SECTION 1

Introduction to shelf life of foods – frequently asked questions

1.1 What is shelf life?

Shelf life has been a frequently used term that can be understood and interpreted differently. A consumer is generally concerned with the length of time a food product can be kept in the home before it can no longer be used. A retailer is particularly interested in the length of time a product can stay on its shelf in order to maximise sales potential. Shelf life is now a legal term within the European Union (EU). Regulation (EC) No. 852/2004 of the European Parliament and of the Council on the hygiene of foodstuffs (EC, 2004a), enforced in England by the Food Safety and Hygiene (England) Regulations 2013 (TSO, 2013), requires food business operators to adopt as appropriate a number of specific hygiene measures (Article 4(3)) including 'compliance with microbiological criteria' as laid down in Commission Regulation (EC) No. 2073/2005 as amended on microbiological criteria for foodstuffs (EC, 2005). This latter regulation defines 'shelf life' (or 'shelf-life' (Article 2(f))) as 'either the period corresponding to the period preceding the "use by" or the minimum durability date, as defined respectively in Articles 9 and 10 of Directive 2000/13/EC', which itself has been repealed by Regulation (EU) No. 1169/2011 on the provision of food information to consumers (EC, 2011a), implemented in the United Kingdom as the Food Information Regulations 2014 (TSO, 2014). A much more helpful and informative definition of shelf life of food has been available for some time (IFST, 1993): It is the period of time under defined conditions of storage, after manufacture or packing, for which a food product will remain safe and be fit for use. In other words, during this period, it should retain its desired sensory, chemical, physical, functional or microbiological characteristics and, where appropriate, comply with any label declaration of nutrition information when stored according to the recommended conditions. It is obvious therefore

Shelf Life, Second Edition. C. M. Dominic Man.

that shelf life is a very important and multifaceted requirement of all manufactured and processed food products. Every food product has in principle, and should be recognised as having, a microbiological shelf life, a chemical shelf life, a functional shelf life and an organoleptic shelf life because all foods deteriorate, often in different ways and at different rates. Ultimately, the shelf life of a food product is intended to reflect the overall effect of these different aspects, ideally under a set of specified storage conditions. Because of this, the study of shelf life of food can often only rightfully be dealt with by the employment of multidisciplinary resources.

1.2 Why are food safety and shelf life related?

Within the EU, of which the United Kingdom is a member, the safety of food is both a fundamental and a legal requirement. Article 14 (Food safety requirements) of the European Regulation (EC) No. 178/2002 (EC, 2002), laying down the general principles and requirements of food law, clearly states the following:

1 Food shall not be placed on the market if it is unsafe.

2 Food shall be deemed to be unsafe if it is considered to be

(a) Injurious to health

(b) Unfit for human consumption

It follows that all food products offered for sale must be safe although they do not necessarily have to be of the highest quality. In the United Kingdom, the Food Safety Act 1990 (as amended) (FSA, 2009) prohibits the sale of food that

- Has been rendered injurious to health
- Is unfit
- Is so contaminated it would be unreasonable to expect it to be eaten
- Is not of the nature or substance or quality demanded
- Is falsely or misleadingly labelled

Table 1.1 gives examples of past food product withdrawals and recalls in the United Kingdom between 2010 and 2014 available on the UK Food Standards Agency (FSA) website. The list should give some insight into the kinds of hazards that can cause food to be unsafe and/or unacceptable to the public; recall and/or withdrawal of the affected food is a legal requirement within the EU (Article 19 of Regulation (EC) No. 178/2002). In effect, a food product, the safety of which has been called into question, be it of microbial, chemical or physical nature has no useful shelf life; its declared shelf life has become meaningless and irrelevant. Food safety and product shelf life are therefore inextricably linked; there can be no quality without food safety. Without exception, the question 'Is this product safe to eat?' must be a first question to be asked in every shelf life study for the simple fact that food safety is a legal requirement. Also, as every product or product concept has to be taste tested at some stage, it is only right and proper for ethical reasons to resolve this question about food safety at the earliest opportunity. Furthermore, the controlling factors for safety and spoilage, particularly those

Table 1.1 Examples of food and drink product withdrawals and recalls in the United Kingdom between 2010 and 2014[a]

Year	Product	Published reason for the recall
2014	Spring still natural mineral water	Contamination with small black particles
	Supermarket own-brand pitted black olives	Contamination with small pieces of glass
	Fresh sandwiches, baguettes and wraps	Production not complying with food hygiene requirements
	Smoked salmon 70-g packs	High levels of *Listeria monocytogenes*
	Bread and butter pudding	Under-processing and food spoilage
	Vacuum-packed organic tofu	Potential risk of botulism
	Organic sultanas	Presence of *Salmonella*
	Unpasteurised cheese	High levels of *Listeria monocytogenes*
2013	Supermarket own-brand curried chicken snack pack with a 'use by' date	*Listeria monocytogenes* was detected in the product
	Coleslaw	Presence of *Listeria monocytogenes*
	Milk and cream products	Possible cross-contamination of milk and insufficient heat processing
	Peach and apricot yoghurt drink	Possible yeast fermentation
	Deli pork and egg slices	A labelling error giving the product an extra 4 months of 'use by' date
	Supermarket own-brand corned beef	Very low levels of the veterinary medicine phenylbutazone ('bute') found in some batches
	Multi-bag crisps	Possible contamination with small pieces of plastic
	Supermarket own-brand frozen beef lasagne and frozen spaghetti bolognese	Some samples found to contain between 30 and 100% horse meat
2012	Salted peanuts	One batch found to contain aflatoxins at levels higher than the regulatory limits
	Smoked prawns	A processing error resulting in inadequate controlling factors to prevent growth of *Clostridium botulinum*
	Mild Cheddar and red Leicester cheeses	Possible presence of small pieces of metal
	Iced rich fruit cake	Signs of mould spoilage in some products
	Peanut butter and peanut-based products	Following a *Salmonella* outbreak in United States
	A jar of olives	Tested positive for *Clostridium botulinum*
	A variety of (24) RTE meat products	Inadequate disinfection of food contact surfaces resulting in potential cross-contamination of the products with pathogenic bacteria
	Various sliced salami chorizo/serrano ham products	High levels of *Listeria monocytogenes* found

Continued

Table 1.1 (*Continued*)

Year	Product	Published reason for the recall
2011	Scottish smoked salmon	*Listeria* detected in a small number of retail samples
	Christmas figures with candy and gumball machine with candy	Products are not labelled with a choking hazard warning for children aged under 3 years
	Smoked Scottish salmon	High levels of *Listeria monocytogenes* found
	Korma sauce	One jar found to be contaminated with *Clostridium botulinum*
	Three Japanese-style snack products	Possible presence of small pieces of glass
	Sports drink lite	Unpleasant smell and taste caused by mould growth
	British extra mature and Welsh extra mature cheeses	Found to contain high levels of histamine
	Seasonal unsalted pistachio nuts in shell	Product found to contain aflatoxins at levels higher than the regulatory limits
2010	Beer bottle packs	May contain glass fragments
	Semolina	Potential contamination as a result of rodent infestation
	Lemon and lime flavour still spring water drink	Unpleasant aroma and possible risk of mould growth
	Crumpets	Contamination with small pieces of aluminium
	Various food supplements	Found to contain folic acid at higher levels than stated on the labels
	Nut luncheon	Due to spoilage and possible microbiological contamination
	Couscous	Contamination with small pieces of metal
	Spring water	Due to the presence of *Escherichia coli*

[a] Taken from Food Standards Agency www.food.gov.uk/

that are related to microbial growth, are often identical; the separate consideration of food safety and shelf life, although convenient in practice, is artificial. Today, the most effective way to ensure the safety of food is to use the internationally recognised hazard analysis critical control point (HACCP) system. Current EU food legislation mandates that, in order to ensure a high level of consumer protection with regard to food safety, food business operators are required to put in place, implement and maintain a permanent food safety management procedure or procedures based on the HACCP principles (EC, 2004a). In England, this legal requirement is contained in the Food Safety and Hygiene (England) Regulations 2013. An in-depth and up-to-date reference on the development, implementation and maintenance of an effective HACCP-based food safety management system as required by EU legislation is available (Mortimore & Wallace, 2013).

In recent years, unsafe food that 'has been rendered injurious to health' or 'is unfit' (for human consumption) has taken on additional but no less serious significance in that 'food defence', that is defending the 'security of food and drink and their supply chains from all forms of malicious attack including ideologically motivated attack leading to contamination or supply failure', has become increasingly important to both the industry and governments alike. In the United Kingdom, advice on defending food and drink against ideologically motivated and other forms of malicious attack is available in the form of a publicly available specification (PAS) – PAS 96:2010 (BSI, 2010), which was first developed by the Centre for the Protection of National Infrastructure in collaboration with the British Standards Institution (BSI) in 2008 and updated in 2010. The intention has been to review this PAS at intervals to reflect the latest practices and developments; the most recent review took place in 2014. Prior to all this, a guidance document on 'Principles for preventing and responding to food incidents' was produced by UK FSA's Taskforce on Incidents in which an incident is defined as 'any event where, based on the information available, there are concerns about actual or suspected threats to the safety or quality of food that could require intervention to protect consumers' interests' (FSA, 2008). This older FSA document therefore has a much wider scope covering 'natural' hazards (i.e. chemical, microbial, physical and radiological) as well as hazards introduced intentionally, and most likely maliciously. Detailed coverage of food defence against all forms of malicious attack that makes use of the threat assessment critical control point (TACCP) approach is beyond the scope of this book.

1.3 Who should be interested in shelf life of foods?

Since shelf life is such an important requirement, it should be of interest to everyone involved in the entire food chain. There is a growing realisation that a high standard of food safety and quality, the two basic aspects of shelf life, can only be achieved by adopting a comprehensive and integrated approach, covering the whole of the food chain 'from farm to fork'. As will be seen later

(see Section 1.6), there are many factors that can influence the shelf life of food. The use of a cleaner ingredient in an ambient cake filling (e.g. roasted chopped almonds as opposed to chopped raw almonds), which has a lower microbial load, could mean a difference between an acceptable and an unacceptable shelf life for the cake as a whole. Suppliers of raw materials and ingredients and food manufacturers and producers can often overcome potential shelf-life problems by working closely together at the earliest opportunity. At the other end of the food chain, consumers, too, have a significant part to play. For instance, by minimising the exposure of foods to high temperatures such as in car trunk, particularly during summer months (Kim *et al.*, 2013), and by observing carefully any recommended storage and usage instructions, consumers are ensuring that the intended shelf lives of their foods will not be compromised, assuring their safety and maximising the quality to be enjoyed. Results of a survey by the UK FSA of public attitudes towards food issues including date labels on food and hence food shelf life were less than encouraging (GfK, 2009). Only half (49%) of respondents in the Public Attitudes to Food Issues survey correctly identified the 'use by' date as the best measure of safety, and just less than half (47%) said they would never eat cooked meat beyond its use by date – suggesting a large proportion were willing to take risks with the (microbial) safety of their food by eating foods beyond the 'use by' date. A quarter (26%) of respondents said they would never eat breakfast cereal beyond its 'best before' date, even though best before dates are an indication of quality (i.e. freshness) rather than safety. People may therefore be throwing away food unnecessarily, as although it may no longer be at its best, it would still be safe to eat. In recent times, growing concerns about food sustainability and food waste have increased focus on the need for more accurately and precisely determined shelf lives in an effort to minimise food waste (see Section 1.5 for more on 'date marking'). The importance of shelf life to everyone along the food chain is not difficult to see. Much remains to be done to educate consumers in the United Kingdom about the meaning and significance of date labels on food. A more recent online survey conducted in Belgium on consumers' understanding and attitude towards shelf life labels has led the researchers to similar conclusions that 'increased understanding and corresponding consumer behaviour in respecting shelf life dates and labels should lead in due time to reduced food safety risk but also reduced food waste and thus contribute to a more sustainable food supply chain' (Van Boxstael *et al.*, 2014).

