Managing frozen foods

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Preface

As I write this preface, the end of the second millennium is rapidly approaching. By the time this text is read, however, the excitement of the millennium will be long forgotten. We will all be back at work, endeavouring in our different ways to supply the world's consumers with exciting frozen food products and to make a Euro or a dollar to live on at the same time. I hope this book will help us all to meet those objectives.

The book was born out of a concerted action that was sponsored by DG XII of the European Commission, under the FAIR Programme of Framework V through research contract FAIR CT96-1180. The action was aimed at improving the preservation of quality and safety of frozen foods throughout the distribution chain. The action brought together experts from industry and academia across the European Union. We met together at six plenary meetings and discussed the many technical and scientific developments being made in the field of frozen foods. The period of our meetings has coincided with a time of rapid development in the industry and in our understanding of science related to the freezing of foods.

From the beginning the emphasis of our action was to promote existing best practice as well as to look to the future. We produced a number of best-practice guides for use by manufacturers and distributors as well as consumer information leaflets. Our aim has been to write at a level that will be of use to the professional food technologist or engineer working in the frozen food industry. This is a philosophy that we have tried to follow in producing this book. I hope we have been able to convey the essentials of frozen food production from farm to freezer in an understandable and straightforward manner. I hope too that we have been able to project a little insight into what the future may hold for this industry.

I would like to thank the many people who have helped in the production of this book, particularly my co-authors for the enthusiastic way in which they have contributed. I should also like to thank Cathy Goundry who has spent many hours reading and correcting our typographic errors and grammatical slips. Her help during the editing of this book has been invaluable to me.

Christopher J. Kennedy

Contents

Preface ix
List of contributors xi
List of acronyms xv

1 Introduction 1
C. J. Kennedy, University of Leeds

2 Maintaining safety in the cold chain 5
L. Bogh-Sorensen, Danish Veterinary and Food Administration, Søborg
2.1 Introduction 5
2.2 Response of micro-organisms to freezing 5
2.3 The main risks in the supply chain for frozen foods 12
2.4 Techniques for microbiological analysis 16
2.5 Sampling 17
2.6 Effects of temperature abuse: viability and recovery 20
2.7 Thawing techniques 21
2.8 New developments in research 24
2.9 Summary: effective monitoring and product quality 25
2.10 References 26

3 Fruit and vegetables: the quality of raw material in relation to freezing 27
A. Maestrelli, IVTPA, Milan
3.1 Introduction 27
3.2 Factors affecting F&V cultivar selection suitable for freezing 30

3.3 Technological factors 33
3.4 Sensory factors 37
3.5 Agronomic and technological aspects of potatoes for freezing 39
3.6 Nutritional factors 40
3.7 How to measure subjective and objective F&V quality characteristics 43
3.8 Future perspective of F&V cultivar selection for frozen products 49
3.9 Summary 51
3.10 Acknowledgements 53
3.11 References 53

4 The pre-treatment of fruits and vegetables 57
D. Torreggiani (IVTPA, Milan), T. Lucas (CEMAGREF), A.-L. Raoult-Wack (CIRAD)
4.1 Introduction 57
4.2 Blanching 59
4.3 Partial dehydration and formulation techniques 60
4.4 Future trends 75
4.5 Summary 75
4.6 References 77

5 The pre-treatment of meat and poultry 81
S.J. James, FRPERC, Bristol
5.1 Introduction 81
5.2 Influence of the live animal 83
5.3 Pre- and post-slaughter handling 86
5.4 New trends 89
5.5 Summary 90
5.6 References 91

6 The selection and pre-treatment of fish 95
N. Hedges (Unilever Research, Sharnbrook) and Jette Nielsen (The Danish Institute for Fisheries Research, Bygning)
6.1 Introduction to the freezing of fish 95
6.2 What are the elements of the frozen fish product supply chain? 96
6.3 The freezing of fish 97
6.4 Changes occurring on frozen storage 100
6.5 Pre-freezing factors that influence the quality of frozen fish products 103
6.6 The effect of freezing rate 106
6.7 The effect of temperature cycling 106
6.8 Summary 106

6.9 References ... 107
6.10 Further reading ... 110

7 Factors affecting the stability of frozen foods ... 111
N.E. Zaritzky, CIDCA, La Plata
7.1 Physical changes during freezing and frozen storage ... 111
7.2 The chemistry of frozen foods ... 122
7.3 The impact of freezing on food quality ... 126
7.4 New trends in research ... 130
7.5 Summary: maximising quality in the freezing processes ... 132
7.6 References ... 133

8 Freezing processed foods ... 137
C. J. Kennedy, University of Leeds
8.1 Introduction ... 137
8.2 Ready meals ... 137
8.3 Bakery products ... 143
8.4 Ice cream ... 149
8.5 Bibliography ... 157

9 Freezer technology ... 159
J.P. Miller (Air Products plc, Basingstoke) and
C. Butcher (CopyWrite, Coventry)
9.1 Introduction ... 159
9.2 Refrigeration systems ... 160
9.3 Freezers ... 172
9.4 Choosing a freezer ... 189
9.5 Further reading ... 193

10 Selecting packaging for frozen food products ... 195
M. George, Campden and Chorleywood Food Research Association, Chipping Campden
10.1 Introduction ... 195
10.2 Essential requirements for frozen food packaging ... 196
10.3 Legislative responsibilities ... 200
10.4 Types of packaging material ... 202
10.5 Assessing the suitability of packaging materials for different products ... 204
10.6 Packaging machinery ... 206
10.7 Future developments in frozen food packaging ... 207
10.8 Summary: how packaging can maximise product quality ... 210
10.9 References ... 210
10.10 Further reading ... 211

11 Storing frozen food: cold store equipment and maintenance .. 213
R. Fuller, Consultant
11.1 Storage, shelf-life and product quality 213
11.2 Cold store design 214
11.3 Detail design features 221
11.4 Monitoring and recording product conditions 225
11.5 Good operating practice 226
11.6 New developments 230
11.7 Summary 231
11.8 References 231
11.9 Further reading 232

12 Retail display equipment 233
G. Cortella (University of Udine) and
F. Polonara (University of Ancona)
12.1 Introduction 233
12.2 Design of display cabinets 234
12.3 Variations for different product types 245
12.4 Installation 245
12.5 Operation, monitoring, maintenance and breakdown 248
12.6 New developments 251
12.7 Legislative issues 254
12.8 Summary 257
12.9 Acknowledgements 259
12.10 References 259

13 Future trends in frozen foods 263
C. J. Kennedy, University of Leeds
13.1 Introduction 263
13.2 Consumers will want more frozen foods – markets 264
13.3 Frozen foods will be more nutritious 265
13.4 Ice crystals will be smaller: controlling ice nucleation 266
13.5 And they will stay smaller: controlling ice crystal growth ... 269
13.6 The frozen food chain will be controlled more effectively .. 273
13.7 We will have wider choice and better display when we go shopping 275
13.8 If we go shopping at all 276
13.9 Summary 276
13.10 Bibliography 277

Index 279

1

Introduction

C. J. Kennedy, University of Leeds

A culinary revolution lies largely unnoticed within the domestic freezers of Western households. The growth of the frozen food market has continued unabated for over 70 years since Clarence Birdseye sold the first plate freezer. The age of frozen foods as a cheap and convenient 'junk' food have, however, passed. Frozen foods are becoming high quality added-value products and are making their presence felt in almost all sectors of the food market.

To compete in this modern food market the manufacturer needs to provide products for an increasingly educated consumer. Consumer awareness of issues relating to nutrition and food safety has never been higher and new developments in these fields are rapidly brought to their attention through the media. Moreover, awareness of the culinary opportunities of 'exotic' meals and designer foods has added an element of fashion to the popularity of many food products. To meet the demands and expectations of this market therefore requires an ever-changing range of products and techniques. To stop swimming is to be carried away by the tide.

The frozen food industry has many advantages over the chilled and fresh sectors in addressing consumer expectations. Low temperatures necessarily result in higher stability and provide an intrinsic advantage, if properly exploited, in bringing nutritionally high value foods to the consumer. The freezing of vegetables after harvest, for example, will guarantee the consumer a higher vitamin C content than could be attained by any other form of preservation and distribution. Furthermore frozen foods have always enjoyed a safety record second to none since, if properly handled before freezing and during distribution, there is no possibility of the growth of microbial contaminants between freezing and thawing.

There are, however, difficulties too which are unavoidable and unique to this preservation method. The first of these stems from the simple fact that water expands by 10% on freezing. The formation and growth of ice during the freezing process and the subsequent growth of ice crystals by recrystallisation during distribution are the major cause of quality loss in frozen products. This has led to the need to control temperatures quite rigorously in the distribution chain. In bulk transport and storage this is not an insurmountable problem. However, in retail display, where the consumer needs high visibility and easy access to consider purchasing a product, and during home transport the problems have been more significant. Second, the freezing of a food product, as with any aqueous solution, leads to the formation of two distinct phases: a solid, pure water ice phase and a concentrated unfrozen solution. The kinetics of reactions in the unfrozen portion will be quite different from those of an unfrozen product. The move from convenience to quality has grown symbiotically with an understanding of the physics and chemistry of freezing solutions and the technology to control and overcome these difficulties.

This book has been written for the technologist working within the frozen food industry. It aims to take the reader from farm to domestic freezer and to present the basic techniques of frozen food manufacture as well as providing an understanding of emerging technologies and a glimpse at future possibilities. Throughout we have tried to present concepts of best practice and the requirements for producing and distributing high quality products.

In all sectors of the food industry safety is a paramount concern. Although frozen foods have a relatively good safety record, the freezing process is not a biocide and safety issues must be addressed in the preparation of foods for freezing. Appropriately therefore we begin this volume with a review of the safety of frozen foods in production and distribution.

For many years frozen food manufacturers shied away from the use of high quality ingredients in frozen foods because low consumer expectations meant that high margins could not be expected for their products. This was a reinforcing negative circle. However, the growth in consumer expectations has brought a realisation that frozen products can indeed be high quality and many frozen products are now commanding premium prices. This makes the need to understand exactly what constitutes a high quality ingredient for a frozen food increasingly important. In Chapters 3 to 6 we investigate this question for fruit and vegetables and for meat and fish.

We begin by looking at the importance of variety selection. For example, a plant species such as the strawberry may have over 2000 different cultivated varieties. Freezing and thawing of the different varieties results in drip losses ranging from 5% in the most freeze-resistant varieties to as high as 45% in the least. Techniques for developing freeze-resistant varieties and the quality parameters to select for are discussed in Chapter 3. Once the variety has been selected and grown, the handling between harvest and freezing can play a major role in the final quality of the thawed product that the consumer will receive. In Chapter 4 we discuss both traditional pre-treatments such as blanching and soaking as well as more recent developments such as osmotic dehydration which are beginning to make even the most difficult of soft fruits into a potential frozen food ingredient.

In Chapter 5 we stay on the farm to review the many elements of animal husbandry that are important in producing high quality meat products. This chapter also reviews the processing of meat through slaughter, chilling, ageing and the freezing process itself. For many frozen meals it is lipid oxidation within the meat component that determines the effective shelf-life. Factors from animal diet to frozen product packaging affect the rapidity and severity of this process.

The many fish species behave remarkably differently when subjected to a freeze–thaw cycle. These differences stem largely from the diversity in ability of muscle fibres to reabsorb water on thawing. The fish industry still accounts for a large portion of foods that are frozen and the rapid deterioration of fish in the unfrozen state results in freezing being the only acceptable way of processing fish caught in deep waters. In Chapter 6 we review the effects of freezing on the different classes of fish species and the technologies that have been developed in the frozen food industry for the processing of fish products.

By Chapter 7 we have arrived in the processing factory. We take a pause in this chapter to review the physical and biochemical processes that take part in the deterioration of frozen food products. If we are to develop techniques for producing and distributing high quality products then there is a need for a clear understanding of the multitude of phenomena against which the product must be protected. We review moisture migration phenomena from Ostwald ripening to freezer burn and discuss the relative importance of different biochemical processes.

In Chapter 8 I have provided an overview of the freezing of the major categories of processed foods. In particular, ready-to-eat meals, bakery products and ice cream are considered. The ready meals market continues to grow at a remarkable pace and the demand for 'healthy' recipes and ethnic cuisine is taking food manufacturers into a wide range of new products and requires a remarkable degree of flexibility to cover changes in food fashion. Ice cream alone accounts for nearly one-third of all frozen food sales. In no other sector has the change from cheap convenient food to high quality fashionable treats been more evident. I outline the basics of the ice cream manufacturing process and highlight the factors for producing a high quality product.

The technology of freezing equipment is going through a revolution of its own in parallel with the rest of the frozen food industry. Rates of heat transfer that seemed impossible just a few years ago are now being achieved in both cryogenic and air blast impingement freezers. Exciting new technologies utilising low adhesion technology have opened a large new market for pelletised and moulded products. Even the refrigeration technique of the late 1800s, the air cycle, has taken on a new lease of life and is offering integrated energy savings for the future. The state of the art and these new developments are reviewed by one of the leading technologists in the field in Chapter 9.

The last line of defence for us to consider before we leave the factory is packaging. Packaging no longer serves the simple roles of providing a physical barrier to keep moisture in and contaminants out. More and more consideration must be given to the suitability of packaging materials to pass unharmed, and unharming, through the cooking process. In Chapter 10 we review the properties of the wide range of materials now in use for the packaging of frozen foods including their handling and processing properties.

In Chapter 11 we begin our journey from the factory to the consumer. The storage of frozen foods would present us with no problems in an ideal world. However, even the best of practical stores must go through a regular defrost cycle and product must be stacked and moved in and out of the store with practical ease. The factors considered here include the design, operation and monitoring of a typical cold store.

Retail display has always been the most challenging stage of the distribution chain for controlling the temperature, and hence the quality, of frozen foods. There is an inherent conflict between the need to control temperature between tight limits and providing an environment that presents the customer with good visibility and easy access to a well-stocked food cabinet in a pleasant surrounding. Progress in the technology of frozen display cabinet design has come a long way towards resolving this conflict in the last few years. Helped by developments in computational fluid dynamics, the design of vertical cabinets with protective air curtains is offering consumers the quality shopping environment which they require. This progress has gone hand in hand with developments in packaging which protect frozen products from absorbing energy from the external heating and lighting systems. These technologies and the current state of the art are addressed in our penultimate chapter.

Finally I close the volume with a peek into the future. The frozen food business has not only become a high quality enterprise but it is beginning to push at the forefront of scientific and technological developments. Glass transitions (the fourth state of matter?), antifreeze proteins, high-pressure processing and ultrasonic techniques are just some of the fundamental areas where the frozen food technologists are following hard on the heels of scientific researchers. Indeed in some instances the food industry is leading the way.

In marketing too the industry is finding new outputs and frozen foods are already a major player in the Internet stakes where home delivery allows control of temperature all the way to the consumer's front door. It is an exhilarating time to be involved in the frozen food industry, and it has been an excellent time for us to compile this volume on the state of the art. It has been great fun for us all to write. We hope you will find it an enjoyable and, above all, profitable book to read.

2

Maintaining safety in the cold chain

L. Bogh-Sorensen, Danish Veterinary and Food Administration, Søborg

2.1 Introduction

Frozen foods have an excellent safety record and freezing has never been reported to be the cause of food poisoning. The great advantage of freezing is that micro-organisms do not grow in foods when the temperature is −10°C or colder. Foods preserved by means of other preservation methods (chilling, drying, curing, canning, etc.) have been more or less directly involved in food safety problems, because these foods are stored at temperatures that allow microbial growth.

However, it should not be overlooked that although freezing kills some micro-organisms, it does not eliminate pathogenic micro-organisms nor microbial toxins present in the food product prior to freezing.

2.2 Response of micro-organisms to freezing

The study of the effect of freezing on the survival of micro-organisms started more than 100 years ago. The effect of freezing on micro-organisms is studied to minimise their survival and growth in foods. However, the objective can also be to preserve the microbial cells, e.g. in the case of industrially important starter cultures and type culture collections.

In favourable environments growth of bacteria normally proceeds as shown in Fig. 2.1, where the logarithm to the number of bacteria is the vertical axis and time is the horizontal axis. First there is a period of adjustment, the lag phase, where the bacteria are more or less inactive, i.e. they do not multiply. The length of the lag time depends on many factors, e.g. temperature, pH, inhibitors in the

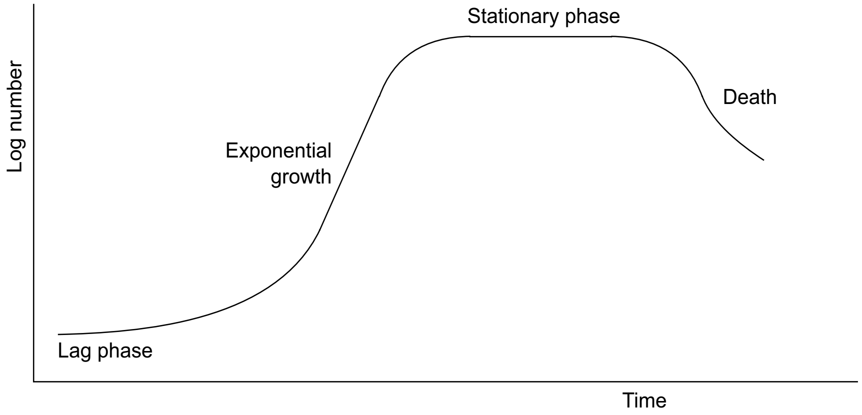

Fig. 2.1 A typical bacterial growth curve.

substrate (the food), etc. After the lag phase, growth begins and reaches a phase of exponential growth. In the exponential growth phase, the number of bacteria may rise very quickly, often expressed by the generation time, i.e. the time required to double the number of bacteria. The generation time varies between bacteria, and depends on several factors, in particular the temperature. The two remaining phases are of less interest.

Inactivation of micro-organisms caused by freezing and thawing may take place in three ways:

1. When a food is cooled so that vegetative micro-organisms are kept at temperatures below their minimum for growth, some loss of viability can be expected.
2. Inactivation of micro-organisms takes place during the freezing process. The response of micro-organisms to freezing is mainly studied in thawed cultures; therefore, the thawing method is a very important aspect that must always be taken into consideration.
3. Finally, inactivation of micro-organisms may take place during storage, depending on storage time and temperature.

During freezing some bacteria are killed, some are in the lag phase, while others may be freeze-damaged (non-lethally injured, sub-lethally injured). The analytical technique used in microbiological analysis of frozen foods must be modified in order to detect and/or enumerate freeze-damaged cells (see section 2.4).

2.2.1 Inactivation during chilling

The minimum growth temperature of micro-organisms is a very important factor for chilled foods also. The organisms grow very slowly (have a long generation time) when the temperature is approaching the minimum. Chill temperature behaviour is of great significance to frozen foods as microbial growth may take

Table 2.1 Minimum growth temperature of some pathogenic bacteria

Micro-organism	Minimum temperature, ºC
Bacillus cereus	5
Campylobacter	30
Clostridium botulinum, type A	10
Clostridium botulinum, type E	3.3
E. coli O157	7
Listeria monocytogenes	0
Salmonella	5
Staphylococcus aureus	7
Vibrio parahaemolyticus	5
Yersinia enterocolitica	0

place before freezing, during thawing and during (chilled) storage after thawing. Table 2.1 indicates the minimum growth temperature of some pathogenic bacteria.

Some micro-organisms may die when kept at temperatures below their minimum for growth. However, above 0ºC the loss of viability is limited, even if micro-organisms are stored more than 10ºC below their minimum temperature. In practice, inactivation of micro-organisms at temperatures above 0ºC is negligible. The inactivation of micro-organisms may be more pronounced when bacteria in the exponential growth phase are cooled quickly.

However, when bacteria experience an abrupt temperature drop, e.g. more than 12–14ºC, they may respond by forming the so-called cold shock proteins. Such proteins may afterwards protect the bacteria against other stresses, e.g. heating, low pH, low water activity, etc. The cold shock effect is discussed in section 2.8.

2.2.2 Inactivation during the freezing process

During the freezing process the product temperature is lowered and most water in the food is transformed into ice crystals. With decreasing temperature the liquid phase becomes more and more concentrated. As the volume of ice is about 10% larger than the volume of water, the internal pressure in the food may rise to 10 bar or more, especially during very rapid freezing.

The exact mechanisms by which freezing, frozen storage and thawing kills or damages microbial cells are not fully understood, although a number of studies have been conducted on the nature and sites of this injury. Several factors may be involved, e.g. low temperature, extracellular ice formation, intracellular ice formation, concentration of solutes and internal pressure.

Of these factors, low temperature and internal pressure seem to be of relatively little importance. The internal pressure in the food may rise to 10 bar or more, especially during very rapid freezing. This pressure is sufficiently high to cause undesirable textural changes in some foods, but not nearly as high as necessary to inactivate micro-organisms.

Extracellular and intracellular ice formation may have mechanical effects, e.g. histological distortion (El-Kest and Marth, 1992). Generally, a faster freezing (higher freezing rate) results in more intracellular ice crystals. Slow freezing encourages growth of a few extracellular ice crystals; the extracellular fluid becomes concentrated, causing dehydration of the cells by forcing water to move out. This makes it difficult for the water molecules to return to their original sites, and may injure or kill the micro-organisms during and after thawing.

It seems that the principal site of bacterial damage during freezing is the membrane, leading to leakage of internal cell material. The cell membrane seems to lose some barrier properties at temperatures below about −15ºC. Besides, ice crystals may cause mechanical damage to the cell membranes. Cell damage could be caused by dehydration of the cells, which could bring intracellular macromolecules in close contact with the membrane (Archer *et al*., 1995). During freezing cells may be injured as a consequence of dissociation of lipid-proteins. The dissociation may be caused by several factors, e.g. the increase in concentration of cell solutes and the resulting increase in ionic strength, changes in pH and physical contact between lipoproteins and the cell wall.

Most studies on the influence of freezing and thawing on death (or survival) of micro-organisms have been model experiments, for example with suspensions of bacteria in small ampoules. Such experiments make it possible to use freezing rates and thawing (heating) rates that are much higher than those normally used in the food industry. One of the conclusions of the experiments is that survival of micro-organisms depends on many factors, including both freezing rate and thawing rate.

Figure 2.2 illustrates that the combination of rapid freezing and slow thawing may kill more bacteria than slow freezing and rapid thawing. This is confirmed by Fig. 2.3, indicating that rapid thawing may increase the survival of micro-organisms. However, other researchers have found that freezing rate was more important than thawing rate.

In practice, during food freezing it is impossible, or at least difficult, to freeze so rapidly as to obtain intracellular ice crystals throughout the food. Also, very high thawing rates are not normally used. In commercial frozen food operations, the influence of freezing rate and thawing rate on the survival of bacteria in foodstuffs is limited.

Food freezing is also complicated because the killing of micro-organisms in food is less than in artificial media, as the different components of food (proteins, fats, etc.) tend to protect the micro-organisms, i.e. act as cryoprotectants. It is well known that glycerol is a good cryoprotectant for biological systems and easily penetrates into the cells.

2.2.3 Inactivation during frozen storage

In practice, foods are frozen to be stored for a certain period, often several months. Frozen storage is always included, and it is the combined effect of the freezing

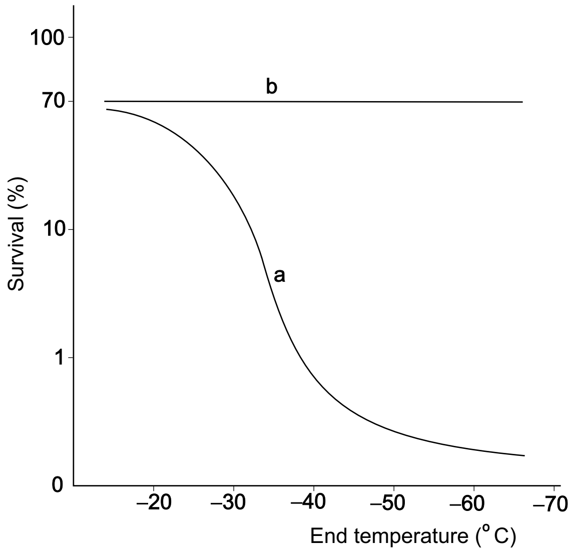

Fig. 2.2 Survival of bacteria after freezing to different end temperatures (a: rapid freezing, slow thawing; b: slow freezing, rapid thawing). (Source: Andersen *et al*., 1965.)

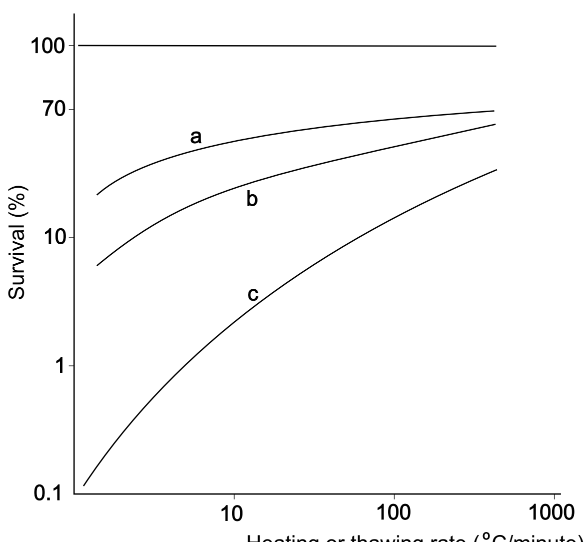

Fig. 2.3 The influence of thawing rate on survival of bacteria (a: frozen rapidly to −30ºC; b: frozen rapidly to −75ºC; c: frozen slowly to −75ºC). (Source: Andersen *et al*., 1965.)

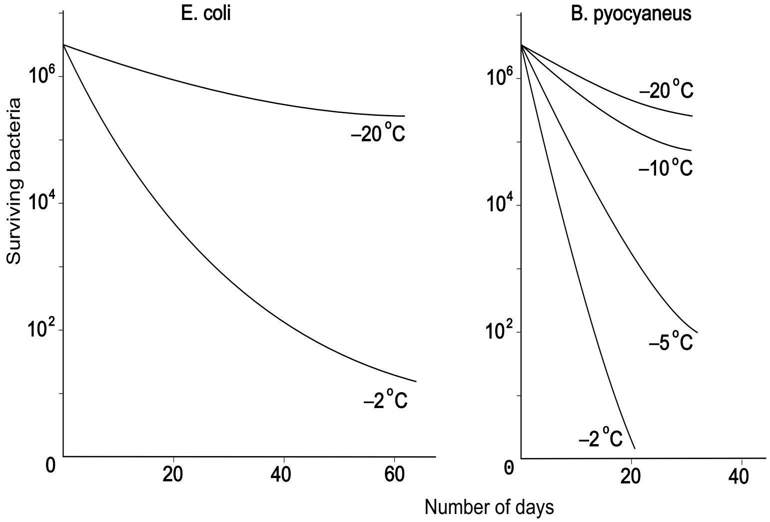

Fig. 2.4 Number of bacteria during storage at different temperatures. The bacteria were frozen to an end temperature of −70ºC.

(and thawing) process and frozen storage that is of interest. When counting micro-organisms in frozen foods during storage at different temperatures, the result will often be as shown in Fig. 2.4. Warm storage, i.e. temperatures warmer than −8ºC, results in much larger inactivation of micro-organisms than storage at −18ºC or colder. Freezing and storage at very low temperatures, down to −150ºC or even colder, seems to result in increasing survival.

During frozen storage the above-mentioned mechanisms (cell dehydration, membrane damage, etc.) continue to act upon the micro-organisms, eventually leading to injury or death of a certain part of the organisms. It is also suggested that the death of micro-organisms may be caused by long-time exposure to concentrated solutions, both internal and external.

The inevitable temperature fluctuations in the cold chain will cause recrystallisation of ice crystals, increasing the salt concentration and increasing the damage to micro-organisms. The increasing size of the ice crystals during storage will reduce the difference between foods frozen very rapidly and foods frozen with a normal freezing rate, and have some influence on the survival of micro-organisms.

2.2.4 Categories of micro-organisms

Micro-organisms can be grouped in the following three categories.

Group 1: Resistant micro-organisms

Bacterial spores are extremely resistant and survival after freezing and storage exceeds 90%. Fungal spores are also resistant, with more than 80% survival. A few Gram-positive staphylococci, streptococci, listeria, etc. are resistant, with more than 50–70% survival.

Group 2: Relatively resistant micro-organisms
Most Gram-positive bacteria including *Bacillus*, *Clostridium*, *Lactobacillus*, *Micrococcus*, *Staphylococcus* and *Streptococcus*, together with some types of yeast, are relatively resistant to freezing.

Group 3: Sensitive micro-organisms
Gram-negative bacteria such as *Escherichia*, *Pseudomonas*, etc. are not resistant to freezing and frozen storage. During one month's storage at −20ºC the number of *Vibrio cholerae* may decrease from about three million to less than ten per gram, i.e. a reduction with a factor of one million (10^6). *Salmonella* may be relatively resistant; in frozen chicken the number of *Salmonella* did not change during several months at −20ºC. However, *Salmonella* may be sensitive as it has been found that the survival of *Salmonella typhimurium* may be less than 0.5% after rapid freezing and rapid thawing. Higher organisms are much more sensitive to freezing than bacteria. Parasitic protozoa and nematodes, etc. are very sensitive and are killed after a certain period, often two weeks or less at −18º or colder. This fact is sometimes utilised in the industry, e.g. in the fish industry to get rid of *Anisakis*.

Changes in microflora
In frozen meat, the microflora before freezing may be 80% Gram-negative and 20% Gram-positive. After freezing and storage, the total number of bacteria could decline from 400 000 to 100 000 per gram, and the flora may be changed into 25% Gram-negative and 75% Gram-positive bacteria. This principle is not used to differentiate between unfrozen and thawed meat, partly because the composition of the flora before freezing is variable, and partly because such changes in the composition of the microflora can be caused by other factors as well.

2.2.5 Conclusion about micro-organisms in frozen foods

The number of micro-organisms in food will decrease after freezing and storage, but freezing must not be regarded as a bacteria-killing process. In most cases, procedures resulting in better maintenance of sensory quality, i.e. rapid freezing and storage at a constant and very low temperature, also result in the best survival of micro-organisms.

If a high number of micro-organisms are found in frozen foods, the reasons are probably as follows:

- A high microbial count in the raw materials.
- Delay before the freezing process is initiated.
- Slow or incomplete freezing process.
- Temperature abuse with partial thawing (product temperatures above 0ºC).

If a low number of micro-organisms is found it may be due to good raw materials and appropriate processing, following good hygienic practice (GHP) and good manufacturing practice (GMP). However, it could also be the case that the frozen foods have been stored at temperatures around −5°C. This will kill some organisms (see Fig. 2.4), but will also result in deterioration of the sensory quality.

2.3 The main risks in the supply chain for frozen foods

Frozen foods are very safe, as micro-organisms cannot grow in them. However, the very nature of foods inevitably leads to some level of contamination at some point in the food chain.

2.3.1 HACCP

The hazard analysis critical control point (HACCP) concept is a systematic approach to hazard identification, assessment and control. The purpose of HACCP is to control the hazards in all stages of the food chain from farm to ultimate consumption. The HACCP system includes the following steps:

1. Identification of hazards and evaluation of severity of these hazards and their risks. This will involve an evaluation of hazards associated with raw materials used and processing steps applied, as well as any packaging and storage conditions, and the intended use of the product.
2. Determination of locations, practices, procedures, or processes – critical control points (CCPs) – where hazards can be controlled.
3. Specifications of criteria, i.e. specifications of limits of physical (e.g. temperature or time), chemical (e.g. salt content or pH) or biological (e.g. sensorial or microbiological) nature, that indicate whether an operation is under control at a particular CCP.
4. Monitoring, i.e. establishment of procedures to monitor each CCP to check that it is under control. This may involve visual inspection, tests, measurements, etc.
5. Corrective actions, i.e. establishment of a set of corrective actions to be taken when a particular CCP is not under control.
6. Verification, i.e. procedures to ensure that the system is working properly.
7. Documentation, to document the activity within the system.

One of the most important aspects (step 3) is the use of microbiological criteria, making it possible to distinguish between an acceptable and unacceptable product (sample, sample unit), or between acceptable and unacceptable food processing and handling practices. This is further discussed in section 2.5.

HACCP is a system that specifically addresses (microbiological) food safety. However, it is possible to include CCPs dealing with quality parameters and/or safety aspects that are not microbial, e.g. foreign matter (see section 2.3.2).

There are very large differences between the HACCP system that is necessary in a large food-producing company and the HACCP system that is appropriate for a small baker. The EU funded a project from 1990 to 1993 (FLAIR concerted action no.7) with cooperation between food scientists and professionals in seven EU countries. One of the results of this project was the publication of the 'HACCP User Guide', which was translated into the languages of the different countries. Another outcome is that in all EU countries institutes with expertise in HACCP can be identified.

Experience has shown that HACCP, properly introduced and properly run, will promote safety in food production, and that HACCP is beneficial to the consumer and food companies. The key benefits are as follows:

- Applicability to the entire food chain.
- Increased confidence in food safety.
- Cost-effective control of food-borne hazards.
- Emphasis moved from retrospective quality control to preventive quality assurance.
- A common approach to food safety.
- Facilitation of trade opportunities within, and beyond, the EU.

2.3.2 Raw materials

In the raw materials, i.e. the food before the freezing process is started, food safety may be compromised in several ways, exactly as for chilled foods. The raw materials may contain residues of pesticides, herbicides, veterinary drugs, heavy metals, etc. that exceed legal limits. This may not be directly dangerous, but health authorities, politicians and increasingly the consumers consider it totally unacceptable. Some larger industries and supermarket chains exercise a degree of analytical control with some of these substances in some raw materials.

Raw materials (and food products) may contain foreign matter. Some of these (adhesive plaster, fragments of insects or small animals, etc.) are aesthetically unacceptable; others such as glass fragments may be dangerous. Many food companies use metal detectors to get rid of metal (iron), but most other foreign matter can only be eliminated by means of visual inspection. Most food companies regard foreign matter as a CCP.

The raw materials entering the food company may contain an unacceptable number of pathogenic micro-organisms (or microbial toxin). Rapid methods for bacteriological (microbiological) analysis are available, but it is effectively impossible to check the microbial quality of all raw materials, ingredients, additives, etc.

Generally, the first CCP in the product flow will be the incoming raw materials. Microbiological analysis is sometimes carried out, but it may be impossible for the processing company to wait for the analytical results. When receiving raw materials such as chilled meat, it is common practice to check the temperature, often by measuring the product temperature on arrival at the processing plant, and to consider this the first CCP. The meat should be rejected if the temperature is higher than the specified limit; the maximum temperature allowed could be 7ºC (EU legislation) or colder, if so agreed with the supplier.

It should not be overlooked that a low bacteriological quality (high, but still acceptable bacterial numbers) in the food product at the beginning of freezing, results in more rapid quality deterioration during storage, thus giving a reduced practical storage life (PSL).

The introduction of rapid microbiological analyses has made it possible to carry out routine tests on raw materials for the presence of pathogens (see section 2.4). Even with very rapid methods, e.g. producing a result in less than one hour, there may be no alternative to starting the processing of the raw materials immediately after receipt. In other cases, the raw materials are not processed before the next day, making it possible to take special precautions against raw materials with too high numbers of pathogens or micro-organisms in general.

2.3.3 Processing before freezing

In the frozen food industry many different processes and procedures are used, depending on the type of frozen food produced. In the production of frozen foods the product formulation (pH, salt content, etc.) will not normally be a CCP, although it may have a pronounced influence on quality and shelf-life. Vegetables are normally blanched, and possibly peeled, sorted, graded, washed, etc. For many of these processes a high hygienic standard should be maintained by adhering to GMP or GHP. One of the purposes of the blanching process is to reduce bacterial numbers; it will be a CCP and blanching time and temperature should be monitored and recorded. Generally, when the food is heat processed, this will be a CCP. Meat, fish, etc. is sometimes cut into smaller parts, e.g. filleted, sliced, etc. These processes must be carefully monitored to make sure that the food is contaminated as little as possible, and that the temperature of the food is not allowed to increase unless a heat process is included in the manufacturing process.

Microbial growth is highly dependent on temperature, but time is also important, as it is the combination of time and temperature that decides the microbial growth and, thus, the increase in number of micro-organisms. It is often recommended (and included in HACCP) that the time that each lot of perishables spends in each part of the plant, including chill rooms, is measured and recorded. In addition, the air temperature in each room should be recorded according to specification. Generally, the entire manufacturing process must be carefully examined in order to determine the CCPs. Frozen-food producers should do everything to ensure that pre-freezing growth is inhibited or minimised. The use of frozen raw materials is further discussed in section 2.7.4.

2.3.4 The freezing process

The freezing process will inactivate a certain percentage of the micro-organisms present in the food (see section 2.2.2). Thus, the freezing process as such should not present a risk. However, in order to inhibit pre-freezing growth, the time until freezing is initiated may be critical, and may be a CCP. If the food is kept for several hours, especially above chill temperatures, before being transferred to the freezing equipment, considerable microbial growth (or toxin formation) may take place before freezing.

Even when the food is placed in the freezing equipment without undue delay, problems may arise. This may happen when large lots of food in corrugated cardboard cartons in palletised stacks are frozen in freezer tunnels. In spite of an appropriate air circulation and air temperatures colder than −30ºC, the very mass of the food may be such that the freezing time of the inner parts is very long, resulting in microbiological or enzymatic deterioration before the freezing is complete. With pre-cooked foods (prepared dinners) the centre cartons may be rotten or mouldy while the outer products are of perfectly good quality. It should always be remembered that it is necessary to separate cartons during freezing, in order to provide air space (air channels) permitting air circulation between cartons. This should also be a CCP. Some practical dividers have been developed, e.g. plastic dividers, somewhat like the well-known egg trays.

Cases have been known where the freezing process was not completed, i.e. the products were taken out of the freezer even though the centre temperature of the food was only about −1.5ºC, the initial freezing point. If these products are not transferred directly into areas with temperatures below −18ºC, thawing can proceed quite quickly and cause microbial and other problems (such as drip). In addition, such practices have a negative influence on the sensory quality and/or shelf-life of frozen foods.

2.3.5 Frozen storage

Microbial growth does not take place during frozen storage. Therefore, frozen storage is not a food safety problem. For vegetables it is common practice to use bulk packaging immediately after harvesting and freezing. Retail packaging is carried out at intervals, and it may be regarded as a CCP to ensure that the vegetables are not thawed during repackaging.

2.3.6 Hygiene during preparation

Only products such as ice cream are consumed in the frozen state. All other frozen foods must be thawed and/or cooked before consumption. They require no special precautions, especially if prepared directly from the frozen state. As discussed in section 2.7.4, thawed foods should be treated as carefully as unfrozen foods in order to prevent cross-contamination from one foodstuff to another, e.g. from uncooked foods to cooked foods, especially if cooked foods have to be stored for one or more days before consumption. When thawing frozen foods, there will normally be a drip loss. For meat and poultry in particular, ensuring that the drip does not come into contact with other foods is strongly recommended either directly or indirectly (through dishes, knives, etc.).

Cleaning and disinfecting of food contact surfaces, dishes, knives, etc. should adequately reduce the microbial population. In catering establishments it may be necessary to take microbiological samples of food contact surfaces to test the effectiveness of cleaning and disinfecting. The major contributory factor in outbreaks of food-borne illness seems to be temperature abuse. Mishandling (storage of chilled foods at too high a temperature, improper chilling process, improper reheating, inadequate cooking, preparation too far in advance of serving) occurs most frequently during the final stages of the food chain, i.e. in the catering industry and households.

2.4 Techniques for microbiological analysis

The methods used in microbiological analysis of frozen foods are, in principle, the same as the methods used for unfrozen foods. The major difference is that some, perhaps a large proportion, of the micro-organisms may be freeze-damaged (sub-lethally injured) by the freezing process, and may not be detected (or enumerated correctly) by conventional methods.

Injured cells require laboratory media containing all essential nutrients and no inhibitory agents. Thus, many selective media designed for enumeration of specific groups of micro-organisms, e.g. *Salmonella*, *Staphylococcus aureus* and *E. coli*, are of limited value for direct analysis of frozen foods, since a large proportion of the viable population will fail to grow, leading to gross under-estimation of numbers (White and Hall, 1985).

It is characteristic in microbiological analysis of frozen food that the injured micro-organisms must be given time to recover under appropriate conditions, i.e. in a suitable medium. This process is called recovery or resuscitation and is done by means of specialised liquid (or solid) media, capable of restoring vigour to freeze-damaged cells.

Resuscitation in liquid media (e.g. a broth) involves the sample being mixed or blended in the medium and incubated for 5–15 minutes, or kept at room temperature for one hour. This method must be carefully considered for enumeration procedures, as growth of uninjured cells cannot be completely ruled out during incubation, especially if the incubation stage is prolonged. This will result in too high bacterial numbers.

Resuscitation in solid media immobilises the cells, as a mixed sample is mixed with molten (and cooled) medium. Uninjured cells may divide and grow, while others are repairing freeze damage, but only one colony is formed from each cell. This method is particularly suited to detecting bacteria that tolerate low oxygen concentration (anaerobic or facultative aerobic organisms). Another problem is that if the temperature of the molten agar is too high, several micro-organisms may be killed.

Resuscitation is especially important when analysing for Gram-negative bacteria, e.g. *E. coli*. When analysing packages of frozen food for total viable count (TVC), *Staphylococcus*, etc. in a routine control, it is standard procedure to thaw the frozen food slowly before sampling, i.e. in a refrigerator at 3–5ºC overnight. In conventional microbiological analysis it will normally take two to four days (at least) before the result is available. Therefore the use of rapid methods has increased dramatically; several are available and have been tested and approved by relevant organisations. Often an added advantage is their relative ease of use. The analytical result is often available after less than 24 hours, making it possible to act upon unacceptable microbiological results. The principles of some of the rapid methods are summarised by Archer (1998).

In some cases the objective of the analysis is to find the total viable number of bacteria, but more often the sample is analysed for indicator organisms or pathogens. With regard to pathogens the situation for frozen foods is exactly the same as for unfrozen foods. The nature of the food product is the main factor in deciding which pathogens are likely to be present. In heat-processed (pasteurised) foods, heat-sensitive bacteria (*Salmonella, E. coli,* vegetative cells of spore-formers, etc.) should be eliminated.

In most raw animal foods, including egg and egg products, *Salmonella* cannot be excluded completely; *Campylobacter* is often present on raw poultry. In raw dairy, meat and fishery products the presence of *Listeria monocytogenes* should be expected, and cross-contamination to heat-treated products is frequently observed. In beef products the presence of pathogenic *E. coli* (e.g. *E. coli* O157: H7) has been demonstrated. *Bacillus cereus* is not uncommon in cereals, pulses and vegetables, and the spores are heat-resistant. Fish products, shellfish, etc. may be associated with pathogenic *Vibrios*; for several fish and fish products *Clostridium botulinum type E* constitutes a risk factor which must be taken into account.

The decision on what to analyse for depends on a number of factors such as specifications agreed upon with the customer (or supplier), legislation, company policy, etc. For several product groups ICMSF (1986) has prepared sampling plans for the bacteria that should be analysed for. The usual method for determination of the level of microbial contamination, total viable count (TVC), of frozen food is to perform a plate count using plate count agar (PCA) and incubation at 30ºC for three to four days. TVC may also be denominated APC (aerobic plate count), CFU (colony forming units), SPC (standard plate count), etc.

2.5 Sampling

No matter how accurate and reproducible microbiological methods are, they are inadequate to appraise the content of a food without a satisfactory sampling plan. The term ‘frozen foods’ covers a very diverse group of products which are processed in a variety of ways; some are cooked or blanched prior to freezing, some are frozen in the raw state, some are sliced or minced, etc. Consequently, the sources of contamination and the composition of the microbial flora are very different, and this influences the sampling points, the sampling frequency, and number and types of specific microbial tests.

Samples for microbiological analysis must be representative of the entire batch of food. If the food is homogeneous or liquid (before freezing, after thawing), relatively few sample units can be used. If there is likely to be relatively heavy contamination in a few places in the lot of food, relatively large numbers of sample units may be necessary to identify it. It is not always easy to evaluate the results from microbiological analysis of food samples, and consultation with experts in food safety and risk assessment is recommendable. The microbial criteria prepared by ICMSF (1986) are very useful, but the ICMSF sampling plans do not include figures for 'new' pathogens such as *Listeria monocytogenes* and *E. coli* O157:H7.

2.5.1 Production line sampling

In all food companies the safety (and quality) monitoring should be based on HACCP. Hazard analysis involves detailed assessment of potential problem areas, such as raw materials, processing, handling, slicing, packaging, etc. The HACCP system requires that the production line is examined in order to find the points where contamination may occur. This assessment is often based upon experience. Some of the critical control points (CCPs) are discussed in section 2.3.1; for each CCP the limits, including microbial limits, must be specified.

Most CCPs are monitored by using methods other than microbiological analysis, for example recording (and/or measuring) temperature and time of a cooking or blanching process. For several CCPs it may be of considerable help to use predictive microbiology models in establishing limits for process or product parameters. It is very difficult to give precise instructions for sampling frequency and method, as this depends on a number of factors such as the monitoring system at the supplier of raw materials, nature of the product(s), production flow, processing steps, packaging, freezing method, legislation, customer demands and specifications, economics (analysis may cost a lot of money), laboratory facilities available, etc.

Equipment hygiene is often monitored every day, normally before starting production. The sampling sites depend on many factors. Hygiene of equipment and food contact surfaces is often assessed by means of surface swab or agar contact techniques. The ATP rapid method seems suitable for surface testing. Generally, it is not easy to assess the hygiene of uneven or irregular surfaces, nozzles, cutting devices, etc. This means that it may be necessary to analyse food samples in order to get a good impression of the hygiene of equipment, conveyors, etc.

In most cases, at least one food sample per day is taken, but this depends on the number of different products that are produced each day. If quick-frozen ready meals are produced, there are several raw materials, some of which may be a potential source of pathogens. Mixing and grinding operations may be critical, as equipment may be difficult to clean, and increasing the surface of the food may result in increased microbial counts. Handling procedures after the heat process should be minimised, and if handling occurs it will often be a CCP.

Control cards

At each CCP it is essential that sampling is carried out in a manner that will best meet the objectives of control at that point. The control card is ideally suited to the concepts of monitoring and process control; normally control cards would be applied to physical and chemical measurements.

Control cards will often have a central line indicating the targeted value of the process parameter, and an upper and lower control limit. If the measured values are within the two control limits the process is 'in control'. If the control limits are exceeded, the reason must be investigated. One of the important features of control cards is that they allow visual tracking of results over time, making it possible to detect obvious trends.

2.5.2 Lot acceptance sampling

Quite often it is necessary to determine whether a lot (a batch) is acceptable or not. This may be necessary when receiving a batch (especially from a new producer), in import control, and in some other instances.

Two-class sampling plans

During the Second World War, statistical quality control and sampling plans were developed. The two-class sampling plans are well known and are used throughout the world in several areas of the industry; in the food industry mainly in net weight control. Principally in a two-class plan, a sample consists of several – n – sample units, drawn from the lot. Each of the sample units is tested to determine whether it is of good or defective quality.

In food microbiology, the two-class sampling plan is most often used as an absence/presence test (acceptance/rejection) for pathogens, e.g. $n = 5$, $c = 0$. The maximum allowable number of defective sampling units is denoted as c. In a two-class plan with $n = 5$, $c = 2$, five sample units are tested. If three or more are positive, the whole batch must be rejected. For different groups of bacteria, different values for n and c will be used, but in most cases ICMSF recommends $n = 5$.

The stringency of the sampling plan depends upon n and c. A larger value of n at a given value of c means a more stringent plan, i.e. the food quality must be better to have the same chance of being accepted. Conversely, an increased c at a given value of n means that the sampling plan becomes more lenient, i.e. there is a higher probability of acceptance of a food lot with a given quality.

Three-class sampling plans

ICMSF (1986) introduced the three-class sampling plans, which are now widely accepted in food microbiology, in industry as well as in official control and legislation. As always, the sample units must be drawn randomly, whether the lot is a number (perhaps several thousands) of retail packages, or a bulk container.

The special feature in a three-class sampling plan is that the results of microbiological examinations are used to divide the sample units into three classes, as each of the tested sample units can be accepted (*m* or below), marginally accepted (above *m* but not above *M*), or rejected (above *M*). Numbers between *m* and *M* are undesirable, but some are tolerated. This means that for three-class plans it is necessary to establish *m* values as well as *M* values. The former should be based on data obtained from producers operating according to GMP and GHP. For some commodities there may not be sufficient information to establish *m* values, making it necessary to rely on expert opinion. The *M* value is normally based on expert opinion, and predictive microbiology models would often back this up.

In most three-class plans, ICMSF recommends testing five samples ($n = 5$). The sampling plan for frozen comminuted meat includes, for TVC, a three-class plan with $n = 5$, $c = 3$, $m = 1\,000\,000$ and $M = 10\,000\,000$ bacteria per gram. Up to three of the five samples tested may contain above *m* (but not above *M*) bacteria, but if counts between *m* and *M* are found in four or five sample units, the batch must be rejected. If the number of bacteria per gram exceeds ten million in any of the five sample units, the whole batch must be rejected.

ICMSF recommends the three-class sampling plan in most cases. For some bacteria (pathogens) in some products, the two-class plan is maintained. For *Salmonella* the question is normally: is it present or absent? For some product groups ICMSF recommends a two-class sampling plan with $n = 5$, $c = 0$. For other product groups, or special consumer groups, it recommends $n = 10$, 20, 30 or even 60, still with $c = 0$.

The choice of sampling plan and its stringency for foods is based on either the hazard to the consumer from pathogenic micro-organisms, or the potential for unacceptable quality deterioration. Thus, the sampling plan should take into account the types of micro-organisms present and their numbers.

2.6 Effects of temperature abuse: viability and recovery

In practice, temperature abuses in the cold chain have no influence on the microbiological quality of the food, as long as the food remains frozen. If thawing, or partial thawing, occurs, microbiological problems may arise, but these will be the same as discussed in section 2.7. Temperature abuses do not normally result in complete thawing. If that is the case, the product must be carefully investigated to check the microbial quality. Of course, other quality parameters must also be checked, i.e. appearance, taste, etc. The possibilities of increased viability after thawing are discussed in section 2.8.

2.7 Thawing techniques

Many frozen foods are thawed before consumption or further processing, and in several ways the thawing process may be as important as the freezing process.

2.7.1 Thawing and tempering

The thawing process is divided into three parts (see Fig. 2.5):

1. Heating the solid to its thawing plateau (tempering).
2. Thawing.
3. Heating the food above its thawing plateau.

The total thawing time of a frozen food is the time elapsed from its initial frozen storage temperature to the point where no ice remains in the product. This point may be defined as the time where the centre temperature has increased to +1ºC, or 0ºC. During thawing the same amount of heat that was removed during freezing must be supplied. The latent heat for melting of ice is about 334 kJ/kg, and changing the average temperature of a foodstuff with a water content of 75% from −20ºC to 0ºC demands around 260 kJ/kg. Many foods, especially fruits and vegetables, contain more than 75% water; thus, more heat must be supplied to thaw them. The necessary amount of energy can be found in enthalpy tables, e.g. IIR (1986). Thawing methods are divided into two groups: surface heating methods and electrical (internal heating) methods.

2.7.2 Surface heating methods

In surface heating methods heat is supplied to the surface and conducted into the food. The rate of thawing is proportional to the transfer of heat from the thawing medium to the food surface, and to the conduction of heat from the surface to the centre of the food.

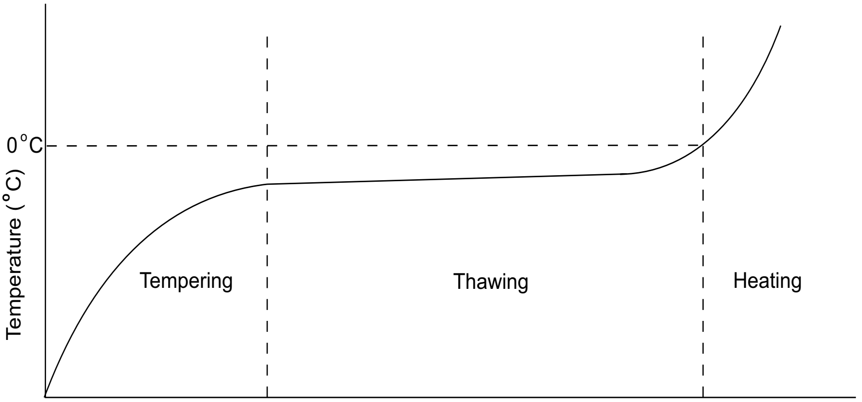

Fig. 2.5 Typical centre temperature curve during thawing of a foodstuff.

Thawing by circulating ‘warm’ air is two to three times slower than freezing in circulating cold air, although the heat transfer coefficient and the temperature difference could be almost identical. The main reason for this is that water has lower thermal conductivity than ice (0.5 versus 2.4 W/m°C), so that during thawing an increasingly thick layer of water will hinder the heat conduction to the centre. In addition, during freezing the temperature of the freezing medium can be as cold as practicable, whereas during thawing the temperature of the thawing medium must be controlled so that the surface temperature does not become so high that microbiological growth or problems with deterioration of appearance or colour occur.

In the food industry air thawing is a common method. Sometimes programmed air temperatures are used. The starting air may be 30–40°C, and when the food surface temperature reaches a predetermined level, often around 7–10°C, the air temperature is reduced to this level. In industrial air thawing of unwrapped products, it is important to control the relative humidity in order to minimise the weight loss.

Water thawing in circulating water is used for fish in particular. The frozen food is sometimes unwrapped. The water temperature should be kept at 20°C or below. Water thawing is faster than air thawing. Vacuum thawing utilises heat transfer by means of condensing steam. The high heat transfer coefficient makes it possible to achieve a thawing of unwrapped foods that is more rapid than air or water thawing.

2.7.3 Electrical thawing methods

The electrical methods involve the use of microwaves in particular, and also the use of radio waves. In both systems heat is generated inside the foodstuff, and it is possible to achieve very fast thawing. The amount of heat generated, and the temperature differences in the food during and after thawing, depend on the electrical characteristics and the homogeneity of the food. The main problem of using microwaves is runaway heating, where some parts of the surface of the food may be unfrozen, while other parts are over 90°C (boiling). The reason is that small differences (food, microwave oven) may lead to small temperature differences; as the frozen food absorption of electromagnetic radiation increases with temperature, the temperature differences may increase dramatically.

Microwaves are often used in the meat industry, e.g. to thaw thick blocks of meat. In order to avoid runaway, the microwaves are used for tempering in particular (see Fig. 2.5). It has been suggested that circulating cold air in microwave ovens may prevent uneven heating, but from an energy point of view this is not a good solution.

2.7.4 Thawed products

It has been common practice to sell thawed lamb as normal chilled lamb. This is still common practice, but in most countries legislation prescribes labelling of thawed products, e.g. 'Previously frozen – do not refreeze'. Generally, thawed meat seems to have the same shelf-life as unfrozen meat. Of course, this necessitates an appropriate thawing process and handling the meat according to GMP, including the freezing process, frozen storage, packaging, etc.

Lag time

It has been found for some bacteria that when changing the temperature from just below the minimum growth temperature to 1–4ºC above, there may be a lag phase of up to two to three days before growth is initiated. Changing to a temperature of more than 5ºC above the minimum growth temperature may result in little (or no) lag phase before exponential growth. Most existing predictive microbiology models would not show such microbial growth when a foodstuff was exposed to severe temperature abuse.

It seems to be necessary to develop new models to predict lag phase and microbial growth when the food temperature is increased from below to above the minimum growth temperature of a certain micro-organism. These data apply to chilled foods in particular (Gill *et al*., 1998), but also to temperature-abused frozen foods and thawed foods. So far the microbiological models have not concentrated on this aspect, probably because relatively little is known about lag phase and the factors influencing it, especially for frozen foods.

The microbiological quality of thawed foods

The number of micro-organisms is reduced during freezing and frozen storage; moreover, the bacteria will remain in the lag phase for some time after thawing, as discussed above. On the other hand, freezing may affect the structural integrity of food, making it more susceptible to microbial attack. Further, thawed foods may have a moist surface due to drip or condensation, and may be a very good substrate for bacteria; in addition, some of the bacteria in frozen food may become more virulent after thawing and lag phase.

The conclusion of most of the studies on thawed foods is that there is very little difference in shelf-life and microbial growth between unfrozen and thawed foods. In some cases, freezing may increase the storage life of the thawed product. In experiments with frozen cod, it was demonstrated that storage of cod for eight weeks at −20ºC extended the shelf-life of thawed cod by several days, i.e. a longer shelf-life than both fresh cod and thawed cod stored at −30ºC, −60 or −80ºC. The reason was that the two most important spoilage bacteria in cod (*Shewanella putrefaciens* and *Photobacterium phosphoreum*) died after eight weeks at −20ºC, but survived eight weeks at −30ºC or colder (anon., 1999).

It should not be overlooked that the fish industry has used freezing and refreezing of fish products for more than 50 years. In other parts of the food industry, frozen raw materials are often used. The thawing method depends on the nature of the raw material, but also on the food product to be produced. If very little further processing takes place, the thawing method must be carefully controlled to avoid problems with appearance and weight loss (drip loss, dehydration). In other cases, e.g. frozen fruit used in the production of jam, the problem is less serious, as the drip loss can be added afterwards. In industry, the thawing time (thawing rate) may be an important factor, and this has led to the development of the electrical methods. Generally, microbiology during thawing should be regarded as a problem, and thawing at room temperature overnight is not recommended.

2.7.5 Thawing and preparation

In catering establishments as well as in households, air thawing is the normal thawing method. Thawing (quick-)frozen foods in the refrigerator is often recommended. From a food safety point of view this is a good process, as it ensures that no part of the food becomes warmer than the temperature of the refrigerator. However, slow thawing does not always result in the best sensory quality; in experiments with fish (trout) it was shown that faster thawing (water thawing) resulted in better quality than slow thawing in a refrigerator (Nilsson, 1994).

If more rapid thawing is necessary, thawing at room temperature can be used, but care should be taken to avoid high surface temperatures for too long, so that microbiological problems do not occur. Another possibility is thawing in water, but for most foods this necessitates packaging in a plastic pouch; a certain water circulation (running tap water) is recommended. Thawing can be done in the microwave oven. As mentioned above, there may be problems with runaway heating, but most new microwave ovens have special programmes for thawing different foodstuffs.

In the EU, retail packed quick-frozen foods must exhibit cooking instructions. These often recommend cooking the product directly from the frozen state, e.g. in a microwave oven, in a conventional oven, in boiling water (boil-in-bag), etc. If the correct final temperature during cooking can be achieved, there are no problems in excluding the thawing process. On the contrary, direct cooking should be a safer procedure. However, some consumers believe it is easier to cook large cuts of meat, turkey, etc. at the right temperature if the food is thawed beforehand. In other cases, thawing before cooking is recommended (normally in refrigerator).

2.8 New developments in research

2.8.1 Cold shock response

Although freezing is a safe preservation method, the food safety issue is still very important. The cold shock response (CSR) could have some implications for frozen foods; often the response is the appearance of cold shock proteins (CSP). The CSR of several micro-organisms is being investigated, but comparatively little is known about the response of pathogens to freezing (Kerr, 1997). It has been suggested that exposure to stress, e.g. freezing, resulting in sub-lethal injury could render the organism more resistant to the effect of heat, so that heating may not reliably destroy all the bacteria present. Freezing could also result in an increase in the acid tolerance of bacteria, including food-borne pathogens. Another concern regarding the CSR of pathogens is that exposure to low temperatures may have a direct effect on virulence. Kerr (1997) concluded that there is little data in this field, and that further studies of the CSR are clearly required. Thus, exposure of bacteria to stress factors may result in 'stress hardening', and this gives cause for concern because it challenges the widely accepted concept of 'hurdle technology'.

2.8.2 Thawing

More than 20 years ago it was said that too little research on thawing methods, and on the influence of thawing time (thawing rate) on the quality of different foods, had been carried out. The situation has not changed; a number of researchers study the influence of different freezing methods on quality, ice crystal size, etc. of food, while thawing is still an area with comparatively little research activity. Furthermore, few studies on the sensory quality as affected by direct cooking from the frozen state in comparison with thawing before cooking can be found in the literature.

Apparently supermarkets receive a number of questions regarding the safety and shelf-life of thawed foods, but such questions are very difficult to answer, other than 'about the same as the unfrozen product, on condition that . . .'. It seems that more studies on thawing are clearly necessary.

As mentioned above, comparatively little is known about the lag phase of micro-organisms after freezing and thawing. As there is some interest in the marketing of chilled thawed foods, this aspect is of interest.

2.9 Summary: effective monitoring and product quality

- The microbiology of frozen foods is not very different from the microbiology of unfrozen (chilled) foods, but frozen foods have the great advantage that micro-organisms do not grow in them while in the frozen state.
- The degree of monitoring of safety is the same as in the production of chilled foods, i.e. manufacturers should use the HACCP system to identify and monitor the critical control points.
- The particular control point for frozen foods is the freezing process. It is important to ensure as little delay as possible and practicable in initiating the freezing process. It is important to ensure that the freezing time is sufficiently short, i.e. the freezing rate is sufficiently high.
- Another important control point is thawing. It must be ensured that the thawing process is appropriate with regard to minimising microbial growth during thawing, and afterwards.
- Microbial growth in thawed foods is the same as in unfrozen foods by and large. However, some persons or groups consider this doubtful. Therefore,

conducting more experiments in this field seems necessary, also regarding the quality and shelf-life of thawed foods.

2.10 References

ANDERSEN, E. A., JUL, M. and RIEMANN, H., *Industriel levnedsmiddelkonservering* (in Danish), Copenhagen, Teknisk Forlag, 1965.

ANON., *Fiskeriforskning info*, Norwegian Institute of Fisheries and Agriculture, no. 1, January 1999.

ARCHER, G. P. (ed.), *An Introductory Guide to the Microbiological Analysis of Frozen Foods*, EU Concerted Action CT96-1180, 1998.

ARCHER G. P., KENNEDY, C. J. and WILSON, A. J., 'Position paper: towards predictive microbiology in frozen food systems – a framework for understanding microbial population dynamics in frozen structures and in freeze–thaw cycles', *Int. J. of Food Sc. & Tech.*, 1995, **30**, 693–710.

EL-KEST, S. E. and MARTH, E. H., 'Freezing of *Listeria monocytogenes* and other micro-organisms: a review', *J. of Food Protection*, 1992, **55**, 639–48.

GILL, C. O., GREER, G. G. and DILTS, B. D., 'Predicting the growth of *Escherichia coli* on displayed pork', *Food Microbiology*, 1998, **15**, 235–42.

ICMSF, *Microorganisms in Foods 2*, 2nd edn, Toronto, University of Toronto Press, 1986.

INTERNATIONAL INSTITUTE OF REFRIGERATION (IIR), *Recommendations for the Processing and Handling of Frozen Foods*, 3rd edn, Paris, IIR, 1986.

KERR, K., 'The bacterial cold-shock response in food borne pathogens', *Plenary Meeting no. 3, CT96-1180*, Leeds, 1997.

NILSSON, K., *Quality of Frozen Rainbow Trout*, Report no. 610, Sweden, SIK, 1994.

WHITE, C. A. and HALL, L. P., 'Laboratory examination of frozen foods', in *Microbiology of Frozen Foods*, ed. R. K. Robertson, London, Elsevier Applied Science Publishers, 1985.

3

Fruit and vegetables: the quality of raw material in relation to freezing

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3.1 Introduction

Over the last few years consumers have been showing much more interest in choosing foods of high quality, and a willingness to pay for such products that the industry can provide. This attitude has created a sort of ‘natural selection’ where preference is given to high quality products automatically, eliminating poor quality foods from the market. This phenomenon has caused the food industry to re-think its ideas about quality, especially considering the competition from internal and foreign markets.

The frozen food industry has realised what is happening, and is one of the most important protagonists, increasing its market quota step-by-step. It was the pioneer in fish and meat freezing, and is now continuing with fruits and vegetables (F&Vs), all contributing towards the success of the industry.

3.1.1 Quality of frozen fruits and vegetables

The winning strategy of the frozen food industry is to improve quality continually, in order to consolidate and increase its presence alongside the large fresh, and minimally processed, F&V market. The best way to increase the range of frozen vegetable products is to ensure that they have similar characteristics to fresh ones, but this depends on many factors, and on two in particular: raw material and technological processing. Technological processing is well defined in other chapters. The raw material quality, which could be notably improved, depends on agronomic factors (e.g. production, sensitivity to disease, suitability for mechanical harvesting) to be considered from development through to harvest.

When the F&Vs reach the processing industry they must have specific attributes defined by the following:[1]

- Technical experience.
- Specific techniques arranged between farmers and industry.
- Quality standards created by expert organisations.

Cultivar selection is the result of these factors, as well as research carried out before and after processing. It is during processing that food can undergo unforeseeable modification which can decrease, or even eliminate, the quality attributes of the fresh material. It is therefore of utmost importance to check quality continually. If the initial raw material is of high quality, and the technological process is correctly applied, then the product's success is assured. Rejected raw material from the fresh market should not be used in the frozen one.

The quality of raw material suitable for freezing needs to be highlighted. A ripe, healthy, well-coloured fruit will obviously be perfect for the fresh market, but it may not be ideal for use in freezing.

F&Vs are very sensitive to freezing damage. The chemical and physical actions of freezing can be highly detrimental to them, since their texture is mainly ensured by turgor. Turgor is the ability to retain water inside the cells. Rupture of cell walls due to the expansion of intracellular ice and/or enzymatic actions during freezing prevents a return to the initial state. The product will exhibit a loss of cellular structure, which can manifest itself in increased drip loss while thawing, loss of shape and less defined texture. This physical change of water within the product can be considered one of the principal reasons for the deterioration of quality.[2]

There are two ways of ensuring better raw material protection:

1. Cultivar selection.
2. Pre-treatments before freezing.

The first point is discussed in this chapter, and the second in Chapter 4.

Each year, breeding centres (public and private) all over the world offer a great number of new F&V cultivars to growers. At the moment there are many for every species of F&V, each with specific characteristics. For example, 2000 different cultivars of strawberries, and hundreds of cultivars of apples, peaches, green beans, etc., are known.

Each cultivar is different from the others in some way. Figure 3.1 shows what can happen after thawing several cultivars of strawberries harvested in the same season: the drip loss values range from 8% to 38%.

The cultivar Miss is a very interesting variety: it has a good yield, pleasant taste and a good colour. After thawing, however, structural collapse results in loss of almost half its weight. The cultivar Don, which has the same general characteristics as Miss, yields much better drip loss results. Thus, Don is a more acceptable cultivar for processing in the frozen food industry. This example demonstrates how the importance of product quality is far more relevant for freezing than for the fresh market.

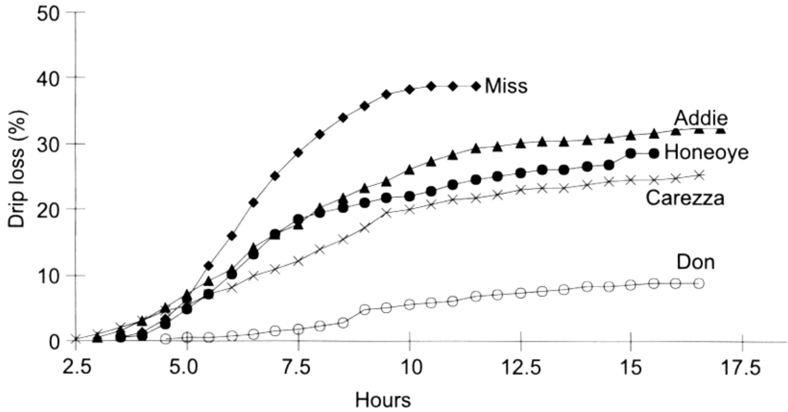

Fig. 3.1 Drip loss from a selection of strawberry cultivars.[2]

It is up to the technologist and biochemist to pinpoint the exact nature of these differences, which can become the real *quality indices* of the cultivars. On the basis of this information, breeders persevere with cultivar selection towards the goal of zero drip loss.

F&Vs for freezing require increasingly precise quality indices. This can only be achieved by creating a strong research network in all the different areas concerned.

3.1.2 Cultivar: definition and description of botanic unit

Plants can be divided into 'groups' according to the similarity of their structural, anatomic and genetic characteristics. Systematic botany has established groups varying in importance (order, family, genus, species).

The word 'cultivar' comes from the abbreviation and fusion of two English words: cultivated variety. A cultivar can be defined as a group of cultivated plants identified by any specific characteristic (morphological, physiological, cellular, cytological, chemical, etc.), which on reproduction, whether sexual or not, preserve their original characteristics.

The *International Code of Nomenclature for Cultivated Plants*[3] recognises the cultivar as the lowest botanic unit. A capital letter is used for the name of the cultivar, followed, or preceded, by the abbreviation 'cv' after the description of its scientific or common name. Letters that indicate the particular resistance to fungi, nematodes and virus often follow the name of the cultivar. For example, Tomato cv Rio Fuego VFN-TMR means the resistance of the cultivar to *Verticillium* (V), *Fusarium* (F), *Meloidogyne incognita* (N) and to the TMR: Tomato Mosaic Resistance.

A new cultivar can be obtained by any one of the following schemes:

- *Cloning* Non-sexual multiplication of a single individual, which produces exact duplicates. This method is common among many tree species and also horticultural products such as artichokes.
- *Variety crossing* The production of genetically homogeneous individuals through different genetic selection techniques. This method is used for herbaceous species such as wheat, spinach and potatoes.
- *Hybrid F1* A cross-formation from pure lines of individual (hybrid F1) in order to improve 'heterosis' phenomena, for example the increase in production or disease resistance. The best-known case is hybrid F1 of maize.
- *Genetic modification* See Chapter 13.

3.2 Factors affecting F&V cultivar selection suitable for freezing

3.2.1 Agronomic factors

Background

Some years ago farmers met market requirements by growing a wide range of cultivated species on their land. However, with the advent of specialised industries for freezing, the use of the land has changed radically. Since the processing industry needs a large amount of one product, large areas of land are required to provide this.

As a matter of fact, in some areas of the Mediterranean, there was a traditional agricultural scheme of repetitive cultivation of wheat. But with the interaction between industry and agriculture, such as the presence of a freezing centre in a specific area, a new agricultural combination has been introduced. For example, a yearly 'wheat–green beans–wheat' rotation scheme, or a biannual rotation of 'wheat–green beans–spinach–tomatoes–wheat'.[4] This means that the interaction between industry and agriculture is getting stronger and more important, because gradually the specialised farming areas are being connected to the freezing industry.

Agronomic planning

In order to plan the correct cultivation and harvesting of crops for industry, farmers have to take timing into account, with respect to the handling and processing capacity of the industry. This is particularly important for annual horticultural products. Whereas planning for tree fruits is obviously different because of the long life cycle of trees (from the beginning of cultivation until the first harvesting season should be at least three years). For this reason, growers have to plan sowing and transplanting of cultivars with different life cycles, but it is not always so easy to programme the life cycle of plants. For example, green beans are very simple, because they can be harvested only in the time period 50–60 days after sowing. In southern and central European areas, under ideal climatic conditions, it is possible to plan sowing from April to August.

The cultivation of broccoli, conversely, presents many more problems: below 10ºC the short life-cycle varieties can have early blossoming. Spinach also has problems with the longer warm days in spring, but already some cultivars exist that have a later flowering, so they are suitable for sowing during or at the end of winter. In southern areas of Europe it is very difficult to organise pea cultivation for industry because, as the temperature rises in spring, the peas become harder. The solution is to use hilly areas with particular exposure to more moderate temperatures.[4]

3.2.2 Specific agronomic factors

The strong connection between the various factors involved in this complex argument should not be ignored. The only way to face this problem is to create a scheme to increase understanding of the interaction.

Soil structure

There are two different soil types in agriculture: clay (maximum 50% clay) and sand (maximum 85% sand). Between these two extremes there are numerous combinations which can affect the success or failure of a culture. The ideal soil mixture would be 20% clay, 40% sand and 40% silt. Table 3.1 describes the advantages and disadvantages of clay or sandy soil.

Fertility

The fertility of soil for cultivation depends on the following:

- Soil structure.
- Availability of nutritional elements (N, P, K, microelements and live organic complex called 'humus').
- pH level.
- Human factors (tillage and fertility maintenance).

Table 3.1 Advantages and disadvantages of clay and sandy soil

Soil	Advantages	Disadvantages
Loamy	High cationic exchange activity (better plant nutrition)	Difficult to work (too sticky or too heavy)
	Better retention of water	Formation of stagnant water
Sandy	Very soft	Low cationic exchange activity (bad plant nutrition)
	No stagnant water The root vegetables are not deformed during development (e.g. carrots, potatoes, etc.)	Low retention of water (water stress)

Exposure/sunlight

These aspects are interlinked because photoperiodism (amount of daylight hours) and thermoperiodism (level of atmospheric temperature – alternating between hot and cold) are both influenced by sunlight.

If you consider an alpine valley, it is easy to understand the importance of exposure. On the north side there are only forests, woods and bushes, while on the south side vegetables, vines and apples can be grown. The soil warms up easily during the day, and stores the accumulated warmth during the night. Besides improving photosynthesis, this favourable situation prevents freezing, diseases and stagnant water. However, the cultivation rows should be placed north–south, thus preventing prolonged exposure and dangerous excesses of temperature. If the temperature rises above 35ºC, lycopene formation is blocked, as in tomatoes and peppers, and high temperatures can cause surface burns and discoloration.[5] If the rows have to be planted east–west, a cultivar with high foliage cover is required to protect the fruit against sunburn. For example, tomato cv Incas can be planted east–west because it has a lot of foliage, whereas the square type of pepper does not have enough foliage to protect the product.

Wind

High winds can interfere with the correct development of the crops, by causing the branches and leaves to knock against the fruit of tree species, resulting in skin and quality defects. During flowering, strong winds can be dangerous, for example the plum cultivar Angeleno is entomophilous – its flowers require pollination by insects. If the insects are disturbed by the wind, fruit set does not happen.

Even horticultural species suffer from high winds. Cauliflower has a lot of foliage which can easily grow deformed, and therefore susceptible to disease. Pepper, aubergine, bean and pea can also be affected by buffeting when there is a high wind. There are some pea cultivars that are able to resist high winds because they produce a strong net of cirri which anchor one to the other. Planting the rows in the direction of the prevailing winds, using cultivars with deep roots and using natural windbreaks (trees, hedges) are all methods of protection.

A secondary effect of high wind is air-borne marine salt, which can be blown many kilometres inland from the coast. The most direct effect on the cultivars is burnt leaves and serious physiological diseases. Once again, cultivar choice is important. For example, tomato cv VF 36 (*Lycopersicon cheesmanii*) does not accumulate sodium in its tissues.[6]

Rain

Rain is the best source of free water for plants. In areas where spring rainfall is followed by a dry summer, the early cultivar should be adopted so that early ripening can occur before the dry season, avoiding the danger of water stress.

In an area of excessive rainfall, a cultivar that grows immediately and rapidly must be chosen, so that its spreading roots prevent erosion. Another problem of excessive rain is damage caused to horticultural products with large foliage. Stagnant water causes mould on peas, and yellowing and death of spinach leaves.

Temperature

Temperature is a crucial factor. At very low temperatures there is no germination of seeds, or fruit set, and at even lower temperatures the danger of freezing is always present.

At the other extreme, when it is excessively hot, physiological and biochemical events occur. For example, pigmentation is blocked and water stress is very difficult to control.

Cauliflower is severely affected by prolonged low temperatures: there can be riceiness (presence of down), internal bractiness (small leaves visible between florets) and looseness of florets.

For peas, a specific parameter called the sum of thermic temperatures can be relied upon to provide the correct harvesting time. This value is obtained by summing the average daily temperature, minus the critical daily temperature value (4ºC = block of growth). For early cultivars, e.g. Spring and Alaska, the value is 1250, whereas for late cultivars it reaches 1500.

Altitude

Apples are an excellent example of how altitude can influence the quality of the crop. When Golden Delicious are grown in the valley, the pulp is less firm than those grown in the mountains.[7] Mountain Golden Delicious have typically five visible angles and a longer shape. Therefore the slices are more suitable for processing. Mountain Golden Delicious even have a better aroma profile (qualitatively and quantitatively) than apples from the valley.[8]

3.3 Technological factors

3.3.1 General considerations

When F&Vs for freezing reach maturity and agronomic factors are taken into account, then technology takes over. Harvesting, pre-refrigeration and handling before freezing demands far greater technological support than is required during the biological cycle. This technological aspect has to be very flexible, as F&Vs are biological material.

There are many important steps to be considered where technology plays an important role.

3.3.2 Mechanical harvesting

In order to minimise labour costs, vegetables and some fruits should be suitable for mechanical harvesting. Nowadays there are special harvesting machines used for a wide range of F&Vs, except for very delicate fruit such as the strawberry, wild strawberry and raspberry (although these problems are being studied.)

If the F&Vs ripen uniformly, reflecting the correct choice of cultivar, then mechanical harvesting can be used successfully. Ideally an entire crop could be used for processing, with minimum waste. In reality, the main problems of

Table 3.2 Handling resistance of some fruit and vegetables

	Resistant	Slightly resistant	Little resistance
Fruit	Melon Kiwi Blueberry Chestnut Clingstone peach Apple	Pear Peach Apricot	Strawberry Blackberry Raspberry Redcurrant
Vegetables	Carrot Artichoke Onion Bean Potato Pea Leek	Green bean Broad bean Fennel Pepper Celery Squash	Asparagus Broccoli Cauliflower Mushroom Aubergine Tomato Spinach Courgette

Source: adapted from Gorini.[10]

mechanical harvesting are related to vegetables growing near the soil. The harvesting equipment (e.g. blades) can damage such low growing plants. By using a long-stalked spinach cv (Carpo, High Pack, XP 1501),[9] yield can be increased. Peas are simultaneously harvested and shelled, then temporarily stored on field. If stones or foreign objects are picked up with the machine, the delicate skin of the peas can be injured. Table 3.2 lists the handling resistance of some F&V species.

3.3.3 Interval between harvesting and processing

After harvesting F&Vs undergo some changes in chemical composition, sensory attributes and nutritional value. The product should be processed as quickly as possible. For example, peas and spinach have an intense metabolism, as shown in Table 3.3, which means a severe decrease in quality if the time between

Table 3.3 Respiration heat (Kcal/t) for 24 hours

	0ºC	10ºC	20ºC
Asparagus	1200–1350	3000–3300	6000–7500
Carrot	200–580	650–900	1850–2800
Cauliflower*	500–1300	2550–2850	6300–8300
Green bean	1170–1450	3350–4250	8150–11900
Pea**	1800–2150	4100–5500	11800–13300
Spinach	1250–1700	4300–6450	13000–18500

Notes: * with leaves, **with pod
Source: Crivelli.[11]

harvesting and processing is too long. By using quick refrigeration these negative phenomena can be stopped.

The best-known methods of pre-refrigeration are pressure cooling, hydrocooling and vacuum cooling. Different categories of F&V require a different pre-refrigeration method, as follows:

- Pressure cooling: for small fruit and delicate vegetables.
- Hydrocooling: for large fruit.
- Vacuum cooling: for leafy vegetables.

Table 3.4 lists the correct pre-refrigeration procedures for different types of vegetables.[12]

Table 3.4 The suitability of various fruit and vegetables for pre-refrigeration methods

	Pressure cooling	Hydrocooling	Vacuum cooling
Fruit			
Kiwi	+	+	□
Apricot	+ +	+	□
Cherry	+ +	+ +	□
Strawberry	+ +	□	–
Apple	+	+ +	□
Pear	+	+ +	□
Peach	+	+ +	□
Plum	+ +	+	□
Vegetables			
Asparagus	+	+ +	–
Broccoli	+	+	+ +
Artichoke	+	–	+
Carrot	+	+ +	–
Cauliflower	+	–	–
Green bean	+	+	+
Fennel	+	+	–
Mushroom	+	□	+
Aubergine	+	–	□
Pepper	+	□	□
Tomato	+	–	□
Leek	+	–	–
Parsley	+	–	–
Pea	+	+ +	–
Celery	+	+ +	+ +
Spinach	+	+	–

Notes: + + very good method; + good method; – good method to be applied with slight changes; □ not good method.
Source: adapted from Gorini.[12]

3.3.4 Specific technological factors

Suitability for de-stalking

Frozen strawberries, whether for direct consumption or as a semi-finished product, are normally prepared without the stalk. The stalk and the calyx (the green part of the fruit) should be eliminated easily, without touching the pith. If this contact is made there is a danger of oxidation in the central cavity (during frozen storage), resulting in loss of the product. Senga Sengana, Camarosa, Don and Miss cultivars are relatively easy to de-stalk, while Pajaro and Seascape are more difficult.

Suitability for de-coring

De-coring is particularly important for cauliflower and broccoli. The parts to be frozen consist of small florets, coming from the whole head. The de-coring machine cuts away the stump and the florets should fall away spontaneously.

The white type of cauliflower, however, has a tendency to form large florets which then have to be reduced (manually) to the correct size, maximum 60mm diameter.[11] One cauliflower cv called Romanesco is ideal for mechanical de-coring because its florets are more uniform in size (less than 60mm and almost 25g each). This means that they require no further intervention and can be directly processed.[13]

The dangers of dehydration and oxidation are present when it is necessary to reduce the size by cutting, exposing the delicate internal part. These phenomena are evident after freezing and during storage.

