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Optimising the safety and quality of thermally processed packaged foods

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1.1 Introduction: reconciling safety and quality

Ever since the invention of thermal processing as a method of preserving packaged foods by the Frenchman Nicolas Appert in the early 19th century, there has been a relentless search to reduce the amount of thermal damage to the quality of food products. Today there is a large range of packaging materials available, metallic cans, glass containers and plastic, which may be presented in a variety of different geometrical shapes. Whatever the material and its shape or the food product it is necessary to apply a suitable *process*, i.e., a given time at a specified temperature, to ensure that the products do not pose a public health problem, e.g., food poisoning. Equally it is necessary to ensure that the product has received sufficient heat to cook it and to maintain the highest possible quality. Thus the art of thermal processing of foods is to select suitable time/temperature combinations and cooling regimes which will ensure the above criteria. The term *process* should not be confused with the more conventional meaning of the word as a sequence of engineering operations.

For the adequate destruction of the spores of pathogenic microorganisms, whose toxins may cause food poisoning, practical processing temperatures of 110–130ºC are required for times depending on the nature of the food product. The higher the temperature the shorter the time required. One of the most heat resistant spores is *Clostridium botulinum*, which unless inactivated will produce the lethal botulin toxin under the anaerobic conditions in the container. Consequently most *processes* are chosen on the basis of the destruction of this microorganism; the argument being that any products containing less resistant

microorganisms will thereby be inactivated by a 'botulinum process'. It is important to realise that there are more heat-resistant organisms, i.e., thermophiles, present in thermally processed foods which do not present a threat to human health. Under normal storage conditions these will be innocuous; however, should the products be stored at tropical temperatures, e.g., 35ºC and above, thermophiles will grow and ultimately swell or burst the container. Processed foods intended for such climatic conditions require a more severe process to stabilise them. Products, which receive a safe 'botulinum process' but still contain thermophiles, are described as 'commercially sterile'. The meaning of sterile as used in these processes differs from the absolute definition of sterility used by the medical profession, indicating free from living organisms.

An important source of post-process contamination is 'leaker spoilage' which, as the name implies, indicates that microorganisms have penetrated the container after processing and usually during cooling with water. Metallic containers are particularly prone to this problem, since during the cooling of the container a vacuum develops and microorganisms may enter through imperfections in the sealing. The problem is resolved by chlorinating or decontaminating the cooling water.

When food products are heated the components are generally affected by the length of the heating process and the level of the temperature. Some of the desirable effects are enzyme destruction (usually in the case of vegetables, this is achieved by pre-process blanching and cooking); undesirable effects include loss of vitamin potency, flavour changes, and texture and structure changes. Each product behaves differently and it is necessary to know the principal components which affect the quality, especially in the processing of formulated food, where the textural attributes are important in the finished product. Whilst this subject is of considerable commercial significance, relatively little is known about the kinetics of these complex processes compared with microbial destruction. In general, biochemical processes are much slower than microbial destruction processes, which is helpful in preserving the quality attributes of the products.

1.2 The kinetics of microbial inactivation during heat treatment

1.2.1 Heat resistance of microorganisms

The amount of heat required to inactivate microorganisms is an important property, which must be known or determined in order to specify a suitable process for a product, usually known as the specified process. Some typical data for some types of organism initially present in foods is given in Table 1.1. Traditional canning technology makes use of two factors to determine the time/temperature process required to produce a heat-stable food. The first of these is the decimal reduction time or D-value, which is defined as the time in minutes at any given temperature to destroy 90% of the spores or vegetative cells in a given

Table 1.1 Some inactivation data for microorganisms

Organism	Time/temperature
Vegetative cells	10 min/80ºC
Yeast ascopspores	5 min/60ºC
Fungi	30–60 min/88ºC
Thermophiles:	
Clostridium thermosccharolyticum	3–4 min/121ºC
Bacillus stearothermophilius	4 min/121ºC
Mesophiles	
Clostridium botulinum	3 min/121ºC
Botulinum A &B toxins	0.1–1 min/121ºC
Clostridium sporogenes	1.5 min/121ºC
Bacillus subtillis	0.6 min/121ºC

organism. It may be obtained from heat-resistance studies by determining the number of survivors resulting from a given process. The plot of logarithm of the number of survivors versus temperature for a given organism versus time, see Fig. 1.1, is used to determine the D-value. This is known as the semi-logarithmic survivor curve, which has a slope of $-1/D$, the equation of the curve being given in equation 1.1.

$$\log N = \log N_o - t/D \tag{1.1}$$

where N is the number of surviving microorganisms, N_o is the initial number of microorganisms, t is the time in minutes and D is the decimal reduction time in minutes. Logarithms to the base 10 are indicated by log. Figure 1.2 shows various types of survivor curves encountered in canning microbiology.

