A *FR 13* MICROBIOLOGICAL GLOBAL RISK MODEL – DEMONSTRATED FOR PASTEURIZATION OF RAW MILK WITH VIABLE *MYCOBACTERIUM AVIUM* SUBSP. *PARATUBERCULOSIS*

by

Saravanan CHANDRAKASH, MEngSc

School of Chemical Engineering
The University of Adelaide

A thesis submitted for the examination for the degree of
Doctor of Philosophy
March 2017

STATEMENT OF DECLARATION

I, Saravanan Chandrakash certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to provisions of the Copyright Act of 1968.

The author acknowledges that the copyright of published works[1] contained within this thesis resides with the copyright holders of those works.

I also give permission for the digital version of my thesis to be made available on the web, via University's digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signature:

Date:

---

[1] Chandrakash, S., Davey, K.R., 2017 a. Advancing the *Fr 1*3 risk framework to an integrated three-step microbiological failure synthesis of pasteurization of raw milk containing *Mycobacterium avium* subsp. *paratuberculosis* (*MAP*). Chemical Engineering Science 171, 1-18. http://dx.doi.org/10.1016/j.ces.2017.05.020

Chandrakash, S., Davey, K.R., 2017 b. A 4-step *Fr 13* microbiological pasteurizer model for raw milk involving a heat-up, holding for thermal inactivation, cool-down and storage of treated milk. AIChE J – *in preparation.*

Chandrakash, S., Davey, K.R., 2017 c. A review of the *Fr 13* risk assessment framework. Food Research International – *in preparation.*

Chandrakash, S., Davey, K.R., O'Neill, B.K., 2015. An *Fr 13* risk analysis of failure in a global food process – illustration with milk processing. Asia Pacific Journal of Chemical Engineering (Special Theme Research Article (**Invited paper**)) 10 (4), 526-541. http://dx.doi.org/10.1002/apj.1887

Chandrakash, S., Davey, K.R., O'Neill, B.K., 2014. A novel risk analysis of failure in a global food process – preliminary application to milk processing. In: Proc. 44th Australasian Chemical Engineering Conference (Processing Excellence, Powering our Future), Perth, Australia, Sept. 27-Oct. 1, Paper 1475. ISBN: 9781922107381

Davey, K.R., Chandrakash, S., O'Neill, B.K., 2014. A novel Friday 13th risk analysis of a global food process – application to pasteurization of raw milk containing *Mycobacterium avium paratuberculosis*. In: Proc. 26th European Modelling and Simulation Symposium - EMSS 2014, Bordeaux, France, Sept. 10-12. ISBN: 9788897999386

EXECUTIVE SUMMARY

Steady-state unit-operations are used globally in chemical engineering processing. Importantly however, there are naturally occurring (random) fluctuations in parameter values about a 'set' mean. These are not sufficient to be considered transient and a random change in one is often off-set by a change in another - with the result that the output remains seemingly steady. Significantly, traditional chemical engineering does not address these random fluctuations explicitly.

Davey and co-workers (e.g. Abdul Halim and Davey, 2015; Zou and Davey, 2016) have shown that these natural fluctuations can combine and accumulate in one direction and leverage unexpected and surprise behaviour across a 'failure - not failure' boundary. Their hypothesis they titled *Fr 13* (*Friday 13th*) to underscore the surprise element of the failure event. Their probabilistic *Fr 13* framework has been usefully applied to a number of 1-step unit-operations including failure in: UV irradiation for potable water (Abdul-Halim and Davey, 2015; 2016); thermal efficiency of a commercial coal-fired boiler (Davey, 2015), metals pitting (Davey et al., 2016), and; failure to remove whey protein deposits in Clean-In-Place milk processing (Davey et al., 2015). A significant advantage is that the framework can be used in quantitative 'second-tier' studies (Abdul-Halim and Davey, 2016) to improve design and safety of unit-operations. A limitation however is that the framework had been applied to only 1-step (single) unit-operations until very recently when Zou and Davey (2016) demonstrated its applicability to integrated 2-step membranes processing. Generally however, it is not known if there is any benefit in developing the framework as a useful tool for integrated, greater multi-step unit-operations and its possible combination (Davey et al., 2013) with existing software to enhance design capability. Davey (2011) had suggested these integrated multi-step analyses be termed 'global' models.

