Critical Evaluation of Commonly Used Objective Functions to Optimize Overall Quality and Nutrient Retention of Heat-Preserved Foods

C. Silva,^a M. Hendrickx,^{b*} F. Oliveira^a & P. Tobback^b

^aEscola Superior de Biotecnologia — UCP, Rua Dr. António Bernardino de Almeida, 4200 Porto, Portugal

^bKatholieke Universiteit Leuven, Laboratory of Food Technology, Kardinaal Mercierlaan 92, 3001 Heverlee, Belgium

(Received 28 August 1991; revised version received 7 November 1991; accepted 14 November 1991)

ABSTRACT

Two objective functions — volume average retention and volume average cook-value — commonly used to optimize the overall quality and nutrient retention of heat-preserved foods, were studied and optimal processing conditions based on the two approaches were compared. Case studies from the literature were run and tested for the two objective functions. The influence of the decimal reduction time (at the reference temperature, D_{ref} value) of the quality factor on the optimal processing temperature was evaluated.

For high D_{ref} values, e.g. for vitamins, the two objective functions give the same results and the D_{ref} value has a minor influence on the optimum processing conditions. For low D_{ref} values, such as for texture and colour, the optimal sterilization temperature is affected by this parameter and the use of volume average cook-value, as objective function, does not take this effect into account, which may result in underestimation of the optimal processing temperature.

NOTATION

ASM	Target volume average survival of microorganisms
C	Cook-value (min)

*M. Hendrickx is Senior Research Assistant with the Belgian National Fund for Scientific Research (NFSR).

C_{ave}	Volume average cook-value (min)
C_{surf}	Surface cook-value (min)
C_S	Integrated cook-value (min)
C_T	Cook-value at temperature T (min)
D_{ref}	Decimal reduction time at reference temperature (min)
D_{refm}	Decimal reduction time at reference temperature, T_{refm} , for the microorganism (min)
D_{refq}	Decimal reduction time at reference temperature, T_{refq} , for the quality factor (min)
D_T	Decimal reduction time at temperature T (min)
F_c	Target-lethality in the coldest spot (min)
F_S	Integrated sterility value (min)
h	Surface heat transfer coefficient ($W/m^2 K$)
k_T	Rate constant at temperature T (s^{-1})
$(N/N_0)_{ave}$	Volume average retention of quality
$(N/N_0)_{surf}$	Surface retention of quality
t	Time (s)
t_p	Total processing time, including the cooling period (min)
T	Temperature ($^{\circ}C$)
T_c	Temperature in the coldest spot ($^{\circ}C$)
T_{op}	Optimal processing temperature ($^{\circ}C$)
T_{ref}	Reference temperature ($^{\circ}C$)
T_{refm}	Reference temperature for the microorganisms ($^{\circ}C$)
T_{refq}	Reference temperature for the quality factor ($^{\circ}C$)
T_w	Cooling temperature ($^{\circ}C$)
T_0	Initial temperature of the food ($^{\circ}C$)
V	Volume (m^3)
X	Level of microorganisms, enzymes or quality attribute
z	z value ($^{\circ}C$)
z_m	z value for the microorganism ($^{\circ}C$)
z_q	z value for the quality attribute ($^{\circ}C$)
α	Thermal diffusivity (m^2/s)

INTRODUCTION

As a result of increasing consumer demand for higher-quality products, research has been undertaken in the area of optimizing quality and nutrient retention of heat-preserved foods (Silva *et al.*, submitted).

Optimization of sterilization processes is possible because inactivation kinetics of microorganisms, enzymes and quality factors show different temperature sensitivities. Thermal inactivation of microorganisms is much more temperature dependent than destruction of quality attributes (Lund, 1977). This is the basis for the principle of High Temperature Short Time (HTST) processing (Mansfield, 1962) used in aseptic processing and rotary sterilization of low-viscosity foods. However, in classical heating techniques, this principle cannot be applied to solid and high-viscosity foods, because to produce a safe product (the major constraint in a heat sterilization process (Holdsworth, 1985)) the slow heat flow rate to the coldest spot increases the total required processing time, and the surface of the product may be completely burnt (Teixeira *et al.*, 1969). Furthermore, the high resistance of some enzymes (e.g. peroxidase) to thermal inactivation also limits the applicability of the HTST principle (Lund, 1977; Saguy, 1988).

A number of workers have calculated optimal sterilization conditions to maximize surface or volume average quality retention (Teixeira *et al.*, 1969, 1975; Thijssen *et al.*, 1978; Saguy & Karel, 1979; Martens, 1980; Ohlsson, 1980a-c; Thijssen & Kochen, 1980; Nadkarni & Hatton, 1985; Hendrickx *et al.*, 1990, 1991, in press; Tucker & Holdsworth, 1990, 1991; Banga *et al.*, 1991; Silva *et al.*, submitted). When we analyse the formulation of the commonly used objective functions, two approaches can be distinguished: (1) maximization of the retention, or (2) minimization of the cook-value (Table 1).