The second factor is the thermal death constant z. This is the change of D-value with temperature and is obtained from a plot of log *D* versus temperature (see Fig 1.3). The equation for the D/z plot is given in equation 1.2:

$$\log D_T = \log D_{ref} - (T - T_{ref})/z \tag{1.2}$$

where D_T is the D-value in minutes at any temperature T and D_{ref} is the corresponding value at the reference temperature T_{ref}, The usual temperature in Celsius is 121.1º (this is the equivalent of 250ºF, previously widely used in the canning industry). The z-value has units of Celsius degrees Cº (for conversion purposes 1ºC ≡ 1.8ºF). Some typical values of D and z values are given in Table 1.2. For extensive tabulated data see Holdsworth (1997).

An alternative method of expressing the kinetics of microbial destruction is to assume first-order kinetics and express equation (1.1) as

$$N = N_0 e^{-kt} \tag{1.3}$$

where k is the specific reaction rate in reciprocal seconds s^{-1} and $D = 2.3/60k$.

Using the Arrhenius kinetic theory $k = Ae^{-E/RT}$, where A is the pre-exponential factor (s^{-1}), R is the molar gas constant (8.135 J /molK) and E is the activation energy kJ/mol and is equivalent 2.303 RT T_{ref}/z.

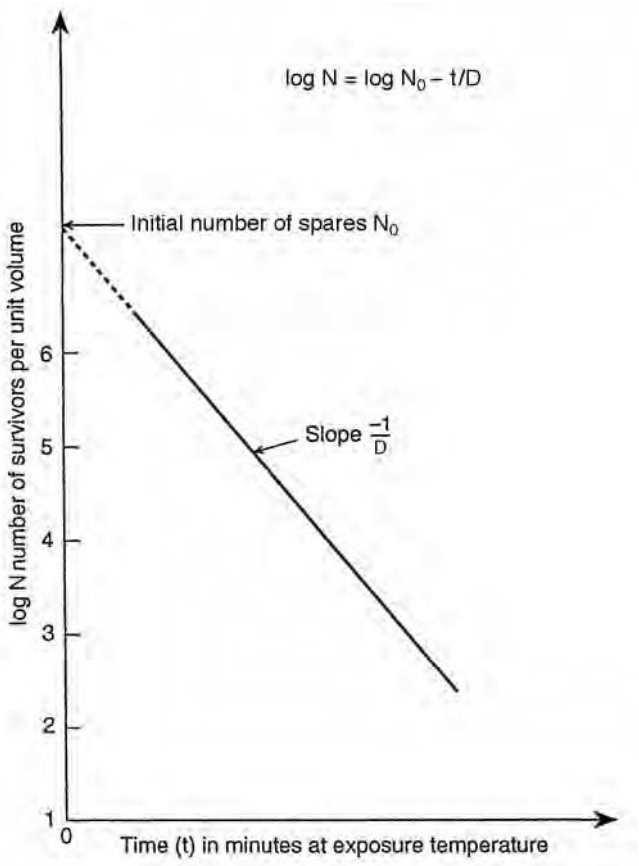

Fig. 1.1 Logarithm of the number of microbial survivors versus time for a given organism showing D-value determination.

Equation 1.2 may be expressed as follows:

$$\ln k = \ln k_{ref} - (E/R[1/T - 1/T_{ref}] \quad (1.4)$$

where ln is the natural logarithm (base 2.303) and k_{ref} is rate constant at the reference temperature T_{ref}.

At normal canning temperatures 120–125ºC, the two approaches give sufficiently similar results for either to be used (Nunes *et al.*, 1993). However, with the use of higher temperatures and shorter times more accuracy will be required for kinetic factors and the k/E approach may be more adventitious. Datta (1993) has made a full analysis of the two approaches and shown that under normal canning conditions relatively low errors are incurred. A new equation is proposed for modifying the D-z approach to take into account the variation of reaction rate constant with temperature. The D-z approach is widely used and a well-proven practical system in the traditional canning industry.

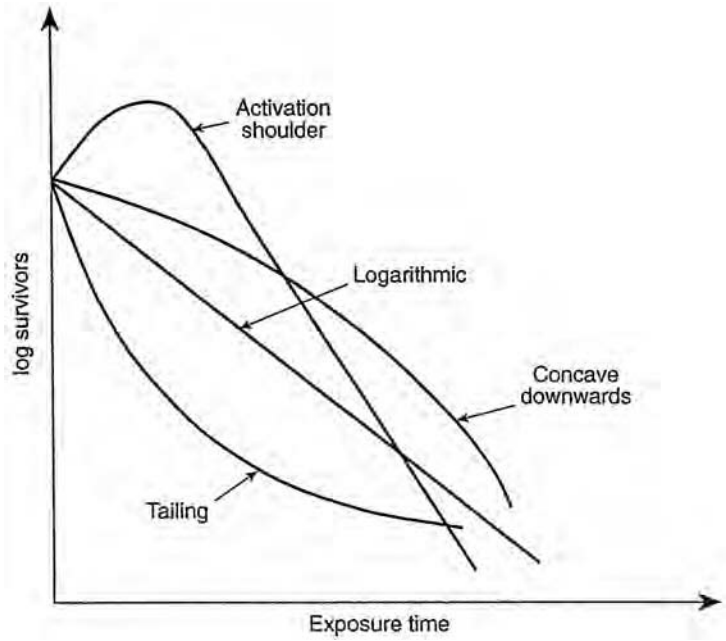

Fig. 1.2 Various types of microbial spore survivor curves encountered in canning microbiology.

