

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

# **PREDICTION OF CHILLING RATES FOR FOOD PRODUCT PACKAGES**

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Food Engineering at Massey University, Palmerston North, New Zealand.

Michael Francis North

2000

## ABSTRACT

Many food product packages contain significant air void fractions in which natural convection and radiation heat transfer occurs. This may significantly affect the cooling rate of the package as a whole. Voids tend to be either rectangular (at the top of the package), approximately triangular (e.g. in corners of the package), or can be represented as a combination of both shapes. For widely used meat cartons containing voids the bulk of the heat transfer can be modelled two-dimensionally, ignoring end effects.

Empirical  $Nu$  vs.  $Ra$  correlations for horizontal rectangular air voids were available from the technical literature. Since corresponding published data were not obtainable for right-angled isosceles triangular air voids cooled from above with a hypotenuse-down orientation, temperature-time data were collected from twenty-eight transient chilling trials using analogue food packages that contained different sized voids (up to 50mm high) with this shape and orientation. A reliable finite element package was used to model the heat transfer as a conduction process throughout the entire analogue package. The effective thermal conductivities that best-fitted modelled and measured temperature-time profiles within each of five sequential time intervals during cooling were determined. The results were then curve-fitted to generate  $Nu$  vs.  $Ra$  correlations.

New two-dimensional finite element models were developed for predicting chilling rates of food packages that contained combinations of isosceles triangular and/or horizontal rectangular air voids. The models were solved by using a customised heat conduction program called FINELX, in which the effective thermal conductivity in the voids was recalculated at the start of every time-step from the  $Nu$  vs.  $Ra$  correlations, but the heat transfer was otherwise modelled as conduction.

The finite element model was tested against twenty independent transient chilling trials using an analogue food package that contained rectangular and triangular voids of various heights. Predictions from the finite element model agreed to within  $\pm 7\%$  and  $\pm 12\%$  (at the 95% level of confidence) of the measured data for packages containing rectangular voids and packages containing combined rectangular and triangular voids respectively. This indicated that the model was an accurate simulator of the overall heat transfer occurring in packages that contained significant air void fractions.

Previously available simple methods for the prediction of chilling rates of such packages assumed that the contents were homogeneous solids with 'effective' thermal properties based upon the packaging arrangement and the relative amounts of solid and air. These methods were shown to be inaccurate.

A simple model based on the semi-infinite slab shape was developed for predicting chilling rates of food packages that contained combinations of isosceles triangular and/or horizontal rectangular void shapes. The simple model accounted for the presence of air voids by the use of effective heat transfer coefficients. Several types of solution method were possible: from analytical methods to simple numerical methods with a run-time of only a few seconds on a 350MHz Pentium II computer, which was significantly less than the 3 hours preparation and 5 hours run-time for the finite element model. Testing of the simple model against measured data from forty-eight transient chilling trials yielded 95% confidence intervals of (-6, +12)%, (-15, +11)%, and (-9, +17)% for packages containing rectangular voids, triangular voids, and combined voids respectively. The quality of prediction indicated that the assumptions employed during the development of the simple model did not worsen its accuracy beyond a level that was likely to be acceptable in industry.

Although the simple model gave relatively accurate results for much less computational effort, the customised finite element approach would allow researchers to extend the applicability of the model to any void shape, provided that natural convection and radiation heat transfer data within that particular void shape were available.

## ACKNOWLEDGEMENTS

Firstly, I would like to sincerely thank my excellent and dedicated supervisors for their continued advice, assistance, guidance and support during this project:

- Dr. Andrew Cleland, Chief Executive Officer, The Institution of Professional Engineers New Zealand Inc. (Chief Supervisor).
- Dr. Simon Lovatt, Team Leader, Processing and Preservation Technology, AgResearch Food Systems and Technology, Hamilton.

A big thank you to the Processing and Preservation Technology team at AgResearch Food Systems and Technology for all their advice and technical support. Craig Lawson, Robert Kemp and Jim Willix for their invaluable experience and assistance, particularly in the experimental phases of this work. Dr. Mark Harris and Dr. Inge Merts for their advice and inspiration. Keith Hill for keeping my car running and my stereo humming. And to the entire team for running all those simulations!

