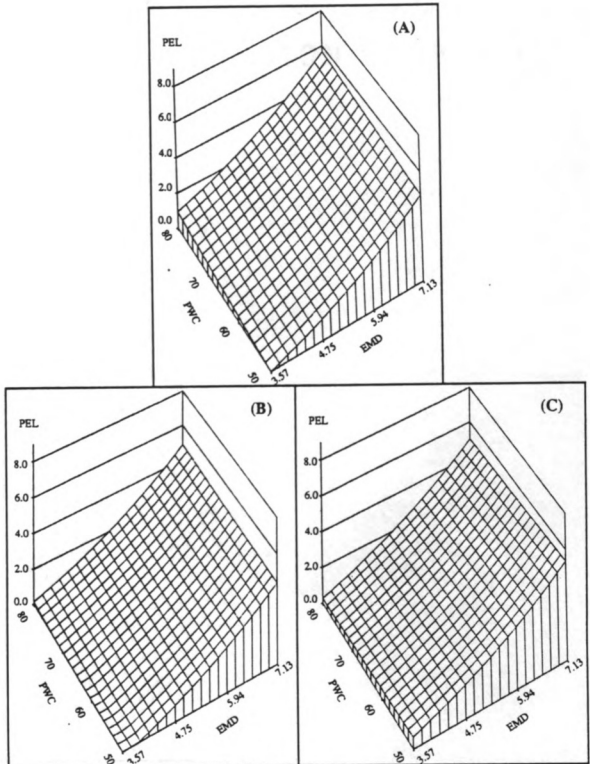
LS = load size in gram.

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.89, C_p=6.01$):

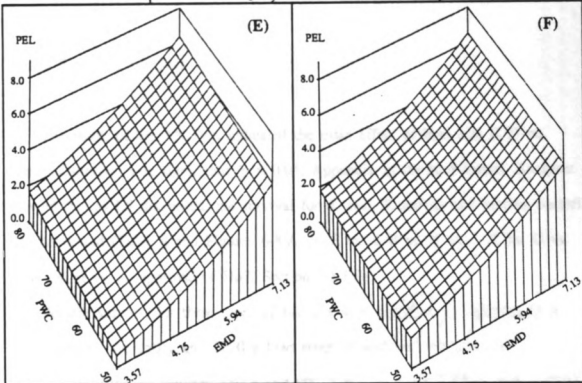
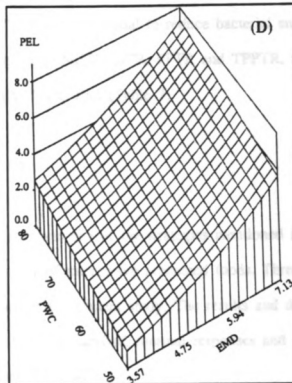
$$\begin{aligned} \text{PEL} = & -3.86636669 + 0.45416655 \cdot \text{EMD} \\ & + 0.009593740 \cdot \text{EMD}^3 \\ & + 0.00000211987 \cdot \text{LS}^2 \\ & + 0.05116813 \cdot \text{PWC} \\ & - 0.009211266 \cdot \text{PW} \cdot \text{PWC} \\ & - 0.000044818 \cdot \text{LS} \cdot \text{PWC} \end{aligned}$$

130a



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.
PWC = PERCENT WATER CONTENT (%).
PEL = PERCENT EVAPORATION LOSS (%).

Figure 18.



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

PEL = PERCENT EVAPORATION LOSS (%).

Figure 18 (cont'd).

In conclusion, PW has the potential to reduce bacterial survival and evaporation loss. The thermal responses, MPTR, STR, PPTR and TPPTR, increased when beef loaf was wrapped with PVDC film (Table 7).

5.1.2 Effect of load size

Decreased load size was one of the strategies mentioned in Section 3.5.1.3 to improve microbial quality of microwave processed foods. Three load sizes (150, 600 and 1200 g) were used in the present study. The results and discussion of the effect of load size (LS) on bacterial survival, thermal responses and evaporation loss of beef loaves are presented below.

5.1.2.1 Bacterial survival

The result of the ANOVA indicated the main effect of load size (LS) on bacterial survival was significant ($p \leq 0.05$; Appendix 2) for beef loaves. Analyses showed that as LS decreased, the survival for *E. coli*, *S. aureus* and aerobic bacteria also decreased (Table 8 and Figures 6-8: A vs. E vs. I, B vs. F vs. J, C vs. G vs. K, D vs. H vs. L; approval of Ho7; Section 3.5.1.3).

Percent survival for three types of bacteria were significantly different ($p \leq 0.05$) between the 150 g and 1200 g load sizes of beef loaf but were not significantly different between 150 g and 600 g or 600 g and 1200 g load sizes of beef loaf. The only exception was the percent survival of *S. aureus* between 150 g

Table 8. The main effect of load size (LS) on bacterial survival, thermal responses and evaporation loss of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).

Subject	LS (g)	Sample size (n)	Mean ° of								
			LEC	LSA	LAB	EPT	MPTR	STR	PPTR	TPTR	PEL
Beef (10, 20 and 30% fat)	150	96	0.626 ^{AB}	0.648 ^B	0.655 ^B	64.1 ^A	53.2 ^A	58.5 ^A	5.3 ^C	74.4 ^C	2.89 ^B
	600	96	0.735 ^{A,B}	0.780 ^A	0.753 ^{A,B}	61.1 ^B	42.6 ^B	55.9 ^B	13.4 ^B	477.6 ^B	2.47 ^C
	1200	96	0.756 ^A	0.810 ^A	0.779 ^A	59.1 ^C	36.4 ^C	52.5 ^C	16.1 ^A	904.0 ^A	3.20 ^A
Beef (10% fat) & Turkey (10% fat)	150	64	0.641 ^B	0.583 ^B	0.654 ^B	59.4 ^A	46.7 ^A	55.7 ^A	9.0 ^B	81.7 ^C	2.88 ^A
	600	64	0.912 ^A	0.904 ^A	0.914 ^A	58.3 ^A	40.9 ^B	55.0 ^A	14.1 ^A	420.1 ^B	2.42 ^B
	1200	64	0.940 ^A	0.935 ^A	0.914 ^A	55.4 ^B	35.8 ^C	51.9 ^B	16.1 ^A	875.0 ^A	2.98 ^A
Turkey (10% fat)	150	32	0.664 ^B	0.640 ^B	0.710 ^B	52.4 ^C	40.0 ^A	52.3 ^B	12.3 ^B	83.8 ^C	2.52 ^B
	600	32	0.927 ^A	0.913 ^A	0.937 ^A	57.7 ^A	41.3 ^A	55.3 ^A	14.0 ^{A,B}	411.8 ^B	2.36 ^B
	1200	32	0.994 ^A	0.951 ^A	0.960 ^A	54.8 ^B	37.1 ^B	52.8 ^B	15.7 ^A	776.8 ^A	2.75 ^A
Beef (10% fat), Turkey (10% fat) & BGB (10% glycerol)	150	24	0.860 ^B	0.773 ^B	0.820 ^B	51.7 ^A	42.9 ^A	48.7 ^{A,B}	5.8 ^B	67.5 ^C	3.90 ^A
	600	24	1.235 ^A	1.199 ^A	1.203 ^A	51.8 ^A	36.8 ^B	49.2 ^A	12.4 ^A	321.2 ^B	3.34 ^B
	1200	24	1.206 ^A	1.295 ^A	1.216 ^A	50.0 ^A	32.4 ^C	46.3 ^B	13.9 ^A	656.3 ^A	4.06 ^A

Key:

BGB = bentonite-glycerol-BHI broth.

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec).

PEL = percent evaporation loss (%).

Footnote:

* Average over polyvinylidene chloride (PW), microwave output power (MP), percent fat content (PFC) and exposed microwave dose (EMD) for the subset of beef (10, 20 and 30% fat); average over polyvinylidene chloride (PW), microwave output power (MP), exposed microwave dose (EMD) for the subset of beef & turkey (10% fat) and turkey (10% fat); average over exposed microwave dose (EMD) for the subset of beef (10% fat) & turkey (10% fat) & BGB (10% glycerol).

Means with the same letter in the same cell are not significantly different (p > 0.05 by Tukey's test).

and 600 g load sizes of beef loaf which was significantly different ($p \leq 0.05$; Table 8).

Spite (1984) also studied the effect of load size on bacterial survival by using 120 g and 360 g load sizes. The percent survival of *S. aureus* in the 360 g load size of Spite was zero compared to the percent survival of *S. aureus* in the 120 g load size of Spite which was 0.29%. Spite speculated that the longer processing time used for the larger load size (9 min. vs. 3 min) was the significant factor. Results of Spite's research were contrary to recommendations of other researchers to use small load size to reduce bacterial survival [Schiffmann, 1986; Decareau, 1975].

Spite's results more accurately reflected the results of prolonged time, not the effect of load size. The 360 load size was not large enough to show the effect of load size because the EPT of 360 g load size was only 1 °C below that of 120 g load size. If the result of bacterial survival in Spite's study was due to the effect of load size, one would expect the 360 g load size had much lower EPT than that of the 120 g load size.

In the present study, the effect of LS was more clearly showed than Spite's results by a wider margin in bacterial survival and EPT. The percent survival of *S. aureus* of the 1200 g load size of beef loaves was 2.0% higher (5 °C lower in EPT) than that of the 150 g load size (Table 8).

5.1.2.2 Thermal responses

The result of the ANOVA indicated the main effect of load size (LS) on thermal responses was significant ($p \leq 0.001$; Appendix 2). Analyses showed that as

LS increased, end-point temperature (EPT), microwave processing temperature rise (MPTR), and sum of temperature rise (STR) decreased significantly ($p \leq 0.05$; Table 8 and Figures 9-15: A vs. E vs. I, B vs. F vs. J, C vs. G vs. K, D vs. H vs. L). On the other hand, post processing temperature rise (PPTR) and time of PPTR (TPPTR) increased as LS increased (Table 8 and Figures 16-17). The lower EPT in the large load size of the present study was in agreement with the finding of Spite (1984).

As LS increased, the thickness of beef loaves also increased. Therefore, the amount of microwave energy which penetrated the loaf was reduced as thickness increased and the result was the lower EPT, MPTR and STR. Hence the bacterial survival in large load sizes of beef loaf was higher than that of small load sizes. The higher PPTR and prolonged TPPTR found in large load sizes of beef loaf was due to the effect of large volume. Heat was retained longer in the large LS.

5.1.2.3 Evaporation loss

The result of the ANOVA indicated the main effect of LS on percent evaporation loss was significant ($p \leq 0.0001$; Appendix 2). Analysis showed that the 600 g load size of beef loaf had the lowest percent evaporation loss among three load sizes. Significant differences in percent evaporation loss were found among three load sizes of beef loaf (Table 8 and Figure 18).

The possible reason why the lowest PEL was found in the 600 g load size of beef loaf was probably due to low heating rate ($0.14\text{ }^{\circ}\text{C/sec}$) and small surface area (174.64 cm^2). Although 150 g load size of beef loaf had the smallest surface area (121.39 cm^2), it was also the one that had the highest elevated temperature in the

shortest period of time (0.53 °C/sec) among three load sizes. On the other hand, the 1200 g load size had the lowest elevated temperature in the longest period of time (0.07 °C/sec) among three load sizes, but the 1200 g load size also was the one that had the largest surface area (280.52 cm²) among three load sizes. Since PEL was affected by the heating rate and surface area and their possible interaction, the 600 g load which had a low heating rate and small surface area had the smallest PEL among three load sizes.

In conclusion, as load size increased, the bacterial survival, PPTR and TPPTTR of beef loaves also increased. The EPT, MPTR and STR of beef loaves decreased as load size increased. Among three load sizes, the 600 load size had the lowest PEL and the 1200 g load size had the highest PEL (Table 8).

5.1.3 Effect of microwave output power

Lowering microwave output power (MP) was one of the strategies mentioned in Section 3.5.2.1 to improve microbial quality of microwave processed foods. Two levels of microwave output power (100% vs. 50%) were used in the present study. The results and discussion of the effect of MP on bacterial survival, thermal responses and evaporation loss of beef loaves are presented below.

5.1.3.1 Bacterial survival

The result of the ANOVA indicated that the main effect of microwave output power (MP) on bacterial survival was significant ($p \leq 0.005$; Appendix 2) for beef

loaves. Analyses showed that percent survival of three types of bacteria was lower in beef loaves that had been microwave processed at 50% output power than those that had been microwave processed at 100% output power (Table 9 and Figures 6-8:A vs.B, C vs.D, E vs. F, G vs. H, I vs. J, K vs. L; approval of Ho8; Section 3.5.2.1). The effect of MP on bacterial survival was enhanced as the LS became larger (Figures 6-8:A, B vs. E, F vs. I, J).

When beef loaves in the present study were microwave processed at 50% output power, the processing time was twice as long as the time of beef loaves that had been processed at 100% output power (Table 2; Section 3.3.2). Since quantity of bacteria killed was a function of both time and temperature [Jay, 1986], the prolonged processing time plus the higher EPT of 50% MP resulted in the expecting lower percent of bacterial survival.

Zimmermann (1982) cooked meat loaves in microwave ovens with varied microwave output power and found that the number of surviving *Trichinella spiralis* was less when low microwave output power was used. The result of the present study confirmed the finding of Zimmermann.

Aleixo et. al. (1985) reported that after cooking to the EPT of 76.6 °C, turkeys microwave processed at the warming setting (10% of microwave output power) had a lower percent survival of *S. aureus* and *S. typhimurium* than did turkeys processed at high setting (100% output power). The effect of MP on bacterial survival in this study confirmed the finding of Aleixo et. al.

Table 9. The main effect of microwave output power (MP) on bacterial survival, thermal responses and evaporation loss of loaves (beef and turkey) after microwave processing (2450 MHz)

Subset	MP (%)	Sample size (n)	Mean ^a of								
			LEC	LSA	LAB	EPT	MPTR	STR	PPTR	TPPTR	PEL
Beef (10, 20 and 30% fat) & Turkey (10% fat)	100	192	0.807 ^A	0.827 ^A	0.809 ^A	58.3 ^B	40.4 ^B	53.5 ^B	13.2 ^A	489.4 ^A	3.00 ^A
	50	192	0.682 ^B	0.710 ^B	0.719 ^B	61.4 ^A	45.4 ^A	56.6 ^A	11.2 ^B	450.6 ^B	2.55 ^B
Beef (10, 20 and 30% fat)	100	144	0.772 ^A	0.812 ^A	0.785 ^A	59.8 ^B	41.4 ^B	54.0 ^B	12.6 ^A	505.0 ^A	3.10 ^A
	50	144	0.640 ^B	0.681 ^B	0.672 ^B	63.1 ^A	46.7 ^A	57.2 ^A	10.6 ^B	465.7 ^B	2.62 ^B
Beef (10% fat) & Turkey (10% fat)	100	96	0.887 ^A	0.862 ^A	0.857 ^A	56.1 ^B	38.7 ^B	52.7 ^B	14.1 ^A	486.0 ^A	2.96 ^A
	50	96	0.776 ^B	0.753 ^B	0.798 ^A	59.3 ^A	43.7 ^A	55.7 ^A	12.0 ^B	431.9 ^B	2.55 ^B
Turkey (10% fat)	100	48	0.914 ^A	0.873 ^A	0.880 ^A	53.6 ^B	37.2 ^B	52.2 ^B	15.0 ^A	442.7 ^A	2.76 ^A
	50	48	0.809 ^A	0.796 ^A	0.858 ^A	56.4 ^A	41.7 ^A	54.7 ^A	13.0 ^B	405.5 ^B	2.32 ^B

Key:

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec).

PEL = percent evaporation loss (%).

Footnote:

* Average over polyvinylidene chloride wrapping (PW), load size (LS), percent fat content (PFC) and exposed microwave dose (EMD) for the subsets of beef (10, 20 and 30% fat) and turkey (10% fat) and beef (10, 20 and 30% fat); average over polyvinylidene chloride wrapping (PW), load size (LS), and exposed microwave dose (EMD) for the subsets of beef (10% fat) & turkey (10% fat) and turkey (10% fat).

Means with the same letter in the same cell are not significantly different ($p > 0.05$ by Tukey's test).

5.1.3.2 Thermal responses

The result of the ANOVA indicated that the main effect of microwave output power (MP) on thermal responses was significant ($p \leq 0.005$; Appendix 2). Analyses showed that beef loaves that had been microwave processed at 50% output power (received same microwave energy per gram of product) had higher end-point temperature (EPT), microwave processing temperature rise (MPTR), sum of temperature rise (STR), but lower post processing temperature rise (PPTR) and time of PPTR (TPPTR) than did beef loaves that had been microwave processed at 100% output power (Table 9; Figures 9-15:A vs.B, C vs.D, E vs. F, G vs. H, I vs. J, K vs. L; Figures 16-17:A vs. B, C vs. D).

Sawyer (1985) reported that PPTR was similar for water (1000 g) microwave heated at 100% and 50% output power. In the same report, the PPTR was 2.1 °C greater after processing chicken frankfurters (44-48 g) in a microwave oven at 50% output power than when compared to the same load size of chicken frankfurters processed at 100% output power. The results of Sawyer were different from the result of the present study. The higher PPTR caused by lowering MP in the study of Sawyer was probably due to (1) the small load sizes (44-48 g) and (2) the longer processing time (50% output power for 110 sec vs. 100% output power for 30 sec) were used in Sawyer's study. Sawyer did not control for microwave energy received per gram of product but relied on a single temperature measurement during microwave heating to determine completion of process.

The effect of decreasing MP was enhanced when LS became larger. This could partially be explained by the simultaneous occurrence of thermal conduction in larger

LS while microwave processing was still taking place. The higher EPT, MPTR, STR; lower PPTR; and shorter TPPTR resulting from lower MP could also be explained by prolonged processing time. As processing time was extended, thermal conduction inside the food (especially the large load size) probably began sooner and lasted longer than in smaller loaves before microwave power was turned off.

5.1.3.3 Evaporation loss

The result of the ANOVA indicated that the main effect of MP on percent evaporation loss was significant ($p \leq 0.0001$). Analysis showed that beef loaves that had been microwave processed at 50% output power had lower percent evaporation loss than did beef loaves that had been microwave processed at 100% output power (Table 9). The same effect of MP on PEL was reported by Sawyer (1985) when cake cones was processed at varied levels of microwave output power.

The lower PEL in beef loaves that had been processed at 50% microwave output power could be explained by the slower heating rate (Heldman, 1981) compared to the beef loaves that had been processed at 100% output power.

In conclusion, percent bacterial survival of beef loaves was enhanced by the low MP. When beef loaves were processed at 50% MP, EPT, MPTR and STR increased, but PPTR, TPPTR and EPL decreased (Table 9).

5.1.4 Effect of percent fat content

The results and discussion of the effect of percent fat content on bacterial survival, thermal responses and evaporation loss are presented below. Three fat contents (10, 20 and 30%) of beef loaves were used in the present study.

5.1.4.1 Bacterial survival

The result of the ANOVA indicated that the main effect of percent fat content (PFC) on bacterial survival varied depending upon the species of bacteria for beef loaves. The main effect of PFC on percent survival of *E. coli* and aerobic bacteria was significant ($p \leq 0.05$) but was not significant on percent survival of *S. aureus* (Appendix 2). This result confirmed the finding of Spite (1984) that the protective effect of fat on bacteria varied depending upon the species of bacteria (rejection of H_0 ; Section 3.2.2.1).

Analyses also showed that beef loaves with 10% fat content had a significantly higher ($p \leq 0.05$) percent survival of *E. coli* than did of beef loaves with 20% and 30% fat content. There was no difference in percent survival of *E. coli* between beef loaf with 20% and 30% fat content.

Aerobic bacteria survived best in beef loaves with 10% fat content. There was no difference in percent survival of aerobic bacteria between beef loaves with 10% and 20% fat content and between beef loaves with 20% and 30% fat content. A significant difference ($p \leq 0.05$) in percent survival of aerobic bacteria was observed

between beef loaves with 10% and 30% fat content (Table 10). In general, percent bacterial survival decreased with increasing fat content up to 30% level.

The protective effect of fat on bacteria [Jay, 1986; Spite; 1984; Sugiyama, 1951] was not observed in the present study. In the study reported by Spite (1984), *S. aureus* survived better in food with a lower lipid content. However, the percent survival of *S. aureus* was not significantly different ($p > 0.05$) among three levels of PFC in the present study. Percent survival of three types of bacteria had tendency to decrease as PFC increased (Table 10). This result could not be explained by PFC alone. Other factors such as percent water content (PWC), which is inversely related to PFC ($R=-0.84$), must also be taken into consideration.

5.1.4.2 Thermal responses

The result of the ANOVA indicated that the main effect of PFC on thermal responses (except post processing temperature rise; PPTR) was significant ($p \leq 0.05$; Appendix 2). Analyses showed that beef loaves with 20% fat content had significantly ($p \leq 0.05$) higher microwave processing temperature rise (MPTR), and sum of temperature rise (STR) than did beef loaves with 10% and 30% fat content. There was no difference in MPTR and STR between beef loaves with 10% and 30% fat content. The end-point temperature rise (EPT) of beef loaves with 20% fat content was the highest among beef loaves with three different fat contents. There was no significant difference in EPT between beef loaves with 20% and 30% fat content but was different between beef loaves with 10% and 20% fat content (Table 10 and Fig 9-15). Beef loaves with 30% fat content had highest TPPTTR, followed

Table 10. The main effect of percent fat or glycerol content (PFC) on bacterial survival, thermal responses and evaporation loss of loaves (beef and BGB) after microwave processing (2450 MHz).

Subset	PFC [§] (%)	Sample size (n)	Mean [*] of									
			LEC	LSA	LAB	EPT	MPTR	STR	PPTR	TPPTR	PEL	
Beef (10, 20 and 30% fat)	10	96	0.801 ^{A,B}	0.780 ^A	0.780 ^A	60.4 ^B	42.9 ^B	55.0 ^B	12.1 ^A	493.8 ^A	2.97 ^A	
	20	96	0.670 ^B	0.768 ^A	0.730 ^{A,B}	62.2 ^A	45.7 ^A	56.5 ^A	10.9 ^A	449.0 ^B	2.86 ^{A,B}	
	30	96	0.647 ^B	0.691 ^A	0.670 ^B	61.6 ^{A,B}	43.6 ^B	55.3 ^B	11.7 ^A	513.3 ^A	2.72 ^B	
BGB (150 g)	10	16	0.968 ^B	0.936 ^B	0.960 ^B	46.5 ^C	34.3 ^B	41.7 ^C	7.3 ^A	74.9 ^A	4.68 ^A	
	20	16	0.873 ^C	0.879 ^B	0.886 ^C	54.2 ^A	44.1 ^A	49.4 ^A	5.3 ^{A,B}	62.8 ^A	4.19 ^B	
	30	16	1.110 ^A	1.095 ^A	1.111 ^A	50.5 ^B	41.1 ^A	45.6 ^B	4.5 ^B	67.6 ^A	4.03 ^B	

Key:

BGB = bentonite-glycerol-BHI broth.

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec).

PEL = percent evaporation loss (%).

Footnote:

[§] Actual values were:

beef(10% fat): 7.88 ± 3.10 %; beef (20% fat): 18.04 ± 0.88 %; beef (30% fat): 25.16 ± 1.39 %.

BGB (10% glycerol): 8.89 ± 0.30 %; BGB (20% glycerol): 18.85 ± 0.26 %; BGB (30% glycerol): 29.06 ± 0.27 %.

* Average over polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP) and exposed microwave dose (EMD) for the subset of beef (10, 20 and 30% fat); average over exposed microwave dose (EMD) for the subset of BGB (150 g).

Means with the same letter in the same cell are not significantly different ($p > 0.05$ by Tukey's test).

by beef loaves with 10% fat content, then by beef loaves with 20% fat content. There was no significant difference in TPPTR between beef loaves with 10% and 30% fat content but was different between beef loaves with 20 and 30 % fat content (Table 10).

Unlike the result of Spite (1984) in which EPT increased substantially (13 °C) when fat content of product was increased by 30%, the average EPT (n=96 loaves) of beef loaf in the present study increased only slightly (1.2 °C) as fat content increased from 10% to 30% (Table 10). In general, increasing fat content resulted in relatively small increases of thermal responses (except PPTR which was decreased).

During microwave processing, one would expect food with a higher fat content to heat at a faster rate and to a higher temperature than food of lower fat content (Schiffmann, 1986). In the present study, beef loaves with 20% PFC (not 30% PFC) had the highest EPT, MPTR and STR among three levels of PFC.

In microwave processing, temperature rise has been reported to be a function of both the power absorbed by the food and its specific heat [Van Zante, 1968]. One must remember that fat was not the only component in beef loaves, therefore, the result of thermal responses of beef loaves after microwave processing may not be able to be explained by PFC alone.

By examining dielectric properties of water and fat (ϵ' :78 vs. 2.49; ϵ'' :12.48 vs. 0.127), one would find that water has better dielectric properties (heats more efficiently in the microwave field) than fat [Kent, 1987; Schiffmann, 1986]. However, the specific heat of fat was only half of that of water [Schiffmann, 1986]. This means that for an equivalent weight, fat can heat twice as rapidly as water for the same amount of energy input. Due to the opposite dielectric and thermal

properties between water and fat and their inverse relationship in meat, the effect of PFC or PWC on thermal responses of beef loaf will always be the combined result of PFC and PWC.

5.1.4.3 Evaporation loss

The result of the ANOVA indicated that the main effect of PFC on percent evaporation loss (PEL) was significant ($p \leq 0.0001$; Appendix 2). Analysis showed that beef loaves with 10% fat content had the highest PEL. The PEL decreased as PFC increased. Results of the present are in contrast to those of Berry and Leddy (1984) in which percent yield (exclusion of drip loss) of beef patties decreased with increasing fat content. The reason for beef loaves with the lowest fat content had the highest yield are: (1) beef loaves retained more fat than that of beef patties after microwave processing (Berry and Leddy, 1984) and (2) drip loss was included in percent yield of beef loaves in the present study.

There was a significant difference ($p \leq 0.05$) in PEL between beef with 10% and 30% fat content, but no difference in PEL between beef loaves with 10% and 20% fat content and beef loaves with 20% and 30% fat content (Table 10).

The percent evaporation loss in beef loaves after microwave processing decreased as PFC increased. This result could be explained by the amount of water in the beef loaves. As PFC increased, PWC in beef loaves decreased (PFC and PWC are inversely related). Since most of evaporation loss was due to water evaporation, one would expect beef loaves with higher water content to have greater evaporation loss than beef loaves with lower water content.

In conclusion, when the PFC of beef loaf increased, the percent survival of bacteria and evaporation loss of beef loaves decreased. The effect of PFC on thermal responses of beef loaves was irregular. Beef loaves with 20% fat content had the highest EPT, MPTR STR, but had the lowest PPTR and the Shortest TPPTR.

5.1.5 Effect of percent water content

Although percent water content (PWC) was not included as a variable being tested by the SAS GLM procedure, it was considered as a covariate and had been included as an independent variable in multiple regression analysis (Section 4.5.1.2) because it had a substantial effect on bacterial survival (see Section 2.3.4.1). The effects of PWC on bacterial survival, thermal responses and percent evaporation loss were presented in Figures 6-11,13-15, and 18, which were plotted from multiple regression equations.

5.1.5.1 Bacterial survival

The percent survival of all types of bacteria increased as percent water content (PWC) increased (Figures 6-8) for beef loaves. These results were in agreement with those of Spite (1984) who reported that increased water content generally enhanced bacterial survival.

5.1.5.2 Thermal responses

The effect of PWC on end-point temperature (EPT) and sum of temperature rise (STR) varied depending upon if beef loaves were wrapped in PVDC film or not. When beef loaves were wrapped with PVDC film, EPT and STR of loaves increased as PWC increased. If beef loaves were not wrapped, EPT and STR of unwrapped loaves decreased as PWC increased (Figures 9-11, 13-15). This result was due to the effect of PVDC wrapping. As previously discussed (Section 5.1.1), PVDC film formed a heat sink to retain heat generated by microwave energy. PVDC film also acted to prevent water from being evaporated into the air and probably condensed back into drip loss which was considered part of product weight in the present study. When beef loaves were not wrapped, not only did heat generated by microwave energy escape easily into the cool environment, but also large amounts of water were evaporated; hence the effect of PWC was diminished when beef loaves were not wrapped.

5.1.5.3 Evaporation loss

Percent evaporation loss of beef loaves was increased as PWC increased (Figure 18). The result of the effect of PWC on PEL has previously been explained in Section 5.1.4, Effect of percent fat content.

5.1.6 Effect of exposed microwave dose

Exposed microwave dose (defined as watts of output power x minutes of processing time/grams of food in Section 3.6) or EMD was adopted to determine end point of microwave processing. The results and discussion of the effect of EMD on bacterial survival, thermal responses and evaporation loss are presented below.

5.1.6.1 Bacterial survival

In this study, exposed microwave dose (EMD) was found to be highly correlated to bacterial survival ($R=-0.82$ to -0.83) and had potential to be used to better describe the percent survival of *E. coli*, *S. aureus* and aerobic bacteria. The result of the ANOVA indicated that the main effect of EMD on bacterial survival was significant ($p \leq 0.0001$; Appendix 2) for beef loaves. Analyses showed that percent survival of three types of bacteria decreased consistently as EMD increased. The differences of percent survival of all three types of bacteria among four EMDs used in this study were significant ($p \leq 0.05$; Table 11 and Figures 6-8). No published research related to EMD has been located.

Based on results of this study, one solution to the problem of temperature measurement (Section 3.3.3) is use of EMD as a safety target for more precise quality control of microwave processed foods. Since EMD is highly correlated to EPT ($R=0.81$) as well as to percent survival of bacteria ($R=-0.82$ to -0.83), it could

Table 11. The main effect of exposed microwave dose (EMD) on bacterial survival, thermal responses and evaporation loss of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).

Subst	EMD (W x min/g)	Sample size (n)	Mean of									
			LEC	LSA	LAB	EPT	MPTR	STR	PPTR	TPPTR	PEL	
Beef (10, 20 and 30% fat)	3.57	72	1.711 ^{AB}	1.719 ^A	1.723 ^A	45.3 ^D	29.0 ^D	39.3 ^D	10.3 ^B	486.2 ^{AB}	0.77 ^D	
	4.75	72	0.905 ^B	1.009 ^B	0.963 ^B	57.7 ^C	39.5 ^C	52.0 ^C	12.6 ^A	519.0 ^A	1.81 ^C	
	5.94	72	0.196 ^C	0.245 ^C	0.221 ^C	67.2 ^B	49.7 ^B	61.7 ^B	12.0 ^{AB}	491.9 ^{AB}	3.46 ^B	
	7.13	72	0.010 ^D	0.012 ^D	0.009 ^D	75.5 ^A	58.1 ^A	69.5 ^A	11.5 ^{AB}	444.3 ^B	5.58 ^A	
Beef (10% fat) & Turkey (10% fat)	3.57	48	1.752 ^A	1.697 ^A	1.736 ^A	42.9 ^D	27.7 ^D	38.9 ^D	11.2 ^B	441.5 ^{B,C}	0.73 ^D	
	4.75	48	1.090 ^B	1.072 ^B	1.076 ^B	53.7 ^C	36.5 ^C	50.1 ^C	13.8 ^A	503.3 ^A	1.78 ^C	
	5.94	48	0.459 ^C	0.434 ^C	0.470 ^C	63.0 ^B	45.6 ^B	60.2 ^B	14.5 ^A	481.9 ^{AB}	3.37 ^B	
	7.13	48	0.024 ^D	0.027 ^D	0.028 ^D	71.3 ^A	55.0 ^A	67.7 ^A	12.7 ^{AB}	409.2 ^C	5.15 ^A	
Turkey (10% fat)	3.57	24	1.805 ^A	1.764 ^A	1.792 ^A	41.9 ^D	27.7 ^D	40.0 ^D	12.2 ^B	408.2 ^{AB}	0.64 ^D	
	4.75	24	1.120 ^B	1.111 ^B	1.109 ^B	50.5 ^C	35.2 ^C	48.9 ^C	13.7 ^{AB}	463.9 ^A	1.65 ^C	
	5.94	24	0.501 ^C	0.443 ^C	0.545 ^C	60.1 ^B	42.7 ^B	59.1 ^B	16.4 ^A	447.5 ^A	3.06 ^B	
	7.13	24	0.019 ^D	0.020 ^D	0.031 ^D	67.4 ^A	52.1 ^A	65.9 ^A	13.7 ^{AB}	377.0 ^B	4.82 ^A	
Beef (10% fat), Turkey (10% fat) & BGB (10% glycerol)	3.57	18	1.930 ^A	1.874 ^A	1.905 ^A	37.3 ^D	24.8 ^D	34.1 ^D	9.3 ^A	325.4 ^A	1.44 ^D	
	4.75	18	1.566 ^B	1.578 ^B	1.547 ^B	48.0 ^C	34.6 ^C	45.6 ^C	11.1 ^A	378.1 ^A	2.80 ^C	
	5.94	18	0.844 ^C	0.809 ^C	0.793 ^C	55.0 ^B	40.6 ^B	51.5 ^B	10.9 ^A	357.0 ^A	4.48 ^B	
	7.13	18	0.061 ^D	0.095 ^D	0.074 ^D	64.2 ^A	49.5 ^A	60.9 ^A	11.4 ^A	332.7 ^A	6.25 ^A	
BGB (150 g)	3.57	12	1.965 ^A	1.919 ^A	1.965 ^A	38.0 ^D	27.4 ^D	33.4 ^D	6.04 ^A	78.1 ^{AB}	2.17 ^D	
	4.75	12	1.663 ^B	1.566 ^B	1.647 ^B	44.5 ^C	33.6 ^C	39.5 ^C	5.79 ^A	84.0 ^A	3.15 ^C	
	5.94	12	0.306 ^C	0.394 ^C	0.332 ^C	57.0 ^B	46.1 ^B	51.6 ^B	5.50 ^A	62.3 ^{B,C}	4.97 ^B	
	7.13	12	0.0001 ^D	0.001 ^D	0.0002 ^D	62.3 ^A	52.1 ^A	57.7 ^A	5.59 ^A	49.5 ^C	6.93 ^A	

Key:

BGB = bacteris-glycerol-BHI broth.

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

Footnote:

^a Average over polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP) and percent fat content (PFC) for the subset of beef (10, 20 and 30% fat), average over polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP) for the subsets of beef (10% fat), turkey (10% fat) and beef (10% fat) & turkey (10% fat) & BGB (10% glycerol); average over percent fat content (PFC) for the subset of BGB (150 g).

^b Means with the same letter in the same cell are not significantly different ($p > 0.05$ by Tukey's test).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec).

PEL = percent evaporation loss (%).

be used to predict bacterial survival in beef loaf that had been processed by microwave radiation.

5.1.6.2 Thermal responses

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on thermal responses was significant ($p \leq 0.01$; Appendix 2). Analyses showed that end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) increased consistently as EMD increased. The differences of EPT, MPTR, and STR among four EMDs (3.57, 4.75, 5.94, and 7.13 watt x min/g) used in this study were significant ($p \leq 0.05$; Table 11 and Figures 9-15).

The effects of EMD on post processing temperature rise (PPTR) and time of PPTR (TPPTR) were irregular. PPTR and TPPTR increased as EMD increased from 3.57 watt x min/g to 4.75 watt x min/g and then PPTR and TPPTR decreased as EMD continued to increase. The only significant difference ($p \leq 0.05$) in PPTR was between 3.57 watt x min/g and 4.75 watt x min/g of EMDs (Table 11 and Figure 16). The only significant difference ($p \leq 0.05$) on TPPTR was between 4.75 watt x min/g and 7.13 watt x min/g of EMDs (Table 11 and Figure 17). The irregular effect of EMD on PPTR and TPPTR suggested that EMD was not as important as other variables (PW and LS) that could improve PPTR and TPPTR significantly.

24519922

MICHIGAN STATE UNIVERSITY LIBRARIES



3 1293 00572 8484

LIBRARY
Michigan State
University

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.

DATE DUE DATE DUE DATE DUE		
1 0 0 6 0 2 SEP 26 2002	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____

MSU Is An Affirmative Action/Equal Opportunity Institution

**MICROWAVE PROCESSING: BACTERIAL SURVIVAL,
THERMAL RESPONSES, EVAPORATION LOSS AND HEATING PATTERN
OF MEAT LOAVES AND
SIMULATED BENTONITE-GLYCEROL-BHI BROTH LOAF**

Volume II

By

Wen-Syi Lin

A DISSERTATION

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

DOCTOR OF PHILOSOPHY

Department of Food Science and Human Nutrition

1989

5.1.6.3 Evaporation loss

The result of the ANOVA indicated that the main effect of EMD on percent evaporation loss was significant ($p \leq 0.0001$; Appendix 2). Analyses showed that PEL consistently increased as EMD increased. The differences of PEL among four EMDs (3.57, 4.75, 5.94, and 7.13 watt x min./g) used in this study were significant ($p \leq 0.05$; Table 11 and Figure 18).

5.1.6.4 Summary

The results of EMD on bacterial survival, thermal responses and percent evaporation loss were due to heat generated by microwave energy. When beef loaves were exposed to a higher dose of microwave energy, more heat was generated; decreased bacterial survival, and higher temperature and evaporation loss would be expected.

The results of bacterial survival, thermal responses (except PPTR and TPTR) and percent evaporation loss in beef loaves after exposure to varied EMD indicated that EMD could be used to predict bacterial survival, thermal responses such as EPT, MPTR and STR and percent evaporation loss. Therefore, EMD is recommended in place of target temperature (EPT) as a predictor of microbial quality in foods that have been microwave processed (approval of Ho9; Section 3.6).

Ideally, if a standard EMD is calculated for microbial safety and applied to individual food products, improved control over microbial quality of foods could

theoretically be achieved on the condition that load size and microwave output power have no significant effect on bacterial survival.

Since this study showed that load size and microwave output power did affect bacterial survival, these two variables must be taken into account when a standard EMD calculated. Safety precautions must be taken to include an allowable safety range that cover a reasonable and likely range of load sizes and the expected range of microwave output powers.

5.2 Turkey Loaves

The data subset for 96 turkey loaves (10% fat) processed for this study were statistically analyzed. Results of the ANOVA showed that significant main effects and possible interactions of independent variables on bacterial survival, thermal responses and percent evaporation loss existed (Appendix 3). The results and discussion of the main effect of PVDC wrapping, load size, microwave output power and exposed microwave dose on bacterial survival, thermal responses and evaporation loss of microwave processed turkey loaves are presented below.

5.2.1 Effect of PVDC wrapping

The objective of wrapping turkey loaves with PVDC film was to determine how PVDC wrapping (PW) affected bacterial survival, thermal responses and evaporation loss of turkey loaves. The results and discussion of the effect of PVDC

wrapping (PW) on bacterial survival, thermal responses and evaporation loss are presented below.

5.2.1.1 Bacterial survival

The result of the ANOVA indicated the main effect of PVDC wrapping (PW) on bacterial survival was significant ($p \leq 0.0001$; Appendix 3) for turkey loaves. The predicted percent survival of *E. coli*, *S. aureus* and aerobic bacteria after microwave processing, derived from multiple regression analyses, are shown in Figures 19-21. Percent survival of three types of bacteria were significantly lower ($p \leq 0.05$) in turkey loaves that had been wrapped in PVDC film than in loaves that had not been wrapped (Table 7 and Figures 19-21:A vs. B). None of three types of bacteria survived in turkey loaves that had been wrapped in PVDC film after exposing them to the highest microwave dose (7.13 watt x min./g; Figures 19-21:A). The effect of PW on bacterial survival of turkey loaves was identical to that of beef loaves and similar to the results of Alcixio et al (1985). When turkey loaves were wrapped with PVDC film, decreased percent survival of bacteria were also observed (Table 7; approval of Ho5; Section 3.5.1.1).

5.2.1.2 Thermal responses

The result of the ANOVA indicated the main effect of PVDC wrapping (PW) on thermal responses (except microwave processing temperature rise; MPTR) was significant ($p \leq 0.0001$; Appendix 3). The predicted response surface of thermal

Figure 19. Predicted response surface of surviving *Escherichia coli** in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).

Fig. 19-A: PW= 1.

Fig. 19-B: PW=-1.

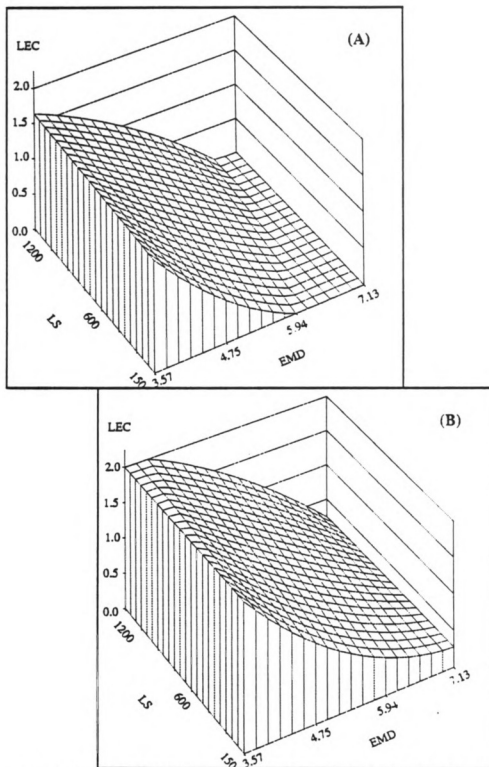
Footnotes:

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.80$, $C_p=6.03$):

$$\begin{aligned} \text{LEC} = & 7.08792691 - 0.25556647 \cdot \text{PW} \\ & - 2.02554027 \cdot \text{EMD} \\ & + 0.14518044 \cdot \text{EMD}^2 \\ & - 0.003964713 \cdot \text{LS} \\ & + 0.001753941 \cdot \text{EMD} \cdot \text{LS} \\ & - 0.000168349 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$

153a



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.
 LS = LOAD SIZE (G).
 LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

Figure 19.

Figure 20. Predicted response surface of surviving *Staphylococcus aureus*^a in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).

Fig. 20-A: PW= 1.

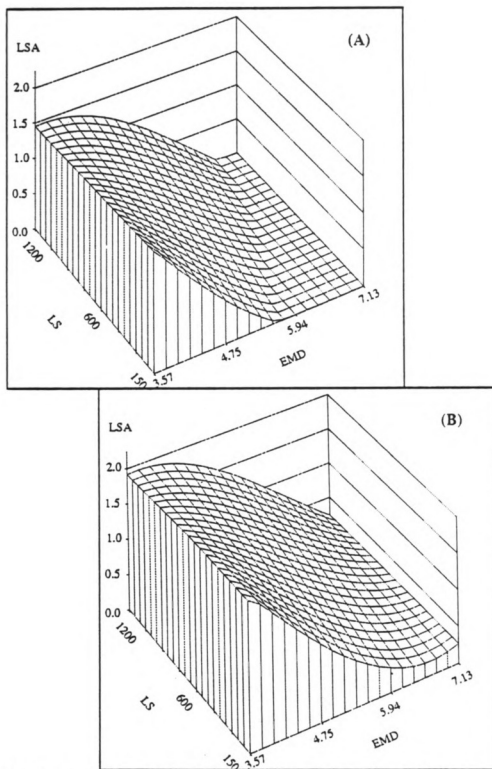
Fig. 20-B: PW=-1.

Footnotes:

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.81$, $C_p=6.98$):

$$\begin{aligned} \text{LSA} = & 4.41898976 - 0.23387088 \cdot \text{PW} \\ & - 0.31825965 \cdot \text{EMD}^2 \\ & + 0.03252045 \cdot \text{EMD}^3 \\ & - 0.006650666 \cdot \text{LS} \\ & + 0.002723858 \cdot \text{EMD} \cdot \text{LS} \\ & - 0.000251357 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.
 LS = LOAD SIZE (G).
 LSA = LOG VALUE OF (% SURVIVING *Staphylococcus aureus*+1).

Figure 20.

Figure 21. Predicted response surface of surviving aerobic bacteria* in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz).

Fig. 21-A: PW= 1.

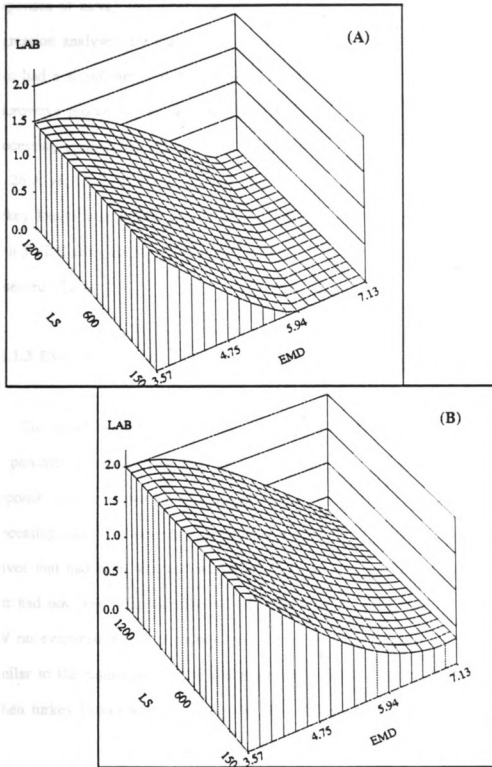
Fig. 21-B: PW=-1.

Footnotes:

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

*** Plotted from multiple regression equation ($R^2=0.78$, $C_p=6.04$):**

$$\begin{aligned} \text{LAB} = & 3.86944961 - 0.28351960 \cdot \text{PW} \\ & - 0.25233915 \cdot \text{EMD}^2 \\ & + 0.02490103 \cdot \text{EMD}^3 \\ & - 0.004704181 \cdot \text{LS} \\ & + 0.001968012 \cdot \text{EMD} \cdot \text{LS} \\ & - 0.000184185 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.
 LS = LOAD SIZE (G).
 LAB = LOG VALUE OF (% SURVIVING AEROBIC BACTERIA+1).
 Figure 21.

responses of turkey loaf after microwave processing, derived from multiple regression analyses, are shown in Figures 22-26. Turkey loaves wrapped with PVDC film had a significantly ($p \leq 0.05$) higher end-point temperature rise (EPT), microwave processing temperature rise (MPTR), sum of temperature rise (STR), post processing temperature rise (PPTR) and time of PPTR (TPPTR; Table 7 and Figures 22-26:A vs. C, B vs. D). In general, the effect of PW on thermal responses of turkey loaves was similar to that of beef loaves. When turkey loaves were wrapped with PVDC film, higher EPT, MPTR, STR, PPTR and prolonged TPPTR were observed (Table 7).

5.2.1.3 Evaporation loss

The result of the ANOVA indicated the main effect of PVDC wrapping (PW) on percent evaporation loss was significant ($p \leq 0.0001$; Appendix 3). The predicted response surface of percent evaporation loss of turkey loaf after microwave processing, derived from multiple regression analysis is shown in Figure 27. Turkey loaves that had been wrapped with PVDC film had lower PEL than turkey loaves that had not been wrapped (Table 7 and Figure 27:A vs.B, C vs. D). The effect of PW on evaporation loss of turkey loaves was identical to that of beef loaves and similar to the results of Ruyack and Paul (1972) and Sawyer and Biglari (1984). When turkey loaves were wrapped with PVDC film, less PEL was observed (Table 7).

Figure 22. Predicted response surface of end-point temperature^a in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 22-A: PW= 1, MP=100.

Fig. 22-B: PW= 1, MP= 50.

Fig. 22-C: PW=-1, MP=100.

Fig. 22-D: PW=-1, MP= 50.

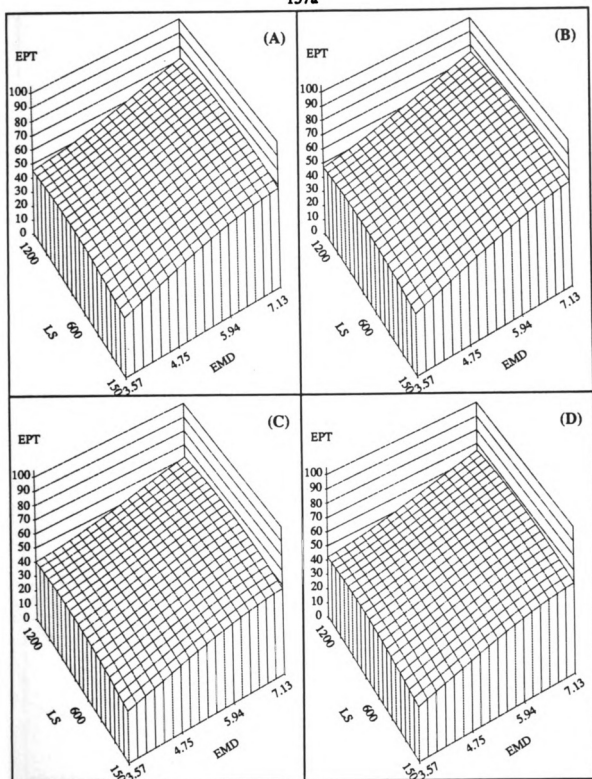
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.90$, $C_p=9.67$):

$$\begin{aligned} \text{EPT} = & 11.25361045 + 2.90353974 \cdot \text{EMD}^2 \\ & - 0.25445763 \cdot \text{EMD}^3 \\ & + 0.06720646 \cdot \text{LS} \\ & - 0.000015716 \cdot \text{LS}^2 \\ & + 0.69901986 \cdot \text{PW} \cdot \text{EMD} \\ & - 0.01012338 \cdot \text{MP} \cdot \text{EMD} \\ & - 0.01657992 \cdot \text{EMD} \cdot \text{LS} \\ & + 0.001481435 \cdot \text{EMD}^2 \cdot \text{LS}; \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

LS = LOAD SIZE (G).

EPT = END-POINT TEMPERATURE (°C).

Figure 22.

Figure 23. Predicted response surface of microwave processing temperature rise^a in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 23-A: PW= 1, MP=100.

Fig. 23-B: PW= 1, MP= 50.

Fig. 23-C: PW=-1, MP=100.

Fig. 23-D: PW=-1, MP= 50.

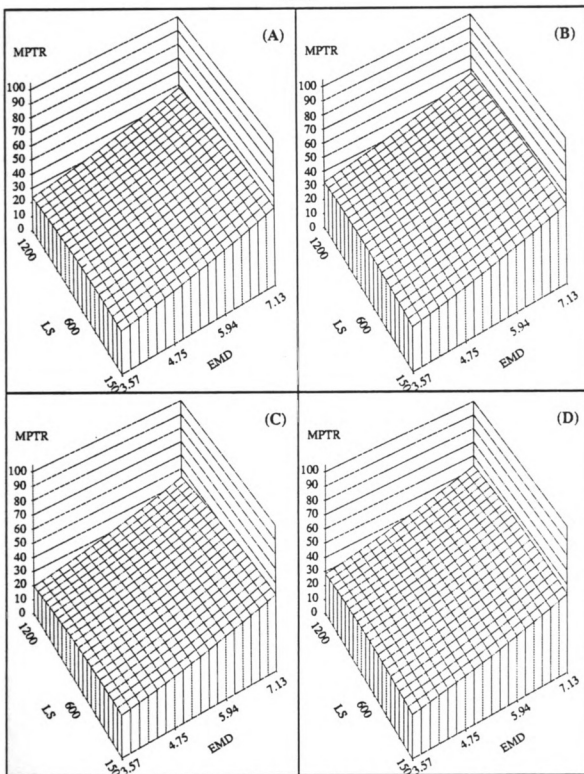
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.81$, $C_p=5.98$):

$$\begin{aligned} \text{MPTR} = & 19.52225194 + 0.63272245 \cdot \text{EMD}^2 \\ & + 0.02106944 \cdot \text{LS} \\ & - 0.000147593 \cdot \text{MP} \cdot \text{LS} \\ & - 0.0000094907 \cdot \text{LS}^2 \\ & + 0.001618827 \cdot \text{PW} \cdot \text{LS} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

LS = LOAD SIZE (G).

MPTR = MICROWAVE PROCESSING TEMPERATURE RISE (°C).

Figure 23.

Figure 24. Predicted response surface of sum of temperature rise^a in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 24-A: PW= 1, MP=100.

Fig. 24-B: PW= 1, MP= 50.

Fig. 24-C: PW=-1, MP=100.

Fig. 24-D: PW=-1, MP= 50.

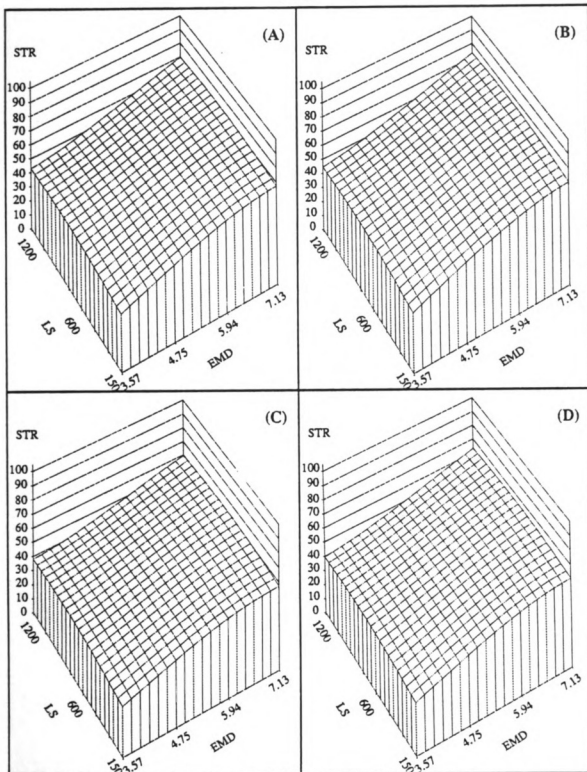
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1) = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.87$, $C_p=8.51$):

$$\begin{aligned} \text{STR} = & 7.93457554 + 3.37766277 \cdot \text{EMD}^2 \\ & - 0.31135163 \cdot \text{EMD}^3 \\ & + 0.06835293 \cdot \text{LS} \\ & - 0.000010549 \cdot \text{LS}^3 \\ & - 0.009369298 \cdot \text{MP} \cdot \text{EMD} \\ & + 0.69274112 \cdot \text{PW} \cdot \text{EMD} \\ & - 0.02067524 \cdot \text{EMD} \cdot \text{LS} \\ & + 0.001874949 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

LS = LOAD SIZE (G).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

Figure 24.

Figure 25. Predicted response surface of post processing temperature rise* in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 25-A: PW= 1, MP=100.