The optimal sterilization temperature to maximize the surface quality and nutrient retention is independent of the decimal reduction time and depends only on the z value for the quality attribute (Hendrickx *et al.*, 1990, in press; Silva *et al.*, submitted). For volume average quality optimization, Teixeira *et al.* (1969) studied the effect of decimal reduction time on the optimal temperature and concluded that this variable has no influence. However, they considered only a narrow range of values (from 146.6 to 202.3 min at a reference temperature of 118.89°C), which is valid for the thermal degradation of thiamin (Felicciotti & Esselen, 1957). It remains to be found whether this statement holds for an expanded range of D_{ref} values valid for vitamins, texture, colour and other quality factors.

Therefore, the purpose of the research presented here was to study and compare the two objective functions, (1) volume average retention or (2) volume average cook-value, used to optimize the sterilization temperature of conduction-heated foods. Several case studies from the literature were run using both these functions.

TABLE 1
Objective Functions Used to Optimize Sterilization Processes

<i>References</i>	<i>Objective function</i>	<i>Constraint</i>	<i>Geometry</i>	<i>Type of solution</i>	<i>Boundary conditions</i>
Teixeira <i>et al.</i> (1969)	$(N/N_0)_{ave}$	ASM	Finite cylindrical can	Finite-difference 2D; h_{∞}	Step-function
Teixeira <i>et al.</i> (1975)	$(N/N_0)_{ave}$	ASM	Finite cylindrical can	Finite difference 2D; h_{∞}	Step-function, sinusoidal function, combination of ramps, single square wave, sequence of steps
Thijssen <i>et al.</i> (1978)	$(N/N_0)_{ave}$	ASM	Finite cylinder; sphere; rectangular body	Analytical 1D 2D; h_{∞} and h_{finite}	Step-function
Saguy and Karel (1979)	$(N/N_0)_{ave}$	ASM	Finite cylindrical can	Finite difference 2D; h_{∞}	Variable surface temperature
Ohlsson (1980a)	C_{ave} and C_{surf}	F_c	Infinite slab	Finite difference 1D; h_{∞}	Step-function with linear come-up-time
Ohlsson (1980b, 1980c)	C_{ave} and C_{surf}	F_c	Finite cylinder	Finite difference 2D; h_{∞}	Step function with linear come-up-time
Thijssen and Kochen (1980)	$(N/N_0)_{ave}$	ASM	Finite cylinder; sphere; rectangular body	Finite difference 2D; h_{∞} and h_{finite}	Variable surface temperature

Martens (1980)	$(N/N_0)_{ave}$	ASM	Infinite slab	Analytical 1D; h_{∞}	Step function, variable surface temperature
Nadkarni and Hatton (1985)	$(N/N_0)_{ave}$	ASM	Finite cylindrical can	Numerical solution 2D; h_{∞}	Variable surface temperature
Hendrickx <i>et al.</i> (1990)	$(N/N_0)_{surf}$	F_c	Infinite cylinder; finite cylinder; sphere	Analytical 1D 2D; h_{∞}	Step-function
Hendrickx <i>et al.</i> (in press)	C_{surf}	F_c	Infinite slab; infinite cylinder; sphere	Finite difference 1D; h_{∞}	Step-function with linear come-up-time
Tucker and Holdsworth (1990, 1991)	C_{ave}	F_c	Rectangular container	Finite difference 3D; h_{finite}	Step-function
Silva <i>et al.</i> (submitted)	C_{surf}	F_c	Infinite slab; infinite cylinder; sphere	Finite difference 1D; h_{finite}	Step-function with linear come-up-time
Banga <i>et al.</i> (1991)	$(N/N_0)_{ave}$ and $(N/N_0)_{surf}$	ASM and F_c	Finite cylindrical can	Finite difference 2D; h_{∞}	Constant and variable surface temperature

$(N/N_0)_{ave}$, volume average retention of quality; $(N/N_0)_{surf}$, surface retention of quality; ASM, target volume average survival of microorganisms; h_{∞} , infinite surface heat transfer coefficient; h_{finite} , finite surface heat transfer coefficient; C_{ave} , volume average cook-value; C_{surf} , surface cook-value; F_c , target lethality in the coldest spot.

THEORETICAL ANALYSIS

Effect of heat on microorganisms and nutrients

In most cases, the thermal inactivation (degradation) of microorganisms, enzymes and quality factors can be described by first-order reaction kinetics (Hayakawa, 1978).

First-order kinetics of thermal inactivation (degradation)

First-order inactivation kinetics can be mathematically written as

$$\frac{dX}{dt} = -k_T X \quad (1)$$

where t is time, k_T is the rate constant at temperature T (s^{-1}) and X is the level of microorganisms, enzymes or quality attribute.

After integration, eqn (1) becomes

$$\ln(X/X_0) = - \int_0^t k_T dt \quad (2)$$

where X_0 and X , respectively, represent the initial and final level at a given time t , and the ratio X/X_0 represents the survival of microorganisms or retention of enzymes or a quality index.