A research program is therefore undertaken with the aim to advance the *Fr 13* framework to gain unique insight into how naturally occurring fluctuations in apparent steady-state plant parameters can be transmitted and impact in progressively complex (in the context of 'integrated' not 'complicated') multi-step processes, and to assess the framework as a new design tool.

A logical and stepwise approach is implemented as a research strategy.

Because foods processing is globally the largest manufacturing sector, and within it, pasteurization is the most widely used unit-operation, a typical 3-step pasteurization unit-

operation, consisting of individual 1) heat-up, 2) holding and 3) cool-down, unit-operations is selected as a prudent and stringent test of the *Fr 13* risk thesis to multi-step unit-operations.

An initial assessment, based on typical commercial pasteurization equipment for raw milk (plate heat exchangers and an external-coil holding tube) is synthesized for the first time (Chandrakash et al., 2015; 2014; Davey et al., 2014) and a generalized method of notation for the *Fr 13* risk framework is developed to unambiguously identify particular unit-operations in integrated multi-step processes. Failure is defined in terms of not meeting a globally used Regulatory combination of temperature (T) - time (t) (72 ^{O}C, 15 s). Results revealed that pasteurization of raw milk is vulnerable to failure in 12.5 % of all cases over the long-term as a result of with-in system fluctuations in flows, and thermal conditions. If each simulation is (reasonably) considered a daily process this translated to some 46 failures each year with a 2 % design *tolerance* [2] to meet the required T - t pasteurization criteria.

Results highlighted that apparent steady-state pasteurization is actually a combination of successful and (potential) failed operations. This insight could not be obtained from existing traditional risk and hazard approaches, with or without sensitivity analyses.

A drawback soon acknowledged however, is that this equipment model did not explicitly address the reduction in unwanted levels of survival of potential contaminant micro-organisms in the treated milk. To overcome this, a microbiological global risk model is developed for the first time for the 3-step pasteurization. The logarithmic reduction of viable *Mycobacterium avium* subsp. *paratuberculosis* (*MAP*), a common bacterial contaminant and pathogen, is selected as an indicator of efficacy of process, and an inactivation model is then synthesized (Chandrakash and Davey, 2017 a).

Results showed that for a design Regulatory reduction of $\log_{10} = 5.5$ in viable *MAP* the 3-step pasteurization is vulnerable to failure in 5.75 % of cases with a 2 % design tolerance averaged over the long term. This equated to ~ 21 failures with viable *MAP* each year based on a daily operation.

To further test applicability of the risk framework to multi-step processing, a fourth integrated step, the storage of the pasteurized milk, is added for the first time (Chandrakash and Davey, 2017 b). A justification is that this simulated commercial practice more closely.

Results of simulation of this 4-step model showed that with a design tolerance of 2 % for a Regulatory design reduction of $\log_{10} = 5.5$ in viable *MAP* on heat-up to 72 ^{O}C with 15 s holding in commercial plate equipment, there would be no further failures i.e. the rate of

[2] *see* Appendix A for a definition of important terms used in this research. The first use appears italicized

vulnerability to failure in a 4-step microbiological model for pasteurizing and storing milk remained 5.75 %, averaged over the long term.

Results from investigative second-tier studies with the new 4-step *Fr 13* model to improve design and safety, revealed vulnerability to microbiological failure can be readily mitigated by installing precise safety-integrity-level (SIL) mass flow control on the raw milk in existing plant to ensure a holding time of ≥ 15 s.

It is concluded the *Fr 13* framework appears generalizable to integrated multi-step steady-state processes without methodological problems and an advance over current existing risk/hazard methodologies. If properly developed, it is believed that this novel framework could be adopted as a new design tool for steady-state processing at both design and synthesis stages.

Research findings will aid a detailed understanding of factors that contribute to failures, and to increased confidence in steady-state unit-operations processing.

This research work is original and not incremental work. Findings will be of direct interest to risk analysts, milk processors and manufacturers of pasteurizer equipment.