1.2.2 Factors affecting heat resistance

A number of factors influence the heat resistance of microorganisms, i.e., water activity, pH, and composition and consistency of the food.

Water activity

The water activity of most food products is sufficiently high for this not to affect the heat resistance. However, in circumstances where dry powders can exist in formulated products or the substrate is oily or fatty then the heat resistance is marked higher. This also applies to direct heating with steam; dry superheated steam will be less effective for inactivation.

pH

pH has a marked effect on microbial inactivation. In general for acidic products, pH < 4.5, e.g., a wide range of fruits and their juices, pathogenic organisms do not cause a problem, hence only a mild heat treatment, usually referred to as pasteurisation, is required for stabilising the product. For pH > 4.5 e.g., most vegetables, fish and meat products, the scheduled process must be sufficient to inactivate *Clostridium botulinum* spores. For products which fall close to the dividing line 4.4–4.7 special care must be taken, e.g., tomato products and pears, depending on the variety and maturity. In some cases it is possible to acidify the product to ensure that a pasteurisation process is adequate. For products for

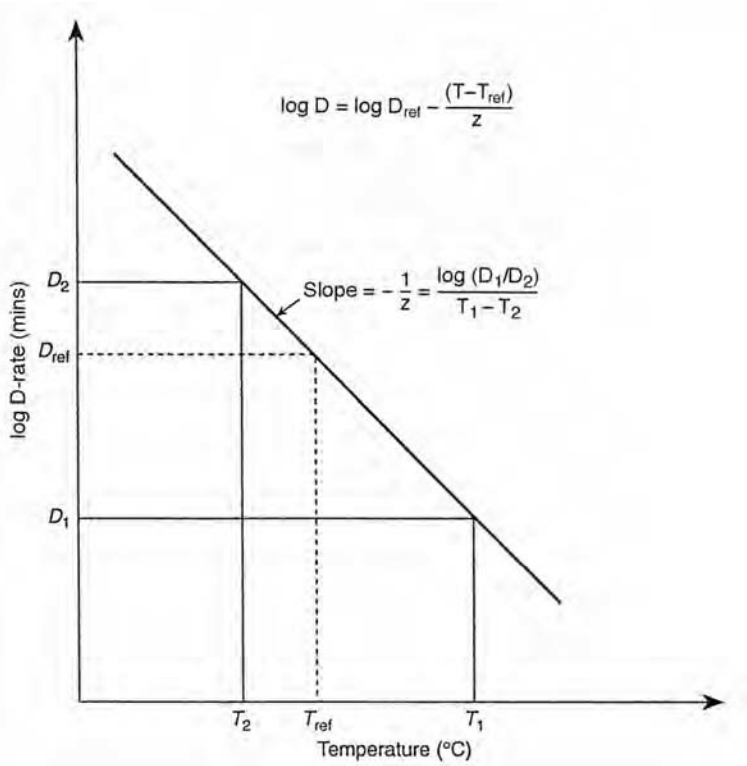

Fig. 1.3 Determination of the z-value from log D versus temperature.

which there is no scheduled process it is necessary to determine the pH beforehand and if this falls into a borderline case to do inoculated or other microbiological tests. It is usual to identify four categories of products as shown in Table 1.3.

Table 1.2 Some typical D values for spores

Organism	Temperature ºC	D-value (min)
Bacillus coagulans	121	3
Bacillus coagulans var. thermoacidurans	96	8
Bacillus licheniformis	100	13
Bacillus stearothermophilus	121	3–5
Bacillus subtilis	121	0.3–0.7
Clostridium botulinum	121	0.2
Clostridium butyricum	85	8
Clostridium sporogenes	121	0.2–1.5
Clostridium thermosaccharolyticum	121	3–5
Desulfotomaculum nigrificans	121	3–5

Source: CCFRA Database.

Table 1.3 pH values for some food products

Category	Designation	pH range	Products
Group 1	low-acid	$\geq$5.0	meat, fish, milk, some soups and most vegetables
Group 2	medium-acid	5.0–4.5	meat and vegetable mixtures, pasta, soups and pears
Group 3	acid	4.5–3.7	tomatoes, figs, pineapple and other fruits
Group 4	high-acid	$\leq$3.7	citrus juices, pickles, grapefruit and rhubarb

Other factors
These include presence of oily or fatty constituents, dielectric constant, ionic species, e.g., salt or nitrite, ionic species, oxygen content, organic acids and antibiotics (Gould, 1995). Some of these materials are used to enhance preservation processes by reducing the scheduled heat process required.

1.3 Setting the limits for sterilisation and pasteurisation processes

1.3.1 F-values and the lethal rate concept

A measure of the lethal effect of a process can be obtained using the decimal reduction time ratio D/D_T and this is known as the lethal rate in minutes defined by equation 1.5

$$L = 10^{(T-T_{ref}/z)} \tag{1.5}$$

The lethal rate for T = 111.1ºC and T_{ref} = 121.1ºC will be $10^{-(10/10)} = 0.1$ min. Thus one minute at 111.1ºC is worth 0.1 min at 121.1ºC.

