Principles of Thermal Processing of Packaged Foods

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KEY TERMS

Heat transfer	Bacterial inactivation	Food sterilization
Microorganism heat resistance	Decimal reduction time	Commercial sterilization

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Variables

α = thermal diffusivity

ρ = density

C_p = specific heat

CUT = time required to come up to retort temperature

D = decimal reduction time

F_0 = cumulative lethality of the process from time 0 to the end of the process

I = inactivation

k = rate constant

K_t = thermal conductivity

N = number

t = time

$$T = \text{temperature}$$
$$T_{\text{ref}} = \text{reference temperature}$$
$$TRT = \text{retort temperature}$$
$$z = \text{temperature change}$$

Introduction

Thermal processing of foods, like cooking, involves heat and food. However, thermal processing is applied to ensure food safety and not necessarily to cook the food. Thermal processing as a means of preservation of uncooked food was invented in France in 1795 by Nicholas Appert, a chef who was determined to win the prize of 12,000 francs offered by Napoleon for a way to prevent military food supplies from spoiling. Appert worked with Peter Durand to preserve meats and vegetables encased in jars or tin cans under vacuum and sealed with pitch and, by 1804, opened his first vacuum-packing plant. This French military secret soon leaked out, but it took more than 50 years for Louis Pasteur to provide the explanation for the effectiveness of Appert's method, when Pasteur was able to demonstrate that the growth of microorganisms was the cause of food spoilage.

The preservation for storage by thermal treatment and removal of atmosphere is known generically as *canning*, regardless of what container is used to store the food. The basic principles of canning have not changed dramatically since Appert and Durand developed the process: apply enough heat to food to destroy or inactivate microorganisms, then pack the food into sealed or "airtight" containers, ideally under vacuum. Canned foods have a shelf life of one to four years at ordinary temperatures, making them convenient, affordable, and easy to transport.

Outcomes

After reading this chapter, you should be able to:

- Identify the role of heat transfer concepts in thermal processing of packaged foods

- Describe the principles of commercial sterilization of foods

- Describe the inactivation conditions needed for some example microorganisms important for food safety

- Define some sterilization criteria for specific foods

- Apply, in simple form, the main thermal food processing evaluation techniques

Concepts

The main concepts used in thermal processing of foods include: (a) heat transfer; (b) heat resistance of microorganisms of concern; and (c) bacterial inactivation.

Heat Transfer

The main heat transfer mechanisms involved in the thermal processing of packaged foods are convection and conduction. Heat transfer by convection occurs due to the motion and mixing of flows. The term *natural convection* refers to the case when motion and mixing of flow is caused by density differences in different locations due to temperature gradients. The term *forced convection* refers to the case when motion and mixing of flow is produced by an outside force, e.g., a fan. Heat transfer by conduction occurs when atoms and molecules collide, transferring kinetic energy. Conceptually, atoms are bonded to their neighbors, and if energy is supplied to one part of the solid, atoms will vibrate and transfer their energy to their neighbors and so on.

The main heat transfer mechanisms involved in the thermal processing of packaged foods are shown in figure 1. Although the figure shows a cylindrical can (a cylinder of finite diameter and height), a similar situation will arise when processing other types of packaging such as glass containers, retortable pouches, and rigid and semi-rigid plastic containers. In general, independent of shape, food package sizes range from 0.1 L to 5 L (Holdsworth and Simpson, 2016).

The main mechanism of heat transfer from the heating medium (e.g., steam or hot water) to the container or packaging is convection. Then heat transfers by conduction through the wall of the container or package. Once inside the container, heat transfer through the covering liquid occurs by convection, and in solid foods mainly by conduction. In case of liquid foods, the main mechanism is convection.

The rate of heat transfer in packaged foods depends on process factors, product factors, and package types. *Process factors* include retort temperature profile, process time, heat transfer medium, and container agitation.
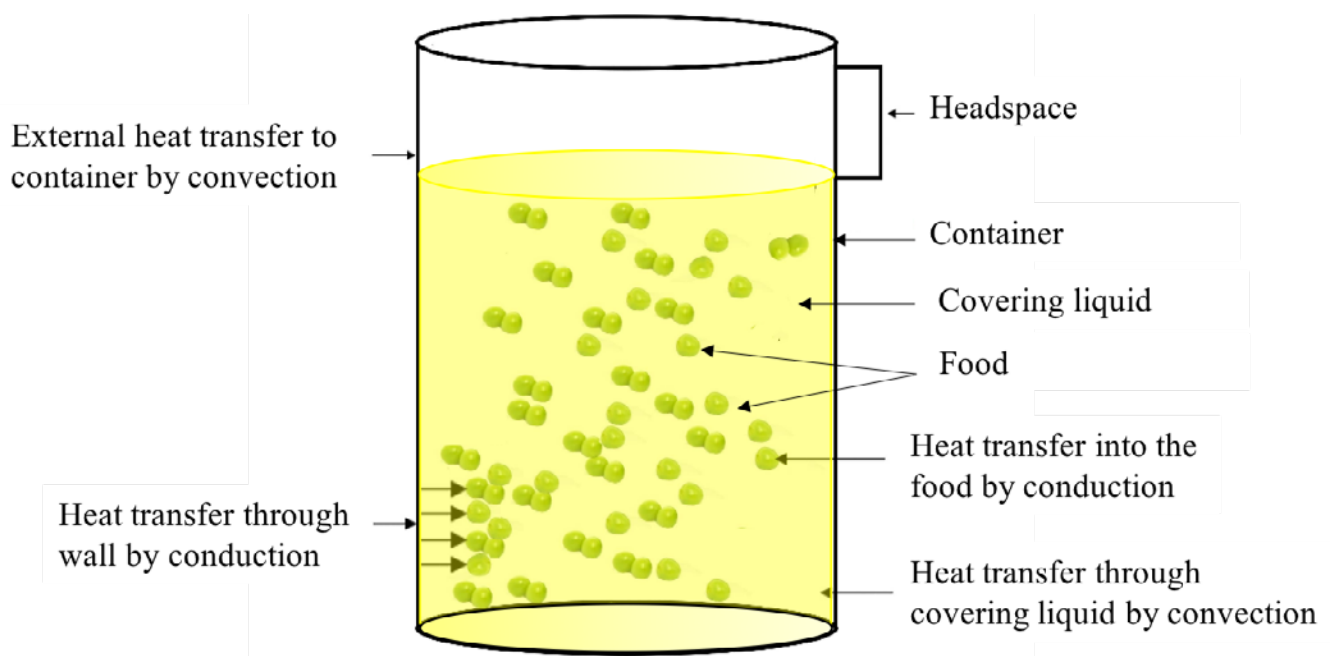

Figure 1. Main heat transfer mechanisms involved in the thermal processing of packaged foods.

Product factors include food composition, consistency, initial temperature, initial spore load, thermal diffusivity, and pH. Factors related to *package type* are container material, because the rate of heat transfer depends on thermal conductivity and thickness of the material, and container shape, because the surface area per unit volume plays a role in the heat penetration rate.