1.4 Who is responsible for determining shelf life?

Basically, the responsibility for determining shelf life lies with the manufacturer or the packer; this arises out of operational as well as legal (labelling) reasons (see Section 1.5). While ideas for new products and for improvements to existing products can originate from within a food business and/or from external sources such as a current or potential customer, shelf life evaluation and testing are very

much an integral part of every product development programme. Therefore, it is in keeping with the established principles of good manufacturing practice (GMP) that a food manufacturer should possess its own in-house shelf life testing and evaluation capability (IFST, 2013). Today, almost without exception, major retailers do independently evaluate the shelf lives of food products, particularly their own-labelled ones. This, however, should neither negate nor reduce the responsibility of a food manufacturer or processor whose duty it is to assign correct shelf lives to their products as a result of evaluation work based on sound and up-to-date food science and technology carried out during product development. Indeed, such responsibility is a fundamental requirement of modern days' quality management system (QMS) standards like the ISO 9001:2008 (BSI, 2009) and the British Retail Consortium (BRC) Global Standard for Food Safety (Issue 6, 2011) (BRC, 2011). Furthermore and specifically, in order to comply with applicable and relevant food safety criteria stipulated in Regulation (EC) No. 2073/2005 on microbiological criteria for foodstuffs, it may be necessary for the food manufacturers to conduct shelf life studies in accordance with Annex II of the regulation in order to investigate compliance with the criteria throughout product shelf life. For instance, this applies to ready-to-eat (RTE) foods that are able to support the growth of *Listeria monocytogenes*, and which may pose a *Listeria monocytogenes* risk for public health (EC, 2005). And, guidance for food business operators on how to determine the microbial shelf life of RTE food in relation to *Listeria monocytogenes* is available (Chilled Food Association Ltd., 2010).

1.5 Is it illegal to give a wrong shelf life to a food product?

Within the EU, shelf lives of food products are communicated to consumers through the use of the date of minimum durability or the 'use by' date, the mandatory use of which goes back to Council Directive 79/112/EEC of 18 December 1978 on the approximation of the laws of the Member States relating to the labelling, presentation and advertising of foodstuffs for sale to the ultimate consumer (EEC, 1978). The 'use by' date is legally required in the case of foods, which, from a microbiological point of view, are highly perishable *and* are therefore likely after a short period to constitute an immediate danger to human health; after the 'use by' date a food shall be deemed to be unsafe in accordance with Article 14(2) to (5) of Regulation (EC) No. 178/2002 (EC, 2011a). For all other foods, the date of minimum durability (defined as the date until which the foodstuff retains its specific properties when properly stored) preceded by either 'Best before…' (when the date includes an indication of the day) or 'Best before end…' (in other cases) is required (EC, 2011a). Additionally, the 'use by' date (in particular) and the 'best before' date must be followed by any necessary mandatory information that covers storage and safe use, such as 'keep refrigerated at 0 to +5°C'. For food safety reasons therefore, it is potentially illegal to place on the market foods with a

wrong 'use by' date whose microbiological shelf lives have been inaccurately determined, and it is illegal to display and sell foods beyond their 'use by' dates. A UK supermarket was fined substantially some years ago for merchandising/selling out-of-date (i.e. beyond the 'use by' date) products, so the penalty for any errors in this matter are not insignificant. While it is the responsibility of food manufacturers and processors to decide whether a 'use by' or 'best before' date is the appropriate indication for their products, guidance is available on what foods should carry a 'use by' date. Foods that require a 'use by' date are likely to fall into the following categories (Crawford, 1998):

- Dairy products, for example dairy-based desserts
- Cooked products, for example RTE meat dishes and sandwiches
- Smoked or cured RTE meat or fish, for example hams and smoked salmon fillets
- Prepared RTE foods, for example vegetable salads such as coleslaw
- Uncooked or partly cooked pastry and dough products, for example pizzas and sausage rolls
- Uncooked products, for example uncooked products comprising or containing meat, poultry or fish
- Vacuum or modified atmosphere packs, for example raw ready-to-cook turkey breast packed in modified atmosphere

The situation is different for foods that carry a 'best before' date. Since food deteriorates continually rather than suddenly, the 'best before' date does not automatically mean the food is not fit for consumption or loses all its acceptability immediately after that date. The 'best before' is used to give an indication of quality deterioration only, not a loss of microbial food safety. Thus some foods, even though they may be microbiologically perishable but do not constitute an immediate danger to human health on spoilage, such as sliced bread, are given a 'best before' rather than 'use by' date. In an attempt to assist food businesses to comply with the 'appropriate durability indication' requirement, the FSA first published voluntary notes in 2003, which gave guidance to the businesses on when to give a 'use by' date on food labels. The document included factors that should be considered when deciding to apply a 'use by' date as well as examples of the types of food that could carry a 'use by' date. A revised and updated document entitled 'Guidance on the application of date labels to food' was produced by the FSA in conjunction with the Department of Food, Environment and Rural Affairs (DEFRA) in 2011 (DEFRA, 2011), which gives advice on both 'use by' and 'best before' dates. Crucially, 'sell by' and 'display until' dates, which are *not* required by law, but whose use in the main by retailers has proliferated in the intervening years, are asked to be removed to avoid confusion by shoppers.

Once a date mark (either 'use by' or 'best before') is set and declared, it becomes a contract between the food company and its customers to the effect that, provided the food is stored according to the recommended conditions, it should last at least as long as its stated shelf life. In order to be confident of its statement, the company must have done the necessary experimental work to

determine the correct shelf life; the marking of a product with either a 'use by' or 'best before' date does imply that this is so. It follows that giving a wrong date mark (i.e. shelf life) to a food product, in particular a 'use by' date that is related to microbial safety, will cause the company to initiate product recalls/withdrawals and/or make it liable to enforcement actions. Retailers have different responsibilities depending on whether or not the products are branded or own-labelled ones. And as mentioned earlier, failures to observe the 'use by' date in a retail environment has, in the past, proved to be just as damaging to the business concerned.

Regulation (EU) No. 1169/2011 (EC, 2011a), applicable throughout the EU and implemented in the United Kingdom as the Food Information Regulations 2014, has been described as the most important piece of legislation on food information particularly food labelling in the EU for 30 years. The Regulation came into force on 13 December 2011, with most of its provisions applying from 13 December 2014. The wide-ranging nature of this Regulation is underlined by the fact that it:

amends

- Regulation (EC) No 1924/2006 on nutrition and health claims made on foods,
- Regulation (EC) No 1925/2006 on the addition of vitamins and minerals and of certain other substances to foods,

and repeals

- Commission Directive 87/250/EEC on the indication of alcoholic strength by volumes in the labelling of alcoholic beverages for sale to the ultimate consumer,
- Council Directive 90/496/EEC on nutrition labelling for foodstuffs,
- Commission Directive 1999/10/EC providing for derogations from the provisions of Article 7 of Council Directive 79/112/EEC as regards the labelling of foodstuffs,
- Commission Directive 2000/13/EC on the approximation of the laws of the Member States relating to the labelling, presentation and advertising of foodstuffs,
- Commission Directive 2002/67/EC on the labelling of foodstuffs containing quinine, and of foodstuffs containing caffeine,
- Commission Directive 2008/5/EC concerning the compulsory indication on the labelling of certain foodstuffs of particulars other than those provided for in Directive 2000/13/EC and
- Commission Regulation (EC) No. 608/2004 concerning the labelling of foods and food ingredients with added phytosterols, phytosterol esters, phytostanols and/or phytostanol esters.

Table 1.2 lists the provisions of the regulation, which are pertinent to shelf life of foods. As has been the case for some time, the words 'packaged in a protective atmosphere' should appear on the labels of 'foods whose durability has been extended by means of packaging gases authorised pursuant to Regulation (EC) No. 1333/2008' (Annex III, Regulation (EC) No. 1169/2011 (EC, 2011a)).

Table 1.2 Provisions of Regulation (EC) No. 1169/2011, which are pertinent to shelf life of foods

Chapter	Section	Article	Provision
IV Mandatory Food Information	1	9	1. (c) any ingredient or processing aid listed in Annex II[a] or derived from a substance or product listed in Annex II causing allergies or intolerances used in the manufacture or preparation of a food and still present in the finished product, even if in an altered form; (f) the date of minimum durability or the 'use by' date; (g) any special storage conditions and/or conditions of use; (j) instructions for use where it would be difficult to make appropriate use of the food in the absence of such instructions; (l) a nutrition declaration
	2	21	Labelling of certain substances or products causing allergies or intolerances
		24	Minimum durability date, 'use by' date and date of freezing (see also Annex X)
		25	Storage conditions or conditions of use
		27	Instructions for use
	3	30	2. (f) any of the vitamins listed in point 1 of Part A of Annex XIII, and present in significant amounts as defined in point 2 of Part A of Annex XIII.

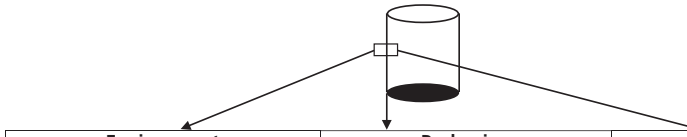
[a] The 14 substances or products causing allergies or intolerances listed in the Regulation are cereals containing gluten, crustaceans, eggs, fish, peanuts, soybeans, milk, nuts (e.g. almonds), celery, mustard, sesame seeds, sulphur dioxide at levels above 10 mg kg^{-1} or 10 mg l^{-1}, lupin and molluscs. From 13 December 2014, food businesses, including delis and restaurants, are required to provide information on the presence of these allergens if used as deliberate ingredients in foods that are not pre-packed

A useful guide to the regulations on 'Food Labelling in the UK', including the minimum durability indication requirement, prepared by Dr David Jukes of the University of Reading, UK, is available at http://www.foodlaw.rdg.ac.uk/label/index.htm.

1.6 How long a shelf life should my product have?

How long is a piece of string? There is really no straightforward answer.

All foods spoil and they do so differently and at different rates; even for the few exceptions such as some wines and cheeses, the acceptability of which improves on storage (i.e. maturation/ripening), their quality invariably deteriorates once their optimal acceptability has been reached. Despite the enormous range and variety of food products available worldwide, much knowledge about food deterioration has been accumulated and published. Although one must



Environment	Packaging	Food
Moisture or water vapour transfer Other physical transfer Oxygen-induced changes Light-induced changes Temperature/humidity-effected changes Pest infestation	Product–packaging interactions Packaging migration Scalping Packaging failure (random or maliciously caused)	Physical changes Microbiological changes Chemical/biochemical changes Physico-chemical changes

Fig 1.1 A basic model for food deterioration and spoilage. Adapted from Ellis & Man (2000).

guard against generalisation, most food spoilage can be explained by one or more of the following general mechanisms (IFST, 1993):

- Moisture and/or water vapour transfer leading to gain or loss
- Physical transfer of substances other than moisture and/or water vapour, for example oxygen, odours or flavours
- Light-induced changes, that is changes caused and/or initiated by exposure to daylight as well as artificial light
- Chemical and/or biochemical changes
- Microbiological changes
- Other mechanisms or changes that cause the food to deteriorate through one or more of the aforementioned mechanisms, for example damage to the pack caused by insect infestation or loss of seal integrity

Furthermore, temperature, the single most important environmental factor, influences all these mechanisms, so the effects of temperature on the relevant mechanism(s) must be evaluated in all shelf life studies. Figure 1.1 provides a model that includes the major changes that can bring about deterioration and spoilage in food and drink.