Food scientists and microbiologists use the decimal reduction time, D_T , instead of k_T , and use the z value to indicate the temperature dependence of D_T . D_T is defined as the time required to reduce the concentration, X , by one log-unit, and the z value is defined as the temperature rise needed to reduce the decimal reduction time by one log-unit:

$$D_T = \frac{\ln(10)}{k_T} \quad (3)$$

$$D_T = D_{ref} \times 10^{(T_{ref} - T)/z} \quad (4)$$

In general, there are two approaches to express the impact of a process: (1) target-lethality at the coldest spot (F_c) or (2) an integrated sterility value (F_s) representing the volume average survival of microorganisms (Stumbo, 1973):

$$F_c = \int_0^t 10^{(T_c - T_{ref})/z} dt \quad (5)$$

$$(X/X_0)_c = 10^{-F_c/D_{refm}} \quad (6)$$

or

$$ASM = \frac{1}{V} \int_0^V 10^{\left[-\frac{1}{D_{refm}} \int_0^t 10^{(T-T_{refm})/z_m} dt \right]} dV \quad (7)$$

$$F_s = D_{refm} \log(ASM) \quad (8)$$

where F_c is the target-lethality at the coldest spot (min), T_c is the time-temperature profile in the coldest spot ($^{\circ}\text{C}$), T_{refm} is the reference temperature for the microorganisms ($^{\circ}\text{C}$), D_{refm} is the decimal reduction time at reference temperature, T_{refm} , for the microorganisms (min), z_m is the z value for the microorganism ($^{\circ}\text{C}$), $(X/X_0)_c$ is the target survival of microorganisms in the coldest spot, ASM is the target mass average survival of microorganisms, V is the volume (m^3) and F_s is the target integrated sterility value (min).

Kinetic parameters for nutrients and quality attributes

The parameters z value and D_{ref} for a given nutrient or quality index, are dependent on intrinsic factors (factors of the food itself, e.g. composition, pH, water activity, oxidation-reduction potential) and extrinsic factors (e.g. gas composition) and their interaction (Lund, 1975; Mauri *et al.*, 1989). However, a limited range of values can be associated with each parameter.

A range of z values between 15 and 45°C includes most of the kinetic data available (Lund, 1977; Ohlsson, 1988; Holdsworth, 1990; Hendrickx *et al.*, in press; Silva *et al.*, submitted).

For the decimal reduction time, Lund (1977) found that $D_{121-15^{\circ}\text{C}}$ values are within 100–1000 min for vitamins and between 5 and 500 min for colour, texture and flavour. This range was set after a detailed review of the available kinetic data (Lund, 1975).

Holdsworth (1990) reviewed the available data in relation to the thermal degradation of nutrients and sensory factors, including colour, texture and flavour. However, he did not present any values for D_{ref} .

Objective functions to optimize food quality

Given the decimal reduction time at a reference temperature and the z value, and knowing the time-temperature profile at a single point in a food, the retention of a nutrient or quality index can be calculated:

$$\frac{N}{N_0} = 10^{\left[-\frac{1}{D_{refq}} \int_0^t 10^{(T-T_{refq})/z_q} dt \right]} \quad (9)$$

where N is the level of nutrients or quality factor at time t , N_0 is the initial level of nutrients or quality factor, D_{refq} is the decimal reduction time at reference temperature for the nutrient or quality factor (min), T_{refq} is the reference temperature for the quality factor ($^{\circ}\text{C}$) and z_q is the z value for the nutrient or quality factor ($^{\circ}\text{C}$).

Mansfield (1962) proposed the concept of cook-value (or C) to compare thermal processes in terms of quality degradation. This parameter is defined similarly to the F_c value:

$$C = \int_0^t 10^{(T - T_{\text{refq}})/z_q} dt \quad (10)$$

where C is the cook-value. Mansfield (1962) presented this concept for aseptic processing of low-viscosity foods, where the time-temperature profile can be assumed to be uniform within the space. The most common reference temperature used to calculate the cook-value is 100°C . When a different reference temperature is intended, the following conversion can be used (Holdsworth, 1985):

$$C_{100} = C_T \times 10^{(T - 100)/z_q} \quad (11)$$

where C_T is the cook-value at temperature T . From eqns (9) and (10) the quality retention for the time-temperature profile under consideration can be written as

$$\frac{N}{N_0} = 10^{-C/D_{\text{refq}}} \quad (12)$$

For conduction-heated foods, when the objective is to maximize the retention of a nutrient in a given position, the maximization of the retention (eqn (9)) and the minimization of the cook-value (eqn (10)) are mathematically equivalent. Silva *et al.* (submitted) presented this conclusion for the optimization of the surface quality of a conduction-heated food. As the cook-value is independent of D_{refq} , this parameter has no influence on the optimal processing temperature.

