# CHAPTER 9

# Thermal Process Calculations

Inactivation of microorganisms by heat is a fundamental operation in food preservation. The concepts learned in this chapter are not only applicable in canning but in any process where heat is used to inactivate microorganisms and induce chemical changes that affect quality. The term "sterilization" used in this chapter refers to the achievement of commercial sterility, defined as a condition where microorganisms that cause illness, and those capable of growing in the food under normal nonrefrigerated storage and distribution, are eliminated.

## 9.1 PROCESSES AND SYSTEMS FOR STABILIZATION OF FOODS FOR SHELF-STABLE STORAGE: SYSTEMS REQUIREMENTS

Different systems are available for treating foods to make them shelf stable. Suitability of a system depends on the type of food processed, production rates, availability of capital, and labor costs. Product quality and economics are the major factors to be considered in system selection. Because the major production costs are overhead and labor, plants with high production capacity are inclined to use systems that have high capitalization and low labor requirements. Products with superior quality will result from systems capable of high-temperature, short-time treatments.

### 9.1.1 In-Can Processing

The simplest and oldest method of modern food preservation involves filling a product into a container, sealing, and heating the sealed containers under pressure. Different types of pressure vessels or retorts are used.

#### *9.1.1.1 Stationary Retorts*

These retorts are cylindrical vessels oriented vertically or horizontally. Crates are used to facilitate loading and unloading of cans. The cans are stacked vertically in the crates, and perforated metal dividers separate the layers of cans. In vertical retorts, the crates are lowered or raised using electric hoists. In horizontal retorts, the crates are of rectangular profile with dimensions to fit the cylindrical retort. The crates are mounted on a carrier with wheels, and tracks within the retort guide the wheels of the crate carrier during introduction and retrieval.

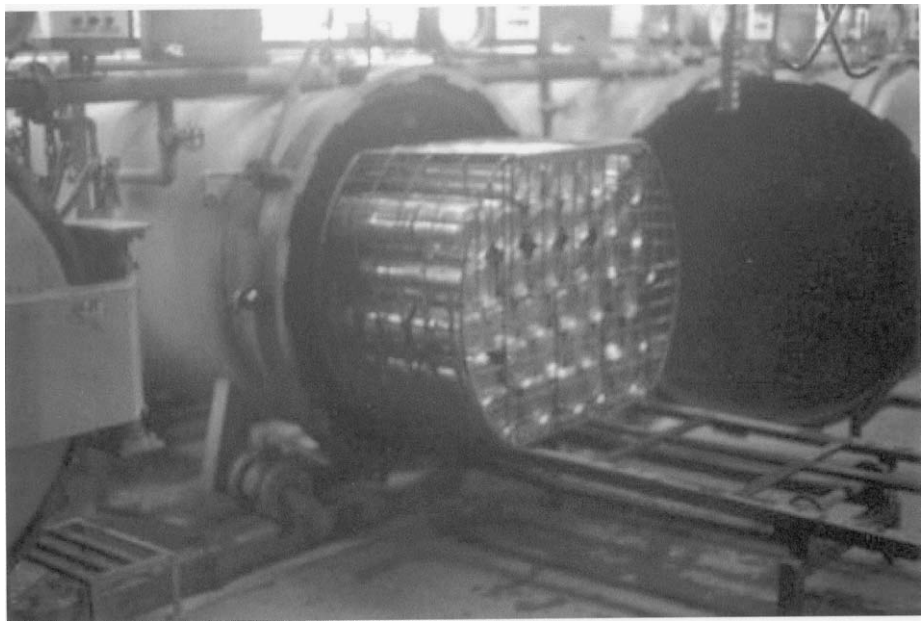

**Figure 9.1** Horizontal stationary retort and crate.

Stationary retorts for processing of canned foods must be equipped with an accurate temperature controller and recording device. In addition, steam must be uniformly distributed inside the retort. A steam bleeder continuously vents small amounts of steam and promotes steam flow within the retort. A fluid-in-glass thermometer is required to provide visual monitoring of the retort temperature by the operator. At the start of the process, the retort is vented to remove air and ensure that all cans are in contact with saturated steam. Figure 9.1 shows a horizontal stationary retort and crate.

Pressure-resistant hatches for the retorts are of various design. Some are secured with hinged bolt-like locks, but more recent designs facilitate opening and closing of the retort. A wheel-type lock advances or retracts locking bars that slip into a retaining slot to secure the cover. Another cover design consists of a locking ring that can be engaged or disengaged with a turn of a lever. A locking ring type of cover assembly is shown in Fig. 9.1.

Typically, stationary retorts are operated by loading the cans, venting the retort, and processing for a specified time at a specified temperature. The time from introduction of steam to attainment of processing temperature is called the "retort come-up time." The process is "timed" when the retort reaches the specified processing temperature. A timed record of the retort temperature for each batch processed is required to be maintained in a file. Cooling may be done inside the retort. However, slow cooling cans may be removed as soon as internal pressure has dropped to just slightly above atmospheric and cooling is completed in canals, where circulating, cold chlorinated water contacts the crates, which are suspended and moved through the water by overhead conveyors.

#### *9.1.1.2 Hydrostatic Cooker*

A photograph of this type of retort is shown in Fig. 9.2. It consists of two water legs that seal steam pressure in the main processing section. When processing at 121.1°C, the absolute pressure of steam is

**Figure 9.2** Hydrostatic cooker. (Courtesy of Food Machinery Corporation, Canning Machinery Division.)

205,740 Pa; therefore, if the atmospheric pressure is 101.325 Pa, a column of water 10.7 m high must be used to counteract the steam pressure. Thus, hydrostatic cookers are large structures that are often in the open. With non-agitating hydrostatic cookers, heat penetration parameters for thermal process calculations are obtained using a stationary retort, and specified processes are similar to those for a stationary retort. The specified process is set by adjusting the speed of the conveyor, which carries cans in and out of the retort such that the residence time in the steam chamber equals the specified process time.

#### *9.1.1.3 Continuous Agitating Retorts*

One type of continuous agitating retort consists of a cylindrical pressure vessel equipped with a rotating reel that carries cans on its periphery. When the reel rotates, cans alternately ride on the reel

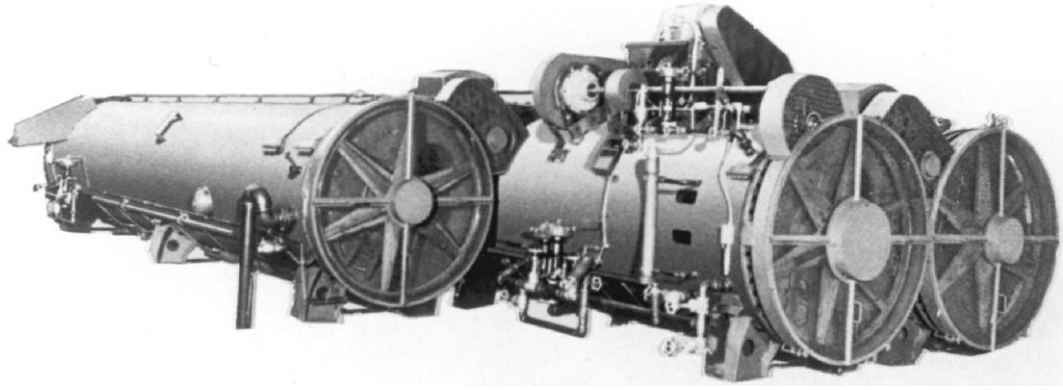

**Figure 9.3** Multiple-shell, continuous rotary retort. (Courtesy of Food Machinery Corporation, Canning Machinery Division.)

or roll along the cylinder wall. Figure 9.3 is a photograph of a three-shell continuous retort viewed from the end that shows the drive system for the reel. Also shown at the top of the retort is the rotary valve, which receives the cans and introduces them continuously into the retort without losing steam from the retort, and the transfer valves, which transfer cans from one retort to the other. Figure 9.4 is a cutaway view showing the reel and the automatic can transfer valve. Agitation is induced by shifting of the headspace as the cans roll. Agitation is maximum in fluid products with small suspended particles, and no agitation exists with a semi-solid product such as canned pumpkin. Agitation minimizes heat-induced changes in a product during thermal processing, when products are of low viscosity. The speed of rotation of the reel determines the rate of heating and the residence time of the cans in the retort, therefore, the heat penetration parameters must be obtained at several reel speeds to match the residence time at a given reel speed to the processing time calculated using heat penetration parameters from the same reel speed. The processing time (t) in a continuous retort is determined as follows:

$$t = \frac{N_t}{N_\rho \, \Omega} \tag{9.1}$$

where $N_t$ is total number of cans in the retort if completely full, $N_p$ is number of pockets around the periphery of the reel, and $\Omega$ is rotational speed of the reel.

A simulator, called the "steritort," is used to determine heat penetration parameters at different rotational speeds of the reel.

Cans enter a continuous retort and are instantaneously at the processing temperature, therefore, the process time is exactly the residence time of the cans within the retort.

#### *9.1.1.4 Crateless Retorts*

The crateless retort is one that has a labor-saving feature over conventional stationary retorts, and it appeals to processors whose level of production can not economically justify the high initial cost

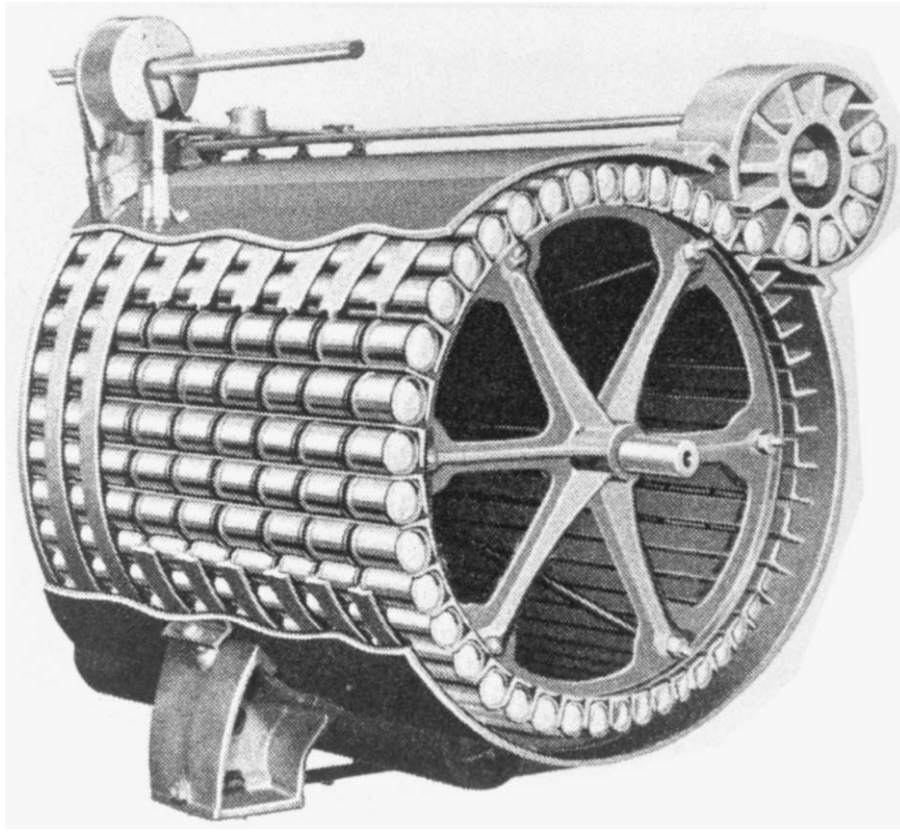

**Figure 9.4** Cross section of a continuous rotary retort showing can positioning on the reel and the can transfer valve, which continuously introduces the cans into the retort without releasing the pressure. (Courtesy of Food Machinery Corporation, Canning Machinery Division.)

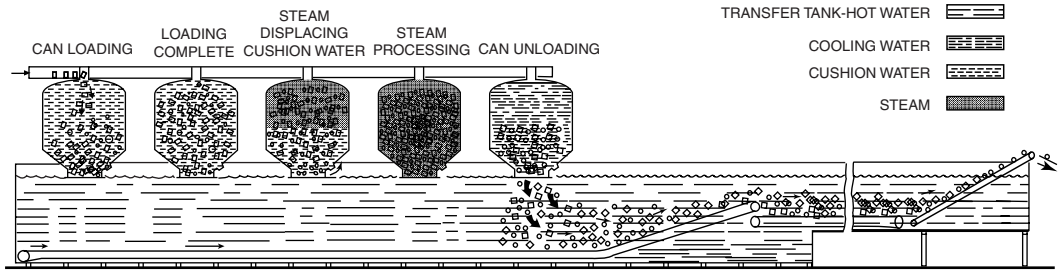


**Figure 9.5** Schematic diagram of the operation of a crateless retort. (Courtesy of Food Machinery Corporation, Canning Machinery Division.)

of a hydrostatic or continuous rotational agitating retort. Figure 9.5 shows a diagram of a crateless retort. A system of pumps and hydraulic operated locks alternately opens the retort, fills it with water, receives the cans, which drop into the retort at random, seals the retort for pressure processing with steam, introduces cold water for cooling, and drops the cans and cooling water into a pool of cold chlorinated water for final cooling and retrieval by a conveyor. Energy is saved if hot water used to initially fill the retorts to receive the cans is stored and reused. Steam waste by venting is eliminated because steam displaces water at the initial phase of the process. The largest saving from this system is in labor and elimination of maintenance cost of the retort crates. Thermal process parameters are determined in the same manner as for stationary retorts.

### 9.1.2 Processing Products Packaged in Flexible Plastic Containers

Containers made out of plastic do not have the strength to resist sudden changes in internal pressure during thermal processing. Thus, the heating and cooling steps must be carried out slowly or air over-pressure must be applied inside the retort all the time during the process to ensure that the pressure in the retort is always greater than the pressure inside the container. Processing with air over-pressure, however, occurs under a nonsaturated steam atmosphere. Heat transfer is slower than in a saturated steam or saturated water medium. Another problem with steam/air processing medium is the possibility of large variations in the temperature within the retort and the difference in heat transfer coefficients with different concentrations of air in the medium. To solve these problems, processing may be done by complete immersion of the product in water, or water may be sprayed on the product throughout the process, or water may be cascading over the product during the process. One retort design (Fig. 9.6)