Thank you to my friends and to my fellow postgraduate students who kept me sane (and *almost* sober) throughout this 'ordeal' – Clint & Emily, Dave, Jules, JB (Guru Sansui), Julz, Karen & Graham, Claire, Jen & Chris, Layton & Julie, Ayn, Katie, Zippy, Amy, Kristen, Rochelle, Michelle, and James.

Thanks to the boys of AFFLUVIUM - Kane 'Lightning' Thomas, Aaron 'Overcast' O'Donnell, 'Kermit' Williams, and Art Davey - for always being there (even if it was an hour late!). And for putting up with my organisational skills, my oversized vocal chords and my love of the word 'No!!!'. We're going to the moon baby!

Finally I would like to thank my family:

- My parents, Jeanette and John, for all your love, and emotional and financial support. I couldn't have done this without knowing you were there.
- Louise & Tyrone, Graeme & Sharon, and all the 'rellys'. Thanks for your well wishes and encouragement.
- Michelle, thank you for your love, support, patience and understanding.

*This work is dedicated to the loving memory of Adele & Bill Wilson ('Nana & Poppa'), and Janina Barycza ('Nana-in-Australia').*

Thank you to the New Zealand Public Good Science Fund for funding this work under project FRST MRI 501.



"If you don't eat yer meat, you can't have any pudding."

Roger Waters, The Wall (Part II), PINK FLOYD

## Table of Contents

Abstract	ii
Acknowledgements	iv
Table of Contents	vi
List of Figures	xiii
List of Tables	xix

<i>Chapter</i>	<i>Page No.</i>
<b>1. Introduction</b>	<b>1.1</b>
<b>2. Literature Review</b>	<b>2.1</b>
2.1 Scope of the Review	2.1
2.2 Unsteady State Heat Transfer by Conduction in Solids	2.1
2.2.1 Physical Models for Chilling of Solid Biological Materials	2.1
2.2.2 Model Formulation	2.2
2.2.3 Boundary Conditions	2.2
2.2.4 Initial Conditions	2.4
2.2.5 Numerical Solutions	2.4
2.2.5.1 The Finite Difference Method	2.4
2.2.5.2 The Finite Element Method	2.7
2.2.5.3 The Boundary Element Method	2.10
2.2.5.4 The Control Volume Method	2.10

2.2.6 Analytical Solutions	2.10
2.2.7 Empirically-adapted Solutions	2.12
2.2.8 Composite Solids - Effective Thermal Properties Theory	2.16
2.3 Natural Convection	2.19
2.3.1 Numerical Solutions (Computational Fluid Dynamics)	2.19
2.3.1.1 Existing Commercial CFD Solvers	2.22
2.3.2 Analytical Solutions	2.23
2.3.3 Empirical Solutions	2.26
2.4 Summary	2.27
<b>3. Preliminary Considerations</b>	<b>3.1</b>
<b>4. Preliminary Collection and Analysis of Data for Packages Containing Triangular Voids</b>	<b>4.1</b>
4.1 Objectives	4.1
4.2 Experimental Methodology	4.1
4.3 Evaluation of Input Data	4.7
4.3.1 Thermal Properties of Test Materials	4.7
4.3.2 Sample Dimensions	4.7
4.3.3 Cooling Medium Temperature	4.8
4.3.4 Surface Heat Transfer Coefficients	4.8
4.3.5 Edge Effects	4.11
4.4 Measured Time-Temperature Data in the Test Samples	4.13
4.5 Development and Testing of a Finite Element Model	4.16
4.5.1 The Preliminary FINEL Model - No edge effect included	4.16

4.5.2	Testing the Preliminary FINEL Grid	4.18
4.5.3	Comparison of the preliminary model with data from blocks containing no voids	4.19
4.5.4	The Second FINEL Model - Edge effect included	4.19
4.5.5	Testing the Second FINEL Grid	4.22
4.5.6	Comparison of second model with data from blocks containing no voids	4.22
4.6	Comparison of Measured and Predicted Data	4.24
4.7	Conclusions	4.28
<b>5.</b>	<b>Improved Data Collection and Model Development for Packages Containing Triangular Voids</b>	<b>5.1</b>
5.1	Experimental Methodology	5.2
5.2	Evaluation of Input Data	5.6
5.2.1	Sample Dimensions	5.6
5.2.2	Thermal Property Data	5.7
5.2.3	Initial and Boundary Conditions	5.7
5.3	Measured Time-Temperature Data in the Test Samples	5.10
5.4	Development of a New Numerical Model	5.14
5.4.1	Effect of varying <i>errlim</i> in PDEase2D	5.14
5.4.2	Accounting for the third dimension edge effect	5.16
5.4.3	Re-estimating the surface heat transfer coefficients	5.19
5.5	Prediction of Cooling Rates for Packages Containing Triangular Filled Voids	5.21