However, when the objective is to optimize the overall quality retention of a homogeneous conduction-heated food, it is necessary to integrate over the total volume to take into account the different time-temperature profiles which are a function of position. The exact definition for volume average quality retention is

$$(N/N_0)_{\text{ave}} = \frac{1}{V} \int_0^V 10^{\left[-\frac{1}{D_{\text{refq}}} \int_0^t 10^{(T - T_{\text{refq}})/z_q} dt \right]} dV \quad (13)$$

where T is the time-temperature profile as a function of position and V is the volume. By analogy with the integrated sterilization value (eqn (8)), one can define the integrated cook-value as

$$C_s = D_{\text{refq}} \log[(N/N_0)_{\text{ave}}] \quad (14)$$

where C_s is the integrated cook-value. Minimizing this function is equal to maximizing $(N/N_0)_{\text{ave}}$.

To evaluate the mean impact of a thermal process, Ohlsson (1980a-c) and Tucker and Holdsworth (1990, 1991) defined and used the volume average cook-value:

$$C_{\text{ave}} = \frac{1}{V} \int_0^V \int_0^t 10^{(T - T_{\text{refq}})/z_q} dt dV \quad (15)$$

However, maximizing the volume average retention (eqn (13)) and minimizing the volume average cook-value (eqn (15)) are not mathematically equivalent.

Furthermore, eqn (15) is independent of the decimal reduction time at the reference temperature (D_{refq}). D_{refq} is a constant but cannot be separated from the equation (eqn (13)) so that the optimum temperature is likely to depend on this parameter. Although Teixeira *et al.* (1969) concluded that this parameter has no impact on the optimal processing temperature, they considered only a narrow range of values which are valid for the thermal degradation of thiamin.

METHODS

A Pascal program, similar to that presented by Silva *et al.* (submitted), was developed to model and optimize heat sterilization of conduction-heated foods. To calculate the temperature distribution within the solid, an explicit finite-difference numerical method, with a non-capacitance surface node (Chau & Gaffney, 1990), was implemented for one-, two- and three-dimensional products. First-order reaction kinetics as discussed above were assumed for the thermal inactivation of microorganisms and degradation of quality attributes. The objective function and restriction of the optimization routine was adapted depending on the case study. Optimal sterilization temperatures were calculated with an associated error smaller than $\pm 0.1^\circ\text{C}$.

TABLE 2
Case Studies Used to Study and Compare the Objective Functions to Optimize Overall Quality

Case no.	Reference	Container	Dimensions (mm)	α (m^2/s)	T_o ($^{\circ}C$)	T_w ($^{\circ}C$)	h_2 ($W/m^2 K$)	D_{refm} (min)	T_{refm} ($^{\circ}C$)	z_{li} ($^{\circ}C$)	D_{refli} (min)	T_{refli} ($^{\circ}C$)	ASM ^a	F_c^* (min)	Objective function	T_{op}^b
1	Teixeira <i>et al.</i> (1969)	Cylindrical can	$\phi 87.3 \times 115.9$	1.7×10^{-7}	71.1	26.1	∞	3.0	121.15	16.7	202	118.9	5.214×10^{-6}	—	$(N/N_o)_{ave}$	≈ 116
2	Teixeira <i>et al.</i> (1969)	Cylindrical can	$\phi 87.3 \times 115.9$	1.7×10^{-7}	71.1	26.1	∞	3.0	121.15	25.0	188.7	118.9	5.214×10^{-6}	—	$(N/N_o)_{ave}$	≈ 122
3	Teixeira <i>et al.</i> (1969)	Cylindrical can	$\phi 87.3 \times 115.9$	1.7×10^{-7}	71.1	26.1	∞	3.0	121.15	33.33	202	118.9	5.214×10^{-6}	—	$(N/N_o)_{ave}$	≈ 126
4	Ohlsson (1980a)	Flat	10 ^d	1.6×10^{-7}	80	20	∞	—	—	25	188	121.1	—	5	C_{ave}	≈ 140
5	Ohlsson (1980a)	Flat	10	1.6×10^{-7}	80	20	∞	—	—	33	188	121.1	—	10	C_{ave}	≈ 145
6	Ohlsson (1980a)	Flat	15	1.6×10^{-7}	80	20	∞	—	—	25	188	121.1	—	5	C_{ave}	≈ 130
7	Ohlsson (1980a)	Flat	15	1.6×10^{-7}	80	20	∞	—	—	33	188	121.1	—	10	C_{ave}	≈ 140
8	Ohlsson (1980a)	Flat	20	1.6×10^{-7}	80	20	∞	—	—	25	188	121.1	—	5	C_{ave}	≈ 130
9	Ohlsson (1980a)	Flat	20	1.6×10^{-7}	80	20	∞	—	—	33	188	121.1	—	10	C_{ave}	≈ 137
10	Ohlsson (1980a)	Flat	25	1.6×10^{-7}	80	20	∞	—	—	25	188	121.1	—	5	C_{ave}	≈ 128
11	Ohlsson (1980a)	Flat	25	1.6×10^{-7}	80	20	∞	—	—	33	188	121.1	—	10	C_{ave}	≈ 140
12	Ohlsson (1980a)	Flat	37	1.6×10^{-7}	80	20	∞	—	—	25	188	121.1	—	5	C_{ave}	≈ 127
13	Ohlsson (1980a)	Flat	37	1.6×10^{-7}	80	20	∞	—	—	33	188	121.1	—	10	C_{ave}	≈ 135
14	Ohlsson (1980a)	Flat	50	1.6×10^{-7}	80	20	∞	—	—	25	188	121.1	—	5	C_{ave}	≈ 125
15	Ohlsson (1980a)	Flat	50	1.6×10^{-7}	80	20	∞	—	—	33	188	121.1	—	10	C_{ave}	—