For liquid foods, the heating rate is determined not only by the thermal diffusivity α, but also by the viscosity. The thermal diffusivity is a material property that represents how fast the heat moves through the food and is determined as:

$$\alpha = K_t/(\rho\ C_p) \tag{1}$$

where α = thermal diffusivity (m²/s)
$\quad K_t$ = thermal conductivity (W/m-K)
$\quad\ \rho$ = density (kg/m³)
$\quad C_p$ = specific heat (W/s-kg-K)

It is extremely difficult to develop a theoretical model for the prediction of a time-temperature history within the packaging material. Therefore, from a practical point of view, a satisfactory thermal process (i.e., time-temperature relationship) is usually determined using the slowest heating point, the *cold spot*, inside the container.

Heat Resistance of Microorganisms of Concern

The main objective in the design of a sterilization process for foods is the inactivation of the microorganisms that cause food poisoning and spoilage. In order to design a safe sterilization process, the appropriate operating conditions (time and temperature) must be determined to meet the pre-established sterilization criterion. To establish this criterion, it is necessary to know the heat resistance of the microorganisms (some examples are given in table 1), the thermal properties of the food and packaging, and the shape and dimensions of the packaged food. From these, it is possible to determine the retort temperature and holding time (that is, the conditions for inactivation), how long it will take to reach that temperature (the come-up time), and how long it will take to cool to about 40°C (the cooling time) (Holdsworth and Simpson, 2016).

The pH of the food is extremely relevant to the selection of the sterilization process parameters, i.e., retort temperature and

Table 1. Some typical microorganisms heat resistance data (Holdsworth and Simpson, 2016).

Organism	Conditions for Inactivation
Vegetative cells	10 min at 80°C
Yeast ascospores	5 min at 60°C
Fungi	30–60 min at 88°C
Thermophilic organisms:	
Bacillus stearothermophilus	4 min at 121.1°C
Clostridium thermosaccharolyticum	3–4 min at 121.1°C
Mesophilic organisms:	
Clostridium botulinum spores	3 min at 121.1°C
Clostridium botulinum toxins Types A & B	0.1–1 min at 121.1°C
Clostridium sporogenes	1.5 min at 121.1°C
Bacillus subtilis	0.6 min at 121.1°C

holding time, because microorganisms grow better in a less acid environment. That is why the standard commercial sterilization process is based on the most resistant microorganism (*Clostridium botulinum*) at the worst-case scenario conditions (higher pH) (Teixeira et al., 2006). The microorganism heat resistance is greater in low-acid products (pH ≥ 4.5–4.6). On the other hand, medium-acid to acidic foods require a much gentler heat treatment (lower temperature) to meet the sterilization criterion. Based on that, foods are classified into three groups:

- low-acid products: *pH* > 4.5–4.6 (e.g., seafood, meat, vegetables, dairy products);
- medium-acid products: 3.7 < *pH* < 4.6 (e.g., tomato paste);
- acidic products: *pH* < 3.7 (e.g., most fruits).

Bacterial Inactivation

Abundant scientific literature supports the application of first-order kinetics to quantify bacterial (spores) inactivation as (Esty and Meyer, 1922; Ball and Olson, 1957; Stumbo, 1973, Holdsworth and Simpson, 2016):

$$\left(\frac{dN}{dt}\right)_I = -kN \qquad (2)$$

where N = viable bacterial (microbial) concentration (microorganisms/g) after
  process time t
  t = time
  I = inactivation
  k = bacterial inactivation rate constant (1/time)

Instead of k, food technologists have utilized the concept of *decimal reduction time*, D, defined as the time to reduce bacterial concentration by ten times. In other words, D is the required time at a specified temperature to inactivate 90% of the microorganism's population. A mathematical expression that relates the rate constant, k, from equation 2 to D is developed by separating variables and integrating the bacterial concentration from the initial concentration, N_0, to $N_0/10$ and from time 0 to D, therefore obtaining:

$$k = \frac{\ln 10}{D} = \frac{2.303}{D} \qquad (3)$$

or

$$D = \frac{\ln 10}{k} = \frac{2.303}{k} \qquad (4)$$

where k = reaction rate constant (1/min)
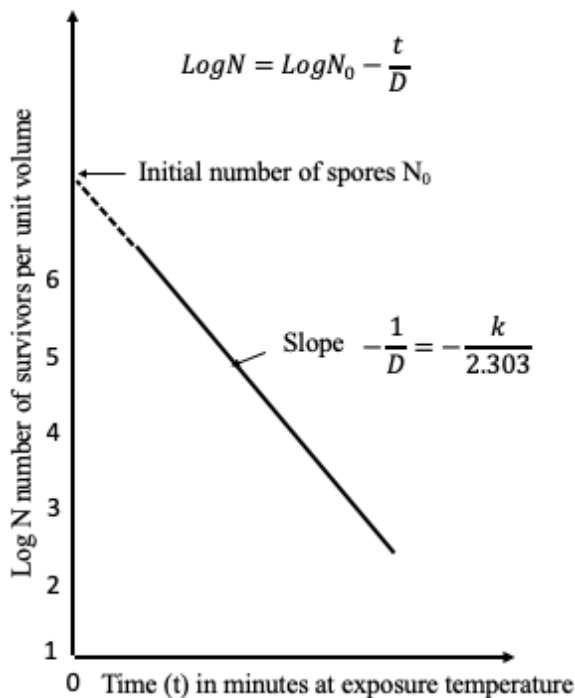 D = decimal reduction time (min)

$$LogN = LogN_0 - \frac{t}{D}$$

Initial number of spores N_0

Slope $-\frac{1}{D} = -\frac{k}{2.303}$

Figure 2. Semilogarithmic survivor curve.

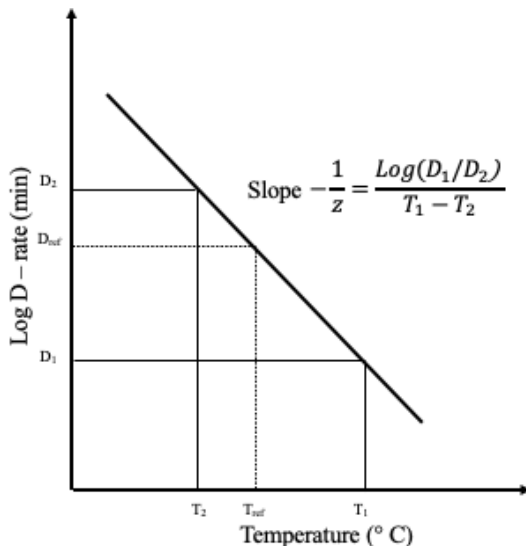Slope $-\frac{1}{z} = \frac{Log(D_1/D_2)}{T_1 - T_2}$

Figure 3. Thermal death time (TDT) curve.

A plot of the log of the survivors (log N) against D is called a *survivor curve* (figure 2). The slope of the line through one log cycle (decimal reduction) is $-1/D$ and

$$\log N = \log N_0 - \frac{t}{D} \tag{5}$$

where N = number of survivors

$N_0 = N$ at time zero, the start of the process

Temperature Dependence of the Decimal Reduction Time, D

Every thermal process of a food product is a function of the thermal resistance of the microorganism in question. When the logarithm of the decimal reduction time, D, is plotted against temperature, a straight line results. This plot is called the *thermal death time (TDT) curve* (figure 3). From such a plot, the thermal sensitivity of a microorganism, z, can be determined as the temperature change necessary to vary *TDT* by one log cycle.

