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Mathematical Models to Evaluate Temperature Abuse Effects During Distribution of Refrigerated Solid Foods*

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ABSTRACT

The increasing consumption of refrigerated foods in the USA opens new opportunities for food processors to satisfy consumer demands for minimally processed foods. Previous work has shown the need to reduce the frequency of temperature abuse. The development of a personal computer-based tool to evaluate the consequences of temperature abuse shows that, even when the fraction of the total storage time at an undesirable room temperature is rather small (2–3%), the reduction in shelf-life can be highly significant (20–30%). The effect of package size and heat transfer properties was also significant. These types of evaluations, needed to help reduce product losses, are expensive and time consuming without the help of the tool here presented.

NOTATION

a_1, a_2, a_3	Half size, directions x, y and z
A	Area (m^2)
A'	Lag phase model constant
b_m	Maximum N_m achieved during stationary growth phase
B'	Lag phase model constant
c	Rate model constant (K^{-1})

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C_p	Specific heat (J/kg K)
CFU	Colony forming units
$\underline{E}$	Specific energy (J/kg)
$F(x, y)$	Arbitrary function
h	Convective heat transfer coefficient (W/m^2 K)
h_e	Convective heat transfer coefficient, external air (W/m^2 K)
h_i	Convective heat transfer coefficient, internal air (trapped) (W/m^2 K)
I	Integral of function $F(x, y)$
I'	Numerical integral of function $F(x, y)$
k	Thermal conductivity (W/m K)
k_p	Thermal conductivity, packaging material
l	Food thickness (m)
L_m	Lag time for microorganism 'm' (days)
M	Mass (kg)
N_m	Colony forming units per unit volume at any location and time θ (CFU/ml)
OD	Optical density
m	Index for a specific microorganism
n_I	Number of intervals, direction x
n_J	Number of intervals, direction y
n_K	Number of intevals, direction z
$P_{i,j}$	Polynomial expression, coefficients
Q'	Heat flow rate (W)
Q'_h	Heat flow rate by convection (W)
Q'_k	Heat flow rate by conduction (W)
r	Specific rate constant (s^{-1})
r_m	Specific growth rate at any temperature
r_0	Standard spoilage rate at 0°C (s^{-1})
R_α	Weight factor, coordinates x_α, y_α
T	Temperature (°C or K)
T_s	Surface temperature (°C or K)
T_∞	Environment air temperature (°C or K)
U	Overall heat transfer coefficient (W/m^2 K)
V	Volume (m^3)
x, y, z	Rectangular coordinates
x_1, x_2, x_3	General variables
δ	Thickness, packaging material
θ	Time (s)
ρ	Density (kg/m^3)

INTRODUCTION

The increasing consumption of prepared refrigerated foods in the USA opens new opportunities for food processors to satisfy consumer demands for minimally processed foods. However, these foods present the industry, the regulatory community and the consumer with serious microbial safety concerns. A recent survey of industry managers and food scientists lists food safety as an area of major research and development effort for the 1990s (Doyle, 1991). Aspects of particular concern include pathogens that grow at referigeration temperature. This phenomenon, while well documented, was not considered important until a few years ago (Doyle, 1991).

Shelf-life predictions based on mathematical models for microbial growth have been published (Schoolfield *et al.*, 1981; Pooni & Mead, 1984; Oz & Farnsworth, 1985; Phillips & Griffiths, 1987) and are being applied to the distribution of chilled foods. For example, Zamora and Zaritzky (1986) presented mathematical equations to estimate the time necessary for refrigerated vacuum packaged beef to reach a bacterial density of 10^7 CFU/cm^3 under various storage conditions. Initial composition of the mixed flora, individual growth rates and lag times were obtained experimentally. The growth rate and lag time for each microorganism were functions of temperature, pH of the meat cut and permeability of the packaging film. Their model permitted a satisfactory prediction of microbial growth for any constant, but not changing storage temperature. Fluctuating temperature conditions require continuous food temperature measurements or heat transfer models to estimate food temperature as a function of time and location within the food, environment temperature records, and the thermal properties of the food and its packaging.

The remaining shelf-life of a refrigerated food is largely determined at any given time by the cumulative effect of temperature during the previous handling of the product. Unfortunately, the existing distribution channel is not well equipped for the optimum control of temperature during the distribution and display of refrigerated foods. Serious microbial stability problems exist because of the frequency of temperature abuse (Corlett, 1988; Mory, 1988; Simpson *et al.*, 1989; Torres, 1989; Doyle, 1991). Distribution temperatures need to be lowered since they are critical in maintaining the quality and safety of the product (Young, 1987). The optimum range for successfully handling and displaying refrigerated foods is -1 to 2°C (30–35°F), certainly never higher than 5°C (40°F). However, many of the retail display cases in use today cycle up to

7 to 10°C (45 to 50°F; Young, 1987). A similar lack of temperature control exists in other steps in the delivery chain of chilled foods.

There is a need to evaluate the effectiveness of temperature monitoring devices and process modifications to lower microbial contamination levels. Packaging strategies are needed to isolate the product from an abusive temperature environment. All these developments must be carefully evaluated (Mistry & Kosikowsky, 1983; Singh & Wells, 1985; Zall *et al.*, 1986; Zuritz & Sastry, 1986; Wells & Singh, 1988*a*, *b*; Corlett, 1988; Mory, 1988). In an era of increasingly limited financial resources and need to protect brand equity, it is necessary to select for further studies those factors that will have the most impact on product quality. Unfortunately, assessing microbial quality is an expensive and time consuming process. A cost-effective approach would be to use mathematical models to conduct 'computer experiments' to evaluate the expected effectiveness of alternative management decisions. Successful computer models could identify a few alternatives worthy of experimental testing.

The objective of this publication is the development of a personal computer-implemented model as a tool to evaluate the shelf-life of refrigerated solid foods in rectangular containers and undergoing temperature abuse. Previously developed numeric strategies allowing efficient heat transfer calculations (Bouzas *et al.*, 1991) were combined with microbial growth models shown by Li (1988) to accurately predict microbial growth under variable temperature. The use of this management tool could help reduce product losses. Gains in consumer confidence in product quality could lead to an increased demand for refrigerated foods.

