

## **Optimisation of Thermal Processing – A Review**

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### *ABSTRACT*

*The mathematical methods for optimising the effects of heat processing food products are reviewed in relation to microbial destruction, nutrient destruction, cooking value and loss of quality. Some data are presented for the kinetics of the various thermal effects. The results obtained by various workers are presented with particular reference to nutrient retention.*

### 1. INTRODUCTION

This review is concerned with the technique which may be used by the food process engineer to estimate the level of retention of heat-labile components, e.g. nutrients, in food products undergoing thermal processing. The methods involve optimizing the various factors affecting the kinetics of the destruction of microbial spores, enzymes and vitamins as well as the loss of quality factors, viz. colour, texture, flavour. This topic is of particular importance in relation to the nutritional value of processed foods, to nutritional labelling and quality aspects. Basically these methods seek to determine the most suitable processing conditions, viz. time-temperature profiles, for achieving the desired objective, e.g. maximum retention of a specified vitamin or best retention of colour or flavour consistent with microbiological stability and safety. A number of general reviews have already been published (Bauder, 1974; Michiels, 1974; Lund, 1975; Hayakawa, 1977; Lund, 1977; Ohlsson, 1977; Herrera, 1978; Rodrigo *et al.*, 1980) which deal with various parts of the subject.

Thermal processing is one of the few production processes in industry which relies on a mathematical model to ensure the safety of the products. The theoretical basis for this is a combination of the

time-temperature profile (as established by heat transfer) and the kinetics of microbial destruction. The methods available for estimating the sterility of processes and for converting processes from one container size to another have been reviewed by Holdsworth and Overington (1975).

The need to optimise processing conditions arises when the kinetic behaviour of the different components is considered because the rate of a chemical reaction generally doubles for a 10°C rise in temperature whereas rates of bacterial destruction increase ten-fold under similar conditions. The major constraint on optimising procedures is that the desired degree of sterility must be achieved. Although the effects of different time-temperature combinations have been recognised by canners for many years, especially in relation to observable differences, there has been little incentive until recently to consider the question of nutrient retention. Although the nutrient levels in canned foods have been known since the earliest years of this century, little attention has been paid to using optimised processes. It should be noted that during this time temperatures of processing have risen progressively, mainly to increase production rates, but generally with the added feeling that the quality would be improved. Indeed, the belief that high temperatures and short times result in better quality retention in a wide range of canned products and can be used in conjunction with aseptic packaging is only correct for certain types of food products, i.e. thin films of liquid products. Under any other conditions, notably with viscous liquid products and particulates, heat transfer to the centre of the material constitutes an important barrier to the application of the HTST principle.

## 2. CRITERIA FOR STERILISATION

### 2.1 Concept of slowest heating point

#### 2.1.1 *Empirical representation*

The basic mathematical model which is widely used and based on the original work of Ball (Ball and Olson, 1957), is:

$$F_0 = \int_0^t 10^{(T-T_{\text{ref}})/z} dt \quad (1)$$

where  $F_0$  = the integrated lethality (at the slowest heating point) (mins),  $t$  = time of processing (mins),  $T$  = temperature ( $^{\circ}\text{C}$ ) at time  $t$ ,  $T_{\text{ref}}$  = reference temperature,  $121.1^{\circ}\text{C}$  (equivalent to  $250^{\circ}\text{F}$ ),  $z$  = slope of the logarithm of the decimal reduction time,  $D$ , versus temperature for the specific organism (for *Clostridium botulinum*  $z = 10^{\circ}\text{C}$ ).

This equation can be used to estimate the  $F_0$  value of any process provided the relationship between the time and temperature is known or can be calculated using heat transfer equations with the appropriate boundary conditions (Overington and Holdsworth, 1974; Holdsworth and Overington, 1975; Holdsworth, 1979; Holdsworth, 1982). The calculated value, or the value obtained from heat penetration experiments, may then be compared with the minimum necessary process determined from the number of decimal reduction times,  $D$ , required on a probability basis of spore survival. If the process aims at a survival of not more than 1 in  $10^x$ , i.e.  $x$  decimal reductions, then it is possible to use  $x D_{121.1}$  as the minimum  $F_0$  value, where  $D_{121.1}$  is the decimal reduction time (in min) at  $121.1^{\circ}\text{C}$ . For low-acid foods of pH greater than 4.5 a value of  $x = 14$  is used in relation to the survival of spores of *Clostridium botulinum*. If the maximum heat resistance of these spores, as expressed as decimal reduction time, is 0.3 then for a probability of 1 in  $10^{14}$  survival,  $F_0 = 4.2$  (Gillespy, 1967). For variations in pack style the basic  $F_0$  value may be different from this value (Gillespy, 1962).

### 2.1.2 Kinetic representations

The  $F_0$  value may also be represented in terms of reaction kinetics constants (eqn (2); Aiba *et al.*, 1965; Aiba and Toda, 1967).

$$F_0 = D_{121.1} \ln(N_0/N) = A \int_0^t e^{-E_a/RT} . dt \quad (2)$$

where  $N_0$  is the initial number of organisms and  $N$  the number at time  $t$ ,  $N = N_0 e^{-kt}$ ,  $k$  is the reaction rate constant,  $A$  is the Arrhenius constant;  $E_a$  is the energy of activation.