Bigelow and co-workers (Bigelow and Esty, 1920; Bigelow, 1921) were the first to coin the term *thermal death rate* to relate the temperature dependence of D. Mathematically, the following expression has been used:

$$\log D = \log D_{ref} - \frac{T - T_{ref}}{z} \tag{6}$$

or

$$D = D_{ref} 10^{\frac{T_{ref} - T}{z}} \tag{7}$$

where D = decimal reduction time at temperature T (min)

D_{ref} = decimal reduction time at reference temperature T_{ref} (min)

z = temperature change necessary to vary *TDT* by one log cycle (°C), e.g., normally $z = 10°C$ for *Clostridium botulinum*

T = temperature (°C)

T_{ref} = reference temperature (normally 121.1°C for sterilization)

The D value is directly related to the thermal resistance of a given microorganism. The more resistant the microorganism to the heat treatment, the higher the D value. On the other hand, the z value represents the temperature dependency but has no relation to the thermal resistance of the target microorganism. Then, the larger the z value the less sensitive the given microorganism is to temperature changes. D values are expressed as D_T. For example, D_{140} means the time required to reduce the microbial population by one log cycle when the food is heated at 140°C.

Food Sterilization Criterion and Calculation

Sterilization means the complete destruction or inactivation of microorganisms. The food science and engineering community has accepted the utilization of a first-order kinetic for *Clostridium botulinum* inactivation (equation 2). Again, this pathogen is the target microorganism in processes that use heat to sterilize foods. Theoretically, the inactivation time needed to fully inactivate *Clostridium botulinum* is infinite. According to equations 2 and 3 and assuming a constant process temperature and that *k* is constant, the following expression is obtained:

$$N_f = N_0 e^{-kt} = N_0 e^{-\frac{\ln 10}{D}t} \tag{8}$$

This equation shows that the final concentration of *Clostridium botulinum* (N_f) tends to zero when time (*t*) tends to infinity; therefore, it is not possible to reach a final concentration equal to zero for the target microorganism. Thus, it is necessary to define a *sterilization criterion* (or *commercial sterilization criterion*) to design a process that guarantees a safe product within a finite time.

The level of microbial inactivation, defined by the *microbial lethality value or cumulative lethality*, is the way in which the sterilization process is quantified. Specifically, the sterilizing value, denoted by F_0, is the required time at 121.1°C to achieve 12 decimal reductions (12*D*). In other words, F_0 is the time required to reduce the initial microorganism concentration from N_0 to $N_0/10^{12}$ at the process temperature of 121.1°C.

> *F* can be calculated for a process temperature other than 121.1°C.

The 12*D* sterilization criterion is an extreme process (i.e., overkill) designed to ensure no cells of *C. botulinum* remain in the food and, therefore, prevent illness or death. According to the FDA (1972), the minimum thermal treatment for a low-acid food should reach a minimum F_0 value of 3 min (that is larger than 12*D*; *D* for *C. botulinum* at 121.1°C is 0.21 min, then 12 × 0.21 = 2.52 min, which is lower than 3 min). Thus, a thermal process for commercial sterilization of a food product should have an F_0 value greater than 3 minutes.

The F_0 attained for a food can be calculated easily when the temperature at the center of the food during the thermal processing is known by:

$$F_0 = \int_0^t 10^{\frac{T - T_{ref}}{z}} dt \tag{9}$$

where F_0 = cumulative lethality of the process from time 0 to the end of the process (t)

  T = temperature measured at the food cold spot, which is the place in the food that heats last

  T_{ref} = temperature of microorganism reference; for sterilization of low-acid foods, T_{ref} = 121.1°C for *C. botulinum*

  z = temperature change necessary to reduce *D* value by ten times; in the case of sterilization of low-acid foods, z = 10°C for *C. botulinum*

  t = process time to reach F_0

Equation 9 can be calculated according to the general method proposed by Bigelow and co-workers 100 years ago (Bigelow et al., 1920; Simpson et al., 2003).

Figure 4. Stages of a typical commercial food canning process.

If the food is heated instantaneously to 121.1°C and maintained at this temperature for 3 min, then the F_0 value for this process will be 3 min. From equation 9,

$$F_0 = \int_0^t 10^{\frac{121.1-121.1}{10}}\, dt = \int_0^t 10^0\, dt = \int_0^3 1\, dt$$

Since the time interval is between 0 to 3 min, then the integral solution is 3 min or $\int_0^3 1\, dt = 3 - 0 = 3$. However, in practice, due to the resistance of the food to the transfer of heat, the thermal sterilization process requires a longer time in order to get a $F_0 \geq 3$ min, because a significant part of the processing time is needed to raise the cold-spot temperature of the food and later to cool the food.

Applications

Commercial Sterilization Process

A general, simplified flow diagram for a typical commercial canning factory is presented in figure 4.

Stage 1: Selecting and preparing the food as cleanly, rapidly, and precisely as possible. Foods that maintain their desirable color, flavor, and texture through commercial sterilization include broccoli, corn, spinach, peas, green beans, peaches, cherries, berries, sauces, purees, jams and jellies, fruit and vegetable juices, and some meats (Featherstone, 2015). The preparation must be performed with great care and with the least amount of
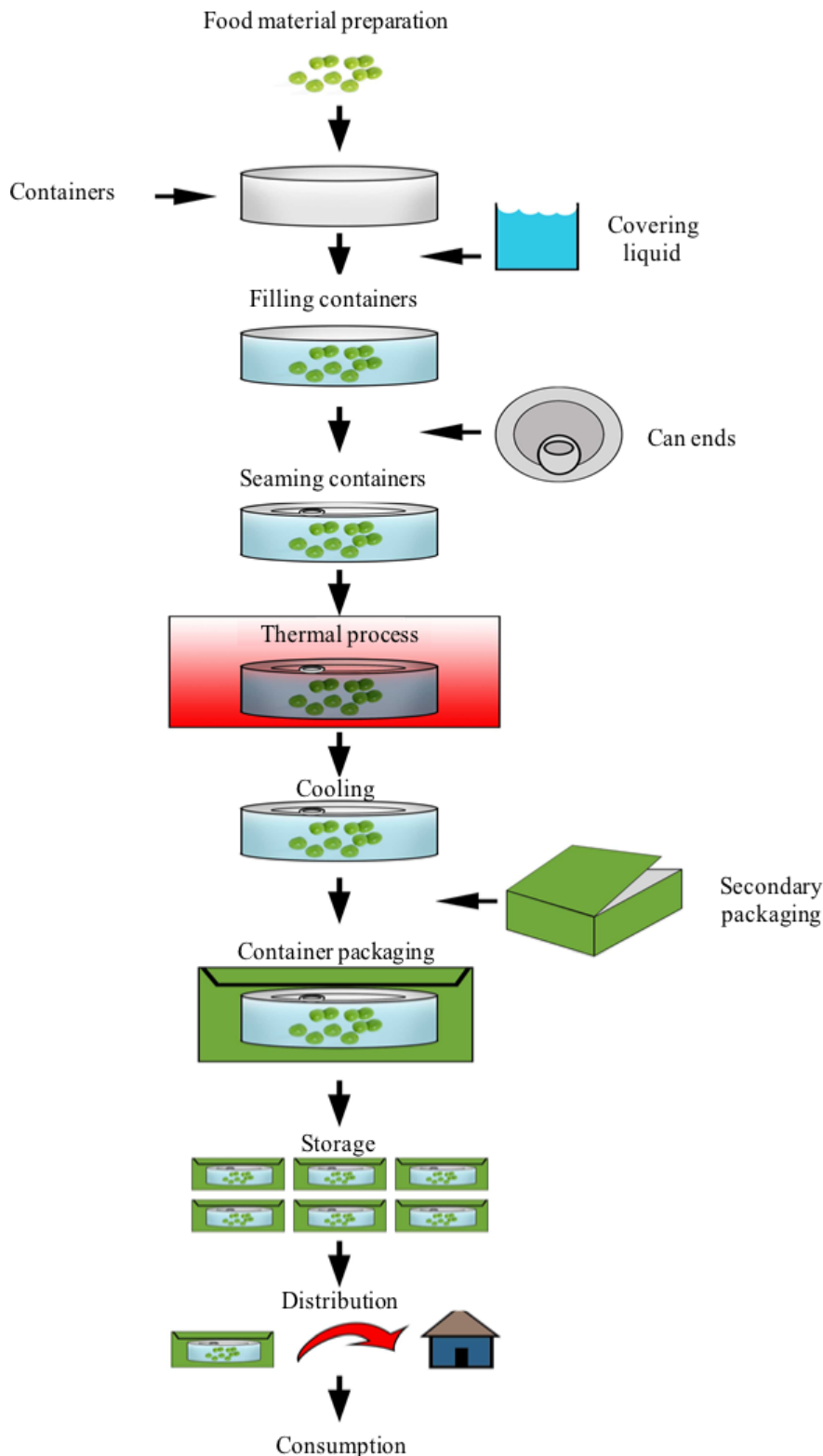
damage and loss to minimize the monetary cost of the operation. If foods are not properly handled, the effectiveness of the sterilization treatment is compromised.