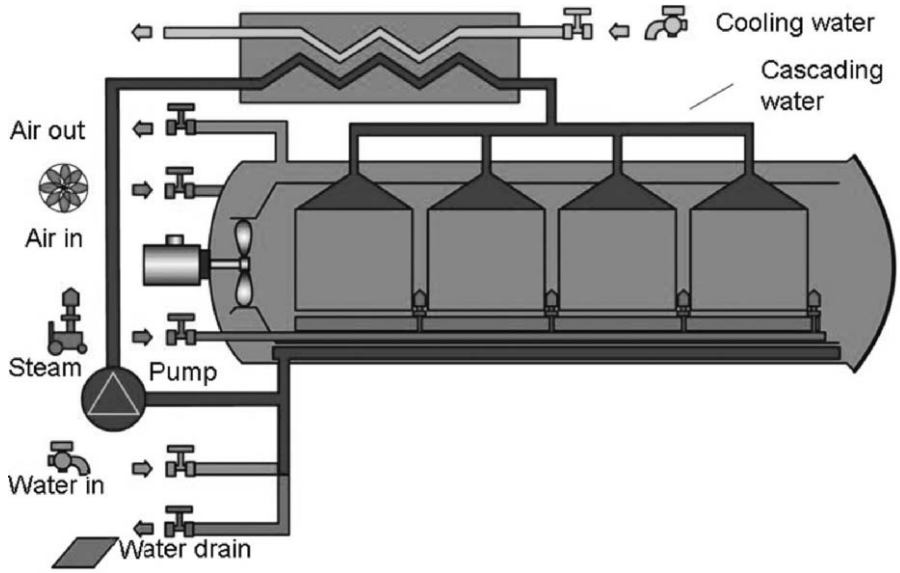


**Figure 9.6** Retort system designed for steam/air mixtures as heating medium. Courtesy of Societe' Lagarde

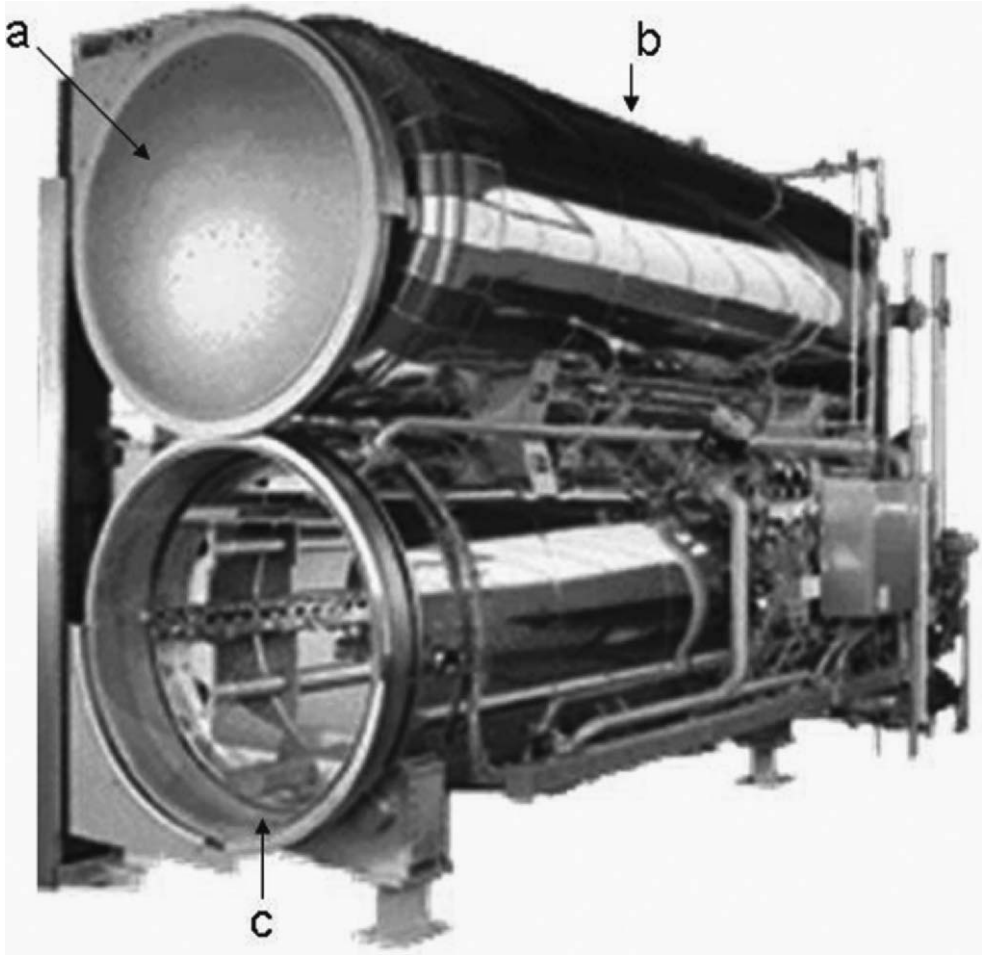


**Figure 9.7** Retort system designed for full water immersion or water spray as heating medium. (Courtesy of Stock America)

has a blower that circulates the steam/air heating medium within the retort, but water may also be sprayed on the product to improve heat transfer and minimize temperature variations at different points in the retort.

Figure 9.7 is a picture of a retort that is capable of processing by complete immersion, or spraying water on the product. In order to save energy and minimize the come-up time of the retort, a second shell is added to accommodate hot water under pressure that is inside the processing shell at the termination of the process. At the start of the process, the hot water from the upper shell is pumped into the processing vessel along with steam. At the termination of the process, steam is cut off and while air over-pressure is maintained in the processing vessel, the hot water is pumped into the upper shell. Then cold water is sprayed over the product for cooling.

### 9.1.3 Processing in Glass Containers

The inability of glass to withstand sudden temperature changes requires a gradual heating and cooling process. Products in glass containers are processed in stationary retorts by first filling the retort with water after the containers are loaded and heating the water by direct injection of live steam. A recirculating pump draws water from a point near the top of the water level in the retort and forces this back into the retort through the bottom. This procedure ensures uniform water temperature and uniform water velocity across all containers in the retort. Water is heated slowly thereby prolonging the come-up time and eliminating thermal shock to the glass. Cooling is accomplished by slowly introducing cold water at the termination of the scheduled process. Water temperature drops slowly eliminating thermal shock to the glass.

Evaluation of thermal precesses in hot water systems is best done using the general method for integrating process lethality. A minimum come-up time to the processing temperature, hold time at the specified temperature, and minimum cool down time must be part of the process specifications.

### 9.1.4 Flame Sterilization Systems

This relatively recent development in thermal processing systems is used primarily for canned mushrooms. The system consists of a conveyor that rotates the cans as they pass over an open flame. The cans themselves act as the pressure vessel, which sterilizes the contents. The fluid inside the cans must be of low viscosity, such as brine, water, or low sugar syrups because rapid heat exchange between the can walls and contents is needed to prevent scorching of product on the inner can surface. Internal vacuum at the time of filling must be at the maximum that can be achieved without paneling of the cans. This ensures that a saturated steam atmosphere will exist inside the can and internal pressure from expanding air and steam will not be too excessive during the high temperatures required for sterilization.

Thermal process determination requires a simulator that rotates the can over an open flame. Internal temperature must be monitored in the geometric center of the largest particle positioned in the geometric center of the can.

### 9.1.5 Continuous Flow Sterilization: Aseptic or Cold Fill

Fluids and small particle suspensions can be sterilized by heating in heat exchangers. Figure 9.8 is a schematic diagram of an aseptic processing system. The liquid phase reaches the processing temperature very rapidly, therefore the small sterilization value of the heating phase of the process is generally neglected. The specified process for sterilization in continuously flowing systems is a time

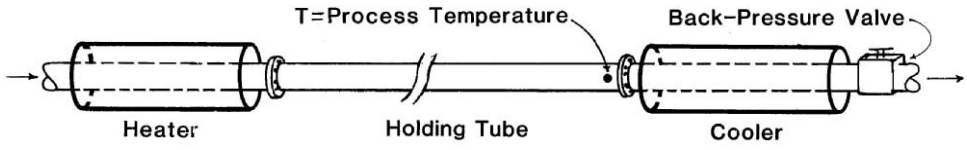


**Figure 9.8** Schematic diagram of an aseptic processing system for product sterilization.

of residence in a holding tube, an unheated section of the piping system that leads the fluid from the heat exchangers for heating to the heat exchangers for cooling. A back pressure valve or a positive displacement timing pump is positioned after the cooler to maintain the pressure within the system at a level needed to keep the product boiling temperature higher than the processing temperature. After cooling, the sterile product must be handled in a sterile atmosphere, therefore the process is called *aseptic processing*. The time of residence is set by the volume of the holding tube and the rate of fluid flow delivered by a positive displacement pump.

$$t_{avg} = \frac{A_c L}{Q} \tag{9.2}$$

where $t_{avg}$. is average fluid residence time, $A_c$ is cross-sectional area of the holding tube, L is length of the holding tube, and Q is volumetric rate of flow.

The average velocity ($V_{avg}. = Q/A_c$) may also be used to calculate the time in the holding tube.

$$t_{avg} = \frac{L}{V_{avg}} \tag{9.3}$$

In most cases, however, the time of residence of the fastest flowing portion of the fluid is used as the required hold time in the thermal process calculations. This is because the highest probability of survivors from the thermal process is contributed by the section of fluid flowing close to the geometric center of the tube. The minimum time is

$$t_{min} = \frac{L}{V_{max}} \tag{9.4}$$

The maximum velocity for Newtonian fluids in laminar flow is:

$$V_{max} = 2V_{avg} \tag{9.5}$$

For power flow fluids in laminar flow:

$$V_{max} = \frac{(3n+1)}{(n+1)} V_{avg} \tag{9.6}$$

For Newtonian fluids in turbulent flow, the following equation was derived by Edgerton and Jones (1970) for $V_{max}$ as a function of the Reynolds number based on the average velocity:

$$V_{max} = \frac{V_{avg}}{0.00336 \log(Re) + 0.662} \tag{9.7}$$

An equation similar to Equation (9.7) can be derived by performing a regression analysis on data by Rothfus et al. (AIChE J. 3:208, 1957) for Reynolds number greater than $10^4$.

### 9.1.6 Steam-Air Mixtures for Thermal Processing

A recent development in thermal processing is the use of a mixture of steam and air instead of water or saturated steam for heating. This system has been touted as ideal in processing of products in retortable pouches and glass. The advantages are elimination of a need for exhausting, and no sudden pressure changes on heating or cooling preventing breakage of the fragile containers.

Heating rates on which the scheduled process is dependent are strongly dependent on the heat transfer coefficient when steam-air is used for heating. The heat transfer coefficient is a function of velocity and mass fraction of steam. Thus, a retort designed for steam-air heating must be equipped

with a blower system to generate adequate flow within the retort to maintain uniform velocity and uniform temperature. Accurate and separate controllers must be used for pressure and temperature. The mass fraction steam ($X_s$) in a steam-air mixture operated at a total pressure P is given by:

$$X_s = \frac{P_s}{P}\left(\frac{18}{29}\right) \tag{9.8}$$

$P_s$ is the saturation pressure of steam at the temperature used in the process.

## 9.2 MICROBIOLOGICAL INACTIVATION RATES AT CONSTANT TEMPERATURE

### 9.2.1 Rate of Microbial Inactivation

When a suspension of microorganisms is heated at constant temperature, the decrease in number of viable organisms follows a first-order reaction.

Let N = number of viable organisms.

$$-\frac{dN}{dt} = kN \tag{9.9}$$

k is the first-order rate constant for microbial inactivation. Integrating Equation (9.9) and using the initial condition, $N = N_0$ at $t = 0$:

$$\ln\left(\frac{N}{N_0}\right) = -kt \tag{9.10}$$

Equation (9.10) suggests a linear semi-logarithmic plot of N against t. Equation (9.10) expressed in common logarithms is

$$2.303 \log\left(\frac{N}{N_0}\right) = -kt; \quad \log\left(\frac{N}{N_0}\right) = \frac{-kt}{2.303}$$

or:

$$\log\left(\frac{N}{N_0}\right) = \frac{-t}{D} \tag{9.11}$$

Equation (9.11) defines D, the decimal reduction time, the time required to reduce the viable population by a factor of 10. $D = 2.303/k$. Thus, the decimal reduction time and the first-order kinetic rate constant can be easily converted for use in equations requiring the appropriate form of the kinetic parameter.

N, the number of survivors, is considered to be the probability of spoilage if the value is less than 1. Any value of N ∃ 1 means certain spoilage (probability of spoilage = 1).

### 9.2.2 Shape of Microbial Inactivation Curves

Microbial inactivation proceeds in a logarithmic function with time according to Equation (9.11). However, although the most common inactivation curve is the linear semi-logarithmic plot shown in Fig. 9.9A, several other shapes are encountered in practice. Figure 9.9B shows an initial rise in numbers followed by first-order inactivation. This has been observed with very heat resistant spores and may be attributed to heat activation of some spores that otherwise would not germinate and form colonies, before the heat treatment reached the severity needed to cause death to the organism. Figure 9.9C

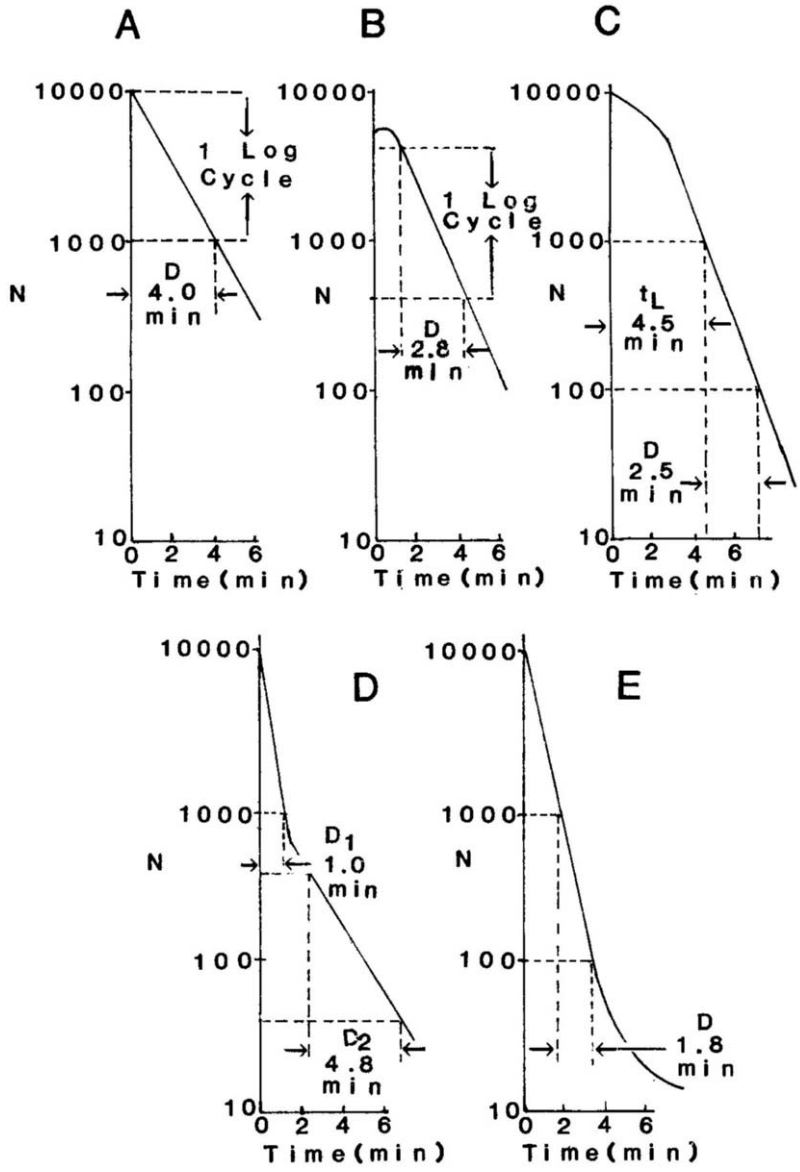


**Figure 9.9** Microbial inactivation curves. (A) First-order inactivation rate. (B) Initial rise in numbers followed by first-order inactivation. (C) Initial lag in the inactivation curve. (D) Inactivation curve exhibited by a mixed culture. (E) Tailing of an inactivation curve.

shows an inactivation curve that exhibits an initial lag or induction period. Very little change in numbers occurs during the lag phase. The curve represented by Fig. 9.9C can be expressed as:

$$\log \frac{N_0}{N} = 1 + \left(\frac{t - t_L}{D}\right); \quad t > t_L \tag{9.12}$$

where $t_L$ is the lag time, defined as time required to inactivate the first 90% of the population. In most cases, the curved section of the inactivation curve does not extend beyond the first log cycle of inactivation, therefore defining $t_L$ as in Equation (9.12) eliminates the arbitrary selection of the lag time from the point of tendency of the curved and the straight line portion of the inactivation curve. In general, $t_L$ approaches D as $N_0$ becomes smaller and as the temperature increases. When $t_L = D$, the first-order inactivation rate starts from the initiation of heating, and Equation (9.12) reduces to Equation (9.11). Equation (9.12) is not often used in thermal process calculations unless the dependence of $t_L$ on $N_0$ and T are quantified. Microbial inactivation during thermal processing is often evaluated using Equation (9.11).

Figure 9.9D represents the inactivation curve for a mixed culture. The inactivation of each species is assumed to be independent of each other.