On comparing the two models  $k$  is proportional to  $1/D$  and  $E_a$  is proportional to  $1/z$ .

There is little to choose between the empirical  $D$ - $z$  model and the  $k$ - $E_a$  kinetic model. The former is based on  $\log_{10} D$  being proportional to  $T$  and the latter is based on  $\log_{10} k$  being proportional to the reciprocal of  $T$  (Gillespy, 1947; Aiba *et al.*, 1965). Jones (1968) made a

comparison of the two approaches and found the results were significantly different; however, the data which he used were not entirely consistent (Cowell, 1968). Jonsson *et al.* (1977) tested the two using data for the inactivation of *Bacillus stearothermophilus* spores and found that both models gave good linear regressions but both had a significant lack of fit, measured by the 'chi-squared' test. It was concluded that the use of these models for the prediction of behaviour outside the range of the experiments might be unreliable. Perkin *et al.* (1977) showed for the same microorganism that the Arrhenius relationship was satisfactory over a temperature range 120–150°C.

## 2.2 Concept of total integrated sterilising value

The concept of  $F_0$  value at the centre of a pack or particle may be extended to the idea of the total integrated sterilising value,  $F_s$ , for the whole container or food particle (Gillespy, 1951; Hicks, 1951; Stumbo, 1953, 1973).

$$F_s = F_0 + D \log [(D + A(F_\lambda - F_0))/D] \quad (3)$$

where:  $D$  is the decimal reduction time,  $F_\lambda$  is the value of  $F$  at the point where the value of the lag factor,  $j^*$ , is equal to half its value at the centre;  $A$  is a constant depending upon the geometry ( $A = 10.73$  for a cylindrical particle, 11.74 for a cubical particle and 9.28 for a spherical particle; Brown and Ayres, 1982; Newman, 1984). This form of the lethality eqn (3) is particularly useful for determining rates of degradation of chemical substances uniformly distributed throughout the particles.

## 3. KINETIC FACTORS

### 3.1 $z$ -values for microbial inactivation

The use of the concepts outlined above requires a knowledge of the  $z$  value and the associated  $D$  value at 121.1°C. *Clostridium botulinum* is

\*The lag factor  $j$  denotes the time for the rate of heating at a point to become logarithmic. It varies with position in the pack or particle and with the initial temperature distribution.

by far the most important spore-forming microorganism in relation to the safety of heat-processed foods and consequently there is a considerable amount of data available for this organism. The bulk of evidence from commercial operations would indicate that a  $z$  value of  $10^\circ\text{C}$  and a  $D_{121.1}$  value of 0.3 is entirely adequate for producing safe, low-acid foods heat processed in the temperature range  $110\text{--}130^\circ\text{C}$ .

Perkins *et al.* (1975) examined the evidence for lower values of  $z$  for *Clostridium botulinum* in food substrates and came to the conclusion that a value of  $8^\circ\text{C}$  would be a better figure. However, these experimental results were associated with much lower  $D_{121.1}$  values which would compensate for a reduced  $z$  value. Stumbo *et al.* (1975) examined the minimum processes required for 41 can sizes, five different heating rates, eleven different initial food temperatures, three different  $D_{121.1}$  values and six different  $z$  values and presented tables of differing degrees of safety in relation to these variables. Pflug and Odlaug (1978) have reviewed in detail the  $z$  and  $f$  values used to ensure the safety of low-acid canned foods and have come to the conclusion that  $z = 10^\circ\text{C}$  and  $D_{121.1} = 0.2$  is adequate in conjunction with a process equivalent to  $F_0 = 3$  min.

Ito and Chen (1978) have reviewed the data on the effect of pH on growth of *Clostridium botulinum* in foods and have come to the conclusion that although a pH of 4.6 will inhibit growth the minimum pH may be higher for some foods.

### 3.2 $z$ -value for destruction of heat-labile chemical constituents

The thermal resistance factors for nutrients are in the range  $z = 25\text{--}30^\circ\text{C}$ ;  $E_a = 20\text{--}30$  kcal mol<sup>-1</sup> and  $D_{121.1} = 100\text{--}1000$  min. Compared with vegetative cells and spores for which  $z = 5\text{--}12^\circ\text{C}$ , the rates of destruction of nutrients are very much less temperature sensitive. Some typical data are given in Table 1.