Knowing the spoilage mechanism of a food product, therefore, is the first step in the process of determining its shelf life. Essentially, how a food spoils and hence how long its shelf life is going to be are influenced by a number of factors. These shelf life–influencing factors are the properties of the final product and of the environment in which it is to be manufactured, stored, distributed and used. These factors can be divided into the following groups:

1 Intrinsic factors (see Section 2.2.1)
- Raw materials
- Product composition and formulation
- Product structure
- Product make-up
- Water activity value (a_w)

- pH value and acidity (total acidity and the type of acid)
- Availability of oxygen and redox potential (E_h)

2 Extrinsic factors (see Section 2.2.2):
- Processing and preservation
- Hygiene
- Packaging materials and system
- Storage, distribution and retail display (in particular with respect to exposure to light, fluctuating temperature and humidity and elevated or depressed temperature and humidity)

3 Other factors
- Consumer handling and use (see Section 2.2.4)
- Commercial considerations (see Section 2.2.5)

Additionally, interactions between intrinsic and extrinsic factors are possible. For example, the interaction of factors such as water activity, pH, salt, nitrite, and storage temperature in controlling the growth of *Clostridia* in cured meat is well known (Roberts & Gibson, 1986). Because levels of established preservatives (e.g. salt, nitrite, sugars and sorbic acid) have been reduced in many traditional products in response to consumer/market demands, to the extent that no single factor is responsible for the microbiological stability and safety of the product, it has become more and more important to understand the effects of factors acting in combination.

Further information about food deterioration and spoilage mechanisms and factors affecting shelf life is given in Section 2.

1.7 What is accelerated shelf life testing?

Accelerated shelf life testing (ASLT) is used to shorten the time required to estimate a shelf life which otherwise can take an unrealistically long time to determine. As a result of globalisation of food trade as well as intensification of national and international competition in the food market, the need for more rapid determination of shelf life has generally become greater. The situation is much more pressing when the shelf life of a product is expected to be long, ranging from a couple of months to a few years. The effect of elevating temperature on many chemical reactions as well as adverse changes in food during storage is well known. The most common form of ASLT therefore relies on storing food at an elevated temperature. The assumption is that by storing food (or drink) at a higher temperature, any adverse effect on its storage behaviour and hence shelf life may become apparent sooner. The shelf life under normal storage conditions can then be estimated by extrapolation using the data obtained from the accelerated testing.

The following are some examples of well-established accelerated storage tests:
- Incubation of canned foods for 4 or 5 days at 55°C (for the examination of thermophilic bacteria)

- Incubation of low- and medium-acid canned foods for a minimum of 1 week at 37°C (for the estimation of tin pickup)
- Storage of ambient cake and pastry products at 27°C (and 75% relative humidity) (for the estimation of mould-free shelf life (MFSL))
- 'forcing' beer at 27°C (for the examination of general spoilage)
- Storage of chocolate and chocolate-coated products at 28°C (and 70% relative humidity) (for the study of bloom development)
- Accelerated storage tests such as the Schaal oven test (at 60–70°C) for the determination of edible oil stability
- Accelerated tests at elevated pressure and temperature carried out using an instrument such as the OXIPRES™ (Mikrolab Aarhus A/S, Denmark) for the determination of oil stability in heterogeneous products like potato crisps, margarine and biscuits, without having to extract the oil and fat from them before analysis; the OXIDOGRAPH™, manufactured by the same company, which employs the principle of the Sylvester test originally developed by J. Lyons & Co., London, is an instrument designed to test, in an accelerated manner, the reactivity of oils and fats towards oxygen.

Accelerated tests are particularly useful when the patterns of changes are practically identical, that is the deterioration follows the same kinetics under both normal and accelerated storage so that shelf life under normal storage can be predicted with a high degree of certainty. For instance, it has been found that changes in quality of orange juice, made from frozen concentrate and packed in TetraBrik™, after 6 months at 20°C corresponded to the changes after 13 days at 40°C and after 5 days at 50°C (Petersen *et al*., 1998).

Accelerated storage tests do have limitations. Essentially, they tend to be product-specific; their results have to be interpreted carefully based on detailed knowledge and sound scientific principles. Other limitations include the following (IFST, 1993; Mizrahi, 2011):

- As temperature rises (or drops), a change of physical state may occur (e.g. melting of solid fats (water turns to ice)), which in turn can affect the rates of certain reactions; an example of such Arrhenius deviations has been observed for hexanal formation in sunflower oil (Calligaris *et al*., 2004).
- Although temperature is often a dominant factor and hence used as an accelerating factor, storage at a constant elevated temperature with a lower-than-normal relative humidity can lead to unexpected results. For example, mould growth on ambient cakes or bread may be delayed or even prevented if they are being stored at 37°C and at a relative humidity of 70% or less.
- During freezing, reactants are concentrated (i.e. freeze-concentration) in the unfrozen part of the food (e.g. frozen meat) resulting in a higher rate of the reaction such as lipid oxidation even at a reduced temperature.
- A change in the way a food spoils at elevated temperatures will give false and/or unexpected results. For instance, it is generally known that quality deterioration of frozen foods containing tomato is due to carotenoid oxidation, which

causes the product to turn from red to yellow; the effect is described as pigment bleaching. The latter, however, has been shown to be masked by the concomitant development of coloured end products of other reactions, notably non-enzymic browning, that become prevalent at temperatures above −7°C (Manzocco *et al*., 2010).

- Accelerated tests are of limited use for short shelf life chilled foods due to changes in spoilage associations at different temperatures, that is different storage temperatures select different spoilage microflora; besides, for short shelf life products, the need for accelerated tests is greatly reduced.
- The Arrhenius model that the temperature-dependent deterioration rate can be expressed by a single constant (see Appendix A) on which many accelerated tests are popularly based is only appropriate for simple chemical systems and often fails for foods that are, in reality, more complex.

The most important point is that all results must be validated to confirm the relationship between changes under ASLT and those under normal storage. To be of practical use, the validated relationship should hold true at least for the product in question if not for the same product type, for instance all tomato-based products packed in unlacquered cans (Ellis & Man, 2000).

The long-held assumptions that generally for ASLTs to be useful, either the deterioration mechanism or spoilage kinetics is known (or can be determined from experimental data) and that the corresponding rate constant's temperature dependence obeys the Arrhenius equation have been challenged. An alternative empirical approach to shelf life estimation from accelerated storage data without any preconceived kinetic model was proposed by Corradini & Peleg (2007). This concept was demonstrated with the prediction of the degradation of vitamin C in frozen spinach using original data from Giannakourou & Taoukis (2003) and with the predictions of the growth of *Pseudomonas fluorescens* and of that of *Candida sake* in an RTE meal using original data from Tyrer *et al*. (2004). The researchers went further to demonstrate that this new approach can probably be applied to accelerated studies by changing an inhibiting microbial factor such as salt concentration and simulation of deterioration processes under non-isothermal conditions.

The use of temperature as an accelerating factor has undoubtedly been popular and attracted much research. In situations where the deterioration processes in food show little or no temperature dependence (e.g. light-induced changes), performing ASLT is either useless or of little value. Indeed, other factors such as pressure, relative humidity, light intensity and oxygen tension are known to influence the kinetics of many quality deterioration processes. In principle, these factors can be used other than temperature as accelerating factors in ASLT. However, the absence of suitable predictive mathematical models and the practical difficulty of exploiting variables such as pressure and relative humidity appear to have prevented them from being used as accelerating factors in ASLT (Calligaris *et al*., 2012).

1.8 What are the resources required for determining shelf life?

A commercially successful food product, among other attributes, is expected to have an acceptable and reproducible shelf life. In a sense, the achievement of such a shelf life epitomises the commitment to food safety and consistent quality of the company in question. Safety and quality do not happen by chance and have to be designed into a product. The shelf life determination of foods therefore demands significant resources, made available by management understanding and commitment. The basic resources needed are listed as follows:

1. People who possess the relevant knowledge (e.g. up-to-date knowledge in meat science and technology in a meat products company) and experience, and who can plan, carry out or supervise the evaluation, analyse the data generated and information obtained and interpret the results.
2. Adequate tools and facilities include (see also Section 1.14) the following:
   - Food product samples preparation facility
   - Storage facility pertinent to the type of product being studied, for example refrigerated cabinets for chilled foods
   - Microbiological examination facility
   - Chemical analysis facility
   - Sensory evaluation facility
3. An appropriate management system that ensures every shelf life study is conducted in a systematic and timely manner according to documented procedures, which facilitates the flow of information and communication among all those involved in it.

Although laboratory facilities for microbiological examination and chemical analysis are not absolutely essential as the required work can be undertaken by an outside accredited laboratory, the responsibility for ensuring that the shelf life is determined accurately and reproduced consistently in production remains with the manufacturer. In the long run, it may be more cost-effective and make commercial sense to have a basic in-house shelf-life determination capability. Sometimes, specialist information and/or non-routine tests such as microbiological challenge testing or packaging migration tests are required. In this case, an external accredited laboratory may have to be used. Without management understanding and commitment, this will not be possible.

The BRC Global Standard for Food Safety, which, over the years, has placed increasing emphasis on senior management commitment to achieving an effective QMS, contains clear and specific requirements concerning the determination of shelf life. Section 5.1.4 of the Standard says (BRC, 2011)

> Shelf-life trials shall be undertaken using documented protocols reflecting conditions experienced during storage and handling. Results shall be recorded and retained and shall confirm compliance with relevant microbiological, chemical and organoleptic

criteria. Where shelf-life trials prior to production are impractical, for instance for some long-life products, a documented science-based justification for the assigned shelf life shall be produced.

1.9 How is the end of shelf life normally decided?

Having established the way(s) by which a food product spoils, the main task of a shelf life study is to find out as accurately as possible, under specified storage conditions, the point in time at which the product has become either unsafe or unacceptable to the target consumers. The period of time from manufacture or processing to this end-point is the maximum shelf life of the product, which has to be determined. Figure 1.2 gives a generic picture of the progression of shelf life to the point when the product becomes unacceptable as a result of microbiological and/or non-microbiological changes that are taking place. In practice, an end-point, that is the end of shelf life, can be fixed with the help of the following:

(i) Relevant food legislation, for example Commission Regulation (EC) 2073/2005 on microbiological criteria for foodstuffs; 'general function' claims under Article 13.1 of Commission Regulation (EC) 1924/2006 on nutrition and health claims made on foods (EC, 2006a)

(ii) Guidelines given by enforcement authorities or agencies in support of their work, for example those given by Public Health England (previously the UK Health Protection Agency incorporating the UK Public Health Laboratory Service (PHLS))

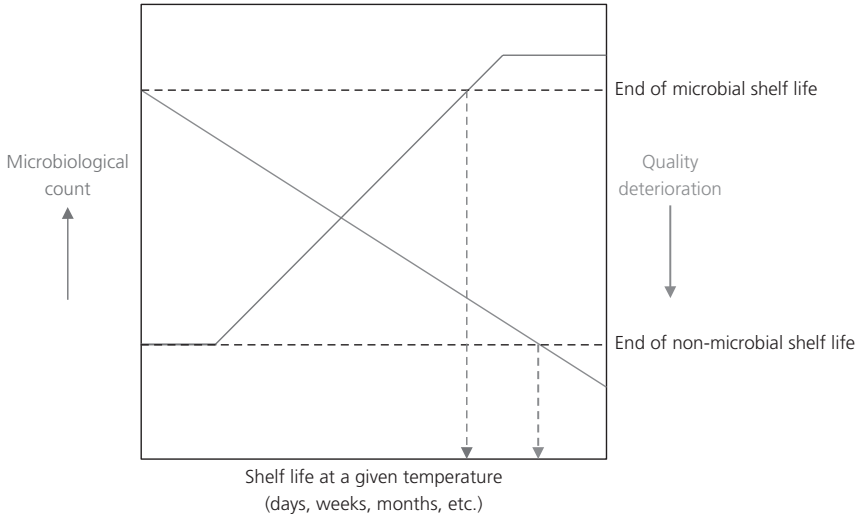


Fig 1.2 Shelf life of food – a schematic representation.