From Equation (9.11), the number of species A and B having decimal reduction times of $D_A$ and $D_B$ at any time are

$$N_A = N_{A0}(10)^{-(t/D_A)}; \quad N_B = N_{B0}(10)^{-(t/D_B)}$$
$$N = N_{A0}(10)^{-(t/D_A)} + N_{B0}(10)^{-(t/D_B)} \tag{9.13}$$

If $D_A < D_B$, the second term will be relatively constant at small values of t, and the first term predominates as represented by the first line segment in Fig. 9.9D. At large values of t, the first term approaches zero and microbial numbers will be represented by the second line segment in Fig. 9.9D.

The required heating time to obtain a specified probability of spoilage from a mixed species with known D values will be the longest heating time calculated using Equation (9.11) for any of the species.

Figure 9.9E shows an inactivation curve that exhibits tailing. Tailing is often associated with very high $N_o$ values and with organisms which have a tendency to clump. As in the case of a lag in the inactivation curve, the effect of tailing is not considered in the thermal process calculation unless the curve is reproducible and the effect of initial number and temperature can be quantified.

**Example 9.1.** Figure 9.10 shows data on inactivation of spores of F.S. 1518 reported by Berry et al. (J. Food Sci. 50:815, 1985). When $6 \times 10^6$ spores were inoculated into a can containing 400 g of product and processed at 121.1°C, the processed product contained 20 spores/g. Calculate the equivalent heating time at 121.1°C to which the product was subjected.

**Solution:**

Both lines in Fig. 9.10 are parallel and the D value of 3.4 min is independent of initial number, as would be expected from either Equations (9.11) or (9.12). However, both lines show a departure from linearity at the initial stage of heating. To determine if a lag time should be considered when establishing survivors from a heating process, data from both thermal inactivation curves will be fitted to Equation (9.12) to determine if $t_L$ is consistent with different initial numbers. A point on each plot is arbitrarily picked to obtain a value for N and t. Choosing a value of N = 10/g, the time required to reduce the population from $N_0$ to N is 20 and 16.2 min, respectively for $N_0 = 6 \times 10^6$ and $4 \times 10^6$. Using Equation (9.12): For $N_0 = 6 \times 10^6$:

$$t_L = 20 - 3.4\,[\log(6 \times 10^6/10) - 1] = 3.75\,\text{min}$$

For $N_0 = 4 \times 10^6$:

$$t_L = 16.2 - 3.4\,[\log(4 \times 10^6/10) - 1] = 0.56\,\text{min}$$

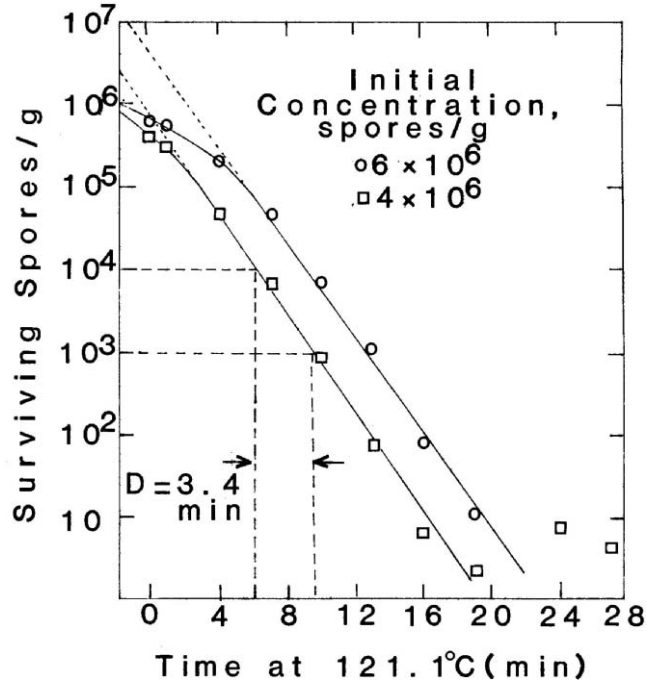


**Figure 9.10** Inactivation curve for spores of FS 1518. (From Berry, M. R. et al., J. Food Sci. 50:815, 1985.)

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Thus, $t_L$ is not consistent at the two levels of $N_0$ tested. At $N_0 = 6 \times 10^6$, $t_L$ is almost equal to the D value of 3.4 min, therefore inactivation was first order at the very start of heating. However, $t_L$ was only 0.56 min when $N_0 = 4 \times 10^6$. Thus the departure from linearity at the start of heating may be considered an anomaly, and for thermal process calculations, the inactivation curve may be considered as first order from the very start of heating. Reduction of viable numbers will be calculated using Equation (9.11).

$$t = -D \log (N/N_0)$$

$$N = 20 \frac{\text{spores}}{\text{g product}} \times 400 \text{ g product} = 8000 \text{ spores}$$

$$N_0 = 6 \times 10^6; \quad t = 3.4 \log \frac{6 \times 10^6}{8000} = 9.77 \text{ min}$$

Thus, the equivalent lethality of the process is 9.77 minutes at 121.1°C.

**Example 9.2.** A suspension containing $3 \times 10^5$ spores of organism A having a D value of 1.5 min at 121.1°C and $8 \times 10^6$ spores of organism B having a D value of 0.8 min at 121.1°C is heated at a uniform constant temperature of 121.1°C. Calculate the heating time for this suspension at 121.1°C needed to obtain a probability of spoilage of 1/1000.

**Solution:**

Using Equation (9.11):

For organism A: $t = 1.5 \log(3 \times 10^5/0.001) = 12.72$ min

For organism B: $t = 0.8 \log(8 \times 10^6/0.001) = 7.92$ min

Thus, the required time is 12.72 minutes.

### 9.2.3 Sterilizing Value or Lethality of a Process

The basis for process lethality is Equation (9.11), the destruction of biological entities in a heated material. The following may be used as means of expressing the sterilizing value of a process:

$S$ = number of decimal reduction = $\log N_0/N$

$F_T$ is process time at constant temperature T, which has the equivalent lethality of the given process. Usually F values are expressed at a reference temperature (121.1°C for sterilization processes or 82.2°C for a pasteurization process). The F and D value at 121.1°C are $F_0$ and $D_0$, respectively. In a constant temperature process, S and F values can be easily converted between each other using Equation (9.11), with F values substituted for t.

$$S = \frac{F_T}{D_T} \tag{9.14}$$

However, if the suspension is heated under changing temperature conditions such as the interior of a can during thermal processing, Equation (9.14) can be used only if the F value is calculated using the same z value as the biological entity represented by $D_T$. The z value is the parameter for temperature dependence of the inactivation rate and will be discussed in more detail in the section "Effect of Temperature on Thermal Inactivation of Microorganisms."

The use of S values to express process lethality is absolute (i.e., S is the expected effect of the thermal process). However, an S value represents a specific biological entity and when several must be inactivated, the S value for each entity may be calculated from the F value using Equation (9.14). The use of F values for expressing process lethality and its calculation under conditions of changing temperature during a process will be discussed in more detail in the section "Sterilizing Value of Processes Expressed as $F_0$."

### 9.2.4 Acceptable Sterilizing Value for Processes

A canned food is processed to achieve commercial sterility. Commercial sterility implies the inactivation of all microorganisms that endanger public health to a very low probability of survival. For canned foods, the critical organism is *Clostridium botulinum*. The 12D concept as a minimum process for inactivation of *C. botulinum* in canned foods is accepted in principle by regulatory agencies and the food industry. However, its interpretation has undergone a process of evolution, from a literal 12 decimal reduction, to what is now generally accepted as a probability of survival of $10^{-12}$.

The latter interpretation signifies a dependence of minimum processes according to the 12D concept on initial spore loads. Thus, packaging materials that have very low spore loads will not require as

**Table 9.1** N and $N_o$ Values Used to Obtain Target In ($N_o$/N) Values for Commercial Sterility of Canned Foods

| *Factor* | *N* | $N_o$ | $D_{mo}$ |
|---|---|---|---|
| Public health | $10^{-9}$ | General 10<br>Meats $10^2$<br>Mushrooms $10^4$<br>Packaging $10^{-5}$ | 0.2 |
| Mesophilic spoilage | $10^{-6}$ | General 10<br>Meats $10^3$ | 0.5 |
| Thermophilic spoilage | $10^{-2}$ | General $10^2$ | 1.5 |

*Source:* From Pflug, I. V., *J. Food Protect. 50:342, 50:347, 50:528, 1987.* Reprinted from Toledo, R. T., *Food Technol. 44(2):72, 1990.*

severe a process as products such as mushrooms which may have very high spore levels. Table 9.1 shows $N_0$ and N values that may be used as a guide in selecting target $N_0$/N values for thermal processing.

Spoilage from microorganisms that pose no danger to public health is called economic spoilage. Spoilage microorganisms often have higher heat resistance than *C. botulinum*, and their inactivation is the basis for the thermal process design. A high level of spoilage will be expected from the minimum process based on the 12D concept for *C. botulinum* inactivation.

**Example 9.3.** The F value at 121.1°C equivalent to 99.999% inactivation of a strain of *C. botulinum* is 1.2 minutes. Calculate the $D_0$ value of this organism.

**Solution:**

A 99.999% inactivation is 5 decimal reductions (one survivor from 100,000). S = 5. Using Equation (9.14):

$$D_0 = \frac{F_0}{S} = \frac{1.2}{5} = 0.24 \text{ min}$$

**Example 9.4.** Calculate $F_0$ based on the 12D concept using the $D_0$ value of *C. botulinum* in Example 9.3 and a most likely spore load in the product of 100.

**Solution:**

$$S = \log 100 - \log(10 - 12) = 14$$

$$F_0 = 14\ (0.24) = 3.30 \text{ minutes}$$

**Example 9.5.** The sterilizing value of a process has been calculated to be an $F_0$ of 2.88. If each can contained 10 spores of an organism having a $D_0$ of 1.5 min, calculate the probability of spoilage from this organism. Assume the $F_0$ value was calculated using the same z value as the organism.

**Solution:**

Using Equation (9.11) for a process time of 2.88 min:

$$\log \frac{N_0}{N} = \frac{2.88}{1.5}; \quad N = N_0[10]^{-(2.88/1.5)}$$

$$N = 10(10^{-1.92}) = 0.12; \quad P_{spoilage} = \text{ 12 in 100 cans.}$$

**Example 9.6.** The most probable spore load in a canned food is 100 and the $D_0$ of the spore is 1.5 minutes. Calculate a target $F_0$ for a thermal process such that the probability of spoilage is 1 in 100,000. If under the same conditions *C. botulinum* type B has a $D_0$ of 0.2 min, would the target $F_0$ value satisfy the minimum 12D process for *C. botulinum*? Assume an initial spore load of 1 per can for *C. botulinum*.

**Solution:**

For the organism, $S = \log(100/10^{-5}) = 7$. Using Equation (9.14): $F_0 = 7(1.5) = 10.5$ minutes. For *C. botulinum*: $S = \log(1/10^{-12}) = 12$. Using Equation (9.14): $F_0 = 12(0.2) = 2.4$ minutes. The $F_0$ for the spoilage organism satisfies the minimum process for 12D of *C. botulinum*.

### 9.2.5 Selection of Inoculation Levels in Inoculated Packs

In order to be reasonably sure of the safety of a process, products may be inoculated with an organism having known heat resistance, processed, and the extent of spoilage compared to the probability of spoilage designed into a process. The organism used must have a higher heat resistance than the background micro flora in the product. The level of spoilage and the inoculation levels are set such that spoiled cans can be easily evaluated. Use of an organism that produces gas facilitates the detection of spoiled cans because spoilage will be manifested by swelled cans. If a flat sour organism is used, it will be necessary to open the cans after incubation to determine the number of spoiled cans. If the whole batch of inoculated cans is incubated, the fraction spoiled will be equivalent to the decimal equivalent of the number of surviving organisms. Inoculation levels can be calculated based on Equation (9.11).

The two examples below represent procedures used for validation of thermal processes using inoculation tests. The first example represents an incubation test, and the second example represents a spore count reduction test.

**Example 9.7.** A process was calculated such that the probability of spoilage from an organism with a $D_0$ value of 1 min is 1 in 100,000 from an initial spore load of 100. To verify this process, an inoculated pack is made. Calculate the level of inoculum of an organism having a $D_0$ value of 1.5 min that must be used on 100 cans such that a spoilage rate of 5 cans will be equivalent in lethality to the calculated process.

**Solution:**

The $F_0$ of the calculated process is determined using Equation (9.11) with $F_0$ substituted for t.

$$F_o = 1[\log(100/1 \times 10^{-5})] = 7 \text{ minutes}$$

For the inoculum:

$$\log \mathrm{No} - \log(5/100) = \mathrm{F_0/D} = 7/1.5 = 4.667$$

$$\mathrm{N_0} = 0.05(10)^{4.667} = 2323 \text{ spores}$$

**Example 9.8.** In an incidence of spoilage, the isolated spoilage organism was found to have a $D_0$ value of 1.35 minutes. It is desired that the probability of spoilage from this organism be 1 in 100,000. Initial spore loads were generally of the order 10/can. Calculate the required $F_0$ for this process to achieve the desired probability of spoilage. If an inoculated pack of FS 1518 is to be made, and an initial inoculation level of $5 \times 10^5$ spores is made into cans that contained 200 g of product, what will be the spore count in the processed product such that the lethality received by the can contents will be equivalent to the desired process for eliminating spoilage from the isolated organism. The $D_0$ value of FS 1518 = 2.7 minutes.

**Solution:**

The $F_0$ of the process can be calculated from the heat resistance and spore reduction needed for the spoilage organism.

$$\mathrm{F_0} = \mathrm{D}\,(\log \mathrm{N_0} - \log \mathrm{N}) = 1.35\,[\log 10 - \log\,(1/100000)] = 8.1 \text{ minutes}$$

For FS 1518:

$$\log \mathrm{N} - \log\,(5 \times 10^5) = -8.1/2.7 = -3.00$$

$$\mathrm{N} = 10^{(-3.00+5.698)} = 500$$

Spore count after processing = 500 spores/200 g = 2.5/g

### 9.2.6 Determination of D Values Using the Partial Sterilization Technique

This technique developed by Stumbo et al. (Food Technol. 4:321, 1950) and by Schmidt (J. Bacteriol. 59:433, 1950) allows the determination of D values using survivor data at two heating times. Appropriate selection of heating times to exceed the lag time for the heated suspension to reach the specified test temperature eliminates the need to correct for temperature changes occurring during the transient period of heating. When this procedure is used, the lag time to bring the suspension to the desired temperature must be established, and the two heating times used for D value determination must exceed the lag time. If $t_1$ and $t_2$ are the heating times and $N_1$ and $N_2$ are the respective number of survivors, the D value is determined by:

$$\mathrm{D} = \frac{t_2 - t_1}{\log\,(N_1) - \log\,(N_2)} \tag{9.15}$$

**Example 9.9.** Sealed tubes containing equal numbers of spores of an isolate from a spoiled canned food were heated for 10 and 15 minutes at 115.5°C. The survivors were, respectively, 4600 and 160. Calculate the D value. The lag time for heating the tubes to 115.5°C was established in prior experiments to be 0.5 minutes.

**Solution:**

Because the heating times are greater than the lag time for the tubes to attain the desired heating temperature, Equation (9.15) can be used.

$$D = \frac{15 - 10}{\log(4600) - \log(160)} = \frac{5}{1.458} = 3.42\,\text{min}$$

### 9.2.7 The Heat Resistance of Spoilage Microorganisms

The heat resistance of microorganisms is expressed in terms of a D value at a reference temperature, and the z value, the temperature dependence of the thermal inactivation rate. The use of the z value in determining D values at different temperatures from D at the reference temperature is discussed in the section "Effect of Temperature on Thermal Inactivation of Microorganisms." Reference temperatures are 121.1°C (250°F) for heat resistant spores to be inactivated in commercial sterilization processes and 82.2°C (180°F) for vegetative cells and organisms of low resistance, which are inactivated in pasteurization processes. D at 121.1°C (250°F) is $D_0$.