Stage 2: Packing the product in hermetically sealable containers (jars, cans, or pouches) and sealing under a vacuum to eliminate residual air. A less common approach is to sterilize the food first and then aseptically package it (aseptic processing and packaging of foods).

Stage 3: Stabilizing the food by sterilizing through rigorous thermal processing (i.e., high temperature to achieve the correct degree of sterilization or the target destruction of the microorganisms present in the food), followed by cooling of the product to a low temperature (about 40°C), at which enzymatic and chemical reactions begin to slow down.

Stage 4: Storing at a temperature below 35°C, the temperature below which food-spoilage organisms cannot grow.

Stage 5: Labeling, secondary packaging, distribution, marketing, and consumption. Although not part of the thermal process per se, this stage addresses the steps required for commercialization of the treated foods.

Stage 3, thermal processing, is the focus of this chapter. The aim of the thermal process is to inactivate, by the effect of heat, spores and microorganisms present in the unprocessed product. The thermal process is performed in vessels known as retorts or autoclaves to achieve the required high temperatures (usually above 100°C).

As depicted in figure 5, a typical sterilization process has three main steps: come-up time, operator process time, and cooling. The first step, the come-up time (*CUT*), is the time required to reach the specified retort temperature (*TRT*), i.e., the target temperature in the retort. The second step is the holding time (P_t), also called operator process time, which is the amount of time that the retort temperature must be maintained to ensure the desired degree of lethality. This depends on the target microorganism or the expected microbiological contamination. The final step is the cooling, when the temperature of the product is decreased by introducing cold water into the retort. The purpose of cooling the food is to minimize the excessive (heat) processing of the food, and avoid the risk of thermophilic microorganism development. During the cooling cycle, it may be necessary to inject sterile air into the food packaging to avoid sudden internal pressure drops and prevent package deformation.
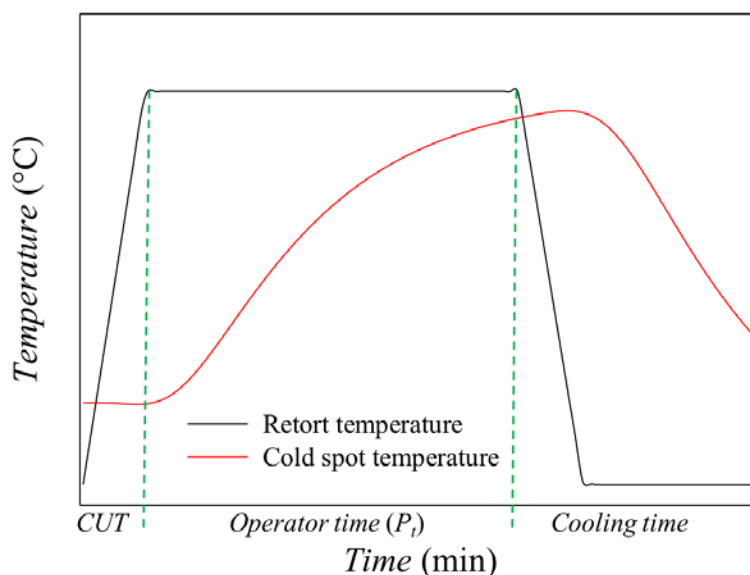

Figure 5. Temperature profiles for a typical thermal process, where *CUT* is come-up time and P_t is operator time.

Thermophilic organisms thrive on heat.

The concepts described in this chapter describe the key principles for applying a thermal process to packaged food to achieve the required lethality for food safety. These concepts can be used to design a thermal process to ensure adequate processing time and food safety while avoiding over pro-cessing the packaged food. This should ensure safe, tasty, and nutritious packaged foods.

Examples

Example 1: Calculation of microbial count after a given thermal process

Problem:

The $D_{120°C}$ value for a microorganism is 3 minutes. If the initial microbial con-tamination is 10^{12} cells per gram of product, how many microorganisms will remain in the sample after heat treatment at 120°C for 18 minutes?

Solution:

Calculate the number of remaining cells using equation 5 with $N_0 = 10^{12}$ cells/g, $t = 18$ minutes, and $D_{120°C} = 3$ minutes.

From equation 5,

$$\log N_{(t)} = \log N_0 - \frac{t}{D}$$

$$\log N_{(18)} = \log 10^{12} \frac{\text{cells}}{\text{g}} - \frac{18 \text{ min}}{3 \text{ min}}$$

Solving for $N_{(18)}$ yields:

$$N_{(18)} = 10^6 \text{ cells/g}$$

Discussion:

Starting with a known microbial concentration (N_0), the final concentration of a specific microorganism for a given thermal process at constant temperature can be calculated if the thermal resistance of the microorganism at a given temperature is known. In this case, $D_{120°C} = 3$ min.

Example 2: Calculation of z value for a particular microorganism

Problem:

D of a given bacterium in milk at 65°C is 15 minutes. When a food sample that has 10^{10} cells of the bacterium per gram of food is heated for 10 minutes at 75°C, the number of survivors is 2.15×10^3 cells. Calculate z for this bacterium.

Solution:

First, calculate D at the process temperature of 75°C, $D_{75°C}$, using equation 5. Then calculate z using equation 6 with $D_{65°C} = 15$ minutes, $N_0 = 10^{10}$ cells/g, and $t = 10$ minutes at $T = 75$°C.

$$\log N_{(t)} = \log N_0 - \frac{t}{D} \tag{5}$$

$$\log 2.15 \times 10^3 \, \text{cells/g} = \log 10^{10} \, \text{cells/g} - \frac{10 \, \text{min}}{D_{75°C}}$$

and $D_{75°C} = 1.5$ min.