(iii) Guides produced by independent food research associations such as Campden BRI in the United Kingdom (Voysey, 2007) or the UK Institute of Food Science and Technology (IFST) (IFST, 1999)

(iv) Current industrial best practice as published in the primary literature, for example using psychrotrophic lactic acid bacteria to set end of shelf life of chilled foods (Pothakos *et al*., 2012)

(v) Self-imposed end-point, for example declared nutrition information such as level of an added vitamin that continues to degrade during storage (in the EU, nutrition labelling will become mandatory for the majority of pre-packed foods from 13 December 2016)

(vi) Predictive models, for example ComBase

(vii) Market intelligence, for example results from the analysis and/or examination of a competitor's product.

Examples of some of the aforementioned are given in Table 1.3. In many situations where established guidance is not available, manufacturers and processors will have to set their own end-points, using microbiological examination, chemical analysis, physical testing and, of course, properly designed and conducted sensory evaluation to define the end of shelf life. Non-microbiological criteria that are used to set shelf life tend to be relatively more product-specific. In an ideal situation, these criteria are either contained in the original marketing brief or can be developed from it. Crucially, the criteria, be they physical, chemical or sensory, need to be correlated to the quality attributes that are critical to product acceptability/consumer requirements, and hence quality (as opposed to safe) shelf life and, where appropriate, they should be agreed between the manufacturer and its customer. Once product safety has been established, sensory evaluation is the most popular means by which the end of shelf life is determined. It has to be said that often even established standards could change over time so that the most up-to-date ones should be used to set shelf life. For example, the original UK PHLS guidelines for the microbiological quality of RTE foods were first published in 1992 and revised in 1996 before the latest guidelines became available in 2000 (Gilbert *et al*., 2000). Likewise, the industry standard in the United Kingdom for tin (inorganic) in canned foods used to be 250 mg kg^{-1}; the current maximum levels in mg kg^{-1} wet weight are 200, 100 and 50 for canned foods other than beverages; canned beverages (including fruit juices and vegetable juices) and canned baby foods, infant formulae and dietary foods, respectively (EC, 2006b).

1.10 How do we ensure that the shelf lives established for our products are accurate and reproducible?

Shelf lives of food products are rarely established and confirmed without repeated determinations. In general, the greater the number of repeated determinations, the more accurate the results and the more confidence we have about the assigned

Table 1.3 Some guidance that can be used to set shelf life end-point

Source of guidance	Useful guidance for shelf life end-point
Food legislation	*The Coffee Extracts and Chicory Extracts (England) Regulations 2000* (TSO, 2000) These Regulations require a minimum of 95% coffee-based dry matter content (i.e. a maximum of 5% moisture content) for coffee extracts in powder, granular, flake, cube or other solid form. *Commission Regulation (EC) No 2073/2005 on microbiological criteria for foodstuffs (as amended)* (EC, 2005) This Regulation requires *Salmonella* to be absent (in 25 g) for minced meat and meat preparations intended to be eaten raw (Annex I, Chapter 1. Food Safety Criteria, 1.4). *Commission Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs* (EC, 2006b) This Regulation prohibits the sale of 'canned foods other than beverages' where they contain tin (inorganic) exceeding 200 mg kg^{-1} wet weight, the maximum level permitted (Annex, Section 3: Metals). *Commission Regulation (EC) No 432/2012 establishing a list of permitted health claims made on foods, other than those referring to the reduction of disease risk and to children's development and health* (EC, 2006a, 2012) Annex, List of permitted health claims: 'Live cultures in yoghurt or fermented milk improve lactose digestion of the product in individuals who have difficulty digesting lactose'. In order to bear the claim, yoghurt or fermented milk should contain at least 10^8 CFU live starter microorganisms (*Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus*) per gram.
Public Health England	*Guidelines for the microbiological quality of some ready-to-eat foods sampled at the point of sale* (Gilbert *et al.*, 2000)
Institute of Food Science and Technology, UK	*Development and Use of Microbiological Criteria for Foods* (IFST, 1999)
Published literature	For minimally processed (equilibrium modified atmosphere packaged) fresh-cut vegetables such as carrots, celeriac, bell peppers and mixtures of non-leafy vegetables, the microbiological criteria for yeasts (>10^5 CFU g^{-1}) and for lactic acid bacteria (>10^7–10^8 CFU g^{-1}) have been found to correlate well with detectable changes in sensory properties and measureable concentrations of non-volatile compounds. These criteria may therefore be used to set end-point for shelf life of these produce (Jacxsens *et al.*, 2003).

shelf life. At least four types of shelf life determinations can be distinguished, each serving slightly different purposes (IFST, 1993), which are as follows:

- Initial shelf life study: This is normally conducted during the concept product development stage when neither the actual production process nor the product or packaging format has been finalised. Safety of the product has either been

evaluated or is evaluated alongside this study. The latter provides an indication of the probable mechanism by which the product is likely to deteriorate.

- Preliminary shelf life determination: This is the first detailed determination. It is normally carried out during the latter part of the pilot development stage or when successful plant or factory trials have been completed. Information obtained is used to assign a provisional, by no means accurate, shelf life for inclusion in the draft product, process and packaging specifications.
- Confirmatory shelf life determination: This is normally carried out towards the end of the product development process, using product samples made under factory conditions and to a set of provisional specifications. Information and data obtained are intended to validate the provisional shelf life previously established. They will be used to finalise the provisional specifications in preparation for product launch; a fairly accurate shelf life is required for date marking to be finalised. It is envisaged, however, for certain types of products such as long-life ones, confirmatory determination will not be completed until long after product launch. In this case, confidence in the provisional shelf life has to be based on results obtained from indirect means such as validated ASLT or experience derived from estimating shelf lives of established products.
- Routine shelf life determination. This is carried out in support of normal production. It provides useful information on which revision of shelf life can be based. In certain types of products such as fresh fruits and vegetables, because of their variable nature, routine shelf life determination is an integral part of the daily packing operations. Here, shelf life tests are used to forewarn packers and retailers of potential quality problems, to inform management regarding any shelf life adjustment, and to reveal temporal patterns in quality that can be used to trigger a change in the source of supply (Aked, 2000).

As pointed out in Section 1.6, there are many factors that can influence shelf life and so its reproducibility will be affected by many factors. A shelf life determined solely on the strength of samples that have been made by highly skilled personnel using ingredients of exceptional quality is unlikely to be reproduced exactly under factory conditions. The following factors, although not exhaustive, will need to be taken into consideration when interpreting shelf-life data generated from the different shelf life determinations (IFST, 1993):

- Trial (sample) versus bulk ingredients quantities and their range of quality
- The age of materials used for trials and for full production
- Variations in the weighing up of full-scale formulations
- Any scale effects as a result of scaling-up to full productions
- Short and controlled trial runs versus fully scheduled production runs separated only by cleaning periods and/or personnel breaks
- Batch processes versus continuous ones
- Fluctuations of processing conditions and their full implications

- Time factors consequent on handling full-production amounts (e.g. where product is being held longer at an elevated temperature)
- Legitimate (i.e. agreed and specified) use of surplus and/or waste materials, for example dough trimmings

It is always advisable, therefore, to set the final shelf life based on data that relate to the 'worst case' manufacturing and storage scenario resulting in a conservative shelf life with a clear margin of safety. This is also to recognise that because variability exists in quality of raw materials (e.g. microbial load) as well as processing conditions, there will be a distribution of shelf lives rather than an absolute shelf life that terminates abruptly. In any case, the shelf life can be reviewed and if necessary, either extended or reduced in the light of further experience gained after product launch, particularly if a conservative shelf life has been found to result in unacceptable product wastage.

The secret of a reproducible shelf life that is acceptable to both the consumers and the manufacturer lies in the careful and diligent application of GMP principles. The latter, when implemented fully and effectively, nowadays as recognised by certification to one of the voluntary QMS standards such as the BRC Global Standard for Food Safety, will ensure the consistent manufacture of safe food products to a previously specified quality appropriate to their intended use (IFST, 2013).

1.11 Can mathematical/computer models help in shelf life determinations?

In the past 30 years, the widespread use of personal computers with their ever-increasing computing power has encouraged and made possible the development of computer-based (mathematical) models that can be used to predict the safety and shelf life of an expanding range of food products. Because of the unequivocal need to assure microbiological safety in foods, the majority of well-known computer-based models are predictive microbiological models for food-borne pathogens. Predictive food microbiology is a new but established field of study that combines elements of microbiology, mathematics, statistics and information systems and technology to develop models, that is mathematical equations that describe and predict the growth and decline of microbes under prescribed (including varying) environmental conditions (Baird-Parker & Kilsby, 1987; Fu & Labuza, 1993; McMeekin *et al.*, 1993; Whiting, 1995; Amézquita *et al.*, 2011; Kreyenschmidt & Ibald, 2012). Predictive microbiological models have been classified as follows (Whiting & Buchanan, 1993; McDonald & Sun, 1999):

- Primary-level models: These describe changes in microbial numbers or other microbial responses (e.g. acid production and toxin synthesis) with time to a single set of conditions, that is they describe microbial growth/responses as a function of time. Examples are the modified Gompertz function (Gibson *et al.*, 1987), Baranyi's non-autonomous differential equation (Baranyi *et al.*, 1993;

Baranyi & Roberts, 1994), three- and four-parameter Logistic models (Dalgaard, 1995) and the three-phase linear model (Buchanan *et al.*, 1997). A useful review of primary models is available (McKellar & Lu, 2003a).

- Secondary-level models: These describe the responses of one or more parameters of a primary model (e.g. lag time, growth rate and death rate) to changes in one or more of the cultural (environmental) conditions such as temperature, pH or a_w. The square root or Ratkowsky model (Ratkowsky *et al.*, 1983), response surface (Gibson *et al.*, 1988), Arrhenius models (Davey, 1989) and cardinal parameter models (Le Marc *et al.*, 2002) are examples of this class of models. A useful review of secondary models is available (Ross & Dalgaard, 2003).
- Tertiary-level models: These are computer programs (i.e. software packages) that enable users to 'interrogate' primary- and secondary-level models to obtain predictions. Examples of model software packages that have gained popularity and widespread use in the food industry and research communities include the Pathogen Modeling Program (PMP) developed at the Agricultural Research Service of the United States Department of Agriculture (USDA) and the Food MicroModel (FMM), incorporated into the now well-known combined database (ComBase), which is freely available (Tamplin *et al.*, 2003).