Tables 9.2 and 9.3 lists the resistance of microorganisms involved in food spoilage.

**Table 9.2** Heat Resistance of Spoilage Microorganisms in Low-Acid Canned Foods

| | | | *z* | |
|---|---|---|---|---|
| *Organism* | *Product* | $D_0$ *(min)* | *(°F)* | *(°C)* |
| *Clostridium botulinum* 213-B | Phosphate buffer (pH7) | 0.16 | 18 | 10 |
| | Green beans | 0.22 | 22 | 12 |
| | Peas | 0.22 | 14 | 8 |
| *Clostridium botulinum* 62A | Phosphate buffer (pH7) | 0.31 | 21 | 12 |
| | Green beans | 0.22 | 20 | 11 |
| | Corn | 0.3 | 18 | 10 |
| | Spinach | 0.25 | 19 | 11 |
| *Clostridium spp.* PA 3679 | Phosphate buffer (pH7) | 1.45 | 21 | 12 |
| | Asparagus | 1.83 | 24 | 13 |
| | Green beans | 0.70 | 17 | 9 |
| | Corn | 1.20 | 18 | 10 |
| | Peas | 2.55 | 19 | 10 |
| | Shrimp | 1.68 | 21 | 12 |
| | Spinach | 2.33 | 23 | 13 |
| *Bacillus stearother-mophilus FS 1518* | Phosphate buffer (pH7) | 3.28 | 17 | 9 |
| | Asparagus | 4.20 | 20 | 11 |
| | Green beans | 3.96 | 18 | 10 |
| | Corn | 4.32 | 21 | 12 |
| | Peas | 6.16 | 20 | 11 |
| | Pumpkin | 3.50 | 23 | 13 |
| | Shrimp | 3.90 | 16 | 9 |
| | Spinach | 4.94 | 21 | 12 |

*Source:* Reed, J. M., Bohrer, C. W. and Cameron, E. J., *Food Res. 16:338–408.*
*Reprinted from:* Toledo R. T. *1980.* Fundamentals of Food Engineering. AVI Pub. Co., Westport, CT.

**Table 9.3** Heat Resistance of Spoilage Microorganisms in Acid and in Pasteurized Foods

| | *Temperature* | | | *Z* | |
|---|---|---|---|---|---|
| *Organism* | *°F* | *°C* | *D (min)* | *°F* | *°C* |
| *Bacillus coagulans* | *250* | *121.1* | *0.07* | *18* | *10* |
| *Bacillus polymyza* | *212* | *100* | *0.50* | *16* | *9* |
| *Clostridium pasteurianum* | *212* | *100* | *0.50* | *16* | *9* |
| *Mycobacterium tuberculosis* | *180* | *82.2* | *0.0003* | *10* | *6* |
| *Salmonella spp.* | *180* | *82.2* | *0.0032* | *12* | *7* |
| *Staphylococcus spp.* | *180* | *82.2* | *0.0063* | *12* | *7* |
| *Lactobacillus spp.* | *180* | *82.2* | *0.0095* | *12* | *7* |
| *Yeasts and molds* | *180* | *82.2* | *0.0095* | *12* | *7* |
| *Clostridium botulinum* Type E | *180* | *82.2* | *2.50* | *16* | *9* |

*Source:* (1) Anderson, E. E., Esselen Jr., W. B. and Fellers, C. R. *Food Res. 14:499–510, 1949. (2)* Crissley, F. D., Peeler, J. T., Angelotti, R. and Hall, H. E., *J. Food Sci. 33:133–137, 1968. (3)* Stumbo, C. R. *77termobacteriology in Food Processing,* Academic Press, New York, *1973. (4)* Townsend, C. T. *Food Res. 4:231–237, 1939. (5)* Townsend, C. T., and Collier, C. P. *Proc. Technical Session of the 48th Annual Convention of the National Canners Association (NCA). NCA information Newsl. No. 1526,* February *28, 1955. (6)* Winter, A. R., Stewart, G. F., McFarlane, V. H. and Soloway, *M. Am. J. Pub. Health 36:451–460, 1946. (7)* Zuccharo. J. B., Powers, J. J., Morse, R. E. and Mills *W. C. Food. Res. 16:3038, 1951*

*Reprinted from:* Toledo, *1980*. Fundamentals of Food Process Engineering, lst. ed. AVI Pub. Co. Westport, Conn.

The type of substrate surrounding the organisms during the heating process affects heat resistance. For a more detailed discussion of techniques for determination of microbial heat resistance and the effect of various factors on thermal inactivation rates, the reader is referred to Stumbo's (1973) book *Thermobacteriology in Food Processing* and NFPA's *Laboratory Manual for Canners and Food Processors,* which are listed in the "Suggested Reading" section at the end of this chapter.

### 9.2.8 $F_0$ Values Used in Commercial Sterilization of Canned Foods

$D_0$, $N_0$, and N values that can be used as a guide for determining $F_0$ values for food sterilization are listed in Table 9.1. $F_0$ must be based on microorganisms involved in economic spoilage, as these have higher heat resistance than *C. botulinum*. Table 9.4 lists $F_0$ values previously used commercially for different types of foods in various size containers. Data in both Tables 9.1 and 9.4 may be used as a base for selection of $F_0$ values needed to calculate thermal process schedules for sterilization.

### 9.2.9 Surface Sterilization

Packaging materials used in aseptic packaging systems and surfaces of equipment may be sterilized using moist heat, dry heat, hydrogen peroxide, high-intensity ultraviolet, and ionizing radiation from either gamma rays or high-energy electron beams. The latter three methods have not been adopted in commercial food packaging, but various forms of heat and hydrogen peroxide combined with heat are commercially utilized.

**Table 9.4** Values of $F_o$ for Some Commercial Canning Processes

| *Product* | *Can sizes* | $F_o$ *(min)* |
|---|---|---|
| Asparagus | All | 2–4 |
| Green beans, brine packed | No. 2 | 3.5 |
| Green beans, brine packed | No. 10 | 6 |
| Chicken, boned | All | 6–8 |
| Corn, whole kernel, brine packed | No. 2 | 9 |
| Corn, whole kernel, brine packed | No. 10 | 15 |
| Cream style corn | No. 2 | 5–6 |
| Cream style corn | No. 10 | 2.3 |
| Dog Food | No. 2 | 12 |
| Dog Food | No. 10 | 6 |
| Mackerel in brine | 301 × 411 | 2.9–3.6 |
| Meat loaf | No. 2 | 6 |
| Peas, brine packed | No. 2 | 7 |
| Peas, brine packed | No. 10 | 11 |
| Sausage, Vienna, in brine | Various | 5 |
| Chili con carne | Various | 6 |

*Source:* Alstrand, D. V., and Ecklund, O. F., *Food Technol. 6(5):185, 1952.*

Dry heat includes superheated steam and hot air. Resistance of microorganisms in these heating media are shown in Table 9.5. Inactivation occurs at a slower rate in dry heat compared with moist heat at the same temperature. The z value in dry heat is also higher than in moist heat. A similar principle is utilized in evaluating microbial inactivation in dry heat as for moist heat.

The D values shown in Table 9.5, and the recommended N and $N_0$ values for commercial sterilization in Table 9.1, may be used to determine exposure times to the sterilant. In dry heat sterilization of

**Table 9.5** Resistance of Microorganisms to Microbicidal Agents

| *Organism* | *Heating Medium* | $D_{176.6^\circ C}$ *(min)* | $D_{121^\circ C}$ *(min)* | *z* (°C) |
|---|---|---|---|---|
| Bacillus subtilis | Superheated steam | 0.57 | 137 | 23.3 |
| Bacillus stearothermophilus (FS 1518) | Superheated steam | 0.14 | 982 | 14.4 |
| Bacillus polymyxa | Superheated steam | 0.13 | 484 | 15.6 |
| Clostridium sporogenes (P.A.3679) | Air | 0.30 | 109 | 21.7 |
| Clostridium botulinum | Air | 0.21 | 9 | 33.9 |
| Bacillus subtilis | $N_z$ + He | 0.17 | 285 | 17.2 |
| Clostridium sporogenes (P.A.3679) | He | 0.45 | 161 | 21.7 |
| Bacillus subtilis | A + $CO_z$ + Oz | 0.13 | 218 | 17.2 |

*Source:* Adapted from Miller, B. M., and Litskey, W. eds, 1976. *Industrial Microbiology,* McGraw-Hill. Used with permission of McGraw-Hill.

**Table 9.6** Resistance of Food Spoilage Microorganisms to Inactivation in Hot Hydrogen Peroxide

| *Organism* | $D_{80^\circ C}$ *(min)* | *z (°C)* |
|---|---|---|
| *Clostridium botulinum 169B* | *0.05* | *29* |
| *Bacillus subtilis ATCC 9372* | *0.063* | *41* |
| *Bacillus subtilis A* | *0.037* | *25.5* |
| *Bacillus subtilis* | *0.027* | *27* |
| *Bacillus stearothermophilus* | *0.07* | *22* |

*Source:* Toledo, R. T., *AIChE Symp. Ser. 78(218):81, 1982.* Reproduced by permission of the American Institute of Chemical Engineers, © *1982*, AIChE.

surfaces, surface temperatures must be used as the basis for the process rather than the temperature of the medium. The surface heat transfer coefficient and the temperature on the opposite side of the surface sterilized determine the actual surface temperature.

Hydrogen peroxide is the only chemical sterilant allowed for use on food contact surfaces. This compound at 35% (w/w) concentration is applied to the surface by atomizing, spraying, or by dipping, in the case of packaging materials in sheet form, followed by heating to vaporize the hydrogen peroxide and eliminate residue from the surface. A maximum tolerance of residual hydrogen peroxide in the package of 0.1 parts per million is required by federal regulations in the United States. Resistance of various microorganisms in hydrogen peroxide is summarized in Table 9.6. Inactivation rate is also temperature dependent.

## 9.3 EFFECT OF TEMPERATURE ON THERMAL INACTIVATION OF MICROORGANISMS

Microbial inactivation is a first-order chemical reaction and the temperature dependence of the rate constant can be expressed in terms of an activation energy or a z value. Equation (8.21) of Chapter 8 expresses the rate constant for inactivation in terms of the activation energy. The activation energy is negative for reactions that increase in rate with increasing temperature.

$$\frac{k}{k_0} = [e]^{E_a/R[1/T-1/T_0]} \tag{9.16}$$

Because $k = 2.303/D$ from Equation 8.23 Section 8.6, the temperature dependence of the D value in terms of the activation energy will be:

$$\frac{D}{D_0} = [e]^{E_a/R[1/T-1/T_0]} \tag{9.17}$$

Because $E_a$ is positive when reaction rates increase with temperature, Equation (9.17) represents a decrease in D value with increasing temperatures.

Thermobacteriologists prefer to use the z value to express the temperature dependence of chemical reactions. The z value may be used on the target F value for microbial inactivation, or on the D value to determine required heating times for inactivation at different temperatures. It may also be used on

heating times at one temperature, to determine equivalence in lethality at a reference temperature. A semi-logarithmic plot of heating time for inactivation against temperature is called the thermal death time plot, therefore equations based on this linear semi-logarithmic plot are called the thermal death time model equations for microbial inactivation at different temperatures.

$$\log \frac{F}{F_0} = \frac{T_0 - T}{z} \tag{9.18}$$

$t_0$ is the equivalent heating $t_T$ at temperature T. When $t_T = 1$, $t_0$ is the lethality factor, L, the equivalent heating time at 250°F for 1 minute at T.

$$\log \frac{D}{D_0} = \frac{T_0 - T}{z} \tag{9.19}$$

$$\log \frac{t_0}{t_T} = -\frac{T_0 - T}{z} \tag{9.20}$$

$$L = [10]^{T - T_0/z} \tag{9.21}$$

The inverse of L is the heating time at T equivalent to 1 minute at 250°F and is the parameter $F_i$ used in thermal process calculations.

$$F_i = [10]^{T_0 - T/z} \tag{9.22}$$

Use of the z value is not recommended when extrapolating D values over a very large temperature range. Equation (9.17) shows that D will deviate from a linear semi-logarithmic plot against temperature when the temperature range between T and $T_0$ is very large.

**Example 9.10.** The $F_0$ for 99.999% inactivation of *C. botulinum* type B is 1.1 minutes. Calculate $F_0$ for 12D inactivation, and the F value at 275°F (135°C) when z = 18°F.

**Solution:**

99.999% inactivation is equivalent to S = 5. For S = 12; $F_0 = SD_0 = 12(0.22) = 2.64$ minutes. Thus the $D_0$ value is 1.1/5 = 0.22 minutes. $F_{275}$ can be calculated using Equation (9.18) or using Equation (9.19) on the D value to obtain D at 275°F.

Using Equation (9.18): $(T_0 - T)/z = -25/18 = -1.389$

$$F_{275} = F_0(10^{-1.389}) = 2.64\,(0.0408) = 0.1078\,\text{min}$$

Using Equation (9.19): $D_{275} = 0.22(10^{-1.389}) = 0.00898\,\text{min}$

$$F_{275} = S\,D = 12(0.00898) = 0.1077\,\text{min}$$

**Example 9.11.** The $D_0$ for PA 3679 is 1.2 minutes and the z value is 10°C. Calculate the process time for 8D inactivation of PA 3679 at 140.5°C using the "thermal death time" model (Eq. 9.18) and the Arrhenius equation (Eq. 9.17). The z value was determined using data on D at 115.5 to 121.1°C.

**Solution:**

Using Equation (9.18):

$$(T - T_0)/z = (140.5 - 121.1)/10 = -1.94$$

$$F_0 = 8(1.2) = 9.6\,\text{min}; F_{140.5} = 9.6(10^{-1.94}) = 9.6(0.01148) = 0.11\,\text{min}$$

From Equation (8.36), Chapter 8:

$$z = \frac{\ln(10)R}{E_a}T_1T_2; \quad E_a = \frac{\ln(10)RT_2T_1}{z}$$
$$T_2 = 121.1 + 273 = 394.1\,K; \quad T_1 = 115.5 + 273 = 388.5\,K;$$
$$R = 1.987\ \text{cal/(gmole} \cdot \text{K)}$$
$$E_a = [\ln(10)](1.987)(388.5)(394.1)/10 = 70{,}050\ \text{cal/gmole};$$
$$E_a/R = 35{,}254$$
$$T = 140.5 + 273 = 413.5\,K; \quad T_0 = 394.1\,K$$
$$(1/T - 1/T_0) = -0.000119$$
$$F_{140.5} = F_0[e]^{35254(-0.000119)} = 9.6(0.015067) = 0.1446\,\text{min}$$

These calculations show that when extrapolating D values to high sterilization temperatures using the z value based on data obtained below 250°F (121.1°C), use of the Arrhenius equation will result in a safer process compared with the TDT (Thermal Death Time) model.

## 9.4 INACTIVATION OF MICROORGANISMS AND ENZYMES IN CONTINUOUSLY FLOWING FLUIDS

The methods for calculating the extent of microbial inactivation that results from a heat treatment is the same regardless of the severity of the heat treatment. Mild heat treatments designed to inactivate vegetative cells of microorganisms is called *pasteurization*. Pasteurized foods will be shelf stable if they are high acid (pH ∃ 4.6) but they would require refrigeration and are perishable if the pH is > 4.6. *Sterilization* is a high-temperature heat treatment designed to inactivate heat-resistant spores to produce a shelf-stable product when stored at ambient temperature. Pasteurization is used on food products to avoid public health hazards from pathogenic microorganisms. On perishable products, pasteurization reduces the number of viable spoilage microorganisms thereby increasing product shelf life. In a system for continuous pasteurization or sterilization of flowing fluids, the product is heated to a specified temperature and held at that temperature for a specified time.