To calculate z, recall equation 6:

$$\log D = \log D_{\text{ref}} - \frac{T - T_{\text{ref}}}{z}$$

Solving for z, equation 6 can be expressed as:

$$z = \frac{\Delta T}{\log\left(\frac{D_1}{D_2}\right)}$$

with $\Delta T = (75 - 65)$°C, $D_1 = D_{65°C}$ and $D_2 = D_{75°C}$,

$$z = \frac{75 - 65}{\log \frac{15}{1.5}} = 10°C$$

Discussion:

As previously explained, the z value represents the change in process temperature required to reduce the D value of the target microorganism by ten times. In this case, the z value is 10°C and accordingly the D value was reduced 10 times, from 15 minutes to 1.5 minutes.

Example 3: Lethality of thermal processing of a can of tuna fish

Problem:

Table 2 presents the values of temperature measured in the retort (*TRT*) and the temperature measured at the cold spot of a can of tuna fish ($T_{\text{cold spot}}$) during a thermal process. The total process time was 63 min until the product was cold enough to be withdrawn from the retort.

(a) Determine *CUT* (the time required to come up to *TRT*), operator process time P_t, and cooling time.
(b) Determine the lethality value (F_0) attained for the can of tuna fish.

Table 2. Retort temperature (*TRT*) and cold spot ($T_{cold\ spot}$) during thermal processing of tuna fish in a can.

Time (min)	*TRT* (°C)	$T_{cold\ spot}$ (°C)
0.97	29.7	45.0
1.97	39.7	45.0
2.97	49.7	45.0
3.97	59.7	45.0
4.97	69.7	44.9
5.97	79.7	44.9
6.97	89.7	44.8
7.97	99.7	44.7
8.97	109.7	44.7
9.97	119.7	44.8
10.97	120.0	45.0
11.97	120.0	45.4
12.97	120.0	46.0
13.97	120.0	46.9
14.97	120.0	48.0
15.97	120.0	49.3
16.97	120.0	50.8
17.97	120.0	52.6
18.97	120.0	54.4
19.97	120.0	56.4
20.97	120.0	58.5
21.97	120.0	60.6
22.97	120.0	62.8
23.97	120.0	65.0
24.97	120.0	67.1
25.97	120.0	69.3
26.97	120.0	71.4
27.97	120.0	73.5
28.97	120.0	75.5
29.97	120.0	77.5
30.97	120.0	79.4
31.97	120.0	81.2
32.97	120.0	83.0
33.97	120.0	84.7
34.97	120.0	86.3
35.97	120.0	87.9
36.97	120.0	89.4
37.97	120.0	90.8

(continued)

Time (min)	TRT (°C)	$T_{cold\ spot}$ (°C)
38.97	120.0	92.2
39.97	120.0	93.6
40.97	120.0	94.8
41.97	120.0	96.0
42.97	120.0	97.2
43.97	120.0	98.3
44.97	120.0	99.3
45.97	120.0	100.3
46.97	120.0	101.3
47.97	120.0	102.2
48.97	120.0	103.0
49.97	120.0	103.9
50.97	120.0	104.7
51.97	120.0	105.4
52.97	120.0	106.1
53.97	120.0	106.8
54.97	120.0	107.4
55.97	120.0	108.0
56.97	120.0	108.6
57.97	120.0	109.2
58.97	120.0	109.7
59.97	120.0	110.2
60.97	120.0	110.7
61.97	120.0	111.1
62.97	120.0	111.6
63.97	120.0	112.0
64.97	120.0	112.4
65.97	120.0	112.8
66.97	120.0	113.1
67.97	120.0	113.4
68.97	120.0	113.8
69.97	120.0	114.1
70.97	120.0	114.4
71.97	120.0	114.6
72.97	120.0	114.9
73.97	120.0	115.2
74.97	120.0	115.4
76	25.0	115.6
77	25.0	115.8
78	25.0	116.0
79	25.0	116.2

(continued)

Table 2. Retort temperature (*TRT*) and cold spot ($T_{cold\ spot}$) during thermal processing of tuna fish in a can. (*continued*)

Time (min)	*TRT* (°C)	$T_{cold\ spot}$ (°C)
80	25.0	116.2
81	25.0	116.0
82	25.0	115.5
83	25.0	114.6
84	25.0	113.4
85	25.0	111.8
86	25.0	110.0
87	25.0	107.9
88	25.0	105.6
89	25.0	103.1
90	25.0	100.6
91	25.0	97.9
92	25.0	95.3
93	25.0	92.6
94	25.0	89.9
95	25.0	87.3
96	25.0	84.7
97	25.0	82.1
98	25.0	79.6
99	25.0	77.2
100	25.0	74.9
101	25.0	72.6
102	25.0	70.5
103	25.0	68.4
104	25.0	66.3
105	25.0	64.4
106	25.0	62.6
107	25.0	60.8
108	25	59.08
109	25	57.46
110	25	55.91
111	25	54.43
112	25	53.01
113	25	51.67
114	25	50.38
115	25	49.15
116	25	47.99
117	25	46.87
118	25	45.81

(continued)

Time (min)	TRT (°C)	$T_{cold\ spot}$ (°C)
119	25	44.8
120	25	43.84
121	25	42.92
122	25	42.05
123	25	41.22
124	25	40.43

Solution:

(a) To determine *CUT* and P_t, plot *TRT* and $T_{cold\ spot}$ against time, which produces the thermal profiles in figure 6.

Figure 6 shows that the CUT is approximately 10 min and P_t, during which process temperature is maintained constant at 120°C, is approximately 64 min.

(b) The lethality value, F_0, can be obtained through numerical integration of equation 9 using the trapezoidal rule (Patashnik, 1953). The calculations can be completed as follows or using software such as Excel.

As presented in table 3, for each time, we can evaluate equation 9:

$$F_0 = \int_0^t 10^{\frac{T-121.1}{10}}\, dt \qquad (9)$$

where $T = T_{cold\ spot}$ and T_{ref} and *z*-value for *Clostridium botulinum* are 121.1°C and 10°C, respectively.