### 3.3 $C$ -value concept

Mansfield (1962) used the concept of a 'lethality-like' value for degradation of sensory value based on a temperature sensitivity  $z_c$ .

$$C_{100} = 10^{(T-100)/z_c} \text{ (in minutes)} \quad (4)$$

TABLE 1  
Some Kinetic Factors for Chemical and Physical Changes in Food

Component or attribute	Product	Kinetic data		Reference
		$z$ ( $^{\circ}\text{C}$ )	$E_a$ ( $\text{kJ mol}^{-1}$ )	
<i>Vitamins</i>				
Thiamin	Milk	29.4-30.6	—	Bayoumi and Reuter (1980), Bayoumi (1981)
	Cured meat	31.4	—	Horak (1980)
	Strained meat	31.3	—	Jackson <i>et al.</i> (1945)
	Peas	25.4	—	Weir (1948)
	Phosphate buffer	31.3	89	Bendix <i>et al.</i> (1951)
	Phosphate buffer	—	—	Pflug and Esselen (1953)
		25.0	—	Feliciotti and Esselen (1957)
	Purée foods	—	113	Mulley <i>et al.</i> (1975)
	Meat	26.7	—	
	Vegetables	—	114-124	
	Ground meat	22	113.3	Skjoldbrand <i>et al.</i> (1983)
	Pork	32	—	Herrman (1969, 1976)
	Meat	26	—	Hayakawa (1969)
	Vegetable	30.7	—	Hayakawa (1977)
Methionine	Model systems/milk	—	125-129	Martens (1980)
	Spinach	—	60.9	Paulus <i>et al.</i> (1975)
Ascorbic acid	Spinach	27.4	—	Hayakawa (1969)
	Model systems	—	40.0	Laing (1978)
<i>Enzymes</i>				
Peroxidase	Vegetables	27.7	—	Aylward and Haisman (1969)

Vegetables	27.8-31.4	--	Adams (1978)
Heat resistant	27.3	--	Ling and Lund (1978)
Heat labile	17.0	--	Ling and Lund (1978)
Potato	35.0	--	Svensson (1977)
Spinach	8.3	--	Aylward and Haisman (1969)
Lipoxygenase	8.7	--	Aylward and Haisman (1969)
Potato	3.6	--	Svensson (1977)
O-Diphenol oxidase	5.5	--	Svensson and Eriksson (1974)
Polyphenol oxidase	7.8	--	Aylward and Haisman (1969), Svensson (1977)
Pectin esterase	16.2	--	Nath and Ranganna (1983)
<i>Sensory quality</i>			
Overall			
Peas	28.3	--	Hayakawa <i>et al.</i> (1977)
Green beans	28.8	--	Hayakawa <i>et al.</i> (1977)
Corn	31.6	--	Hayakawa <i>et al.</i> (1977)
Vegetables	14.44	--	Mansfield (1974, 1962)
Haricot beans	25	--	Michiels (1973)
Range	13-29	--	Ohlsson (1980b)
Range	16-33	--	Ohlsson (1980b)
Range	17-34	--	Ohlsson (1980b)
Vegetables	39-42	--	Hayakawa <i>et al.</i> (1977)
Betanin	30	--	Herrman (1969)
Milk (browning)	21.3 (95-120°C)	--	Burton (1954, 1983)
Milk (browning)	26.2 (95-120°C)	107 (25-150°C)	Horak and Kessler (1981)
Milk (browning)	28.2 (100-150°C)	--	

This gives a measure of the destruction of a particular sensory attribute and can be used to compare different effects, e.g. microbial destruction, enzyme inactivation, 'degree of cookedness' and consequently to optimise processes. Ball and Olson (1957) expressed the same concept in terms of an  $E$  value, the corresponding  $z$  value being designated as  $i$ ; however, these terms are no longer in use.

For different reference temperatures the following conversion is used

$$C_{100} = C_{121.1} \times 10^{(121.1 - 100)/z_c} \quad (5)$$

and from eqns (1) and (4) it can be shown that

$$\log_{10} C = \frac{z}{z_c} \log_{10} F + \frac{(121.1 - 100)}{z_c} \quad (6)$$

The possibility of an optimum condition arises primarily from the very different effect of temperature on the rates of destruction of microbes and chemical substances.

Some examples of kinetic data are given in Table 1. Further data are given by Lund (1975), Kessler (1981) and Burton (1983), including activation energies and  $D_{121.1}$  values. Care should be taken to examine the order of a particular reaction, since it is usually assumed that the reactions are kinetically first-order but this is not always so.

#### 4. COMBINED GRAPHICAL REPRESENTATION

Figure 1 shows the relationship between time and temperature for the destruction of microbial spores (line FF) and for the cooking of a food product to a specified degree (line CC). From this it can be seen that the only acceptable combinations of time and temperature fall within the area 'cooked sterile', all other combinations of time and temperature being unacceptable. Greenwood *et al.* (1944) were the first to publish this technique which they used to study the destruction of thiamin in cured pork luncheon meat at three levels, 50%, 20% and 10% compared with microbial destruction. Since then many publications have referred to this technique to optimise processing conditions. Table 2 lists some and gives details of each including the microbial destruction conditions and the other chemical and sensory factors.