Broccoli presents a similar problem. It is almost impossible for the mechanical de-corer to reach the top of the head and correctly separate all the florets. Therefore they have to be cleaned up manually, thereby increasing costs. An interesting solution to producing high quality frozen broccoli has been found, combining agronomic factors with technological needs. After cutting the main large head (suitable for the fresh market), the small florets which spontaneously grow along the main stalk can be used as a product for freezing. These small florets are usually uniform in size, thin, with a long stalk, and they have edible leaves. Several trials have been carried out, over a period of several years, on the cultivars Mercedes and Granvert, both of them yielding good results. Because of these studies, mechanical harvesting has been introduced, reducing the cost and eliminating any need for manual intervention before processing.[14]

Suitability for cleaning

Leafy vegetables require the most cleaning before processing. A good example is spinach, where the choice of cultivar reflects the time and cost of washing. Carpo, High Pack and XP 1501 cv all have smooth leaves to which soil particles do not attach, facilitating the washing step. In contrast, rough-leafed cultivars require prolonged washing.[9]

Suitability for de-stoning

Prior to freezing, apricots, plums and clingstone peaches have to be de-stoned before being cut into slices, halves or cubes. This step requires great care, because if the stones get into the dicing machine they can cause severe damage to the blades. To prevent this problem, a manual control is necessary, so increasing the final cost of the product. The simplicity of the de-stoning procedure also depends upon the cultivar. Among the clingstones, for example, there is the Baby Gold cultivar which can be de-stoned with a negligible amount of problems.

Suitability for size reduction
The handling of artichokes can be influenced by cultivar choice. Talpiot and 044 varieties have a very high yield (almost 180 000 artichokes/hectare = 30 tonnes/hectare). The average weight for Talpiot is 200g, with the diameter over 13cm, while 044 weigh 150–170g each. Even though Talpiot is qualitatively interesting, the de-stoning machine cannot be used. Thus, this good cultivar remains unused until a more flexible technological solution can be found.[15]

3.4 Sensory factors

F&V colour, taste and texture are the most important elements for farmers, industry and the consumer.

3.4.1 Colour

A good cultivar should keep its original colour, even after freezing, as uniformity of colour is of great importance to the industry. Sometimes peaches, apricots, etc. have different coloured skin, and even pulp: half-green, half-orange/yellow. This is due to excessive foliage on the tree, shading only part of the fruit, and slowing down the ripening. The solution would be to reduce foliage by pruning.

Even in the strawberry there can be a difference in colour where the stalk end is white, and the rest of the fruit is red. This can be due to premature harvesting or an irregular stage of ripening; in this case the choice of cultivar has to be questioned. Another defect in the strawberry is the difference in colour externally and internally. For example, cv Addie has good general characteristics, but is white internally. This means that it is unsuitable for freezing, and for all other industrial processing which requires only uniformly coloured fruit.

It is rare to have colour problems in vegetables if they have been harvested correctly and processed immediately. In fact, the blanching of all green vegetables can produce a more intense colour, owing to breakage of chloroplasts and the diffusion of chlorophyll in the tissues.[16] Sometimes cauliflower and broccoli have a violet or pink nuance (from anthocyanin pigments). However, this is not a serious defect because it can be easily eliminated by blanching.

Cultivar choice of a specific colour is often influenced by culinary traditions in different countries. For example, the white asparagus is preferred in North and Central Europe, while in southern Europe consumers prefer the green varieties.

3.4.2 Taste

Cultivar factor and harvesting period influence taste just like the other organoleptic parameters. When harvesting is too early, the aroma characteristics of the species have not completely developed. Fruit, especially, retains a herbaceous aroma through freezing. When harvesting is late, fermented flavour (in fruit) and 'off' flavour (in vegetables) can be present.

Peas are a good example of the influence of cultivar plus harvesting period. Consumers and the frozen food industry prefer sweet and tender varieties with small seeds, which are completely different from what is required by the canning industry and the fresh market. When peas are ripening, their sweetness is due to the sugars (about 6%) and to the low starch content (1%). Immediately after harvesting there is a rapid reaction conversion of sugar into starch which can exceed 4%. This reaction determines a gradual reduction of sweetness, an increase in firmness and the sensation of mealiness. This is also apparent in the increase of alcohol insoluble substances (AISs), which is 14% in shelled peas after 24 hours at 20°C.[17]

Therefore processing the product as soon as possible or using a pre-refrigeration stage is crucial, to halt these reactions.

3.4.3 Texture

Of the sensory attributes, texture is most susceptible to negative change after freezing. Often this is easily visible, especially in fruit. The structural collapse is evident because of drip loss and reduction of the original turgor.

Fruit is mainly protected by pectins which are quite delicate and undergo irreversible biochemical modifications after freezing and during storage. An in-depth analysis of pectin composition shows that there are three different components: water-soluble pectin, oxalate-soluble pectin and insoluble pectin or protopectin. Figure 3.2 presents three cultivars of strawberry (1503, 1505 and 1509), observed over two years. Among the parameters concerning texture, there is a correlation between protopectin content and texture index. The higher the R fraction (protopectin), the higher the texture values of the strawberry.[18] This signifies that in order to choose the correct strawberry cultivar for freezing, the R fraction in the fruit should be as high as possible.

The cellular structure and the pectolytic enzymatic activity in fruit also play an important role in identifying cultivars resistant (or otherwise) to freezing. For instance, the Pavie peach has thicker cellular walls and less active pectolytic enzymes, making it less susceptible to freezing damage than other peaches.[19] Osmotic pre-treatments can also help, improving frozen fruit texture for specific food applications (see Chapter 4).

Vegetables, however, are usually consumed cooked, so defects in texture are less evident. Furthermore, lignin, fibre cellulose, starches and other polysaccharides protect the structure of most vegetables, with the exception of leaves. Other products, such as pre-cooked F&Vs or purées, have already lost most of their texture during the heating stage. This does not mean that the

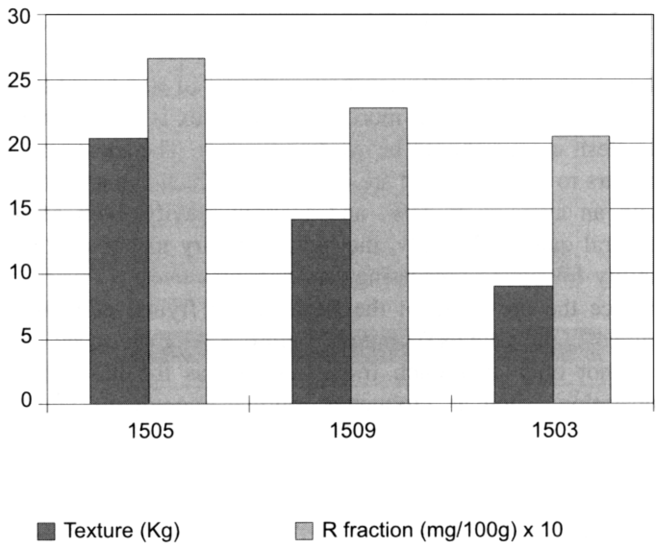

Fig. 3.2 Texture index and R pectin fraction content (on fr. Wt.) of three strawberry cultivars. (Source: adapted from Torreggiani *et al.*[18])

texture of vegetables has to be ignored; on the contrary, selecting the correct harvesting period and cultivars with good initial texture can limit the influence of blanching, freezing and final cooking on softness.

3.5 Agronomic and technological aspects of potatoes for freezing

In this chapter, we have not dealt with specific cultivars, only citing them as reference examples. However, potatoes require a special mention to summarise the influence of different factors on the raw material, because the consumption of frozen potatoes is multiplying in many countries. In fact they have become the most important frozen vegetable product, overtaking peas and spinach which have always been the traditional market leaders. Researchers have made numerous interesting studies to improve the performance of this product.[20]

Industry has an enormous choice of potato cultivars. The general trend is towards those with high productivity and large tubers in the 4–8cm size range.[21] In order to increase production of such tubers, low plant density per unit area should be used. The most requested shape is the regular oblong, because there is very little waste during dicing. The skin should be thin and resistant to post-harvest handling, and there should be no deep eyes which make it difficult to peel. The depth of the eyes depends on the cultivar.

Since this product is so highly dispersed and of great interest to the industry, there has to be total uniform maturity of the crop so that it can be mechanically harvested.

Some of the best harvesting indices are the percentage of starch and the total solid content in the tuber, but a much more practical index is the yellowing of the leaves.[22] The flesh colour should be white or cream. The most important processing parameters to be considered are dry matter, which can vary between 18 and 35%, with an average of 25%, and specific gravity, both of which determine the textural quality. Notably, the higher the dry matter content, the greater the suitability for potato processing.

In order to reduce the browning of the flesh during frying, cultivars with reduced sugar (glucose and fructose) content, below 20%, have to be chosen. Potatoes are used not only as French fries, but also as the base for other gastronomic preparations such as croquettes, purées, ingredients and semi-finished products.

3.6 Nutritional factors

F&Vs are among the most important sources of vitamins, minerals, sugars and fibre. The nutritional benefits for human health have not been completely investigated or described. Studies are under way on the natural antioxidants in many species, and there are even studies on compounds present in many crucifers (cauliflower, broccoli, etc.) which may help in the prevention of some diseases.

The nutritional profile of F&V is becoming more important as almost all the range of species is suitable for freezing. This is why cultivars used in the freezing process must start off with a high level of vitamins (especially the water-soluble ones, like vitamin C) and mineral salts, to ensure that after the pre-treatments (e.g. blanching), freezing and during storage, the nutritional value remains high. As we will see in Chapter 4, there are pre-freeze treatments for some fruits that can enrich the product by adding sugars, vitamins and mineral salts.

Ascorbic acid is an important biochemical indicator of the nutritional value of F&V. Ascorbic acid changes into dehydroascorbic acid, and successively into 2,3 diketogluconic acid, with no vitamin C activity in the presence of oxygen. This process starts immediately after harvesting and continues slowly even through cold storage. Therefore it is important to use cultivars with a high initial content of ascorbic acid.

Figure 3.3 shows the ascorbic acid content in several strawberry cultivars directly after harvesting. In theory the strawberries with the best nutritional aspect are Lambada, Maradebois and Chandler, because even after losing 30–50% of ascorbic acid, they reach the consumer with a satisfactory nutritional content.

An example of the nutritional variability of cultivars is demonstrated by sugar content. Figure 3.4 shows the total sugar content of strawberries measured immediately after harvesting.

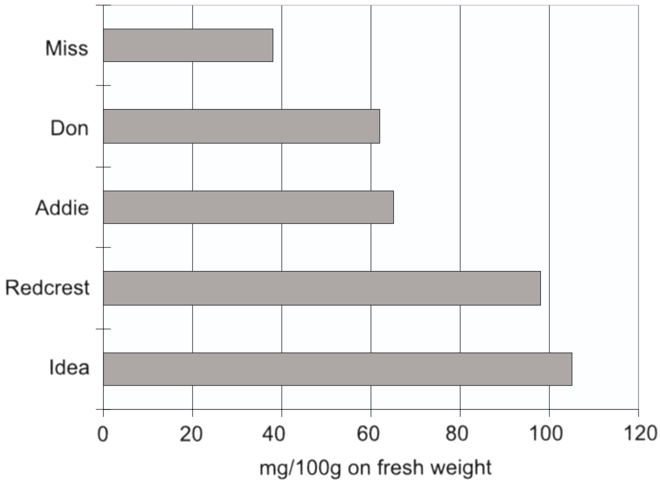

Fig. 3.3 Ascorbic acid content in strawberry cultivars harvested in 1997. (Source: adapted from Testoni and Lovati.[23])

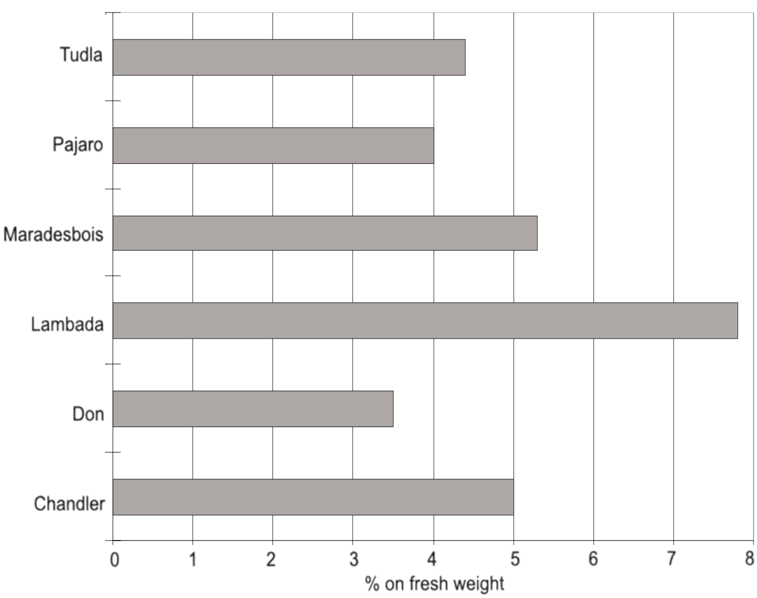

Fig. 3.4 Total sugars content (glucose, fructose and sucrose) of strawberry cultivars harvested in 1996. (Source: adapted from Lovati *et al*.[24])

Figure 3.1 clearly illustrates the direction of sugar content in the strawberry cultivars Miss and Don. Miss loses almost half its weight as drip loss and, at the same time, half its original sugar content in the liquid. Don loses much less. It is evident that there is a big nutritional gap between the two cultivars after thawing. For several frozen strawberry products (e.g. semi-finished, thawed, etc.) it is practically impossible to recover this rich liquid, so wasting a good source of nutrients.

The same type of cultivar variability is found in vegetables. Under the same agronomic conditions, this depends on the cultivar. Enzymatic activity in different carrot cultivars emphasises how they can differ from one to the other. Peroxidase is the enzyme considered in this example. It is fundamental to deactivate this enzyme before freezing (by blanching) to stabilise the product qualitatively during its storage life. From research by Pizzocaro and Croci[25] it is possible to divide eight carrot cultivars into two groups: one with low peroxidase activity (100–300 U/l) – Demi Longue de Nantes, Plastika, Scarlet de Nantes, and Red Core Danvers; and the other with high enzymatic activity (300–500 U/l) – improved Demi Longue de Nantes, Gigante Flakker, Danvers 126 and Red Core Ch.503. Subdividing the cultivars can help toward understanding the intensity of the pre-treatments and suitable frozen storage temperature. These conditions must be respected, otherwise there is a reactivation of the enzyme, even at low temperature, which causes biodegradation of different nutritional substances.

As mentioned previously, there is a decrease of some nutritional factors when F&Vs are blanched and subsequently stored. For this reason it is imperative that the frozen food industry chooses cultivars with a high initial nutrient content, as nutritional information is now provided on the packet. Even if these are only average values of proteins, sugars, fats, vitamins, etc., it can be considered a sort of ‘contract’ between the industry and the consumer, and the industry should respect this agreement.

This is just a brief look at the nutritional aspects of raw F&V material, but there is another point that must not be ignored: namely contamination by pesticides. The absence of pesticides from F&V is one of the fundamental requirements that contribute to the nutritional profile of the product. It is imperative for farmers to respect the pesticide-spraying treatment calendar, so that crops do not arrive at the industry in a potentially dangerous state which could harm human health.

Herbicides, for example, should be used with caution. Residues can remain in the soil even after the end of the cultivation, and can interfere with successive rotation crops. The effect of this can be that some plants may fail, or develop with nutritional deficiency, affecting the final product. A typical example is the influence of Trifluralin and Pendimethalin residues on the correct growth of spinach.[4]

The World Health Organization, United Nations Food and Agriculture Organization and others have issued recommendations for the use of pesticides, particularly for the permissible residue in each product.

The maximum residue levels (MRLs) arose from these proposals. They indicate the maximum amount of active molecule in any specific pesticide that is permissible in the product. In many countries these proposals have been incorporated into legislation. Farmers and industry must both comply with these laws as an act of responsibility towards the health of consumers.

3.7 How to measure subjective and objective F&V quality characteristics

3.7.1 Sensory characteristics

In section 3.4 we introduced the concept of sensory characteristics. Such characteristics are very important in order to ascertain whether a cultivar is suitable for freezing.

Research centres and quality control laboratories should have experts to carry out organoleptic testing. However, these tests should conform to the rigorous methodology that already exists in the literature.[26] Generally, the sensory profile should include evaluation of: appearance, colour, taste/aroma and firmness. Such evaluations can take into account how pronounced the single characteristic is (intensity), and how much it is appreciated (acceptance). Employing a numerical scale is the simplest method, where each panellist casts their vote. Other methods include ‘difference tests’, for example the triangle test. The sensory evaluation results should be statistically analysed in order to ascertain their mathematical validity. If the cultivar sensory profile is correctly obtained, a quality chart can be created, including useful information about the identification, description and control of the cultivar, year by year.

The behaviour of cultivars (especially vegetables) even after cooking has to be observed. The sensory parameters of fresh produce can be of high quality, but after cooking (grilling, boiling or frying) there can be some defects which may make it unmarketable. For this reason, there should be another panel test on the cooked product using the same methodology as for the fresh product. If vegetables are being boiled, for example, they should be timed with a chronometer. The sample presented to the panellists must be boiled in water without salt or, at most, with 0.5% of NaCl. The ratio between product and water should be 1:5 or 1:10, depending on the cooking time.

When a new cultivar appears, it is worth putting it through the whole cycle of processing (washing, blanching, freezing and storing) by using a pilot plant. The results can quickly yield interesting information about the behaviour of the cultivar during the processing cycle.

Another interesting test is over-cooking. Most frozen vegetable packets have cooking information (e.g. ‘cook for 5 minutes in boiling water’), but the consumer may make a mistake. It is interesting to see what happens if the product is cooked for double the recommended time, because a cultivar resistant to such drastic treatment may have particular value.

Apples, pears, plums, etc. can often be refrigerated for medium to long periods before freezing. Sensory characteristics of this fruit change during cold storage. For example, the apples of group Red Delicious cv Staymann can manifest mealiness after long-term refrigeration. Pears of cultivar William are very delicate and even slight change of refrigeration temperature signifies an unstoppable ripening, browning and cavities in the pulp. Such sensory modifications (arising from the chemical, physical and biological events) should be taken into account when the product has to be successively frozen.

3.7.2 Morphology

Morphology can help in the definition of cultivar maturity. Size can be measured very simply by using specific calipers (see Fig. 3.5). For weight data, a digital caliper is used. When connected to a normal PC, this instrument accurately records data, and statistical calculations are obtained.

Another interesting morphological aspect is the ratio between the pulp and stone of a fruit, and the total amount of waste (stalk, skin, stump and seeds). Leafy vegetable cultivars (broccoli, cauliflower and spinach) produce a lot of waste. They can be considered valuable when the processable part is high in relation to the waste. The higher the waste, the higher the handling costs.

Asparagus provides a good example of how to select the right cultivar for freezing, in relation to the edible part of the plant. However, it is very difficult for a sensory panellist to judge the edible part precisely, because each has a different personal preference, and even different teeth. The IVTPA has studied

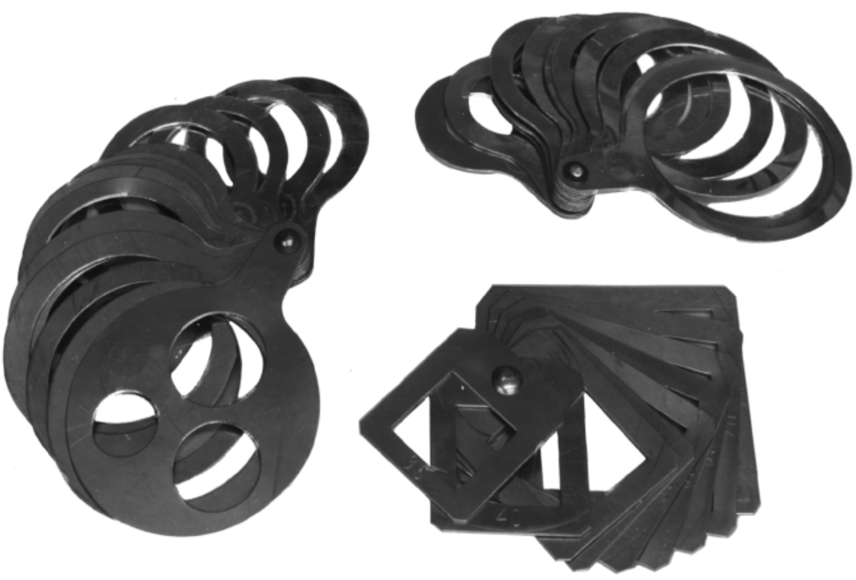

Fig. 3.5 Gauges for checking fruits and vegetables. (Source: courtesy of Bertuzzi SA, Italy.)

this problem and developed a mechanical prototype which already provides good results. The equipment incorporates a special blade which cuts the asparagus only when it meets a small resistance, very similar to the bite of a human being.

3.7.3 Texture

Texture is a crucial factor in defining the quality of raw material destined for freezing, especially when faced with many cultivars. Texture of F&V should be monitored throughout development, to find the exact moment for harvesting.

The penetrometer is the simplest instrument for measuring texture. It consists of a plunger (star, needle, cylindrical) of variable diameter, and a mechanism that translates the force into a numerical display. The data is usually expressed in kg or lb (see Fig. 3.6). The penetrometer is pocketable and is often used in the field, particularly for apples, pears, peaches, etc.

The manual dynamometer works in the same way, but is more suitable for large farms with small laboratories, because it is stand-mounted. Penetration is made easier because there is a mechanical lever facilitating the regularity of strength. Electronic versions of this equipment are now available. Another

Fig. 3.6 Portable fruit tester for measuring the consistency degree of fruit. (Source: courtesy of Bertuzzi SA, Italy.)

Fig. 3.7 Portable and laboratory dynamometer for measuring the consistency of peas. (Source: courtesy of Bertuzzi SA, Italy.)

dynamometer is shown in Fig. 3.7. It can be used for measuring the degree of consistency of peas and also, with the addition of a pressure gauge, for measuring grapes, strawberries and fruit in syrup. It is both usable in the laboratory and can be portable for field measurements.

One of the most sophisticated instruments is the Instron dynamometer. All the large food industries use this kind of equipment where texture is a major factor to be considered. This tool has high precision, and a flexible measurement capacity. Measurement of tension, compression, elasticity, breakage, cutting, etc. are all possible on a wide range of products, from the most delicate to the hardest, singularly or *en masse* (see Fig. 3.8).

3.7.4 Colour

During development almost all F&Vs have a continual evolution of colour, a factor that must be evaluated. If this objective analysis is carried out effectively, it is easier to judge the validity of different cultivars and to choose the optimum harvest moment.

The oldest method for classifying colours is the Munsell System based on colorimetric charts, where the measure is made visually with a specimen colour. This method was modified (Munsell Renotation System) using a letter/number combination for each colour, but still utilising the colorimetric charts. There are also colorimetric charts for specific products, widening the range of the letter/number combinations considerably.[27]

Fig. 3.8 Instron Universal Testing Machine. (Source: courtesy of Instron Ltd, UK.)

Other methods for expressing colour numerically were developed by an international organisation concerned with light and colour, the Commission Internationale de l'Eclairage (CIE). The two most widely known of these methods are the Xxy colour space, based on the tristimulus values XYZ defined by CIE, and the L* a* b* colour space to provide more uniform colour differences in relation to visual differences. Colour spaces such as these are now used throughout the world for colour communication.[28]

Minolta has created an up-to-date Chroma Meter from these two efficient methods. The colorimeter has the advantage of being used both in the laboratory

Fig. 3.9 Minolta Chroma Meter. (Source: courtesy of Minolta Ltd, Japan.)

and in the field (see Fig. 3.9). It provides a series of numbers corresponding to the colour characteristics, for example L* (lightness), a* (red-green) and b* (yellow-blue) values.

3.7.5 Refractometric index (ºBx)

This index provides the soluble solids content. It is employed for fruit, in particular, where the ºBx value corresponds approximately to the sugar content. There is an empirical correlation between dry matter and ºBx of fruit:

$$^{\circ}\mathrm{Bx} = \mathrm{DM}\% - 1.5$$

The refractometer is an optical instrument used for measuring ºBx. Some refractometers can be used directly in the field (see Fig. 3.10), while other more precise models are used in the laboratory (see Fig. 3.11). The ºBx index value can be obtained either by homogenising lots of fruit, or by taking each one individually. In the latter case, it is very important *where* within the fruit the juice is taken from. For example, only the central area of the plum (nº2) should be considered (see Fig. 3.12), because there is a great variability between the stalk end (nº1) and the opposite side (nº3). This variation can be from four to seven points.[29]

3.7.6 Photographic file

Slides and photographs of the cultivars are always taken using the same camera, film, aperture diaphragm and light conditions. The photographs must be taken

Fig. 3.10 Portable refractometer. (Source: courtesy of Bertuzzi SA, Italy.)

during the different physiological stages, with pictures of flowers, the axial section of a fruit or vegetable, and leaf profiles, at the correct ripening stage.

These photographs should become part of an archive, which includes an identification file and description of every cultivar. This kind of data bank can be useful for breeders, farmers and also for processors' quality control groups. For example, crops arriving at the freezing centre can be compared with the previously established quality. An example of this file is shown in Fig. 3.13. It concerns fruit only, but for vegetables the necessary corrections should be made.

3.8 Future perspective of F&V cultivar selection for frozen products

This chapter has highlighted the importance of improving the quality of cultivars for freezing by having a strong collaboration between breeders and technologists. A new cultivar can become interesting when it is within the borders established by technologists. These borders are represented by quality indices which have to become more specific and numerous. From these indices the quality standard specifications should be created.

Almost all European countries are interested in creating official F&V standards for freezing. Farmers, processors, researchers, distributors, retailers and consumer organisations are all involved in creating such standards.

Cultivars, especially vegetables, that require little or no blanching (because they have a negligible enzymatic activity) represent an important area of research in the future.

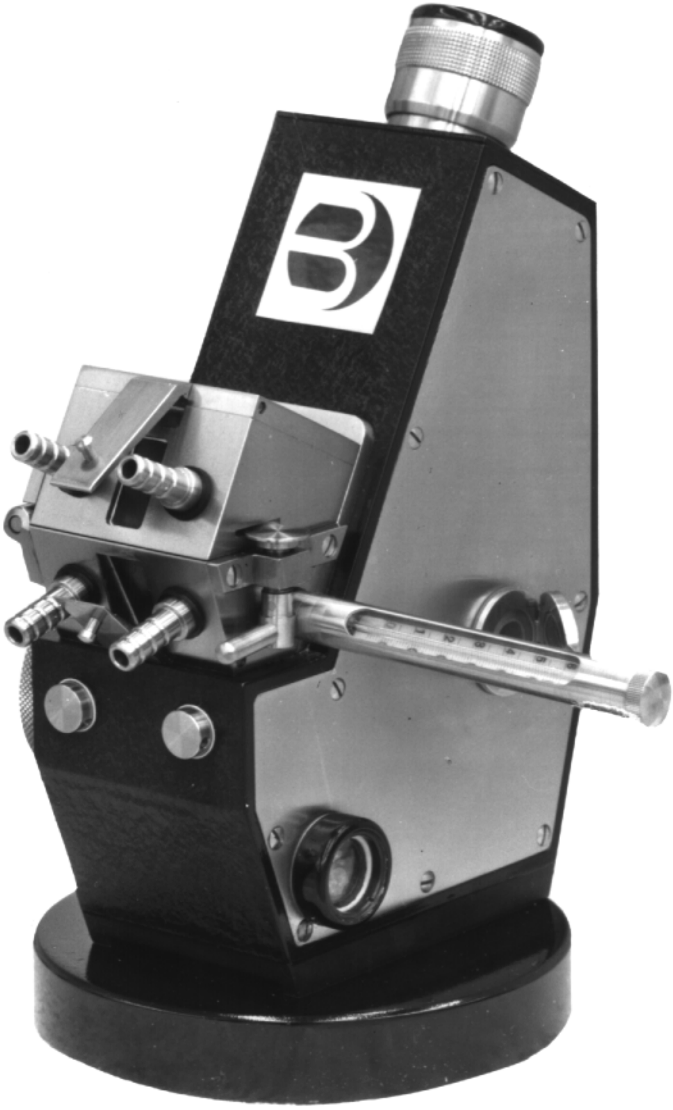

Fig. 3.11 Laboratory refractometer. (Source: courtesy of Bertuzzi SA, Italy.)

Finally, another new cultivar research area should be consideration of the environmental life cycle assessment of products (shortened to 'life cycle assessment' and abbreviated as LCA).[30] The definition of LCA includes the combination of production, usage and waste processing, which describe the life cycle of tradable goods, i.e. its life 'from the cradle to the grave'. The LCA can be considered as a global system of studies of the whole productive process, applicable to anything from cars to pea cultivars, referring to environmental effects in particular. The LCA does not propose absolute ontological judgements

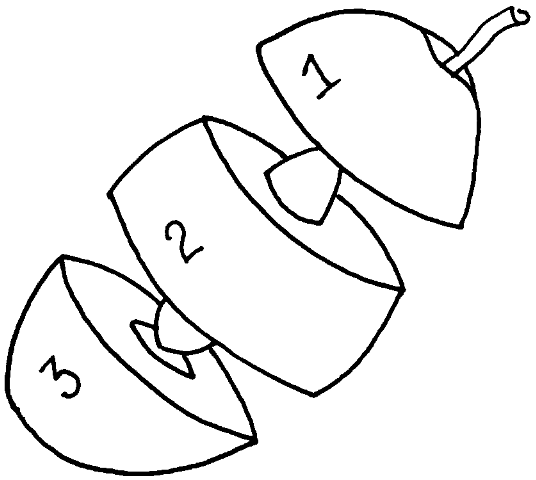

Fig. 3.12 Measurement of °Bx in a fruit.

such as ‘good’ or ‘environmentally friendly’, but instead qualitative or quantitative statements.

If one wishes to compare two cultivars of F&V, for example, an LCA analysis would consider, say, whether one needs more tillage than the other, or whether herbicides must be used (and how much energy is required for the production of such herbicides). It can say whether the mechanical harvesting machines are simple (low energy consumption and low gas emission) or complicated (expensive and polluting); whether post-harvest handling and storage are necessary (cold storage, CFC pollution); and whether the waste processing is too complicated and costly.

Many food industries have already used LCA analysis to conduct in-depth research into the processing of some of their products. The results have been utilised as guidelines to correct errors and to create new market strategies.

It should not be too difficult to apply this type of study to frozen F&V, considering the whole process cycle, starting from the choice of cultivar seeds, through to consumption when the packet of frozen F&V is opened in the family kitchen.

3.9 Summary

It is very important to realise that there is a great difference between the quality indices of F&V raw material for freezing and for the fresh market. The freezing process can influence the behaviour of F&V, such as texture reduction, colour modification and nutrient content decrease. Therefore a high quality frozen product must come from high quality raw material. The most variable contributor to F&V quality is the selection of cultivar: the lowest botanic unit.

Genus: .... Species: .... cv: ....

Morphology:

shape : ....
average weight : ....
skin colour (L*, a*,b* or colorimetric charts) : ....
specific characteristics : ....
pulp colour (L*, a*, b* or colorimetric charts) : ....

Cultivar yield (t/hectare) : ....

Harvesting period:

Mechanical harvesting : ....

Manual harvesting : ....

% damage : ....

Chemical-physical-technological parameters:

de-stalking : ....
de-stoning : ....
chemical peeling : ....
mechanical peeling : ....
manual dinamometer (g/lbs) : ....
°Bx : ....
pH, acidity : ....

Need for refrigeration pre-processing:

pre-refrigeration methods : ....
refrigeration:
T°C : ....
R.H.% : ....
Controlled Atmosphere conditions : ....

Sensitivity to specific parasite : ....

Photographic file : ....

Fig. 3.13 Example of identification file for fruit cultivar.

The suitability of a cultivar for the freezing process depends on agronomic, technological, organoleptic and nutritional factors, which are often connected to each other. In order to illustrate these links, several examples concerning the cultivars' variability are presented.

It is necessary to study the behaviour of the cultivars before and after industrial processing, so as to define the quality indices and determine whether they are suitable raw material for freezing. With the help of these quality indices it is easier to understand the importance of the agronomic factors (e.g. yield, mechanical harvesting), technological factors (e.g. cleaning, de-stalking, de-coring), organoleptic factors (value of attributes even after freezing and cooking) and nutritional factors (retaining the nutrients).

There are many analytical techniques that play an important role in defining these quality indices. Only the most interesting techniques are introduced here, since they are able to show the differences, however slight, among the various cultivars. Almost all European countries are interested in having official standards for F&V quality, and these can only be achieved by studying the quality indices.

Future trends in F&V cultivar selection for frozen products are aimed at an ever closer collaboration between breeders and technologists in order to create new and increasingly suitable cultivars. The influence of everything involved in the creation of a new cultivar and its impact on the environment cannot be ignored.

3.10 Acknowledgements

Dr Nazareno Acciarri of the Istituto Sperimentale Orticoltura, Dep. Monsampolo del Tronto, provided a lot of interesting information about the influence of agronomic factors on F&V cultivars.

Many of my colleagues at IVTPA allowed me to describe interesting examples of many cultivars, some of which are unpublished.

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3.11 References

1 CRIVELLI, G. and SENESI, E., 'La materia prima fattore determinante la qualità dei prodotti ortofrutticoli trasformati', *Nuove strategie per la valutazione qualitativa dei prodotti alimentari: dalla scelta varietale al prodotto consumato*, Macfrut, Cesena, 1993.

2 MAESTRELLI, A., TORREGGIANI, D., LUCAS, T., RAOULT-WACK, A.L. and PHILIPPON, J., 'Factors affecting the quality of frozen F&V', in *Maximising Quality and Stability of Frozen Food: A Producers Guide to the State of the Art*, ed. C. J. Kennedy and G. P. Archer, Leeds, EC Concerted Action FAIR CT96-1180, 1998.

3 GILMOUR, J.S.L. *et al.* (eds) *International Code of Nomenclature for Cultivated Plants*, Utrecht, International Bureau for Plant Taxonomy and Nomenclature, 1969, p. 17.

4 MAGNIFICO, V. and SARLI, G., 'Gli avvicendamenti nell'orticoltura per l'industria negli ambienti meridionali', *Orticoltura per la surgelazione*, Oristano, CRAS, 1989.

5 GOODWIN, T.W. and JAMIKRON, M., 'Byosynthesis of carotens in ripening tomatoes', *Nature*, 1952, **170**, 104–5.
6 RUSH, D.W. and EPSTEIN, E., 'Genotypic response to salinity: differences between salt-sensitive and salt-tolerant genotypes of the tomato', *Pl. Phisyol.*, 1976, **57**, 162–6.
7 ASIRELLI, A., SANSAVINI, S., BALDASSARRI, M.T. and PIAZZA. R., 'Un'indagine al mercato ortofrutticolo di Bologna: la qualità percepibile delle mele di pianura e di montagna', *Melicoltura di pianura: quale futuro,* Verona, Camera di Commercio Industria Artigianato e Agricoltura, 1997.
8 RIZZOLO, A. and VISAI, C., 'Studies on the quality of Golden Delicious apples coming from different localities of Trentino', 23rd International Horticultural Congress, Firenze, ISHS, 1990.
9 LEONI, S., POTZOLU, F., CADINU, M. and CARLETTI, M.G., 'Caratteri agronomici ed attitudine alla surgelazione di cultivar ed ibridi di spinacio e di peperone', *Orticoltura per la surgelazione,* Oristano, CRAS, 1998.
10 GORINI, F.L., 'Comportamento dei frutti nel corso della commercializzazione', *Atti IVTPA,* 1989, **XII**, 185–210.
11 CRIVELLI, G., 'Requisiti della materia prima per ortaggi surgelati di qualità', *Orticoltura per la surgelazione*, Oristano, CRAS, 1998.
12 GORINI, F.L., 'Interventi per valorizzare la qualità degli ortofrutticoli', *Orticoltura per la surgelazione*, Oristano, CRAS, 1998.
13 ACCIARRI, N., SCHIAVI, M., VITELLI, G., MAESTRELLI, A., FORNI, E. and GIOVANESSI, L., 'Breeding of green curded cauliflower for fresh market and for freezing', 10th Crucifer Genetic Workshop, Rennes, Thomas & Monteiro, 1997.
14 CRIVELLI, G., DALLACECCA, V., BIGELLI, G., MAESTRELLI, A. and ERBA, M.L., 'Research on varieties and techniques suitable for improving the quality of broccoli for freezing', 23rd International Horticultural Congress, Firenze, ISHS, 1990.
15 ELIA, A., CALABRESE, N. and BIANCO, V.V., 'Tecnica di coltivazione e aspetti qualitativi del carciofo da industria propagato per seme', *Orticoltura per la surgelazione*, Oristano, CRAS, 1998.
16 LEE, C.Y., VAN BOURNE, M.C. and VAN BUREN, J.B., 'Effect of blanching treatments on the firmness of carrots', *J. Food Science*, 1979, **44,** 615–19.
17 CRIVELLI, G., *La surgelazione dei prodotti ortofrutticol*, Bologna, Edagricole, 1993.
18 TORREGGIANI, D., MAESTRELLI, A., FORNI, E. and GIOVANESSI, L., 'High Quality Frozen Fruits by Cultivar Selection and Partial Dehydration before Freezing', in *The Preservation of Frozen Food Quality and Safety Throughout the Distribution Chain*, ed. C.J. Kennedy and G.P. Archer, Leeds, Concerted Action CT96-1180, 1997.
19 SOUTY, M., 'Adaptation du matériel végétal à la qualité des produits transformés', *Industries Alimentaires et Agro-industrielles*, 1991, **6**, 453–5.
20 SALUNKHE, D.K., KADAM, S.S. and JADHAU, S.J., *Potato: Production, Processing and Product*, Boston, CRC Press, 1991.

21 GRAY, D. and HUGHES, J.C., 'Tuber quality', in *The Potato Crop: The Scientific Basis for Improvement*, ed. P. M. Harris, New York, Chapman & Hall, 1978.

22 PANTASTICO, E.B., CHATTOPADHYAY, T.K. and SUBRAMANYAM, H., *Post-harvest Physiology, Handling and Utilization of Tropical and Subtropical Fruits and Vegetables*, Westport, AVI, 1975.

23 TESTONI, A. and LOVATI, F., 'Considerazioni su alcuni aspetti qualitativi dei frutti di fragola', *La fragola verso il 2000,* Verona, Camera di Commercio Industria Artigianato e Agricoltura di Verona, 1998.

24 LOVATI, F., PIANEZZOLA, A., GRAZIANETTI, S., MASTELLONE, F. and TESTONI, A., 'Aspetti qualitativi e merceologici dei frutti di diverse varietà di fragola alla raccolta e dopo la conservazione', *Rivista di Frutticoltura*, 1997, **9**, 65–71.

25 PIZZOCARO, F. and CROCI, C., 'Stabilità dei lipidi nella carota surgelata', *Annali IVTPA*, 1984, **XV**, 23–32.

26 MEILGAARD MORTEN, C., *Sensory Evaluation Techniques*, Boca Raton, CRC Press, 1988.

27 ANON., *CTIFL 1997 Publications*, Paris, Centre technique interprofessionnel des fruits et légumes, 1997.

28 MINOLTA, *Precise Color Communication*, Osaka, Minolta, 1994.

29 CARTIER, R., *Conseils pour l'amélioration du séchage de la prune d'Ente*, Villeneuve Sur Lot, Bureau National Interprofessionnel du Pruneau, 1988.

30 AAVV, *Environmental Life Cycle Assessment of Products*, Leiden, Centre of Environmental Science, 1992.

4

The pre-treatment of fruits and vegetables

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Frozen fruits and vegetables undergo quality deterioration during freezing and frozen storage, due to the large amount of water in the fresh product. In addition, texture degradation, structural collapse and drip loss will occur during and after thawing. If pre-freezing, freezing and storage operations are not carried out adequately, frozen products may resemble their fresh counterparts in name only. In this chapter, we discuss the ways in which pre-freeze treatments, in particular formulation, can be used to maximise the quality and stability of frozen foods.

4.1 Introduction

Due to the rapid growth in consumption of frozen food (per capita) throughout the world, the industry is adapting itself to changing market forces, such as an increased demand for prepared food, a need for diversification and enhanced control of quality and safety (Mallett, 1994). This applies to fruits and vegetables in particular, whose market can be divided into two sections: whole frozen fruit and vegetables (conventional market) and fruit and vegetable pieces to be incorporated, as ingredients, into prepared foods.

Over the past three years, many new fruit- and vegetable-based products have appeared on the market, for example frozen vegetable pieces coated with sauce, fruit pieces pre-dipped in sugar and pre-dried frozen fruit pieces. They are widely used as basic materials, or as additional components, in many food formulations; examples include cooked dishes, pastry and confectionery products, ice cream, frozen desserts and sweets, fruit salads, cheese and yoghurt. In most cases, fruit and vegetable pieces impart a fresh and healthy image to the food, giving it an additional value appreciated by the consumer and providing higher margins for the producer.

The fruit and vegetable pieces must preserve their natural flavour and colour, retain a pleasant texture and preferably be free of antioxidants or other additives. As a general rule, fresh-like values are required for high moisture products, such as ingredients to be incorporated into fruit salads or ice cream, while some colour and flavour changes, and relatively increased consistencies, may be still acceptable for lower moisture foods, such as cakes or various baked products. Besides sensory properties relating to acceptance and quality, well-defined functional properties are also required, with reference to the physico-chemical environment and the shelf-life of the food. The 'compatibility' of ingredients with food, as a physico-chemical system, is mainly dependent upon the equilibrium vapour pressures or water activities of the components. Water activity should be matched to avoid (or to allow a controlled rate of) diffusion of moisture between the fruit and the food, and to properly adjust the shelf-life and storage behaviour according to the specific food formulation.

Chemical and physical actions of freezing are highly detrimental to fruit and vegetables, since their texture is mainly ensured by turgescence (apple, berry, peach, tomato, lettuce, spinach, etc.). Turgescence is the ability to retain water inside the cells. Rupture of cell walls due to growth of ice crystals and/or enzymatic actions during freezing prevents a return to the initial state. The product will exhibit a loss of cellular structure, which can manifest itself in increased drip loss while thawing, loss of shape and a less defined texture. Water within food can also migrate towards cold outer surfaces and then evaporate, recrystallising as ice. Food surfaces become dry and colour tarnishes. Even at $-18^{\circ}C$, a fraction of food-constituent water remains liquid and free for these reactions. Water can also migrate from ice crystals present in food. A food's surface is affected first, as it is in direct contact with the refrigerating medium (usually air). During freezing and frozen storage, water is the molecule most involved in deterioration reactions. Freezing contributes to cell rupture on a food surface, so interactions between previously separated substances then become possible. It provides a medium for diffusion of all other molecules involved in deterioration reactions. Water can also participate directly in deterioration reactions, which are many and include the following:

- Production of off-flavours.
- Changes in colour due to enzymatic or non-enzymatic reactions on pigments (especially browning).

The use of pre-freeze treatments can help to reduce (or avoid) these detrimental phenomena, either by inactivating the deterioration reactions, or by reducing the water content in the material. Conventional pre-treatments include washing, blanching and soaking, and presentational treatments such as comminuting, coating, grinding and packaging. Washing fruit and vegetables is important to remove soil and other contaminants, and reduce the microbial load on fresh material. Until now, browning and off-flavours have been successfully avoided for most products by blanching or chemical treatments, such as soaking in antioxidant solutions, before freezing. However, heat treatments are likely to be detrimental to food texture and nutritional quality.

The implementation of washing and chemical pre-treatments presents no major technical difficulty, and packaging is described elsewhere in this book (Chapter 10). Therefore, only blanching as a conventional pre-treatment will be described further in this chapter (section 4.2). Currently there is renewed interest in implementing partial dehydration and formulation stages prior to freezing. The reason for this is the versatility of the technique, which makes it possible to reduce water content, improve quality and/or develop new products. These techniques are further described in section 4.3.

4.2 Blanching

Blanching is a heat pre-treatment commonly used for most vegetables that are to be frozen and ultimately cooked before use. The imposed temperature is close to 100ºC at the surface. The aim of blanching is to inactivate enzymes responsible for deterioration in food. Inactivation is achieved by denaturing the proteins that would otherwise take part in reactions leading to deterioration.

There are, however, certain drawbacks to blanching. Cellular tissues are also affected by high temperature, and effects similar to those caused by freezing may be observed. These include loss of texture, and an increased risk of microbial contamination due to the removal of the food's natural microbial flora. Quality loss through blanching can be minimised by implementing short-time high-temperature exposure, rather than longer times at relatively lower temperatures.

Blanching can be achieved by immersion or steaming. Blanching by steam has the advantage of minimising the leaching out of soluble materials (lixiviation). This factor is becoming increasingly important as environmental regulations regarding wastewater are tightened. At present, blanching is responsible for 60–70% of organic pollution in food industry water outputs.

From this point of view, steam blanching is preferable, provided that the cooling stage is not achieved by immersion – this applies to finely chopped foods (e.g. carrot slices) in particular. However, at the same operating temperature, steam blanching takes 20–40% longer than immersion blanching because of poorer thermal exchange. The advantages and disadvantages of immersion blanching are summarised in Table 4.1.

Immersion of foods in aqueous solutions containing specific molecules can complement blanching. For instance, addition of citric acid (0.5%) to the immersion bath decreases pH, and hence the threshold of thermal denaturation of enzymes. This technique is used when processing artichokes. When combined with blanching, it reduces the operation by 20–30%. Addition of sodium

Table 4.1 Advantages and disadvantages of immersion blanching as a pre-freeze treatment

Advantages	Disadvantages
1. Inactivates enzymes responsible for browning and off-colours	Leads to the death of cellular tissue with high possible deterioration of texture
2. Enhances colour of green vegetables and carrots	
3. Partially destroys micro-organisms	Higher sensitivity to microbial growth afterwards
4. Decreases pesticide or nitrate levels (in spinach, carrots, etc.)	Loss of food's own solutes, resulting in pollution of the blanching bath
5. Specific applications: • Reduces bitter taste of cabbage • Adjusts sugar content in potato pieces, reduces frying time and improves product texture	Absorption of water by food and modification of yield

bisulfite (0.5%) prevents mushroom browning, and the yellowing of cauliflower may be avoided by metabisulfite. The addition of chemicals to the immersion bath to enhance frozen food quality is attractive, but permissible quantities are often regulated by law, for example calcium chloride which is used to enhance food texture.

A cooling stage between the blanching and freezing processes is highly recommended. It helps to control the duration of food exposure to high temperature, and rapid cooling avoids microbial growth on the exposed surfaces. Higher food yields have been obtained when combining immersion blanching with air blast chilling (with use of fog).

4.3 Partial dehydration and formulation techniques

There are various techniques, depending on the food to be transformed and on the final use of the product. These techniques include partial air-drying, osmotic dehydration (also termed de-watering and impregnation soaking – DIS), and immersion chilling and freezing in concentrated aqueous solutions. The latter makes it possible to combine formulation (de-watering and impregnation) with pre-cooling. So far, these techniques have been developed primarily for fruits, and vegetables to a lesser extent. Therefore, the following examples relate mainly to fruits.

Figure 4.1 presents the main areas of application for partial dehydration and formulation pre-freeze techniques. For practical purposes, a rough classification of foods (based on their moisture condition) could rate 'high moisture' systems with water activities in the range 0.95–1, 'reduced moisture' systems with 0.85 <

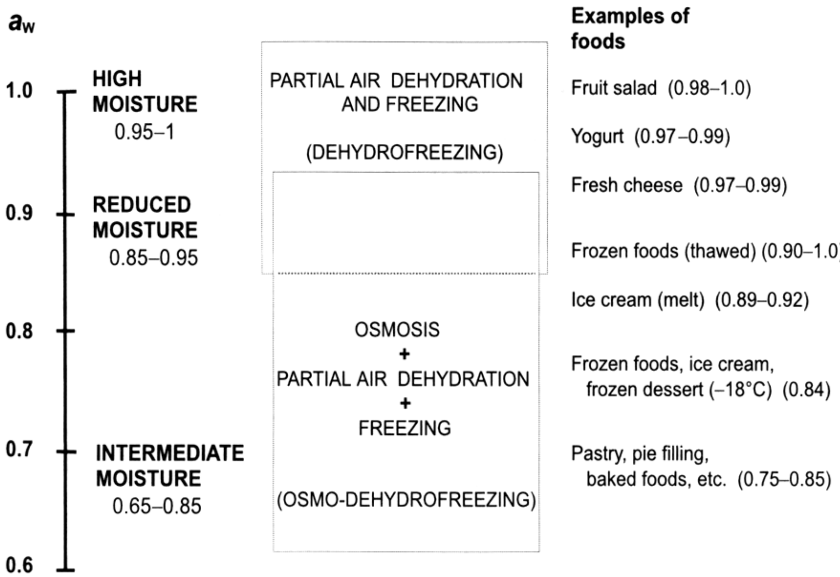

Fig. 4.1 Examples of a_w process relationships for some typical fruit ingredients.

$a_w < 0.95$, and 'intermediate moisture' systems with a_w in the range of 0.65–0.85. The proposed classification is only an operative one, and should not correspond to specific classes of foods. For frozen, or partially frozen systems (ice cream, sherbet, frozen dessert, etc.), two different levels of a_w must be considered: one for the unfrozen (or thawed) system, where the a_w is composition-dependent, and one for the frozen system where a_w is temperature-dependent if an ice phase is present until equilibrium conditions are achieved (Fennema, 1981).

4.3.1 Partial air drying

Partial dehydration is generally achieved by air drying. The resulting process is termed dehydrofreezing. The advantages over conventional freezing include: (1) energy savings, since the water load to the freezer is reduced, as well as transport, storage and wrapping costs; (2) better quality and stability (colour, flavour), as well as thawing behaviour (lower drip loss) (Lazar, 1968; Huxsoll, 1982). When using partial air drying, food ingredients of high water activity ($a_w > 0.96$) are generally obtained, since water removal is limited to 50–60% of the original content. To avoid browning during air drying, blanching or other treatments such as dipping in antioxidant solutions (ascorbic or citric acid, sulphur dioxide) can be used.

The air dehydration step usually produces a weight loss of up to 50%, corresponding to 60% water reduction, and a 10% relative increase of total solids on the fresh weight. Dehydrofrozen fruits may be used as fresh substitutes in frozen fruit salads, surface garniture or filling for tarts and pies. The wetting effect of the fruits is reduced, due to the lower water content. Dehydrofreezing may produce a weight loss of 75–80%, with solid contents ranging from 20–50%. Such products are suitable for pastry foods where wetting has to be avoided, and for yoghurt preparations where they can absorb moisture, avoiding the separation of whey (Giangiacomo *et al*., 1994).

Partial water removal from the food prior to the freezing process leads to the concentration of cytoplasmatic components within the cells, to the depression of the freezing point, and to an increase of supercooling. Thus, there are relatively fewer large ice crystals, and a lower ratio of ice crystals to unfrozen phase, with a consequent reduction of structural and sensory modifications. These partial dehydration effects prior to freezing have proved suitable for apple, pear and clingstone peach. The light photomicrographs of freeze–thawed strawberry tissues, shown in Fig. 4.2, clearly indicate the reduction of freezing damage due to the decrease in moisture content. In fact, pre-dehydrated strawberry slices have greater retention of tissue organisation after thawing than untreated ones, which show a definite continuity loss and thinning of the cell wall.

For these applications a limited, but uniform, dehydration of the individual pieces is required, together with ‘free-flowing’ properties of the bulk product, for continuous in-line operations. These requirements are not well satisfied by conventional drying techniques on a static bed, as an even dehydration is reached only in the last stages of the process due to the heat and mass transfer gradients across the bed of the particulate food. Free flowing of the product is often hindered by particle agglomeration. If the particle’s bed is mixed, there is an improvement in the evenness of dehydration, but better results could be obtained by fluidised bed drying. Fluidisation is highly efficient for partial dehydration, as the lower the weight losses, the higher the drying rate. Moreover, heat and mass transfer are significantly improved by fluidisation: a 50% weight loss for 10mm apple cubes at 80ºC and 25kg/m^2 product load is reached in 15 minutes using fluidisation, compared with 30 minutes using a static bed (Maltini *et al*., 1990a).

However, whatever the air drying technique, the colour of certain fruits, such as kiwi fruit and strawberry, is susceptible to heat modification. For example, kiwi fruit shows a definite yellowing of the typical green colour when air dehydrated to 50% weight reduction, even at 45ºC. For these fruits, air drying must be replaced by osmotic dehydration, which is effective even at room temperature, and which operates away from oxygen. This is described in section 4.3.2.

4.3.2 Osmotic dehydration

Conventional air drying can be substituted by (or combined with) osmotic dehydration as a pre-freeze treatment. This process involves placing the solid food (whole or in pieces) into solutions of high sugar or salt concentration. Le

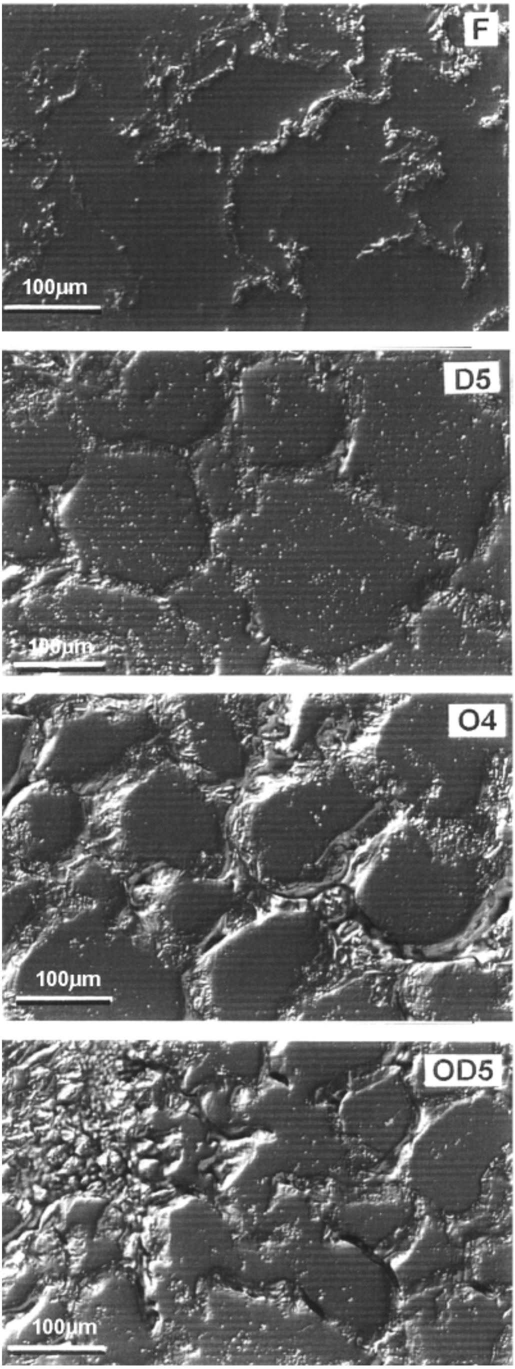

Fig. 4.2 Photomicrographs of strawberry slices after thawing. Pre-treatments before freezing: F = none; D5: air drying to 50% weight loss; O4 = 4hrs osmotic dehydration; OD5 = 2hrs osmotic dehydration + air drying to final 50% weight loss. (Source: Sormani *et al*., 1999.)

Maguer (1988), Raoult-Wack *et al*. (1992), Torreggiani (1993), and Raoult-Wack (1994) have recently reviewed the basic principles, modelling and control, and specific applications of osmotic dehydration on fruit and vegetables. Additionally, the most recent research advances in this field can be obtained from the European-funded network on 'Osmotic Treatments' (FAIR, 1998).

Soaking gives rise to at least two major counter-current flows: an important outflow of water from the food into the concentrated solution, and a simultaneous transfer of solute from the concentrated solution into the food. Osmotic dehydration combined with partial air drying uses less energy than air drying alone (Collignan *et al*., 1992). However, the main unique feature of osmotic pre-freeze treatment is the penetration of solutes into the food material. Under practical conditions, with an osmotic treatment of 1–2 hours at ambient temperature, a solid gain of up to 5–10% can be attained (expressed as grams of dry solids gained per 100g of initial fresh product). This gain corresponds to a 50–100% increase, if referred to an initial soluble solid content of 10%. As a result, it is possible to adapt further the functional properties of the dehydrofrozen fruit, and thereby formulate new fruit products suitable for various industrial uses, by the following:

- adjusting the physico-chemical composition of food by reducing water content, or adding water activity lowering agents;
- incorporating ingredients or additives with antioxidant, or other preservative properties (herbs, spices, sugars, ascorbic acid, sulphur dioxide, etc.) into the food prior to freezing;
- adding solutes of nutritional or organoleptical interest;
- providing a larger range of food consistency.

The consistency increases significantly with de-watering. An Instron standard Shear-Press value of 220–40kg, corresponding to a_w in the order of 0.80–0.75, may be acceptable for some ingredients, where the fruit is generally present as a thin layer (as in wafers and cookies). However, a softer consistency is generally required and this can be obtained if an osmotic step is introduced *before* air dehydration.

Owing to the soluble solid intake, the overall effect of osmosis is a decrease in water activity, with only a limited increase in consistency. Consistency is actually associated with the plasticising and swelling effect of water on the pectic and cellulosic matrix of the fruit tissues. Hence, it depends primarily on the insoluble matter and water content, rather than on the soluble solids and water activity. In this way, low water activities may be achieved while maintaining an acceptable consistency. Some of the solute may not migrate into the cells, but simply penetrate the intercellular spaces. This is because of the wide variation in permeability and selectivity of the tissue structures, which is dependent upon maturity, storage conditions and heat and chemical pre-treatments of the raw materials.

A general representation of the extent to which physical changes can be induced and functional properties can be controlled in practical processing for a given fruit species can be obtained by developing a 'functional compatibility map' (Maltini *et al.*, 1993). This illustrates that functional properties gained by using single or combined steps are related to the water activity, which is the main parameter making the ingredients compatible with the food.

The example in Fig. 4.3 shows the relationship between the phase composition (i.e. the relative amount of insoluble solids, soluble solids and water), the consistency index and the water activity of apricot cubes after processing. The two sets of data, referring to partial dehydration of raw fruit and partial dehydration of osmotically treated fruit, are presented in the same figure and give a pair of curves for phase composition and for texture. A single curve is obtained for water activity.

The difference between the upper and lower curve for phase composition and texture, at equal water activity, is the result of the solid gain after osmotic treatment (for 45 minutes at 25ºC): intermediate values could be obtained if shorter osmosis times were used. For each water activity the diagram gives the following:

- The range of phase compositions that give that water activity.
- The range of consistencies corresponding to that phase composition and water activity.
- The freezing temperature, as related to the water activity (Fennema, 1981).
- The freezable fraction of water at any temperature, or the differential fraction of freezable water between two temperatures, which can be calculated with reference to the corresponding phase composition and freezing points. Information on the equilibrium freezing properties is useful for the formulation of fruit components for use in ice cream, sherbet and frozen desserts. Choices are possible between fruit ingredients that do not form ice (at a determined sub-zero temperature), i.e. with an a_w lower, or equal to, the equilibrium a_w at that temperature, and fruit with water activities higher than the equilibrium one, in which a definite amount of ice will separate according to freezing behaviour.
- The potential amount of water that can be absorbed by fruit pieces with water activities lower than that of the food system, assuming a determined rehydration ratio.
- The mass of processed fruit obtained from a unit mass of raw material.

Compared to simple air dehydration, the combination of osmosis and air drying can produce a softer product that is more pleasant to eat as a snack item, or to incorporate into pastries, ice cream, cheese, etc. Further, partial concentration through the combined processes may increase the resistance of fruit texture and colour to heat treatments that are unavoidable.

The choice of solutes used in the soaking solution depends mainly on taste, cost and a_w lowering capacity. Sucrose, corn starch syrup at various fructose/glucose ratios, concentrated fruit juices and other mono- and disaccharides have been used as osmotic solutions. Also, mixtures of sugar and salts have been used for fruit and vegetables, for instance, carrot (Flink, 1975; Lenart and Lewicki,

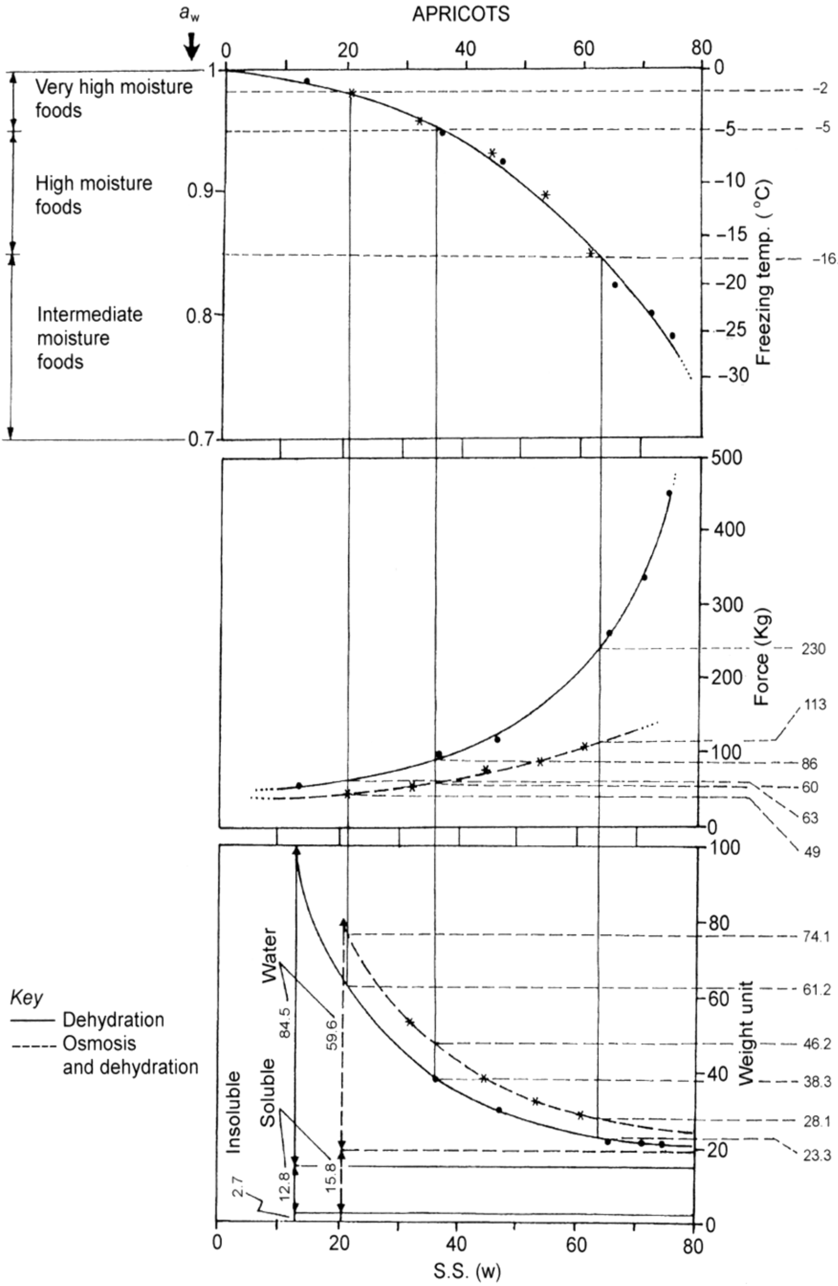

Fig. 4.3 Water activity (a_w), freezing temperature, consistency (force) and phase composition (weight units) of 10mm apricot cubes, as related to percentage soluble solids in the water phase [SS (w)]. (Source: Maltini *et al.*, 1993.)

1987; Mastrocola *et al*., 1987), potato (Islam and Flink, 1982; Lenart and Flink, 1984), cauliflower (Jackson and Mohamed, 1971; Jayaraman *et al*., 1990), apple (Lerici *et al*., 1985) and seaweed (Raoult-Wack and Collignan, 1993). The main interest in a ternary salt/sugar mixture is due to the fact that the presence of sucrose makes it possible to reduce salt impregnation dramatically, as compared to soaking in binary salt mixtures (Raoult-Wack and Collignan, 1993). This is particularly relevant to the pre-treatment of vegetables destined for cooked dishes or soups, where high sugar impregnation levels are incompatible.

Sucrose and its mixture with high glucose syrups may result in excessive sweetness and high viscosity. High fructose syrups exhibit lower sweetness and viscosity, which make the solid–liquid exchanges easier, with an increase in solid gain. Fruit juice concentrates have similar osmotic properties to high fructose syrups (Maltini *et al*., 1990b), and the resulting products are of total fruit origin, with relevant merceological aspects. Concentrated clear apple juice may be regarded as the most available and suitable natural osmotic solution for the treatment of different fruit species. If a concentrated fruit juice is used as osmotic solution, an even softer product is obtained because of the higher content of monosaccharides in the fruit juice, compared to the amount contained in syrups from starch hydrolysis, and because of the higher relative water content at a determined a_w. If a fructose syrup contains sorbitol, softer osmodehydrated apricot, clingstone peach cubes and sweet cherry halves can be obtained, when compared with the same fruit osmodehydrated in fructose alone (Erba *et al*., 1994; Torreggiani *et al*., 1997). This process has also been applied to vegetables. Red pepper cubes have been osmodehydrated in a new type of osmotic solution: hydrolysed lactose syrup (HLS) which is extracted from cheese whey permeate (Torreggiani *et al*., 1994). Figure 4.4 shows the influence of an osmotic dehydration pre-treatment on the consistency of apple and red pepper cubes prior to freezing. The presence of sorbitol leads to a lower consistency in osmodehydrated cubes. Moreover, sorbitol has a specific protective effect on colour during the air drying step.

In recent years, among the effects of solute uptake, the kinetic hindering of diffusion controlled reactions and molecular mobility has also been considered. According to the kinetic interpretation based on the glass transition concept, chemical and physical stability is related to the molecular mobility of the unfrozen phase, which in turn is related to the glass transition temperature. Therefore, it has been hypothesised that the choice of osmotic solution could also be made on the basis of its ability to increase the glass transition temperature of the system, thus improving stability (Levine and Slade, 1988; Slade and Levine, 1991). However, the relationship between glass transition temperature and chemical reactions in frozen foods still has to be fully investigated, and has been the subject of much discussion.

The incorporation of different sugars into kiwi fruit slices modified their low temperature phase transitions, and significantly influenced chlorophyll stability during storage at −10ºC (see Fig. 4.5) (Torreggiani *et al*., 1993). The chlorophyll contained in kiwi fruit osmodehydrated in maltose, and thus having the highest

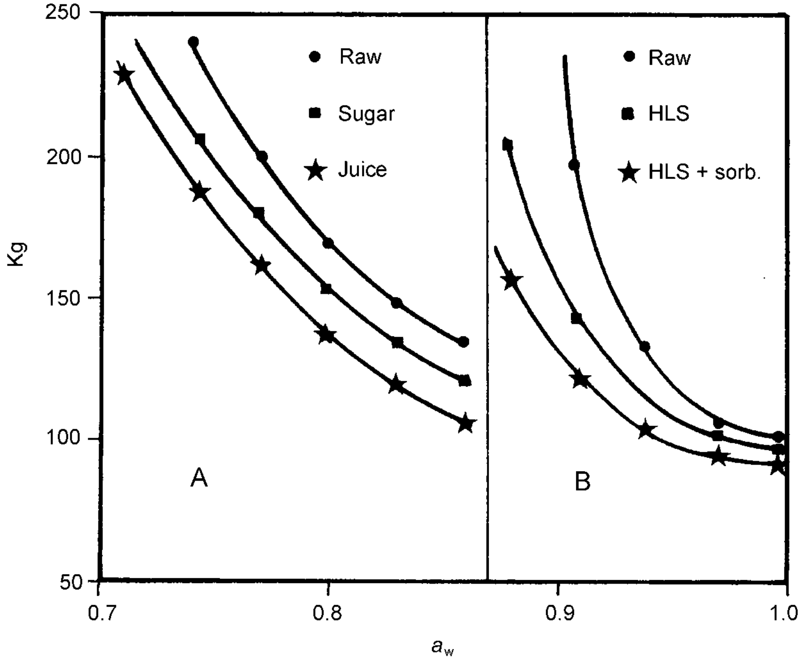

Fig. 4.4 Consistency index (kg) of: (A) apple cubes dried without osmotic dehydration (raw), after osmotic dehydration in syrup from starch hydrolysis (sugar) and in concentrated apple juice (juice); (B) red pepper cubes dried without osmotic dehydration (raw), after osmotic dehydration in HLS (HLS) and in HLS + sorbitol (HLS + sorb.). (Source: Torreggiani *et al.*, 1988 and 1994.)

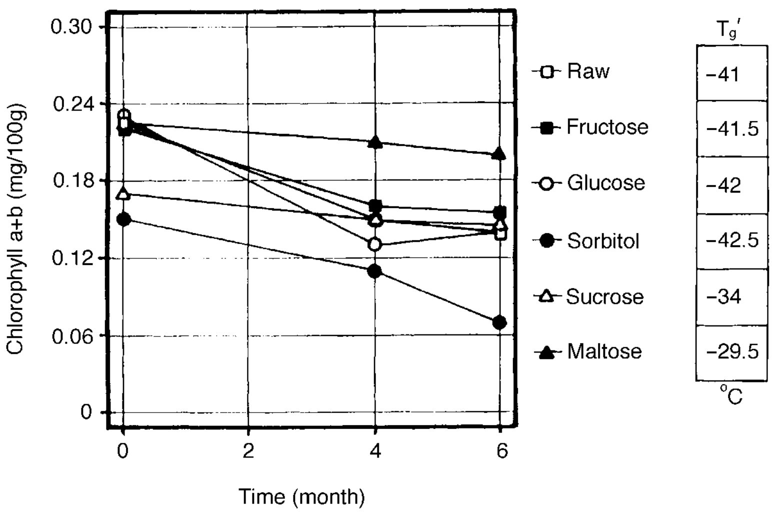

Fig. 4.5 Total chlorophyll contents of raw and osmodehydrated kiwi fruit during storage at −10ºC. and Tg′ values before and after osmotic dehydration. (Source: Torreggiani *et al.*, 1993.)

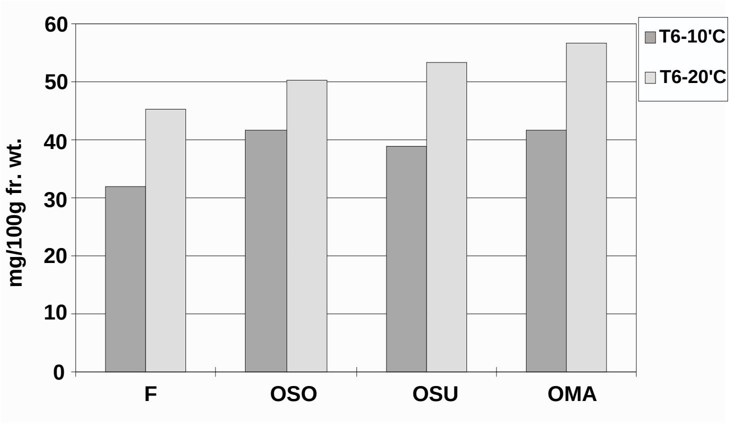

Fig. 4.6 Anthocyanin content of fresh (F) and osmodehydrated cultivar Chandler strawberry halves (OSO, in sorbitol; OSU, in sucrose; OMA, in maltose), after six months of frozen storage (unfrozen strawberry content = 75.18 mg/100g fr.wt.). (Source: Forni *et al.*, 1998.)

Tg′ values, showed the highest stability. This was confirmed by studying both colour and vitamin C retention in osmodehydrofrozen apricot cubes (Forni *et al.*, 1997) and anthocyanin stability in osmodehydrofrozen strawberry halves (Forni *et al.*, 1998) (see Fig. 4.6). While for some sugars (e.g. maltose) the kinetic interpretation holds, the protective effect of sorbitol observed both in osmodehydrated strawberry halves and apricot cubes could not be explained through the 'glass transition' concept. Further research is required to define all the different factors influencing pigment degradation, such as pH, viscosity, water content and specific properties of this sugar-alcohol. Greater knowledge about the physico-chemical parameters that affect reaction kinetics above Tg′ are being seen as the key to understanding and utilising product formulation.

4.3.3 Immersion chilling and freezing in concentrated aqueous solutions

The third technique, immersion chilling and freezing (ICF), is quite similar to osmotic dehydration in that both involve direct contact between food pieces and a concentrated solution. However, ICF is carried out at lower temperatures ranging from −20ºC to 0ºC whereas operating temperatures range from 30ºC–80ºC in the case of osmotic dehydration. The characteristics of the dissolved solutes added to the solution (number, concentration and molecular mass) determine the extent in temperature to which the solution remains in the liquid state. Binary solutions comprising 23% sodium chloride or 40% ethanol allow operating temperatures as low as −20ºC and −30ºC respectively.

Because of low operating temperatures, and the freezing process occurring inside food during ICF, mass transfer rates are much lower than in osmotic dehydration, ranging from 1 to 7% w/w water loss, and 0.5 to 1% w/w solute gain. Hence, ICF should be considered as a quick pre-cooling stage, associated with a surface formulation effect. Lucas and Raoult-Wack (1998) have recently reviewed the ICF process. It offers numerous advantages that make it an interesting alternative to conventional freezing techniques such as air-blast freezing: rapid heat transfer, individualised freezing, and lower operating and investment costs. Freezing time of small fruits and vegetables (from 0ºC to −7ºC) can be reduced by a factor of 4 to 7 when using ICF instead of air-blast freezing. Consequently better product quality can be achieved through ICF, as quick freezing preserves the texture of fruit and vegetable tissues more successfully (at least for products to be quickly commercialised) and causes less dehydration during the freezing process.

Up to now, the influence of solute gain or water loss on the quality of the ICF product, compared with a conventional (non-impregnated) chilled or frozen food, has been investigated very little. Nevertheless, as achieved using osmotic dehydration, solute impregnation (sugars, vitamins, etc.) during ICF could improve food flavour and its nutritional or colour qualities, and also reduce freezing and storage damage. Coating the frozen product with the remaining ICF solution can also help to improve the food colour, mainly by increasing food brightness; to slow food deterioration during cold storage by creating a protective barrier to oxidation and water losses; or to develop new technological features in food, e.g. reducing the stickiness of the food surfaces.

In spite of its numerous potentialities, the ICF process has been developed little on an industrial scale, mainly because of an inadequate control of mass transfer (water and solutes) between the product and the refrigerating solution. Industrial applications remain centred on sodium chloride solutions used on products prone to uncontrolled salt uptake, such as fish or seafood, often destined for further processing (e.g. cannery). However, the process can be used with a wide range of fruit and vegetable products, as illustrated in Table 4.2, which lists various products and processing conditions tested on a laboratory scale.

Most recent scientific advances have brought better understanding of the underlying mechanisms, together with key parameters for the control of simultaneous mass transfer, heat transfer and phase change. It has been shown that solute impregnation coupled with heat transfer can be divided into three stages as described below, and illustrated in Fig. 4.7. The first stage is characterised by high mass transfer rates, as long as the food product has not begun to freeze. A recent theoretical work showed that in product surface layers, diffusion phenomena can be quick enough to depress the water freezing point and impede the freezing of some of the impregnated area (Lucas *et al.*, 1998c). This means that freezing does not initiate on the food surface, but somewhere inside the material. The thickness of the unfrozen impregnated surface layer was estimated to be less than one millimetre, which explains why it is often not visible to the naked eye. During this very short stage of ICF, surface treatments are particularly efficient for controlling the extent of mass transfer. Table 4.3

Table 4.2 Immersion chilling and freezing applied to fruit and vegetable products: materials and processing conditions tested at the laboratory scale

Processed foodstuffs	Solute(s)	Concentration	Temperature (ºC)	Reference
Diced carrot	NaCl	23%m.	−18	Robertson *et al.* (1976)
	Ethanol/NaCl	15/15%?	−21.5	Cipolletti *et al.* (1977)
				Biswal and Le Maguer (1989)
Peppers, tomatoes, squash	NaCl	*	[−16; −14]	Fikiin (1994)
		*	−20	Gol'berg (1978)
Beans, peas, corn	NaCl	23%m.	−18	Robertson *et al.* (1976)
		22%m.	−20.5	Taylor (1939)
		*	[−16; −14]	Fikiin (1994)
	Ethanol/NaCl	15/15%?	−21.5	Cipolletti *et al.* (1977)
				Biswal and Le Maguer (1989)
			−18	Elias (1978)
	Sucrose/levulose	*	[−17; −4]	Noyes (1942)
French fries	Ethanol/NaCl	15/15%?	−18	Elias (1978)
Apple cylinders		[5.5; 10.5%m.]	[−10; −2]	Sterling (1968)
		[5; 23%m.]	[−18; +2]	Lucas *et al.* (1998b)
	$MgSO_4$	10.8%m.	[−10; −2]	Sterling (1968)
	Sucrose	[5; 20%?]	[−17; −2]	Sterling (1968)
	Glycerol	[5; 20%?]	[−78; −5]	Sterling (1968)
	Ethanol	[5; 20%?]	[−78; −5]	Sterling (1968)
	Ethylene glycol	[5; 20%?]	−17	Sterling (1968)
	Sorbitol			
	Corn syrup			
	PVP, DMSO			
Berries	Sucrose/levulose	*	[−17; −4]	Noyes (1942)
	Sucrose/invert sugar	*	*	Bartlett (1947)
	Invert sugars	57%m.	−15	Taylor (1939)
Packed orange juice, hacked spinach, carrot, mashed potatoes	$CaCl_2$	29.8%m.	[−40; −15]	Cornier and Groussiaut-Monboisset (1983)
Packed sugar beet samples	Ethanol	*	−40	Biancardi *et al*. (1995)

Notes: *: data not provided.
Empty cell: as for the cell above in the same column.
%?: proportion type not known, probably corresponds to a mass or volumetric concentration where a solid or liquid respectively is dissolved in water.
[a; b]: between a and b.
DMSO: dimethyl sulfoxide.
PVP: polyvinyl pyrollidone.
Source: adapted from Lucas and Raoult-Wack, 1998.

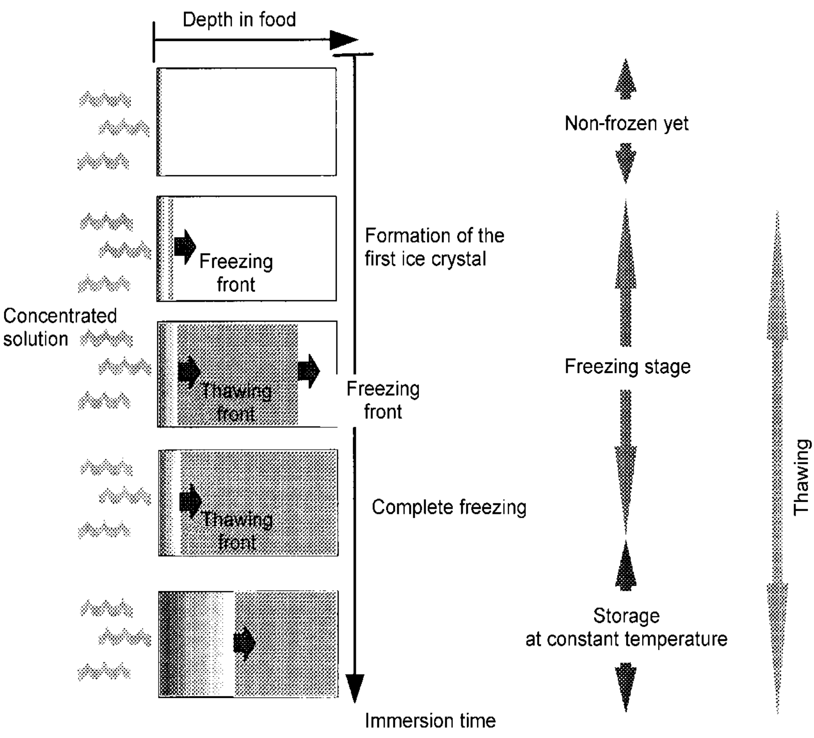

Fig. 4.7 Diagram of simultaneous mass transport and heat transport (including phase change) inside food frozen by immersion in high concentration aqueous solutions.

shows the effect on salt gains and water losses of surface (pre-)treatments of apple cylinders (initial temperature 5ºC, radius 1cm, height 3cm) immersed in an agitated 21% NaCl solution at −17.8ºC (data adapted from Lucas *et al.*, 1998b).

Salt gain was reduced by at least 30% after one-hour processing when 2 moles of sucrose per kg of solvent were added to the binary NaCl solution, with all other parameters remaining constant. The addition of high molecular mass solutes (especially sucrose) to sodium chloride solutions has been widely used to achieve the same effects, with the osmotic dehydration process at higher temperatures (> 10ºC), and has also been scientifically investigated. The effect of sucrose in reducing salt gain has mainly been associated with the formation of a concentrated sucrose layer on the food surface, resulting in a physical barrier to further salt impregnation.

Pre-soaking apple cylinders in distilled water at 0ºC produced a reduction of at least 40% in salt gain. It can no doubt be attributed to the formation of a film of frozen soaking water all around the food surface, which in turn creates a barrier to further mass transfer into food. Mass transfer is reinforced in sliced or diced products (Cipolletti *et al.*, 1977), therefore one would expect even lower solute impregnation and water losses for a smaller-sized product than the

Table 4.3 Effect on salt gains (a) and water losses (b) of surface (pre-)treatments of apple cylinders (initial temperature 5ºC, radius 1cm, height 3cm) immersed in an agitated 21% NaCl solution at −17.8ºC. Thermal equilibrium between apple and solution is reached just before 15-minute immersion.