Fig. 25-B: PW= 1, MP= 50.

Fig. 25-C: PW=-1, MP=100.

Fig. 25-D: PW=-1, MP= 50.

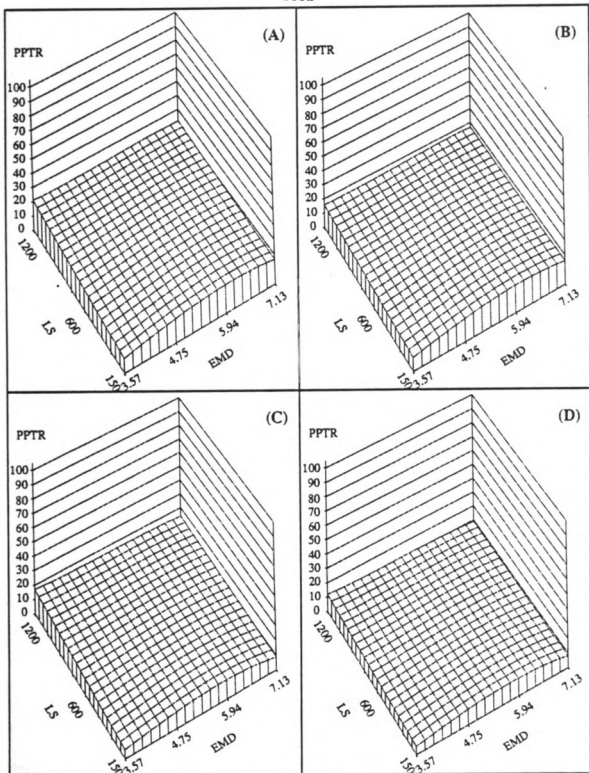
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.50$, $C_p=7.52$):

$$\begin{aligned} \text{PPTR} = & -10.22079347 + 2.20300724 \cdot \text{EMD}^2 \\ & - 0.24717213 \cdot \text{EMD}^3 \\ & + 0.04662721 \cdot \text{LS} \\ & + 0.000084362 \cdot \text{MP} \cdot \text{LS} \\ & + 0.54225513 \cdot \text{PW} \cdot \text{EMD} \\ & - 0.01801230 \cdot \text{EMD} \cdot \text{LS} \\ & + 0.001535834 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

LS = LOAD SIZE (G).

PPTR = POST PROCESSING TEMPERATURE RISE (°C).

Figure 25.

Figure 26. Predicted response surface of time of post processing temperature rise^a in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 26-A: PW= 1, MP=100.

Fig. 26-B: PW= 1, MP= 50.

Fig. 26-C: PW=-1, MP=100.

Fig. 26-D: PW=-1, MP= 50.

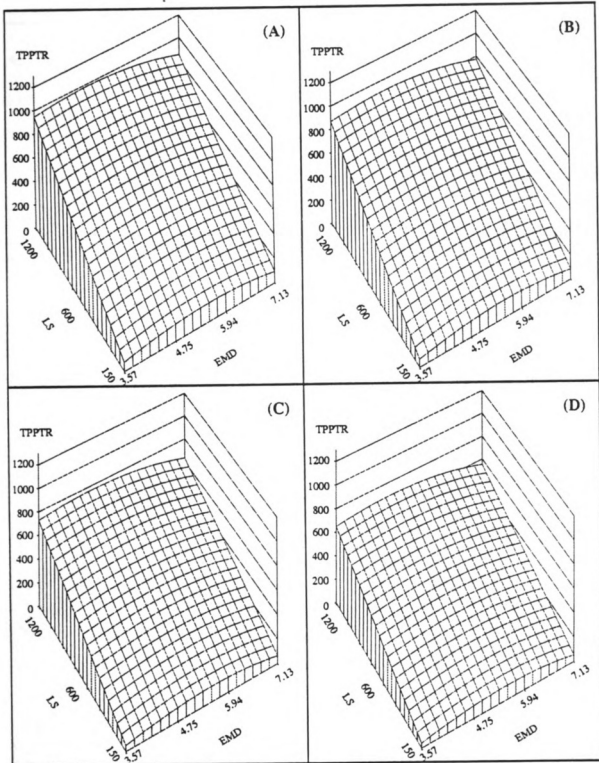
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film, -1 = not wrapped.

^a Plotted from multiple regression equation ($R^2=0.93$, $C_p=8.29$):

$$\begin{aligned} \text{TPPTR} = & -430.27178 + 122.96761 \cdot \text{EMD} \\ & - 1.27114633 \cdot \text{EMD}^3 \\ & + 0.64520417 \cdot \text{LS} \\ & + 0.09094650 \cdot \text{PW} \cdot \text{LS} \\ & + 0.001295267 \cdot \text{MP} \cdot \text{LS} \\ & - 0.002804514 \cdot \text{EMD}^2 \cdot \text{LS} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

LS = LOAD SIZE (G).

TPPTR = TIME OF POST PROCESSING TEMPERATURE RISE (SEC).

Figure 26.

Figure 27. Predicted response surface of percent evaporation loss* in turkey loaf wrapped or not wrapped in polyvinylidene chloride (PVDC) film after microwave processing (2450 MHz) at 100% and 50% output power.

Fig. 27-A: PW= 1, MP=100.

Fig. 27-B: PW= 1, MP= 50.

Fig. 27-C: PW=-1, MP=100.

Fig. 27-D: PW=-1, MP= 50.

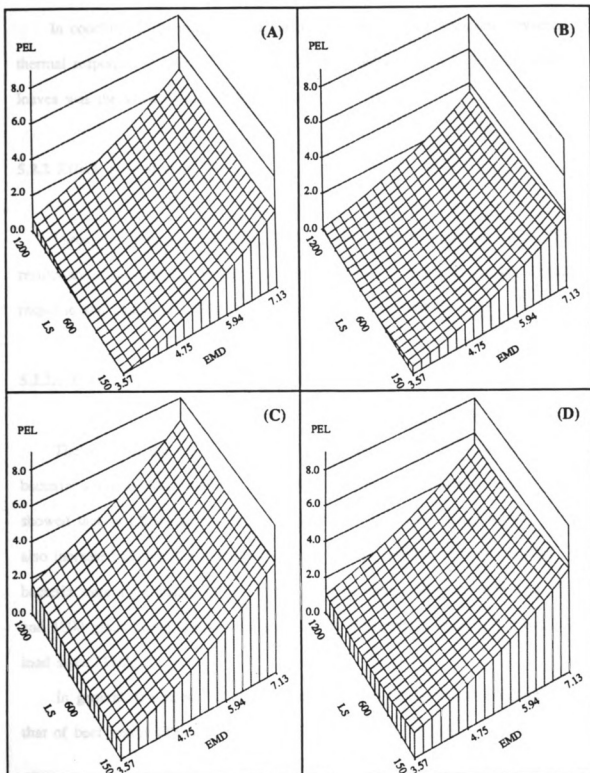
Footnotes:

MP, 100 = 100% output power (713 ± 5 W); 50 = 50% output power (356 ± 3 W).

PW, 1 = wrapped in PVDC film, -1 = not wrapped.

* Plotted from multiple regression equation ($R^2=0.96$, $C_p=9.31$):

$$\begin{aligned} \text{PPL} = & 1.21383538 + 0.009706844 \cdot \text{EMD}^3 \\ & - 0.002561175 \cdot \text{LS} \\ & + 9.55853\text{E-}07 \cdot \text{LS}^2 \\ & - 0.02628480 \cdot \text{MP} \\ & + 0.004129582 \cdot \text{MP} \cdot \text{EMD} \\ & + 0.000019868 \cdot \text{MP} \cdot \text{LS} \\ & - 0.12955005 \cdot \text{PW} \cdot \text{EMD} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

LS = LOAD SIZE (G).

PEL = PERCENT EVAPORATION LOSS (%).

Figure 27.

In conclusion, the effect of WP on bacterial survival ($\downarrow$ bacterial survival), thermal responses ($\uparrow$ thermal responses) and evaporation loss ($\downarrow$ PEL) of turkey loaves was the same as that of beef loaves (Table 7).

5.2.2 Effect of load size

Three load sizes (150, 600 and 1200 g) were used in the present study. The results and discussion of the effect of load size (LS) on bacterial survival, thermal response and evaporation of turkey loaves are presented below.

5.2.2.1 Bacterial survival

The result of the ANOVA indicated the main effect of load size (LS) on bacterial survival was significant ($p \leq 0.01$; Appendix 3) for turkey loaves. Analyses showed that as LS increased, the survival of *E. coli*, *S. aureus* and aerobic bacteria also increased (Table 8 and Figures 19-21). Percent survival of three types of bacteria were significantly different ($p \leq 0.05$) between 150 g and 600 g or 150 g and 1200 g load sizes, but was not significantly different between 600 g and 1200 g load sizes (Table 8).

In general, the effect LS on bacterial survival of turkey loaves was similar to that of beef loaves (Table 8; approval of Ho7; Section 3.5.1.3).

5.2.2.2 Thermal responses

The result of the ANOVA indicated that the main effect of load size (LS) on thermal responses of turkey loaves was significant ($p \leq 0.05$; Appendix 3). Analyses showed that as LS increased from 150 g to 600 g load size, end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) of turkey loaves increased, then decreased as LS increased to 1200 g load size. (Table 8 and Figures 22-24). Unlike the result of beef loaves, the EPT, MPTR and STR decreased as LS increased, these different thermal responses could not be explained by a comparison of thermal or dielectric properties of turkey and beef. Since beef and turkey have the similar thermal and dielectric properties (Table 1), the reason for different thermal responses on varied LS of turkey loaves needs to be further investigated. On the other hand, post processing temperature rise (PPTR) and time of PPTR (TPPTR) increased as LS increased (same responses as beef loaves did). However, differences among results for PPTR were not significant between 150 g and 600 g load sizes and 600 g and 1200 g load sizes but was significant ($p \leq 0.05$) between 150 g and 1200 g load sizes (Table 8 and Figures 25-26).

5.2.2.3 Evaporation loss

The result of the ANOVA indicated the main effect of LS on percent evaporation loss was significant ($p \leq 0.0001$). Analysis showed that 600 g load size of turkey loaf had the lowest PEL among three load sizes (similar to that of beef loaves). There was no significant difference in PEL between 150 g and 600 g load

sizes (Table 8 and Figure 27). The effect of LS on PEL of turkey loaves was the same as that of beef loaves (Table 8).

In conclusion, the effect of LS on bacterial survival ($\downarrow$ LS= $\downarrow$ bacterial survival) and evaporation loss ($\uparrow$ LS to 600g= $\downarrow$ PEL, then $\uparrow$ PEL as $\uparrow$ LS to 1200 g) was the same regardless of types of meat. The effect of LS on thermal responses was somewhat different between beef loaves and turkey loaves (Section 5.2.2.2).

5.2.3 Effect of microwave output power

Two levels of microwave output power (100% vs 50%) were used in the present study. The results and discussion of the effect of microwave output power (MP) on bacterial survival, thermal response and evaporation of turkey loaves are presented below.

5.2.3.1 Bacterial survival

The result of the ANOVA indicated that the main effect of microwave output power (MP) on bacterial survival was not significant ($p > 0.05$; Appendix 3) for turkey loaves. Analyses confirmed that percent survival of three types of bacteria in turkey loaves that had been processed at 100% output power and 50% output power, although decreased at 50% output power, was not significantly different (Table 9). The effect of MP on bacterial survival was more intensive in beef loaves than in turkey loaves. This was probably due to some unknown thermal properties

that reduced the effect of MP in turkey loaves. Further investigation is needed to answer this question.

5.2.3.2 Thermal responses

The result of the ANOVA indicated that the main effect of microwave output power (MP) on thermal responses was significant ($p \leq 0.05$; Appendix 3). Analyses showed that turkey loaves that had been processed at 50% output power had higher end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR), but lower post processing temperature rise (PPTR) and time of PPTR (TPPTR) than turkey loaves that had been processed at 100% output power (Table 9 and Figures 22-26:A vs. B, C vs. D). The effect of MP on thermal responses of turkey loaves was similar to that of beef loaves (Table 9).

5.2.3.3 Evaporation loss

The result of the ANOVA indicated that the main effect of MP on percent evaporation loss (PEL) was significant ($p \leq 0.0001$). Analysis showed that turkey loaves that had been microwave processed at 50% output power had lower PEL than turkey loaves that had been microwave processed at 100% output power (Table 9 and Figure 27:A vs. B, C vs. D). The effect of MP on PEL of turkey loaves was the same as that of beef loaves (Table 9) and the results of Sawyer (1985)

In conclusion, the effect of MP on bacterial survival ($\downarrow$ MP= $\downarrow$ bacterial survival) of turkey loaves was less effective than that of beef loaves. The effect of

MP on thermal responses ($\downarrow$ MP= $\uparrow$ EPT, MPTR, STR; $\downarrow$ PPTR, TPPTR) and evaporation loss ($\uparrow$ MP= $\downarrow$ PEL) of turkey loaves was similar to that of beef loaves (Table 9).

5.2.4 Effect of exposed microwave dose

Four exposed microwave doses (3.57, 4.75, 5.94 and 7.13 watt x min/g) were used in the present study. The results and discussion of the effect of exposed microwave dose (EMD) on bacterial survival, thermal response and evaporation of turkey loaves are presented below.

5.2.4.1 Bacterial survival

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on bacterial survival was significant ($p \leq 0.0001$; Appendix 3) for turkey loaves. Analyses showed that percent survival of three types of bacteria decreased as EMD increased. The differences of percent survival of all three types of bacteria among four EMDs used in this study were significant ($p \leq 0.05$; Table 11 and Figures 19-21). The effect of EMD on bacterial survival of turkey loaves was the same as that of beef loaves (Table 11; approval of Ho9; Section 3.6).

5.2.4.2 Thermal responses

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on thermal responses was significant ($p \leq 0.05$; Appendix 3). Analyses showed that end-point temperature rise (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) increased consistently as EMD increased. The differences of EPT, MPTR and STR among four EMDs used in this study were significant ($p \leq 0.05$; Table 11 and Figures 22-24). The effect of EMD on post processing temperature rise (PPTR) and time of PPTR (TPPTR) were irregular. PPTR increased to the maximum as EMD increased from 3.57 to 5.94 watt x min/g then decreased as EMD increased to 7.13 watt x min/g. TPPTR increased to the maximum as EMD increased from 3.57 to 4.75 watt x min/g then decreased as EMD continued to increase. The only significant difference on PPTR was between 3.57 and 5.94 watt x min/g of EMDs (Table 11 and Figure 25). As for TPPTR, significant differences on TPPTR were found between 4.75 and 7.13 watt x min/g of EMDs as well as 5.94 and 7.13 watt x min/g of EMDs (Table 11 and Figure 26). The irregular effect of EMD on PPTR and TPPTR suggested that EMD was not as important as other variables (PW and LS) that could improve PPTR and TPPTR significantly.

5.2.4.3 Evaporation loss

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on percent evaporation loss (PEL) was significant ($p \leq 0.0001$;

Appendix 3). Analysis showed that PEL consistently increased as EMD increased. The differences of PEL among four EMDs used in this study were significant ($p \leq 0.05$; Table 11 and Figure 27). The effect of EMD on PEL of turkey loaves was identical to that of beef loaves.

In conclusion, the effect of EMD on bacterial survival ($\uparrow$ EMD= $\downarrow$ bacterial survival), thermal responses ($\uparrow$ EMD= $\uparrow$ EPT, MPTR, STR) and evaporation loss ($\uparrow$ EMD= $\downarrow$ PEL) was the same as that of beef loaves (Table 11).

5.3 BGB Loaves

Bentonite-glycerol-BHI (BGB) loaf was tested as a possible simulation model for beef loaf and turkey loaf. Data on BGB loaves for bacterial survival, thermal responses and evaporation loss of meat loaves after microwave processing were collected. The data subset for 48 BGB loaves (150 g load size) were statistically analyzed using SAS GLM procedures. Sixty-four (64) BGB loaves, including 600 g and 1200 g load sizes, were used for multiple regression analysis. The results of the ANOVA showed that significant main effects and possible interactions of independent variables on bacterial survival, thermal responses and percent evaporation loss existed (Appendix 4). The detailed results and discussion of the main effect of percent glycerol content and exposed microwave dose on bacterial survival, thermal responses and evaporation loss of microwave processed BGB loaves are presented below.

5.3.1 Effect of percent glycerol content

No research has been reported which evaluated the effect of percent glycerol content (PFC; equivalent to PFC in beef loaves and turkey loaves) on bacterial survival, thermal responses and evaporation loss of microwave processed BGB loaves. The results and discussion of the effect of PFC on bacterial survival, thermal responses and evaporation loss are presented below.

5.3.1.1 Bacterial survival

The result of the ANOVA indicated the main effect of percent glycerol content (PFC) on bacterial survival was significant ($p \leq 0.0001$; Appendix 4) for BGB loaves (150 g load size). The predicted survival curves for *E. coli*, *S. aureus* and aerobic bacteria after microwave processing, derived from multiple regression analyses, are shown in Figure 28.

Analysis showed that as PFC increased from 10% to 20%, percent survival of three types of bacteria decreased. As PFC increased from 20% to 30%, percent survival of three types of bacteria increased. The differences of percent survival of *E. coli* and aerobic bacteria among three levels of PFC were significant ($p \leq 0.05$). The difference of percent survival of *S. aureus* between BGB loaves with 10% and 20% PFC was not significant ($p > 0.05$) but was significant between BGB loaves with 10% and 30% as well as 20% and 30% PFC. Among three levels of PFC, BGB loaves with 30% PFC had highest percent survival for all three types of bacteria.

Figure 28. Predicted response surface of surviving bacteria* in 150 g load size of unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).

Fig. 28-A: *Escherichia coli*.

Fig. 28-B: *Staphylococcus aureus*.

Fig. 28-C: Aerobic bacteria.

Footnotes:

LS= load size in gram.

* Plotted from multiple regression equations:

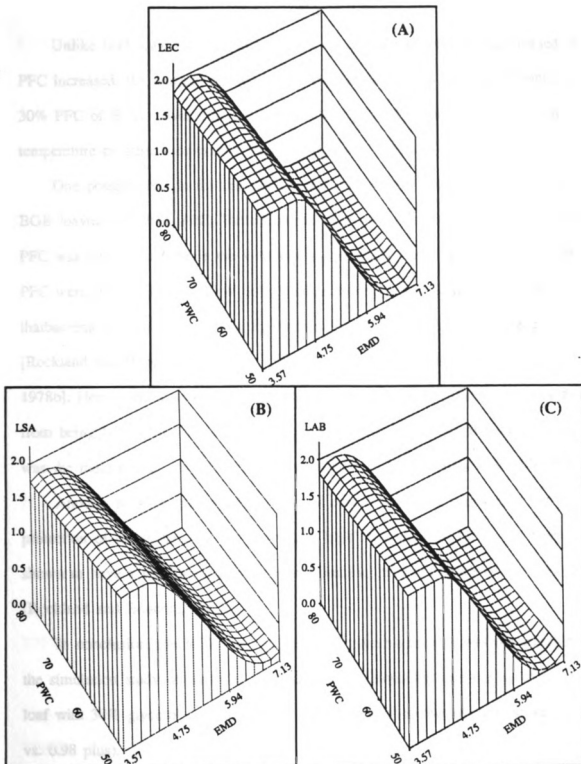
$$\begin{aligned} \text{LEC} = & -8.56558915 + 15.65295254 \cdot \text{EMD} \\ & - 3.13861005 \cdot \text{EMD}^2 \\ & + 0.19522391 \cdot \text{EMD}^3 \\ & - 0.09138736 \cdot \text{LS} \\ & - 0.0000015795 \cdot \text{LS}^2 \\ & - 0.19616798 \cdot \text{PWC} \\ & + 0.001256166 \cdot \text{LS} \cdot \text{PWC} \quad (R^2=0.94, C_p=7.13) \end{aligned}$$

$$\begin{aligned} \text{LSA} = & -15.62647552 + 11.45142613 \cdot \text{EMD} \\ & - 2.29658854 \cdot \text{EMD}^2 \\ & + 0.14144531 \cdot \text{EMD}^3 \\ & - 8.16069\text{E-}07 \cdot \text{LS}^2 \\ & - 0.01090045 \cdot \text{PWC} \\ & + 0.000018114 \cdot \text{LS} \cdot \text{PWC} \quad (R^2=0.93, C_p=9.78) \end{aligned}$$

$$\begin{aligned} \text{LAB} = & -8.83567547 + 14.88148372 \cdot \text{EMD} \\ & - 2.98171128 \cdot \text{EMD}^2 \\ & + 0.18507944 \cdot \text{EMD}^3 \\ & - 0.08138472 \cdot \text{LS} \\ & - 0.0000014841 \cdot \text{LS}^2 \\ & - 0.17628146 \cdot \text{PWC} \\ & + 0.001120539 \cdot \text{LS} \cdot \text{PWC} \quad (R^2=0.94, C_p=7.51) \end{aligned}$$

LSA = L
PWC = L
LEC = L
LSA = L
LAB = L

171a



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

LSA = LOG VALUE OF (% SURVIVING *Staphylococcus aureus*+1).

LAB = LOG VALUE OF (% SURVIVING AEROBIC BACTERIA+1).

Figure 28.

Unlike beef loaves whose percent survival of bacteria tended to decreased as PFC increased, the unusual phenomena of the higher percent survival of bacteria in 30% PFC of BGB loaves could not be solely explained by products' end-point temperature or other temperature factors (see Table 10).

One possible reason for this phenomena was the low water activity (a_w) in BGB loaves with 30% PFC. The measured value of a_w for BGB loaves with 30% PFC was 0.90 ± 0.03 while the values of a_w for BGB loaves with 10% and 20% PFC were 0.97 ± 0.04 and 0.94 ± 0.02 respectively. It was well established that bacteria survive better in low a_w environment than high a_w environment [Rockland and Beuchat, 1987; Jay, 1986; ICMSF, 1980; Troller and Christian, 1978b]. Hence, the lower a_w of BGB loaves with 30% PFC might protect bacteria from being killed after microwave processing. It was very likely that the low a_w was the main reason why bacteria survived better in BGB loaves with 30% PFC.

Another possible reason which was not observed in beef loaves was the protection of fat on bacteria [Jay, 1986]. A high fat content in foods had been shown to have a significant influence on increasing heat resistance of bacteria [Rockland and Beuchat, 1987].

In conclusion, the BGB loaf with 30% of glycerol content was not suitable for the simulation study of bacterial survival in meat loaves because the a_w of BGB loaf with 30% glycerol content was too low compared to that of meat loaves (0.90 vs. 0.98 plus).

53.

resp

(p <

BGE

are

point

with

micro

of P

with

BGE

10%

How

leav

TPP

resp

TPP

10).

MPT

them

5.3.1.2 Thermal responses

The result of the ANOVA indicated that the main effect of PFC on thermal responses (except time of post processing temperature rise; TPPTR) was significant ($p \leq 0.005$; Appendix 4). The predicted response surface of thermal responses of BGB loaves after microwave processing, derived from multiple regression analyses, are shown in Figures 29-33.

Analyses showed that BGB loaves with 20% PFC had significantly higher end-point temperature (EPT) and sum of temperature rise (STR) than did BGB loaves with 10 and 30% PFC (Table 10). BGB loaves with 20% PFC had the highest microwave processing temperature rise (MPTR) among BGB loaves with three levels of PFC. Although there was no significant difference in MPTR between BGB loaves with 20 and 30% PFC, the difference in MPTR was significant ($p \leq 0.05$) between BGB loaves with 10 and 20% as well as 10 and 30% (Table 10). BGB loaves with 10% PFC had the highest PPTR among BGB loaves with three levels of PFC. However, the only significant difference ($p \leq 0.05$) on PPTR was between BGB loaves with 10 and 30% PFC (Table 10). There was no significant difference on TPPTR among BGB loaves with three levels of PFC.

In general, the effect of PFC on thermal responses ($\uparrow$ PFC to 20% = $\uparrow$ thermal responses, except PPTR and TPPTR; then $\downarrow$ thermal responses, except PPTR and TPPTR as $\uparrow$ PFC to 30%) of BGB loaves was the same as for beef loaves (Table 10). The possible reason why BGB loaves with 20% PFC had the highest EPT, MPTR, STR, and TPPTR was discussed in Section 5.1.4.2. The effect of PFC on thermal responses of BGB loaves was the combined result of PFC and PWC.

Figure 29. Predicted response surface of end-point temperature^a in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).

Fig. 29-A: LS=150.

Fig. 29-B: LS=600.

Fig. 29-C: LS=1200.

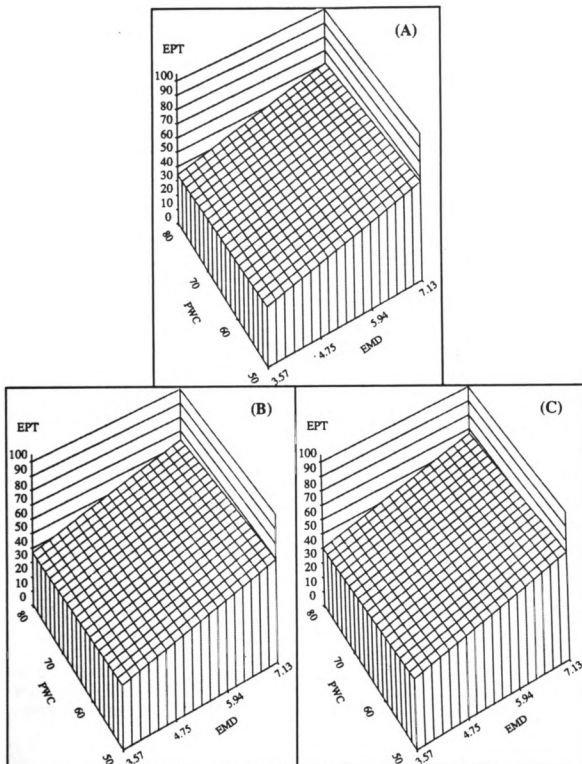
Footnotes:

LS= load size in gram.

^a Plotted from multiple regression equations ($R^2=0.84$, $C_p=3.05$):

$$\begin{aligned} \text{EPT} = & 23.15206206 + 7.45180749 \cdot \text{EMD} \\ & + 0.005580810 \cdot \text{LS} \\ & - 0.20565062 \cdot \text{PWC} \end{aligned}$$

174a



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

EPT = END-POINT TEMPERATURE (°C).

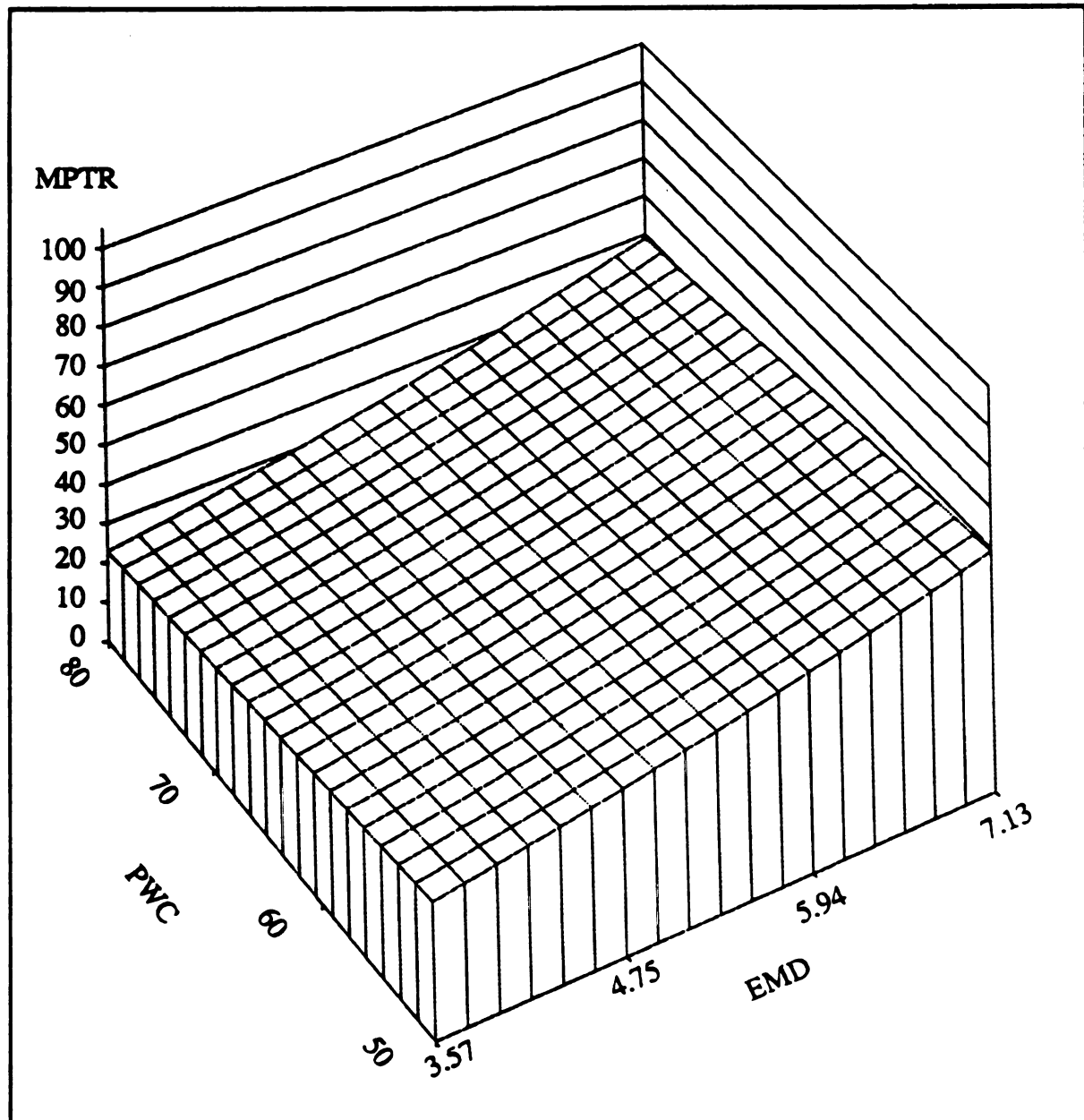
Figure 29.

Figure 30. Predicted response surface of microwave processing temperature rise* in unwrapped 150 load size of bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).

Footnotes:

* Plotted from multiple regression equations ($R^2=0.78$, $C_p=2.76$):

$$\begin{aligned} \text{MPTR} = & 41.74449937 + 0.67554333 \cdot \text{EMD}^2 \\ & - 0.34350877 \cdot \text{PWC} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

MPTR = MICROWAVE PROCESSING TEMPERATURE RISE (°C).

Figure 30.

Figure 31. Predicted response surface of sum of temperature rise* in unwrapped bentonite-glycerol-BHI broth (BGB) loaf without wrapping after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).

Fig. 31-A: LS=150.

Fig. 31-B: LS=600.

Fig. 31-C: LS=1200.

Footnotes:

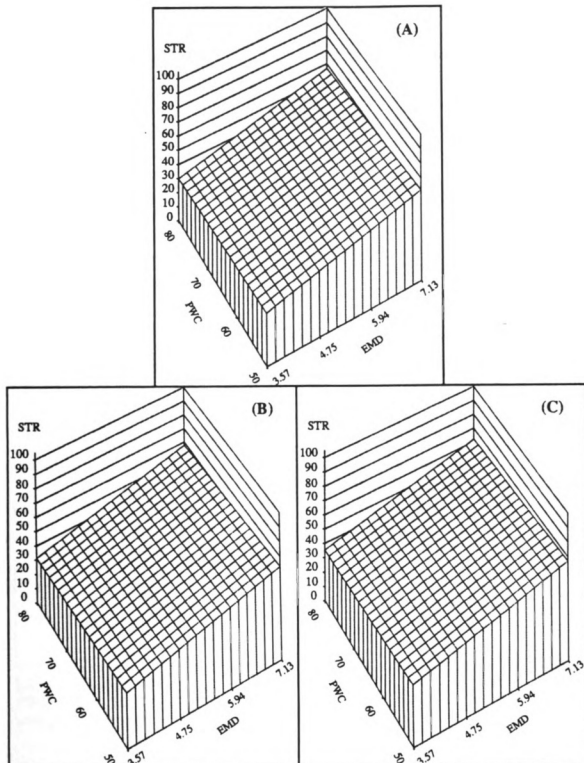
LS= load size in gram.

* Plotted from multiple regression equations ($R^2=0.83$, $C_p=1.80$):

$$\begin{aligned} \text{STR} = & 17.40465753 + 7.40484582 \cdot \text{EMD} \\ & - 0.17396030 \cdot \text{PWC} \\ & + 0.00000379155 \cdot \text{LS}^2 \end{aligned}$$

S
100
90
80
70
60
50
40
30
20
10
0
%

EMD
PWC
STR



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PWC = PERCENT WATER CONTENT (%).

STR = SUM OF TEMPERATURE RISE OR MPTR+PPTR (°C).

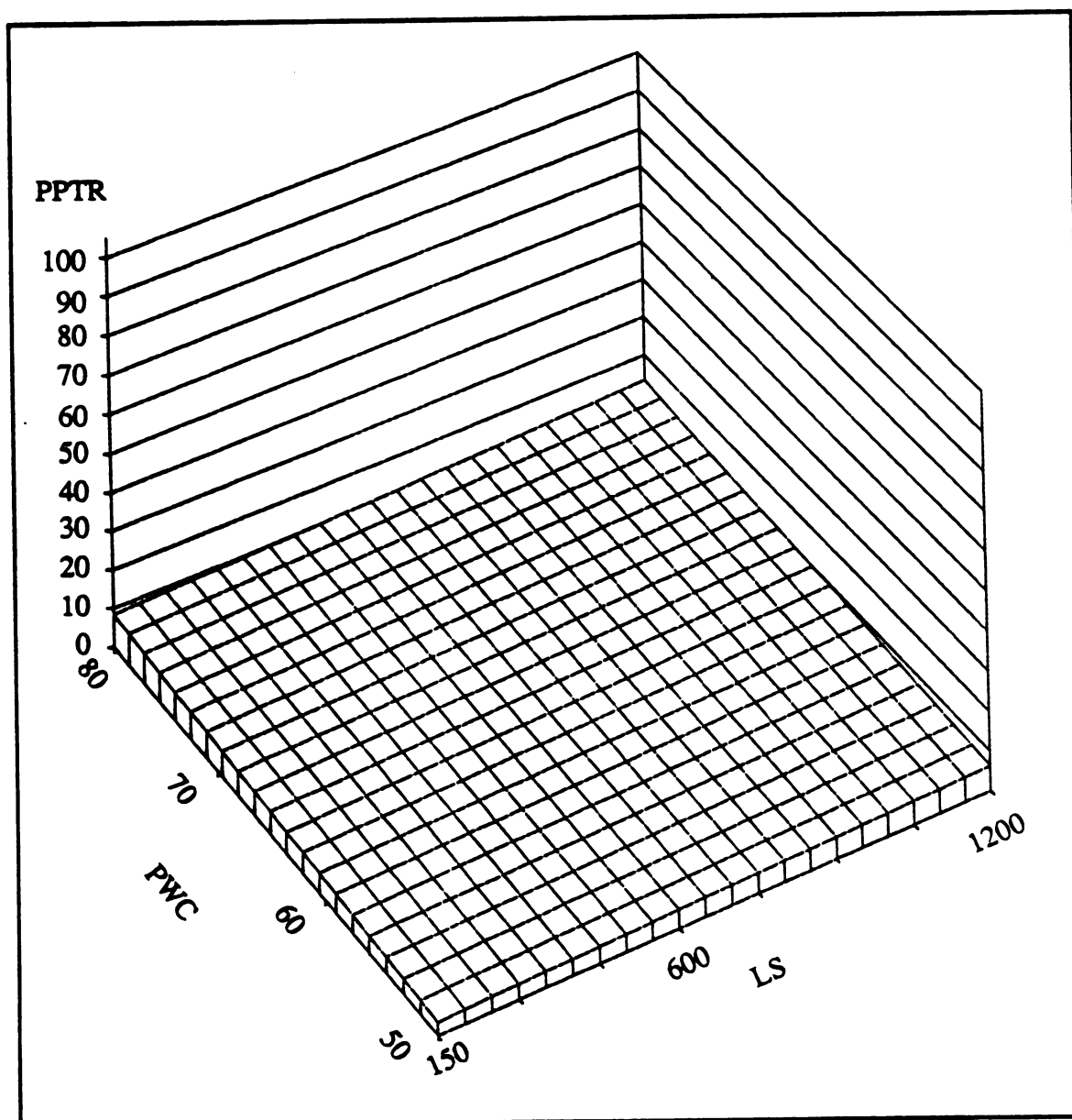
Figure 31.

Figure 32. Predicted response surface of post processing temperature rise* in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).

Footnotes:

* Plotted from multiple regression equations ($R^2=0.39$, $C_p=1.72$):

$$\begin{aligned} \text{PPTR} = & -5.29940017 + 0.16289145 \cdot \text{PWC} \\ & + 0.000058752 \cdot \text{LS} \cdot \text{PWC} \end{aligned}$$



LS = LOAD SIZE (G).

PWC = PERCENT WATER CONTENT (%).

PPTR = POST PROCESSING TEMPERATURE RISE (°C).

Figure 32.

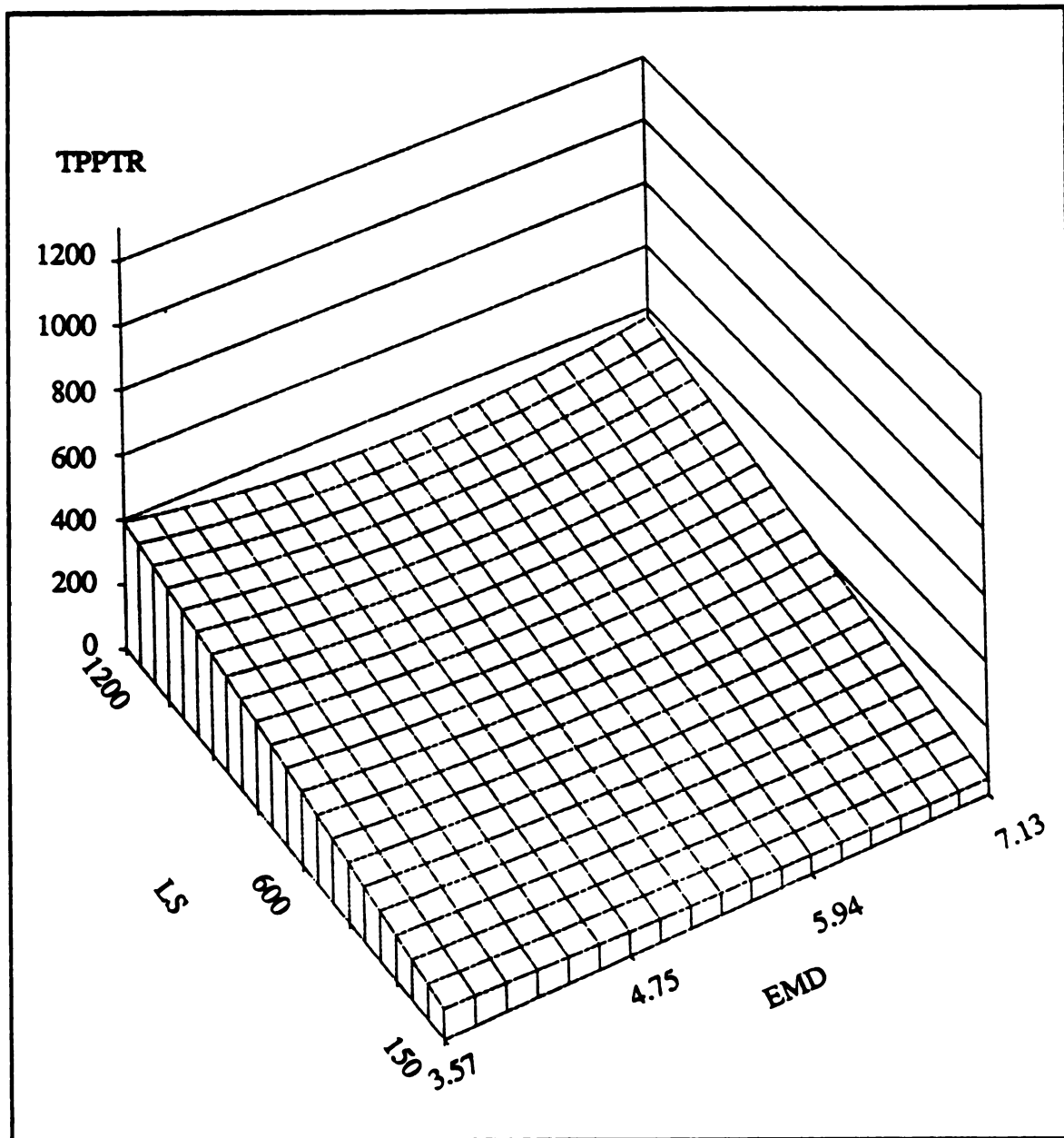
Figure 33. Predicted response surface of time of post processing temperature rise* in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).

Footnotes:

* Plotted from multiple regression equations ($R^2=0.86$, $C_p=5.14$):

$$\begin{aligned} \text{TPPTR} = & 61.97130498 - 1.17779936 * \text{EMD}^2 \\ & + 0.77022802 * \text{LS} \\ & - 0.20538993 * \text{EMD} * \text{LS} \\ & + 0.01966963 * \text{EMD}^2 * \text{LS} \end{aligned}$$

178a



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.
LS = LOAD SIZE (G).
TPPTR = TIME OF POST PROCESSING TEMPERATURE RISE (SEC).

Figure 33.

5.3.1.3 Evaporation loss

The result of the ANOVA indicated that the main effect of percent glycerol content (PFC) on percent evaporation loss (PEL) was significant ($p \leq 0.0005$; Appendix 4). The predicted response surface of PEL of BGB loaves after microwave processing, derived from multiple regression analyses, is shown in Figure 34. Analysis showed that BGB loaves with 10% PFC had the highest PEL. PEL decreased as PFC increased. There was a significant difference ($p \leq 0.05$) in PEL between BGB loaves with 10% and 20% PFC as well as 10% and 30% PFC, but had no significant difference in PEL between BGB loaves with 20% and 30% PFC (Table 10).

In general, the effect of PFC on evaporation of BGB loaves was similar to that of beef loaves (Table 10). The possible reason why PEL of BGB loaves decreased as PFC increased was discussed in Section 5.1.4.3. The PEL was related to the amount of water in the BGB loaves.

In conclusion, the effect of PFC on bacterial survival of BGB loaves was different from that of beef loaves. The reason was the low a_w in BGB loaf with 30% glycerol content. The effect of PFC on thermal responses ($\uparrow$ PFC to 20% = $\uparrow$ thermal responses, except PPTR and TPPTTR; then $\downarrow$ thermal responses, except PPTR and TPPTTR as $\uparrow$ PFC to 30%) and evaporation loss ($\uparrow$ PFC = $\downarrow$ PEL) was similar to that of beef loaves.

Figure 34. Predicted response surface of percent evaporation loss* in unwrapped bentonite-glycerol-BHI broth (BGB) loaf after microwave processing (2450 MHz) at 100% output power (713 ± 5 W).

Fig. 34-A: LS=150.

Fig. 34-B: LS=600.

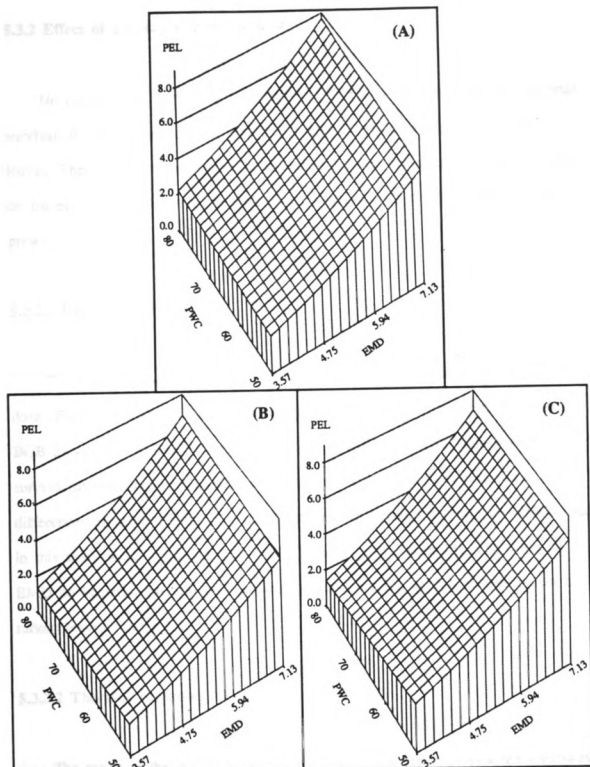
Fig. 34-C: LS=1200.

Footnotes:

LS= load size in gram.

*** Plotted from multiple regression equations ($R^2=0.95$, $C_p=4.09$):**

$$\begin{aligned} \text{PPL} = & 0.91041427 + 0.05017020 \cdot \text{EMD}^2 \\ & + 0.00000202497 \cdot \text{LS}^2 \\ & - 0.000044074 \cdot \text{LS} \cdot \text{PWC} \\ & + 0.001143891 \cdot \text{EMD}^2 \cdot \text{PWC} \end{aligned}$$



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.
 PWC = PERCENT WATER CONTENT (%).
 PEL = PERCENT EVAPORATION LOSS (%).

Figure 34.

5.3.2 Effect of exposed microwave dose

No research has been done to study the effect of microwave dose on bacterial survival, thermal responses and evaporation loss of microwave processed BGB loaves. The results and discussion of the effect of exposed microwave dose (EMD) on bacterial survival, thermal responses and evaporation loss of BGB loaves are presented below.

5.3.2.1 Bacterial survival

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on bacterial survival was significant ($p \leq 0.0001$; Appendix 4) for BGB loaves (150 g load size; Section 3.5.1.3). Analyses showed that percent survival of three types of bacteria consistently decreased as EMD increased. The differences of percent survival of all three types of bacteria among four EMDs used in this study were significant ($p \leq 0.05$; Table 11 and Figure 28). The effect of EMD on bacterial survival of BGB loaves was the same as that of beef loaves and turkey loaves (Table 11).

5.3.2.2 Thermal responses

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on thermal responses (except post processing temperature rise; PPTR) was significant ($p \leq 0.0001$; Appendix 4). Analyses showed that end-point

temperature rise (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) increased consistently as EMD increased. The differences of EPT, MPTR and STR among four EMDs used in this study were significant ($p \leq 0.05$; Table 11 and Figures 29-31).

There was no significant difference in PPTR among four EMDs. Time of PPTR (TPPTR) of BGB loaves increased to the maximum as EMD increased from 3.57 to 4.75 watt x min/g, then decreased as EMD continued to increase. Significant difference in TPPTR of BGB loaves was observed between loaves which were exposed to 3.57 watt x min/g and 7.13 watt x min/g as well as 4.75 and 7.13 watt x min/g microwave doses (Table 11 and Figure 33).

In conclusion, the effect of EMD on EPT, MPTR and STR of BGB loaves ($\uparrow \text{EMD} = \uparrow \text{EPT, MPTR and STR}$) was the same as that of beef loaves and turkey loaves. The effect of EMD on PPTR and TPPTR of BGB loaves (irregular) was similar to that of beef loaves and turkey loaves (Table 11).

5.3.2.3 Evaporation loss

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on percent evaporation loss (PEL) was significant ($p \leq 0.0001$; Appendix 4). Analysis showed that PEL consistently increased as EMD increased. The differences of PEL among four EMDs used in this study were significant ($p \leq 0.05$; Table 11 and Figure 39). The effect of EMD on PEL was identical to that of beef loaves and turkey loaves (Table 11).

In conclusion, the effect of EMD on bacterial survival ($\uparrow$ EMD= $\downarrow$ bacterial survival), thermal responses ($\uparrow$ EMD= $\uparrow$ thermal responses, except PPTR and TPPTR) and evaporation loss ($\uparrow$ EMD= $\uparrow$ PEL) of BGB loaves was similar to that of beef loaves.

5.4 Beef Loaves versus Turkey Loaves

The data subset for 96 beef loaves (10% fat) and 96 turkey loaves (10% fat) were statistically analyzed to compare bacterial survival, thermal responses and evaporation loss between two types of meat loaf. The results of the ANOVA showed that significant main effects and possible interactions of independent variables on bacterial survival, thermal responses and percent evaporation loss existed (Appendix 5).

The detailed results and discussion of type of loaf, PVDC wrapping, load size, microwave output power and exposed microwave dose on bacterial survival, thermal responses and evaporation loss of beef loaves and turkey loaves are presented below.

5.4.1 Effect of type of loaf

Although many types of meat products have been used to study microbial survival of varied species of bacteria after microwave processing [Rosenberg and Bögl, 1988; Fung and Cunningham, 1980], no research has been done to compare bacterial survival directly among types of meat. The results and discussion of the

comparison of bacterial survival, thermal responses and evaporation loss between beef loaves and turkey loaves are presented below.

5.4.1.1 Bacterial survival

The result of the ANOVA indicated that the main effect of type of loaf (TL) on bacterial survival was not significant ($p > 0.05$; Appendix 5) for the data subset for beef loaves (10% fat) and turkey loaves (10% fat). Analyses confirmed that when all other conditions were constant, there was no significant difference ($p > 0.05$) in percent survival of all three types of bacteria between beef loaves and turkey loaves (Table 12; approval of Ho1, Section 3.2.1.1).

In conclusion, the similar bacterial survival between beef loaves and turkey loaves suggested that food products which contained similar major meat components of similar thermal and dielectric properties (contain the same major composition such as fat, moisture and/or formulated from the same recipe) might be categorized as one item for the purpose of microwave processing studies on microbial quality.

5.4.1.2 Thermal responses

The result of the ANOVA indicated that the main effect of type of loaf (TL) on thermal responses was significant ($P \leq 0.05$; Appendix 5). Analyses showed that beef loaves had higher end-point temperature (EPT), microwave processing temperature rise (MPTR), sum of temperature rise (STR), post processing temperature rise (PPTR) and longer time of PPTR (TPPTR) than that of turkey

Table 12. The main effect of type of loaf (TL) on bacterial survival, thermal responses and evaporation loss of loaves (beef, turkey and BGB) with 10% fat after microwave processing (2450 MHz).

Subject	TL	Sample size (n)	Mean [*] of									
			LEC	LSA	LAB	EPT	MPTR	STR	PPTR	TPPTR	PEL	
Beef (10% fat) & Turkey (10% fat)	1	96	0.861 ^{A#}	0.835 ^A	0.869 ^A	60.4 ^A	42.9 ^A	55.0 ^A	12.1 ^B	493.8 ^A	2.97 ^A	
	2	96	0.801 ^A	0.780 ^A	0.786 ^A	55.0 ^B	39.5 ^B	53.5 ^B	14.0 ^A	424.1 ^B	2.54 ^B	
Beef (10% fat), Turkey (10% fat) & BGB (10% glycerol)	1	24	1.107 ^A	1.082 ^A	1.076 ^A	53.4 ^A	39.1 ^A	49.2 ^A	10.2 ^A	446.4 ^A	3.71 ^B	
	2	24	1.175 ^A	1.089 ^A	1.134 ^A	49.3 ^B	36.8 ^A	48.8 ^{A,B}	12.0 ^A	396.4 ^B	3.42 ^C	
	3	24	1.019 ^A	1.096 ^A	1.029 ^A	50.8 ^{A,B}	36.2 ^A	46.1 ^B	9.9 ^A	202.1 ^C	4.11 ^A	

Key:

BGB = bentonite-glycerol-BHI broth.

TL(1) = beef, TL(2) = turkey, TL(3) = BGB.

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec).

PEL = percent evaporation loss (%).

Footnote:

* Average over polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP) and exposed microwave dose (EMD) for the subset of beef (10% fat) & turkey (10% fat); average over load size (LS) and exposed microwave dose (EMD) for the subset of beef (10% fat) & turkey (10% fat) & BGB (10% glycerol).

Means with the same letter in the same cell are not significantly different ($p > 0.05$ by Tukey's test).

loaves. The difference of EPT, MPTR, STR, PPTR and TPPTR between beef loaves and turkey loaves was significant ($p \leq 0.05$; Table 12). The significant but rather small difference in thermal responses between beef loaves and turkey loaves was due to the similar but different dielectric and thermal properties between beef loaves and turkey loaves (Table 1).

Similar bacterial survival but significant different thermal responses were found between beef loaves (10% fat) and turkey loaves (10% fat). The reason for the similarity in bacterial survival was probably the small difference (1.5 °C) in STR between beef loaves and turkey loaves (Table 12). The differences in thermal responses were probably not large enough to affect bacterial survival.

5.4.1.3 Evaporation loss

The result of the ANOVA indicated that the main effect of type of loaf (TL) on percent evaporation loss (PEL) was significant ($p \leq 0.0001$). Analysis showed that beef loaves had higher PEL than turkey loaves. The difference of PEL between beef loaves and turkey loaves was significant ($p \leq 0.05$; Table 12). It is known that water-holding capacity (the ability of a matrix of molecules, such as proteins, to entrap large amounts of water in such a manner that exudation of water is prevented) and cooking loss (drip loss plus evaporation loss) are inversely correlated [Trout and Schmidt, 1987]. In other words, foods which have a high water-holding capacity will have lower evaporation loss. The higher PEL in beef loaves after microwave processing was most likely due to their lower water-holding capacity.

In conclusion, the bacterial survival was similar between beef loaves and turkey loaves when loaves were processed under the same conditions. The thermal responses and evaporation of turkey loaves were different from that of beef loaves.

5.4.2 Effect of PVDC wrapping

The effect of PVDC wrapping (PW) on bacterial survival, thermal responses and evaporation loss of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) are presented below. The results of this data subset were compared to other data subsets such as beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat).

5.4.2.1 Bacterial survival

The result of the ANOVA indicated that the main effect of PVDC wrapping (PW) on bacterial survival was significant ($p \leq 0.0001$; Appendix 5) for beef loaves and turkey loaves with 10% fat. Analyses showed that percent survival of three types of bacteria were significantly lower ($p \leq 0.05$) in loaves that had been wrapped in PVDC film than in loaves that had not been wrapped (Table 7).

In general, the effect of PW on bacterial survival of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) were the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat) (Table 7).

5.4.2.2 Thermal responses

The result of the ANOVA indicated that the main effect of PVDC wrapping (PW) on thermal responses was significant ($p \leq 0.0002$; Appendix 5). Analyses showed that loaves wrapped with PVDC film had significantly higher end-point temperature (EPT), microwave processing temperature rise (MPTR), sum of temperature rise (STR), post processing temperature rise (PPTR) and longer time of PPTR (TPPTR) than loaves that had not been wrapped ($p \leq 0.05$; Table 7).