Since the temperature at the slowest-heating point in the food in a container changes with time it is necessary to determine the lethal contribution of each temperature. The summation of the lethal rate or lethality obtained at each temperature for unit time is known as the F-value.

$$F = \int L \, dt \tag{1.6}$$

In using these two formulae it is necessary to know the z-value of the target organism. For low-acid foods z = 10ºC corresponding to the generally used value for *Clostridium botulinum*. The most usual form for F-value equation is given in equation 1.7:

$$F = \int 10^{(T-T_{ref})/z} dt \tag{1.7}$$

or for a low-acid food cook the F-value at the reference temperature of 121.1°C, known universally as the F_0-value and referred to as F-nought or F-zero:

$$F = \int 10^{(T-121.1)/10} dt \tag{1.8}$$

A typical temperature-time profile obtained for a canned food undergoing processing is shown in Fig 1.4. This has been obtained by placing a thermocouple at the point of slowest heating in the food product and it includes the effect of the coming-up to retort temperature time and also the cooling time (see Section 1.3.5). The argument is that if the F-value at this point is greater than the minimum specified for the process then all other points in the container will have received at least the minimum required. On the plot the lethal rate is also shown and from the area under the curve the total integrated lethality, i.e., the F-value, can be obtained.

F_c is sometimes used to indicate the F-value at the centre, i.e., the slowest heating point, and F_s for the total integrated lethality. The standard F-value is also written using adscripts F^z_T or $F^{10}_{121.1°C.}$

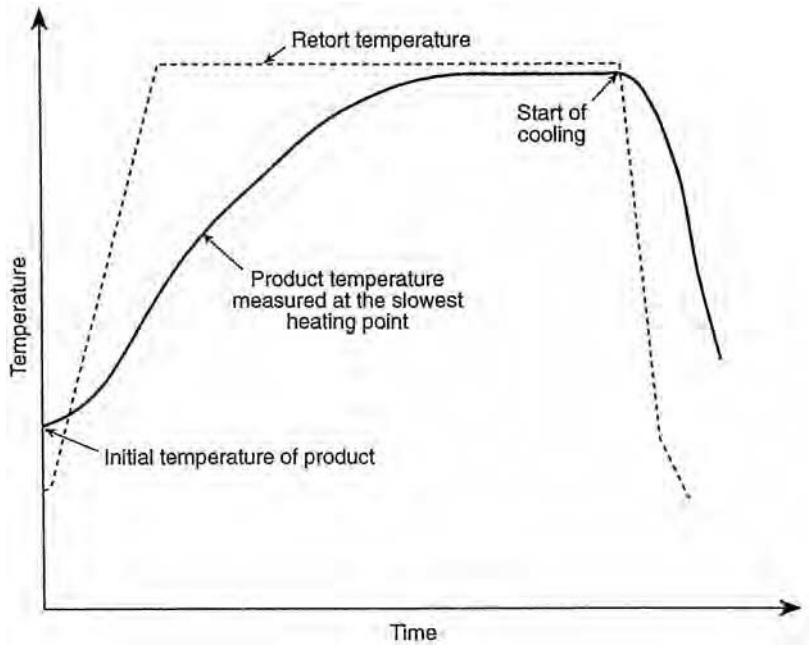

Fig. 1.4 A typical temperature-time profile obtained from a canned food undergoing processing.

For some applications the conduction errors inherent in commercial thermocouples are too great for accuracy and consequently thin thermocouple wires of thickness of the order of 0.1 mm are used. It is essential for temperature measurement work that the sensor is calibrated to an appropriate standard using a constant temperature source and a thermometer calibrated to a national standard, (ASTM, 1988; Cossey and Richardson, 1991; Dobie, 1993).

Thermocouple location should be made at the point of slowest heating, often known as the critical point. This point varies, depending on the nature of the product and the type of cooker, e.g., stationary or rotating. One method of determining this point is to place a number of thermocouples in the container at differing positions and to observe which is the slowest heating. For small sized cans of conduction-heating food the critical point will be near the geometrical centre of the food mass. For large sized cans, e.g., A10 and larger, this is not necessarily so because the centre of the can will continue to heat until the cooling effect is felt. There will therefore be an additional contribution to the lethality. Flambert and Deltour (1972) showed that the critical point location depended on the h/d ratio for the can. For the particular conditions of their experimental work they showed that the critical point would be at the geometrical centre of the food mass for $h/d < 0.3$ and greater than 0.95. For $0.3<h/d<0.95$ the critical point was located symmetrically along the vertical axis with respect to the central plane. For values $0.95<h/d< 1.9$ the critical point lies in a ring-shaped space across the can. For convection heating products the critical point is located on the central axis of the container but at points lower than the geometrical centre. The UK recommendation is that the thermocouple should be placed at a height from the base of 20% of the total height (CCFRA 1977).