(a)

Experimental conditions	After 15 mins		After 60 mins	
	SG	$\pm\sigma$	SG	$\pm\sigma$
Coating with water at 0ºC	0.27	0.03	0.29	0.07
Adding 2mol of sucrose per kg of solvent to the immersion solution (then monophasic)	0.28	0.03	0.41	0.08
No coating (reference treatment)	0.47	0.08	0.57	0.08

Notes: SG: mean salt gain of three experimental runs, in kg per kg of initial material; σ: corresponding standard deviation.

(b)

Experimental conditions	After 15 mins		After 60 mins	
	WL	$\pm\sigma$	WL	$\pm\sigma$
Coating with water at 0ºC	−0.77	0.31	0.80	0.27
Adding 2mol of sucrose per kg of solvent to the immersion solution (then monophasic)	3.10	0.47	4.04	0.51
No coating (reference treatment)	1.20	0.27	1.38	1.55

Notes: WL: mean water loss of three experimental runs, in kg per kg of initial material; σ: corresponding standard deviation.
Source: data adapted from Lucas *et al*., 1998b.

example given in this paragraph, or with a protective epiderm (e.g. strawberry, bean, etc.).

In the second stage, the formation of a continuous freezing front beneath the food surface slows down solute impregnation (Lucas and Raoult-Wack, 1996). Conversely, retarding freezing favours solute gain. Based on the reference treatment in Table 4.3, increasing the solution temperature by just 1ºC doubled the salt gain. Generally, control of the relative rapidity of heat transfer and mass transfer during ICF, and thus the extent of the impregnated surface layer, can be achieved by means of two adimensional numbers, and the initial and boundary conditions in concentration and temperature (Lucas *et al*., 1998c).

In the third stage, after the freezing front has been formed, solute penetration persists, as shown in Fig. 4.8. It presents the evolution of the flux density of NaCl at the food/solution interface, and of the surface and core temperatures of apple cylinders (initial temperature 5ºC, radius 1cm, height 3cm) immersed in an

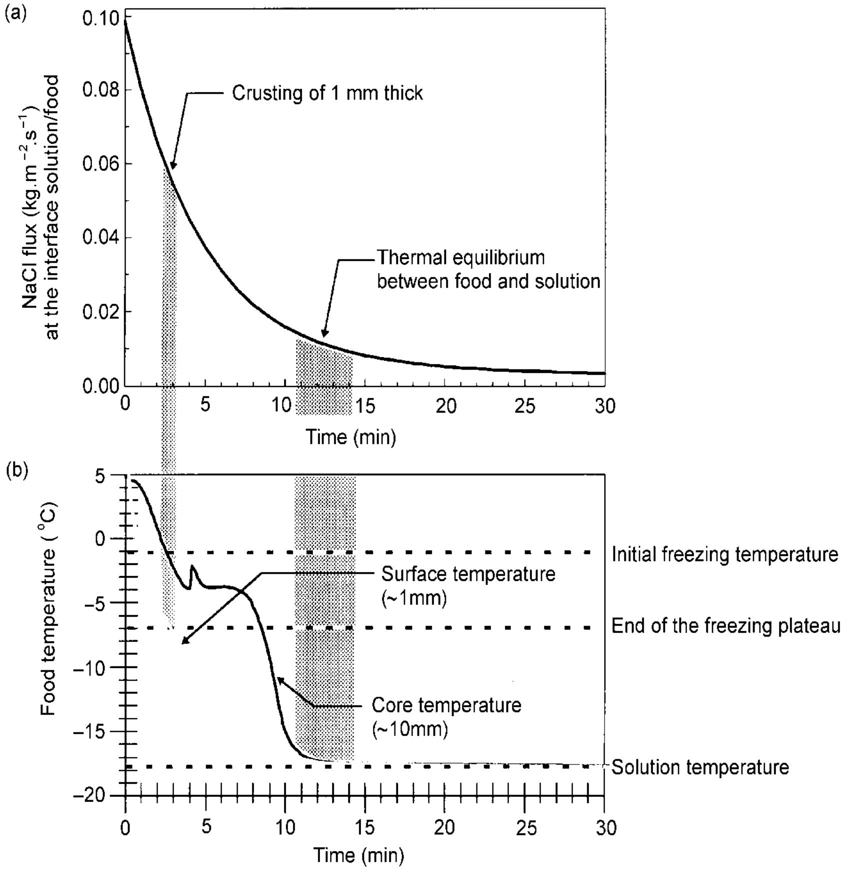

Fig. 4.8 Evolution of the flux density of NaCl at the food/solution interface (a) and of surface and core temperatures (b) of apple cylinders (initial temperature 5°C, radius 1cm, height 3cm) immersed in an agitated 21% NaCl solution at −17.8°C. (Source: data adapted from Lucas *et al.*, 1998b.)

agitated 21% NaCl solution at −17.8°C (data adapted from Lucas *et al.*, 1998b). The freezing front is considered to be 1mm beneath the surface after 1–2 minute treatment, i.e. when the temperature at this point drops below −7°C, marking the end of the freezing plateau (Fig. 4.8b). When reported in Fig. 4.8a, the freezing front formation was insufficient to stop solute penetration fully: solute impregnation persists, and its rate slows down only once thermal equilibrium is reached between food and solution (i.e. for immersion times over 15 minutes).

Hence, the applications of ICF are twofold. It can be considered a quick pre-cooling stage associated with a slight surface formulation effect. In this case, food items should be removed from the solution as soon as their surface has been frozen by a few millimetres; complete freezing is then achieved by an air-blast technique. However, it is also possible to further formulate or dehydrate food items by keeping them soaked in solutions. This impregnation stage is closely linked to the thawing of the food surface, which in turn increases the thickness of the non-frozen food surface layer to be formulated. The extent and rapidity of these coupled impregnation/thawing phenomena can be controlled through a restricted number of process variables (Lucas *et al.*, 1998a). Notably, for small-sized products (less than 1cm thick), thawing phenomenon is not perceptible because of the short time scale involved, and its impregnation remains low. For this kind of product, formulation effects remain on the surface, while complete freezing can be achieved by immersion.

4.4 Future trends

Producing fruit and vegetables that could better meet consumer demand, and be less susceptible to temperature abuses occurring throughout the cold chain, is one of the frozen food sector challenges for the decade to come. Conventional pre-freeze treatments (such as blanching and soaking techniques), which combine formulation together with dehydration and/or quick pre-cooling, can be a means of meeting this challenge.

The elaboration of new formulated products in the industry is very much dependent upon the extent of formulation/dehydration. The first technical challenge is to be able to control mass exchange (water out, solute in) during the soaking operation. Recent research advances in osmotic dehydration, and more recently in immersion chilling and freezing, have developed practical tools to help. The second challenge is to be able to control the influence of solute impregnation on food quality and functionality (stability during cold storage, thawing behaviour, suitability for further processing as food ingredients). So far, recent research advances have mainly involved an osmotic pre-step of fruits prior to freezing. Complementary studies should be carried out for vegetables, if the industrial demand for vegetable-based novel food and cooked dishes is confirmed. Moreover, pre-cooling and surface formulation through ICF should be further assessed, in terms of quality and stability of the food item. Furthermore, recent studies of the glass transition temperatures in impregnated frozen food showed the need for further understanding of the influence of solute presence on molecular diffusion, biochemical or chemical reactions, physical state, crystallisation of ice and surface properties in frozen food systems.

4.5 Summary

Fruit and vegetables are very sensitive to freezing damage. The implementation of pre-freeze treatments makes it possible to improve their suitability for freezing and cold storage. The treatments include conventional techniques (washing, blanching, chemical and presentational treatments) and non-conventional soaking techniques which aim to modify the food material composition prior to freezing, through partial dehydration and direct formulation (partial air drying, osmotic dehydration, immersion chilling and freezing).

Blanching is a surface heat pre-treatment commonly used for most vegetables, which are to be frozen and ultimately cooked before use. The aim of blanching is to inactivate enzymes responsible for food deterioration, and can be achieved by immersion or steaming. Steam blanching has the advantage of being much shorter, and minimises lixiviation (thus reducing organic pollution).

So far, non-conventional techniques have been developed primarily for fruits. Partial dehydration is generally achieved by air drying, and the resulting overall process has been commonly termed dehydrofreezing. Claimed advantages of dehydrofreezing (over freezing alone) include energy savings and improvement of quality (storage and thawing behaviour). However, the colour of the food may be affected by heat during the pre-freeze air drying. In such cases, air drying can be replaced by osmotic dehydration, which involves soaking foods in concentrated aqueous solutions prior to freezing. During soaking, the food undergoes simultaneous partial dehydration and direct formulation (solute penetration from the solution into the food). As compared to air drying, osmotic dehydration presents many advantages (processing away from oxygen, lower temperatures, shorter duration, etc.) and the direct formulation effect with solutes of nutritional and functional properties.

The effect of formulation upon food quality and stability during freezing and cold storage has been studied extensively. Depending on the solutes used in the concentrated solutions, and on the extent of formulation (dehydration and impregnation levels), it has been shown that osmotic dehydration can lead to softer texture, improved pigment stability during storage and higher vitamin content, as compared to freezing alone or dehydrofreezing. The effect of formulation has been tentatively related to the 'glass transition' concept. Indeed, it has been shown that the incorporation of different sugars in fruits modified their glass transition temperatures, and significantly improved pigment stability during cold storage. However, the relationship between glass transition temperature and chemical reactions in frozen food still has to be fully investigated, and has been the subject of much discussion.

The third technique, ICF, is quite similar to osmotic dehydration, in that both involve direct contact between food pieces and a concentrated solution. However, ICF is carried out at lower temperatures ranging from −20ºC to 0ºC whereas operating temperatures range from 30ºC–80ºC in the case of osmotic dehydration). Because of low operating temperatures and the freezing process occurring inside food during ICF, mass transfer rates are much lower than in osmotic dehydration. As a result, ICF should be considered as a quick pre-cooling stage, associated with a light surface formulation effect.

Up to now, the influence of solute gain or water loss on the quality of the ICF product compared with a conventional (non-impregnated) chilled or frozen food has been investigated very little. Nevertheless, as achieved using de-watering and impregnation soaking, solute impregnation (sugars, vitamins, etc.) during ICF could also improve food flavour and nutritional or colour quality, and reduce freezing and storage damage. Coating the frozen product with the remaining ICF solution can also help improve the food colour (mainly by increasing food brightness); to slow food deterioration during cold storage (creating a protective barrier to oxidation and water losses); or to develop new technological features in food (e.g. reducing the stickiness of the frozen food surfaces).

So far, the ICF process has been developed little on an industrial scale, mainly because of an inadequate control of mass transfer (water and solutes) between the product and the refrigerating solution. However, it has been shown that the process could be used with a wide range of fruit and vegetable products. As a whole, non-conventional techniques involving partial dehydration and formulation of the food item open up the way to new product development, to meet consumer demand for a wider range of frozen food.

4.6 References

BARTLETT, L.H. 'Quick freezing of foodstuffs', *US Patent 2,418,745 Apr. 8.*, 1947.

BIANCARDI, E., COLOMBO, M. and OLIMPIERI, R. 'A rapid freezing system for technological analysis of sugar beet samples', *Zuckerind*, 1995, **1**, 59–61.

BISWAL, R.N. and LE MAGUER, M. 'Mass transfer in plant materials in contact with aqueous solutions of ethanol and sodium chloride: equilibrium data', *J. Food Process Eng.*, 1989, **11**(3), 159–76.

CIPOLLETTI, J.C., ROBERTSON, G.H. and FARKAS, D.F. 'Freezing of vegetables by direct contact with aqueous solutions of ethanol and sodium chloride', *J. Food Sci.*, 1977, **42**(4), 911–16.

COLLIGNAN, A., RAOULT-WACK, A.L. and THEMELIN, A. 'Energy study of food processing by osmotic dehydration and air-drying', *Agricultural Engineering Journal*, 1992, **1**(3), 125–35.

CORNIER, G. and GROUSSIAUT-MONBOISSET, H. 'Etude de la congélation des produits alimentaires liquides, pateux, solides fractionnés par un système à immersion en saumure', *Proceedings of the XVIth Int. Congr. Refrig., Paris,* 1983, **4**, 137–44.

ELIAS, S. 'Direct immersion freezing . . . (cold) wave of the future?', *Food Engineering Int'l*, 1978, **12**, 44–5.

ERBA, M.L., FORNI, E., COLONNELLO, A. and GIANGIACOMO, R. 'Influence of sugar composition and air dehydration levels on the chemical-physical characteristics of osmodehydrofrozen fruit', *Food Chem.*, 1994, **50**, 69–73.

FAIR. 'Improvement of overall food quality by application of osmotic treatments in conventional and new processes', Concerted action FAIR-CT96-1118 of the 4th Framework Program of the European Union, 1998. http://www.dainet.de

FENNEMA, O. 'Water activity at subfreezing temperatures', in *Water Activity: Influence on Food Quality*, ed. L. B. Rockland and G. F. Steward, London, Academic Press, 1981, pp. 713–32.

FIKIIN, A. G. ‘Quick freezing of vegetables by hydrofluidization’, *IIR Proceedings Series ‘Refrigeration Science and Technology’*, Istanbul, 1994, **3**, 85–90.

FLINK, J. M. ‘Process conditions for improved flavour quality of freeze-dried foods’, *J. Agr. Food Chem.*, 1975, **23**, 1019–26.

FORNI, E., GENNA, A. and TORREGGIANI, D. ‘Modificazione della temperatura di transizione vetrosa mediante disidratazione osmotica e stabilità al congelamento del colore delle fragole’, Proceeding 3rd CISETA (Congresso Italiano di Scienza e Tecnologia degli Alimenti), *Ricerche e innovazioni nell’industria alimentare*, ed. S. Porretta, 1998, Pinerolo, Chiriotti Editori.

FORNI, E., SORMANI, A., SCALISE, S. and TORREGGIANI, D. ‘The influence of sugar composition on the colour stability of osmodehydrofrozen intermediate moisture apricots’, *Food Res. Int.*, 1997, **30**, 87–94.

GIANGIACOMO, R., TORREGGIANI, D., ERBA, M. L. and MESSINA, G. ‘Use of osmodehydrofrozen fruit cubes in yoghurt’, *Italian J. Food Sci.*, 1994, **3**, 345–50.

GOL’BERG, L. D. ‘Continuous freezing of products of vegetable origin in brine’, *Kholodil’naya Tekhnika*, 1978, **4**, 42–5.

HUXSOLL, C. C. ‘Reducing the refrigeration load by partial concentration of food prior to freezing’, *Food Technol.*, 1982, **5**, 98–102.

ISLAM, M. N. and FLINK, J. N. ‘Dehydration of potato. II. Osmotic concentration and its effect on air drying behaviour’, *J. Food Technol.*, 1982, **17**, 387–403.

JACKSON, T. H. and MOHAMED, B. B. ‘The shambat process: new development arising from the osmotic dehydration of fruits and vegetables’, *Sudan J. Food Sci. Technol.*, 1971, **3**, 18–22.

JAYARAMAN, K. S., GUPTA, D. K. D. and RAO, N. B. ‘Effect of pre-treatment with salt and sucrose on the quality and stability of dehydrated cauliflower’, *Int. J. Food Sci. Technol.*, 1990, **25**, 47–60.

LAZAR, M. E. ‘Dehydrofreezing of fruits and vegetables’, in *The Freezing Preservation of Foods*, ed. D. K. Tressler, W. B. V. Arsdel and M. J. Copley, Westport CT, The AVI Publishing Company, 1968.

LENART, A. and FLINK, J. M. ‘Osmotic concentration of potato: criteria for the end point of the osmotic process’, *J. Food Technol.*, 1984, **19**, 45–63.

LENART, A. and LEWICKI, P. ‘Kinetics of osmotic dehydration of plant tissue’, in *Drying 87*, ed. A. S. Mujumdar, New York, Hemisphere, 1987, 239–48.

LEVINE, H. and SLADE, L. ‘Principles of “cryostabilization” technology from structure/property relationships of carbohydrate/water systems: a review’, *Cryoletters*, 1988, **9**, 21–63.

LE MAGUER, M. ‘Osmotic dehydration: review and future directions’, *Symposium on Progress in Food Reservation Processes*, Brussels, 1988, **1**, 283–309.

LERICI, C. R., PINNAVAIA, G., ROSA, M. D. and BARTOLUCCI, L. ‘Osmotic dehydration of fruits: influence of osmotic agents on drying behaviour and product quality’, *J. Food Sci.*, 1985, **50**, 1217–26.

LUCAS, T., CHOUROT, J. M., RAOULT-WACK, A. L. and FLICK, D. ‘Modelling and control of thawing phenomena in impregnated frozen food products’, to be submitted to *Intnl J. Food Eng.*, 1998a.

LUCAS, T., FRANÇOIS, F. and RAOULT-WACK, A. L. ‘Transport phenomena in immersion-cooled apples', forthcoming, to be published in *Intnl J. Food Sci. and Tech.*, 1998b.

LUCAS, T. and RAOULT-WACK, A. L. 'Immersion chilling and freezing in aqueous concentrated solutions: heat and mass transfer on model food', *J. Food Sci.*, 1996, **61**(1), 127–31.

LUCAS, T. and RAOULT-WACK, A. L. 'Immersion chilling and freezing in aqueous refrigerating media: review and future directions', *Intnl J. Refrig.*, 1998, **21**(6), 419–29.

LUCAS, T., RAOULT-WACK, A. L. and FLICK, D. 'Mass and thermal behaviour food surface during immersion freezing', to be submitted to *Intnl J. Food Eng.*, 1998c.

MALLETT, C. P. editorial introduction in *Frozen Food Technology*, ed. C. P. Mallett, 1994, London, Blackie Academic & Professional, pp. 19–25.

MALTINI, E., TORREGGIANI, D. and CAVECCHIA, T. 'Fluidised bed drying for partial dehydration of foods in multiple-stage processes', presented at 10th International Congress CHISA'90, Praha, 1990a, n. 1724.

MALTINI, E., TORREGGIANI, D., FORNI, E. and LATTUADA, R. 'Osmotic properties of fruit juice concentrates', in *Engineering and Food: Physical Properties and Process Control*, ed. W. L. E. Spiess and H. Schubert, London, Elsevier Science, 1990b, pp. 567–73.

MALTINI, E., TORREGGIANI, D., RONDO BROVETTO, B. and BERTOLO, G. 'Functional properties of reduced moisture fruits as ingredients in food systems', *Food Res. Int.*, 1993, **26**, 413–19.

MASTROCOLA, D., SEVERINI, C. and LERICI, C. R. 'Disidratazione per via osmotica della carota', *Industrie Alimentari*, 1987, **26**(2), 133–8.

NOYES, H. A. 'Freezing process', *US patent 2,286,225 June 16*, 1942.

RAOULT-WACK, A. L. 'Recent advances in the osmotic dehydration of foods', *Trends in Food Sci. and Tech.*, 1994, **5**(8), 255–60.

RAOULT-WACK, A. L. and COLLIGNAN, A. 'Dewatering through immersion in concentrated solutions: an interesting alternative for seafood stabilisation', Sixth International Congress on Engineering and Food (ICEF), Chiba, Japan, in *Developments in Food Engineering*, ed. T. Yano, R. Matsuno, and K. Nakamura, 1993, Part 1: 397–400.

RAOULT-WACK, A. L, GUILBERT, S. and LENART, A. 'Recent advances in drying through immersion in concentrated solutions', in *Drying of Solids*, ed. A. S. Mujumdar, 1992, London, Elsevier Science, 21–51.

ROBERTSON, G. H., CIPOLLETTI, J. C., FARKAS, D. F. and SECOR, G. E. 'Methodology for direct contact freezing of vegetables in aqueous freezing media', *J. Food Sci.*, 1976, **41**, 845–51.

SLADE, L. and LEVINE, H. 'Beyond water activity: recent advances based on an alternative approach to the assessment of food quality and safety', *Crit. Rev. Food Sci. Nutr.*, 1991, **30**, 115–360.

SORMANI, A., MAFFI, D., BERTOLO, G. and TORREGGIANI, D. 'Textural and structural changes of dehydrofreeze–thawed strawberry slices: effects of different dehydration pre-treatments', *Food Sci. and Tech. Int.*, 1999, **5**(6), 479–85.

STERLING, C. 'Effect of low temperature on structure and firmness of apple tissue', *J. Food Sci.*, 1968, **33**, 577–80.

TAYLOR, R. B. 'Freezing foods', *US Patent 2,164,362 July 4*, 1939.

TORREGGIANI, D. 'Osmotic dehydration in fruit and vegetable processing', *Food Res. Int.*, 1993, **26**, 59–68.

TORREGGIANI, D., FORNI, E., ERBA, M. L. and LONGONI, F. 'Functional properties of pepper osmodehydrated in hydrolysed cheese whey permeate with or without sorbitol', *Food Res. Int.*, 1994, **28**(2), 161–6.

TORREGGIANI, D., FORNI, E. and LONGONI, F. 'Chemical-physical characteristics of osmodehydrofrozen sweet cherry halves: influence of the osmodehydration methods and sugar syrup composition', in *1st Int. Cong. Food Ingredients: New Technologies. Fruits & Vegetables*, 1997, Allione Ricerca Agroalimentare S.p.A., pp. 101–9.

TORREGGIANI, D., FORNI, E. and PELLICCIONI, L. 'Modificazione della temperatura di transizione vetrosa mediante disidratazione osmotica e stabilità al congelamento del colore di kiwi', in *Ricerche e innovazioni nell'industria alimentare*, 1st Congresso Italiano di Scienza e Tecnologia degli Alimenti (CISETA 1), ed. S. Porretta, 1993, Pinerolo, Chiriotti Editori, pp. 621–30.

TORREGGIANI, D., MALTINI, E., BERTOLO, G. and MINGARDO, F. 'Frozen intermediate moisture fruits: studies on techniques and products' properties', in *Proc. Int. Symposium 'Progress in Food Preservation Processes'*, 1988, CERIA, Bruxelles, vol. 1, pp. 71–8.

5

The pre-treatment of meat and poultry

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5.1 Introduction

Red meat and poultry are very perishable raw materials. If stored under ambient conditions at 16–30ºC, the shelf-life of both can be measured in tens of hours to a few days. Under the best conditions of chilled storage, close to the initial freezing point of the material, the storage life can be extended to approaching six weeks for some red meat. Even with the best commercial practice (strictly hygienic slaughtering, rapid cooling, vacuum packing and storage at super chill (-1 ± 0.5ºC)), the maximum life achievable in red meat is approximately 20 weeks. Freezing will extend the storage life of meat to a number of years.

The quality of meat is judged by its bacterial condition and appearance. Appearance criteria are primarily colour, percentage of fat and lean, and amount of drip exuding from the meat. After cooking, eating quality is judged partially by its appearance, but mainly by its tenderness, flavour and juiciness. If the frozen storage life is not exceeded, freezing and frozen storage of meat has little (if any) effect on the main quality parameters. Drip is the only exception, as it is substantially increased by freezing.

The quality of meat after thawing (especially its eating quality) is therefore determined before it is frozen. In the past, factors such as poor packaging and poor temperature control could result in freezer burn and rancid off-odours and flavours in frozen meat. Now, unless storage times are exceeded or temperature control abused, the quality of meat after frozen storage will be identical to that before freezing.

In a perfect world, red meat and poultry would be completely free of pathogenic (food poisoning) micro-organisms when produced. However, under normal methods of production pathogen-free meat cannot be guaranteed. For

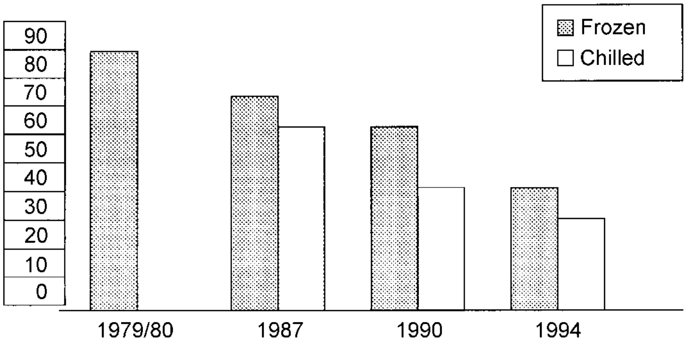

Fig. 5.1 Percentage of chilled and frozen poultry carcasses contaminated with salmonella found in UK surveys carried out in 1979/80–1994.

example, salmonella contamination of chilled and frozen poultry carcasses has been significantly reduced in the United Kingdom (see Fig. 5.1). However, over one-third were still contaminated in 1994.[1] While the internal musculature of a healthy mammal or bird is essentially sterile after slaughter, all meat animals carry large numbers of different micro-organisms on their skin/feathers and in their alimentary tract. Only a few types of bacteria directly affect the safety and quality of the finished carcass. Of particular concern are food-borne pathogens such as *Campylobacter* spp., *Clostridium perfringens, Salmonella* spp., and pathogenic serotypes of *Escherichia coli.*

In general, the presence of small numbers of pathogens is not a problem because meat is normally cooked before consumption. Adequate cooking will substantially reduce the numbers, if not completely eliminate all the pathogenic organisms present on the meat. Most meat-based food poisoning is associated with inadequate cooking or subsequent contamination after cooking. The purpose of refrigeration is to reduce, or prevent, the growth of pathogens so that they do not reach levels that could cause problems. None of the pathogens of concern can grow at temperatures below −1°C.[1]

Normally the growth of spoilage organisms limits the shelf-life of meat. The spoilage bacteria of meats stored in air under chill conditions include species of *Pseudomonas, Brochothrix* and *Acinetobacter/Moraxella.* Varnam and Sutherland state that, in general, there is little difference in the microbial spoilage of beef, lamb, pork and other meat derived from mammals.[2] They also state that micro-organisms do not grow at less than −10°C, and that spoilage considerations will only relate to handling before freezing or during thawing.

The presence of exudate or 'drip', which accumulates in the container of prepackaged meat, or on trays or dishes of unwrapped meat, substantially reduces its sales appeal.[3] Drip can be referred to by a number of different names including 'purge loss', 'press loss' and 'thaw loss', depending on the method and time of measurement. Drip loss occurs throughout the cold chain and represents a considerable economic loss to the red meat industry. Poultry meat is far less prone to drip. The potential for drip loss is inherent in fresh meat and is influenced by many factors. Some of these include breed, diet and physiological history, which are inherent in the live animal. Others, such as the rate of chilling, storage temperatures, freezing and thawing, occur during processing.

Meat colour can be adversely affected by a variety of factors, including post-mortem handling, chilling, storage and packaging.[4] In general, poultry breast meat will have a red/brown appearance if frozen slowly, and a cream/white appearance if frozen quickly. After thawing the difference in colour disappears. Beef, pork and lamb tend to darken during freezing.

In Australia CSIRO stated that 'Toughness is caused by three major factors – advancing age of the animal, ''cold shortening'' (the muscle fibre contraction that can occur during chilling) and unfavourable meat acidity (pH).'[5] There is general agreement on the importance of these factors, with many experts adding cooking as a fourth, equally important, influence.

If we wish to produce frozen red meat and poultry that retain the optimum qualities after thawing, we need to understand the factors that govern the pre-freezing quality.

5.2 Influence of the live animal

Some of the factors that influence the toughness of meat are inherent in the live animal. Church and Wood state that it is the properties of the connective tissue proteins, and not the total amount of collagen in meat, that largely determine whether meat is tough or tender.[4] As the animal grows older, the number of immature reducible cross-links decreases. The mature cross-links result in a toughening of the collagen, and this in turn can produce tough meat. Increasing connective tissue toughness is probably not commercially significant until a beast is about 4 years old.[6]

5.2.1 Between species and breeds

The red meat industry considers the frozen storage life of pork to be less than that of other species. Recommended storage lives from the IIR and those found on domestic deep freezers reflect this view (see Table 5.1).[7] However, when all the available data found in the literature are considered, the picture becomes confusing. Average values for the storage lives show differences between the species (Table 5.1) but with a ranking different to that generally accepted. In all species the range of storage lives found in the literature is very large, and indicates that factors other than species have a pronounced effect on storage life. Overall, species alone has little effect on the practical storage life of meat.

In general, beef tends to lose proportionately more drip than pork or lamb. Unfrozen poultry meat loses little (if any) drip. Since most of the exudate comes from the cut ends of muscle fibres, small pieces of meat drip more than large intact carcasses. In pigs, especially, there are large differences in drip loss from meat from different breeds and between different muscles. Taylor showed that

Table 5.1 Recommended frozen storage life (months) for meat from different species

Source	Deep freeze	IIR	Average	Range
Temperature (ºC)	−18	−18	−18	−18
Species				
Beef	12	18	10.2	2.8–19.4
Pork	8	12	17.4	2.8–23.3
Lamb	12	24	7.8	2.8–24.3
Chicken	10	18	13.6	6.0–23.3

there was a substantial difference, up to 2.5 fold, in drip loss between four different breeds of pig (see Table 5.2). He also showed that there was a 1.7 to 2.8 fold difference in drip between muscle types (see Table 5.3).[8]

Although there is a common belief that breed has a major effect on meat quality, CSIRO state that 'although there are small differences in tenderness due to breed, they are slight and currently of no commercial significance to Australian consumers'.[9] That said, there are substantial differences in the proportion of acceptable tender meat and toughness between *Bos indicus* and *Bos taurus* cattle. The proportion of acceptable tender meat has been found to decrease from 100% in Hereford Angus crosses, to 96% in Tarentaise, 93% in Pinzgauer, 86% in Braham and only 80% in Tsahiwal.[10] Toughness of meat increases as the proportion of *Bos indicus* increases.[11]

Table 5.2 Drip loss after two days' storage at 0ºC, from leg joints from different breeds of pig cooled at different rates

Breed	Drip loss (% by weight)	
	Slow	Quick
Landrace	0.47	0.24
Large White	0.73	0.42
Wessex X Large White	0.97	0.61
Pietrain	1.14	0.62

Table 5.3 Drip loss after two days' storage at 0ºC from four muscles from two breeds of pig cooled at different rates

		Drip (% as muscle weight)				
	Cooling rate	Semi-tendinosus	Semi-membranous	Adductor	Biceps femoris	Combined (four muscles)
Pietrain	Quick	2.82	4.40	5.52	2.69	3.86
	Slow	3.99	6.47	6.61	4.11	5.30
Large White	Quick	1.69	2.01	2.92	1.04	1.92
	Slow	1.95	3.50	5.07	2.32	3.21

5.2.2 Animal-to-animal variation

Animal-to-animal variation is believed to cause wide variations in frozen storage life. Differences can be as great as 50% in lamb,[12,13] and seem to be caused by genetic, seasonal or nutritional variation between animals, although there is little reported work to confirm this view. Variations were found between the fatty acids and ratio of saturated/unsaturated fatty acids in lambs from New Zealand, America and England.[14] Differences related to sex, area and cut were mainly a reflection of fatness, with ewes having a greater percentage of body fat than rams. However, differences between areas were found to produce larger variations between animals than sex differences. A number of other trials have detailed differences between animals.

The gender of the animal appears to have little or no influence on tenderness. Huff and Parrish compared the tenderness of meat from 14-month-old bulls and steers and cows (55 to 108 months old).[15] No differences were found between the tenderness of bulls and steers. Tenderness decreased with the age of the animal. Hawrysh *et al*. reported that beef from bulls may be less tender than that from steers.[16] However, longissimus dorsi shear force values for double-muscled Belgium Blue White bulls were significantly higher than those of the same breed with normal conformation.[17]

Gender can have a substantial influence on flavour. For example, cooking the meat from entire male pigs can produce an obnoxious odour known as 'boar taint'. Problems can also occur with meat from intact males of other species. However, they can still be attractive to industry because of their higher rate of growth and lower fat content.

5.2.3 Feeding

The way in which an animal is fed can influence its quality and frozen storage life. It has been reported that chops from pigs fed on household refuse have half the storage life of those fed on a milk/barley ration.[18,19] Again, pork from pigs that had been fed materials containing offal had half the practical storage life (PSL) and higher iodine numbers in the fat than that of pigs that had not been fed this type of diet.[20] Conversely, Bailey *et al*. did not find any differences between meal- and swill-fed pigs after four and nine months at −20°C.[21] Rations with large amounts of highly unsaturated fatty acids tend to produce more unstable meat and fat.

The fatty acid composition of 'depot fat' in poultry and its stability have been shown to be directly related to the fatty acid composition of ingested fats.[22,23] Feeding fish oils or highly unsaturated vegetable oils (such as linseed oil) to poultry is known to produce fishy flavours in the meat.[22,24]

The use of vitamin E supplements is recommended for both beef and turkey. This would 'result in delayed onset of discoloration in fresh, ground and frozen beef, and in suppression of lipid rancidity, especially in fresh, ground and frozen beef and less so in cooked beef'.[25] With turkey, vitamin E supplements have been shown to improve oxidative stability of cooked and uncooked turkey burgers during six months' frozen storage at −20°C.[26]

5.2.4 Variations within an animal

Reports of variations in the storage life of different cuts of meat are scarce, and primarily deal with dark and light meat. Both Ristic[27] and Keskinel *et al*.[28] have found that poultry breast meat stores better than thigh meat. Ristic states that breast meat will store for 16 months, while thigh meat can only be stored for 12 months due to its higher fat content. Judge and Aberle also found that light pork meat stored for a longer time than dark meat.[29] This was thought to be due to either higher quantities of haem pigments in the dark muscle (which may act as major catalysts of lipid oxidation) or higher quantities of phospholipids (which are major contributors to oxidised flavour in cooked meat).

5.3 Pre- and post-slaughter handling

5.3.1 Red meat

The way that animals are handled and transported before slaughter affects meat quality and storage life. Increased stress or exhaustion can produce PSE (pale, soft and exudative) or DFD (dark, firm and dry) meat, which is not recommended for storage, mainly due to its unattractive nature and appearance. Jeremiah and Wilson found that frozen storage may increase shrinkage, especially in PSE muscle.[30] PSE muscle was found to give low yields after curing, and it was concluded that PSE meat was unsuitable for freezing or further processing.

In general, meat is not frozen until rigor is complete and a degree of conditioning has taken place, otherwise toughening (thaw rigor) and increased drip can occur. Overall, there appears to be little correlation between chilling rates or chilling systems and bacterial numbers after chilling. Rapid chilling reduces drip loss (see Tables 5.2 and 5.3). However, chilling has serious effects on the texture of meat if it is carried out rapidly when the meat is still in the pre-rigor condition, i.e. before the meat pH has fallen below 6.2.[31] In this state, the muscles contain sufficient amounts of the contractile fuel, adenosine triphosphate (ATP), for forcible shortening to set in as the temperature falls below 11ºC, the most severe effect occurring at about 3ºC. This is the so-called 'cold shortening' phenomenon, first observed by Locker and Hagyard[32] and its mechanism described by Jeacocke.[33] The meat 'sets' in the shortened state as rigor begins, and this causes it to become extremely tough when it is subsequently cooked.[34] If no cooling is applied and the temperature of the meat is above 25ºC at completion of rigor, then another form of shortening 'rigor' – or 'heat-shortening' – will occur.[35]

Electrical stimulation (ES) of the carcass after slaughter can allow rapid chilling without much of the toughening effect of cold shortening. However, Buts *et al*. reported that in veal, ES followed by moderate cooling affected tenderness in an unpredictable way.[36] Electrical stimulation will hasten rigor and cause tenderisation to start earlier at the prevailing higher temperature. In meat from carcasses given high or low voltage stimulation and slow cooling, adequate ageing in beef can be obtained in about half of the time of non-stimulated beef.[35] Consequently, this will reduce the requirement and cost of storage.

When meat is stored at above freezing temperatures it becomes progressively more tender. This process, known as ageing, conditioning or maturation is traditionally carried out by hanging the carcass for periods of 14 days or longer. The rate of ageing differs significantly between species, and necessitates different times for tenderisation. Beef, veal and rabbit age at about the same rate and take about 10 days at 1ºC to achieve 80% of ageing (see Table 5.4). Lamb ages slightly faster than beef, but more slowly than pork. The ultimate tenderness will depend on the initial 'background' tenderness of the meat and the tenderisation that has occurred during chilling. In veal, acceptable tenderness can be obtained after five days at 1ºC, compared with ten days for beef.

The major improvement in tenderness has been shown to occur in less than 14 days. In a study by Martin *et al*.,[37] in which more than 500 animals were examined, it was concluded that for beef carcasses, a period of six days is sufficient for a consumer product of satisfactory tenderness. Butcher also showed that no significant increase in tenderness occurs after 4–5 days for calves, and 8–10 days for young bulls at 4ºC.[38]

The ageing process can be accelerated by raising the temperature, and the topic was well studied in the 1940s, 1950s and 1960s. Ewell found that the rate of tenderising more than doubled for each 10ºC rise.[39] Meat from a 3-year-old steer required ten days at 0ºC to reach the same tenderness as two days at 23ºC. Sleeth *et al*. showed that the tenderness, flavour, aroma and juiciness of beef quarters and ribs aged for 2–3 days at 20ºC were comparable to those aged 12–14 days at 2ºC.[40] Busch *et al*. demonstrated that steaks from excised muscles held at 16ºC for two days were more tender than those stored at 2ºC for 13 days.[41]

The microbiological hazards of high temperature ageing were well recognised, and several investigators used antibiotics and/or irradiation to control bacterial growth.[40,42,43] Although high temperature ageing in conjunction with ultraviolet (UV) radiation has been used in the United States, its use has not expanded owing to its high cost.[44]

Table 5.4 Time (days) taken to achieve 50% and 80% ageing at 1ºC for different species

Species	50%	80%
Beef	4.3	10.0
Veal	4.1	9.5
Rabbit	4.1	9.5
Lamb	3.3	7.7
Pork	1.8	4.2
Chicken	0.1	0.3

Source: Dransfield.[35]

With the use of irradiation gaining more acceptance in the United States, its use to accelerate ageing in conjunction with modified atmosphere packaging and high temperature storage has been investigated by Mooha Lee *et al*.[45] Irradiated steaks stored for two days at 30ºC were more tender than unirradiated controls stored at 2ºC for 14 days (see Table 5.5).

In red meat, there is little evidence for a relationship between chilling rates and frozen storage life. However, there is evidence for a relationship between storage life and the length of time that elapses before freezing occurs. Chilled storage of lamb for one day at 0ºC, prior to freezing, can reduce the subsequent storage life by as much as 25% when compared to lamb that has undergone accelerated conditioning and two hours' storage at 0ºC.[13] It has been shown that pork held for seven days deteriorated at a faster rate during storage than carcasses chilled for one and three days.[46] Zeigler found that ageing for periods greater than seven days produced meat with high peroxide and free fatty acid values, when stored at −18ºC or −29ºC.[47] Although shorter ageing times appear to have a beneficial effect on storage life, there is obviously a necessity for it to be coupled with accelerated conditioning to prevent any toughening effects.

5.3.2 Poultry

After bleeding and death, poultry carcasses are scalded by immersing them in hot water for approximately three minutes. Scalding loosens the feathers so that they can be removed easily. Carcasses can either be soft scalded at 52–3ºC, or hard scalded at 58ºC. Hard scalding removes the cuticles on chicken skin, which gives an unattractive appearance after air chilling. Generally, if the poultry is to be frozen it will be hard scalded and water chilled.

Spray washing is used at numerous points during processing to remove visual contamination. The EU Poultry Meat Directive requires poultry to be washed inside and out immediately prior to water chilling, and defines the amount of water to be used (i.e. 1.5 litres for a carcass up to 2.5 kg).

Water chillers are designed to operate in a counter-current manner to minimise cross-contamination. The carcasses exit from the chillers at the point where the clean, chilled water enters the system. Again, the Directive defines a minimum water flow through the chiller, i.e. at least 1 litre per 2.5 kg carcass.

Table 5.5 Shear values for steaks after post-mortem ageing

Storage time (d)	Treatment Unirradiated 2ºC	Irradiated 15ºC	Irradiated 30ºC
1	4.47 ± 1.76	4.89 ± 1.40	4.24 ± 1.65
2	–	4.81 ± 0.73	3.44 ± 1.34
3	–	4.07 ± 1.03	3.33 ± 1.21
7	3.62 ± 1.00	–	–
14	3.52 ± 1.51	–	–

In poultry, the type of chilling method used has an effect on storage life. Grey *et al.* found that air-chilled broilers had significant flavour changes after three months at −12ºC and −20ºC, whereas immersion-chilled birds only exhibited changes at −12ºC after six months and were stable at −20ºC.[48] The air-chilled birds had a better texture initially, but became tougher than the immersion-chilled birds after six months. Ristic also found that water chilling of broilers produced a more favourable taste in the leg and breast meat than air chilling.[27] Significant differences were found by a taste panel after three months in the thigh meat and four months in the breast.

Chicken breast muscle ages ten times faster than beef (Table 5.4). Hence, ageing in poultry carcasses occurs during processing, and is usually accomplished before they reach the chiller/freezer. Pool *et al.* have shown that there were no detectable flavour differences over an 18-month period between turkey that had been frozen immediately and turkey that had been held at +2ºC for 30 hours.[49]

5.4 New trends

Freezing has been used to preserve meat successfully for over 120 years. The requirements of the meat industry were the main driving force behind the developments that ultimately resulted in our current cold chain. In the late 1800s, the market for meat was in Europe with potential sources in Australia, New Zealand, South America and the United States. Freezing was required to link the two. The first successful frozen meat shipment was that of the S.S. Paraguay from Buenos Aires to Have in 1877.[50] By 1899 frozen beef exports from Queensland to the United Kingdom alone exceeded 25,000 tons per year.

Despite the obvious success of the frozen meat trade, the Victorians still preferred ‘fresh’ chilled meat. Numerous experiments and blind testings had already shown that consumers could not tell the difference between frozen and chilled meat. However, they were still willing to pay up to twice as much for the chilled article.

This trend persists today, and consumer preference is likely to have a substantial effect on the future development of the frozen red meat and poultry market. Despite a large price differential in favour of the frozen product, it is the ‘fresh’ chilled market that is growing fastest. For example, there is a growing trend for retailers to sell bulk packs of chilled chicken breasts specifically for home freezing. The breasts are individually packed, and the consumer is happy to pay a premium price and freeze them slowly in a domestic freezer.

There are no obvious technical developments that are likely to change the trend towards chilled poultry products. The product is more convenient for the consumer, and there are no quality advantages with frozen poultry. If food safety becomes much more of an issue, then freezing directly after decontamination may become common. The low temperature will stop any growth of pathogenic or spoilage organisms that survive the decontamination process.

Frozen boned-out poultry meat is increasingly used as a main raw material in many chilled and frozen convenience meals, and other products. Currently, most of this meat is hand boned and air frozen. There is substantial interest in the automation of the boning process and the use of more efficient plate or immersion freezing systems.

In the red meat industry there is an increasing demand for meat of a consistent, guaranteed high eating quality. Specifications already take into account breed, age, feed and handling of the live animal. Slaughter, chilling and ageing conditions are also carefully controlled. However, at the end of this process we have a quality chilled product with a very limited shelf-life. Small changes in levels of initial contamination or ageing temperatures, or times, can result in unacceptable levels of pathogenic and spoilage micro-organisms. As with poultry, one way of overcoming this problem would be to combine decontamination with subsequent freezing. The challenge will be in the marketing. Can the consumer be persuaded that buying frozen meat will guarantee them a high quality product?

5.5 Summary

- The eating quality of red and poultry meat after freezing and thawing is substantially identical to that before freezing. The animal, its treatment before slaughter and the treatment of the meat before freezing will therefore govern its acceptability and eating quality.
- When purchased, the quality of the meat is judged by its bacterial condition and appearance. After cooking its eating quality is judged primarily by its tenderness, flavour and juiciness.
- Age and diet of the live animal have more influence on eating quality than breed. Meat from older animals will be less tender, and there may be flavour problems in meat from entire males.
- Increasing the level of stress or exhaustion in the animal will reduce the eating quality of the meat.
- The muscle tissue of the live, healthy mammal or bird is sterile. The surface of the meat becomes contaminated from the hide, fleece or feathers, and to a lesser extent the gut and events during slaughter and handling. Post-process handling is the usual source of microbial contamination in cooked products, provided that adequate processing has taken place. Reducing the temperature of the surface below -1°C and -10°C as rapidly as possible will minimise the growth of pathogenic and spoilage organisms, respectively.
- Rapid cooling of poultry meat has more advantages than disadvantages.
- Tenderness is the most important eating characteristic of red meat. The two most important refrigeration factors controlling the texture of meat are the rate of chilling, and the length of time and the temperature during ageing. Both need to be carefully controlled to maximise eating quality.

- Drip is a problem with red meat and is considerably increased by freezing. Although the potential for drip loss is predetermined to a large extent by breed and conditions before slaughter, the realisation of this potential is influenced by the temperature time history in the cold chain. Rapid cooling substantially reduces drip production, especially over the critical range from 40ºC to just below 30ºC.

5.6 References

1 ANON. *Safer Eating: Microbiological Food Poisoning and its Prevention*, London, Parliamentary Office of Science and Technology, 1997.

2 VARNAM, A.H. and SUTHERLAND, J.P. *Meat and Meat Products*, London, Chapman & Hall, 1995.

3 MALTON, R. and JAMES, S.J. 'Drip loss from wrapped meat on retail display', *Meat Industry*, 1983, **56**(5), 39–41.

4 CHURCH, P.N. and WOOD, J.M. *The Manual of Manufacturing Meat Quality*, London and New York, Elsevier Applied Science, 1992.

5 CSIRO 'Tender Beef', *Meat Research News Letter*, 1988, 88/4.

6 HUSBAND, P.M. and JOHNSON, B.Y. 'Beef tenderness: the influence of animal age and post mortem treatment', *CSIRO Food Res. Q.*, 1985, **45**, 1–4.

7 *Recommendations for the Processing and Handling of Frozen Foods*, 3rd edn, Paris, International Institute of Refrigeration, 1984.

8 TAYLOR, A.A. 'Influence of carcass chilling rate on drip in meat', in *Meat Chilling: Why and How?*, ed. C.L. Cutting, Langford, Meat Research Institute Symp. no. 2, 5.1–5.8, 1972.

9 CSIRO 'Does breed influence the tenderness of beef?', *CSIRO Newsletter*, 92/4, 1992.

10 KOCH, R.M., DIKEMAN, M.E. and CROUSE, J.D. 'Characterization of biological types of cattle (cycle-iii), 3. Carcass composition, quality and palatability', *J. Anim. Sci.*, 1982, **54**, 35.

11 CROUSE, J.D., CUNDIFF, L.V., KOCH, R.M., KOOHMARAIE, M. and SEIDEMAN, S.C. 'Comparisons of bos-indicus and bos-taurus inheritance for carcass beef characteristics and meat palatability', *J. Anim. Sci.*, 1989, **67**, 2661.

12 WINGER, R.J. 'Storage life of frozen foods: new approaches to an old problem', *Food Technology in New Zealand*, 1984, **19**, 75, 77, 81, 84.

13 WINGER, R.J. 'Storage life and eating related quality of New Zealand frozen lamb: a compendium of irrepressible longevity', in *Thermal Processing and Quality of Foods*, eds. P. Zeuthen, J.C. Cheftel, C. Eriksson, M. Jul, H. Leniger, P. Linko, G. Varela and G. Vos, London, Elsevier Applied Science, 1984, 541–52.

14 CRYSTALL, B.B. and WINGER, R.J. *Composition of New Zealand Lamb as influenced by Geographical Area, Sex of Animal and Cut*, Hamilton, Meat Industry Research Institute of New Zealand (MIRINZ), no. 842, 1986.

15 HUFF, E.J. and PARRISH Jnr, F.C. 'Bovine longissimus muscle tenderness as affected by post mortem ageing time, animal age and sex', *J. Food Sci.*, 1993, **58**(4), 713–16.
16 HAWRYSH, Z.J., PRICE, M.A. and BERG, R.T. 'The influence of cooking temperature on the eating quality of beef from bulls and steers fed three levels of dietary roughage', *J. Inst. Can. Sci. Technol. Aliment.*, 1979, **12**(2), 72–7.
17 UYTTERHAEGEN, L., CLAEYS, E., DEMEYER, D., MARIJKE LIPPENS, FIEMS, L.O., BOUCQUÉ, C.Y., VAN DE VOORDE, G. and BASTIAENS, A. 'Effects of double-muscling on carcass quality, beef tenderness and myofibrillar protein degradation in Belgian Blue White bulls', *Meat Sci.*, 1994, **38**, 255–67.
18 WISMER-PEDERSON, J. and SIVESGAARD, A. 'Some observations on the keeping quality of frozen pork', *Kulde*, 1957, **5**, 54.
19 PALMER, A.Z., BRADY, D.E., NAUMAN, H.D. and TUCKER, L.N. 'Deterioration in freezing pork as related to fat composition and storage treatments', *Food Technology*, 1953, **7**, 90–5.
20 BØGH-SØRENSEN, L. and HOJMARK JENSEN, J. 'Factors affecting the storage life of frozen meat products', *Intnl J. Refrig.*, 1981, **4**(3), 139–42.
21 BAILEY, C., CUTTING, C.L., ENSER, M.B. and RHODES, D.N. 'The influence of slaughter weight on the stability of pork sides in frozen storage', *J. Sci. Food and Agri.*, 1973, **24**, 1299–304.
22 KLOSE, A.A., HANSON, H.L., MECCHI, E.P., ANDERSON, J.H., STREETER, I.V. and LINEWEAVER, H. 'Quality and stability of turkeys as a function of dietary fat', *Poultry Science*, 1953, **32**, 83–8.
23 KUMMEROW, F.A., HITE, J. and KLOXIN, S. 'Fat rancidity in eviscerated poultry', *Poultry Science*, 1948, **6**, 689–94.
24 WEBB, J.E., BRUNSEN, C.C. and YATES, J.D. 'Effects of dietary fish meal level on flavour of pre-cooked frozen turkey meat', *Poultry Science*, 1974, **53**, 1399–404.
25 LIU, Q., LANARI, M.C. and SCHAEFER, D.M. 'A review of dietary vitamin E supplementation for improvement of beef quality', *J. Anim. Sci.*, 1995, **73**, 3131–40.
26 WEN, J., MORRISSEY, P.A., BUCKLEY, D.J. and SHEEHY, P.J.A. 'Oxidative stability and α-tocopherol retention in turkey burgers during refrigerated and frozen storage as influenced by dietary α-tocopheryl acetate', *British Poultry Science*, 1996, **37**, 787–95.
27 RISTIC, M. 'Influence of the water cooling of fresh broilers on the shelf life of poultry parts at −15°C and −21°C', *Lebensmittel-Wissenschaft und-Technologie*, 1982, **15**, 113–16.
28 KESKINEL, A., AYRES, J.C. and SNYDER, H.E. 'Determination of oxidative changes in raw materials by the 2-thiobarbituric acid method', *Food Technology*, 1964, **13**(2), 101–4.
29 JUDGE, M.D. and ABERLE, E.D. 'Effect of pre-rigor processing on the oxidative rancidity of ground light and dark porcine muscles', *J. Food Sci.*, 1980, **45**, 1736–9.

30 JEREMIAH, L.E. and WILSON, R. 'The effects of PSE/DFD conditions and frozen storage upon the processing yields of pork cuts', *Canadian Inst. Food Sci. and Tech. J.*, 1987, **20**, 25–30.

31 BENDALL, J.R. 'The influence of rate of chilling on the development of rigor and "cold shortening"', *Meat Chilling – Why and How?*, ed. C.L. Cutting, Langford, Meat Research Institute Symp. no. 2, 3.1–3.6, 1972.

32 LOCKER, R.H. and HAGYARD, C.J. 'Cold shortening in beef muscles', *J. Sci. Food and Agric.*, 1963, **14**, 787.

33 JEACOCKE, R.E. 'The mechanism of cold shortening', *IIR Meat Chilling 86*, 1986, 13–16.

34 MARSH, B.B. and LEET, N.G. 'Meat tenderness 3', *J. Food Sci.*, 1966, **31**, 450–60.

35 DRANSFIELD, E. 'Optimisation of tenderisation, ageing and tenderness', *Meat Sci.*, 1994, **36**, 105–21.

36 BUTS, B., CASTEELS, M., CLAEYS, E. and DEMEYER, D. 'Effects of electrical stimulation, followed by moderate cooling, on meat quality characteristics of veal *Longissimus dorsi*', *Meat Sci.*, 1986, **18**, 271–9.

37 MARTIN, A.H., FREDEEN, H.T. and WEISS, G.M. 'Tenderness of beef longissimus dorsi muscle from steers, heifers and bulls as influenced by source, post mortem ageing and carcass characteristics', *J. Food Sci.*, 1971, **36**, 619.

38 BUTCHER, L. 'Development of a standardised procedure for the slaughter of experimental beef animals from the Danish Progeny Station "Egtved"', *Proc. 16th Meeting European Meat Res. Workers*, Bulgaria, 1970, 45.

39 EWELL, A.W. 'The tenderising of beef', *Refrigeration Engineering*, 1940, **39**, 237–40.

40 SLEETH, R.B., KELLEY, G.G. and BRADY, D.E. 'Shrinkage and organoleptic characteristics of beef aged in controlled environments', *Food Tech.*, 1958, **12**, 86.

41 BUSCH, W.A., PARRISH, F.C. Jnr and GOLL, D.E. 'Molecular properties of post mortem muscle. 4. Effect of temperature on adenosine triphosphate degradation, isometric tension parameters, and shear resistance of bovine muscle', *J. Food Sci.*, 1967, **32**, 390.

42 DEATHERAGE, F.E. and REIMAN, W. 'Measurement of beef tenderness and tenderisation of beef by Tenderay process', *Food Res.*, 1946, **11**, 525.

43 WILSON, G.D., BRAWN, P.D., CHESBRO, W.R., GINGER, B. and WEIR, C.E. 'The use of antibiotics and gamma irradiation in the ageing of steaks at high temperatures', *Food Tech.*, 1960, **14**, 143.

44 MARAIS, G.J.K. 'Aspects of the meat trade in the USA', *Meat Ind. Pretoria*, 1968, October–December, 33.

45 LEE, M.F., SEBRANEK, J. and PARRISH Jnr, F.C. 'Accelerated post mortem ageing of beef utilising electron-beam irradiation and modified atmosphere packaging', *J. Food Sci.*, 1995, **1**(5), 133–6.

46 HARRISON, D.L., HALL, J.L., MACKINTOSH, D.L. and VAIL, G.E. 'Effect of post mortem chilling on the keeping quality of frozen pork', *Food Tech.*, 1956,

10, 104–8.

47 ZEIGLER, P. T., MILLER, R. C. and CHRISTIAN, J. A. 'Preservation of meat and meat products in frozen storage', The Pennsylvania State College, School of Agriculture, bulletin no. 530, 1950.

48 GREY, T. C., GRIFFITHS, N. M., JONES, J. M. and ROBINSON, D. 'The effect of chilling procedures and storage temperatures on the quality of chicken carcasses', *Lebensmittel-Wissenschaft und-Technologie*, 1982, **15**, 362–5.

49 POOL, M. F., HANSON, H. L. and KLOSE, A. A. 'Effect of pre-freezing hold time and anti-oxidant spray on storage stability of frozen eviscerated turkeys', *Poultry Science*, 1950, **29**, 347–50.

50 CRITCHELL, J. and RAYMOND, J. A. *A History of the Frozen Meat Trade*, London, Constable, 1912.

6

The selection and pre-treatment of fish

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Although this chapter describes the problems associated with freezing of fish and fish products it should not be forgotten that freezing is one of the best methods of preserving fresh fish quality for periods greater than a few days. This chapter describes key factors that are likely to impact upon the final quality of fish and fish products, as experienced by the consumer. The areas covered are: key supply chain elements; the freezing process; changes occurring in the frozen state (both textural and flavour change); pre-freezing factors that influence the rate of deteriorative changes in the frozen state; the effect of freezing rate; and the effect of temperature cycling. It is the aim of this chapter to give an overview of each of these areas and to provide readers with sufficient references to enable them to 'read around' key points of interest.

6.1 Introduction to the freezing of fish

Most fish used in the manufacture of fish products belong to the superorder *Teleostei*. These are the bony fish with vertebrae. This superorder includes all freshwater fish and many of the marine fish species. The remainder belong to the *Elasmobrachii*, or cartilaginous fish. This order includes rays, skates and sharks. It is the aim of this chapter to discuss in most detail the properties of fish from the *Teleostei* superorder and, more particularly, the factors that are likely to influence the final sensory quality of frozen fish and frozen fish products derived from these fish. Our aim is to give an overview of important areas and make suggestions as to how fish quality might be improved. However, due to the diversity of the subject matter, detailed reviews of each topic will not be given, but key research papers will be cited, enabling the reader to ‘read around’ areas of interest.

Teleost fish may be divided into two groups: the demersal (or bottom-dwelling) and the pelagic (surface-dwelling) fish. Demersal fish tend to drift with ocean currents, and therefore do not swim actively for long periods. Consequently, they do not possess much of the red, or dark, muscle required for prolonged aerobic metabolism of energy reserves. Demersal fish only use their muscles for short bursts of activity, which they are able to sustain by anaerobic metabolism of available energy stores. Of this family, cod (*Gadus morhua*) and Alaska pollack (*Theragra chalcogramma*) have received the most attention, and have been cited as representative of the demersal or white flaky fish. They are also the fish species that dominate world trade for human consumption, although other commercially important members of the demersal group include, for example, hake, whiting and haddock.[1]

The second group of teleosts is the pelagic or oily fish. These fish swim actively for long periods and consequently their muscles are equipped for prolonged aerobic muscle activity. Therefore these fish have more of the dark muscle required for aerobic metabolism and they have fat deposits throughout the muscle tissue and just beneath the skin.

The problems in preparing and distributing frozen products made from these two groups of fish tend to be different. For the oily fish, development of rancid flavours due to oxidative changes in the lipids is a major problem. In contrast, the most noticeable problems with white flaky fish are textural changes that can occur in the frozen state. In order to control these deleterious changes it is necessary to understand the factors that may affect quality and how these factors interact throughout the total supply chain. For all practical purposes, it should be remembered that the supply chain extends from the starting raw material, i.e. the freshly caught fish, to the cooked product experienced by the consumer. Unfortunately, due to the complexity of studying the entire supply chain, most studies are confined to a small part, or parts thereof. In addition, no ‘standard’ supply chain conditions exist. Consequently, experimental conditions employed by different research groups may vary considerably, and it is often difficult, if not impossible, to compare studies.

6.2 What are the elements of the frozen fish product supply chain?

Figure 6.1 shows a simplified fish supply chain, going from catch through to the retail cabinet. The main factors that determine frozen fish quality can be grouped into three main areas: pre-freezing, the freezing process and frozen storage/product distribution. These main areas will be general to the processing of any fish (because of its importance, packaging is treated separately in Chapter 10). It

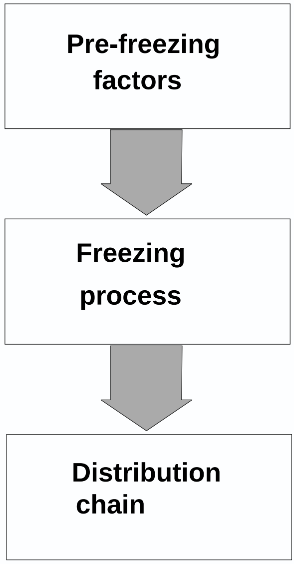

Fig. 6.1 A simplified diagram of key stages in the supply chain for frozen fish products.

should also be borne in mind that one of the least well-defined areas in any supply chain is the consumer handling stage, and it is during this phase that potentially severe thermal abuse may occur. Indeed, thermal abuse may not be confined to the frozen state but may extend to poor cooking of products also. The influence of cooking on product quality will not be discussed in this chapter, but clearly, even the best possible 'quality' fish can be destroyed by inappropriate cooking.

Before discussing the factors that influence the frozen stored quality of fish and fish products, it is worth discussing the nature of the changes that can occur in frozen fish.

6.3 The freezing of fish

Although this chapter describes some of the problems associated with freezing fish, it should be remembered that freezing is a very effective way of preserving food quality. Paradoxically, freezing fish may be the only way of preserving 'fresh fish quality' for time periods of greater than a few days, since it is difficult to control enzymatic and microbial spoilage of fish fillets at chill temperatures.[2] Although these processes can be controlled by canning, this requires high temperature cooking in order to render canned products stable at ambient temperatures.

6.3.1 The freezing process

Fish fillet contains a large amount of water, and on cooling below the freezing point of the tissue fluids (*c.* −1.5ºC), water in the fluid will be converted into ice. As ice forms, proteins and solutes etc. will become concentrated in the non-frozen fraction. The freezing point of the non-frozen fraction will be depressed as the solute concentration increases. Ultimately, the freezing point of the non-frozen fraction will equal that of the freezing temperature. Once this point is reached, an equilibrium will be established between the ice phase and the non-frozen fraction. The amount of non-frozen fraction will depend upon the composition of the fish product, and on the temperature at which the product is frozen/stored. The lower the temperature, the more ice will be formed and the more concentrated the solutes will become. Conversely, on increasing the temperature the amount of non-frozen water will increase. Table 6.1 shows the amount of unfrozen water in cod fillet as a function of temperature.[3]

As a consequence of forming a highly concentrated non-frozen phase, potential reactants (for example, enzymes and substrates) will become far more concentrated than in the living tissue. Reactions will, potentially, be accelerated. However, lowering the temperature will decrease rates of these reactions. Therefore two antagonistic effects occur on cooling: an increase in reaction rate due to freeze concentration and a decrease in reaction rate due to a lowering of the temperature. In addition, in some foods, reaction rates may become diffusion controlled.[4] Thus, as the viscosity of the non-frozen fraction increases (caused by increases in the amount of ice), diffusion rates of reactants and products will be reduced. This in turn will reduce the rate of reactions. Reaction kinetics in the non-frozen fraction are therefore likely to be complex, and optimum temperatures for 'quality loss reactions' may exist.[5]

Freezing produces an ice phase and a freeze-concentrated phase. In addition, the rate of freezing determines the position and size of ice crystals in the fish structure. Figure 6.2 shows the structural hierarchy that exists within fish muscle. For most practical purposes ice forms externally to the myofibrils, and it is most likely that the ice will form between the muscle cells. Figure 6.3 shows a frozen section of cod muscle, which has been blast frozen at −30ºC. The ice and condensed muscle fibres are labelled. Ice can be made to form within fibres but

Table 6.1 Variation of percentage of water that remains unfrozen for cod fillet

Temperature (ºC)	% unfrozen water
−1	92
−2	48
−3	33
−4	27
−5	21
−10	16
−20	11

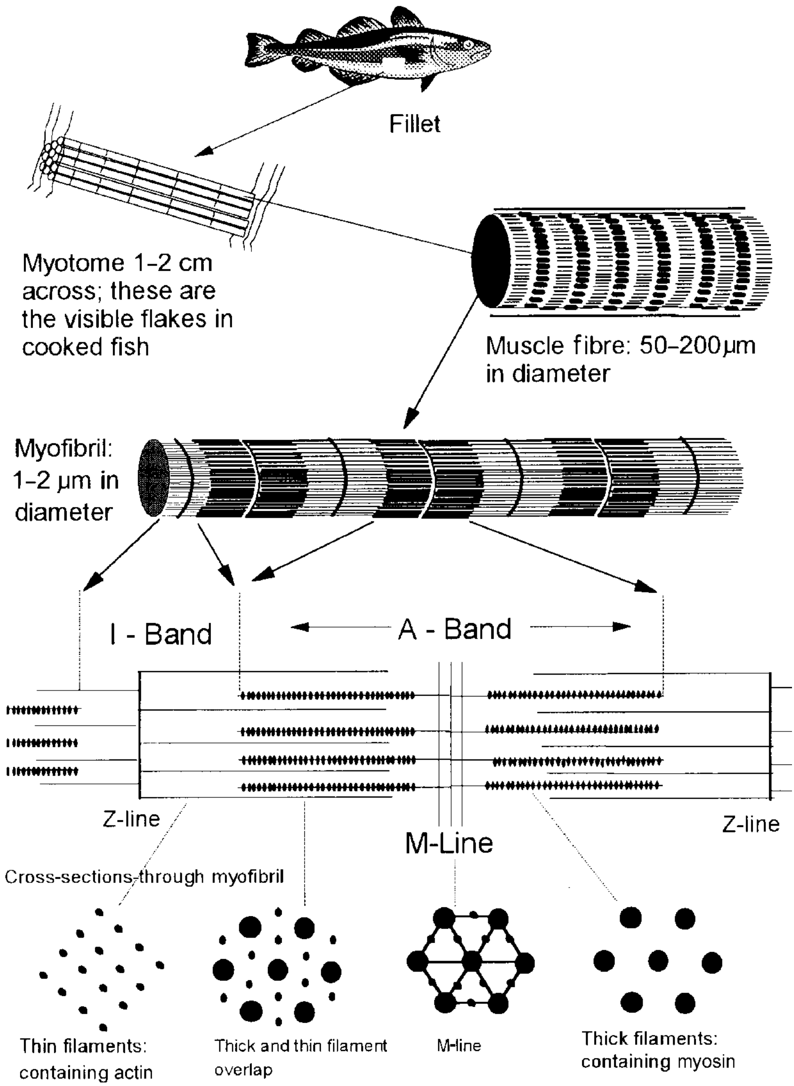

Fig. 6.2 The structural hierarchy in fish muscle.

this requires extremely rapid cooling. For example, liquid nitrogen freezing of small fillet pieces can cause ice to be formed within the muscle cells.[6] In addition to the freezing process, temperature cycling after freezing causes the amount of ice to fluctuate (see Table 6.1, which shows how ice content varies with temperature). It is this partial melting and refreezing that may change the distribution of ice crystal sizes (larger crystals growing at the expense of smaller ones).

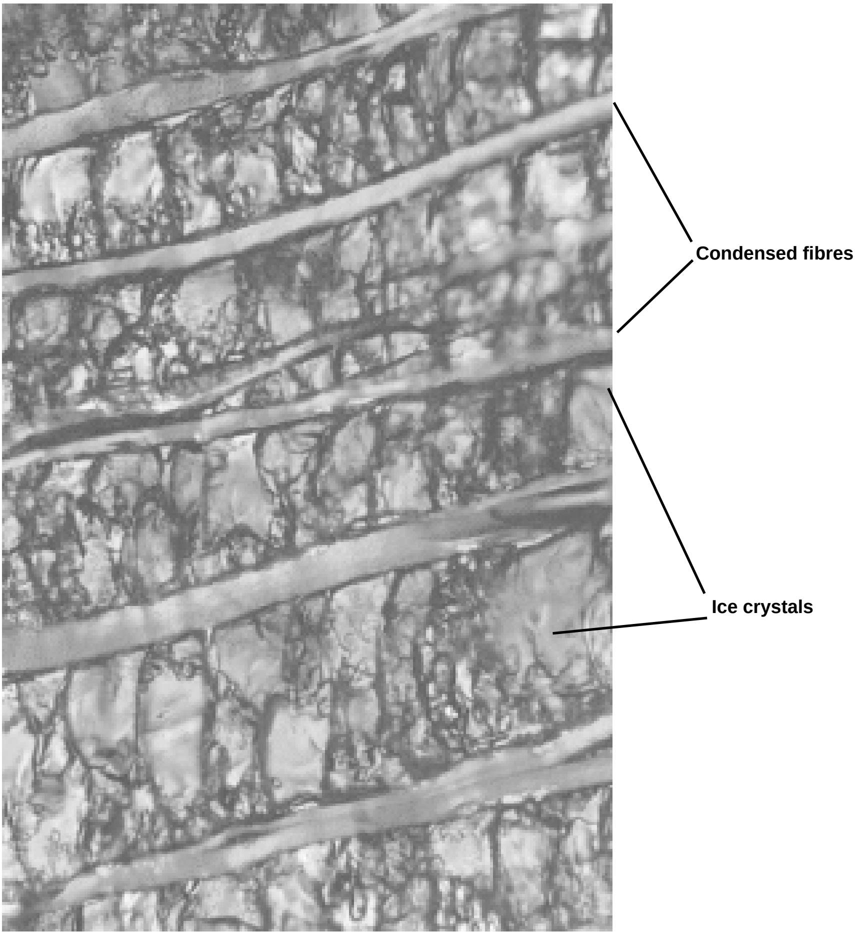

Fig. 6.3 The ice crystal location in cod muscle, blast frozen at −30ºC.

6.4 Changes occurring on frozen storage

6.4.1 Textural changes

During the freezing and subsequent frozen storage of certain fish species, changes occur which result in deterioration of the textural quality of the cooked fillet. The textural change has been described as a tendency to express liquid on initial compression in the mouth, with the remaining material being often hard, dry and fibrous.

The textural changes that occur have been attributed to changes in the myofibrils. Many observations of myofibrillar change have been made; for example, work by Jarenback and Liljemark showed that, during frozen deterioration of cod (*Gadus morhua*), a decrease in the dimensions of the myosin lattice (shown in Fig. 6.2) was observed, coupled with disturbances to the regular hexagonal lattice spacing (based on a comparison of thawed, deteriorated muscle with fresh cod).[7] It was also noted that the myofibrils within a thawed, frozen deteriorated muscle fibre were pushed closer together, with a commensurate disappearance of the sarcoplasmic reticulum vesicles lying between the myofibrils.

Similar effects have also been reported for Alaska pollack muscle which had been subjected to −20ºC frozen storage for two months.[8] On thawing, the myofibrils within each muscle cell did not recover their original diameter, and also appeared closer together. Further frozen storage (i.e. 12 months at −20ºC) rendered the myofibrils even less able to effect a recovery of their original diameters on thawing, and a substantial loss of the order within individual myofibrils was also observed. Another consequence of the increased inter- and intra-myofibril association is that a change in water location occurs. Thus, water that was originally within the myofibril prior to freezing/frozen deterioration, and which was abstracted during the freezing, is unable to return to its original location on thawing.

6.4.2 Mechanisms of textural change

As already discussed, it has been proposed that the textural changes that occur are attributable to changes in the myofibrils, and that these changes result in the inability of the thawed muscle fibres to reabsorb the water extracted by freezing. This results in development of a drier and more chewy texture. The change in texture is reported to be most severe for the white flaky fish belonging to the gadoid family of fish (for example, cod and Alaska pollack); however, the exact mechanism(s) by which these changes occur is not clear. A number of hypotheses have been proposed to explain the observed changes. For example, it has been suggested that textural changes are linked with aggregation of the thick filaments (containing myosin), and are concomitant with losses in myosin enzymatic activity.[9,10] In addition, one of the most widely reported mechanisms to explain why protein aggregation occurs, involves the cross-linking of proteins by formaldehyde. Formaldehyde is a cross-linking agent which may be produced by the degradation of trimethylamine oxide,[11,12] present in gadoid fish as an osmo-regulator. Other hypotheses include interaction of myosin with lipids[13] and lipid oxidation products.[14] Also, it has been observed that species that are most resistant to frozen deterioration of texture are from warmer waters.[15,16]

Although a number of mechanisms have been proposed, the exact route by which textural change occurs is still uncertain. It is interesting to note that, while the rate of toughness development is fastest in the gadoid family of fish, textural changes occur in non-gadoid fish, especially in those fish from temperate waters.[17,18] Thus, it seems unlikely that a single hypothesis can fully explain textural change in all of these cases.

6.4.3 Flavour changes

As already stated, fish may be divided into two categories depending on whether they store lipid in the fish muscle or in the liver. However, lean fish, such as cod, still have some lipids in their muscle. These are in the form of phospholipids or lipoproteins, located in cellular membranes, but at relatively low levels (around 0.5% to 1.5%). For pelagic fish, lipid contents in the muscle are much higher, *c.* 15–25%, and are in the form of triglycerides.[19] These triglycerides are unsaturated and are prone to oxidation, which leads to the development of a number of volatile compounds. It is the development of volatile molecules, such as aldehydes and ketones, that is responsible for the characteristic flavours and aromas that typify rancidity development in oily fish. Under most circumstances it is the development of off-flavours that limits the shelf-life of oily fish products; however, lowered nutritional value, textural changes and colour changes may also be attributed to lipid oxidation and lipid oxidation products.[20] The development of rancidity can still occur quite rapidly even in the frozen state.[21] The rate of rancidity development once frozen may also be influenced by a number of enzymatic and non-enzymatic events occurring prior to freezing.[22] In the living muscle the effects of agents that accelerate lipid oxidation (pro-oxidants) are balanced by those that inhibit oxidation (antioxidants). Post-mortem, however, this balance is disrupted and this stimulates the initiation of lipid oxidation. In fresh fillets stored at chill temperature, off-flavour development is less problematic since microbial spoilage will render fish inedible before rancidity has developed to any great extent. However, in the frozen state, where microbial-induced changes are effectively arrested, rancidity is most likely to become the process that limits shelf-life.[23]

Although textural change may be significant during the storage of cod and Alaska pollack, flavour changes may also occur. One flavour change is often described as development of cold-store flavour and has been attributed to the development of hept-cis-4-enal, a product of oxidation of specific membrane phospholipids.[24] It has also been suggested that starving cod prior to slaughter reduces off-flavour development.[25]

6.4.4 Mechanisms of flavour change

It has been proposed that lipid oxidation in fish may be initiated and promoted by a number of mechanisms. These include the production of singlet oxygen, enzymatic and non-enzymatic generation of partially reduced or free radical oxygen species (for example, hydrogen peroxide and hydroxyl radicals), active iron complexes and thermal or iron-mediated homolytic cleavage of hydroperoxides.[26]

Although a number of generic mechanisms can be proposed to describe how rancid off-flavours develop in frozen fish, it is likely that species-specific factors need to be determined in order to devise successful methods of controlling off-flavour development.

6.5 Pre-freezing factors that influence the quality of frozen fish products

6.5.1 Fish type

Many parameters affect the shelf-life of fish. For example, fish of different types spoil at different rates. In general it can be stated that larger fish spoil more slowly than small fish, flat fish keep better than round fish,[27] lean fish keep longer than fatty fish (under aerobic storage) and bony fish are edible for longer periods than cartilaginous fish.

6.5.2 Handling

Rough handling will result in a faster spoilage rate. This is due to the physical damage to the cells of the fish, resulting in easy access for enzymes and spoilage bacteria. Also, rough handling may lead to damage/bruising which may accelerate deteriorative processes. If fish are kept alive in containers until processing and freezing then microbial spoilage can be avoided. The fish is, however, starved under these conditions and uses up glycogen. Thus, as with catching and handling procedures which cause energy stored to become depleted before death, the pH of the muscle will tend to be higher.

6.5.3 Effect of post-mortem pH

The post-rigor pH varies between fish species but is generally higher than in meat from warm-blooded animals. Catching method,[28] handling prior to death, time of year and fishing ground may all influence the final pH of the fish fillet.[29,30] The ultimate pH of the fish fillet will have a direct effect on the water-holding capacity of the muscle and on the fish texture.[31] Figure 6.2 (page 99) shows the lattice arrangement of thick and thin myofibres within fish myofibrils. It has been shown that the myofibrils occupy a substantial proportion of the volume of muscle, and that changes in water-holding capacity of whole muscle arise from changes in the water-holding capacity of the myofibrils.[32] Thus, as the pH of the fillet increases, the charge on the myofibres within each myofibril lattice increases, causing the myofibrils to expand. This expansion allows the myofibrils to hold more water. In addition, the pH of the muscle may influence the shelf-life of fish stored on ice, shelf-life increasing with decreasing pH.[30] The final pH may also influence the properties of the connective tissue, and especially the propensity for fillets to gape.[33] Gaping is a phenomenon whereby the connective tissue is unable to hold the muscle blocks together.

6.5.4 Pre-chilling

The post-catch and post-mortem handling of fish is different to that of meat, even though they are both usually chilled. Fish temperature reduction to about 0ºC is by far the most important factor for the quality of fish. This should be achieved as rapidly as possible.[34] Rapid chilling will slow down the rates of enzymatic- (and microbial-) induced changes occurring post-mortem. Of these post-mortem changes, the earliest ones observed by trained sensory panellists are those that relate to changes in appearance and texture. The most dramatic change is the onset of rigor mortis. The rate of onset and resolution of rigor varies from species to species and is affected by temperature, handling, size and physical condition of the fish. Indeed, for farmed salmon it has been shown that stress prior to slaughter can influence the speed of rigor development and the textural quality of the fillets.[35] The effect of temperature on rigor onset is not simple. Previously it was accepted that onset of rigor came rapidly after death at high temperatures and slowly at low temperatures, but it has been seen, especially in tropical fish, that lowering of the temperature in fact gives an accelerated onset of rigor. In accordance with this it has been suggested that onset of rigor depends on the difference in sea temperature and storage temperature. Therefore it is only in cold-water fish (but still depending on the sea temperature) that rapid chilling can be recommended as a way to avoid a fast and strong rigor that can cause gaping, i.e. weakening of the connective tissue and rupture of the fillet. Rapid chilling may have a beneficial effect by controlling the rate of rigor development. When the chill storage temperature is high, the time from death to onset of rigor is short. In the case of cod, for example, a high storage temperature results in a fast and very strong rigor mortis. This should be avoided because the strong rigor tensions can cause gaping, i.e. weakening of the connective tissue and rupture of the fillet.

The technological significance of rigor mortis is of major importance, depending on whether the fish is filleted before or in rigor. In rigor the fish body will be completely stiff and the filleting yield will be very poor and rough handling can cause gaping. If the fillets are removed from the bone pre-rigor, the muscle can contract freely and the fillets will shorten following the onset of rigor. Dark muscle may shrink up to 52% and white muscle up to 15% of the original length.

When pre-rigor fillets are cooked they can shrink by about 50%, losing fluid and getting a rubbery texture. If the fish is cooked pre-rigor, the texture will be very soft and pasty. Cooking in rigor results in flesh that is tough but not dry. Post-rigor the cooked flesh will become firm, succulent and elastic. Whole fish and fillets frozen pre-rigor can give good products if they are carefully thawed at a low temperature in order to give rigor mortis time to pass while the muscle is still frozen.

6.5.5 Super-chilling

Traditionally ice is used in the pre-chilling of fish. This has several advantages. The first one is that the ice and fish are in good contact, allowing good heat transfer from the fish to the ice. The second is that melting of the surrounding ice requires a large amount of heat energy to be removed from the fish. The disadvantage with icing is that it can be labour intensive, and for fish in boxes, the contact between the fish and ice may not be very good. Fish may be cooled in refrigerated sea water. This allows faster heat removal from the fish and makes the chilling processes faster. Also, the temperature of the fish can be reduced to −1ºC to −2ºC, and this may offer advantages in reducing rates of spoilage.

An extension to super-chilling is to allow the fish to freeze partially. By reducing the temperature of the fish to −2ºC to −4ºC fish can be partially frozen. It has been claimed that such partial freezing of fish can extend shelf-life.[36,37,38] This may offer advantages for preserving fish quality on board trawlers that do not freeze fish at sea.[38]

6.5.6 Addition of cryoprotectants

Cryoproctectants are compounds that improve the quality and extend the shelf-life of frozen foods. A wide variety of cryoprotective compounds are available, and these include sugars, amino acids, polyols, methyl amines, carbohydrates,[39] some proteins[40] and inorganic salts such as potassium phosphates and ammonium sulfate. The selection of cyroprotectants will depend on whether the application is for a comminuted product, that is a system into which the cryoprotectants can be intimately mixed, or whole fish fillet. Probably the most extensive applications of cryoprotectant molecules has been in the stabilisation of surimi. For example, cryoprotectants such as carbohydrates (particularly sugars) and polyphosphates (only allowed in some countries) have been used to minimise the loss of protein functionality properties caused by the freezing and frozen storage processes on surimi. A useful review of general principles of cryopreservation of food quality is given by MacDonald and Lanier.[41]

For whole-fillet applications the most frequently used cryoprotectant to control the water-holding capacity is tripolyphosphate. It has been reported that polyphosphate addition will improve the texture and colour of fish products also.[42,43]

6.5.7 Pre-freezing treatments that may reduce storage life

Product preparation has a considerable effect on quality. It is better to eviscerate fish before they are frozen since blood and kidney tissue can be removed. Blood contains iron, a co-factor for TMAOase activity, and kidney remnants may contain proteolytic enzymes which will degrade the fillet structure. Whole fish have a longer shelf stability than fillets, which are more stable than minces. This increasing instability, which is more apparent in white fish, probably results from the release of salts and enzymes due to tissue damage which then leads to more rapid deterioration. Also, mixing of red and white muscle (red muscle containing more fat and more haem proteins) may result in the dispersion of lipids and enzymes, leading to more deteriorative changes.

The procedures used to gut fish are an important determinant of shelf-life for fish. The complete removal of gut tissues and enzymes reduces gut enzyme activity, which would otherwise lead to reduction in the quality characteristics of the fish. Incomplete or careless gutting, which leads to the spreading of gut material onto the fillets, is often worse than no gutting at all.

6.6 The effect of freezing rate

For any study where attempts are made to vary freezing rate, it is important to remember that a range of time/temperature profiles are likely to exist across a sample, and this situation will be exacerbated as the sample size is increased. Therefore it should not be assumed that changing the external freezing temperature changes the overall rate at which a sample has frozen. However, a study by Doong indicated that ice crystal size could be manipulated by changing freezing conditions, and that ice crystal size correlated with the rate of change of, for example, the water-holding capacity of the fillet on subsequent frozen storage.[44] Also, Fucetola *et al*. suggested that deep, or more rapid, freezing was more beneficial than slower freezing processes as it was more likely to produce smaller, less damaging ice crystals.[45] A number of papers have also reported distinct advantages in freezing fish using liquid nitrogen.[46,47,48] Lee, for example, suggested that freezing fish in liquid nitrogen improved subsequent storage stability at −20ºC, compared with air-blast frozen samples. Lee also suggested that freeze–thaw cycling and temperature cycling in the frozen state were particularly damaging to fish quality.[48]

6.7 The effect of temperature cycling

There are a number of papers that suggest that temperature fluctuations will increase the rate at which fish quality is lost.[48,49] Indeed, Love suggested that due to a logarithmic relationship between quality loss and temperature, temperature fluctuation may greatly reduce quality and therefore should be avoided.[49] Also, Scudder suggested that the degradation of TMAO to formaldehyde and dimethylamine may have a maximum rate around −18ºC.[50] Thus it was recommended that the storage temperature on lean demersal fish should be −24ºC to −30ºC. For oily fish, storage temperatures of −50ºC to −60ºC have been recommended in order to reduce the rate of oxidative changes.[51]

6.8 Summary

Clearly, in any fish product supply chain there are many points at which improvements may be made. However, to obtain real benefits the supply chain must be viewed in its entirety. Thus there may be little to be gained by controlling the quality of raw materials if inappropriate freezing and storage conditions are employed during processing and distribution. It is hoped that this chapter gives the reader sufficient background information about factors that are likely to impact upon quality. However, to ascribe relative importance to each step in determining the final fish quality is difficult as each fish supply chain will be different.