In general, the effect of PW on thermal responses of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) were the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat) (Table 7).

5.4.2.3 Evaporation loss

The result of the ANOVA indicated that the main effect of PVDC wrapping (PW) on percent evaporation loss was significant ($p \leq 0.0001$; Appendix 5). Analysis showed that loaves wrapped in PVDC film had significantly lower percent evaporation loss (PEL) than loaves that had not been wrapped ($p \leq 0.05$; Table 7). The effect of PW on PEL of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) were the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat) (Table 7).

In conclusion, the effect of PW on bacterial survival ($\downarrow$ bacterial), thermal responses ($\uparrow$ thermal responses) and evaporation loss ($\downarrow$ PEL) was the same regardless of the types of meat loaf with varied percent of fat content.

5.4.3 Effect of load size

Three load sizes (150, 600 and 1200 g) were used in the present study for beef loaves and turkey loaves with 10% fat. The effect of load size (LS) on bacterial survival, thermal responses and evaporation of beef loaves and turkey loaves with 10% fat are presented below.

5.4.3.1 Bacterial survival

The result of the ANOVA indicated that the main effect of load size (LS) on bacterial survival was significant ($p \leq 0.0001$; Appendix 5) for beef loaves and turkey loaves with 10% fat. Analyses showed that as LS increased, the percent survival of three types of bacteria increased (Table 8). Percent survival of three types of bacteria were significantly different ($p \leq 0.05$) between the 150 g and 600 g load sizes as well as between the 150 g and 1200 g load sizes for beef loaves and turkey loaves with 10% fat. The difference of percent survival of three types of bacteria between 600 g and 1200 g load sizes of loaves was not significant. The effect of LS on bacterial survival of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) were similar to that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat) (Table 8).

5.4.3.2 Thermal responses

The result of the ANOVA indicated the main effect of LS on thermal responses of the data subset for beef loaves (10% fat) and turkey (10% fat) was significant ($p \leq 0.0001$; Appendix 5). Analyses showed that as LS increased, end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) decreased. On the other hand, post processing temperature rise (PPTR) and time of PPTR (TPPTR) increased as LS increased (Table 8). MPTR and TPPTR were significantly different among three load sizes. As for EPT and STR, significant differences were found between the 150 g and 600 g load sizes as well as the 600 g and 1200 g load sizes of loaves (Table 8).

Significant differences ($p \leq 0.05$) of PPTR were the found between the 150 g and 600 g load sizes as well as between the 150 g and 1200 load sizes of the data subset of beef loaves (10% fat) and turkey loaves (10% fat) (Table 8). In general, The effect of LS on thermal responses ($\uparrow$ LS= $\uparrow$ EPT, MPTR and STR) of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) were similar to that of the data subset for beef loaves (10, 20 and 30% fat), but were different from that of the data subset for turkey loaves (10% fat) (Table 8).

5.4.3.3 Evaporation loss

The result of the ANOVA indicated the main effect of LS on percent evaporation loss (PEL) was significant ($p \leq 0.0001$; Appendix 5). Analysis showed that the 600 g load size of the data subset for beef loaves (10% fat) and turkey

loaves (10% fat) had the lowest PEL among three load sizes. There was no significant difference between the 150 g and 1200 g load sizes of loaves (Table 8). The effect of LS on PEL of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat) (Table 8).

5.4.4 Effect of microwave output power

Two levels of microwave output power (100% vs. 50%) were used in the present study for the data subset for beef loaves (10% fat) and turkey loaves (10% fat). The effect of microwave output power (MP) on bacterial survival, thermal responses and evaporation loss of this data subset are presented below.

5.4.4.1 Bacterial survival

The result of the ANOVA indicated that the main effect of microwave output power (MP) on bacterial survival of *E. coli* and *S. aureus* was significant ($p \leq 0.02$) for the data subset for beef loaves (10% fat) and turkey loaves (10% fat). The main effect of MP on percent survival of aerobic bacteria was not significant (Appendix 5). Analyses showed that percent survival of *E. coli* and *S. aureus* were lower in beef loaves and turkey loaves with 10% fat that had been microwave processed at 50% output power than loaves that had been microwave processed at 100% output power. There was no significant difference in percent survival of aerobic bacteria between loaves that had been processed at 100% and 50% output power (Table 9).

The effect of MP on bacterial survival (except aerobic bacteria) of beef loaves and turkey loaves with 10% fat was the same as that of data subset for beef loaves (10, 20 and 30% fat), but was different from that of the data subset for turkey loaves (10% fat).

The effect of MP on the survival of aerobic bacteria of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was the same as that of the data subset for turkey loaves (10% fat), but was different from that of the data subset for beef loaves (10, 20 and 30% fat). The result of different bacterial survival was probably related to the types of meat and the fat level. Since each batch of ground meat might have different natural aerobic bacteria flora and each batch of meat loaves were prepared by using one fat level of ground meat, the surviving aerobic bacteria were expected to be different from batches to batches.

5.4.4.2 Thermal responses

The result of the ANOVA indicated that the main effect of microwave output power (MP) on thermal responses of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was significant ($p \leq 0.002$; Appendix 5). Analyses showed that beef loaves and turkey loaves with 10% fat that had been microwave processed at 50% output power had higher end-point temperature (EPT), microwave processing temperature rise (MPTR), sum of temperature rise (STR), but lower post processing temperature rise (PPTR) and time of PPTR (TPPTR) than loaves that had been microwave processed at 100% output power (Table 9). The effect of MP on thermal

responses was the same as that of data subsets for beef loaves (10, 20 and 30% fat) and turkey (10% fat) (Table 9).

5.4.4.3 Evaporation loss

The result of the ANOVA indicated that the main effect of microwave output power (MP) on percent evaporation loss (PEL) of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was significant ($p \leq 0.0001$). Analysis showed that beef loaves and turkey loaves with 10% fat that had been microwave processed at 50% output power had lower PEL than loaves that had been microwave processed at 100% output power (Table 9). The effect of MP on PEL was the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey (10% fat).

In conclusion, the effect of MP on bacterial survival ($\downarrow$ MP= $\downarrow$ bacterial survival) of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was different from that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey (10% fat). However, the effect of MP on thermal responses ($\downarrow$ MP= $\uparrow$ EPT, MPTR, STR; $\downarrow$ PPTR and TPPTTR) and evaporation loss ($\downarrow$ MP= $\downarrow$ PEL) was the same.

5.4.5 Effect of exposed microwave dose

Four exposed microwave doses (3.57, 4.75, 5.94 and 7.13 watt x min/g) were used in the present study of the data subset for beef loaves (10% fat) and turkey

loaves (10% fat). The effect of exposed microwave dose (EMD) on bacterial survival, thermal responses and evaporation of this data subset are presented below.

5.4.5.1 Bacterial survival

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on bacterial survival was significant ($p \leq 0.0001$; Appendix 5) for the data subset for beef loaves (10% fat) and turkey loaves (10% fat). Analyses showed that percent survival of three types of bacteria consistently decreased as EMD increased. The differences of percent survival of all three types of bacteria among four EMDs used in this study were significant ($p \leq 0.05$; Table 11). The effect of EMD on bacterial survival of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey (10% fat) (Table 11).

5.4.5.2 Thermal responses

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on thermal responses of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was significant ($p \leq 0.002$; Appendix 5). Analyses showed that end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) increased consistently as EMD increased. The differences of EPT, MPTR and STR among four EMDs used in this study were significant ($p \leq 0.05$; Table 10).

loaves (10% fat). The effect of exposed microwave dose (EMD) on bacterial survival, thermal responses and evaporation of this data subset are presented below.

5.4.5.1 Bacterial survival

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on bacterial survival was significant ($p \leq 0.0001$; Appendix 5) for the data subset for beef loaves (10% fat) and turkey loaves (10% fat). Analyses showed that percent survival of three types of bacteria consistently decreased as EMD increased. The differences of percent survival of all three types of bacteria among four EMDs used in this study were significant ($p \leq 0.05$; Table 11). The effect of EMD on bacterial survival of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey (10% fat) (Table 11).

5.4.5.2 Thermal responses

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on thermal responses of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was significant ($p \leq 0.002$; Appendix 5). Analyses showed that end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) increased consistently as EMD increased. The differences of EPT, MPTR and STR among four EMDs used in this study were significant ($p \leq 0.05$; Table 10).

The effect of EMD on post processing temperature rise (PPTR) and time of PPTR (TPPTR) were irregular. PPTR increased to the maximum as EMD increased from 3.57 to 5.94 watt x min/g then decreased as EMD increased to 7.13 watt x min/g. TPPTR increased to the maximum as EMD increased from 3.57 to 4.75 watt x min/g then decreased as EMD continued to increase. Significant differences in PPTR were found between 3.57 and 4.75 watt x min/g as well as between 3.57 and 5.94 watt x min/g of EMDs (Table 11).

Significant differences in TPPTR were found between 3.57 and 4.75 watt x min/g of EMDs as well as 4.75 and 7.13 watt x min/g of EMDs (Table 11).

The effect of EMD on thermal responses of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was similar to that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey (10% fat) (Table 11).

5.4.5.3 Evaporation loss

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on percent evaporation loss (PEL) of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was significant ($p \leq 0.0001$; Appendix 5). Analysis showed that PEL consistently increased as EMD increased. The differences of PEL among four EMDs used in this study were significant ($p \leq 0.05$; Table 11). The effect of EMD on PEL of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey (10% fat) (Table 11).

In conclusion, the effect of EMD on bacterial survival ($\uparrow$ EMD= $\downarrow$ bacterial survival), thermal responses ($\uparrow$ EMD= $\uparrow$ thermal responses) and evaporation loss ($\uparrow$ EMD= $\uparrow$ PEL) of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) was the same as that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat).

5.5 Beef Loaves versus Turkey Loaves versus BGB Loaves

The data subset for 24 beef loaves (10% fat), 24 turkey loaves (10% fat) and 24 BGB loaves (10% glycerol) were statistically analyzed to compare bacterial survival, thermal responses and evaporation loss among the three types of loaf. The results of the ANOVA showed that significant main effects and possible interactions of independent variables on bacterial survival, thermal responses and percent evaporation loss existed (Appendix 6). The detailed results and discussion of effects of type of loaf, loaf size and exposed microwave dose on bacterial survival, thermal responses and evaporation loss of meat loaves with 10% fat and BGB loaves with 10% glycerol are presented below.

5.5.1 Effect of type of loaf

No research has been done to compare the bacterial survival of microwave processed BGB loaves to meat loaves. The results and discussion of the effect of type of loaf (TL) on bacterial survival, thermal responses and evaporation loss of

the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) are presented below.

5.5.1.1 Bacterial survival

The result of the ANOVA indicated that the main effect of type of loaf (TL) on bacterial survival was not significant ($p > 0.05$; Appendix 5) for the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol). Analyses confirmed the result of the ANOVA that percent survival of all three types of bacteria were not significantly different ($P > 0.05$) among beef, turkey and BGB loaves (Table 12).

In conclusion, the percent survival of three species of bacteria showed similar pattern of survival regardless of type of loaf. Hence, the BGB loaf (10% glycerol) has the potential to be a simulation model for meat loaves (10% fat) to study the bacterial survival in a microwave field (approval of Ho3; Section 3.2.1.2).

5.5.1.2 Thermal responses

The result of the ANOVA indicated that the main effect of type of loaf (TL) on thermal responses (except post processing temperature rise; PPTR) of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was significant ($P \leq 0.05$; Appendix 6). Analyses showed that beef loaf had the highest end-point temperature (EPT; 53.4 °C), microwave processing temperature rise (MPTR; 39.1 °C), sum of temperature rise (STR; 49.2 °C) and the

longest time of PPTR (TPPTR; 446.4 sec). Turkey loaf had the highest PPTR (12.0 °C) and the lowest EPT (49.3 °C). BGB loaf had the lowest MPTR (36.2 °C), STR (46.1 °C), PPTR (9.9 °C) and the shortest TPPTR (202.1 sec). The lowest PPTR and the shortest TPPTR of BGB loaf was probably due to its low thermal conductivity (Table 1). Although turkey loaf had the highest PPTR, no significant differences in PPTR were found among three types of loaf.

A significant difference in EPT was found between beef loaves and turkey loaves (mean difference=4.1 °C), but was not found between beef loaves and BGB loaves or turkey loaves and BGB loaves. A significant difference in STR was found between beef loaves and BGB loaves (mean difference=3.1 °C), but was not found between beef loaves and turkey loaves or turkey loaves and BGB loaves. There was no significant difference in MPTR and PPTR among three types of loaf. The difference of TPPTR among three types of loaf was significant ($p \leq 0.05$; Table 12).

Unklesbay et al. (1988) studied energy consumption by using bentonite-glycerol-water (20:10:70) dispersions to simulate turkey rolls during convective heating. Unklesbay et al. found that energy consumption was not significantly different ($p > 0.05$) between bentonite model and turkey rolls when products were heated to 77 °C. The results of Unklesbay et al. (1988) suggested that the thermal responses of bentonite to convective heating might be similar to that of turkey rolls. The result of the present study confirmed the finding of Unklesbay et al. (1988). Furthermore, it also suggested that the BGB loaf reacted in a similar manner in a microwave field to that of turkey loaf.

In conclusion, the thermal responses of BGB loaf were more similar to that of turkey loaf than to that of beef loaf after microwave processing because the difference in thermal responses (except TPPTR) between BGB loaf and turkey loaf were not significant (Table 12).

5.5.1.3 Evaporation loss

The result of the ANOVA indicated that the main effect of type of loaf (TL) on percent evaporation loss (PEL) was significant ($p \leq 0.0001$). Analysis showed that the BGB loaf had the highest PEL and turkey loaf had the lowest PEL among three types of loaf. The difference of PEL among three types of loaf was significant ($p \leq 0.05$; Table 12). The significant difference in PEL among three types of loaf was probably due to the varied water holding capacities among loaves.

Unklesbay et al. (1988) reported that although the processing losses of bentonite models were higher or lower than that of turkey rolls depending on the oven temperature, the amount of loss was not significantly different between bentonite and turkey. Unlike the result of Unklesbay et al. a significantly higher PEL was found in the BGB loaf compared to turkey of the present study.

The different results between the study of Unklesbay et al. (1988) and this study in processing loss of bentonite and turkey were probably due to (1) the different processing temperatures or (2) the different processing methods (microwave vs. convection). Berry and Leddy (1984) reported that substantially higher weight losses were found when beef patties were microwave processed compared to other

conventional methods. These authors suggested that choice of processing methods might influence the processing losses of foods.

In conclusion, BGB dispersions (10% glycerol) have the potential to be a simulation model for bacterial survival and thermal responses of turkey loaves (10% fat) after microwave processing because of the similarity of bacterial survival and thermal responses (except TPPTR) to turkey loaves.

5.5.2 Effect of load size

Three load sizes (150, 600 and 1200 g) were used in the present study of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol). The results and discussion of the effect of load size (LS) on bacterial survival, thermal responses and evaporation loss of this data subset are presented below.

5.5.2.1 Bacterial survival

The result of the ANOVA indicated the main effect of load size (LS) on bacterial survival was significant ($p \leq 0.0001$; Appendix 6) for the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol). Analyses showed that as LS increased, the survival of *E. coli*, *S. aureus* and aerobic bacteria also increased (Table 8). Percent survival of three types of bacteria were significantly different ($p \leq 0.05$) between the 150 g and 600 g of load sizes as well as the 150 g and 1200 g load sizes, but was not significantly different between the

600 g and 1200 g load sizes (Table 8). The effect of LS on bacterial survival of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was similar to that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat) (Table 8).

5.5.2.2 Thermal responses

The result of the ANOVA indicated that the main effect of load size (LS) on thermal responses (except end-point temperature; EPT) of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was significant ($p \leq 0.05$; Appendix 6). Analyses showed that as LS increased from 150 g to 600 g load size, EPT and sum of temperature rise (STR) increased, then decreased as LS increased to 1200 g load size. No significant difference in EPT was found among three load sizes. Although a significant difference in STR was found between the 600 g and 1200 g load sizes, no significant difference was found between the 150 g and 600 g of load sizes or between the 150 g and 1200 g of load sizes .

As LS increased, microwave processing temperature rise (MPTR) decreased significantly (Table 8). On the other hand, PPTR and time of PPTR (TPPTR) increased as LS increased. However, the difference of PPTR was not significant between the 600 g and 1200 g load sizes but was significant ($p \leq 0.05$) between the 150 g and 600 g load sizes as well as the 150 g and 600 g load (Table 8).

In general, the effect of LS on thermal responses ($\uparrow$ LS= $\uparrow$ thermal responses; except EPT and PPTR) of the data subset for beef loaves (10% fat), turkey loaves

(10% fat) and BGB loaves (10% glycerol) was similar to that of the data subsets for beef loaves (10, 20 and 30% fat) and turkey loaves (10% fat) (Table 8).

5.5.2.3 Evaporation loss

The result of the ANOVA indicated the main effect of load size (LS) on percent evaporation loss (PEL) of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was significant ($p \leq 0.0001$). Analysis showed that the 600 g load size for three types of loaf (10% fat) had the lowest PEL among three load sizes. There was no significant difference in PEL between the 150 g and 1200 g load sizes (Table 8). The effect of LS on PEL of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was the same as that of the data subset for beef loaves (10% fat) and turkey loaves (10% fat) (Table 8).

5.5.3 Effect of exposed microwave dose

Four exposed microwave doses (3.57, 4.75, 5.94 and 7.13 watt x min/g) were used in the present study of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol). The results and discussion of the effect of exposed microwave dose (EMD) on bacterial survival, thermal responses and evaporation loss of this data subset are presented below.

5.5.3.1 Bacterial survival

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on bacterial survival was significant ($p \leq 0.0001$; Appendix 6) for the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol). Analyses showed that percent survival of three types of bacteria consistently decreased as EMD increased. The differences of percent survival of all three types of bacteria among four EMDs used in this study were significant for three types of loaves ($p \leq 0.05$; Table 10). The effect of EMD on bacterial survival of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was the same as that of the data subsets for beef loaves (10, 20, 30% fat) and turkey loaves (10% fat) (Table 11).

5.5.3.2 Thermal responses

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on thermal responses (except post processing temperature rise; PPTR and time of PPTR; TPPTR) of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was significant ($p \leq 0.0001$; Appendix 6). Analyses showed that end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) increased consistently as EMD increased. The differences for EPT, MPTR and STR among four EMDs used in this study were significant ($p \leq 0.05$; Table 10). The effect of EMD on PPTR and TPPTR was not significant ($p > 0.05$; Table 10). In general, the

effect of EMD on thermal responses of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was similar to that of the data subsets for beef loaves (10, 20, 30% fat) and turkey loaves (10% fat) (Table 11).

5.5.3.3 Evaporation loss

The result of the ANOVA indicated that the main effect of exposed microwave dose (EMD) on percent evaporation loss (PEL) of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was significant ($p \leq 0.0001$; Appendix 6). Analysis showed that PEL consistently increased as EMD increased. The differences of PEL among four EMDs used in this study were significant ($p \leq 0.05$; Table 10). The effect of EMD on PEL of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was the same as that of the data subsets for beef loaves (10, 20, 30% fat) and turkey loaves (10% fat) (Table 11).

In conclusion, the effect of EMD on bacterial survival ($\uparrow$ EMD= $\downarrow$ bacterial survival), thermal responses ($\uparrow$ EMD= $\uparrow$ thermal responses; except PPTR and TPTR) and evaporation loss ($\uparrow$ EMD= $\downarrow$ PEL) of the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol) was similar to that of the data subsets for beef loaves (10, 20, 30% fat) and turkey loaves (10% fat) (Table 11).

5.6 Interactions

The data subset for 288 beef loaves (10, 20 and 30% fat) were chosen to study the effect of interactions of independent variables on bacterial survival, thermal responses and percent evaporation loss because it contained all of the independent variables (except type of loaf) used in this study. The interactions that involved type of loaf were analyzed by using the data subset for beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol).

The results of the ANOVA and multiple regression analyses indicated that interactions existed which affected bacterial survival, thermal responses, and evaporation loss (Appendix 2 and Figures 6-18). The plotted response lines of each significant two-way interaction ($p \leq 0.1$) are shown in Figures 35-39. Nonparallel response lines suggested interactions even if the lines did not cross. Three-way plus interactions were considered as experimental error statistically and were not interpreted [Gill, 1978].

5.6.1 Effect of interactions on bacterial survival

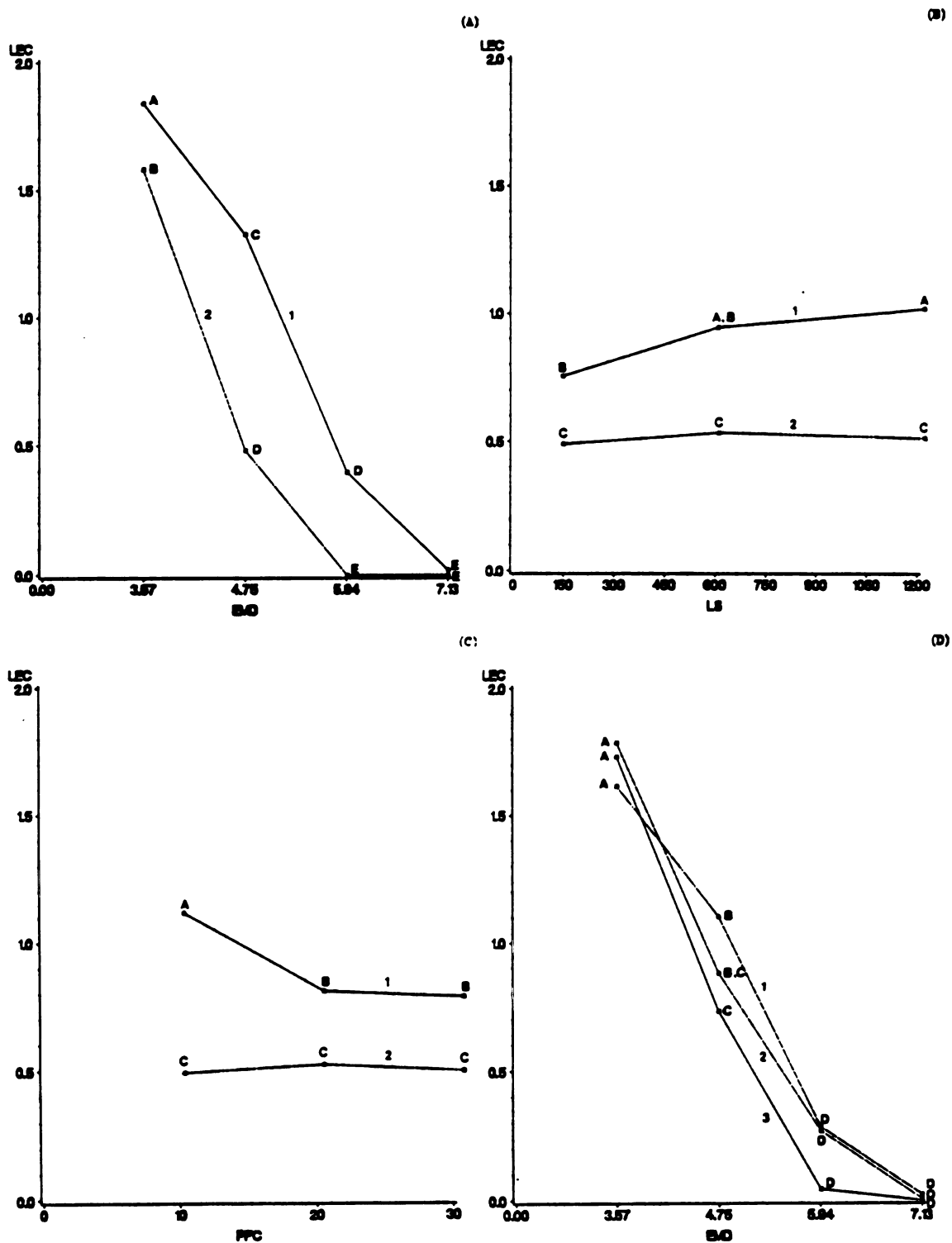
Mudgett (1982) proposed that microwave processing was the result of "mutual interactions between the product and the processing equipment". Information however, is limited on the interactions of product and processing variables related to bacterial survival in foods after microwave processing. In the present study, the two-way interactions between the product variables of PVDC film wrapping (PW), load size (LS) and percent fat content (PFC) and the processing variables of microwave

Figure 35. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean* of percent survival of *Escherichia coli* in beef loaf after microwave processing (2450 MHz).

- Fig. 35-A:** Interaction plot of PW and EMD, line 1 - not wrapped, line 2 - wrapped with PVDC film.
- Fig. 35-B:** Interaction plot of PW and LS, line 1 - not wrapped, line 2 - wrapped with PVDC film.
- Fig. 35-C:** Interaction plot of PW and PFC, line 1 - not wrapped, line 2 - wrapped with PVDC film.
- Fig. 35-D:** Interaction plot of LS and EMD, line 1 - LS=1200 g, line 2 - LS=600 g, line 3 - LS=150 g.
- Fig. 35-E:** Interaction plot of MP and EMD, line 1 - MP=100% output power (713 ± 5 W), line 2: MP=50% output power (356 ± 3 W).
- Fig. 35-F:** Interaction plot of PFC and EMD, line 1 - PFC=10%, line 2 - PFC=20%, line 3: PFC=30%.
- Fig. 35-G:** Interaction plot of LS and MP, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).
- Fig. 35-H:** Interaction plot of LS and PFC, line 1 - PFC=10%, line 2 - PFC=20%, line 3: PFC=30%.

* Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points are not significantly different ($p > 0.05$ by Tukey's test).



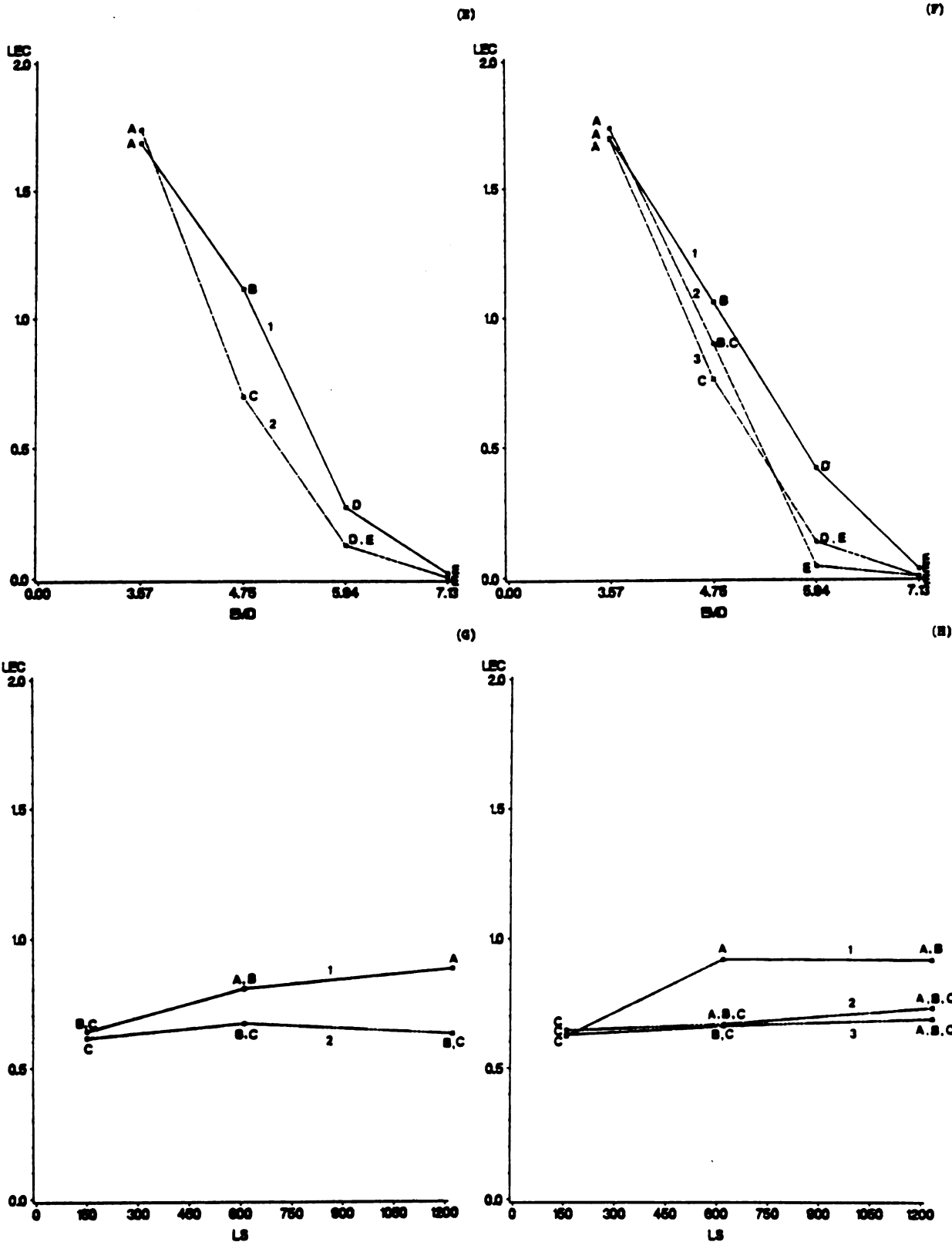
LS = LOAD SIZE (G).

PFC = PERCENT FAT CONTENT (%).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

Figure 35.



LS = LOAD SIZE (G).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

Figure 35 (cont'd).

Figure 36. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean* of microwave processing temperature rise (MPTR) in beef loaf after microwave processing (2450 MHz).

Fig. 36-A: Interaction plot of LS and EMD, line 1 - LS=150 g, line 2 - LS=600 g line 3 - LS=1200 g.

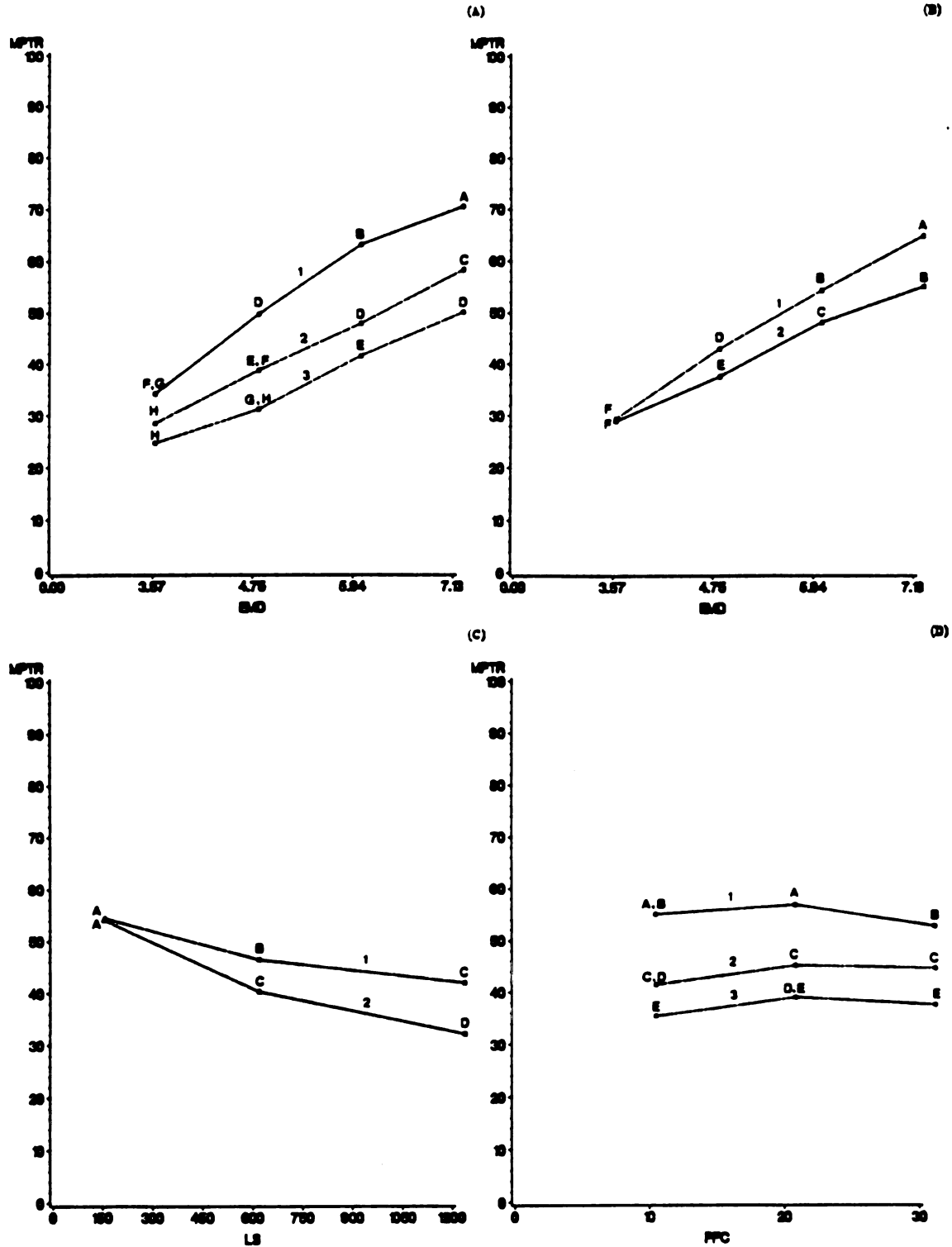
Fig. 36-B: Interaction plot of MP and EMD, line 1 - MP=50% output power (356 ± 3 W), line 2 - MP=100% output power (713 ± 5 W).

Fig. 36-C: Interaction plot of LS and MP, line 1 - MP=50% output power (356 ± 3 W), line 2 - MP=100% output power (713 ± 5 W).

Fig. 36-D: Interaction plot of LS and PFC, line 1 - LS=150 g, line 2 - LS=600 g, line 3 - LS=1200 g.

* Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).



LS = LOAD SIZE (G).

PFC = PERCENT FAT CONTENT (%).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

MPTR = MICROWAVE PROCESSING TEMPERATURE RISE (°C).

Figure 36.

Figure 37. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean* of post processing temperature rise (PPTR) in beef loaf after microwave processing (2450 MHz).

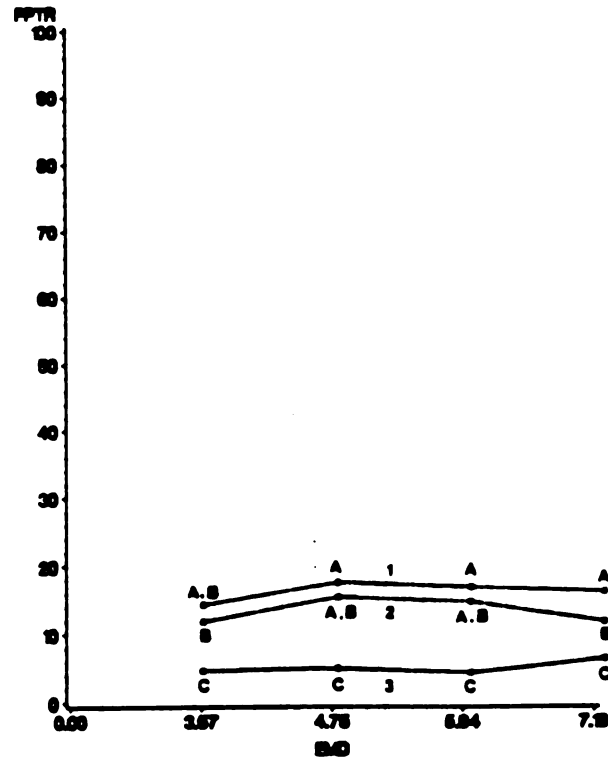
Fig. 37-A: Interaction plot of LS and EMD, line 1 - LS=1200 g, line 2 - LS=600 g line 3 - LS=150 g.

Fig. 37-B: Interaction plot of MP and EMD, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).

Fig. 37-C: Interaction plot of LS and MP, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).

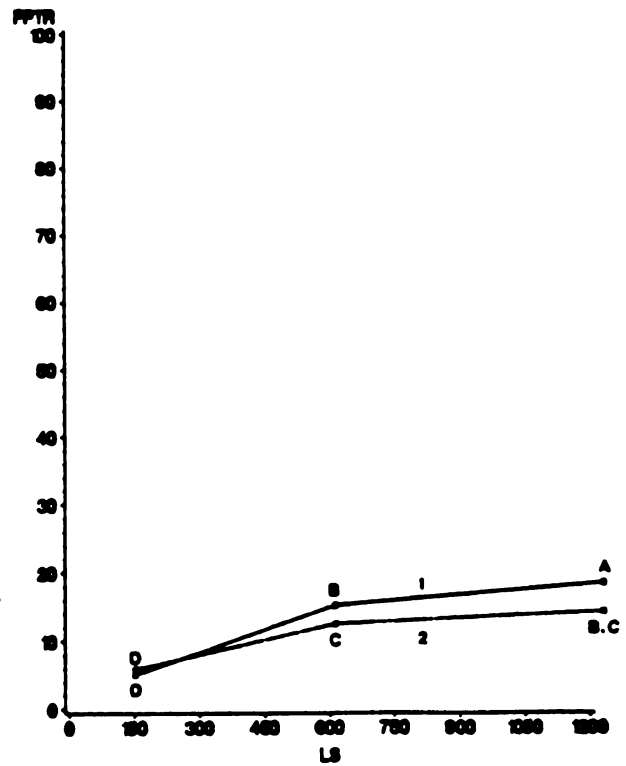
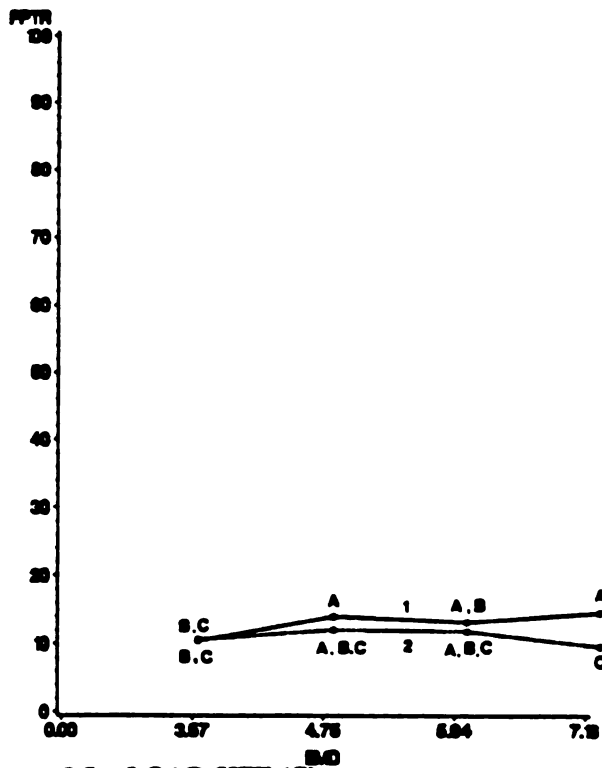
*** Average over the rest of factors not involved in a specific 2-way interaction.**

**Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).**



(b)

(c)



LS = LOAD SIZE (G).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PPTR = POST PROCESSING TEMPERATURE RISE (°C).

Figure 37.

Figure 38. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean* of time of post processing temperature rise (TPPTR) in beef loaf after microwave processing (2450 MHz).

Fig. 38-A: Interaction plot of PW and LS, line 1 - wrapped with PVDC film, line 2 - not wrapped.

Fig. 38-B: Interaction plot of LS and EMD, line 1 - LS=1200 g , line 2 - LS=600 g line 3 - LS=150 g.

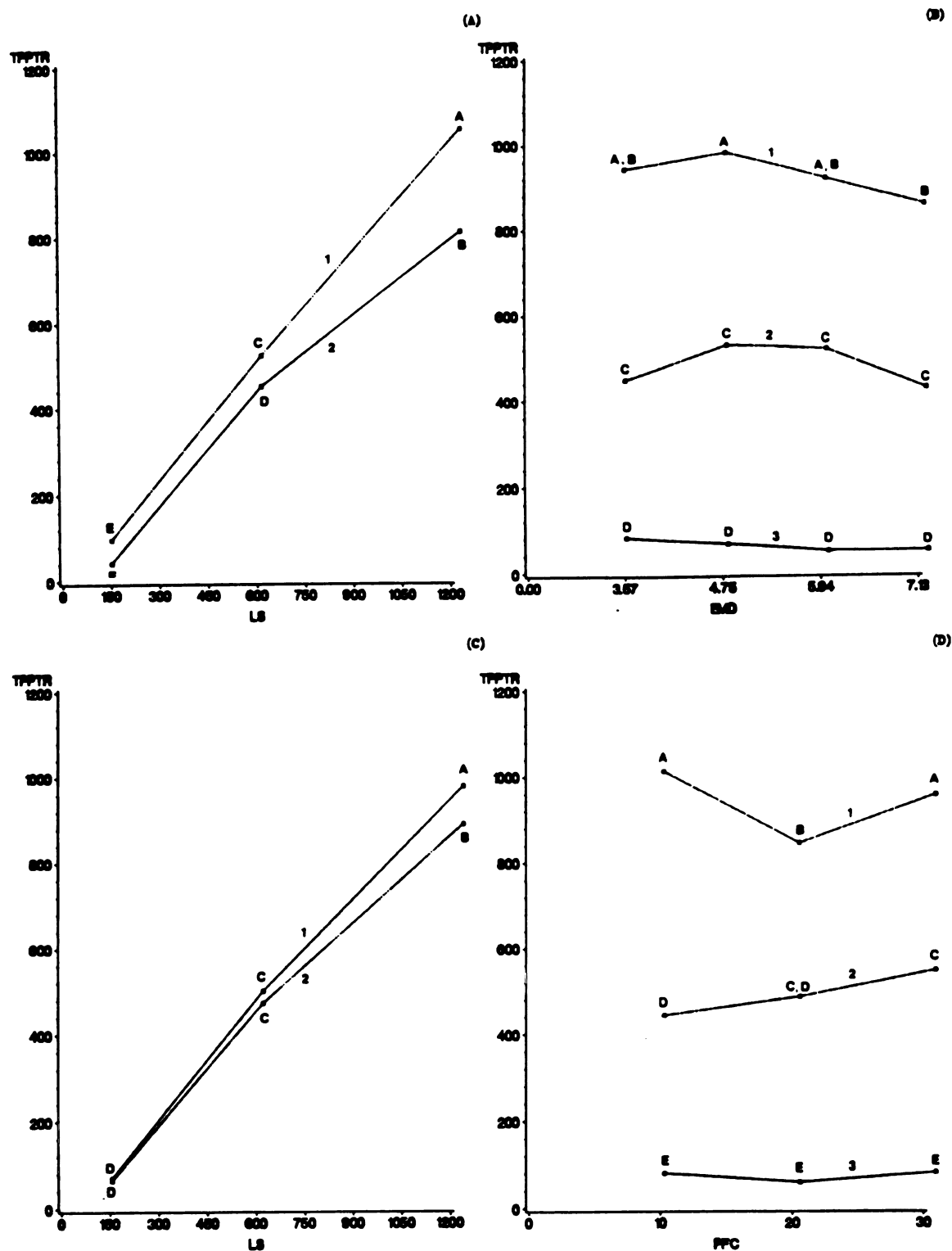
Fig. 38-C: Interaction plot of LS and MP, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).

Fig. 38-D: Interaction plot of LS and PFC, line 1 - LS=1200 g, line 2 - LS=600 g, line 3 - LS=150 g.

* Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).

209a



LS = LOAD SIZE (G).

PFC = PERCENT FAT CONTENT (%).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

TPPTR = TIME OF POST PROCESSING TEMPERATURE RISE (SEC).

Figure 38.

Figure 39. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean* of percent evaporation loss (PEL) in beef loaf after microwave processed (2450 MHz).

Fig. 39-A: Interaction plot of PW and EMD, line 1 - not wrapped, line 2 - wrapped with PVDC film.

Fig. 39-B: Interaction plot of PW and MP, line 1 - not wrapped, line 2 - wrapped with PVDC film.

Fig. 39-C: Interaction plot of PW and PFC, line 1 - not wrapped, line 2 - wrapped with PVDC film.

Fig. 39-D: Interaction plot of LS and EMD, line 1 - LS=1200 g, line 2 - LS=150 g, line 3 - LS=600 g.

Fig. 39-E: Interaction plot of MP and EMD, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).

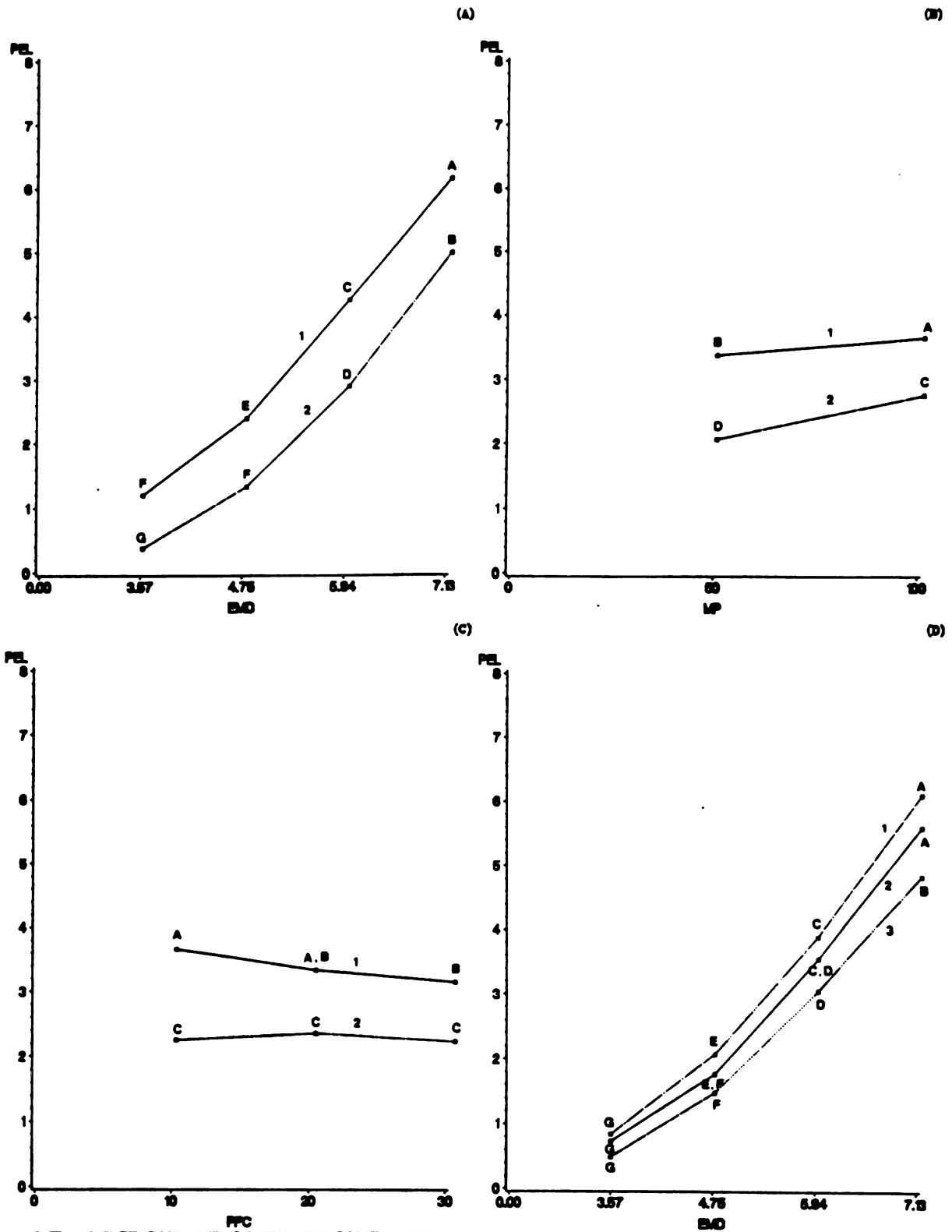
Fig. 39-F: Interaction plot of LS and MP, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).

Fig. 39-G: Interaction plot of LS and PFC, line 1 - PFC=10%, line 2 - PFC=20%, line 3 - PFC=30%.

* Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).

210a



MP = MICROWAVE OUTPUT POWER (%).

PFC = PERCENT FAT CONTENT (%).

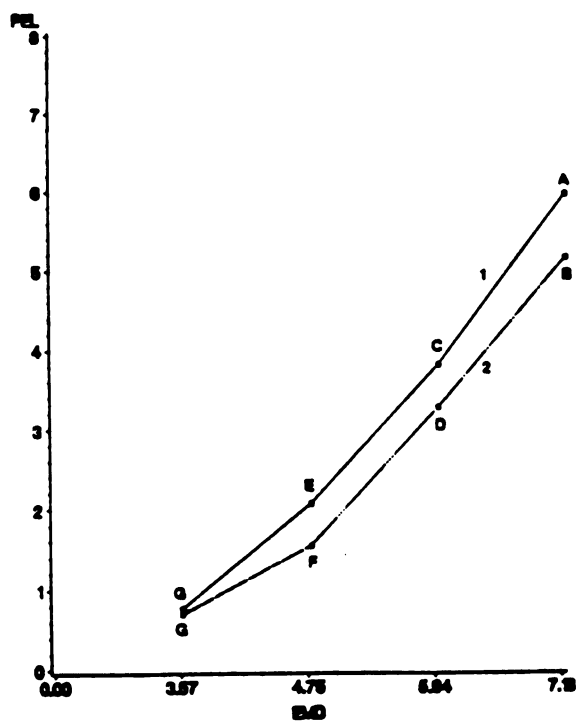
EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PEL = PERCENT EVAPORATION LOSS (%).

Figure 39.

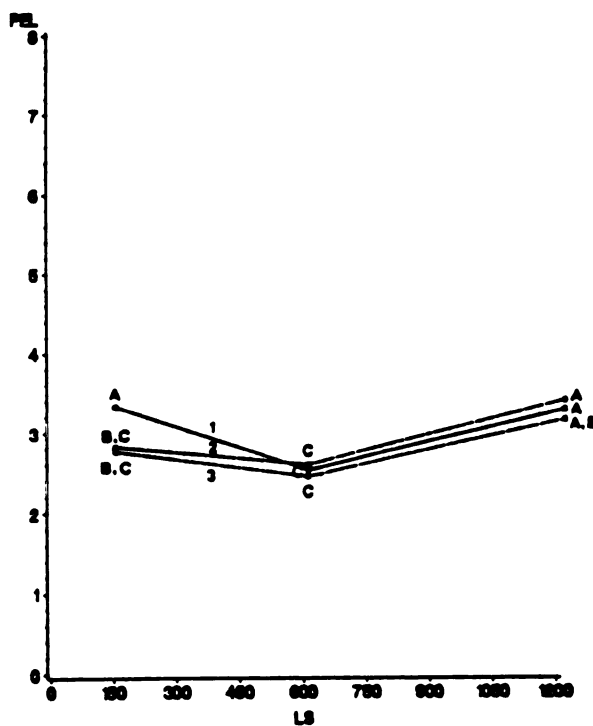
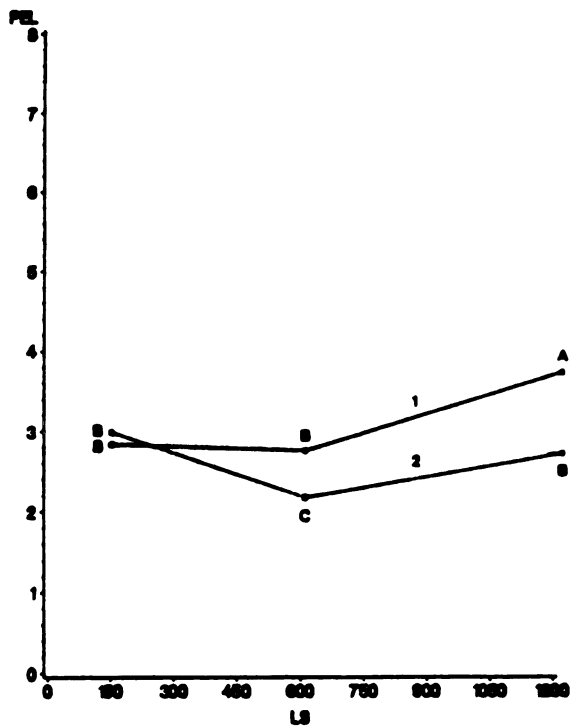
210b

(E)



(F)

(G)



LS = LOAD SIZE (G).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN /G), 2450 MHz.

PEL = PERCENT EVAPORATION LOSS (%).

Figure 39 (cont'd).

output power (MP) and exposed microwave dose (EMD) were statistically analyzed; the results and discussion of significant ($p \leq 0.1$) two-way interactions are present below.

Analyses showed that bacterial survival such as percent survival of *E. coli* was affected by the interactions of PW and EMD, PW and LS, PW and PFC, LS and EMD, MP and EMD, PFC and EMD, LS and MP as well as LS and PFC (Figures 35:A-H). The percent survival of *E. coli* was chosen to illustrate the effect of interactions on bacterial survival. Figure 35:A illustrates the effect of PW and EMD interaction on percent survival of *E. coli*.

In Figure 35:A, eight data points, the mean of percent survival of *E. coli* averaged over the rest of factors (LS, MP, PFC) represented each treatment combination of PW and EMD. The means were significantly different ($p \leq 0.05$ by Tukey's test) if the letters, next to the data points, were not the same. The result of interaction of PW and EMD showed that beef loaves wrapped with PVDC film only needed the second highest microwave dose (5.94 watt x min/g) to achieve safe microbial quality (> 99.99% kill; Figure 35:A - line 2). The second highest microwave dose was the planned processing treatment for safe microbial quality of beef loaves (Section 3.3.2). On the other hand, unwrapped beef loaves needed the highest microwave dose (7.13 watt x min/g; contrary to plans of present study; Section 3.3.2) to achieve the same microbial quality as beef loaves wrapped with PVDC film did.

The result of the interaction of PW and LS showed that when beef loaves were wrapped with PVDC film, the effect of LS ($\downarrow$ LS= $\downarrow$ bacterial survival, Section

5.1.2) diminished. This may be interpreted to mean that the effect of LS could be ignored if beef loaves were wrapped with PVDC film (Figure 35:B - line 2).