The form of graphical representation used in this method implies instantaneous heating and cooling of the product and whilst this might



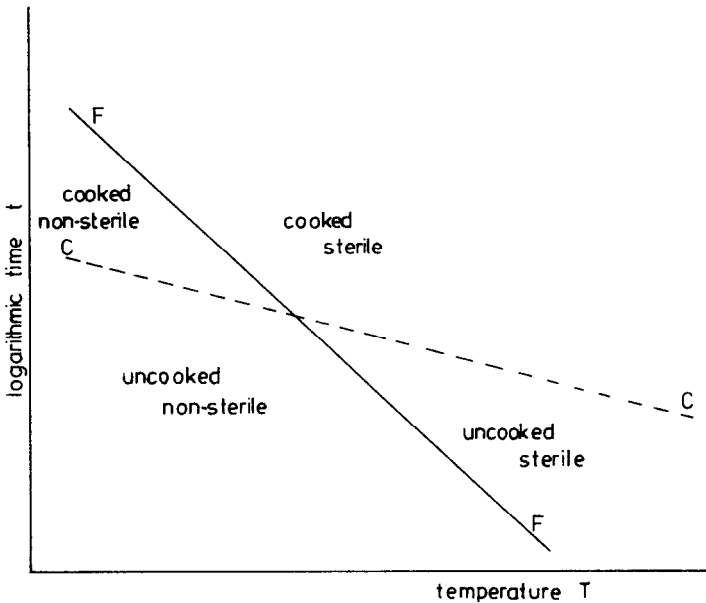


Fig. 1. Diagram of  $t$ - $T$  relationship for microbial destruction,  $F$ , and cooking,  $C$ .

be possible with small quantities of material, e.g. thin films of low viscosity liquids, it is not the case for cans of food or food pieces. Figure 2 shows the effect of heat transfer resistance on cooking and sterilisation at the centre of a spherical food particle, radius 1 cm (Holdsworth and Newman, 1977; Newman and Steele, 1978) obtained by calculating the centre lethality and chemical destruction rates using the appropriate kinetic factors for a range of time-temperature combinations.

This technique may be extended to  $F_s$ , the total integrated value, rather than the centre  $F$  value. This is necessary when studying the destruction of quality factors distributed throughout the product.

## 5. PREDICTIVE METHODS

### 5.1 Application of the general and formula methods

The earliest published method for calculation of nutrient retention was due to Ball and Olson (1957), who extended the mathematical pro-

**TABLE 2**  
Graphical Optimisation of Chemical Versus Biological Factors (*F* Values Based on 121.1°C and *C* Values at 100°C, Both in Minutes)

<i>System</i>		<i>Reference</i>
<i>Microbial</i>	<i>Chemical or other</i>	
$z = 10^{\circ}\text{C}; F = 0.25$	Thiamin destruction, 10, 20, 50%	Greenwood <i>et al.</i> (1944), Ball and Olson (1957)
$z = 10^{\circ}\text{C}; F = 2-30$	Cured meat Cooking $z = 33^{\circ}\text{C}; C = 5-30$	Jackson <i>et al.</i> (1945) Mansfield (1962)
$z = 10^{\circ}\text{C}; F = 1$	Betanin, 5-99% destruction	Herrman (1969)
$z = 10^{\circ}\text{C}; F = 0.1-50$	Cooking $z = 33^{\circ}\text{C}; C = 0.1-50$	Preussker (1970) (also includes effect of linear heating)
$z = 10^{\circ}\text{C}; F = 2.5$	$z = 10.3^{\circ}\text{C}$ , enzymes in potatoes	Reichert (1977)
$z = 8.9^{\circ}\text{C}; F = 0.9$	$z = 17.5^{\circ}\text{C}$ , enzymes $z = 23.2^{\circ}\text{C}$ , ascorbic acid $z = 25^{\circ}\text{C}$ , cooking $z = 26.1^{\circ}\text{C}$ , vitamin B <sub>1</sub> $z = 26.5^{\circ}\text{C}$ , sensory $z = 33^{\circ}\text{C}$ , cooking $z = 40^{\circ}\text{C}$ , cooking $z = 42^{\circ}\text{C}$ , potatoes $z = 48.9^{\circ}\text{C}$ enzymes (green beans) $z = 87.8^{\circ}\text{C}$ , chlorophyll (green beans)	
$z = 10^{\circ}\text{C}; F = 1$	$z = 33^{\circ}\text{C}; C = 10, 36, 52$	Reichert (1974, 1977)
$z = 10^{\circ}\text{C}; F = 76$	$z = 29^{\circ}\text{C}; E = 42, 45, 62$ (peas)	
$z = 10^{\circ}\text{C}; F = 5 + 10$	Vitamin B <sub>1</sub> $z = 26.1^{\circ}\text{C}; 5-90\%$ destruction in liver	Bauder and Heiss (1975)
$z = 10^{\circ}\text{C}; F = 2.7$	Microbial lipase	Svensson (1977)
$z = 10^{\circ}\text{C}; F = 10$	$z = 3.1^{\circ}\text{C}$ , peroxidase $z = 35^{\circ}\text{C}$ , potato	
$z = 10^{\circ}\text{C}; F = 5$	Thiamin, 90-99.5% retention	Ohlsson (1980 <i>b</i> )
$z = 10^{\circ}\text{C}; F = 3$	Browning of milk	Burton (1954, 1965, 1983), Samuelsson (1977)
$z = 10^{\circ}\text{C}; F = 6$	Thiamin, 1, 5, 20, 50%	Lund (1977)

TABLE 2 – contd.