ACKNOWLEDGEMENTS

I would like to express my sincere and heartfelt gratitude to Dr K R (Ken) Davey FIChemE, FAIFST, my principal supervisor from the School of Chemical Engineering, The University of Adelaide, for providing me an opportunity to pursue this research work and for his guidance and help throughout my candidature. Also I wish to thank Dr Brian O'Neill FIChemE, my co-supervisor from the School of Chemical Engineering, The University of Adelaide, for providing guidance and valuable insights throughout my candidature.

I would also like to thank The University of Adelaide, for providing me with an Adelaide Graduate Research Scholarship (AGRS) to undertake my PhD studies.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

I would like to thank all the staff members in the School of Chemical Engineering and all my friends and my colleagues here in Australia for providing me with support and guidance when needed.

I am greatly indebted to my Father Mr Chandrakash Mariappan and my mother Mrs Muthuselvi Chandrakash who gave me an opportunity to come here and study in Australia.

I trust that the results of my research work justify the expectations and confidence of all the people concerned, and the interest and encouragement of my family, friends and colleagues.

DEDICATION

I would like to dedicate this thesis to my father Mr Chandrakash Mariappan. He passed away on September 6, 2013, the year I started my PhD candidature.

PUBLICATIONS MADE DURING RESEARCH CANDIDATURE

REFEREED SCIENTIFIC JOURNALS

Chandrakash, S., Davey, K.R., 2017 a. Advancing the *Fr 13* risk framework to an integrated three-step microbiological failure synthesis of pasteurization of raw milk containing *Mycobacterium avium* subsp. *paratuberculosis* (*MAP*). Chemical Engineering Science 171, 1-18. http://dx.doi.org/10.1016/j.ces.2017.05.020

Chandrakash, S., Davey, K.R., O'Neill, B.K., 2015. An *Fr 13* risk analysis of failure in a global food process – illustration with milk processing. Asia Pacific Journal of Chemical Engineering, (Special Theme Research Article (**Invited paper**)) 10 (4), 526-541. http://dx.doi.org/10.1002/apj.1887

REFEREED CONFERENCE PROCEEDING(S)

Davey, K.R., Chandrakash, S., O'Neill, B.K., 2014. A novel Friday 13th risk analysis of a global food process – application to pasteurization of raw milk containing *Mycobacterium avium paratuberculosis*. In: Proc. 26th European Modelling and Simulation Symposium - EMSS 2014, Bordeaux, France, Sept. 10-12. ISBN: 9788897999386

Chandrakash, S., Davey, K.R., O'Neill, B.K., 2014. A novel risk analysis of failure in a global food process – preliminary application to milk processing. In: Proc. 44th Australasian Chemical Engineering Conference (Processing Excellence, Powering our Future), Perth, Australia, Sept. 27-Oct. 1, paper 1475. ISBN: 9781922107381

OTHER RELATED

Davey, K.R., Chandrakash, S., O'Neill, B.K., 2015. A Friday 13th failure assessment of clean-in-place removal of whey protein deposits from metal surfaces with auto-set cleaning times. Chemical Engineering Science 126, 106-115. http://dx.doi.org/10.1016/j.ces.2014.12.013

Davey, K.R., Chandrakash, S., 2015. Modelling the effect of pH, sodium chloride and sodium pyrophosphate on the thermal resistance of *Escherichia coli* 0157:H7 in ground beef. Food Research International 75, 11-12. http://dx.doi.org/10.1016/j.foodres.2015.05.030

MANUSCRIPTS IN PREPARATION

Chandrakash, S., Davey, K.R., 2017 b. A 4-step *Fr 13* microbiological pasteurizer model for raw milk involving heat-up, holding for thermal inactivation of *Mycobacterium avium* subsp. *paratuberculosis* (*MAP*), cool-down and storage. AIChE J – *in preparation.*

Chandrakash, S., Davey, K.R., 2017 c. A review of the *Fr 13* risk assessment framework. Food Research International – *in preparation.*

TABLE OF CONTENTS **PAGE**

STATEMENT OF DECLARATION ii
EXECUTIVE SUMMARY iii
ACKNOWLEDGEMENTS vi
PUBLICATIONS MADE DURING RESEARCH CANDIDATURE vii
TABLE OF CONTENTS viii
LIST OF FIGURES xii
LIST OF TABLES xiv