The processing system used to heat-treat fluids to destroy unwanted microorganisms or enzymes is discussed in the section "Continuous Flow Sterilization: Aseptic or Cold Fill." The process is essentially a constant temperature heating process with the residence time in the holding tube considered as the processing time and the temperature at the point of exit from the holding tube as the processing temperature.

### 9.4.1 Time and Temperature Used in the Pasteurization of Fluid Foods

The basis for pasteurization time and temperature for high-acid foods that will be refrigerated post-pasteurization is the resistance of pathogenic microorganisms. Liquid egg and egg product pasteurization and milk pasteurization are regulated by local and federal agencies. Data in Table 9.7 can be used to calculate minimum time/temperature combinations for safety of pasteurized low-acid products. The following data have been compiled from the literature and from discussions with processors of the different food products listed. In general, the main objective of pasteurization is the inactivation of microorganisms of public health significance. For high-acid foods, heat resistance of pathogenic and

**Table 9.7** Heat resistance of spoilage and pathogenic microorganisms in pasteurized food products

| *Organism* | *Substrate* | *D (min) 60 °C* | *z °C* | *Reference* |
|---|---|---|---|---|
| Low acid foods (pH ∃ 4.6) | | | | |
| Aeromonas hydrophila | LWE | 0.04 | 5.6 | 1 |
| Mycobacterium tuberculosis | Milk | 14.1 | 4.4 | 2 |
| Listeria monocytogenes | Milk | 2.03 | 5.5 | 3 |
| Listeria monocytogenes | Egg yolk | 1.34 | 9.4 | 4 |
| | Egg white | 2.29 | 9.4 | 4 |
| Salmonella spp. | Egg white | 0.58 | 4.3 | 4 |
| | Egg yolk | 0.91 | 4.3 | 4 |
| E. Coli O157:H7 | Milk | 1.5 | 6.9 | 3 |
| Salmonella spp. | Milk | 0.52 | 6.9 | 3 |
| Listeria monocytogenes | LWE | 1.27 | 7.2 | 5 |
| Salmonella enteritidis | LWE | 0.25 | 6.9 | 5 |
| Staphylococcus aureus | Milk | 0.9 | 9.5 | 3 |
| Aeromonas hydrophyla | Milk | 0.18 | 7.7 | 3 |
| Yersinia enterocolitica | Milk | 0.51 | 5.8 | 3 |
| High acid foods (pH < 4.6) | | | | |
| E. Coli 0157:H7 | Apple Juice | 0.33 | 6.9 | 6 |
| Salmonella enteritidis | Model pH4.4 | 0.24 | 6.9 | 3 |
| Leuconostoc: | SSOJ | 0.19 | 7 | 7 |
| Lactobacilli: | SSOJ | 1.30 | 7 | 7 |
| Yeast: | SSOJ | 1.63 | 6 | 7 |
| Leuconostoc | 42BxOJ | 0.36 | 10 | 7 |
| Lactobacilli | 42BxOJ | 0.091 | 18 | 7 |
| Yeast | 42BxOJ | 1.02 | 9 | 7 |

LWE is liquid whole eggs. SSOJ is single strength orange juice and 42BxOJ is 42 brix orange juice concentrate. References: 1. Schuman JD, Sheldon BW, and Foegeding PM. (1997) J. Food Prot. 60:231; 2. Keswani J, and Frank JF (1998). J. Food Prot. 61:974; 3. ICMSF 1996 Microorganisms in Foods, Book 5. Blackie Publishers, London; 4. Schuman JD, and Sheldon BW (1997). J. Food Prot. 60:634; 5. Foegeding PM and Leasor SB (1990). J. Food Prot. 53:9; 6. Splitstoesser, DF. (1996) J. Food Prot. 59:226; 7. Murdock et al. (1953) Food Research 18:85.

aciduric spoilage microorganisms are relatively low, therefore pasteurization processes can produce a commercially sterile product.

*Pasteurization processes for high-acid products (pH #4.6) or acidified products:* The following time and temperature combinations are used as a guideline by the food industry for producing shelf-stable high-acid food products. Times and temperature are dependent on the product pH.

Acidified or naturally high acid products: pH $< 4.0 = 1$ minute at 87.8°C (190°F) ; pH $4.0 = 30$ seconds at 96.1°C (205°F); pH $4.1 = 30$ seconds at 100°C (212°F); pH $4.2 = 30$ seconds at 102.2°C (216°F); pH $> 4.2$ to $4.5 = 30$ seconds at 118.3°C (245°F). If sugar or starch is added to the product, the time/temperature for the next higher pH should be used. For example, if starch or sugar is a component of a product with a pH of 4.1, use a process of 30 seconds at 102.2°C (process for pH 4.2 if no sugar or starch is added).

Tomato products: The pasteurization process is based on an equivalent F value at 200°F (93.3°C). The following $F_{200F}$ values are generally used: 1 minutes at pH 4.1; 3 minutes at pH 4.2; and 5 minutes

**Table 9.7a** Heat treatment conditions for long-life pasteurized products

| *pH* | *Temperature for a 40 s process* | *Temperature for a 20 min. Process* |
|---|---|---|
| 4.6 | 140°C | 115°C |
| 4.5 | 130 | 110 |
| 4.4 | 120 | 105 |
| 4.3 | 110 | 100 |
| 4.2 | 100 | 95 |
| 4.1 | 98 | 90 |
| 4.0 | 94 | 85 |
| 3.9 | 90 | 75 |

at pH 4.3. If temperatures other than 93.3°C is used, use a z value of 16°F (8.9°C) to obtain the equivalent process time from the $F_{200F}$ values. For products with starch or sugar added at pH 4.3, use an $F_{250F}$ of 0.5 minutes (z = 16°F) as a basis for the process.

Pineapple juice: The following $F_{200F}$ values are used: pH > 4.3, F = 10 minutes; pH between 4.0 and 4.3, F = 5 minutes. Use a z value of 15°F (8.33°C) for other temperatures. Example: Juice with a pH of 4.0 processed at 210°F (98.9°C) will need a process time of 1.06 minutes.

Other juices, flash pasteurization: Flash pasteurization refers to very rapid heating to the processing temperature followed by an appropriate hold, cooling, and aseptic filling. Hold time for peach juice, pH < 4.5 is 30 seconds at 110°C; orange juice: 1 minute at 90°C or 15 seconds at 95°C; grapefruit juice: 16 seconds at 74°C or 1 second at 85°C. FDA regulations mandate a minimum pasteurization requirement of 5 log reduction of pathogenic microorganism capable of growing in the product (FDA 1998). For a typical flash pasteurization temperature of 80°C, products with pH < 4.4 will require 0.2 s to obtain 5 log reduction of *E. coli* 0157:H7 and *Salmonella* spp. Thus, the time and temperature specified above are more than adequate to meet the minimum pasteurization requirement.

*Pasteurization requirements for milk:* (U.S. Grade A Pasteurized milk ordinance–1978 Recommendations of the USPHS/FDA) specify the following temperature and times: 63°C (145°F) for 30 minutes; 72°C (161°F) for 15 seconds; 89°C (192.2°F) for 1 second; 90°C (194°F) for 0.1 second; 96°C (204°F) for 0.05 second.

*Pasteurization requirements for liquid whole eggs*: The USDA specifies a pasteurization time and temperature of 3.5 minutes at 60°C (140°F).

Comparing the process times and temperature and the heat inactivation kinetics of pathogens in Table 9.7 gives the following log reduction of pathogens. For milk, a 15-second process at 72°C = 58 log reduction of *M. tuberculosis*; = 18.7 log reduction of *L. monocytogenes*; > 100 log reduction of *E. coli* 0157:H7; > 100 log reduction of *Salmonella* spp. For liquid whole eggs, a 3.5-minute process at 60°C = 2.75 log reduction of *L. monocytogenes*; = 14 log reduction of *Salmonella enteritidis.*

*Commercial pasteurization processes*: Commercial processors may use processing time and temperature higher than those specified by regulations to obtain long product shelf life. For example, shelf life (defined as time for CFU to reach $10^6$/mL) at 5°C of milk processed at different time and temperature (from: Kessler and Horak, Milchwissenschaft 39:451, 1984) are as follows: 21 days at 74°C/40 seconds or 78°C/15 seconds; 17 days at 74°C/15 seconds or 71°C/40 seconds; 16 days at 78°C/14 seconds or 85°C/15 seconds; 12 days at 71°C/15 seconds.

For liquid whole eggs, TetraPak recommends processing at 70°C for 90 seconds to obtain a 3-month shelf life at 5°C.

For acidified milk (flavored, yogurt-like), von Bockelman (1998) gave the heat treatment conditions to obtain a 3-month shelf life at ambient temperature storage as follows:

pH and temperature (°C) for a 40 second continuous flow process: pH 4.6, 140 °C; pH 4.5, 130 °C; pH 4.4, 120 °C; pH 4.3, 110 °C; pH 4.2, 100 °C; pH 4.1, 98 °C; pH 4.0, 94 °C; pH 3.9, 90 °C.

pH and temperature (°C) for a 20 minute batch process: pH 4.6, 115 °C; pH 4.5, 110 °C; pH 4.4, 105 °C; pH 4.3, 100 °C; pH 4.2, 95 °C; pH 4.1, 90 °C; pH 4.0, 85 °C; pH 3.9, 75 °C.

### 9.4.2 Microbial Inactivation in Continuously Flowing Fluids

The time and temperature for pasteurization in the previous section is based on the residence time of the fluid in a holding tube following elevation of the product temperature to the designated processing temperature. The residence time is a function of the fluid velocity. Because there is a velocity distribution in fluids flowing through a pipe, residence time of the fluid will vary at different positions in the pipe. The integrated lethality of microoganisms in the fluid leaving a hold tube must be used as the basis for the process.

The velocity distribution in a fluid flowing through a pipe has been derived for a power law fluid in laminar flow. Equation (6.16), Chapter 6 is

$$V = \overline{V}\left(\frac{3n+1}{n+1}\right)\left[1 - \left[\frac{r}{R}\right]^{(n+1)/n}\right] \tag{9.23}$$

Consider an area element of thickness dr within a tube of radius R: If $N_o$ is the total number of organisms entering the tube, N is the number leaving, $n_o$ is the organisms/unit volume entering, and n is organisms/unit volume leaving:

$$N_o = n_o[2\pi \int_0^R Vrdr] \tag{9.24}$$

The expression in brackets in Equation (9.24) is the volumetric rate of flow, $nR^2\overline{V}$. Thus Equation (9.24) becomes:

$$N_o = nR^2 n_o \overline{V} \tag{9.25}$$

The residence time of fluid within the area element is L/V, and the number of survivors, $N = N_o[10^{-L/(VD)}]$. Thus:

$$N = 2\pi n_o \int_0^R Vr[10]^{-L/(VD)}dr \tag{9.26}$$

In Equation (9.23), let: $A = (3n + 1)/(n + 1)$; $B = (n + 1)/n$; $y = r/R$. Equation (9.23) becomes:

$$V = A(1 - y^B)\overline{V} \tag{9.27}$$

The ratio $L/(\overline{V} \cdot D)$ is the lethality, $S_v$, based on the average velocity. Substituting Equation (9.27) into Equation (9.26), and $S_v = L/(\overline{V} \cdot D)$; $r = yR$; $dr = Rdy$. The integrated lethality, Si will be $\log N_0/N$:

$$N = 2\pi n_0 \int_0^1 \overline{V}(A)(1 - y^B)[10]^{-S_v/[A(1-y^B)]}R^2 y\, dy \tag{9.28}$$

**Table 9.8** Integrated Lethality in the Holding Tube of a Continuous Sterilization System for Fluids in Laminar Flow

| | Integrated Lethality, $S_i$ Fluid flow behavior index, n | | | | | | |
|---|---|---|---|---|---|---|---|
| $S_v$ | *0.4* | *0.5* | *0.6* | *0.7* | *0.8* | *0.9* | *1.0* |
| **0.1** | **0.093** | **0.093** | **0.092** | **0.091** | **0.091** | **0.091** | **0.091** |
| **0.5** | **0.426** | **0.419** | **0.414** | **0.409** | **0.406** | **0.401** | **0.401** |
| 1 | **0.809** | **0.792** | **0.779** | **0.768** | **0.759** | **0.747** | **0.747** |
| **2** | **1.53** | **1.49** | **1.46** | **1.44** | **1.42** | **1.40** | 1.38 |
| 4 | **2.92** | **2.82** | 2.75 | **2.69** | **2.64** | 2.59 | 2.56 |
| 6 | 4.27 | 4.11 | 3.99 | 3.89 | 3.81 | 3.74 | 3.68 |
| 8 | **5.60** | **5.38** | **5.20** | 5.06 | 4.95 | 4.86 | 4.78 |
| 10 | 6.92 | 6.63 | 6.41 | **6.23** | **6.08** | **5.96** | 5.86 |
| 12 | **8.23** | **7.88** | **7.60** | **7.38** | **7.20** | 7.05 | 6.92 |
| 14 | **9.54** | **9.12** | **8.79** | **8.52** | **8.31** | 8.13 | 7.98 |
| 16 | **10.84** | **10.35** | **9.97** | **9.66** | **9.41** | **9.20** | 9.03 |
| 18 | **12.14** | **11.58** | **11.14** | **10.79** | 10.51 | 10.27 | 10.07 |
| 20 | **13.44** | **12.81** | **12.32** | **11.93** | **11.60** | **11.34** | **11.11** |
| **22** | **14.73** | **14.03** | **13.49** | **13.05** | **12.69** | **12.40** | **12.15** |
| **24** | **16.03** | **15.26** | **14.66** | **14.18** | **13.79** | **13.46** | **13.18** |
| **26** | **17.32** | **16.48** | **15.83** | **15.30** | **14.87** | **14.52** | **14.22** |

$\mathbf{S_v}$ = sterilization value as number of decimal reductions based on the average velocity ($L/D \bullet \overline{V}$)

Dividing Equation (9.25) by Equation (9.28):

$$\frac{N_0}{N} = \frac{\pi R^2 n_0 \overline{V}}{2\pi n_0 \int_0^1 \overline{V}(A)(1 - y^B)[10]^{-S_v/[A(1-y^B)]} R^2 y dy}$$

Canceling $\pi R^2 n_0 \overline{V}$, taking the logarithm of both sides, and making the logarithm of the denominator of the right-hand side negative to bring it to the numerator:

$$\log\left(\frac{N_0}{N}\right) = -\log\left[\int_0^1 \left[2A(1 - y^B)[10]^{-S_v/[A(1-y^B)]} y\, dy\right]\right] \tag{9.29}$$

$\log(N_0/N)$ in Equation (9.29) is the integrated lethality, $S_i$.

Equation (9.29) can be evaluated by graphical integration. The integrated sterility in the holding tube is independent of the size of the tube and the average velocity if the length and average velocity are expressed as the sterilization value based on the average velocity, $S_v$.

Thus Equation (9.29) can be solved and the solution will yield a generalized table for the integrated lethality of heat in the holding tube when fluid is flowing through that tube in laminar flow. Values of $S_i$ at different values of n and $S_v$ obtained by graphical integration of Equation (9.29) are shown in Table 9.8. The data in Table 9.8 shows that $S_i/S_v$ is approximately $\overline{V}/V_{max}$. Thus, use of the maximum velocity to calculate lethality produces results much closer to the integrated lethality than if the average velocity is used.

**Example 9.12.** A fluid food product with a viscosity of 5 cP and a density of 1009 kg/m$^3$ is to be pasteurized in a continuous system that heats the food to 85°C followed by holding in a 1.5-in. sanitary pipe from which it leaves at 82.2°C. The process should give 12 decimal reduction of *Staphylococcus aureus*, which has a $D_{82.2EC}$ of 0.0063 minutes. Calculate the length of the holding tube if the flow rate is 19 L/min.