6.9 References

1 ANON. *FAO Year Book of Fisheries Statistics, Catches and Landings*, Rome, FAO, 1989, vol. 68.

2 HAARD, M. F. 'Technological aspects of extending prime quality of seafood: a review', *J. Aquat. Food Prod. Technol.*, 1992, **1**(3/4), 9–27.

3 NOIKOV, V. in *Handbook of Fishery Technology*, vol. I, New Delhi, Amerind, 1981.

4 SLADE, L. and LEVINE, H. 'Principles of cryo-stabilisation technology from structure/property relationships of carbohydrate/water systems: a review', *Cryo-Lett.*, 1988, **9**, 21–63.

5 PARKER, R. and RING, S. G. 'A theoretical analysis of diffusion-controlled reactions in frozen solutions', *Cryo-Lett.*, 1995, **16**, 197–208.

6 TANEKO, S., KANNA, K. and TANAKA, T. 'Protein denaturation of fish frozen in liquid nitrogen', *Proc. Int. Symp.*, 1965, 118–21.

7 JARENBACK, L. and LILJEMARK, A. 'Ultrastructure changes during frozen storage of cod. I. Structure of myofibrils as revealed by freeze etching preparation', *J. Food. Technol.*, 1975, **10**, 229–39.

8 TANAKA, T. 'Electron microscopic studies on toughness in frozen fish', *Proc. Int. Symp.*, 1964, 121–6.

9 SOLETO, C. G., PINERO, C. and PEREZ-MARTIN, R. I. 'Denaturation of fish proteins during frozen storage: role of formaldehyde', *Z. Lebens. Unters. Forsch.*, 1995, **200**(1), 14–23.

10 JIANG, S. T., HWANG, B. S. and TSAO, C. Y. 'Protein denaturation and changes in nucleotides of fish muscle during frozen storage', *J. Agric. Food Chem.*, 1987, **35**(1), 22–7.

11 CASTELL, C. H., NEAL, W. and SMITH, B. 'Formation of dimethylamine in stored frozen sea fish', *J. Fish. Res. Bd. Can.*, 1970, **10**, 1685–90.

12 SOKORSKI, Z. and KOSTUCH, S. 'Trimethylamine N-oxide demethylase: its occurrence, properties and role in technological changes in frozen fish', *Food Chem.*, 1982, **9**, 213–22.

13 SHENOUDA, S. Y. K. and PIGGOT, G. M. 'Lipid-protein interaction during aqueous extraction of fish proteins: myosin-lipid interaction', *J. Food Sci.*, 1974, **39**(4), 726–34.

14 TAKAMA, K. 'Insolubilisation of rainbow trout actomyosin during storage at -20^{o}C. I. Properties of insoluble protein formed by reaction of propanol or caproic acid with actomyosin', *Bull. Jap. Soc. Sci. Fisheries*, 1974, **40**(6), 585–8.

15 TSUCHIMOTO, M., TANAKA, N., MISA, T., YADA, S., SENTA, T. and YASUDA, M. 'The influence of rearing temperature on the relative thermostability of myofibrillar Ca^{2+} ATP-ases and on the lowering speed of freshness in carp', *Nippon Suisan Gakkaishi*, 1988, **54**, 117–22.

16 HOWELL, B.K., MATHEWS, A.D. and DONNELY, A.P. 'Thermal stability of fish myofibrils: a differential scanning calorimetry study', *Int. J. Food Sci. Technol.*, 1991, **26**, 283–95.

17 SIMEONIDOU, S., GOVARIS, A. and VARELTZIS, K. 'Effect of frozen storage on the quality of whole fish and fillets of horse mackerel (Trachurus trachurus) and Mediterranean hake (Merluccius mediterraneus)', *Z. Lebens. Unters. Forsch.*, 1997, **204**(6), 405–10.

18 DIAS, J., NUNES, M.L. and MENDES, R. 'Effect of frozen storage on the chemical and physical properties of black and silver scabbardfish', *J. Sci. Food Agric.*, 1994, **66**(3), 327–35.

19 CASTELL, C.H. 'Metal catalysed lipid oxidation and changes of proteins in fish', *J. Am. Oil Chem. Soc.*, 1971, **48**, 645–9.

20 ERIKSSON, C.E. 'Lipid oxidation catalysts and inhibitors in raw materials and in processed foods', *Food Chem.*, 1982, **9**, 3–19.

21 ORTIZ, H. and BELLO, R. 'Composition and stability of fatty fish acids from deboned cachama and sardine meat during frozen storage', *Arch. Latinoam. Nutr.*, 1992, **42**(4), 460–6.

22 HAARD, N.F. 'Biochemical reactions in fish muscle during frozen storage', in *Seafood Science and Technology*, ed. E.G. Bligh, Cambridge, MA, Blackwell Scientific, 1994.

23 HARRIS, P. and TALL, J. 'Rancidity in fish', in *Rancidity in Foods*, ed. J.C. Allen and R.J. Hamilton, Glasgow, Blackie Academic and Professional, 1994, 256–72.

24 MCGILL, A.S., HARDY, R. and GUNSTONE, F.D. 'Further analysis of the volatile components of frozen cold stored cod and the influence of these on flavour', *J. Sci. Food Agric.*, 1977, **28**, 200–5.

25 ROSS, D.A. and LOVE, R.M. 'Decrease in the cold store flavour developed by frozen fillets of starved cod (Gadus morhua)', *J. Food Technol.*, 1979, **14**, 15–122.

26 KUBOW, S. 'Routes of formation and toxic consequences of lipid oxidation products in foods', *Free Radical Biol. Med.*, 1992, **12**(1), 63–81.

27 KIM, H.K., ROBERTSON, I. and LOVE, R.M. 'Changes in the muscle of lemon sole (Pleuronectes microcephalus) after very long cold storage', *J. Sci. Food Agric.*, 1977, **28**(8), 699–700.

28 BOTTA, J.R., BONNELL, G. and SQUIRES, B.E. 'Effect of method of catch and time of season on sensory quality of fresh raw Atlantic cod (Gadus morhua)', *J. Food Sci.*, 1987, **52**(4), 928–31, 938.

29 LOVE, R.M. 'Variability in Atlantic cod (Gadus morhua) from the Northeast Atlantic: a review of seasonal and environmental influences on various attributes of the flesh', *J. Fisheries Res. Board Can.*, 1975, **32**(12), 2333–42.

30 LOVE, R.M. 'The influence of fishing grounds on quality', *Fishing News Int.*, 1975, **14**(4), 16–18.
31 LOVE, R.M. 'The post-mortem pH of cod and haddock muscle and its seasonal variation', *J. Sci. Food Agric.*, 1979, **30**(4), 433–8.
32 OFFER, G. and TRINICK, J. 'On the mechanism of water holding in meat: the swelling and shrinkage of myofibrils', *Meat Sci.*, 1983, **8**, 245–81.
33 LOVE, R.M. and HAQ, M.A. 'Connective tissue of fish. III. The effects of pH on gaping in cod entering rigor mortis at different temperatures', *J. Food Technol.*, 1970, **5**(3), 241–8.
34 HANSEN, C.P. 'Ice chilling of trawl catches in containers and boxes', *INFOFISH Int.*, 1998, **1**, 40–5.
35 SIGHOLT, T., ERIKSON, U., RUSTAD, T., JOHANSEN, S., NORDVELT, T.S. and SELAND, A. 'Handling stress and storage temperature affect meat quality of farm-raised Altantic salmon (Salmo salar)', *J. Food Sci.*, 1997, **62**(4), 898–905.
36 KE, L.C.B., CHANG, J., CHYUAN, Y.S. and PAN, B.S. 'Biochemical, microbiological and sensory changes of sea bass (Lateolabrax japonicus) under partial freezing and refrigerated storage', *J. Agric. Food Chem.*, 1998, **46**(2), 682–6.
37 LEE, C.M. and TOLEDO, R.T. 'Comparison of shelf-life and quality of mullet stored at zero and sub-zero temperature', *J. Food Sci.*, 1984, **49**(2), 317–22, 344.
38 GIBBARD, G., LEE, F., GIBBARD, S. and BILINSKI, E. 'Transport of salmon over long distances by partial freezing in RSW vessels', *Refrigeration Sci. Technol.*, 1981, **4**, 285–90.
39 MACDONALD, G.A. and LANIER, T.C. 'The role of carbohydrates as cryoprotectants in meat and surimi', *Food Technol.*, 1991, March, 101–5.
40 ANESE, M. and GORMLEY, R. 'The effects of dairy ingredients on some chemical, physico-chemical and functional properties of fish mince on freezing and frozen storage', *Food Sci. Technol. Leb.*, 1996, **29**(1,2), 151–7.
41 MACDONALD, G.A. and LANIER, T.C. 'Cryoprotectants for improving frozen food quality', in *Quality in Frozen Foods*, M.C. Erickson and Y.C. Hung (eds), New York, International Thompson Publishing, 1997, 197–232.
42 SCHOBER, P. and DUERR, F. 'Effects of polyphosphate on the quality and yield of fish products', *Fischerei Forschung*, 1989, **27**(3), 71–6.
43 CORMIER, A. and LEGER, L.W. 'Effect of sodium polyphosphate on frozen cod fillets (Gadus morhua)', *Can. Inst. Food Sci. Technol. J.*, 1987, **20**(4), 222–8.
44 DOONG, N.F.G. 'The effect of freezing and frozen storage on the status of fish tissue', *Diss. Abs. Int. B.*, 1998, **48**(8), 2159.
45 FUCETOLA, F., SALFI, V., CARLUCCI, G. and ARATA, P. 'Deep frozen fish products: biological problems', *Industrie Alimentari*, 1985, **24**(225), 263–5.
46 SEMENOV, B.N., NATELOV, I.A., KHAR'KIN, A.A., ERYSHEVA, M.G., NALETOVA, I.A. and SHALAEVA, T.P. 'Extending the cold storage period of tuna', *Rybnoe Khozyaistvo*, 1986, **5**, 61–4.

47 YAY, L.C. and BONIE, S.P. ‘Morphological changes in tilapia muscle following freezing by airblast and liquid nitrogen methods’, *Int. J. Food Sci. Technol.*, 1997, **32**(2), 159–68.
48 LEE, C.M. ‘Physical and biochemical changes in fish muscle under various freezing conditions’, *Quick Frozen Foods*, 1982, **45**(3), 30–2.
49 LOVE, R.M. ‘Time-temperature tolerance’, *IFST Proc.*, 1969, **2**(3), 62–7.
50 SCUDDER, B. ‘Icelandic warning on frozen fish’, *Seafood Int.*, 1995, **10**(6), 51.
51 MAGNUSSEN, O.M. ‘Superfreezing low temperature technology’, *Scan. Ref.*, 1992, **21**(4), 34–41.

6.10 Further reading

ERICKSON, M.C. and HUNG, Y.C. (eds) *Quality in Frozen Foods*, New York, International Thomson Publishing, 1997.

LOVE, R.M. (ed.) *The Food Fishes: Their Intrinsic Variation and Practical Implications*, London, Farrand Press, 1988.

ALLEN, J.C. and HAMILTON, R.J. (eds) *Rancidity in Foods*, 3rd edn, Glasgow, Academic and Professional, 1994.

7

Factors affecting the stability of frozen foods

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Freezing is recognised as one of the best methods of preserving food quality. Freezing inhibits the growth of deteriorative and pathogenic micro-organisms, and low temperatures retard biochemical and enzymatic reactions that would otherwise occur in unfrozen food. Freezing involves the removal of heat accompanied by a phase change, converting water to ice. Meanwhile in the remaining unfrozen portion, the concentration of dissolved substances increases and water activity of the product decreases. Although the physico-chemical reactions slow down at low temperatures, they will, nevertheless, continue during frozen storage conditions.

The rate at which heat is removed depends on factors directly related to the object to be frozen (size, surface area, thermal properties) and factors that are characteristic of the freezing system such as the temperature and heat transfer coefficient of the cooling medium. However, heat removal alone is not sufficient to induce a phase change. Additional factors, such as the rate of nucleation of ice crystals and the rate of ice propagation, are involved.

7.1 Physical changes during freezing and frozen storage

Ice formation involves a series of physico-chemical modifications that decrease food quality. The principal physical changes in frozen foods that will be discussed are freeze-cracking, moisture migration, recrystallisation of ice and drip losses during thawing.

7.1.1 Ice formation: nucleation and crystallisation

Freezing involves different factors in the conversion of water into ice: thermodynamic factors that define the position of the system under equilibrium conditions, and kinetic factors that describe the rates at which equilibrium might be approached. The freezing process includes two main stages: (a) the formation of ice crystals (nucleation), and (b) subsequent increase in crystal size (growth).

Thermodynamic knowledge indicates that below 0°C, ice is the stable form of pure water. However, for the crystalline phase to grow there must be an initiation seed or nucleus. Nucleation is the combining of molecules into an ordered particle of a sufficient size to survive and serve as a site for further crystal growth.[1] An energy barrier (activation energy) must be surpassed before nucleation can occur. Supercooling (also termed undercooling)[2] is necessary to overcome the free energy that accompanies the formation of a new phase (an ordered solid particle) from the melted phase. Nucleation is necessary for freezing to initiate, thus the temperature can fall below 0°C without crystallisation occurring. At some temperature, which depends mainly on the rate of cooling and the sample volume, nucleation will occur. Homogeneous nucleation is produced in pure systems free from all impurities. Heterogeneous nucleation (catalytic nucleation) takes place when water molecules aggregate in a crystalline arrangement on nucleating agents such as active surfaces; this type of nucleation predominates in food systems. Nucleation rate is highly dependent on the temperature of the freezing medium and on freezing rate. High initial undercooling values (i.e. low temperatures below the equilibrium melting point) increase nucleation rates. Figure 7.1 shows typical curves of nucleation and

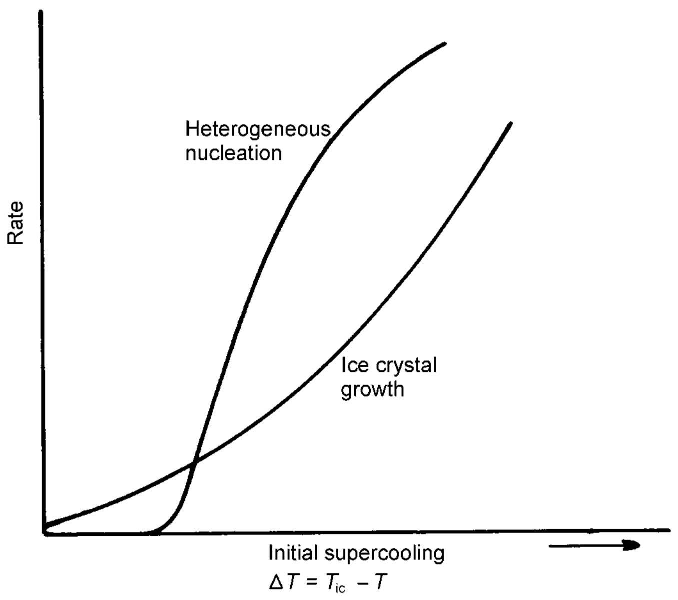

Fig. 7.1 Schematic curves for ice nucleation and crystal growth.

crystal growth. However, at very low temperatures, viscosity increases and nucleation can stop. Nucleation can be avoided only in very small objects exposed to extremely low temperatures (below the glass transition temperature which is approximately −135ºC in water). The glassy state is characterised by a reduced molecular mobility and a very high viscosity (higher than 10^{14} Pa.s).

The probability of nucleation depends on the volume of the sample and on the rate of heat removal. When the sample volume is small, the probability of nucleation is low, and very low freezing temperatures are required. At high freezing rates cooling advances more rapidly than crystal growth, making nucleation sites active, and there is an increase in the number of ice crystals formed.

Once nuclei have been formed, crystals can grow. Growth is not instantaneous. It is controlled by the rate of removal of the heat released during the phase change, as well as by the rate of mass transfer (diffusion of water from the surrounding solutions to the surface of the ice crystals). While nucleation requires several degrees of undercooling, crystal growth is possible with minimal undercooling (e.g. 0.01ºC).[2] As long as a stable ice crystal is present, further growth is possible. Crystal size varies inversely with the number of nuclei formed. Hence the mass of ice is distributed in a large number of small crystals when freezing rates are high, and conversely, at low freezing rates fewer nuclei are formed, leading to large crystal sizes.

The freezing of foodstuffs is more complex than the freezing of pure water.[1] Foodstuffs contain water and solutes, and their behaviour is similar to that of a solution. In the case of pure water (Fig. 7.2), temperature decreases from A to B and sensible heat is removed (4.18 KJ/kgºC); point S represents the supercooling. During nucleation heat is released in the system. This causes a rise in temperature to the melting point of 0ºC, and the temperature remains at 0ºC until all the water is converted to ice. (The latent heat of fusion for water is 333.15 J/g.) In the case of foodstuffs it is convenient to analyse the temperature–time curve obtained under the slowest freezing conditions, since this reasonably represents an equilibrium situation (Fig. 7.2). Following the onset of crystallisation at temperature S, the released heat of crystallisation causes the temperature to increase, reaching the initial freezing point of the system, which is determined by the number of dissolved solute molecules. Section B′C′ represents the period during which the major portion of the water is crystallised, and solute concentration shows a moderate increase in the unfrozen phase. During the last stages of the zone B′C′ and beyond, the possibility exists for the formation of eutectic mixtures and complex solids.

The initial freezing point of a solution directly depends on the molar concentration of the dissolved substances present in the system. Using basic thermodynamic principles, it is possible to predict the initial freezing point of different foodstuffs. Heldman[3] reported the following equation to calculate the initial freezing point (T_K, absolute temperature) and referred to the equilibrium freezing point of pure water (To = 273ºK):

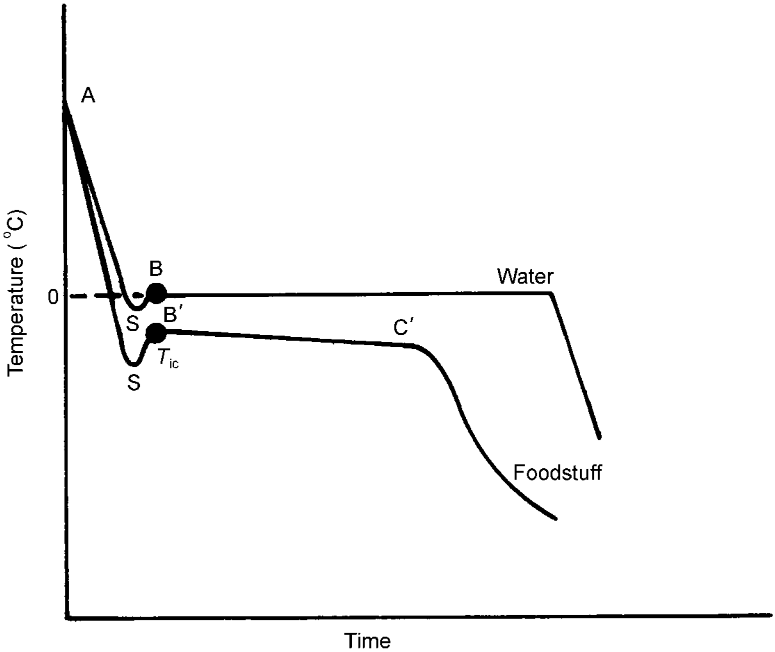

Fig. 7.2 Temperature–time curves for (a) pure water, (b) a foodstuff.

$$\Delta Tf = To - T_K = \frac{RTo^2 M_A m}{1000\lambda_A} = 1.86m \qquad 7.1$$

where: λ_A is the latent heat of fusion for pure water (6003 kJ/mol); M_A is the molecular weight of water (18 g/mol); m is the molality of the solution representing the food system (moles of solute/1000 g of solvent).

Foodstuffs with higher solute content show a lower initial freezing point. Table 7.1 shows typical values of melting points for different food systems.[1] As the products are progressively cooled below the initial freezing point, more water is turned into ice and the residual solution becomes more concentrated. The ratio of the ice to the residual solution is a function of temperature and initial concentration of solutes. At low temperatures (colder than −40°C) there is

Table 7.1 Initial freezing point of different foods

Type of food	Initial freezing point (°C)
Beef	−1.1
Common fruits	−0.9 to −2.7
Common vegetables	−0.8 to −2.8
Eggs	About −0.5
Milk	About −0.5

Source: adapted from Fennema.[1]

Table 7.2 Effect of temperature on frozen water percentage

Product	Total water content %	Frozen water in % of total water					Non-freezable water in % of total water
		−5C	−10C	−15C	−20C	−30C	
Lean beef	74	74	82	85	87	88	12
Haddock	83.5	80	87	89	91	92	8
Cod	80.5	77	84	87	89	91	9
Whole eggs liquid	74	85	89	91	92	93	7
White bread	40	15	45	53	54	54	46
Fruit juice	88	72	85	90	93	96	3
Spinach	90	88	93	95	96	97	2

Source: adapted from IIR.[5]

little or no measurable change in the amount of ice present in most frozen foods. Riedel has estimated that the amount of non-freezable water remaining is 0.2 to 0.4 g/g of dry matter.[4] At each temperature there is a determined mass of ice in equilibrium with the unfrozen solution. This is characteristic of each type of foodstuff and depends on water content (see Table 7.2). For example, in the case of beef tissue, with a total water content of 74 g water/g tissue, 80% of the water is converted to ice at −7ºC.

The first simple definition of freezing rate is a rate of temperature change. The characteristic local freezing time (tc) can be defined as the time needed to change the temperature from the initial freezing point to a temperature for which 80% of the total water content is converted to ice, in a given point of the system. However, this definition is of limited application because this rate varies with the position in the system; it is large in the surface near the refrigerated border and lower inside the product. A better definition of freezing rate might be to consider the rate of ice formation, or the rate of advance of the freezing interface, which is related to the rate of heat removal.

The freezing process is, for practical purposes, complete when most of the freezable water at the thermal centre of the product has been converted to ice. It is recommendable to freeze the product until the equilibrium temperature is −18ºC or colder, the desired storage temperature. According to the International Institute of Refrigeration,[5] the freezing rate of a food is defined as the ratio between the minimum distance from the surface to the thermal centre, and the time elapsed between the surface reaching 0ºC and the thermal centre 10ºC colder than the temperature of initial ice formation. In commercial practice mean freezing rates vary between 0.2–100 cm/h; 0.2–0.5 cm/h correspond to slow freezing (bulk freezing in cold chambers), 0.5–3 cm/h to quick freezing (air blast and contact plate freezers), 5–10 cm/h to rapid freezing (individual quick freezing of small-sized products in fluidised beds), and 10–100 cm/h to ultra rapid freezing by spraying or immersion in cryogenic fluids (liquid nitrogen, carbon dioxide).[5]

Characteristics of the ice–liquid interphase

During freezing of large food pieces, the heat released during the phase change is transferred across the unfrozen phase, and temperature decreases when moving away from the interphase. Simultaneously, the accumulation of solutes in the unfrozen phase near the interphase produces a concentration gradient that gives rise to a modification in the solid–liquid equilibrium temperatures (see Fig. 7.3). Equilibrium temperature decreases with increasing solute concentration; thus, a zone where supercooling ($\Delta T = T - Tf$) increases in front of the interphase can be generated. This situation leads to an unstable condition where the front of the ice is not flat, and protuberances grow ahead of the interphase due to greater supercooling.[6] This type of supercooling is known as constitutional supercooling, and cells of ice grow adjacent to each other with segregation of solute between them. In large food pieces nucleation is only produced in the border that is in contact with the refrigerating medium. The

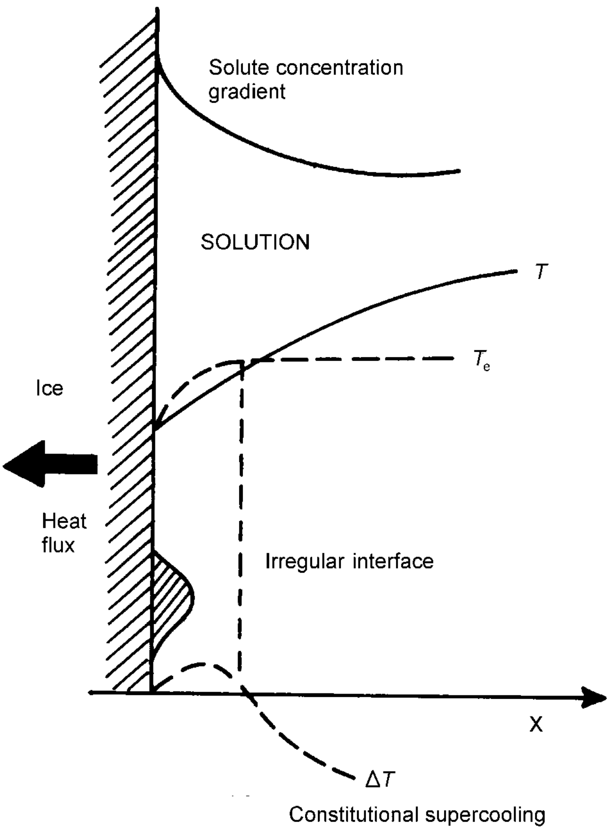

Fig. 7.3 Constitutional supercooling. The accumulation of solutes in the unfrozen phase of the ice–liquid interface produces a concentration gradient that modifies the equilibrium temperatures. Supercooling ($\Delta T = T - Tf$) increases in front of the interface and an irregular ice front is produced.

temperature rise caused by the crystallisation of these protuberances impedes any subsequent nucleation in the system. Supercooling takes place only in the near-surface layers of the food; in the inner zones, freezing proceeds more slowly. Growth of ice crystals is produced from the border towards the interior forming columns, where those oriented closest to the direction of the thermal gradient predominate, increasing the diameter of these columns from the refrigerated border to the centre of the foodstuff.

Food tissues are multicomponent systems composed of intra- and extracellular spaces. Ice nucleation starts generally in the extracellular spaces. However, if the rate of heat removal is high enough to eliminate the heat of crystallisation of the extracellular ice nuclei and to produce high supercooling inside the cells, intracellular nucleation also occurs. The existence of intracellular ice is an index of high freezing rates. The rate of ice crystal growth depends on the rate of heat removal and the diffusion of water to the surface of the growing crystal. Freezing inside the cells is related to the loss of water from the external environment via osmotic gradients. When ice starts to be formed in the extracellular space, solute concentration increases and water activity is reduced. In order to maintain chemical potential equilibrium, water migrates from the intracellular to the extracellular environment. A cell wall, or membrane, that is not a good barrier to water molecules will favour intracellular dehydration and growth of extracellular ice. In an attempt to balance the chemical potential, intracellular water migrates outwards, leading to dehydration and to an increase in the ionic strength of the cell. Water drawn from the interior of the cells will freeze onto the existing extracellular ice crystals.[7]

Most studies on freezing and ice crystal formation in foods, published in scientific literature prior to 1980, were performed on small samples where temperature gradients cannot, in practice, be detected. Therefore the extrapolation of these results to large food pieces has been difficult. Several works have been performed using meat cylinders to simulate the freezing process in a plate freezer with thermal flux parallel or perpendicular to muscle fibres. These studies permitted the system to be analysed in similar conditions to those of industrial processes. The effect of freezing rate on ice crystal size distribution in tissues was analysed by using the freeze fixation technique at low temperatures to determine the size of the ice crystals. Histological analysis in frozen beef tissues showed the formation of intracellular ice in a narrow zone only, adjacent to the area in contact with the cooling medium, that is where high freezing rates (or, in other words, low local freezing times) were observed.[8,9] The characteristic local freezing time (tc) in meat tissues was defined by the authors as the time necessary to change the temperature from −1ºC (initial freezing point for beef tissue) to −7ºC (80% of total water is converted to ice) in a given point of the system. Intracellular ice was observed when tc is lower than 0.5 min (see Fig. 7.4). Ice crystals that were nucleated in the surface grow towards the thermal centre of the meat piece in the form of columns (cell growth). As tc increases, intracellular ice disappears, and only the growth of extracellular columns is observed at the expense of the water from the fibre interior (Fig. 7.4).

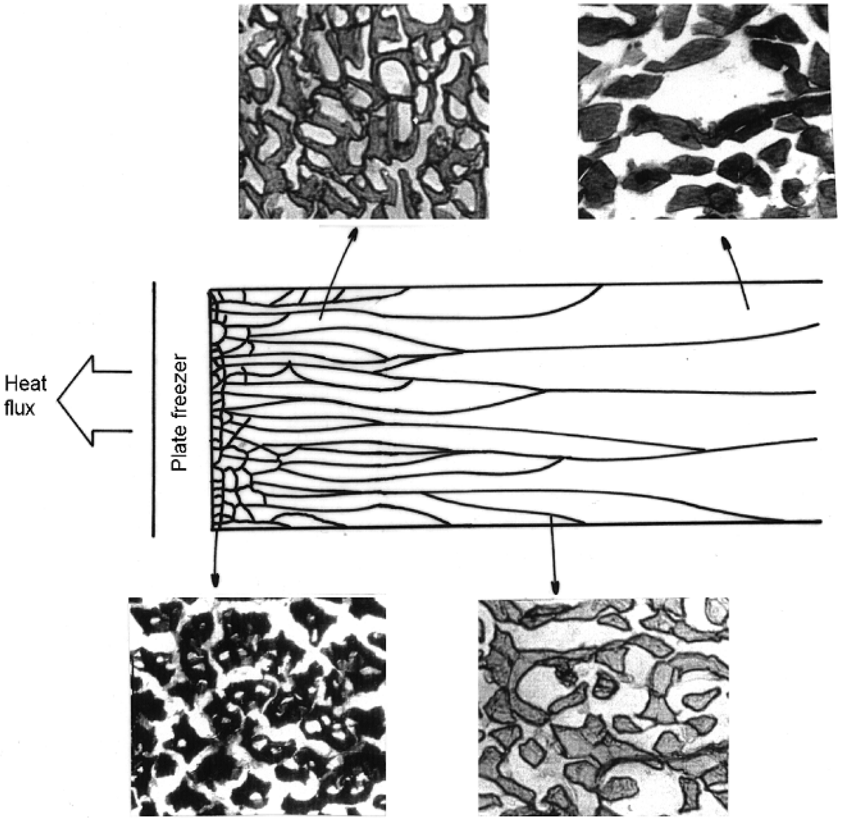

Fig. 7.4 Micrographs of the ice crystal pattern in a large piece of beef frozen with the heat flux parallel to muscle fibres. Intracellular ice is only observed at high freezing rates in the zone in contact with the cooling medium. (Source: adapted from Bevilacqua *et al.*)[8]

As a consequence of this dehydration, the shape of the fibres becomes irregular and distorted. In both works the mathematical relationship between the average diameter of the ice crystals and the local characteristic freezing time in the beef piece was determined.

Freezing rate also affects the surface colour of frozen systems, as in the case of beef liver tissues. High freezing rates lead to a pale colour, owing to the fact that crystals are small and produce a light scattering.[10]

7.1.2 Freeze-cracking

In general, high freezing rates lead to small ice crystal sizes and to better quality food systems. The formation of small ice crystals contributes to a homogeneous structure; little damage to the tissue can be detected, and drip losses are minimal. However, some products may crack when they are submitted to very high freezing rates or very low temperatures, as in cryogenic fluids. Freeze-cracking has been reported in the literature for different food products, and was reviewed recently by Hung.[11] Kim and Huang suggested that the crust formed during freezing on the surface of a product serves as a shell that prevents further volume expansion, when the internal portion of the unfrozen material undergoes phase transition.[12] If the internal stress is higher than the frozen material strength, the product will crack during freezing. Systems with high void spaces show a higher probability that internal stress will dissipate, instead of accumulate, reducing the possibility of freeze-cracking. Pre-cooling prevents freeze-cracking because it reduces the differences in temperature between the product and the freezing medium. Pre-cooling also reduces the time delay between the freezing of the border and the centre of the system; thus the centre of the food expands during ice formation at an earlier stage. When the phase change of the core region occurs before the surface becomes brittle, food products can support the internal pressure and freeze-cracking does not occur.

7.1.3 Moisture migration

During freezing, supercooling of cell contents can lead to moisture movement through an osmotic mechanism. During storage, the driving force for moisture migration is the temperature difference and resultant vapour pressure difference.[7]

Moisture losses in foods produce surface desiccation and freezer burn. Freezer burn is produced when frozen tissues are stored without an adequate moisture barrier and manifest as an opaque dehydrated surface; it is caused by the sublimation of ice on the surface region of the tissue when the water pressure of the ice is higher than the vapour pressure in the environment.[1] Moisture migration in packaged frozen food leads to ice formation inside the package. During thawing it produces drip, which leads to loss of nutrients, affects texture and juiciness and modifies the appearance of the product. Weight losses during freezing and frozen storage have economic consequences, unless the product is packaged in films of low water vapour permeability. According to Pham and Mawson,[13] typical weight losses during meat processing amount to 1–2% during chilling, 1% during freezing and about 0.5%–1% per month of storage and transport, unless the product is packaged in an impervious film. The rate of sublimation doubles for every 10ºC rise in temperature.

Moisture absorption and redistribution in the different food components is produced by differences in water activities. Components of a foodstuff that differ in their water activities produce moisture redistribution, and textural characteristics are lost. Moisture migration can be minimised by maintaining small temperature fluctuations and small internal temperature gradients, and by the inclusion of internal barriers within the product and within the packaging. Temperature fluctuations (cooling–warming cycles) lead to a net migration of moisture from the interior towards the surface of the foodstuff, or to the wrap. As ambient temperature decreases, moisture inside the pores sublimes and diffuses to the packaging film; when ambient temperature increases, the ice on the wrap tends to diffuse back to the surface of the food. However, reabsorption of water in the original location is improbable, and the process can be considered irreversible.

7.1.4 Recrystallisation of ice

Storage and transport conditions have great influence on the quality of frozen foods. Ice recrystallisation can be defined as the increase of the average size of the ice crystals. The driving force for this phenomenon is the difference in the surface energy of two adjacent crystals, this energy being proportional to the crystal curvature. Recrystallisation reduces the advantages of fast freezing, inducing physico-chemical changes that alter product quality. There is a direct relationship between crystal size and the number of faces the crystal has.[14] Small crystals with three or four faces show concave surfaces, and tend to disappear because the limit of the crystal migrates toward the centre of the curvature. Six-sided crystals have plane surfaces and are stable, and those with a higher number of faces tend towards growth. Crystal growth occurs at a constant temperature but is accelerated by fluctuations and thermal steps. Microscopic analysis of an aqueous solution that simulates the freezing point curve of beef tissue, and allows the behaviour of the ice crystal borders to be observed, was carried out by Martino and Zaritzky,[15] using polarised light. This technique allowed quantifying crystal size distribution as a function of storage temperature. A kinetic model based on the crystal mean curvature of the frozen system was postulated. Histograms of the relative frequencies of crystal diameters as a function of equivalent diameter were obtained for different freezing rates and storage conditions. Ice crystal size distributions were analysed from the micrographs. In meat tissues ice crystal size reached a limiting value *Dl*, that was related to the tissue matrix characteristics.[16] A mathematical model was fitted by Martino and Zaritzky,[16] considering that the driving force of this phenomenon is the difference between the instantaneous curvature of the system and the limit curvature:[14,16]

$$\frac{dD}{dt} = k\left(\frac{1}{D} - \frac{1}{Dl}\right) \qquad 7.2$$

where D is the mean equivalent ice crystal diameter at time t, Dl is the limit equivalent diameter and k the kinetic constant. Integration of equation 7.2 leads to the following expression:

$$\ln\left(\frac{Dl - Do}{Dl - D}\right) + \frac{1}{Dl}(Do - D) = \frac{k}{Dl^2}t \qquad 7.3$$

with Do = mean initial equivalent diameter. This model satisfactorily fitted the experimental data (see Fig. 7.5).

Activation energy of the recrystallisation process in frozen meat tissue (Ea = $42.37 \pm 4.75 \times 10^3$ J/mol) was comparable to that obtained in previous works by Bevilacqua and Zaritzky using short storage times, even though the limit diameters were not reached.[17] The activation energy was similar to the value

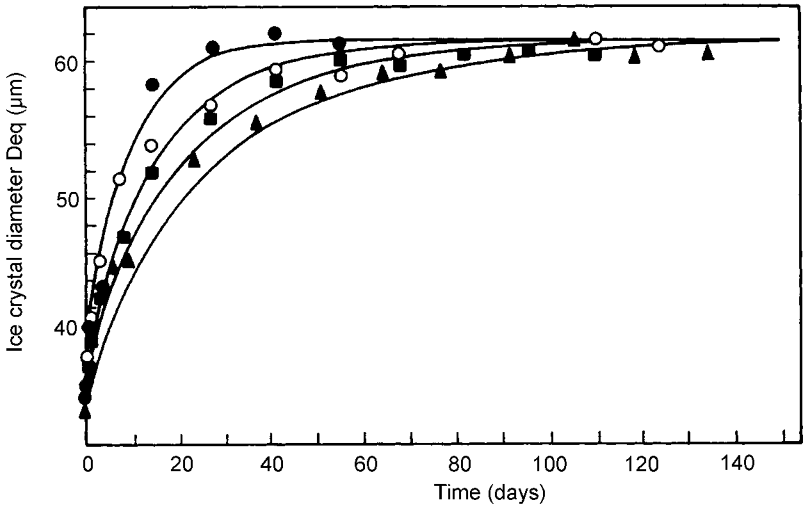

Fig. 7.5 Recrystallisation of ice in beef tissues. Effect of time and storage temperatures on mean equivalent diameters of the ice crystals. Solid line: theoretical model. Experimental data: ● −5ºC; ❍ −10ºC; ■ −15ºC; ▲ −20ºC. (Source: adapted from Martino and Zaritzky.)[14]

reported by Wagner and Añón,[18] obtained in the first stage of myofibrillar protein denaturation process in frozen beef tissues. These findings show the importance of recrystallisation during the initial storage period, before ice crystals reach their limit sizes. Concepts like dehydration, increase of the ionic strength and concentration gradients can be applied to recrystallisation. In the course of freezing and storage, each crystal is surrounded by a saline solution of a determined concentration. The increase in ice crystal diameter during recrystallisation leads to a redistribution of this solution around the tissue; its interaction with the protein structure contributes to denaturation, which also produces an increase of the exudate released by the tissue after thawing. Temperature fluctuations accelerate the rate of recrystallisation. As temperature increases, the small ice crystals melt. Then when temperature decreases again, since new nuclei cannot be formed, water is converted to ice on the existing crystals, hence increasing their size.[15,16]

Similar recrystallisation studies were performed in starch pastes (10% w/w wet basis) by Ferrero *et al.*[19,20] The addition of hydrocolloids such as xanthan gum (0.3% w/w wet basis) to corn starch pastes did not show a significant effect on ice crystal size at different freezing rates, compared to pastes without the gum;[21] indeed, xanthan gum did not avoid ice recrystallisation at all. Commonly hydrocolloids are recommended as ice crystal inhibitors, but different studies show that the stabilisation character of hydrocolloids should be explained on another basis,[22] such as their capability to undergo molecular entanglement in the freeze-concentrated matrix surrounding ice crystals.[21]

7.1.5 Drip loss

During freezing, pure water is separated from the system in the form of ice crystals. Solute concentration increases and melting temperature decreases following the thermodynamic equilibrium line. Freezing can also be considered as a dehydration process in which frozen water is removed from the original location in the foodstuff, and forms ice crystals. During thawing, water may not be reabsorbed in the original regions, leading to the formation of drip. Factors that affect drip losses are: size and location of ice crystals, rate of thawing, the extent of water reabsorption, the status of the tissue before freezing and the water-holding capacity of the tissue. In vegetable tissues water does not reabsorb into the cells; however, in animal tissues significant reabsorption of water occurs.[13] The thawing process must be conducted with care if quality and yield are to be preserved. Regardless of the selected procedure, energy must be provided to melt the ice. Thawing must be designed in order to minimise microbial growth, water release, evaporation losses and deteriorative reactions. Thawing requires longer times than freezing for comparable temperature driving forces. This is because during thawing the heat is transferred through the unfrozen zone of the foodstuff where thermal conductivity is lower than that of the frozen zone. With regard to exudate production, in frozen meats a slow thawing process at low temperatures is sometimes recommended to permit water diffusion in the thawed tissue and its relocation in the fibres.[6]

7.2 The chemistry of frozen foods

7.2.1 Chemical consequences of freezing and frozen storage

As the freezing process converts a large proportion of liquid water into ice, it also concentrates the remaining solution. Enzymes increase the possibility of water being in contact with different substrates. The most common chemical changes that can proceed during freezing and frozen storage are: lipid oxidation, enzymatic browning, flavour deterioration, protein denaturation and degradation of pigments and vitamins. Freezing can give unusual effects on chemical reactions. Temperature and concentration of the reactants in the unfrozen phase (freeze concentration effects) are the main factors responsible for changes in the reaction rates of enzymatic and non-enzymatic reactions during freezing. Formation of ice crystals can produce the release of enclosed contents in food tissues (enzymes and chemical substances) affecting the product during freezing and storage, leading to quality deterioration.

7.2.2 Lipid oxidation

Lipid oxidation is a complex process. A free radical process is the basic mechanism upon which lipid oxidation proceeds, and the process includes a number of stages.[23] During the initiation stage a hydrogen atom is abstracted from a fatty acid (RH), leaving a fatty acid alkyl radical (R•) that is converted in the presence of oxygen to a fatty acid peroxyl radical (ROO•) during the propagation step. In the next step, the peroxyl radical abstracts a hydrogen from an adjacent fatty acid (RH), forming a hydroperoxide molecule and a new fatty acid alkyl radical (ROO• + RH → R• + ROOH). Breakdown of the hydroperoxide is responsible for further propagation of the free radical process. One electron transfer from metal ions like haem and non-haem iron would dominate hydroperoxide breakdown during frozen storage.

Enzymatic and non-enzymatic pathways can initiate lipid oxidation. One of the enzymes that is considered important in lipid oxidation is lypoxygenase, which catalyses the addition of molecular oxygen to a cic-cis-4 pentadiene containing unsaturated fatty acid, releasing a stereo specific conjugated diene hydroperoxy fatty acid product.[23] Lipoxygenases are present in many plants and animals. If they are not inactivated by blanching then these enzymes can generate offensive flavours and loss of pigment colours. Membrane systems that reduce iron constitute another important system in the process of lipid oxidation. Redox active transition metals are major factors catalysing lipid oxidation in biological systems; iron in particular is a well-known catalyst.

The occurrence of lipid oxidation in frozen foods leads to loss of quality: flavour, appearance, nutritional value and protein functionality. Decomposition of hydroperoxides of fatty acids to aldehydes and ketones is responsible for the characteristic flavours and aromas known as rancidity.

Oxidative flavour deterioration is produced in both plant and animal products. It is identified more with frozen muscle than with frozen vegetable products, because blanching is typically applied to vegetables prior to freezing. Pigment degradation and colour quality deterioration is also related to lipid oxidation. Haem pigments in red meats and carotenoid-fading in salmonid flesh are subjected to oxidative degradation during storage. Chlorophyll is also capable of serving as a secondary substrate in lipid oxidation.[23]

7.2.3 Protein denaturation

The main causes of freeze-induced damage to proteins are ice formation and recrystallisation, dehydration, salt concentration, oxidation, changes in lipid groups and the release of certain cellular metabolites. Freeze-induced protein denaturation and related functionality losses are commonly observed in frozen fish, meat, poultry, egg products and dough.

Losses in functional properties of proteins are commonly analysed by comparing water-holding capacity, viscosity, gelation, emulsification, foaming and whipping properties. Freeze-induced protein denaturation is often attributed to the formation of ice crystals, dehydration and concentration of solutes in the tissue or in the protein solution.[24] Freezing has an important effect in decreasing water-holding capacity of muscle systems on thawing. This decrease occurs during freezing, because water–protein associations are replaced by protein–protein associations or other interactions. Oxidative reactions such as lipid peroxidation are also involved in deterioration of functional attributes of muscle proteins during frozen storage.

Dehydration of the cells caused by ice formation is an important factor that leads to protein denaturation. Proteins exposed to the aqueous medium of the biological tissues have a hydrophobic interior, and charged (or polar) side chains in the surface. During freezing, upon migration of water molecules from the interior of the cells (that is, in a more dehydrated state) protein–solvent interactions are disrupted; protein molecules exposed to a less polar medium increase the exposure of hydrophobic chains that modify protein conformation. To maintain the minimum free energy, protein–protein interactions via hydrophobic and ionic interactions occur, resulting in protein denaturation and the formation of aggregates. Hydrophobic interactions are generally weakened as temperature decreases; thus low temperatures destabilise proteins.

During freezing, proteins are exposed to increased concentration of salts in the unfrozen phase; a significant increase in the ionic strength can produce competition with existing electrostatic bonds, modifying the native protein structure. Oxidative processes during frozen storage can also contribute to protein denaturation; oxidising agents (enzymes, haem and transition metals) can react with proteins via lipid and non-lipid radicals. Texture deterioration in frozen muscle can be attributed to protein denaturation. Free fatty acids and formaldehyde are responsible for the changes.[24]

In the case of beef tissues, studies by differential scanning calorimetry and measurements of ATPase activity have demonstrated that the slower the freezing rate is, the higher the denaturation effect on myofibrillar proteins will be.[25] Sarcoplasmic proteins do not undergo denaturation by freezing. The head of the myosin molecule (HMM-S1; heavy meromyosin) is one of the most sensitive points to denaturation by freezing and frozen storage, although the contribution of other parts of the myosin molecule, and also of proteins of the thin filaments (actin) to the total denaturation, cannot be discarded. Denaturation of myofibrillar proteins observed during freezing can be attributed to the unfolding of the myosin molecule that exposes the hydrophobic groups. This induces protein aggregation during storage. During freezing (particularly in slow freezing) there is a marked decrease in myosin–actin affinity, with a parallel denaturation of the myosin head. The myosin head experiences gradual denaturation during storage. Moreover, the myosin tail is also denatured during storage but the thin filaments remain unaltered. Denaturation of myofibrillar proteins proceeds in two consecutive first-order reactions.

7.2.4 Enzyme activity

Storage at low temperatures can slow (but not inactivate) the enzymes in the tissue; enzymatic reactions occur in frozen foods. In raw and non-heated products, hydrolytic enzymes (hydrolases like lipases, phospholipases, proteases, etc., which catalyse the transfer of groups to water) may remain active during frozen storage. Blanching of vegetables or cooking of meat inactivate these enzymes. Hydrolytic enzymes can produce quality deterioration, a problem most commonly observed in meat products because plant tissues are submitted to pasteurisation and blanching.

Lipolytic enzymes, like lipases and phospholipases, hydrolise ester linkages of triacylglycerols and phospholipids respectively. If they are not controlled during storage, the hydrolysis of lipids can lead to undesirable flavour and textural changes. Certain lipases can remain active in frozen food systems stored at −29ºC.[26] Lipase activity has also been evident in the accumulation of free fatty acids in frozen fish samples. Freezing may accentuate lipolysis by disrupting the lysosomal membrane that releases hydrolytic enzymes, especially at low freezing rates and under fluctuating temperatures.[27] As the amount of unfrozen water changes during freezing, salt concentration also varies and would accelerate lysosomal release of lipases. During storage, lipolytic activity has detrimental consequences; release of short-chain free fatty acids can lead to hydrolytic rancidity, and may interact with proteins forming complexes that affect texture. The release of free fatty acids from triacylglycerol matrix may accelerate the rate of lipid oxidation and production of off-flavours.

Hydrolysis of proteins to peptides and amino acids is catalysed by proteases. In meat endogenous proteinases are considered beneficial, providing tenderisation of the muscle during rigor mortis. Yamamoto observed the degradation of Troponin T and myosin, by cathepsins released from damaged lysosomes.[28] Conditioned meat on freezing not only retained the texture quality, but also had a lesser tendency to drip on thawing.

In vegetable and fruit tissues, endogenous pectin methyl estearases catalyse the removal of the methoxyl groups from pectins. In the case of frozen strawberries, these enzymes produce gelation during storage. Hydrolytic enzymes, like chlorophylases and anthocynases present in plants, may catalyse destruction of pigments in frozen tissues affecting the colour, if they are not inactivated by blanching.

Hydrolytic rancidity, textural softening and colour loss are direct consequences of hydrolytic enzyme activities. However, textural toughening and acceleration of lipid oxidation may be secondary consequences. Other enzymes that contribute to deterioration during frozen storage of vegetables include several oxido-reductases such as lipoxygenases, catalases, peroxidases and polyphenoloxydase, as well as lipases and cystine liase.[29] The browning of plant tissue is caused by enzymatic oxidation of phenolic compounds in the presence of oxygen. Disruption of cells by ice crystals can start enzymatic browning by facilitating contact between o-diphenol oxidase and its substrate. The oxidoreductases are of primary importance because their action leads to off-flavour and pigment bleaching in vegetables, and to browning in some fruits. Lipoxygenase is the main enzyme responsible for pigment bleaching and off-odours in frozen vegetables.[30,31]

7.3 The impact of freezing on food quality

The period within which a food is safe to consume and has an acceptable quality can be considered as the shelf-life of a food. Micro-organisms are not usually a problem in frozen foods, since they cannot grow at freezing temperatures. The main factors that affect product quality of any given frozen food are initial quality of the original foodstuff, processing and packaging of the product, and temperature and duration of storage.

A great number of different fruits, vegetables and meats were tested at different storage temperatures for various lengths of time in the time–temperature–tolerance (TTT) experiments, performed by the USDA Western Regional Research Center in Albany, California,[32,33] since 1950. The quality was measured by organoleptic testing carried out by taste panels, and by various objective measurements such as ascorbic acid deterioration, the change of chlorophyll to pheophytin, colour, etc. Results were expressed as straight lines in a semi-logarithmic diagram as stability time vs. storage temperature. The practical storage life (PSL) of frozen foods depends not only on time and temperature of storage, but also to a large extent on product, process and packaging; these are the so-called PPP factors (product, process and packaging) introduced by Jul.[32] Another sensory method applied to frozen foods is known as 'just noticeable difference' (JND) or 'high quality life' (HQL) test, which is usually based on flavour changes.[32,33] Data on PSL and HQL of different frozen foods have been reported in the literature.[5,32,33] Mean values of the ratio PSL/HQL are: 1.95 for lean meat, 2.20 for fatty meat, 2.55 for fatty fish, 3.30 for vegetables, 2.95 for fruit and 2.9 for pre-cooked foods.[34]

7.3.1 Sensory quality: flavour, colour and texture

Meats have excellent frozen storage life.[35] However, freezing and thawing of myosystems decrease the water-holding capacity of the tissues, resulting in drip losses. Some muscles are susceptible to cold shortening and thaw rigor, and in general allowing the muscle to undergo rigor mortis prior to freezing is recommendable. The two important causes of quality loss in frozen meat are lipid oxidation and protein denaturation. The development of oxidative rancidity in frozen stored muscles (mainly pork and fish) is caused by the accumulation of carbonyl compounds formed during autoxidation of muscle lipids. Enzymatic hydrolysis of lipids, with the liberation of free fatty acids, occurs during the frozen storage of meats. In red meats, colour is determined by the relative concentration of purple myoglobin, bright red oxymyoglobin and brown metmyoglobin. Freezing/thawing accelerates pigment oxidation and the production of metmyoglobin.[36,37]

Metmyoglobin formation in red meats and carotenoid bleaching in fish and poultry tend towards parallel fat oxidation.[31] In the case of fish, the major problems found during freeze processing are oxidative deterioration, dehydration, toughening, loss of juiciness and excessive drip. Fish fat contains a higher proportion of polyunsaturated fatty acids, and is more susceptible to the development of rancidity by oxidation; myofibrillar proteins of fish are denatured by freezing.

Vegetables preserved by freezing compare favourably with the unfrozen equivalents from the organoleptic and nutritional point of view. During freezing, the formation of ice in the tissues of fruits and vegetables results in undesirable changes in texture, e.g. loss of turgor during thawing. Preservation by freezing is applicable to those vegetables that are cooked for consumption only. During slow freezing of fruit tissues, extracellular ice crystals can damage cell walls and middle lamellae to such an extent that the thawed product is much softer than the fresh fruit; rapid freezing is better to maintain the textural quality of the tissue. The texture damage often observed in frozen thawed plant tissues is attributed to the semi-rigid nature of the cells and the less orderly packaging of the cells in the tissue. Muscle cells are less susceptible to break as a consequence of freezing and thawing.

Loss of membrane semi-permeability and disruption of cellular compartments in fruits and vegetables can be minimised using rapid freezing rates, low storage temperatures and slow thawing. Softening caused by freeze–thawing can sometimes be minimised by pre-treatment of the tissue with calcium chloride and/or sucrose. Other procedures that are applied to maintain the texture of fruits, besides the chemical treatment, include blanching and control of ice crystal size during nucleation and growth.

The most common chemical changes related to quality deterioration in frozen fruits and vegetables are reactions that produce off-odours and off-flavours, pigment degradation, enzymatic browning and autoxidation of ascorbic acid. Certain frozen fruits undergo enzymatic oxidative discoloration due to the action of the polyphenoloxidases on naturally phenolic constituents. Ascorbic acid was introduced alone (or in combination with bisulphite)[5] as an inhibitor of enzymatic reactions. Vegetables undergo such browning if they are not blanched. Another change in colour is the partial loss of anthocyanin pigments in frozen berries. Improvement of colour and flavour can be achieved by packaging the fruits with sugar or syrup, and by decreasing storage temperature to −18ºC. Chlorophylls and carotenes are usually well retained in frozen vegetables, but some degradation occurs during storage. During frozen storage of blanched green vegetables at −18ºC or above, the bright green colour of the recently frozen product (a and b chlorophyll pigments) slowly changes to brownish green (pheophytin). The rate of pigment degradation depends on the amount of tissue damaged prior to freezing.

Unblanched (or underblanched) vegetables change in flavour due to the action of lipases and lipoxygenases. Volatile compounds such as carbonyl compounds and ethanol accumulate in the tissue, producing off-odours.[1]

In the case of pre-cooked frozen foods, they normally include starch-based systems (sauces, gravies, etc.) which act as protective agents for the solid elements, minimising dehydration and chemical changes during storage. In starch-based foodstuffs, after starch gelatinisation, an amylose matrix filled with granules of different degrees of fragmentation is obtained. Starch gels are metastable and non-equilibrium systems, and therefore undergo structural transformation during storage and processing. Upon ageing, starch retrogradation is produced, which involves partial crystallisation of starch components. Starch molecules reassociate, depending on the affinity of hydroxyl groups and the attractive forces or hydrogen bonding between hydroxyl groups on adjacent chains. The process induces an increase of paste rigidity in the viscoelastic system. Starch retrogradation consists of two distinct processes: a rapid gelation of amylose via formation of double helical chain segments that is followed by helix–helix aggregation, and a slow recrystallisation of short amylopectin chain segments.[38,39] Starch systems undergo freezing damage like rheological changes and syneresis after thawing, which may alter the desired characteristics of the products, reducing consumer acceptability. Freezing rate has an important effect on exudate production in corn starch pastes.[21] High freezing rates (>100 cm/h) lead to lower exudate values. During frozen storage at −5°C a spongy matrix is formed. This structure was not observed when samples were frozen in liquid nitrogen. The spongy structure is attributed to the water release caused by slow freezing, producing local high starch polymer concentrations and interaction between molecular chains. Amylopectin retrogradation measured by differential scanning calorimetry (DSC)[21] was only detected for corn starch pastes frozen at low rates (<1 cm/h). Storage temperature also has an effect on starch retrogradation. Amylopectin retrogradation was detected at −1°C and −5°C, but not at lower temperatures. Textural characteristics of sponginess observed at low freezing rates, and at high storage temperatures, can be attributed to amylose retrogradation, described as the coarsening of the fibrillar network.

The use of hydrocolloids is highly recommended in the food industry, in order to restrict syneresis and ice crystal growth besides their traditional role of texturisers and emulsion stabilisers. The addition of xanthan gum to starch gelatinised systems decreases exudate production and avoids the formation of the spongy structure, even at low freezing rates and at high storage temperatures. These effects can be explained, considering that amylose–hydrocolloid interaction competes with amylose–amylose aggregation, decreasing the probability of amylose retrogradation occurrence. However, xanthan gum did not modify the effect of freezing on amylopectin retrogradation, because amylopectin remains within the starch granule, and xanthan gum does not act at this level.[19,21]

7.3.2 Nutritional aspects

In general, freezing preservation is considered to be a method that delivers a product comparable in nutritional quality to the fresh product. Available experimental data tend to show that this method is less destructive than other processing methods. When the nutritive value of fresh and frozen food is compared, one should be careful to measure the nutritive value as it is eaten with the percentage of nutrient retained from the original cooked product, otherwise variations in cooking yields may lead to errors.

Several of the unsaturated fatty acids are considered nutritionally essential or beneficial. Although they are one of the major substrates for lipid oxidation, the losses are not limiting in most of the frozen products.[23] Protein damage in frozen tissues is considered minimal in comparison to total available protein. The degradation of vitamins during the freezing process, in contrast to lipid and protein degradation, generally has a more significant impact on nutritional value. Ascorbic acid losses have been studied in fruits and vegetables generally, and are attributed to oxidative mechanisms during frozen storage. However, blanching is an important contributor to vitamin degradation.

The main adverse effect of extended frozen storage on nutritive value may be the losses in the more labile vitamins, such as some of the water-soluble B vitamins (B1, thiamin; B2, riboflavin) and vitamin C (ascorbic acid), which are frequently used as indicators of the severity of food processing.[32] However, rates of deterioration are extremely slow in comparison to ambient or chilled storage. No specific effect of temperature fluctuations regarding the retention of B group vitamins was detected in frozen meat.[32]

In the presence of dissolved oxygen, ascorbic acid in aqueous solution is oxidised to dehydroascorbic acid and other oxidised products. Ascorbate oxidase exists naturally in many plant tissues, and if it is not inactivated, it catalyses ascorbic acid oxidation during the freezing process.

7.3.3 Microbiology of frozen products

The major objective of freezing as a method for food preservation is to prolong storage life of the products by retarding or inhibiting microbial growth. Freezing (and the subsequent frozen storage) can produce certain lethality in some micro-organisms but this process is very slow and variable, depending on the type of foodstuff. Freezing cannot be regarded as a method to reduce microbial contamination; for this reason, hygienic and sanitary conditions prior to processing are very important. Storage temperatures below −10ºC inhibit bacterial growth, whereas yeasts and moulds cannot multiply below −12ºC and −18ºC, respectively.[5]

Thawed food deterioration occurs at the same rate as in unfrozen products; however, humidity condensation on the surface and release of nutrients through drip loss can accelerate microbial multiplication.

Freezing is an important method to preserve foods from microbiological spoilage and to control proliferation of food-borne pathogens. The detrimental effects of freezing on micro-organisms are related to cold shock, concentration of extracellular solutes, toxicity of intracellular solutes, cell dehydration and internal ice formation. Souzu *et al*. reported that the freeze-induced injury in micro-organisms is mainly due to dehydration of lipid-rich membranes, being the phospholipid fraction the most involved in the membrane structural changes.[40] Higher levels of unsaturated fatty acids in microbial membranes preserve the functionality of the membrane maintaining the lipid in a fluid and mobile state. Gram-positive bacteria are generally more resistant to freezing than Gram-negative bacteria.[41,42] Quick freezing favours microbial survival; the rate of microbial decline is generally high during the initial stages of freezing but then decreases with time. Micro-organisms are injured more between −2°C and −10°C than at −15°C. Lethality at these temperatures is attributed to protein denaturation. At −30°C the effects of freezing are less pronounced; below −60°C microbial destruction is slow. Sensitivity of micro-organisms to freezing depends on physiological activities of the cells. Micro-organisms in exponential growth rate are more sensitive to freeze damage than cells in stationary phase. During lag phase, micro-organisms are not practically susceptible to a rapid temperature decrease. An increase of the proportion of unsaturated acids is considered one of the reasons that explain the increase of microbial tolerance to freezing (see Chapter 2 for further detail).

7.4 New trends in research

One of the new trends in research is related to the analysis of glass transitions in frozen foods. Most food materials can be considered biopolymers and exist in an amorphous state, which is a non-equilibrium state at temperatures below the equilibrium melting temperature of the material. Melting of crystalline polymers results in the formation of an amorphous melt, which can be supercooled to a viscoelastic, rubbery state or to a solid glassy state. The transition between the rubbery and glassy states is known as the glass transition. Glass transitions, as physico-chemical phenomena, govern food properties and stability. Below the glass transition temperature (T_g), polymer material becomes glassy, and the molecular motion is so slow that crystallisation does not occur in a finite period of time. Thus, deterioration governed by diffusion is inhibited. At temperatures above T_g and below the crystal melting temperature (T_m), the material is rubbery and sufficient motion of polymers occur to allow crystallisation. Ice formation in food materials results in freeze concentration of the solutes. Non-equilibrium ice formation is a typical phenomenon of rapidly cooled biological materials at low temperatures. Freeze concentration and lowering temperature increases the viscosity of the unfrozen phase until this concentrated solution becomes a glass.[43] Rapidly cooled materials can be rewarmed to a devitrification temperature to allow ice formation. The glass transition temperature of a slowly frozen sample is higher than that of a rapidly cooled sample, and is considered to be the glass transition temperature of the freeze-concentrated solute matrix surrounding the ice crystals in a maximally frozen solution (T'_g).[44]

Roos and Karel suggested that formation of such maximally frozen solutions with a solute concentration (C'_g) in the unfrozen matrix requires annealing slightly below the initial ice melting temperature within the maximally frozen solution.[45] Solutions cooled rapidly to temperatures lower than T'_g show non-equilibrium ice formation. The cryostabilisation of frozen foods is related to the possibility of maintaining the product below the glass transition temperature of the freeze-concentrated matrix (T'_g), or to modify the formulation of the food to increase glass transition temperatures to above normal storage temperatures. Frozen foods stored below T'_g are stable to ice recrystallisation and other physical changes.[46] Levine and Slade postulated that stability is related to temperature difference between storage temperature and T'_g.[47]

Ferrero *et al.*[48] using differential scanning calorimetry reported T'_g onset values ranging between −4.5°C and −5.5°C for annealed frozen starch pastes (see Fig. 7.6); Slade and Levine,[49] reported similar temperature ranges. This is an important finding and can explain the physical behaviour of frozen starch pastes. Lack of detectable starch retrogradation, during frozen storage at −10°C and −20°C, can be explained by considering that below T'_g amylose and amylopectin chains have a reduced mobility that limits the molecular association responsible for the retrogradation problems. Rapid freezing and storage at low temperatures (below T'_g) avoids the crystallisation of amylose and amylopectin

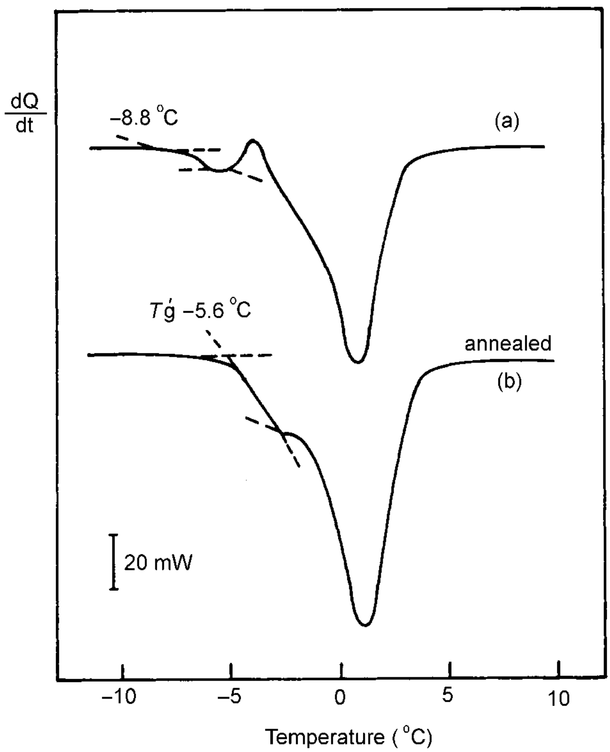

Fig. 7.6 Differential scanning calorimetry thermograms of gelatinised starch pastes (0.5 g starch/g mixture) during thawing. The temperatures shown represent the onset values of the glass transitions. Curve (a) corresponds to a sample without annealing. Curve (b) corresponds to a sample annealed 30 min at −4.5°C; the indicated value is the glass transition temperature of the freeze-concentrated solute matrix surrounding the ice crystals (T'_g). (Source: adapted from Ferrero *et al.*)[48]

in the concentrated matrix, leading to a homogeneous structure without a spongy network, and the absence of amylopectin retrogradation. Knowledge of the influence of factors such as freezing rate and composition of the system on glass transition temperature would help to determine adequate formulations, processing or storage conditions in order to enhance the shelf-life of frozen foods.

As previously discussed, the addition of hydrocolloids like xanthan gum helps to maintain the rheological characteristics of unfrozen starch pastes, even under low freezing conditions. Xanthan gum does not prevent amylopectin retrogradation, but inhibits the development of a spongy structure produced by amylose retrogradation. Ferrero *et al.*[48] demonstrated that the addition of hydrocolloids did not modify the value of T'_g in frozen starch systems. These findings allowed us to conclude that hydrocolloids stabilised frozen starch pastes without changing the value of T'_g, but simply by increasing the system viscosity.

7.5 Summary: maximising quality in the freezing processes

Freezing is an excellent method for food preservation. The removal of water by converting it into ice reduces water activity. Furthermore, low temperatures inhibit the growth of micro-organisms and decrease the rate of biochemical reactions that normally occur in unfrozen foods. Freezing should not, however, be regarded as a method of reducing microbial contamination; for this reason, hygienic and sanitary conditions before processing are very important. Storage temperatures below −10ºC prevent all bacterial growth. Conversion of water into ice starts complex physico-chemical changes, which causes deteriorative modifications. Water is removed from the original location forming ice crystals; their sizes depend mainly on the freezing rate. The conversion of water into ice increases the concentration of solutes in the unfrozen fraction of the tissue, increasing ionic strength, changing pH, etc. Crystal growth and the ultimate size and shape of the ice crystals in the cellular spaces are highly related to eventual quality and drip loss.

Physical changes in frozen foods include drip losses, moisture migration, freeze-cracking and ice recrystallisation. Other important changes that can be detected during freezing and frozen storage are protein denaturation, lipid oxidation, enzymatic browning, flavour deterioration and degradation of pigments and vitamins. Formation of ice crystals can cause disruption in the frozen tissues, leading to the release of enzymes and chemical substances that affect quality. Discoloration can be produced mainly by enzymatic and non-enzymatic browning and freeze burn.

Shelf-life of a frozen product can be increased, depending on the quality of raw materials, pre-freezing treatment, rate of freezing, packaging film and storage conditions. Quality deterioration is accentuated by fluctuating time–temperature conditions during storage. High freezing rates and storage at low temperatures minimise deteriorative changes.

Frozen food stored below T_g' (the glass transition temperature of the freeze-concentrated solute matrix surrounding the ice crystals in a maximally frozen solution) can be considered stable to physical changes. However, the glass transition concept does not explain all the changes occurring in frozen foods.

7.6 References

1 FENNEMA. O., POWRIE, W. and MARTH, E. *Low Temperature Preservation of Foods and Living Matter*, New York, Marcel Deker, 1973.

2 REID, D. S. 'Fundamental physicochemical aspects of food freezing', *Food Technol.*, 1983, **37**, 110–15.

3 HELDMAN, D. R. 'Predicting the relationship between unfrozen water fraction and temperature during food freezing using freezing point depression', *ASHRAE Transactions*, 1974, 91 part 2B, 371–84.

4 RIEDEL, L. 'Calorimetric investigations of the meat freezing process', *Kaltetechnik*, 1957, **9**(2), 38–40.

5 International Institute of Refrigeration *Recommendations for the Processing and Handling of Frozen Foods*, Paris, 1972.

6 CALVELO, A. 'Recent studies on meat freezing', in *Developments in Meat Science*, vol. 2, ed. R. Lawrie, London, Applied Science Publishers, 1981, 125–58.

7 REID, D. S. 'Overview of physical/chemical aspects of freezing', in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997.

8 BEVILACQUA, A., ZARITZKY, N. and CALVELO, A. 'Histological measurements of ice in frozen beef', *J. Food Technol.*, 1979, **14**, 237–51.

9 BEVILACQUA, A. and ZARITZKY, N. 'Ice morphology in frozen beef', *J. Food Technol.*, 1980, **15**, 589–97.

10 ZARITZKY, N. E., AÑÓN, M. C. and CALVELO, A. 'Rate of freezing effect on the colour of frozen beef liver', *Meat Sci.*, 1982, **7**, 299–312.

11 HUNG, Y. C. 'Freeze cracking', in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997.

12 KIM, N.K. and HUANG, Y. C. 'Freeze cracking in foods as affected by physical properties', *J. Food Sci.*, 1994, **59**, 669–74.

13 PHAM, Q. T. and MAWSON, R. F. 'Moisture migration and ice recrystallization in frozen food', in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997.

14 MARTINO, M. N. and ZARITZKY, N. E. 'Ice recrystallization in a model system and in frozen muscle tissue', *Cryobiol.*, 1989, **26**, 138–48.

15 MARTINO, M. N. and ZARITZKY, N. E. 'Effects of temperature on recrystallization of polycrystalline ice', *Sciences des Aliments*, 1987, **7**, 147–66.

16 MARTINO, M. N. and ZARITZKY, N. E. 'Ice crystal size modifications during frozen beef storage', *J. Food Sci.*, 1988, **53**, 1631–7, 1649.

17 BEVILACQUA, A. E. and ZARITZKY, N. E. 'Ice recrystallization in frozen beef',

J. Food Sci., 1982, **47**, 1410–14.

18 WAGNER, J.R. and AÑÓN, M.C. 'Effect of frozen storage on protein denaturation in bovine muscle. I. Myofibrillar ATPase activity and differential scanning calorimetric studies', *J. Food Technol.*, 1986, **21**, 9–18.

19 FERRERO, C., MARTINO, M. and ZARITZKY, N. 'Stability in frozen starch pastes. Effect of freezing storage and xanthan gum addition', *J. Food Process Preserv.*, 1993, **17**(3), 191–211.

20 FERRERO, C., MARTINO, M. and ZARITZKY, N. 'Corn starch, xanthan gum interaction and its effect on the stability during storage of frozen gelatinized suspensions', *Starch*, 1994, **46**, 300–8.

21 FERRERO, C., MARTINO, M. and ZARITZKY, N. 'Effect of freezing rate and xanthan gum on the properties of corn starch and wheat flour pastes', *Int. J. Food Sci. and Technol., 1993,* **28**, 481–98.

22 REID, D.S., ALVIER, M.S. and LIM, M.H. 'The rates of change of ice crystal size in model systems stored at different temperatures relevant to the storage of frozen food', in *Proceedings of the XVIth International Congress of Refrigeration*, Austria, vol. C, pp. 397–401, 1987.

23 ERICKSON, M.C. 'Lipid oxidation: flavor and nutritional quality deterioration in frozen food', in *Quality in Frozen Food*, ed. M.C. Erickson and Y.C. Hung, New York, Chapman & Hall, 1997.

24 XIONG, Y.L. 'Protein denaturation and functionality losses', in *Quality in Frozen Food*, ed. M.C. Erickson and Y.C. Hung, New York, Chapman & Hall, 1997.

25 WAGNER, J.R. and AÑÓN, M.C. 'Effect of freezing rate on the denaturation of myofibrillar proteins', *J. Food Technol.*, 1985, **20**, 735–44.

26 ZARITZKY, N.E. 'Mathematical simulation of the thermal behavior of frozen meat during its storage and distribution', *J. Food Proc. Eng.*, 1982, **6**, 15–36.

27 SISTA, R.V., ERICKSON, M.C. and SHEWFELT, R.L. 'Quality deterioration in frozen foods associated with hydrolitic enzyme activities', in *Quality in Frozen Food*, ed. M.C. Erickson and Y.C. Hung, New York, Chapman & Hall, 1997.

28 YAMAMOTO, K. 'Electron microscopy of thermal aggregation of myosin', *J. Biochem.*, 1990, **108**(6), 896–8.

29 WILLIAMS, D.C., LIM, M.H., CHEN, A.O., PANGBORN, R.M. and WHITAKER, J.R. 'Blanching of vegetables for freezing: which indicator enzyme to choose', *Food Technol.*, 1986, **40**, 130–40.

30 VELASCO, P.J., LIM, M.H., PANGBORN, R.M. and WHITAKER, J.R. 'Enzymes responsible for off-flavor and off-aroma in blanched and frozen-stored vegetables', *Biotech. Appl. Biochem.*, 1989, **11**, 118–27.

31 HAARD, N.F. 'Product composition and the quality of frozen foods', in *Quality in Frozen Food*, ed. M.C. Erickson and Y.C. Hung, New York, Chapman & Hall, 1997.

32 JUL, M. *The Quality of Frozen Foods*, London, Academic Press, 1984.

33 VAN ARSDEL, W. B., COPLEY, M. J. and OLSON, R. L. *Quality and Stability of Frozen Foods: Time–Temperature–Tolerance and its Significance*, New York, Wiley Interscience, 1969.

34 FU, B. and LABUZA, T. ‘Shelf life testing: procedures and prediction methods’, in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997.

35 MARSDON, J. L. and HENDRICKSON, R. L. ‘Meat and meat products’, in *Frozen Food Technology*, ed. C. P. Mallet, New York, Chapman & Hall, 1993.

36 LANARI, M. C., BEVILACQUA, A. E. and ZARITZKY, N. E. ‘Pigments modifications during freezing and frozen storage of packaged beef’, *J. Food Proc. Eng.*, 1990, **12**, 49–66.

37 LANARI, M. C. and ZARITZKY, N. E. ‘Effect of packaging and frozen storage temperatures on beef pigments’, *Int. J. Food Sci. Technol.*, 1991, **26**, 629–40.

38 MILES, M. J., MORRIS, V. J., ORFORD, P. D. and RING, S. G. ‘The roles of amylose and amylopectin in the gelation and retrogradation of starch’, *Carbohydr. Res.*, 1985, **135**, 271–81.

39 MORRIS, V. J. ‘Starch gelation and retrogradation’, *Trends Food Sci. Technol.*, 1990, **7**, 1–6.

40 SOUZU, H., SATO, M. and KOJIMA, T. ‘Changes in chemical structure and function in Escherichia coli cell membranes caused by freeze thawing. II. Membrane lipid state and response of cells to dehydration’, *Biochim. Biophys. Acta*, 1989, **978**, 112–18.

41 MAZUR, P. ‘Cryobiology: the freezing of biological systems’, *Science*, 1970, **168**, 939–49.

42 GOLDEN, D. A. and ARROYO GALLYOUN, L. ‘Relationship of frozen food quality to microbial survival’, in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997.

43 ROOS, Y. *Phase Transitions in Foods*, Food Science and Technology International Series, San Diego, Academic Press, 1995.

44 LEVINE, H. and SLADE, L. ‘A polymer physicochemical approach to the study of commercial starch hydrolysis products (SHPs)’, *Carbohydr. Polym.*, 1986, **6**, 213–44.

45 ROOS, Y. and KAREL, M. ‘Applying state diagrams to food processing and development’, *Food Technol.*, 1991, **45**, 66, 68–71, 107.

46 GOFF, H. D. ‘Measurement and interpretation of the glass transition in frozen foods’, in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997.

47 LEVINE, H. and SLADE, L. (eds) *Water Relationship in Foods*, New York, Plenum Press, 251–73, 1991.

48 FERRERO, C., MARTINO, M. and ZARITZKY, N. ‘Effect of hydrocolloids on starch thermal transitions, as measured by DSC’, *J. Thermal Anal.*, 1996, **47**, 1247–66.

49 SLADE, L. and LEVINE, H. ‘Beyond water activity: recent advances based on an alternative approach to the assessment of food quality and safety’, *Crit. Rev. Food Sci. Nutr.*, 1991, **30**, 115–360.

8

Freezing processed foods

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8.1 Introduction

The prepared consumer foods sector, embracing ready meals and convenience foods, is growing steadily in most European countries as a result of lifestyle changes including one-parent families, two partners working, increased longevity, and other factors. The demand is leading to an increasingly diverse range of foods, many of them multi-component, and many of them frozen. It is essential that these frozen foods are of high sensory and nutritional quality, and are safe, as they are forming an increasingly significant part of the food intake on a population basis. These foods create a new challenge for food technologists and the food industry.

In this chapter we will discuss three categories of processed foods: ready-to-eat meals, bakery products and ice cream. In each case the levers that the manufacturer has to control quality are the following:

- choice of ingredients;
- pre-treatments of ingredients;
- choice of freezing method.

The factors that determine these choices may, however, be quite different in the different categories.

8.2 Ready meals

Frozen ready meals first appeared in the form of TV dinners. These were usually three-component meals, meat and potato plus one other vegetable, which could be reheated from frozen. They were mainly targeted at the busy consumer who did not have, or did not wish to take, the time for traditional meal preparation. Over the last 10–15 years, however, the frozen ready meal has extended to cover a large variety of meal types and there are now few dishes that can not be purchased in this form.

Consumer perception of frozen foods is moving away from a traditional view of these products as cheap convenience meals towards an appreciation of quality factors. The frozen food manufacturer needs to be increasingly aware of the parameters that go towards making a high quality frozen food.

In 1998 frozen food sales in the United Kingdom had reached £3.756 billion, an increase of 3.7% on the previous year. Of these sales, ready meals accounted for £574.5 million. These can be broken down into three categories:

1. Traditional meals (£207.8 million).
2. International meals (£309.3 million). This category is marked by high rates of innovation, particularly in Indian authentic. However, the Indian mainstream market is the biggest sector, currently worth £56m.
3. Healthy meals (£57.3 million). These are meals that pay particular attention to fat content in recipe design. This market has declined significantly by £14.7m versus 1997.

Product lives (i.e. the time period over which a product is in production) have fallen rapidly and the average product life in the ready meals sector is now as low as six months. This reflects the high demand for variety in the prepared meals sector and its susceptibility to food fashion.

8.2.1 Quality parameters

Quality parameters for frozen meals can be readily divided into nutritional parameters and those affecting eating quality and appearance. As consumers become increasingly aware of the needs for a balance in nutritional intake, the emphasis on nutritional content of frozen ready meals is likely to increase, particularly where these are being used as a fast, convenient method of catering to families.

It is a common perception that fresh foods prepared in the home will automatically have a higher nutritional content than manufactured foods. In fact the converse may well be true. First, the domestic cook will often have access to ‘market-fresh’ produce only, rather than ‘garden fresh’. In terms of vitamin C and folate content, this may be greatly reduced within the first 24 hours after harvesting and market-fresh produce may be expected to be at least this old. The manufacturer with a well-controlled supply chain should be able to improve on this routinely. The manufacturer should also have greater control of selection of varieties which is the major source of variation in nutritional content of vegetables.

The loss of water-soluble vitamins in frozen foods is largely connected with processing before freezing. In particular vitamin C and folate content are dependent on blanching times and process. The B vitamins and carbohydrate and protein content are less affected by process and more by loss through drip following a freeze–thaw cycle. The heat-labile nutrients include thiamin, carotene, vitamin C and many proteins. Retention of these nutrients will be a function of heating and chilling treatments.

Recipe design and ingredient selection play the major role in determining the nutritive value of a prepared meal. In assessing an individual's dietary intake, account needs to be taken of their entire diet and not just individual meals. However, if ready meals are to represent a 'healthy' portion of this intake then recipes need to be targeted towards recommended energy intake balances. In developed countries the increase in fat intake, and saturated fat intake in particular, has been linked by many studies to the increase in coronary heart disease and obesity. This has led to recommendations by the World Health Organization (WHO) and others that the degree of energy intake from these food types needs to be reduced. Total fat intake should provide less than 30% of energy intake and saturated fats less than 10%.

A balanced diet, however, needs to contain at least two essential fats, linoleic acid and alpha linoleic acid. The major link between fat intake and coronary disease is identified as high levels of cholesterol in the blood. Linoleic acid is believed to reduce cholesterol and perhaps therefore to aid in protection against such disease. Energy intake from protein is, on average, 10–15% in the developed world. This is generally accepted as a suitable level.

Vitamin intake is monitored according to recommended daily intake. The majority of vitamin C intake comes from vegetable matter while meats provide the majority of the B vitamins. Initial vitamin C content can vary widely between different varieties of the same vegetable. Retention of this vitamin is often used as a marker for quality as it is the most readily reduced by heating or storage. Retaining ascorbic acid requires rapid chilling or freezing after harvest, and good control of the blanching process. Insufficient blanching will leave residual enzyme activity with consequent reduction of ascorbic acid during storage. Excessive blanching or slow chilling after blanching will lead to reduction from the heat-labile nature of this vitamin.

The salt content of meals is also a quality factor because of the links between excessive sodium consumption and hypertension. The recommended daily intake of salt for adults is 0.6 g per day. Currently in the United Kingdom average daily intake is 10–12 g with 50% of this added in food processing. The design of healthy ready meals needs to find a balance between control of sodium intake and the satisfying of consumer tastes.