CHAPTER 1 INTRODUCTION 1

CHAPTER 2 LITERATURE REVIEW 5
2.1 Introduction 6
2.2 Traditional deterministic single value assessment (SVA) solution 7
2.3 Risk, risk assessment and communication of risk findings 7
2.4 Probabilistic *Fr 13* framework 11
2.4.1 Development of the probabilistic *Fr 13* risk framework 11
2.4.2 A *Fr 13* risk assessment 12
2.5 Critical review of published case studies using probabilistic *Fr13* failure method 14
2.6 Advantages of *Fr 13* framework over current existing risk and hazard approaches 19
2.6.1 Other current existing probabilistic risk approaches 23
2.6.2 Advantages of *Fr 13* framework over current existing probabilistic risk approaches 23
2.7 *Fr 13* as a terminology 24
2.8 Benefits and current limitations of *Fr 13* 24
2.9 Milk processing 25
2.10 Pasteurization 28
2.11 Chapter summary and conclusions 30

CHAPTER 3 A *FR 13* RISK ASSESSMENT OF AN INTEGRATED 3-STEP PASTEURIZER CONSISTING OF HEATING, HOLDING AND COOLING UNIT-OPERATIONS 32

3.1 Introduction 33

3.2 Equipment unit-operations model 34

3.2.1 Heating ($PHE_{1\text{-}1}$) 34

3.2.2 Holding ($HT_{1\text{-}2}$) 36

3.2.3 Cooling ($PHE_{2\text{-}3}$) 37

3.3 Traditional single value assessment (SVA) solution 39

3.4 Establishing a *Fr 13* failure model for global pasteurization process 41

3.5 Defining pasteurization failure 43

3.5.1 *Fr 13* risk factor (*p*) 43

3.6 Results 44

3.7 Discussion 49

3.7.1 Pasteurization failures 49

3.7.2 Effect of *%tolerance* 49

3.7.3 Probability distributions used 49

3.7.4 Presentation of risk results 50

3.7.5 *Fr 13* second-tier simulations 50

3.7.6 Review of overall findings 51

3.7.7 Defining failure in *Fr 13* 53

3.8 Chapter summary and conclusions 55

CHAPTER 4 ADVANCING THE *FR 13* RISK FRAMEWORK TO AN INTEGRATED 3-STEP MICROBIOLOGICAL FAILURE SYNTHESIS OF PASTEURIZATION OF RAW MILK CONTAINING *MYCOBACTERIUM AVIUM* SUBSP. *PARATUBERCULOSIS* (*MAP*) 57

4.1 Introduction 58

4.2 Microbiological unit-operations model 58

4.2.1 Heat-up ($PHE_{1\text{-}1}$) 60

4.2.2 Holding for thermal inactivation ($HT_{1\text{-}2}$) 62

4.2.3 Cool-down ($PHE_{2\text{-}3}$) 63

4.3 Traditional single value assessment (SVA) solution 65

4.4 *Fr 13* model 67
4.4.1 Risk factors and defining failure 67
4.4.2 *Fr 13* pasteurizer simulations 68
4.5 Results 70
4.6 Discussion 80
4.6.1 *Fr 13* simulations 80
4.6.2 Mitigating vulnerability to *Fr 13* microbiological failures 80
4.6.3 Unexpected accumulations in the integrated 3-step synthesis 84
4.6.4 Establishing distributions for inputs and defining pasteurizer failure 85
4.6.5 Presentation of overall findings from *Fr 13* results 86
4.6.6 Results overview 89
4.6.7 Closing-the-loop on the pasteurizer vulnerability and advancing the *Fr 13* framework 92
4.7 Chapter summary and conclusions 94

CHAPTER 5 A 4-STEP *FR 13* MICROBIOLOGICAL PASTEURIZER MODEL FOR RAW MILK INVOLVING HEAT-UP, HOLDING FOR THERMAL INACTIVATION, COOL-DOWN AND STORAGE OF TREATED MILK 95

5.1 Introduction 96
5.2 4-step *Fr 13* microbiological pasteurizer model 96
5.2.1 Heat-up ($PHE_{1\text{-}1}$) 97
5.2.2 Holding for thermal inactivation ($HT_{1\text{-}2}$) 98
5.2.3 Cool-down ($PHE_{2\text{-}3}$) 99
5.2.4 Storage of pasteurized (treated) milk ($ST_{1\text{-}4}$) containing *MAP* 100
5.3 Traditional single value assessment (SVA) solution 101
5.4 *Fr 13* global model with storage of pasteurized milk 104
5.4.1 Risk factors and defining failure 104
5.4.2 *Fr 13* pasteurizer simulations 105
5.5 Results 106