Alternatively, predictive microbiological models may also be classified by the microbial response that they are intended to describe (Legan, 2007):

- Kinetic growth models built using growth curves generated over a range of environmental conditions, which are able to predict growth rates, time to a critical level of growth or even a complete growth curve.
- Growth boundary ('growth'/'no growth') models built from qualitative observations or quantitative measurements of 'growth' or 'no growth' over time, which can predict the limits of conditions permitting 'growth' as defined by the model builder.
- Probabilistic growth models built from the proportion of 'growth' and 'no growth' responses throughout the experimental design space at a defined point in time, which can be used to predict the probability of growth occurring at the defined point in time for other conditions within the experimental design space. What constitutes 'growth' is again defined by the model builder such as a defined increase in microbial count or change in measured conductivity.
- Kinetic death models built from death curves under conditions of interest, which can be used to predict the extent of microbial destruction occurring during a deliberately applied lethal treatment (e.g. pasteurisation).
- Time-to-inactivation models built using qualitative 'dead' or 'not dead' responses from different initial microbial loads, which can be used to predict the time to the desired end-point (i.e. no survivors from the initial microbial load of interest) independent of the underlying death kinetics.
- Survival models built from measured viable counts over time under the conditions of interest, which relate to transitional conditions where either growth or death may occur; compared with the aforementioned, there are relatively fewer models of this type.

Some of the well-known computer software systems and electronic resources are as follows:

1 Food MicroModel (McClure *et al.*, 1994)
This was the product of a large multicentre and nationally coordinated 5-year research project (1989–1994) initiated and funded by the then UK Ministry of Agriculture, Fisheries and Food (MAFF), and was available for a while as a commercial package of models most of which are for the major food-borne organisms, but a number are for spoilage organisms. All models within the package have been shown to generate predictions relevant to most food groups. FMM is no longer available in its original form. In 2001, the Institute of Food Research (IFR), UK, won a contract from the FSA to maintain and improve the FMM database, the data behind which has since been merged with those from international collaborators (i.e. microbiology laboratories in academia, government agencies and the industry) as well as from the published literature to build ComBase.

2 ComBase (www.combase.cc) (Baranyi & Tamplin, 2004)
ComBase is a freely available Web-based system designed with the aim to contribute to the improvement of the following:
(a) Microbiological food safety
(b) Design, production, storage and retail of food
(c) Cost in the assurance of microbiological safety and stability
(d) Microbiological risk assessment of foods
Currently, ComBase is one of the three 'national capabilities' funded by the UK Biotechnology and Biological Sciences Research Council, hosted and maintained at the IFR, Norwich, UK. The concept of ComBase was conceived by researchers from the United Kingdom and United States between 2001 and 2003. In May 2003, the IFR, the FSA and the USDA Agricultural Research Service signed an agreement affirming their commitment to pool their respective data sets in the systematically formatted database developed at IFR and to implement predictive tools as add-ins to it. The mathematical models enabling this were developed at the IFR. In 2007, the Australian Food Safety Centre of Excellence joined the partnership further strengthening this predictive microbiology initiative.
ComBase comprises two major parts and resources, which are as follows:
- A systematically formatted database of quantified microbial responses to the food environment with over 50,000 records, which is accessed via the ComBase Browser and which allows search of static or dynamic data; the database is continually being updated.
- A set of validated predictive models on the growth and survival of food-borne organisms under various environmental conditions; these include growth models, thermal inactivation models, non-thermal survival models, a perfringens predictor and a Salmonella-in-egg model.
- Resources: DMFit is an application to fit bacterial curves where a linear phase is preceded and followed by a stationary phase. Included in this application

Table 1.4 Pathogen Modeling Program 7.0 Version[a]

Types of models	Bacteria
Growth	*Aeromonas hydrophila*
Survival (non-thermal inactivation)	*Bacillus cereus*
Thermal inactivation	*Clostridium perfringens*
Cooling	*Escherichia coli (O157:H7)*
Transfer	*Listeria monocytogenes*
	Salmonella dublin
	Salmonella enteritidis
	Salmonella hadar
	Salmonella kentucky
	Salmonella typhimurium
	Salmonella spp.
	Shigella flexneri
	Staphylococcus aureus
	Yersinia pseudotuberculosis

[a] US Department of Agriculture http://ars.usda.gov/Services/docs.htm?docid=6786

are two different types of models (and their partial forms) for fitting bacterial curves. The first type comprises the models of Baranyi and Roberts: complete, without lag phase and without asymptote. The second type comprises the trilinear model, the biphasic models (without lag phase and without asymptote) and the linear model. Having fitted a model, the application shows a graphical representation of the microbiological growth/survival data and displays the parameter estimates for maximum growth/death rate, lag time (or shoulder), initial cell count, final cell count and estimate standard errors on these parameters, as well as an evaluation of fit (adjusted R^2, and standard error of fit). There is a Web edition and a desktop version of DMFit, the latter downloadable from http://www.combase.cc.

3 Pathogen Modeling Program

This is a predictive pathogen modelling program developed by the USDA, which is available free on the Internet and can be downloaded from http://www.ars.usda.gov/services/docs.htm?docid=6786. The majority of PMP models are growth models; other types of models are also available. All the models are based on extensive experimental data of microbial behaviour in liquid microbiological media and food. Table 1.4 lists the types of models and bacteria available in the program. And Figure 1.3 shows the predictions obtained for aerobic growth of *Listeria monocytogenes* in broth culture.

4 Forecast (Anon, 2009)

This is a collection of predictive models developed by the Campden and Chorleywood Food Research Association, now Campden BRI, in the United Kingdom, which can be used to assess the microbial spoilage rates or likely

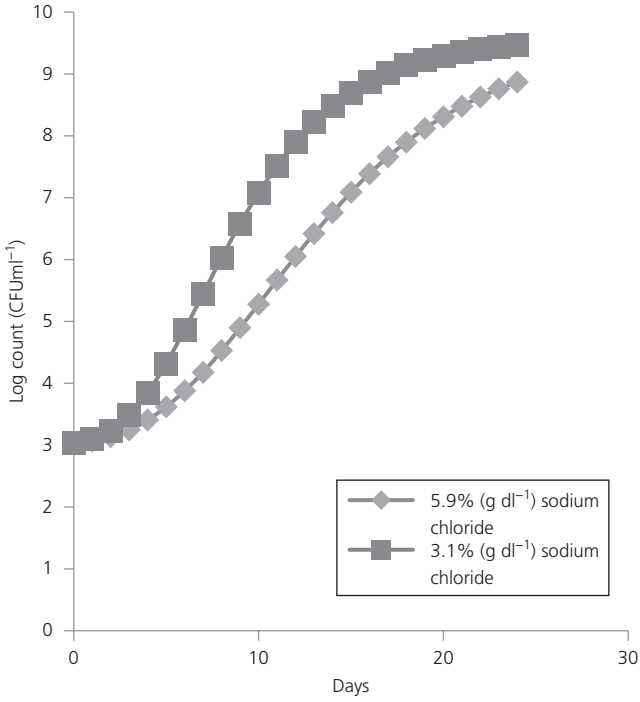


Fig 1.3 The effect of salt contents on the aerobic growth of *Listeria monocytogenes* with a lag phase in broth culture at 5°C, pH 7, 100 ppm sodium nitrite and an initial microbial load of 10^3 CFU ml^{-1}. Drawn from predictions obtained using the PMP 7.0 Version.

stability of foods. Included in the Forecast system are models for fish, meat, fresh produce and yeasts in fruits and drinks as well as a range of models relevant to acidified foods. The Forecast system is offered as a paid service by Campden BRI (see Fig. 1.4).

5 *Pseudomonas* Predictor

This is a temperature function integration (TFI) software developed at the Department of Agricultural Science, University of Tasmania, Australia (McMeekin & Ross, 1996). It is based on work undertaken to model the effects of temperature, water activity and pH on the growth rate of psychrotrophic spoilage pseudomonads in a wide range of moist proteinaceous foods. The software has been commercialised and is marketed in Australia under the name Food Spoilage Predictor (Blackburn, 2000). It can be used to predict the remaining shelf life of meat, fish, poultry or dairy products based on a fluctuating temperature history collected with a light-weight data logger. The software can also be used to predict the total shelf lives of these products based on a fixed temperature (Hastings Data Loggers, 2014).

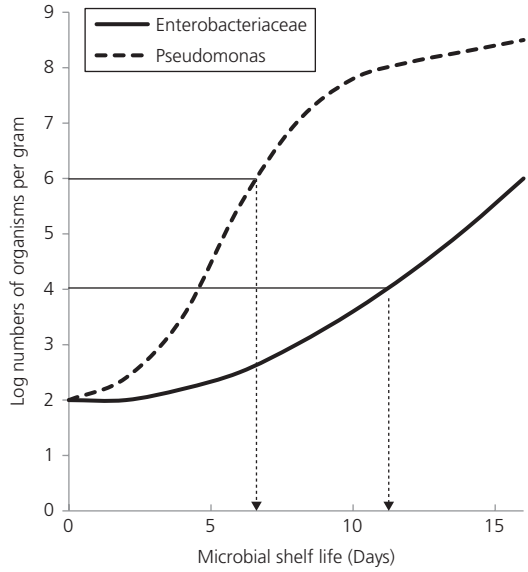


Fig 1.4 Graphical representation of predictions made using Campden BRI Forecast – conditions: pH 6.0, salt 3% w/v, temperature of storage 6°C. Reproduced with kind permission of Campden BRI.

6 ERH CALC™

This is part of a computer-based 'Cake Expert System' for the baking industry originally developed by the UK Flour Milling and Baking Research Association (which is now part of Campden BRI). It allows users to run simulations on flour confectionery formulations and rapidly calculate their theoretical equilibrium relative humidities (ERHs) and hence estimate their MFSLs (Fig. 1.5). The complete system is available from Campden BRI.

7 Seafood Spoilage and Safety Predictor

This was originally developed at the Danish Institute for Fisheries Research in Lyngby (Dalgaard *et al.*, 2002). The software contains essentially two types of model, namely, the relative rate of spoilage (RRS) model and the microbial spoilage (MS) model. The latest version of the software has been significantly expanded, which includes growth and growth boundary model for *Listeria monocytogenes* and models to predict growth and histamine formation of *Morganella psychrotolerans* and *Morganella morganii*. It can be downloaded free of charge from the home page of the National Institute of Aquatic Resources at the Technical University of Denmark (http://sssp.dtuaqua.dk/).

8 MicroFit

This is a stand-alone software program designed to analyse microbial growth data (Fig. 1.6). It allows the user to compare the specific growth rates of different bacterial growth curves and to measure statistical significance. It was developed

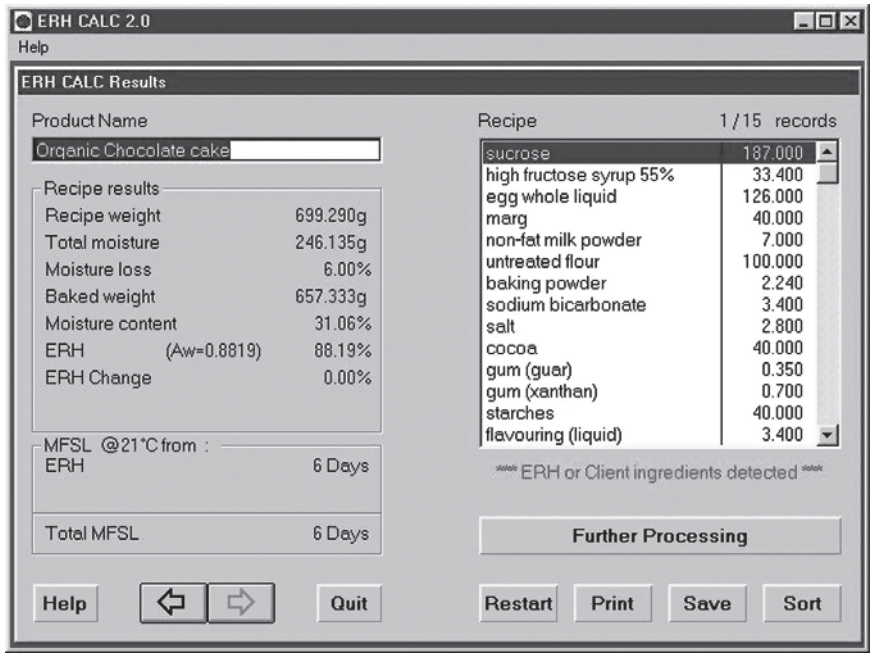


Fig 1.5 Predicting mould-free shelf-life of baked goods using ERH Calc. Reproduced with kind permission of Campden BRI.