For products that show a change of heating from convection to conduction during the processing, i.e., broken-heating curves, the convection heating position should be used. Complex heating products should always be studied with multiple thermocouple positions initially. For experimental purposes involving the study of steriliser performance it is convenient to use simulant materials. The most common of these is a carefully prepared suspension of a clay mineral, bentonite in water. Dilute suspensions 1% may be used to simulate convection heating packs and more concentrated ones for broken-heating 3.5% and conduction heating packs 5%. A useful simulant for conduction-heating packs is the silicone elastomer – Sylgard.

1.3.6 Factors affecting heat penetration

(a) Process-related factors. These include retort temperature and process time, the nature of the heat transfer medium and container agitation. Saturated steam is the most effective heat transfer medium and provides an effective pressure to balance the internal pressure developed in the container. With water and steam air mixtures the heat transfer rate depends on the velocity of the heating medium. In batch retorts, there is an initial period, known as the come-up time before the retort reaches processing temperature and this

must be considered in process determination. Conversely, continuous retorts are at a steady-state before the cans are introduced.

(b) Product-related factors. These include product consistency, initial temperature. Initial spore load, thermal properties, pH, additives. It is possible to categorise various types of behaviour, namely, most rapid convection heating – thin liquids, juices, broths and milk, less rapid convection heating – fruits/syrup, vegetables/brine, low-starch purées, some vegetable soups, slower convection/conduction heating products – cream soups, noodle soups, tomato juice; conduction-heating products containing water – cream-style corn, thick purées, solid pack products, pet foods, rice, spaghetti and conduction-heating products not water based – high fat or oil meat and marine products, high sugar products and low-moisture puddings.

(c) Packaging-related factors. These include container materials and shape. The thermal properties of the material determine the rate of heat penetration; metallic materials have a low resistance whereas glass and plastic materials have a higher resistance.

1.3.7 Analysis of heat penetration data

The typical temperature time profile for a canned product heated in a batch steam retort is shown in Fig. 1.5. This may be converted to a linear curve using a

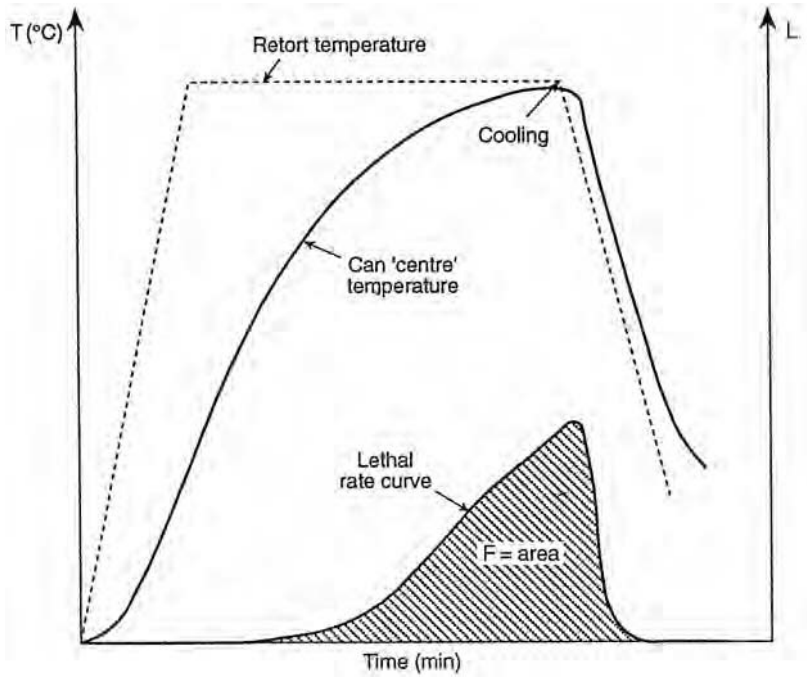

Fig. 1.5 Determination of F-value from lethal rate versus temperature.

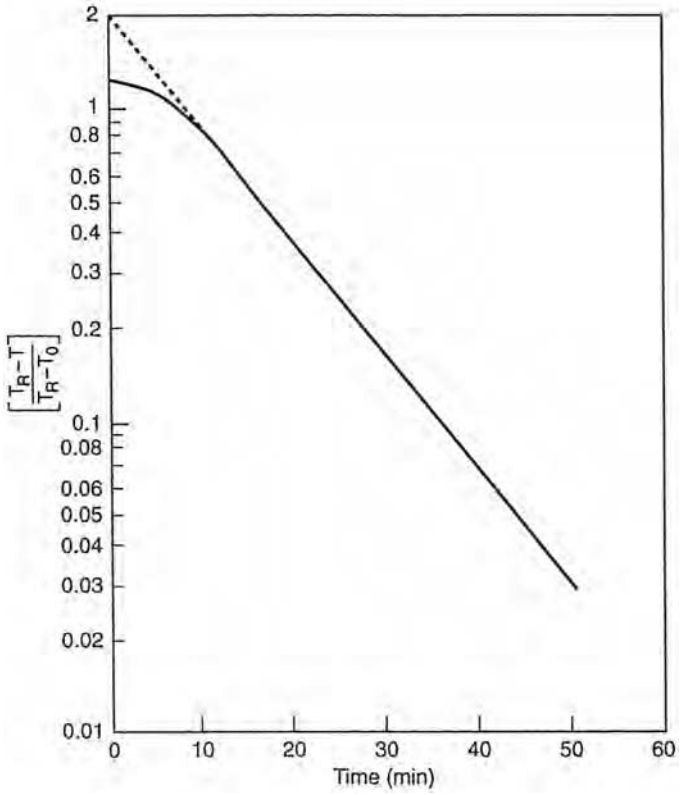

Fig. 1.6 Heat penetration curve for the heating process.