The result of the interaction of PW and PFC showed that when beef loaves were wrapped with PVDC film, the effect of PFC ($\uparrow$ PFC= $\downarrow$ bacterial survival, Section 5.1.4) diminished. This may be interpreted to mean that the effect of PFC could be ignored if beef loaves were wrapped with PVDC film (Figure 35:C - line 2).

The result of the interaction of LS and EMD showed that when 150 g load size of beef loaves were exposed to 5.94 watt x min/g microwave dose, safe microbial quality could be achieved (> 99.9% kill; Figure 35:D - line 3). On the other hand, the 600 g and 1200 g load sizes of beef loaves must be exposed to 7.13 watt x min/g microwave dose to achieve the equal microbial quality.

The result of the interaction of MP and EMD showed that when beef loaves were processed at 50% output power, the bacterial survival between loaves that had been exposed to 5.94 and 7.13 watt x min/g microwave doses were not significantly different (Figure 35:E - line 2). On the other hand, when loaves were processed at 100% output power, differences in bacterial survival were found between loaves that had been exposed to 5.94 and 7.13 watt x min/g microwave doses.

The result of the interaction of PFC and EMD showed that beef loaves with 10% PFC must be exposed to 7.13 watt x min/g of EMD to achieve a safe microbial quality (< 99.9% kill; Figure 35:F - line 1). On the other hand, beef loaves with 20 or 30% PFC only needed 5.94 watt x min/g of EMD to achieve the same microbial quality.

The result of the interaction of LS and MP showed that when beef loaves were processed at 50% output power, the effect of LS diminished. This may be interpreted to mean that the effect of LS could be ignored if beef loaves were processed at 50% output power (Figure 35:G - line 2).

The result of the interaction of LS and PFC showed that when beef loaves with 20 or 30% fat were processed, the effect of LS diminished. This may be interpreted to mean that the effect of LS could be ignored if beef loaves with 20 and 30% fat were processed (Figure 35:H - line 2 and 3). On the other hand, when beef loaves with 10% fat were processed, the effect of LS must be taken into account.

Based on the significant interactions of independent variables on bacterial survival in beef loaves, the optimal processing conditions to achieve the best microbial quality would be: (1) wrapped with PVDC film; (2) used 150 g load size; (3) contained 20 or 30% fat; (4) used 50% or less output power and (5) used 5.94 watt x min/g of EMD. Such optimallt treated beef loaves should have the best microbial quality.

5.6.2 Effect of interactions on thermal responses

Information is limited on the interactions of product and processing variables on thermal responses such as microwave processing temperature rise (MPTR), post processing temperature rise (PPTR) and time of PPTR (TPPTR) in foods after microwave processing. In the present study, the interactions between the product variables of wrapping with PVDC film (PW), load size (LS) and percent fat content

(PFC) and the processing variables of microwave output power (MP) and exposed microwave dose (EMD) were statistically analyzed and the results and discussion of significant ($p \leq 0.1$) 2-way interactions are present below. MPTR, PPTR and TPPTR were chosen to illustrate the effect of interactions on thermal responses because this research was focus on improvement of microwave processing. If MPTR, PPTR and TPPTR could be improved by knowing how the processing and product variables interated with MPTR, PPTR and TPPTR, then end-point temperature (EPT) or sum of temperature rise (STR) could also be improved because $MPTR+PPTR=STR$. Analyses showed that thermal responses such as MPTR, PPTR and TPPTR were affected by the interactions of LS and EMD, MP and EMD, LS and MP, LS and PFC as well as PW and LS (Figures 36-38).

5.6.2.1 Effect of interactions on microwave processing temperature rise

The result of the interaction of LS and EMD showed that the microwave processing temperature rise (MPTRs) of 1200 g load size of beef loaves were not significantly different when loaves were exposed to 3.57 or 4.75 watt x min/g of EMD (Figure 36:A - line 3). On the other hand, the MPTRs of smaller sizes (150 g and 600 g) of beef loaves were signifcnatly different regardless of varied EMD. This could be interpreted to mean that the 1200 g load size of beef loaves needed at least 4.75 watts x min/g of EMD to improve MPTR. As for the smaller load sizes of beef loaves, 3.57 watt x min/g of EMD was sufficient to improve MPTR.

The result of the interaction of MP and EMD showed that the main effect of MP ($\uparrow MP = \uparrow MPTR$, Section 5.1.3) was enhanced as EMD increased. No

significant difference in MPTR was found between beef loaves that were processed at 50% and 100% output power at 3.57 watt x min/g of EMD. As EMD increased, the effect of MP became more enhanced (Figure 36:B - lines 1 vs.2).

The result of the interaction of LS and MP showed that the main effect of MP was enhanced as LS increased. No significant difference in MPTR was found between 150 g load size of beef loaves that were processed at 50% and 100% output power. As LS increased, the effect of MP was enhanced (Figure 36:C -lines 1 vs.2).

The result of the interaction of LS and PFC showed that the main effect of PFC on MPTR ($\uparrow$ PFC to 20%= $\uparrow$ MPTR; then $\downarrow$ MPTR as $\uparrow$ PFC to 30%, Section 5.1.4) was not observed in 600 g and 1200 g load sizes of beef loaves (Figure 36:D - lines 2 and 3). This may be interpreted to mean that when 600 g or 1200 g load sizes of beef loaves were processed, the effect of PFC on MPTR could be ignored.

5.6.2.2 Effect of interactions on post processing temperature rise

The result of the interaction of LS and EMD showed that significant differences in post processing temperature rise (PPTR) were not found among four microwave doses for all sizes of beef loaves. However, 150 g load size of beef loaves had significant lower PPTR than that of 600 g and 1200 g load sizes of loaves (Figure 37:A - line 1 vs. 2 vs.3). This may be interpreted to mean that PPTR could be improved by increasing LS effectively but could not be improved by EMD.

The result of the interaction of MP and EMD was that the main effect of MP on PPTR ($\uparrow$ MP= $\uparrow$ PPTR, Section 5.1.3) did not showed up until beef loaves were exposed to the highest microwave dose (7.13 watt x min/g; Figure 37:B). The effect of the interaction of LS and MP showed that the main effect of MP on PPTR was not significant for the 150 g and 600 g load sizes of beef loaves, but was significant for the 1200 g load size of loaves (Figure 37:C). Therefore, lowering MP was needed to improve PPTR if the 1200 g load size of beef loaves was used.

5.6.2.3 Effect of interactions on time of post processing temperature rise

The result of the interaction of PW and LS showed that the main effect of PW on time of post processing temperature rise or TPPTR ($\uparrow$ TPPTR, Section 5.1.1) was enhanced by LS. The largest difference in TPPTR (+232 sec) was found between the 1200 g load size of beef loaves wrapped with PVDC film and not wrapped. The difference in TPPTR became insignificant as LS decreased to 150 g load size (Figure 38:A - line 1 vs. 2).

The result of the interaction of LS and EMD showed that the effect of EMD on TPPTR was LS dependent. For the 150 g and 600 g load sizes of beef loaves, EMD had no effect on TPPTR, while EMD had significant effect on TPPTR for the 1200 g load size. The change pattern of TPPTR at varied EMDs was also LS dependent (Figure 38:B).

The result of the interaction of LS and MP showed that the main effect of MP on TPPTR ($\uparrow$ MP= $\uparrow$ PTPTR, Section 5.1.3) was enhanced by LS. The largest difference in TPPTR (+85 sec) was found between the 1200 g load size of beef

loaves processed at 50% and 100% output power. The difference in TPPTR became insignificant as LS decreased to the 600 g load size or smaller (Figure 38:C - line 1 vs. 2).

The result of the interaction of LS and PFC showed that the effect of PFC on TPPTR was LS dependent. For the 150 g load size of beef loaves, PFC had no effect on TPPTR, while PFC had a significant effect on TPPTR for 600 g and 1200 g loadsize of loaves. This may be interpreted to mean that when 150 g load size of beef loaves were processed, the effect of PFC on TPPTR could be ignored. The change pattern of TPPTR at varied EMDs was also LS dependent (Figure 38:D). Unlike the 600 g load size of loaves that TPPTR increased as PFC increased, the shortest TPPTR was observed in 20% PFC among three fat levels of 1200 g load size of loaves (Figure 38:D - line 1 vs. 2).

The optimal processing conditions for thermal responses of foods should be to use as little microwave energy as possible to achieve the highest thermal responses such as MPTR, PPTR and TPPTR. Based on the results of the significant interactions of independent variables on thermal responses, the optimal processing conditions to achieve the highest thermal responses would be: (1) wrapped with PVDC film; (2) used 150 g load size; (3) contained 20 or 30 % fat; (4) used 50% or less output power and (5) uses 7.13 watt x min/g of EMD. Such optimally treated beef loaves should have the highest thermal responses.

5.6.3 Effect of interactions on percent evaporation loss

Information is limited for the interactions of product and processing variables on evaporation loss of foods after microwave processing. In the present study, the interactions among the product variables of wrapping with PVDC film (PW), load size (LS) and percent fat content (PFC) and the processing variables of microwave output power (MP) and exposed microwave dose (EMD) were statistically analyzed and the results and discussion of significant ($p \leq 0.1$) 2-way interactions are presented below.

Analyses showed that percent evaporation loss (PEL) was affected by the interactions of PW and EMD, PW and MP, PW and PFC, LS and EMD, MP and EMD, LS and MP, as well as LS and PFC (Figure 39:A-G).

The result of the interaction of PW and EMD showed that when beef loaves were wrapped with PVDC film, the PEL of the loaves was significantly lower at varied EMDs than unwrapped loaves. The main effect of EMD on PEL ($\uparrow$ EMD = $\uparrow$ PEL, Section 5.1.5) remained valid regardless of varied PW (Figure 39:A).

The result of the interaction of PW and MP showed that when beef loaves were wrapped with PVDC film and processed at 50% output power, they had the lowest PEL. Unwrapped loaves that were processed at 100% output power had the highest PEL (Figure 39:B). The result of the interaction of PW and PFC showed that when beef loaves were wrapped with PVDC film, effect of PFC ($\uparrow$ PFC = $\downarrow$ PEL, Section 5.1.4) on PEL could be ignored (Figure 39:C - line 2).

The result of the interaction of LS and EMD showed that the 600 g load size of beef loaves had the lowest PEL among three load sizes. However, the significant

difference of PEL did not exist until the higher EMDs ($> 3.57 \text{ watt} \times \text{min/g}$) were used. The main effect of EMD on PEL remained valid regardless of varied LS (Figure 39:D).

The result of the interaction of MP and EMD showed beef loaves that had been processed at 50% output power had lower PEL than loaves that had been processed at 100% output power. However, the significant difference of PEL did not exist until the higher EMDs ($> 3.57 \text{ watt} \times \text{min/g}$) were used. The main effect of EMD on PEL remained valid regardless of varied MP (Figure 39:E).

The result of the interaction of LS and MP showed varied size (Except 150 g) of beef loaves that had been processed at 50% output power had lower PEL than loaves that had been processed at 100% output power. Contrary to the main effect of MP on PEL ($\uparrow \text{MP} = \uparrow \text{PEL}$, Section 5.1.3), the PEL of 150 g load size of loaves that had been processed at 50% output power, although was not significant, was higher than loaves that had been processed at 100% output power. The main effect of LS on PEL ($\uparrow \text{LS to } 600 \text{ g} = \downarrow \text{PEL}$, then $\uparrow \text{PEL as } \uparrow \text{LS to } 1200 \text{ g}$) remained valid regardless of varied LS (Figure 39:F).

The result of the interaction of LS and PFC showed that the 150 g load size of beef loaves with 10% fat had significantly higher PEL than the same size of loaves with 20 or 30% fat. No significant differences in PEL were found among three fat levels for larger load sizes (600 g and 1200 g) of loaves. This may be interpreted to mean that when 150 g load size of beef loaves were processed, the effect of PFC on PEL must be taken into account (Figure 39:G).

Based on the results of the significant interactions of independent variables on evaporation loss, the optimal processing conditions to achieve the lowest evaporation

loss be: (1) wrapped with PVDC film; (2) used 600 g load size; (3) contained 30% fat; (4) used 50% or less output power and (5) used 3.75 watt x min/g of EMD.

Such optimally treated beef loaves should have the lowest evaporation loss.

To achieve the best quality (microbial and organoleptic) of beef loaves after microwave processing, the optimal processing conditions are selected based on the result of main effects and interactions of independent variables used in present study. The optimal microwave processing conditions are the combination of: (1) wrapped with PVDC film; (2) used 150 g load size; (3) contained 20% fat; (4) used 50% or less output power and (5) used 5.94 watt x min/g of EMD. Among five selected conditions, wrapped with PVDC film and use of 50% or less output power had consistent favorable results on bacterial survival, thermal responses and evaporation loss for beef loaves. To use 150 g load size is the compromise between optimal thermal responses and lower evaporation loss. Beef loaves with 20% fat are required to achieve satisfactory bacterial survival and optimal thermal responses and yet still remain acceptable from fat-intake nutritional point of view. Use of 5.94 watt x min/g of EMD is the minimum requirement to assure beef loaves are microbially safe.

5.6.4 Effect of interactions that related to type of loaf

The data subset for 24 beef loaves (10% fat), 24 turkey loaves (10% fat) and 24 BGB loaves (10% glycerol) were statistically analyzed to explore the possible effect of interactions between type of loaf and other independent variables on bacterial survival, thermal responses and evaporation loss. Two significant ($p \leq 0.1$)

two-way interactions that related to type of loaf were found, they were (1) type of loaf and load size and (2) type of load and exposed microwave dose. The results and discussion of the effect of these two interactions on bacterial survival, thermal responses and evaporation loss are presented below.

5.6.4.1 Effect of interaction of type of loaf and load size

The significant interaction ($p \leq 0.1$) of type of loaf (TL) and load size (LS) was observed on bacterial survival, thermal responses and evaporation loss. The plotted response lines of significant interaction of TL and LS are showed in Figure 40:A-E. Unlike beef loaves, the percent survival of *E. coli* in the 1200 g load size of turkey and BGB loaves, although not statistically significant ($p \leq 0.05$), was lower than in the 600 g load size of turkey and BGB loaves. BGB was the only type of loaf that had no significant difference in percent survival of *E. coli* among varied LS (Figure 40:A).

The result of percent survival of bacteria on BGB loaf was related to the unique microwave processing temperature rise (MPTR) and post processing temperature rise (PPTR) observed in the varied load sizes of BGB loaf. For meat loaves (beef and turkey), MPTR decreased but PPTR increased as LS increased. However, the same relationship of MPTR and PPTR was not observed in BGB loaves. In BGB loaves, MPTR was increased (although not statistically significant, $p > 0.05$) as LS increased (Figure 40:B). Unlike meat loaves whose PPTR was significantly different ($P \leq 0.05$) between 150 g and 600 g load sizes as well as between 150 g and 1200 g load sizes, PPTR in BGB loaf also increased, but was

Figure 40. The significant two-way interaction plots of type of loaf (TL) and load size (LS) and exposed microwave dose (EMD) on means* of percent survival of *E. coli* (LEC), microwave processing temperature rise (MPTR), post processing temperature rise (PPTR), time of TPPR (TPPTR) and percent evaporation loss (PEL) in loaves after microwave processing (2450 MHz).

Fig. 40-A: Interaction plot of TL and LS on LEC, line 1 - beef loaf, line 2 - turkey loaf, line 3 - bentonite-glycerol-BHI broth (BGB) loaf.

Fig. 40-B: Interaction plot of TL and LS on MPTR, line 1 - beef loaf, line 2 - turkey loaf, line 3 - BGB loaf.

Fig. 40-C: Interaction plot of TL and LS on PPTR, line 1 - turkey loaf, line 2 beef loaf, line 3 - BGB loaf.

Fig. 40-D: Interaction plot of TL and LS on TPPR, line 1 - beef loaf, line 2 - turkey loaf, line 3 - BGB loaf.

Fig. 40-E: Interaction plot of TL and LS on PEL, line 1 - beef loaf, line 2 - turkey loaf, line 3 - BGB loaf.

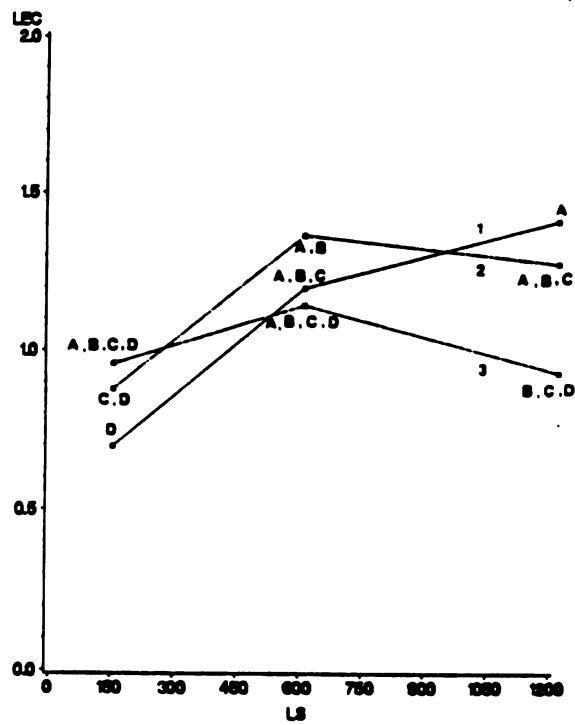
Fig. 40-F: Interaction plot of TL and EMD on LEC, line 1 - beef loaf, line 2 - turkey loaf, line 3 - BGB loaf.

* Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).

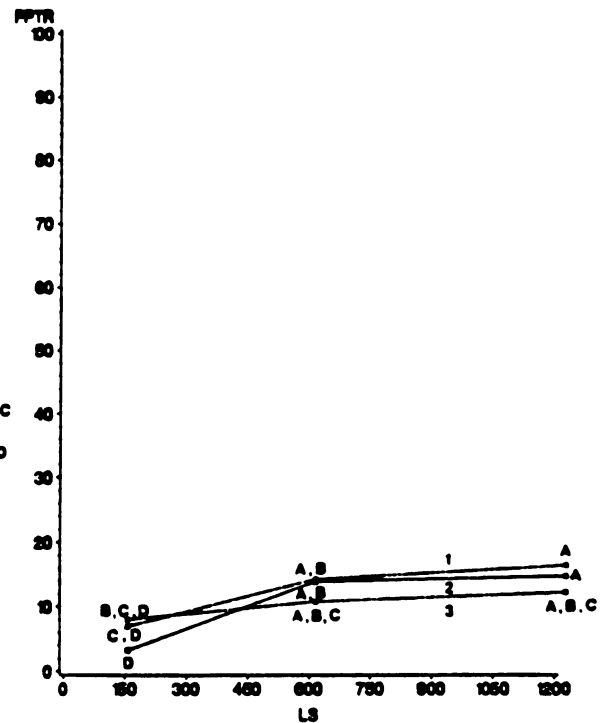
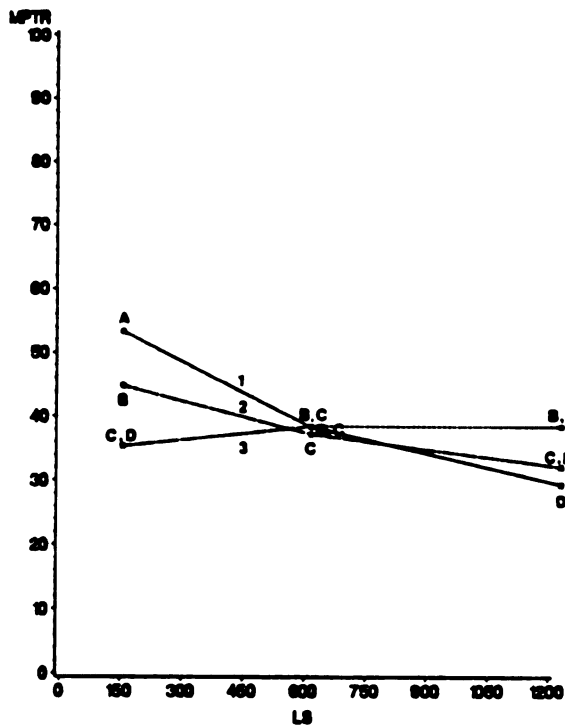
222a

(A)



(B)

(C)



LS = LOAD SIZE (G).

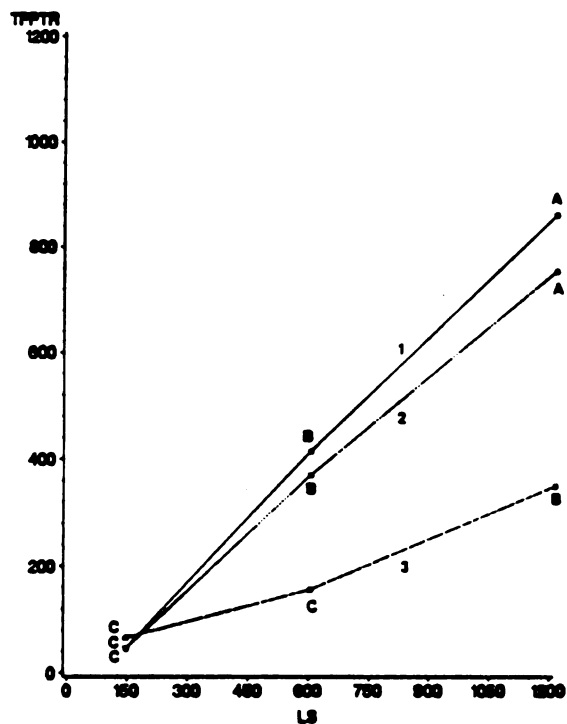
LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

MPTR = MICROWAVE PROCESSING TEMPERATURE RISE (°C).

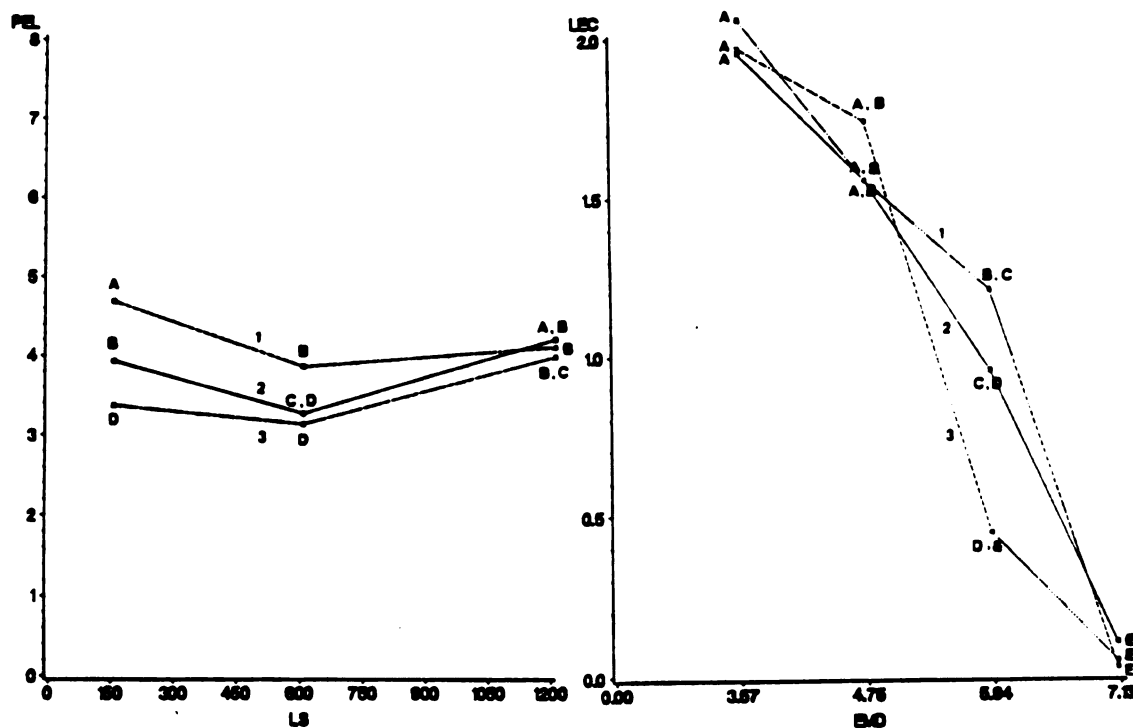
PPTR = POST PROCESSING TEMPERATURE RISE (°C).

Figure 40.

(D)



(F)



LS = LOAD SIZE (G).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN/G), 2450 MHz.

TPPTR = TIME OF POST PROCESSING TEMPERATURE RISE (SEC).

PEL = PERCENT EVAPORATION LOSS (%).

LEC = LOG VALUE OF (% SURVIVING *Escherichia coli*+1).

Figure 40 (cont'd).

not significantly different among varied load sizes (Figure 40:C). The unique thermal responses in BGB loaves were probably due to the small thermal conductivity of BGB loaves (Table 1). Since PPTR was related to thermal conduction, the small thermal conductivity meant poor conduction. For BGB loaves, not much thermal conduction took place after microwave power was turned off. This was the reason why the effect of LS on PPTR was not significant in BGB loaf. The dielectric properties of BGB loaves were not measured in this study, nor were they found in the published literatures (Table 1).

Times of PPTR (TPPTR) in 600 g and 1200 g load sizes of BGB loaf were significantly lower than those in 600 g and 1200 g load sizes of meat loaves. The difference in TPPTR among three types of loaf of the 150 g load size was not significant ($p > 0.05$). In general, TPPTR in meat loaves increased significantly as LS increased. However, the difference of TPPTR between 150 g and 600 g load sizes of BGB loaf was not significant ($P > 0.05$; Figure 40:D). This result was due to the small thermal conductivity of BGB loaf (Table 1).

The insignificant effect of LS on bacterial survival and thermal responses for BGB loaves suggested that when BGB loaf was used to study bacterial survival and thermal responses in a microwave field, LS could be excluded from processing variables. In other words, the data gathered from one load size of BGB loaf can be applied to varied load sizes (150 g to 1200 g).

Among three types of loaf, BGB loaf had the highest percent evaporation loss (PEL) and turkey loaf had the lowest PEL. The difference in PEL among the 150 g load size of three types of loaf was found significant ($p \leq 0.05$). However, as LS increased, the difference of PEL among three types of loaf was narrowed until it

was not significantly different for the 1200 g load size of loaves. Among three load sizes for each type of loaf, 600 g load of loaf had the lowest PEL (significant at $p \leq 0.05$ for beef loaf only). This may be interpreted to mean that the 600 g and 1200 g load sizes of BGB loaf could be used to simulate the evaporation loss of turkey loaf and only the 1200 g load size could be used to simulate the evaporation of beef loaf (Figure 40:E - line 1 vs. 2 vs.3).

5.6.4.2 Effect of interaction of type of loaf and exposed microwave dose

The significant interaction ($p \leq 0.1$) of type of loaf (TL) and exposed microwave dose (EMD) was observed on bacterial survival. The plotted response lines of significant interaction of TL and EMD are shown in Figure 40:F. The percent survival of *E. coli* was similar among three types of loaf that had been exposed to identical EMDs (Except 5.94 watt x min/g). When loaves were exposed to 5.94 watt x min/g of EMD, significant difference ($p \leq 0.05$) of percent survival of *E. coli* was found between beef loaf and BGB loaf, but was not found between beef loaf and turkey loaf or turkey loaf and BGB loaf. This may be interpreted to mean that the survival pattern of bacteria in the BGB loaf was more similar to that of turkey loaf than to that of beef loaf.

5.6.4.3 Summary

Based on the main effect of type of loaf (see Section 5.5.1) and the the effect of interactions that related to type of loaf mentioned above, author concludes that

600 g load size of BGB loaf has the potential to be a simulation model for bacterial survival, thermal responses and evaporation loss of turkey loaf (10% fat).

The use of 600 g load size of BGB loaf to simulate turkey loaf had several advantages over two other load sizes:

- (1) Bacterial survival was similar to that of turkey loaf (Figure 40:A and F - line 2 vs.3).
- (2) Thermal responses (except TPPTR) was similar to that of turkey loaf (Figure 40:B and D - line 2 vs 3, Figure 40:C - line 1 vs 3).
- (3) Evaporation loss was similar to that of turkey loaf (Figure 40:E line - 2 vs. 3).
- (4) The data for bacterial survival and thermal responses (except TPPTR) gathered from 600 g load size of BGB loaf can be applied to varied load sizes (150 g to 1200 g).

5.7. Effect of Other Independent Variables

Two independent variables, pH and replication, had less significant effects or no effect on bacterial survival, thermal responses and percent evaporation loss in loaves after microwave processing. The results and discussion of effect of pH and replication are briefly present below.

5.7.1 pH

The effect of pH on bacterial survival in all three types of loaf was not significant ($p > 0.05$). Although pH has been identified as an important factor in

bacterial survival [Pflug and Holcomb, 1983], the percent survival of three types of bacteria in three types of loaf was not affected by pH. This situation can be explained by two reasons: (1) Initial pH values of beef, turkey and BGB loaf were similar. The averaged initial pH of beef (n=288 loaves), turkey (n=96 loaves) and BGB (n=64 loaves) were 5.65, 5.95 and 6.6 respectively. The minor difference in pH among three types of loaf would probably not have any significant effect on bacterial survival [Jay, 1986; ICMSF, 1980]. (2) The pH change (+0.1 to +0.2) before and after microwave processing in three types of loaf were minimum.

5.7.2 Replication

The main effect of replication on bacterial survival, thermal responses and percent evaporation loss was not significant ($p > 0.05$; Appendices 2-6). Although some significant interactions ($p \leq 0.1$) involved with replication were present (Appendix 2-6), they were much less important than other main effects and interactions. Therefore, these interactions involved with replication (see Section 5.9.2) will not be discussed. Analyses of three types of loaf also confirmed the result of the ANOVA that the main effect of replication (n=2) was not significant ($p > 0.05$; Appendices 2-6).

5.8 Temperature Pattern

Two data sets (NEW1, n=448; and NEW2, n=1792) which were rearranged (see Section 4.5.2.1) from the raw data set (TEMP, n=448) were used for analyses

of temperature patterns. Statistical analyses for temperature distribution and temperature variation were performed according to methods described in Section 4.5.2. Results showed that the temperature differences among 16 locations within a loaf were highly significant ($p \leq 0.0$; Appendices 7,8). Analyses showed that temperature distribution as well as temperature variation were affected by independent variables used in this study. A more detailed discussion of these effects is presented below. The distribution of lowest and highest temperature locations within a loaf will also be discussed.

5.8.1 Temperature distribution within a loaf

Two temperature variables, (1) after-processing temperature (APT), which represented measured product temperature immediately after microwave processing and (2) end-point temperature (EPT), which represented measured product temperature at the end of time of post processing temperature rise, were used for analyses of temperature distribution analyses. The results of the ANOVA indicated that the differences of APT and EPT among 16 locations within a loaf were highly significant ($P \leq 0.0$). Significant interaction between location and other independent variables also existed (Appendices 7,8).

Although the relative locations for temperature measurement within a loaf were the same regardless of load sizes, the absolute locations for temperature measurement inside the microwave oven cavity were different when varied load sizes were used. Therefore, it was recommended that data used for frequency and crosstabulation analyses be broken down by load size (LS). This recommendation

was supported by the result of crosstabulation analysis. Two-way crosstabulation analysis indicated that LS affected the distribution of location of the lowest and the highest APT and EPT within a loaf (Table 13). When the second rearranged data set (NEW2, n=1792) was further broken down by independent variables such as TL, PW, MP and EMD, the result of 2-way crosstabulation indicated that these independent variables also affected the distribution of location of the lowest and the highest APT and EPT within a loaf (Table 14).

The results of analyses for the frequency of temperature distribution showed that the frequency of location distribution for the lowest and the highest APT and EPT within a loaf was affected by load size. Sixteen locations within a loaf can be categorized into three geometric areas: outer, including locations 1-8; middle, including locations 9-12; and inner, including locations 13-16 (Figure 1). The locations of the lowest APT and EPT of the 150 g load size were concentrated within the outer area, with the highest concentration at location 4. As load size increased to 600 g and then to 1200 g, location of the lowest APT and EPT shifted from the outer area to middle area, with the highest concentration at location 10 for the 600 g load size and location 12 for the 1200 g load size (Figures 41 and 43).

The locations of the highest APT were concentrated within the inner area for 150 g and 1200 g load sizes. The locations of the highest APT were more evenly distributed in the 600 g load (Figure 42). The locations of the highest EPT were concentrated within the inner and outer areas for 150 g load size, and were concentrated within the outer area for 600 and 1200 g load sizes (Figure 44).

The overall means (°C) of APT and EPT for three load sizes of loaves are shown in Figures 45-47. Usually, the overall means of APT and EPT (Figure 45 for

Table 13. Statistical results of two-way crosstabulation table of load size (LS) by location in loaves (beef, turkey and BGB) after microwave processing (2450 MHz).

Independent variable	Likelihood ratio chi-square	Location for a group of the four			
		Lowest		Highest	
		APTs	EPTs	APTs	EPTs
LS	Value	391.12	360.79	131.89	342.92
	Degrees of freedom	26	30	30	30
	Significance	0.000	0.000	0.000	0.000

Key:

APT = after-processing temperature (°C).

EPT = end-point temperature (°C).

Table 14. Statistical results of two-way crosstabulation tables of type of loaf (TL), polyvinylidene chloride wrapping (WP), microwave output power (MP) and exposed microwave dose (EMD) by location in varied sizes of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).

		150 g load size						600 g load size						1200 g load size					
														</					

Figure 41. The frequency of location distribution for the lowest after-processing temperature (APT) within in a loaf (varied load sizes [LS] of beef, turkey and BGB).

231a

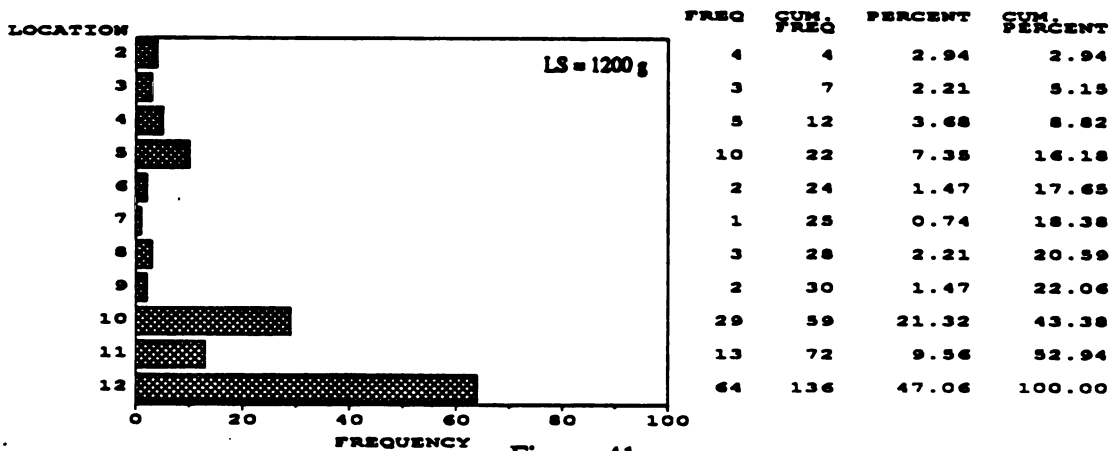
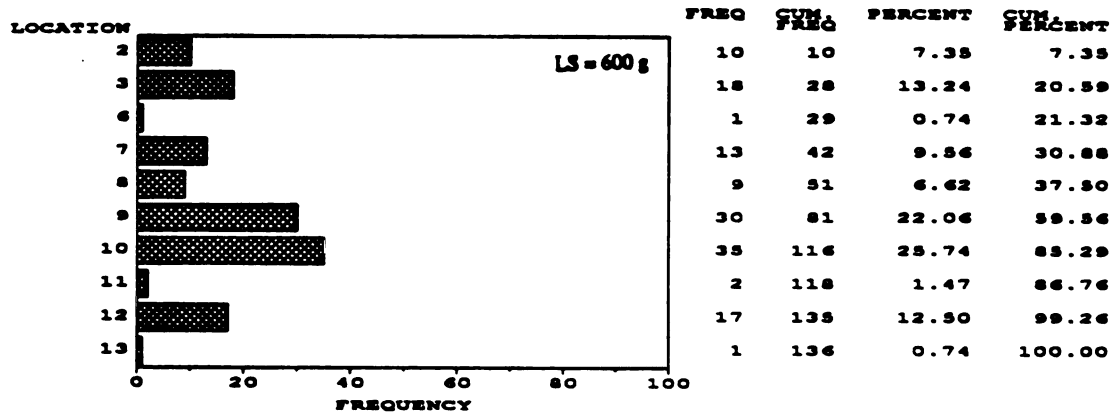
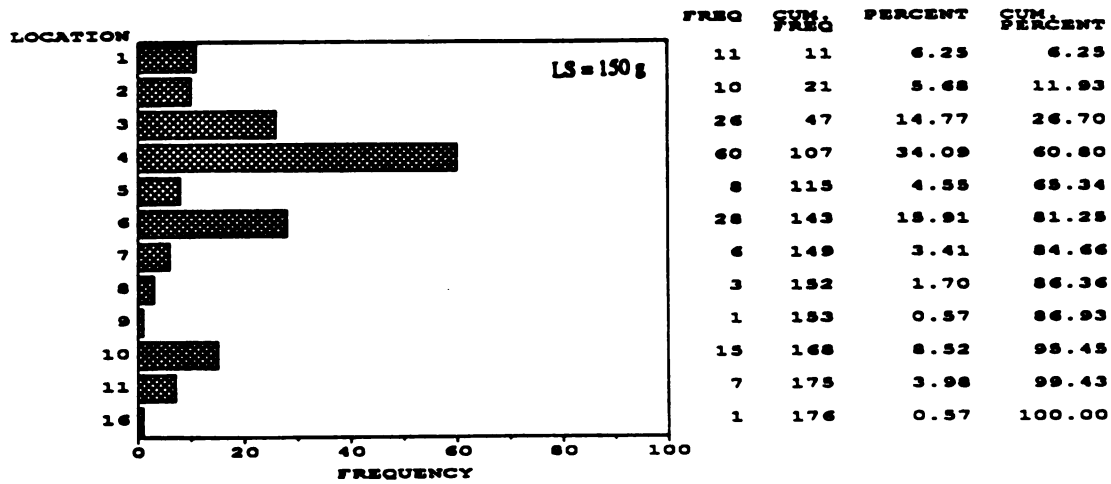
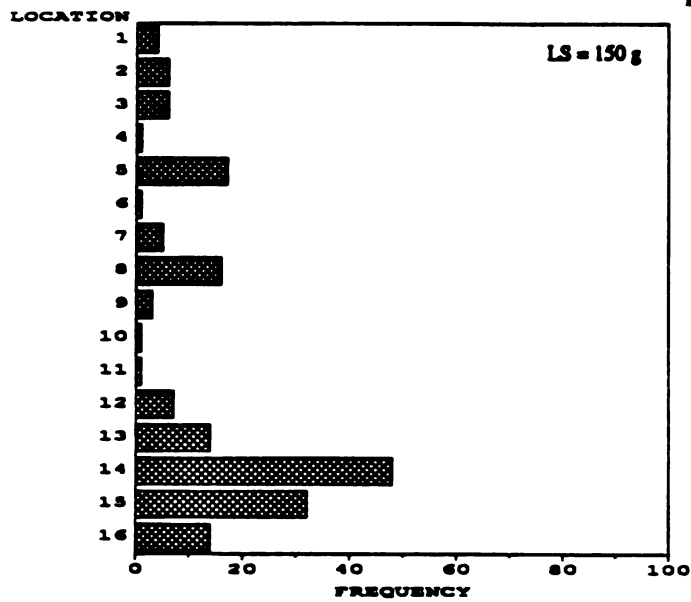


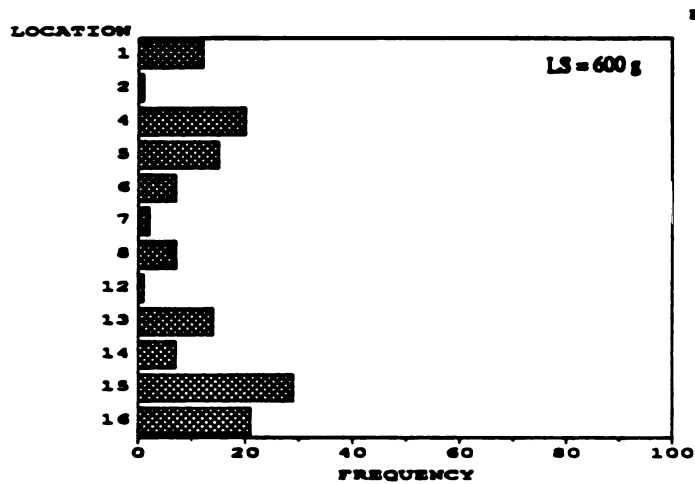
Figure 41.

Figure 42. The frequency of location distribution for the highest after-processing temperature (APT) within in a loaf (varied load size [LS] of beef, turkey and BGB).

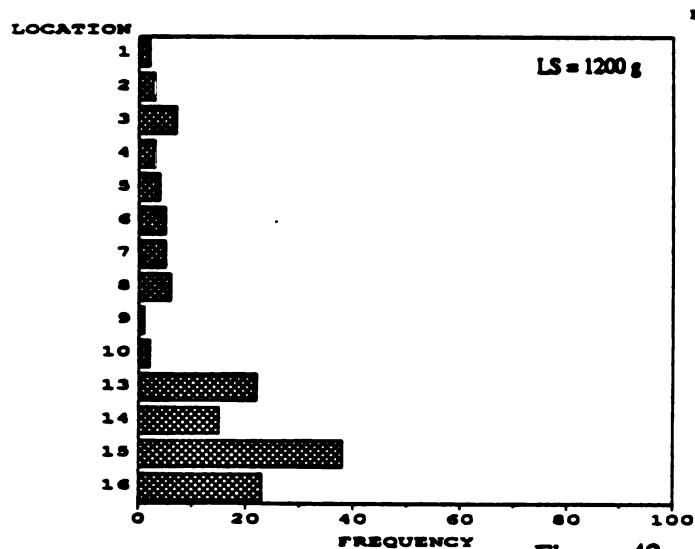
232a



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
4	4	2.27	2.27
6	10	3.41	5.68
6	16	3.41	9.09
1	17	0.57	9.66
17	34	9.66	19.32
1	35	0.57	19.89
3	40	2.84	22.73
16	56	9.09	31.82
3	59	1.70	33.52
1	60	0.57	34.09
1	61	0.57	34.66
7	68	3.98	38.64
14	82	7.95	46.59
48	130	27.27	73.86
32	162	18.18	92.05
14	176	7.95	100.00



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
12	12	8.82	8.82
1	13	0.74	9.56
20	33	14.71	24.26
18	48	11.03	35.29
7	55	5.15	40.44
2	57	1.47	41.91
8	64	5.15	47.06
1	65	0.74	47.79
14	79	10.29	58.09
7	86	5.15	63.24
29	115	21.32	84.56
21	136	15.44	100.00

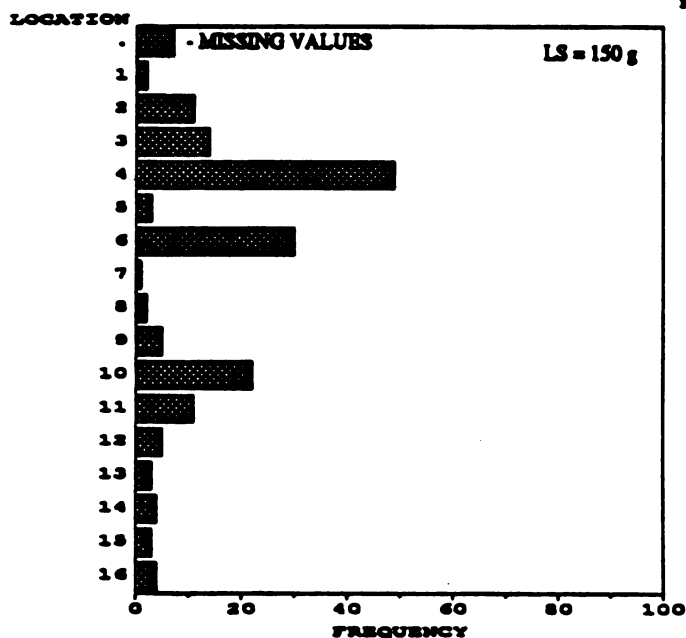


FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
2	2	1.47	1.47
3	5	2.21	3.68
7	12	5.15	8.82
3	15	2.21	11.03
4	19	2.94	13.97
5	24	3.68	17.65
5	29	3.68	21.32
6	35	4.41	25.74
1	36	0.74	26.47
2	38	1.47	27.94
22	60	16.18	44.12
15	75	11.03	55.15
38	113	27.94	83.09
23	136	16.91	100.00

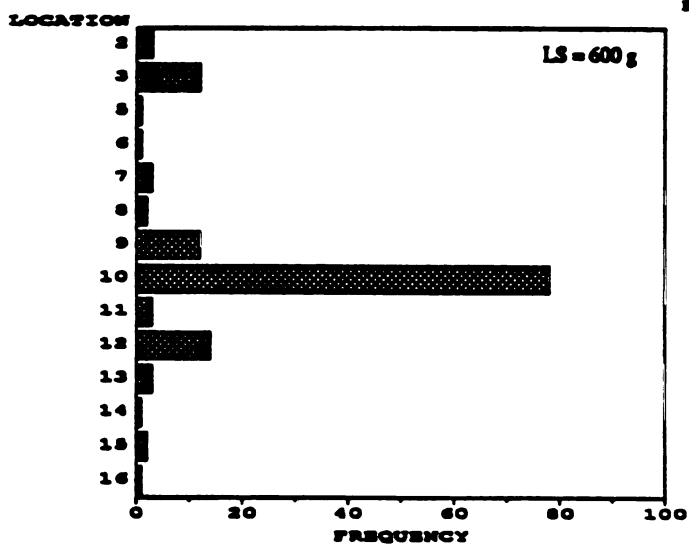
Figure 42.

Figure 43. The frequency of location distribution for the lowest end-point temperature (EPT) within in a loaf (varied load size [LS] of beef, turkey and BGB).

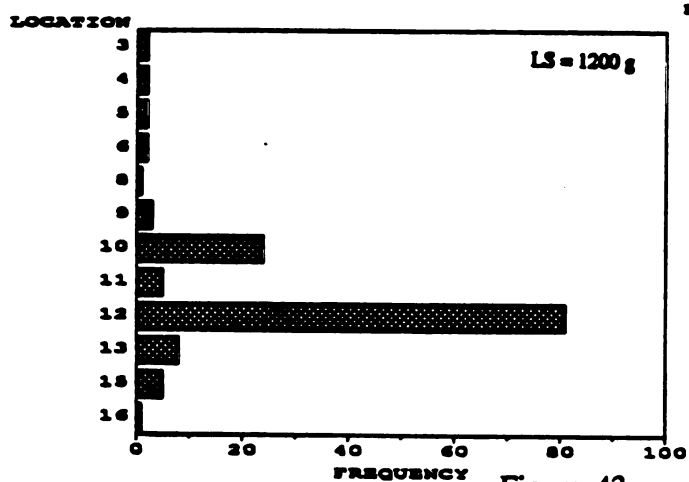
233a



LOCATION	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
1	7	7	3.98	3.98
2	2	9	1.14	5.11
3	11	20	6.28	11.36
4	14	34	7.98	19.32
5	49	83	27.84	47.16
6	3	86	1.70	48.86
7	30	116	17.08	65.91
8	1	117	0.57	66.48
9	2	119	1.14	67.61
10	5	124	2.84	70.45
11	22	146	12.50	82.95
12	11	157	6.28	89.20
13	5	162	2.84	92.05
14	3	165	1.70	93.75
15	4	169	2.27	96.02
16	3	172	1.70	97.73
17	4	176	2.27	100.00



LOCATION	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
2	3	3	2.21	2.21
3	12	15	8.82	11.03
4	1	16	0.74	11.76
5	1	17	0.74	12.50
6	3	20	2.21	14.71
7	2	22	1.47	16.18
8	12	34	8.82	25.00
9	78	112	57.35	82.35
10	3	115	2.21	84.56
11	14	129	10.29	94.85
12	3	132	2.21	97.06
13	1	133	0.74	97.79
14	2	135	1.47	99.26
15	1	136	0.74	100.00
16	1	136	0.74	100.00



LOCATION	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
3	2	2	1.47	1.47
4	2	4	1.47	2.94
5	2	6	1.47	4.41
6	2	8	1.47	5.88
7	1	9	0.74	6.62
8	3	12	2.21	8.82
9	24	36	17.65	26.47
10	5	41	3.68	30.15
11	61	122	59.86	89.71
12	8	130	5.88	95.59
13	5	135	3.68	99.26
14	5	135	3.68	99.26
15	1	136	0.74	100.00
16	1	136	0.74	100.00

Figure 43.

Figure 44. The frequency of location distribution for the lowest end-point temperature (EPT) within in a loaf (varied load sizes [LS] of beef, turkey and BGB).

234a

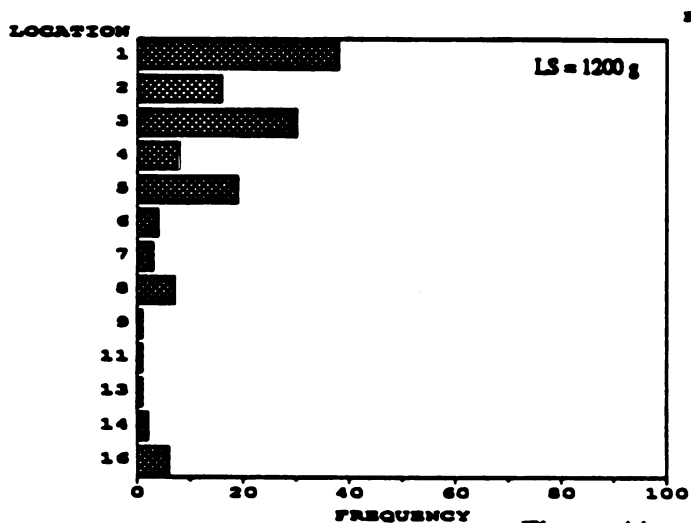
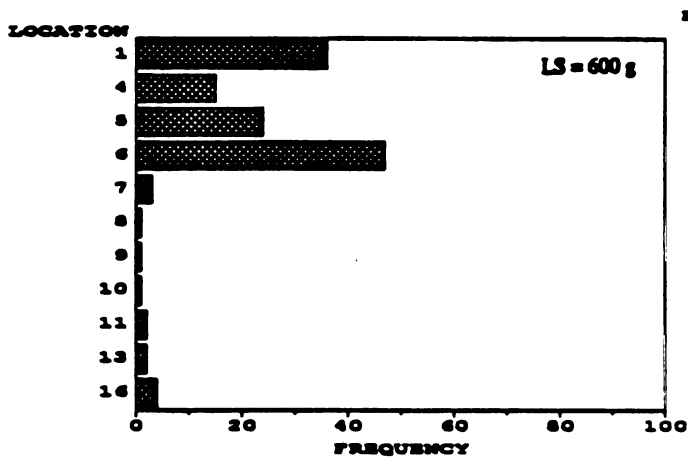
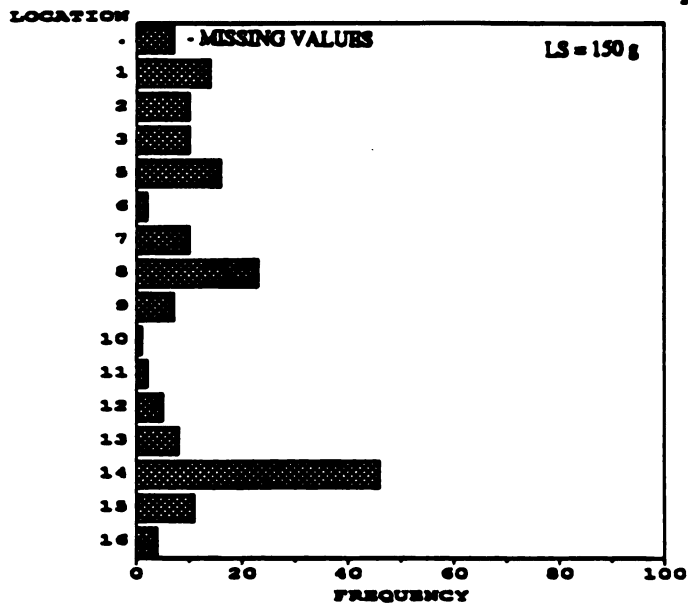
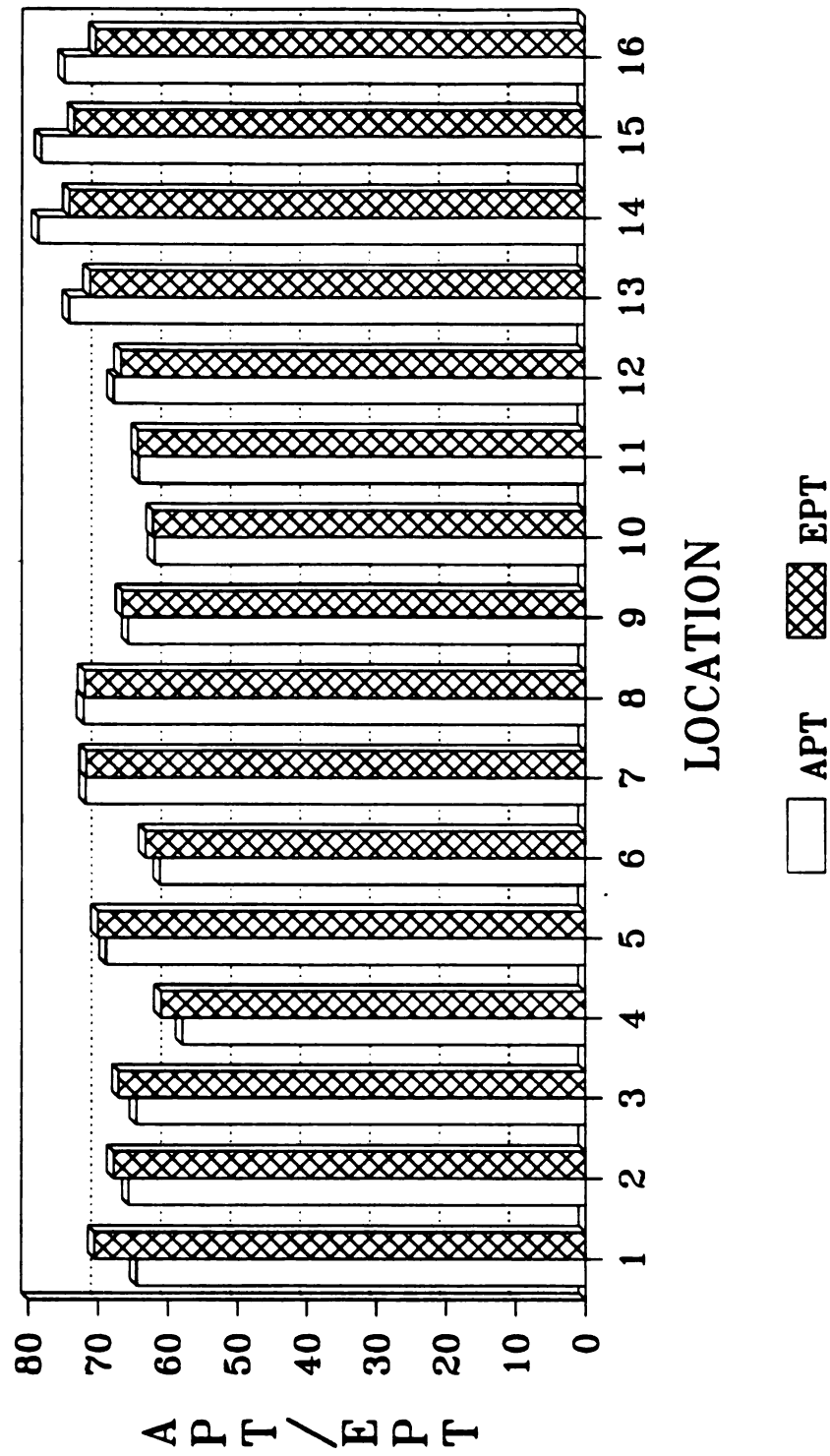


Figure 44.