MATERIALS AND METHODS

Heat transfer model

The temperature of solid foods in rectangular containers and undergoing temperature abuse can be calculated numerically on the basis of energy balance calculations (Chang & Toledo, 1989; Bouzas *et al.*, 1991). Assuming heat transfer symmetry, one-eighth of the total food volume was partitioned into n_I, n_J and n_K intervals in the x, y and z directions, respectively. This partition generates $(n_I+1)\times(n_J+1)\times(n_K+1)$ nodes whose temperature is predicted using an energy balance for the control volume surrounding each node. The node location affects these calculations and defines eight situations, seven of which are seen in Fig. 1, the eighth type corresponds to those with no surface boundaries.

The first law of thermodynamics for a closed system with no deformation can be written as

$$\delta Q' = M_{\text{system}} \frac{\mathrm{d}(\underline{E})_{\text{system}}}{\mathrm{d}\theta} \tag{1}$$

Assuming

$$\mathrm{d}\underline{E} = c_{\mathrm{p}}\,\mathrm{d}T \tag{2}$$

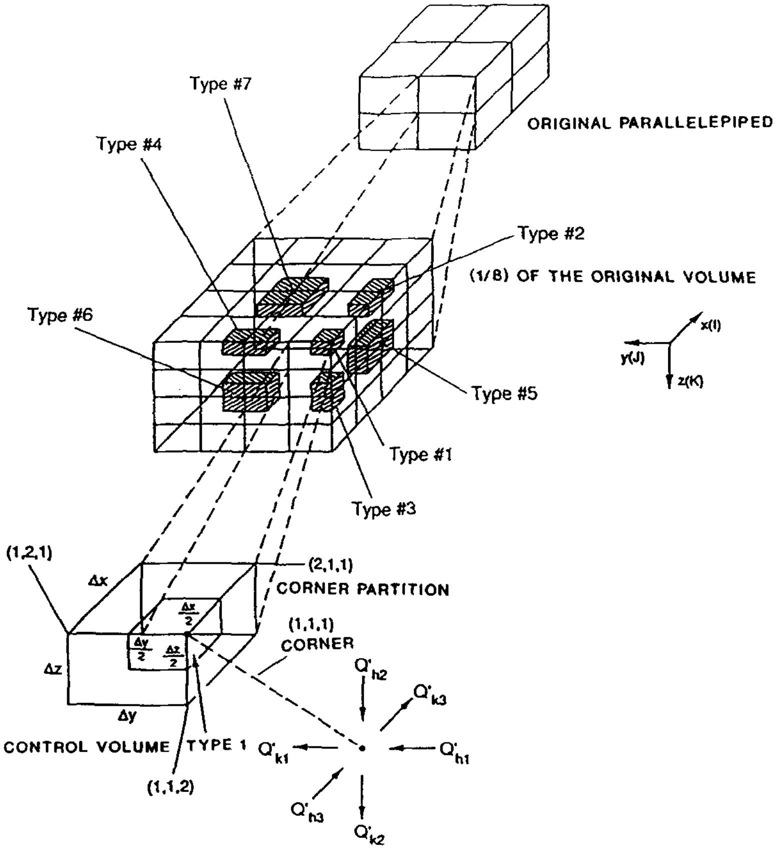


Fig. 1. Schematic representation of the numeric method for heat transfer calculations. Q'_{h}, convection heat transfer from environment; Q'_{k}, conduction heat transfer within the food.

and changing to finite differences:

$$\Sigma Q' = Mc_{\mathrm{p}} \frac{\Delta T}{\Delta \theta} = \rho V c_{\mathrm{p}} \frac{\Delta T}{\Delta \theta} \tag{3}$$

In the case of volume element type 1 (Fig. 1), this equation can be written as

$$Q'_{\mathrm{h1}} + Q'_{\mathrm{h2}} + Q'_{\mathrm{h3}} + Q'_{\mathrm{k1}} + Q'_{\mathrm{k2}} + Q'_{\mathrm{k3}} = \rho c_{\mathrm{p}} \frac{\Delta x}{2} \frac{\Delta y}{2} \frac{\Delta z}{2} \frac{\Delta T}{\Delta \theta} \tag{4}$$

where

$$Q'_{\mathrm{h1}} = hA(T_\infty - T_{\mathrm{s}}) \tag{5}$$

$$Q'_{\mathrm{k1}} = -kA \frac{\Delta T}{\Delta x} \tag{6}$$

Equation (4) can be written in finite difference form as

$$\begin{aligned} & h \frac{\Delta z}{2} \frac{\Delta x}{2} (T_\infty - T_{i,j,k})_\theta + h \frac{\Delta x}{2} \frac{\Delta y}{2} (T_\infty - T_{i,j,k})_\theta + h \frac{\Delta y}{2} \frac{\Delta z}{2} (T_\infty - T_{i,j,k})_\theta \\ & \quad + k \frac{\Delta x}{2} \frac{\Delta z}{2} \frac{(T_{i,j,k+1} - T_{i,j,k})_\theta}{\Delta y} + k \frac{\Delta x}{2} \frac{\Delta y}{2} \frac{(T_{i+1,j,k} - T_{i,j,k})_\theta}{\Delta z} \\ & \quad + k \frac{\Delta z}{2} \frac{\Delta y}{2} \frac{(T_{i,j+1,k} - T_{i,j,k})_\theta}{\Delta x} = \rho c_{\mathrm{p}} \frac{\Delta x}{2} \frac{\Delta y}{2} \frac{\Delta z}{2} \frac{[(T_{i,j,k})_{\theta + \Delta\theta} - (T_{i,j,k})_\theta]}{\Delta \theta} \end{aligned} \tag{7}$$