logarithm temperature scale (Fig 1.6). From this, two important parameters may be obtained – the lag of the heating curve j and the f value f_h for heating and f_c for cooling. The relationship for the logT/t curve is given by equation (1.10)

$$(T_R - T_t)/(T_R - T_0) = j\ 10^{-t/f}\ j\ e^{-2.303t/f} \qquad (1.10)$$

where T_R is the retorting temperature, T_t is the measured temperature in the can at any time t, T_0 is the initial temperature of the food in the can at time $t = 0$, j is the lag factor in mins and f is the heating time for one log cycle of temperature.

For convection-heating foods $j = 1$ and for conduction-heating packs j is usually about 2. Some typical f_h-values are given in Table 1.5. The importance of the f_h-value is that all aspects of the heat penetration are contained in the one parameter. The f_h-value is inversely related to the thermal diffusivity α of the product. Equation (1.11), which is derived from heat transfer considerations (Holdsworth, 1997), may be used to determine the f_h-value for differing sizes of cylindrical container.

$$f_h = 0.398/[\alpha(1/a^2 + 0.427/4b^2)] \qquad (1.11)$$

where 2a is the diameter and 2b the height of the can respectively.

Table 1.5 Some typical values for f_h for canned products processed in steam-heated static retorts.

Can size D × h mm	Conduction-heating food min	Convection-heating food min
66 × 54 (5oz)	25	4.0
66 × 78 (picnic)	34	4.5
66 × 102 (A1)	39	5.0
73 × 62 (8Z)	34	4.5
73 × 115 (UT)	47	4.5
74 × 116 (16Z)	52	5.5
84 × 114 (A2)	62	6.0
99 × 119 (A2½)	83	7.0
154 × 235 (A10)	198	11.0

Source: Collected data CCFRA, Chipping Campden.

1.4 Setting thermal process parameters to maximise product quality: C-values

1.4.1 Problems with thermal processing

The thermal process delivered to a packaged food not only inactivates potential spoilage organisms, but it also cooks the food, in many cases to produce a food with an acceptable texture, in accordance with producer's brand image. Many canned foods are essentially pre-cooked so that, as convenience foods, they only require the minimum of reheating before being eaten. The amount of cooking depends very much on the nature of the produce. For convection-heating foods such as vegetables in brine heat penetration is fairly rapid and uniform across the contents of the can. With conduction-heating products, where the contents of the can are not mobile then the product nearest the outside of the container receives far more heat than that delivered at the point-of-slowest heating near the centre of the product mass. Whilst can foods have played a very important part in feeding people, under varying circumstances, they have generally been perceived as being of a lower quality then their chilled or frozen counterparts. However, because heat-preserved foods may be stored at ambient temperatures, they are extremely useful for a variety of purposes. Consequently, there has been considerable effort to reduce the thermal processes for canned foods so that less heat damage is done to the food components, e.g., vitamins, colour and other thermo-labile components. Some of the methods, which have been used to reduce thermal processes, have included: (a) alteration of container geometry, e.g., using thin layers of product in flexible plastic packages and trays, (b) higher temperatures and shorter times, which require special processing techniques to counteract the internal pressures developed in the containers, (c) reducing the processes and storing under chilled conditions, (d) acidification of the products followed by pasteurisation, and (e) the use of microwave or ohmic heating.

Table 1.6 Minimum equivalent times (min) for sterilisation and cooking of beans in tomato sauce in a rotary cooker

		Process temperature (C)		
Can size		115.5	121.1	126.6
A1	Sterilisation	22	13½	10
	Cooking	38	26	19
A2	Sterilisation	25	16½	12½
	Cooking	40	28	21
A2½	Sterilisation	27	18	14½
	Cooking	41	29	22
A10	Sterilisation	35	26	21
	Cooking	46	34	47

Source: CCFRA Tech. Bulletin No.4.

'botulinum process.' C-values for $T_{ref} = 100$ºC are usually of the order of 5–30 min., but for $T_{ref} = 121$ºC rather lower at 1–7 min. Some typical z_c-values for heat vulnerable components are given in Table 1.7

Sterilising values are usually evaluated at the point of slowest heating, but C-values are for the whole of the contents and are often designated C_s-values as defined by the equation

$$C_s = D_{ref} \log(c/c_o) \tag{1.13}$$

where c_0 and c are the concentrations of the heat-labile component at time 0 and t.