Figure 45. The overall means of after-processing temperature (APT) and end-point temperature (EPT) at varied locations within a 150 g load size of loaf (beef, turkey and BGB).

150 G LOAD SIZE



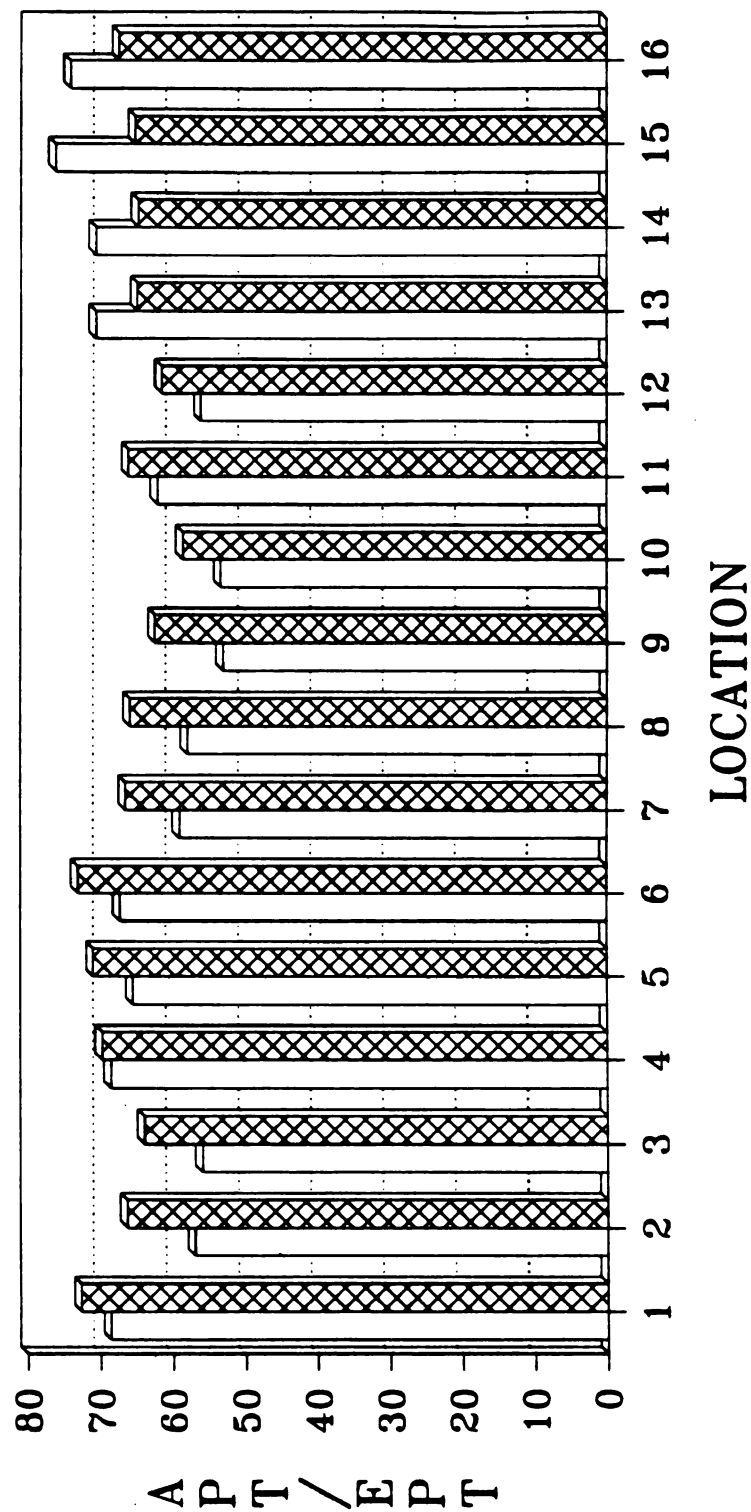
APT = AFTER-PROCESSING TEMPERATURE (°C).

EPT = END-POINT TEMPERATURE (°C).

Figure 45.

Figure 46. The overall means of after-processing temperature (APT) and end-point temperature (EPT) at varied locations within a 600 g load size of loaf (beef, turkey and BGB).

600 G LOAD SIZE



APT
 EPT

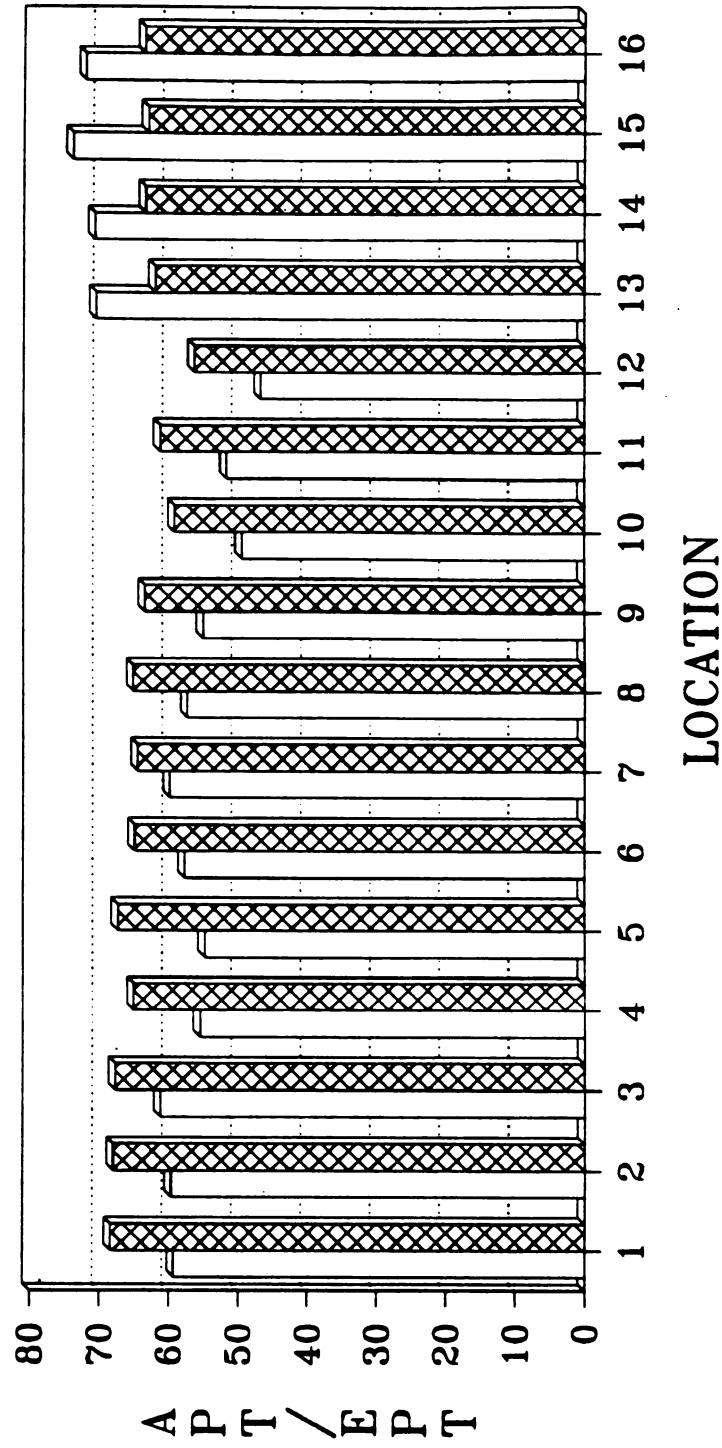
APT = AFTER-PROCESSING TEMPERATURE (°C).

EPT = END-POINT TEMPERATURE (°C).

Figure 46.

Figure 47. The overall means of after-processing temperature (APT) and end-point temperature (EPT) at varied locations within a 1200 g load size of loaf (beef, turkey and BGB).

1200 G LOAD SIZE



APT
 EPT

APT = AFTER-PROCESSING TEMPERATURE (°C).

EPT = END-POINT TEMPERATURE (°C).

Figure 47.

150 g, Figure 46 for 600 g and Figure 47 for 1200 g) corresponded to the frequency distribution of APT and EPT (Figure 41-44). The overall means of APT and EPT (except APT for 600 g load size) were the smallest at the locations where the lowest APT and EPT were most concentrated and vice versa. For example, the lowest overall mean of APT (57.96 °C) in the 150 g load size was at location 4, where the lowest APT was mostly concentrated. The highest overall mean of APT (78.65 °C) in the 150 g load size was at location 14, where the highest APT was mostly concentrated. The doughnut-shaped containers used in the present were proved to be able to eliminate cold spots in the center [Copson, 1975b; approval of Ho6; Section 3.5.1.2].

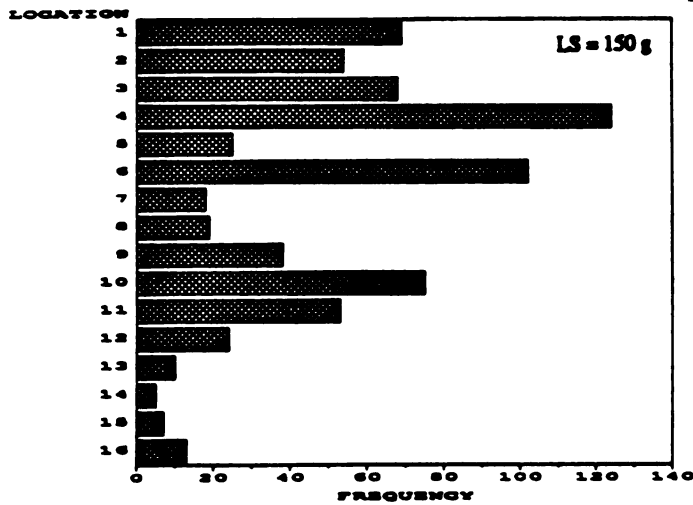
In general, the frequency of location distribution for a group of the four lowest and highest APTs and EPTs (Figure 48-51) followed the same distribution pattern of the lowest and the highest APT and EPT (Figure 41 vs. 48; 42 vs. 49; 43 vs. 50; 44 vs. 51).

5.8.2 Effects of experimental variables on temperature variation within a loaf

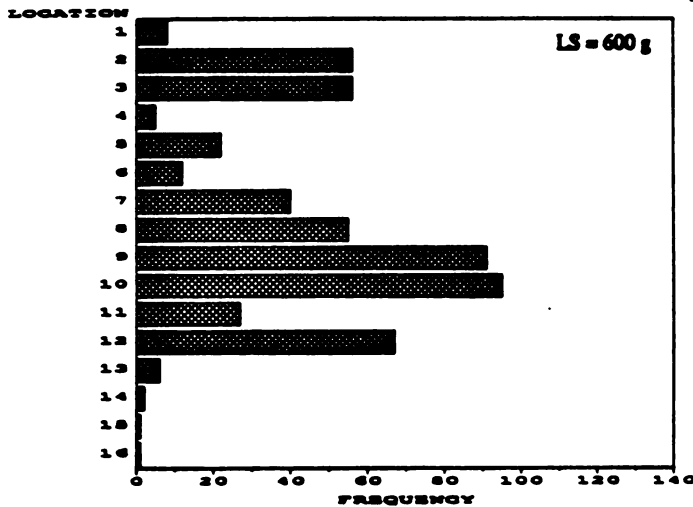
A data subset, which contained 16 APTs and EPTs within a loaf for 288 beef loaves (10, 20 and 30% fat), was chosen to illustrate the effect of the experimental variables - PVDC wrapping (PW), percent fat content (PFC), microwave output power (MP), load size (LS) and exposed microwave dose (EMD) on temperature variation. In order to eliminate the variation caused by inconsistent initial product temperature, LMPTR, LPPTR, LSTR: the log value of standard deviation of 16 microwave processing temperature rise (MPTRs), post processing temperature rise

Figure 48. The frequency of location distribution for a group of the four lowest after-processing temperatures (APTs) within in a loaf (varied load sizes [LS] of beef, turkey or BGB).

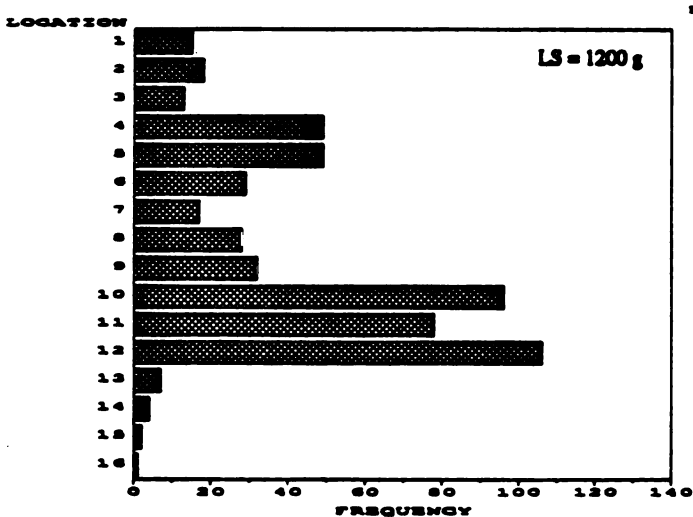
239a



FREQ	SUM FREQ	PERCENT	SUM PERCENT
69	69	9.80	9.80
84	123	7.67	17.47
68	191	9.66	27.13
124	315	17.61	44.74
28	340	3.88	48.30
102	442	14.48	62.78
18	460	2.86	65.34
19	479	2.70	68.04
38	517	5.40	73.44
78	595	10.68	84.09
82	648	7.83	91.62
24	669	3.41	95.03
10	679	1.42	96.45
8	684	0.71	97.16
7	691	0.99	98.15
13	704	1.68	100.00



FREQ	SUM FREQ	PERCENT	SUM PERCENT
8	8	1.47	1.47
56	64	10.29	11.76
56	120	10.29	22.06
8	128	0.92	22.98
22	147	4.04	27.02
12	159	2.21	29.23
40	199	7.38	36.61
55	254	10.11	46.69
91	345	16.73	63.42
95	440	17.46	80.88
27	467	4.96	85.85
67	534	12.32	98.16
6	540	1.10	99.26
2	542	0.37	99.63
1	543	0.18	99.82
1	544	0.18	100.00

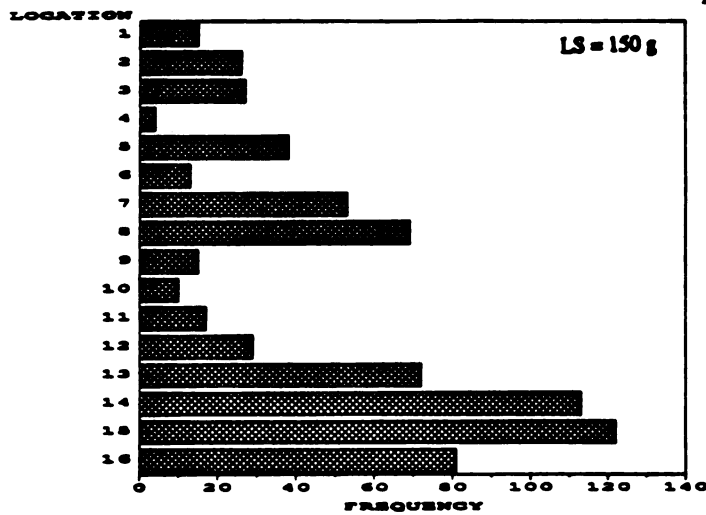


FREQ	SUM FREQ	PERCENT	SUM PERCENT
18	18	2.76	2.76
18	36	3.31	6.07
13	49	2.39	8.46
49	98	9.01	17.46
49	144	9.01	26.47
29	173	5.33	31.80
17	190	3.13	34.93
28	218	5.18	40.07
32	250	5.88	45.95
96	346	17.68	63.60
78	424	14.34	77.94
106	530	19.49	97.43
7	537	1.29	98.71
4	541	0.74	99.45
2	543	0.37	99.82
1	544	0.18	100.00

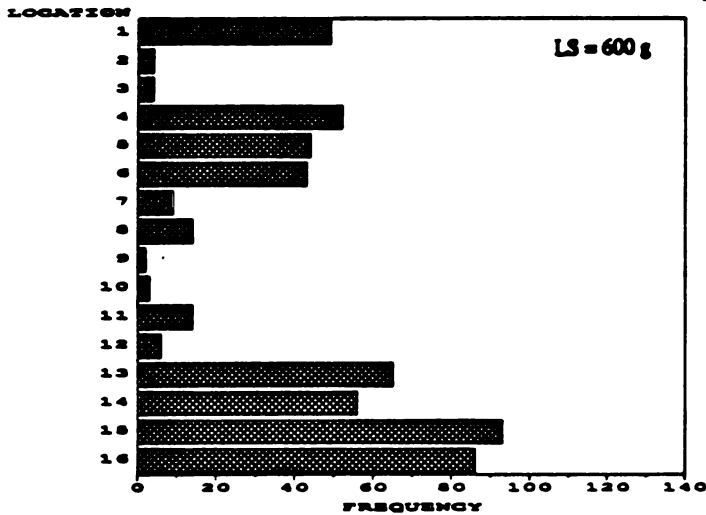
Figure 48.

Figure 49. The frequency of location distribution for a group of the four highest after-processing temperatures (APTs) within in a loaf (varied load size [LS] of beef, turkey or BGB).

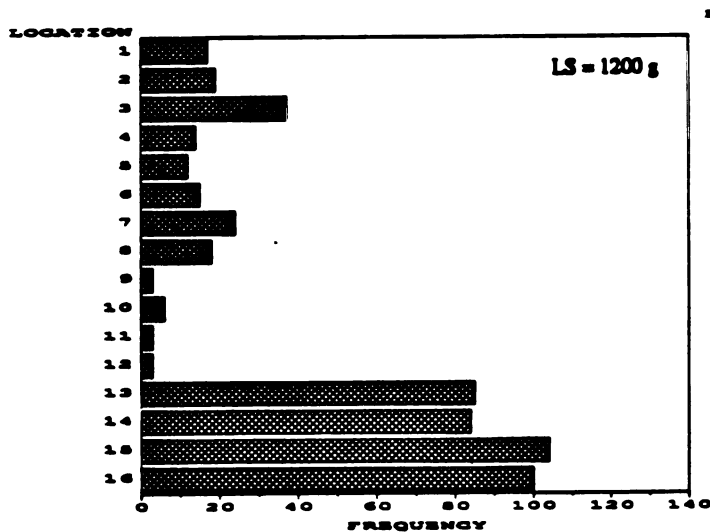
240a



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
15	15	2.13	2.13
25	41	3.69	5.82
25	66	3.64	9.46
5	72	0.87	10.33
35	110	5.40	15.73
15	123	1.66	17.47
50	176	7.53	25.00
65	245	9.80	34.80
15	260	2.13	36.93
10	270	1.42	38.35
15	287	2.41	40.77
25	316	4.12	44.89
72	388	10.23	55.11
113	501	16.08	71.19
122	623	17.33	88.52
81	704	11.51	100.00



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
49	49	9.01	9.01
4	53	0.74	9.74
4	57	0.74	10.48
52	109	9.56	20.04
44	153	8.09	28.13
43	196	7.90	36.03
9	205	1.68	37.71
14	219	2.87	40.58
2	221	0.37	40.95
3	224	0.58	41.53
14	238	2.87	44.40
6	244	1.10	45.50
65	309	11.98	57.48
56	365	10.29	67.77
93	458	17.10	84.87
56	514	15.11	100.00

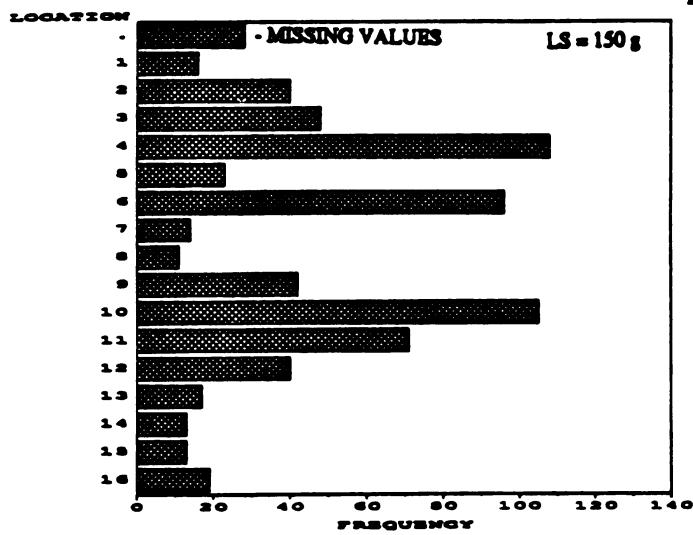


FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
17	17	3.13	3.13
19	36	3.49	6.62
37	73	6.80	13.42
14	87	2.87	16.29
12	99	2.21	18.50
15	114	2.76	21.26
24	138	4.41	25.67
18	156	3.31	28.98
3	159	0.88	29.86
6	165	1.10	30.96
3	168	0.88	31.84
3	171	0.88	32.72
85	256	15.63	48.35
84	340	15.44	63.79
104	444	19.12	82.91
100	544	18.38	100.00

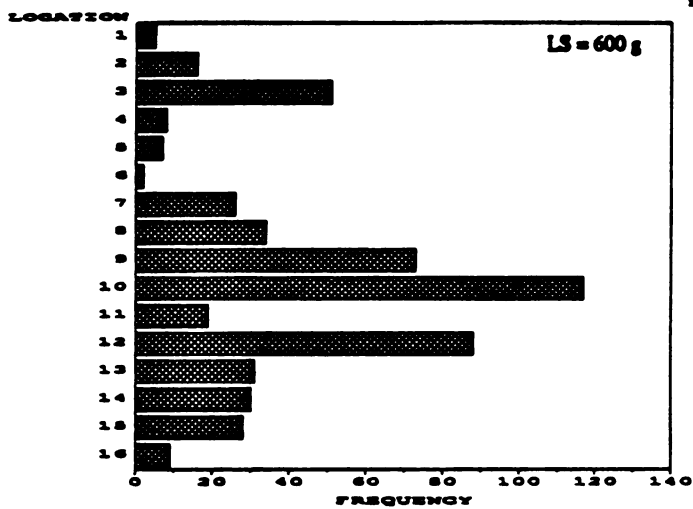
Figure 49.

Figure 50. The frequency of location distribution for a group of the four lowest end-point temperatures (EPTs) within in a loaf (varied load size [LS] of beef, turkey or BGB).

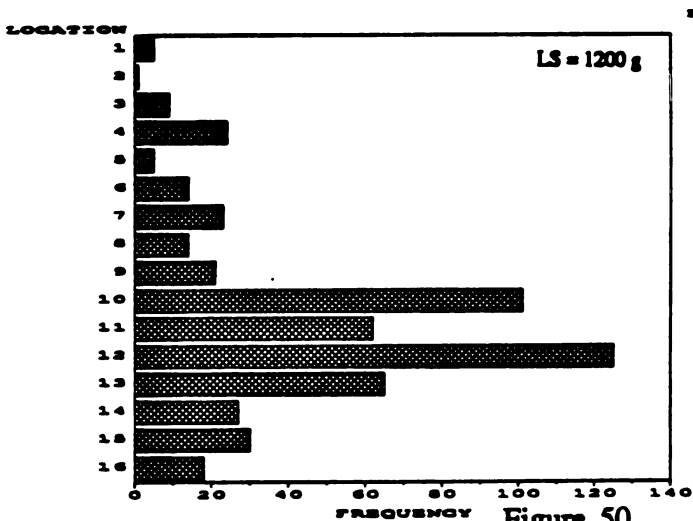
241a



FREQ	SUM FREQ	PERCENT	SUM PERCENT
25	25	3.98	3.98
15	44	2.27	6.28
40	84	8.68	11.93
45	132	6.82	18.75
105	240	18.34	34.09
23	263	3.27	37.36
95	389	13.64	50.99
14	373	1.99	52.98
11	384	1.86	54.85
42	426	8.97	60.81
105	531	14.91	75.43
71	602	10.09	85.51
40	642	8.68	91.19
17	659	2.41	93.61
13	672	1.88	95.48
13	685	1.88	97.30
19	704	2.70	100.00



FREQ	SUM FREQ	PERCENT	SUM PERCENT
5	5	0.92	0.92
15	21	2.94	3.86
51	72	9.38	13.24
8	80	1.47	14.71
7	87	1.29	16.00
2	89	0.37	16.36
25	115	4.78	21.14
34	149	6.28	27.39
73	222	13.42	40.81
117	339	21.81	62.32
19	358	3.49	65.81
85	443	16.18	81.99
31	477	8.70	87.68
30	507	8.81	93.20
25	532	8.18	98.38
9	544	1.68	100.00

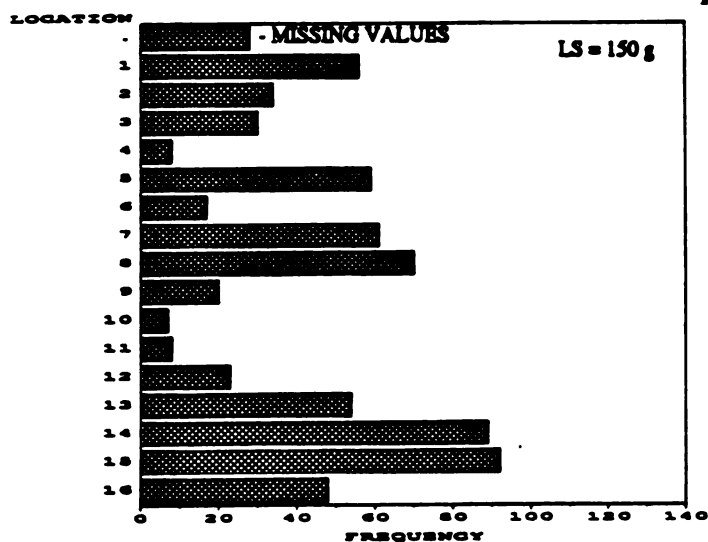


FREQ	SUM FREQ	PERCENT	SUM PERCENT
5	5	0.92	0.92
1	6	0.18	1.10
9	15	1.68	2.76
24	39	4.41	7.17
5	44	0.92	8.09
14	58	2.87	10.86
23	81	4.23	14.89
14	95	2.87	17.46
21	116	3.86	21.32
101	217	18.87	39.89
52	279	11.40	51.29
125	404	22.98	74.26
55	459	11.98	86.21
27	486	4.96	91.16
30	526	8.81	95.69
18	544	3.31	100.00

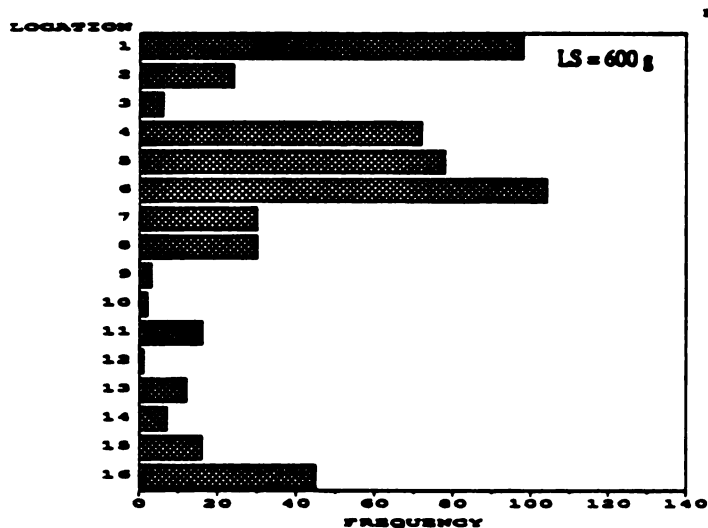
Figure 50.

Figure 51. The frequency of location distribution for a group of the four highest end-point temperatures (EPTs) within in a loaf (varied load size [LS] of beef, turkey or BGB). and EPTs within a loaf to evaluate the effects of experimental variables on temperature variation.

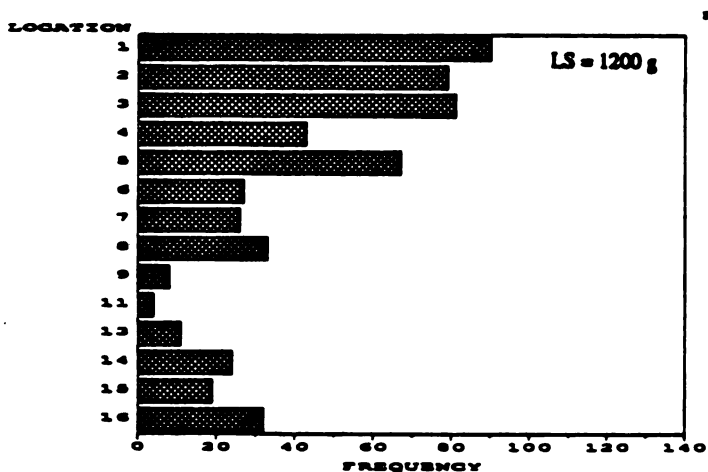
242a



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
28	28	3.98	3.98
56	84	7.98	11.93
34	118	4.83	16.76
30	148	4.26	21.02
8	156	1.14	22.16
59	215	8.38	30.54
17	232	2.41	32.95
61	293	8.66	41.62
70	363	9.94	51.56
20	383	2.84	54.40
7	390	0.99	55.40
8	398	1.14	56.53
23	421	3.27	59.80
54	475	7.67	67.47
89	564	12.64	80.11
92	656	13.07	93.18
48	704	6.82	100.00



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
98	98	18.01	18.01
24	122	4.41	22.43
8	130	1.10	23.53
72	200	13.24	36.76
78	278	14.34	51.10
104	382	19.12	70.22
30	412	5.51	75.74
30	442	5.51	81.25
3	445	0.55	81.80
2	447	0.37	82.17
16	463	2.94	85.11
1	464	0.18	85.29
12	476	2.21	87.50
7	483	1.29	88.79
16	499	2.94	91.73
45	544	8.27	100.00



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
90	90	16.84	16.84
79	169	14.82	31.67
81	250	14.89	46.56
43	293	7.90	54.46
67	360	12.32	66.78
27	387	4.96	71.74
26	413	4.78	76.52
33	446	6.07	82.59
8	454	1.47	84.06
4	458	0.74	84.80
11	469	2.02	86.82
24	493	4.41	91.23
19	512	3.49	94.72
32	544	5.88	100.00

Figure 51.

(PPTRs) and sum of temperature rise (STRs) within a loaf and RMPTR, RPPTR, RSTR: the range of 16 MPTRs, PPTRs and STRs within a loaf were used in place of the log value of standard deviation and range of 16 after-processing temperatures (APTs) within a loaf.

The result of the ANOVA showed that all of the main effects of independent variables (except PW) on LMPTR and RMPTR were significant ($p \leq 0.002$; Appendix 9). All of the main effects of independent variables on LPPTR and RPPTR were significant ($p \leq 0.01$). The main effect of independent variables on LMPTR, RMPTR, LPPTR and RPPTR were identical, but were not for LSTR and RSTR (Appendix 9). As for the variation of 16 STRs within a loaf, all of the main effects of independent variables (except MP) had significant effect ($p \leq 0.05$) on LSTR, but only PW, LS and EMD had significant effect ($p \leq 0.001$) on RSTR (Appendix 9). The significant interactions ($p \leq 0.1$) of independent variables on temperature variation were also existed and will be discussed later (Appendix 9).

Analyses showed that although the LPPTR and RPPTR of beef loaves that were wrapped in PVDC film were increased, the temperature variation in terms of LSTR and RSTR was reduced (Table 15). This result confirmed the study of Sawyer et al. (1984) that PVDC wrapping improved the microwave heating patterns.

One would expect PW had no effect on LMPTR and RMPTR, because PVDC film was transparent to microwave (no microwave energy was reduced by wrapping with PVDC film). Therefore beef loaves, whether wrapped with PVDC film or not were exposed to identical microwave energy when other treatments were identical. Although beef loaves that were wrapped with PVDC film, had higher PPTR and

Table 15. The main effect of polyvinylidene chloride (PW), percent fat content (PFC), microwave output power (MP), load size (LS) and exposed microwave dose (EMD) on temperature variation of beef loaves after microwave processing (2450 MHz).

Independent variables	Treatment	Sample size (n)	Mean* of					
			LMPTR	RMPTR	LPPTR	RPPTR	LSTR	RSTR
PW	1	144	2.309 ^{A#}	35.4 ^A	2.116 ^A	30.5 ^A	1.651 ^B	18.8 ^B
	-1	144/137 [†]	2.336 ^A	35.9 ^A	1.944 ^B	26.8 ^B	1.726 ^A	20.8 ^A
LS (g)	150	96/89 [†]	2.195 ^B	32.3 ^C	1.521 ^C	18.0 ^C	1.895 ^A	23.9 ^A
	600	96	2.368 ^A	36.0 ^B	2.191 ^B	31.1 ^B	1.678 ^B	19.7 ^B
	1200	96	2.404 ^A	38.7 ^A	2.347 ^A	36.1 ^A	1.493 ^C	15.7 ^C
MP (%)	100	144/141 [†]	2.403 ^A	38.1 ^A	2.107 ^A	30.8 ^A	1.693 ^A	19.8 ^A
	50	144/140 [†]	2.242 ^B	33.2 ^B	1.957 ^B	26.5 ^B	1.684 ^A	19.9 ^A
PFC (%)	10	96	2.388 ^A	37.2 ^A	2.092 ^A	30.4 ^A	1.638 ^A	19.3 ^A
	20	96/89 [†]	2.302 ^B	35.2 ^{A,B}	1.994 ^A	27.5 ^B	1.718 ^A	20.2 ^A
	30	96	2.277 ^B	34.6 ^B	2.009 ^A	28.0 ^{A,B}	1.710 ^A	19.9 ^A
EMD (W x min/g)	3.57	72	2.424 ^A	38.9 ^A	2.094 ^A	30.2 ^A	1.779 ^A	22.7 ^A
	4.75	72	2.374 ^{A,B}	37.2 ^{A,B}	2.043 ^A	29.4 ^{A,B}	1.757 ^{A,B}	21.1 ^{A,B}
	5.94	72/68 [†]	2.309 ^B	35.5 ^B	2.057 ^A	29.0 ^{A,B}	1.675 ^B	19.2 ^B
	7.13	72/69 [†]	2.183 ^C	31.1 ^C	1.931 ^B	25.9 ^B	1.544 ^C	16.3 ^C

Key:

LMPTR = log value of standard deviation of 16 microwave processing temperature rises (MPTRs) within a loaf.

RMPTR = range of 16 microwave processing temperature rises (MPTRs) within a loaf.

LPPTR = log value of standard deviation of 16 post processing temperature rises (PPTRs) within a loaf.

RPPTR = range of 16 post processing temperature rises (PPTRs) within a loaf.

LSTR = log value of standard deviation of 16 sum of temperature rises or MPTRs + PPTRs (STRs) within a loaf.

RSTR = range of 16 sum of temperature rises or MPTRs + PPTRs (STRs) within a loaf.

PW, 1 = wrapped in PVDC film; -1 = not wrapped.

Footnotes:

* Average over the rest of independent variables not involved in a specific main effect.

† Sample size for LPPTR and RPPTTR (due to missing values).

Means with the same letter in the same cell are not significantly different ($p > 0.05$ by Tukey's test).

As LS decreased, temperature variation in terms of LMPTR, RMPTR, LPPTR and RPPTR was decreased significantly (approval of H_0 ; Section 3.5.1.3). This result confirmed the suggestion of Schiffmann (1986) and Decareau (1975) that use of small load size decreased temperature variability after microwave processing. On the other hand, LSTR and RSTR significantly increased as LS decreased (Table 15). Beef loaves that had been processed at 50% output power had significantly lower LMPTR, RMPTR, LPPTR and RPPTR, than did beef loaves that had been processed at 100% output power, but had no effect on LSTR and RSTR (Table 15). Temperature uniformity was improved by using lower output power because prolonged processing time allowed temperature to be equilibrated better within a loaf.

Although beef loaves with higher PFC had lower LMPTR and RMPTR, the effect of PFC on LSTR and RSTR was not significant ($p > 0.05$; Table 15). When beef loaves were exposed to a greater microwave dose, the temperature variation in terms of LMPTR, RMPTR, LPPTR and RPPTR had a tendency to decrease. So did the LSTR and RSTR (Table 15).

The inconsistent results among variations of MPTR, PPTR and STR mentioned above were due to the existence of correlation ($R=-0.33$) between MPTR and PPTR. Since STR was the total of MPTR and PPTR, one would expect STR had small variation if the variations of both MPTR and PPTR were small. This was truth only if there was no correlation between MPTR and PPTR. When MPTR and PPTR were correlated, the variance of STR was the total of the variances of MPTR and PPTR plus twice of their covariance (Gill, 1978).

In the present study, the variance of STR was larger than that of MPTR and PPTR, therefore, from the statistical point of view, STR was not as strong as MPTR or PPTR to be used to evaluate the effect of independent variables on temperature variation within a loaf. The results of LSTR and RSTR should be ignored.

Based on the results of the effect of independent variables on temperature variation within a loaf, the optimal microwave processing conditions, which can improve temperature uniformity, are the combination of: (1) wrapped with PVDC film; (2) used 150 g load size; (3) contained 20% fat; (4) used 50% or less output power and (5) used 7.13 watt x min/g of EMD.

The plotted response lines of each significant two-way interaction ($p \leq 0.1$) on temperature variation are shown in Figures 52-54. The result of ANOVA (Appendix 9) showed that the variation of 16 MPTRs within a loaf (LMPTR and RMPTR) were affected by the interactions of PW and EMD, LS and EMD, LS and MP, as well as PFC and EMD (Figure 52:A-H). LMPTR was affected by the interaction of MP and EMD, and RMPTR was affected by the interaction of PW and MP (Figure 52:I and J).

The variation of 16 PPTRs within a loaf (LPPTR) was affected by the interactions of PW and LS, PFC and EMD, LS and PFC, LS and EMD, as well as LS and MP (Figure 53:A-E). The RPPTR was affected by the interactions of LS and MP as well as PW and EMD (Figure 53:F and G). The variation of 16 STRs within a loaf (LSTR and RSTR) were affected by the interaction of LS and EMD. The RSTR was also affected by the interaction of PW and EMD (Figure 54:A-C).

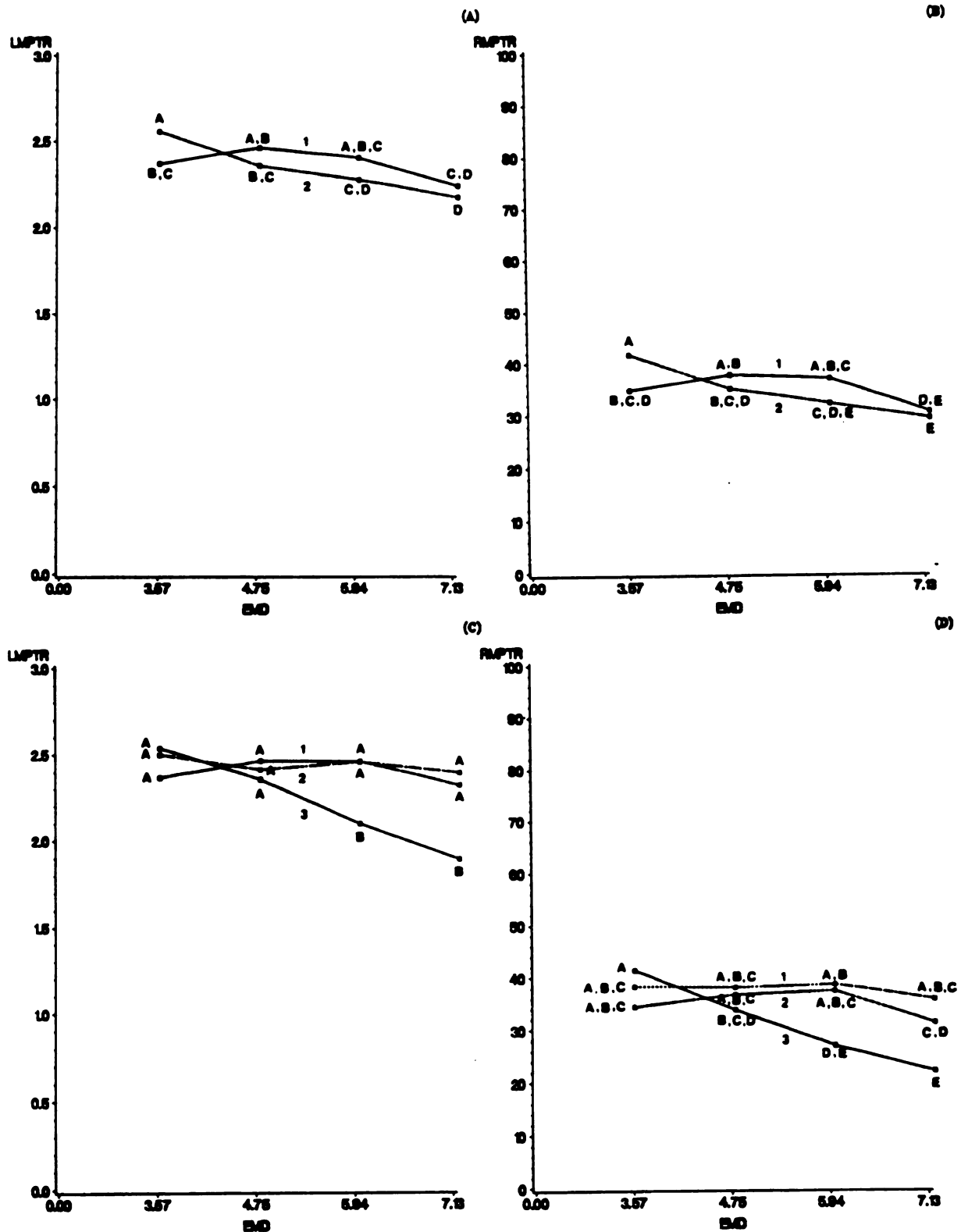
In general, either log value of standard deviation or range of 16 temperature rises (MPTRs, PPTRs and STRs) within a loaf could be used as an indicator for

Figure 52. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean* log value and range of 16 microwave processing temperature rises (LMPTRs and RMPTRs) within a loaf for beef loaves after microwave processing (2450 MHz).

- Fig. 52-A:** Interaction plot of PW and EMD on LMPTR, line 1 - not wrapped, line 2 - wrapped with PVDC film.
- Fig. 52-B:** Interaction plot of PW and EMD on RMPTR, line 1 - not wrapped, line 2 - wrapped with PVDC film.
- Fig. 52-C:** Interaction plot of LS and EMD on LMPTR, line 1 - LS=600 g, line 2 - LS=1200 g, line 3 - LS=150 g.
- Fig. 52-D:** Interaction plot of LS and EMD on RMPTR, line 1 - LS=1200 g, line 2 - LS=600 g, line 3 - LS=150 g.
- Fig. 52-E:** Interaction plot of LS and MP on LMPTR, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).
- Fig. 52-F:** Interaction plot of LS and MP on RMPTR, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).
- Fig. 52-G:** Interaction plot of PFC and EMD on LMPTR, line 1 - PFC=10%, line 2 - PFC=20%, line 3 - PFC=30%.
- Fig. 52-H:** Interaction plot of PFC and EMD on RMPTR, line 1 - PFC=10%, line 2 - PFC=20%, line 3 - PFC=30%.
- Fig. 52-I:** Interaction plot of MP and EMD on LMPTR, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).
- Fig. 52-J:** Interaction plot of PW and MP on RMPTR, line 1 - not wrapped, line 2 - wrapped with PVDC film.

* Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

LMPTR = LOG VALUE OF STANDARD DEVIATION OF 16 MICROWAVE PROCESSING TEMPERATURE RISES (MPTR_s) WITHIN A LOAF (°C).

RMPTR = RANGE OF 16 MICROWAVE PROCESSING TEMPERATURE RISES (MPTR_s) WITHIN A LOAF (°C).

Figure 52.

247b

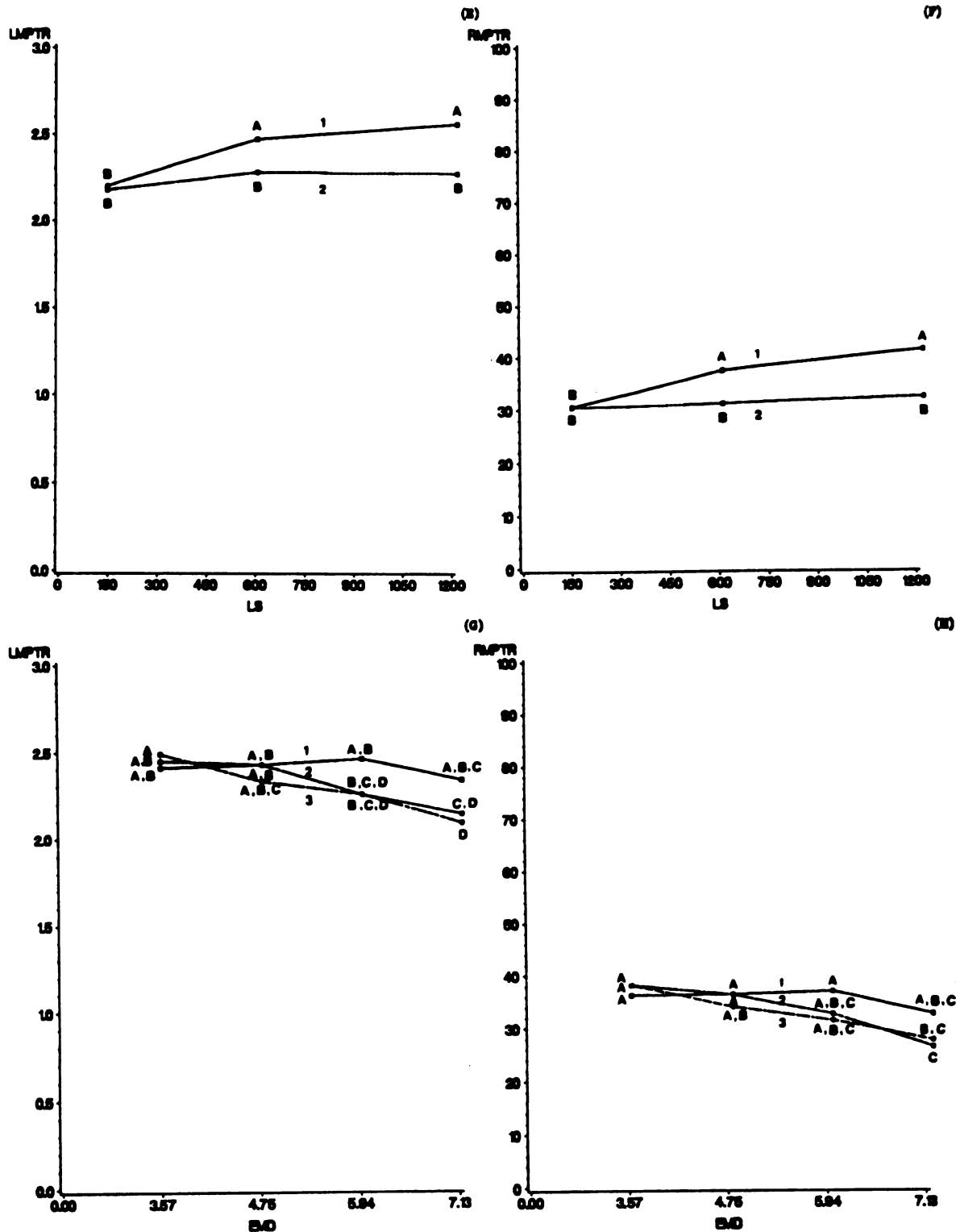
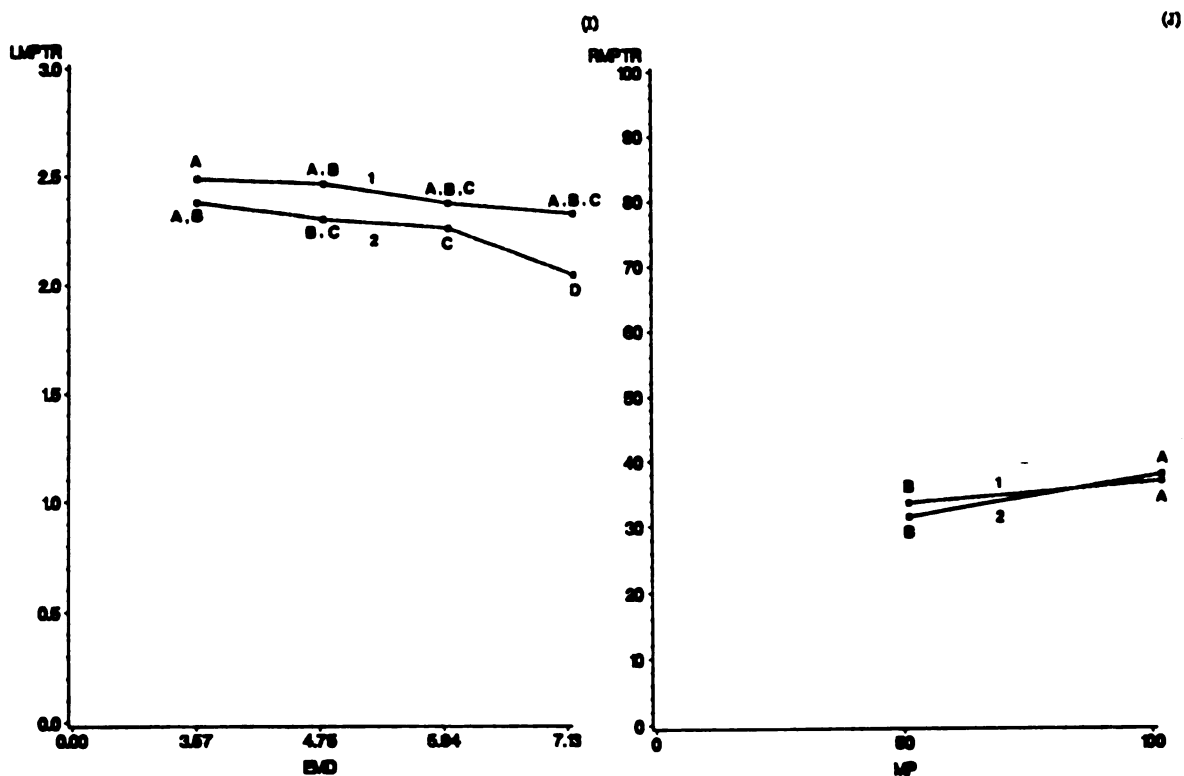


Figure 52 (cont'd).



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

MP = MICROWAVE OUTPUT POWER (%).

LMPTR = LOG VALUE OF STANDARD DEVIATION OF 16 MICROWAVE PROCESSING TEMPERATURE RISES (MPTR_s) WITHIN A LOAF (°C).

RMPTR = RANGE OF OF 16 MICROWAVE PROCESSING TEMPERATURE RISES (MPTR_s) WITHIN A LOAF (°C)

Figure 52 (cont'd).