5.6 Prediction of Cooling Rates for Packages Containing Triangular Air Voids	5.25
5.7 Estimating the Effective Thermal Conductivity of Triangular Air Voids	5.27
5.8 Finding a Relationship Between $Ra$ and $Nu$ for Triangular Air Voids	5.29
<b>6. Development and Testing of a Model for Predicting Heat Transfer During Chilling of Packages Containing Horizontal Rectangular Voids</b>	<b>6.1</b>
6.1 Introduction	6.1
6.2 Selection and Development of Numerical Method	6.2
6.2.1 Increasing the Capacity of FINELX	6.3
6.2.2 Including Natural Convection in Air Voids based upon the Rayleigh Number	6.3
6.2.3 Including Radiation Heat Transfer in Rectangular Voids	6.4
6.2.4 Constructing Spatial Grids for FINELX	6.6
6.2.5 Testing the Natural Convection and Radiation Calculations within FINELX	6.6
6.3 Experimental Methodology for Model Testing	6.7
6.3.1 Accounting for Radiation Heat Transfer in Rectangular Voids	6.9
6.3.2 Experimental Apparatus and Design	6.9
6.4 Evaluation of Input Data	6.12
6.4.1 Sample Dimensions	6.12
6.4.2 Thermal Property Data	6.12
6.4.3 Initial and Boundary Conditions	6.12
6.4.3.1 Cooling Medium Temperatures	6.12



<b>8. Development of a Simple Method for Predicting Heat Transfer During Chilling of Packages Containing Rectangular and Triangular Voids</b>	<b>8.1</b>
8.1 Simplification of the Prediction Method	8.1
8.2 Dealing With Asymmetric Heat Transfer Coefficients	8.3
8.3 Food Packages Containing Rectangular Voids	8.4
8.3.1 Development of a Simple Physical Model	8.4
8.3.2 Calculation Method and Relevant Equations	8.5
8.3.3 Averaging Temporal Variations – One Step Calculations	8.7
8.4 Food Packages Containing Triangular Voids	8.7
8.4.1 Development of a Simple Physical Model	8.7
8.4.2 Averaging Temporal Variations	8.9
8.4.3 Averaging Spatial Variations	8.9
8.5 Food Packages Containing Combined Void Spaces	8.13
8.6 Accuracy of Predictions by the Simple Models	8.15
8.6.1 Food Packages Containing Rectangular Voids	8.16
8.6.2 Food Packages Containing Triangular Voids	8.21
8.6.3 Food Packages Containing Combined Voids	8.30
8.6.4 Cooling Times vs. Cooling Rates	8.33
8.7 Comparison Against Other Existing Prediction Methods	8.35
8.8 Commercial Applications of the New Models	8.41
8.9 Discussion and Conclusions	8.41
<b>9. Conclusions</b>	<b>9.1</b>

Notation	Not.1
References	Ref.1

### **Appendices:**

A1. Determination of Thermal Conductivity for Test Materials	A1-1
A1.1 Polycarbonate Sheeting	A1-1
A1.2 'Styrodur' Polystyrene Insulation	A1-4
A2. User's Guide to FINELX Program	A2-1
A3. Worked Examples Using The Simpler Prediction Method	A3-1
A4. Published Work:	A4-1
Prediction of Chilling and Freezing Rates of Cartoned Meat	A4-2
Methods for Evaluating the Effect of Large Voids on Food Package Cooling Times	A4-4
The Effect of Void Space on Chilling Times for Food Product Packages	A4-13