Many factors contribute to the eating quality of frozen ready meals. Most importantly all of the quality factors that apply to freshly prepared meals need to be observed, such as the use of high quality ingredients to provide good texture, flavour, aroma and appearance. In addition, qualities specific to frozen foods such as recrystallisation damage and lipid oxidation need to be considered.

The development of off-flavours in ready meals is most likely to occur in the fat components of meat and sauce portions. Figure 8.1 shows the relative rates at

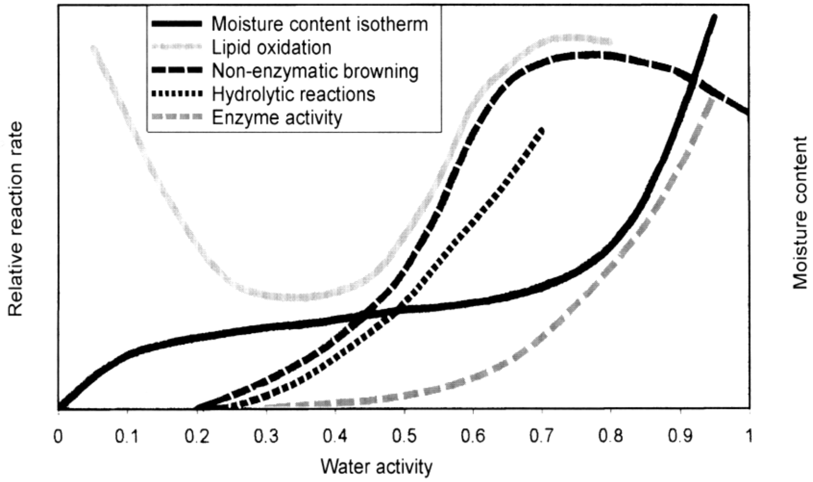

Fig. 8.1 Relative biochemical reaction rates in foods as a function of water activity.

which different types of reaction occur in foods as a function of water activity. As a food is frozen, the water is removed into the ice crystals and solutes in the remaining unfrozen matrix will become increasingly concentrated. This leads to an initial increase in all reaction rates but most types of reaction then slow as the viscosity of the unfrozen solution increases and mobility of the reactants drops.

The exception to this is the oxidation of unsaturated fatty acids. In this case the removal of the monolayer of water which is bound to free radicals on the fats allows for more rapid oxidation and hence the production of rancidity and other off-flavours. Although all reactions are slowed by the reduction of temperature, the relative rates of different types of reaction change. For this reason accelerated storage tests (at elevated sub-zero temperatures) will not usually give true extrapolations of the rate of biochemical deterioration of a complex food product. It is important therefore to control unsaturated fat content of ready meals from an eating quality as well as a nutritional perspective. The addition of antioxidants through marinating processes can enhance shelf-life and eating quality by reducing the rate at which lipid oxidation occurs. Traditionally rosemary and vitamin E have both been added to meat products because of their antioxidant properties.

Texture also plays a significant role in the determination of eating quality for ready meals. Meat components are unlikely to experience significant changes in texture unless dehydration occurs during storage. This can be readily avoided by ensuring total coverage of the meat components with suitable moisture content sauces. The determining factor for meat texture is the quality of meat used. However, for vegetable components the texture may undergo considerable changes during processing, freezing and storage. In Chapter 3 the advantages of selecting cultivars that undergo a minimal degree of freeze–thaw damage were discussed. Additional control of vegetable texture in ready meals is provided by achieving the correct choice of blanching process. The process should reduce enzymatic activity without excessive changes to texture. This is best achieved by a high temperature, short-time process followed by rapid chilling of vegetables using a spray chilling technique.

Migration of moisture during storage can also lead to changes in the texture of the different meal components. This problem is normally overcome in one of two ways. For tray meals the components are stored in different moulded indentations and each compartment is separately sealed by the covering sheet. Increasingly for boil-in-the-bag type products the different meal components are sealed in separate packaging and the problem of moisture migration between components is overcome altogether.

Rapid freezing techniques such as the use of cryogenic freezers, or immersion freezing where suitable, will reduce the loss of turgor through ice crystal damage but at some cost. Similar recrystallisation problems are likely to occur during thawing. Where possible, therefore, the design of containers and portions with dimensions that permit (a) rapid freezing using air and (b) cooking straight from frozen, is to be preferred.

8.2.2 Processing ready meals

Meats

For many recipes meats will be marinated before cooking. The marinade serves a number of purposes. It allows the addition of flavours to the meat and may also alter the texture through changes in the protein structure by inclusion of proteolytic enzymes. Typical solutions are composed of salt, vinegar, oil and spices. The marinade can be included by simple soaking of the meat pieces but is usually accelerated by tumbling in a drum. Where the processor desires the marinade to penetrate deep into the muscle structure, the process can be enhanced by injection of the marinade into the core of the meat.

For the majority of recipe meals an oven cooking process is the most suitable. The destruction of pathogens must be achieved at this stage and cannot be relied on to occur during consumer reheating of the product. The centre of the product must therefore reach at least 70ºC. The range of ovens available for the cooking of meat products is large and includes batch and continuous processes. Static and fan-assisted ovens are available and steam injection may also be used. The choice of process is likely to be determined by the dimensions of the product pieces and the previous processing of the product.

The usual alternative to oven cooking is frying or grilling. Both have the advantage of sealing the meat and preventing further moisture loss during the cooking process. Frying should be performed with care to ensure minimum absorption of unwanted fats. Many breaded and battered products require frying to produce their characteristic browning and crispiness. However, previous cooking of the meat product followed by breading and a short fry time can produce the desired textural effects without additional fat absorption.

Sauces

Sauces form an important component of many prepared meals. They are the primary differential between different dishes with the same meat components. The three most common sauce types are (a) tomato-based, (b) cream- or cheese-based, and (c) stock-based sauces. Sauces allow the addition of flavours to meats as well as offering control of moisture, and protection from dehydration and freezer burn.

In order to ensure consistency between sauce batches it is common to use dried components for most of the sauce ingredients. These will be added to a tomato paste, milk or protein stock base. The use of dried ingredients facilitates the measuring of components to be added to each batch. The drying process and long storage that it facilitates may, however, both lead to a large reduction in nutritional content within these components.

It is usual to blend these components by adding a portion of the liquid components or water at low temperature where sufficient time can be allowed for rehydration. Most sauce cooking is then performed in steam jacketed kettles where the temperature of the sauce is raised to between 85ºC and 90ºC for a period of several minutes. To ensure consistency between batches it is advisable to measure viscosity at the end of the cooking period and to adjust the water or solids content at this stage. Additional quality control of colour is possible but flavour measurements are generally impractical because of time constraints.

Once the sauce has been cooked it should be chilled as rapidly as possible. Many bulk coolers will require time periods of several hours to reduce sauce temperatures from 90ºC to below 5ºC where further processing can occur. Long chill times will result in the additional decomposition of nutrients and may allow the germination of spore forming micro-organisms as the sauce passes through their optimum growth temperature range. This will lead to a reduced storage life after thawing but should not present a significant problem for cook-from-frozen products.

Vegetables

The most successful strategy for the ready meals manufacturer to produce high quality vegetable components is to outsource the blanching and freezing process to the vegetable producer. The use of vegetables blanched and frozen within a few hours of harvest guarantees the retention of the maximum nutritional quality. The degree of blanching or cooking required will be specific to both the vegetable and to the other components of the meal. Vegetables must be blanched for long enough to remove any enzyme reactivity which might lead to quality loss during storage. However, the reheat specifications for the full meal are likely to be determined by the meat components. Hence blanch time should be the minimum necessary as some degree of over-cooking during reheat is inevitable.

8.2.3 Mixing and packaging

Assembly of the components is performed in their cooked, chilled form. It must be performed in a ‘high risk’ area which is separated from the ‘low risk’ area where uncooked foods have been handled and separate personnel should be operating in each area. An HACCP (hazard analysis critical control point) system should be in place to assess and monitor potential hazards to product safety. Any transfer of personnel between the two areas should always be accompanied by a change of the outer layer of clothing, and washing and disinfecting of hands.

Assembly of components is performed in two basic types of product. For ‘boil-in-the-bag’ products such as stews and curries it is common to dispense product into extruded copolymer packaging which is sealed as a vacuum is drawn. These products are designed for reheating by immersion in boiling water or by microwave cooking.

The majority of other meals are dispensed into ovenable trays which have moulded compartments for the various meal components. Since most production lines are required to produce a number of different meal recipes, the degree of automation in assembly is often limited. Typically meat portions will be deposited by hand from a rack of cooked, chilled products. A measured quantity of sauce can then be deposited on this meat portion and should completely cover the meat to prevent dehydration during storage. A depositor with a blow-back nozzle to prevent dribbling of sauces across the connecting section of the tray is important both from an ascetic point of view and to ensure that moisture-tight sealing of the tray can be attained.

Vegetable portions are ideally added in the frozen state. For small vegetable pieces this can be measured and deposited automatically with a reasonable degree of accuracy. Carbohydrate portions can be added by a similar system in the case of rice or roasted potatoes or by the use of a second depositor nozzle in the case of mashed potato. It is usual at this stage that the trays are sealed with a moisture-tight film and packed into their individual cartons. The assembled meal is then passed into a blast freezer for a residence time determined in most cases again by the meat portion. After freezing the individual packages can be bulk packed and taken to the cold store.

8.3 Bakery products

Freezing of bread and bakery products has been performed for a long time. It has, however, seen a large increase in popularity over the last decade. There are a number of forces driving this increase in popularity. The consumer’s desire to have bread ‘as fresh as possible’ is met by the supplier being able to perform the baking in small batches throughout the day. The consumer is therefore able to make purchases of freshly baked bread at the most convenient time for their needs.

This trend is taken further with the sale of part-baked breads which can receive their final few minutes of baking ‘at home’ just prior to consumption.

Dough freezing also enables the central manufacture of dough, which can then be baked at retail sites, reducing the need for large amounts of equipment. It has also enabled entry into more distant markets. For example, frozen dough and part-baked breads have led to the ability for 'genuine' French breads to be retailed in the United Kingdom.

The freezing of complete cooked breads and bread rolls remains the best method of longer-term storage of these products. It is, however, less common in the retail market largely because of the greater acceptability of part-baked products.

Research patterns have largely followed developments in the retail market. Little recent research has been performed on the freezing of complete cooked breads. This trend is beginning to change with the realisation that staling may be a form of glass transition within starch compounds. A large research effort has gone into research on the improvement of the stability of frozen dough.

8.3.1 Ageing and staling

In general, bread products freeze well under the range of freezing conditions applied to other foods. However, bread products are more susceptible to changes in freezing parameters and to poor control of storage conditions.

The major quality issue when considering the shelf-life of bread is the staling process. This is characterised by changes in the resilience of the crumb which becomes less able to spring back from deformations and, conversely, by softening of the crust. The characteristics of freshly baked bread change rapidly in the first few hours after baking. High quality bread is perceived as bread that has a crisp crust and a soft but resilient crumb.

A typical starting dough has a moisture content of around 45%. In the baking process the crust dries and becomes brown and crisp. Moisture is also lost from below the surface but the moisture gradient is very high. Breads are relatively good insulators because of their large air content. The centre of a typical loaf of bread may come close to the boiling point of water for a few minutes only at the end of baking. Water migration is therefore slow and 2–3 cm below the surface the moisture content will be close to the value of the starting mix. There is hence a large moisture gradient in the last few centimetres to the surface.

The rigidity of the crumb comes about during baking due to the uptake of water by the starch granules. These become swollen and flexible enough to bend around the gas pockets. The protein forming the continuum of the dough is resistant to heat denaturation. At the end of baking it is still soft and the bread can be permanently deformed. As the bread cools, the crumb develops a degree of resilience which enables it to be deformed and spring back. As the bread ages it becomes more brittle and will rupture and crumble easily. At the same time moisture migrates out to the crust, softening it and changing its fresh character.

The firming of the crumb is temperature dependent. It is probably brought about by the crystallisation of the starch due to a reorganisation of amylose and amylopectin chains. This philosophy is supported by X-ray diffraction studies.

Some recent evidence is interpreted rather as a glass transition occurring within the starch granules.

In either case the rate of firming of the crumb is seen to peak at around +2ºC. Figure 8.2 shows the data of Pence (1969) measuring the rate of change of compressibility as a function of storage temperature.

Most firming of the crumb occurs in the first 30 hours after baking. Flavour changes which occur at the same time are due to volatility of some of the flavour compounds, oxidation of the more reactive components and continuation of Maillard browning reactions. These flavour changes are all reduced by lowering the temperature.

8.3.2 Freeze–thaw cycles

In a typical freeze–thaw cycle (blast freeze/room temperature thaw) approximately 24 hours is added to the age of the bread. That is, firmness measurements are comparable, after a freeze–thaw cycle, with those of fresh bread stored at room temperature for 24 hours. Most of this ageing comes from the period spent between 0ºC and +5ºC. A rapid freeze–rapid thaw cycle can be shown to reduce greatly the degree of ageing experienced by the bread. This is one of the major drives to the part-baked market, where a rapid freezing process can be followed by rapid thawing in the oven.

The ageing of bread during freezing and thawing has been less of a problem than might be anticipated because of a second change to the ageing phenomenon. It has been demonstrated by a large number of researchers that ageing after a freeze–thaw cycle is retarded. Firmness measurements suggest that 48 hours after thawing, frozen bread records similar firmness scores to unfrozen 48-hour-old bread. At later times the frozen thawed bread generally scores better than the fresh comparison. This suggests some rearrangement of

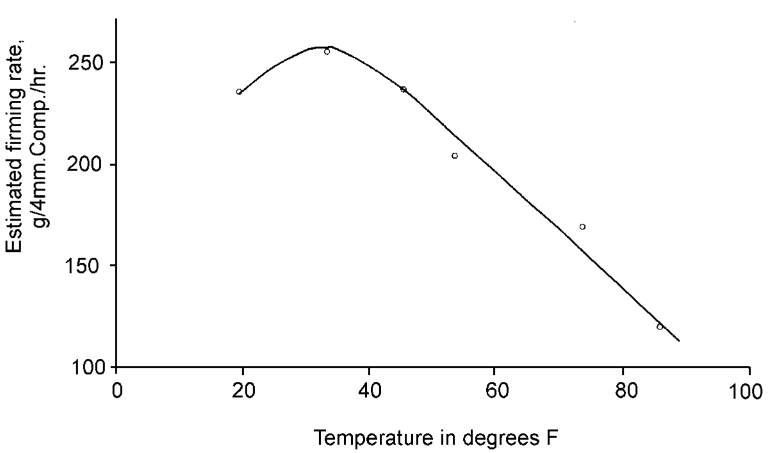

Fig. 8.2 The rate of change of compressibility as a function of temperature.

the moisture component in the starch granules. Although the explanation of this effect is not clear, it seems to be easily reproducible.

These measurements of compressibility show good correlation with taste panel trials of acceptability performed on bread at different stages in the staling process.

8.3.3 Frozen storage

Storage temperature is an important factor in preserving bread quality by freezing. Although most of the latent heat is removed at around −8ºC for a typical bread mix there is still a large portion of unfrozen water at −18ºC (approx. 25%). Storage at temperatures much above −18ºC therefore shows considerable continuation of staling reactions. In one trial, bread stored for seven weeks at −9ºC had become totally unacceptable by test panellists while bread stored at −18ºC was still comparable to day-old fresh bread.

Long storage of frozen bread, for times in excess of ten weeks at −18ºC, introduces another problem. This is the formation of white rings. These occur in the region of high moisture gradient below the crust. Rings form probably due to a combination of water migration and sublimation of the pure water component. These dehydrated rings remain after thawing and reduce the visual acceptability of the product.

8.3.4 Part-baked breads

The combination of the desire by the consumer to have fresh-baked bread and to have frozen bread available in the freezer has led to the rise in the marketing of part-baked breads. The key to the success of these products is to pass rapidly through the region of rapid staling both on cooling and on warming. Cryogenic techniques offer the possibility of a rapid transit of this region during cooling. If the consumer or retailer can then thaw the partially baked bread in the oven then this ensures that the product makes its second transition through this region rapidly. The part-bake process also has the advantage of finishing with the aromas and temperature attributes that are subliminally associated with a fresh-baked product.

8.3.5 Frozen dough

There is a growing trend in the baking industry to produce large volumes of dough which are then frozen and stored for later baking. This strategy offers two principal advantages. The small baker can produce all of the dough at one time and then bake batches of this dough throughout the day. This allows a continuous supply of fresh-baked bread at the time of sale to the consumer. Larger manufacturers and large retail chains are able to mix and freeze dough at a central facility and then bake it at smaller retail outlets. The same advantages of freshness and the attractive bakery aromas are offered to the consumer. The frozen storage of dough has not yet reached a stage where products are stable enough for direct sale to the consumer. This market is in any case largely filled by part-baked products.

There are two major problems in the freezing and frozen storage of dough. These are the death of the yeast cells and damage to the gluten matrix of the dough, reducing its strength and its gas retention capabilities. These problems are manifest in the requirement for longer proofing times after thawing and an eventual lower volume of the loaf after baking. Figure 8.3 shows some typical measurements of these effects.

There is some confusion in most of the literature between the effects of freezing and thawing and the effects of prolonged frozen storage on yeast viability. This confusion has been somewhat resolved by the experiments of Inoue *et al.* (1994). They performed measurements of the gassing power (rate of CO_2 production) on dough subjected to a number of consecutive freeze–thaw

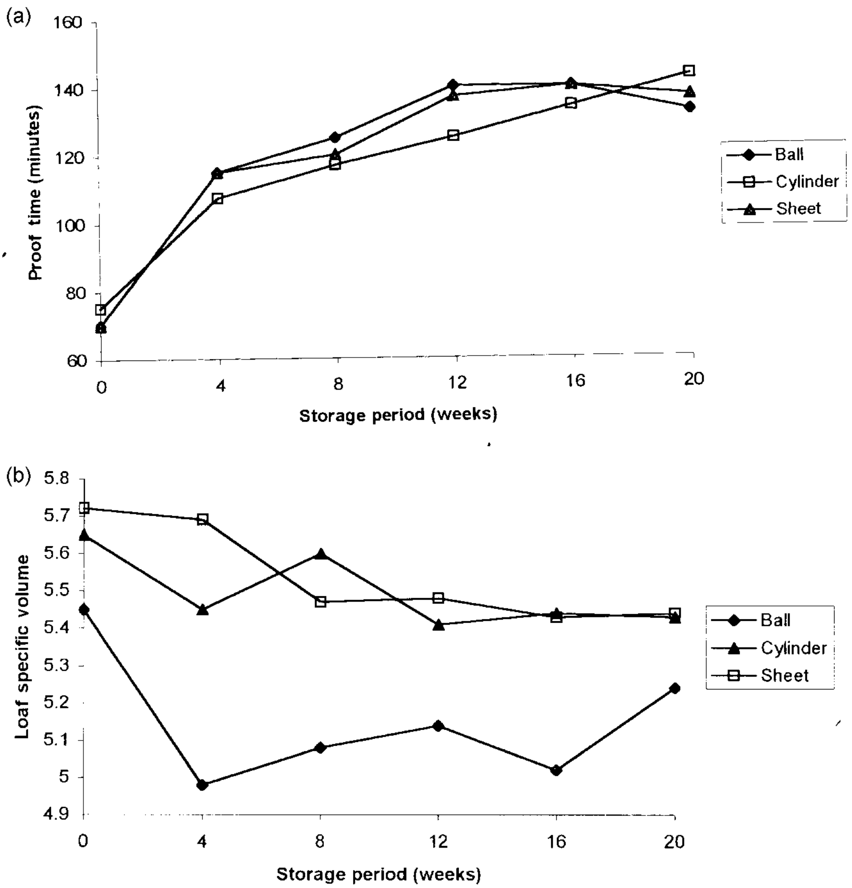

Fig. 8.3 The effects of frozen storage on (a) proofing time and (b) final loaf volume.

cycles and at different stages of frozen storage. They demonstrate that both processes have an effect on yeast viability. Dough subjected to three consecutive freeze–thaw cycles have their gassing power reduced to approximately 80% of the unfrozen dough. Yeast viability continues to be reduced with extended cold storage. After their longest experiments, 70 days, gassing power was reduced to 55% of the unfrozen dough. Gassing power in dough is proportional to the yeast content, so these measurements can be converted directly to values for the yeast viability.

Neyreneuf and Delpuech (1993) investigated the effects of cooling rate on yeast viability. They used a cryogenic freezer at a range of operating temperatures and compared the loaf volumes obtained after thawing and baking with those obtained in a blast freezer. Core cooling temperatures were in the range from 0.3ºC to 3ºC per minute. Yeast viability was largely unaffected by the faster cooling rates for temperatures down to −70ºC (1.6ºC per minute at the core). Lower air temperatures began to have a detrimental effect on yeast viability. As they were experimenting with one shape and size only, it is not possible to determine whether this was a cooling rate or temperature effect, nor is it possible to distinguish between yeast viability in this case and damage to the gluten matrix. They did, however, demonstrate that cryogenic freezing of dough is possible without detriment to yeast viability and with the advantage of a more rapid throughput.

Most early experiments were performed on dough manufactured with standard strains of baker’s yeast, *Saccharomyces cerevisiae*. Considerable effort has gone into isolating and culturing freeze-tolerant strains of this yeast. This has largely involved the crossing of yeast isolated from frozen dough with commercially available baker’s yeast. These new strains, though highly resistant to freezing and frozen storage, usually have lower gassing powers. The simple solution adopted is to use larger quantities of them.

The second major problem in the freezing of dough is damage to the proteins that make up the gluten matrix. This reduces its strength and its gas retention ability. The effect of this is again to increase proofing time after thawing and to give a reduced loaf volume. Inoue *et al.* (1994) performed measurements on the resistance and extensibility of their samples. They demonstrated that the major proportion of the weakening of the protein structure comes from the freeze–thaw cycle. Prolonged storage did reduce the strength but not to the same extent as the original cycle. This evidence was supported by protein solubility measurements which showed the same characteristics.

There is some evidence from SDS gel electrophoresis measurements that the weakening is brought about by denaturation of the glutenin proteins. Analysis of the protein structure of frozen thawed dough shows a considerable increase in the number of lower molecular weight oligomers which are presumably manifest from the de-polymerisation of glutenin. The changes are particularly noticeable after several freeze–thaw cycles.

Other changes that are reported to eventual loaf characteristics after freezing and thawing of dough are enhancement of flavours and darker crust colour. Both of these effects are probably brought about by freeze concentration of solutes which is not totally reversed on thawing, hence some Maillard reactions, which are primarily responsible for browning effects in the crust, are likely to occur faster in freeze–thawed dough. There is, however, no evidence from sensory panelling that these factors are perceived as lowering the quality or acceptability of the final product.

8.3.6 Solutions and standard practice

There are now many solutions to these problems and the freezing of dough is a widely accepted practice. Choice of ingredients for a dough that is to be frozen is the major factor. Frozen dough should include an increased proportion of a freeze-tolerant yeast strain, typically 6–7% instead of 5%. Strong flours should be used with protein contents of around 12%.

Yeast becomes more susceptible to freeze damage after fermentation has begun. The temperature during mixing needs to be controlled and kept below 20ºC. The dough should be allowed only a short proofing time after mixing and then frozen within 30 minutes. Yeast is particularly susceptible to temperature fluctuations which create osmotic pressures so that the storage temperature should be held as constant as possible.

8.4 Ice cream

Ice cream is a complex food emulsion of dispersed water and fat phases incorporating air emulsifiers, stabilisers and flavourings. Hence the physical structure of ice cream is that of a partially frozen foam with ice crystals (diameter $< 50\mu$m) and air bubbles ($< 70\mu$m) making up most of the volume. Fat globules ($<2\mu$m) surround the air bubbles and form a dispersed phase. The fat globules in turn are surrounded by emulsifiers and other proteins. The continuous phase comprises of an unfrozen solution of sugars.

Ice cream is bought and eaten as a luxury product, hence the consumer equates quality of ice cream far more with eating quality than with nutritional values. Indeed the two are, to a degree, mutually exclusive in this case and low-calorie low-fat ice cream products with good eating quality simply do not exist at this stage. Eating quality is a function of particle size within the ice cream, in particular the size of ice crystals and fat globules, and the smoothness of the texture imparted by the milk fats and other ingredients used.

Typical ice cream compositions will be as follows:

- milk fat 10–16%;
- other milk solids 10–12%;
- sweeteners 12–16%;
- stabilisers and emulsifiers 0.2–0.5%;
- water (from milk) 55–65%.

The large range in composition is a reflection of the current variation in ice cream products from standard to premium mixes. In addition between 50% and 150% of volume is added to the mix by the incorporation of air, or over-run.

8.4.1 Effects of ingredients

Milk fats
Milk fats in ice cream are important for high quality flavours and come directly from the use of fresh milk cream. The range of melting temperatures for the triglycerides in milk fat are from +40ºC to −40ºC. Milk fat in ice cream is therefore always a combination of liquid and crystalline fat. Reproducing the structure of milk fat with vegetable sources is difficult and leads to a perceptibly different texture and flavour.

Milk solids not-fat
The milk solids not-fat (MSNF) typically consist of lactose, caseins, whey proteins and minerals. They alter the texture of ice cream and provide the chew strength of the final product. These MSNF are also important to the incorporation of air into the mix. For high quality products MSNF are provided by the addition of skimmed and condensed milks or milk powders. Other sources of solids include condensed whole milk and dried or condensed whey. The limitation to the amount of non-fat solids added is the concentration of lactose. If lactose crystallises out of the mix solution the product will develop a sandy texture which is detected by the consumer.

Emulsifiers
Emulsifiers are added to ice cream to maintain the distribution of air and fat in the frozen product and to provide the smooth characteristics during its meltdown during consumption. Emulsifiers are proteins that have a hydrophilic and a lypophilic portion. This results in their location at the interfaces between the different phases in the ice cream. The traditional emulsifier for ice cream production was egg yolk. Today mono- and di-glycerides, and Polysorbate 80, a glucose molecule bound to oleic acid, are used almost exclusively.

Stabilisers
Stabilisers are added to ice cream primarily to increase the viscosity of the unfrozen water phase and to limit migration of water in this phase and hence reduce ice recrystallisation during storage. They also help to produce a stable foam and prevent shrinkage of the frozen products. Additional functions include suspension of flavour particles and reduction of moisture migration out of the product. Common stabilisers include the following:

- Gelatin: the traditional stabiliser protein, which has increasingly been replaced with plant polysaccharides because of cost and effectiveness.

- Carboxymethyl cellulose (CMC): extracted from pulp cellulose and other plant material.
- Locust bean gum: derived from the beans of a number of trees grown mostly in Africa.
- Guar gum: obtained from the guar bush and grown in India and, to a limited extent, in the United States.
- Carrageenan: extracted from Irish moss or red algae, originally harvested on the Irish coast near the village of Carragheen.
- Sodium alginate: extracted from brown kelp.

Commonly two or more of these stabilisers will be used in combination since their properties and effectiveness at performing the different stabilising tasks vary.

Sweeteners and flavourings

A large variety of sweeteners and flavourings are used in the production of ice cream. Ice cream is generally eaten at a temperature of around -12ºC. However, as it is consumed the temperature will rise towards that of the mouth. The expression and release of different flavour components across this temperature range requires careful design of ice cream flavourings. Furthermore, the different phases will have different effects on the flavour compounds. For example, high fat contents will depress the sensation of sweetness in a milk-based product. However, stabilisers and fat replacers may also bind some flavour components, making them unexpressed to the consumer.

Sweetness in ice cream is determined by the amount of added sugar. A standard ice cream product might contain 12% sucrose and 6% corn syrup solids, whereas a premium product may contain 16% sucrose and no corn syrup solids. The sugar plays a second role of adding non-fat solids to the mix and so controlling melting temperature and recrystallisation effects. A large number of different sweeteners may be used in ice cream manufacture.

Sucrose is the most abundantly available sweetener and it is used as a standard against which other sweeteners are measured. It comprises a mixture of fructose and glucose and is obtained from both beet and cane sugar. The only limitation to the addition of sucrose is the degree of sweetness required in the product.

Invert sugar refers to sucrose that has been hydrolysed to its component sugars, fructose and glucose. Invert sugars, because of their greater solubility and sweetness in comparison to sucrose, allow a smaller volume of sugars to be used. Fructose has also been shown to impart a ‘creaminess’ in lower-fat ice cream products.

Sweeteners derived from corn syrups are also commonly used in ice cream manufacture. It is added in either liquid or solid form and its efficacy as a sweetener is measured as its dextrose equivalence (DE). Increasing DE values for corn syrup correspond to increasing sweetness and reduced molecular weights of the sugars due to the degree of hydrolysis. High DE corn syrup will have lower melting points and lower DE corn syrup contains more dextrins which can tie up more water in the mix, thus supplying greater stabilising effects.

High fructose corn syrup (HFCS) is produced by enzymatic hydrolysis which converts glucose to fructose increasing the level of sweetness. HFCS can therefore be more readily used as a sucrose replacement. However, HFCS blends reduce the melting point considerably, resulting in a very soft ice cream at normal storage temperatures.

Vanilla is still the most common ice cream flavour. The vanilla flavour is provided either by natural extract, by the addition of vanillin, or most commonly by a combination of the two. There are still not enough vanilla beans grown in the world to provide natural flavourings for all the vanilla ice cream that is consumed. Moreover, there is a wide variation in the flavour profiles of different vanilla extracts, depending on the quality and growing location of the beans. Consistent flavour production therefore relies strongly on the use of vanillin or of vanilla extract WONF (with other natural flavours).

Fruits are a common flavouring for ice cream products. Ice cream has an approximately neutral pH and the addition of acids could lead to changes in the protein structure of the milk components. For this reason the attainment of sharp fruity flavours in ice cream requires care. The problem is usually overcome by the separation of the fruit from the ice cream phases such as in a ripple technique or by the soaking of fruit pieces in sugar. The addition of up to 30% sugars to fruit pieces included in ice cream products also has the benefit of reducing the hardness of the fruit component by lowering the melting temperature.

Chocolate is another common flavouring added to ice cream, both as a sryup and in the form of chocolate pieces and chocolate coating. The quality and properties of chocolate are as complex as those of ice cream. Typically chocolate for use in ice cream has a low melting point to reduce brittleness and to enable melting when consumed cold, and will have an above-average addition of sugars to match the sweetness of the rest of the product.

8.4.2 Processing of ice cream

Pasteurisation, homogenisation and ageing

Figure 8.4 shows the typical sequence of processes in ice cream production. After initial mixing the ice cream is pasteurised to destroy pathogenic bacteria and to reduce the number of spoilage organisms. The high temperature at this stage may also help to hydrate some of the components such as proteins and stabilisers. Typically the blend is heated to at least 70°C and held for 30 minutes to satisfy legal requirements for pasteurisation, necessary for the destruction of pathogenic bacteria. Other time–temperature combinations may be used. The heat treatment must be such as to ensure destruction of pathogens and to reduce the bacterial count to a maximum of 100,000 per gram.

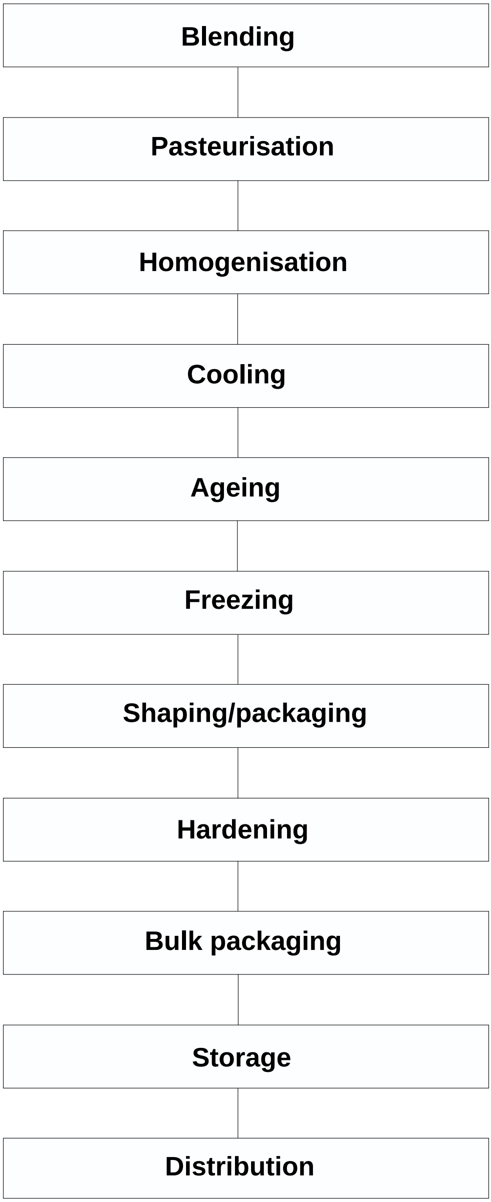

Fig. 8.4 Flow diagram of a typical ice cream production process.

Continuous pasteurisation is usually performed in a high-temperature short-time (HTST) process. Some preheating is necessary for solution of the components. The HTST system is equipped with a heating section, a cooling section and a regeneration section. After pasteurisation, the mix is homogenised by means of high pressures and then cooled rapidly to around 5ºC.

Before cooling the mix is homogenised which breaks down the fat to globules of approximately 1μm diameter. Homogenisation is performed by forcing the mix through a small aperture at high pressure. The size reduction may be performed in one or more stages. The reduction of fat globule size makes a smoother ice cream and provides a better whipping ability as well as increasing resistance to melting. The mix is then aged for at least four hours. This process allows the fat to cool and crystallise and allows the proteins and polysaccharides to hydrate. Ageing is performed at a temperature of around 4°C.

Freezing

After ageing, liquid flavours, colours and fruit pieces, etc., are added before freezing. The freezing of ice cream is performed in two stages. The initial freezing is performed in a scraped surface heat exchanger with an outlet temperature of around −6°C. The goal of this stage is to produce a large number of small ice crystals while the ice cream mix still remains fluid enough to be pumped for further processing or packaging.

A typical scraped surface heat exchanger (see Fig. 8.5) consists of a barrel surrounded by boiling refrigerant (typically ammonia). Ice cream is pumped through the barrel where one or more blades rotate and remove ice crystals

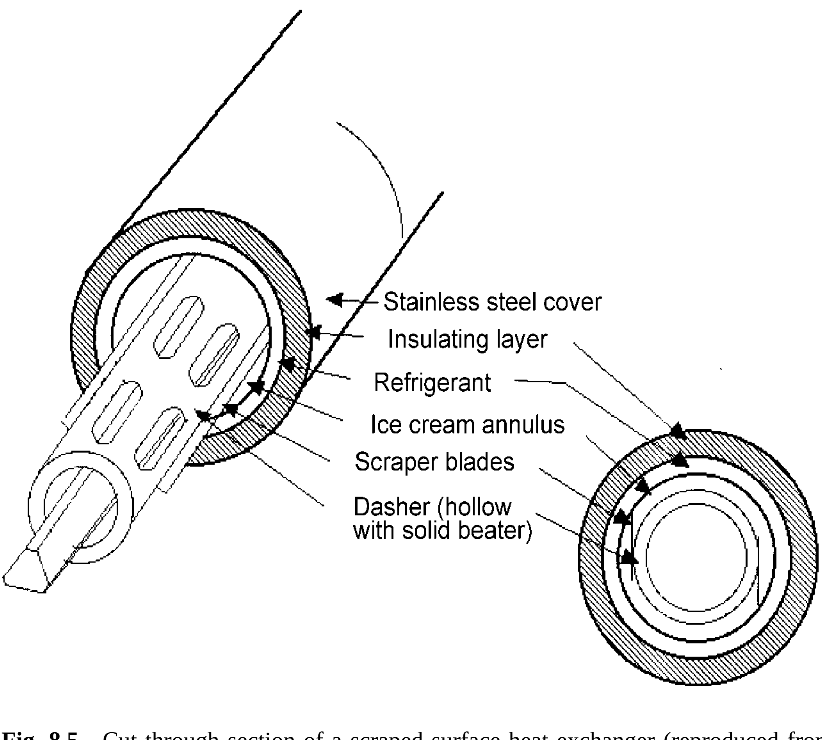

Fig. 8.5 Cut-through section of a scraped surface heat exchanger (reproduced from Goff).

formed on the surface. High-speed video of this process has suggested that this is a combination of crystal shattering as well as new crystal nucleation. A combination of the throughput of the warm ice cream mix and flow of the refrigerant control the output temperature. The rapid change in viscosity of the ice cream with temperature results in the efficiency of this stage being very sensitive to the output temperature.

The barrel also contains a rotating dasher, which is responsible for the mixing of air into the ice cream. The displacement of the dasher and the flow rate of the mix combine to determine the amount of over-run of the ice cream product. The proportion of air to solids included at this stage can range from 50% to 150%, depending upon the type of product being manufactured and the required texture.

Hardening

After freezing in a scraped surface heat exchanger the ice cream will be packaged or will undergo further processing for the production of novelty ice cream. Where the ice cream needs to be shaped or moulded this will be performed before further reduction in temperature occurs. Coatings such as chocolate for choc-ices are added at this stage. The product will then be individually packaged and the remainder of the heat is removed in a hardening tunnel. Typical hardening tunnels are air-blast freezers with a secondary refrigerant temperature of −30ºC to −40ºC. The residence time is determined by the final storage temperature required for the product which is likely to be −25ºC or lower. Once individually wrapped products have been through the hardening tunnel they can then be bulk packed for storage and distribution.

8.4.3 Distribution and packaging

Control of the distribution chain is particularly important for ice cream products because of the problems of ice recrystallisation. Invariably a frozen product will have a distribution of ice crystal sizes. Even without fluctuations in temperature, surface energy considerations provide a driving force for recrystallisation. As long ago as 1960 Earl and Tracy performed measurements that showed that an ice cream product that could be stored at 26ºC for 16 weeks with only slight changes in texture had developed a noticeably coarse texture after just two weeks' storage at −13.3ºC. Recrystallisation rates in sugar solutions proceed as a function of time to the power 0.3 to 0.5, dependent on the composition of the solution. In every case this rate is strongly dependent on temperature.

A second recrystallisation problem results from fluctuations in temperature. Raising the temperature alters the relative distribution of water between the ice crystals and the surrounding, concentrated unfrozen solution. When the temperature is again reduced the water molecules will preferentially return to the surface of the larger ice crystals, resulting in an increase in the mean size. Figure 8.6 shows the distribution of ice crystal size in vanilla ice cream as a function of time, measured by Donhowe and Hartel (1996) with and without oscillations in the storage temperature.

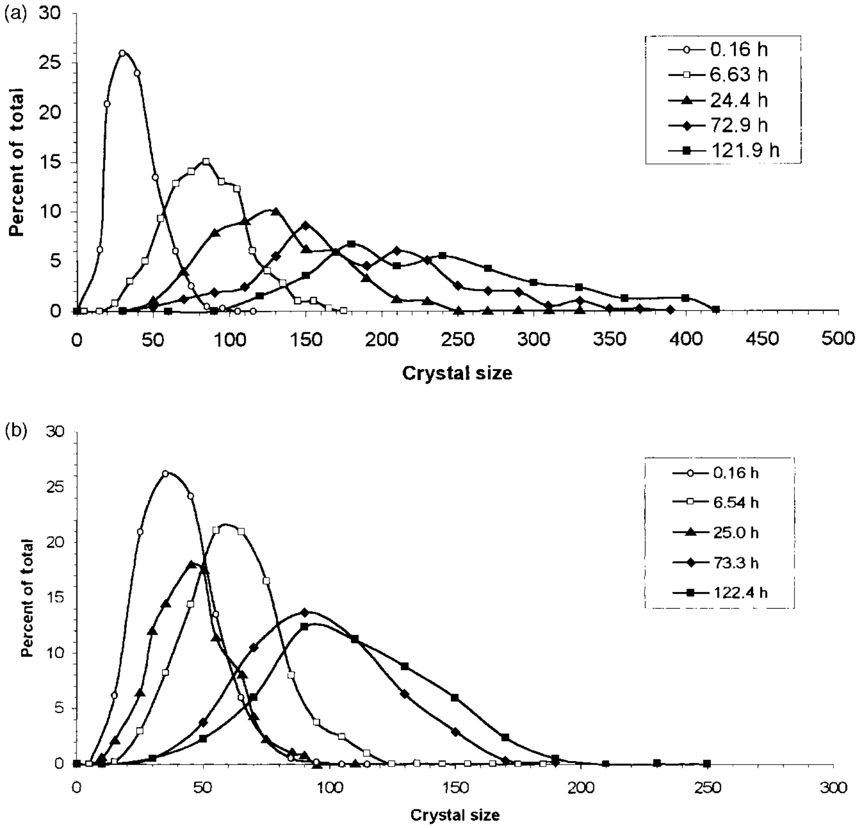

Fig. 8.6 Change in ice crystal size distribution during accelerated recrystallisation on a cold stage microscope slide.

The final recrystallisation concern for ice cream comes from transfer of ice to surface and to the packaging. This is the most visible representation of moisture migration. Moisture, which evaporates from the ice cream product during temporary rises in temperature, will be re-deposited on the surface as pure water ice crystals.

Stabilisers within the ice cream will help to reduce the rate at which recrystallisation occurs. The other major protection that the manufacturer has against recrystallisation is the product packaging. Bulk packaging even in the form of corrugated cardboard can protect products against temporary fluctuations in temperature. Unfortunately the majority of recrystallisation effects occur during retail display. This is particularly enhanced when products are displayed for a long period during the winter season. Individual wrappings are designed to sell the product and not to provide any significant thermal insulation. Where possible, individual products should be displayed within their bulk packaging and minimal stocks should be on display in times of low turnover.

8.5 Bibliography

BALD, W. B. (ed.) *Food Freezing Today and Tomorrow*, London, Springer Verlag, 1990.

CHEN, C. S. 'Thermodynamic analysis of the freezing of bread', *Lebensmittel-Wissenschaft-Technologie*, 1985, **18**(3), 192–6.

DONHOWE, D. P. and HARTEL, R. W. 'Recrystallization of ice in ice cream during controlled accelerated storage', *Int. Dairy J.*, 1996, **6**, 1191–208.

EARL, F. A. and TRACY, P. H. 'The importance of temperature in the storage of ice cream', *Ice Cream Trade*, 1960, **56**(11), 36–7, 40, 42, 78–80.

ERIKSON, M. C. and YEN-CON, H. (eds) *Quality in Frozen Foods*, New York, Chapman & Hall, 1997.

GELINAS, P., DEAUDELIN, I. and GRENIER, M. 'Frozen dough: effects of dough shape, water-content, and sheeting-molding conditions', *Cereal Foods World*, 1995, **40**(3), 124–6.

GOFF, D. 'Ice cream technology', University of Guelph website http://www.foodsci.uoguelph.ca/dairyedu/home.html.

HINO, A., TAKANO, H. and TANAKA, Y. 'New freeze-tolerant yeast for frozen dough preparations', *Cereal Chemistry*, 1987, **64**(4), 269–75.

INOUE, Y., SAPIRSTEIN, H. D., TAKAYANGI, S. and BUSHUK, W. 'Studies on frozen doughs. 3. Some factors involved in dough weakening during frozen storage and thaw–freeze cycles', *Cereal Chemistry*, 1994, **71**(2), 118–21.

KERR, W. L., JU, J. and REID, D. S. 'Enthalpy of frozen foods determined by differential compensated calorimetry', *J. Food Sci.*, 1993, **58**(3), 675–9.

LEIGHFIELD, M., GHEBREMESKEL, K., DOYLE, W. and CRAWFORD, M. A. 'Proximate composition of some ready-meal foods: total fat, fatty acids and tocopherols', *J. Human Nutr. and Diet.*, 1993, **6**, 113–23.

MALLETT, C. P. (ed.) *Frozen Food Technology*, London, Blackie Academic and Professional, 1993.

MIHORI, T. and WATANABE, H. 'An online method for predicting freezing time using time–temperature data collected in the early stages of freezing', *J. Food Eng.*, 1994, **23**(3), 357–73.

NAKAGAWA, S. and OUCHI, K. 'Improvement of freeze tolerance of commercial bakers yeasts in dough by heat-treatment before freezing', *Biosci. Biotechnol. and Biochem.*, 1994, **58**(11), 2077–9.

NEYRENEUF, O. and DELPUECH, B. 'Freezing experiments on yeasted dough slabs: effects of cryogenic temperatures on the baking performance', *Cereal Chemistry*, 1993, **70**(1), 109–11.

ODA, Y., UNO, K. and OHTA, S. 'Selection of yeasts for breadmaking by the frozen-dough method', *Appl. and Environ. Microbiol.*, 1986, **52**(4), 941–3.

PEARCE, A. 'Frozen food statistics, Birds Eye Wall's frozen food factfile – 1999', www.bfff.co.uk/statistics.html.

PENCE, J. W. 'Quality and stability of frozen bakery products', in *Quality and Stability of Frozen Foods*, ed. W. B. Van Arsdel, 1969, New York, Wiley.

SUTTON, R. L., LIPS, A., PICCIRILLO, G. and SZTEHLO, A. 'Recrystallization phenomena in aqueous fructose solutions', *J. Food Sci.*, 1996, **61**(4), 741–5.
WHO *Diet, Nutrition, and the Prevention of Chronic Diseases*, Technical Report Series No. 797, 1990, Geneva, WHO.

9

Freezer technology

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9.1 Introduction

The number of different refrigeration systems and freezer designs can be bewildering, but it is important to choose correctly. Suitable equipment helps to maximise product quality, operating flexibility and return on investment, while minimising waste, costs and down-time. This chapter explains the principles of the various freezing systems, gives examples of commercial equipment and sets out the main factors affecting choice.

One way to classify freezers is by their source of refrigeration (section 9.2). Most users have two options: mechanical refrigeration or cryogenics. Mechanical refrigeration generates the cold on-site, generally using electricity as the power source. In cryogenic refrigeration, the source of cold is a liquefied gas – usually nitrogen or carbon dioxide – supplied by tanker or pipeline. Choosing between mechanical and cryogenic refrigeration involves both technical and commercial decisions.

Another classification scheme is based on design families, grouping together freezers with similar design principles or modes of operation. Blast, tunnel and spiral freezers, for example, share many features even though they may use different sources of refrigeration. As a result, freezers within this family are suitable for many of the same applications. Classification by families is the basis of the discussion of freezer types in section 9.3.

Once we have a clear idea of the freezer types available, we can choose the best freezer for the job. Often the type of food to be frozen dictates this. For individually quick frozen (IQF) vegetables and prawns, for example, the most suitable equipment is usually either a fluidised bed or a cryogenic immersion freezer. Whole turkeys are so large that a brine immersion freezer is the only practical way to freeze them. Cooked chicken needs rapid freezing in a cryogenic tunnel or spiral freezer if it is not to suffer from unacceptable dehydration losses during freezing. For bulk freezing of fish, a plate freezer is often the best choice, and so on.

In other cases several different freezer types may be more or less suitable, and the final choice comes down to a detailed analysis of cost and commercial risk. In such decisions the refrigeration method is often a significant factor. Cryogenic freezers are noted for their low capital costs and ability to handle varying throughputs, so they are often a good choice for new food products. Established lines and high-volume products may be better off with mechanical refrigeration freezers, which generally have lower running costs. Section 9.4 summarises the important questions when choosing a freezer for a specific application.

9.2 Refrigeration systems

9.2.1 Introduction

Commercial food freezing relies on artificial refrigeration to generate temperatures below 0ºC. The design of any refrigeration system is a compromise between performance and economy. Lower temperatures mean faster freezing; smaller freezers mean better product quality and longer shelf-life, but also higher costs.

From the user's perspective there are two main ways to generate cold: mechanical refrigeration and cryogenics. Mechanical refrigeration (section 9.2.2) generates cold at or near the point of use. Most mechanical refrigeration systems for food freezing work at temperatures around −40ºC, using a vapour-compression cycle with electricity as the power source. Sites using mechanical refrigeration often have a central refrigeration plant from which refrigerant is piped to and from the freezers.

Although leasing deals are possible, most mechanical refrigeration plants are owned by the companies whose sites they serve. Mechanical refrigeration therefore tends to be expensive to buy, but relatively cheap to run. The reliability of the plant is the responsibility of the owner, and maintenance needs properly qualified staff, especially in view of the safety and environmental issues surrounding the phase-out of CFC refrigerants.

The alternative source of cold, cryogenic refrigeration, uses a cold liquefied gas (nitrogen or carbon dioxide) supplied by tanker or pipeline (section 9.2.3). Cryogenic liquids are actually produced using mechanical refrigeration, but as far as users are concerned they are very different from on-site mechanical refrigeration in terms of applications, equipment requirements and commercial aspects. The supplier of the cryogenic liquid carries the responsibility of owning and running the refrigeration plant, so users see low capital costs but higher running costs.

Cryogenic liquids can produce temperatures down to −80ºC and below. This allows them to tackle some freezing tasks that are difficult or impossible using mechanical refrigeration, especially when fast freezing is required. The design of most cryogenic freezers, and the ability to store refrigerant for future use, also make cryogenic freezing a flexible way to handle varying production rates.

Section 9.2.2 includes two other refrigeration techniques not currently in wide use. Absorption refrigeration is effectively a mechanical refrigeration technique driven by heat instead of mechanical energy. Another mechanical technique, closed-cycle air refrigeration (CCAR), may in the next few years provide temperatures that previously required cryogenics (−60ºC and below), but at costs comparable to those of traditional mechanical refrigeration. Three further techniques – steam-jet systems, thermoelectric and acoustic refrigeration – are not used for food freezing and so are not discussed here.

Refrigeration capacity is measured in kW or MW. Older plants may still use Btu/h, and occasionally the 'ton of refrigeration', a historical unit equal to 3.52 kW. Whatever the units, it is essential to know where the capacity is measured. Does it refer to the heat load on the evaporator, for instance, or at the point of use? Different suppliers use different conventions.

The UK Institute of Refrigeration (http://www.ior.org.uk/) provides information on suppliers of refrigeration systems and freezers.

9.2.2 Mechanical refrigeration

Depending on the choice of working fluid and process conditions, mechanical refrigeration can generate temperatures from ambient down to −250ºC and below. Most commercial freezing systems run at −40ºC, a temperature that simplifies the design of systems based on R 22 and ammonia.

A typical air-blast freezer handling 2 t/h of product needs around 160 kW of refrigeration, which in turn requires around 140 kW of electrical energy. Commercial stand-alone refrigeration plants range in size from 20 kW, for a single small freezer, to 2 MW for a large site with several freezers. Small freezers in the 20–50 kW range may have their own built-in refrigeration systems (direct expansion or DX freezers).

The vapour-compression cycle

Figure 9.1 shows a simplified version of a typical mechanical vapour-compression refrigeration system. The main components of the system are a loop of pipework, two heat exchangers (the evaporator and the condenser), a compressor and an expansion valve. The working fluid in this example is ammonia. Refrigeration takes place in a continuous cycle with four distinct stages:

1. Ammonia vapour at a temperature of −40ºC and a pressure of 0.7 bar a enters the suction inlet of the compressor, which raises its pressure to 12.5 bar a. The compression also raises the temperature of the vapour.
2. Next, the ammonia vapour flows into the condenser, where it gives up heat to a stream of cooling water at 25ºC. The ammonia condenses, and leaves the condenser as a liquid at 30ºC.

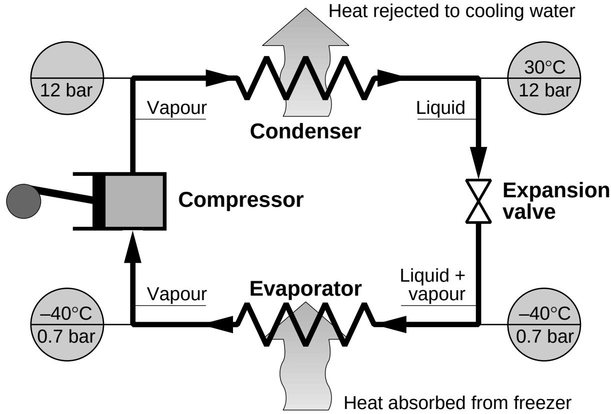

Fig. 9.1 A simplified mechanical vapour-compression refrigeration system using ammonia. The compressor increases the pressure and temperature of the ammonia vapour. The condenser removes the heat of compression and converts the ammonia vapour to a liquid. A drop in pressure across the expansion valve causes the liquid to boil, producing a mixture of liquid and vapour at −40ºC. The evaporator transfers heat from the food to be frozen to the liquid ammonia, converting it to vapour which returns to the compressor.

3. The liquid ammonia then flows through the expansion valve, inside which is a narrow orifice designed to cause a drop in pressure. Downstream of the valve, the pressure is 0.7 bar a. The fall in pressure causes the ammonia to boil, converting 25% by weight of the liquid back into vapour. The energy required for boiling causes the temperature of the ammonia to fall to −40ºC.
4. The ammonia, now a mixture of liquid and vapour at −40ºC and 0.7 bar a, flows through the evaporator. Here it absorbs heat, either directly from the air or brine inside the freezer itself, or from a secondary refrigerant that is piped to the freezer. The liquid ammonia boils and turns back into vapour, absorbing heat as it does so. Now completely in the form of vapour at −40ºC, the ammonia returns to the compressor to complete the cycle.

Real-world refrigeration systems designed for maximum operating efficiency and flexibility are more complicated than Fig. 9.1. Refrigerant may leave the evaporator as a mixture of liquid and vapour, rather than entirely as vapour. Both compression and expansion may take place in more than one stage, and the entire cycle may be split into two or more sub-cycles. Incondensible gases such as air reduce efficiency, so there are often arrangements for venting these. Centralised refrigeration plants serving several freezers need pipework, pumps and storage tanks to distribute the refrigerant to the points of use. Figure 9.2 shows a typical commercial refrigeration plant for food freezing.

CoP and efficiency

A mechanical refrigeration system uses mechanical energy P, in the form of shaft work, to move heat energy Q from a lower to a higher temperature. The

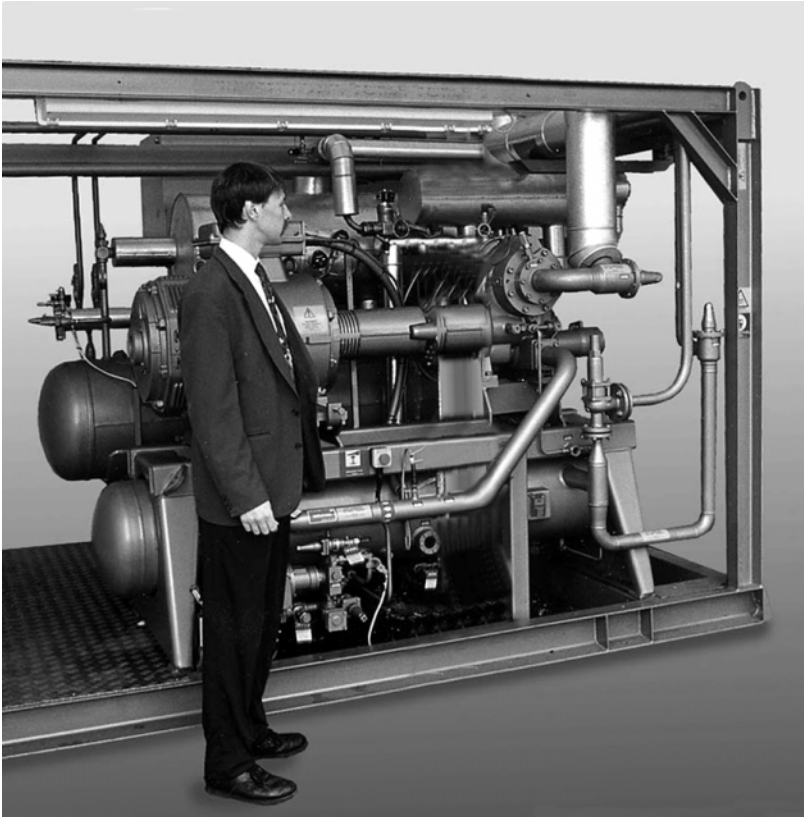

Fig. 9.2 The Frigoscandia FRIGoPAK LVS (low volume system) is a compact packaged refrigeration plant using ammonia as the working fluid. The condenser is a separate unit not shown in the photograph.

ratio *Q*/*P* is known as the coefficient of performance (CoP or ε). In thermodynamic terms, the system is a Carnot cycle whose maximum theoretical CoP, ε_C, is:

$$\varepsilon_C = T_0/(T_C - T_0) \qquad 9.1$$

where T_0 is the absolute temperature at which heat is absorbed – in other words, the refrigeration temperature – and T_C is the temperature at which heat is rejected, which is usually close to ambient.

A system absorbing heat at −5ºC (268 K) and rejecting it to cooling water at 30ºC (303 K) has an ε_C of 268/(303 − 268) = 7.7; in other words, 1 kW of shaft power provides nearly 8 kW of theoretical refrigeration capacity. For a refrigeration temperature of −40ºC (233 K), ε_C falls to 3.3. At temperatures below −122ºC (151 K), ε_C is less than 1.

The CoP of a real refrigeration system, ε, is equal to the theoretical CoP, ε_C, multiplied by the efficiency, η, of the system. η is the product of three terms: the thermodynamic efficiency of the refrigeration cycle (typically 0.5–0.8), the isentropic efficiency of the compressor (also 0.5–0.8) and the efficiency of the electric motor driving the compressor (0.7–0.95). Typical values of η are thus in the range 0.25–0.6, giving real CoP values of between a quarter and a half of the theoretical value from equation 9.1.

Refrigerants

An ideal vapour-compression refrigerant has a vapour pressure slightly above atmospheric at the temperature of the evaporator, so that air cannot enter the system in the event of a leak. At the same time the curve of vapour pressure against temperature should be shallow; the steeper the curve, the higher the pressure in the condenser and the more expensive the equipment needed to contain the refrigerant safely.

A good refrigerant has a low specific volume (m^3/kg) in the vapour phase and a high enthalpy of vaporisation (kJ/kg). The refrigerant should be chemically and thermally stable, and must not attack any of the materials used in the system, including seals and compressor lubricants. It should ideally also be environmentally benign, non-flammable and non-toxic. In practice, the choice of vapour-compression refrigerant is almost entirely confined to ammonia or one of a number of halogenated organic compounds (CFCs, HCFCs and HFCs) (see Table 9.1).

Ammonia is cheap and has good thermodynamic properties. It is toxic and somewhat flammable, so it can be handled safely in large industrial plants but is less suitable for retail and domestic applications. Ammonia attacks copper, so it cannot be used for sealed systems in which the compressor motor, with its copper windings, comes into direct contact with the refrigerant.

CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons) have found wide use as refrigerants since their discovery in the 1930s. They are stable, non-toxic, and have excellent thermodynamic properties. Unfortunately the chlorine they contain destroys the stratospheric ozone that humans, animals and plants rely on to protect them from ultraviolet radiation from the sun. They are also powerful ‘greenhouse gases’ which many environmentalists believe contribute to global climate change.

As a result of the 1987 Montreal Protocol and subsequent legislation, new refrigeration plant across most of the world is now forbidden to use CFCs. In many cases CFCs can be replaced by HFCs (hydrofluorocarbons) which do not attack ozone, although they are still greenhouse gases.

R 12, the most widely used of the half-dozen or so common CFC refrigerants, has in most cases been replaced directly with an HFC, R 134a. The change to R 134a requires synthetic compressor lubricants to be substituted for the mineral oils generally used with R 12, and entails a loss of refrigeration capacity of 8–15%. New refrigeration plant designed specifically for R 134a does not suffer from this loss of efficiency.

Only one HCFC, R 22, is widely used in food freezing, but finding a direct replacement has proved difficult. For this reason, and because R 22 is thought to

Table 9.1 Refrigerants

Refrigerant	R number	Class	Formula	Temperature range, ºC	Applications
Ammonia	R 717	Ammonia	NH_3	−60 to +10	Medium-size and large refrigeration systems; all compressor types
Trichlorofluoromethane	R 11	CFC	$CFCl_3$	−10 to +20	Chilled water; turbine compressors
Dichlorofluoromethane	R 12	CFC	CF_2Cl_2	−40 to +20	Refrigeration and heat pumps; all compressor types
Azeotrope R 12/R 152a	R 500	CFC		−40 to +20	Refrigeration and heat pumps; reciprocating and screw compressors
Azeotrope R 22/R 115	R 502	CFC		−60 to 0	Refrigeration; reciprocating compressors
Chlorodifluoromethane	R 22	HCFC	CHF_2Cl	−70 to +20	Widely used for refrigeration; all compressor types
Tetrafluoroethane	R 134a	HFC	$C_2H_2F_4$		More environment-friendly replacement for R 22
Ethane	R 170	HC	C_2H_6	−110 to −70	Low-temperature cascade refrigeration, usually with turbine compressors
Ethene (ethylene)	R 1150	HC	C_2H_4	−110 to −80	As for ethene
Propane	R 290	HC	C_3H_8	−60 to −20	Large refrigeration systems, usually with turbine compressors
Propene (propylene)	R 1270	HC	C_3H_6	−60 to −20	As for propene

Notes:
R numbers: a compound with the formula $C_aH_bCl_c\ F_d$ is numbered R [a − 1][b + 1][d]
Unsaturated compounds take a leading ‘1’; ‘a’, ‘b’ etc. denote isomers; ‘B’ = brominated; ‘C’ = cyclic

have only around 5% of R 12's ozone depletion potential (ODP), R 22 is likely to remain in service until 2030.

The lack of ozone-friendly halogenated refrigerants for many applications is likely to lead to a rise in the popularity of ammonia for large industrial systems. Ammonia is a good candidate to replace R 22, since the required compressor loads and pipe sizes are similar. Retail and domestic freezers are likely to stick with R 134a and, until it is phased out, R 22.

Hydrocarbons such as ethane and propane also have the right thermodynamic properties to make good refrigerants. Unlike ammonia they are non-toxic, but they are extremely flammable. Hydrocarbon refrigerants find wide use in the oil and chemical industries, which are used to handling hazardous substances, but they are unlikely to catch on in the food business.

Equipment and maintenance

Compressors for refrigeration systems come in several types: reciprocating (piston), sliding vane, screw, and centrifugal ('turbocompressors'). Small and medium-sized plants commonly use reciprocating compressors, while screw compressors and turbocompressors are popular for medium and large plants. Axial-flow rotodynamic compressors are rarely used. The compressor driver is usually an electric motor, but internal combustion engines, gas turbines and steam turbines are also possible.

Condensers may be cooled using air or water, the latter generally recirculated through a cooling tower where it is cooled by contact with air. Air-cooled condensers are popular for small and medium-sized systems, especially in locations where cooling water is scarce. A third type of condenser, the evaporative condenser, effectively combines the functions of a water-cooled condenser and a cooling tower.

The evaporator often forms part of the freezer itself, with banks of coiled pipe over which air is blown. Occasionally a secondary refrigerant such as calcium chloride brine or ethylene glycol is used to transfer heat from the refrigeration plant to the freezer. In this case the evaporator is likely to take the form of a shell-and-tube heat exchanger.

Mechanical refrigeration systems have always needed skilled maintenance, although improvements in equipment design mean that modern systems are more reliable and less labour-intensive than those of the past. Refrigeration plant may have a working life of 15 years or more. Until recently, most operators of refrigeration plant considered it acceptable to vent large amounts of refrigerant to atmosphere, either through leaks or in purging air from their systems. Modern refrigeration engineers place much more emphasis on leak-tightness.

Absorption refrigeration

Instead of a compressor to drive a vapour-compression refrigeration cycle, it is possible to use heat. In an absorption refrigerator (Fig. 9.3), refrigerant vapour leaving the evaporator is absorbed in another liquid, the absorbent, thus lowering the pressure at this point in the system. The absorbent is then pumped into a

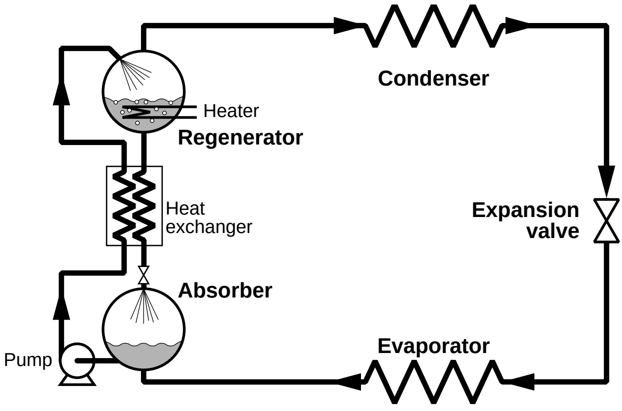

Fig. 9.3 An absorption refrigeration system replaces the compressor of Fig. 9.1 with two vessels – the absorber and the regenerator – and a circulation pump. In this example, a solution of ammonia in water absorbs ammonia vapour returning from the evaporator. The solution is then pumped to the regenerator, where it is boiled to release ammonia as a high-pressure vapour.

vessel called the regenerator, where it is boiled to release the refrigerant as a high-pressure vapour. Such a system can be made to run on waste heat from other industrial processes, and can even be designed without any moving parts.

The commonest absorption-refrigeration systems are water-lithium bromide (LiBr) and ammonia-water. Water-LiBr is used at temperatures down to 0ºC, generally for air-conditioning applications. Ammonia-water absorption units can provide temperatures down to −60ºC, although they are seldom used for food freezing.

Closed-cycle air refrigeration

Another mechanical technique, closed-cycle air refrigeration (CCAR), shows promise for the future. CCAR differs in principle from conventional mechanical refrigeration because it uses an incondensible gas – air – as the working fluid, instead of a condensible vapour such as ammonia. In practice, CCAR is different because it is most likely to be economic at temperatures down to −80ºC, well beyond the reach of most mechanical systems.

Open-cycle air refrigerators (‘air machines’) operating at low pressures were widely used in the nineteenth century, but were superseded by vapour-compression systems with higher efficiencies. At high pressures, and temperatures below −60ºC, however, the CoP of a modern air machine can equal that of a vapour-compression system.

Fig. 9.4 shows a simplified CCAR system. Air is compressed to 83 bar and 56ºC before cooling to −63ºC, using first cooling water and then the cold gas stream returning to the compressor. Next, a turboexpander reduces the pressure to 65 bar, causing the temperature to drop to −75ºC and generating shaft work that helps drive the compressor. The cold air passes through a heat exchanger

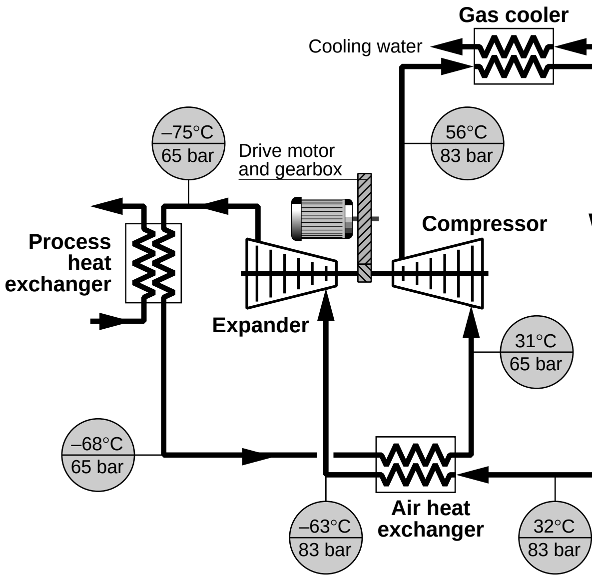

Fig. 9.4 Closed-cycle air refrigeration (CCAR) uses a single-phase refrigerant – air – instead of a condensible vapour. With CoP values competitive with those of vapour-compression refrigeration at temperatures below −60ºC, CCAR may in the future compete with both mechanical and cryogenic refrigeration.

where it absorbs heat from the freezer, raising its temperature to −68ºC. A second heat exchanger further raises the temperature of the air by transferring heat from the stream leaving the compressor. The warm air, still at 65 bar but now at 31ºC, returns to the compressor to repeat the cycle. Such processes are related to those used to make cryogenic liquefied gases (section 9.2.3).

9.2.3 Cryogenics

Cryogenic refrigerants – liquefied gases such as nitrogen and carbon dioxide – are made using mechanical refrigeration processes similar in principle to the vapour-compression and CCAR cycles described in section 9.2.2, though a good deal more complex in practice (see below).

At cryogenic temperatures, the maximum theoretical CoP of a refrigeration plant falls to around 0.3, so each kW of refrigeration requires more than 3 kW of input energy. To operate economically, cryogenic plants therefore have to use specialised technology. They also need to be large: a typical plant might yield 425 t/d of liquid nitrogen (LIN) as well as 175 t/d of liquid oxygen (Fig. 9.5).

Because cryogenic plants are so large, they are almost always owned and operated by specialist industrial gas suppliers. Users are supplied by tanker – or, for very large consumers such as steelworks, by pipeline – and pay only for what they take. Liquid nitrogen prices vary considerably, depending on the size of the contract and the cost of electricity.

Fig. 9.5 Cryogenic liquids are only economic to manufacture on a large scale. This plant at Didcot, UK, is owned and operated by Air Products. One of the largest plants of its kind in Europe, it produces 425 t/d of liquid nitrogen as well as 175 t/d of liquid oxygen.

Liquid nitrogen

At atmospheric pressure, liquid nitrogen boils at −196ºC. It is generally transported by road tanker, and stored on the user's site at atmospheric pressure in insulated tanks of 20–50 t capacity. Heat leaking into the tank is removed by allowing it to boil off some of the liquid nitrogen, with the resulting gas vented to atmosphere. Typical loss from a large storage tank is 0.5% per day.

Liquid nitrogen has a refrigerating capacity of 384 kJ/kg, split almost equally between the latent heat of vaporisation at −196ºC and the heat absorbed in raising the temperature of the resulting vapour to −20ºC. By comparison, ice at

0ºC has a refrigerating capacity of 333 kJ/kg. A useful rule of thumb is that 1 t/h of liquid nitrogen is approximately equivalent to 100 kW of mechanical refrigeration.

Liquid nitrogen is made from air, so its costs are entirely those of manufacture – dominated by the costs of capital and electricity – and distribution. Liquid nitrogen is traded either by weight or by volume in the gas phase, in the latter case measured in units of 100 m^3 at NTP (15ºC and 1.013 bar).

Both liquid and gaseous nitrogen are safe for direct contact with food, and harmless when vented to the atmosphere. Like any other cryogen, however, liquid nitrogen needs to be handled carefully. If spilled, it burns skin and can make materials such as steel, rubber and plastics dangerously brittle. Systems for storing and handling cryogenic liquids are generally made from suitable grades of stainless steel, aluminium and copper, which keep their toughness at low temperatures.

Nitrogen gas can form an asphyxiation hazard wherever ventilation is limited, such as in confined spaces or in low-lying areas where clouds of cold gas can collect. Liquefied gases are particularly hazardous since a small spill of liquid will generate several hundred times its volume of vapour.

A further hazard is liquid oxygen, which boils at −183ºC and so can condense out of the air onto the surfaces of tanks and pipes containing liquid nitrogen at −196ºC. If liquid oxygen drips onto flammable materials, including lubricants and rubber seals, it can cause explosions and fires.

Liquid and solid carbon dioxide

Carbon dioxide, usually extracted from natural gas, is becoming increasingly popular for cryogenic freezing applications. Solid carbon dioxide (dry ice) at −78ºC has for many years found application in specialist cooling duties and has the advantage of a high refrigerating capacity: 618 kJ/kg. It is not widely used, however, because it is less convenient to handle than a liquid refrigerant.

The lowest pressure at which liquid carbon dioxide can exist is that of the triple point: 5.2 bar a, corresponding to a temperature of −57ºC. For economy in thermal insulation, higher temperatures are often preferred. Liquid carbon dioxide is therefore generally supplied either at ambient temperature (e.g. 25ºC and 65 bar), giving a refrigerating capacity of 199 kJ/kg, or at −16ºC and 22 bar, giving a refrigerating capacity of 311 kJ/kg. At the point of use, spray nozzles reduce the pressure of the liquid, generating a mixture of cold vapour and solid carbon dioxide ‘snow’.

Safety precautions for cold burns and asphyxiation are similar to those for liquid nitrogen, although at high concentrations carbon dioxide has an acid taste that makes it easier to detect than nitrogen, which is odourless.

Gas liquefaction processes

Gas liquefaction processes differ greatly in detail, but most use the same principle: gas is compressed at constant temperature, before being expanded without being allowed to absorb energy from the surroundings. If the original pressure is high enough, the expansion cools the gas sufficiently to liquefy part of it. In the case of air, the liquefied gas can then be distilled to recover separate streams of liquid oxygen, liquid nitrogen and other more valuable gases such as helium, xenon and krypton.

The simplest of such processes is the Linde–Hampson system. After being compressed to around 200 bar, the gas is cooled in a heat exchanger and then passes through an expansion valve into a separator vessel at around atmospheric pressure. The expansion cools the gas stream, some of which condenses to a liquid and flows out from the base of the separator. The remaining cold gas passes back through the heat exchanger, where it cools the high-pressure gas leaving the compressor, and returns to the inlet side of the compressor.

The Linde–Hampson process becomes more efficient if a separate refrigeration cycle, for instance using ammonia, is added to pre-cool the compressed gas before it reaches the expansion valve. Another modification is to use two compressors in series, and to compress only part of the feed gas through the full pressure range (the Linde dual-pressure system).

Another variant, the Claude process (Fig. 9.6), uses a turboexpander as well as a valve to expand the gas. Because the turboexpander recovers energy that can be used to help compress the gas, the Claude system is the most efficient of the basic gas liquefaction processes. Designers of cryogenic plants pay great attention to heat recovery and use multi-stage processes to approximate the curves of the ideal Carnot cycle. Food producers can ignore these subtleties and treat liquefied gases simply as convenient refrigerants.

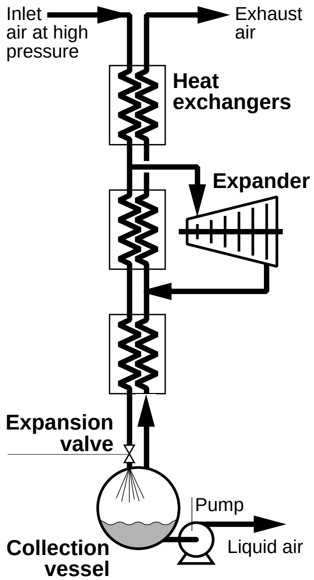

Fig. 9.6 Based round a turboexpander, the Claude system is the most energy efficient of the basic gas liquefaction processes.

9.3 Freezers

9.3.1 Introduction

Freezing food almost always involves a compromise between speed, effectiveness and cost. Compactness, reliability, versatility and cleanability are other important issues in freezer design. Sections 9.3.3–9.3.11 discuss the most important types of commercial food freezing equipment, arranged by design family. Our starting point is the basic mechanical refrigeration blast or tunnel freezer (section 9.3.3), and its cryogenic counterpart (section 9.3.4), before we move on to what is perhaps the commonest and most versatile type of continuous food freezer: the spiral freezer (section 9.3.5). Sections 9.3.6–9.3.11 deal with plate freezers, immersion freezers, fluidised-bed freezers, tumbling and rotary freezers, stationary tunnels and carton freezers, and specialised freezers such as those for ice lollies. They include both batch and continuous freezers, using mechanical and cryogenic refrigeration.

Whatever the product, rapid freezing is generally better than slow freezing. Rapid freezing improves product quality by ensuring that ice crystals remain small, by reducing dehydration, and by speeding the formation of a frozen crust that helps to reduce product damage. Rapid freezing also increases throughput for a given size of freezer.

Before we look at individual freezer designs, we should therefore look at the factors governing the speed of freezing. An understanding of the different modes of heat transfer also helps in making clear the similarities and differences between different freezer types, and in matching freezers to products.

9.3.2 Heat transfer

Heat transfer – the movement of heat energy from a hotter body to a colder one – is central to the design of both refrigeration systems and freezers. There are three basic heat transfer mechanisms: convection, conduction and radiation. Of these, only convection and conduction are important in food freezing. Their relative importance depends on the type of freezer and the product to be frozen.

Convection

Convection is important in almost all freezer types. It describes the transfer of heat between a surface, which may be either solid or liquid, and a moving liquid or gas. The movement may be imposed externally, for instance by a fan, pump or mixer (forced convection), or it may be self-generating, driven by changes in density as the fluid is heated or cooled (natural convection). The important point is the constant renewal of the fluid in contact with the heat transfer surface.

The fundamental equation in convective heat transfer is:

$$Q = \mathrm{U}\, A \Delta T \qquad 9.2$$

where Q is the rate at which heat is transferred (W), A is the area over which heat transfer takes place (m^2), ΔT is the temperature difference driving the heat transfer (K), and U is a constant known as the heat transfer coefficient (W/m^2K).

For our purposes the surface area of interest is that of the food itself, which is normally fixed. We can therefore increase the rate of heat transfer, and hence reduce the freezing time, by increasing the temperature difference, the heat transfer coefficient, or both.

Temperature difference

A typical mechanical refrigeration freezer with an evaporator temperature of −40ºC might take in a food product at 40ºC and discharge it at −20ºC (Fig. 9.7). The temperature difference available to drive heat transfer therefore varies from 80 K (80ºC) at the freezer entry, to 20 K at the exit; 20 K is the minimum temperature difference likely to be of practical use in food freezing.

If the temperature of the refrigerant varies, as with cryogenic freezing, the situation is more complicated. To maximise the average temperature difference along the length of the tunnel, cryogenic freezers are designed for counter-current flow: product and refrigerant move in opposite directions (Fig. 9.7).

Since the cold gas leaving the freezer is not recycled, it makes economic sense to make the discharge temperature as high as possible – in practice, around −20ºC. In a typical liquid nitrogen freezer, food entering at 40ºC contacts nitrogen leaving the freezer at −20ºC, giving a temperature difference of 60 K. Food leaving the freezer at −20ºC contacts nitrogen entering at −150ºC, giving a temperature difference of 130 K.

Heat transfer coefficient

Convective heat transfer coefficients vary widely, from less than 10 W/m^2K to more than 1000 W/m^2K. The main factors influencing the heat transfer coefficient are the physical properties of the fluid, its velocity and the geometry of the heat transfer surface.

Heat transfer coefficients can be calculated from empirical equations found in engineering textbooks, but the results are not likely to be very accurate. For food freezing the usual approach is to measure heat transfer coefficients under real conditions and to use these values as guides when extrapolating to new conditions.

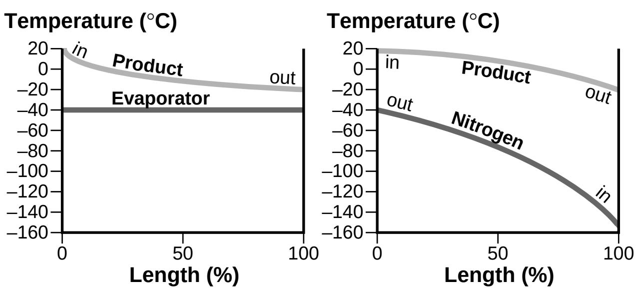

Fig. 9.7 Temperature differences driving heat transfer in (a) a mechanical refrigeration freezer with a constant evaporator temperature, and (b) a cryogenic freezer operating in counter-current mode.

Heat transfer by convection from solid to gas, as in a blast freezer, gives inherently low heat transfer coefficients (15–50 W/m^2K). Gas–solid heat transfer is improved by high gas velocities and gas flow at right angles to the surface of the food. Impingement freezers (section 9.3.3) use high gas velocities to achieve heat transfer coefficients of up to 175 W/m^2K. Cryogenic tunnel freezers (section 9.3.4) can reach 120 W/m^2K.

Heat transfer from solid to liquid, either by direct convection or via conduction through a metal dividing wall, gives higher heat transfer coefficients. Cryogenic immersion freezers (section 9.3.7) can achieve 280 W/m^2K. Heat transfer coefficients in some plate freezers (section 9.3.6) reach 1000 W/m^2K.

Conduction

Conduction describes the transfer of heat by direct contact, normally through a solid material. The fundamental equation is similar to that for convection:

$$Q = \mathrm{k}\, A \Delta T / L \qquad 9.3$$

where Q is the rate at which heat is transferred (W), A is the area over which heat transfer takes place (m^2), ΔT is the temperature difference driving the heat transfer (K), L is the distance across which the heat is transferred, and k is a constant known as the thermal conductivity (W/mK).

Conduction takes place at many points in a typical refrigeration system and freezer, but usually through thin metal items whose resistance to heat transfer is negligible when compared to that of convection. There is, however, one important place where we cannot always ignore conduction: the food product itself, and any packaging material associated with it. If the product is thin, or if the convective heat transfer coefficient at the surface of the product is low, then the limiting factor in the heat transfer process is how fast heat can be removed from the surface of the product. In this case the freezing time depends only on the convective heat transfer coefficient, and we can ignore conduction. If the product is thick, however, the time taken to conduct heat from the inside of the product to the surface becomes significant. The simplest freezing model that includes both conduction and convection is known as Plank's equation:

$$t_{\mathrm{f}} = \frac{\rho L}{T_{\mathrm{F}} - T_{\infty}} \left[\frac{Pa}{U} + \frac{Ra^2}{k} \right] \qquad 9.4$$

where t_{f} is the freezing time (s), ρ is the density of the food (kg/m^3), L is the latent heat of freezing of the food (J/kg), T_{F} is the freezing temperature of the food (K), T_{∞} is the final temperature of the frozen food (K), P and R are dimensionless constants reflecting the geometric shape of the product, a is a characteristic dimension of the product (m), U is the surface heat transfer coefficient (W/m^2K), and k is the thermal conductivity of the product (W/mK).