Equation (7) can be used to evaluate temperature $T_{i,j,k}$ at time $\theta + \Delta\theta$ as a function of physical properties and known temperature values at time θ for control volumes of the first type ($i = 1, j = 1, k = 1$) and can be modified for the other seven situations. The finite differences, Δx, Δy, Δz and $\Delta\theta$, are restricted by a stability condition. The case of conduction heat transfer in a solid infinite slab will be used as an example of the derivation of this condition:

$$\frac{\mathrm{d}^2 T}{\mathrm{d}x^2} = \frac{\rho c_{\mathrm{p}}}{k} \frac{\mathrm{d}T}{\mathrm{d}\theta} \tag{8}$$

and changing to finite differences we obtain

$$\frac{(T_{x+1}-2T_x+T_{x-1})_\theta}{\Delta x^2}=\frac{\rho c_p}{k}\frac{(T_x)_{\theta+\Delta\theta}-(T_x)_\theta}{\Delta\theta} \tag{9}$$

which when rearranged can be expressed as

$$(T_x)_{\theta+\Delta\theta}=(T_x)_\theta\left[1-\frac{2\Delta\theta}{(\Delta x)^2}\frac{k}{\rho c_p}\right]+\frac{\Delta\theta k}{\rho c_p}\left[\frac{(T_{x+1}+T_{x-1})_\theta}{(\Delta x)^2}\right] \tag{10}$$

If the coefficient of $(T_x)_\theta$, the temperature at x at time θ, were negative, then this formula would dictate that the lower $(T_x)_\theta$ was, the higher $(T_x)_{\theta+\Delta\theta}$ would be at the new time $\theta+\Delta\theta$. However, this would violate thermodynamic principles and it follows that a necessary condition for nonviolation is that $\Delta\theta$ should be chosen, for a given Δx, so that the coefficient of $(T_x)_\theta$ is non-negative (Croft & Lilley, 1977):

$$1-\frac{2\Delta\theta}{(\Delta x)^2}\frac{k}{\rho c_p}\geq 0 \tag{11}$$

which leads to the following upper limit for the time increment

$$\Delta\theta\leq\frac{(\Delta x)^2\rho c_p}{2k} \tag{12}$$

In the case of the situation described schematically in Fig. 1, it is possible to derive specific expressions for each control volume type; however, two of them represent the most restrictive conditions and can be quantified as follows:

$$\Delta\theta\leq\frac{\rho c_p}{2\left(\frac{h}{\Delta x}+\frac{h}{\Delta y}+\frac{h}{\Delta z}+\frac{k}{(\Delta x)^2}+\frac{k}{(\Delta y)^2}+\frac{k}{(\Delta z)^2}\right)} \tag{13}$$

for control volumes type 1

and

$$\Delta\theta\leq\frac{\rho c_p}{4\left(\frac{k}{(\Delta x)^2}+\frac{k}{(\Delta y)^2}+\frac{k}{(\Delta z)^2}\right)} \tag{14}$$

for control volumes type 8.

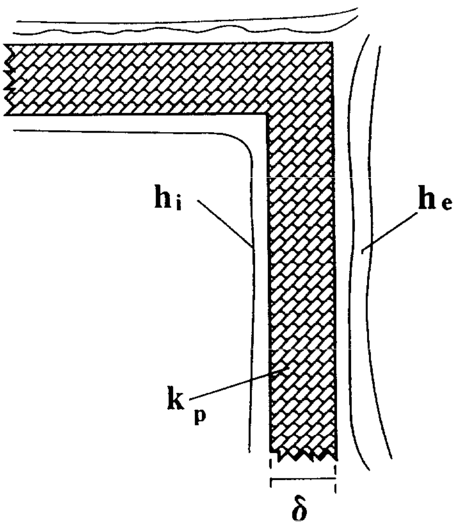
Most commercial packages have significant heat transfer resistance (Bormett, 1982) and could be used to dampen the effect of temperature abuse. Boundary conditions (Fig. 2) can be mathematically described as follows (Zuritz & Sastry, 1986):

$$U=\frac{1}{\dfrac{1}{h_{\mathrm{i}}}+\dfrac{\delta}{k_{\mathrm{p}}}+\dfrac{1}{h_{\mathrm{e}}}} \tag{15}$$

Equation (15) is strictly valid only for steady state conditions; however, it can be used in unsteady state conditions when the transient effect of the packaging material can be ignored. This is valid only if (Zuritz & Sastry, 1986)

$$\delta \ll \frac{l(\rho c_{\mathrm{p}})_{\mathrm{food}}}{2(\rho c_{\mathrm{p}})_{\mathrm{package}}} \tag{16}$$

Consequently, when eqn (16) is satisfied, the parameter h can be replaced by U in the derivation of the numeric algorithm (Bouzas *et al.*, 1991) (eqns (5 to 14)).



$$U=\frac{1}{\dfrac{1}{h_i}+\dfrac{\delta}{k_p}+\dfrac{1}{h_e}}$$

Fig. 2. Schematic representation of the boundary conditions for the heat transfer model.

Microbial growth model

Microbial growth in foods involves usually more than one type of microorganism, multiple alternative substrates and changing environment (e.g. temperature, pH and oxygen tension). Li (1988) used liquid media to validate a microbial growth model which included predictions under variable temperature for the lag and exponential growth phase. Experimental and predicted microbial counts agreed well in spite of the large and abrupt temperature changes allowed by experimenting with liquid media. Li's (1988) data and model were therefore selected for use in this study.

The kinetics of microbial growth is governed by the following expression (Li, 1988; Li & Torres, 1989; Simpson *et al.*, 1989):

$$\frac{dN_m}{d\theta} = r_m \frac{(b_m - N_m)}{b_m} N_m; \quad \theta \geq L_m \tag{17}$$

Microbial counts associated with the stationary phase reflect spoiled products and thus the microbial model can be limited to lag and exponential phase growth estimations as follows:

$$\frac{dN_m}{d\theta} = r_m N_m; \quad \theta \geq L_m \tag{18}$$

The rate constant (r_m) is assumed to change with temperature according to a linear model (Spencer & Baines, 1964; Li, 1988):

$$r = r_0(1 + cT) \tag{19}$$

Microbial growth lag models

Temperature affects lag time (L) by influencing the adaptation rate of a microorganism to a new environment. An adaption rate can be defined as the reciprocal of lag time ($1/L$). An early report by Cooper (1963) noted that the ratio of lag to generation time was nearly constant. This suggested that a linear relationship might exist between lag time and the reciprocal of the specific growth rate. Regression equations on the basis of this relationship have been successfully used to predict lag time (Li, 1988).