## List of Figures

2.1 A banded matrix	2.8
2.2 Boundary conditions on a horizontal infinite cylinder	2.24
3.1 Photographs showing cross sections of four types of boneless primal cut packages	3.2
3.2 Diagram of the thermal resistances within a full meat carton undergoing three-dimensional cooling	3.3
3.3 Diagram of simplified physical model	3.4
4.1 Diagram of simplified physical model with and without a headspace void	4.1
4.2 Photograph of test sample holder	4.2
4.3 Diagram of test sample holder	4.4
4.4 Diagram of plate cooler	4.4
4.5 Diagram of the heat transfer pathways of edge effects	4.12
4.6 Plot of centre temperature vs. time for Tylose blocks containing no voids, and blocks containing 50mm high air voids and 50mm high filled voids	4.13
4.7 Plot of log unaccomplished temperature change ( $\ln Y_C$ ) vs. time for same data in Figure 4.5	4.14
4.8 FINEL grid with no edge effect (data taken from Run 6)	4.17
4.9 Plot of measured and predicted $\ln Y_{LS}$ vs. time (Run 4)	4.20
4.10 Plot of measured and predicted $\ln Y_C$ vs. time (Run 4)	4.20
4.11 Plot of measured and predicted $\ln Y_{US}$ vs. time (Run 4)	4.20
4.12 FINEL grid with edge effect included (data taken from Run 6)	4.21
4.13 Plot of measured and predicted $\ln Y_{LS}$ vs. time (Run 4)	4.23
4.14 Plot of measured and predicted $\ln Y_C$ vs. time (Run 4)	4.23

4.15	Plot of measured and predicted $\ln Y_{US}$ vs. time (Run 4)	4.23
4.16	Diagram of three treatments used to determine the third dimension edge effect	4.27
5.1	Side elevation of polycarbonate sample holder containing two Tylose blocks	5.2
5.2	Photograph of a sample holder	5.3
5.3	Diagram of two sample holders within the plate cooler	5.4
5.4	Plot of centre temperature vs. time for Tylose blocks containing no voids, and for blocks containing 50mm high filled voids and 50mm high air voids	5.10
5.5	Plot of $\ln Y_c$ vs. time for the same samples shown in Figure 5.4	5.11
5.6	Plot of $[d(\ln Y_c)/dt]$ vs. time for the same samples shown in Figure 5.4	5.11
5.7	(Cooling time)/(Solid block cooling time) at higher HTC	5.13
5.8	(Cooling time)/(Solid block cooling time) at lower HTC	5.13
5.9	Example data file from PDEase2D	5.15
5.10	Example of the grid created by PDEase2D	5.22
5.11	Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 20mm voids, high HTC (Run 2)	5.23
5.12	Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 20mm voids, low HTC (Run 1)	5.23
5.13	Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 30mm voids, high HTC (Run 9)	5.23
5.14	Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 30mm voids, low HTC (Run 6)	5.23
5.15	Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 40mm voids, high HTC (Run 15)	5.23
5.16	Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 40mm voids, low HTC (Run 11)	5.23

5.17 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 50mm voids, high HTC (Run 5)	5.23
5.18 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks with filled voids – 50mm voids, low HTC (Run 6)	5.23
5.19 Plot of percentage difference between measured and predicted times vs. void height	5.25
5.20 Comparison of predicted $\ln Y_c$ vs. time plots for a Tylose block containing filled voids and still-air voids ( $HTC = 12.7 \text{ Wm}^{-2}\text{K}^{-1}$ )	5.26
5.21 Diagram of transverse void positions for triangular voids cooled from above and below	5.29
5.22 Plot of $Ra$ vs. $Nu$ for triangular voids cooled from below (conduction and radiation only)	5.31
5.23 Plot of $Ra$ vs. $Nu$ for triangular voids cooled from above (conduction, radiation and natural convection)	5.33
6.1 Diagram of a sample holder containing rectangular horizontal voids	6.8
6.2 Side elevation of a sample holder containing rectangular horizontal voids	6.9
6.3 Diagram of a sample holder arrangement within the plate cooler	6.10
6.4 Plot showing an increase in the cooling rate of a block due to radiation heat transfer occurring in rectangular horizontal voids (data taken from Run 6)	6.15
6.5 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks containing horizontal rectangular voids with transparent walls – 10mm void, high HTC (Run 7)	6.17
6.6 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks containing horizontal rectangular voids with transparent walls – 10mm void, low HTC (Run 8)	6.17