System		Reference
Microbial	Chemical or other	
$z = 10^{\circ}\text{C}; F = 3$	$z = 27^{\circ}\text{C}$ , enzymes (centre of food particles)	Brown and Ayres (1982), Newman and Steele (1978)
$z = 10^{\circ}\text{C}; F = 24$	Grape anthocyanin destruction $z = 23^{\circ}\text{C}; F = 28, 90\%$	Jelen (1983)
$z = 10^{\circ}\text{C}; F = 4$	Browning of protease	Jelen (1983)

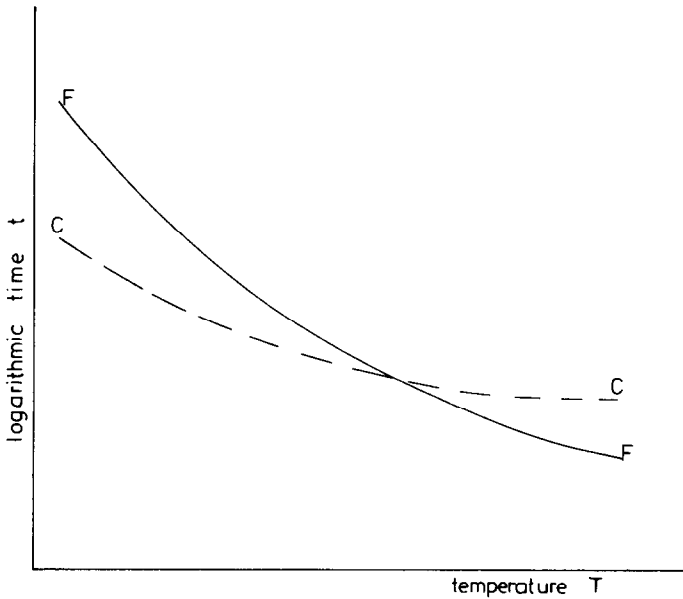


Fig. 2. Calculated  $t$ - $T$  relationship for microbial destruction, F, and cooking, C, at the centre of a spherical particle (radius = 1 cm).

cedures for estimating the thermal processes required for sterilisation. This involved use of the corresponding  $z$  value ( $i$  in Ball and Olson's notation) for the destruction of a particular nutrient. The  $F$  value ( $E$  in Ball and Olson's notation) was then redefined as the number of

minutes at 121.1°C required to reduce the thermolabile constituent to a given fraction.

This method underestimates the contribution of the cooling phase and in many ways is unnecessarily complicated. It was also referred to the slowest heating point whereas, as pointed out earlier, the total integrated value  $F_s$  is more important. The concept of 'average destruction' of microbial species was first put forward in 1948 (Ball and Olson, 1957) and this has proved valuable. The initial concept was that the average  $E$  value for a container at a given instant was represented as a weighted average of the  $E$  values for all iso- $j$  regions in a container and this weighted value was a direct indication of the overall reduction up to that time. Stumbo (Ball and Olson, 1957), however, showed that this concept was not correct and used the actual  $E$  value corresponding on a survivor curve to the overall percentage survival of the heat vulnerable component. This was developed further (Stumbo, 1948, 1949; Ball, 1949) using the concept of the surfaces of a nest of hypothetical containers with equal  $j$  values (i.e. heating lags); these were known as iso- $j$  surfaces. This enabled the total destruction to be calculated for the whole container and this value was designated  $F_s$  to distinguish it from the value at the centre or point of slowest heating,  $F_c$ . Stumbo (1953) derived an equation for the  $F_s$  value assuming a linear relationship between  $F_\lambda - F_c$  and  $v$  the fractional volume of the element, where  $F_\lambda$  is the  $F$  value of heat received at any point in the container and  $F_c$  the  $F$  value at the centre. However, Stumbo (1973) found that a better relationship was between  $F_\lambda - F_c$  and  $\log(1 - v)$  and this resulted in eqn (3) which was applicable to microbial and biochemical components.

Two other workers, Gillespy (1951) and Hicks (1951) independently developed similar concepts of a total integrated value, but neither of these was extended to the evaluation of nutrient destruction.

Herrman (1969, 1976) used a graphical technique similar to that of Patashnik (1953) which converted the lethalties into thiamin retention and cooking values. This involved the solution of the heat transfer equations of Reidel (1947) which were used by Gillespy (1953) for complex processes, e.g. those involved in hydrostatic cookers.

Jan *et al.* (1971) extended the original concepts of Stumbo (1953, 1965) to the estimation of nutrient retention in conduction-heating packs. They were particularly interested in producing a method which was equivalent to the 'formula method' (Ball and Olson, 1957). Jan *et al.* also pointed out the essential difference between sterilisation and

nutrient destruction in terms of Stumbo's (1953) relationship between the volume fraction of the container and the  $F_\lambda-F_c$  value. This relationship was shown to be satisfactory for microbial destruction provided the value of  $v$ , the volume fraction, was not greater than 0.4; however, for nutrient destruction, values in excess of 0.4 were required for which Stumbo's relationship was not applicable. This led to the use of the linear relationship  $F_\lambda-F_c$  versus  $\log(1-v)$ . Jan *et al.* (1971) showed that for thiamin retention in pea puree in  $211 \times 300$  size cans there was good agreement between this method of prediction and the experimental data.