Figure 9.8 shows how freezing time varies with heat transfer coefficient for a typical food product. At low heat transfer coefficients such as those found in a typical blast freezer, convection dominates the freezing process. At high heat

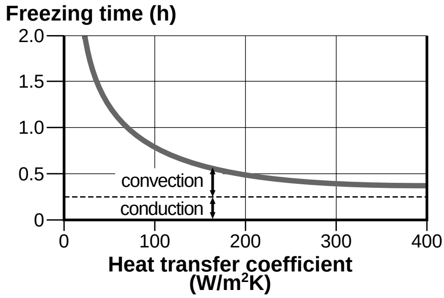

Fig. 9.8 The time required to freeze a given product is the sum of two terms: one describing the conduction of heat through the product, and the second describing convective heat transfer at the surface. When the surface heat transfer coefficient is low we can ignore conduction; at high heat transfer coefficients, conduction becomes the limiting factor. The graph is for a typical 450 g package of fish fillets measuring 32 mm thick.

transfer coefficients, such as in a plate-type freezer, conduction sets a lower limit on the freezing time that can be achieved.

9.3.3 Blast freezers

Belt-type freezers – variously referred to as blast freezers, belt freezers, tunnel freezers and spiral freezers – make up the most common family of continuous food freezers. They are available for both mechanical and cryogenic refrigeration, and can be used for most food types. In this section we will look at the simplest mechanical refrigeration freezer of this type, generally called a blast freezer.

The blast freezer (Fig. 9.9) has a conveyor belt, usually made from perforated stainless steel, to carry the product to be frozen. Electric fans mounted above the conveyor circulate chilled air down over the product, through the perforations in the belt and back up over the evaporator coils. Multi-pass designs are sometimes used to increase the residence time that the food spends in the freezer. Applications include burgers, chicken joints, pizzas, vegetables and ready meals.

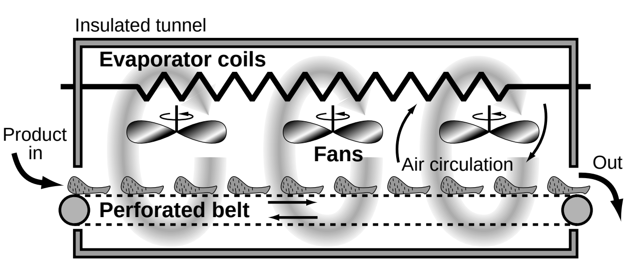

Fig. 9.9 The blast freezer has a horizontal belt to carry the food. Above the belt are fans to mix the cold air and improve heat transfer.

Heat transfer from the upper surface of the product is mainly by convection to the chilled air, so a well-designed air circulation system is essential for good performance. The aim is to maximise heat transfer by creating turbulence and high air velocities, especially in a direction at right angles to the surface of the product. At the same time the fan power must be kept to a reasonable level, since the refrigeration system has to remove all the heat added by the fans. Evaporation of moisture from the food also plays a part in heat transfer.

Heat transfer from the lower surface of the product is partly by direct convection but largely by conduction to the stainless steel belt, which is itself cooled by convection. A variant sometimes called a belt freezer uses a solid stainless steel belt whose underside is sprayed with cold brine. In this design, which is more like the plate freezers described in section 9.3.6, conduction dominates the whole heat transfer process.

Blast freezers range in throughput from 200 kg/h to 5000 kg/h. A blast freezer handling 2000 kg/h of beefburgers might measure 2.5 m wide, 3 m high and up to 25 m long, with a belt width of 700 mm. Residence time in the freezer is 3–4 minutes. The refrigeration power is around 160 kW at an evaporator temperature of −40ºC, and typical overall heat transfer coefficients are in the range 15–50 W/m^{2}K.

Figure 9.10 shows the Frigoscandia Flat Product Freezer, a blast freezer designed with high air velocities to give quick freezing in cases where internal heat transfer is not the limiting factor. Also known as an impingement freezer, this design gives high air velocities at right angles to the product surface, on both sides of the belt. Overall heat transfer coefficients can reach 175 W/m^{2}K.

Some products such as fish fillets may suffer damage caused by sticking to the perforated belt of a standard blast freezer. A variant called the Torry tunnel has a smooth belt that reduces product damage. The original Torry tunnel was built by scientists working for the UK government's Ministry of Agriculture, Fisheries and Food at the Torry Research Station, Aberdeen. Several freezer manufacturers now offer variants of this design, for both mechanical and cryogenic refrigeration.

9.3.4 Cryogenic tunnel freezers

The cryogenic version of the mechanical refrigeration blast freezer is known as a tunnel freezer. The general design is like that of the blast freezer, but instead of a bank of evaporator coils it has nozzles to spray liquid nitrogen or carbon dioxide 'snow' directly onto the food. Evaporation or sublimation of refrigerant from the surface of the product makes an important contribution to the overall heat transfer.

Applications are mostly similar to those for blast freezers, but the cryogenic tunnel has some advantages over the blast freezer. The first of these is speed of freezing. The very low temperatures that characterise both liquid nitrogen and liquid carbon dioxide mean that the temperature differences available to drive heat transfer are much greater than in a similar mechanical refrigeration freezer.

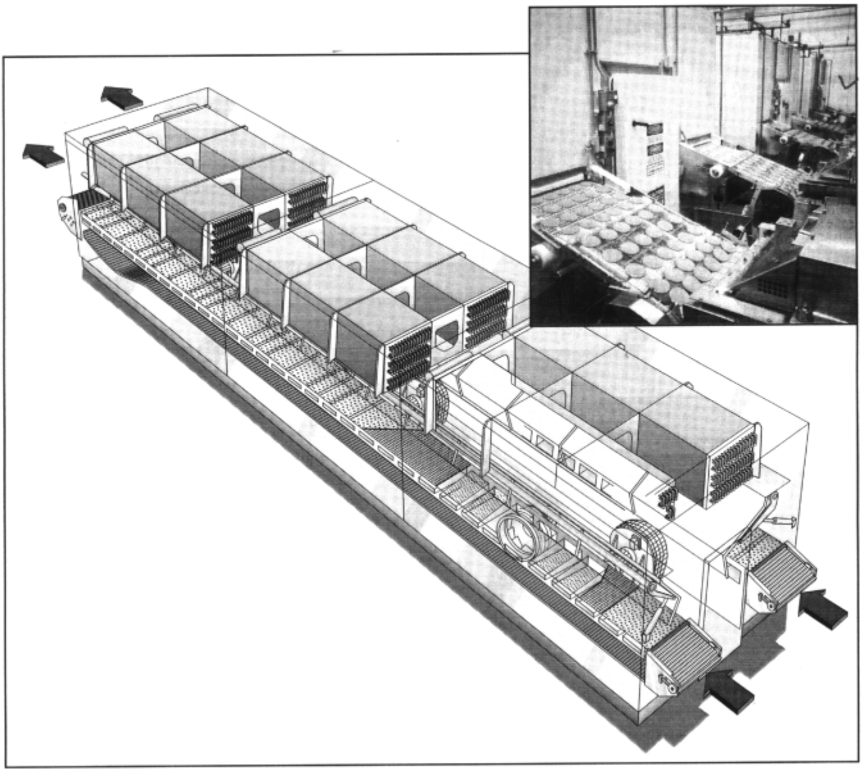

Fig. 9.10 The Frigoscandia Flat Product Freezer is a blast freezer designed for high air velocities. The direction of air movement is vertical rather than horizontal. The result is rapid freezing of thin products such as burgers, where heat transfer is not limited by conduction within the product.

Because the refrigerant is in direct contact with the food, heat transfer coefficients also tend to be high, especially in the case of liquid nitrogen.

The second advantage is flexibility. In a blast freezer, the amount of heat given up to the evaporator coils is limited by the maximum air velocity inside the freezer, which in turn is fixed by the design. In a cryogenic tunnel, the rate at which refrigerant is added is more or less independent of the gas velocity. This gives cryogenic tunnels considerable flexibility in responding to changes in production rate.

Figure 9.11 shows a modern cryogenic tunnel: the Air Products Cryo-Quick VT, which uses liquid nitrogen. Most cryogenic tunnels have a single refrigerant spray zone, near the point where the product leaves the tunnel, and one or more gas transfer fans to move the cold gas along the tunnel to the product inlet. The Cryo-Quick VT design is unusual because it has multiple liquid nitrogen spray zones, providing better control and eliminating the need for gas transfer fans.

Again in contrast to normal practice, the gas circulation fans in the Cryo-Quick VT are mounted beneath the belt. By increasing the distance between the fans and

Fig. 9.11 Cryogenic tunnel freezers are similar to mechanical refrigeration blast freezers, but with spray nozzles for liquid nitrogen or liquid carbon dioxide instead of evaporator coils. This Air Products Cryo-Quick VT freezer is an unusual design. Fans beneath the belt reduce liquid nitrogen consumption, while a vortex-inducing curved upper section gives vertical gas velocities and hence rapid freezing.

the product, this arrangement provides a more uniform gas flow. Above the belt is a specially shaped hood designed to create a pair of vortices which mix the gas and direct it back downwards onto the product. According to Air Products, this arrangement gives maximum heat transfer coefficients of 120 W/m^2K – up to twice the value for a standard cryogenic tunnel.

Refrigerant consumption is measured as a 'consumption ratio' equal to the weight of refrigerant used divided by the weight of product frozen. For a typical liquid nitrogen freezer the consumption ratio ranges from 0.3 for foods with a low moisture content, up to 2 for difficult foods such as seafood. High refrigerant consumption can be a significant problem with cryogenic tunnels,

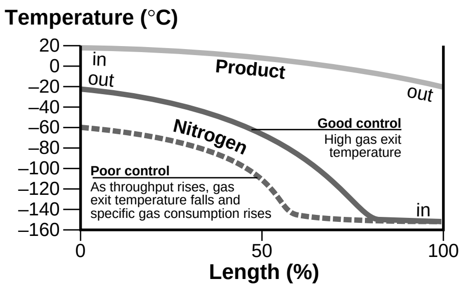

Fig. 9.12 Understanding and controlling the temperature profile along the freezer is key to minimising gas consumption in a cryogenic tunnel freezer. Conventional single-point control, as here, is not a good control strategy.

especially following a change in throughput or product type. The reason for this is poor control.

Figure 9.12 shows the gas temperature profile along the length of a typical liquid nitrogen tunnel with one spray zone. The inlet temperature is fixed at around −150ºC, just above the boiling point of liquid nitrogen. To avoid wasting energy, the gas exit temperature should be close to the entry temperature of the food – say −30ºC for a product entering at 20ºC.

Liquid nitrogen injection rate and fan speed are normally controlled so as to maintain a constant temperature at a single point part-way along the tunnel (Fig. 9.12). This is not a good control strategy, because it causes the gas exit temperature to change whenever the load on the freezer changes, and this in turn either causes under-freezing or wastes refrigerant. The Air Products multi-zone approach gives better control and hence lower liquid nitrogen consumption.

9.3.5 Spiral freezers

A significant drawback with conventional blast and tunnel freezers is the floor area they take up. Replacing the straight belt with a vertical-axis spiral reduces the floor area considerably, at the cost of extra mechanical complexity, and allows longer residence times. Spiral freezers almost always use mechanical refrigeration, although cryogenic versions are available.

Spiral freezers are one of the commonest freezer types in the food industry. Capacities are in the range 500–10 000 kg/h, with a typical 2600 kg/h unit measuring 7.6 m long, 5.3 m wide and 4.6 m high. Applications and performance are generally as for straight blast and tunnel freezers, with overall heat transfer coefficients around 35 W/m^{2}K.

Early spiral freezers used a system of rails to guide the flexible belt. Modern designs such as the mechanical refrigeration Frigoscandia GYRoCOMPACT (Fig. 9.13) have a self-supporting and ‘self-stacking’ belt with side plates that allow each turn of the spiral to rest directly on the one below. The continuous belt enters the spiral at the bottom, via a drive mechanism that supports the whole weight of the spiral. On reaching the top of the spiral, the belt changes

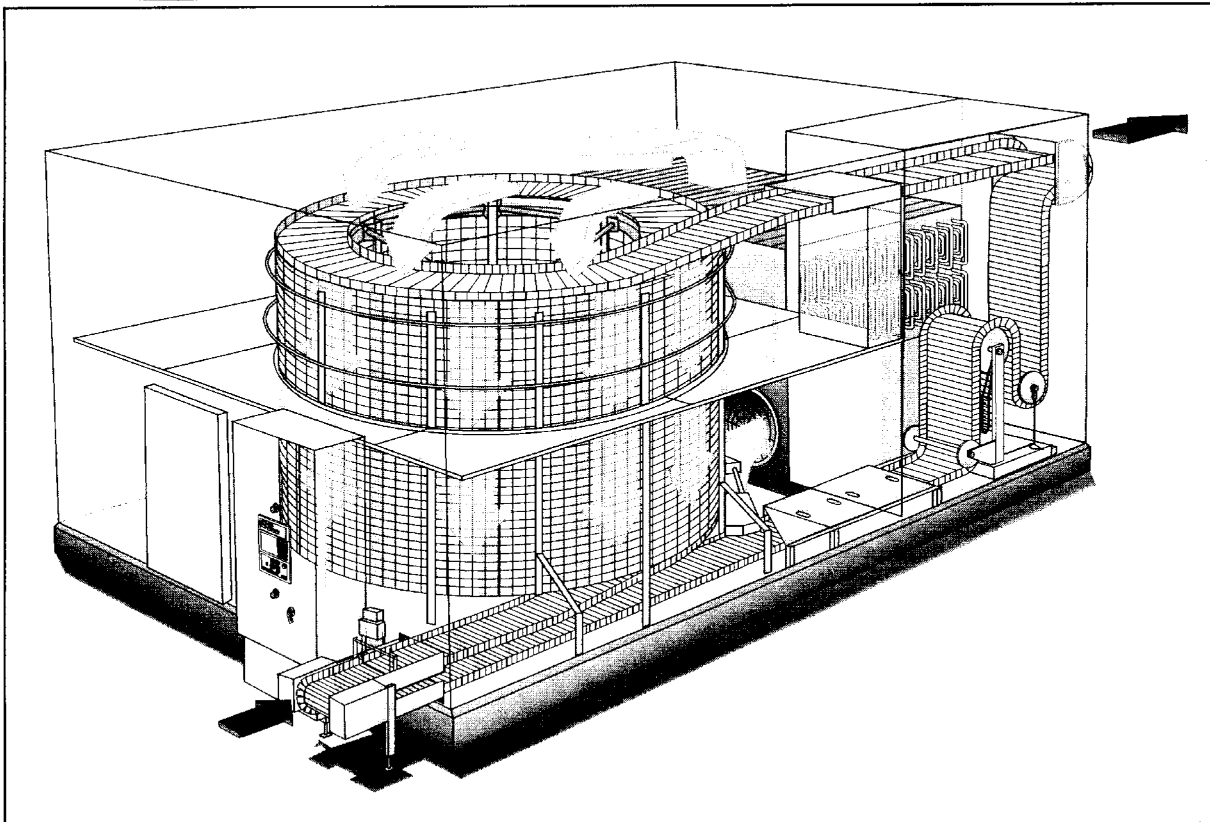

Fig. 9.13 The GYRoCOMPACT spiral freezer from Frigoscandia is a typical modern spiral freezer with vertical airflow.

direction, discharges the frozen product and then returns to the feed point at the base of the freezer. Air flows vertically, from the top to the bottom of the spiral.

Jackstone Food Systems favours horizontal airflow for its spiral freezers (Fig. 9.14). This arrangement minimises the fan power needed to circulate the air. It also allows delicate products to use a belt with a closely spaced mesh that would cause too high a pressure drop in a vertical-airflow freezer.

Another Jackstone unit, the Spiral 2000, has a spiral in which the belt moves first upwards and then downwards. This allows the feed and the discharge points to be on the same level, at the base of the freezer. Such an arrangement is possible with a conventional spiral freezer, but only by having two spirals mounted side by side.

9.3.6 Plate freezers

Used to freeze large blocks of product, plate freezers are aimed at bulk storage and distribution rather than individual product portions for retail sale. Typical applications are in freezing whole fish or fillets, including on board ship; offal and other animal by-products; fruit and vegetables, including purees and juices; liquid egg; and coffee concentrates. All commercial plate freezers operate batchwise and use mechanical refrigeration. They are also known as contact freezers.

The Jackstone Food Systems vertical plate freezer (Fig. 9.15) has between 20 and 32 ‘freezing stations’ separated by aluminium plates carrying channels through which refrigerant circulates. The plates are spaced at intervals of 50–100 mm, giving frozen product blocks of corresponding thickness. The blocks are strong and of consistent dimensions, so they are easy to handle and stack.

With liquid refrigerant on one side of the plate and wet product on the other, heat transfer coefficients are high: 100–1000 W/m^2K. A typical 25-station freezer producing blocks 75 mm thick has a throughput of 10 000 kg/d. Each freezing cycle takes around 150 minutes, including a 20-minute defrost, after which the blocks are unloaded mechanically. Some plate freezers have automatic loading and discharge systems to provide quasi-continuous freezing.

Turning the vertical plate freezer on its side gives a horizontal plate freezer. Some horizontal designs are very similar to their vertical counterparts, with freezing plates at the top and bottom of each product block. Hydraulic cylinders compress the plate pack, improving heat transfer and ensuring that the blocks are of uniform dimensions. This design suits applications where headroom is tight, such as on board ship.

Other horizontal plate designs lack the hydraulic mechanism and freeze from the bottoms of the blocks only. A variant on this type is the Jackstone Platoblast, which adds a flow of cold air to freeze the top surfaces. These freezers are more like the carton freezers discussed in section 9.3.10, although they are suitable for a wider range of products.

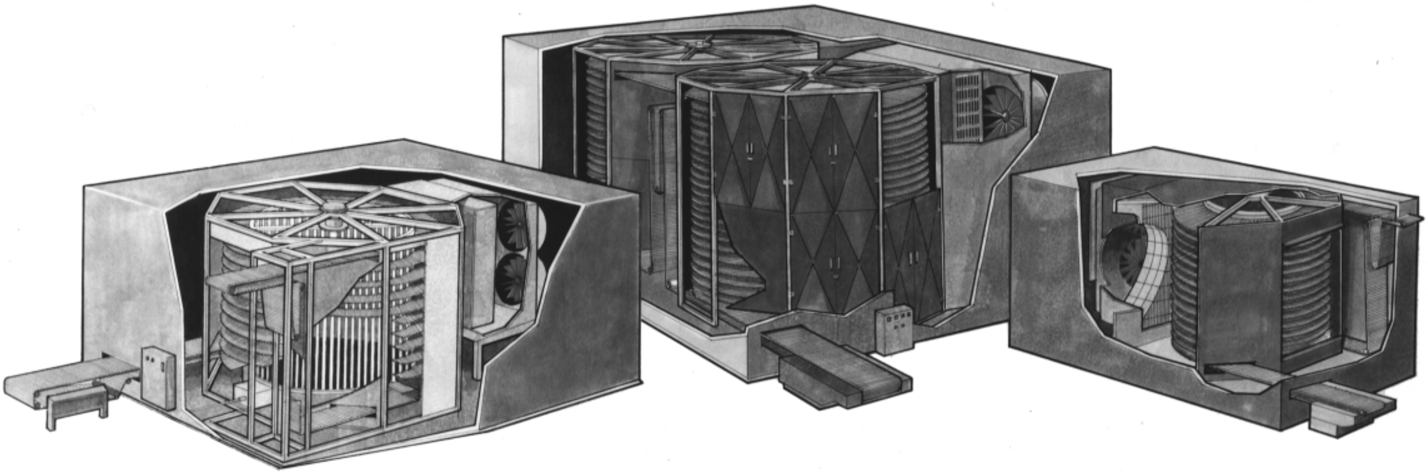

Fig. 9.14 This spiral freezer from Jackstone Food Systems uses horizontal airflow to reduce fan power or allow the use of a closely spaced belt mesh for fragile products.

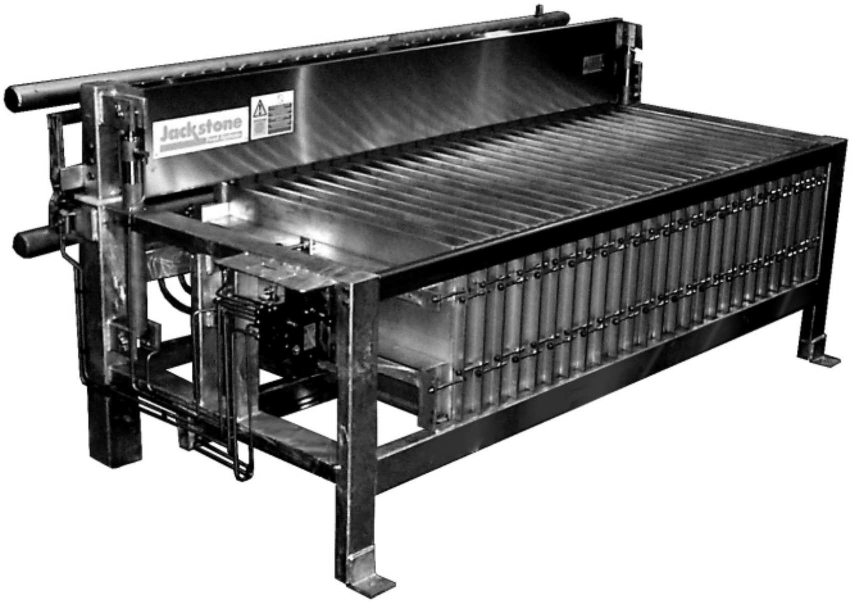

Fig. 9.15 Plate freezers like this one from Jackstone Food Systems have very high heat transfer coefficients for rapid freezing of bulk products.

9.3.7 Immersion freezers

Immersion freezers, in which products come into direct contact with liquid refrigerant, are important for two quite different classes of foodstuffs: prawns and other IQF products on the one hand, and bulky items such as turkeys on the other.

IQF products need quick freezing in a non-water-based refrigerant. Early immersion freezers for this duty used R 12 or other halocarbon refrigerants, giving rise to huge atmospheric emissions of these substances. Now that halocarbons are being phased out, liquid nitrogen has completely replaced them in immersion freezers. The violent boiling of the liquid nitrogen produces turbulence which helps to keep the products separate, and ensures high heat transfer coefficients (140–280 W/m^2K).

A liquid nitrogen immersion freezer such as the Air Products Cryo-Dip (Fig. 9.16) is often used to crust-freeze IQF products, after which a cryogenic tunnel completes the freezing process. This arrangement gives rapid freezing and good flavour retention with minimal dehydration, avoids the danger of over-freezing, and minimises liquid nitrogen consumption by exhausting the nitrogen gas at close to room temperature. Residence time in the liquid nitrogen is just a few seconds.

Turkeys and other bulky items, in which the thermal conductivity of the food limits the freezing rate, need a different kind of immersion freezer. However good the heat transfer at the surface of the product, freezing still takes several hours. A convenient way to provide this length of residence time is to wrap the turkeys in polythene and drop them into a tank of chilled calcium chloride brine.

Fig. 9.16 Immersion freezers use a bath of liquid nitrogen to give rapid freezing of prawns and other IQF products. This Air Products Cryo-Dip has a throughput of 2–5 t/h.

Control of residence time is simple: as fresh turkeys enter the tank at one end, they displace a similar number of frozen turkeys at the other end.

9.3.8 Fluidised-bed freezers

Gas or liquid flowing upwards through a layer of solid particles can cause the solid material to behave somewhat like a fluid (Fig. 9.17). This is a fluidised bed, and freezers using this operating principle are a good way to freeze small IQF items such as prepared fruit and vegetables. Fluidised beds are characterised by high heat transfer coefficients and good mixing, which ensures uniform temperature distribution and stops frozen product clumping together.

The simplest batch fluidised-bed freezer is a simple vessel with a perforated floor through which cold air is blown. All that is needed to turn the batch freezer into a continuous version are two pipes to provide the feed and remove the frozen product, but with this arrangement the residence time is hard to control and there is a risk of over- or under-freezing.

Commercial fluidised-bed freezers therefore tend to use a moving belt to control residence time. Product is loaded onto one end of a perforated belt and

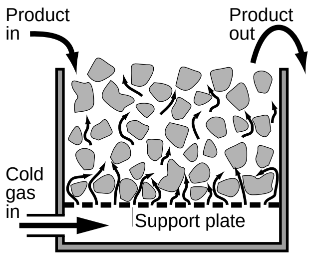

Fig. 9.17 The principle of the fluidised bed. A uniform stream of cold air or other gas can lift a 'bed' of solid particles, causing them to behave like a fluid. Fluidised beds transfer heat well and stop frozen product from clumping.

fluidised by an upward flow of cold air or nitrogen. On reaching the other end of the belt, the frozen product falls into a chute and is discharged.

Figure 9.18 shows the FLoFREEZE M fluidised-bed freezer from Frigoscandia, available in different sizes for throughputs of 5–12 t/h. Food entering the machine travels through the first of two freezing zones, where it is crust-frozen to provide strength and minimise moisture loss. The partly frozen product then falls onto a second belt and is carried into the second zone, where freezing is completed. Air is blown up through the bed, down across the evaporator coils, and back to the underside of the belts. Optional mechanical vibrators agitate the belts to stop sticky products from clumping.

BOC's ºKwikFreeze is a cryogenic version of the fluidised-bed freezer. It produces high-quality IQF chicken pieces and prawns as well as frozen vegetables. Available in two sizes, for nominal throughputs of 900 kg/h and 2200 kg/h respectively, the ºKwikFreeze is a compact freezer. The main freezer box on the larger model measures 1730 mm long, 1630 mm wide and 1980 mm high.

9.3.9 Tumbling and rotary tunnel freezers

As an alternative to fluidised-bed freezers for IQF products, tumbling or rotary tunnel cryogenic freezers offer high product quality and high throughput for a given floor area. The product must be able to withstand the tumbling action. Typical applications are coating diced vegetables with breadcrumbs, and minced or diced meat, either cooked or raw.

Product enters an insulated stainless steel tube mounted at a slight angle to the horizontal and rotated at several r.p.m. by a set of external driving wheels (Fig. 9.19). Liquid nitrogen is sprayed into the same end of the tube. As the tube rotates, the product is thrown about in a mixture of liquid nitrogen and cold nitrogen gas. The inclination of the tube causes the product to move slowly towards the other end, along with the exhaust nitrogen. The tumbling motion stops the product from sticking together.

Counter-current flow between the product and the nitrogen means that, compared to a counter-current tunnel freezer, the rotary design wastes more heat

Fig. 9.18 The Frigoscandia FLoFREEZE M is a fluidised-bed mechanical refrigeration freezer with two freezing zones. Inset: peas are a typical application of IQF freezing in a fluidised bed.

Fig. 9.19 A tumbling freezer such as this Air Products Cryo-Tumbler is a batch device ideal for coating IQF products with sauces or breadcrumbs. A unit measuring 3.1 m high, 3.5 m long and 2.9 m wide has a capacity of 850 kg of product. The continuous version, known as a rotary tunnel freezer, works in a similar way but is longer (6–12 m) and smaller in diameter (800–1200 mm).

in the nitrogen exhaust. Gas velocities are lower, too, but the area of product exposed to the cold gas is higher, so overall heat transfer coefficients can match those of a conventional tunnel. The lack of gas circulating fans means less heat input to the tunnel, and this helps to keep liquid nitrogen consumption down.

9.3.10 Stationary tunnels and carton freezers

The stationary tunnel (Fig. 9.20) is one of the simplest types of mechanical-refrigeration freezer. Product is placed on trays, racks or trolleys and loaded into

Fig. 9.20 The Air Products Cryo-Batch is an example of a cryogenic stationary tunnel freezer. Although mechanically simple, it is available with a control system which can store temperature/time profiles for up to eight different products.

an insulated box equipped with refrigerated coils and air circulation fans. The freezer can operate entirely batchwise, in which case product is loaded into the freezer and left there until it freezes. In a more sophisticated variant, wheeled trolleys are moved continuously through the freezer, either by hand or automatically. Heat transfer coefficients are generally in the range 20–40 W/m^2K.

The stationary tunnel is a versatile freezer but it is labour-intensive and dehydration losses can be high. The racks of product must be carefully positioned to ensure a uniform airflow, with gaps that are neither too large nor too small.

A similar device, the carton freezer, is used to freeze large cartons containing products such as ice cream. Cartons are placed on a series of shelves which are moved automatically through the freezer.

9.3.11 Specialist freezers

The freezer types described so far cover the great majority of food freezing applications, but there are also many other specialist freezer designs. One example is Air Products' Cryo-ZAT technology for cryogenic freezing of ice lollies.

Ice lollies are normally frozen at around −20ºC in metal moulds that have been pre-cooled by mechanical refrigeration. Once frozen, the lollies are released either by hitting the moulds or by warming them briefly in hot water. Neither method is completely satisfactory; impact can damage the product, while warming the moulds tends to destroy fine surface detail.

Food manufacturers believed for many years that the lower the temperature, the greater the tendency of the lolly to stick to the mould. Air Products, however, discovered that this is true only down to temperatures of around −80ºC, below which mould adhesion falls dramatically. The Cryo-ZAT process, which uses liquid nitrogen as the refrigerant, allows lollies to be made with intricate surface detail that was previously impossible.

9.4 Choosing a freezer

9.4.1 Introduction

Section 9.2 described the basics of mechanical and cryogenic refrigeration, while section 9.3 set out the main points of each freezer type. With this background, we can now summarise the main issues involved in choosing a freezer. Some products have special characteristics or quality requirements that restrict the choice of freezer to a single type. Often this will also limit the choice of refrigeration method, as section 9.4.2 makes clear. If more than one freezer design or refrigeration method will do the job, the choice comes down to a detailed comparison of costs, product quality, flexibility and other commercial issues (sections 9.4.3–9.4.5).

9.4.2 Matching the freezer to the product

Small or thin products, where heat conduction through the food itself is not the limiting factor in determining the speed of freezing, are often frozen in blast, tunnel and spiral freezers. Products of this kind that are prone to high dehydration losses freeze best in a cryogenic tunnel, or a blast freezer that has been optimised for rapid freezing.

IQF and 'difficult' products are better suited to a cryogenic immersion freezer, or to a fluidised-bed freezer, where high gas velocities ensure that the product does not stick together. Fluidised-bed freezers offer rapid freezing and high throughput, although they are more expensive than blast and tunnel freezers. Wet products to be frozen in bulk require some kind of plate freezer. Vertical plate freezers, or horizontal models with hydraulic closing, have a high throughput for their size and produce uniform blocks that are easy to handle.

Pre-packaged foods such as ready meals can use an open-type horizontal plate freezer, in which only the base of the product is in contact with the refrigerated surface, or a stationary blast freezer. Both of these are batch-loading alternatives to continuous blast and tunnel freezers. Specialist cryogenic tunnel freezers also exist for pre-packaged foods. For large products, speed of freezing is increasingly limited by internal heat transfer. For items such as frozen turkeys, which need a residence time of several hours, a brine immersion freezer is the most practical choice.

Some freezer types are effectively limited to a single source of refrigeration. Plate-type freezers, for instance, are only available for mechanical refrigeration. Immersion freezers for IQF products require cryogenic refrigerants now that CFCs are no longer approved for this purpose.

9.4.3 Costs and flexibility

If more than one type of freezer or refrigeration system can do a particular freezing job, the final choice is likely to depend largely on cost. The uncertainties of the frozen food market, however, mean that this is not always as straightforward as it sounds.

Only around one in three new frozen food products is commercially successful, and lead times for new products need to be short. Typical investment-related questions to minimise commercial risk include the following:

- What are the capital and operating costs of a freezer to freeze the product at the planned rate?
- How long do we have to acquire and install the necessary equipment?
- If this product does not sell, what is the cost of withdrawing from the market? Can the freezer be used for something else?
- If the product sells well, what flexibility is there to increase production at short notice?
- If the product is seasonal, such as fruit or ice cream, will the freezer be shut down out of season, or can it be used for another product?

In general, cryogenic freezers have the lowest capital costs, while mechanical refrigeration freezers are the cheapest to run. Figure 9.21 compares the capital and operating costs of mechanical refrigeration and cryogenic freezers across the life of the plant. In fact, many cryogenic freezers are leased from the gas suppliers and so have even lower capital costs than Fig. 9.21 would suggest.

For new products, or when demand is hard to predict, cryogenic freezing is attractive because of its lower capital cost and greater flexibility in throughput. High electricity costs, shortage of skilled maintenance staff and the need to get a freezer up and running in a hurry also favour cryogenics.

Mechanical refrigeration is often best for established products such as frozen vegetables, especially when the market is flat and demand is steady throughout the year. If the site already has a mechanical refrigeration plant with spare capacity, plus the staff needed to run it, then a mechanical refrigeration freezer is likely to be the best option. Leasing is not currently available for mechanical refrigeration freezers, although it may become an option in the future.

9.4.4 Product quality

As we have previously discussed, rapid freezing normally improves product quality by reducing the size of ice crystals and cutting dehydration losses. Uneven temperature distribution, however, is sometimes a drawback with rapid freezing. Product leaving any freezer shows a ‘temperature gradient’ – coldest on the outside, warmest at the core – which disappears during storage. Faster freezing generates steeper temperature gradients, so the product takes longer to reach its equilibrium temperature during storage.

Surface temperatures that are too low can also cause the product to become brittle (‘over-freezing’). Otherwise, mechanical damage should not be an issue if the freezer is chosen correctly, although sometimes it is reasonable to trade off quality for cost savings. Some creasing of fish fillets, for instance, may be acceptable if it allows the operator to run at a higher throughput.

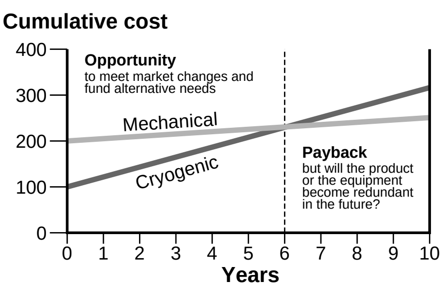

Fig. 9.21 Cryogenic freezing systems typically have low capital costs, while systems based on mechanical refrigeration are more expensive to buy but cheaper to run. The expected lifetime of a new food product is an important factor when choosing a freezer, as this graph of total investment shows. (Source: Air Products.)

Sometimes a combination of two different freezer types is the best way to ensure a good-quality product. An example is the use of a mechanical refrigeration spiral freezer for fish fillets, which can be damaged when the inner edge of the belt collapses as it travels round a curve. A cryogenic tunnel upstream of the spiral freezer can eliminate this damage by crust-freezing the product before it enters the spiral.

Dehydration during freezing is both a quality issue and a direct financial cost in terms of lost product. Hot cooked chicken can lose 8% of its weight when frozen slowly; fast freezing reduces dehydration to 2% or less. Cryogenic freezers, which can freeze food in only a quarter of the time needed by their mechanical refrigeration counterparts, ensure an acceptable level of dehydration losses even with difficult products. A typical arrangement is to use a cryogenic tunnel upstream of a mechanical refrigeration spiral freezer. By crust-freezing the chicken before it enters the spiral freezer, the cryogenic tunnel greatly reduces dehydration losses.

Legislation can complicate the dehydration issue. In the United States it is becoming accepted practice for burger manufacturers to compensate for dehydration loss by misting the burgers with water before freezing. As a result, US manufacturers may tolerate slower freezing than their European counterparts.

9.4.5 Operability issues

Cryogenic freezers tend to be more compact than those using mechanical refrigeration, in some cases needing only half the floor space for the same throughput. The importance of this varies. If the factory has plenty of room, the ‘footprint’ of the freezer may not be a problem. If space is tight, or if the freezer is to be installed in a new hygienic processing area where floor space is expensive, a compact freezer may be essential.

Good control is important, especially with cryogenic freezers, where gas consumption can rise dramatically when the product or the throughput changes. Regular tuning by the gas supplier’s staff will help, but the best solution is a well-thought-out control scheme, preferably based on multiple zones with independent temperature controls.

Ice build-up on the evaporator coils reduces the performance of a mechanical refrigeration freezer. Most freezers can run for two shifts before defrosting becomes necessary, and the defrosting process itself is often automatic. Freezers for blanched vegetables or other products that give off a lot of moisture, however, may need to be oversized by 20% to allow for frosting. Cryogenic freezers do not usually need defrosting. All freezers need to be cleaned regularly. Choose a design that is adapted for cleaning in place (CIP) or one that provides easy access to the working parts.

9.5 Further reading

GOSNEY, W. B. *Principles of Refrigeration*, Cambridge, Cambridge University Press, 1982. Now out of print, this is still one of the best textbooks of refrigeration engineering.

MALLETT, C. P. (ed.), *Frozen Food Technology*, London, Blackie Academic and Professional, 1993.

10

Selecting packaging for frozen food products

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10.1 Introduction

Packaging can play an important role in preserving quality within frozen foods. By selecting the appropriate material and design of package, the food producer can help to protect the food product from damage and loss of quality during its distribution from the factory to the consumer. Packaging also makes a key contribution in minimising quality loss within the food during periods of frozen storage. The capacity of packaging to provide an effective barrier to the ingress of moisture, gases and contaminants from the environment to the food is essential for preserving both sensory and nutritional characteristics. Similarly, suitable packaging has the ability to provide an effective barrier to the loss of moisture and flavour volatiles from the food to the external environment.

Although the type of packaging selected by the food producer will depend primarily on the technical and legislative requirements for the individual product, a well-designed and consumer-appealing package will also help to portray an image of high quality and responsible food production to the consumer. Packaging for frozen foods, as for other food sectors, is constantly changing. The dynamics of change reflect not only technical advances, but also demographic and social changes. Increased competition for space on supermarket shelves is often a driving force behind new packaging developments. The 'novelty value' of innovative and niche-directed food packaging can create a short-term competitive advantage. However, such developments should be the result of considerable research and development of the technical and legislative issues dictating the choice of package for the particular product. The package is often the first point of contact between the consumer and the food product and, consequently, plays an important role in marketing the product. Modern packaging materials and printing techniques can produce high-quality graphics on the outer layer of the package, and this often has a key role in the primary advertising of the frozen food product.

The food processor's choice of packaging is dictated by a combination of factors, including technical, legislative and commercial. In practice, there are also other considerations, including the availability of packaging equipment, the cost and the company's own packaging philosophy. In addition, consideration must be given to other important functions of the food package, e.g. ensuring that the food producer can easily handle and transport the product, and ensuring that the consumer can easily handle and regenerate the product. This chapter suggests the major considerations for the food producer in selecting packaging for frozen foods, encompassing the following:

- essential requirements for frozen food packaging;
- legislative responsibilities;
- types of packaging material;
- assessing the suitability of packaging for different products;
- packaging machinery;
- future developments in frozen food packaging.

10.2 Essential requirements for frozen food packaging

The primary function of food packaging is to protect the food from external hazards. At the same time, the packaging material itself should not affect the food in any way. The packaging material chosen should meet certain minimum technical, legislative, environmental and commercial requirements. Many of these requirements are intended to ensure that the packaging material provides the product with the necessary protection to ensure both food safety and quality. The key functions of a food package can be summarised as follows:

- protection;
- preservation;
- presentation.

In terms of protecting the product during handling, distribution and storage, the package needs to provide adequate mechanical strength (e.g. to withstand crushing or deformation) and barrier properties (e.g. to prevent the ingress of microbial, chemical or physical contamination). It is also highly desirable to provide protection from the possibility of deliberate contamination or tampering, and also an indication of whether such events have occurred.

In terms of preservation, the package must be able to encapsulate the food adequately so as to minimise quality loss from the product. In order to extend the quality storage life of a frozen food product, the packaging material should restrict the rate at which the volatiles responsible for the flavour of the food are lost. Again, barrier properties are important as they dictate the transfer rates of moisture, gases and aroma molecules from the product to the outside environment. An important property is that of providing a light barrier to minimise any light-induced oxidative changes.

In terms of presentation, the package must provide a medium to convey a representation of the product to the consumer. Optical properties of the package material such as gloss (brightness/lustre) and haze (ability of the material to scatter light) are important, as they dictate the aesthetic qualities of the package. Surface properties of the material dictate the likely quality and definition of the final printing and reproduction of graphics on the package surface. They also provide the surface upon which the printing of instructions and information to the consumer are made. In combination, these properties are highly important, as they are likely to have a bearing on the overall success of the product in the marketplace.

All three of these major factors are influenced by the physical, chemical and barrier properties of the package material. Each of these, in turn, requires other factors to be considered, namely temperature stability, barrier properties, insulation properties, compatibility with packaging machinery and consumer appeal.

10.2.1 Temperature stability

The package material should be both physically and chemically stable over a wide range of temperatures. This should encompass the range of temperatures likely to be experienced by the product during each stage of production, distribution, storage and consumer handling. Generally, this should extend from freezer temperatures (−40ºC and above) to normal ambient temperatures. However, if the food product is also likely to be reheated or cooked in the package (e.g. a ready meal intended for direct consumer preparation in a conventional or microwave oven), the packaging material should also be capable of withstanding temperatures up to 300ºC or above.

The temperature of the food package also plays an important role in defining other characteristics of the package, as quoted below. Consequently, the design and selection of a frozen food package should consider the individual properties of the packaging material over the intended temperature range of application.

10.2.2 Barrier properties

The barrier properties that are provided by the food package material should be sufficient to prevent loss of moisture from the food product to the external environment. Ultimately, moisture loss from the product leads to dehydration, weight loss, possible desiccation and development of off-flavours at the food surface. The selection of a package material with barrier properties that prevents moisture loss from the food product can contribute significant benefits to the quality of a frozen food. This is particularly important for frozen foods, as the product may be held under frozen storage conditions for several months. The permeability of packaging materials to water vapour is dependent upon material permeability, surface area and temperature. Packaging materials with high water permeability may allow an acceleration of undesirable biochemical reactions, such as protein denaturation and lipid oxidation. These reactions, in turn, cause resultant increases in rancidity and the development of off-flavours. Also, physical quality losses that are induced by dehydration of the food material, e.g. loss of texture, can be minimised by the selection of packaging materials which provide a barrier to the ingress of moisture from the environment to the food, or moisture loss from within the food package to the external environment.

Under certain conditions of frozen storage, moisture migration may take place from the centre to the surface of the food, and this can result in the formation of a 'frost' within the food package, often visible on the inside surface of the package. This can be remedied by designing the food package to be a close fit around the food. It is at this crucial package design stage that the permeability to gas, light and water vapour, which can result in deterioration of colours, lipids, proteins and sensory qualities, should be taken into account.

The permeability of the package material to gases influences the micro-climate within the food package. In the majority of cases, it is desirable that the food package should prevent the ingress of gases from the external environment to the food. The exclusion of oxygen from frozen foods markedly reduces the rates of oxidative reactions that lead to rancidity and the development of off-flavours. Packaging materials with low oxygen permeability can, therefore, increase the quality shelf-life of the frozen food product. Packaging materials with low oxygen permeabilities also help to reduce other detrimental reactions within the food material, including the formation of thiobarbituric acid (TBA), which is a measure of lipid oxidation, and the destruction of carotenoids and ascorbic acid, which are key sensory descriptors of many oxygen-sensitive frozen foods. However, it should be noted that in some foods the anaerobic conditions formed within a frozen food package possessing low oxygen permeability might itself lead to tissue breakdown and development of off-flavours. In such cases, the package micro-climate may need to be controlled, e.g. by modified atmosphere or controlled atmosphere packaging (MAP or CAP).

Another important, but often overlooked, requirement for packaging some types of frozen food is to provide a barrier to visible light, ultraviolet (UV) light, or infrared radiation. In some food materials (e.g. fish, vegetables), photo-degradation of carotenoids can severely affect the appearance and sensory qualities of the food. This can be a potential problem when the frozen food package has been stored in retail frozen display cabinets that are constantly illuminated. Also, light in conjunction with oxygen is known to accelerate undesirable oxidative reactions. The choice of suitable, non-transparent packaging materials can limit the effects of such deteriorative reactions. Packaging materials that incorporate light-impermeable materials or ultraviolet (UV) light absorbers will improve the surface colour retention of many frozen foods and help to prevent lipid and pigment oxidation.

In addition to the important barrier properties above, the inner surface of the package material should also be resistant to staining and fouling from the components within the food, e.g. water and grease. Some of these components can penetrate the package fibres and lead to loss of mechanical strength and physical stability, and an unsightly appearance to the inside of the package.

10.2.3 Insulation properties

For certain, specific food products, it may also be required for the packaging material to possess some degree of thermal insulation. These properties may be required to help maintain a low temperature throughout the bulk of the food during periods outside the freezer, e.g. ice cream or frozen confectionery, where a single portion is taken from the bulk, which is then returned to the freezer. Insulated frozen food packages may also help to minimise temperature fluctuations in the food product, at all stages within the frozen food chain. Temperature fluctuation is known to be a major cause of quality degradation. Insulated packages may be constructed of a thermally insulating material (e.g. polystyrene foam) or by co-laminating synthetic packaging materials into structures which form thermally insulating layers. In such circumstances, the need for well-insulated packaging materials increases as the mass of the frozen food portion decreases. The susceptibility of the product to temperature abuse and the amount of value added to the product will determine whether or not the additional cost of such packaging is economically feasible.

10.2.4 Compatibility with packaging machinery

The choice of a suitable food packaging material will also be influenced by its suitability for use with mechanical packaging machinery and packing systems. This characteristic is particularly important for high-speed, automated packing lines, where the package will require tightly controlled tolerances on properties such as package dimensions, frictional characteristics, stiffness, resistance to crushing, sealability, ease of separation, and cutting and folding characteristics. It is necessary to specify such characteristics stringently to ensure that the operation of packaging and filling machinery is not compromised.

The choice of the frozen food package is, therefore, also dictated by the access and availability of food packaging machinery and/or the cost of new food packaging equipment, including conveying systems, filling lines, and package-forming and sealing systems.

10.2.5 Consumer appeal

In a competitive and demanding food marketplace, it is vital that the frozen food package presents the food product to the consumer in an appealing manner. A key factor in this respect is the ability to produce high quality printing and reproduction of graphics onto the outer surface of the package material. This requirement of the package can be described in terms of surface smoothness, gloss, absorbency, 'wettability', and tolerance to the appropriate ink medium. Finally, the material must be capable of surviving the ink-drying process, which is often a high-temperature 'curing' process.

The presentation of the food product to the consumer is also very important. Advances in high barrier, anti-fog, shrink-wrap films are currently combining good gas-barrier properties with high package transparency and gloss. Such features help to ensure added merchandising and consumer appeal. A recent new development in frozen food packaging technology has addressed the retention of colour in frozen red meats and some poultry products. The technique, designed to reduce colour deterioration of the products, entails placing the portioned meat in a high-pressure, pure oxygen atmosphere. This helps to restore the oxygen content of the meat to pre-slaughter levels. By combination of this innovative technique with incorporation of a suitable packaging material, with appropriate oxygen barrier properties, frozen meat products have retained their colour ('bloom') during lengthy periods of frozen storage.

For the majority of frozen food products, the printing is often made on an external carton or flexible bag, within which is the primary food package. However, the drive towards 'minimal packaging' and the legislative requirement to recycle or reclaim food packaging materials effectively, will undoubtedly mean that future packaging developments may need to have a single packaging material possessing all-encompassing properties governing protection, preservation and presentation.

10.3 Legislative responsibilities

Legislation on the essential requirements of food packaging are contained within the European Community Directives on Packaging and Packaging Waste, incorporated in the United Kingdom as Statutory Instrument No. 1165.[1] The regulations came into force in May 1998, with enforcement action allowed from January 1999. The main requirements of the regulations are that no person responsible for packing or filling products into packaging, or importing packed or filled packaging, may place packed or filled packaging on the market unless the packaging fulfils certain essential requirements and complies with prescribed heavy metals limits.

The essential requirements are as follows:

- Packaging must be minimal subject to safety, hygiene and acceptance for the packed product and for the consumer.
- Noxious or hazardous substances in packaging must be minimised in emissions, ash or leachate from incineration or landfill.
- Packaging must be recoverable through at least one of the following:
  – material recycling;

– incineration with energy recovery;
– composting or biodegradation.

- Packaging may be reusable.

The heavy metal limits, which apply to cadmium, mercury, lead and hexavalent chromium, are that the total should not exceed:

- 250 parts per million after 30 June 1999.
- 100 parts per million after 30 June 2001.

In addition, there are requirements specific to the manufacturing and composition of packaging, the reusable nature of packaging and the recoverable nature of packaging.

The environmental aspects of packaging and the responsibility imposed upon the food producer by European directives also need careful consideration. Directive 94/62/EC on packaging and packaging waste has major implications for all sectors of the food chain.[2] The aim of the directive is to diminish the impact of packaging and packaging waste on the environment and to limit the consumption of energy and raw materials. The directive sets European Community member states targets for recovery and recycling to be reached by the year 2001. These targets are that 50–60% of packaging waste must be recovered. Within this figure, 25–45% must be recycled, and a minimum of 15% by weight of each packaging material must be recycled. The means by which individual member states achieve these targets is directed by individual states.

The broad definition of packaging – 'products made of material of any nature to be used for the containment, protection, handling, delivery and presentation of goods' – means that the food industry has to take responsibility for ensuring that these targets are met. This will force the industry to take a closer look at its current methods of waste disposal and its use of packaging. From 1999, packaging may only be placed on the market if it complies with certain criteria, which includes ensuring that pack volume and weight is limited to the minimum necessary to maintain safety, hygiene and product acceptability. Thus, even at the packaging design stage it will be necessary to take into account the environmental impact of the package.

The above regulations refer generally to packaging in all sectors of industry. There are specific requirements covering packaging intended for foods, such as that in the United Kingdom under the regulations governing materials and articles in contact with food.[3] These regulations dictate that packaging materials and articles do not transfer their constituents to food in quantities that could: (a) endanger human health, or (b) bring about a deterioration in the sensory characteristics of such food or an unacceptable change in its nature, substance or quality. There are also specific EC directives relevant to plastic materials and articles in contact with foods,[4] covering, for example, permitted material composition, chemical migration limits (from the packaging to the food) and methods of testing for migration.

10.4 Types of packaging material

A wide variety of materials have been used for the packaging of frozen foods, including plastics, metals and card/paperboard. Each of these options has individual advantages and limitations. Advances in the science and technology of food packaging materials, together with new innovative food handling, preparation and preservation techniques, have revolutionised the food packaging sector. These developments provide the frozen food producer with a wide choice of packaging options. The following section summarises the main categories of packaging materials in current use throughout the food industry.

10.4.1 Plastic packaging materials

The characteristics of standard plastic packaging materials in common use for frozen food packaging are given below.

Polyethylene (PE), low density polyethylene (LDPE) and high density polyethylene (HDPE)

These materials are commonly used for the packaging of individually quick frozen (IQF) foods, e.g. fruits, vegetables and shellfish. The bags can be filled on a 'form, fill and seal' basis (see section 10.6). The material is relatively easy to seal using standard heat-sealing equipment and good quality printing can be achieved on the surface of the package. PE and LDPE films are relatively inexpensive. HDPE can also tolerate temperatures in excess of 100ºC and is often used in 'boil-in-the-bag' applications. Both HDPE and LDPE, however, provide relatively poor barrier protection from oxygen, although good barrier protection to water vapour (see Table 10.1).

Polyester terephthalate (PET)

These films can withstand high temperatures and are resilient to grease and water vapour. PET and crystallised polyester terephthalate (cPET) form a large and growing sector of packaging materials used in the prepared foods market. The trays are suitable for reheating in both conventional and microwave ovens, with stability at temperatures in excess of 250ºC. The materials, however, are relatively expensive and some forms can be 'brittle' at freezer temperatures. The material provides good barrier characteristics (semi-barrier) to both oxygen and water vapour (see Table 10.1).

Polystyrene (PS)

PS is a general plastic for frozen food applications. It has a high resistance to breakage at freezer temperatures but is relatively expensive and allows relatively high transmission of water vapour and oxygen between the food product and freezer environment. PS is a good thermal insulator and is consequently used as a secondary package material for cases of frozen products.

Polyvinyl chloride (PVC)
PVC is generally used for rigid containers. It is cheaper than PS and, when unplasticised, has a much lower permeability to water vapour and reduced permeability to oxygen. However, PVC possesses less impact resistance than PS and other plastics and consequently can become damaged during transit.

Polyamide (PA)
PA forms a plastic with good strength and moulding characteristics. It is suitable for thermoforming laminations, commonly used in 'boil-in-the-bag' applications.

Polypropylene (PP)
Modified films have found a niche for certain products and are becoming more widely used as a flow-wrap film. As a primary packaging material for frozen foods, PP has relatively poor barrier characteristics to both oxygen and water vapour.

Laminates and co-extrusions
It is evident from the characteristics of packaging materials described above that no single synthetic packaging material offers all the desirable features. In such cases, the food producer has to select the package material carefully and tolerate some degree of 'trade-off'. However, a great deal of development in the field of laminates and co-extrusions aims to combine the desirable characteristics of individual materials to provide a single protective package. By combining films of plastics with different properties it is possible to optimise the material to gain the specific properties required, e.g. the combination of a high water vapour barrier with a high oxygen barrier.

10.4.2 Metal packaging materials

Metal packaging materials can provide highly effective barrier properties for both water vapour and oxygen, along with good mechanical strength and ease of handling. The two most common metals used in food packaging are aluminium and steel.

Aluminium's compatibility with foods contributes to its utility as a packaging material. Aluminium foil is used for trays and may also be laminated to plastic films and paper and board to provide specific additional requirements. Aluminium foil is an excellent light and moisture barrier for frozen foods. The applications of aluminium packaging in frozen foods are increasing rapidly. Many prepared foods, e.g. ready meals and ready-to-cook products, are commonly enclosed in aluminium trays. The trays offer good rates of heat transfer, such that the product can be frozen and reheated (conventional oven) in the original packaging. It is now also becoming commonly accepted that aluminium foil trays can be safely used within microwave ovens.[5] This feature will add to the attractiveness of aluminium as a food packaging material.

Steel trays are also becoming common as food packaging materials and offer the same advantages of barrier properties, mechanical strength and good heat transfer as aluminium. An important advantage of metal trays and containers over synthetic food packaging materials is the recyclability of metals. This becomes ever more important as environmental directives drive the food producer towards recyclable and reusable food packaging.

Aluminium is also used in microwave susceptor boards for certain frozen foods (e.g. pizzas and pies). Susceptor boards consist of a thin PET film or paperboard layer, which is very lightly vacuum-metallised with aluminium. During microwave heating, the aluminium layer can reach a temperature of 240ºC, facilitating browning and crisping of foods in contact with this hot surface.

10.4.3 Paper and card packaging materials

Paperboard and card are also commonly used for packaging frozen foods. These packaging materials are usually considered in three groups:

1. Paper (thickness up to 3 mm).
2. Board (thickness between 3 mm and 11 mm).
3. Fibreboard.

All are made from wood pulp which is manufactured from virgin pulp or recycled waste paper. Paper is also used as a surface coating material to provide a smooth surface for high quality printing.

Board is used to produce both folding and rigid cartons. Board often consists of plies made from different materials, e.g. white lined chipboard has a white surface on one side made from a bleached virgin pulp, with the bulk being composed of ‘chip’ which is usually grey and made from a high proportion of waste paper. Fibreboard is used in the production of outer cartons for individual products and cases, which enclose batches of products.

Both paper and board have relatively poor barrier properties and mechanical strength unless they are laminated with an additional material. To provide adequate barrier protection, paper or board layers can be laminated with synthetic plastics, e.g. polyethylene. They can also be waxed or varnished to provide adequate moisture barriers. Paper and board containers coated with polyester can also be used as dual-ovenable trays, i.e. they can be used during regeneration of the product in either conventional or microwave ovens.

10.5 Assessing the suitability of packaging materials for different products

The choice of packaging material for a particular frozen food will depend upon the major deteriorative reactions governing the physical and biochemical changes within the food during frozen storage. These, in turn, have significant bearing on the sensory and nutritional qualities of the food following periods of frozen storage.

In this section, the temptation to suggest suitable packaging to different foods has been resisted. This decision is based upon the ‘golden rule’ that selection of packaging should take into account a full knowledge of the nature of the food, the precise characteristics of the distribution and storage systems and a realistic estimate of the required quality shelf-life of the food product. The following guidance is, however, intended to help the food producer through to an informed choice of packaging for the frozen food.

From the food product’s perspective, the packaging material can have a major role in minimising the physical and biochemical reactions that lead to sensory and nutritional quality losses. Physical changes to the food product can include colour, syneresis and texture. In terms of colour retention in foods, a major factor is the oxygen permeability of the packaging material. High oxygen permeability has been associated with loss of colour in meat and poultry products, as oxygen has the effect of increasing production of metmyoglobin, particularly at the surface of the packaged product. This, in turn, has the effect of reducing depth of surface colour and gloss. Pigment degradation and associated colour losses can also result from lipid oxidation within the product, and has been suggested as a major cause of colour quality degradation in oxygen-sensitive foods, e.g. meats, poultry and fish. Similarly, high oxygen concentrations in packaged fruits and vegetables can act on the chlorophyll substrate to produce fading of the natural colour characteristics of the food.[6] A similar trend has been reported with light transmission through the package. Syneresis (drip loss) is also influenced by the choice of packaging material. High oxygen permeability of the package is a major factor which can lead to high drip loss, particularly for high-fat foods (e.g. hamburger patties and processed meat products).

Textural changes within frozen foods can also be influenced by the permeability of the package to both oxygen and water vapour. Textural properties are closely related to the number and size of ice crystals within the food during frozen storage. It is well known that packages with high permeability to water vapour can ultimately lead to loss of moisture from the product and dehydration at the surface of the food. This is a particular problem if temperatures are fluctuating during frozen storage. Concurrently, loss of moisture from within the package often results in an increase in oxygen tension within the package, with resultant problems of oxidation as mentioned earlier.

Chemical and biochemical reactions are undoubtedly the major cause of deteriorative reactions in frozen foods. Quality deterioration in frozen foods can be associated with enzymic activity, protein denaturation and lipid oxidation. Enzymic and hydrolytic activities can be minimised by adequate pre-treatment of the food prior to freezing, e.g. the blanching of fruits and vegetables and the cooking of meats. However, even after adequate pre-treatments, it is recommended that the food manufacturer minimises the effects of slow freezing

Table 10.1 Relative oxygen and water vapour permeabilities of selected packaging materials[9]

Package material	Relative O_2 permeability (relative units)	Relative H_2O vapour transmission rate (relative units)
Aluminium (Al)	<50 (barrier)	<10 (barrier)
Ethylene-vinyl acetate (EVOH)	<50 (barrier)	Variable
Modified nylon (MXDE)	<50 (barrier)	10–30 (semi-barrier)
Modified polyester (PETG)	50–200 (semi-barrier)	30–100 (medium)
Polycarbonate (PC)	200–5000 (medium barrier)	100–200 (very high)
Polyester (PET)	50–200 (semi-barrier)	10–30 (semi-barrier)
Polyethylene (PE)		
High density (HDPE)	200–5000 (medium)	<10 (barrier)
Low density (LDPE)	5000–10 000 (high)	10–30 (semi-barrier)
Polypropylene (PP)	200–5000 (medium barrier)	10–30 (semi-barrier)
Polystyrene (PS)	200–5000 (medium barrier)	100–200 (high)
Polyvinylidene chloride (PVdC)	<50 (barrier)	<10 (barrier)
Polyvinyl chloride (PVC)		
Unplasticised	50–200 (semi-barrier)	Variable
Plasticised	5000–10 000 (high)	200–300 (very high)

and recrystallisation, to minimise the release of enzymes from the cellular infrastructure.[7] It is known that the denaturation of proteins in frozen foods is caused by ice formation and recrystallisation, dehydration, oxidation and concentration imbalance of salts. Again, fast freezing and prevention of ice recrystallisation are among the methods suggested to minimise the effects.[8] Although the role of packaging materials in this respect is less clear, all major food categories undoubtedly benefit from rapid freezing and constant, low frozen storage temperatures. This dictates the production method and food packing system used by the food manufacturer to some extent, i.e. whether to freeze the food product within the package (which may substantially increase the freezing time), or to fill the frozen food product into a pre-cooled package (which may add to production complexity and cost). The decision is dictated as much by the availability of processing equipment and the economics of the operation as the possible effects on food quality.

Table 10.1 shows some relative oxygen and water vapour transmission rates of selected packaging materials.

10.6 Packaging machinery

The choice of a frozen food package will also depend upon the availability of packaging machinery, which usually forms part of an integrated production line. The following is a list of typical packaging systems (not exhaustive) which are commonly used for the packaging of frozen foods.

10.6.1 Form, fill and seal (FFS)

These machines form pouch- or tray-shaped packages from sealable films of synthetic packaging material. The packages are simultaneously, or consecutively, formed and filled with the product in the machine. They generally work in a vertical plane for 'loose' products (e.g. frozen fruits or vegetables) and in a horizontal plane for 'wet' products (e.g. ready meals, ice cream products).

10.6.2 Cartoning systems

Cartons for packaging frozen foods can be top filled (generally irregular products), end filled (small, regular products) or side filled (large, regular products, such as trays of ready meals). Machines generally perform the operations of erecting, filling and sealing at speeds of between 50 and 400 cartons per minute.

10.6.3 Shrink and stretch film wrapping

For frozen foods, these machines can be applied to the packaging of individual meat cuts, or can be used to apply packaging material from rolls around a given number of consumer-portion sized packages. If used to wrap the product prior to freezing, these films can provide an effective barrier to product dehydration, while allowing efficient heat transfer from the product to the freezing medium.

10.6.4 Vacuum packaging and gas flushing

Certain refrigerated food products need to have an oxygen-free atmosphere to enable long shelf-life to be achieved. Although this is more common in the chilled food sector, certain products, e.g. red meats, are now being packaged in a controlled atmosphere. Partial vacuum or gas flushing of sealed packs is used in such cases.

10.7 Future developments in frozen food packaging

10.7.1 Active packaging

Active packaging, designed to perform some function in addition to physical and barrier properties, and based upon both chemical and physical effects, is rapidly emerging within several food sectors. Such developments can also potentially contribute improved quality retention to frozen foods.

Developments such as modified atmosphere packaging (MAP) have provided significant extensions to the quality shelf-life of fresh and chilled agricultural and horticultural produce. This is by the reduction of rates of respiration and ethylene production, and retarding biochemical and physical deteriorative processes.[10] Similarly, polymer films impregnated with chemically or physically active ingredients can function as oxygen/carbon dioxide/ethylene scavengers, moisture controllers/humidity buffers, taint removers and ingredient releasers, e.g. anti-microbial, antioxidant or enzymatic.[11]

Other innovative forms of packaging are edible films and coatings. These can be used to control gas exchange (water vapour, oxygen, carbon dioxide, etc.) between the food product and the ambient atmosphere, or between mixed components in a food product. Such films can therefore act as an additional tool to improve overall food quality and stability. Typically, such films and coatings are formed directly on to the food product surface, and become an integrated part of the product enclosed. As a consequence, much recent activity in this area has concentrated on achieving both product protection and neutral sensory properties.[12]

Edible films and coatings are generally made from natural constituents and can be categorised into polysaccharide (e.g. gums, starches, cellulose), protein (e.g. collagen, casein, gluten) and lipid (e.g. natural waxes, acetoglycerides). Many of the required functions of the films are similar to those required from synthetic packaging materials, including acting as barriers to moisture, gas and liquid ingress, and providing adequate mechanical strength and opacity. However, as with synthetic food packaging materials, the films themselves must be chosen according to their specific application, notably the type of food product and main deteriorative mechanisms. An added complication in the choice of edible films and coatings is that that they should have sensory properties that are either undetectable or complementary to those of the enclosed product. Alongside the desired physical, chemical and barrier properties, this latter property is often very difficult to achieve.

10.7.2 Intelligent or smart packaging

Intelligent (or smart) packaging refers to packaging that 'senses and informs'. Intelligent packaging devices are capable of providing information about the function and properties of a packaged food and can provide assurances of pack integrity, tamper evidence, product safety and quality. Intelligent packaging can also be utilised in applications such as product authenticity, anti-theft and product traceability. Intelligent packaging devices include time–temperature indicators, gas sensing dyes, microbial growth indicators and physical shock indicators. Day *et al*. recently compiled a review of active packaging in the food industry.[13]

Within this category of packaging are temperature and time–temperature indicators (TIs and TTIs). These devices are generally indicators that are attached to an existing food package, and are designed to monitor the temperature or time–temperature history of the product from the factory to the consumer. TIs usually display either the current temperature, or respond to some pre-defined threshold temperature (e.g. freezing point). TTIs usually utilise a physico-chemical mechanism that responds to the integration of the temperature history to which the device has been exposed. A review of time–temperature indicators has been given by Selman.[14] George and Shaw provided a food industry specification for the use and application of TIs and TTIs.[15] More recently, a British Standard defining the performance requirements for general use of such devices has been developed.[16]

10.7.3 Temperature control packaging

Temperature control packaging includes the use of innovative insulating materials designed to guard against undue temperature abuse during storage and distribution. This may be in the form of 'thermal blankets' for wrapping over pallets of frozen food, or individual thermally lined food packages, designed to minimise temperature fluctuation in individual products.

10.7.4 Novel packaging developments: regulatory issues

Any development of novel or active packaging must address at least four regulatory or food safety criteria. These are: food-contact approval; environmental regulations; a need for labelling (e.g. where the active package may give rise to end-user/consumer confusion); and consideration of the effects of the package on the microbial ecology and safety of the food. The latter is important to minimise the risk of creating an unnatural 'micro-climate' within the food package; for example, an active package that removes oxygen from within the package may also create favourable conditions for the growth of anaerobic

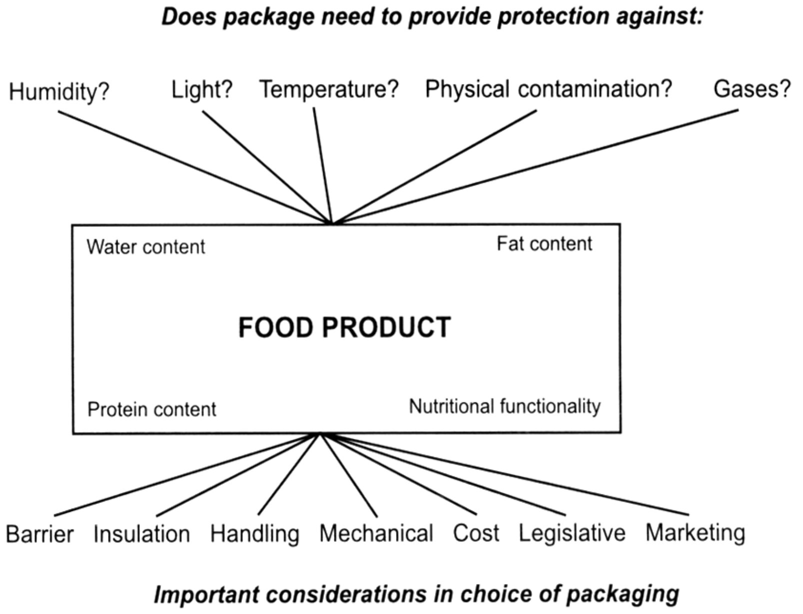

Fig. 10.1 A summary of the main considerations in the choice of frozen food packaging.

pathogenic bacteria. Currently, the wide range and diversity of active packaging used within the food industry makes it difficult to define generic rules, and such issues are addressed on a case-by-case basis.

10.8 Summary: how packaging can maximise product quality

Packaging plays an important role in preserving the quality of frozen food during the journey from food producer to consumer. Careful consideration of the technical aspects of packaging materials and applications provides the food producer with a means of minimising the undesirable physical, chemical, biochemical and sensory changes that occur during storage. However, it is likely that future improvements in frozen food packaging will be dictated as much by changing consumer demands as by further technological developments. Ultimately, packaging has a key role in determining the consumer's acceptance of the frozen food product. Figure 10.1 summarises the main considerations for the food producer.

10.9 References

1 European Community *Packaging (Essential Requirements) Regulations*, SI No. 1165, 1998.

2 European Community *European Parliament and Council Directive 94/62/EC on Packaging and Packaging Waste*. Official Journal L365, 31 December 1994, 10–23.

3 *Materials and Articles in Contact with Food Regulations*, SI No. 1523, 1987.

4 *The Plastics, Materials and Articles in Contact with Foods Regulations*, SI No. 3145, 1992.

5 ALCAN ECKO PACKAGING *Aluminium Foil Container Use in Microwave Ovens*, Chesham, Alcan Ecko Packaging, 1989.

6 ERICKSON, M.C. 'Lipid oxidation: flavour and nutritional quality deterioration in frozen foods', in *Quality in Frozen Food*, ed. M.C. Erickson and Y.C. Hung, New York, Chapman & Hall, 1997, 141–73.

7 SISTA, R.V., ERICKSON, M.C. and SHEWFELT, R.L. 'Quality deterioration in frozen foods associated with hydrolytic enzyme activities', in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997, 101–10.

8 XIONG, Y.L. 'Protein denaturation and functionality losses', in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997, 111–40.

9 DAY, B. P. F. 'Modified atmosphere packaging and active packaging of fruits and vegetables', International Symposium on Minimal Processing of Foods, Majvik, Kirkkonummi, Finland, 1994.

10 DAY, B. P. F. 'Extension of shelf-life of chilled foods', *European Food and Drink Review*, Autumn 1989, 47–56.
11 ROONEY, M.L. 'Active packaging in polymer films', in *Active Food Packaging*, ed. M.L. Rooney, Glasgow, Chapman & Hall, 1995, 74–110.
12 CUQ, B., GONTARD, N. and GUILBERT, S. 'Edible films and coatings as active layers', in *Active Food Packaging*, ed. M. L. Rooney, Glasgow, Chapman & Hall, 1995, 111–42.
13 DAY, B. P. F., LEADLEY, C. E. and WILLIAMS, A. *CCFRA New Technologies Bulletin No. 17*, Chipping Campden, Campden & Chorleywood Food Research Association, 1998.
14 SELMAN, J. D. 'Time–temperature indicators', in *Active Food Packaging*, ed. M. L. Rooney, Glasgow, Chapman & Hall, 1995, 215–37.
15 GEORGE, R. M. and SHAW, R. *A Food Industry Specification for Defining the Technical Standards and Procedures for the Evaluation of Temperature and Time–Temperature Indicators*, Technical Manual No. 35, Chipping Campden, Campden & Chorleywood Food Research Association, 1992.
16 BS 7908 *Packaging – Temperature and Time–Temperature Indicators – Performance Specification and Reference Testing*, British Standards Institution, 1999.

10.10 Further reading

BALASUBRAMANIAN, V. M. and CHINNAN, M. S. 'Role of packaging in quality preservation of frozen foods', in *Quality in Frozen Food*, ed. M. C. Erickson and Y. C. Hung, New York, Chapman & Hall, 1997.

KADOYA, T. *Food Packaging*, San Diego, Academic Press, 1990.

ROBERTSON, G. L. *Food Packaging: Principles and Practice*, New York, Marcel Dekker, 1993.

11

Storing frozen food: cold store equipment and maintenance

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11.1 Storage, shelf-life and product quality

11.1.1 Storage

Cold storage techniques can be applied at any stage of the cold chain between the production process and consumption. Consequently cold stores range between smaller ‘batch’ holding units at the production plant prior to transfer to large bulk stores and, nearer the retailer, smaller, geographically convenient ‘order picking’ stores to match consumer demand.

Whatever the stage in the cold chain, close adherence to temperature and identification of the production batch is vitally important; in essence, a controlled state with a full history positively identified. Each stage of the cold chain almost invariably starts and ends with a transfer by refrigerated transport. Site handling therefore must address the needs of transfer to and from the vehicle prior to entering the main chamber. Buffer zones, large enough to accept a refrigerated container load, serve a valuable function bridging the requirement of releasing the vehicle and enabling product temperature checks prior to acceptance, etc. Outward-bound product loads can be assembled in the buffer zone, which is a particularly useful feature for mixed loads. In each case movements into the main chamber, with the inevitable loss of cold air, are minimised.

Industrial handling of frozen food has standardised on the nominal one-tonne pallet for racking and transport which is therefore used as a basis here. The choice of a storage system is highly dependent of the policy of retrieval; a high-volume multi-pallet load-out system can use simple cubic storage, whereas the need to select individual pallets will require a full pallet identification and location for reliable operation. Detailed discussion of these and illustrations are given in section 11.2.1.

Facilities are required for operators normally working in the cold chamber to recover in a warm environment, in addition to normal changing facilities demanded by EU directives. Appropriate warm clothing, gloves and boots should be available.

11.1.2 Shelf-life

Extensive testing and experience shows that long-term frozen storage is well proven for the preservation of a wide range of foodstuff. Indeed it can be argued that quick-frozen foods, handled correctly through the cold chain, are higher in quality than many so called ‘fresh’ foods which have dissipated their shelf-life during their passage through markets, shops and journey to the consumer without the preservative advantage of low temperatures.

Note that not all food is suitable for freezing; for example, salad vegetables, which are usually eaten raw, lose their crispness when thawed. Generally an inverse relationship exists between the textural attributes of the thawed frozen product eaten raw and the water content of the fresh vegetable. Careful selection and preparation of fruits and vegetables is discussed in Chapters 3 and 4. Table 11.1 shows the practical storage life (PSL) in months at several storage temperatures. PSL is a function of temperature. While stabilised temperatures of −18ºC or colder are required to meet EU regulations, commercial designs generally use −25ºC, thus allowing some tolerance for loading and travelling.

11.1.3 Product quality

The freezing and cold storage of food is a preservation process. In itself it will not create quality that was not present before freezing commenced. In other words, if poor quality food is frozen, when thawed the food will still be of poor quality. Preparation of food for freezing is extremely important: some fruits and vegetables need blanching; careful selection of varieties can offer advantages and this is discussed in Chapters 3 and 4. Packaging of the food has particular attributes in terms of creating vapour barriers to prevent moisture loss and freezer burn; appropriate materials and their commercial advantages are discussed in Chapter 10.

Attention to the store temperature monitoring and recording is necessary in relation to product identification. These aspects are explored in section 11.4. Above all, the contribution that a good cold store adds to the cold chain is consistency of temperature control, safe handling and a firm identification of records including an established temperature storage history.

11.2 Cold store design

11.2.1 Chamber size and layout

The method used to stack pallets of product in a chamber has major implications in the store capacity. The choice of system depends primarily on the policy of

Table 11.1 Practical storage life in months at several storage temperatures

Product	−12ºC	−18ºC	−24ºC
Fruits			
Raspberries/strawberries (raw)	5	24	>24
Raspberries/strawberries in sugar	3	24	>24
Peaches, apricots, cherries (raw)	4	18	>24
Peaches, apricots, cherries in sugar	3	18	>24
Fruit juice concentrate	–	24	>24
Vegetables			
Asparagus (with green spears)	3	12	>24
Beans, green	4	15	>24
Beans, lima	–	18	>24
Broccoli	–	15	24
Brussels sprouts	6	15	>24
Carrots	10	18	>24
Cauliflower	4	12	24
Corn-on-the-cob	–	12	18
Cut corn	4	15	>24
Mushrooms (cultivated)	2	8	>24
Peas, green	6	24	>24
Peppers, red and green	–	6	12
Potatoes, French fried	9	24	>24
Spinach (chopped)	4	18	>24
Meat and poultry			
Beef carcass (unpackaged)*	8	15	24
Beef steaks/cuts	8	18	24
Ground beef	6	10	15
Veal carcass (unpackaged)*	6	12	15
Veal steaks/cuts	6	12	15
Lamb carcass, grass fed (unpackaged)*	18	24	>24
Lamb steaks	12	18	24
Pork carcass (unpackaged)*	6	10	15
Pork steaks/cuts	6	10	15
Chicken, whole	9	18	>24
Chicken, parts/cuts	9	18	>24
Turkey, whole	8	15	>24
Ducks, geese, whole	6	12	18
Liver	4	12	18
Seafood			
Fatty fish, glazed	3	5	>9
Lean fish**	4	9	>12
Lobster, crab, shrimps in shell (cooked)	4	6	>12
Clams and oysters	4	6	>9
Shrimps (cooked/peeled)	2	5	>9

Notes:
* Carcass may be wrapped in stockinette.
** The practical storage life of single fillets of lean fish would be 6, 9 and 12 months at −18ºC, −24ºC and −30ºC respectively.
Source: IIR, *Recommendations for the Processing and Handling of Frozen Foods*, 1986.

retrieval of foodstuff. A series of figures illustrates the advantages of the principal systems in use, which are all based upon a similar-sized chamber for comparison purposes.

High volume capacities with bulk multi-pallet load-out can use a simple block storage system as shown in Fig. 11.1, i.e. an almost complete cubic format. Palletised loads use a ‘pallet converter’ or ‘post pallet’ arrangement that has four legs secured around the pallet and a top frame. The resulting unit requires very little space in addition to a pallet but is capable of supporting up to four pallets stacked on top without imposing load onto the product (actual load capacity depending on unit design). Simple management techniques are required to ensure separation of product type and/or consignment lots; for example, a floor marking system to help segregate types or customers might be employed.

High volume and individual pallet retrieval requirements can effectively use mobile racking systems, particularly when arranged for five- or six-high pallet storage as indicated in Fig. 11.2. They operate using a series of powered mobile longitudinal racks moving upon rails and arranged to allow an aisle to be opened for truck access between each rack in turn. This system combines very high chamber capacities together with access to individual pallet positions. Capital cost is higher, given that the motorised system and support rails need building into the floor structure. Financial viability is improved at racks of five or more pallets in height. This system is usually only fitted to new chambers when support rails can be built into the floor structure.

Lower storage intensity methods using static racking provide individual pallet access at lower capital costs and are suitable for most existing chambers. A typical plan is shown in Fig. 11.3. Racking is fixed and the minimum aisle width is determined in conjunction with the choice of fork truck: while narrow aisle reach trucks are effective at four- or five-high racks, higher stores or other site conditions may demand a counterbalance fork truck with a larger turning circle. A very wide range of static racking is available from proprietary manufacturers, enabling almost any combination of storage and access to be installed. Such alternatives include the following:

- Double-deep racking: pallets are stored two deep from one side – requires a truck with extendible forks and individual pallet access is halved.
- Narrow aisle racking: aisles are required at little more than a pallet width – this arrangement requires special side-loading trucks; slightly slower access to individual pallets may occur.
- Drive in: block stacking of pallets supported on cantilevered rails each side of the pallet – requires good quality pallets, block access only, access is not practical for individual pallets.
- Push-back racking: pallets stored up to four deep on rising roller rails – access from one side only for loading or unloading, no stock rotation.
- Live roller racking: pallets, usually up to six deep, on sloping roller railwork with gravity feed to discharge – separate feed and retrieval aisles.

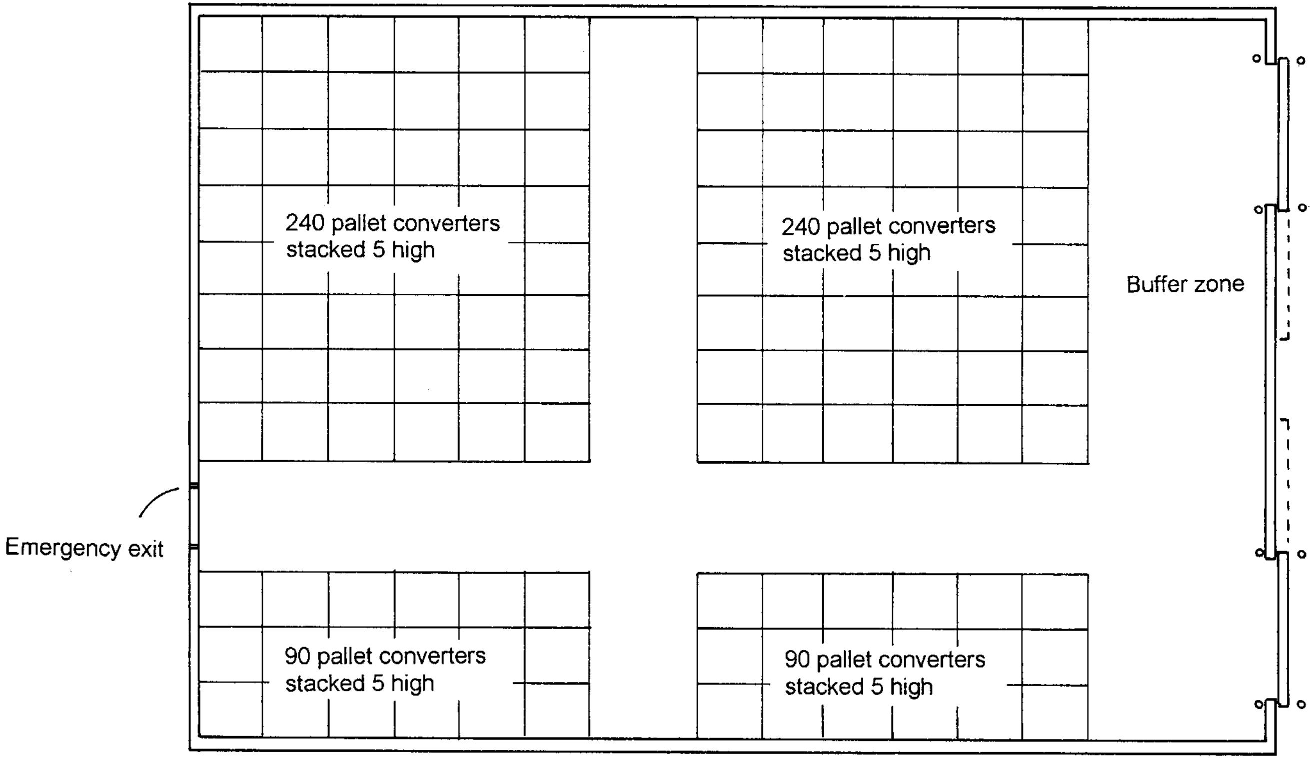

Fig. 11.1 Pallet converter or post pallet type storage: 660 pallet capacity, bulk access operation.