6.7 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks containing horizontal rectangular voids with transparent walls – 30mm void, high HTC (Run 9)	6.17
6.8 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks containing horizontal rectangular voids with transparent walls – 30mm void, low HTC (Run 10)	6.17
7.1 Two-dimensional roll-like flow in a rectangular void	7.1
7.2 Expected two-dimensional roll-like flow in a combined void	7.2
7.3 Simplified physical model for combined voids	7.2
7.4 Areas of overlap in a combined void	7.3
7.5 Side elevation of a sample holder containing combined rectangular and triangular voids	7.4
7.6 Plot showing an increase in the cooling rate of a block due to the presence of triangular voids (data taken from Runs 2A & 2B)	7.8
7.7 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks containing combination of voids – 25mm rectangular and 50mm triangular voids, high HTC (Run 1B)	7.10
7.8 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks containing combination of voids – 25mm rectangular and 50mm triangular voids, high HTC (Run 2B)	7.10
7.9 Plot of $\ln Y_c$ vs. time for measured and predicted data from blocks containing combination of voids – 25mm rectangular and 50mm triangular voids, low HTC (Run 3B)	7.10

- 7.10 Plot of  $\ln Y_c$  vs. time for measured and predicted data from blocks containing combination of voids – 25mm rectangular and 50mm triangular voids, low HTC (Run 4B) 7.10
- 7.11 Plot of  $\ln Y_c$  vs. time for measured and predicted data from blocks containing combination of voids – 10mm rectangular and 30mm triangular voids, high HTC (Run 5A) 7.10
- 7.12 Plot of  $\ln Y_c$  vs. time for measured and predicted data from blocks containing combination of voids – 10mm rectangular and 50mm triangular voids, high HTC (Run 5B) 7.10
- 7.13 Plot of  $\ln Y_c$  vs. time for measured and predicted data from blocks containing combination of voids – 10mm rectangular and 30mm triangular voids, low HTC (Run 6A) 7.11
- 7.14 Plot of  $\ln Y_c$  vs. time for measured and predicted data from blocks containing combination of voids – 10mm rectangular and 50mm triangular voids, low HTC (Run 6B) 7.11
- 7.15 Plot of  $\ln Y_c$  vs. time for measured and predicted data from blocks containing combination of voids – 10mm rectangular and 30mm triangular voids, low HTC (Run 7A) 7.11
- 7.16 Plot of  $\ln Y_c$  vs. time for measured and predicted data from blocks containing combination of voids – 10mm rectangular and 50mm triangular voids, low HTC (Run 7B) 7.11
- 8.1 Simple physical model for food packages containing rectangular air voids 8.4
- 8.2 Simple physical model for food packages containing triangular air voids 8.8
- 8.3 A physical model treating the triangular air void as an effective heat transfer coefficient 8.9

8.4 A physical model treating the triangular air void as part of the solid material with an effective heat transfer coefficient	8.11
8.5 A physical model showing averaging of spatially varying heat transfer coefficients	8.12
8.6 Simple physical model for food packages containing combined air spaces	8.14
8.7 Plot of percentage differences from the measured data for prediction method A and prediction method B (with one step)	8.20
8.8 Plot of percentage differences from the measured data for prediction methods D and F	8.25
8.9 Sideways heat flow in the polycarbonate packaging layer	8.26
8.10 Diagram of the steady-state FINELX simulation to determine the effect of sideways heat flow	8.26
8.11 Plot of percentage differences from the measured data for prediction method A and prediction method F (with effective area adjustment included)	8.30
8.12 Plot of percentage differences from the measured data for prediction methods G and H	8.32