**Solution:**

From Chapter 6, Table 6.2, the inside diameter of a 1.5-in. sanitary pipe is 0.03561 m.

$$\overline{V} = \frac{19\text{L}}{\text{min}} \frac{1\,\text{m}^3}{1000\,\text{L}} \frac{1\,\text{min}}{60\,\text{s}} \frac{1}{\pi[0.5(0.03561)]^2\text{m}^2}$$

$\overline{V} = 0.318$ m/s. Re $= (0.03561)(0.318)(1009)/5(0.001) = 2285$. Flow is in the transition zone from laminar to turbulent flow. For safety, assume flow is laminar, and $V_{max} = 2\overline{V} = (0.318) = 0.636$ m/s.

Using Equation (9.14): The F value is the required process time that must equal the residence time in the tube for the fastest-flowing particle. $F = t_{min} = S \cdot D = 12(0.0063) = 0.0756$ minutes.

Using Equation (9.4):

$$L = 0.0756\,\text{min}(60\text{s/ min})(0.636\ \text{m/s}) = 2.88\ \text{m}$$

Length based on the integrated lethality for a Newtonian fluid: From Table 9.8, by interpolation, to obtain $S_i = 12$, $n = 1$, $S_v = 22 - 0.17(12.17 - 11.13)/2 = 21.91$. Because $S_v = L/(\overline{V} \cdot D)$, $L = 21.91(0.318)(0.0063)(60) = 2.63$ m.

The integrated lethality gives a length much closer to that based on the maximum velocity compared to results using the average velocity.

At the Reynolds number in the range 3000 to 5000, the maximum velocity cannot be obtained using Equation (9.7). Thus, the safest approach to determination of holding tube length in this range of Reynolds number will be to assume laminar flow.

**Example 9.13.** An ice cream mix having a viscosity of 70 cP and a density of 1015 kg/m$^3$ is being canned aseptically in a system which uses a 100-ft-long, 1.0-in. sanitary pipe for a holding tube. Flow rate through the system is 5 gal/min. The fluid temperature at the exit from the holding tube is 285°F (140.6°C).

Calculate (a) the sterilizing value of the process for PA 3679 ($D_0 = 1.83$ min; $z = 24$°F).

**Solution:**

From Table 6.2: $D = 0.02291$ m, $R = 0.01146$ m.

Solving for the average velocity:

$$\overline{V} = \frac{5\ \text{gal}}{\text{min}} \frac{3.78541 \times 10^{-3}\ \text{m}^3}{\text{gal}} \frac{1\,\text{min}}{60\text{s}} \frac{1}{\pi(0.01146)^2\ \text{m}^2}$$

$\overline{V} = 0.765$ m/s. Re $= 0.02291(0.765)(1015)/70(0.001) = 254$. Flow is laminar. $L = 100$ ft(1 m/ 3.281 ft) $= 30.48$ m.

(a) Solving for $V_{max:}$

$$V_{max} = 2\overline{V} = 2(0.785) = 1.57 \text{ m/s}$$

The residence time of the fastest-flowing particle is

$$t = L/V_{max} = 19.41 \text{ s.}$$

The process occurs at 285°F; therefore, the number of survivors from the process is calculated using the D value at 285°F for D in Equation (9.11). The D value at 285°F is determined using Equation (9.19):

$$\log D = [\log Do + (To - T)]/z = [\log[(1.83)(60)] + (250 - 285)]/24 = 2.0406 - 1.458$$

$$D = 10^{0.5826} = 3.8247 \text{ s at } 285^{\circ}\text{F}$$

Using Equation (9.11): $S = 19.41/3.8247 = 5.075$. The process will result in at least 5.075 decimal reduction of PA 3679.

The number of decimal reductions based on the integrated lethality is

$$S_v = L/(\overline{V} \cdot D) = 30.48/[(0.765)(3.8247)] = 10.42$$

From Table 9.6, $S_v = 10.42$, $n = 1$, by interpolation:

$$Si = 5.86 + 0.42(6.93 - 5.86)/2 = 6.08$$

The integrated lethality is 6.08 decimal reductions of PA 3679.

### 9.4.3 Nutrient Degradation

Nutrient degradation can be calculated the same way as for microbial inactivation. Equations (9.24) to (9.29) are also applicable for loss of nutrients if the appropriate kinetic parameters of D and z values are used.

Nutrient retention with increasing processing temperature can be derived by simultaneously solving the rate equations for microbial inactivation and nutrient degradation. Using the subscript c and m to signify parameters for nutrient degradation and microbial inactivation respectively, Equations (9.11) and (9.19) may be combined to determine the heating time at various temperatures for microbial inactivation.

$$t = D_{mo}\left[\log\left(\frac{N_0}{N}\right)\right][10]^{(T_0 - T)/z_m} \tag{9.30}$$

A similar expression can be formulated for nutrient degradation.

$$\log\left(\frac{C}{C_0}\right) = -\frac{t}{D_{co}[10]^{(T_0 - T)/z_c}} \tag{9.31}$$

Substituting $S_v$ for $\log (N_0/N)$ and combining Equations (9.30) and (9.31):

$$\log\left(\frac{C}{C_0}\right) = -\left[\frac{D_{mo}}{D_{co}}S_v\right][10]^{(T_0 - T)(1/z_m - 1/z_c)} \tag{9.32}$$

Equation (9.32) is based on constant temperature processes and is applicable for estimating nutrient retention in holding tubes of aseptic processing systems. The derivation is based on plug flow of fluid at the average velocity through the tube, and adjustments will have to be made to obtain the integrated lethality and nutrient degradation. Table 9.8 can be used to determine $S_v$ needed to obtain the microbial

lethality required expressed as $S_i$. $-\text{Log}(C/C_o)$ will be the $S_v$ for nutrient degradation which can be converted to $S_i$ using Table 9.8.

**Example 9.14.** The data for thiamin inactivation at 95°CE to 110°C from Morgan et al. (J. Food Sci. 51:348, 1986) in milk show a $D_{100EC}$ of $3 \times 10^4$ s and a z value of 28.4°C. Chocolate milk with a flow behavior index of 0.85 and a consistency index of 0.06 Pa s $^n$ is to be sterilized at 145°C. The density is 1006 kg/m$^3$. If the rate of flow is 40 L/min, and the holding tube is 1.5-in. sanitary pipe, calculate the holding tube length necessary to give an integrated lethality of 7 decimal reductions of an organism having a $D_o$ value of 0.5 minutes and a z value of 10°C. Assume the z value of the organism was determined in the temperature range that included 145°C. Calculate the retention of thiamin after this process.

**Solution:**

Because the z value for thiamin was determined at low temperatures, Equation (9.17) will be used to extrapolate the D value to 145°C. From Equation (8.25), Chapter 8:

$$E_a = \frac{[\log(10)]R}{z} T_1 T_2 = \frac{[\log(10)](1.987)(368)(383)}{28.4}$$

$E_a = 22{,}706$; $E_a/R = 11{,}427$; $T = 145 + 273 = 418$ K; $T_r = 100 + 273 = 373$ K.

Using Equation (9.17) and the subscript c to represent chemical degradation:

$$[1/T - 1/T_r] = (1/418 - 1/373) = -0.000289$$
$$D_c = 3 \times 10^4 (e)^{11427(-0.000289)} = 1109 \text{ s}$$

Equation (9.19) is used to determine $D_m$ at 145°C.

$$[(T_o - T)/z] = [(121.1 - 145)/10] = -2.39$$
$$D_m = 0.5(10)^{-2.39} = 0.002037 \text{ min} = 0.1222 \text{ s}$$

Equation (9.32) will be used, but because $D_m$ and $D_c$ are already calculated at 145°C, $T = T_0$ , the exponential term $10^{(To-T)(1/zm-1/zc)} = 1$ and :

$$\log\left(\frac{C}{C_0}\right) = -\frac{D_m}{D_c} S_{vm} \tag{9.30a}$$

$S_{vm}$ is the sterilizing value for the microorganisms based on the average velocity.

The Reynolds number is

$$\text{Re} = \frac{8V^{2-n}R^n\rho}{K[3 + 1/n]^n}$$

From Table 6.2, $R = 0.5(0.03561) = 0.017805$ m

$$\overline{V} = \frac{40 \text{ L}}{\text{min}} \frac{1 \text{ min}}{60 \text{ s}} \frac{\text{m}^3}{1000 \text{ L}} \frac{1}{\pi(0.017805)^2 \text{ m}^2} = 0.669 \text{ m/s}$$

$[(3n + 1)/n] = 4.176$

$$\text{Re} = \frac{8(0.669)^{1.15}(0.017805)^{0.85}(1006)}{0.06(4.176)^{0.85}} = 816.7$$

Flow is laminar, and the integrated lethality can be evaluated using Table 9.8. The integrated sterilizing value for the microorganism, $S_{mi}$ is the desired outcome of the process and the value is 7.0 The

sterilizing value based on the average velocity must be determined to obtain the length of the holding tube.

From Table 9.8, $S_{vm}$ is obtained for $S_i = 7$ and $n = 0.85$, by interpolation:

$$\text{At } S_i = 7,\ n = 0.8,\ S_v = 10 + [2/1.11](0.91) = 11.64$$
$$n = 0.9,\ S_v = 10 + [2/1.1](1.04) = 11.89$$

Solving for $S_v$ at $n = 0.85$, $S_v = 11.64 + [0.25/0.1](0.05) = 11.77$

The sterilizing value based on the average velocity = 11.77 and the $D_m$ value at 145 C = 0.1222 seconds. Average retention time at 145 C = 11.77(0.1222) = 1.438 seconds. The length of the holding tube, $L = \overline{V} \cdot t = 0.669(1.438) = 0.962$ m.

The thiamine retention will be calculated using Equation (9.30a): $D_c = 1109$ s, $D_m = 0.1222$ s, and $S_{vm} = 11.77$.

$$\log\left(\frac{C}{C_0}\right) = -\frac{0.1222}{1109}11.77 = -0.001317$$

$C/C_0 = (10)^{-0.001317} = 0.997$ or 99.7% retention.

**Example 9.15.** Tomato paste ($n = 0.5$, $k = 7.9$ Pa. $s^n$, $\rho = 1085$ kg/$m^3$) is sterilized at 95°C using a holding tube with an inside diameter of 0.03561 m. The system operates at the rate of 50 L/min. Each package to be filled with the sterilized product contains 200 L and the probability of spoilage to be expected from the process is 1 in 10,000 from spores of *Bacillus polymyxa,* which has $D_{80EC} = 0.5$ minutes and z = 9°C

The unprocessed paste contains 4 spores/mL. Calculate the length of the holding tube necessary to achieve an integrated sterility, which is the desired spoilage probability. Calculate the extent of nonenzymatic browning that occurs during this process expressed as percentage increase over brown color before processing. Assume the $D_0$ value of non-enzymatic browning is 125 minutes at 80°C and the z value is 16°C.

**Solution:**

Determine if flow is laminar or turbulent.

$$\overline{V} = \frac{50\text{ L}}{\text{min}}\frac{1\text{ min}}{60\text{ s}}\frac{\text{m}^3}{1000\text{ L}}\frac{1}{\pi[(0.5)(0.03561)]^2\text{ m}^2} = 0.837\text{m/s}$$

$$\text{Re} = \frac{8(\overline{V})^{2-n}\,R^n\rho}{K[3+1/n]^n}\left[\frac{(3n+1)}{n}\right]^n = 2.24$$

$$\text{Re} = \frac{8(0.837)^{1.5}(0.017805)^{0.5}(1085)}{7.9(2.24)} = 50$$

Flow is laminar. For each 200-L package, $N_0 = 80000$. $N = 1/10{,}000$. $\text{Log}(N_0/N) = 9.9$. This is to be evaluated on the integrated sterility, therefore, $S_i = 9.9$. From Table 9.8, to obtain $S_i = 9$, for n = 0.5, $S_v$ is obtained by interpolation:

$$S_v = 14 + (2/1.24)(9.9 - 9.12) = 15.26 = L/(V - D)$$
$$D_{95} = D_{80}[10]^{(80-95)/9} = 0.0215(0.5) = 0.01077\text{ min}$$

Substituting and solving for L:

$$L = S_v\quad \overline{V}\,D = 15.26(0.837\text{ m/s})(0.01077\text{ min})(60\text{ s/min}) = 8.25\text{ m}.$$

Equation (9.32) will be used for determining the increase in brown color that results from the process. Because the reaction involves the appearance of a brown color, the negative sign in Equation (9.32) is changed to positive. The reference temperature, $T_0 = 80^\circ C$; $T = 95^\circ C$, $z_m = 9$ and $z_c = 16$.

$$\log\left(\frac{C}{C_0}\right) = \frac{0.5}{125}(15.26)[10]^{(80-95)(1/9-1/16)} = 0.011$$

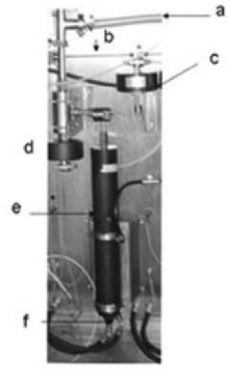
At very small values of S, $S_v = S_i$, therefore integrated $C/C_0$ at $S = 0.011 = 100.011 = 1.026$. An increase of 2.6% in the intensity of browning will be expected in the process. Calculations of integrated lethality for fluids in turbulent flow is not possible without an expression for velocity distribution within the tube. Currently available expressions for velocity distributions in turbulent flow is too unwieldy for a generalized treatment of the integrated sterility as was done with Equation (9.27). A possible approach to determination of an integrated lethality will be to determine experimentally the fluid residence time distribution and express this as a distribution function for velocity within the tube relative to the average velocity. In the absence of velocity distribution functions, lethality in the holding tube of continuous sterilization systems in turbulent flow must be calculated using the maximum velocity (Equation 9.7, $Re > 5000$). Examples shown above for nutrient degradation during high-temperature, short-time sterilization demonstrate very low values for log $(C/C_0)$ such that the integrated value approaches the value based on the average velocity. Thus, $\log(C/C_0)$ can be based on the average velocity. On the other hand, holding tube length calculations must be based on the integrated lethality.

### 9.4.4 High-Pressure Pasteurization

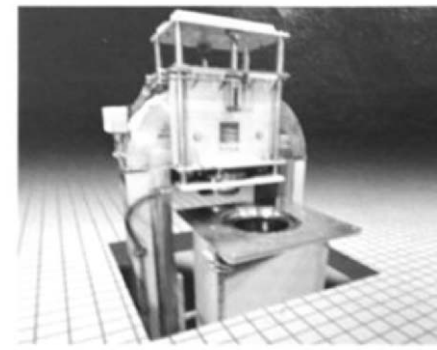
The momentum toward adoption by the food industry of high pressure as a means of food preservation has increased because reliable equipment is now available for applying the process and adequate data have been accumulated on inactivation of pathogenic and spoilage microorganisms to increase user's confidence in the process. High-pressure processes have the advantage of inactivating microorganisms with minimal exposure of the food product to heat. Thus, the potential for preserving the fresh-like quality of the preserved food is very good. High-pressure food preservation may be applied as a pasteurization or a sterilization process. High-pressure pasteurization of high-acid products may produce a product that is stable during ambient storage. Use of the process on acid products may extend refrigerated shelf-life post-treatment. High-pressure sterilization is considered by the U.S. Food and Drug Administration as a nonconventional process, therefore careful scrutiny and proof of safety must be provided before the process can be approved for commercial use. The units of pressure used in high-pressure processing are usually expressed in megapascals (MPa). Some reports expresses the pressure in Bars. A Bar is a technical atmosphere and is equivalent to 14.5 $lb_f/in^2$ (psi) or 0.1 MPa.