16	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 73 \times 31$	1.6×10^{-7}	80	20	∞	—	—	25	200	100.0	—	6	C_{ave}	= 125
17	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 73 \times 31$	1.6×10^{-7}	80	20	∞	—	—	33	200	100.0	—	6	C_{ave}	= 128
18	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 73 \times 58$	1.6×10^{-7}	80	20	∞	—	—	25	200	100.0	—	6	C_{ave}	= 120
19	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 73 \times 58$	1.6×10^{-7}	80	20	∞	—	—	33	200	100.0	—	6	C_{ave}	= 125
20	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 73 \times 108$	1.6×10^{-7}	80	20	∞	—	—	25	200	100.0	—	6	C_{ave}	= 117.5
21	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 73 \times 108$	1.6×10^{-7}	80	20	∞	—	—	33	200	100.0	—	6	C_{ave}	= 121
22	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 99 \times 119$	1.6×10^{-7}	80	20	∞	—	—	25	200	100.0	—	6	C_{ave}	= 115
23	Ohlsson (1980 <i>b</i>)	Cylindrical can	$\phi 99 \times 119$	1.6×10^{-7}	80	20	∞	—	—	33	200	100.0	—	6	C_{ave}	= 120
24	Tucker and Holdsworth (1990)	Rectangular	150×100 $\times 35^d$	1.6×10^{-7}	10	20	Finite ^e	—	—	33	200	100.0	—	3	C_{ave}	= 120
25	Tucker and Holdsworth (1990)	Rectangular	$150 \times 100 \times 40$	1.6×10^{-7}	10	20	Finite	—	—	33	200	100.0	—	3	C_{ave}	= 119
26	Tucker and Holdsworth (1990)	Rectangular	$150 \times 100 \times 45$	1.6×10^{-7}	10	20	Finite	—	—	33	200	100.0	—	3	C_{ave}	= 118
27	Tucker and Holdsworth (1990)	Rectangular	$150 \times 100 \times 50$	1.6×10^{-7}	10	20	Finite	—	—	33	200	100.0	—	3	C_{ave}	= 117.5

^aASM and F_0 are calculated with $z_m = 10^\circ\text{C}$.

^bOptimal temperature as reported in the reference.

^cDiameter $\times$ height.

^dThickness.

^e50 W/m² K on the top face and 600 W/m² K on sides and bottom.

RESULTS AND DISCUSSION

Study of the objective functions to optimize overall quality

Twenty-seven case studies from the literature were run, using (1) volume average cook-value (eqn (15)) and (2) volume average retention (eqn (13)). The case studies have been reported by Teixeira *et al.* (1969), Ohlsson (1980*a, b*) and Tucker and Holdsworth (1990) for one of these objective functions. The constraint, target lethality at the coldest spot (eqn (5)) or integrated lethality (eqn (7)) was set as reported by the researchers. For the examples taken from Ohlsson (1980*a*), kinetic data were assumed as given by him for thiamin. For Ohlsson's (1980*b*) and Tucker and Holdsworth's (1990) cases a value of $D_{100^{\circ}\text{C}} = 200$ min was considered (these workers did not report a D_{refq} value, as they used the volume average cook-value concept as defined in eqn (15)). The value of 200 min is in the range of kinetic data for the thermal degradation of chlorophyll *a*, chlorophyll *b* and betanin (Lund, 1975). Table 2 summarizes the input data, and Table 3 presents the calculation results. For all case studies, our results are in line with the published results, when the same objective function was used.

For the case studies taken from Teixeira *et al.* (1969), no significant differences were observed between the results obtained using the two objective functions, although optimal temperatures (T_{op}) resulting from the volume average retention approach were always slightly higher, with corresponding smaller total processing times (t_p), and optimal global quality retentions were also about 0.1% higher. Ohlsson's (1980*a*) case studies for thicker flat containers and larger z_q values showed differences between the results obtained by using the two objective functions. Although the optimum volume average retentions did not differ by more than 0.3%, differences of 4°C for optimal sterilization temperatures were observed. Ohlsson's (1980*b*) and Tucker and Holdsworth's (1990) examples showed the largest differences (up to 8°C) between the optimum processing conditions obtained by the two approaches. This can be explained by the small D_{refq} value ($D_{100^{\circ}\text{C}} = 200$ min) assumed for the quality attribute to be optimized.