The volume average C-value for a container is given by the equation

$$C_{ave} = (1/V) \int \int 10^{(T-T_{ref})/z_c} dt dV \tag{1.14}$$

For applications of this concept see Ohlsson (1980a,b,c). This was also used indirectly by Tucker and Holdsworth (1990, 1991). However, Silva *et al*. (1992b)

Table 1.7 Some typical z-values for heat-vulnerable components

Component	z-value range ºC
Bacterial spores	7–12
Vegetative cells	4–8
Enzymes	10–50
Vitamins	25–30
Proteins	15–37
Sensory factors	
Overall	25–47
Texture-softening	25–47
Colour	24–50

Source: Holdsworth (1992).

pointed out that the C_s-value depends on the D_{ref} for the specified component and this should be taken into account by using equations (1.15) and (1.16):

$$c/c_0 = (1/V) \int 10^{C_c/D_{ref}}.dV \tag{1.15}$$

$$\text{where } C_c = (1/V) \int 10^{(T-T_{ref})/z_c}.dt \tag{1.16}$$

This allows for the use of different heating profiles. Equations (1.14) and (1.15) give essentially the same results for high D_{ref}-values found for vitamin destruction; however for low values of, e.g. colour degradation or texture softening then the latter is superior. McKenna and Holdsworth (1990) have reviewed the published models for determining both F_s and C_s. Using the simple relation equation (1.12) Figure 1.7 compares the rate of establishment of the C-value with that of the F-value for the same process.

Relatively little data has been obtained comparing C_0-values for food products; however, Preussker (1970) produced some for static processes, and Eisner (1988) for rotary processes. More recently Tucker and Holdsworth (1991) have determined $C_{121.1}$-values for a number of ready meals (see Table 1.8.). These data help to determine the magnitude of the effect of the process and to give some practical processes for sterilising ready meals.

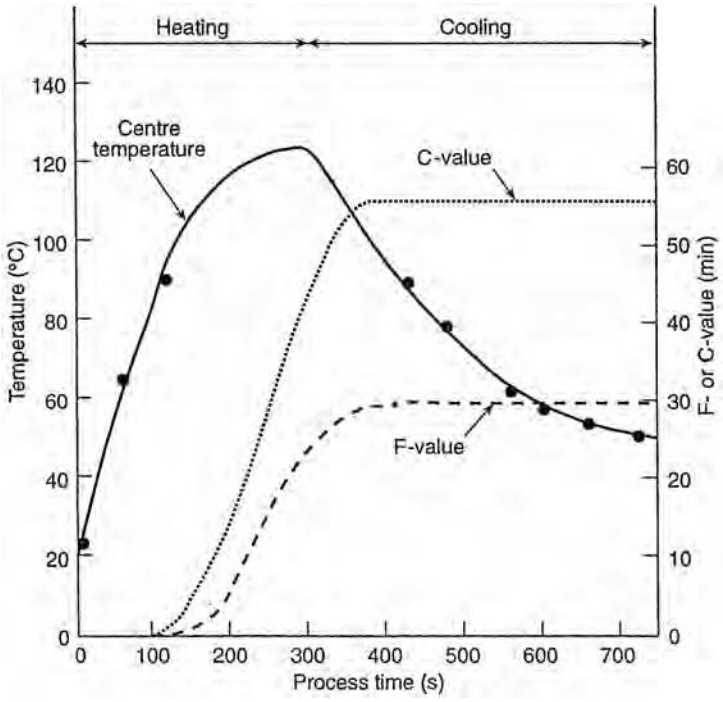

Fig. 1.7 C-value variation with heating profile.

Table 1.9 Optimisation of heat–vulnerable components in canned foods using graphical procedures in chronological order

Heat-vulnerable components			Sterilisation conditions		Reference
Description	z_c (ºC)	C_{100} (min)	z (ºC)	$F_{121.1}$ (min)	
Thiamin/cured meat	–	–	10.0	0.25	Greenwood *et al* (1944)
Thiamin/cured meat					Jackson *et al.* (1945)
Thiamin/cured meat					Ball and Olson (1957)
Cooking	33	5–30	10.0	2–30	Mansfield (1962)
Betanin	–	–	10.0	1.0	Hermann (1969)
Cooking/linear heating	33	0.1–50	10.0	0.1–50	Preussker (1970)
Enzymes/green beans	48.9	–	8.9	0.9	Reichert (1977)
Enzymes/potatoes	10.3	–	10.0	2.5	Reichert (1977)
Enzymes	17.5	–	8.9	0.9	Reichert (1977)
Vitamin C	23.2	–	8.9	0.9	Reichert (1977)
Vitamin B_1	26.1	–	8.9	0.9	Reichert (1977)
Cooking	25–40	–	8.9	0.9	Reichert (1977)
Sensory	26.5	–	8.9	0.9	Reichert (1977)
Cholorphyll/green beans	87.8	–	8.9	0.9	Reichert (1977)
Cooking	33.0	10,36,52	10.0	1.0	Reichert (1974, 1977)
Cooking/peas	29.0	42,45,62	10.0	76.0	Reichert (1974, 1977)
Vitamin B_1/liver	26.1	–	10.0	5–10	Bauder and Heiss (1975)
Lipase (microbial)	3.1	–	10.0	2.7	Svensson (1977)
Peroxidase	35.0	–	10.0	10.0	Svensson (1977)
Thiamin	–	–	10.0	6.0	Lund (1977)
Anthocyanin/grapes	23.0	18.0	10.0	24.0	Newman and Steele (1978)
Thiamin	–	–	10.0	5.0	Ohlsson (1980b)
Thiamin/milk	–	–	10.5	2.0	Kessler (1981)
Lysine/milk	–	–	10.5	2.0	Kessler (1981)
Protease	–	–	10.5	2.0	Kessler (1981)
Lipase	–	–	10.5	2.0	Kessler (1981)
Colour	–	–	10.5	2.0	Kessler (1981)
Enzymes/particulates	27.0	–	10.0	3.0	Brown and Ayres (1982)
Browning/protease	25.0	–	10.0	4.0	Jelen (1983)
Quality/tomato purée	–	–	10.0	various	Zanoni *et al.* (2003)