Lag phase models for changing temperature conditions

Methodology to predict microbial growth under fluctuating temperature conditions has been developed (Li, 1988). First, microbial growth rate determinations are conducted at constant temperature conditions. Statistical methods are then used to find the best fit specific growth rate–temperature model (eqn (19)). The reciprocal of the specific growth rate is then correlated to the lag time (L). The lag time under fluctuating conditions (θ_{total}) is calculated by noting that if L_i and θ_i are the lag time and incubation period at temperature T_i, respectively, then

$$\Delta\theta_i\left(\frac{1}{L_i}\right) = \text{lag phase fraction accumulated during incubation period } \Delta\theta_i$$

Therefore

$$\frac{\Delta\theta_1}{L_1}+\frac{\Delta\theta_2}{L_2}+\frac{\Delta\theta_3}{L_3}+\ldots\frac{\Delta\theta_n}{L_n}=1 \Rightarrow \text{lag phase completed} \qquad (20)$$

L_i is related to temperature (T_i) according to the following expression (Li, 1988):

$$L_i = A'/r(T_i) + B' \qquad (21)$$

After time $\theta_{\mathrm{total}} = \Sigma\Delta\theta_i$, the microorganisms begin to grow exponentially and cell numbers can be calculated using eqns (18) and (19).

A demonstration example of this prediction methodology for growth as temperature fluctuates was given by Li (1988). *Brochothrix thermosphacta* was chosen for its ability to grow at low temperatures and reduced water activity. An experimental liquid medium was agitated vigorously and exposed to a temperature cycle of 24 h at 2°C and 24 h at 14°C. Predicted microbial growth under these stepped temperature changes fell within the prediction interval at the 95% confidence level until the growth curve reached the stationary phase.

Combined heat transfer and microbial growth model

Temperature calculations using heat transfer equations can be combined with growth models to estimate food spoilage. The form of the microbial model (Li, 1988) should be valid for liquid or solid media with parameters determined for each food. Lag and exponential phase models were combined by Simpson *et al.* (1989) with heat transfer calculations for an infinite slab to analyze the microbial spoilage of solid foods whose temperature fluctuates with the environment in a rather complex form. In this paper we use a similar approach for foods in rectangular containers. The number of microorganisms at any time and location in the food is estimated using the trapezoidal integration method (Singh, 1983).

Average microbial counts at any time are calculated by a multivariable numerical integration method described as follows for a two variable integral (Tyler, 1953):

$$I=\int_{-a_1}^{a_1}\int_{-a_2}^{a_2} F(x,y)\,\mathrm{d}x\,\mathrm{d}y \tag{22}$$

with

$$F(x,y)=\sum_{i=0}^{2n}\sum_{j=0}^{2n} P_{i,j}x^i y^j; \quad i+j\leq 2n \tag{23}$$

A weighted average expression to calculate numerically eqn (22) is obtained as follows (Tyler, 1953):

$$I'=4a_1a_2\sum_{\alpha=1}^{m} R_\alpha F(x_\alpha, y_\alpha) \tag{24}$$

where R_α are weight factors for m points with coordinates (x_α, y_α). The condition $I=I'$ for a polynomial of order $2n$ and m points with location (x_α, y_α) determines the values of the weight factors R_α. In the case of functions of three variables, a 21 point fifth-order polynomial is used, giving the final expression (Tyler, 1953):

$$\int_{-a_1}^{a_1}\int_{-a_2}^{a_2}\int_{-a_3}^{a_3} F(x_1,x_2,x_3)\,\mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}x_3$$

$$\approx\frac{a_1a_2a_3}{45}[-496F_1+128\Sigma F_2+8\Sigma F_3+5\Sigma F_4] \tag{25}$$

where F_i correspond to values of the function $F(x_1,x_2,x_3)$ evaluated at the geometrical center (F_1), six points located midway from the center of each side (F_2), six points located on the center of each side (F_3), and the eight vertices (F_4) of the food volume. Figure 3 shows the 21 points and their corresponding weight factors.

An expression for average microbial counts was derived as follows:

$$N_{\text{average}}\approx\frac{\frac{a_1a_2a_3}{45}[-496F_1+128\Sigma F_2+8\Sigma F_3+5\Sigma F_4]}{2a_1\,2a_2\,2a_3} \tag{26}$$

$$N_{\text{average}}\approx\tfrac{1}{45}\tfrac{1}{8}[-496F_1+128\Sigma F_2+8\Sigma F_3+5\Sigma F_4] \tag{27}$$

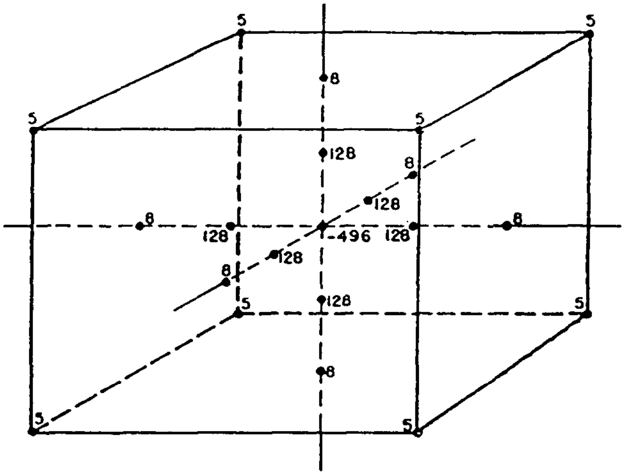


Fig. 3. Weight factors and location for the numerical integration for microbial count estimations.