From the 27 optimization problems performed it can be concluded that different results are obtained by using the two objective functions. Cases which have lower optimal final overall quality retention present larger differences between the optimum processing conditions obtained using either of the two objective functions. There is a need to study how the D_{refq} value, z_q value, food properties and processing conditions affect

TABLE 3
Optimal Processing Conditions for Case Studies in Table 2

Case no.	Objective function							
	C_{ave}				$(N/N_0)_{ave}$			
	C_{ave}^a	$(N/N_0)_{ave}$	t_p^b	T_{op}^c	C_{ave}	$(N/N_0)_{ave}$	t_p	T_{op}
1	54.43	0.5421	153.1	115.7	54.44	0.5425	148.8	116.1
2	64.44	0.4641	119.0	120.2	64.73	0.4644	113.6	121.3
3	66.56	0.4774	70.9	124.6	66.60	0.4784	99.4	125.5
4	3.85	0.9541	3.4	136.1	3.85	0.9541	3.4	136.3
5	4.05	0.9518	3.0	145.0	4.06	0.9518	3.0	145.0
6	6.22	0.9271	7.4	132.7	6.22	0.9271	7.4	132.5
7	7.07	0.9178	6.6	141.5	7.09	0.9176	6.5	142.3
8	8.74	0.8994	12.7	130.5	8.76	0.8992	12.6	130.7
9	10.48	0.8809	11.3	139.2	10.48	0.8810	11.3	139.4
10	11.36	0.8715	19.7	128.1	11.41	0.8713	18.8	129.6
11	14.22	0.8427	17.2	137.6	14.26	0.8426	16.9	138.7
12	17.99	0.8054	40.9	125.1	18.08	0.8053	39.1	126.7
13	24.29	0.7484	36.8	133.7	24.39	0.7493	34.8	136.4
14	25.58	0.7369	71.2	123.0	25.68	0.7371	68.8	124.2
15	36.61	0.6497	64.2	131.7	37.00	0.6516	59.5	135.6
16	130.88	0.2336	32.9	121.7	131.67	0.2350	30.8	123.2
17	84.51	0.3872	28.3	125.5	84.78	0.3878	27.1	126.9
18	188.11	0.1286	62.9	119.3	192.76	0.1319	55.6	122.6
19	128.94	0.2402	54.5	123.2	129.55	0.2431	51.1	125.5
20	230.16	0.0827	86.7	117.8	240.94	0.0864	73.3	122.6
21	162.99	0.1681	73.4	122.5	166.45	0.1699	66.9	126.2
22	311.47	0.0365	143.4	115.7	347.77	0.0412	112.7	123.3
23	231.67	0.0834	121.1	120.5	239.75	0.0871	107.5	125.4
24	129.51	0.2449	79.4	120.4	132.17	0.2471	72.3	124.3
25	146.72	0.2049	94.5	119.3	151.15	0.2071	84.7	123.9
26	162.78	0.1742	108.8	118.6	165.23	0.1777	100.6	121.8
27	176.68	0.1509	123.8	117.6	180.68	0.1543	112.7	121.4

^aCalculated with the reference temperature T_{refq} (Table 2).

^b t_p , total processing time, including the cooling period (min).

^c T_{op} , optimal processing temperature ($^{\circ}\text{C}$).

the results given by both objective functions. However, the D_{refq} value is expected to be the most important parameter, as can be seen from the mathematical formulation of both objective functions (eqns (13) and (15)).

Effect of D_{ref} value for the quality factor

To study the effect of the decimal reduction time at the reference temperature on the optimal processing temperature, maximizing the overall quality of the food, the case study of Teixeira *et al.* (1969) (Table 4) was run for an enlarged range of D_{refq} values. Considering the same reference temperature, 118.9°C, optimization problems with D_{refq} values between 5 and 1000 min were solved. Table 5 presents results using either the volume average retention (eqn (13)) or the volume average cook-value (eqn (15)) as the objective function.

For D_{refq} values higher than approximately 150 min (Fig. 1) the two objective functions supply the same results. In this range of D_{refq} values, which is valid for vitamins, the decimal reduction time at reference temperature for the quality factor has almost no influence on optimum processing conditions for the objective function $(N/N_0)_{\text{ave}}$. However, for D_{refq} values smaller than approximately 150 min, this parameter clearly affects the optimal processing temperature. For lower D_{refq} values the optimal processing temperature increases, with a corresponding decrease in total processing time (Fig. 1). The results supplied by the two

TABLE 4
Case Study Used to Study the Effect of D_{ref} , for the Quality Factor, on the Optimal Processing Temperature

<i>Product</i>	
Can	307 × 409
Diameter (m)	0.0873
Height (m)	0.1159
a (m ² /s)	1.696×10^{-7}
T_0 (°C)	71.1
T_w (°C)	26.1
h (W/m ² K)	Infinite
Come-up-time (min)	0
<i>Microorganism</i>	
z_m (°C)	10.0
D_{refm} (min)	3
T_{refm} (°C)	121.15
<i>Quality attribute</i>	
z_q (°C)	25.0
D_{refq} (min)	146.6; 188.7; 202.3
T_{refq} (°C)	118.9
<i>Constraint</i>	
ASM	5.214×10^{-6}