## List of Tables

2.1 Models for effective thermal conductivity of composite solids	2.18
2.2 Solutions to CFD of natural convection within various enclosure types	2.21
2.3 Analytical solutions of steady state natural convection within horizontal layers (adapted from Goldstein <i>et al.</i> , 1990)	2.25
2.4 Empirical solutions of steady state natural convection within various enclosure types	2.27
4.1 Treatment table for preliminary data collection	4.6
4.2 Thermal properties of test materials used in preliminary data collection	4.7
4.3 Individual estimates of lower surface (LS) and upper surface (US) HTC	4.11
4.4 Measured times for one $\ln Y_c$ reduction of blocks with filled voids or air voids	4.15
4.5 Comparison of prediction methods – centre temperatures	4.18
4.6 Comparison of prediction methods – centre temperatures	4.22
4.7 Comparison of measured and predicted times for one $\ln Y_c$ reduction	4.25
5.1 Treatment table for improved data collection	5.6
5.2 Thermal properties of test substances	5.7
5.3 Times for one $\ln Y_c$ reduction for blocks with triangular voids of various heights	5.12
5.4 Percentage difference between measured and predicted times for one $\ln Y_c$ reduction for runs with no voids	5.20
5.5 Measured and predicted times for one $\ln Y_c$ reduction for blocks with triangular filled voids	5.24
5.6 Thermal and physical properties of air	5.26

5.7 $Nu$ values for triangular air voids estimated by matching the measured and predicted data	5.28
6.1 Comparison of predicted cooling times of blocks containing rectangular voids with and without natural convection and radiation heat transfer	6.7
6.2 Treatment for trials with horizontal rectangular voids	6.11
6.3 Percentage difference between measured and predicted times for one $\ln Y_c$ reduction of blocks containing no voids	6.14
6.4 Comparison of predicted times for one $\ln Y_c$ reduction of blocks containing rectangular voids with and without natural convection and radiation heat transfer	6.15
6.5 Comparison of measured and predicted times for one $\ln Y_c$ reduction of blocks containing voids that had transparent or blackened walls	6.17
7.1 Treatment table for trials with combined voids	7.6
7.2 Comparison of measured and predicted times for one $\ln Y_c$ reduction of blocks containing 25mm high rectangular voids	7.9
7.3 Comparison of measured and predicted times for one $\ln Y_c$ reduction of blocks containing combined voids of various heights	7.11
8.1 Description of prediction methods used in section 8.6	8.16
8.2 Results from prediction method B (with 5 steps)	8.17
8.3 Comparison of measured data and results from prediction methods A and B (with 5 steps) - Times for one $\ln Y_c$ reduction	8.18
8.4 Comparison of times for one $\ln Y_c$ reduction predicted by method B with a different number of steps	8.19
8.5 Results from prediction method C	8.19
8.6 Comparison of measured data and results from prediction methods B (with one step) and C - Times for one $\ln Y_c$ reduction	8.20

8.7 Comparison of measured data and results from prediction methods D and E - Times for one $\ln Y_c$ reduction	8.22
8.8 Results from prediction method F	8.23
8.9 Percentage differences between prediction method F, the measured data, and prediction methods D and E	8.24
8.10 Combinations of boundary conditions for Figure 8.10	8.27
8.11 Estimated total heat flow values (with and without sideways heat flow)	8.27
8.12 Results from prediction method F with effective area adjustment included	8.28
8.13 Percentage differences between prediction method F (with effective area adjustment), the measured data, and prediction methods D and F	8.29
8.14 Results from prediction method H	8.31
8.15 Comparison of measured data and results from prediction methods G and H - Times for one $\ln Y_c$ reduction	8.32
8.16 Comparison of measured data and results from prediction methods A and B (with one step) - Times for 1.5 $\ln Y_c$ reductions	8.33
8.17 Comparison of measured data and results from prediction methods D and F (with effective area adjustment included) - Times for 1.5 $\ln Y_c$ reductions	8.34
8.18 Comparison of measured data and results from prediction methods G and H - Times for 1.5 $\ln Y_c$ reductions	8.35
8.19 Comparison of times for one $\ln Y_c$ reduction predicted by new and existing prediction methods for packages containing rectangular air voids	8.37
8.20 Percentage differences from measured data for new and existing prediction methods of packages containing rectangular air voids	8.38
8.21 Comparison of times for one $\ln Y_c$ reduction predicted by new and existing prediction methods for packages containing triangular air voids	8.38

8.22 Percentage differences from measured data for new and existing prediction methods of packages containing triangular air voids	8.39
8.23 Comparison of times for one $\ln Y_c$ reduction predicted by new and existing prediction methods for packages containing combined air voids	8.40
8.24 Percentage differences from measured data for new and existing prediction methods of packages containing combined air voids	8.40