#### *9.4.4.1 High-Pressure Systems*

High-pressure systems may be classified as batch or continuous processes. The batch process is also known as "Isostatic High Pressure" or "High Hydrostatic Pressure" (HHP). The HHP system consists of a pressure vessel that holds the product to be treated; a pressure intensifier that raises the pressure of the pressurizing fluid to the target operating pressure and pumps this high pressure fluid into the processing vessel, a hydraulic pump to operate the intensifier, and appropriate controls for pressurization, temperature control, and depressurization. Because time for loading and sealing the pressure vessel then unsealing and unloading postprocess are all part of the batch cycle, reducing these elements of the batch cycle time are just as important as reducing the high-pressure exposure time




Pressure Intensifier a=low pressure fluid inlet; b=high pressure fluid exit; c=exit valve; d=inlet valve; e=piston; f = hydraulic fluid drive inlet and return



High hydrostatic pressure system.

**Figure 9.11** Pressure intensifier system for generating high pressure in high-pressure processing systems and photograph of a high hydrostatic pressure processing system. High hydrostatic pressure system reprinted from Food Technology. Used with permission.

itself. HHP pressure vessels are equipped with seals that easily engage and disengage to shorten the time for loading and unloading the pressure vessel. For large systems, a product carrier is used to enable loading and unloading a full load of product rapidly. Product treated by HHP may be prepackaged and may contain large particulate material. Water is usually used as the pressurizing fluid, hence the term "Hydrostatic." Because temperature is as important as pressure in effectively inactivating microorganisms, it is important that the system incorporate temperature monitors that can measure actual temperature inside a product within the pressure vessel.

A continuous high-pressure system can be used only on homogeneous liquids. The system consists of a feed pump, a pressure intensifier, a hydraulic system to operate the intensifier pistons, and a throttling device to reduce the pressure from high pressure to atmospheric pressure. Because the throttling device also generates extremely high shear rates on the fluid and because particle size reduction or homogenization also occur during depressurization, the continuous high-pressure system may be considered a "High-Pressure Homogenization" system. High-pressure piston type homogenizers have been used for this purpose in the past, but microbial reduction has been inadequate for successful pasteurization because of the pressure cycling inherent in piston-type pumps. Recent designs of continuous flow intensifiers incorporating two separate pistons operated with programmable logic controllers to time the cycling between the two pistons have greatly reduced the amplitude of pressure oscillation. Thus, a continuous flow high-pressure system can now be used for pasteurization of fluid food products.

Figure 9.11 shows a pressure intensifier system for continuous flow pasteurization of liquids and a HHP system. An important feature of a HHP system is ease of loading and unloading. In Fig. 9.11, the pressure chamber can be lowered and moved out of the cover to expose the chamber for loading and unloading. Pressure intensifiers have the same basic features whether used to directly pasteurize

fluids or used to generate the pressurizing fluid for a HHP processing vessel. The high-pressure intensifer consists of in-line dual cylinders where a drive piston is directly connected to the intensifier piston. The ratio of the area of the drive piston to that of the intensifier piston determines the pressure intensification. Standard hydraulic pumps that generate hydraulic fluid pressure of 20 MPa can be used to produce high-pressure fluid at 400 MPa if the drive and intensifer piston diameter ratio is 20:1. Each intensifier cylinder must have an inlet valve that opens to admit liquid into the intensifier and an exit valve that opens when the intensifier piston is discharging fluid at high pressure. The two valves alternately open and close, while the inlet valve is open the exit valve is closed and *vice versa*. The opening and closing of the valves are timed to the position of the drive piston. When the drive piston is at the apex of its forward travel, the exit valve closes and the inlet valve opens. The hydraulic fluid in the drive piston is released so that the drive piston is pushed back to the farthermost backward position by the pressure of the fluid entering the intensifier. At this point, the inlet valve closes and the exit valve opens and high pressure hydraulic fluid is fed into the drive piston, thus allowing the intensifier piston to advance to deliver the high pressure fluid. It is very important that the inlet and exit valves maintain positive closure when closed and that the timing of the opening and closing be properly set. A programmable logic controller may be used to control the timing of opening and closing of the valves, or a mechanical/pneumatic system may be used as a control system.

#### *9.4.4.2 High-Pressure Pasteurization*

Data in Table 9.9 can be used to determine the time and temperature needed for successful HHP pasteurization of food products. Microbial inactivation at high pressure has been shown to be first order and inactivation rate can be expresses as a D value as with thermal processes. Processes at 50°C will take less time than those at ambient temperature. Minimum pressure for inactivating microorganisms by HHP is 300 MPa. Increasing pressure to 700 MPa rapidly decreases the D value but a point of diminishing returns occur at pressures greater than 700 MPa. Microbial inactivation should be at least 5D for pathogenic microorganisns and 8D for spoilage microorganisms. Using this criteria, HHP processing of meat products at 500 MPa and 50°C will require 15 minutes to obtain 5D reduction of *Staphylococcus aureus*. *Staphylococcus aureus* in milk will require 12.5 minutes at 50°C and 500 MPa Orange juice will require 7.8 minutes at 500 MPa and 37°C while apple juice will require 2.3 minutes at 40°C and 450 MPa to obtain a 8 log reduction of *Saccharomyces cerevisiae*.

Microbial inactivation kinetics in continuous flow pasteurization does not follow the same trend as HHP. Hold time at high pressure prior to pressure reduction is only in the order of 0.5 seconds, yet substantial microbial inactivation results. Pressurizing to 242 MPa and releasing the pressure to 1 atm permits very rapid flow of fluid across the pressure reducing valve resulting in a breakdown of microbial cell walls killing the microorganisms. Continuous flow high-pressure pasteurization is very similar to the action of homogenizers to break down microbial cells to release cellular proteins. However, the constant pressure and controlled flow of fluid through the throttling valve results in the exposure of all suspended cells to the same high shear rates thus resulting in effective pasteurization. Cells of *Saccharomyces cerevisiae* in orange juice are reduced 8 log at 242 Mpa. Cells of *Listeria inocua* are reduced 5 log. Cells of *Lactobacillus sake* are reduced 5 log by this treatment. Orange juice processed by continuous flow pasteurization at 242 MPa retained the fresh-squeezed orange juice flavor and was stable both microbiologically and biochemically when stored for 90 days at 4°C. Temperature rise during continuous flow pasteurization must be minimized. Temperature increases instantaneously on reduction of pressure due to the conversion of potential energy at the high pressure into heat. Temperature rise is about 24°C/100 MPa pressure. To minimize exposure to high temperature, feed temperature should me kept at the lowest temperature above the freezing point and liquid must be

**Table 9.9** Resistance of microorganisms important in high pressure pasteurization processes

| *Organism* | *Substrate* | *D* | *P* | *T* | *Reference* |
|---|---|---|---|---|---|
| *Solid medium* | | | | | |
| Salmonella Enteritidis | meat | 3 | 450 | N/A | 1 |
| Salmonella Typhimurium | meat | 1.48 | 414 | 25 | 2 |
| | Meat | 0.6 | 345 | 50 | 3 |
| E coli | Meat | 2.5 | 400 | NA | 4 |
| S aureus | meat | 3 | 500 | 50 | 4 |
| l monocytogenes | meat | 2.17 | 414 | 25 | 2 |
| L monocytogenes | pork | 1.89–4.17 | 414 | 25 | 5 |
| L monocytogenes | pork | 0.37–0.63 | 414 | 50 | 3 |
| C. botulinum Type E (Beluga) | Crab meat | 3.38 | 758 | 35 | 6 |
| C. botulinum Type E (Alaska) | Crab meat | 1.76 | 827 | 35 | 6 |
| *Liquid medium* | | | | | |
| Salmonella Typhimurium | milk | 3.0 | 350 | N/A | 1 |
| E coli | Milk | 1.0 | 400 | 50 | 7 |
| E. coli 0157H7 | Milk | 3.0 | 400 | 50 | 4 |
| S aureus | Milk | 2.5 | 500 | 50 | 4 |
| L. monocytogenes | Milk | 3.0 | 375 | N/A | 1 |
| L. inocua | Eggs | 3.0 | 450 | 20 | 8 |
| C. botulinum Type E (Alaska) | Buffer | 2.64 | 827 | 35 | 6 |
| Saccharomyces cerevisiae | Orange Juice | 0.97 | 400 | 37 | 9 |
| Saccharomyces cerevisiae | Apple juice | 0.28 | 450 | 40 | 9 |

*References:* 1. Patterson ME, Quinn M, Simpson R, and Gilmour A. (1955) J. Food Prot. 58:524; 2. Ananth V, Dickson JS, Olson DG, and Murano EA (1998) J. Food Prot. 61:1649; 3. Kalchayanand N, Sikes A, Dunne CP, and Ray B. (1998) J. Food Prot. 61:425; 4. Patterson MF and Kilpatrick DJ. (1998) J. Food Prot. 61:432; 5. Murano EA, Murano PS, Brennan RE, Shenoy K and Moriera R. (1999). J. Food Prot. 62:480; 6. Reddy NR, Solomon HM, Fingerhut G, Balasubramanian VM, and Rodelhamel EJ. (1999) NCFST, Sumit-Argo, IL. 7. Gervilla R, Capellas M, Farragut V and Guamis B. (1997) J. Food Prot. 60:33; 8. Ponce E, Pla R, Mor-Mur M, Gervilla R and Guamis B. (1998) J. Food prot. 61:119; 9. Zook CD, Parish ME, Braddock RJ and Balaban MO. (1999) J. Food Sci. 64:533

cooled rapidly through a heat exchanger after exiting the throttling valve. This process is mild enough to permit the inactivation of 6 log of *Listeria inocua* in liquid whole eggs without coagulating the protein.

#### *9.4.4.3 High-Pressure Sterilization*

Because high pressure alone is inadequate to inactivate spores, it is necessary to raise the temperature during the high-pressure treatment to above 121.1°C. For HHP, the temperature rise that occurs with pressurization can be utilized to advantage in sterilization processes. Temperature rise on subjecting water to HHP range from 2.8°C to 4.4°C/100 Mpa pressure. The higher the initial temperature, the larger the temperature rise with increase in pressure. Foods with low density and specific heat

such as oils will have higher temperature rise than water, while most fluid foods that are high in moisture content such as fruit juices have similar temperature rise as water. A food product with a temperature rise of 3°C/100 Mpa pressure will exhibit a temperature rise of 21°C going from one atmosphere to 700 Mpa. Thus, if the product initial temperature prior to pressurization is 100°C, temperature after pressurization will be 121°C, a temperature that is lethal to spore-forming microorganisms. Of interest is inactivation of heat tolerant spores of *Clostridium botulinum*. Type 62A in pH 7 buffer at 75°C and 689 MPa has a D value of 10.59 minutes. Because sterilization will require at least 12D of *C. botulinum*, a 132-minute exposure time will be required. There are currently no data on high-pressure inactivation of spores at T > 108°C. An advantage of HHP sterilization is that upon release in pressure, the temperature instantaneously drops to the temperature at the start of pressurization. The same principles may be used in continuous flow sterilization. If a fluid is heated to 80°C while under pressure at 241 Mpa, release of that pressure to atmospheric pressure will result in a temperature rise of about 55°C resulting in an exit fluid temperature of 135°C after pressure release. At this temperature, the D value for *C. botulinum* is about 0.7 second, therefore a 9-second hold will be adequate to achieve 12D inactivation of *C. botulinum*.

Sterilization by high pressure is still not an approved process for low-acid products by U.S. regulatory agencies.

### 9.4.5 Sterilization of Fluids Containing Discreet Particulates

Discreet particulates within a flowing fluid will be heated by heat transfer from the suspending fluid. Thus, heat transfer coefficients between the particle and the fluid play a significant role in the rate of heating. Simplified equations for heat transfer will not be applicable because the fluid temperature is not constant as the mixture passes through the heater, and temperature of fluid in an unheated holding tube may not be constant because of heat exchange between the fluid and the suspended particles. Taking a conservative approach of ignoring the heat absorbed by the particles in the heaters can result in a significant over-processing, particularly if the suspended particles have less than 0.5 cm as the thickness of the dimension with the largest area for heat transfer. Finite element or finite difference methods for solving the heat transfer equations with appropriate substitutions for changes in the boundary conditions when they occur is the only correct method to determine the lethal effect of heat in the holding tube. Residence time distribution of particles must also be considered, and as in the case of fluids in turbulent flow, the use of a probability distribution function for the residence time in the finite difference or finite element methods will allow calculation of an integrated sterility.

A discussion of the finite difference methods for evaluating heat transfer is beyond the scope of this textbook.

## 9.5 STERILIZING VALUE OF PROCESSES EXPRESSED AS $F_0$

The sterilizing value of a process expressed as the number of decimal reduction of a specific biological entity has been discussed in the section "Selection of Inoculation Levels in Inoculated Packs." When comparing various processes for their lethal effect, it is sometimes more convenient to express the lethality as an equivalent time of processing at a reference temperature. The term, the $F_0$, is a reference process lethality expressed as an equivalent time of processing at 121.1°C calculated using a z value of 10°C (18°F). If the z value used in the determination of F is other than 10°C, the z value is indicated as a superscript, $F_0^z$.

For constant temperature processes, the $F_0$ is obtained by calculating L in Equation (9.21), and multiplying L by the heating time at T. $F_0 = L\ t$.

For processes where product is subjected to a changing temperature, such as the heating or cooling stage in a canning process, a lethality is calculated over the length of the process . The process is separated into small time increments, $\Delta t$. The average temperature at each time increment is used to calculate L using Equation (9.21). The $F_0$ will be $3L_T\Delta t$. The z value of Eused in Equation (9.21) to calculate L is 10 °C to determine $F_o$. If the $F_0$ value is to be used later to express lethality as the number of decimal reduction of a particular biological entity, the appropriate z value for that entity has to be used to calculate $F_0^z$.

## 9.6 THERMAL PROCESS CALCULATIONS FOR CANNED FOODS

When sterilizing foods contained in sealed containers, the internal temperature changes with time of heating. Lethality of the heating process may be calculated using the "general method," which is a graphical integration of the lethality-time curve, or by "formula methods," which utilize previously calculated tabular values of parameters in an equation for the required process time or process lethality. Problems in thermal process calculation can either be (I) the determination of process time and temperature to achieve a designed lethality or (II) the evaluation of a process time and temperature. These are referred to by some authors as Type I or Type II problems. Fundamental in the evaluation of thermal process schedules is heat transfer data, an equation or experimental data for temperature in the container as a function of time. Lethality may be expressed as the value achieved in a single point (i.e., the slowest heating point in the container) or it may be expressed as an integrated lethality. For microbial inactivation, where microbial numbers are nil at regions within the container nearest the wall, lethality at a single point is adequate and results in the safest process schedule, or a most conservative estimate of the probability of spoilage. However, when evaluating quality factor degradation, an integrated lethality must be determined because a finite level of the factor in question exists at all points in the container.

### 9.6.1 The General Method

Process lethality is calculated by graphical integration of the lethality value (Equation 9.21) using time-temperature data for the process.

$$F_0{}^z = \int_0^t L_t dt$$

Equation (9.14) may also be used to determine process lethality. However, because D is not constant, the sterilizing value expressed as the number of decimal reductions of microorganisms will be integrated over the process time, using the value of D at various temperatures in the process.

$$S = \int_0^t \frac{dt}{D_t}$$

If a process schedule is to be determined, the heating and cooling curves are used to determine the lethality curve, which is then graphically integrated to obtain either $F_0$ or S. The process lethality must

equal the specified values for $F_0$ or S for the process to be adequate. If the lethality value differs from the specified, the heating time is scaled back, a cooling curve parallel to the original is drawn from the scaled back heating time, and the area is recalculated. The process is repeated until the specified and calculated values matches. Evaluation of the process lethality is done directly on the time-temperature data. Simpson's rule may be used for integration. From the section "Graphical Integration (Chapter 1 Section 1.15)" Simpson's rule is applied to thermal process determination by the general method as follows: Select time increments $\delta t$ such that at the end of process time t, $t/\delta t$ will be an even number. Using i as the increment index, with $I = 0$ at $t = 0$, $I = 1$ at $t = \delta t$, $i = 2$ at $t = 2\ \delta t$; $i = 3$ at $t = 3\delta t \ldots$ and so forth.

$$A = \left(\frac{\delta t}{3}\right)[L_0 + 4L_1 + 2L_2 + +4L_3 + 2L_4 + \ldots\ldots 2L_{i-2} + 4L_{i-1} + L_t]$$

The area under the cooling curve may be evaluated separately from that under the heating curve.