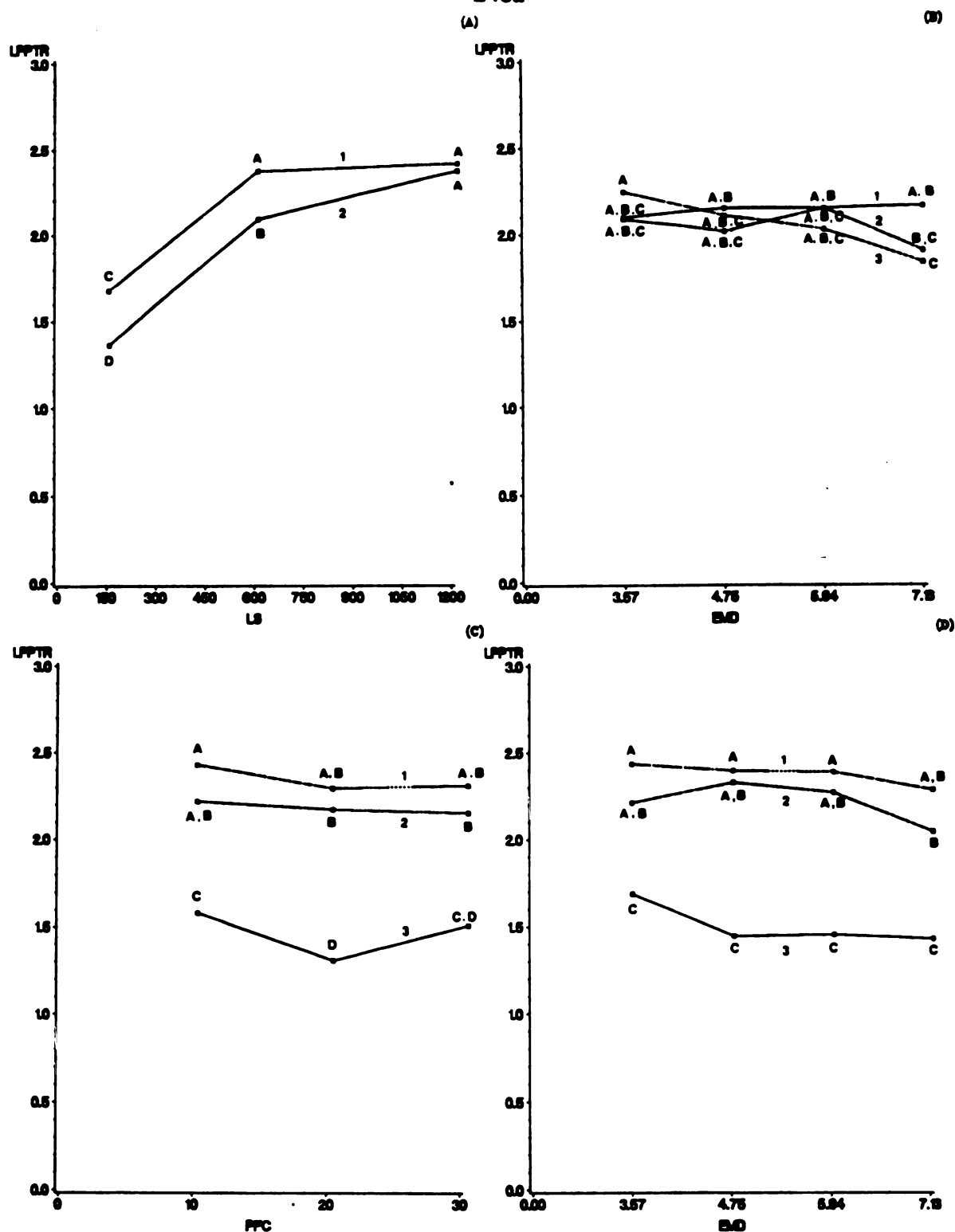
Figure 53. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), microwave output power (MP), percent fat content (PFC), and exposed microwave dose (EMD) on mean^{*} log value and range of 16 post processing temperature rises (LPPTRs and RPPTRs) within a loaf for beef loaves after microwave processing (2450 MHz).

- Fig. 53-A:** Interaction plot of PW and LS on LPPTR, line 1 - not wrapped, line 2 - wrapped with PVDC film.
- Fig. 53-B:** Interaction plot of PFC and EMD on LPPTR, line 1 - PFC=10%, line 2 - PFC=20%, line 3 - PFC=30%.
- Fig. 53-C:** Interaction plot of LS and PFC on LPPTR, line 1 - LS=1200 g, line 2 - LS=600 g, line 3 - LS=150 g.
- Fig. 53-D:** Interaction plot of LS and EMD on LPPTR, line 1 - LS=1200 g, line 2 - LS=600 g, line 3 - LS=150 g.
- Fig. 53-E:** Interaction plot of LS and MP on LPPTR, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).
- Fig. 53-F:** Interaction plot of LS and MP on RPPTR, line 1 - MP=100% output power (713 ± 5 W), line 2 - MP=50% output power (356 ± 3 W).
- Fig. 53-G:** Interaction plot of PW and EMD on RPPTR, line 1 - wrapped with PVDC film, line 2 - not wrapped.

^{*} Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).

248a



LS = LOAD SIZE (G).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

PFC = PERCENT FAT CONTENT (%).

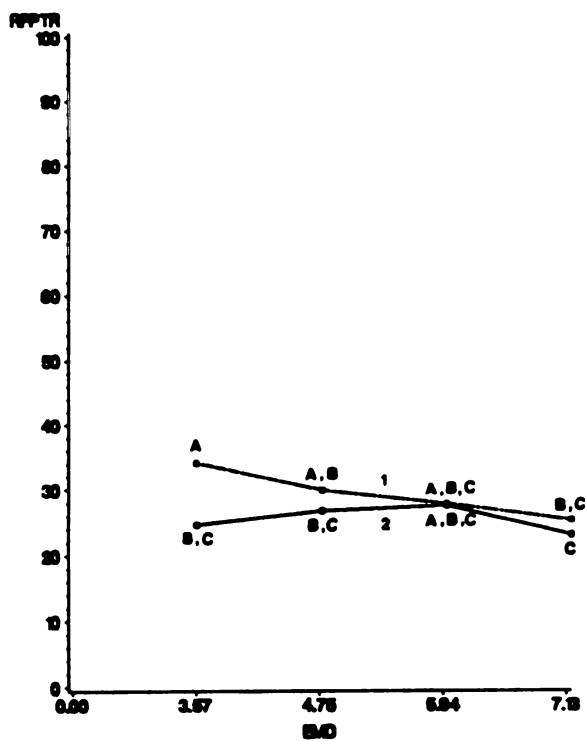
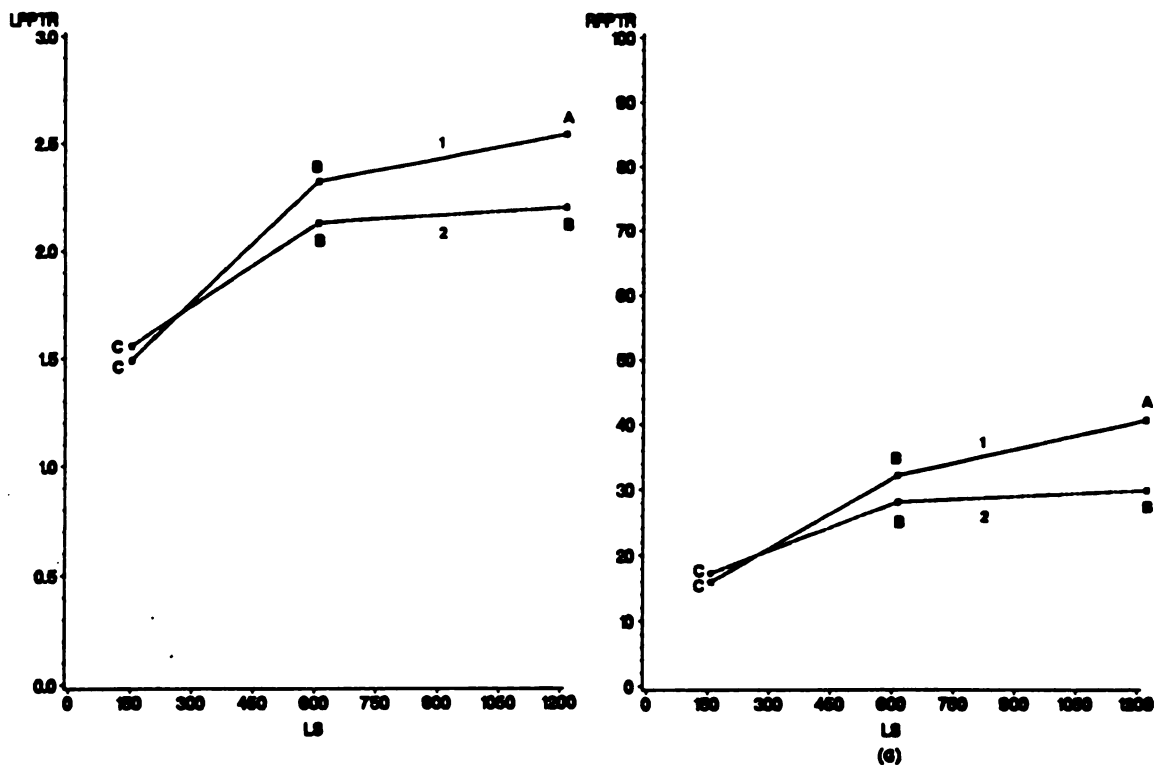
LPPTR = LOG VALUE OF STANDARD DEVIATION OF 16 POST PROCESSING TEMPERATURE RISES (PPTRs) WITHIN A LOAF (°C).

Figure 53.

248b

(B)

(7)



LS = LOAD SIZE (G).

EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

LPPTR = LOG VALUE OF STANDARD DEVIATION OF 16 POST PROCESSING TEMPERATURE RISES (PPTRs) WITHIN A LOAF (°C).

RPPTR = RANGE OF 16 POST PROCESSING TEMPERATURE RISES (PPTRs) WITHIN A LOAF (°C).

Figure 53 (cont'd).

Figure 54. The significant two-way interaction plots of polyvinylidene chloride wrapping (PW), load size (LS), and exposed microwave dose (EMD) on mean log value and range of 16 post processing temperature rises (LSTRs and RSTRs) within a loaf for beef loaves after microwave processed (2450 MHz).

Fig. 54-A: Interaction plot of LS and EMD on LSTR, line 1 - LS=150g, line 2 - LS=600 g, line 3 - LS=1200 g.

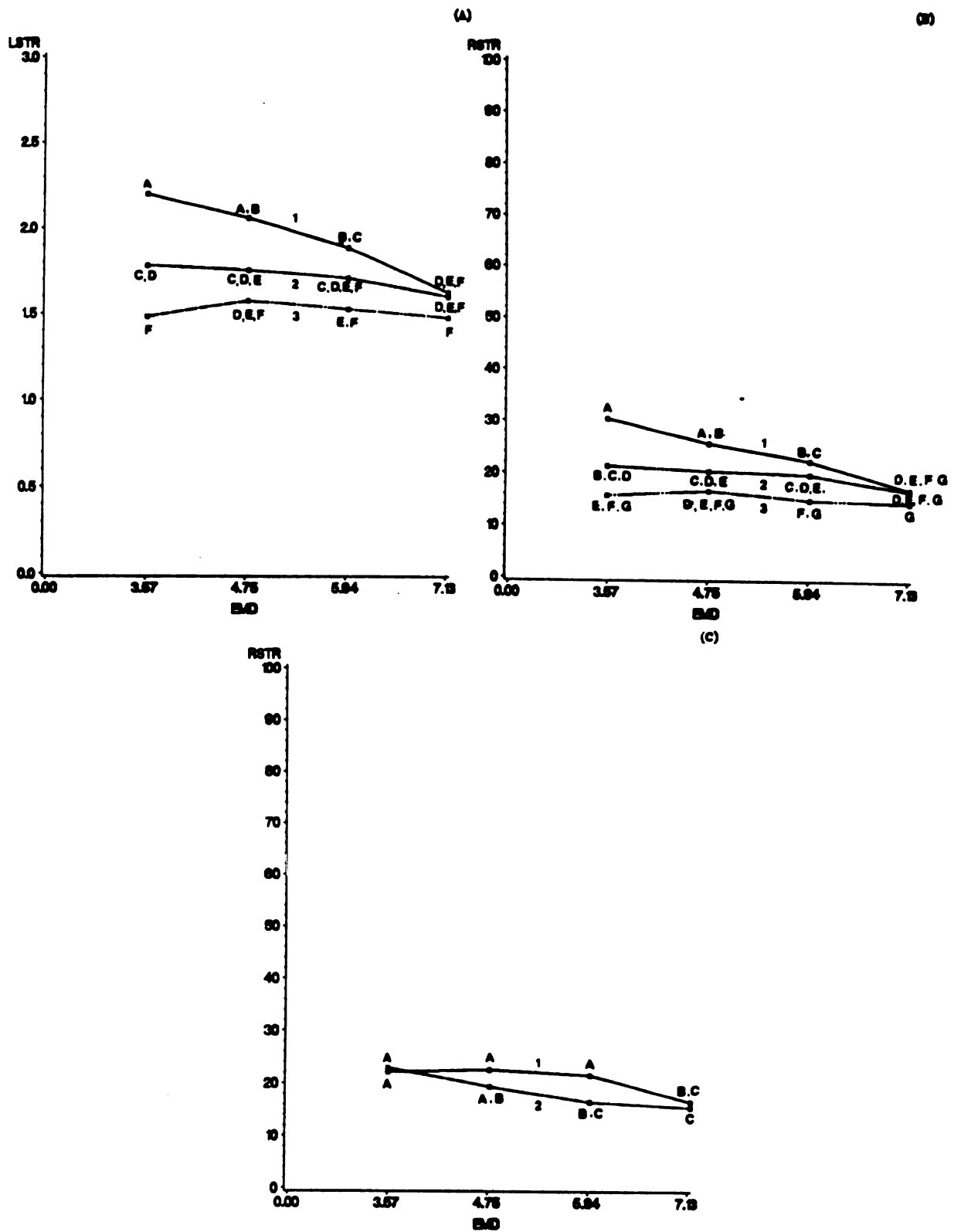
Fig. 54-B: Interaction plot of LS and EMD on RSTR, line 1 - LS=150g, line 2 - LS=600 g, line 3 - LS=1200 g.

Fig. 54-C: Interaction plot of PW and EMD on RSTR, line 1 - not wrapped, line 2 - wrapped with PVDC film.

* Average over the rest of factors not involved in a specific 2-way interaction.

Footnote: nonparallel lines = significant ($p \leq 0.1$) interactions.
means with the same letter next to data points were not significantly different ($p > 0.05$ by Tukey's test).

249a



EMD = EXPOSED MICROWAVE DOSE (WATT x MIN / G), 2450 MHz.

LSTR = LOG VALUE OF STANDARD DEVIATION OF 16 SUM OF TEMPERATURE RISES or MPTR_s + PPTR_s (STR_s) WITHIN A LOAF (°C).

RSTR = RANGE OF 16 SUM OF TEMPERATURE RISES or MPTR_s + PPTR_s (STR_s) WITHIN A LOAF (°C).

Figure 54.

evaluating the temperature variation. The interaction plots between a pair of LMPTR and RMPTR or LPPTR and RPPTR or LSTR and RSTR responded similar to the interactions of independent variables, hence either log value of standard deviation or range of temperature rise could be considered good indicators for evaluating temperature variation (Figure 52:A vs. B, C vs. D, E vs. F, G vs. H; Figure 53:E vs. F; Figure 54:A vs. B).

When compared to meat loaves, the temperature variation within a BGB loaf (LMPTR or RMPTR, LPPTR or RPPTR, and LSTR or RSTR) was not significantly decreased. This may be interpreted to mean that the temperature variation was not improved by using a theoretically more homogeneous product such as BGB loaf. It was very likely that the homogeneity of meat loaves was good enough to keep temperature variation to a satisfactory range so that even the introduction of BGB could not improve the temperature variation (rejection of H_0 ; Section 3.2.1.2).

Although BGB dispersions could not further improve the temperature variation within a product, it still has the potential to be a simulation model for meat loaves (10% fat) to study bacterial survival, thermal responses and evaporation loss after microwave processing. To use BGB is economical because bentonite is much cheaper than meat and is reprocessible.

5.9 Summary of Results

The significant levels of main effects and the significant ($p \leq 0.1$) two-way interactions of independent variables (PVDC wrapping or PW, load size or LS, microwave output power or MP, percent fat content or PFC, exposed microwave

diose or EMD and type of loaf or TL) on dependent variables (bacterial survival, thermal responses, evaporation loss and temperature variation within a loaf; Tables 3, 4) are summarized in this section. Lastly, the summary of the effects of independent variables on dependent variables and the optimal microwave processing to achieve best microbial quality, improved thermal responses, evaporation loss and temperature variation for beef loaves are given.

Although target temperature has been used to indicate the microbial safety of food products that have been processed by microwave radiation [F.D.A., 1988; USDHEW,1978], the results of this study were in agreement with those of Bakanowski and Zoller (1984) and Bryan and Lyon (1984) who reported that it was almost impossible to accurately locate and measure the location of lowest temperature in food products processed by microwave energy. In the present study, only 11 out of 367 temperature readings recorded by a Luxtron thermoprobe (single channel) were within $\pm 2^{\circ}\text{C}$ accuracy of the lowest temperature readings recorded by 16 thermocouples placed in a loaf after microwave processing.

5.9.1 Significant levels of main effects of independent variables

The ANOVA results of bacterial survival, thermal responses, evaporation loss and temperature variation within a loaf for beef loaves, turkey loaves and BGB loaves are shown in Table 16. The significant levels of main effects of independent variables (PW, LS, MP, PFC, EMD and TL) on bacterial survival, thermal responses, evaporation loss and temperature variation within a loaf are summarized in Table 16.

Table 16. Summary of the significant levels of main effects of polyvinylidene chloride (PW), load size (LS), microwave output power (PM), percent fat content (PFC), exposed microwave dose (EMD) and type of loaf (TL) on bacterial survival, thermal responses, evaporation loss and temperature variation of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).

Dependent variables	Independent variables																													
	PW					LS					MP					PFC					EMD					TL				
	1 ^a	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5					
LAB	hs	hs	na	hs	na	s	s	na	na	na	s	na	hs	na	na	hs	hs	hs	hs	hs	hs	na	na	na	na	na				
LBC	hs	hs	na	hs	na	s	hs	na	na	s	hs	na	hs	na	na	hs	hs	hs	hs	hs	hs	na	na	na	na	na				
LSA	hs	hs	na	hs	na	hs	hs	na	na	s	hs	na	hs	na	na	hs	hs	hs	hs	hs	hs	na	na	na	na	na				
EPT	hs	hs	na	hs	na	hs	hs	na	na	hs	hs	na	hs	na	na	hs	hs	hs	hs	hs	hs	na	na	na	na	na				
MPTR	hs	na	na	hs	na	hs	s	na	na	hs	hs	na	hs	na	na	hs	hs	hs	hs	hs	hs	na	na	na	na	s				
PPTR	hs	hs	na	hs	na	hs	hs	s	na	s	hs	na	hs	na	na	hs	s	na	s	na	na	na	na	na	na	na				
STR	hs	hs	na	hs	na	hs	s	na	hs	na	hs	na	hs	na	na	hs	hs	hs	hs	hs	hs	na	na	na	na	na				
TPPTR	hs	hs	na	hs	na	hs	hs	na	na	hs	s	s	na	hs	na	na	na	na	na	na	na	na	na	na	na	na				
PEL	hs	hs	na	hs	na	hs	hs	na	na	hs	hs	na	hs	na	na	hs	hs	hs	hs	hs	hs	na	na	na	na	hs				
LAPT	na	na	na	na	na	hs	na	na	na	hs	na	na	na	na	na	hs	na	hs	na	na	na	na	na	na	na	na				
LEPT	s	na	na	na	na	hs	hs	na	na	hs	na	na	na	na	na	s	na	na	na	na	na	na	na	na	na	na				
LMPTR	na	na	na	na	na	hs	hs	na	na	hs	na	na	na	na	na	hs	na	hs	na	na	na	na	na	na	na	na				
LPTR	hs	s	na	s	na	hs	na	na	s	na	hs	na	hs	na	na	s	na	hs	na	na	na	na	na	na	na	na				
LSTR	s	na	na	na	na	hs	na	na	na	hs	na	na	na	na	na	s	na	hs	na	na	na	na	na	na	na	na				
RAPT	na	na	na	na	na	hs	s	na	na	hs	na	na	na	na	na	s	na	hs	na	na	na	na	na	na	na	na				
REPT	hs	na	na	hs	na	hs	hs	na	na	s	na	na	hs	na	na	na	hs	na	s	hs	na	na	na	na	na	s				
RMPTTR	na	na	na	na	na	hs	s	na	na	hs	na	s	na	hs	na	na	hs	na	na	na	na	na	na	na	na	na				
RPPTTR	hs	na	na	s	na	hs	hs	na	na	hs	na	s	na	hs	na	s	na	hs	na	na	na	na	na	na	na	na				
RSTR	hs	na	na	hs	na	hs	hs	na	na	s	na	na	hs	na	na	na	hs	na	s	hs	na	na	na	na	na	s				

Key:

hs = highly significant ($p \leq 0.001$), na = not applicable, ns = not significant ($p > 0.05$), s = significant ($p \leq 0.05$).

LAB = log value of (% surviving aerobic bacteria+1), LBC = log value of (% surviving *Escherichia coli*+1), LSA = log value of (% surviving *Staphylococcus aureus*+1), EPT = end-point temperature ($^{\circ}\text{C}$), MPTR = microwave processing temperature rise ($^{\circ}\text{C}$), PPTR = post processing temperature rise ($^{\circ}\text{C}$), STR = sum of temperature rise or MPTR+PPTR ($^{\circ}\text{C}$), TPPTR = time of PPTR (sec.), PEL = percent evaporation loss (%), LAPT = log value of standard deviation of 16 after-processing temperature (APT) within a loaf, LEPT = log value of standard deviation of 16 end-point temperature (EPT) within a loaf, LMPT = log value of standard deviation of 16 microwave processing temperature rises (MPTRs) within a loaf, LPPTTR = log value of standard deviation of 16 post processing temperature rises (PPTRs) within a loaf, LSTR = log value of standard deviation of 16 sum of temperature rises or MPTRs + PPTRs (STRs) within a loaf, RAPT = range of 16 after-processing temperature (APT) within a loaf, REPT = range of 16 end-point temperature (EPT) within a loaf, RMPTTR = range of 16 microwave processing temperature rises (MPTRs) within a loaf, RPPTTR = range of 16 post processing temperature rises (PPTRs) within a loaf, RSTR = range of 16 sum of temperature rises or MPTRs + PPTRs (STRs) within a loaf.

Footnote:

Subjects of data analysed:

- 1 = beef (10, 20 and 30% fat), 2 = turkey (10% fat), 3 = 150 g of benzonite-glycerol-BHI broth (BGB), 4 = beef & turkey (10% fat), 5 = beef (10% fat) & BGB (10% glycerol).

^a The main effect of replication (REP) was not significant in all cases (except on LPPTTR and RPPTTR for the subset of BGB (150 g)).

In general, PW had significant effect on bacterial survival, thermal responses and evaporation loss of meat loaves. The effect of PW on temperature variation were more selective. PW had a significant effect on the variation of post processing temperature rise and sum of temperature rise (LPPTR, RPPTR, LSTR and RSTR) but had no effect on the variation of microwave processing temperature rise.

LS had significant effect on bacterial survival, thermal responses, evaporation loss and temperature variation within a loaf (beef, turkey and BGB). The effect of MP on bacterial survival varied depending on the type of loaf and the species of bacteria. MP had significant effect on the survival of three types of bacteria in beef loaves and BGB loaves (except survival of aerobic bacteria in BGB loaves). On the other hand, MP had no effect on bacterial survival and temperature variation within a turkey loaf. The effect of MP on thermal responses and evaporation loss was significant for turkey loaves and beef loaves. The effect of MP on temperature variation within a loaf was also significant for beef loaves.

The effect of PFC on bacterial survival, thermal responses, evaporation loss and temperature variation within a loaf was significant for beef loaves and BGB loaves (except for REPT and RSTR in beef loaves). The effect of EMD on bacterial survival, thermal responses and evaporation loss was significant for beef loaves, turkey loaves and BGB loaves (except for PPTR in BGB loaves). The effect of EMD on temperature variation within a loaf was not significant for turkey loaves, but was significant for beef loaves and BGB loaves (except for LEPT in BGB loaves).

The effect of TL on bacterial survival was not significant, but was significant for thermal responses, evaporation loss for beef loaves and turkey loaves (10% fat)

as well as meat loaves (10% fat) and BGB loaves (10% glycerol). The effect of TL on temperature variation within a loaf was selective. TL had significant effect on the temperature variation of end-point temperature (LEPT and REPT) and sum of temperature rise (LSTR and RSTR).

5.9.2 Significant two-way interactions of independent variables

The significant ($p \leq 0.1$) two-way interactions of independent variables on bacterial survival, thermal responses and evaporation are listed in Table 17. The significant two-way interactions of independent variables on temperature variations within a loaf are listed in Table 18. The high frequency of appearance (24/92) of interactions which involved replication (REP) in Table 18 indicated that uneven heating was an important factor among loaves that were treated identically.

Based on the sources of variables in Tables 17 and 18, the significant two-way interactions observed in this study can be categorized into three different types: (1) processing-product interaction such as EMD*LS, or PW*MP; (2) product-product interaction such as LS*PFC, PW*LS or TL*PFC and (3) processing-processing interaction such as EMD*MP. These interactions show how complicated the microwave processing is. To better understanding microwave processing, these interactions should be taken into account while studying microwave processing.

The existence of interactions between processing and product and equipment (have not been studied here) in microwave processing is important for developing microwaveable products. The interactions present in this study just lay the basic groundwork for the future study.

Table 17. List of significant two-way interactions of independent variables on bacterial survival, thermal responses and evaporation loss of loaves (beef, turkey and BGB) after microwave processing (2450 MHz)

Dependent variables	Significant two-way interactions
LAB	EMD*LS (1 ⁰ 2,4,5); EMD*MP (1,4); EMD*PFC (1,3); LS*MP (2,4); LS*PFC (1); MP*REP (2); PW*EMD (1,2,4); PW*LS (1,4); PW*MP (4); PW*PFC (1); TL*EMD (5); TL*LS (5).
LEC	EMD*LS (1,2,4,5); EMD*MP (1,4); EMD*PFC (1,3); LS*MP (1,4); LS*PFC (1); PFC*REP (1); PFC*EMD (1,2,4); PW*LS (1); PW*PFC (1); TL*EMD (5); TL*LS (5).
LSA	EMD*LS (1,2,4,5); EMD*MP (1,4); EMD*PFC (1,3); LS*MP (1,4); LS*PFC (1); PW*EMD (1,2,4); PW*LS (4); PW*PFC (1); TL*EMD (5); TL*LS (5).
EPT	EMD*LS (1); EMD*MP (1,2); EMD*PFC (3); EMD*REP (3); LS*MP (1); LS*PFC (1); LS*REP (2); PFC*REP (3); PW*EMD (1,2); PW*LS (2,4); PW*PFC (1); PW*REP (1,2); TL*EMD (4); TL*LS (4,5); TL*PW (4); TL*REP (5).
MPTR	EMD*LS (1); EMD*MP (1,4); LS*MP (1,2,4); LS*PFC (1); LS*REP (2); PW*LS (2,4); PW*REP (1); TL*EMD (4); TL*LS (4,5).
PPTR	EMD*LS (1); EMD*MP (1); EMD*PFC (3); EMD*REP (1,3); LS*MP (1,2,4); PFC*REP (3); TL*LS (4,5).
STR	EMD*LS (1); EMD*MP (1,2); LS*MP (1); LS*PFC (1); LS*REP (2); PFC*REP (3); PW*EMD (1,2,4); PW*LS (4); PW*PFC (1); PW*REP (1,2); TL*EMD (4); TL*LS (4,5).
TPPTR	EMD*LS (1,2,4); LS*MP (1,2,4); LS*PFC (1); LS*REP (4); PW*EMD (4); PW*LS (1,2,4); PW*MP (2); PW*REP (1,2); TL*LS (4,5).
PEL	EMD*LS (1); EMD*MP (1,2,4); EMD*PFC (3); EMD*REP (5); LS*MP (1,2,4); LS*PFC (1); MP*REP (1); PFC*REP (3); PW*EMD (1,2,4); PW*LS (2,4); PW*MP (1,2,4); PW*PFC (1); TL*LS (4,5).

Key:

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec).

PEL = percent evaporation loss (%).

EMD = exposed microwave dose (watts x min/g).

LS = loaf size (g).

MP = microwave output power (%).

PFC = percent fat content (%).

PW = polyvinylidene chloride (PVC) wrapping.

TL = type of loaf.

Footnote:

Numbers within parenthesis represent the subsets of data for which two-way interactions were significant ($p \leq 0.1$).

1 = beef (10, 20 and 30% fat).

2 = turkey (10% fat).

3 = 150 g of bentonite-glycerol-BHI broth (BGB).

4 = beef & turkey (10% fat).

Table 18. List of significant two-way interactions of independent variables on temperature variation of loaves (beef, turkey and BGB) after microwave processing (2450 MHz)

Dependent variables	Significant two-way interactions
LAPT	EMD*LS (1 ⁹ , 4, 5); EMD*MP (1, 2, 4); EMD*PFC (1, 3); EMD*PW (1, 2); LS*MP (1); LS*PW (2, 4); LS*REP (2); MP*REP (2); PFC*REP (1, 3); TL*EMD (5); TL*MP (4); TL*PW (4); TL*REP (5).
LEPT	EMD*LS (1, 4); EMD*PFC (3); EMD*REP (3); LS*REP (1); PFC*REP (3); PW*REP (2); TL*LS (5).
LMPTR	EMD*LS (1, 4, 5); EMD*MP (1, 2, 4); EMD*PFC (1, 3); EMD*PW (1, 2); LS*MP (1); LS*PW (2, 4); LS*REP (2); MP*REP (2); PFC*REP (1, 3); TL*EMD (5); TL*MP (4); TL*PW (4); TL*REP (5).
LPPTR	EMD*LS (1); EMD*PFC (1); EMD*REP (4); LS*MP (1); LS*PFC (1); LS*PW (1, 2, 4); LS*REP (1, 2); MP*PW (4); TL*EMD (5); TL*LS (4); TL*MP (4).
LSTR	EMD*LS (1, 4); EMD*PFC (3); EMD*REP (3); PFC*REP (3); PW*REP (2); TL*LS (5).
RAPT	EMD*LS (1, 4, 5); EMD*PFC (1, 3); EMD*PW (1, 4); LS*MP (1, 4); LS*PW (2, 4); MP*PW (1); MP*REP (1); TL*LS (5); TL*MP (4).
REPT	EMD*LS (1, 4); EMD*MP (4); EMD*PFC (3); EMD*PW (1); PW*REP (2); TL*LS (4); TL*PW (4).
RMPTR	EMD*LS (1, 4, 5); EMD*PFC (1, 3); EMD*PW (1, 4); LS*MP (1, 4); LS*PW (2, 4); MP*PW (1); MP*REP (2); PFC*REP (1); TL*LS (5); TL*MP (4).
RPPTR	EMD*PW (1); EMD*REP (4); LS*MP (1, 4); LS*PW (2, 4); MP*PW (4); TL*LS (5); TL*MP (4).
RSTR	EMD*LS (1, 4); EMD*MP (4); EMD*PW (1); EMD*PFC (3); PW*REP (2); TL*EMD (4); TL*LS (4); TL*PW (4).

Key:

LAPT = log value of standard deviation of 16 after-processing temperature (APT₁₆) within a loaf.

LEPT = log value of standard deviation of 16 end-point temperature (EPT₁₆) within a loaf.

LMPTR = log value of standard deviation of 16 microwave processing temperature rises (MPTR₁₆) within a loaf.

LPPTR = log value of standard deviation of 16 post processing temperature rises (PPTR₁₆) within a loaf.

LSTR = log value of standard deviation of 16 sum of temperature rises or MPTR₁₆ + PPTR₁₆ (STR₁₆) within a loaf.

RAPT = range of 16 after-processing temperature (APT₁₆) within a loaf.

REPT = range of 16 end-point temperature (EPT₁₆) within a loaf.

RMPTR = range of 16 microwave processing temperature rises (MPTR₁₆) within a loaf.

RPPTR = range of 16 post processing temperature rises (PPTR₁₆) within a loaf.

RSTR = range of 16 sum of temperature rises or MPTR₁₆ + PPTR₁₆ (STR₁₆) within a loaf.

Footnote:

Numbers within parenthesis represent the valid loaves in which two-way interactions were significant ($p \leq 0.1$).

1 = beef (10, 20 and 30% fat).

2 = turkey (10% fat).

3 = 150 g of benzonis-glycerol-BHI broth (BGB).

4 = beef & turkey (10% fat).

5 = beef & turkey (10% fat) & BGB (10% glycerol).

5.9.3 Summary of effects of independent variables

The effects of independent variables on bacterial survival, thermal responses, evaporation loss and temperature variation within a loaf are summarized in Table 19. Results showed that PVDC wrapping reduced bacterial survival (approval of Ho5; Section 3.5.1.1) as well as evaporation loss and improved thermal responses as well as temperature variation within a loaf of meat loaves.

Reducing load size could reduce bacterial survival (approval of Ho7; Section 3.5.1.3), increase microwave processing temperature rise (MPTR), post processing temperature rise (PPTR) and sum of temperature rise (STR) as well as improve temperature variation within a loaf of meat loaves. On the other hand, increasing load size could increase post processing temperature rise (PPTR) and time of PPTR (TPPTR) of meat loaves. The effect of load size was minimum in relation to BGB loaf.

By reducing microwave output power to a half of the full power, bacterial survival (approval of Ho8; Section 3.5.2.1), PPTR and TPPTR as well as evaporation loss was decreased. Meanwhile, end-point temperature (EPT), MPTR and STR of meat loaves was increased. Improvement on temperature variation within a meat loaf was also observed.

The effect of fat content was somewhat irregular. In general, increasing fat content of beef loaf could reduce bacterial survival (rejection of Ho4; Section 3.2.2.1). Beef loaves with 20% fat had optimal thermal responses and evaporation loss. The temperature variation within a loaf was improved as fat content of beef loaf increased.

Table 19. Summary of the effects of polyvinylidene chloride (PW), load size (LS), microwave output power (PM), percent fat content (PFC), percent water content (PWC) and exposed microwave dose (EMD) on bacterial survival, thermal responses, evaporation loss and temperature variation of loaves (beef, turkey and BGB) after microwave processing (2450 MHz).

Independent variables	Bacterial survival				Thermal responses				Evaporation loss		Temperature variation					
	LEC	LSA	LAB	EPT	MPTR	STR	PPTR	TPPTR	PEL	LMPTR	RMPTTR	LPPTTR	RPPTTR	LSTR	RSTR	
PW (wrapped)	↓	↓	↓	↑	↑	↑	↑	↑	↓	↓*	↓*	↑	↑	↓	↓	↓
LS ↓	↓	↓	↓	↑†	↑†	↑†	↓	↓	↑†	↓	↓	↓	↓	↑	↑	↑
MP ↓	↓†	↓†	↓†	↑	↑	↑	↓	↓	↓	↓	↓	↓	↓	↓*	↓*	↓*
PFC ↑ (PWC ↓)	↓†	↓*†	↓†	↑§	↑§	↑§	I	I	↓	↓	↓	↓	↓	↑§	↑§	↑§
EMD ↑	↓	↓	↓	↑	↑	↑	I	I	↑	↓	↓	↓	↓	↓	↓	↓

Footnotes:

↓ = decreased.

↑ = increased.

I = irregular.

* not significant ($p > 0.05$).

† except 600 g load size of turkey which had the highest value.

the 600 g load size had the lowest value.

† not significant ($p > 0.05$) for turkey.

‡ except 30% PFC of BGB which had the highest value.

§ 20% PFC of loaves had the highest value.

Key:

LEC = log value of (% surviving *Escherichia coli*+1).

LSA = log value of (% surviving *Staphylococcus aureus*+1).

LAB = log value of (% surviving aerobic bacteria+1).

EPT = end-point temperature (°C).

MPTR = microwave processing temperature rise (°C).

STR = sum of temperature rise or MPTR+PPTR (°C).

PPTR = post processing temperature rise (°C).

TPPTR = time of PPTR (sec.).

PEL = percent evaporation loss (%).

LMPT = log value of standard deviation of 16 microwave processing temperature rises (MPTRs) within a loaf.

RMPTTR = range of 16 microwave processing temperature rises (MPTRs) within a loaf.

LPPTTR = log value of standard deviation of 16 post processing temperature rises (PPTRs) within a loaf.

RPPTTR = range of 16 post processing temperature rises (PPTRs) within a loaf.

LSTR = log value of standard deviation of 16 sum of temperature rises or MPTRs + PPTRs (STRs) within a loaf.

RSTR = range of 16 sum of temperature rises or MPTRs + PPTRs (STRs) within a loaf.

Increasing exposed microwave dose could decrease bacterial survival and increase thermal responses (except PPTR and TPPTR) and evaporation loss of meat loaves and BGB loaf (approval of Ho9; Section 3.6). Improvement of temperature variation within a loaf for beef loaves was observed as exposed microwave dose increased.

The similar bacterial survival among beef loaf, turkey loaf and BGB loaf suggested that BGB loaf had the potential to be a simulation model for bacterial survival of meat loaves (10% fat) after microwave processing (approval of Ho3; Section 3.2.1.2). However, when other factors such as thermal responses and evaporation loss was considered, BGB loaf was a much better simulation model for turkey loaf than beef loaf because the thermal responses were similar between turkey loaf and BGB loaf but not between beef loaf and BGB loaf.

5.9.4 Summary of optimal microwave processing conditions

Based the results of main effects and interactions of independent variables used in the present study, the conditions for microwave processing to achieve the optimal microbial quality, thermal responses, evaporation loss and temperature uniformity are summarized in Table 20.

To achieve the best quality (microbial and organoleptic) and temperature uniformity of beef loaves after microwave processing, the optimal processing conditions are the combination of: (1) wrapped with PVDC film; (2) used 150 g load size; (3) contained 20% fat; (4) used 50% or less output power and (5) used 5.94 watt x min/g of EMD.

Table 20. Summary of optimal microwave processing conditions for microbial quality, thermal responses, evaporation loss and temperature uniformity of beef loaves.

Improvement on	Optimal combination of				
	PW	LS	PFC	MP	EMD
Microbial quality	wrapped	150	≥ 20	≤ 50	≥ 5.94
Thermal responses	wrapped	150	≥ 20	≤ 50	7.13
Evaporation loss	wrapped	600	20	≤ 50	3.75
Temperature uniformity	wrapped	150	20	≤ 50	≥ 5.94
overall quality	wrapped	150	20	≤ 50	5.94

Key:

PW = polyvinylidene chloride (PVDC) wrapping.

LS = load size (g).

PFC = percent fat content (%).

MP = percent microwave output power, 50% = 356 ± 3 watts; 2450 MHz.

EMD = exposed microwave dose (watt x min/g).

The similar combination of optimal microwave processing conditions have a potential to be applied to wide variety of foods. To assure optimal processing conditions can be carried out, the effort of food scientists/microbiologists, food manufacturers and consumers must be put together.

Food scientists can develop the best formula (i.e., choose 20% fat) for microwavable foods. Food microbiologists then determine the proper EMD (i.e., 5.94 watt x min/g) for the products to assure safely microbial quality. Food manufacturers follow the formula developed by food scientist to make into single portion (i.e., 150 g load size). Lastly, consumers must follow the exact processing instruction on the package to wrap the product (if wrapping is not provided in the package) and processing at 50% or less microwave output power.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions drawn from the results of the present study are given in this chapter. Also questions which arose from this study plus areas from the present study in need of improvement are pointed out. Recommendations for the optimal microwave processing of meat loaves as well as for the future studies on microwave processing are also given.

6.1 Conclusions

Major conclusions drawn from the results of this study are given below:

(1) Wrapping foods in which a crispy texture is not required, with a PVDC type film, could be considered an advantage for microwave processing because: microbial quality, product yield and temperature uniformity were improved (approval of Ho5: Section 3.5.1.1) while target end-point temperatures were achieved in shorter times (hence saving energy; Tables 7,15).

(2) The significant effect of load size (approval of Ho7; Section 3.5.1.3) and microwave output power (approval of Ho8; Section 3.5.2.1) on bacterial survival suggested that both factors should be taken into account (explanation in Section 6.2) for the microbial safety of food products that have been microwave processed (Tables 8,9).

(3) Lower bacterial survival (rejection of Ho4; Section 3.2.2.1), higher thermal responses, lower product yield and better temperature uniformity could be achieved

by increasing fat content of the meat loaves from 10% to 30% (Tables 10,15, 19) which is about the fat level for regular hamburger meat. Fat content of higher than 30% is considered too high for consumption by humans.

(4) Although end-point temperature had been used to indicate the microbial safety of food products that had been microwave processed, researchers have repeatedly reported difficulty when trying to accurately locate and measure the location of the lowest temperature in food products processed in microwave ovens. One possible solution to this problem suggested by results of this study was use of exposed microwave dose (EMD). Since EMD was highly correlated to percent survival of bacteria ($R=-0.82$ to -0.83) and the lowest EPT ($R=0.81$) in food and BGB models (Table 11), EMD has the potential to be used to predict bacterial survival in food products that have been processed by microwave radiation (approval of Ho8; Section 3.6). If a standard EMD were to be calculated, an allowable safety range must be included to cover possible consumer ranges of load sizes (150 to 1200 g) and microwave output powers.

(5) The similar bacterial survival between beef loaves and turkey loaves (Table 12) suggested that food products which contained similar ingredients (contain the same major composition such as fat, moisture and/or formulated from the same recipe) but different meats might be categorized into one classification of items for the purpose of microwave processing studies on microbial quality (approval of Ho1; Section 3.2.1.1) because the thermal and dielectric properties of these products would be similar and would have the similar thermal responses in a microwave field.

(6) Similar bacterial survival, microwave processing temperature rise and post processing temperature rise were found in turkey loaf (10% fat) and in BGB dispersions (10% glycerol; Table 12 and Figure 40). Therefore, BGB dispersions have the potential to be a simulation model for bacterial survival and thermal responses of turkey loaf (10% fat) after microwave processing (approval of Ho3; Section 3.2.1.2). However, the use of homogeneous BGB loaves did not improve temperature variation after microwave processing as expected (rejection of Ho2; Section 3.2.1.2).

(7) The distribution of the location of the lowest and the highest temperature within a loaf was mainly affected by the load size (Section 5.8.1). PVDC wrapping, microwave output power, exposed microwave dose and type of loaf also had effects on the temperature distribution (Table 4). Doughnut-shaped containers used in the present study were able to eliminate cold-spots in the center as expected [Copson, 1975a; Starrack, 1980; approval of Ho5; Section 3.5.1.2].

(8) Temperature uniformity could be improved by: (a) wrapping loaves with PVDC film, (b) using smaller load sizes (approval of Ho7; Section 3.5.1.3), (c) lowering microwave output power, (d) increasing percent fat content, (e) increasing exposed microwave dose (Table 15).

(9) Microwave heating processes must be developed on a highly selective basis. For future study, researchers must consider the mutual interaction between the product and the processing equipment to achieve better microbial quality control of foods that have been processed in microwave ovens.

(10) Because there were no collectable drip losses in BGB loaves with 30% glycerol, the weight loss of loaves due to processing measured in the present study

was only the evaporation loss. Other processing studies usually define weight loss to be evaporation plus drip losses. Thus, weight loss in the present study may not have been conventionally represented. Future studies should include drip loss as part of product weight loss and not as part of product weight. This technique would make results of future studies more comparable with results of other researchers.

6.2 Recommendations

Based on the results and the questions which arose from the present study, recommendations for optimizing microwave processing conditions for meat loaves and for the future microwave processing studies are given below:

(1) The optimal microwave processing conditions recommended for meat loaves follow. To achieve safe microbial and the best organoleptic qualities for meat loaves with the maximum heating uniformity and minimal microwave energy requirement, recommendation is made that meat loaves with fat content around 20% should be prepared as homogeneous as possible and placed into a small load size container and wrapped with water- and heat-resistant plastic film such as polyvinylidene chloride film. The products should be processed at low microwave output power ($\leq 50\%$ of full power) and receive 5.94 watts x min/g of EMD (Table 20).

(2) The use of bentonite-glycerol-BHI broth (BGB) dispersions with 10% glycerol as a simulation model for bacterial survival of meat loaves with 10% fat is recommended for further use. The potential to use BGB dispersion with 20% glycerol to simulate meat loaves with 20% fat also exists. However, BGB

dispersions with 30% glycerol are not recommended because their a_w (0.9) is much lower than that of raw meat products (> 0.98). Additional modification is needed for the current BGB's formulation (10% glycerol) used in the present study to achieve better simulation for thermal responses of beef.

(3) For the future study of BGB dispersions, emphasis should be on (a) modification of the formula to simulate a variety of foods; (b) the study of dielectric properties of bentonite such as dielectric constant and dielectric loss factor in a microwave field; (c) the exploration of interactions between product and processing variables by using other variables such as shape, microwave output power and microwave frequency than the present study which only used three variables (EMD, PFC, LS); (d) the study of thermal destruction of bacteria in a microwave field by using exposed microwave dose to replace time-temperature profile. The basic concepts of thermal destruction of bacteria such as thermal death time, D value, z value, F value and thermal destruction are not appropriate for microwave processing (Section 2.3.4.1). Modification of these concepts is needed because a constant temperature can not be maintained during microwave processing.

(4) Further studies of the responses of turkey meat in a microwave field are recommended. In general when turkey loaves were processed at varied microwave output power, the thermal responses were similar to that of beef loaves; the bacterial survival in turkey loaves processed at 50% microwave output power (MP) was not, however, as expected when compared to beef loaves processed at 50% MP (Tables 9,19). Also different thermal responses were found among varied sizes of turkey loaf. Unlike beef loaf in which end-point temperature (EPT), microwave processing temperature rise (MPTR) and sum of temperature rise (STR) increased as load size

increased, 600 g load size of turkey loaves had the highest EPT, MPTR and STR among three load sizes (Table 8). Perhaps some unique factors in the turkey meat were involved. The author recommends confirmation of these results and if necessary, further exploration of the reason why the bacterial survival in turkey meat is the same regardless of varied MP and why the 600 g load size had the highest EPT, MPTR and STR.

(5) Further intensive investigation of the thermal and dielectric properties of food ingredients is recommended. Food ingredients which possess similar thermal and dielectric properties can probably be categorized into one group. The purpose of categorization is to facilitate the study of bacterial survival after microwave processing. The data on bacterial survival obtained from representative food formulations in the same category might be able to apply to the other formulations in the same category (e.g. beef-turkey group in Table 1). Hence, labor and supply costs can be better controlled compared to situations in which all formulations are tested.

(6). The use of heat-resistant spore-forming bacteria such as *Clostridium perfringens* or *Bacillus cereus* is recommended for future microwave processing studies. The target bacteria used for the present study were heat sensitive. The results of this study only represented mesophilic aerobic bacteria. The optimal microwave processing conditions recommended above can not guarantee the complete destruction of heat-resistant bacteria. Therefore, additional microwave research using heat-resistant bacteria seems appropriate to assure the safe microbial quality of foods.

(7) In addition to basic microwave processing research, the practical development of quantitative models to predict temperature, bacterial survival, and product quality is recommended. The potential for developing food processing equipment with combined frequencies to achieve uniform temperatures and combined heating modes to improve bacterial survival should also be considered.

LIST OF REFERENCES

REFERENCES

- Aleixo, J.A.G., Swaminathan B., Jamesen K.S., and Pratt, D.E. 1985. Destruction of pathogenic bacteria in turkeys roasted in microwave ovens. *J. Food Sci.* 50(4):873-875, 880.
- A.O.A.C (Analysis of the Association of Official Analytical Chemists). 1984. *A.O.A.C. Methods*, 14th ed. Official Methods of Analysis of the Association of Official Analytical Chemists. Washington, D.C.
- Anonymous. 1988. NFPA, SPI to cooperate on microwave susceptor data. *Food Chemical News* 30(22):59.
- Anonymous. 1985. Microwave ovens continue as dominant retail force. *Microwave world* 6:4,13.
- Anonymous. 1984. 1983-best year since 1979 for home appliances (press release). Assoc. Home Appliance manuf., Chicago, IL..
- Anonymous. 1947a. Electronic cooking goes commercial. *Electronics* 20(6):140,158,160.
- Anonymous. 1947b. Frozen meals plus Radarange for speedy service. *Quick Frozen Foods* 10(11):65,99.
- Anonymous. 1946a. How electronic griddle serves hot sandwiches. *Food Ind.* 18(3):336.
- Anonymous. 1946b. Radarange for cooking. *Electronics* 19(11): 178-180.
- Baba, T., Tamaru, Y., Kono, T., and Watanabe, A. 1987. Development of snack foods produced from sweet potatoes. IV. Effects of microwave irradiation on amylolytic activities in dehydrated sweet potato flour. *Nippon Shokuhin Kogyo Gakkaishi* 34(3):178-184.
- Baer, E.F., Messer, J.W., Leslie, J.E., and Peeler, J.T. 1975. Direct plating method for enumeration of *Staphylococcus aureus*: collaborative study. *J. Asso. Off. Anal. Chem.* 58(6):1154-1158.
- Baird-Parker, A.C., Bryan, F.L., Olson, J.C. Jr., Van Schothorst, M., Silliker, J.H., Simonsen, B., Koulikovaskii, A., and Matyas, Z. 1982. Report on the WHO/ICMSF meeting on hazard analysis critical control point system in food hygiene, World Health Organization, Geneva.
- Baird-Parker, A.C., and Davenport, E. 1965. The effect of recovery medium on the isolation of *Staphylococcus aureus* after heat treatment and after the storage of frozen or dried cells. *J. Appl. Bacteriol.* 28(3):390-402.

- Bakanowski, S.M., and Zoller, J.M. 1984. Endpoint temperature distributions in microwave and conventionally cooked pork. *Food Technol.* 38(2):45-51.
- Baker, R.C., Poon, W., and Vadehar, D.V. 1983. Destruction of *Salmonella typhimurium* and *Staphylococcus aureus* in poultry products cooked in a conventional and microwave oven. *Poultry Sci.* 62(5):805-810.
- Baldwin, D.R., Anantheswaran, R.C., Sastry, S.K., and Beelman, R.B. 1986. Effect of microwave blanching on the yield and quality of canned mushrooms. *J. Food Sci.* 51(4):965-966.
- Baldwin, R.E. 1982. Microwave cooking: An overview, *J. Food Protect.* 45(10):1178.
- Barnes, F.S., and Hu, C.J. 1977. Models for some nonthermal effects of radio and microwave field on biological membranes. *IEEE Trans. on Microwave Theory and Technique* 25(9):742-746.
- Berry, B.W. and Leddy, K. 1984. Beef patty composition: Effects of fat content and cooking method. *J. Am. Diet. Assoc.* 84(6):654-658.
- Berteaud, A.J., Dardalhon, M., Rebeyrotte, N. and Averback, D. 1975. Action d'un rayonnement electromagnétique à longueur d'onde millimétrique sur la croissance bactérienne. *C.R. Hebd. Seances Acad. Sci.* 281:843-853.
- Bobeng, B.J. and David B.D. 1978a. HACCP models for quality control of entrée production in hospital foodservice systems. I. Development of hazard analysis critical control point models. *J. Am. Diet. Assoc.* 73(5):524-529.
- Bobeng, B.J. and David B.D. 1978b. HACCP models for quality control of entrée production in hospital foodservice systems. II. Quality assessment of beef loaves utilizing HACCP models. *J. Am. Diet. Assoc.* 73(5):530-535.
- Borodinsky, L. 1988. FDA perspectives on microwavable packaging: Material and food/package interaction. Paper presented at MW Foods '88, 1st Intl. Conf. on Formulating Food for the Microwave Oven, Chicago, March 8-8. The Packaging Group, Inc., Miltown, N.J.
- Brown, M.H. 1982. Bacteria of Public Health Significance In "Meat Microbiology". Ch. 9. Appl. Sci. Publishers LTD. London. p. 319-386.
- Bryan, F.L., and Lyon, J.B. 1984. Critical control points of hospital foodservice operations. *J. Food Protect.* 47(12):405-409.
- Brydson, J.A. 1982. Miscellaneous Vinyl Thermoplastics" In *Plastics Materials*" 4th ed. Ch. 17. Butterworth Scientific, London. P. 423-434.

- Campbell, G.S., and Gardner, W.H. 1971. Psychrometric measurement of soil water potential: temperature and bulk density effects. *Soil. Sci. Soc. Am. Proc.* 35:8-12.
- Carlin, F., Zimmermann, W., and Sundberg, A. 1982. Destruction of trichina larva in beef-pork loaves cooked in microwave ovens, *J. Food Sci.* 47(4):1096-1099.
- Cathcart, W.H. 1946a. High-frequency heating produces mold-free bread. *Food Ind.* 18(6):864-865.
- Cathcart, W.H. 1946b. Frozen foods defrosted by electronic heat. *Food Ind.* 18(10):1524-1525.
- Cathcart, W.H., and Parker, J.J. 1946. Defrosting foods with high-frequency heat. *Food Res.* 11:341-344.
- CDC, Center for Disease Control 1979. Staphylococcal food poisoning - New York. *Morbidity and Mortality Weekly Report* 28:45.
- Charm S. E. 1978. "The Fundamentals of Food Engineering" 3rd. ed. AVI Publishing Co., Inc. Westport, CT. 646 pp.
- Chen, H.K., Shen Z.Y., Fu, C.S., and Wu, D. 1982. The development of microwave power applications in China. *J. Microwave Power* 17(1):11-15.
- Chiu, C.P., Tateishi, K., Kosikowski, F.V., and Armbruster, G. 1984. Microwave treatment of pasteurized milk. *J. Microwave Power* 19(4):269-272.
- Cipra J.S. and Bowers J.A. 1971. Flavor of microwave- and conventionally- reheated turkey. *Poultry Sci.* 50(3):703-706.
- Cope, F.W. 1976. Superconductivity - a possible mechanism for non-thermal biological effects of microwaves. *J. Microwave power* 11(3):267-270.
- Copson, D.A. 1975a. Nutritional, Microbiological, and Other Experimental Aspects. In "Microwave Heating". Ch. 18. 2nd ed. AVI Publishing Co., Inc., Westport, CT. p. 438-477.
- Copson, D.A. 1975b. Theory of Microwave Heating. In "Microwave Heating". Ch. 1. 2nd ed. AVI Publishing Co., Inc., Westport, CT. p. 1-34
- Correlli, J.C., Gutmann, R.J., Kahzi, S., and Leby, J. 1977. Effect of 2.6-4.0 GHz microwave radiation on *E. coli* B. *J. Microwave Power* 12(2):141-144.
- Crespo, L.R., and Ockerman, H.R. 1977. Thermal denaturation of microorganisms in meat by microwave and conventional cooking. *J. Food Protect.* 40(7):442-444.

Crespo, L.R., Ockerman, H.R., and Irvin, K.M. 1977. Effect of conventional and microwave heating on *Pseudomonas putrefaciens*, *Streptococcus faecalis* and *Lactobacillus plantarum* in meat tissue. J. Food Protect. 40(9):588-591.

Culkin, K.A., and Fung, D.Y.C. 1975. Destruction of *Escherichia coli* and *Salmonella typhimurium* in microwave-cooked soups. J. Milk Food Technol. 38(1):8-15.

Darsch, G.A., Shaw, C.P., and Tuomy, J.M. 1979. Examination of patient tray foodservice equipment: an evaluation of the Sweetheart foodservice cart. Technical Report Natick/TR-79/026. Food Engineering laboratory, U.S. Army Natick Research and Development Command, Natick, MA.

Dahl, C.A., and Matthews, M.E. 1980. Cook/Chill foodservice system with a microwave oven: Thiamin content in portions of beef loaf after microwave-heating. J. Food Sci. 45(3):608-612.

Dahl, C.A., Matthews, M.E., and Marth, E.H. 1980a. Cook/chill foodservice systems with a microwave oven: Injured aerobic bacteria during food product flow. European J. Appl. Microbiol. and Biotech. 11:125-130.