Mulley *et al.* (1975) also applied this technique and showed reasonable agreement with the experimental results for thiamin retention using  $z$  values of 28.3–31.6 for peas, green beans and sweet corn.

Downes and Hayakawa (1977) took into account the cooling phase more precisely, pointing out that most other methods make the assumption that the rates of heating,  $f_h$ , and of cooling,  $f_c$ , are similar, which is not necessarily the case. They used a method developed by Hayakawa (1970) for estimating the cooling contributions.

A computerised method for determining average sterilisation values was developed by Cohen and Wall (1971) which could be extended to determining nutrient retention.

## 5.2 Application of numerical methods using computers

Teixeira *et al.* (1969) published the first paper on the computer optimisation of nutrient retention in the thermal processing of conduction-heated foods. A digital computer program was developed using the finite-difference method of solving the two-dimensional heat transfer equation for determining the time-temperature distribution within a cylindrical container. This was then used to estimate the effect of the thermal history on microbial destruction and nutrient retention. The mathematical model used involved step-function heating and cooling with the external heat transfer coefficient neglected (Holdsworth, 1976). Basically, the optimisation technique determined the process times and temperatures equivalent to a given process: 84 min at  $121.1^\circ\text{C}$  with  $z = 10^\circ\text{C}$  for microbial destruction, and then proceeded to calculate the nutrient retention for  $z = 25^\circ\text{C}$  corresponding to the different equivalent processes. The results showed that there was a maximum retention of thiamin at  $120^\circ\text{C}$  and 90 min – which is very near to the

given process. This seemed at variance with the high temperature-short time concept applicable to convection packs or sterilisation of liquid products but is due to the non-uniform temperature distributions occurring in conduction packs. It was also shown that for a component with a greater  $z$  value the optimum occurred at higher temperatures whereas for smaller values of  $z$  the optimum occurred at lower temperatures. Thus, in the cooking of food, for which  $z = 17^{\circ}\text{C}$ , lower temperatures and longer times are preferred for a high degree of cookedness, which is in agreement with experience. Changes in the  $D$  value for a constant  $z$  value for thiamin did not alter the optimum temperature, only the percentage retention, which increased with increasing  $D$  value. Manson *et al.* (1970) developed a complete programme for nutrient retention in rectangular containers which allowed for the effects of come-up time and the cooling phase.

Teixeira *et al.* (1975*b*) extended their computer model (Teixeira *et al.* (1969) to allow for the effects of variable retort temperature profiles and differing container geometries on thiamin degradation. With regard to the former, three general types of behaviour for the retort temperature history were considered, viz. step functions, ramp functions and sinusoidal functions and these were combined to give different surface temperature profiles. However, the maximum thiamin retention was very similar for all the different processes of equivalent sterilising value. With regard to the latter, the effect of height-to-diameter ratio on thiamin retention was entirely different and this factor proved to be very significant. Maximum retention greater than 60% was found to occur for height-to-diameter ratios less than 0.2 and greater than 10.0. A minimum retention of about 40% occurred with ratios in the region of 1, i.e. most of the standard sizes of container! This result gives quantitative support for the thin retortable pouch and continuous flow sterilisation of food products followed by aseptic packaging.

A similar program of work was carried out by Sjöström and Dagerskog (1977) to see if it was possible to reduce the difference in heating effect between the surface and centre and to establish optimum conditions for specific products -- chopped fish (entirely conduction heating) and liver paste (part convection heating) and specific can sizes. In this study the results of computer simulation were compared with experimental work using the sterilisation effect, enzyme inactivation and a sensory quality  $C$  value, i.e. the rate of browning in fish ( $z = 26^{\circ}\text{C}$ ).

The effect of varying the  $z$  value at a constant temperature was that the  $C$  value decreased with increasing  $z$  value. However, for a given  $z$  value there was an optimum  $C$  value within the temperature range. This optimum point moves to a higher temperature with increasing  $z$  value; thus, it is necessary to know the  $z$  value for the particular component under consideration.

When the authors considered the series of experiments carried out with varying surface temperature profiles the differences in nutrient retention were found to be so small as to be of no practical significance. In another series of tests in which the same maximum temperature was reached, it was found that a double-ramp (a linear increase in temperature followed a linear decrease) produced the smallest cooking value whereas a combination of a ramp and constant holding was significantly better than a step, i.e. constant holding for the total time period.

A more detailed study of the optimisation of heat sterilisation operations was reported by Ohlsson (1980a), who determined the  $z$  value for a range of products, viz. fish, liver paste, strained beef, strained vegetables, tomato sauce and vanilla sauce for a range of different sensory qualities, viz. odour, off-odour, appearance, taste, off-taste, consistency, hardness, coarseness and lightness. These values were then used to calculate the  $C$  values and compare them with other variables –  $F_0$ , temperature, time, thickness and height/diameter ratios. For flat containers (Ohlsson, 1980d) it was shown that the average optimum  $C$  value increased with increasing thickness corresponding to a decrease in the temperature at which the optimum occurred. A similar effect was found on increasing the height of a range of cans with the same diameter (Ohlsson, 1980c). This led to the generalisation: the larger the container the lower the processing temperature to obtain an optimum degree of cooking.