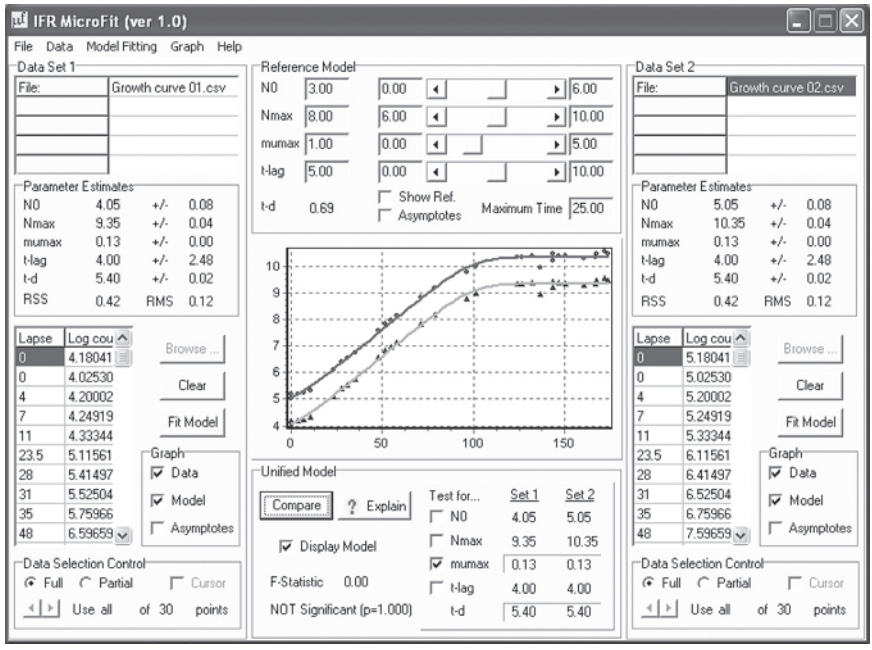


Fig 1.6 A screen dump of the MicroFit program. Courtesy of Professor Tim Brocklehurst, Institute of Food Research, Norwich, UK.

in the IFR, Norwich, with funding from MAFF and four food companies. It was available as freeware for a number of years but is no longer supported by the IFR; the analysis that is possible with MicroFit can be carried out using DMFit, which is part of ComBase.

9 Sym'Previus (www.symprevius.org)

Sym'Previus is a collection of online decision-making tools that include predictive microbiology (Leporq *et al.*, 2005). An annual subscription must be paid in order to gain unlimited access to all these software tools. The modules available in Sym'Previus are as follows:

- Probabilistic module
- HACCP assistance
- Growth interfaces – growth/no growth interface simulation module
- Growth simulation module
- Growth curve–fitting tool
- Thermal destruction simulation module
- Bacterial survival simulation module
- Database

10 Purac® *Listeria* Control Model 2012

Purac, headquartered in the Netherlands, is an international manufacturer of food ingredients, lactic acid–based bioplastics and biobased chemicals. Purac *Listeria* Control Model 2012 is the culmination of a decade of *Listeria* research at the company. It is a kinetic growth model of *Listeria monocytogenes* based on product characteristics that include moisture, pH, salt, potassium chloride, sodium nitrite and water activity, with or without the addition of a formulated ingredient containing potassium lactate and sodium diacetate manufactured by Purac. Unlike earlier versions of the model that were available on a free CD or as a download, Purac *Listeria* Control Model 2012 is an online version, which can be accessed, after registration, at http://www.purac.com/EN/Food/Calculators/Listeria-Control-Model.aspx.

The main uses of predictive microbiological models are as follows (Walker, 2000; Anon, 2009; Legan *et al.*, 2009):

- New product design and development: Validated models can be used to assess the likely microbiological safety and stability of a product formulation. Furthermore, models will enable the following example questions that are central to shelf life determination to be answered:
  - What level of specific microorganisms will be present at various storage periods?
  - What is the effect on microbiological shelf life of reducing the salt content by 1%?

  In this respect, where available, food-based rather than media-based models are more useful as the latter tend to give more conservative and fail-safe predictions.
- Process design: Processing is one of the major shelf life–determining factors. With the aid of validated models for inactivation, the process can be designed to ensure that the target microorganism(s) are effectively eliminated.

- HACCP: Models can be useful in various steps of HACCP, such as the following (McMeekin & Ross, 2002):
  - Hazard analysis – in the identification of microbial hazards.
  - Determination of critical control points (CCPs) – in identifying steps at which significant microbial growth or death is possible and whether critical control can be achieved or lost.
  - Establishment of critical limits – 'what-if' scenarios can be performed for different product formulations to establish critical limits for each CCP.
  - Establishment of a corrective action plan – if a loss of control occurs at a CCP, the change in microbial numbers associated with the process deviation can be quantified and appropriate corrective steps specified.

Although HACCP is generally used only for the assurance of food safety hazards being a legal requirement within the EU/United Kingdom, its principles can be applied to assure product quality and shelf life (Rodrigues *et al.*, 2010). This will involve identifying the major quality hazards that influence shelf life and determining their critical control points.

- Risk assessment: Assessing microbial food safety risk requires knowledge of the number of organisms in foods at the time of consumption. Predictive models can assist to meet this requirement. Microbiological risk assessment is a rapidly developing area, and models will contribute more and more towards quantitative risk assessment for the major food-borne pathogens as part of an overall effort to raise food safety standards (Voysey *et al.*, 2007; Blackburn & McClure, 2009).
- Time–temperature profiles: During storage, food products are often subject to fluctuating environment conditions such as temperature variations. If these conditions are known, predictive models can be used to determine their cumulative effects on the microbiological shelf life of foods, especially chilled foods. TFI has been shown to predict accurately the growth of mesophilic indicator and pathogenic microorganisms in chilled foods (McMeekin *et al.*, 1993). The technique uses the previous temperature history of the product and integrates it with the temperature-related characteristics of specific microorganisms. TFI has been applied to food storage, cooling, distribution and display (Gill, 1996).
- Training and education: Increasingly, predictive models are being used as a useful training and education tool. Used with care, they will allow food scientists and technologists to appreciate more fully how different factors such as pH, temperature and composition can act independently as well as in combination to affect the microbiological safety and quality of food products.

Table 1.5 provides a summary of current applications of predictive microbiology relevant to (microbiological) shelf life of food (McMeekin *et al.*, 2007).

Despite the near-explosive developments in predictive modelling for food microbiology in recent years, besides the inherent uncertainty and variability, predictive models do have their limitations. In general, extrapolation cannot be made outside the ranges of factors used to produce the data in a model. Growth models will give incorrect predictions for foods that contain, for instance, natural

Table 1.5 Current applications of predictive microbiology[a]

Area of application	Examples
HACCP	Preliminary hazard analysis Identification and establishment of critical control point(s) Establishment of corrective actions Evaluation of importance of interaction between variables
Risk assessment	Estimation of changes in microbial numbers in a production chain Assessment of exposure to a particular pathogen
Microbial shelf life studies	Prediction of the growth of specific food pathogens Prediction of the growth of specific spoilage organisms
Product development	Effect of changing product composition on food safety and spoilage Effect of processing on food safety and spoilage Evaluation of effect of out-of-specification circumstances
Temperature function integration and food safety and hygiene regulatory activity	Consequences of temperature change/fluctuation in the cold chain for safety and spoilage

[a] Adapted from McMeekin *et al*. (2007)

antimicrobial substances. Also, models complement, but do not replace, the experience and skills of a food microbiologist. Using Sym'Previus, PMP and Growth Predictor, it has been demonstrated that, under conditions of 10°C, pH 6 and a_w 0.996, a 2-log increase in *Listeria monocytogenes* can be achieved in 48, 62 and 82 h, respectively (Membré & Lambert, 2008). These results will either represent false predictions or cause confusion, for instance among product developers who are likely users of predictive microbiology but not necessarily experts in predictive modelling. The ability of predictive models to indicate the microbiological shelf life of food will remain limited, unless our understanding of the relationship between microbial numbers, the microbial ecology of the food system (including microbial competition, interactions, etc.) and its spoilage mechanism continues to improve. Furthermore, potential users of computer-based systems like ComBase who may not be qualified food microbiologists or model developers will need to be trained adequately to be able to use predictive models competently and confidently, and to know their strengths and limitations.

The growing importance of predictive microbiological models has been further underlined by the investment of EU funds in a collaborative research project, the SOPHY project, which is supported under the Seventh Framework Programme (FP7) of the European Commission for a period of 3 years between 1 February 2012 and 31 January 2015 (Gering *et al*., 2012). The overall aim of the project is to 'develop a software tool for prediction of RTE food product shelf-life, quality and safety'. The SOPHY project is coordinated by ttz Bremerhaven, Germany; the project consortium includes Campden BRI, UK; the Agricultural University of Athens and a number of other European universities as well as industrial partners

such as Chainfood in the Netherlands (see http://sophy-project.eu/ for further information).

Besides models available electronically, much information about predictive modelling as well as models can be found elsewhere. For example, in 2013, an entire issue of the *Journal of Food Control* is devoted to predictive modelling, which contains 21 selected papers drawn from the Seventh International Conference on Predictive Modelling of Food Quality and Safety (ICPMF7) held in Dublin, Ireland, between 12 and 16 September 2011 (Valdramidis *et al*., 2013).

Models for predicting shelf life of foods that undergo non-microbiological deterioration (e.g. moisture- and oxygen-related changes) have also been developed and published (Floros & Gnanasekharan, 1993; McMurrough *et al*., 1999; Bourlieu *et al*., 2008; Knol *et al*., 2009; Van Bree *et al*., 2012). With some exceptions (Corradini & Peleg, 2006), many of these models are product-specific and require prior knowledge of some critical level of moisture, oxygen or other factor that causes the product to become unacceptable. As in the case of microbiological models, the complexity of foods makes it critical to validate models using experimentally determined data in order to ensure appropriate and accurate prediction of shelf life. A useful review of 'modelling chemical and physical deterioration of foods and beverages' is available (Gallagher *et al*., 2011).