Given that F_0 corresponds to the integral of $10^{[(Tcold\ spot\ -Tref)/z]}$, this can be solved numerically by the trapezoidal rule method, i.e., by determining the area under the curve by dividing the area into trapezoids, computing the area of each trapezoid, and summing all trapezoidal areas to yield F_0. (More details about the trapezoidal rule are included in the appendix.) The calculations are summarized in table 3. In this particular case, F_0 was about 6.07 min. The change of F_0 along the thermal process is shown as the blue line in figure 7.
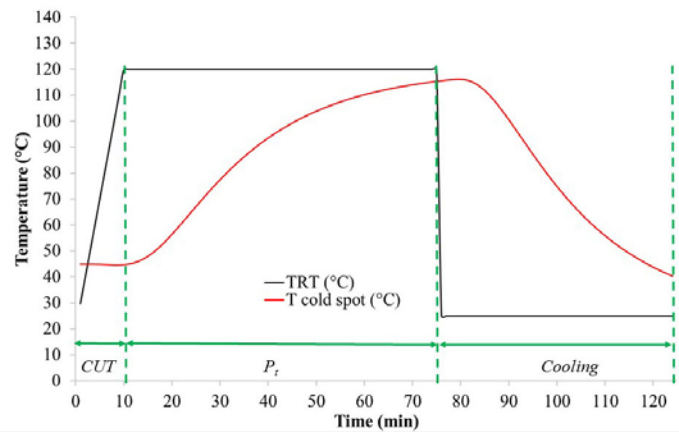

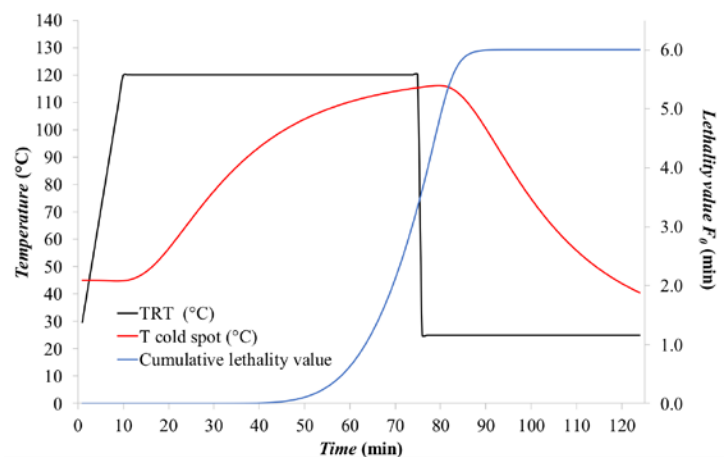**Figure 6.** Temperature profile of thermal processing data in table 2.

Figure 7. Thermal process temperature profiles including the cumulative lethality value (*F* at any time *t*).

Table 3. Numerical integration of equation 9 for the estimation of F_0.

Time (min)	TRT (°C)	$T_{cold\ spot}$ (°C)	$(T_{cold\ spot} - T_{ref})/z$	$10^{[(T_{cold\ spot} - T_{ref})/z]}$	Trapezoidal Area	Sum of Areas
0.97	29.67	45	−7.6	0.000	0.000	0.000
1.97	39.67	45	−7.6	0.000	0.000	0.000
2.97	49.67	44.99	−7.6	0.000	0.000	0.000
3.97	59.67	44.97	−7.6	0.000	0.000	0.000
4.97	69.67	44.93	−7.6	0.000	0.000	0.000
5.97	79.67	44.85	−7.6	0.000	0.000	0.000
6.97	89.67	44.76	−7.6	0.000	0.000	0.000
7.97	99.67	44.69	−7.6	0.000	0.000	0.000
8.97	109.67	44.68	−7.6	0.000	0.000	0.000
9.97	119.67	44.77	−7.6	0.000	0.000	0.000
10.97	120	45	−7.6	0.000	0.000	0.000
11.97	120	45.41	−7.6	0.000	0.000	0.000
12.97	120	46.03	−7.5	0.000	0.000	0.000
13.97	120	46.88	−7.4	0.000	0.000	0.000
14.97	120	47.97	−7.3	0.000	0.000	0.000
15.97	120	49.29	−7.2	0.000	0.000	0.000
16.97	120	50.83	−7.0	0.000	0.000	0.000
17.97	120	52.55	−6.9	0.000	0.000	0.000
18.97	120	54.42	−6.7	0.000	0.000	0.000
19.97	120	56.41	−6.5	0.000	0.000	0.000
20.97	120	58.49	−6.3	0.000	0.000	0.000
21.97	120	60.63	−6.0	0.000	0.000	0.000
22.97	120	62.79	−5.8	0.000	0.000	0.000
23.97	120	64.97	−5.6	0.000	0.000	0.000
24.97	120	67.14	−5.4	0.000	0.000	0.000
25.97	120	69.29	−5.2	0.000	0.000	0.000
26.97	120	71.41	−5.0	0.000	0.000	0.000
27.97	120	73.48	−4.8	0.000	0.000	0.000
28.97	120	75.5	−4.6	0.000	0.000	0.000
29.97	120	77.46	−4.4	0.000	0.000	0.000
30.97	120	79.36	−4.2	0.000	0.000	0.000
31.97	120	81.2	−4.0	0.000	0.000	0.000
32.97	120	82.97	−3.8	0.000	0.000	0.001
33.97	120	84.67	−3.6	0.000	0.000	0.001
34.97	120	86.31	−3.5	0.000	0.000	0.001
35.97	120	87.89	−3.3	0.000	0.001	0.002
36.97	120	89.4	−3.2	0.001	0.001	0.003
37.97	120	90.84	−3.0	0.001	0.001	0.004
38.97	120	92.22	−2.9	0.001	0.002	0.005
39.97	120	93.55	−2.8	0.002	0.002	0.007

(continued)

Time (min)	TRT (°C)	$T_{cold\ spot}$ (°C)	$(T_{cold\ spot} - T_{ref})/z$	$10^{[(T_{cold\ spot} - T_{ref})/z]}$	Trapezoidal Area	Sum of Areas
40.97	120	94.81	−2.6	0.002	0.003	0.010
41.97	120	96.02	−2.5	0.003	0.004	0.014
42.97	120	97.17	−2.4	0.004	0.005	0.018
43.97	120	98.27	−2.3	0.005	0.006	0.024
44.97	120	99.31	−2.2	0.007	0.007	0.032
45.97	120	100.31	−2.1	0.008	0.009	0.041
46.97	120	101.27	−2.0	0.010	0.012	0.053
47.97	120	102.17	−1.9	0.013	0.014	0.067
48.97	120	103.04	−1.8	0.016	0.017	0.084
49.97	120	103.86	−1.7	0.019	0.021	0.105
50.97	120	104.65	−1.6	0.023	0.025	0.130
51.97	120	105.39	−1.6	0.027	0.029	0.159
52.97	120	106.1	−1.5	0.032	0.034	0.193
53.97	120	106.78	−1.4	0.037	0.040	0.233
54.97	120	107.42	−1.4	0.043	0.046	0.279
55.97	120	108.04	−1.3	0.049	0.053	0.332
56.97	120	108.62	−1.2	0.056	0.060	0.393
57.97	120	109.18	−1.2	0.064	0.068	0.461
58.97	120	109.7	−1.1	0.072	0.077	0.538
59.97	120	110.21	−1.1	0.081	0.086	0.624
60.97	120	110.69	−1.0	0.091	0.096	0.720
61.97	120	111.14	−1.0	0.101	0.106	0.826
62.97	120	111.57	−1.0	0.111	0.117	0.943
63.97	120	111.99	−0.9	0.123	0.129	1.072
64.97	120	112.38	−0.9	0.134	0.140	1.212
65.97	120	112.75	−0.8	0.146	0.153	1.365
66.97	120	113.11	−0.8	0.159	0.165	1.530
67.97	120	113.44	−0.8	0.171	0.178	1.708
68.97	120	113.76	−0.7	0.185	0.191	1.899
69.97	120	114.07	−0.7	0.198	0.205	2.104
70.97	120	114.36	−0.7	0.212	0.219	2.323
71.97	120	114.63	−0.6	0.225	0.233	2.555
72.97	120	114.9	−0.6	0.240	0.247	2.802
73.97	120	115.15	−0.6	0.254	0.261	3.063
74.97	120	115.38	−0.6	0.268	0.275	3.338
76	25	115.61	−0.5	0.282	0.290	3.628
77	25	115.83	−0.5	0.297	0.304	3.932
78	25	116.02	−0.5	0.310	0.316	4.248
79	25	116.17	−0.5	0.321	0.322	4.570
80	25	116.19	−0.5	0.323	0.315	4.885
81	25	115.97	−0.5	0.307	0.290	5.175