TABLE 5
Optimization Results for the Study of the D_{refq} Effect on Optimum Sterilization Conditions

D_{ref2}	Objective function							
	C_{ave}				$(N/N_0)_{\text{ave}}$			
	C_{ave}	$(N/N_0)_{\text{ave}}$	t_p^a	T_{op}^b	C_{ave}	$(N/N_0)_{\text{ave}}$	t_p	T_{op}
5	64.44	0.0000	119.0	120.2	—	—	—	—
12.15	64.44	0.0000	119.0	120.2	—	—	—	—
18.22	64.44	0.0012	119.0	120.2	449.69	0.0045	64.2	166.1
24.29	64.44	0.0054	119.0	120.2	220.60	0.0113	68.9	153.5
50	64.44	0.0659	119.0	120.2	72.67	0.0722	93.6	128.0
80	64.44	0.1731	119.0	120.2	65.90	0.1768	106.0	123.3
100	64.44	0.2421	119.0	120.2	65.21	0.2447	109.1	122.4
146.6	64.44	0.3748	119.0	120.2	64.70	0.3757	113.8	121.3
188.7	64.44	0.4641	119.0	120.2	64.73	0.4644	113.6	121.3
202.3	64.44	0.4881	119.0	120.2	64.59	0.4887	114.4	121.1
300	64.44	0.6144	119.0	120.2	64.56	0.6143	116.4	120.7
500	64.44	0.7452	119.0	120.2	64.48	0.7453	116.3	120.7
750	64.44	0.8214	119.0	120.2	64.51	0.8214	116.0	120.8
1000	64.44	0.8627	119.0	120.2	64.48	0.8627	117.3	120.5

^a t_p , total processing time, including the cooling period (min).

^b T_{op} , optimal processing temperature (°C).

Fig. 1. Optimal processing temperature and optimal processing time as a function of D_{ref} value for the quality attribute. Objective function: Δ , $(N/N_0)_{\text{ave}}$; $\circ$, C_{ave} .

objective functions are different. The volume average cook-value objective function does not take into account the influence of D_{refq} on optimum conditions. The use of volume average retention as the objective function can improve the overall retention, in this range of D_{refq} values, by more than 100%. However, for small D_{refq} values the overall retention is very small.

The volume average cook-value is not a good choice of objective function to optimize volume average quality retention. Although the final volume average retentions using both approaches are about the same, the optimal temperature can be severely underestimated using the volume average cook-value approach, which is reflected in the associated processing times. This, in turn, seriously affects production economy. If a definition of an average cook-value is to be used it should be defined as a 'volume integrated cook-value' (eqn (14)), C_s , in analogy to the integrated lethality, F_s . From the data we can also conclude that both z value and D_{ref} value for the quality attribute are of importance and consequently should be reported for optimization studies.

For this example, the limit at which the D_{refq} value has no effect on the optimal processing temperature was approximately 150 min. However, there is a need to study how this limit is influenced by the food properties (thermal diffusivity and z value for the quality attribute), the processing conditions (geometry and dimensions of the food or container, surface heat transfer coefficient, initial temperature of the food and heating medium come-up-time) and the processing criteria lethality of (target microorganisms).

CONCLUSIONS

Depending on the range of D_{ref} values for the quality attribute, the results obtained by solving optimization problems using either the volume average retention or the volume average cook-value objective functions are or are not equivalent.

The use of volume average cook-value as the objective function does not take into account the effect of the D_{refq} value on the optimum processing conditions. The use of the volume average retention as the objective function, for low values of D_{refq} , can result in important savings in energy and a higher productivity.

There is a need to study the limits of D_{refq} values for which the optimal sterilization temperature is not affected by this parameter.