Application example

The combined heat transfer and microbial growth model has been tested by analyzing the effect of temperature abuse on microbial growth. The program considered the presence of only one microorganism, but included the effect of the packaging material and the product dimensions. Simulation parameters for this assumed product and package are described in Table 1. Figure 4 shows the flowchart of the program developed. Finally, it is important to note that the computer model is not restricted to a particular mathematical function for the environment temperature. The information could be provided as an arbitrarily changing time-temperature record.

Four assumed environment temperature records, with and without temperature abuse (Fig. 5), were used in the computer simulation examples. Product shelf-life, defined as the time required to reach 10^7 CFU/ml, was estimated for two different packages (Table 1(c)) containing food with an initial temperature of 1°C.

RESULTS AND DISCUSSION

Several simulations were conducted to evaluate the effect of temperature abuse on shelf-life, as affected by abuse severity and packaging characteristics with shelf-life of the abused product as a reference for comparisons.

TABLE 1
Simulation Parameters

(a) Heat transfer model				
Product thermal conductivity (W/m^2 K)	0·56			
Product specific heat (J/kg K)	3680			
Overall heat transfer coefficient (W/m^2 K)	3 or 2			
Number of partitions (X)	4			
Number of partitions (Y)	4			
Number of partitions (Z)	4			
Initial temperature (°C)	1			
Time increment (s)	30			
(b) Microbial growth model				
Initial cell counts (CFU/ml)	$1{\cdot}0 \times 10^3$			
r_0 (s^{-1})	0·007			
c (K^{-1})	0·05			
A' (units)	3·01			
B' (units)	−28·97			
(c) Packaging characteristics				
Package no. 1 ('small')	0·126[a]	0·090[b]	0·052[c]	3[d]
Package no. 2 ('large')	0·230[a]	0·180[b]	0·130[c]	2[d]

[a] Height (m).
[b] Width (m).
[c] Length (m).
[d] U (W/m^2 K).

Effect of environment temperature fluctuations

Two package size and two overall heat transfer coefficient (U) values (Table 1c) were considered to analyze the effect of temperature fluctuations. The U value used for the large package was 2 W/m^2 K (Bormett, 1982). The U value for the small package was 3 W/m^2 K which is equivalent to using a 50% thinner packaging material.

Simulations for the effect of environmental temperature fluctuations for the small and the large package show significant differences between environment and product temperature, particularly for the large package with a lower overall heat transfer coefficient (Fig. 6(b)). This suggests that time–temperature indicators placed on product surfaces could overestimate the effect of temperature abuse and result in unnecessary disposal of product still acceptable for consumption.

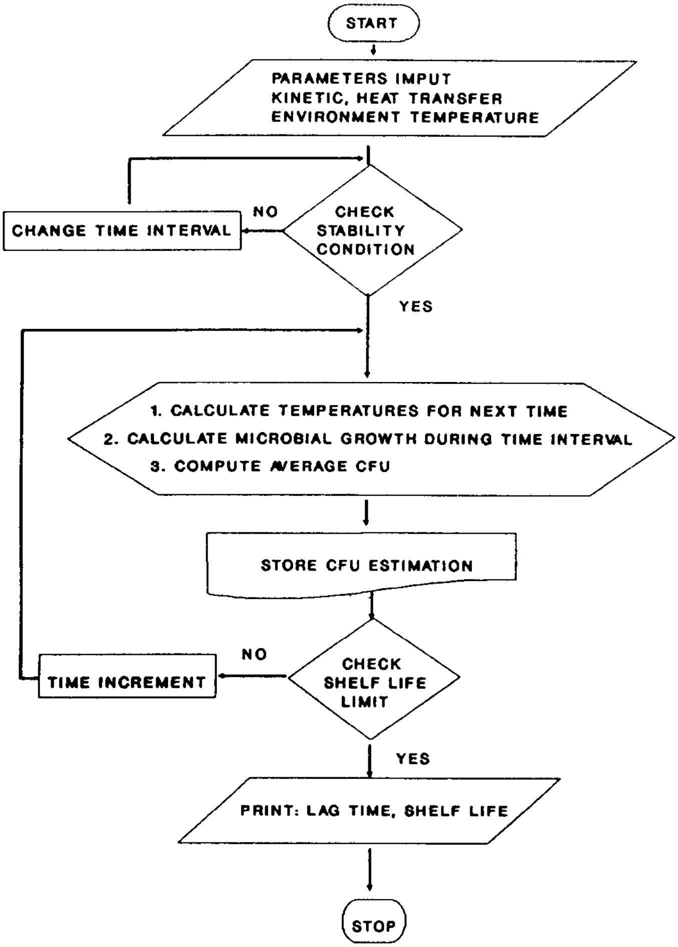


Fig. 4. Flowchart for implementation of combined heat transfer and microbial growth model.

Effect of food location

Microbial spoilage simulations for the 'small' package stored at 6°C with two abuse events show no practical differences in growth rate among food locations (Fig. 7(a)). Only an insignificant (15 min) difference in time to complete the lag phase and a rather small (2 h) delay to reach the shelf-life limitation of 10^7 CFU/ml can be observed between center and corner food locations. The differences are so minor that it is not possible to observe the line corresponding to average microbial spoilage (Fig. 7(a)). As expected, differences were magnified when the simulation