5.6 Discussion 109
5.6.1 Integrated 4-step global *Fr 13* pasteurizer 109
5.6.2 Second-tier studies to mitigate failures in the integrated 4-step global microbiological model 109
5.7 Chapter summary and conclusions 111

CHAPTER 6 CONCLUSIONS AND FUTURE DEVELOPMENT 112
6.1 Conclusions 113
6.2 Recommendations for future research 116

APPENDICES A – C
A A definition of some important terms used in this research 117
B Synthesis of the risk factor for Chapters 3, 4 and 5 119
C Refereed publications from this research 122

NOMENCLATURE 123

REFERENCES 126

LIST OF FIGURES **PAGE**

Fig. 2-1 Block diagram depicting a typical milk processing plant 26

Fig. 3-1 A typical pasteurization process of raw milk consisting of integrated 3-steps 1) heating, 2) holding, and; 3) cooling processes 34

Fig. 3-2 A typical *Fr 13* pasteurization process of raw milk consisting of integrated 3-steps 1) heating, 2) holding, and; 3) cooling processes 41

Fig. 3-3 *Fr 13* simulation output graph highlighting all failures for $PHE_{1\text{-}1}$ (milk heating), all $p_1 > 0$ 46

Fig. 4-1 Schematic of an integrated 3-step pasteurization of raw milk containing *Mycobacterium avium* subsp. *tuberculosis* (*MAP*) showing the three unit-operations 1) heat-up of raw milk, 2) holding for thermal inactivation, and; 3) cool down of treated milk 59

Fig. 4-2 *Fr 13* integrated 3-step global model for pasteurization of raw milk containing *MAP* 69

Fig. 4-3 *Fr 13* simulation of risk factor for heat-up of raw milk containing *MAP* with 10,000 simulated scenarios. To the R of the figure is shown the 5,637 failures in heat-up of raw milk ($p_1 > 0$) 73

Fig. 4-4 Summary of corresponding risk factor data of Table 4-3 highlighting that of the initial 10 selected failures to heat-up the raw milk ($p_1 > 0$) eight failed in the overall global pasteurizer ($p_2 > 0$) to reduce viable *MAP* numbers. For completeness corresponding milk cool-down (p_3) is also shown 76

Fig. 4-5 Impact of stdev on the number of failures in pasteurization of raw milk containing *MAP* per 10,000 scenarios for each of heat-up ($p_1 > 0$), holding and thermal inactivation of *MAP* ($p_2 > 0$), and; cool-down ($p_3 > 0$) with constant *tolerance* = 2 % on each unit-operation. Pasteurization failure is characterized by the number of $p_2 > 0$ 82

Fig. 4-6 Comparative summary of the impact of *tolerance* on the number of failures in pasteurization of raw milk containing *MAP* per 10,000 scenarios for each of heat-up ($p_1 > 0$), holding and thermal inactivation of *MAP* ($p_2 > 0$), and; cool-down ($p_3 > 0$) with stdev = 2 % in each unit-operations. Pasteurization failure is characterized by the number of $p_2 > 0$ 83

Fig. 4-7 Summary 3-D plot ($n = 64$) of the impact of *tolerance* (increasing process flexibility) and stdev (increasing process control and cost) on the number of *Fr 13* global microbiological failures to reduce viable *MAP* ($p_2 > 0$) per 10,000 scenarios 87

Fig. 4-8 3-D plot showing the '*p*-cloud' of corresponding values of the risk factors (p_1, p_2, p_3) for all 10,000 scenarios of apparent steady-state pasteurization of the raw milk. Pasteurization failures are shown in the volume in the top, R, quadrant 91

Fig. 5-1 Schematic of 4-step pasteurization of raw milk containing *MAP* showing individual 1) heat-up of raw milk, 2) holding for thermal inactivation, 3) cool-down of processed milk, and; 4) storage of treated milk unit-operations 97