ACKNOWLEDGEMENT

C. Silva and F. Oliveira acknowledge support from the Junta Nacional de Investigação Científica e Tecnológica (JNICT).

REFERENCES

- Banga, J. R., Perez-Martin, R. I., Gallardo, J. M. & Casares, J. J. (1991). Optimization of the thermal processing of conduction-heated canned foods: study of several objective functions. *Journal of Food Engineering*, **14**, 25–51.
- Chau, K. V. & Gaffney, J. J. (1990). A finite-difference model for heat and mass transfer in products with internal heat generation and transpiration. *Journal of Food Science*, **55**, 484–7.
- Feliciotti, E. & Esselen, W. B. (1957). Thermal destruction rates of thiamin in puréed meats and vegetables. *Food Technology*, **11**, 77–84.
- Hayakawa, K. (1978). A critical review of mathematical procedures for determining proper heat sterilization processes. *Food Technology*, **3**, 59–65.
- Hendrickx, M., Van Genechten, K. & Tobback, P. (1990). Optimizing quality attributes of conduction heated foods, a simulation approach. In *Engineering and Food: Preservation Processes and Related Techniques*, Vol. 2, ed. W. E. L. Spiess & H. Shubert. Elsevier Applied Science, London, pp. 167–76.
- Hendrickx, M., Silva, C., Oliveira, F. & Tobback, P. (1991). Optimization of heat transfer in thermal processing of conduction foods. In *International Workshop on the Role of Food Engineering Research in the Development of Indonesian Food Industry*, 2–9 September 1991, Jakarta.
- Hendrickx, M., Silva, C., Oliveira, F. & Tobback, P. (in press). Generalized (semi)-empirical formulas for optimal sterilization temperatures of conduction heated foods with infinite surface heat transfer coefficients. *Journal of Food Engineering*.
- Holdsworth, S. D. (1985). Optimisation of thermal processing — a review. *Journal of Food Engineering*, **4**, 89–116.
- Holdsworth, S. D. (1990). Kinetic data — what is available and what is necessary. In *Processing and Quality of Foods*, Vol. 1: *HTST Processing*. Elsevier Applied Science, London, pp. 1.74–90.
- Lund, D. B. (1975). Effects of blanching, pasteurization and sterilization on nutrients. In *Nutritional Evaluation of Food Processing*, ed. R. S. Harris & E. Karmas. AVI, Westport, CT, pp. 205–40.
- Lund, D. B. (1977). Design of thermal processes for maximizing nutrient retention. *Food Technology*, **2**, 71–8.
- Mansfield, T. (1962). High temperature, short-time sterilization. In *Proc. 1st International Congress on Food Science and Technology*, Vol. 4. Gordon & Breach, London, pp. 311–16.
- Martens, T. (1980). Mathematical model of heat processing in flat containers. PhD thesis, Katholieke Universiteit Leuven.

- Mauri, L. M., Alzamora, S. M., Chirife, J. & Tomio, M. J. (1989). Review: kinetic parameters for thiamine degradation in foods and model solutions of high water activity. *International Journal of Food Science and Technology*, **24**, 1-9.
- Nadkarni, M. M. & Hatton, T. A. (1985). Optimal nutrient retention during the thermal processing of conduction-heated canned foods: application of the distributed minimum principle. *Journal of Food Science*, **50**, 1312-21.
- Ohlsson, T. (1980a). Optimal sterilization temperatures for flat containers. *Journal of Food Science*, **45**, 848-52.
- Ohlsson, T. (1980b). Optimal sterilization temperatures for sensory quality in cylindrical containers. *Journal of Food Science*, **45**, 1517-21.
- Ohlsson, T. (1980c). Optimization of heat sterilization using C-values. In *Food Process Engineering*. Applied Science Publishers, London, pp. 137-45.
- Ohlsson, T. (1988). The cook-value as tool in optimizing thermal processes. In *Proceedings of the International Symposium on Progress in Food Preservation Processes*, Vol. 1. CERIA, Brussels, 12-14 April, pp. 51-8.
- Saguy, I. (1988). Constraints to quality optimization in aseptic processing. *Journal of Food Science*, **53**, 306-7.
- Saguy, I. & Karel, M. (1979). Optimal retort temperature profile in optimizing thiamin retention in conduction-type heating of canned foods. *Journal of Food Science*, **44**, 1485-90.
- Silva, C., Hendrickx, M., Oliveira, F. & Tobback, P. (submitted). Optimal sterilization temperatures for conduction heated foods with finite surface heat transfer coefficients. *Journal of Food Science*.
- Stumbo, C. (1973). *Thermobacteriology in Food Processing*. 2nd edn. Academic Press, New York.
- Teixeira, A. A., Dixon, J. R., Zahradnik, J. W. & Zinsmeister, G. E. (1969). Computer optimization of nutrient retention in the thermal processing of conduction-heated foods. *Food Technology*, **23**, 137-42.
- Teixeira, A. A., Zinsmeister, G. E. & Zahradnik, J. W. (1975). Computer simulation of variable retort control and container geometry as a possible means of improving thiamine retention in thermally processed foods. *Journal of Food Science*, **40**, 656-9.
- Thijssen, H. A. C. & Kochen, L. H. P. (1980). Calculation of optimum sterilization conditions for packed conduction-type foods. *Journal of Food Science*, **45**, 1267-72.
- Thijssen, H. A. C., Kerkhof, P. J. A. M. & Liefkens, A. A. A. (1978). Short-cut method for the calculation of sterilization conditions yielding optimum quality retention for conduction-type heating of packaged foods. *Journal of Food Science*, **43**, 1096-101.
- Tucker, G. S. & Holdsworth, S. D. (1990). Optimisation of quality factors for foods thermally processed in rectangular containers. In *Process Engineering in the Food Industry*. Vol. 1. *Convenience Foods and Quality Assurance*, ed. R. W. Field & J. A. Howell. Elsevier Applied Science, London, pp. 59-74.
- Tucker, G. S. & Holdsworth, S. D. (1991). Mathematical modelling of sterilisation and cooking processes for heat preserved foods: applications of a new heat transfer model. *Trans IChemE*, **69**, 5-12.