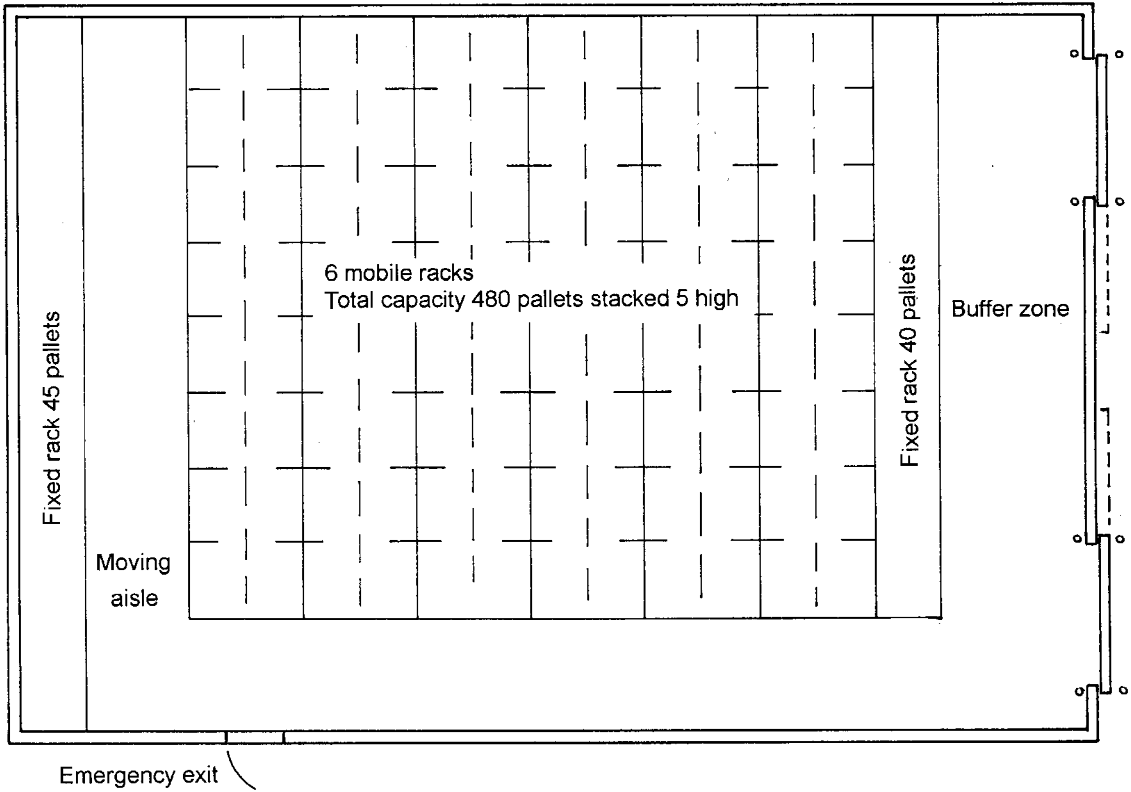

Fig. 11.2 Mobile racking: 565 pallet capacity, individual pallet access.

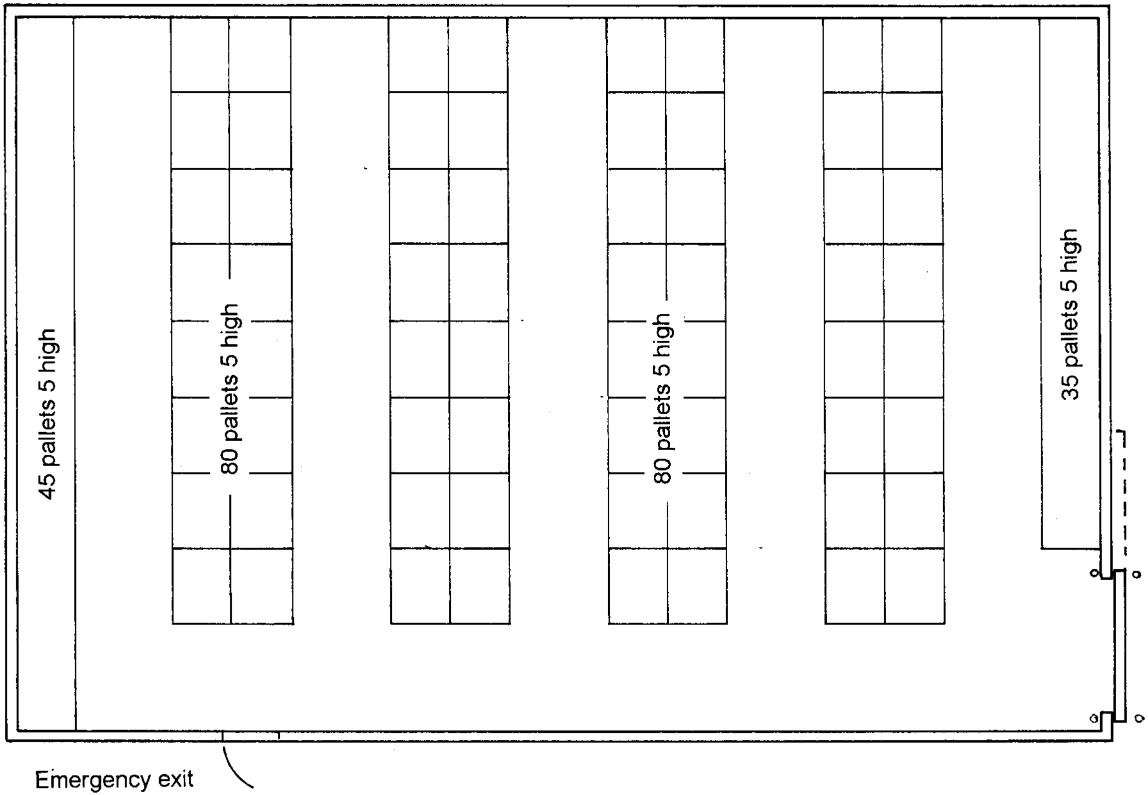

Fig. 11.3 Fixed racking: 400 pallet capacity, individual pallet access, single fork truck access door, no buffer zone.

In principle a higher chamber attracts lower capital construction cost per pallet position, and ten pallet high stores are feasible, giving overall building heights of approximately 23 m. However, the cost of access to higher positions rises considerably. Typically, the time to reach pallets 9 m above floor level can be twice that compared with 2 m high locations. Other restrictions encountered may include local authority planning objections and rack stability. Current practice indicates that six high is practicable. If an order picking operation is functioning, the top sections can be allocated to goods requiring lower frequency of access.

Selection of a particular racking principle rests in essence with the dispatch style demanded of the store. Whichever system is used, the equipment specification must require a suitable grade of materials for the construction including all services, finishes and lubrication commensurate with the low temperatures demanded.

11.2.2 Energy conservation

Cooling consumes more energy to change the temperature of goods per degree Celsius than heating and it is worth reducing the energy demand both as an economic measure and environmentally by restricting the consumption of electrical power. Measures to save energy are available on both existing stores and new premises; in the latter by relatively minor improvement to the specification.

Existing stores

Simply keeping the doors closed at all possible times is effective in preventing ambient and therefore relatively warm, moist air entering the chamber. This air directly adds to the cooling load and indirectly affects operations by increasing the build-up of frost upon the cooling coils, thereby reducing the effectiveness of the refrigeration and demanding additional use of defrost heating. Various automatic powered door systems are available and strip curtains can be helpful. If strip curtains are used they must be complete; just one missing strip or inadequate cover of the door opening will dramatically decrease the energy saving.

One should ensure that incoming product is as close to the store temperature as possible. Sodium lights consume less energy in direct terms and also reduce the heat absorbed into the store. Load the store correctly; allow sufficient space between pallets and walls to permit good circulation of the cooling air.

Engineering maintenance is important, and can save up to 20% of energy in some installations.[1] The evaporator defrost function should be checked to match plant workloads and kept clean. Condensers, both air- and water-cooled, should be regularly cleaned. The compressor capacity control should allow the system to operate at optimum efficiency – ideally at 100% for any given condition. Avoid operating compressors at part load if possible, especially for screw compressors with slide valves.

New stores

Thicker insulation can effect savings throughout the life of the store; for instance, doubling the insulation thickness on a 29 000 cubic metre store saves 26 500 Euros per year based on electricity costing .06Euro/kWh.[2] It should be noted that doubling the insulation thickness does not double its cost.

Select large condensers, as improvements in efficiency of up to 20% are achievable if condenser size is increased by 50%. Avoid the use of compressor head pressure control (it has been estimated that this can improve efficiency by up to 30%).

Select larger evaporators; savings of up to 14% are achievable if the evaporator's size is increased by 50%. This will also result in lower frost build-up and hence diminish the requirement for defrosting.

Sodium lighting is more efficient, giving at least twice the output per watt consumed when compared with fluorescent and mercury systems.[2]

Entrances and exits

While the site layout will largely determine the position of fork truck entrances and exits, in terms of the control of air movement (and potential loss of cold air) it is advantageous if through-draught situations are avoided. Do not position doors at diametrically opposite sides of the chamber if this can be avoided.

Protective barriers, or at least bollards, are recommended to avoid damage to the door track, door and reveals. The barriers should be securely fixed to the floor and designed such that they may be simply removed for repair. An emergency exit must always be provided. It must not be obstructed either within or outside the store or be locked without provision to release the door from the inside. The door should be provided with emergency lighting, possibly using illuminated exit signs. Likewise an audible warning system or light (fixed or flashing) should be provided, operable from inside the chamber. An independent light is required inside every room that cannot be switched off from outside the room and with an indicator outside the room.

The insulation of the doors should be comparable with the cold store wall insulation and preferably be located on the outside (warm) side of the cold store wall. Gaskets are required to form a seal around the door opening. Strip curtains may be fitted to the opening to restrict the loss of cold air during constant traffic access but care is required, as the loss of a strip has a significant effect on cold store losses. Automatic door closers may be used; a range of electric and pneumatic actuators are available which can be programmed to shut the door after the passing of a truck. If an automatic door is used as a personnel door, a manual over-ride is required to allow opening in the event of power failure.

11.3 Detail design features

11.3.1 Floors

While a cold store floor appears simple, it is a multi-layer construction with each layer performing a vital function if long life is to be experienced. Understanding the various functions will help to emphasise the maintenance requirements. Breakdown in the function of a layer can be catastrophic as demolition of part or all of the floor may be required. The floor must support the considerable weight of the product stored, possibly located as point loading if racking is used or carry built-in rails if a mobile racking system is in place. Therefore professional design with full specification and construction following proven practices to known parameters such as BS ISO 9000 quality assurance is recommended. Thorough examination of the site, including ground-bearing strength, possible inclusions and water table, is required. A typical cross-section of a simple floor is shown in Fig. 11.4 to illustrate the common essential features, described briefly as follows:

- *Sub base*: A consolidated hardcore base is required to provide a flexible but sound support for the construction.
- *Base slab*: This forms the firm support for the erection of the whole cold store envelope and base upon which the frost heave protection and floor can be built. Temperature sensor bulb(s) to enable ongoing monitoring of base slab temperatures are frequently incorporated into the upper slab surface.

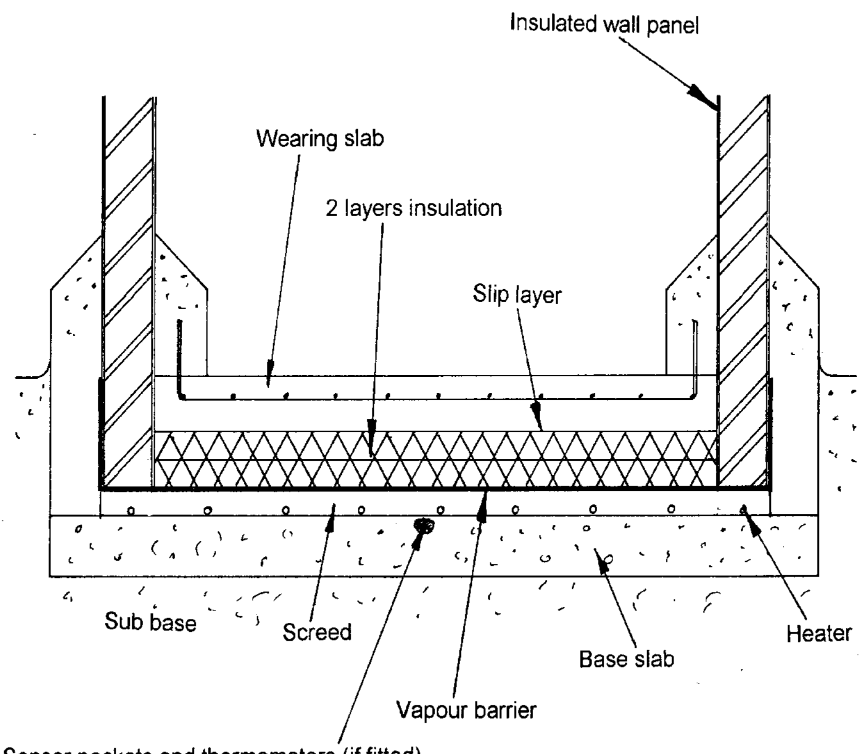

Fig. 11.4 Section of a typical cold store floor construction.

- *Heaters and screed*: The heater is necessary to prevent temperatures below the insulation falling below freezing and ice forming. Failure can allow frost to form and has caused frost heave, some floors rising considerably as the ice layer builds. Remedial action entails the excavation of the whole floor and ice formation before replacement is possible. Heaters can either be supplied using low voltage electrical mats or using a heated fluid within pipework. Circuits of either are laid to cover the whole area; consideration may be given to arranging parallel circuitry such that some standby facility is present in the event of breakdown. The heater mat or piped system is laid into a cement screed. Typical heater load is 18 W/m^2. Note that floor areas outside the chamber, e.g. in doorways, require heaters to prevent frost build-up; these are described in section 11.3.2.
- *Vapour barrier*: A vital component, which must be sealed to the *outside* leaf of the store's wall vapour barrier. Its function is to restrict the passage of moisture vapour from below the cold store floor construction to within the cold store. Vapour pressure inside a cold store is considerably lower than the pressure outside the envelope. The moisture will therefore travel naturally into the store thereby forming ice inside the chamber unless an effective barrier is fitted. Considerable care is required to prevent any puncturing of the barrier during construction. Careful sweeping and preferably vacuum cleaning the floor is recommended before installation.
- *Insulation*: Increases the temperature gradient of the whole cross-section of the floor construction between the store and under screed. The insulation forms a resilient layer supporting the wearing floor and of course the cold store load. It should be installed in at least two layers with staggered joints to prevent thermal bridging occurring. Each layer is skewered into place with wooden skewers to hold close contact with adjacent boards.
- *Slip layer*: Gives protection to the top surface of the insulation during construction of the wearing floor and allows relative movement of the floor and insulation without damage.
- *Wear floor*: Designed to achieve the required abrasion, impact and slip resistance in the surface together withstanding the thermal movement due to the large temperature range experienced by the floor. Reinforcement may be incorporated to control and distribute cracking of the surface due to shrinkage between free movement joints. Protective kerbs, firmly anchored to the wearing floor, form very useful protection of the wall from pallets.

11.3.2 Floor and door heaters

The function of the heaters in both cases is to prevent the formation of ice.

Floor zones

Floor areas immediately outside the chamber doorways are usually at a lower temperature than their surroundings due to thermal transfer from the cold store wear floor. Separation of the concrete floor slabs with sealed thresholds helps.

Given the lower temperature, air condensation occurs which may freeze as cold air ‘falls out’ of the open doorway, passing over the condensed droplets. Potentially this may cause accidents and an effective solution is to heat this floor zone using an electrical low voltage heater mat, similar to the heater described in section 11.3.1.

Door surrounds

If ice is allowed to form on the junction of the door and its surround, the door’s function is impaired. Opening and shutting becomes difficult or impossible, in serious cases with operators resorting to force. Successful cold store operation becomes uneconomic with rising repair and energy costs. Surround heaters operate at low voltage and fit behind fascia plates, maintaining a temperature of about 10ºC to 15ºC, i.e. amply sufficient to prevent ice formation.

11.3.3 Walls and ceilings

Walls and ceilings of modern cold stores are essentially insulating members built up using composite panels of plastic-coated steel bonded to an insulating core which is usually expanded polystyrene, extruded polystyrene, polyurethane or mineral fibre. The first three should preferably include a fire-retardant additive while the mineral fibre can be constructed into a panel of various fire-resisting capabilities, albeit at increased cost.

Noise attenuation will be achieved through all panels but if this feature is important, mineral fibre core panels give particularly greater attenuation. All panels must effect a positive moisture barrier continuously around the envelope. Joints at the intersection of panels must be sealed to keep the vapour barrier intact. Failure of the barrier will allow ingress of moisture vapour, which may saturate areas of the core, dramatically reducing the insulation value.

If post pallets or pallet converters are to be used for product, protective rails, sometimes called dunnage rails, are useful. Dunnage railing is a system of galvanised steel rails approximately 75 mm deep, placed vertically on the inside wall face at about 900 mm spacing. They guard against occasional contact with the wall and encourage vertical air movement. Alternatively with static or mobile racking systems local protection barriers give added safeguard.

The insulated walls and ceiling may be positioned inside or outside the building structure provided that adequate provision is made to protect the structure and floor from moisture and eventual ice formation.

11.3.4 Vapour barrier

An effective vapour barrier on the outside of the cold chamber insulation is possibly the most important single feature of a successful cold store and one of the most difficult to achieve.

At the low temperatures encountered inside a cold store (−25ºC), the moisture vapour pressure is considerably lower than that outside the chamber.

According to the laws of physics there is a natural movement of moisture from the outside into the chamber; it is very important therefore to ensure that the vapour barrier is maintained intact throughout the whole chamber. Potential weaknesses include the sealing on the underside of the floor insulation to the outside of the wall cladding, sealing between wall and ceiling panels and sealing around any opening in the walls and ceiling.

Failure of the vapour barrier will result in ice forming as the moisture reaches 0ºC at a point within the panel. If the wall panel barrier fails, moisture may saturate the wall insulation, rendering severe damage to the insulation effectiveness, initially raising energy demand in an attempt to maintain cold temperatures but may potentially cause structural failure and collapse.

11.4 Monitoring and recording product conditions

11.4.1 Monitoring the structure

An essential part of maintenance is simple regular checks of the function of the structure components. Records form a valuable tool for maintenance engineers and ease the task of locating faults if they occur.

Under-floor temperatures should be monitored using the sensors built into the floor base slab. Usually these will register above 5–10ºC. Temperatures below freezing signify problems, possibly of heater failure, and investigations are required. Initial investigations should include possible failure of the electrical supply, transformers, wiring failure or inadvertent isolation or alternatively valve/circuitry faults/pump failure if a liquid system was installed. Knowledge of low temperature of the base slab can alert attention to prevent potentially extensive and financially very damaging remedial works.

Pressure relief valve(s) fitted to the insulated panel work must be checked to ensure free movement and that the heater is working. These valves equalise air pressures within and outside the chamber.

Door and threshold heater operations require monitoring; failure of door heaters is exhibited by frost appearing but a simple check is merely a hand touch to register slight warmth. Threshold heaters are usually very reliable and problems are more often with the electrical supply; failure can lead to ice formation in the doorway.

Panels forming the walls and ceiling of the envelope can become damaged or, worse, the outer skins may be punctured. Repair of the panel, replacement even, is important to protect the integrity of the insulation envelope complete with its vapour barrier. Similar attention should be given to the panel joints and any trimming sheets.

11.4.2 Product conditions

Good temperature control is vital, and may form part of commercial contracts for the supply of cold store facilities. Stores conforming to Lloyds Classified

Register are subject to frequent inspections on many aspects including temperatures.

Temperature recordings of the store should be maintained for at least one year, or longer if the food has a storage life labelling of over a year. Very large stores, or those that are very long, may require temperature sensors at several points throughout the chamber. Data may be kept in electronic form.

Automatic monitoring systems are available commercially where it is possible to maintain a wide range of data including the temperature of chambers, ambient and refrigeration machinery operation, energy consumption, etc. Relevant parameters can be compared and automatic call-out procedures implemented to alert engineers in the event of problems. Depending on the plant complexity, remote interrogation of the technical operation is feasible, allowing faster response.

Within each pallet, stacking should be even, boxed layers of product interlocked brick fashion to form a stable unit. Whichever form of racking or pallet support system is used, maintenance and care are required. Pallet converters are often built to a collapsible design to minimise storage space when not in use. Reassembly must ensure that a safe unit is available, ready to support several pallets stacked upon the lowest unit. Suspect units should be separated for closer examination or rejection.

Mobile and static racking systems offer individual positions for each pallet – usually arranged for a nominal one-tonne load per unit. Care is required to ensure that each pallet is located correctly on the load support beams. Racks are installed to carry substantial loads in a compact area; they are not designed to withstand fork trucks colliding into legs or other members. If damage has occurred the load must be removed and repairs undertaken before any reuse.

Adequate lighting both within the chamber and in the proximity of doorways constitutes a firm basis for good housekeeping and safety. Clear sight lines are necessary for effective truck operation both at high and low levels – manoeuvring pallets carefully into position five or more tiers high while avoiding high-level coolers requires well-lit areas. Lighting levels should be at least 200 lux generally and within any close working or inspection zones this should be increased to 450 lux. Various types of lighting are available including fluorescent, sodium and mercury, etc. If fluorescent fittings are used, special low temperature tubes are available which give longer life and better starting performance. Sodium lighting gives at least twice the output per watt consumed compared with fluorescent and mercury lights.[2] Light fittings require cleaning regularly to maintain adequate light levels.

11.5 Good operating practice

Like any commercial operation an efficient store depends upon regular attention to cleaning, housekeeping and maintenance. Understanding the technology of the various aspects should help operators and management alike to build up efficient methods.

11.5.1 Incoming product

The basis of a cold store is to maintain foodstuff at consistently low temperatures, usually −25ºC unless otherwise specified. If incoming product is at higher temperatures, refrigeration energy is required to cool the food, otherwise the heat will be absorbed into other food stored in the chamber. Records of incoming produce are a useful tool, typically as shown in Table 11.2. They may be in a computerised format together with the store workplan and business records.

Incoming loads at significantly higher temperatures may require transfer to a separate blast freezer, and products may attract additional charges to defray the extra energy cost, handling charges, etc.

11.5.2 Cold store

Control of door openings and the duration of doors being left open are an important part of management, which is easily overlooked. When the door is open, cold air 'falls out' at the base of the opening quite naturally. Equal amounts of warmer air flood in at the top – not only is it warm, but this air also carries moisture, which precipitates then freezes on the cooler. Therefore three aspects must be overcome by the refrigeration machinery, cooling make-up air, coolers working through extra ice and overcoming additional defrost heat to remove the ice collected.

Automatic doors, which close behind fork trucks or pedestrians, reduce losses – lightweight ultra-fast action blinds reduce losses further and may be appropriate depending on traffic frequency. The use of rapid action blinds provides extra protection whilst working but they are not a substitute for fully insulated doors which should always be closed outside working periods.

Housekeeping and hygiene in cold stores demonstrate efficiency and help staff morale, especially regarding safety. Any debris possibly arising from broken packaging or pallets, discarded paper, etc., should be removed and the store left clean. Cold store safety is important to everybody and the whole management and operating team have a responsibility to keep the area safe – should any damage occur, this must be reported immediately, likewise any failed

Table 11.2 Sample incoming load record sheet

Time Date	Load identification	Type	Weight k tonne	Temperature ºC Incoming	 Store	 Difference	Comment
10,00 1/9/98	AB 34	Beef	12	−15	−25	10	B/Freeze Charge
21,00 2/9/98	AF 35	Mixed vegetables	35	−18	−25	7	
8,00 3/9/98	AC 12	Fish	12	−25	−25	0	

lighting. Fork truck traffic can increase the potential danger, particularly given the low temperature to which machines and staff are subjected; operators' reactions can be slower. Workers should not be left alone, or if this is unavoidable then checks at hourly intervals are advisable. Emergency exits should be kept clear (both inside and outside) at all times. An audible warning and/or a light warning signal system must be maintained as a precaution against persons becoming locked inside the store.

Records of product entry time and date with identities, quantities, locations and eventual discharge are essential as this information forms the commercial base of the operation. Spatial planning can only proceed with knowledge of the current stock and its location within the store.

11.5.3 Product handling – fork lift trucks

Cold store environments are predominantly mechanical handling zones combined with strict recording of foodstuff movements, temperature and location which add up to form the backbone of any efficient store.

The key mechanical handling tool is the electric battery-operated fork or reach truck, used to transport and stack pallets of product. The choice depends upon a number of factors including stack height, aisle width, 'round trip' duration, type of racking, response time, etc. While the initial truck selection takes note of three- or four-wheel formats, the former giving smaller turning circle, reach trucks (with their ability to withdraw the load within the reach legs) and counterbalance trucks predominate for the lower stores. Sophisticated narrow aisle trucks are particularly suited for high turnover sites, while 'order picker' trucks with a separate dual lifting fork ease and speed the operators' work rate where smaller, part-pallet loads are required by the customer. Truck wheels should be fitted with composite tyres to protect the cold store wear floor.

The cold environment imposes special requirements on the truck. They are manufactured using particular steels designed for cold-working conditions; finishes, lubricants and controls must operate satisfactorily at low temperatures. Trucks that alternate between above and below 0ºC require extensive corrosion protection in the freeze–thaw cycles. Less corrosion occurs in constant cold conditions. Control panels are fitted with heaters to treat the condensation of moisture; operators' controls are designed to suit operators wearing gloves, usually with greater spacing. Heated cabs are available which improve the working conditions for the truck driver. Truck driving is a skilled occupation for which training is a legal requirement.

While the choice of truck is apparently very wide, careful analysis of the particular method of operation – ranging from bulk handling to detailed order picking of part loads – should be matched to the commercial aim of the cold store.

Truck battery charging is much simplified with modern trucks. Heavy use installations may find that exchangeable battery packs with standby units which extend the working period are useful as this incurs little interruption of service.

Recharging should be undertaken in a separate warm area fitted with ventilation to remove battery gases safely while charging proceeds. Batteries would normally operate down to 20% of the fully charged state and require regular charging to avoid progressive sulphating of the battery plates.

11.5.4 Fire precautions

All fire protection matters must be discussed with and approved by the local Fire Protection Officer. Local statutory regulations must be complied with but the following is recommended. There are several contributory factors in the fire risk including the following:

- The combustible nature of organic foam insulation materials, notwithstanding the flame-retardant properties claimed.
- The readily combustible wooden pallets, particularly when dehydrated by long exposure to low temperatures.
- The high calorific value of many stored foods.
- The embrittlement at low temperatures and deterioration with age of some electrical insulating materials.

Flame-retardant grades of foam insulation do inhibit ignition from a small source but they may burn fiercely if they are subject to a major conflagration. Sandwich panel outer surfaces are available with proven flame spread ratings. Fire compartmentation in accordance with statutory regulation must be provided. Mineral fibre panels with certified fire resistance are available which would need to be installed in conjunction with an overall design appraisal.

Various fire detection and prevention systems and devices are commercially available and their use is good practice. Before adopting any device, such as heat and smoke detectors, fixed water sprinklers (particularly for ancillary areas), flameproof barriers, fire breaks between separate chambers, etc., they should be shown to operate satisfactorily at low temperatures.

An approved hydraulic fire main with the associated fire fighting equipment must be provided to protect the store and the ancillary buildings. Approved portable fire extinguishers shall be provided in approved locations as defined in BS 5306. An audible fire alarm is necessary with actuating buttons in approved positions as defined in BS 5839. A fire plan in weather-proof resistant materials should be located outside the main store access, showing the position of all fire fighting equipment and giving concise instructions, i.e. alarms to be given, pumps to be started, fans to be stopped, etc.

Emergency plans

Emergency plans are necessary and should be updated at regular intervals. All personnel must be well acquainted with emergency plans. Training in fire fighting is necessary including use of the equipment supplied. Fires often start slowly and in a small way, which means that there are some 3–5 minutes to fight the fire with on-site resources. Obviously the overriding importance is the safety of personnel, and training both in action and evacuation to prearranged meeting points could be vital in saving life.

11.6 New developments

11.6.1 Refrigerants

Since the Montreal Protocol when dramatic changes were agreed to improve the environment, the almost traditional use of CFC refrigerants has all but ceased. Existing installations using CFCs can continue providing that no pollution is released but replacement refrigerant is becoming difficult to obtain. Likewise HCFC refrigerants including R22 are being rapidly phased out across Europe. New equipment should not use R22 without secure knowledge of a replacement refrigerant. Alternatives are becoming available through the major chemical companies. Hydrocarbons are another solution but care is required in regard to the flammability aspects for some installations. Any change must recognise the possible requirement of different lubrication media. Professional guidance should be sought.

Replacement refrigerants for existing systems need careful evaluation; some 'drop-in' gases are available but components throughout the system, e.g. lubrication, seals, gauges, etc., may require changes. Any rise in system pressure could affect the safety of pressure vessels in addition to compressors. Standard specifications for new systems are BS 4434-1995 and EN 378 Part 4: 2000 at the time of writing.

11.6.2 Spatial management

Given the nature of commercial cold store management together with the rapid developments in the frozen food industry, significant changes from the longer-term storage to faster, higher turnover are certain to continue.

While the mass production 'just-in-time' scenario is unlikely for frozen foods, lead times are decreasing and turnaround periods are more critical. Vehicle dispatch must meet strict schedules. The introduction of 'best before' labelling has had a big impact on frozen food logistics and emphasises the need to access individual pallets.

Management of chamber space and the ability to gain higher throughput requires tools. The growth in barcodes is shown to be 15% annually, according to Frost and Sullivan's 'European Market for Barcode Equipment' report in May 1998. Industrial laser scanners modified with heating elements, thermostats and a stronger aluminium casing are reportedly capable of operating at temperatures down to -30^{o}C. Paper-borne systems in the cold store need not last far into the future.

Computerised planning and loading systems are proven for general ambient storage with printers and readers capable of accommodating some 2k of data on the equivalent area of a postage stamp. Not all computer equipment needs to operate in the low temperature zones of a cold store. Some models of laser scanner have been proven at low temperatures.

11.7 Summary

The essential features of a cold store are as follows:

- A consistent, specified temperature maintained in the product at all times throughout its period on site or within the control of the cold store.
- Efficient handling of product loads from intake to dispatch without damage either mechanically to packaging, exposure to taint or any other aspects that could affect the appearance or organoleptic properties of the food.
- Smooth relocation or dispatch as scheduled by the client.
- An energy-efficient and safe operation.
- Full documentation.

Continual attention to detail is required to ensure the wellbeing of the store. Each site has its own characteristics, which precludes setting a standard checklist, but typical entries for inclusion in a site record would be as follows:

General management

- Chamber temperatures.
- Load in, time, material type, weight and temperature.
- Load out, time, temperature and identification.
- Chamber loading.
- Door closure.
- Housekeeping.
- Chamber safety.
- Lighting.
- Documentation.

Engineering management

- Chamber and ambient temperatures (wet and dry bulb temperatures, preferably).
- Energy use.
- Refrigeration compressor data including refrigerant and oil pressures.
- Defrost pattern and operation.
- Lighting function.
- Threshold and door heater functions.

11.8 References

1. TAIT, J. ‘Taking the heat out of cooling bills’, *Refrigeration and Air Conditioning*, 20 September 1998.
2. ETSU, *Energy Consumption Guide No. 37 Cold Storage Sector*, Department of

the Environment, Transport and the Regions' Energy Efficiency Best Practice Programme, 1994, Didcot, ETSU.

11.9 Further reading

INTERNATIONAL INSTITUTE OF REFRIGERATION *Recommendations for the Processing and Handling of Frozen Food*, 3rd edn, 1986, Paris.

FULLER, R. L. *A Practical Guide to the Cold Chain: From Factory to Consumer*, European Union FAIR programme concerted action CT96-1180, University of Leeds.

Cold Storage & Distribution Federation Directory (The Red and Gold Books), Downmill Road, Bracknell, Berkshire RG12 1GH, United Kingdom. Tel +44 (0) 1344 869533; Fax +44 (0) 1344 869527; e-mail *dg@csdf.org.uk*.

Cold Store Code of Practice Part 1 Enclosure Construction; Part 2 Design and Construction of Refrigeration Systems, The Institution of Refrigeration, Kelvin House, 76 Mill Lane, Carshalton, Surrey SM5 2JR, United Kingdom. Tel + 44 (0) 20 8647 7033; Fax +44 (0) 20 8773 0165.

British Standard 4434, 1995, amended 1997.

EN 378: 2000 Refrigeration Systems and Heat Pumps – Safety. Part 2 – Design, Construction, Testing, Marking and Documentation. Part 3 – Installation, Site and Personal Protection. Part 4 – Operating, Maintenance, Repair and Recovery.

12

Retail display equipment

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12.1 Introduction

Retail display is one of the 'weak' links in the frozen food cold chain, mainly due to the contrasting purposes that retail display cabinets have to serve, i.e. persuading the customer to buy the product, while at the same time preserving it adequately. For merchandising purposes, the product must be clearly visible and easy to reach in order to tempt potential customers; however, these features tend towards product temperature fluctuation (i.e. in excess of the recommended −18ºC). This is known to be the primary cause of a loss of quality and safety in frozen foods. The best way to protect the product from temperature fluctuations is to keep it as far as possible from the shop environment, and from all possible heat sources (ambient air, lighting, etc.); but this means keeping it out of sight of customers. Matching these two conflicting needs is the main technological challenge facing display cabinet manufacturers.[1–6]

In more technical terms, display cabinets have to display and preserve their contents simultaneously. Shop managers are likely to be more interested in the display function, which is crucial to their business, i.e. the display cabinet has to be able to promote the products, even tempting customers who had no intention to purchase them. In the specific case of frozen foods, it is also essential to make the product competitive in relation to fresh foods. This is achieved, in part, by optimal exploitation of the display function. In contrast, the preserving function (and scrupulous compliance with the specifications for preserving the product) may sometimes take second place. Nevertheless, the customer needs to be assured that the product has been stored in the right conditions; in other words, that the display cabinet's preserving function has been fully utilised by the shop. Consequently, it is essential that compliance with the preserving function is governed by stringent standards, both for the manufacturer, who must design appliances capable of keeping the products in established conditions (even in the event of the most severe operating conditions), and for the shop manager, whose compliance with the specifications must be verifiable by the consumer by means of a clear definition of the loading limits and environment temperature conditions.

To cope with the two contrasting requirements, the display cabinet manufacturer must find the right balance by means of an optimisation process that increases the technological content of the equipment. The refrigerated display cabinet's energy consumption can be taken as an example: generally, it can be correlated with its capacity to attract customers and promote the product it contains. Unfortunately, a better displaying feature generally coincides with higher energy consumption. Here, the manufacturers of frozen food cabinets face a considerable technological challenge to come up with solutions, both from the energy consumption standpoint and in merchandising terms.

The main characteristics of a good frozen food retail display cabinet can be summarised as follows:

- It has to guarantee good product temperature control, whatever the external ambient conditions; complying with the standards is crucial in this matter.
- It has to prove an efficient seller, so the foodstuff must be visible and easily accessible for the customer.
- It has to be cost effective, not only in terms of the initial investment, but also in running costs: therefore, its energy consumption is extremely important, but so is easy access for loading, since this reduces the staff-hours required to re-stock the shelves.

While these are the main features of a good frozen food retail display cabinet, nobody – from the manufacturer to the shop managers, to their employees – must forget that it is designed neither to freeze food, nor to reduce its temperature: its purpose is simply to maintain the frozen food at the right temperature.

Naturally, the environment where the cabinet is installed plays a major part in establishing how it will behave: air conditioning and exposure to warm air streams and lighting must be carefully evaluated to guarantee best use of the cabinet.

12.2 Design of display cabinets

Various criteria can be adopted in the classification of display cabinets for frozen foods.[1–6] The most common are cabinet geometry and product display, for example:

- open-top, single-deck, chest units; and
- vertical multi-deck units, with or without glass doors.

12.2.1 The open-top type

Open-top chest cabinets are the classical appliance for selling frozen foods; two examples are shown in Fig. 12.1 (arrows indicate air streams, while the line with triangular symbols is the 'load limit line', defined in section 12.5). The merchandise is stacked from the floor of the unit. Due to cold air stratification, the infiltration of ambient air is relatively insignificant, and the heating load is represented mainly by radiant heat transfer from the surroundings and by convective and conductive heat transfer through the walls of the case.

These units are designed for self-service, and different types are available. The wall-site unit (Fig. 12.1(a)) is designed to stand against a shop wall, thus allowing shopping from one side. To improve the display function the front of the unit is often fitted with a glass panel, ensuring visibility of the stacked products via a shop window effect. The island-unit (Fig. 12.1(b)), on the other hand, can be accessed from all sides. Here again, glass side panels may be used to enhance product visibility.

Cold air distribution through the stacked products may be ensured by forced circulation (Fig. 12.1) or, less often, by natural convection. This latter type is most frequently encountered in small, self-contained cabinets intended for smaller shops.

The characteristics of open-top cabinets make them energy efficient and effective in terms of their preserving function. They are not so good in terms of display function, however, because only the top layer of products is directly in view. In addition, the shopper also has to bend over to pick up the packages. These units also take up rather a lot of shop-floor space; by comparison, the vertical cabinets are much more effective, since they enable storage of much greater volumes of product per unit of floor space.

12.2.2 The vertical type

Vertical cabinets are also meant for self-service operation: they are multi-decked (ranging from two to six) in order to save on space. In terms of their display function, cabinets with an open front are the most suitable (Fig. 12.2), although this open front is a source of ambient air infiltration, resulting in a high risk of temperature fluctuation and high energy consumption.

Temperature fluctuations can be avoided by providing two or three parallel air curtains, as described below. This improves temperature control on the product side, but fails to reduce energy consumption. To prevent any air infiltration from the environment (and thus reduce any temperature fluctuation and improve energy efficiency), vertical cabinets are fitted with glass doors generally (Fig. 12.3). If the glazing is treated with a reflective layer, the doors prevent not only convective flows, but also the infrared radiant heat from the room.

Unfortunately, glass doors diminish the effectiveness of the display function, since consumers must open them to reach the product. While the doors are open, unwanted air infiltration is inevitable: incoming air humidity tends to condense

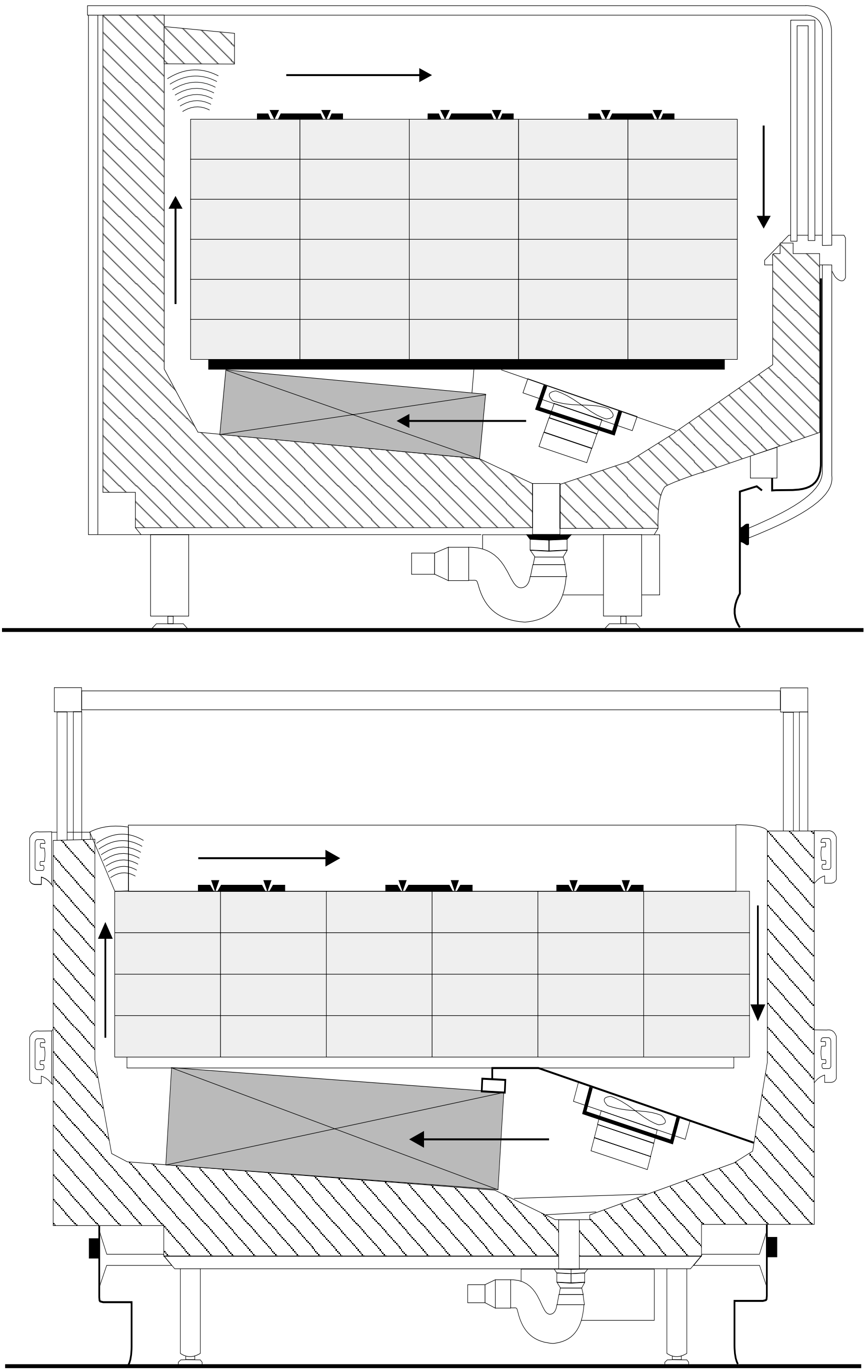

Fig. 12.1 (a) Open-top chest cabinet, wall-site unit. (b) Open-top chest cabinet, island-type unit.

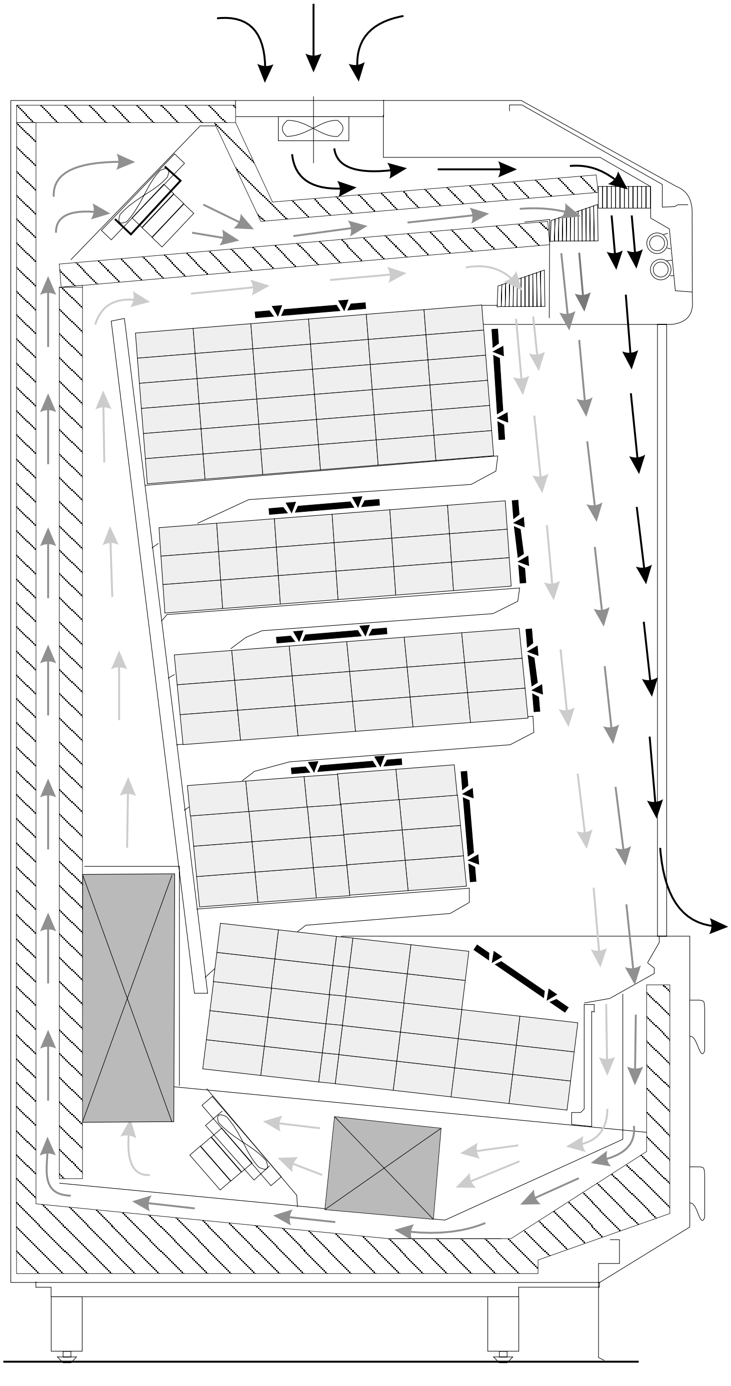

Fig. 12.2 Vertical cabinet with open front.

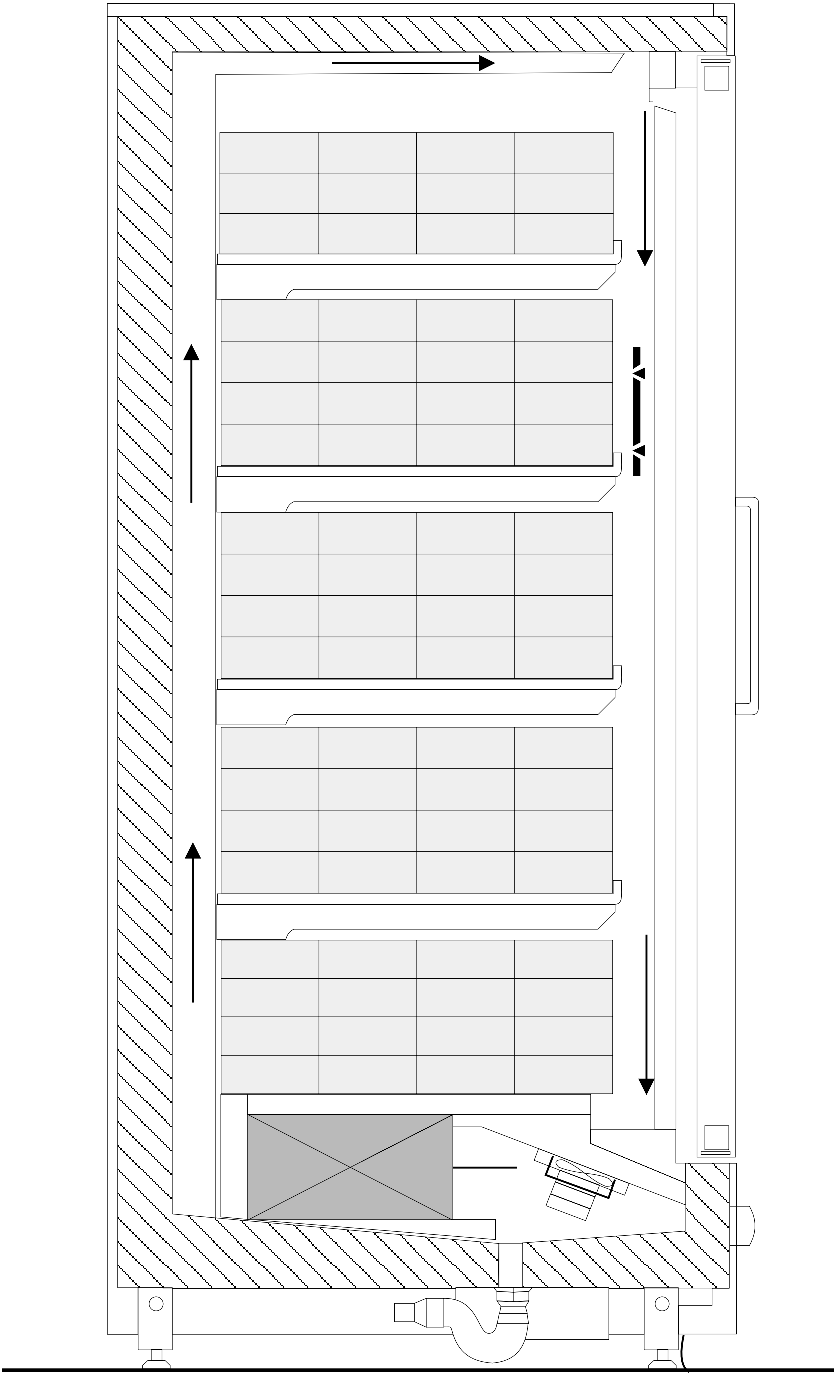

Fig. 12.3 Vertical cabinet with glass door.

on the inside of the glass door as soon as it is closed. This has a very negative impact because, for several seconds, it prevents the shopper from seeing the products on display. To overcome this problem, the doors are usually triple-glazed and have electric heaters with a de-misting function.

Larger stores are often equipped with so-called combination cabinets, comprising an open-top cabinet with an upright unit above it – typically a multi-deck cabinet with a glass door (Fig. 12.4). This combination offers the advantage of a large capacity per unit of floor space. It is also worth mentioning the compact, open-top chest cabinets especially suitable for special offers: usually these units are self-contained, for plug-in applications, and are suitable for storing both chilled and frozen foods.

12.2.3 Refrigerating equipment

Although they cannot reduce the temperature of products if they are too warm when loaded into the cabinet, none the less display cabinets have to perform a heavy refrigerating duty to keep the product at a temperature of −18ºC or colder. Therefore, the refrigerating equipment plays a major part in characterising a display cabinet, which can be classified in these terms: essentially there are stand-alone, self-contained cabinets, and appliances with remote compressor and condenser assemblies. In both cases, refrigeration is achieved by a vapour compression thermodynamic cycle, using a working medium, or refrigerant, that absorbs heat from the refrigerated compartment and transfers it to the warmer surroundings.

In stand-alone equipment, the entire refrigerating assembly, with its four main components (compressor, condenser, expansion valve and evaporator), is contained within the cabinet, usually in the base. Apart from the drainage piping, a mains power supply plug point is the only connection necessary. Installation is extremely simple and flexible, making this arrangement particularly suitable for small shops with just one or two cabinets, and for spot-merchandising cabinets.

Remote refrigeration systems are more energy efficient: only the evaporator and its expansion valve are on board the cabinets, which are connected by pipes carrying refrigerant to and from the compressor and condenser, located in a machine room. More complicated installation demands and the need for a machine room make this type of arrangement most suitable for medium- to large-sized stores.

Centralised refrigeration allows for more sophisticated plant designs, such as multi-compressor systems, different condensation heat sinks and computer-controlled monitoring. Moreover, the heat released at the condenser can be usefully recovered by heat exchangers and used for such purposes as water heating.

The working media used in commercial refrigeration are almost exclusively halogenated hydrocarbons. However, their usage has been highly criticised over the last decade for environmental reasons, i.e. their well-known contribution to ozone layer depletion and the greenhouse effect. Although they will presumably

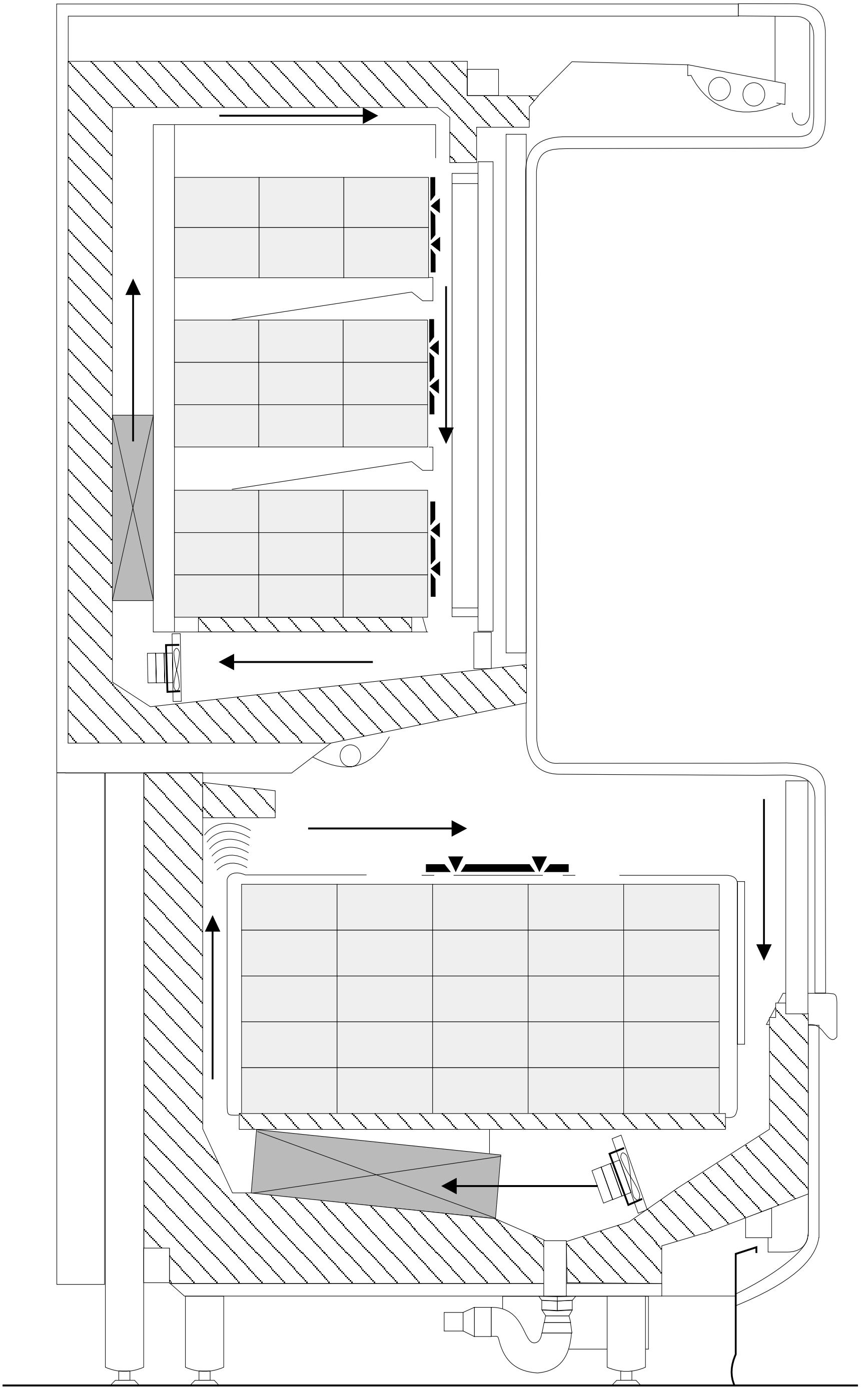

Fig. 12.4 Combination cabinet (open-top plus multi-deck unit with glass door).

continue to account for the bulk of refrigerants in commercial refrigeration systems for at least 20 years, a lot of research is under way to find a better solution that can match environmental requirements with the energy efficiency and reliability that halogenated refrigerants have offered the industry so far.

Before the so-called 'CFC issue' (awareness that chlorofluorocarbons deplete the stratospheric ozone layer) came to the attention of the public, almost all retail display cabinets for frozen foods were equipped with direct expansion refrigeration systems charged with the ubiquitous R502. The first reaction to the CFC phase-out was to switch to R22, which meant coping with the problem of high compressor-discharge temperatures. However, R22 turned out to be a new concern and not the solution to the ozone problem (it will also be phased out by the year 2008 or earlier). Other solutions were found for low temperature applications with R404A and R507. These are mixtures, yet they behave very much like pure substances and pose no operating problems in terms of reliability. But, once again, R404A and R507 are not energy efficient enough and, considering the 'global warming issue', they are not likely to be the final solution. The next potential alternative is R410, even if it is not specifically designed for low temperature operations. It requires higher operating pressures than its predecessors, and therefore involves the use of new compressors. Consequent changes to design and manufacturing procedures will take a few years.

In short, it is now clear that halocarbon refrigerants will not solve all problems, and that something new must be found through in-depth investigations into new thermodynamic cycles, new working media and new secondary coolants. In the past all these areas were set aside in the conviction that, for the needs of commercial refrigeration, nothing could beat the vapour-compression cycle with halocarbon refrigerants. As innovative technologies, these topics will be discussed in section 12.6.

In considering environmental impact, it is also worth mentioning another problem that the industry has to face: the cabinet's sandwich wall panels. Apart from their structural function, the main purpose of sandwich panels is to prevent heat transfer from the surroundings into the cabinet. Polyurethane foam is used for insulation, injected *in situ* by means of a blowing agent. R11 was the most effective blowing agent until it was banned in 1995 as a CFC. Despite intensive research efforts, the most promising alternative seems to be cyclopentane, a hydrocarbon with a good thermal performance, but with the drawback that it is flammable. This is not hazardous for the end user, but poses severe safety problems at the site where the sandwich panels are made, thus requiring major plant investments by the manufacturers. To avoid the consequent increase in costs, many manufacturers still rely on halocarbons, such as R134a, as blowing agents. They are not as effective in terms of properties, but are hoped to be only for temporary use, while awaiting the development of a new generation of halocarbon fluids (such as propane and butane derivatives).

12.2.4 Thermal balance

To achieve the best design for a display cabinet, it is essential to know its thermal energy balance, i.e. all the heat exchanges between the stored goods and the outside environment. This serves to establish the most efficient air distribution inside the cabinet, and to calculate the refrigerating power necessary to keep the goods at the correct storage temperature. A theoretical approach can be adopted, but experimental tests are usually required to validate the calculations. The operation of a display cabinet is strongly influenced by many external factors, which are sometimes unpredictable.

The thermal balance of the load in a display cabinet depends on several heat sources outside the compartment, or other heat sources close to the load itself.[7] First of all, heat exchange with the outside environment at ambient temperature must be considered: in closed cabinets, this occurs mostly by conduction through the cabinet walls and doors, if any. Its contribution is not the most important though, because the walls are made of sandwich panels that are usually well insulated. However, during shopping hours the doors of the closed cabinets are opened frequently, as customers approach the compartment to handle or pick up the food. This leads to an unavoidable infiltration of warm air through the opening. The same heat gain is also encountered in open cabinets, in which the door is replaced by an air curtain. This curtain is effective to some degree in open-top chest cabinets, where stratification of the cold air helps to minimise any mingling of warm air from the outside and the refrigerated air inside the cabinet; but in vertical cabinets, the creation of a barrier to the incoming warm air remains a crucial problem.

A further important heat source from the outside environment, especially in open cabinets, is the radiant heat exchange between the refrigerated compartment and the walls, ceiling and lighting in the surrounding room.[8] Heat exchange by radiation is governed by the difference in the fourth power of the absolute temperature of the two bodies, and by their emissivity, which is a characteristic of the surface of the body with regard to thermal energy radiation and absorption, and ranges from 0 (for a perfect reflector) to 1 (for a 'black body'). Usually, both the food packages and the walls of the room have a high emissivity of approximately 0.8–0.9. The absorption of radiant heat from the environment leads to an increase of up to 5–10ºC in the temperature of the uppermost layer of goods in comparison with the least exposed layer.

Heat gains from internal sources are primarily due to lighting, defrosting and de-misting devices. The refrigerated compartment has to be adequately lit, but high-intensity lighting raises product temperature by several degrees. For example, the lights in a vertical multi-deck cabinet are placed under each shelf, very close to the top layer of goods on the shelf below: this causes a concentrated heating effect on the packages, which are also affected by radiant heat transfer. Defrosting devices are installed in all cabinets. They are used to keep the air ducts and cooling coils clear of ice, and represent a temporary (but inevitable) heat source. De-misting heaters are installed wherever transparent surfaces have to be kept clear of condensation, i.e. the doors of closed cabinets (when they are opened in a humid room, water vapour condenses on the inside). Further sources of heat can be found in additional electric heaters fitted into the rim around the top of open-top chests, which might come into contact with the customers' hands and feel unpleasant if particularly cold.

12.2.5 Air distribution

Most frozen food display cabinets are cooled by forced air circulation, because a large amount of refrigerating power is required, and this would be difficult to transfer by air circulating merely by natural convection.

In an open-top display unit, air is extracted through a linear grill near the top opening (on one side) and forced, by means of fans, through air ducts around the refrigerated compartment to a heat exchanger, usually a finned coil, situated underneath the bottom compartment. Here the air is cooled, by exchanging heat with an evaporating refrigerant (in an evaporating coil) or with a secondary refrigerant (in a heat exchanging coil). Finally the air is forced through a symmetrical supply grill on the other side of the opening. The circulating cold air refrigerates the compartment and, in the case of open cabinets, helps to limit the infiltration of air from the room. Forced air velocity strongly influences the performance of an open-top cabinet: if the air velocity is too low, the necessary refrigerating effect (and consequently the correct storage temperature) cannot be guaranteed; if its velocity is too high, the air stream becomes more turbulent, thus increasing heat and mass transfer with the environment.

In a closed vertical cabinet, air circulation is very similar to that of an open-top unit. The air curtain operates with the door closed or open and its velocity is high enough to guarantee that only a minimal amount of warm air from the environment is entrained when the door is opened. In the case of small closed vertical cabinets whose door is not opened frequently, i.e. units that are not intended for supermarkets, the evaporating coil is placed in the top of the refrigerated compartment and fans eject cold air directly towards the goods. Consequently a powerful air circulation is created, and the temperature is easily balanced and kept under control. When the door is opened, the fans stop in order to restrict the flow of cold air from the cabinet.

In an open vertical cabinet, the air circulation is very different. Air is extracted through a linear grill at the base of the opening, and fans then force it through the cooling coil situated underneath the bottom of the cabinet. The cooled air is forced to a supply plenum located behind the compartment. A small fraction of the air is fed into the unit at an approximate velocity of 0.1 m/s through a perforated plate at the back of the cabinet, while the bulk of the cold air is blown through one or more linear diffusers situated in front of the canopy. These adjacent layers of air are usually called 'air curtains', since they act as vertical barriers to warm air infiltration from the room into the refrigerated compartment. Each linear diffuser is supplied by a separate plenum, in which a honeycomb panel ensures uniform air distribution and an accurate control of the air velocity.

The energy consumption of a vertical cabinet is influenced mainly by the behaviour of the air jet blown through the upper diffuser in the canopy. The resulting cold air curtain, supplied at a temperature ranging from −25°C to −30°C, moves down the front of the cabinet, until a strong fluctuation periodically entrains warm room air, which has to be cooled and dehumidified; at the return opening, the air temperature rises to −17/−18°C. That is why an in-depth understanding of the fluid dynamics in the cabinet is so important to establish the right thermal energy balance; and also why the theoretical calculations must invariably be supported by experimental tests to validate the mathematical model used.

12.2.6 How to reduce heat gains

It is possible to reduce the effect of some of the heat gains affecting the thermal energy balance of the cabinet. Lowering the emissivity of the load can effectively contain radiant heat transfer. From a technical point of view, food packages should incorporate low-emissivity materials, such as aluminium. Numerical calculations and experimental tests prove that when such materials are used (with an emissivity of about 0.1) the first layer of food is colder by 3–5°C, thus giving rise to better storage conditions and a lower energy consumption.

Radiant heat transfer can be also reduced by providing so-called ‘radiant shielding’, i.e. reflective surfaces (e.g. aluminium) around the open-top chest to intercept radiation from other shop surfaces. One drawback of these reflecting screens is that they are difficult to implement.

Heat from lighting can be reduced by replacing incandescent floodlights with fluorescent tubes, and by restricting illumination to a maximum value of 600 to 700 lux. Air exchange with the room can only be reduced by a better air curtain design (in the case of open cabinets), or by limiting the number of times the doors are opened (if the cabinet is closed). In the latter case, the customer’s behaviour becomes very important. The prime objective of a display cabinet is to induce consumers to buy the products, but without handling the food or opening the doors unnecessarily. Consumer handling also has an influence on food temperature due to direct product warming.

12.2.7 Overall performance

At the end of this section it is worth summarising the overall performance of display cabinets in terms of refrigerating capacity, power input and loading capacity, as shown in Table 12.1. Performance is indicated per unit length of cabinet, and is purely for guidance, reliable merely as an order of magnitude.

Table 12.1 Cabinet performance (at EN441 Climate Class 3 conditions)

	Refrigerating capacity (W/ml)	Power input (W/ml)	Loading capacity (m^3/ml)
Open-top, wall site	400–500	250–400	0.2–0.3
Open-top, island site	500–700	350–600	0.3–0.7
Vertical, multi-deck glass door	600–700	400–600	0.7–0.9
Vertical, multi-deck triple air curtain	1900–2200	1200–1900	0.7–0.8

12.3 Variations for different product types

Different frozen foods require no specific treatment when inside the display cabinet, since they only need to be kept at the correct temperature without fluctuation (which is common to all frozen foods). So there are no particular differences between cabinet types with respect to the products they can display, although one criterion adopted in combination cabinets is for bulk products to be placed in the open-top chest, and more select products in the upright section. Moreover, soft-packaged products are usually best stacked in open-top chest units, while hard-packaged products are best presented in vertical cabinets.

Because ice creams require a different temperature from other frozen foods (between −20ºC and −24ºC),[1,4] they are best displayed in separate cabinets, although these can be of the same design as for other frozen foods. However, specifically designed cabinets do have to be provided for soft ice cream on sale to customers for immediate consumption. One side of the cabinet is open for staff to access the ice cream containers and prepare portions of the various flavours available. Particular attention has to be paid to the top surface of the small containers, which is the area most susceptible to temperature fluctuations and a risk of the top layer of ice cream melting. The subsequent formation of ice crystals produces a coarse texture, which is not appreciated by customers.

12.4 Installation

Good cabinet performance, in terms of both its display and its preservation functions, depends largely on where it is installed. For the preservation function, which is of interest here, the aim is to maintain the correct temperature and avoid its fluctuation. This is achieved by (a) providing the right environment, and (b) correctly positioning the cabinet in the store plan.

12.4.1 Providing the right environment

The main requirement to providing the right environment for the cabinet is proper air conditioning of the shop space.[9–11] In principle, air conditioning is meant to guarantee comfortable conditions for people, but it has more far-reaching effects in a shop environment where refrigerated cabinets are installed. The main ambient micro-climate parameters controlled by air conditioning are temperature, relative humidity and air velocity – and all three play a part in people's comfort and in the display cabinets' performance. First of all, this is because a controlled micro-climate enables a correct display cabinet choice, and guarantees that the design conditions will not be exceeded in practice.

In this respect, the European Standard (EN441)[12] defines six 'climate classes', each identifying the most severe ambient operating conditions. Cabinet manufacturers will rate and test their product to a specific climate class. The six classes are presented in Table 12.2 according to the EN441. It is worth noting, however, that the standard aims to compare cabinet performance and specifies test conditions for determining test package temperatures in refrigerated display cabinets. Compliance of a display cabinet with the EN441 standard consequently does not guarantee that food will be kept at the correct storage temperature when the cabinet is operating on the premises, due both to differences in the thermal properties of real foodstuffs as opposed to test packages (made mostly of water and oxyethylmethylcellulose) and to differences between test conditions and the real shop environment.[13,14]

If the shop is air conditioned, a cabinet rated for 'class 3' is acceptable, while a cabinet rated at 'class 6' (at least) must be installed if the shop is not air conditioned. Second, year-round air conditioning allows almost constant environmental conditions to be maintained inside the store (with temperatures ranging from +20ºC in winter to +25ºC in summer). In addition, relative humidity and air velocity are constantly under control, thus enabling a smoother and less energy-consuming operation of the cabinet's refrigeration equipment.

The effects of minimum temperature control are easily recognisable in an increased risk of temperature fluctuation within the cabinet and the frozen product, and increased energy consumption accompanied by a greater strain on the refrigerating unit. Less obvious, but none the less highly relevant, are the effects of inadequate humidity control, which again leads to increased energy consumption, but also, and more important, to an increased frost build-up at the high relative humidity levels that occur in summer in rooms with no air conditioning. Ambient air with a high humidity content enters the cabinet openings and flows through the evaporator, increasing frost production, the negative effects of which will be explained in detail later.

Air flow around the cabinets also plays an important role: if its velocity is too high, convective heat transfer is increased, causing temperature fluctuation.

Table 12.2 Climate classes according to the EN441 standard

Test room climate class	1	2	3	4	5	6
Dry bulb temperature (ºC)	16	22	25	30	40	27
Relative humidity (%)	80	65	60	55	40	70
Dew point (ºC)	12	15	17	20	24	21

Good refrigeration practice calls for the air-conditioning plant to retain air velocity levels lower than 0.2 meters per second, especially in areas where display cabinets are located. Moreover, the air-conditioning designer must pay special attention to the aisles between cabinets, to avoid customer discomfort due to cold streams escaping from the units.

In order to avoid all these problems for large stores, it has been suggested recently that air distributed by the air-conditioning plant should be differentiated:[15] while the rest of the shop receives air at the usual conditions, the display cabinet area will receive relatively warm air (to keep the aisles between cabinets at a comfortable temperature) that is kept very dry (to minimise frost formation inside the cabinets).[16,17] To counter the 'cold aisles' phenomenon, locating air return grids in the floor below the cabinets has also been suggested.

When designing an air-conditioning plant for a shop, special attention must be paid to the type of display cabinets to be installed: if self-contained equipment is chosen, with the condenser on board the cabinet, this releases heat to the immediate surroundings, inside the shop itself. This heat affects climatic conditions for the cabinet's operation negatively, and emphasises the need for proper air conditioning – even in small shops that are usually equipped with stand-alone cabinets. With remotely refrigerated cabinets, the situation is different: the net energy balance of the cabinet in the shop environment is negative, as a result of heat extracted by the evaporator from the cabinet and, ultimately, also from the room. This may well reduce the summer air-conditioning load, but it will never entirely overcome the need for micro-climate control in the shop.

In combination with the air-conditioning plant, certain ancillary devices (enabling a better shop micro-climate control) may also contribute to smoother display cabinet operation. For example, shop door air curtains, automatically controlled opening mechanisms or double doors have a positive effect, and are therefore always advisable.

In conclusion, strict control over the shop environment will reduce a cabinet's refrigeration requirements, but will be more energy demanding on the air-conditioning side. On the other hand, less micro-climate control by the air-conditioning plant may induce a saving on its energy requirements, but make it harder for the refrigerated display cabinets to function properly, not only as far as energy demand is concerned, but also in terms of product safety (due to an increased number of defrosting cycles, for example). Again, it is a matter of optimising contrasting requirements by means of a properly integrated design of all the infrastructures involved in the shop.

12.4.2 Positioning the cabinet

Proper positioning in the store's layout also has a marked effect on the cabinet's performance. Obviously cabinets must be installed as far as possible from direct sunlight, doors, windows, and air diffusers in order to keep any operating condition problems to a minimum. Special care is necessary in positioning self-contained cabinets to leave sufficient space around the condenser, to allow for unobstructed air flow through the condenser coil.

Last but not least, a cabinet's position is also important in allowing customers to retain food safety and quality after purchase, i.e. frozen foods must always be located near the check-out points, so that they are the last items picked up before leaving the store.

12.5 Operation, monitoring, maintenance and breakdown

12.5.1 Operation

It has already been pointed out that retail cabinets are only intended to maintain the right storage temperature of the frozen food on sale. They are not designed to lower the product's temperature, so a display cabinet must be loaded with particular care. First of all, the product must be loaded at the right storage temperature. It is worth emphasising that, according to the European Directive 89/108/EEC on the storage temperature of frozen foods,[18] a tolerance of −15ºC is permitted for short periods, so the retailer should check the food's temperature on delivery and, if necessary, place it in a cold storage room in order to load the goods at a temperature of −18ºC. The time it takes to get the food into the cabinet should also be minimised, because a rise in temperature is bound to occur during cabinet defrosting cycles, and the quality of ice cream, for instance, deteriorates very quickly at temperatures warmer than −18ºC.

A 'load limit line' establishes the permissible volume of the load inside a display cabinet (open or closed). This line indicates the area within which the load can be kept below the limits for the declared temperature class. The goods should always be placed below the load limit line in chest cabinets, or behind it in the case of vertical display cabinets. Packages stored beyond this limit will not be kept at the right temperature, and their obstruction of the supply or return air grills will negatively affect the refrigerated compartment.

Stock rotation should be followed when loading the compartment, preferably on the 'first in, first out' principle. Newly loaded products must be placed behind those already there in order to reduce the time that the products stay in the display cabinet.

12.5.2 Frosting and defrosting

In a display cabinet, frosting is a crucial problem. The humid air entrained from the room deposits frost on almost all the cold surfaces, but especially on the evaporating coils and return air ducts, and this usually has a severe, detrimental effect on performance. In fact, obstruction of the coils and air ducts reduces the circulation of refrigerated air, leading to poor load cooling and air curtain instability in vertical cabinets. Every cabinet therefore needs defrosting regularly, usually by means of electrical heaters, or by reversing the refrigerating cycle. The main purpose of defrosting is to remove ice on and around the evaporating coil and air ducts. These components are heated so that the ice melts and the resulting water drains out of the cabinet through a condensation drainage line. During defrosting, it would be advisable to stop the fans, in order to minimise the circulation of warm, humid air inside the refrigerated compartment. A certain rise in load temperature is always detectable, however, especially in the outer and upper layers, which are more susceptible to radiant and convective heat exchanges with the store environment. Defrosting frequency has to be adapted to the operating conditions. An excessive interval between defrosting cycles leads to the build-up of ice on the evaporator and air ducts, especially when the cabinet is operating in a very damp environment. On the other hand, excessively frequent defrosting exposes the load to temperature fluctuations, which can reduce food quality. There are also ways to reduce the need for defrosting, the most important of which include: maintaining ambient temperature and, more important, humidity within the range of the cabinet's climate class; installing the cabinet well away from air streams caused by air-conditioning systems, windows or doors, in order to reduce warm air infiltration through the air curtains; and loading the cabinet properly, without obstructing the air grills.

The refrigerating unit must also be properly designed, without being oversized: oversize induces an excessively low evaporating temperature, which leads to greater air dehumidification, and consequently greater ice production.

Defrosting frequency can be controlled by means of a clock, while its duration is usually determined by a temperature probe on the evaporating coil, which makes sure that all the ice has been melted. Smart controls are being developed to monitor evaporator frosting by means of air temperature and mass flow rate measurements, with a view to minimising the number of defrosting operations.[19–21]

While the retail store is closed, open cabinets should be protected with 'night covers'. These may be rigid panels (with or without insulation), and with a reflective surface on the underside, or plastic curtains with a reflective outer surface for use with vertical cabinets. Their use is strongly recommended, because they lower the food temperature, which may have risen during opening hours for various reasons. At least one defrosting operation should be scheduled during closing time.

12.5.3 Monitoring

The load temperature in a display cabinet is influenced by many important factors, such as the loading pattern, the convective and radiant heat exchange with the room, defrosting cycles, and consumer handling. Load temperature distribution is also extremely variable, especially in cabinets with an ample display area and temperature differences of up to 15ºC between the warmest and coldest packages. In many cases, it is difficult to achieve a product temperature of −18ºC, especially close to the load limit line where heat gains from radiation and air infiltration are most influential. This is a crucial factor when monitoring the proper operation of the cabinet, because it is difficult to say whether all the loaded products are stored at (or below) the correct temperature. A correlation can be established, however, between forced air temperature and load temperature during preliminary temperature tests in the laboratory, when the cabinet is certified to comply with the standards. Therefore, monitoring the air temperature would be sufficient to keep a check on the proper operation of the cabinet.

The European Directive 92/1/EEC on temperature control in display cabinets calls for a temperature probe close to the return air grill, at the load limit line.[22] The reading given by this thermometer is not representative of the temperature of the load, but serves as an indication of cabinet function, providing that the above-mentioned correlation has been established. The air temperature at the return grill depends largely on the heat transfer between the load and the surrounding room, and also on frost build-up on the evaporating coil and air ducts (due to the lower circulating mass flow rate).

Monitoring the inlet and return air temperature may also prove useful for an automatic defrosting device. Also, any warning system should be based on these temperature readings instead of on product temperatures, which may vary more slowly and independently of the cabinet's operation.

After the recent introduction of the HACCP (hazard analysis and critical control points) with the European Directive 93/43/EEC,[23] the display cabinet could be identified as a 'critical control point', in which the food's temperature should be monitored. Many interesting new devices are being developed for this purpose. Cheap data loggers have been available for some years, capable of recording the time–temperature history of a single package or of a whole pallet of food for a period of many days. Special paints are available, which change colour when the temperature reaches a given value, thus giving an immediate indication of whether the cold chain has been interrupted.

12.5.4 Maintenance

The cabinet should be inspected daily to make sure that everything is working properly, particularly that:

- the temperature recordings show no deviation from the usual operating values;
- the defrosting device is operating correctly;
- the load has been rearranged after customer handling in order to comply with the load limit line.

Moreover, the cabinet must always be kept clean: the outside must be cleaned daily, while the refrigerated compartment must be periodically emptied and washed with hot water and suitable detergent. Before re-loading the cabinet, the refrigerating unit must be started again, and the storage temperature restored.

The refrigerating unit also requires regular servicing. In stand-alone cabinets, the air-cooled condensers must be cleaned at regular intervals to remove dust.

Fouling in water-cooled condensers must be avoided, and if necessary a water softener should be installed. A qualified technician should service the compressor according to the manufacturer's recommendations. All safety devices must be efficient at all times.

12.5.5 Breakdown

In the event of a breakdown, it is essential to take the necessary precautions to avoid the products' temperature rising. If the failure is expected to be long lasting, the whole load should be transferred to other cabinets or cold stores as soon as possible. In the case of short-term failure, the thermal capacity of the load can help to maintain a low storage temperature. Night covers should be applied immediately, and customer access prevented; all defrosting and de-misting devices and fans should be switched off.

12.6 New developments

12.6.1 Air distribution

There is still room for improvement in the design of display cabinets. Open display units present the main problem, since numerous unpredictable factors influence their operation. It is common knowledge that even minuscule differences in the geometry of an open display cabinet can lead to a substantially different performance in terms of load temperature and energy consumption. This is particularly true for the multi-deck open-front vertical frozen food cabinets, which are the most sensitive to surrounding environmental conditions.[24,25] Even the transit of customers in front of the opening can cause warm air infiltration to enter the refrigerated compartment through the air curtains. To reduce this effect, three curtains at different air velocities and temperatures are used, creating a complex flow pattern at the front of the cabinet.

These considerations suggest that a better display cabinet design can be achieved mainly by investigating the fluid dynamic behaviour of the air curtains. Numerical and experimental methods can be employed.[26–36] The CFD (computational fluid dynamics) technique is a numerical method that helps predict air movements inside the cabinet, with a parametric analysis of the influence of single components on the cabinet's performance. It is difficult to obtain absolute results with this technique (because practical operation involves ambient conditions that are less stable and controlled than those imposed for the model), but the comparative analysis is effective none the less. Even the cabinet energy balance can be established. The heat transfer from the load, and the difference in enthalpy fluxes between the return air grill and the cold air inlets, can be calculated simply. The cabinet's energy consumption is divided into two fractions due to load refrigeration and warm air infiltration respectively. This procedure enables a better understanding of the influence of different parameters (e.g. the cabinet's geometric configuration, the number, velocity and temperature of the air curtains, the presence of lighting, etc.) on the refrigerating unit's performance and energy consumption.

On the other hand, certain experimental techniques can be used for measuring the cabinet air curtains. The most common method for assessing the air stream pattern is to inject smoke or oil particles into the air ducts, thus revealing cross-sections of the air curtains with a flat sheet of light created by a coherent light source. Numerical processing of these images also permits a quantitative evaluation of the infiltration of warm air through the air curtain. The air velocity in the curtains can be evaluated more precisely using laser-Doppler anemometers. With such an effective measurement, the air stream is not disturbed at all, and a two-dimensional map of the air velocity can be obtained in a cross-section of the cabinet.

12.6.2 Refrigerating equipment

In the future new developments are most likely to be seen in the refrigeration technology that accompanies display cabinets, because of the environmental impact problems relating to halogenated working media (already discussed). In the last decade, events have shown that it is impossible to find a single solution to all the problems, and optimal solutions can only be found if specific application niches with comparable characteristics are addressed. The display cabinets situation is a good example because it is too varied to be considered a single niche: display cabinets for small shops can no longer be treated in the same way as cabinets for big supermarkets, and different solutions have to be found.

For individual display cabinets it is difficult to imagine an alternative to the halocarbon refrigerants – the most adventurous innovation might be a system charged with hydrocarbons (a plug-in unit usually has a refrigerant charge of less than 1 kg), whereas researchers can chart a totally new course for larger retail display cabinets in supermarkets.

An obvious potential option involves using secondary coolants and the so-called 'indirect systems', which rely on vapour-compression technology but employ more environmentally benign working media than halocarbon refrigerants: the refrigerating unit does not cool the air inside the cabinet; instead, the evaporator cools a secondary medium that is forwarded to a heat exchanger in the cabinet.[37,38]

The entire refrigerating machine can be relegated to a machine room that is not accessible to the public, making it feasible to use ammonia, for example, which is toxic and flammable, or hydrocarbons (propane, butane, or their mixtures). The machine room can be equipped with all the necessary means to comply with safety standards and regulations.[39,40]

The secondary refrigerant coupled with the ammonia or hydrocarbon system requires a circuit and a pump for its circulation to the cabinets: this introduces a thermodynamic irreversibility due to the temperature gradient needed to transfer heat between the two media, and requires power for the fluid to be pumped through the circuit. The outcome is a deterioration in the energy effectiveness of the system as a whole, the extent of which depends mainly on the thermophysical properties of the secondary coolant.