Dahl, C.A., Matthews, M.E., and Marth, E.H. 1980b. Cook/chill foodservice systems with a microwave oven: Survival of *Streptococcus faecium* in beef loaf and potatoes after microwave-heating. J. Food Protect. 43(2):128-133.

Dahl, C.A., Matthews, M.E., and Marth, E.H. 1980c. Fate of *Staphylococcus aureus* in beef loaf, potatoes and frozen and canned green beans after microwave-heating in a simulated cook/chill hospital foodservice system. J. Food Protect. 43(12):916-923.

Decagon Manual 1981. Operator's manual for SC-10A thermocouple psychrometer sampl changer. Decagon devices Inc. Pullman, WA.

Decareau, R.V. 1975. Microwaves and Nutrition, in Future Impact of Microwave Ovens and the Food Industry, ed. McConnell, D.R., Transactions of the International Microwave Power Institute, Edmonton, Alberta, Canada. 4:69-81.

Decareau, R.V. 1982. Microwave research and development at the U.S. Army Natick Research and Development Laboratories. J. Microwave Power 17(2):127-135.

Decareau, R.V. 1985. Microwave in The Food Processing Industry. Academic Press, Inc., Orlando, FL. 234 pp.

Dreyfuss, M.S., and Chipley, J.R. 1980. Comparison of effects of sublethal microwave radiation and conventional heating on metabolic activity of *Staphylococcus aureus*. Appl. and Environ. Microbiol. 39(1): 13-16.

- Dziezak, J.D. 1987. Microwavable foods-industry's response to consumer demands for convenience. *Food Technol.* 41(6):52-62.
- Ede, A.J., and Haddow, R.R. 1951. The electrical properties of foods at high frequencies. *Food Manuf.* 26(4):156-160.
- Edgar, R. 1986. The economics of microwave processing in the food industry. *Food Technol.* 40(6):106-112.
- F.D.A. 1988. Food Protection Unicode rev. 3/10/88. Food and Drug Administration, Center for Food Safety and Applied Nutrition, Washington D.C..
- F.D.A. 1978. Bacteriological Analytical Manual. 5th ed. U.S. Food Drug Administration, Washington D.C..
- Flower, R.S., Martin, S.E., Brewer, D.G., and Ordal, Z.J. 1977. Catlase and enumeration of stressed *Staphylococcus aureus* cells. *Appl. and Environ. Microbiol.* 33(5):1112-1117.
- Freese, E., Sheu, C.W., and Galliers, E. 1973. Function of lipophilic acids as antimicrobial food additives. *Nature (London)* 241:321-325.
- Fruin, J.T., and Guthertz, L.S. 1982. Survival of bacteria in food cooked by microwave oven, conventional oven and slow cookers. *J. Food Protect.* 45(8):695-698.
- Fung, D.Y.C., and Cunningham, F.E. 1980. Effect of microwaves on microorganisms in foods. *J. Food Protect.* 43(8):641-650.
- Garrick, P. 1966. Recent advances in the use of microwave energy in the food industry, in "Microwave Applications in the Food Industry Symposium, London, 1966".
- Gill, J.L. 1978. Design and Analysis of Experiments in Animal and Medical Sciences Vol. 1. The Iowa State University Press, Ames, Iowa. p. 22, 155, 175-185.
- Goldblith, S.A., and Wang, D.I.C. 1967. Effect of microwaves on *Escherichia coli* and *Bacillus subtilis*. *Appl. Microbiol.* 15(6):1371-1375.
- Grim R.E. and Guven N. 1978. Bentonites: Geology, Mineralogy, Properties and uses. Elsevier/North-Holland, New York, NY. 234 pp.
- Haines, Y. 1987. Survival and dormancy of bacteria In "Survival and Dormancy of Microorganisms", Ch.1. eds. Haines, Y. John Wiley & Sons, New York, N.Y. p. 1-108.

- Hamrick, P.E., and Butler, B.T. 1973. Expose of bacteria to 2450 MHz microwave radiation. *J. Microwave Power* 8(3):227-233.
- Hansen, N.H., and Riemann, H. 1963. Factors affecting the heat resistance of nonsporing organisms. *J. Appl. Bacteriol.* 26(3):314-333.
- Hartman, P.A., Hartman, P.S. and Lanz, W.W. 1975. Violet red bile 2 agar for stressed coliforms. *Appl. Microbiol.* 29(4):537-539.
- Hassoun, V. 1981. Food: Applications in microwave. *Microwave World* 2(6):14.
- Hauser, E.A. and Reed, C.E. 1937. Studies in thixotrophy. 2. The thixotropic behavior and structure of bentonite. *J. Phys. Chem.* 41(7):911-934.
- Heldman, D.R. 1981. "Food Processing Engineering" 2nd ed. AVI Publishing Co., Inc. Westport, CO. 415 pp.
- Hocking, R.R. 1972. Criteria for selection of a subset regression: Which one should be used. *Technometrics.* 14:967-970.
- Hoffman, C.J. and Zabik, M.E. 1985a. Current and future foodservice applications of microwave cooking/reheating. *J. Am. Diet. Assoc.* 85(8):929-933.
- Hoffman, C.J. and Zabik, M.E. 1985b. Effects of microwave cooking/reheating on nutrients and food system: A review of recent studies. *J. Am. Diet. Assoc.* 85(8):922-926.
- Holden, E.G. 1948. Preservation of baked cereal foods. U.S. patent 2,443,138.
- Hossain, M.A. and Dutta, S.K. 1982. Comparison of bacterial growth to high-intensity microwave exposure and conventional heating. *Bioelectromagnetics* 3:471-474.
- Hsieh, J., and Baldwin, R.E. 1984. Storage and microwave reheating effects on lipid oxidation of roast beef. *J. Microwave Power* 19(3):187-194.
- Hunter, D.r., and Segel, I.H. 1973. Effect of weak acids on amino acids transport by *Penicillium chrysogenum*: Evidence for a proton or charge gradient as the driving force. *J. bacteriol.* 113(3):1184-1192.
- ICMSF (International Commission on the Microbiological Specifications for Foods). 1980. Reduced Water activity. In "Microbial Ecology of Foods. Vol. 1:Factors Affecting Life and Death of Microorganisms". Ch. 4. eds Silliker J.H., Elliott R.P., Baird-Parker, A.C., Bryan, F.L., Christian, J.H.B., Clark, D.S., Olson, J.C. Jr., and Roberts, T.A. Academic Press, New York, U.S.A., p. 70-91.

- ICMSF (International Commission on the Microbiological Specifications for Foods). 1978. "Microorganisms in Foods. Part I: Their Significance and Methods on Enumeration", 2nd ed., eds Thatcher F.S. and Clark, D.S. University of Toronto Press, Toronto, Canada, 434 pp.
- IFT (Institute of Food Technologists). 1989. Microwave food processing. A Scientific Status Summary by the Inst. of Food Technologists' Expert Panel on Food Safety and Nutrition. Food Technol. 43(1):117-126.
- IFT (Institute of Food Technologists). 1988. Migration of toxicants, flavors, and odor-active substances from flexible packaging materials to food. A Scientific Status Summary by the Inst. of Food Technologists' Expert Panel on Food Safety and Nutrition. Food Technol. 42(7):95-102.
- Jackson, J.M., and Olson, F.C.W. 1953. Thermal processing of canned foods in tin containers. IV. Studies of the mechanisms of heat transfer within the container. In Sterilization of Canned Foods, Theoretical Considerations in The Sterilization Canned Foods. American Can Company, Barrington, IL. p. 35-47.
- Jay, J.M. 1986. Modern Food Microbiology, 3rd ed., Van Nostrand Reinhold Co., New York NY. 642 pp.
- Kashket, E.R., and Wong P.T.S. 1969. The intracellular pH of *Escherichia coli*. Biochem. Biophys. Acta 193:212-214.
- Kashyap, S.C. and Wyslouzil, W. 1977. Methods for improving heating uniformity of microwave ovens. J. Microwave Power 12(3): 223-230.
- Kazbekov, E.N., and Vyacheslavov L.G. 1987. Effects of microwave irradiation on some membrane-related processes in bacteria. Gen. Physiol. Biophys. 6:57-64.
- Kent, M. 1987. Electrical and Dielectrical Properties of Food Materials. Science and Technology Publishers Ltd. Essex, England. pp. 135.
- Khalil, H., and Villota, R. 1988. Comparative study on injury and recovery of *Staphylococcus aureus* using microwaves and conventional heating. J. Food Protect. 51(3):181-186.
- Kinn, T.P. 1947. Basic theory and limitations of high frequency heating equipment. Food Technol. 1(2):161-173.
- Kotula, A.W. Murrell, K.D. Acosta-Stein L., and Tennent I., 1982. Influence of rapid cooking methods on the survival of *Trichinella spiralis* in pork chops from experimental infected pigs. J. Food Sci. 47(3):1006-1007.
- Krauskopf, K.B. 1979. Introduction to Geometry. 2 ed. McGrawHill Book Co., N.Y. pp 617.

- Lacey, B.A., and Winne, H.R. 1965. Effects of microwave cookery on the bacterial counts of food. *J. Applied Bacteriol.* 28(2):331-335.
- Lederberg, J. and Lederberg E.M. 1952. Replica plating and indirect selection of bacteria mutants. *J. Bact.* 63(3):399-406.
- Lund, A.A. 1945. Electronics makes a first beach-head in frozen food field. *Food Mater. Equip.* 5(9):2.
- Lund, D.B. 1977. Design of thermal process for maximum nutrient retention. *Food Technol.* 31(2):71-78.
- Marcum, J. 1944. Electronic processing. *Sci. Am.* 170(3):106-108.
- Marcum, J., and Kinn, T.P. 1947. Heating with microwaves. *Electronics* 20(3):82-85.
- Marshall, C.E. 1937. The colloidal properties of the clays as related to their structure. *J. Phys. Chem.* 41(7):935-942.
- Masi J. 1988. Microwave oven technology - What's new, what's coming. Paper presented at MW Foods '88. 1st Intl. Conf. on Formulating Food for the Microwave Oven, Chicago, March 8-9. The Packaging Group, Milltown, N.J..
- McGinnis D.S. 1986. Prediction of transient conduction heat transfer in foods packaged in flexible retort pouches. *J. Can. Inst. Food Sci. Technol.* 19(4):148-157.
- McProud, L.M. and Lund, D.B. 1983. Thermal properties of beef loaf produced in foodservice systems. *J. Food Sci.* 48(3):677-680.
- Meisel, N. 1973. Microwave applications to food processing and food system in Europe. *J. Microwave Power* (8)2:143-148.
- Mezykowski, T., Bal, J., Debiec, H., and Kwarecki, K. 1980. Response of *Aspergillus nidulans* and *Physarium polycephalum* to microwave radiation. *J. Microwave Power* 15(2):75-80.
- Mohsenin, N.N. 1983a. Application of Electrical Properties. In "Electromagnetic Radiation Properties of Foods and Agricultural products". Ch. 10. Gordon and Breach Science Publishers, New York N.Y. p. 489-580.
- Mohsenin, N.N. 1983b. Measurement of Electrical Properties of Foods and Agricultural Products. In "Electromagnetic Radiation Properties of Foods and Agricultural products". Ch. 9. Gordon and Breach Science Publishers, New York N.Y. p. 401-487.

- Mohsenin, N.N. 1983c. Relative Concepts of Microwaves, Radiowaves, and Electric Currents. In "Electromagnetic Radiation Properties of Foods and Agricultural products". Ch. 8. Gordon and Breach Science Publishers, New York N.Y. p. 375-399.
- Moore, N.H. 1966. Microwave energy in the food field. Act. Rep. Res. Dev. Assoc. Military Food and Packaging System, Inc. 18(2):163-172.
- Morse, P.W., and Rvercomb, H.W. 1947. UHF heating of frozen foods. Electronics 20(10):85-89.
- Mossel, D.A.A., and Ratto, M.A. 1970. Rapid detection of sublethally impaired cells of Enterobacteriaceae in dried foods. Appl. Microbiol. 20(2):273-275.
- Moyer, J.C., and Stotz, E. 1945. The electronic blanching of vegetables. Science 102(2638):68-69.
- Moyer, J.C., and Stotz, E. 1947. The blanching of vegetables by electronics. Food Technol. 1(2):252-257.
- Mudgett, R.E. 1986. Microwave properties and heating characteristics of foods. Food Technol. 40(6):84-93.
- Mudgett, R.E. 1982. Electrical properties of foods in microwave processing. Food Technol. 36(2):109-115.
- Mudgett, R.E., Wang D.I.C., Goldblith S.A. and Decareau R.V. 1974. Dielectric properties of food materials. J. Microwave Power 9(4):303-315.
- Myers, R.H. 1986. Criteria for Choice of Best Model. In "Classical and Modern Regression with Applications". Ch. 4. Duxbury Press, Boston, MA. P. 100-126.
- Neal, A.L., Weinstock, J.O., and Lampen, J.O. 1970. Mechanisms of fatty acid toxicity for yeast. J. Bacteriol. 104(1):518-528.
- Nickamp, A.A., Unklesbay, K.B., Unklesbay, N.F., and Ellersieck, M. 1984. Thermal properties of bentonite-water dispersions used for modeling foods. J. Food Sci. 49(1):28-31.
- Nickamp, A.A., Unklesbay, N.F., Unklesbay, K.B., and Ellersieck, M. 1983. Bentonite-water dispersions - an effective dietetic tool. J. Am. Diet. Assoc. (82)5:516-520.
- Noh, B.S., Heil, J.R., and Patino, H. 1985. Effect of processing variables on flame pasteurization of liquids in aluminum cans. J. Food Sci. 50(5):1448-1452.
- NRA. 1981. USDA Studying Microwave Cooked Pork, Washington Report. 24:2-6.

Ohlsson, T., and Risman, P.O. 1978. Temperature distribution of microwave heating - spheres and cylinders. *J. Microwave Power* 13(4):303-310.

Penner, K.K., and Bowers, J.A. 1973. Flavor and Chemical characteristics of conventionally and microwave reheated pork. *J. Food Sci.* 38(4):553-555.

Peterson W.R. and Adams J.P. 1983. Water velocity on heat penetration parameters during institutional retort pouch processing. *J. Food Sci.* 48(2):457-459,464.

Pflug, I.J., and Holcomb, R.G. 1983. Principles of thermal destruction of microorganisms. In "Disinfection, Sterilization and Preservation" Ch. 5. eds. Block, S.S. Lea & Febiger. Philadelphia, PA. p. 751-810.

Pikul, J., Leszczynski, D.E., and Kummerow, F.A. 1985. Oxidation products in chicken meat after frozen storage, microwave and convention oven cooking, refrigerated storage, and reheating. *Poultry Sci.* 64(1):93-100.

Pikul, J., Leszczynski, D.E., Bechtel, P.J., and Kummerow, F.A. 1984. Effects of frozen storage and cooking in lipid oxidation in chicken meat. *J. Food Sci.* 49(3):838-843.

Proctor, B.E., and Goldblith, S.A. 1948. Radar energy for rapid cooking and blanching and its effect on vitamin content. *Food Technol.* 2(2):95-104.

Riley, L.W., Remis, R.S., Helgerson, S.D., McGee, H.B., Wells, J.G., Davis, B.R., Herbert, R.J., Olcott, E.S., Johnson, L.M., Hargrett, N.T., Blake, P.A., and Cohen, M.L. 1983. Hemorrhagic colitis associated with a rare *Escherichia coli* serotype. *The New England Journal of Medicine.* 308:681-685.

Ringle, E.C. and David, B.D. 1975. Measuring electric distribution in a microwave oven. *Food Technol.* 29(12):46-54.

Rockland L.B., and L.A. Beuchat. 1987. Survival and death of microorganisms In "Water Activity: Theory and Applications to Food" Ch. 6. Marcel Dekker, Inc. New York N.Y. p. 119-136.

Rosén G.G. 1972. Effects of microwaves on foods and related materials. *Food Technol.* 26(7):36-40, 55.

Rosenberg, B., Kemeny, G., Switzer, R., and Hamilton, T.C. 1971. Quantitative evidence for protein denaturation as the cause of thermal death. *Nature (London)* 232:471-473.

Rosenberg U., and Bögl W. 1987a. Microwave-systems - New industrial food technology. *GIT Fachz lab.* 31(3):162-164, 167-169.

- Rosenberg U., and Bögl W. 1987b. Microwave pasteurization, sterilization, blanching, and pest control in the food industry. *Food Technol.* 41(6):92-99.
- Rosenberg U., and Bögl W. 1987c. Microwave thawing, drying, and baking in the food industry. *Food Technol.* 41(6):85-91.
- Ruyack D.F. and Paul P.C. 1972. Conventional and microwave heating of beef: Use of plastic wrap. *J. Home Econ. Res.* 1(2):98-103.
- Saeed, M.A., and Gilbert, P. 1981. Influence of low intensity 2,450 MHz microwave radiation upon the growth of various microorganisms and their sensitivity towards chemical inactivation. *Microbios* 32:135-142.
- Sanborn, M.R., Wan, S.K., and Bulard, R. 1982. Microwave sterilization of plastic tissue culture vessels for reuse. *Appl. and Environ. Microbiol.* 44(4):960-964.
- SAS User's Guide: Statistics 1985. Ver. 5 edition. S.A.S. Institute Inc. Cary, NC. 956 pp.
- Sawyer, C.A. 1983. Microwave Ovens - Theory and Use in Foodservice Study Kit. Am. Diet. Assoc., Chicago, IL., 67 pp. and 3 double-sides tapes.
- Sawyer, C.A. 1985. Post-processing temperature rise in foods: conventional hot air and microwave ovens. *J. Food Protect.* 48(5):429-434.
- Sawyer, C.A., Naidu, Y.M., and Thompson, S. 1983. Cook/chill foodservice systems: microbiological quality and end-point temperature of beef loaf, peas and potatoes after reheating by conduction, convention and microwave radiation. *J. food Protect.* 46(12):1036-1043.
- Sawyer, C.A. and Biglari, S.D. 1984. Effects of a polyvinylidene chloride wrap on the quality of microwave cooked foods. *J. Microwave Power.* 19(1):25-33.
- Sawyer, C.A., Biglari S.D., and Thompson S.S. 1984. Internal end temperature and survival of bacteria on meats with and without a polyvinylidene chloride wrap during microwave cooking. *J. Food Sci.* 49(3):972-974.
- Sawyer, C.A. and Pestka, J.J. 1985. Foodservice system: presence of injured bacteria in foods during food product flow. *Ann. Rev. Microbiol.* 39:51-67.
- Schiffmann, R.F. 1973. The applications of microwave power in the food industry in the United States. *J. Microwave Power* 8(2):137-142.
- Schiffmann, R.F. 1976a. An update on the application of microwave power in the food industry in the United States. *J. Microwave Power* 11(3):221-224.

Schiffmann, R.F. 1976b. Basic Principles of Microwaves In "Cooking with Microwaves". ed. Tinga, W.R. The International Microwave Power Institute, Alberta, Canada. p. 11-28.

Schiffmann, R.F. 1981. Problems in the development of food products for microwave ovens. Digest Microwave Power Symposium, International Microwave Power Institute, Vienna, VA.

Schiffmann, R.F. 1986. Food product development for microwave processing. Food Technol. 40(6):94-98.

Schiffmann, R.F. 1988. Food product development for microwave processing. Paper presented at MW Foods '88, 1st Intl. Conf. on Formulating Food for the Microwave Oven, Chicago, March 8-9. The Packaging Group, Milltown, N.J.

Sherman, V.M. 1946. Electronic heat in the food industries. Food Ind. 18(4):506-509.

Speck, M.L., Ray, B., and Read, R.B. 1975. Repair and enumeration of injured coliforms by a plating procedure. Appl. Microbiol. 29(4):549-550.

Spite, G.T. 1984. Microwave-inactivation of bacterial pathogens in various controlled frozen food compositions and in a commercially available frozen food product. J. Food Protect. 47(6):458-462.

SPSSX User's Guide 1988. Ver. 3 edition. SPSS INC, Chicago, IL.

Stack, D. 1974. The Microwave Sterilization of Water. unpublished Ph.D. thesis, University of Wyoming, 56 pp. (Dissertation Abstracts 35(7): 3332-B).

Starrack, G. 1980. Techniques and timings assure microwave burger quality. National Livestock and Meat Board Newsletter, Chicago, IL. p. 1-4.

Stumb, C.R. 1973. Thermobacteriology in Food Processing. 2nd ed. Academic Press, N.Y. 329 pp.

Sugiyama, H. 1951. Studies on factors affecting the heat resistance of spores of *Clostridium botulinum*. J. Bacteriol. 62:81-96.

Suzuki, T. and Oshima, K. 1973. Applications of microwave power to the food industry in Japan. J. Microwave power 8(2):149-159.

Swami, S., and Mudgett, R.E. 1981. Effect of moisture and salt contents on the dielectric behavior of liquid and semi-solid food. Proc. Intl. Microwave Power Inst. Symp. 16:48.

Troller, J.A., and Christian, J.H. 1978. Methods. In "Water Activity and Food". Ch. 2. Academic Press, New York N.Y. p. 14-44.

Troller, J.A., and Christian, J.H. 1978. Microbial survival. In "Water Activity and Food". Ch. 7. Academic Press, New York N.Y. p. 118-129.

Trout, G.R. and Schmidt, G.R. 1987. Nonprotein Additives. In "Advances in Meat Research. Volume 3: Restructured Meat and Poultry Products". Ch. 8. eds. Pearson A.M. and Dutson T.R. Van Nostrand Reinhold Co., N.Y. p. 308.

Unklesbay, N.F., Brown, N.E., Matthews, M.E. 1988. Bentonite models simulate turkey rolls during convective heating. J. Am. Diet. Assoc. 88(8):928-931.

Unklesbay N.F., Unklesbay, K.B., Buergler, D., and Stringer, W. 1981. Bentonite-water dispersions simulate foodservice energy consumption of sausage patties. J. Food Sci. 46(6):1808-1809,1816.

Unklesbay, N.F., Unklesbay, K.B., and Henderson, J.M. 1980. Simulation of energy used by foodservice infrared heating equipment with bentonite models of menu items. J. Food Protect. 43(10):789-794.

USDHEW 1978. Food Service Sanitation Manual. Public Health Service, FDA, Division of Retail Food Protection, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C..

Vadehra, D.V. 1970. "Cooking Poultry with Microwave Energy", Report of Consumer Microwave Systems Conference, Cornell University, Ithaca, N.Y. p. 26-29.

van de Voort, F.R., Laureano, M., and Smith, J.P. 1987. A practical thermocouple for temperature measurement in microwave ovens. J. Can. Inst. Food Sci. Technol. 20(4):279-284.

Van Zante, H.J. 1973. The Microwave Oven. Houghton Mifflin Co., Boston, MA. 184 pp.

Vela, G.R., and Wu, J.F. 1979. Mechanism of lethal action of 2,450-MHz radiation on microorganisms. Appl. and Environ. Microbiol. 37(3):550-533.

Wang, S.H., and Toledo, M.C.F. 1987. Inactivation of Soybean Lipoxygenase by microwave heating: Effect of moisture content and exposure time. J. Food Sci. 52(5):1344-1347.

Warseck, M., Ray, B., and Speck, M.L. 1973. Repair and enumeration of injured coliforms in frozen foods. Appl. Microbiol. 26(6):919-924.

Webb, S.J., and Booth, A.D. 1968. Absorption of microwaves by microorganisms. *Nature (London)* 222:1119-1201.

Webb, S.J., and Dodds, D.D. 1968. Inhibition of bacterial growth by 136 gc microwaves *Nature (London)* 218:374-375.

Weizerrick, J.T. 1972. System approach to consumer microwave cooking. *J. Microwave Power.* 7(1):57-61.

Wenger, W. 1945. Use of dielectric heating for sterilization, cooking and enzyme control in foods and drugs. *Electronics* 18(3):154,156.

Whistler R.L., and Daniel J.R. 1985. Carbohydrates In "Food Chemistry" 2nd ed. eds. Fennema, O.R. Marcel Dekker Inc. New York, N.Y. p. 69-138.

Woodams, E.E. and Nowrey, J.E. 1968. Literature values of thermal conductivities of foods. *Food Technol.* 22(4):150-157.

Wright-Rudolph, L., Walker, H.W., and Parrish, Jr. F.C. 1986. Survival of *Clostridium perfringens* and aerobic bacteria in ground beef patties during microwave and conventional cookery. *J. Food Protect.* 49(3):203-206.

Yamano, Y., Ejiri, K., Endo, T., and Senda, M. 1975. Heat penetration into flexible package with food-simulated materials. *Japan J. food Sci. Technol.* 22:199-204.

Zimmermann, W.J. 1983. An approach to safe microwave cooking of pork roasts containing *Trichinella spiralis*. *J. Food Sci.* 48(6):1715-1718, 1722.

Zimmermann, W.J., and Beach, P.J. 1982. Efficacy of microwave cooking for devitalizing Trichinae in pork roasts and chops. *J. Food Protect.* 45(5):405-409.

APPENDICES

Appendix 1. The Fortran subroutines used to rearrange TEMP data set.	283
Appendix 2. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>beef loaves (10, 20 and 30% fat)</u>	284
Appendix 3. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>turkey loaves (10% fat)</u>	289
Appendix 4. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>BGB loaves (150 g)</u>	294
Appendix 5. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>beef loaves (10% fat) and turkey loaves (10% fat)</u>	297
Appendix 6. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of <u>beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol)</u>	302
Appendix 7. The ANOVA results of location of after-processing temperature (APT) computed by the SAS GLM procedure with REPEATED statement for loaves (beef, turkey and BGB).	307
Appendix 8. The ANOVA results of location of end-point temperature (EPT) computed by the SAS GLM procedure with REPEATED statement for loaves (beef, turkey and BGB)	308
Appendix 9. The ANOVA results of temperature variation within a loaf computed by SAS GLM procedure for a data subset of <u>beef loaves (10, 20 and 30% fat)</u>	309

Appendix 1. The Fortran subroutines used to rearrange TEMP data set.

```

      dimension apt(800,20),ept(800,20),ls(800),
+         loca(800,20),loce(800,20),tampi(800),
+         sp(800),pw(800),mp(800),pt(800),tpptr(800),id(800)

c ---- sort temperatures in ascending order for each case -----c
c ---- temperatures include apt and ept -----c
c ---- loca contains location information for apt -----c
c ---- loce contains location information for ept -----c
c ---- The maximum # of cases allowed = 800 -----c
c ---- The maximum # of locations = 20 -----c

      open (unit = 7)
      open (unit = 8)
      open (unit = 9)
      do 20 i=1,500
      do 20 j=1,20
      loca(i,j)=j
      loce(i,j)=j
20  continue
      write (*,22)
22  format(3x,'input # of locations and # of cases with free format')
      read(*,*) nl,nc
      do 30 i=1,nc
      read(7,111) id(i),sp(i),pw(i),mp(i),pt(i),ls(i),tpptr(i),tampi(i),
+ (apt(i,j),j=1,nl), (ept(i,j),j=1,nl)
30  continue
111 format(i3,f1.0,f2.0,t15,i3,f4.0,i4,f4.0,t30,f3.1,32f4.1)
      do 40 i=1,nc
      do 40 j=1,nl
      apt(i,j)=ept(i,j)-tampi(i)
      ept(i,j)=ept(i,j)-tampi(i)
40  continue

c ---- This do-loop does the ascending sorting for temperatures ---- c

      do 60 i=1,nc
      na=nl-1
      do 60 j=1,na
      do 60 k=j+1,nl
      if (apt(i,j) .gt. apt(i,k)) then
      qt=apt(i,j)
      apt(i,j)=apt(i,k)
      apt(i,k)=qt
      nt=loca(i,j)
      loca(i,j)=loca(i,k)
      loca(i,k)=nt
      end if
      if (ept(i,j) .gt. ept(i,k)) then
      qt=ept(i,j)
      ept(i,j)=ept(i,k)
      ept(i,k)=qt
      nt=loce(i,j)
      loce(i,j)=loce(i,k)
      loce(i,k)=nt
      end if
60  continue
80  continue
      do 150 i = 1,nc
      write(8,211) id(i),sp(i),pw(i),mp(i),pt(i),ls(i),tpptr(i),
+ (loca(i,j),j=1,nl), (apt(i,j),j=1,nl),
+ (loce(i,j),j=1,nl), (ept(i,j),j=1,nl)
150 continue
211 format(i6,f6.0,f6.0,i6,f6.0,i6,f6.0 / 16i5
0 + / 16f5.1 / 16i5 / 16f5.1)
      do 170 i = 1,nc
      ia1=1
      write(9,222) ia1,id(i),sp(i),pw(i),mp(i),pt(i),ls(i),tpptr(i),
+ (loca(i,j),j=1,nl,4), (apt(i,j),j=1,nl,4),
+ (loce(i,j),j=1,nl,4), (ept(i,j),j=1,nl,4)
c
      ia2=2
      write(9,222) ia2,id(i),sp(i),pw(i),mp(i),pt(i),ls(i),tpptr(i),
+ (loca(i,j),j=2,nl,4), (apt(i,j),j=2,nl,4),
+ (loce(i,j),j=2,nl,4), (ept(i,j),j=2,nl,4)
c
      ia3=3
      write(9,222) ia3,id(i),sp(i),pw(i),mp(i),pt(i),ls(i),tpptr(i),
+ (loca(i,j),j=3,nl,4), (apt(i,j),j=3,nl,4),
+ (loce(i,j),j=3,nl,4), (ept(i,j),j=3,nl,4)
c
      ia4=4
      write(9,222) ia4,id(i),sp(i),pw(i),mp(i),pt(i),ls(i),tpptr(i),
+ (loca(i,j),j=4,nl,4), (apt(i,j),j=4,nl,4),
+ (loce(i,j),j=4,nl,4), (ept(i,j),j=4,nl,4)
c
170 continue
222 format(2i6,2f6.0,i6,f6.0,i6,f6.0 / 4i5,4f5.1,4i5,4f5.1)
      stop
      end

```


Appendix 2. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of beef loaves (10, 20 and 30% fat).

General Linear Models Procedure					
Dependent Variable: LEC LOG (%SURVIVING E. COLI+1)					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	160.4886299	3.2097726	32.72	0.0001
Error	237	23.2477308	0.0980917		
Corrected Total	287	183.7363607			
	R-Square	C.V.	Root MSE	LEC Mean	
	0.873472	44.36744	0.313196	0.70591384	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	10.3980911	10.3980911	106.00	0.0001
END	3	128.9739803	42.9913268	438.28	0.0001
LS	2	0.9290601	0.4645301	4.74	0.0096
MP	1	1.2381662	1.2381662	12.62	0.0005
PFC	2	1.3304039	0.6652020	6.78	0.0014
REP	1	0.2228048	0.2228048	2.27	0.1331
PW*END	3	6.5071238	2.1690413	22.11	0.0001
PW*LS	2	0.6543297	0.3271648	3.34	0.0373
PW*MP	1	0.0723918	0.0723918	0.74	0.3912
PW*PFC	2	1.6715731	0.8357865	8.52	0.0003
PW*REP	1	0.0010991	0.0010991	0.01	0.9158
END*LS	6	1.9707009	0.3284502	3.35	0.0035
END*MP	3	2.3333535	0.7777845	7.93	0.0001
END*PFC	6	1.6235602	0.2705934	2.76	0.0131
END*REP	3	0.5859061	0.1953020	1.99	0.1160
LS*MP	2	0.5556209	0.2778105	2.83	0.0609
LS*PFC	4	0.7933743	0.1983436	2.02	0.0921
LS*REP	2	0.4727790	0.2363895	2.41	0.0920
MP*PFC	2	0.0372066	0.0186033	0.19	0.8274
MP*REP	1	0.0080778	0.0080778	0.08	0.7744
PFC*REP	2	0.1090266	0.0545133	0.56	0.5744
Dependent Variable: LSA LOG (%SURVIVING S. AUREUS+1)					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	160.8859964	3.2177199	32.18	0.0001
Error	237	23.6956841	0.0999818		
Corrected Total	287	184.5816804			
	R-Square	C.V.	Root MSE	LSA Mean	
	0.871625	42.36173	0.316199	0.74642610	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	11.1125260	11.1125260	111.15	0.0001
END	3	129.9983906	43.3327969	433.41	0.0001
LS	2	1.4258953	0.7129476	7.13	0.0010
MP	1	1.2387504	1.2387504	12.39	0.0005
PFC	2	0.4517274	0.2258637	2.26	0.1067
REP	1	0.0836749	0.0836749	0.84	0.3612
PW*END	3	6.4456538	2.1485519	21.49	0.0001
PW*LS	2	0.4350720	0.2175360	2.18	0.1158
PW*MP	1	0.1395017	0.1395017	1.40	0.2387
PW*PFC	2	1.1052098	0.5526049	5.53	0.0045
PW*REP	1	0.0060176	0.0060176	0.06	0.8064
END*LS	6	1.2544051	0.2090675	2.09	0.0550
END*MP	3	1.6569637	0.5523212	5.52	0.0011
END*PFC	6	2.3774482	0.3962414	3.96	0.0008
END*REP	3	0.0997665	0.0332555	0.33	0.8018
LS*MP	2	0.6758663	0.3379332	3.38	0.0357
LS*PFC	4	1.9434212	0.4858553	4.86	0.0009
LS*REP	2	0.2568770	0.1284385	1.28	0.2787
MP*PFC	2	0.0632205	0.0316102	0.32	0.7292
MP*REP	1	0.0678303	0.0678303	0.68	0.4110
PFC*REP	2	0.0477760	0.0238880	0.24	0.7877

Dependent Variable: LAB LOG (%SURVIVING AEROBIC BACTERIA+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	161.9937560	3.2398751	34.68	0.0001
Error	237	22.1394926	0.0934156		
Corrected Total	287	184.1332485			
	R-Square	C.V.	Root MSE	LAB Mean	
	0.879764	41.93288	0.305640	0.72887815	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	11.8242126	11.8242126	126.58	0.0001
END	3	130.9777403	43.6592468	467.37	0.0001
LS	2	0.8245669	0.4122834	4.41	0.0131
MP	1	0.9186418	0.9186418	9.83	0.0019
PFC	2	0.6420432	0.3210216	3.44	0.0338
REP	1	0.1447028	0.1447028	1.55	0.2145
PW*END	3	6.7236803	2.2412268	23.99	0.0001
PW*LS	2	0.5414301	0.2707150	2.90	0.0571
PW*MP	1	0.1445958	0.1445958	1.55	0.2147
PW*PFC	2	1.1130974	0.5565487	5.96	0.0030
PW*REP	1	0.0006005	0.0006005	0.01	0.9362
END*LS	6	2.0330860	0.3388477	3.63	0.0018
END*MP	3	2.0463900	0.6821300	7.30	0.0001
END*PFC	6	1.7350993	0.2891832	3.10	0.0062
END*REP	3	0.3606776	0.1202259	1.29	0.2795
LS*MP	2	0.3825139	0.1912570	2.05	0.1313
LS*PFC	4	1.0337911	0.2584478	2.77	0.0282
LS*REP	2	0.4128719	0.2064360	2.21	0.1120
MP*PFC	2	0.0568271	0.0284136	0.30	0.7380
MP*REP	1	0.0037630	0.0037630	0.04	0.8411
PFC*REP	2	0.0734242	0.0367121	0.39	0.6755

Dependent Variable: TPTTR (TIME OF POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	36031904.36	720638.09	64.35	0.0001
Error	237	2654077.97	11198.64		
Corrected Total	287	38685982.33			
	R-Square	C.V.	Root MSE	TPTTR Mean	
	0.931394	21.80416	105.8236	485.336806	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	991584.03	991584.03	88.55	0.0001
END	3	206293.23	68764.41	6.14	0.0005
LS	2	33041742.72	16520871.36	1475.26	0.0001
MP	1	111195.42	111195.42	9.93	0.0018
PFC	2	208801.13	104400.57	9.32	0.0001
REP	1	6.42	6.42	0.00	0.9809
PW*END	3	20424.98	6808.33	0.61	0.6104
PW*LS	2	473274.81	236637.41	21.13	0.0001
PW*MP	1	28900.09	28900.09	2.58	0.1095
PW*PFC	2	33495.65	16747.82	1.50	0.2262
PW*REP	1	37789.59	37789.59	3.37	0.0675
END*LS	6	139164.92	23194.15	2.07	0.0574
END*MP	3	65315.04	21771.68	1.94	0.1231
END*PFC	6	44996.34	7499.39	0.67	0.6743
END*REP	3	29693.15	9897.72	0.88	0.4501
LS*MP	2	81870.01	40935.00	3.66	0.0273
LS*PFC	4	397650.45	99412.61	8.88	0.0001
LS*REP	2	33523.01	16761.50	1.50	0.2260
MP*PFC	2	39353.38	19676.69	1.76	0.1748
MP*REP	1	16065.28	16065.28	1.43	0.2322
PFC*REP	2	30764.72	15382.36	1.37	0.2552

Dependent Variable: PEL (PERCENT EVAPORATION LOSS)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	1046.806342	20.936127	67.62	0.0001
Error	237	73.376719	0.309606		
Corrected Total	287	1120.183061			
	R-Square	C.V.	Root MSE	PEL Mean	
	0.934496	19.49416	0.556423	2.85430556	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	80.2644500	80.2644500	259.25	0.0001
END	3	879.7269917	293.2423306	947.15	0.0001
LS	2	25.9055465	12.9527733	41.84	0.0001
MP	1	15.2996681	15.2996681	49.42	0.0001
PFC	2	2.9427507	1.4713753	4.75	0.0095
REP	1	0.2990222	0.2990222	0.97	0.3267
PW*END	3	2.4024472	0.8008157	2.59	0.0538
PW*LS	2	0.7673396	0.3836698	1.24	0.2915
PW*MP	1	2.6258681	2.6258681	8.48	0.0039
PW*PFC	2	3.1040063	1.5520031	5.01	0.0074
PW*REP	1	0.2134222	0.2134222	0.69	0.4072
END*LS	6	5.1659729	0.8609955	2.78	0.0124
END*MP	3	4.5914236	1.5304745	4.94	0.0024
END*PFC	6	0.8733021	0.1455503	0.47	0.8302
END*REP	3	0.8362194	0.2787398	0.90	0.4417
LS*MP	2	14.9924215	7.4962108	24.21	0.0001
LS*PFC	4	4.0333576	1.0083394	3.26	0.0126
LS*REP	2	0.2752840	0.1376420	0.44	0.6416
MP*PFC	2	0.3525674	0.1762837	0.57	0.5666
MP*REP	1	1.8081681	1.8081681	5.84	0.0164
PFC*REP	2	0.3261132	0.1630566	0.53	0.5913

Dependent Variable: MPTR (MICROWAVE PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	54838.34806	1096.76696	45.81	0.0001
Error	237	5673.59847	23.93923		
Corrected Total	287	60511.94653			
	R-Square	C.V.	Root MSE	MPTR Mean	
	0.906240	11.11135	4.892774	44.0340278	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	584.25014	584.25014	24.41	0.0001
END	3	34405.49181	11468.49727	479.07	0.0001
LS	2	13841.49132	6920.74566	289.10	0.0001
MP	1	1970.87347	1970.87347	82.33	0.0001
PFC	2	409.82132	204.91066	8.56	0.0003
REP	1	1.62000	1.62000	0.07	0.7950
PW*END	3	71.67903	23.89301	1.00	0.3945
PW*LS	2	23.44507	11.72253	0.49	0.6134
PW*MP	1	44.96681	44.96681	1.88	0.1718
PW*PFC	2	66.01049	33.00524	1.38	0.2539
PW*REP	1	71.20222	71.20222	2.97	0.0859
END*LS	6	1084.10674	180.68446	7.55	0.0001
END*MP	3	719.12347	239.70782	10.01	0.0001
END*PFC	6	90.42174	15.07029	0.63	0.7066
END*REP	3	86.94528	28.98176	1.21	0.3065
LS*MP	2	986.04049	493.02024	20.59	0.0001
LS*PFC	4	256.50139	64.12535	2.68	0.0325
LS*REP	2	7.29021	3.64510	0.15	0.8588
MP*PFC	2	3.96924	1.98462	0.08	0.9205
MP*REP	1	31.73389	31.73389	1.33	0.2507
PFC*REP	2	81.36396	40.68198	1.70	0.1850

Dependent Variable: PPTR (POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	9863.467014	197.269340	11.14	0.0001
Error	237	4196.025174	17.704748		
Corrected Total	287	14059.492188			
	R-Square	C.V.	Root MSE	PPTR Mean	
	0.701552	36.34182	4.207701	11.5781250	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	2045.334201	2045.334201	115.52	0.0001
END	3	213.252604	71.084201	4.01	0.0082
LS	2	6041.546875	3020.773437	170.62	0.0001
MP	1	281.042535	281.042535	15.87	0.0001
PFC	2	78.911458	39.455729	2.23	0.1099
REP	1	7.507812	7.507812	0.42	0.5156
PW*END	3	38.842882	12.947627	0.73	0.5342
PW*LS	2	31.720486	15.860243	0.90	0.4097
PW*MP	1	14.896701	14.896701	0.84	0.3599
PW*PFC	2	29.335069	14.667535	0.83	0.4380
PW*REP	1	4.375868	4.375868	0.25	0.6195
END*LS	6	214.286458	35.714410	2.02	0.0642
END*MP	3	236.717882	78.905961	4.46	0.0046
END*PFC	6	130.755208	21.792535	1.23	0.2911
END*REP	3	147.405382	49.135127	2.78	0.0421
LS*MP	2	284.501736	142.250868	8.03	0.0004
LS*PFC	4	42.197917	10.549479	0.60	0.6660
LS*REP	2	2.598958	1.299479	0.07	0.9293
MP*PFC	2	1.251736	0.625868	0.04	0.9653
MP*REP	1	0.105035	0.105035	0.01	0.9387
PFC*REP	2	16.880208	8.440104	0.48	0.6214

Dependent Variable: STR (SUM OF TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	46313.22132	926.26443	54.55	0.0001
Error	237	4024.58615	16.98138		
Corrected Total	287	50337.80747			
	R-Square	C.V.	Root MSE	STR Mean	
	0.920048	7.409975	4.120847	55.6121528	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	4815.89337	4815.89337	283.60	0.0001
END	3	36812.28677	12270.76226	722.60	0.0001
LS	2	1744.90799	872.45399	51.38	0.0001
MP	1	763.42781	763.42781	44.96	0.0001
PFC	2	129.74007	64.87003	3.82	0.0233
REP	1	16.10281	16.10281	0.95	0.3312
PW*END	3	113.55038	37.85013	2.23	0.0855
PW*LS	2	4.35549	2.17774	0.13	0.8797
PW*MP	1	8.10031	8.10031	0.48	0.4905
PW*PFC	2	148.93965	74.46983	4.39	0.0135
PW*REP	1	110.88087	110.88087	6.53	0.0112
END*LS	6	870.68729	145.11455	8.55	0.0001
END*MP	3	183.88649	61.29550	3.61	0.0140
END*PFC	6	87.24187	14.54031	0.86	0.5278
END*REP	3	22.22705	7.40902	0.44	0.7272
LS*MP	2	215.45646	107.72823	6.34	0.0021
LS*PFC	4	207.00347	51.75087	3.05	0.0178
LS*REP	2	1.46312	0.73156	0.04	0.9578
MP*PFC	2	2.98312	1.49156	0.09	0.9159
MP*REP	1	28.18753	28.18753	1.66	0.1989
PFC*REP	2	25.89938	12.94969	0.76	0.4676

Dependent Variable: EPT (END-POINT TEMPERATURE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	50	46559.80903	931.19618	52.82	0.0001
Error	237	4178.15972	17.62937		
Corrected Total	287	50737.96875			
	R-Square	C.V.	Root MSE	EPT Mean	
	0.917652	6.835314	4.198734	61.4270833	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	5295.92014	5295.92014	300.40	0.0001
END	3	36395.05903	12131.68634	688.15	0.0001
LS	2	1245.19271	622.59635	35.32	0.0001
MP	1	760.50000	760.50000	43.14	0.0001
PFC	2	160.32812	80.16406	4.55	0.0115
REP	1	1.25347	1.25347	0.07	0.7900
PW*END	3	183.90625	61.30208	3.48	0.0167
PW*LS	2	34.23090	17.11545	0.97	0.3803
PW*MP	1	2.72222	2.72222	0.15	0.6947
PW*PFC	2	179.11632	89.55816	5.08	0.0069
PW*REP	1	52.53125	52.53125	2.98	0.0856
END*LS	6	717.38368	119.56395	6.78	0.0001
END*MP	3	199.35417	66.45139	3.77	0.0114
END*PFC	6	115.56076	19.26013	1.09	0.3675
END*REP	3	86.58681	28.86227	1.64	0.1814
LS*MP	2	194.92187	97.46094	5.53	0.0045
LS*PFC	4	856.38542	214.09635	12.14	0.0001
LS*REP	2	66.36632	33.18316	1.88	0.1545
MP*PFC	2	8.31771	4.15885	0.24	0.7900
MP*REP	1	4.01389	4.01389	0.23	0.6337
PFC*REP	2	0.15799	0.07899	0.00	0.9955

Appendix 3. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of turkey loaves (10% fat).

General Linear Models Procedure

Dependent Variable: LEC LOG (%SURVIVING E. COLI+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	57.99973882	1.81249184	15.79	0.0001
Error	63	7.23017539	0.11476469		
Corrected Total	95	65.22991421			
	R-Square	C.V.	Root MSE	LEC Mean	
	0.889159	39.33342	0.338769	0.86127615	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	6.27016518	6.27016518	54.63	0.0001
EMD	3	43.14094508	14.38031503	125.30	0.0001
LS	2	1.94714195	0.97357098	8.48	0.0005
MP	1	0.26737682	0.26737682	2.33	0.1319
REP	1	0.22127627	0.22127627	1.93	0.1699
PW*EMD	3	3.42973100	1.14324367	9.96	0.0001
PW*LS	2	0.16727537	0.08363768	0.73	0.4865
PW*MP	1	0.00242245	0.00242245	0.02	0.8849
PW*REP	1	0.07350380	0.07350380	0.64	0.4265
EMD*LS	6	1.29372614	0.21562102	1.88	0.0984
EMD*MP	3	0.45138961	0.15046320	1.31	0.2787
EMD*REP	3	0.09328501	0.03109500	0.27	0.8461
LS*MP	2	0.45965145	0.22982573	2.00	0.1435
LS*REP	2	0.13041333	0.06520667	0.57	0.5694
MP*REP	1	0.05143537	0.05143537	0.45	0.5056

Dependent Variable: LSA LOG (%SURVIVING S. AUREUS+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	56.36638043	1.76144939	15.49	0.0001
Error	63	7.16321925	0.11370189		
Corrected Total	95	63.52959968			
	R-Square	C.V.	Root MSE	LSA Mean	
	0.887246	40.40418	0.337197	0.83455997	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	5.25077665	5.25077665	46.18	0.0001
EMD	3	42.20760326	14.06920109	123.74	0.0001
LS	2	1.84423731	0.92211865	8.11	0.0007
MP	1	0.14298287	0.14298287	1.26	0.2664
REP	1	0.13118741	0.13118741	1.15	0.2869
PW*EMD	3	2.78466469	0.92822156	8.16	0.0001
PW*LS	2	0.19012460	0.09506230	0.84	0.4382
PW*MP	1	0.03242920	0.03242920	0.29	0.5952
PW*REP	1	0.00072113	0.00072113	0.01	0.9368
EMD*LS	6	2.70273385	0.45045564	3.96	0.0020
EMD*MP	3	0.36031088	0.12010363	1.06	0.3741
EMD*REP	3	0.19925373	0.06641791	0.58	0.6276
LS*MP	2	0.49624136	0.24812068	2.18	0.1212
LS*REP	2	0.01022704	0.00511352	0.04	0.9561
MP*REP	1	0.01288644	0.01288644	0.11	0.7375

Dependent Variable: LAB LOG (%SURVIVING AEROBIC BACTERIA+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	57.84275091	1.80758597	15.04	0.0001
Error	63	7.56959932	0.12015237		
Corrected Total	95	65.41235022			
	R-Square	C.V.	Root MSE	LAB Mean	
	0.884279	39.88254	0.346630	0.86912716	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	7.71680301	7.71680301	64.23	0.0001
EMD	3	41.19163474	13.73054491	114.28	0.0001
LS	2	1.22750111	0.61375055	5.11	0.0088
MP	1	0.01213269	0.01213269	0.10	0.7517
REP	1	0.03563907	0.03563907	0.30	0.5879
PW*EMD	3	3.91948645	1.30649548	10.87	0.0001
PW*LS	2	0.00958387	0.00479193	0.04	0.9609
PW*MP	1	0.08394545	0.08394545	0.70	0.4064
PW*REP	1	0.00052369	0.00052369	0.00	0.9476
EMD*LS	6	1.97663772	0.32943962	2.74	0.0197
EMD*MP	3	0.48164834	0.16054945	1.34	0.2706
EMD*REP	3	0.23323861	0.07774620	0.65	0.5877
LS*MP	2	0.82154248	0.41077124	3.42	0.0389
LS*REP	2	0.07762773	0.03881386	0.32	0.7251
MP*REP	1	0.05480596	0.05480596	0.46	0.5019

Dependent Variable: TPPTR (TIME OF POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	8634527.167	269828.974	51.23	0.0001
Error	63	331797.792	5266.632		
Corrected Total	95	8966324.958			
	R-Square	C.V.	Root MSE	TPPTR Mean	
	0.962995	17.11173	72.57156	424.104167	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	373252.042	373252.042	70.87	0.0001
EMD	3	110413.375	36804.458	6.99	0.0004
LS	2	7691236.083	3845618.042	730.19	0.0001
MP	1	33301.500	33301.500	6.32	0.0145
REP	1	6767.042	6767.042	1.28	0.2613
PW*EMD	3	7124.708	2374.903	0.45	0.7175
PW*LS	2	112737.583	56368.792	10.70	0.0001
PW*MP	1	24704.167	24704.167	4.69	0.0341
PW*REP	1	21063.375	21063.375	4.00	0.0498
EMD*LS	6	174232.500	29038.750	5.51	0.0001
EMD*MP	3	24182.583	8060.861	1.53	0.2153
EMD*REP	3	5459.208	1819.736	0.35	0.7925
LS*MP	2	32058.250	16029.125	3.04	0.0547
LS*REP	2	1978.083	989.042	0.19	0.8292
MP*REP	1	16016.667	16016.667	3.04	0.0861

Dependent Variable: PEL (PERCENT EVAPORATION LOSS)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	303.5891875	9.4871621	90.71	0.0001
Error	63	6.5887615	0.1045835		
Corrected Total	95	310.1779490			
	R-Square	C.V.	Root MSE	PEL Mean	
	0.978758	12.72004	0.323394	2.54239583	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	48.0675510	48.0675510	459.61	0.0001
EMD	3	237.4540865	79.1513622	756.82	0.0001
LS	2	2.4565396	1.2282698	11.74	0.0001
MP	1	4.5544594	4.5544594	43.55	0.0001
REP	1	0.0001260	0.0001260	0.00	0.9724
PW*EMD	3	2.3117365	0.7705788	7.37	0.0003
PW*LS	2	2.0743521	1.0371760	9.92	0.0002
PW*MP	1	0.3162510	0.3162510	3.02	0.0869
PW*REP	1	0.0731510	0.0731510	0.70	0.4061
EMD*LS	6	0.1256354	0.0209392	0.20	0.9755
EMD*MP	3	1.5043948	0.5014649	4.79	0.0045
EMD*REP	3	0.2109115	0.0703038	0.67	0.5723
LS*MP	2	4.3855188	2.1927594	20.97	0.0001
LS*REP	2	0.0195896	0.0097948	0.09	0.9107
MP*REP	1	0.0348844	0.0348844	0.33	0.5656

Dependent Variable: MPTR (MICROWAVE PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	9769.776042	305.305501	13.23	0.0001
Error	63	1453.757292	23.075513		
Corrected Total	95	11223.533333			
	R-Square	C.V.	Root MSE	MPTR Mean	
	0.870472	12.17153	4.803698	39.4666667	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	52.806667	52.806667	2.29	0.1353
EMD	3	7856.405833	2618.801944	113.49	0.0001
LS	2	303.630208	151.815104	6.58	0.0025
MP	1	476.150417	476.150417	20.63	0.0001
REP	1	43.201667	43.201667	1.87	0.1761
PW*EMD	3	28.620833	9.540278	0.41	0.7439
PW*LS	2	295.287708	147.643854	6.40	0.0030
PW*MP	1	10.533750	10.533750	0.46	0.5017
PW*REP	1	40.041667	40.041667	1.74	0.1925
EMD*LS	6	53.272292	8.878715	0.38	0.8861
EMD*MP	3	66.632083	22.210694	0.96	0.4161
EMD*REP	3	10.570833	3.523611	0.15	0.9276
LS*MP	2	373.938958	186.969479	8.10	0.0007
LS*REP	2	153.732708	76.866354	3.33	0.0422
MP*REP	1	4.950417	4.950417	0.21	0.6448

Dependent Variable: PPTR (POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	1926.078125	60.189941	2.78	0.0003
Error	63	1362.911458	21.633515		
Corrected Total	95	3288.989583			
	R-Square	C.V.	Root MSE		PPTR Mean
	0.585614	33.24748	4.651184		13.9895833

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	782.0416667	782.0416667	36.15	0.0001
EMD	3	217.1145833	72.3715278	3.35	0.0246
LS	2	190.8177083	95.4088542	4.41	0.0161
MP	1	92.0416667	92.0416667	4.25	0.0433
REP	1	0.2604167	0.2604167	0.01	0.9130
PW*EMD	3	88.7916667	29.5972222	1.37	0.2607
PW*LS	2	89.2239583	44.6119792	2.06	0.1357
PW*MP	1	1.2604167	1.2604167	0.06	0.8100
PW*REP	1	2.0416667	2.0416667	0.09	0.7597
EMD*LS	6	164.3697917	27.3949653	1.27	0.2857
EMD*MP	3	37.8750000	12.6250000	0.58	0.6280
EMD*REP	3	26.7812500	8.9270833	0.41	0.7445
LS*MP	2	220.2239583	110.1119792	5.09	0.0089
LS*REP	2	13.0677083	6.5338542	0.30	0.7404
MP*REP	1	0.1666667	0.1666667	0.01	0.9303

Dependent Variable: STR (SUM OF TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	11831.53750	369.73555	23.74	0.0001
Error	63	981.31875	15.57649		
Corrected Total	95	12812.85625			
	R-Square	C.V.	Root MSE		STR Mean
	0.923411	7.383058	3.946706		53.4562500

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	1241.281667	1241.281667	79.69	0.0001
EMD	3	9345.120417	3115.040139	199.98	0.0001
LS	2	172.750000	86.375000	5.55	0.0060
MP	1	149.500417	149.500417	9.60	0.0029
REP	1	50.170417	50.170417	3.22	0.0775
PW*EMD	3	180.312500	60.104167	3.86	0.0134
PW*LS	2	69.465833	34.732917	2.23	0.1160
PW*MP	1	4.506667	4.506667	0.29	0.5925
PW*REP	1	60.166667	60.166667	3.86	0.0538
EMD*LS	6	162.348333	27.058056	1.74	0.1270
EMD*MP	3	117.107083	39.035694	2.51	0.0670
EMD*REP	3	42.060417	14.020139	0.90	0.4462
LS*MP	2	33.885833	16.942917	1.09	0.3432
LS*REP	2	199.560833	99.780417	6.41	0.0029
MP*REP	1	3.300417	3.300417	0.21	0.6469

Dependent Variable: EPT (END-POINT TEMPERATURE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	32	11550.92708	360.96647	29.87	0.0001
Error	63	761.25781	12.08346		
Corrected Total	95	12312.18490			
	R-Square	C.V.	Root MSE		EPT Mean
	0.938170	6.323224	3.476127		54.9739583

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PW	1	1331.315104	1331.315104	110.18	0.0001
EMD	3	8926.299479	2975.433160	246.24	0.0001
LS	2	447.286458	223.643229	18.51	0.0001
MP	1	182.877604	182.877604	15.13	0.0002
REP	1	0.585938	0.585938	0.05	0.8264
PW*EMD	3	93.632812	31.210937	2.58	0.0611
PW*LS	2	108.848958	54.424479	4.50	0.0148
PW*MP	1	32.085937	32.085937	2.66	0.1082
PW*REP	1	56.273437	56.273437	4.66	0.0347
EMD*LS	6	130.442708	21.740451	1.80	0.1136
EMD*MP	3	85.153646	28.384549	2.35	0.0809
EMD*REP	3	22.445313	7.481771	0.62	0.6052
LS*MP	2	27.098958	13.549479	1.12	0.3323
LS*REP	2	94.890625	47.445313	3.93	0.0247
MP*REP	1	11.690104	11.690104	0.97	0.3291

Appendix 4. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of BGB leaves (150 g).