### **5.3 Application of analytical procedures based on the concept of total integrated lethality**

One of the first papers to describe a mathematical procedure for estimating the total integrated lethality based on the heat transfer equations for both heating and cooling phases was by Hicks (1951). He was, however, not alone in his thinking and Gillespy (1951) and Stumbo (1953) produced, independently, similar theoretical treatments although

they used the basic first-term approximation for heating and empirical equations for estimating the effects of the cooling phase.

Hayakawa (1969) extended the concept of Hicks but used a different mathematical technique involving dimensional analysis and the concept of mass-average sterilising value. This was subsequently extended (Hayakawa, 1971) to estimating the mass average value for a physical, chemical or biological change resulting from thermal processing. This work led to formulae which could be used to compute values for nutrient retention which were then intended to be used with standard manual procedures. Preusser (1970) presented an analytical treatment of cooking effect and lethality for a linear change in temperature (ramp function) as well as heating followed by cooling and presented the results in a log time versus temperature diagram. From this type of representation combinations of time and temperature can be estimated which will achieve the desired effect and, at the same time, indicate the corresponding  $F_0$  value.

Barreiro-Mendez *et al.* (1977) derived models for the loss of nutrients during heating and cooling in cylindrical containers using analytical equations. These equations gave the percentage nutrient retention and experimental results obtained using an analogue system of 6% maize starch and 1.75% carboxymethyl cellulose were in good agreement with the predicted results.

Hayakawa (1977) used a computer model to estimate the percentage of thiamin retention in carrot purée, pea purée, pork purée and spinach, and compared the results with experimental determinations. For the processes at 115.6°C the results were within  $\pm 3\%$ ; however, at the higher temperature of 121.1°C and 60 min, the differences varied between 10 and 16%. Spinach gave the worst comparative results, the predictions being up to 16% less than the experimental results.

Lenz and Lund (1977b) used a method of lethality calculation which made use of a new dimensionless group, the lethality/Fourier number  $L$  where

$$L = -\frac{\alpha \ln x}{k_r R^2}$$

in which  $\alpha$  is the thermal diffusivity,  $x$  is the fraction of constituent retained (ratio of concentration at any time  $t$  to the initial concentration),  $k_r$  is the rate constant at the reference temperature  $T_r$  and  $R$  is the container radius (i.e. half thickness). This was derived by combining



the first-order kinetic equation and the Arrhenius temperature relationship and substituting the time from the Fourier number  $\alpha t/R^2$ . The latter is obtained from the unsteady state heat transfer equation solution for a finite cylinder and cooling is included by solving the equation for the appropriate boundary conditions at the end of heating. Using this  $L$ -concept the authors used an average value  $L$  based on  $x$ , the average fraction of constituent retained, and compared the theoretical predictions with the experimental results for thiamin, chlorophyll and betanin degradation in various purées after differing times and temperatures of processing. The results, in general, were considered to be well within experimental error; the standard deviation between measured and predicted retentions was 6%.

Thijssen *et al.* (1980) developed a method of process calculation which eliminated the use of tabulated data and interpolation. The model used was based on the following equation

$$\frac{C}{C_0} = \int_0^v \exp \left[ - \int_0^t k \, dt \right] dV \quad (7)$$

where  $C$  is the concentration of specified component at time  $t$ ,  $C_0$  is the concentration of specified component at time 0,  $V$  is the volume of the pack for averaging purposes and  $k$  is a temperature-dependent kinetic factor.

For a uniform initial product temperature  $T_0$ , a constant temperature of the heating medium,  $T_h$ , and a constant temperature of the cooling medium,  $T_c$ , the reduction in a heat-labile component is a function of five dimensionless groups, viz. Fourier number, Biot number, reduced temperature and two groups related to kinetic factors. The method uses the analytical solutions for the heat transfer equation for sphere, cylinder and rectangular bodies, and also other geometrical shapes. These workers showed that for maximum quality retention a value of the Fourier number of 0.5 is required. Thijssen and Kochen (1980) extended the method to variable external heating and cooling conditions and showed that the accuracy of this 'short-cut' method was equivalent to the detailed finite difference computer methods.

Castillo *et al.* (1980) extended the method of Barreiro-Mendez *et al.* (1977) to deal with rectangular retortable pouches of food. The interesting point which emerges from the use of this model is that the predicted and experimental temperatures at the end of heating were in

good agreement. However, at the end of cooling differences of up to 16% were observed, probably due to assuming a very high heat transfer coefficient at the surface of the pouch. The predicted thiamin retentions after the thermal processing were in good agreement with the experimental results.

#### 5.4 Applications of optimisation procedures

The productivity of industrial operations in most cases involves conflicting and opposing influences and, consequently, it is necessary to balance these out to give the optimum production rate. The retention of nutrient value of processed food products is a similar situation and consequently an optimum solution is necessary. This type of optimum may be overridden by the demand for high production rates and minimum cost factors. However, with the present climate of opinion tending to favour high nutrient value in processed foods it is necessary to consider this factor outside the constraints of production economics.