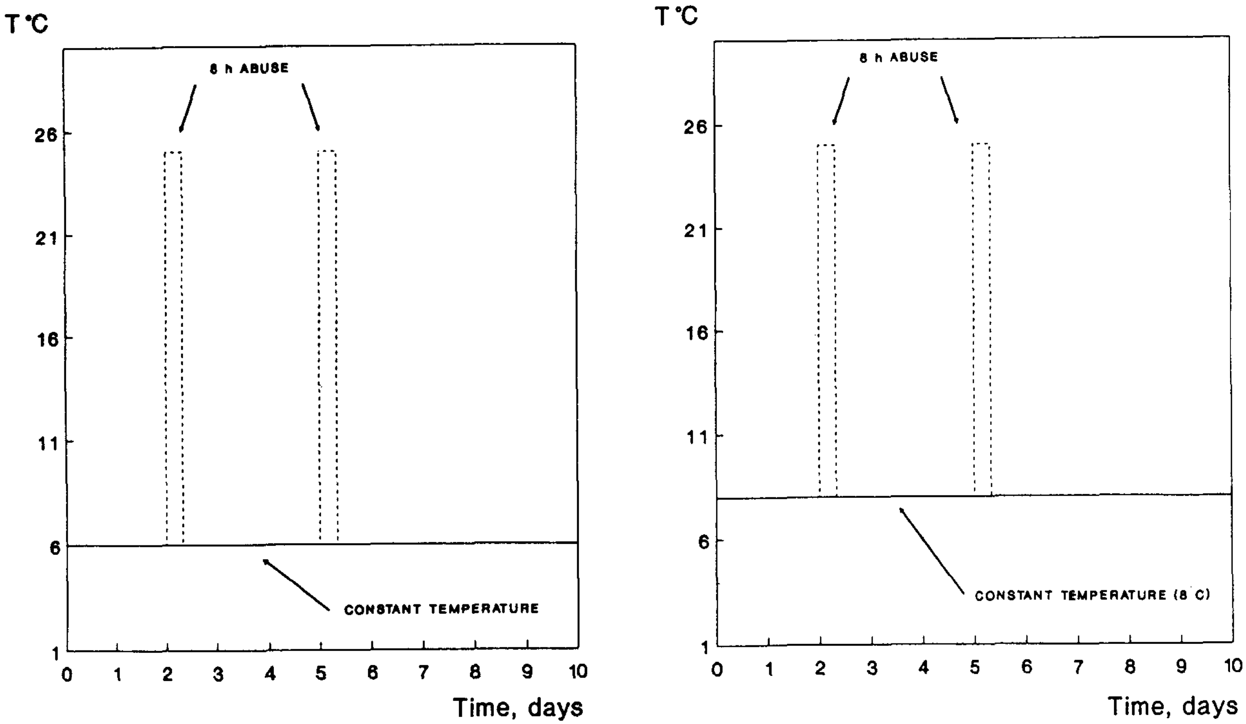
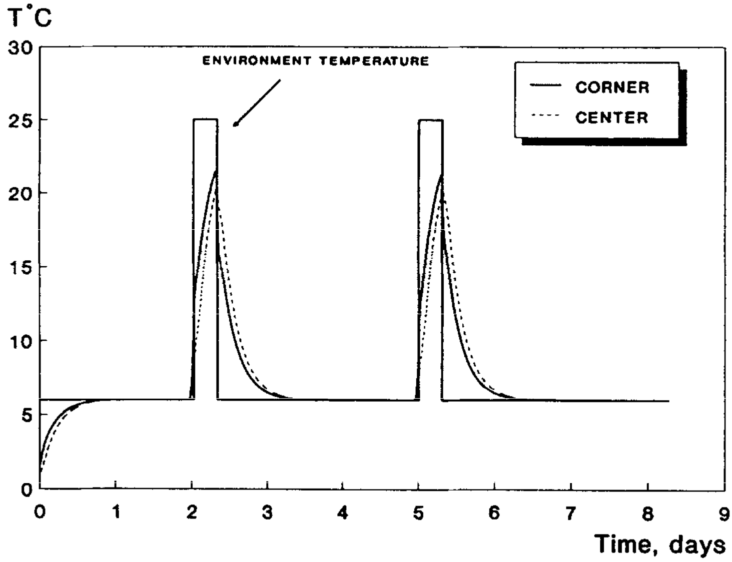
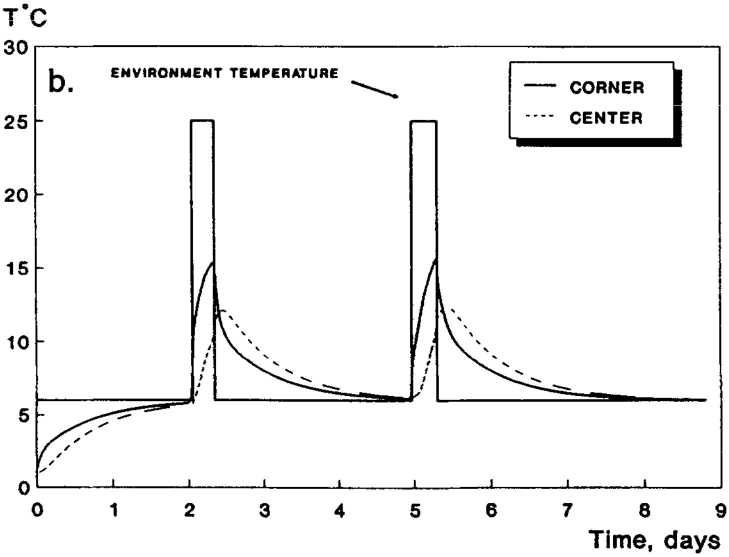


Fig. 5. Temperature abuse scenarios.