General Linear Models Procedure

Dependent Variable: LEC LOG (%SURVIVING E. COLI+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	35.78538310	2.10502254	255.52	0.0001
Error	30	0.24714797	0.00823827		
Corrected Total	47	36.03253108			
	R-Square	C.V.	Root MSE	LEC Mean	
	0.993141	9.227846	0.090765	0.98359781	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
EMD	3	34.21017218	11.40339073	1384.20	0.0001
PFC	2	0.45389323	0.22694662	27.55	0.0001
REP	1	0.02401304	0.02401304	2.91	0.0981
EMD*PFC	6	1.01636440	0.16939407	20.56	0.0001
EMD*REP	3	0.02773721	0.00924574	1.12	0.3557
PFC*REP	2	0.05320305	0.02660152	3.23	0.0537

Dependent Variable: LSA LOG (%SURVIVING S. AUREUS+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	32.26377478	1.89786910	142.50	0.0001
Error	30	0.39953763	0.01331792		
Corrected Total	47	32.66331241			
	R-Square	C.V.	Root MSE	LSA Mean	
	0.987768	11.89477	0.115403	0.97020179	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
EMD	3	30.31583444	10.10527815	758.77	0.0001
PFC	2	0.40052514	0.20026257	15.04	0.0001
REP	1	0.00000059	0.00000059	0.00	0.9947
EMD*PFC	6	1.51038321	0.25173054	18.90	0.0001
EMD*REP	3	0.01771623	0.00590541	0.44	0.7237
PFC*REP	2	0.01931516	0.00965758	0.73	0.4925

Dependent Variable: LAB LOG (%SURVIVING AEROBIC BACTERIA+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	35.14649466	2.06744086	246.27	0.0001
Error	30	0.25184937	0.00839498		
Corrected Total	47	35.39834403			
	R-Square	C.V.	Root MSE	LAB Mean	
	0.992885	9.291789	0.091624	0.98607614	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
EMD	3	33.52796490	11.17598830	1331.27	0.0001
PFC	2	0.42110528	0.21055264	25.08	0.0001
REP	1	0.00705449	0.00705449	0.84	0.3666
EMD*PFC	6	1.15307097	0.19217849	22.89	0.0001
EMD*REP	3	0.01518473	0.00506158	0.60	0.6182
PFC*REP	2	0.02211430	0.01105715	1.32	0.2830

Dependent Variable: TPPTR (TIME OF POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	11918.02083	701.06005	3.27	0.0022
Error	30	6431.79167	214.39306		
Corrected Total	47	18349.81250			
	R-Square	C.V.	Root MSE	TPPTR Mean	
	0.649490	21.39495	14.64217	68.4375000	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
EMD	3	8881.229167	2960.409722	13.81	0.0001
PFC	2	1179.875000	589.937500	2.75	0.0799
REP	1	63.020833	63.020833	0.29	0.5917
EMD*PFC	6	791.958333	131.993056	0.62	0.7160
EMD*REP	3	736.395833	245.465278	1.14	0.3470
PFC*REP	2	265.541667	132.770833	0.62	0.5451

Dependent Variable: PEL (PERCENT EVAPORATION LOSS)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	166.9754937	9.8220879	54.07	0.0001
Error	30	5.4501542	0.1816718		
Corrected Total	47	172.4256479			
	R-Square	C.V.	Root MSE	PEL Mean	
	0.968391	9.907040	0.426230	4.30229167	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
EMD	3	158.4782229	52.8260743	290.78	0.0001
PFC	2	3.7019292	1.8509646	10.19	0.0004
REP	1	0.3383521	0.3383521	1.86	0.1825
EMD*PFC	6	2.3322708	0.3887118	2.14	0.0778
EMD*REP	3	0.9910896	0.3303632	1.82	0.1651
PFC*REP	2	1.1336292	0.5668146	3.12	0.0587

Dependent Variable: MPTR (MICROWAVE PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	5712.093542	336.005502	16.92	0.0001
Error	30	595.609583	19.853653		
Corrected Total	47	6307.703125			
	R-Square	C.V.	Root MSE	MPTR Mean	
	0.905574	11.18655	4.455744	39.8312500	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
EMD	3	4585.917292	1528.639097	77.00	0.0001
PFC	2	797.253750	398.626875	20.08	0.0001
REP	1	4.501875	4.501875	0.23	0.6374
EMD*PFC	6	167.619583	27.936597	1.41	0.2444
EMD*REP	3	79.002292	26.334097	1.33	0.2842
PFC*REP	2	77.798750	38.899375	1.96	0.1586

Dependent Variable: PPTR (POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	255.5729167	15.0337010	2.80	0.0066
Error	30	160.9062500	5.3635417		
Corrected Total	47	416.4791667			
	R-Square	C.V.	Root MSE	PPTR Mean	
	0.613651	40.42354	2.315932	5.72916667	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
END	3	2.10416667	0.70138889	0.13	0.9410
PFC	2	68.26041667	34.13020833	6.36	0.0050
REP	1	4.08333333	4.08333333	0.76	0.3898
END*PFC	6	64.11458333	10.68576389	1.99	0.0981
END*REP	3	84.62500000	28.20833333	5.26	0.0049
PFC*REP	2	32.38541667	16.19270833	3.02	0.0639

Dependent Variable: STR (SUM OF TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	5150.666458	302.980380	34.98	0.0001
Error	30	259.828333	8.660944		
Corrected Total	47	5410.494792			
	R-Square	C.V.	Root MSE	STR Mean	
	0.951977	6.459441	2.942948	45.5604167	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
END	3	4408.092292	1469.364097	169.65	0.0001
PFC	2	480.501667	240.250833	27.74	0.0001
REP	1	0.010208	0.010208	0.00	0.9728
END*PFC	6	60.863333	10.143889	1.17	0.3477
END*REP	3	37.577292	12.525764	1.45	0.2490
PFC*REP	2	163.621667	81.810833	9.45	0.0007

Dependent Variable: EPT (END-POINT TEMPERATURE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	5335.697917	313.864583	56.29	0.0001
Error	30	167.281250	5.576042		
Corrected Total	47	5502.979167			
	R-Square	C.V.	Root MSE	EPT Mean	
	0.969602	4.685634	2.361364	50.3958333	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
END	3	4530.562500	1510.187500	270.84	0.0001
PFC	2	476.760417	238.380208	42.75	0.0001
REP	1	6.020833	6.020833	1.08	0.3071
END*PFC	6	69.031250	11.505208	2.06	0.0877
END*REP	3	78.062500	26.020833	4.67	0.0086
PFC*REP	2	175.260417	87.630208	15.72	0.0001

Appendix 5. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of beef loaves (10% fat) and turkey loaves (10% fat).

General Linear Models Procedure

Dependent Variable: LEC LOG (%SURVIVING E. COLI+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	113.2014959	2.7610121	27.11	0.0001
Error	150	15.2743436	0.1018290		
Corrected Total	191	128.4758395			

R-Square	C.V.	Root MSE	LEC Mean
0.881111	38.39041	0.319106	0.83121415

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	0.17351500	0.17351500	1.70	0.1938
PW	1	14.69573004	14.69573004	144.32	0.0001
END	3	81.78561104	27.26187035	267.72	0.0001
LS	2	3.48854829	1.74427415	17.13	0.0001
MP	1	0.58886998	0.58886998	5.78	0.0174
REP	1	0.10918757	0.10918757	1.07	0.3021
TL*PW	1	0.08542066	0.08542066	0.84	0.3612
TL*END	3	0.09381035	0.03127012	0.31	0.8202
TL*LS	2	0.05373440	0.02686720	0.26	0.7684
TL*MP	1	0.00130394	0.00130394	0.01	0.9101
TL*REP	1	0.11209827	0.11209827	1.10	0.2958
PW*END	3	6.46378631	2.15459544	21.16	0.0001
PW*LS	2	0.21877695	0.10938848	1.07	0.3442
PW*MP	1	0.09743093	0.09743093	0.96	0.3296
PW*REP	1	0.13325207	0.13325207	1.31	0.2545
END*LS	6	2.84562214	0.47427036	4.66	0.0002
END*MP	3	0.94332859	0.31444286	3.09	0.0290
END*REP	3	0.02829827	0.00943276	0.09	0.9640
LS*MP	2	1.06248419	0.53124209	5.22	0.0065
LS*REP	2	0.09380360	0.04690180	0.46	0.6318
MP*REP	1	0.12688332	0.12688332	1.25	0.2661

Dependent Variable: LSA LOG (%SURVIVING S. AUREUS+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	109.5073840	2.6709118	27.44	0.0001
Error	150	14.6005705	0.0973371		
Corrected Total	191	124.1079546			

R-Square	C.V.	Root MSE	LSA Mean
0.882356	38.63841	0.311989	0.80745811

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	0.14102607	0.14102607	1.45	0.2306
PW	1	12.86251433	12.86251433	132.14	0.0001
END	3	77.25803963	25.75267988	264.57	0.0001
LS	2	4.86225855	2.43112928	24.98	0.0001
MP	1	0.56740392	0.56740392	5.83	0.0170
REP	1	0.04521712	0.04521712	0.46	0.4966
TL*PW	1	0.11959476	0.11959476	1.23	0.2694
TL*END	3	0.15853602	0.05284534	0.54	0.6537
TL*LS	2	0.08532788	0.04266394	0.44	0.6459
TL*MP	1	0.04774423	0.04774423	0.49	0.4848
TL*REP	1	0.08974948	0.08974948	0.92	0.3385
PW*END	3	5.54718972	1.84906324	19.00	0.0001
PW*LS	2	0.76791583	0.38395791	3.94	0.0214
PW*MP	1	0.24018562	0.24018562	2.47	0.1183
PW*REP	1	0.00431896	0.00431896	0.04	0.8335
END*LS	6	4.06978835	0.67829806	6.97	0.0001
END*MP	3	1.31680212	0.43893404	4.51	0.0046
END*REP	3	0.08506317	0.02835439	0.29	0.8316
LS*MP	2	1.19310682	0.59655341	6.13	0.0028
LS*REP	2	0.03244631	0.01622316	0.17	0.8466
MP*REP	1	0.01315513	0.01315513	0.14	0.7137

Dependent Variable: LAB LOG (%SURVIVING AEROBIC BACTERIA+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	112.5323284	2.7446909	27.90	0.0001
Error	150	14.7546152	0.0983641		
Corrected Total	191	127.2869436			
	R-Square	C.V.	Root MSE	LAB Mean	
	0.884084	37.89776	0.313631	0.82757005	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	0.33158276	0.33158276	3.37	0.0683
PW	1	15.81753919	15.81753919	160.81	0.0001
END	3	79.40567233	26.46855744	269.09	0.0001
LS	2	2.88086854	1.44043427	14.64	0.0001
MP	1	0.16832011	0.16832011	1.71	0.1928
REP	1	0.00627405	0.00627405	0.06	0.8010
TL*PW	1	0.00235848	0.00235848	0.02	0.8772
TL*END	3	0.13767940	0.04589313	0.47	0.7060
TL*LS	2	0.03486015	0.01743008	0.18	0.8378
TL*MP	1	0.06476763	0.06476763	0.66	0.4184
TL*REP	1	0.03525786	0.03525786	0.36	0.5503
PW*END	3	6.59210054	2.19736685	22.34	0.0001
PW*LS	2	0.47157748	0.23578874	2.40	0.0945
PW*MP	1	0.29467485	0.29467485	3.00	0.0855
PW*REP	1	0.04776900	0.04776900	0.49	0.4870
END*LS	6	3.61639603	0.60273267	6.13	0.0001
END*MP	3	1.09899079	0.36633026	3.72	0.0128
END*REP	3	0.07987142	0.02662381	0.27	0.8465
LS*MP	2	1.35168657	0.67584329	6.87	0.0014
LS*REP	2	0.03466387	0.01733194	0.18	0.8386
MP*REP	1	0.05941728	0.05941728	0.60	0.4383

Dependent Variable: TPPTR (TIME OF POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	23117764.82	563847.92	64.75	0.0001
Error	150	1306167.55	8707.78		
Corrected Total	191	24423932.37			
	R-Square	C.V.	Root MSE	TPPTR Mean	
	0.946521	20.33271	93.31551	458.942708	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	233035.01	233035.01	26.76	0.0001
PW	1	775843.88	775843.88	89.10	0.0001
END	3	252840.39	84280.13	9.68	0.0001
LS	2	20284034.89	10142017.44	1164.71	0.0001
MP	1	140454.42	140454.42	16.13	0.0001
REP	1	3476.51	3476.51	0.40	0.5284
TL*PW	1	282.76	282.76	0.03	0.8572
TL*END	3	1462.35	487.45	0.06	0.9825
TL*LS	2	389790.64	194895.32	22.38	0.0001
TL*MP	1	13618.17	13618.17	1.56	0.2130
TL*REP	1	3291.80	3291.80	0.38	0.5396
PW*END	3	56671.72	18890.57	2.17	0.0940
PW*LS	2	345310.82	172655.41	19.83	0.0001
PW*MP	1	202.13	202.13	0.02	0.8791
PW*REP	1	14928.38	14928.38	1.71	0.1924
END*LS	6	413661.53	68943.59	7.92	0.0001
END*MP	3	15284.02	5094.67	0.59	0.6257
END*REP	3	35265.43	11755.14	1.35	0.2604
LS*MP	2	97355.34	48677.67	5.59	0.0046
LS*REP	2	40917.01	20458.51	2.35	0.0989
MP*REP	1	37.63	37.63	0.00	0.9477

Dependent Variable: PEL (PERCENT EVAPORATION LOSS)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	690.2815500	16.8361354	47.87	0.0001
Error	150	52.7540979	0.3516940		
Corrected Total	191	743.0356479			
	R-Square	C.V.	Root MSE	PEL Mean	
	0.929002	21.51530	0.593038	2.75635417	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	8.7894083	8.7894083	24.99	0.0001
PW	1	91.6045021	91.6045021	260.47	0.0001
EMD	3	535.2038688	178.4012896	507.26	0.0001
LS	2	11.4919073	5.7459536	16.34	0.0001
MP	1	8.2170750	8.2170750	23.36	0.0001
REP	1	0.0954083	0.0954083	0.27	0.6032
TL*PW	1	0.0546750	0.0546750	0.16	0.6939
TL*EMD	3	2.0890125	0.6963375	1.98	0.1194
TL*LS	2	2.9878885	1.4939443	4.25	0.0161
TL*MP	1	0.0229687	0.0229687	0.07	0.7986
TL*REP	1	0.0858521	0.0858521	0.24	0.6220
PW*EMD	3	4.3448854	1.4482951	4.12	0.0077
PW*LS	2	7.2726323	3.6363161	10.34	0.0001
PW*MP	1	1.7176333	1.7176333	4.88	0.0286
PW*REP	1	0.4070083	0.4070083	1.16	0.2838
EMD*LS	6	1.0278094	0.1713016	0.49	0.8172
EMD*MP	3	3.4123292	1.1374431	3.23	0.0241
EMD*REP	3	1.1087292	0.3695764	1.05	0.3720
LS*MP	2	9.4510406	4.7255203	13.44	0.0001
LS*REP	2	0.0986635	0.0493318	0.14	0.8692
MP*REP	1	0.7982521	0.7982521	2.27	0.1340

Dependent Variable: MPTR (MICROWAVE PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	29996.68359	731.62643	36.45	0.0001
Error	150	3011.00760	20.07338		
Corrected Total	191	33007.69120			
	R-Square	C.V.	Root MSE	MPTR Mean	
	0.908779	10.88602	4.480333	41.1567708	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	548.43880	548.43880	27.32	0.0001
PW	1	294.77297	294.77297	14.68	0.0002
EMD	3	19929.95474	6643.31825	330.95	0.0001
LS	2	3817.52510	1908.76255	95.09	0.0001
MP	1	1194.50630	1194.50630	59.51	0.0001
REP	1	24.29630	24.29630	1.21	0.2730
TL*PW	1	47.50130	47.50130	2.37	0.1261
TL*EMD	3	287.06141	95.68714	4.77	0.0033
TL*LS	2	2457.35948	1228.67974	61.21	0.0001
TL*MP	1	13.70672	13.70672	0.68	0.4099
TL*REP	1	19.06380	19.06380	0.95	0.3314
PW*EMD	3	90.61391	30.20464	1.50	0.2157
PW*LS	2	94.71594	47.35797	2.36	0.0980
PW*MP	1	50.73797	50.73797	2.53	0.1140
PW*REP	1	0.01172	0.01172	0.00	0.9808
EMD*LS	6	196.70698	32.78450	1.63	0.1417
EMD*MP	3	323.75391	107.91797	5.38	0.0015
EMD*REP	3	35.83057	11.94352	0.59	0.6192
LS*MP	2	548.76573	274.38286	13.67	0.0001
LS*REP	2	18.43448	9.21724	0.46	0.6327
MP*REP	1	2.92547	2.92547	0.15	0.7032

Dependent Variable: PPTR (POSR PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	5079.105469	123.880621	6.64	0.0001
Error	150	2800.455729	18.669705		
Corrected Total	191	7879.561198			
	R-Square	C.V.	Root MSE	PPTR Mean	
	0.644592	33.08484	4.320845	13.0598958	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	165.949219	165.949219	8.89	0.0033
PW	1	1362.667969	1362.667969	72.99	0.0001
END	3	310.587240	103.529080	5.55	0.0012
LS	2	1744.111979	872.055990	46.71	0.0001
MP	1	201.105469	201.105469	10.77	0.0013
REP	1	2.636719	2.636719	0.14	0.7076
TL*PW	1	6.938802	6.938802	0.37	0.5430
TL*END	3	98.993490	32.997830	1.77	0.1558
TL*LS	2	540.617187	270.308594	14.48	0.0001
TL*MP	1	0.376302	0.376302	0.02	0.8873
TL*REP	1	5.501302	5.501302	0.29	0.5881
PW*END	3	87.524740	29.174913	1.56	0.2008
PW*LS	2	13.101562	6.550781	0.35	0.7046
PW*MP	1	20.345052	20.345052	1.09	0.2982
PW*REP	1	0.574219	0.574219	0.03	0.8610
END*LS	6	115.065104	19.177517	1.03	0.4099
END*MP	3	96.983073	32.327691	1.73	0.1630
END*REP	3	21.701823	7.233941	0.39	0.7622
LS*MP	2	262.414063	131.207031	7.03	0.0012
LS*REP	2	21.898438	10.949219	0.59	0.5576
MP*REP	1	0.011719	0.011719	0.00	0.9800

Dependent Variable: STR (SUM OF TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	28058.38750	684.35091	40.05	0.0001
Error	150	2562.95917	17.08639		
Corrected Total	191	30621.34667			
	R-Square	C.V.	Root MSE	STR Mean	
	0.916302	7.624167	4.133569	54.2166667	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	111.02083	111.02083	6.50	0.0118
PW	1	2925.00188	2925.00188	171.19	0.0001
END	3	22399.77167	7466.59056	436.99	0.0001
LS	2	514.42198	257.21099	15.05	0.0001
MP	1	415.36333	415.36333	24.31	0.0001
REP	1	10.92521	10.92521	0.64	0.4252
TL*PW	1	18.13021	18.13021	1.06	0.3046
TL*END	3	221.18250	73.72750	4.31	0.0060
TL*LS	2	693.30948	346.65474	20.29	0.0001
TL*MP	1	9.54083	9.54083	0.56	0.4561
TL*REP	1	45.04687	45.04687	2.64	0.1065
PW*END	3	145.49229	48.49743	2.84	0.0400
PW*LS	2	86.08156	43.04078	2.52	0.0839
PW*MP	1	6.82521	6.82521	0.40	0.5283
PW*REP	1	0.75000	0.75000	0.04	0.8343
END*LS	6	184.74552	30.79092	1.80	0.1023
END*MP	3	107.04167	35.68056	2.09	0.1042
END*REP	3	33.47562	11.15854	0.65	0.5822
LS*MP	2	55.26573	27.63286	1.62	0.2019
LS*REP	2	72.42823	36.21411	2.12	0.1237
MP*REP	1	2.56687	2.56687	0.15	0.6989

Dependent Variable: EPT (END-POINT TEMPERATURE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	41	30347.89583	740.19258	50.80	0.0001
Error	150	2185.68229	14.57122		
Corrected Total	191	32533.57813			
	R-Square	C.V.	Root MSE	EPT Mean	
	0.932818	6.615285	3.817226	57.7031250	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	1	1430.08333	1430.08333	98.14	0.0001
PW	1	3780.75000	3780.75000	259.47	0.0001
END	3	21420.75521	7140.25174	490.02	0.0001
LS	2	556.78906	278.39453	19.11	0.0001
MP	1	500.52083	500.52083	34.35	0.0001
REP	1	0.02083	0.02083	0.00	0.9699
TL*PW	1	97.75521	97.75521	6.71	0.0105
TL*END	3	212.82292	70.94097	4.87	0.0029
TL*LS	2	1764.00260	882.00130	60.53	0.0001
TL*MP	1	10.54688	10.54688	0.72	0.3963
TL*REP	1	1.50521	1.50521	0.10	0.7484
PW*END	3	69.73958	23.24653	1.60	0.1929
PW*LS	2	139.08594	69.54297	4.77	0.0098
PW*MP	1	18.13021	18.13021	1.24	0.2664
PW*REP	1	7.92187	7.92187	0.54	0.4621
END*LS	6	156.03385	26.00564	1.78	0.1058
END*MP	3	76.19792	25.39931	1.74	0.1606
END*REP	3	8.69792	2.89931	0.20	0.8970
LS*MP	2	35.22135	17.61068	1.21	0.3015
LS*REP	2	27.14323	13.57161	0.93	0.3963
MP*REP	1	34.17188	34.17188	2.35	0.1278

Appendix 6. The ANOVA results of bacterial survival, thermal responses and evaporation loss computed by the SAS GLM procedure for a data subset of beef loaves (10% fat), turkey loaves (10% fat) and BGB loaves (10% glycerol).

General Linear Models Procedure

Dependent Variable: LEC LOG (%SURVIVING E. COLI+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	44.96520324	1.45049043	18.09	0.0001
Error	40	3.20655558	0.08016389		
Corrected Total	71	48.17175881			
	R-Square	C.V.	Root MSE		LEC Mean
	0.933435	25.73789	0.283132		1.10006024

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	0.29335455	0.14667727	1.83	0.1736
EMD	3	36.91457129	12.30485710	153.50	0.0001
LS	2	2.09282923	1.04641462	13.05	0.0001
REP	1	0.25594576	0.25594576	3.19	0.0815
TL*EMD	6	1.57364461	0.26227410	3.27	0.0103
TL*LS	4	1.08519504	0.27129876	3.38	0.0178
TL*REP	2	0.02586163	0.01293082	0.16	0.8516
EMD*LS	6	2.13953742	0.35658957	4.45	0.0015
EMD*REP	3	0.28335205	0.09445068	1.18	0.3301
LS*REP	2	0.30091164	0.15045582	1.88	0.1663

Dependent Variable: LSA LOG (%SURVIVING S. AUREUS+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	42.40748584	1.36798341	19.46	0.0001
Error	40	2.81229784	0.07030745		
Corrected Total	71	45.21978368			
	R-Square	C.V.	Root MSE		LSA Mean
	0.937808	24.34857	0.265156		1.08899811

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	0.00253432	0.00126716	0.02	0.9821
EMD	3	34.60578145	11.53526048	164.07	0.0001
LS	2	3.70902411	1.85451205	26.38	0.0001
REP	1	0.01452168	0.01452168	0.21	0.6519
TL*EMD	6	0.83961325	0.13993554	1.99	0.0898
TL*LS	4	0.72693621	0.18173405	2.58	0.0514
TL*REP	2	0.02576566	0.01288283	0.18	0.8333
EMD*LS	6	2.26066705	0.37677784	5.36	0.0004
EMD*REP	3	0.15033194	0.05011065	0.71	0.5502
LS*REP	2	0.07231018	0.03615509	0.51	0.6019

Dependent Variable: LAB LOG (%SURVIVING AEROBIC BACTERIA+1)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	43.24666565	1.39505373	18.74	0.0001
Error	40	2.97708404	0.07442710		
Corrected Total	71	46.22374970			
	R-Square	C.V.	Root MSE		LAB Mean
	0.935594	25.27048	0.272813		1.07957327

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	0.13447842	0.06723921	0.90	0.4133
EMD	3	35.87156173	11.95718724	160.66	0.0001
LS	2	2.43216944	1.21608472	16.34	0.0001
REP	1	0.09386347	0.09386347	1.26	0.2681
TL*EMD	6	1.18085987	0.19680998	2.64	0.0296
TL*LS	4	0.92798091	0.23199523	3.12	0.0253
TL*REP	2	0.02688491	0.01344245	0.18	0.8354
EMD*LS	6	2.20358284	0.36726381	4.93	0.0007
EMD*REP	3	0.16642224	0.05547408	0.75	0.5314
LS*REP	2	0.20886183	0.10443091	1.40	0.2577

Dependent Variable: TPPTR (TIME OF POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	5776689.333	186344.817	32.07	0.0001
Error	40	232451.944	5811.299		
Corrected Total	71	6009141.278			
	R-Square	C.V.	Root MSE		TPPTR Mean
	0.961317	21.88649	76.23187		348.305556

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	799225.194	399612.597	68.76	0.0001
EMD	3	31070.278	10356.759	1.78	0.1661
LS	2	4187211.028	2093605.514	360.26	0.0001
REP	1	10416.056	10416.056	1.79	0.1882
TL*EMD	6	52728.139	8788.023	1.51	0.1991
TL*LS	4	606493.556	151623.389	26.09	0.0001
TL*REP	2	4702.528	2351.264	0.40	0.6699
EMD*LS	6	62756.639	10459.440	1.80	0.1238
EMD*REP	3	8121.389	2707.130	0.47	0.7077
LS*REP	2	13964.528	6982.264	1.20	0.3114

Dependent Variable: PEL (PERCENT EVAPORATION LOSS)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	251.8737667	8.1249602	77.53	0.0001
Error	40	4.1918778	0.1047969		
Corrected Total	71	256.0656444			
	R-Square	C.V.	Root MSE		PEL Mean
	0.983630	8.649286	0.323724		3.74277778

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	5.9087194	2.9543597	28.19	0.0001
EMD	3	233.8530333	77.9510111	743.83	0.0001
LS	2	6.0402194	3.0201097	28.82	0.0001
REP	1	0.0264500	0.0264500	0.25	0.6181
TL*EMD	6	0.9662917	0.1610486	1.54	0.1913
TL*LS	4	3.0665556	0.7666389	7.32	0.0002
TL*REP	2	0.2349083	0.1174542	1.12	0.3360
EMD*LS	6	0.5398250	0.0899708	0.86	0.5334
EMD*REP	3	1.1612056	0.3870685	3.69	0.0194
LS*REP	2	0.0765583	0.0382792	0.37	0.6963

Dependent Variable: MPTR (MICROWAVE PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	8925.086667	287.906022	17.70	0.0001
Error	40	650.453333	16.261333		
Corrected Total	71	9575.540000			
	R-Square	C.V.	Root MSE		MPTR Mean
	0.932071	10.79180	4.032534		37.3666667

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	105.885833	52.942917	3.26	0.0490
EMD	3	5826.857778	1942.285926	119.44	0.0001
LS	2	1345.080833	672.540417	41.36	0.0001
REP	1	6.360556	6.360556	0.39	0.5352
TL*EMD	6	102.876389	17.146065	1.05	0.4056
TL*LS	4	1423.253333	355.813333	21.88	0.0001
TL*REP	2	7.521944	3.760972	0.23	0.7946
EMD*LS	6	74.464722	12.410787	0.76	0.6031
EMD*REP	3	30.695000	10.231667	0.63	0.6004
LS*REP	2	2.090278	1.045139	0.06	0.9378

Dependent Variable: PPTR (POST PROCESSING TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	1483.815972	47.865031	2.99	0.0006
Error	40	639.402778	15.985069		
Corrected Total	71	2123.218750			
	R-Square	C.V.	Root MSE	PPTR Mean	
	0.698852	37.40943	3.998133	10.6875000	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	63.1875000	31.5937500	1.98	0.1519
EMD	3	48.3437500	16.1145833	1.01	0.3992
LS	2	895.7708333	447.8854167	28.02	0.0001
REP	1	50.8368056	50.8368056	3.18	0.0821
TL*EMD	6	96.8958333	16.1493056	1.01	0.4324
TL*LS	4	149.5416667	37.3854167	2.34	0.0716
TL*REP	2	24.8819444	12.4409722	0.78	0.4660
EMD*LS	6	88.4791667	14.7465278	0.92	0.4892
EMD*REP	3	7.8715278	2.6238426	0.16	0.9199
LS*REP	2	58.0069444	29.0034722	1.81	0.1761

Dependent Variable: STR (SUM OF TEMPERATURE RISE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	8152.088750	262.970605	17.03	0.0001
Error	40	617.770000	15.444250		
Corrected Total	71	8769.858750			
	R-Square	C.V.	Root MSE	STR Mean	
	0.929558	8.178099	3.929917	48.0541667	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	139.435833	69.717917	4.51	0.0171
EMD	3	6799.134861	2266.378287	146.75	0.0001
LS	2	119.947500	59.973750	3.88	0.0288
REP	1	21.233472	21.233472	1.37	0.2479
TL*EMD	6	119.276389	19.879398	1.29	0.2851
TL*LS	4	725.511667	181.377917	11.74	0.0001
TL*REP	2	55.646944	27.823472	1.80	0.1782
EMD*LS	6	100.548056	16.758009	1.09	0.3878
EMD*REP	3	26.430417	8.810139	0.57	0.6377
LS*REP	2	44.923611	22.461806	1.45	0.2456

Dependent Variable: EPT (END-POINT TEMPERATURE)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	8448.239583	272.523858	19.20	0.0001
Error	40	567.840278	14.196007		
Corrected Total	71	9016.079861			
	R-Square	C.V.	Root MSE	EPT Mean	
	0.937019	7.362699	3.767759	51.1736111	

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TL	2	206.298611	103.149306	7.27	0.0020
EMD	3	6845.843750	2281.947917	160.75	0.0001
LS	2	48.173611	24.086806	1.70	0.1962
REP	1	27.503472	27.503472	1.94	0.1716
TL*EMD	6	100.145833	16.690972	1.18	0.3385
TL*LS	4	986.451389	246.612847	17.37	0.0001
TL*REP	2	75.756944	37.878472	2.67	0.0817
EMD*LS	6	109.270833	18.211806	1.28	0.2870
EMD*REP	3	27.121528	9.040509	0.64	0.5957
LS*REP	2	21.673611	10.836806	0.76	0.4728

Appendix 7. The ANOVA results of location of after-processing temperature (APT) computed by the SAS GLM procedure with REPEATED statement for loaves (beef, turkey and BGB).

General Linear Models Procedure
Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

SOURCE	DF	TYPE III SS	MEAN SQUARE	F VALUE	PR > F
PW	1	28218.21052272	28218.21052272	42.66	0.0001
PFC	2	52365.36700016	26182.68350008	39.58	0.0001
MP	1	34324.55751265	34324.55751265	51.89	0.0001
LS	2	98278.60430600	49139.30215300	74.28	0.0001
EMD	3	824758.85620368	274919.61873456	415.60	0.0
PW*PFC	2	892.78400657	446.39200328	0.67	0.5098
PW*LS	2	2092.68333594	1046.34166797	1.58	0.2068
PW*EMD	3	4547.88613421	1515.96204474	2.29	0.0776
PFC*LS	4	4714.20827768	1178.55206942	1.78	0.1316
MP*LS	2	807.95321672	403.97660836	0.61	0.5435
MP*EMD	3	6593.49683829	2197.83227943	3.32	0.0198
LS*EMD	6	9029.09435821	1504.84905970	2.27	0.0358
ERROR	416	275184.81372515	661.50195607		

General Linear Models Procedure
Repeated Measures Analysis of Variance
Tests of Hypotheses for Within Subjects Effects

SOURCE	DF	TYPE III SS	MEAN SQUARE	F VALUE	PR > F	ADJUSTED G - G	PR > F H - F
LOCATION	15	189343.07638933	12622.87175929	209.48	0.0	0.0	0.0
LOCATION*PW	15	4756.69820315	317.11321354	5.26	0.0001	0.0001	0.0001
LOCATION*PFC	30	18086.22029336	602.87400978	10.00	0.0001	0.0001	0.0001
LOCATION*MP	15	3729.73523474	248.64901565	4.13	0.0001	0.0001	0.0001
LOCATION*LS	30	73983.50752012	2466.11691734	40.93	0.0	0.0	0.0
LOCATION*EMD	45	35014.96053548	778.11023412	12.91	0.0	0.0001	0.0001
LOCATION*PW*PFC	30	6203.72825249	206.79094175	3.43	0.0001	0.0001	0.0001
LOCATION*PW*LS	30	10829.26576247	360.97552542	5.99	0.0001	0.0001	0.0001
LOCATION*PW*EMD	45	4865.21748734	108.11594416	1.79	0.0009	0.0034	0.0022
LOCATION*PFC*LS	60	16253.54436566	270.89240609	4.50	0.0001	0.0001	0.0001
LOCATION*MP*LS	30	2694.65448917	89.82181631	1.49	0.0415	0.0643	0.0561
LOCATION*MP*EMD	45	3478.68539180	77.30411982	1.28	0.0976	0.1276	0.1173
LOCATION*LS*EMD	90	18706.54627458	207.85051416	3.45	0.0001	0.0001	0.0001
ERROR (LOCATION)	6240	376011.78467097	60.25829883				

GREENHOUSE-GEISSER EPSILON = 0.7438
HUYNH-FELDT EPSILON = 0.8228

Appendix 8. The ANOVA results of location of end-point temperature (EPT) computed by the SAS GLM procedure with REPEATED statement for loaves (beef, turkey and BGB).

General Linear Models Procedure
Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

SOURCE	DF	TYPE III SS	MEAN SQUARE	F VALUE	PR > F
PW	1	64468.45754332	64468.45754332	191.59	0.0001
PFC	2	27411.49646476	13705.74823238	40.73	0.0001
MP	1	21130.13345632	21130.13345632	62.80	0.0001
LS	2	36361.99952470	18180.99976235	54.03	0.0001
EMD	3	722058.87755248	240686.29251749	715.29	0.0
PW*PFC	2	3072.98541321	1536.49270660	4.57	0.0109
PW*LS	2	630.51470076	315.25735038	0.94	0.3927
PW*EMD	3	1649.87499609	549.95833203	1.63	0.1808
PFC*LS	4	2290.92250875	572.73062719	1.70	0.1486
MP*LS	2	727.23498586	363.61749293	1.08	0.3403
MP*EMD	3	1270.72813868	423.57604623	1.26	0.2881
LS*EMD	6	1959.39808871	326.56634812	0.97	0.4448
ERROR	409	137623.11060386	336.48682299		

General Linear Models Procedure
Repeated Measures Analysis of Variance
Tests of Hypotheses for Within Subjects Effects

SOURCE	DF	TYPE III SS	MEAN SQUARE	F VALUE	PR > F	ADJUSTED G - G	PR > F H - F
LOCATION	15	41480.43083668	2765.36205578	146.17	0.0	0.0	0.0
LOCATION*PW	15	6970.68864051	464.71257603	24.56	0.0001	0.0001	0.0001
LOCATION*PFC	30	5386.00238667	179.53341289	9.49	0.0001	0.0001	0.0001
LOCATION*MP	15	966.36755297	64.42450353	3.41	0.0001	0.0001	0.0001
LOCATION*LS	30	36315.28574370	1210.50952479	63.99	0.0	0.0	0.0
LOCATION*EMD	45	9337.89251026	207.50872245	10.97	0.0001	0.0001	0.0001
LOCATION*PW*PFC	30	849.21733596	28.30724453	1.50	0.0401	0.0621	0.0539
LOCATION*PW*LS	30	3394.79923052	113.15997435	5.98	0.0001	0.0001	0.0001
LOCATION*PW*EMD	45	1650.43694566	36.67637657	1.94	0.0002	0.0009	0.0005
LOCATION*PFC*LS	60	5280.90503537	88.01508392	4.65	0.0001	0.0001	0.0001
LOCATION*MP*LS	30	812.80554377	27.09351813	1.43	0.0597	0.0852	0.0759
LOCATION*MP*EMD	45	1077.88949186	23.95309982	1.27	0.1097	0.1397	0.1291
LOCATION*LS*EMD	90	7342.82610200	81.58695669	4.31	0.0001	0.0001	0.0001
ERROR (LOCATION)	6135	116064.13498443	18.91835941				

GREENHOUSE-GEISSER EPSILON = 0.7473
HUYNH-FELDT EPSILON = 0.8282

Appendix 9. The ANOVA results of temperature variation within a loaf computed by the SAS GLM procedure for a data subset of beef loaves (10, 20 and 30% fat).

GENERAL LINEAR MODELS PROCEDURE					
DEPENDENT VARIABLE: LMPTR (LOG VALUE OF 16 MPTRs WITHIN A LOAF)					
SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	14.66250257	0.29325005	5.96	0.0001
ERROR	237	11.65988697	0.04919784		
CORRECTED TOTAL	287	26.32238955			
		R-SQUARE	C.V.	ROOT MSE	LMPTR MEAN
		0.557035	9.5507	0.22180585	2.32239824
SOURCE	DF	TYPE III SS	F VALUE	PR > F	
PW	1	0.05074145	1.03	0.3109	
PFC	2	0.64489854	6.55	0.0017	
MP	1	1.86177137	37.84	0.0001	
LS	2	2.39630193	24.35	0.0001	
END	3	2.34877410	15.91	0.0001	
REP	1	0.00126211	0.03	0.8729	
PW*PFC	2	0.19736160	2.01	0.1368	
PW*MP	1	0.09593928	1.95	0.1639	
PW*LS	2	0.14715022	1.50	0.2262	
PW*END	3	1.03757529	7.03	0.0002	
PW*REP	1	0.06414542	1.30	0.2547	
PFC*MP	2	0.08472757	0.86	0.4240	
PFC*LS	4	0.14077500	0.72	0.5822	
PFC*END	6	0.87715187	2.97	0.0081	
PFC*REP	2	0.35756336	3.63	0.0279	
MP*LS	2	0.77354857	7.86	0.0005	
MP*END	3	0.31067431	2.10	0.1003	
MP*REP	1	0.01916336	0.39	0.5332	
LS*END	6	3.14169448	10.64	0.0001	
LS*REP	2	0.09214992	0.94	0.3934	
END*REP	3	0.01913283	0.13	0.9424	
DEPENDENT VARIABLE: LSTR (LOG VALUE OF 16 STRs WITHIN A LOAF)					
SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	14.88898433	0.29777969	5.26	0.0001
ERROR	237	13.41649591	0.05660969		
CORRECTED TOTAL	287	28.30548024			
		R-SQUARE	C.V.	ROOT MSE	LSTR MEAN
		0.526011	14.0912	0.23792790	1.68848128
SOURCE	DF	TYPE III SS	F VALUE	PR > F	
PW	1	0.40283550	7.12	0.0082	
PFC	2	0.36732955	3.24	0.0407	
MP	1	0.00679180	0.12	0.7294	
LS	2	7.78969402	68.80	0.0001	
END	3	2.45187565	14.44	0.0001	
REP	1	0.19817713	3.50	0.0626	
PW*PFC	2	0.02149217	0.19	0.8272	
PW*MP	1	0.00453555	0.08	0.7774	
PW*LS	2	0.21584840	1.91	0.1509	
PW*END	3	0.28791532	1.70	0.1687	
PW*REP	1	0.03200104	0.57	0.4529	
PFC*MP	2	0.03410904	0.30	0.7402	
PFC*LS	4	0.27031351	1.19	0.3142	
PFC*END	6	0.12280995	0.36	0.9027	
PFC*REP	2	0.07599164	0.67	0.5121	
MP*LS	2	0.04457506	0.39	0.6750	
MP*END	3	0.13257677	0.78	0.5058	
MP*REP	1	0.06266418	1.11	0.2938	
LS*END	6	1.94126806	5.72	0.0001	
LS*REP	2	0.02125450	0.19	0.8290	
END*REP	3	0.40492548	2.38	0.0700	

DEPENDENT VARIABLE: LAPT (LOG VALUE OF 16 APTs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	14.66250257	0.29325005	5.96	0.0001
ERROR	237	11.65988697	0.04919784		
CORRECTED TOTAL	287	26.32238955			
		R-SQUARE	C.V.	ROOT MSE	LAPT MEAN
		0.557035	9.5507	0.22180585	2.32239824

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	0.05074145	1.03	0.3109
PFC	2	0.64489854	6.55	0.0017
MP	1	1.86177137	37.84	0.0001
LS	2	2.39630193	24.35	0.0001
END	3	2.34877410	15.91	0.0001
REP	1	0.00126211	0.03	0.8729
PW*PFC	2	0.19736160	2.01	0.1368
PW*MP	1	0.09593928	1.95	0.1639
PW*LS	2	0.14715022	1.50	0.2262
PW*END	3	1.03757529	7.03	0.0002
PW*REP	1	0.06414542	1.30	0.2547
PFC*MP	2	0.08472757	0.86	0.4240
PFC*LS	4	0.14077500	0.72	0.5822
PFC*END	6	0.87715187	2.97	0.0081
PFC*REP	2	0.35756336	3.63	0.0279
MP*LS	2	0.77354857	7.86	0.0005
MP*END	3	0.31067431	2.10	0.1003
MP*REP	1	0.01916336	0.39	0.5332
LS*END	6	3.14169448	10.64	0.0001
LS*REP	2	0.09214992	0.94	0.3934
END*REP	3	0.01913283	0.13	0.9424

DEPENDENT VARIABLE: LEPT (LOG VALUE OF 16 EPTs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	14.88898433	0.29777969	5.26	0.0001
ERROR	237	13.41649591	0.05660969		
CORRECTED TOTAL	287	28.30548024			
		R-SQUARE	C.V.	ROOT MSE	LEPT MEAN
		0.526011	14.0912	0.23792790	1.68848128

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	0.40283550	7.12	0.0082
PFC	2	0.36732955	3.24	0.0407
MP	1	0.00679180	0.12	0.7294
LS	2	7.78969402	68.80	0.0001
END	3	2.45187565	14.44	0.0001
REP	1	0.19817713	3.50	0.0626
PW*PFC	2	0.02149217	0.19	0.8272
PW*MP	1	0.00453555	0.08	0.7774
PW*LS	2	0.21584840	1.91	0.1509
PW*END	3	0.28791532	1.70	0.1687
PW*REP	1	0.03200104	0.57	0.4529
PFC*MP	2	0.03410904	0.30	0.7402
PFC*LS	4	0.27031351	1.19	0.3142
PFC*END	6	0.12280995	0.36	0.9027
PFC*REP	2	0.07599164	0.67	0.5121
MP*LS	2	0.04457506	0.39	0.6750
MP*END	3	0.13257677	0.78	0.5058
MP*REP	1	0.06266418	1.11	0.2938
LS*END	6	1.94126806	5.72	0.0001
LS*REP	2	0.02125450	0.19	0.8290
END*REP	3	0.40492548	2.38	0.0700

DEPENDENT VARIABLE: RMPTR (RANGE OF 16 MPTRs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	13646.40104167	272.92802083	5.22	0.0001
ERROR	237	12392.01475694	52.28698210		
CORRECTED TOTAL	287	26038.41579861			
		R-SQUARE	C.V.	ROOT MSE	RMPTR MEAN
		0.524087	20.2747	7.23097380	35.66493056

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	14.00086806	0.27	0.6053
PFC	2	360.42881944	3.45	0.0335
MP	1	1757.75086806	33.62	0.0001
LS	2	2010.64756944	19.23	0.0001
EMD	3	2476.41927083	15.79	0.0001
REP	1	2.25781250	0.04	0.8356
PW*PFC	2	59.80381944	0.57	0.5652
PW*MP	1	171.89670139	3.29	0.0711
PW*LS	2	109.38715278	1.05	0.3529
PW*EMD	3	1265.86371528	8.07	0.0001
PW*REP	1	30.35503472	0.58	0.4469
PFC*MP	2	152.48090278	1.46	0.2348
PFC*LS	4	241.15972222	1.15	0.3323
PFC*EMD	6	609.89062500	1.94	0.0746
PFC*REP	2	267.44270833	2.56	0.0796
MP*LS	2	935.81423611	8.95	0.0002
MP*EMD	3	136.50260417	0.87	0.4572
MP*REP	1	12.70920139	0.24	0.6225
LS*EMD	6	2796.60937500	8.91	0.0001
LS*REP	2	196.23437500	1.88	0.1554
EMD*REP	3	38.74565972	0.25	0.8634

DEPENDENT VARIABLE: RSTR (RANGE OF 16 STRs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	7243.48097222	144.86961944	5.49	0.0001
ERROR	237	6259.14121528	26.40987855		
CORRECTED TOTAL	287	13502.62218750			
		R-SQUARE	C.V.	ROOT MSE	RSTR MEAN
		0.536450	25.961	5.13905425	19.79479167

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	315.21420139	11.94	0.0007
PFC	2	39.68520833	0.75	0.4729
MP	1	0.05281250	0.00	0.9644
LS	2	3229.41645833	61.14	0.0001
EMD	3	1637.06177083	20.66	0.0001
REP	1	11.64031250	0.44	0.5074
PW*PFC	2	27.01756944	0.51	0.6003
PW*MP	1	10.01281250	0.38	0.5387
PW*LS	2	54.26548611	1.03	0.3595
PW*EMD	3	336.07815972	4.24	0.0061
PW*REP	1	18.86003472	0.71	0.3989
PFC*MP	2	47.47895833	0.90	0.4084
PFC*LS	4	93.28770833	0.88	0.4747
PFC*EMD	6	140.88145833	0.89	0.5035
PFC*REP	2	115.97687500	2.20	0.1135
MP*LS	2	10.06020833	0.19	0.8267
MP*EMD	3	37.55343750	0.47	0.7007
MP*REP	1	0.99170139	0.04	0.8465
LS*EMD	6	936.09187500	5.91	0.0001
LS*REP	2	18.58520833	0.35	0.7037
EMD*REP	3	163.26871528	2.06	0.1061

DEPENDENT VARIABLE: RAPT (RANGE OF 16 APTs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	13646.40104167	272.92802083	5.22	0.0001
ERROR	237	12392.01475694	52.28698210		
CORRECTED TOTAL	287	26038.41579861			
		R-SQUARE	C.V.	ROOT MSE	RAPT MEAN
		0.524087	20.2747	7.23097380	35.66493056

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	14.00086806	0.27	0.6053
PFC	2	360.42881944	3.45	0.0335
MP	1	1757.75086806	33.62	0.0001
LS	2	2010.64756944	19.23	0.0001
END	3	2476.41927083	15.79	0.0001
REP	1	2.25781250	0.04	0.8356
PW*PFC	2	59.80381944	0.57	0.5652
PW*MP	1	171.89670139	3.29	0.0711
PW*LS	2	109.38715278	1.05	0.3529
PW*END	3	1265.86371528	8.07	0.0001
PW*REP	1	30.35503472	0.58	0.4469
PFC*MP	2	152.48090278	1.46	0.2348
PFC*LS	4	241.15972222	1.15	0.3323
PFC*END	6	609.89062500	1.94	0.0746
PFC*REP	2	267.44270833	2.56	0.0796
MP*LS	2	935.81423611	8.95	0.0002
MP*END	3	136.50260417	0.87	0.4572
MP*REP	1	12.70920139	0.24	0.6225
LS*END	6	2796.60937500	8.91	0.0001
LS*REP	2	196.23437500	1.88	0.1554
END*REP	3	38.74565972	0.25	0.8634

DEPENDENT VARIABLE: REPT (RANGE OF 16 EPTs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	7243.48097222	144.86961944	5.49	0.0001
ERROR	237	6259.14121528	26.40987855		
CORRECTED TOTAL	287	13502.62218750			
		R-SQUARE	C.V.	ROOT MSE	REPT MEAN
		0.536450	25.9616	5.13905425	19.79479167

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	315.21420139	11.94	0.0007
PFC	2	39.68520833	0.75	0.4729
MP	1	0.05281250	0.00	0.9644
LS	2	3229.41645833	61.14	0.0001
END	3	1637.06177083	20.66	0.0001
REP	1	11.64031250	0.44	0.5074
PW*PFC	2	27.01756944	0.51	0.6003
PW*MP	1	10.01281250	0.38	0.5387
PW*LS	2	54.26548611	1.03	0.3595
PW*END	3	336.07815972	4.24	0.0061
PW*REP	1	18.86003472	0.71	0.3989
PFC*MP	2	47.47895833	0.90	0.4084
PFC*LS	4	93.28770833	0.88	0.4747
PFC*END	6	140.88145833	0.89	0.5035
PFC*REP	2	115.97687500	2.20	0.1135
MP*LS	2	10.06020833	0.19	0.8267
MP*END	3	37.55343750	0.47	0.7007
MP*REP	1	0.99170139	0.04	0.8465
LS*END	6	936.09187500	5.91	0.0001
LS*REP	2	18.58520833	0.35	0.7037
END*REP	3	163.26871528	2.06	0.1061

DEPENDENT VARIABLE: LPPTR (LOG VALUE OF 16 PPTRs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	50.88817109	1.01776342	10.59	0.0001
ERROR	230	22.10125346	0.09609241		
CORRECTED TOTAL	280	72.98942455			
		R-SQUARE	C.V.	ROOT MSE	LPPTR MEAN
		0.697199	15.2533	0.30998775	2.03226560

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	3.25888103	33.91	0.0001
PFC	2	1.31577862	6.85	0.0013
MP	1	1.64488958	17.12	0.0001
LS	2	37.21611944	193.65	0.0001
EMD	3	1.54843416	5.37	0.0014
REP	1	0.02435365	0.25	0.6151
PW*PFC	2	0.35134011	1.83	0.1630
PW*MP	1	0.10992101	1.14	0.2859
PW*LS	2	1.18636203	6.17	0.0024
PW*EMD	3	0.54490719	1.89	0.1320
PW*REP	1	0.06105738	0.64	0.4262
PFC*MP	2	0.27881302	1.45	0.2365
PFC*LS	4	0.89131580	2.32	0.0579
PFC*EMD	6	1.38639424	2.40	0.0284
PFC*REP	2	0.29096781	1.51	0.2222
MP*LS	2	1.66583866	8.67	0.0002
MP*EMD	3	0.48975707	1.70	0.1680
MP*REP	1	0.03461613	0.36	0.5490
LS*EMD	6	1.05442291	1.83	0.0944
LS*REP	2	0.46286771	2.41	0.0922
EMD*REP	3	0.21556844	0.75	0.5246

DEPENDENT VARIABLE: RPPTR (RANGE OF 16 PPTRs WITHIN A LOAF)

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	50	25280.92883487	505.61857670	7.40	0.0001
ERROR	230	15705.83230392	68.28622741		
CORRECTED TOTAL	280	40986.76113879			
		R-SQUARE	C.V.	ROOT MSE	RPPTR MEAN
		0.616807	28.8343	8.26354811	28.65871886

SOURCE	DF	TYPE III SS	F VALUE	PR > F
PW	1	1399.39194735	20.49	0.0001
PFC	2	808.12887735	5.92	0.0031
MP	1	1291.26131727	18.91	0.0001
LS	2	16553.55433440	121.21	0.0001
EMD	3	997.95577320	4.87	0.0026
REP	1	2.99897932	0.04	0.8342
PW*PFC	2	0.01081682	0.00	0.9999
PW*MP	1	150.87265412	2.21	0.1385
PW*LS	2	237.95806576	1.74	0.1774
PW*EMD	3	505.47430647	2.47	0.0629
PW*REP	1	8.01485112	0.12	0.7322
PFC*MP	2	237.16331739	1.74	0.1784
PFC*LS	4	371.88466941	1.36	0.2481
PFC*EMD	6	564.34697252	1.38	0.2245
PFC*REP	2	138.04381230	1.01	0.3655
MP*LS	2	1474.32126691	10.80	0.0001
MP*EMD	3	184.89545313	0.90	0.4406
MP*REP	1	0.43097007	0.01	0.9367
LS*EMD	6	521.92630974	1.27	0.2702
LS*REP	2	257.49615288	1.89	0.1541
EMD*REP	3	134.67686113	0.66	0.5791

MICHIGAN STATE UNIV. LIBRARIES



31293005728484