Source: Holdsworth (1985).

earliest was due to Teixeira *et al.* (1969), who used a finite-difference method to solve the sterilisation and cooking equations involving the heat transfer into the cans and the process conditions. Using the models and experimental data for the retention of thiamin the effect of various process times/temperatures was studied. Figure 1.10 shows that percentage of thiamin retained reached an optimum value for a process of 90 min/120ºC. The effect of container size was also studied and it was shown that for equal volumes the thiamin retention decreased from 68 to 41% for values of L/D increasing from 0.96 to 1.270 and

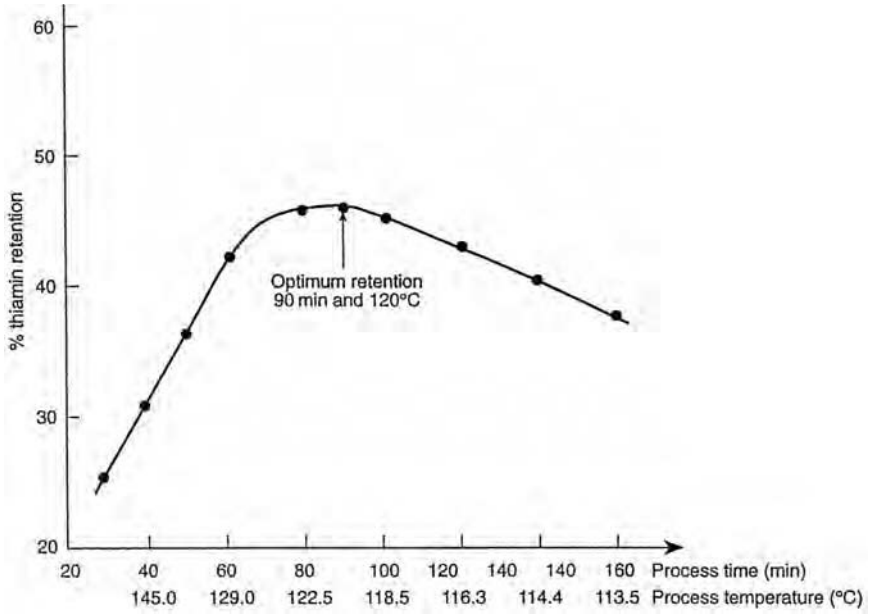

Fig. 1.10 Optimisation curve for the percentage thiamin retention for various time/temperature combinations.

then increased from 43 to 63% for values of L/D increasing from 1.710. Using time varying surface temperature profiles had little effect on thiamin retention.

Lenz and Lund (1977) studied the statistical distribution of C_s-values and found this to be normal for processing times of less than 20 min; however, for longer times an increase in the standard deviation was observed with pronounced skewness of the distribution.

Sjöström and Dagerskog (1977) reported an important study of the browning of canned chopped fish ($z_c = 33$ºC) for processing at temperatures between 110 and 145ºC. For a range of times and temperatures equivalent to $F_0 = 7.5$ min they showed that for a t/T combination of 60 min at 127ºC the C-value was a minimum for a position intermediate between the surface and the centre of the food. Again variable temperature profiles had little effect on colour retention.

Ohlsson (1980a,b,c) made an extensive study of the C-values for a range of products, including fish paste, liver paste, strained beef, strained vegetables, tomato sauce and vanilla sauce and a range of sensory factors, odour, appearance, taste, consistency, hardness, coarseness and lightness. This work showed that the volume average cook value C_{av} for a given F-value, showed minimum values, which decreased with increasing temperatures and decreasing can sizes. The optimal processing temperature was found to be between 117 and 199ºC for a 73 $\times$ 99 mm can, which was found to be consistent with the earlier work of Teixeira *et al.* (1969). Richardson *et al.* (1988) used a finite-difference model to determine nutrient retention in conduction-heating packs. This work showed that the experimental results correlated better with the theoretical results