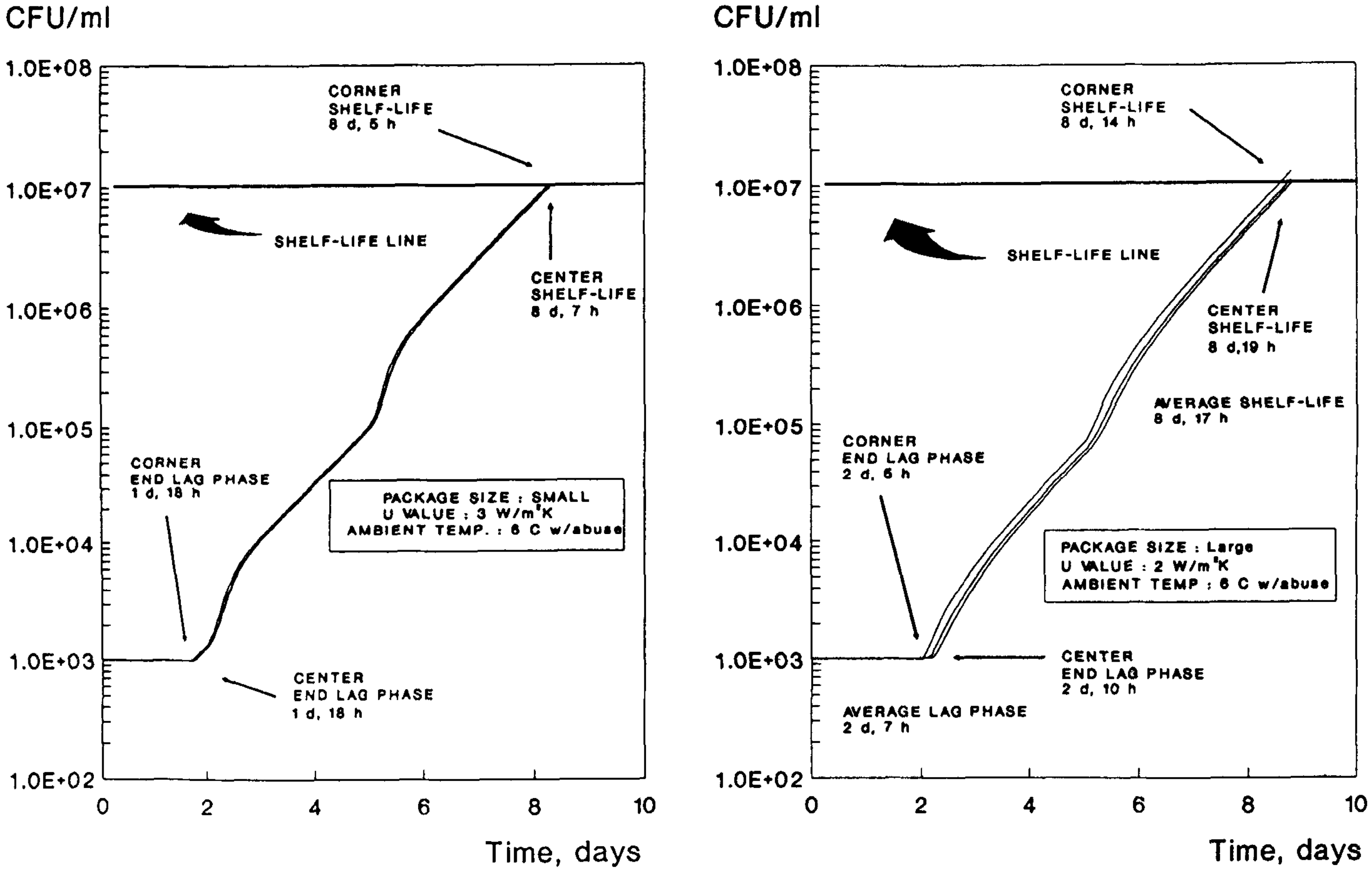


(a)



(b)

Fig. 6. Predicted food temperature — effect of packaging characteristics: (a) small package; (b) large package.



(a)

(b)

Fig. 7. Microbial spoilage simulations — effect of food location: (a) small package; (b) large package.

corresponded to the larger size package with a smaller overall heat transfer coefficient (Fig. 7(b)). However, differences in lag time (5 h) and in predicted shelf life (5 h) are of no practical significance. In view of the absence of significant thermal inertia (Fig. 6) for the given simulated conditions reflected by the lack of a food location effect, it is not necessary to estimate an average microbial spoilage. Figures 8 and 9 report only values for the apparent critical spoilage point — the food package corner.

Effect of package characteristics

Simulations for the effect of package characteristics for storage at 6°C, with and without abuse, are depicted in Fig. 8(a) and similarly for storage at 8°C in Fig. 8(b). These simulations show differences large enough to be considered of practical importance — up to a 25% extension in shelf life for the two packages evaluated. The largest shelf-life difference was found between the large package (No. 2) without abuse and the small package (No. 1) with abuse, 2 days: 14 h and 2 days when stored at 6 and 8°C, respectively. The impact of package characteristics on shelf-life, differences of 9 and 13 h at 6°C and 17 h for storage at 8°C, represents 5 to 10% of the product shelf-life.

Effect of environment temperature

Industry personnel frequently face the decision whether to upgrade distribution facilities by changing to lower average operating storage temperature (alternative A), or to invest in management strategies to reduce the frequency of product exposure to undesirably high temperatures (alternative B). Simulations for the effect of temperature abuse for the small (Fig. 9(a)) and large package (Fig. 9(b)) demonstrate the use of mathematical models to evaluate the effect of these alternatives on product quality. A longer shelf-life extension is observed for alternative A for both package types. In the case of the small package, alternative A extends shelf-life by 31 h (20%), while alternative B extends it by 46 h (30%), beyond the original value of 6 days: 7 h. In the case of the larger unit, the values are 31 h (18·5%) and 38 h (23%) over the original value of 7 days for alternatives A and B, respectively.

It is impractical and expensive to conduct microbial tests to estimate shelf-life under all possible temperature scenarios. The above analysis suggests a much better approach, that is, to conduct a few and simple constant temperature experiments to determine microbial kinetics data and then use mathematical modeling techniques to estimate microbial