(continued)

Table 3. Numerical integration of equation 9 for the estimation of F_0. (continued)

Time (min)	TRT (°C)	$T_{cold\ spot}$ (°C)	$(T_{cold\ spot} - T_{ref})/z$	$10^{[(T_{cold\ spot} - T_{ref})/z]}$	Trapezoidal Area	Sum of Areas
82	25	115.45	−0.6	0.272	0.248	5.422
83	25	114.58	−0.7	0.223	0.196	5.618
84	25	113.36	−0.8	0.168	0.143	5.761
85	25	111.81	−0.9	0.118	0.097	5.858
86	25	109.96	−1.1	0.077	0.062	5.920
87	25	107.87	−1.3	0.048	0.038	5.958
88	25	105.57	−1.6	0.028	0.022	5.980
89	25	103.12	−1.8	0.016	0.012	5.992
90	25	100.57	−2.1	0.009	0.007	5.999
91	25	97.94	−2.3	0.005	0.004	6.003
92	25	95.26	−2.6	0.003	0.002	6.005
93	25	92.58	−2.9	0.001	0.001	6.006
94	25	89.91	−3.1	0.001	0.001	6.007
95	25	87.26	−3.4	0.000	0.000	6.007
96	25	84.66	−3.6	0.000	0.000	6.007
97	25	82.11	−3.9	0.000	0.000	6.007
98	25	79.63	−4.1	0.000	0.000	6.007
99	25	77.22	−4.4	0.000	0.000	6.007
100	25	74.88	−4.6	0.000	0.000	6.007
101	25	72.62	−4.8	0.000	0.000	6.007
102	25	70.45	−5.1	0.000	0.000	6.007
103	25	68.35	−5.3	0.000	0.000	6.007
104	25	66.34	−5.5	0.000	0.000	6.007
105	25	64.41	−5.7	0.000	0.000	6.007
106	25	62.55	−5.9	0.000	0.000	6.007
107	25	60.78	−6.0	0.000	0.000	6.007
108	25	59.08	−6.2	0.000	0.000	6.007
109	25	57.46	−6.4	0.000	0.000	6.007
110	25	55.91	−6.5	0.000	0.000	6.007
111	25	54.43	−6.7	0.000	0.000	6.007
112	25	53.01	−6.8	0.000	0.000	6.007
113	25	51.67	−6.9	0.000	0.000	6.007
114	25	50.38	−7.1	0.000	0.000	6.007
115	25	49.15	−7.2	0.000	0.000	6.007
116	25	47.99	−7.3	0.000	0.000	6.007
117	25	46.87	−7.4	0.000	0.000	6.007
118	25	45.81	−7.5	0.000	0.000	6.007
119	25	44.8	−7.6	0.000	0.000	6.007
120	25	43.84	−7.7	0.000	0.000	6.007

(continued)

Time (min)	TRT (°C)	$T_{cold\ spot}$ (°C)	$(T_{cold\ spot} - T_{ref})/z$	$10^{[(Tcold\ spot\ -Tref)/z]}$	Trapezoidal Area	Sum of Areas
121	25	42.92	−7.8	0.000	0.000	6.007
122	25	42.05	−7.9	0.000	0.000	6.007
123	25	41.22	−8.0	0.000	0.000	6.007
124	25	40.43	−8.1	0.000	0.000	6.007

Discussion:

The cumulative lethality, F_0, was about 6.01 min, meaning that the process is safe according to FDA requirements, i.e., $F_0 \geq 3$ min (see the Food Sterilization Criterion and Calculation section above).

Example 4: Lethality of thermal processing of a can of mussels

Problem:

Temperatures measured in the retort and the temperature measured at the cold spot of a can of mussels during a thermal process performed at 120°C were recorded. The total process time was 113 min until the product was cold enough to be withdrawn from the retort. The measured thermal profiles (TRT and $T_{cold\ spot}$) were plotted, as was done in Example 3. The resulting plot (figure 8) shows that CUT was approximately 10 min and P_t was approximately 53 min. The lethality value, F_0, was obtained through numerical integration of equation 9. In this case, F_0 attained in the mussels can with a processing temperature of 120 °C was 2.508 min. The evolution of F_0 along the thermal process is shown in figure 9 as the blue line.
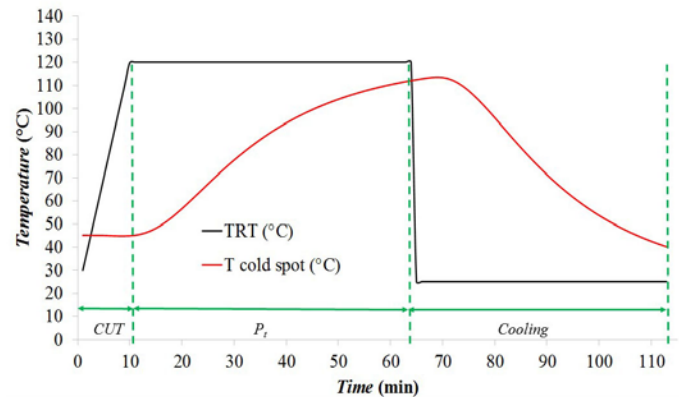

Figure 8. Temperature profile of thermal processing data for a can of mussels.

Discussion:

The cumulative lethality, F_0, attained along the thermal process was 2.5 min, meaning that the process is *not* safe according to FDA requirements ($F_0 \geq 3$ min). Thus, the thermal processing time of canning process of mussels must be extended in order to reach the safety value recommended by the FDA.

Example 5: Processing time at different retort temperatures

Problem:

Determine the required processing time to get a lethality of 6 min (F_0 = 6 min) when the retort
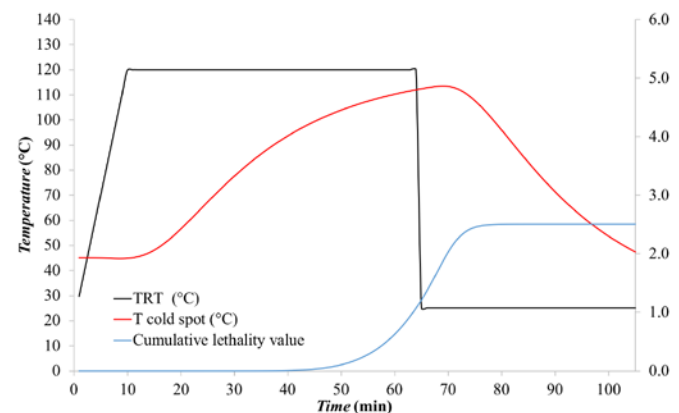

Figure 9. Thermal process temperature profiles including the cumulative lethality value (F at any time t).

temperature is (a) 120°C and considered equal to the cold spot temperature, (b) 110°C, and (c) 130°C.