1.12 What is challenge testing?

A challenge test is a laboratory investigation of the behaviour of a product when subjected to a set of controlled experimental conditions. In the context of shelf life determination, challenge testing refers to microbiological challenge testing, the aim of which is to simulate what can happen to a food product during processing, distribution and subsequent handling, following inoculation with one or more relevant microorganisms. The origin of microbiological challenge testing is believed to have come from the inoculated pack studies carried out in the early days of the canning industry. In these studies, a highly heat resistant spore suspension of *Clostridium sporogenes*, a known spoilage organism, was used to challenge a processing system to determine the processing conditions which would reduce possible contamination with *Clostridium botulinum* to acceptable limits. A well-known example of microbiological challenge testing is microbiological composition analysis (MCA) of edible emulsions developed by Tuynenburg Muys at the Unilever Research Laboratory in the Netherlands in the 1960s (Tuynenburg Muys, 1965, 1971). MCA has since been developed into the code for the production of microbiologically safe and stable emulsified and non-emulsified sauces containing acetic acid, commonly called the CIMSCEE Code (CIMSCEE, 1992). The code has two main parts: the first consists of formulae for predicting if a product is safe or stable at ambient temperature based on product composition (see Appendix B); the second consists of protocols for challenge testing products to establish safety and stability (Jones, 2000a). Clearly, challenge testing is a specialised laboratory

exercise that is expensive, time-consuming and demanding on facilities and skills. Moreover, when a product formulation or the time–temperature profile to which it is subjected changes, challenge tests must be repeated. The main areas of application of microbiological challenge testing include the following:

- Determining product safety and assessing the risk of food poisoning after HACCP has identified the organisms likely to be a hazard for the product at some stage during production and distribution
- Establishing microbiological shelf life by inoculating the product with food spoilage organisms likely to contaminate it
- Evaluating the effects of different formulations of the food on a target organism, that is either a pathogen or a spoilage organism
- Validating thermal processes such as aseptic processing and packaging, the effectiveness of which is expected to be very high and cannot therefore be established by monitoring failure rate during ordinary operations

In all cases, relevant expertise and experience and the necessary laboratory facility must be available to produce meaningful results. Detailed guidelines for the design and planning of microbiological challenge testing have been published (Rose, 1987; Notermans *et al*., 1993; Notermans & in't Veld, 1994; Betts, 2010). Betts (2010) provides a helpful and informative overview of microbiological challenge testing for food businesses who are considering the test (Fig. 1.7). Besides complying with prevailing applicable health and safety legislation, laboratories are reminded to ensure the requirements of The Anti-terrorism, Crime and Security Act (2001) (TSO, 2001) are fully met, which may cover the organism(s) of interest. In recent years, the use of challenge test to assess the microbial safety and stability of foods, particularly in respect of psychrotrophic *Clostridium botulinum* and *Listeria monocytogenes*, has increased. Some of the reasons responsible for this include the need to assure microbiological safety and stability of more and more new food products especially chilled foods and the arrival in the EU of new food legislation such as Commission Regulation on Microbiological Criteria for Foodstuffs (2073/2005/EC) (as amended).

1.13 Can the shelf life of my product be extended?

In many cases, the shelf life of food can be extended. Methods of shelf life extension, however, must be founded on our understanding of the various mechanisms of food deterioration if they are not to compromise food safety and/or quality. From a purely scientific standpoint, our ability to extend the shelf life of a food product should reflect our increasing understanding of its mechanism(s) of deterioration. A final decision to extend the shelf life of a food product is almost always a commercial one. It is pointless, for instance, to significantly increase the shelf life of a chilled food only to destroy its image of 'freshness' as a result. In practice, however, shelf life extension that brings about the following benefits is often welcome:

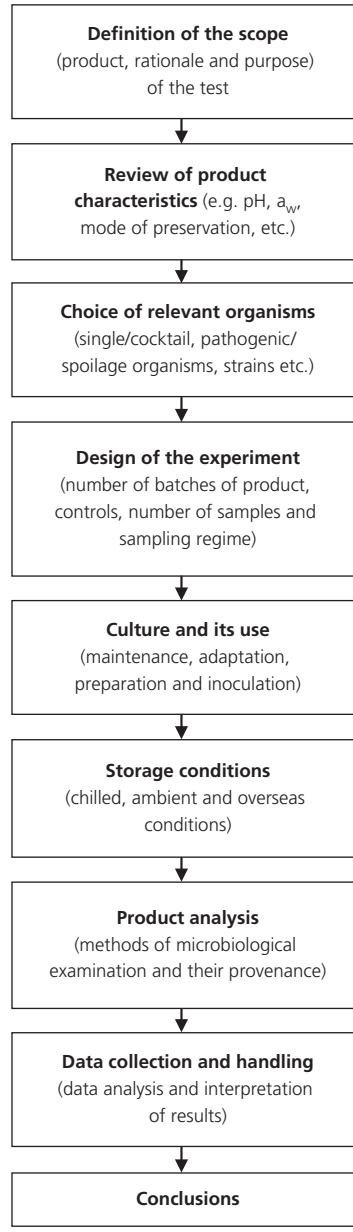


Fig 1.7 Overview of microbiological challenge testing. Adapted from Betts (2010).

- Smoothing out production peaks and troughs
- Offering wider choice to consumers
- Stockpiling for seasonal increase in sale or special promotions
- Widening of distribution
- Less product wastage from actual product failure or insufficient time on the retail shelf (this has become an increasingly important benefit in recent years)

Thus, establishing the main mechanism(s) of spoilage of a food product is the first step towards extending its shelf life. The next step is to see if the current shelf life can be extended simply by doing things better; this is a case of optimisation. It may mean repeating the original storage trial, revisiting the major spoilage mechanism and re-examining the factors that contribute to it. Alternatively, new technology may have to be used in an attempt to extend shelf life. While there are different techniques of food preservation and extension of shelf life, the overriding objective in all these is always to minimise the occurrence and growth of microorganisms, although other non-microbiological forms of spoilage are usually controlled to varying degrees at the same time. A good understanding of the various preservation techniques that confer microbiological safety and stability to food can also aid the selection of the most appropriate method for shelf life extension. Principally, the major preservation techniques act by the following mechanisms (Gould, 1996):

- Inactivating microorganisms, for example pasteurisation, sterilisation, irradiation and high-pressure processing
- Preventing or inhibiting microbial growth, for example chilling, freezing, drying, curing, conserving, vacuum packaging, modified atmosphere packaging (MAP), acidifying, fermenting and adding preservatives
- Restricting the access of microorganisms to products, for example aseptic processing, decontamination (of raw materials, plant and environment) and packaging

In practice, these preservation techniques can be used independently, or more commonly, in combination. A more recent trend is towards the use of procedures that deliver food products that are less severely preserved or minimally processed, without compromising safety, and often of higher quality, both real and perceived (Ansorena *et al.*, 2014). Such procedures that make use of preservation factors acting in concert to give less damage to product quality have been called hurdle technologies (Leistner, 2000). Figure 1.8 illustrates the principles of 'hurdle effect' together with two examples (Leistner, 1992).

Table 1.6 gives some examples of successful shelf life extensions that serve as evidence of our understanding of the deterioration mechanism involved in each case. In some cases (e.g. in commercial production of jams, sauces, salad dressings, hams, sausages and avocado purée), besides shelf life extension, the employment of a modern preservation technology such as high-pressure processing has resulted in superior product quality compared with conventionally processed products (Johnston, 1994; Sizer, 2000). A concept that is developing into an important shelf-life extension technology is the use of active and intelligent packaging materials and articles intended to come into contact with food (Vermeiren *et al.*, 1999; Dainelli *et al.*, 2008). For instance, the use of oxygen

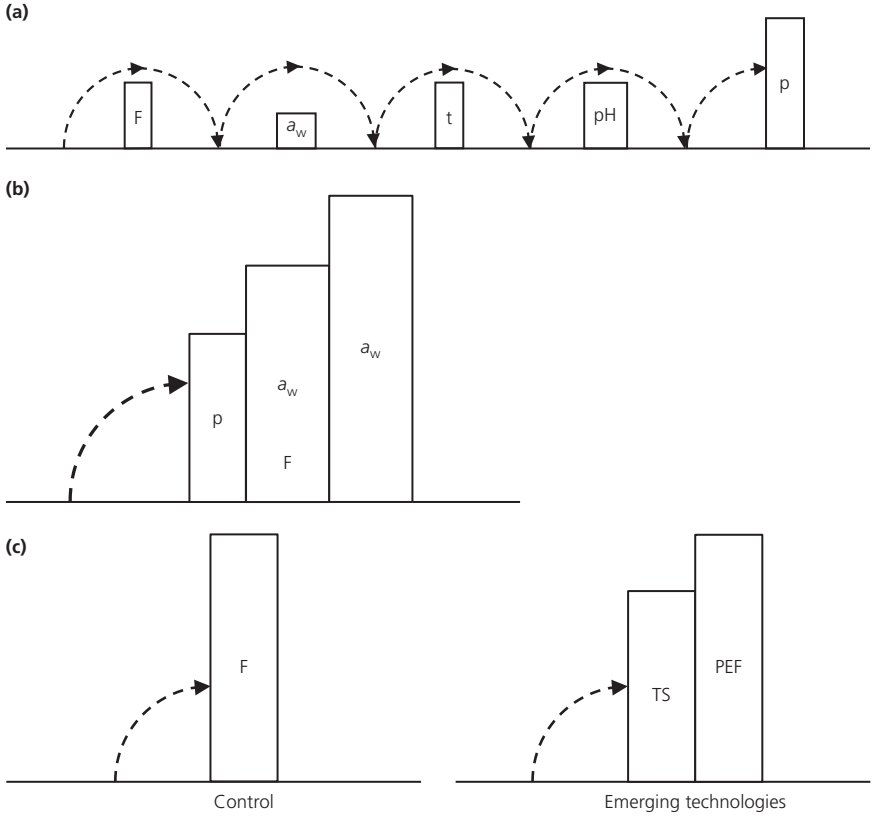


Fig 1.8 The Hurdle effect. (a) Principles of hurdle technology – individual hurdles may be encountered simultaneously or sequentially. a_w, low water activity; F, heating; p, preservatives; pH, acidification; t, chilling. Adapted from Leistner (1992) and Leistner & Gorris (1995). (b) Chinese sausage (Guangdong La Chang (Cantonese lap cheong)) – a traditional meat (pork) product preserved by combined factors. F, quick drying over charcoal at 45–60°C to an $a_w < 0.92$; p, nitrate/nitrite, salt, sugar, soya sauce. a_w, further drying at ambient to an $a_w < 0.80$. Adapted from Leistner (1999). (c) Orange juice exposed to thermo-sonication and pulsed electric fields. F, high-temperature short-time (HTST) pasteurisation (94°C/26 s); PEF, continuous pulsed electric fields (40 kV cm^{-1} for 150 µs); TS, thermo-sonication (55°C/10 min). Adapted from Walkling-Ribeiro *et al.* (2009).

scavenging technology combined with MAP has extended the refrigerated storage lives of RTE red meat products. Such is the commercial significance and importance of this development that the use of active and intelligent materials and articles intended to come into contact with food is now regulated within the EU (EC, 2009; Restuccia *et al.*, 2010). The relevant regulation, Regulation (EC) No. 450/2009, defines 'active materials and articles' as materials and articles that are intended to extend the shelf life or to maintain or improve the condition of packaged food; they are designed to deliberately incorporate components

Table 1.6 Some examples of successful shelf life extensions

Food product	Main spoilage mechanisms	Technique of shelf life extension
Chilled foods, for example RTE sliced ham	Microbiological changes	Chilling and refrigerated storage Modified atmosphere packaging
	Biochemical changes	Use of oxygen scavengers
Refrigerated processed foods of extended durability (REPFEDs) – sous vide products	Microbiological changes	Vacuum packing Low-temperature processing (65–95°C) Chill storage (0–3°C)
Sliced bread	Mould growth Staling Moisture transfer – redistribution and loss	Use of preservatives Use of emulsifiers Use of barrier packaging
Milk	Microbiological changes	Pasteurisation Microfiltration (e.g. PurFiltre™)
Large ambient fruit pies	Mould growth	UV irradiation
Orange juice	Microbiological changes Biochemical changes	High-pressure processing (Mermelstein, 1998)
Fresh chicken breast fillets	Microbiological changes Biochemical changes Organoleptic changes	High hydrostatic pressure Liquid antimicrobial edible coating Modified atmosphere packaging (Rodríguez-Calleja *et al.*, 2012)

that would release or absorb substances into or from the packaged food or the environment surrounding the food. Examples of active absorbing/scavenging systems include moisture absorbers designed to deliberately absorb the drip from meat, poultry and fish in display packs and oxygen scavengers designed to deliberately capture residual oxygen from the environment surrounding the foodstuff or from the foodstuff in packaged pasta, milk powder and biscuits. Applications that have attracted much research and development effort are on systems with a substance (conventional and in nano forms) such as an additive (e.g. a preservative) or enzyme grafted or immobilised on the wall of the packaging, which has a technological effect on the food (Cushen *et al.*, 2012; Sung *et al.*, 2013). The same regulation defines 'intelligent materials and articles' as materials and articles which monitor the condition of packaged food or the environment surrounding the food. Well-known examples of these are time–temperature indicators that give information on whether a threshold temperature has been exceeded over time and/or estimate the minimum amount of time a product has spent above the threshold temperature (i.e. time temperature history), for example from the moment the food is packed until consumption. Published guidance to Regulation (EC) No. 450/2009 is available from the EU (EC, 2011b).