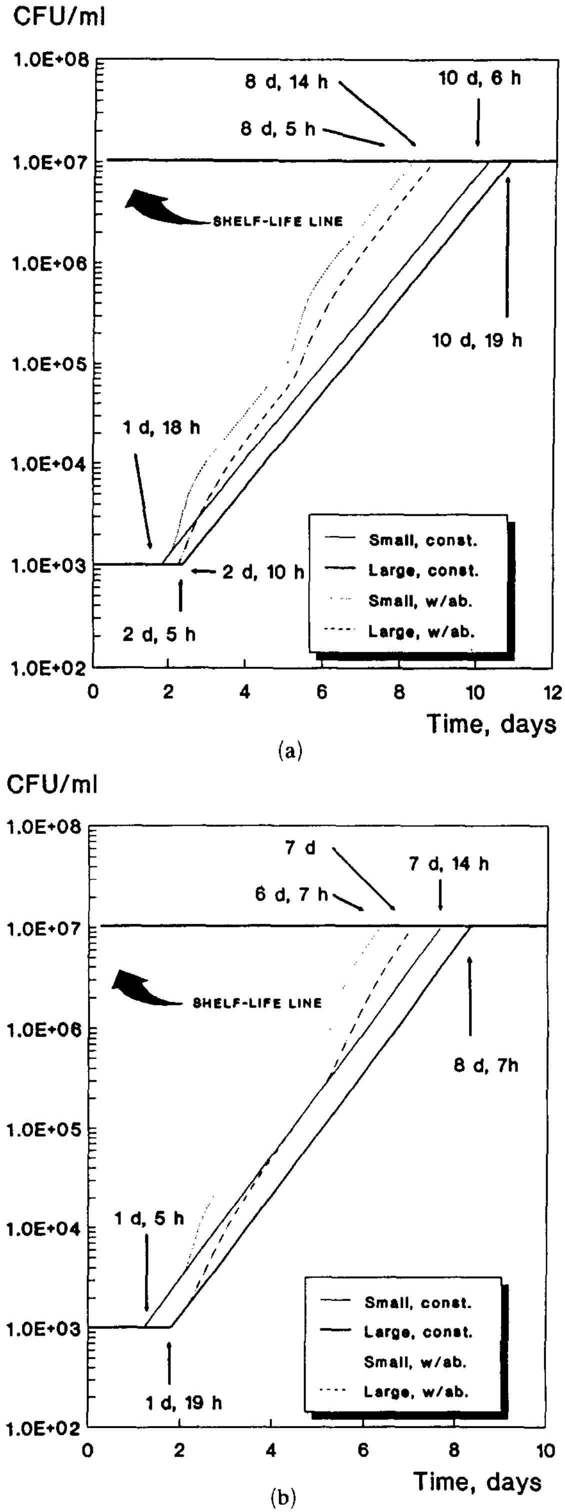
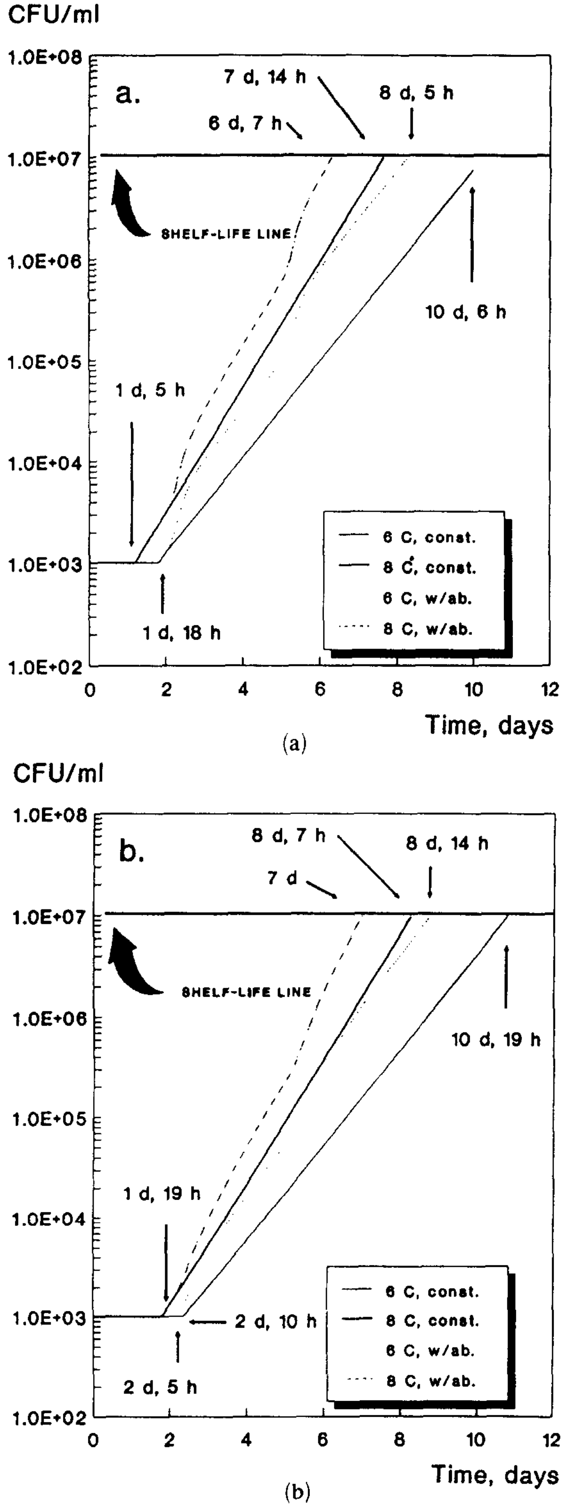


Fig. 8. Microbial spoilage simulations — effect of package characteristics: (a) storage at 6°C with and without temperature abuse; (b) storage at 8°C with and without temperature abuse.



(a)

(b)

Fig. 9. Microbial spoilage simulations — effect of environmental temperature: (a) small package; (b) large package.

spoilage for any desired temperature history (changing or constant). The same approach could be used to evaluate packaging alternatives and also to facilitate the control by regulatory agencies of the marketing of temperature sensitive foods.

CONCLUSIONS

The channels for distribution and display of chilled foods are not well equipped for their optimum handling. Temperature surveys have shown that refrigerated foods are frequently exposed to undesirable storage temperatures. New technologies facilitate data acquisition and more information is available to identify existing problems. The management tool presented in this paper highlights the consequences of temperature abuse and shows that, even when the fraction of the total storage time at an inappropriate temperature is rather small (2–3%), the reduction in shelf-life can be significant. Moreover, this method can be used to identify those improvements in facility and product handling with the most impact on product quality. The computer model can help estimate the benefits of more costly packaging alternatives (e.g. using a thicker cardboard) and can generate curves for shelf-life as a function of package characteristics (size, material and selected thickness) for given temperature scenarios. The availability to the food industry of this and other similar management tools would allow for more informed management decisions.

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