Fig. 5-2 *Fr 13* integrated 4-step global model for pasteurization of raw milk containing *MAP* 105

LIST OF TABLES **PAGE**

Table 2-1	Summary and chronological listing of published *Fr 13* risk assessments for steady-state 1-step and integrated 2-step unit-operations	15
Table 2-2	Comparison between HACCP and novel *Fr 13* framework	20
Table 2-3	Comparison between HAZOP and novel *Fr 13* framework	21
Table 2-4	Comparison between Reliability Engineering (RE) and novel *Fr 13* framework	22
Table 3-1	Summary of the deterministic single value assessment (SVA) for each of 1) heating ($PHE_{1\text{-}1}$), 2) holding ($HT_{1\text{-}2}$), and; 3) cooling ($PHE_{2\text{-}3}$) unit-operations	40
Table 3-2	Comparative summary example of SVA and *Fr 13* results for $PHE_{1\text{-}1}$ (milk heating) with a 2 % tolerance on Eq. (3.27)	45
Table 3-3	Selected 10 of 3,697 *Fr 13* failure scenarios in $PHE_{1\text{-}1}$ with a 2 *% tolerance*	47
Table 3-4	Corresponding 10 *Fr 13* failure scenarios from $PHE_{1\text{-}1}$ as inputs to $HT_{1\text{-}2}$ with 2 *% tolerance*	48
Table 3-5	Corresponding 10 *Fr 13* failure scenarios from $HT_{1\text{-}2}$ as inputs to $PHE_{2\text{-}3}$ with 2 *% tolerance*	48
Table 3-6	Ten selected *Fr 13* scenarios in global integrated 3-step milk pasteurization model	52
Table 3-7	A visual summary of the ten selected *Fr 13* scenarios of Table 3-6 of the global integrated 3-step milk pasteurization model	53

Table 4-1 Summary of the deterministic single value assessment (SVA) for corresponding milk heat-up, holding for thermal inactivation of *MAP*, and; cool-down 66

Table 4-2 a Summary of the *Fr 13* results for corresponding milk heat-up 71

Table 4-2 b Summary of the *Fr 13* results for corresponding holding for thermal inactivation of *MAP* 71

Table 4-2 c Summary of the *Fr 13* results for corresponding cool-down respectively 72

Table 4-3 Ten failures (of 5,637) in heat-up of raw milk ($p_1 > 0$) with corresponding outcomes in milk holding and thermal inactivation of *MAP* in the global *Fr 13* microbiological model for pasteurization of raw milk (p_2). For completeness corresponding milk cool-down (p_3) is also shown 74

Table 4-4 Visual summary of the 10 failures in heat-up of raw milk of Table 4-3 (p_1) and the corresponding eight global *Fr 13* microbiological failures (p_2) to pasteurize the raw milk containing *MAP* 77

Table 4-5 Ten (10) mixed scenarios in heat-up of raw milk with corresponding outcomes in milk holding and thermal inactivation of *MAP* and cool-down of the heated milk in the global *Fr 13* microbiological model for pasteurization. For completeness corresponding milk cool-down (p_3) is also shown 78

Table 4-6 Chromatic summary of the 10 mixed scenarios for heat-up (p_1) of Table 4-5 and corresponding three global *Fr 13* microbiological failures ($p_2 > 0$) to pasteurize the raw milk containing *MAP* 79

Table 4-7 Spearman Rank correlation coefficient (Snedecor and Cochran, 1989) for the controlling parameters in raw milk heat-up on the heating risk factor p_1 81

Table 4-8 Summary *Fr 13* risk matrix of the impact of varying *tolerance* (%) and stdev (%) on global microbiological pasteurizer failures (%) 89

Table 5-1 Summary of the deterministic single value assessment (SVA) for corresponding milk heat-up, holding for thermal inactivation of *MAP*, cool-down, and; storage of treated milk 103

Table 5-2 a Summary of the *Fr 13* results for corresponding 1) milk heat-up 106

Table 5-2 b Summary of the *Fr 13* results for corresponding 2) holding for thermal inactivation of *MAP* 107

Table 5-2 c Summary of the *Fr 13* results for corresponding 3) cool-down 107

Table 5-2 d Summary of the *Fr 13* results for corresponding 4) storage of pasteurized (treated) milk 108