Beveridge and Schechter (1970) have presented the basis for optimisation as applied to the chemical industry; however, their models are also applicable to the present problem. When multivariable situations are considered it is possible to express the results in a three-dimensional diagram which is known as a response surface relationship; however, in more complex situations such representation cannot be made and computer optimisation of the prescribed variables is required.

A comparison of optimisation techniques for food product and process development applications has been given by Nakai (1982). The results are particularly useful because the difficulties encountered in the applications are evaluated. Several techniques are available and these are summarised in Table 3.

Evans (1982) has indicated how optimisation techniques may be applied to food processing as an aid to management and control of process plants, but the examples did not include thermal processing.

Saguy and Karel (1979) were the first to apply a formal optimisation theory to optimising thiamin retention during sterilisation. The continuous maximum principle (Pontryagin *et al.*, 1962), a multi-iterative, was used to determine the optimum temperature profile for nutrient retention. The use of this technique is required for solving the transcendental equation involving the control variable. Several search techniques are available for this, for example: the Fibonacci method

**TABLE 3**  
Some Techniques for Optimisation (Nakai, 1982)

<i>Technique</i>	<i>Comments</i>
1. Multi-factorial designs	Not very efficient; true optimum not easily found
2. Linear programming (linear objective functions and inequality restrictions)	Efficient and versatile: linear equations correlating variables must be known
3. Quadratic programming (non-linear)	Used for quadratic relationships (Boot, 1964)
4. Geometric programming (non-linear)	Used for relationships involving sums of products of functions
5. Evolutionary operation (EVOP)	Involves using responses to the small changes in operating conditions: systematic variations of systems variables (Box, 1957)
6. Rotating square evolutionary operation (ROVOP)	Eliminates uncertainty due to size of variant used: involves multiple regression analysis (Lowe, 1964)
7. Random evolutionary operation (REVOP)	Useful for large numbers of variables where relationships between variables unknown (non-parametric) (Lowe, 1964)
8. Simplex EVOP	Requires less experimental work and reaches the optimum of a process much more quickly (Spendley <i>et al.</i> , 1962; Lowe, 1964; Nelder and Mead, 1965; Morgan and Denning, 1974)
9. Super Simplex EVOP	Uses a quadratic curve fitting procedure (Rounth <i>et al.</i> , 1977)
10. Modified Super Simplex EVOP	Uses quadratic factorial regression analysis to obtain rapid convergence (Nakai, 1982)

(Beveridge and Schechter, 1970), where only one variable is being optimized; steepest ascent method (hill climbing) (Storey, 1962; Storey & Rosenbrock, 1967) (multivariable); quasi-linearisation (Lee, 1966, 1967) (multivariable); calculus of variations (Katz, 1960) (multivariable); and 'dynamic programming' (Fan, 1966).

The most interesting feature of the work of Saguy and Karel (1979) is the determination of the profile of the temperature–time relationship

to be applied to the retort to obtain maximum retention of thiamin. Two examples given by these workers relate to pea purée processed in a  $303 \times 406$  can and pork purée in a  $401 \times 411$  can.

The profiles are slightly different, but both show an initial steep ramp followed for the pea purée by a trough and a second peak, and for the pork purée by a less steep downward ramp.

Hildenbrand (1980) used a different approach to obtaining an optimal temperature profile for the retort. The problem is treated in two parts. The first is to determine how the temperature of each volume element inside the container must be raised in order to achieve the desired microbial destruction and also retain the quality factors at a maximum level. The second -- the control engineering problem -- is to determine the necessary temperature-time profile on the outside of the container to achieve the first objective. This is known as a 'tracking problem' and is solved using a version of the maximum principle (Butkovskiy, 1969). The response profiles to two types of control strategy are given, the first on-off control and the second quasi-continuous. However, this work does not give results for the retention levels of various nutrients, only the mathematical technique for dealing with the control problem. Martens (1980) also produced temperature profiles for optimisation of nutrient retention in thin flat containers; these were 'inverted-V shape' in profile. These papers are important because they relate to developments in control systems for thermal processing of food products which are taking place at the present time. The concept of using mathematical models for controlling the sterilisation operation (Holdsworth, 1974, 1983) can now be extended using these techniques to maximise nutrient retention by controlling the temperature profile of the retort.

## 6. CONCLUSION

From comparison of the methods of optimising nutrient retention by most authors, in general there is little to choose between them, especially when the reliability of chemical analyses is considered. However, if the calculation time is considered then the short-cut method (Thijssen *et al.*, 1980) should be considered as well as finite-difference methods (Teixeira *et al.*, 1969, 1975*a,b*). The main problems arise when the mathematical models are used for process control and it is in this area

that the methods require testing. It is necessary for the models to produce results sufficiently quickly to keep up with the process and with changes in process variables. The limitation is usually in relation to the computer system chosen; sophisticated multi-tasking microprocessor-based systems will be suitable for this type of control but many of the low-cost programmable systems available at the present time will not have sufficient computing ability to make the main objective of using mathematical models to control the operation achievable.

The subject of processes optimised especially for nutrient retention is likely to assume greater importance in the future and methods of processing to maximise nutrient and quality factors will be important aspects of food preservation.

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