The use of single-phase secondary coolants (or brines, as they are commonly called) is not new in refrigeration: brines have been used extensively in industrial applications, but rarely in commercial refrigeration, especially at the low temperatures needed for frozen food. Brines can be divided into two main classes, i.e. aqueous solutions and non-aqueous fluids. The first class of fluids includes the well-known glycol/water mixtures and calcium chloride/water mixtures, as well as the new generation of fluids based on potassium formate or potassium acetate; the second class includes many of the new synthetic fluids, which have a better performance in terms of pumping power, but a comparatively poor heat transfer, and require higher volume flows.[41]

Moreover, all the fluids' properties are temperature dependent, and their behaviour deteriorates as the temperature drops: this poses problems for their use in display cabinets, where fluid temperatures of −30ºC (or colder) are necessary. Apart from their thermophysical properties, other features of the fluids have to be taken into consideration, i.e. corrosion, environmental impact, toxicity, flammability and handling safety; in this respect, there is no ideal secondary coolant, and the most suitable option has to be chosen for each individual case.

For low-temperature applications, such as those regarding frozen foods, carbon dioxide (CO_2) – used as a phase-changing secondary refrigerant – may be an interesting option.[42,43] Generally, from an energetic standpoint, CO_2 is more convenient as a phase-changing secondary coolant than single-phase secondary refrigerants. It has a higher volumetric heat capacity, a lower viscosity, and can take thermodynamic advantage of the near-zero temperature gradient experienced in heat exchangers. These features also lead to more compact heat exchangers, piping and valves. The advantages become more evident as the temperature approaches values as low as −40ºC. Also, there are no problems with corrosion and environmental impact, and no health hazards for users.

The real drawback of CO_2 lies in its critical temperature (31.1ºC), which corresponds to a critical pressure of 7.38 MPa. When operating at temperatures around −30ºC this is no problem, but when the unit is switched off the temperature tends towards ambient levels, and the pressure rises well above 1.9 MPa (the maximum permissible operating pressure according to current standards). Therefore something must be done to prevent this unwanted pressure rise – but this is neither easy nor cheap.

Be that as it may, one wonders whether CO_2 is best used as a secondary coolant in low-temperature applications, or if it might be better as a refrigerant in a direct system, using a vapour-compression cycle (cascade, or possibly trans-critical), thus avoiding the irreversibilities linked to heat transfer.[43,44] But how carbon dioxide is best employed in refrigerating equipment is still a matter for research.

Another line of research in refrigeration technology for display cabinet systems concerns air cycle (also known as the Joule/Brayton reverse cycle), which produces cold air by removing energy from the air itself in the form of work. The air cycle features a good environmentally benign working medium, i.e. air. Moreover, with the 'open air cycle' system, the air cooled by the refrigerating machine can be delivered directly to the refrigerated compartment, thereby eliminating the need for a heat exchanger. In principle, the 'open' system is particularly suitable for display cabinet applications: its advantages include delivering air to the cabinet at very low temperatures and, in vertical multi-deck cabinets, the amount of infiltration can be significantly reduced. Problems with this type of application arise from condensation and ice build-up on components and ducts, and from the high-frequency noise due to the use of turbo machinery.[45,46]

12.7 Legislative issues

12.7.1 Performance tests

Refrigerated display cabinets are affected by a number of international and national standards, which mainly concern cabinet performance and are intended for manufacturers, but it is very important for retailers to have a sound knowledge of them as well, since they are expected to comply with certain specifications.

The international standards currently in force in the European Union are:

- ISO Standard 1992[47]: Commercial refrigerated cabinets – methods of test.
- ISO Standard 5160[48]: Commercial refrigerated cabinets – technical specifications.
- EN Standard 441[12]: Refrigerated display cabinets – parts 1 to 12.

The EN Standard has almost entirely absorbed the former ISO Standard, and they both define the methods for testing cabinets, particularly in terms of the temperature of the load, so only the EN Standard is briefly outlined here. It has the following parts:

1. Terms and definitions.
2. General mechanical and physical requirements.
3. Linear dimensions, areas and volumes.
4. General test conditions.
5. Temperature test.
6. Classification according to temperature.
7. Defrosting test.
8. Water vapour condensation test.
9. Electrical energy consumption test.
10. Test for absence of odour and taste.
11. Installation, maintenance and user's guide.

12. Measurement of the heat extraction rate of the cabinets when the condensing unit is remote from the cabinets.

After the necessary general definitions, the first three parts of the EN441 state several mechanical and physical requirements, which have to be declared by the manufacturer, concerning dimensions, the defrosting system, door fasteners and the effectiveness of doors, pipes, connections, as well as the basic requirements for the refrigerating system. The load limit line is defined, together with its marking.

Part 4 is one of the most important, because it defines the test room conditions, together with the instruments, measuring equipment and tolerances. Tests on temperature, defrosting, water vapour condensation, electrical energy consumption and physical dimensions must be performed in the test room. Six test room climate classes are defined, as illustrated earlier in Table 12.2, where the dry bulb temperature, relative humidity and dew point temperature are listed for each class.

Air movement in the test room is required to be parallel to the longitudinal axis of the cabinet, with an air velocity of between 0.1 and 0.2 m/s. Part 4 also defines another important aspect, i.e. the packages used to fill the refrigerated compartment, which must have a mass of 1000, 500 or 125 g, the filling material being a mixture of particular cellulose and water, with specific thermal properties.

Part 5 is devoted to the temperature test, which is the main concern of the Standard. The loading of the cabinet, the position of the temperature probes, the use of night covers, the opening of doors, and the preparation of test reports are just some of the topics considered. The temperature test aims to measure the cabinet's performance in terms of load temperature. The temperature is measured at the centre of certain special packages (the so-called M-packages) containing a temperature probe. The cabinet is classified according to the temperature test results, using the symbols illustrated in Table 12.3, as stated in Part 6 of the Standard.

A defrosting test has to be carried out, as specified in Part 7, to check whether the automatic defrosting system operates correctly and effectively. The same goes for the water vapour condensation test (Part 8), which checks that there is

Table 12.3 Temperature classes of cabinets (ºC)

Class	L1	L2	M1	M2	H	S
The highest temperature of the warmest package equal to or lower than	−15	−12	+5	+7	10	Special
The lowest temperature of the coldest package equal to or higher than	–	–	−1	−1	+1	Special
The lowest temperature of the warmest package equal to or lower than	−18	−18	–	–	–	Special

no evidence of condensed water vapour on the outer surfaces of packages or dripping onto the packages. During the temperature test, the electrical power consumption is recorded as stated in Part 9, and the resulting daily energy consumption is recorded in the test report. The test for the absence of odour and taste is performed as outlined in Part 10, using samples of water and butter. Part 11 concerns the installation of the cabinet, and emphasises some important siting and operating conditions, which have to be met by the retailer. Part 12 specifically concerns cabinets with remote condensing units, and specifies heat extraction rate measurements and conditions for this kind of installation.

It has to be pointed out that the EN Standard 441 is currently under revision, and that probably some modifications in the section regarding the test room conditions will take place. Moreover, the inclusion of some other topics like ergonomics and safety are under discussion.

Two other important standards in force in the United States are:

1. ASHRAE Standard 72/1983R[49]: Methods of testing open refrigerators for food stores.
2. ASHRAE Standard 117/1992[50]: Methods of testing self-service closed refrigerators for food stores.

So there are two different standards, one for open and one for closed display cabinets. The ASHRAE standards only consider temperature test procedures, with the exception of remote refrigerators, for which energy consumption measurements are also taken into account. It specifies only one test room condition (a dry bulb temperature of 24 ± 1ºC and a wet bulb temperature of 18 ± 1ºC). Instead of test packages, it calls for the use of 'test simulators', which are boxes of at least 473 ml in volume, closed by a lid, and containing a sponge. They are filled with a mixture of propylene glycol and water 50/50% by volume. The position of the temperature probes in the cabinet is similar to that of the EN standard.

12.7.2 Energy labelling

Energy consumption has recently become one of the primary issues in comparing different display cabinets, but it would be unreasonable to compare the energy consumption of cabinets intended for different uses. Consequently guidelines are being developed to group cabinets into a number of categories and compare their energy consumption within each category, adjusting them for certain differences such as loading capacity and temperature.[51,52] This adjustment can be made after the basic step of defining the 'functional features' of the cabinet, which could be expressed in terms of total display area (following the Eurovent/Cecomaf 'Recommendation for energy consumption evaluation of remote refrigerated display cabinets') or in terms of size and temperature. The final goal is a classification of all cabinets with an energy efficiency index, depending on the relationship between total energy consumption and functional features.

12.7.3 Legislation on temperature control and monitoring

The temperature of frozen foods stored in display cabinets must comply with national legislation. In Europe this has to be consistent with EU Directives. Directive 89/108/EEC[18] states that food has to be kept at −18ºC or colder, with permissible temperature fluctuations up to −15ºC for short periods of time.

As mentioned earlier, there are two ways to control the correct storage of foods in retail display cabinets.[53] The first (and most commonly used) is based on monitoring the temperature of air circulating inside the cabinet. In Europe, according to Directive 92/1/EEC,[22] each cabinet must be equipped with a thermometer to measure air temperature at the return air grill. A certain correlation can be established between this temperature and the proper operation of the cabinet because insufficient cooling, whatever the reason for it, will certainly increase the return air temperature. However, proper operation of a cabinet does not guarantee the right storage temperature for the goods. Temperature differences of up to 15ºC may be encountered between the warmest and coldest packages loaded in the same cabinet, particularly in open-top chest cabinets.[54] The only way to monitor load temperature is by inserting a temperature probe in a special package, made of a material with thermal properties similar to those of food, and placed where the warmest temperatures are experienced. It is worth noting that, for display cabinets, Directive 92/1/EEC[22] does not demand that any record be kept of the air temperatures; it simply specifies the need for the thermometer. If in doubt as to the temperature of the frozen food, Directive 89/108/EEC[18] suggests a destructive test on a package, following the guidelines given in Directive 92/2/EEC.[55]

Finally, it is important to bear in mind the recent introduction of the HACCP with the European Directive 93/43/EEC,[23] which could make specific load temperature monitoring and recording a necessity.

12.8 Summary

Refrigerated display cabinets are intended to display and preserve food in retail stores simultaneously. These are contrasting requirements because keeping frozen food clearly visible and easy to reach leads to product temperature fluctuations, which are known to be the primary cause of quality and safety loss in frozen foods. Furthermore, the capacity of a cabinet to attract customers and promote the product it contains usually demands a high energy consumption, thus requiring design optimisation by the manufacturer.

Many types of display cabinets are commonly used; they may be open or closed and are classified, depending on their shape, as chest cabinets or vertical multi-deck cabinets. This classification is also important from a technical standpoint, because the performance of the two types is very different. Open-top single-deck chests are energy efficient and effective in terms of their preserving function, but less so in terms of their display function. Vertical multi-deck cabinets are much more suitable in terms of their display function, especially when they are open. However, their open front is a source of ambient air filtration, resulting in a high risk of temperature fluctuation and high energy consumption. Open cabinets suffer particularly from radiant heat transfer and air infiltration from the environment: while the first problem can only be reduced by lowering the emissivity of the surface of packages and the room's walls, air infiltration is prevented by means of one or more refrigerated air curtains at the opening. An understanding of the cabinet's thermal energy balance becomes an essential part of its design, and can be achieved by numerical calculations supported by experimental validation.

Proper installation of cabinets in specific climatic conditions is very important, because each manufacturer rates and tests the units to specific 'climate classes', defined in terms of air temperature and humidity. Therefore air conditioning should always be provided, and all air streams should be carefully controlled because the cabinets are rated for specific conditions, and any open doors, windows and air diffusers can significantly affect their performance.

Regarding the loading of food, retail cabinets are only intended to maintain the right storage temperature of the frozen food on sale, not to lower the product's temperature. Therefore the food must be at the right storage temperature when loaded. A rise in temperature is bound to occur during cabinet defrosting cycles, which are needed to clear air ducts and refrigerating coils of ice, and the food might thus reach the permissible temperature limit. The goods should always be stacked according to the cabinet manufacturer's instructions, i.e. below the load limit line, without obstructing the supply or return air grills.

Because the load temperature in a display cabinet is strongly influenced by many factors, and the load temperature distribution in the refrigerated compartment is also highly variable, monitoring the storage conditions is somewhat difficult. An EU directive only specifies the need for a thermometer measuring the return air temperature, while recording the values is not required. A correlation can be established between air temperature and load temperature, and monitoring the air temperature would thus suffice to keep a check on the proper operation of the cabinet. After the recent introduction of the HACCP, the display cabinet could be identified as a 'critical control point', in which the food's temperature should be monitored. Cabinets are also required to respect some specific standards, which mainly concern the capability of the unit to maintain a maximum load temperature at certain ambient conditions.

There is still room for improvement in the design of display cabinets, particularly for open display units. Advanced techniques are necessary to investigate the fluid dynamic behaviour of the air curtains: numerical and experimental methods are available, such as the CFD technique and laser-Doppler velocimetry. The refrigerating equipment itself is also undergoing technological improvements, due to the environmental impact of halogenated refrigerants. Indirect systems, using a secondary coolant, are a potential alternative to traditional vapour-compression machines, but innovative cycles (the trans-critical cycle with carbon dioxide or the air cycle) are also considered promising options.

12.9 Acknowledgements

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12.10 References

1 INTERNATIONAL INSTITUTE OF REFRIGERATION, *Recommendations for the Processing and Handling of Frozen Foods*, 3rd edn, Paris, IIR/IIF, 1986.
2 GAC, A. and GAUTHERIN, W. *Le Froid dans les Magasins de Vente de Denrées Périssables*, Paris, Pyc Edition, 1987.
3 RIGOT, G. *Meubles et Vitrines Frigorifiques*, Paris, Pyc Edition, 1990.
4 AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR CONDITIONING ENGINEERS, *Handbook 1998 Refrigeration*, ch. 47, Retail Food Store Refrigeration and Equipment, ASHRAE, Atlanta, 1998.
5 POLONARA, F., CORTELLA, G. and SCHIESARO, P. 'Retail display: equipment and maintenance', in *A Practical Guide to the Cold Chain from Factory to Consumer*, ed. R.L. Fuller, EU Concerted Action CT96-1180, Report 1, 1998, 9–12.
6 THE REFRIGERATED FOOD INDUSTRY CONFEDERATION, *Guide to the Storage & Handling of Frozen Foods* ('The Gold Book'), Grantham, British Frozen Food Federation, 1994.
7 BILLIARD, F. and GAUTHERIN, W. 'Heat balance of an open type freezer food display cabinet', Proc. Int. Conf. *Cold Chain Refrigeration Equipment by Design*, International Institute of Refrigeration Comm. B1, B2, D1, D2/3, Palmerston North, New Zealand, 1993, 322–32.
8 NESVADBA, P. 'Radiation heat transfer to products in refrigerated display cabinets', Proc. Int. Conf. *Storage Lives of Chilled and Frozen Fish and Fish Products*, International Institute of Refrigeration Comm. C2, D3, Aberdeen, 1985, 323–9.
9 GAUTHERIN, W. and SROUR, S. 'Effect of climatic conditions on the operation of refrigerating equipment in a hypermarket', *19th Int. Congr. of Refrigeration*, IIR/IIF, The Hague, 1995, Vol. II, 705–12.
10 TASSONE, A. 'Hypermarchés: le casse-tête de la climatisation', *Rev. Prat. Froid*, 1997, **845**, 35–8.
11 GAUTHERIN, W. 'Influence des conditions climatiques internes et externes sur le fonctionnement des équipements frigorifiques d'un hypermarché', Journées Européennes du Froid *Froid et Climatisation dans la Distribution*, Association Française du Froid, Paris, 1997, 49–68.
12 EN STANDARD 441 – Refrigerated display cabinets.
13 MORILLON, C., PENOT, F. and BERTIN, F. 'Analysis of the effect of testing rooms on the operation of refrigerated display cases', *19th Congr. Int. of Refrigeration*, IIR/IIF, The Hague, 1995, Vol. II, 735–43.
14 MORILLON, C., BERTIN, F. and PENOT, F. 'Analyse du comportement de

chambres d'essai pour meubles frigorifiques de vente', *Revue Gén. Froid*, 1996, **963**, 21–4.

15 FOSTER, A. M. and QUARINI. G. L. 'Using advanced modelling techniques to reduce the cold spillage from retail display cabinets into supermarket stores', Proc. Int. Conf. *Refrigerated Transport, Storage & Retail Display*, International Institute of Refrigeration Comm. D1, D2/3, Cambridge, 1998, 217–25.

16 HOWELL, R. H., ROSARIO, L., RIISKA, D. and BONDOC, M. 'Potential savings in display case energy with reduced supermarket relative humidity', *20th Int. Congr. of Refrigeration*, IIR/IIF, Sydney, 1999.

17 BERNET, L. 'Dessiccation et déshumidification de l'air des G.M.S.', Journées Européennes du Froid *Froid et Climatisation dans la Distribution*, Association Française du Froid, Paris, 1997, 49–68.

18 European Directive 89/108/EEC – On the approximation of the laws of the member states relating to quick-frozen foodstuffs for human consumption.

19 CHAMIELEC, O. 'Conception: le dégivrage à l'heure du futur', *Rev. Prat. Froid*, 1996, **840**, 32–3.

20 LEGO, F. 'Meubles frigorifiques de vente: l'autodégivrage à continuité de temperature', *Rev. Prat. Froid*, 1996, **839**, 54–5.

21 DATTA, D., TASSOU, S. A. and MARRIOTT, D. 'Experimental investigations into frost formation on display cabinet evaporators in order to implement defrost on demand', *Proc. Int. Refrigeration Conference at Purdue*, West Lafayette, Indiana, 1998, 259–64.

22 European Directive 92/1/EEC – Monitoring of temperatures in the means of transport, warehousing and storage of quick-frozen foodstuffs intended for human consumption.

23 European Directive 93/43/EEC – Hygiene of foodstuffs.

24 MORILLON, C. 'Meubles verticaux à rideaux d'air – état des développements et perspectives', Journées Européennes du Froid *Froid et Climatisation dans la Distribution*, Association Française du Froid, Paris, 1997, 27–48.

25 DUPRE, F. 'Les meubles à rideaux d'air', *Rev. Gén. Froid*, 1995, **85**(953), 47–8.

26 VAN OORT, H. and VAN GERWEN, R. J. M. 'Air flow optimisation in refrigerated cabinets', *19th Int. Congr. of Refrigeration*, IIR/IIF, The Hague, 1995, Vol. II, 446–53.

27 BALEO, J. N., GUYONNAD, L. and SOLLIEC, C. 'Numerical simulation of air flow distribution in a refrigerated display case air curtain', *19th Int. Congr. of Refrigeration*, IIR/IIF, The Hague, 1995, Vol. II, 681–8.

28 PENOT, F., MORILLON. C. and MOUSSET, S. 'Analyse et numérisation d'images d'écoulements pour l'étude des meubles frigorifiques de vente', *19th Int. Congr. of Refrigeration*, IIR/IIF, The Hague, 1995, Vol II, 106–13.

29 MORILLON, C. and PENOT, F. 'La modélisation: une aide à la conception thermoaéraulique des meubles frigorifiques de vente', *Revue Gén. Froid*, 1996, **968**, 48–53.

30 STRIBLING, D., TASSOU, S. A. and MARRIOTT, D. 'A two-dimensional

computational fluid dynamic model of a refrigerated display case', *ASHRAE Transactions*, 1997, **103**(1), 88–94.

31 CORTELLA, G., MANZAN, M. and COMINI, G. 'Computation of air velocity and temperature distributions in open display cabinets', Proc. Int. Conf. *Advances in the Refrigeration Systems, Food Technologies and Cold Chain*, IIR/IIF, Sofia, 1998.

32 SCHIESARO, P. and CORTELLA, G. 'Optimisation of air circulation in a vertical frozen food display cabinet', *20th Int. Congr. of Refrigeration*, IIR/IIF, Sydney, 1999.

33 PENOT, F., FUENTES, C., TUHAULT, J.L. and MOUSSET. S. 'Étude des champs dynamiques produits dans une maquette industrielle par PIV et LDV', *6ème Congrès Francophone de vélocimétrie laser*, Session C, Numéro 1, ISL 1998, pp. C1.1–C1.8.

34 PENOT, F. and GROS, N. 'Développement de moyens expérimentaux pour l'étude de jets d'air bidimensionnels à Re=10000', *13ème Congrès Français de Mécanique*, Poitiers Futuroscope, France, 1997, vol. 1, 475–78.

35 PENOT, F. and MOUSSET, S. 'Traitement d'images de tomographies de rideaux d'air de meubles frigorifiques de vente comparé à des mesures thermiques', *20th Int. Congr. of Refrigeration*, IIR/IIF, Sydney, 1999.

36 SCHIESARO, P. and CORTELLA, G. 'Optimisation of air circulation in a vertical frozen food display cabinet', *20th Int. Congr. of Refrigeration*, IIR/IIF, Sydney, 1999.

37 HRNJAK. P. 'The benefits and penalties associated with the use of secondary loops', Proc. *ASHRAE/NIST Refrigerant Conf.*, Gaithersburg, Maryland, 1997, 85–95.

38 MAO, Y., TERRELL, W. and HRNJAK, P. 'Performance of a display case at low temperatures refrigerated with R404A and secondary coolants', Proc. Int. Conf. *Refrigerated Transport, Storage & Retail Display*, International Institute of Refrigeration Comm. D1, D2/3, Cambridge, 1998, 181–9.

39 EGGEN, G. and AFLEKT, K. 'Commercial refrigeration with ammonia and CO_2 as refrigerant', Proc. Int. Conf. *Natural Working Fluids '98, Gustav Lorentzen Conference*, International Institute of Refrigeration Comm. B1, B2, E1, E2, Oslo, Norway, 1998, 281–92.

40 NYVAD, J. and LUND, S. 'Indirect cooling with ammonia in supermarkets', Proc. Int. Conf. *Applications for Natural Refrigerants*, International Institute of Refrigeration Comm. B1, B2, E1, E2, Aarhus, Denmark, 1996, 207–17.

41 VERWOERD, M., LIEM, N. and VAN GERWEN, R.J.M. 'Performance of a frozen food display cabinet with potassium formate as secondary refrigerant', *20th Int. Congr. of Refrigeration*, IIR/IIF, Sydney, 1999.

42 INFANTE FERREIRA, C.A. and SOESANTO, S. 'CO_2 in comparison with R404', Proc. Int. Conf. *Heat Transfer Issues in Natural Refrigerants*, International Institute of Refrigeration Comm. B1, E1, E2, College Park, Maryland, 1998, 141–9.

43 CHRISTENSEN, K.G. 'Use of CO_2 as primary and secondary refrigerant in supermarket applications', *20th Int. Congr. of Refrigeration*, IIR/IIF, Sydney, 1999.

44 NEKSÅ, P., GIROTTO, S. and SCHIEFLOE, P.A. 'Commercial refrigeration using CO_2 as refrigerant', Proc. Int. Conf. *Natural Working Fluids '98, Gustav Lorentzen Conference*, International Institute of Refrigeration Comm. B1, B2, E1, E2, Oslo, Norway, 1998, 270–80.

45 RUSSELL, S.L. and FITT, P. 'The application of air cycle refrigeration technology to supermarket retail display cabinets', Proc. Int. Conf. *Refrigerated Transport, Storage & Retail Display*, International Institute of Refrigeration Comm. D1, D2/3, Cambridge, 1998, 199–207.

46 RUSSELL, S.L., GIGIEL, A.J. and JAMES, S.J. 'Progress in the use of air cycle technology in food refrigeration and retail display', Proc. Int. Conf. *Advances in the Refrigeration Systems, Food Technologies and Cold Chain*, IIR/IIF, Sofia, Bulgaria, 1998.

47 ISO Standard 1992 – Commercial refrigerated cabinets – methods of test.

48 ISO Standard 5160 – Commercial refrigerated cabinets – technical specifications.

49 ASHRAE Standard 72/1983R – Methods of testing open refrigerators for food stores.

50 ASHRAE Standard 117/1992 – Methods of testing self-service closed refrigerators for food stores.

51 VAN DER SLUIS, S.M. 'Energy labelling of refrigerated display cases', *19th Int. Congr. of Refrigeration*, IIR/IIF, The Hague, 1995, Vol. II, 752–9.

52 EVANS, J.A., VAN DER SLUIS, S.M. and GIGIEL, A.J. 'Energy labelling of supermarket refrigerated cabinets', Proc. Int. Conf. *Refrigerated Transport, Storage & Retail Display*, International Institute of Refrigeration Comm. D1, D2/3, Cambridge, 1998, 252–63.

53 GIGIEL, A.J., JAMES, S.J. and EVANS, J.A. 'Controlling temperature during distribution and retail', *3rd Karlsruhe Nutrition Symposium, European Research towards Safer and Better Food*, ed. V. Gaukel and W.E.L. Speiss, 1998, 284–92.

54 BOBBO, S., CORTELLA, G. and MANZAN, M. 'The temperature of frozen foods in open display freezer cabinets', *19th Int. Congr. of Refrigeration*, IIR/IIF, The Hague, 1995, Vol. II, 697–704.

55 European Directive 92/2/EEC – Sampling procedure and Community method of analysis for the official control of the temperatures of quick-frozen foods intended for human consumption.

13

Future trends in frozen foods

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13.1 Introduction

This is the most exciting chapter of any text to write and I hope it will be the most fun to read. Nobody can claim to look into the future and accurately predict what will occur. However, we can review the areas that are currently causing a lot of excitement in the research community and in the frozen food industry and discuss how these developments may find their way into the products and practices of the future.

In writing this chapter I plan to take the reader along the frozen food chain of the future. I believe this is an exciting time in the development of the frozen food industry and a time when it is beginning to shed its image of cheapness and convenience to be replaced with an image of quality and value.

In the future, I believe consumers are going to want more frozen food products and that those foods will have a higher nutritional quality because of improvements in available varieties and in the handling of materials between harvest and processing. The textural quality and the retained nutritional content of frozen foods after thawing will be improved by new manufacturing processes such as pressure shift freezing which allow the production of smaller ice crystals during freezing. These products will be more stable because the ice crystals will remain small during distribution due to the incorporation of anti-freeze proteins and other novel ice actives. Stability will also be improved by formulation and by understanding of mobility and biochemistry in the unfrozen component. I think the distribution chain will be better controlled through the use of predictive modelling and through monitoring with time–temperature integrators. Finally, when consumers go shopping they will be presented with a wider variety of foods which will be more attractively and efficiently displayed – if they choose to go shopping at all.

In the rest of this chapter I will explain my reasons for these beliefs.

13.2 Consumers will want more frozen foods – markets

The market for frozen foods grew continuously throughout the twentieth century. The demand was driven by the changes in lifestyle and demography which occurred with an increase in one-parent families and families where both partners are employed, together with an increase in the availability of technology to produce and store frozen foods. In 1998 in the United States the frozen foods market was worth $64.3 billion, of which $25.7 billion was in the retail sector (18% of total retail food sales) and $38.6 billion was in food service. This compares with a market of $53 billion in 1990 and $25 billion in 1980. In the United Kingdom the frozen food market was worth £4.96 billion in 1998 and was growing at 3.5% per annum. Part of the reason for this dramatic growth is illustrated by the breakdown of frozen food sales shown in Table 13.1. Frozen foods are now represented in almost all categories of food products.

As far as one can predict, these two trends in Western lifestyle and technology are likely to continue in the future, leading to further growth in this sector. Western lifestyles are increasing both the consumption of convenience food products and leading to more food consumption outside the home. In the

Table 13.1 Frozen foods in supermarket sales

Appetisers/snacks	$463 million
Baked goods	$372 million
Breakfast foods	$886 million
Desserts/toppings	$731 million
Dinners/entrees	$4 800 million
Fruit	$178 million
Ice cream/sherbet	$4 100 million
Juices	$1 100 million
Meat	$754 million
Novelties	$1 800 million
Pasta	$252 million
Pies	$367 million
Pizza	$2 100 million
Plain vegetables	$1 700 million
Pot pies	$291 million
Potatoes/onions	$842 million
Poultry	$1 400 million
Prepared vegetables	$109 million
Seafood	$877 million
Side dishes	$236 million

Source: IRI 1998.

food service sector, reliance on frozen products is greater because they offer the ability to control supply with variable demand.

However, the greatest growth in the consumption of frozen foods is likely to be seen in the developing countries. In eastern European states, frozen foods are regarded as a luxury product and their consumption reflects a more Western lifestyle. This has led to their being marketed as high margin quality goods and as these economies pick up in the next decade we can expect the same increase in domestic freezers and microwave cookers that fuelled growth in the West to increase demand for frozen foods in these states.

Perhaps surprisingly, many other developing countries are seeing a similar increase in frozen food consumption. However, world-wide consumers view the adoption of Western lifestyles as a demonstration of progress. We should not therefore be surprised to see developing markets in Asia and Africa, showing increased consumption of Western-style convenience foods as the amount of time available to adults outside work decreases. Certainly we are already seeing the major food multinationals investing in these future markets.

13.3 Frozen foods will be more nutritious

Nutrition is featuring more highly in the minds of Western consumers when making food purchasing decisions. Awareness of the need for a balanced diet in terms of vitamin requirements and the dangers of over-consumption of fats has been common for a long time. In the past decade, however, public understanding of nutritional requirements has become much more sophisticated and media interest in food topics has led to the results of academic research on nutrition rapidly becoming common knowledge. Consumer awareness exists, for example, of the difference between saturated and unsaturated fats and of discoveries such as the effects of food antioxidants on cancer prevention.

The frozen food industry cannot escape the commercial pressures exerted by this desire for more nutritionally balanced diets, and indeed it is probably in the best position to deliver such ‘healthy’ products to the consumer. Careful selection of ingredients, good formulation and processing and a well-controlled frozen food chain have the ability to deliver products much closer to their original nutritional content than can possibly be achieved through the chilled chain where relatively rapid deterioration is inevitable.

The frozen food industry has for many years used selective breeding of plants to develop cultivars that show the best resistance to freeze–thaw damage as outlined in Chapter 3. The same breeding criteria could be used to enhance the nutritional content of plant material. At the time of writing, public opinion has turned strongly away from the use of genetic modification of plants to improve their agricultural and food quality properties. This is largely because of concerns over effects on the environment and worries about the effects of ingesting material from these plants. Time will tell whether such worries are well founded or not. However, should this technology prove acceptable, then the breeding of plants for frost resistance, for nutritional content and for freeze resistance during processing are all desirable goals which could bring benefits to consumers of frozen food products.

After breeding and selection the key stage in maintaining nutritional content is the transfer of ingredients from farm to factory. Rapid chilling techniques or immediate freezing by the producer is the most important step in ensuring high quality material for the frozen food processor.

Academic research has recently been focused on these two alternatives, immediate freezing and accelerated chilling, and is likely to continue so in the near future. If materials are to be frozen by the producer on the farm, or at sea for fish, then we need a good understanding of the effects of multiple freeze–thaw cycles on the final quality and safety of such products. Questions arise regarding the effects on texture and microbial ingress during the thawing stages. However, understanding of the requirements to protect products during multiple freeze–thawing and the use of cryoprotectants during freezing stages shows promise in producing high quality final products that have been frozen and thawed at more than one point in the food chain.

Accelerated chilling techniques are already available for the rapid chilling of materials on the farm or at later stages of processing where nutritional content may be lost. These include cryogenic techniques, immersion in aqueous solutions, mist chilling and vacuum chilling techniques. The adoption of these techniques has largely been limited by understanding of the effects of different chilling protocols on different food types. The growing body of research in this area should assist in the decision making involved with selection of appropriate chilling technologies and result in higher quality ingredients being readily available to the food processor.

13.4 Ice crystals will be smaller: controlling ice nucleation

Quality changes during the freezing process itself are related to the way in which ice crystals are made to grow. Typically if we cool a plant or animal tissue then ice crystals will initially form on the surface. The way in which ice growth continues from this point depends largely on the rate at which heat is extracted from the freezing product. If the product is cooled slowly then the initial ice crystals continue to grow into the intercellular tissue. As they do so, the concentration of the unfrozen solution outside the cells increases, drawing water out of the cells by osmosis. This water in turn is added to the growing ice crystals. The net result is shrunken cells and a few large ice crystals which have grown between the cells, causing maximum disruption to the structure. If we cool at a faster rate then heat is removed ahead of the growing ice crystals and new nucleation sites can be found. This leads to more ice crystals being formed of a smaller average size and less shrinking of the cells. This has been shown to reduce the degree of freeze damage as it causes smaller changes to texture and less loss of nutrients through drip on thawing.

As discussed in Chapter 9, this and other effects have led to an increasing use of cryogenic techniques which achieve faster freezing rates, particularly near the surface of the food. One way in which the frozen food industry could enhance the quality of its products is to control the nucleation of ice and ensure that the water-to-ice transition occurs through the formation of lots of small ice crystals. A number of areas of research are beginning to offer control of nucleation which could achieve this goal.

13.4.1 Pressure release nucleation

Figure 13.1 shows a simplified phase diagram of the ice–water system. One of the unusual properties of water is that if the pressure is raised from ambient pressure, the melting temperature is reduced. This is directly related to the fact that water expands on freezing rather than contracting, like the majority of substances. The melting curve reaches a minimum at 4 kbars where the melting temperature has dropped to around −20°C. After this, further increases in pressure result in a higher melting temperature.

This unusual property of water led to researchers investigating the effects of pressure shift freezing. If water is cooled under high pressure, temperatures down to −20°C can be achieved in the liquid phase. If the pressure is then suddenly released, the sample can be expected to freeze extremely rapidly. This technique has been demonstrated to cause the formation of a large number of small ice crystals throughout a solution or a food sample.

On its own this technique is not enough to produce the matrix of small crystals that would be desirable in a frozen food product. This is because the heat removed in cooling to −20°C under pressure is not as large as the latent heat required in order to turn all of the water to ice. The pressure release must therefore be followed by a relatively rapid cooling process which allows the rest of the latent heat to be removed before these small ice crystals re-melt. Nevertheless, this technique has been demonstrated to achieve a matrix of small crystals in small samples of a wide range of foodstuffs.

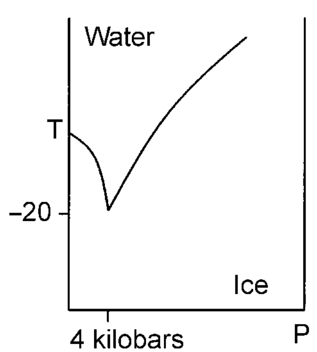

Fig. 13.1 A simplified phase diagram of the ice–water system.

13.4.2 Ultrasonic control of nucleation

Ultrasound, like all forms of sound, is a pressure wave. It has long been known that pressure waves passed through supercooled water can bring about the transition to ice. As early as 1908 research was published which showed that striking an anvil with a hammer in supercooled water initiated the formation of ice. Later experiments included firing a starting pistol in a freezing fog in order to precipitate ice. Indeed, attempts were made to measure the amplitude of the pressure wave required by detonating controlled explosions in a fog and collecting the deposited ice.

These demonstrations, together with more controlled laboratory experiments, all showed that a pressure wave with an amplitude of a few tenths of an atmosphere could bring about ice nucleation.

A quick glance at the phase diagram of Fig. 13.1 reveals a bit of a quandary in interpreting this result. First, the pressures involved are not particularly significant on the scale of the ice–water phase diagram and, second, an increase in pressure should bring about a reduction in the melting temperature and hence make the supercooled water less likely to freeze. It was the study of other nucleating technologies that revealed the answer to this quandary. It had been shown that ice nucleation could be brought about by tapping or scratching the side of a container, by large electric fields on falling drops or by tearing the surface of ice by the rapid motion of a hydrophobic object such as a wax-covered glass rod. High-speed photography revealed that for all three of these methods the formation or release of an oscillating air bubble preceded the nucleation event. Theoretical calculations by Hickling and others showed that when such a bubble approaches the minimum in its oscillations, then a small shell of the liquid at the bubble surface is squeezed to produce a pressure that may be several tens of kilobars. Thus the water in this shell is carried adiabatically across the phase diagram to a point where it is well below the melting curve and ice nucleation follows. Pressure waves from sound experiments were having the same effect on air bubbles within the supercooled water and operating by the same mechanism.

In the 1980s, with or without an understanding of the mechanisms involved, a number of devices were patented that claimed to produce smaller ice crystals in frozen foods if ultrasound was applied during freezing. Development of this technique in the future may again offer the food industry a way of creating a large number of nucleation sites within a frozen food. As with pressure shift freezing, this will need to be followed by a rapid removal of heat to ensure that these crystals grow to provide a lattice of small ice crystals throughout the frozen food structure.

13.4.3 Biological control of ice nucleation

In the next section we will discuss anti-freeze proteins which have evolved to allow organisms to inhabit regions of the world where the temperature is a few degrees below their freezing point by avoiding the onset of ice formation.

However, there are many organisms that live in environments where the temperature is just too cold to avoid freezing altogether. These organisms have evolved methods of controlling where in their bodies ice forms in such a way as to minimise the damage from their annual freeze–thaw cycle and allow them to repair and function in the spring.

Part of this strategy involves the expression of biological ice nucleating agents. These are lipoproteins which are generated usually on the outer surface of the cell membranes. They act as a template for ice growth and encourage ice formation to occur in the gaps between cells where the organism is least sensitive to damage.

These ice nucleators have been found in many insects, frogs and bacteria. In an interesting variation they are used by the bacterium *Pseudomonas syringae* to initiate freezing on the leaves of plants. This ice formation results in freeze damage to the leaves which releases nutrients for the bacterium to feed on. *Pseudomonas syringae* that has been heat- and pressure-treated to make it harmless is now sold commercially as a nucleating agent for use in the generation of snow on ski slopes. Another bacterium *Xantamonas campestris* has been used in the freeze concentration of fruit for jam-making processes.

It is possible in the future that if suitable plants are located, and shown to express ice nucleating lipoproteins naturally, that they may be bred into varieties suitable for use in the frozen food industry. Despite much interest in this idea, little progress has been made recently in locating such sources.

13.5 And they will stay smaller: controlling ice crystal growth

13.5.1 Anti-freeze proteins

An area of research that has caused great excitement in the scientific community and increasingly in the frozen food industry is the field of anti-freeze proteins. These proteins were first discovered in Antarctic and Arctic fish species. The freezing point of sea water is −1.9°C. The freezing point of fish serum is −1.0°C. These proteins were able to allow fish to survive at almost a degree below their melting point without freezing.

It was rapidly determined that these proteins were not simply lowering the melting point by the Raoult effect, as occurs with increasing concentrations of, for example, salt solutions. The same degree of supercooling would require concentrations of protein over a 1000 times higher than the concentrations that are in fact present. The proteins were therefore interacting in an active way with the ice water structure.

In fact we now know that anti-freeze proteins do not entirely prevent the formation of ice. Rather, whenever an ice nucleus is formed, they act to limit the growth of the ice crystal by binding to specific crystallographic planes. It is well understood that supercooling of solutions occurs because of the local kinetics of nucleation. When a liquid is below its melting temperature, then on a macroscopic scale it is energetically favourable for it to undergo a transition

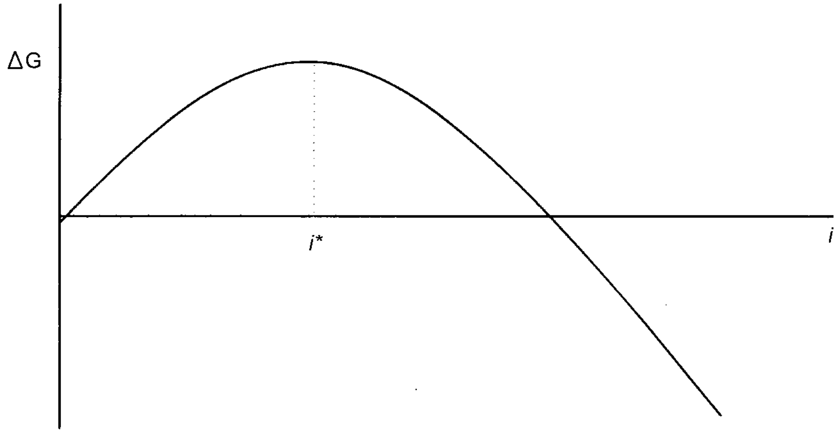

Fig. 13.2 The free energy of an ice nucleus as a function of the number of molecules in the crystal.

to the solid state, i.e. to freeze. However, on the microscopic scale the formation of the initial solid crystal nucleus is often energetically unfavourable. A simple pictorial explanation of this is to consider the energy balance when a water molecule encounters a very small ice crystal (see Fig. 13.2). If it is below the melting temperature the molecule will wish to bind to the ice crystal and release its latent energy (a favourable process). However, if the crystal is small and hence has a high radius of curvature then in order to form this bond there must be some readjustment of the bond angles of the incoming molecule (an energetically unfavourable process). This leads to the concept of a critical radius, which is the radius at which these two energy considerations balance. A crystal with a radius larger than this value will continue to grow. On the other hand, a crystal with a radius smaller than this value will not be stable and will re-melt.

Finally, the amount of latent heat available will increase as the temperature drops and the amount of supercooling increases and hence the required critical radius becomes smaller. So for a drop of pure water up to 40°C of supercooling can be attained before the critical radius corresponds to just a few molecules and nucleation occurs spontaneously as molecules form ice embryos by random thermal meetings of water molecules. In most other cases water freezes not onto itself, but onto impurities and surfaces which act as templates with enough curvature for the water molecules to bind.

The button mattress model (see Fig. 13.3) provides the explanation of how anti-freeze proteins affect the growth of ice crystals. The proteins contain a hydrophilic and hydrophobic section. When a growing ice front is encountered by the proteins, the hydrophilic portion will bind to specific planes in the crystal structure. This forces the ice to grow between the molecules and changes a planar ice front into a series of curved ice fronts. If this curvature is less than the critical radius, growth of this ice front is halted.

Fig. 13.3 The button mattress model.

This phenomenon has no effect on the melting point of the ice and there is of course a limit to the amount of supercooling that can be allowed in this way before ice growth swamps the anti-freeze protein's ability to limit growth. This gives rise to the concept of *thermal hysteresis* which is a measure of the effectiveness of anti-freeze protein solutions. Thermal hysteresis is the difference between the melting temperature and the freezing temperature of anti-freeze solutions. This is another distinguishing feature between the anti-freeze action and the Raoult effect where salt solutions lower the freezing and melting points equally.

Thermal hysteresis on its own is not of much interest in the field of food preservation (unless proteins are discovered that allow cooling to −18ºC or lower without freezing and this currently seems unlikely). However, it is the effects that the proteins have on the stability of ice crystals after they are formed that excite most interest and in particular the limiting effects they have on the recrystallisation of ice during storage. As explained in Chapter 7, the growth of ice crystals is the major cause of instability in the quality of frozen foods and a method of limiting this damage could be of great benefit to the frozen food manufacturer.

How can anti-freeze proteins effect recrystallisation? As a food freezes, the ice is removed as pure water molecules and the remaining unfrozen solution has an increasing concentration of solutes. The freezing point of this unfrozen portion decreases as the concentration increases. Typically in a frozen food at −18ºC we have 95% of the water frozen to form a collection of ice crystals of various sizes. These ice crystals are surrounded by a highly concentrated solution made up of the remaining 5% of unfrozen water and all of the solutes. On a microscopic scale this is not a static situation and water molecules are continuously being exchanged between the crystal surface and the surrounding liquid. The effect of anti-freeze proteins can most easily be understood by the same pictorial argument as described above to explain the critical radius. In a normal frozen food, because the curvature of a large ice crystal is less than for a small ice crystal, it is more energetically favourable for the unfrozen water molecules to be deposited on the surface of large ice crystals. The net effect over time is that the average size of the ice crystals increases as the smaller ice crystals disappear and the larger ones grow. This effect is accelerated by oscillations in temperature. The anti-freeze proteins bound to the surface of an ice crystal alter the energetics of this situation in the same way as in our previous argument. Since they bind to the surface and cause all of the ice crystals to grow on a surface that microscopically has the same curvature, the energetic advantage of the larger crystals is lost. A collection of ice crystals containing anti-freeze proteins is therefore more stable than those in a regular food solution and will not recrystallise as rapidly.

Four quite different anti-freeze proteins have been identified in different fish species. They are known simply as AFP I, AFP II, etc. They are characterised by their binding characteristics to the ice crystal lattice. Some anti-freezes such as AFP I have very clear binding sites because of the rigid nature of the molecule which has very specific distances between the hydrophilic groups. Others have been less easy to determine because of the flexibility of the molecule which allows it to bind to more than one crystal plane particularly at higher solute concentrations.

In the past decade it has become clear that similar proteins have evolved in a number of other environmental niches. In particular anti-freeze proteins have been extracted and identified in grasses such as winter rye, in carrots and in a number of insects. The largest degree of thermal hysteresis is currently seen in an anti-freeze protein extracted from the spruce bud worm. Further claims for anti-freeze activity have been made for extracts from many food plant materials including brussels sprouts.

Such discoveries have begun to show us a possible future for anti-freeze proteins in the food industry. The potential can be seen to breed plants selectively that are capable of expressing anti-freeze proteins and therefore could be expected to have a greater resistance to recrystallisation damage during distribution, with the resultant effect of increased textural quality and retention of nutrients on thawing.

There is still a lot of work to be performed yet before such plant material is readily available to the industry. Current research efforts are focused on locating new sources of anti-freeze proteins and on understanding their expression and mode of action. As anti-freeze proteins are found to have developed in more and more niches of nature the time is ripe for a comprehensive survey of plant materials to locate suitable proteins. This is not always straightforward as the expression often occurs in response to external environmental conditions such as changes in weather and location, e.g. the onset of winter or changes in tide. Understanding the acclimation effects that cause the plants to generate these proteins will play an important role in the breeding of plants and to their handling before and during harvest.

Despite the need for continuing developments in this area, the field of anti-freeze technology is beginning to show much promise in the medium term. We can look forward to frozen food products in the future that will be less susceptible to recrystallisation and therefore less sensitive to events occurring in the distribution chain.

13.5.2 Large molecules and the glass transition

The authors of Chapter 4 have described the ways in which large carbohydrate molecules affect the properties of a frozen food. In summary, as a food freezes, the water molecules separate out into pure ice and an increasingly concentrated solution. If this solution contains large carbohydrate molecules, and if the solutes do not themselves crystallise, then there is the possibility that at a specific, concentration-dependent, temperature (the glass transition temperature) they will become locked together to form a glass. Once the glass has formed, the mobility of the molecules is greatly reduced. The effect on mobility will be different for the different molecules in the solution. The large molecules themselves will be essentially static while the mobility of smaller ions and water molecules will be reduced to a lesser extent. This transition then will reduce the biochemical processes that cause deterioration of frozen foods by limiting the ability of the reactants to come in contact with each other. If foods can be formulated or infused with these carbohydrates the glass transition temperature is raised and, if raised above the storage temperature, the stability and shelf-life of the products can be increased.

Typical carbohydrate molecules which have been shown to raise the glass transition temperature of foods include sucrose, fructose and maltodextrin. Balancing of the relative content of these molecules in the food has already found some use in the formulation of ice cream to bring the glass transition up to the storage temperature. Furthermore, some products such as surimi which have a limited storage life at −20ºC are now transported at lower temperatures (−60ºC) in order to take them below their glass transition temperature.

Use of this phenomenon in the future is likely to be limited to products that can have their formulation changed easily, such as ice cream, and to products that are particularly sensitive to frozen storage such as soft fruits. Soaking techniques, which allow the inclusion of sugars into soft fruits to raise their glass transition temperatures as well as removing some of their water content to reduce damage from ice formation, are under development and may find further use (dehydrofreezing).

13.6 The frozen food chain will be controlled more effectively

To produce a product at −20ºC and transport it through the food chain to the consumer is, from a technological point of view, not at all difficult. Problems arise because of the need to use real people, machinery and buildings and to perform the operation at a reasonable price. The greatest difficulties arise at the transfer points, for example between cold stores and transport, in retail display where high visibility and easy access conflict with good temperature control, and during home transport by the consumer.

Controlling and monitoring of the cold chain is further complicated by the fact that different products will respond to changes in temperature in different ways. What is a drastic temperature abuse to one product may have no significant effect on another. Despite this difficulty there is no doubt that legislative pressure for traceability throughout the food industry is going to affect the logistics of frozen food distribution. Further economic pressures are likely to make retailers and manufacturers keen to understand the limits within which they must maintain the cold chain to protect quality and *in extremis* safety of frozen food products.

For this reason interest is focused on understanding the kinetics of deterioration of frozen food products and in the development of devices that monitor temperature and can respond with similar kinetics to changes in the environment. This is the province of predictive modelling and time–temperature integrators (TTIs).

As an example, let us suppose that we have a ready meal whose shelf-life when stored at −25ºC is determined by the rate of lipid oxidation in the meat component. However, if it is stored at −15ºC the fastest deterioration occurs due to enzyme action in the vegetable component and at −5ºC shelf-life is determined by dehydration due to moisture migration from the mashed potato. In storing and transporting this hypothetical product, the manager may be asked to decide:

- the limits of temperature fluctuation allowed in the defrost cycle of the cold store;
- the amount of time allowed in a loading day at 0ºC;
- when his truck breaks down for two hours, whether he or she should throw away the product, reduce its shelf-life or carry on as if nothing had happened.

Currently such decisions are made by educated guesswork. The development of predictive software models of quality in frozen foods are likely to put such decisions on a much firmer footing.

Even with such models the manager requires a way of monitoring the actual temperatures acquired by his products. Many devices for integrating temperature–time history have been developed in the 1980s and 1990s which perform this task for products in the chill chain. They are usually small chemical sachets which change colour after exposure to higher than desired temperatures for a given time period. By and large, such devices have found good use in bulk transport of chilled foods where temperature control is in the hands of professionals but their use on individual packaging has been largely resisted for a number of reasons. Not least of these is that, since the major concern in the chill chain is microbial safety, and the growth and contamination by micro-organisms is so complex to predict, it is extremely difficult to determine what criteria should be set for such devices to monitor. If they monitor the worst possible case then much good produce will have to be disposed of. Furthermore, since the poorest temperature control is likely to be performed by the consumer, limits set would not necessarily ensure best practice during distribution.

For frozen foods, however, these problems are not as severe. The kinetics of food biochemistry should be much easier to predict and imitate than microbiology in the chill chain. Successful devices could then find more ready acceptance among manufacturers and retailers as a way of ensuring quality in the food chain.

The combination of good predictive modelling and temperature monitoring offers the opportunity in the near term for better control of the frozen food distribution chain.

13.7 We will have wider choice and better display when we go shopping

The number of frozen food products available to consumers is already increasing rapidly. Nowhere is this truer than in the ready meals sector. The introduction of 'healthy meals' and ethnic and international recipe dishes has greatly increased the variety of products available. Food has become much more of a fashion market and many manufacturers now see successful product lives, the time period over which a product is manufactured, as being of the order of six months or less. This has led to much greater flexibility in the industry and product lines are designed with this flexibility in mind. As long as consumers continue to be adventurous in their tastes and demanding in their quality requirements the industry is going to be forced to respond to their requirements and the resultant choice can only increase.

For a long time, retail store design and refrigerated cabinet design was static and utilitarian. The majority of frozen foods were displayed in chest cabinets located close to the checkout counters so that consumers could purchase frozen items at the end of their shopping trip and minimise the problems of temperature abuse. Moreover most display cabinets were either open top and therefore created an uncomfortable environment or closed top which formed a barrier to the consumer wishing to view and access product. This together with the need to bend into the cabinet to attain products made the frozen shopping experience a relatively unpleasant one.

The advent of computational fluid dynamics and the better understanding of air flows together with computer aided design tools has led to a revolution in the design of frozen retail display. Control of the cold airflow to form a curtain between the displayed product and the consumer has reduced the need for physical closure of the cabinet and brought the advent of vertical display cabinets for frozen foods.

There is still much work to be done. A retail display cabinet is too complex a system to be modelled by a single CFD model. However, piecewise modelling of the cabinet components together with analogue testing is improving design and making the shopping experience more enjoyable. Retail cabinet manufacturers are addressing the problems of cold air escaping, leading to a cold floor environment, and are developing understanding of the many environmental factors, lighting, heating, etc., which influence the performance in retail display. Current research on reflexive packaging will allow the use of well-illuminated cabinets without adding excessively to the refrigeration energy demands. The cabinets of the near future may well overcome the conflicting demands that have hampered the display of frozen foods, namely providing easy access and high visibility to products while maintaining a well controlled storage temperature.

13.8 If we go shopping at all

It is not possible to look into the future in the late 1990s without considering the effects of e-commerce on the food industry. Possibly no other sector of the food industry can make greater use of developments in this area. Already it is possible to perform our food shopping from a computer at home and have products delivered to the door. For frozen foods this eliminates two of the trickiest stages of control of the food chain, namely retail display and home transport. The Internet provides the frozen food industry with the opportunity for managed control of the food chain right up to the consumer's front door. One retailer in the United Kingdom, who specialises in frozen foods only, currently offers an Internet shopping and home delivery service to 97% of the population.

Food shopping for the majority of consumers involves three components:

1. The weekly essentials.
2. Products that attract their attention while shopping.
3. Small items that they buy between major shopping expeditions.

All areas of the food retail industry are able to dispense the requirements of the weekly essentials over the Internet. For many food sectors, however, area 2 is the most difficult area of e-commerce since store design, promotional stands and the use of sound and smell have all been incorporated into the psychology of most food retail. However, for frozen foods these types of selling have always been difficult because of the need for good temperature control. For frozen foods, then, a judicious amount of promotion of new or popular products on Internet shopping pages may provide the opportunity to compete more easily with other food sectors.

13.9 Summary

The reader will by now have gathered that I regard the current period as an extremely exciting time in the development of the frozen food industry. Recent developments in our understanding of the biochemistry and physics of frozen foods together with the application of new developments in biological science are all combining to offer the frozen food sector a high tech and high quality future. Developments in retail display and e-commerce are taking frozen foods out of the cold corner of the retailer's store.

The ugly duckling is awakening and discovering that he's a swan after all.

13.10 Bibliography

ALMONACID-MERINO, S.F. and TORRES, J.A. 'Mathematical models to evaluate temperature abuse effects during distribution of refrigerated solid foods', *J. Food Eng.*, **20**, 223–45.

ANESE, M. and GORMLEY, T.R. 'Effect of dairy ingredients on some chemical, physicochemical and functional properties of minced fish during freezing and frozen storage', *Food Sci. and Technol. (LWT)*, 1996, **29**, 151–7.

BARRY, H., DUMAY, E. and CHEFTEL, J.C. 'Influence of pressure-assisted freezing on the structure, hydration and mechanical properties of a protein gel', in *High Pressure Food Science, Bioscience and Chemistry*, ed. N.S. Isaacs, London, Royal Society of Chemistry, 343–53.

BOGNAR, A., BOHLING, H. and FORT, H. 'Nutrient retention in chilled foods', in *Chilled Foods: The State of the Art*, ed. T.R. Gormley, 1990, Elsevier, London, 305–36.

CHENG, C.H.C. 'Evolution of fish antifreeze proteins', *Abstracts of Papers of The American Chemical Society*, 1998, **216**(1), 44–AGFD.

FUCHIGAMI, M., MIYAZAKI, K., KATO, N. and TERAMOTO, A. 'Histological changes in high pressure frozen carrots', *J. Food Sci.*, 1997, 62, 809–12.

GORMLEY, T.R. 'Developments in fish freezing in Europe, with emphasis on cryoprotectants', in *Processing Foods: Quality Optimisation and Process Assessment*, ed. F.A.R. Oliveira and J.C. Oliveira, 1999, Boca Raton FL, CRC Press, 163–74.

HICKLING, R. 'Nucleation of freezing by cavity collapse and its relation to cavitation damage', *Nature*, 1965, **206**, 915–17.

HUNT, J.D. and JACKSON, K.A. 'Nucleation of solid in an undercooled liquid by cavitation', *J. Applied Physics*, 1966, **37**, 254–7.

HURLING, R. and MCARTHUR, H. 'Thawing, re-freezing and frozen storage effects on muscle functionality and sensory attributes of frozen cod (*Gadus morhua*)', *J. Food Sci.*, 1996, **61**(6), 1289.

KENNEDY, C.J. 'Formation of ice in frozen foods and its control by physical stimuli', in *The Properties of Water in Foods ISOPOW 6*, ed. D.S. Reid, 1998, London, Blackie Academic & Professional.

KOCH, H., SEYDERHELM, I., WILLE, P., KALICHEVSKY, M.T. and KNORR, D. 'Pressure shift freezing and its influence on texture, colour, microstructure and rehydration behaviour of potato cubes', *Nahrung*, 1996, **40**, 125–31.

LEVY, J., DUMAY, E., KOLODZIEJCZYK, E. and CHEFTEL, J.C. 'Freezing kinetics of a model oil-in-water emulsion under high pressure or by pressure release: impact on ice crystals and oil droplets', *Lebensmittel Wissenschaft und Technologie*, 1999, **32**(7), 396–405.

LILLFORD, P.J. and HOLT, C.B. 'Antifreeze proteins', *J. Food Eng.*, 1994, **22**, 475–82.

LUCAS, T. and RAOULT-WACK, A.L. 'Immersion chilling and freezing in aqueous refrigerating media: review and future trends', *Int. J. Refrig.*, 1998, **21**(6), 419–29.

MALLETT, C.P. (ed.) *Frozen Food Technology*, 1993, London, Blackie Academic and Professional.

MIN, S.G., BYUN, M.H., CHOI, M.J. and SPIESS, W.E.L. 'Influence of synergism between k-carregeen and locust bean gum on the recrystallization of ice in a model system', in *Engineering and Food at ICEF 7*, vol. 1, ed. R. Jowitt, 1997, Sheffield, Sheffield Academic Press, A168–A171.

NILSSON, K. and EKSTRAND, B. 'Refreezing rate after glazing affects cod and rainbow trout muscle tissue', *J. Food Sci.*, 1994, **59**(4), 797.

SMITH, M.H., GRIFFITHS, R.F. and LATHAM, J. 'The freezing of raindrops falling through strong electric fields', *Quarterly J. Royal Met. Soc.*, 1971, **97**, 495–505.

VAN LOEY, A., HAENTJENS, T., SMOUT, C. and HENDRICKX, M. 'Enzymic time–temperature integrators for the quantification of thermal processes in terms of food safety', in *Processing of Foods: Quality Optimization and Process Assessment*, ed. F.A.R. Oliveira and J.C. Oliveira, 1999, Boca Raton, CRC Press, 13–40.

WIERZBICKI, A., TAYLOR, M.S., KNIGHT, C.A., MADURA, J.D., SIKES, C.S. and HARRINGTON, J.P. 'Investigations of stereospecifity of binding of type 1 antifreeze proteins to ice', *Biophysical Journal*, 1996, **70**(2), Pt 2, MP439.

YU, Z.W., YU, W.M., DEVRIES, A.L. and CHENG, C.H.C. 'Fluorescent microscopic imaging of antifreeze protein adsorption to ice', *Biophysical Journal*, 1998, **74**(2), 370.

Websites

Website of the British Frozen Food Federation: http://www.bfff.co.uk/
Website of Iceland on-line shopping: http://www.iceland.co.uk/
Website of the National Frozen Food Association: http://www.nffa.org/

Acronyms

AIS	alcohol insoluble substance
APC	aerobic plate count
ASU	air separation unit
ATP	adenosine triphosphate
CAP	controlled atmosphere packaging
CCAR	closed-cycle air refrigeration
CCP	critical control point
CFC	chlorofluorocarbon
CFD	computational fluid dynamics
CFU	colony forming units
CIE	Commission Internationale de l'Eclairage
CIP	cleaning in place
CMC	carboxymethyl cellulose
CoP	coefficient of performance
CPET	crystallised polyester terephthalate
CSP	cold shock proteins
CSR	cold shock response
DE	dextrose equivalence
DFD	dark, firm and dry
DIS	de-watering and impregnation soaking
DSC	differential scanning calorimetry
DX	direct expansion
ES	electrical stimulation
F&V	fruits and vegetables
FFS	form, fill and seal
GHP	good hygienic practice

GMP	good manufacturing practice
HACCP	hazard analysis critical control point
HCFC	hydrochlorofluorocarbon
HDPE	high density polyethylene
HFC	hydrofluorocarbon
HFCS	high fructose corn syrup
HLS	hydrolysed lactose syrup
HQL	high quality life
HTST	high-temperature short-time
ICF	immersion chilling and freezing
IQF	individually quick frozen
JND	just noticeable difference
LCA	life cycle assessment
LDPE	low density polyethylene
LVS	low volume system
MAP	modified atmosphere packaging
MRL	maximum residue level
MSNF	milk solids not-fat
ODP	ozone depletion potential
PA	polyamide
PCA	plate count agar
PE	polyethylene
PET	polyester terephthalate
PP	polypropylene
PPP	product, process and packaging
PS	polystyrene
PSE	pale, soft and exudative
PSL	practical storage life
PVC	polyvinyl chloride
SPC	standard plate count
TBA	thiobarbituric acid
TI	temperature indicator
TMAO	trimethylamino oxalate
TTI	time–temperature indicator (latterly time–temperature integrator)
TTT	time–temperature–tolerance
TVC	total viable count
UV	ultraviolet
WONF	with other natural flavours

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Index

absorption refrigeration 161, 166–7
accelerated chilling techniques 266
active packaging 207–8
ageing
  bakery products 144–5
  ice cream 152–4
  meat and poultry 87–8
agronomic factors 30–3
air conditioning 245–7
air cycle 254
air distribution 243–4, 251–2
air drying, partial 61–2, 63
Air Products
  Cryo-Batch freezer 188
  Cryo-Dip freezer 183, 184
  Cryo-Quick VT freezer 177–8
  Cryo-Tumbler 187
  Cryo-ZAT process 189
air thawing 22
altitude 33
aluminium 203–4
ammonia 161–2, 164, 165, 166
amylopectin 128, 131–2
animal-to-animal variation 85
animals, live 83–6
anti-freeze proteins 269–72
apples 33
artichokes 37
ascorbic acid 40, 41, 127, 129, 139
ASHRAE Standards 256
asparagus 44–5

bacteria *see* micro–organisms
bakery products 143–9
  ageing and staling 144–5
  freeze-thaw cycles 145–6
  frozen dough 146–9
  frozen storage 146
  part-baked breads 146
  solutions and standard practice 149
barrier properties 197–9
base slab 222
belt freezers 176
biological ice nucleating agents 268–9
blanching 59–60, 76, 142
blast freezers 175–6, 177
blowing agents 241
board packaging materials 204
BOC ºKwikFreeze freezer 185
'boil-in-the-bag' products 143
bread products *see* bakery products
breakdown 251
breeds 83–4
brines 253
broccoli 36
browning, enzymatic 125, 127
buffer zones 213
button mattress model 270–1

carbohydrate molecules, large 65–9, 272–3
carbon dioxide
  liquid and solid 170
  secondary coolant 253

card packaging materials 204
carton freezers 187–9
cartoning systems 207
cauliflower 36
ceilings, cold store 224, 225
characteristic local freezing time 115, 117–18
chemical changes 58, 122–5, 205
  enzyme activity 42, 124–5, 205
  lipid oxidation 102, 122–3, 140, 205
  protein denaturation 123–4, 205
  see also glass transition
chilling
  accelerated 266
  inactivation of micro-organisms 6–7
  rapid chilling for fish 103–4
  super-chilling 104–5
chlorofluorocarbons (CFCs) 164, 165, 230, 239–41
chocolate 152
choice 275–6
Claude process 171
cleaning, vegetables and 36
climate classes 246
cloning 30
closed-cycle air refrigeration (CCAR) 161, 167–8
closed vertical display cabinets 235–9, 243, 245
coefficient of performance (CoP) 162–4
co-extrusions 203
cold shock response (CSR) 24–5
cold shortening 86
cold store 4, 213–32
  design 214–21
    chamber size and layout 214–20
    energy conservation 220–1
  detail design features 221–5
  engineering management 231
  general management 231
  good operating practice 226–30
    fire precautions 229–30
    incoming product 227
    minimising door openings 227
    product handling 228–9
    records 228
    safety 227–8
  monitoring 225–6
    product conditions 225–6
    structure 225
  new developments 230–1
  spatial management 230–1
  storage, shelf-life and product quality 213–14
colour
  fruit and vegetables 37, 46–8
  impact of freezing 126–8
  meat and poultry 83, 200
  packaging materials and 200, 204–6
combination cabinets 239, 240
compressors 166
computational fluid dynamics (CFD) technique 251–2
condensers 166
conduction 174–5
constitutional supercooling 116–17
consumer appeal 199–200
consumer demand 264–5
control cards 19
convection 172–4
corn syrups 65, 151–2
costs 190–1
critical radius 270
cryogenic freezers 191
  refrigerants 160–1, 168–71
  tunnel freezers 176–9
cryoprotectants 105
crystallisation 112–18
  controlling ice crystal growth 269–73
  in fish 98–100
  recrystallisation 120–1, 155–7, 271–2
cultivar selection 2, 27–55
  agronomic factors 30–3
  future research areas 49–51
  methods of producing new cultivars 29–30
  and nutrition 40–3, 265–6
  potatoes 39–40
  quality of fruit and vegetables 27–9
    measuring 43–9
  sensory factors 37–9
  technological factors 33–7

dark and light meat 86
defrosting 248–9
dehydration 192
  partial 60–75, 76
dehydrofreezing 61–2, 63
denaturation of proteins 123–4, 206
de-coring 36
demersal fish 96
de-stalking 36
de-stoning 36–7
developing country markets 265
dextrose equivalence (DE) 151–2
display cabinets 4, 233–62

air distribution 243–4, 251–2
breakdown 251
design 234–45
different product types and 245
frosting and defrosting 248–9
future trends 275–6
installation 245–8
legislative issues 254–7
maintenance 250–1
monitoring 249–50, 257
new developments 251–4
open-top 235, 236, 243, 245
operation 248
overall performance 244–5
reducing heat gains 244
refrigerating equipment 239–41, 252–4
thermal balance 242–3
vertical 235–9, 243–4, 245, 251–2
distribution
effective control 273–5
ice cream 155–7
doors, cold store 221, 227
surround heaters 224, 225
dough, frozen 146–9
drip loss 82–3, 83–4, 91, 122, 205
dunnage rails 224
dynamometers 45–6, 47

eating quality *see* sensory quality
e-commerce 276
edible films and coatings 208
efficiency 162–4
electrical stimulation (ES) 86–7
electrical thawing 22
emergency plans 229–30
emissivity 244
emulsifiers 150
EN Standard 441 254–6
energy conservation 220–1
energy intake 139
energy labelling 256
entrances 221
environment, for display cabinets 245–7
enzyme activity 42, 124–5, 205
European Community Directives on Packaging and Packaging Waste 200–1
evaporators 166
existing stores 220
exits 221
exposure 32

fat intake 139
feeding animals 85
fertility, soil 31
fibreboard packaging materials 204
fire precautions 229–30
fish 3, 95–110, 126–7
changes during storage 100–2
freezing process 97–100
freezing rate 106
pre-freezing factors and quality 103–6
product supply chain 96–7
temparature cycling 106
type and shelf–life 103
fixed racking systems 216–20
flavour
changes in fish 102
fruit and vegetables 38, 127
impact of freezing 126–8
ready meals 139–40
flavourings 151–2
flexibility 190–1
floors, cold store 221–3, 225
heaters 222, 223, 223–4
fluidised-bed freezers 184–5, 186
fork trucks 228–9
form, fill and seal (FFS) 207
formulation 60–75, 76–7
freeze-cracking 118–19
freeze-thaw cycles 145–6
freezer burn 119
freezers 3, 159–93
blast freezers 175–6, 177
choosing a freezer 159–60, 189–92
costs and flexibility 190–1
matching to product 190
operability issues 192
product quality 191–2
cryogenic tunnel freezers 176–9
fluidised-bed freezers 184–5, 186
heat transfer 172–5
immersion freezers 183–4
plate freezers 181, 183
refrigeration systems 160–71
specialist freezers 189
spiral freezers 179–81, 182
stationary tunnels and carton freezers 187–9
tumbling and rotary tunnel freezers 185–7
freezing
chemical changes *see* chemical changes
fish 97–100
ice cream 154–5

freezing *continued*
immediate 266
impact on food quality 126–30
maximising quality 132–3
micro-organisms and 7–8, 9, 15
physical changes *see* physical changes
rapid 8, 9, 172
freezing rate 106, 115, 117–18
freezing time 115, 117–18, 174–5
Frigoscandia
Flat Product freezer 176, 177
FLoFREEZE M freezer 185, 186
GYRoCOMPACT freezer 179–81
frosting 248–9
frozen food chain 273–5
fructose 151, 273
fruit juice concentrates 67, 68
fruit and vegetables 2–3, 57–80
blanching 59–60, 76, 142
chemical changes 127
cultivar selection *see* cultivar selection
fruit flavourings for ice cream 152
future trends 75
partial dehydration and formulation techniques 60–75, 76–7
air drying 61–2, 63
ICF 69–75
osmotic dehydration 61, 62–9
processing vegetables for ready meals 142
functional compatibility map 65, 66
future trends 4, 263–78
choice and display 275–6
consumers and markets 264–5
controlling frozen food chain 273–5
controlling ice crystal growth 269–73
controlling ice nucleation 266–9
e-commerce 276
nutrition 265–6

gas flushing 207
gas liquefaction processes 170–1
genetic modification 30, 265–6
glass transition 67–9
controlling ice crystal growth 272–3
new trends in research 130–2
gluten matrix 147, 148
gutting fish 105–6

halogenated hydrocarbons (halocarbons) 164–6, 230, 239–41
handling
in cold store 228–9
fish 103
meat and poultry 86–9
hardening 155
harvesting
interval to processing 34–5
mechanical 33–4
hazard analysis critical control point (HACCP) system 12–13, 18, 250
heat exchanges *see* thermal balance
heat transfer 172–5
coefficient 172, 173–4
heaters
floor 222, 223, 223–4
threshold 223, 223–4, 225
high density polyethylene (HDPE) 202
high fructose corn syrup (HFCS) 152
high quality life (HQL) 126
high–temperature short–time (HTST) process 153
homogenisation 152–4
hybrid F1 30
hydrocarbons (HCs) 165, 166
hydrochlorofluorocarbons (HCFCs) 164–6, 230
hydrofluorocarbons (HFCs) 164, 165
hydrocolloids 121, 128, 132
hydrocooling 35
hydrolytic enzymes 124–5
hygiene 15–16, 18

ice cream 149–57, 245
distribution and packaging 155–7
effects of ingredients 150–2
processing 152–5
ice formation *see* crysallisation; nucleation
ice-liquid interphase 116–18
ice lollies 189
identification file for cultivars 49, 52
immediate freezing 266
immersion blanching 59–60
immersion chilling and freezing (ICF) 69–75, 76–7
immersion freezers 183–4
indirect refrigerating systems 252–3
initial freezing point 113–14
installation of display equipment 245–8
Instron Universal Testing Machine 46, 47
insulation
floor of cold store 222, 223
properties of packaging materials 199
intelligent packaging 208–9
Internet 276

intracellular ice 117–18
invert sugars 151
IQF products 183

Jackstone Food Systems
  plate freezers 181, 183
  spiral freezers 181, 182

lag phase 5–6, 23
laminates 203
large carbohydrate molecules 65–9, 272–3
laser scanners 230–1
legislation/regulation
  display cabinets 254–7
  packaging 200–1, 209–10
life cycle assessment (LCA) 50–1
light 198
light and dark meat 86
lighting 226
Linde-Hampson process 171
lipid oxidation 102, 122–3, 140, 205
lipolytic enzymes 125
lipoproteins 269
lipoxygenase 123, 125
liquefaction of gases 170–1
liquid carbon dioxide 170
liquid nitrogen 168, 169–70, 183
live animals 83–6
load limit line 248
local characteristic freezing time 115, 117–18
lot acceptance sampling 19–20
low density polyethylene (LDPE) 202

maintenance
  display cabinets 250–1
  mechanical refrigeration systems 166
maltodextrin 273
marinating meat 141
markets 264–5
mass transfer rates 70–3
maximum residue levels (MRLs) 43
meat and poultry 3, 81–94, 124
  influence of the live animal 83–6
  micro-organisms 81–2, 90
  new trends 89–90
  packaging 200
  pre- and post-slaughter handling 86–9
  processing ready meals 141
  quality 126
mechanical harvesting 33–4
mechanical refrigeration 160, 161–8, 191
  absorption refrigeration 166–7
  CCAR 167–8
  CoP and efficiency 162–4
  equipment and maintenance 166
  refrigerants 164–6
  vapour-compression cycle 161–2
metal packaging materials 203–4
micro-organisms 129–30
  categories of 10–11
  growth curve 5–6
  inactivation 6–10
  meat and poultry 81–2, 90
  microbiological analysis 16–17
    sampling for 17–20
  packaging and 209–10
  quality of thawed foods 23–4
  response to freezing 5–12
  see also safety, food
microwave susceptor boards 204
milk fats 150
milk solids not-fat (MSNF) 150
Minolta Chroma Meter 47–8
mixing 143
mobile racking systems 216, 218
modified atmosphere packaging (MAP) 207
moisture migration 58, 119–20
  packaging materials and 141, 197–8
monitoring
  cold store 225–6
  display cabinets 249–50, 257
morphology 44–5
myofibrils 98, 99, 100–1, 103
myosin 99, 101, 124

new stores 221
night covers 249
nitrogen, liquid 168, 169–70, 183
nucleation 112–18
  controlling 266–9
nutrition 1, 128–9
  fruit and vegetables 40–3, 265–6
  future trends 265–6
  ready meals 138–9

open air cycle system 254
open-top display cabinets 235, 236, 243, 245
open vertical display cabinets 235, 237, 243–4, 245, 251–2
osmotic dehydration (osmo-dehydrofreezing) 61, 62–9, 76
osmotic solution 65–7, 68
ovenable trays 143, 204

oxygen permeability 198

packaging 4, 195–211
  essential requirements 196–200
  future developments 207–10
  ice cream 155–7
  legislation/regulation 200–1, 209–10
  machinery 206–7
    compatibility of packaging materials with 199
  maximising product quality 210
  ready meals 143
  suitability of material for product 204–6
  types of material 202–5
pallet converter 216, 217
pallet stacking systems 214–20, 226
paper packaging materials 204
part-baked breads 146
partial dehydration 60–75, 76
  air drying 61–2, 63
  osmotic dehydration 61, 62–9
pasteurisation 152–4
peas 33, 34, 38
pectins 38, 39
pelagic (oily) fish 96
penetrometer 45
performance tests 254–6
peroxidase 42
pesticides 42–3
pH, post-mortem 103
photographic file 48–9
physical changes 58, 111–22
  drip loss 82–3, 83–4, 91, 122, 205
  freeze-cracking 118–19
  ice formation 112–18
    controlling crystal growth 269–73
    controlling nucleation 266–9
  moisture migration 58, 119–20, 141, 197–8
  packaging and 204–6
  recrystallisation of ice 120–1, 155–7, 271–2
  see also glass transition
Planck's equation 174
planning, agronomic 30–1
plastic packaging materials 202–4
plate freezers 181, 183
polyamide (PA) 203
polyester terephthalate (PET) 202
polyethylene (PE) 202
polypropylene (PP) 203
polystyrene (PS) 202
polyvinyl chloride (PVC) 203
positioning display cabinets 247–8
post-mortem pH 103
post pallet storage 216, 217
potatoes 39–40
poultry *see* meat and poultry
practical storage life (PSL) 126, 214, 215
pre-chilling 103–4
predictive modelling 274–5
preparation
  hygiene during 15–16
  thawing and 24
pre-refrigeration methods 35
presentation 196–7, 199–200
preservation 196–7
pressure cooling 35
pressure release nucleation 267
processed foods 3, 137–58
  bakery products 143–9
  ice cream 149–57, 245
  ready meals 137–43, 275
processing
  interval between harvesting and 34–5
  and safety 14
product lives 138
production line sampling 18–19
protection 196–7
proteins
  anti-freeze 269–72
  denaturation of 123–4, 206

quality 126–30, 214
  fish 103–6
  freezer selection and 191–2
  fruit and vegetables 27–9
    measuring 43–9
  maximising in the freezing process 132–3
  micro-organisms and 23–4, 129–30
  nutrition *see* nutrition
  parameters for ready meals 138–41
  sensory *see* sensory quality

R22 164–6, 241
R404A 241
R410 241
R507 241
racking systems 216–20
radiant shielding 244
rain 32
rancidity 102, 123
Raoult effect 269, 271
raw materials 13–14

ready meals 137–43, 275
mixing and packaging 143
processing 141–2
quality parameters 138–41
records
cold store 225–6, 228
cultivars 48–9, 52
recovery 16–17
recrystallisation of ice 120–1, 271–2
ice cream and 155–7
refractometric index (ºBx) 48, 51
refractometers 48, 49, 50
refrigerants 164–6
consumption 178–9
environment and 230, 239–41
secondary 252–3
refrigerating equipment 239–41, 252–4
refrigeration systems 159, 160–71
cryogenics 168–71
mechanical refrigeration 161–8
regulation *see* legislation/regulation
relatively resistant micro-organisms 11
remote refrigeration systems 239
resistant micro-organisms 10–11
resuscitation 16–17
retail display equipment *see* display cabinets
rigor mortis 104
rotary tunnel freezers 185–7

safety, food 1, 2, 5–26
effects of temperature abuse 20
microbiological analysis 16–17
new developments in research 24–5
packaging and 209–10
response of micro-organisms to freezing 5–12
risks in the supply chain 12–16
sampling 17–20
thawing 21–4, 25
safety, physical (in cold stores) 227–8
salmonella 82
salt intake 139
sampling 17–20
sandwich wall panels 241
sauces 142
scraped surface heat exchanger 154–5
screed 222, 223
secondary refrigerants 252–3
sensitive micro-organisms 11
sensory quality
fruit and vegetables 37–9, 43–4
impact of freezing 126–8
ready meals 139–41
see also colour; flavour; texture
shelf-life *see* storage life
shopping, future trends in 276
shrink and stretch film wrapping 207
size reduction 37
slaughter, handling during 86–9
slip layer 222, 223
smart packaging 208–9
soil 31
solid carbon dioxide 170
solute impregnation 70–5
sorbitol 67, 69
spatial management 230–1
specialist freezers 189
species 83–4
spinach 36
spiral freezers 179–81, 182
stabilisers 150–1
stability of frozen foods 3, 111–35
chemical changes *see* chemical changes
impact of freezing on quality 126–30
maximising quality in the freezing process 132–3
new trends in research 130–2
physical changes *see* physical changes
staling 144–5
stand-alone refrigeration equipment 239
starch 121, 127–8, 131–2
static racking system 216–20
stationary tunnel freezers 187–9
steam blanching 59
steel 204
storage, frozen 15, 213–14
bakery products 146
changes in fish 100–2
chemical changes *see* chemical changes
inactivation of micro-organisms 8–10
physical changes *see* physical changes
see also cold store
storage life 126, 214, 215
fish 105–6
meat 83, 84, 88, 89
strawberries 28–9, 36, 37, 38, 39, 40–2, 61, 62
sub base 222
sucrose 65–7, 151, 273
sugar content 40–2
sunlight 32
super-chilling 104–5

supercooling 112, 113
  constitutional 116–17
supply chain
  fish 96–7
  main risks in 12–16
surface heating methods 21–2
surimi 105, 273
susceptor boards 204
sweeteners 151–2
syneresis (drip loss) 82–3, 83–4, 91, 122, 205

taste *see* flavour
technology
  factors in cultivar selection 33–7
  freezer technology *see* freezers
teleost fish 95–6
temperature
  abuse and micro–organisms 20
  difference in a freezer 173
  display cabinets 248, 249–50, 257
  temperature tests/classes 255
  fluctuations and fish 106
  growing temperature and cultivar selection 33
  monitoring cold store 225–6
  stability and packaging 197
  TTIs 208–9, 274–5
temperature control packaging 209
temperature indicators (TIs) 208–9
tempering 21
tenderness of meat 86–8
testing, performance 254–6
texture
  changes in fish 100–1
  fruit and vegetables 38–9, 45–6
  impact of freezing 126–8
  packaging and 205
  ready meals 140–1
thawed products 22–4
thawing 122
  bread and freeze–thaw cycles 145–6
  and safety 21–4, 25
  survival of micro–organisms 8, 9
thermal balance 242–3
  reducing heat gains 244
thermal hysteresis 271, 272
three-class sampling plans 19–20
threshold heaters 223, 223–4, 225
time–temperature indicators/integrators (TTIs) 208–9, 274–5
time–temperature–tolerance (TTT) experiments 126
Torry tunnel 176
total viable count (TVC) 17
trays, ovenable 143, 204
trucks, fork 228–9
tumbling freezers 185–7
tunnel freezers
  cryogenic 176–9
  rotary 185–7
  stationary 187–9
turgescence 58
turkey 85, 183–4
two-class sampling plans 19

ultrasonic control of nucleation 268

vacuum cooling 35
vacuum packaging 207
vanilla 152
vapour barrier 222, 223, 224–5
vapour-compression cycle 161–2
variety crossing 30
variety selection *see* cultivar selection
vegetables *see* fruit and vegetables

vertical display cabinets 235–9, 243–4, 245, 251–2
vitamins 129, 138–9

walls, cold store 224, 225
water activity 60–1, 64–5, 66
water permeability 198
water thawing 22
wear floor 222, 223
wind 32

xanthan gum 121, 128, 132

yeast 147–8, 149