In other cases, even if shelf life extension is not appropriate or necessary, better understanding of food deterioration mechanisms should lead to improved assurance of and greater confidence in the established shelf lives of foods.

1.14 How are storage tests and trials set up for determining shelf life?

The most common and direct way of determining shelf life is to conduct storage trials of the product in question under conditions that mimic those it is likely to experience during storage, distribution, retail display and consumer use. The direct approach may be unacceptable if the expected shelf life is very long. In this case, alternative approaches such as ASLT have to be used (see Section 1.7). Of course, if the product being studied is a variant of established lines, an educated guess based on in-house technical expertise and sound scientific judgement is often sufficient for arriving at an estimate of its shelf life. The following aspects of direct storage trials deserve careful considerations.

1.14.1 Objective of the storage trial

The objective of the storage trial is a prime factor that determines how the experiment should be designed, planned and undertaken and how the results should be interpreted. The same chilled food destined for both retail sale and food service from a delicatessen counter where portions of the food are expected to be sold over a period of time (i.e. a secondary shelf life) would require two different experimental designs to reflect the two different applications.

1.14.2 Storage conditions

Storage conditions may be fixed or fluctuating. The actual storage conditions used will depend on the product being investigated and the amount of knowledge the experimenter has about the anticipated distribution chain through to consumer storage and use. Ideally, for a given set of storage conditions, the following variations should be available:

- Optimum conditions: They are the most desirable conditions of temperature, humidity, light and so on. Storage under these conditions should provide the most optimistic shelf life data.
- Typical or average conditions: They are the conditions most commonly experienced by the product. Storage under these conditions should provide shelf life data that apply practically to the entire future production most of the time.
- Worst-case conditions: They are the most extreme conditions that the product is likely to encounter. Storage under these conditions should provide the most conservative shelf life data, which, if used to assign a shelf life, should give it a margin of safety ensuring that product failures due to insufficient shelf life are highly unlikely in practice.

Fixed storage conditions that are commonly used include the following:

- Frozen: −18°C or lower (relative humidity is usually near 100%).
- Chilled: 0 to +5°C, with a maximum of +8°C (relative humidity is usually very high) (TSO, 2013).
- Temperate: 25°C, 75% relative humidity (Cairns, 1974).

- Tropical: 38°C, 90% relative humidity (Cairns, 1974).
- Control: control conditions (for storage of control samples) are usually the optimum conditions, be they ambient, chilled or frozen.

Different countries, even within the EU, may have different requirements. For instance, Belgium (and the Netherlands) and Spain, respectively, stipulated a maximum of 7 and 0–3°C for the storage of chilled foods (Goodburn, 2000). For chilled foods destined for exports, the storage conditions stipulated by the country of destination must be used for storage trials. Storage under fluctuating conditions generally makes use of a programmed storage facility that creates a set of artificial conditions (e.g. heating and/or lighting coming on and off according to a predetermined pattern) that are designed to mimic the real-life conditions expected to be experienced by the product. Such a facility is obviously expensive, and so fixed conditions storage tends to be the preferred storage for the direct determination of shelf life. Whatever the conditions, they must be closely monitored and recorded to ensure correct and proper execution of the storage experiments and hence correct and meaningful interpretation of shelf life data.

1.14.3 Samples for storage trials

The product composition or formulation, the way the samples have been produced as well as the packaging materials used are important factors; they need to be noted and controlled. For instance, pilot-scale samples are likely to have been produced on a batch basis, whereas production-scale samples are more likely to have been processed on a semi-continuous or fully continuous basis. The differences in product characteristics between pilot-scale and production-scale samples may well be enough to have significant bearing on the outcome of the storage trials.

The number and the size of the samples need to be carefully chosen, consistent with the objective of the storage trial. Ideally, the food should be stored in the same pack or container that has been designed and developed for full-scale production. Care must be taken to ensure that all sample packs are exposed to exactly the same storage conditions.

The number of samples to be taken is very much dictated by the sampling schedule for the storage trial. In turn, the sampling schedule is influenced by the type of product, its end-use application, the anticipated or required shelf life and the tests to be carried out for assessing food safety and/or quality changes during storage. In one example, ambient shelf-stable pasta shapes in savoury tomato sauce packed in multilayered plastic trays with a desired shelf life of 1 year was studied. A total of some 350 samples were required for storage trials at three different temperatures, that is 2°C (control), 25°C (normal) and 35°C (worst case) (Goddard, 2000). If necessary, one should be prepared to err on the generous side in order to avoid running out of samples during a storage trial.

Not all types of product are unaffected by freezing and thawing. When frozen storage is unsuitable as a means of keeping control samples, facilities must be available for the preparation of fresh reference (i.e. control) samples that are identical to the test samples in every way, at any time during a storage trial.

1.14.4 Sampling schedule

Different designs of shelf life experiment based on a statistical approach have been published (Gacula, 1975). In practice, however, the actual sampling schedule chosen is often determined by the shelf life anticipated by the experimenter or the shelf life required by the customer. As an illustration, the following are some possible sampling schedules:

- Short–shelf life products: For chilled foods with shelf life of up to 1 week (e.g. ready meals), samples can be taken off daily for evaluation.
- Medium–shelf life products: For products with a shelf life of up to 3 weeks (e.g. some ambient cakes and pastry), samples can be taken off on days 0, 7, 14, 19, 21 and 25.
- Long–shelf life products: For products with a shelf life of up to 1 year (e.g. some breakfast cereals and heat-processed shelf-stable products), samples can be taken off at monthly intervals or at months 0, 1, 2, 3, 6, 12 and (perhaps) 18. The exact frequency will depend on the product and on how much is already known of its storage behaviour.

1.14.5 Shelf life tests

The exact shelf life tests are often product-specific and may include some or all of the following types of tests (see also Section 1.9):

- Chemical analysis
- Microbiological examination including challenge testing
- Physico-chemical analysis
- Physical testing, measurement and analysis such as rheological measurements, microscopical examination, vibration test and so on

  And in all cases
- Sensory evaluation

Given the assurance of product safety, sensory evaluation is unquestionably the most appropriate type of test for evaluating changes during storage trials. To ensure the generation of meaningful, accurate and reliable sensory data, some basic and interrelated requirements have to be fulfilled; they are as follows (Kilcast, 2011):

1 Objectives of the sensory evaluation must be clearly defined.
2 A dedicated sensory testing environment must be available.
3 Suitable test procedures must be used.
   - Analytical tests (product-oriented tests): difference (discrimination) tests and qualitative tests, for example quantitative descriptive analysis
   - Hedonic tests (consumer-oriented tests): preference and acceptability tests

4 Suitable assessors (i.e. taste panellists) must be selected and trained.
5 Data handling and analysis must be correct and the results presented effectively.

Detailed discussions and guidance on the use of sensory evaluation in shelf life testing can be found in a number of publications (IFT, 1981; O'Mahony, 1986; Labuza & Schmidl, 1988; Lawless & Heymann, 1998; Carpenter *et al.*, 2000;

Stone & Sidel, 2004; Kilcast, 2011). In recent years, there has been a growing interest in the use of consumer methods, principally survival analysis, in evaluating shelf life of food. Early indications are that survival analysis using direct consumers' experience could offer a means of estimating quality shelf life more precisely but for food safety reasons, the technique is unsuitable for products in which microbial safety rather than quality deterioration is a major shelf life consideration (Chambault, 2013).

1.15 Food waste and shelf life: What is the problem?

According to the Food and Agriculture Organisation of the United Nations (FAO), about one-third of the food for human consumption, around 1.3 billion tonnes, is wasted globally per year (FAO, 2013). In Europe, based on figures from the European Commission, about 90 million tonnes of food or 180 kg per capita per year, excluding agricultural food waste and fish discards, is wasted annually. The European Parliament has called for 2014 to be designated as 'European year against food waste' (EC, 2013). Apparently, food waste in industrialised nations is just as high as in developing countries; in the former, over 40% of the waste occurs at retail and consumer levels while in the latter, the same level of food loss happens after harvest and during processing. Food is wasted throughout the entire food chain: by farmers, by the food industry, by retailers, by caterers and by consumers. The causes of food waste are diverse and often sector-specific, but the main ones cited are as follows (EC, 2013):

- Lack of awareness
- Lack of shopping planning
- Confusion about 'use by' and 'best before' dates
- Lack of knowledge on how to cook with 'leftovers' at home
- Standard portion sizes; difficulty to anticipate the number of clients (catering)
- Stock management inefficiencies
- Marketing strategies (2 for 1; buy 1 get 1 free)
- Aesthetic issues (retail)
- Overproduction
- Product and packaging damage (farming and food manufacturing)
- Inadequate storage (entire food chain)
- Inadequate packaging

Confusion about 'use by' and 'best before' and what they actually mean have been identified by the FSA as an issue of concern (see Section 1.3). More education is needed to assist consumers to use these declarations of 'minimum durability' properly primarily for food safety and quality reasons but also to help reduce food waste. For food manufacturers and processors, there is now a greater incentive than ever before for them to determine their product shelf lives accurately for legal, quality as well as economic reasons.

1.16 Summary

The following are a number of the key points:

- Shelf life is an important requirement of today's food products.
- Food safety and consistent quality that meet customer expectations are the two main aspects of an acceptable shelf life.
- Within the EU and in the United Kingdom, the provision of an appropriate and reliable date of minimum durability on food labels is a legal requirement; this date depends and should reflect the product's shelf life consistently, which is expressed legally either as a 'use by' or as a 'best before' date.
- The responsibility of determining shelf life of a food product lies with its manufacturer and/or packer.
- Management understanding and commitment are essential if shelf life determination is to be taken seriously as it should be because significant resources are needed to do the work properly.
- Shelf life is determined directly by conducting storage trials of the product under defined storage conditions.
- In many cases, and for a number of reasons, shelf life may be estimated, predicted or determined indirectly by accelerated tests, microbiological challenge tests and/or the use of suitable computer programs.
- Knowledge of the relevant spoilage mechanism(s) of a food product is crucial to its shelf life determination, and if necessary, its shelf life extension, too.
- Shelf life of foods is rarely affected by a single factor; a number of factors influencing shelf life are usually at work.
- The most effective way of managing shelf life is the careful application of GMP principles in food manufacture, processing and distribution, which form a cornerstone of modern days' QMS standards.
- The provision of a 'use by' or 'best before' date that expresses accurately the shelf life of a food product not only is a legal requirement in the United Kingdom and within the EU, it also makes commercial/economic sense, as a way of helping to minimise unnecessary food waste.