Solution:

The F_0 is typically set for the 12D value to give a 12 log reduction of heat-resistant species of mesophilic spores (typically taken as *C. botulinum*). The T_{ref} = 121.1°C and z = 10°C. Therefore, equation 9 can be used directly by replacing T by the retort temperature, given that cold spot temperature can be assumed equal to retort temperature:

$$F_0 = \int_0^t 10^{\frac{T-121.1}{z}} dt \tag{9}$$

$$6 = \int_0^t 10^{\frac{120-121.1}{10}} dt$$

$$t = \frac{6}{10^{\frac{120-121.1}{10}}}$$

Solving the integral yields a processing time, t, of 7.7 min.

(b) When the temperature of the retort is reduced to 110°C, the lethality must be maintained at 6 min. Solving equation 9:

$$6 = \int_0^t 10^{\frac{110-121.1}{10}} dt$$

gives the required processing time t of 77.2 min.

(c) When the temperature of the retort is increased to 130°C, and maintaining the F_0 = 6 min, the processing time is reduced to 0.77 min

$$6 = \int_0^t 10^{\frac{130-121.1}{10}} dt$$

Discussion:

The results showed that as the temperature in the food increased in 10°C increments, the processing time was reduced by one decimal reduction. This variation is due to a z value of 10°C.

Appendix: The Trapezoidal Rule

A trapezoid is a four-sided region with two opposite sides parallel (figure 10). The area of a trapezoid is the average length of the two parallel sides multiplied by the distance between the two sides. In figure 11, the area (A) under function $f(x)$ between points x_0 and x_n is given by:

$$A = \int_a^b f(x) dx \tag{10}$$

Figure 10. Example of a trapezoid.

An approximation of the area A is the sum of the areas of the individual trapezoids (T), where T can be calculated using equation 11:

$$T = \frac{1}{2}\Delta x_1\left[f(x_o)+f(x_1)\right]+\frac{1}{2}\Delta x_2\left[f(x_1)+f(x_2)\right]+...+\frac{1}{2}\Delta x_n\left[f(x_{n-1})+f(x_n)\right] \quad \textbf{(11)}$$

where $\Delta x_i = x_i - x_{i-1}$, for $i = 1, 2, 3, \ldots, n$

In the particular case where $\Delta x_1 = \Delta x_2 = \Delta x_3 = \ldots = \Delta x_n = \Delta x$, equation 11 can be expressed as:

$$T = \Delta x\left[\frac{f(x_0)}{2}+f(x_1)+f(x_2)+f(x_3)+..+\frac{f(x_n)}{2}\right] \quad \textbf{(12)}$$

or, in the following reduced form:

$$T = \Delta x\left[\frac{f(x_0)}{2}+\sum_{i=1}^{n-1}f(x_i)+\frac{f(x_n)}{2}\right] \quad \textbf{(13)}$$

Finally, to estimate area A under the trapezoidal rule,

$$A = \int_{x_0}^{x_n}f(x)dx \cong \frac{1}{2}\Delta x_1\left[f(x_o)+f(x_1)\right]+\frac{1}{2}\Delta x_2\left[f(x_1)+f(x_2)\right]+...+\frac{1}{2}\Delta x_n\left[f(x_{n-1})+f(x_n)\right] \quad \textbf{(14)}$$

When all intervals are of the same size ($\Delta x_1 = \Delta x_2 = \Delta x_3 = \ldots = \Delta x_n = \Delta x$), the following expression can be applied:

$$A = \int_{x_0}^{x_n}f(x)dx \cong \Delta x(\frac{f(x_0)}{2}+\sum_{i=1}^{n-1}f(x_i)+\frac{f(x_n)}{2}) = \frac{1}{2}\Delta x(f(x_0)+2\sum_{i=1}^{n-1}f(x_i)+f(x_n)) \quad \textbf{(15)}$$

Figure 11. Curve divided into n equal parts each of length ΔX.

Example

Problem:

Using the heat penetration data at the cold spot of a canned food in table 4, calculate the cumulative lethality, F_0, in the range of 23 to 27 min using the trapezoidal rule.

Solution:

From equation 9,

$$F_o = \int_{23}^{27}10^{\frac{T-121.1}{10}}dt$$

Applying the trapezoidal rule and considering that all time steps are equal ($\Delta t = 1$ min), calculate F_0 using equation 15,

$$F_o = \int_{23}^{27}10^{\frac{T-121.1}{10}}dt \cong \frac{1}{2}\left[f(23)+2f(24)+2f(25)+2f(26)+f(27)\right]$$

where $\Delta t = 1$ (1 min interval), and:

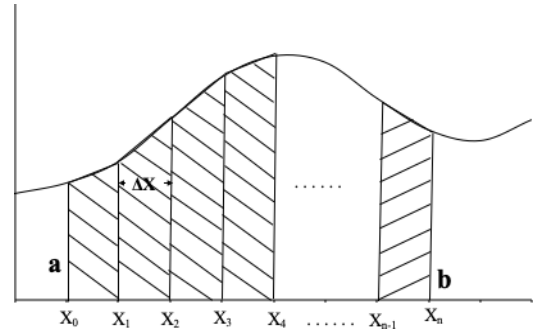$$f(23) = 10^{\frac{118.5-121.1}{10}} = 0.549541$$

Table 4. Heat penetration data at the slowest heating point.

Time (min)	Temperature (C)
. . .	. . .
23	118.5
24	118.7
25	118.9
26	119.1
27	119.3
. . .	. . .

$$f(24) = 10^{\frac{118.7-121.1}{10}} = 0.57544$$

$$f(25) = 10^{\frac{118.9-121.1}{10}} = 0.6025596$$

$$f(26) = 10^{\frac{119.1-121.1}{10}} = 0.63095734$$

$$f(27) = 10^{\frac{119.3-121.1}{10}} = 0.66069345$$

Replacing into equation (15):

$$F_o = \int_{23}^{27} 10^{\frac{T-121.1}{10}} dt \cong \frac{1}{2}(0.549541 + 2 \times 0.57544 + 2 \times 0.6025596 + 2 \times 0.63095734 + 0.66069345)$$

Therefore, F_0 ~ 2.41407394 ~ 2.41 min.

Discussion:
The applied process to sterilize the target food is *not* safe since $F_0 < 3$ minutes.

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Figure 3. Holdsworth, S. Donald-Simpson, R. (CC By 4.0). (2020). Thermal death time (TDT) curve. Retrieved from https://www.springer.com/la/book/9783319249025.

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Figure 5. Ramírez, C. (CC By 4.0). (2020). Temperature profiles for a typical thermal process, where *CUT* is come-up time and P_t is operator time.

Figure 6. Ramírez, C. (CC By 4.0). (2020). Temperature profile of thermal processing data in table 2.

Figure 7. Ramírez, C. (CC By 4.0). (2020). Thermal process temperature profiles including the cumulative lethality value (*F* at any time *t*).

Figure 8. Ramírez, C. (CC By 4.0). (2020). Temperature profile of thermal processing data (Table 4).

Figure 9. Ramírez, C. (CC By 4.0). (2020). Thermal process temperature profiles including the cumulative lethality value (*F* at any time *t*).

Figure 10. Simpson, R. (CC By 4.0). (2020). Example of a trapezoid.

Figure 11. Simpson, R. (CC By 4.0). (2020). Curve divided into n equal parts each of length Δ*X*.

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