**Example 9.16.** The following data represent the temperature at the slowest heating point in a canned food processed at a retort temperature of 250°F. Calculate the $F_0$ value for this process. What will be the required process time to have a lethality equal to an $F_0$ of 9 minutes.

| *Time (min)* | *Temp. (°F)* | *Time (min)* | *Temp. (°F)* |
|---|---|---|---|
| 0 | 140 | 55 | 238 |
| 5 | 140 | 60 | 241 |
| 10 | 140 | 65 | 235 |
| 15 | 140 | 70 | 245 |
| 20 | 163 | 75 | 246.3 |
| 25 | 185 | 80 | 247.3 (cool) |
| 30 | 201 | 85 | 247.0 |
| 35 | 213 | 90 | 245.2 |
| 40 | 224 | 95 | 223.5 |
| 45 | 229.4 | 100 | 175 |
| 50 | 234.5 | 105 | 153 |

**Solution:**

From $t = 0$ to $t = 80$ minutes, $\delta t = 5$ minutes will give 16 increments. L is calculated using Equation (9.21). $T_0 = 250°F$. The values of the lethality are as follows:

$$L_0 = 10^{-0.05555(110)} = 0 = L_1 = L_2 = L_3$$
$$L_4 = 10^{-0.05555(87)} = 1.5 \times 10^{-5}$$
$$L_5 = 10^{-0.05555(65)} = 2.45 \times 10^{-4}$$
$$L_6 = 10^{-0.05555(54)} = 0.001001$$
$$L_7 = 10^{-0.05555(32)} = 0.016688$$
$$L_8 = 10^{-0.05555(26)} = 0.035938$$
$$L_9 = 10^{-0.05555(20.6)} = 0.071725$$
$$L_{10} = 10^{-0.05555(15.5)} = 0.1377$$
$$L_{11} = 10^{-0.05555(12)} = 0.2155$$

$L_{12} = 10^{-0.05555(9)} = 0.3163$
$L_{13} = 10^{-0.05555(6.5)} = 0.4354$
$L_{14} = 10^{-0.05555(5)} = 0.5275$
$L_{15} = 10^{-0.05555(3.7)} = 0.6229$
$L_{16} = 10^{-0.05555(2.7)} = 0.7079$

The area under the heating curve will be

$$4(L_1 + L_3 + L_5 + L_7 + L_9 + L_{11} + L_{13} + L_{15}) = 5.4498$$
$$2(L_2 + L_4 + L_6 + L_8 + L_{10} + L_{12} + L_{14}) = 2.0363$$
$$A = (5/3)(0 + 5.4498 + 2.0363 + 0.7079) = 13.57$$

The area under the cooling curve will be

$L_0 = 10^{-0.05555(2.7)} = 0.70797$
$L_1 = 10^{-0.05555(3)} = 0.61829$
$L_2 = 10^{-0.05555(4.8)} = 0.54187$
$L_3 = 10^{-0.05555(26.5)} = 0.03371$
$L_4 = 10^{-0.05555(75)} = 0$
$L_5 = 0$
$4(L_1 + L_3 + L_5) = 2.8600$
$2(L_2 + L_4 + L_6) = 1.08374$
$A = (5/3)(0.70797 + 2.8600 + 1.0837 + 0) = 7.753$
Total area $= 13.57 + 7.753 = 21.32$

The cooling curve contributed about one-third of the total lethality in this example.

The calculated total lethality is much higher than the specified $F_0$ of 9 minutes. Thus, it will be necessary to reduce the heating time. Reduction of heating time will result in a reduction of the can temperature prior to cooling. Let the heating time be equal to 60 minutes. There are now only 12 area increments. The can temperature at 60 minutes of heating is 241°F. The cooling curve will start at 241°F. The cooling temperature will be parallel to the cooling curve of the original process (Fig. 9.12). Using Simpson's rule on the new heating and cooling curve, Table 9.10 may be constructed.

The area under the heating curve is $(1.17479 + 0.35019 + 0.316228)(5/3) = 1.8420(5/3) = 3.07$.

The area under the cooling curve is $(1.114881 + 0.430887 + 0.316228)\ (5/3) = 1.96199(5/3) = 3.27$.

The total area $= F_o = 6.3$.

Ten more minutes of heating will add approximately 3 minutes to the $F_0$ because one minute of heating at 241°F is equivalent to 0.31 minutes at 250°F. Thus the heating time will be 70 minutes to give an $F_0$ of approximately 9 minutes.

This example underscores the importance of the contribution of the cooling part of the process to the total lethal value of the process. The relative contribution of the cooling curve to total lethality increases when product characteristics or processing conditions result in a slow rate of cooling.

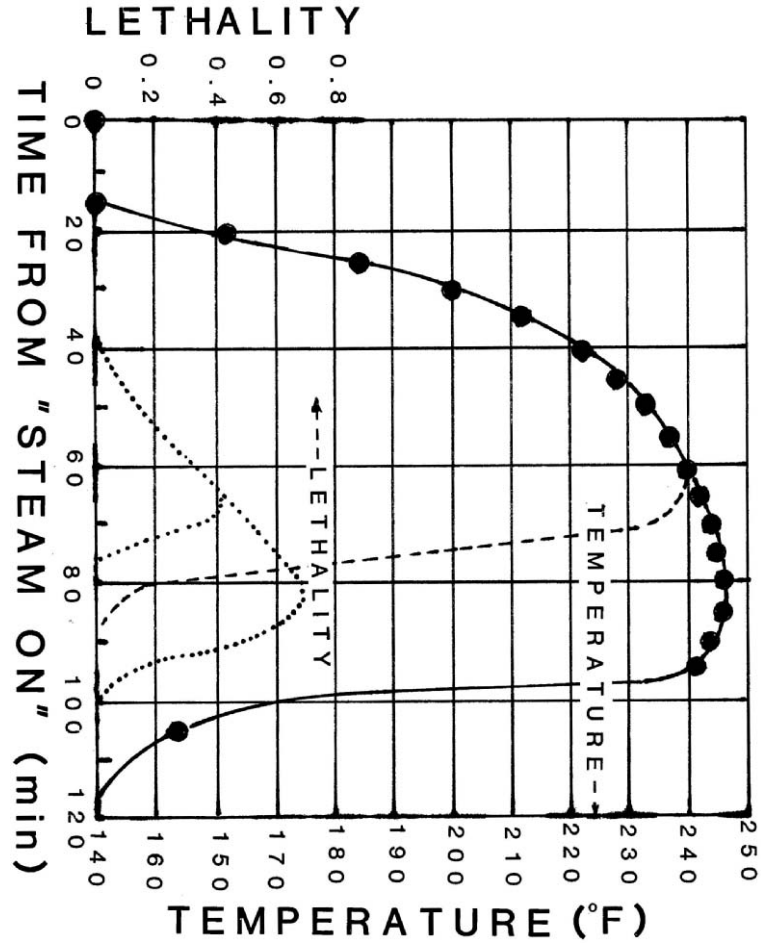



**Figure 9.12** Graph showing retort temperature, lethality of the heat treatment, and the procedure for adjusting the processing time to obtain the specified process lethality.

### 9.6.2 Heat Transfer Equations and Time-Temperature Curves for Canned Foods

In the section "Heating of Solids Having Infinite Thermal Conductivity" Chapter 7 (Section 7.6.1), the transient temperature of a solid having an infinite thermal conductivity was derived. Equation (7.84) in Section 7.6.1 may be used to represent the temperature at a single point in a container. If the point considered is at the interior of the container, a time lag will exist from the start of heating to the time temperature at that point actually changes. The following symbols are used for thermal process heat penetration parameters.

I = initial temperature difference = $(T_r - T_0)$; $T_r$ = heating medium temperature = retort temperature; $T_0$ = can temperature at the start of the heating process.

g = unaccomplished temperature difference at the end of a specified heating time = $(T_r - T)$; T = temperature at the point considered at any time, t, during the heating process.

**Table 9.10** Lethality of a Process Calculated Using the General Method and Simpson's Rule for Graphical Integration

| *Time (min)* | *Temp (°F)* | *L* | *4L* | *2L* | *L* |
|---|---|---|---|---|---|
| 0 | 140 | 0 | — | — | 0 |
| 5 | 140 | 0 | 0 | — | — |
| 10 | 140 | 0 | — | 0 | — |
| 15 | 140 | 0 | 0 | — | — |
| 20 | 163 | 0 | — | 0 | — |
| 25 | 185 | 0.000245 | 0.000980 | — | — |
| 30 | 201 | 0.001896 | — | 0.003791 | — |
| 35 | 213 | 0.008799 | 0.035214 | — | — |
| 40 | 244 | 0.035938 | — | 0.071858 | — |
| 45 | 229.4 | 0.071706 | 0.286824 | — | — |
| 50 | 234.5 | 0.137686 | — | 0.275371 | — |
| 55 | 238 | 0.215443 | 0.861774 | — | — |
| 60 | 241 | 0.316228 | — | — | 0.316228 |
| Sum | | | 1.17479 | 0.351019 | 0.316228 |
| 60 | 241 | 0.316228 | — | — | 0.316228 |
| 65 | 240 | 0.278256 | 1.113024 | — | — |
| 70 | 238 | 0.215443 | — | 0.430887 | — |
| 75 | 190 | 0.000464 | 0.001857 | — | — |
| 80 | 149 | 0.052079 | — | 0 | — |
| 85 | 142 | 0 | 0 | — | — |
| 90 | 140 | 0 | — | — | 0 |
| Sum | | | 1.114881 | 0.430887 | 0.316228 |

j = lag factor, also known as the intercept index for the linear semi-logarithmic temperature versus time plot of the heating curve. jh refers to the heating curve and jc refers to the cooling curve.

f = the slope index of the linear semi-logarithmic temperature versus time plot of the heating curve. If the heating curve consists of n line segments, $f_i$(i = 1 to n) is used to represent the slope index of each line segment with 1 representing the first line segment from the start of the heating process. fc refers to the cooling curve.

Expressing Equation (7.84), Chapter 7, in terms of the above parameters:

$$\log\left(\frac{g}{jI}\right) = -\frac{t}{f_h} \tag{9.33}$$

$$\log\left(\frac{(T_r - T)}{jI}\right) = -\frac{t}{f_h} \tag{9.34}$$

$$\log(T_r - T) = \log(jI) - \frac{t}{f_h} \tag{9.35}$$

$$T = T_r - jI[10]^{-t/f_h} \tag{9.36}$$

Equation (9.35) shows that a semi-log plot of the unaccomplished temperature difference $(T_r - T)$ against time will have a slope of $-1/f_h$ and an intercept of log (jI). The latter is the reason that j is

called the intercept index. j is also called the lag factor because the higher the value of j the longer it will take for the temperature at the point being monitored, to respond to a sudden change in the heating medium temperature.

The cooling curve expressed in a form similar to Equation (9.35) with $T_c$ as the cooling water temperature is:

$$\log(T - T_c) = \log(j_c I_c) - \frac{t_c}{f_c} \tag{9.37}$$

where $I_c = (T_g - T_c)$; $T_g =$ temperature at the end of the heating process $= (T_r - g)$.

Equation (9.37) shows that a semi-logarithmic plot of $\log(T - T_c)$ versus time $t_c$ (with $t_c = 0$ at the start of cooling) will be linear and the slope will be $-1/f_c$. The temperature at any time during the cooling process, is

$$T = T_c + j_c I_c [10]^{-t_c/f_c} \tag{9.38}$$

Equation (9.38) represents only part of the cooling curve, and is not the critical part that contributes significantly to the total lethality. The initial segment just after the introduction of cooling water is nonlinear and accounts for most of the lethality contributed by the cooling curve. Thus, a mathematical expression which correctly fits the curved segment of the temperature change on cooling will be essential to accurate prediction of the total process lethality.

The initial curved segment of cooling curves has been represented as hyperbolic, circular, and trigonometric functions. A key parameter in any case, is the intersection of the curved and linear segments of the cooling curve. The linear segment represented by Equation (9.38) can be easily constructed from $f_c$ and $j_c$ and temperature at any time within this segment can be calculated easily using Equation (9.38) from the point of intersection of the curved and linear segments. Hayakawa (Food Technol. 24:1407, 1970) discussed the construction of the curved segment of the cooling curve using a trigonometric function. The equations which are valid for for $1 \leq j_c \leq 3$ are

$$T = T_c + [T_g - T_c]^{\cos(Bt_c)} \tag{9.39}$$

$$B = \frac{1}{t_L}\left[\arccos\left[\frac{\log(j_c I_c) - t_L/f_c}{\log(I_c)}\right]\right] \tag{9.40}$$

The cosine function in Equation (9.39) uses the value of the angle in radians as the function argument. The arccos function in Equation (9.40) returns the value of the angle in radians.

$t_L$ is the time when the curved and linear segments of the cooling curve intersect. $t_L$ may be derived from the intersection of a horizontal line drawn from the temperature at the initiation of cooling and the linear segment of the cooling curve represented by Equation (9.38). At the intersection, $(T - T_c) = I_c$, and $t_c = t_L$. Substituting in Equation (9.38), solving for $t_L$ and introducing a factor k to compensate for the curvature in the cooling curve:

$$t_L = f_c \log\left(\frac{j_c}{k}\right) \tag{9.41}$$

The factor k in Equation (9.41) may be determined from the actual cooling curves, when plotting heat penetration data. $k = 0.95$ has been observed to be common in experimental cooling curves for canned foods. Equation (9.41) represents cooling data for canned foods better than the equation for $t_L$ originally given by Hayakawa (1970).

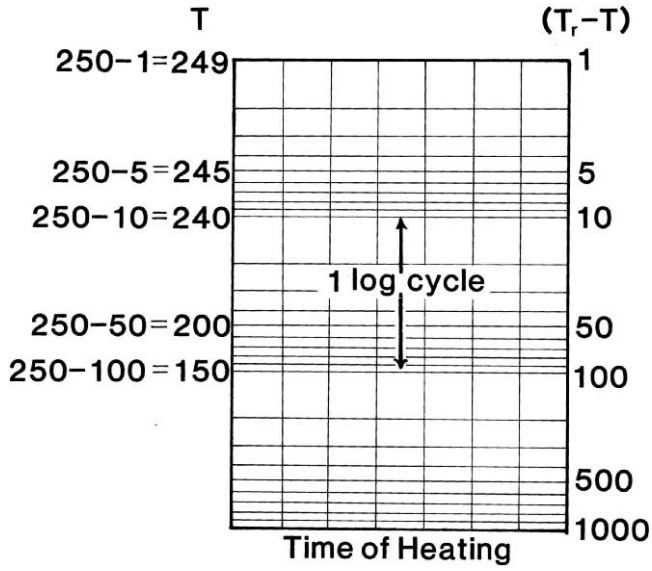



**Figure 9.13** Diagram showing how the axis of semi-logarithmic graphing paper is marked for plotting heat penetration data. Retort temperature = 250°F.

### 9.6.3 Plotting Heat Penetration Data

Raw time-temperature data may be plotted directly on semi-log graphing paper to produce the linear plot needed to determine $f_h$ and j, by rotating the paper 180 degrees. The numbers on the graph that mark the logarithmic scale are marked as $(T_r - T)$ and the can temperature is marked on the opposite side of the graphing paper. Figures 9.13 and 9.14 show how the can temperature is marked on 3-cycle semi-log graphing paper for retort temperature of 250°F and 240°F, respectively.

#### *9.6.3.1 Determination of $f_h$ and j*

Can temperature is plotted on the modified graphing paper and a straight line is drawn connecting as much of the experimental data points as possible. There will be an initial curvature in the curve, but the straight line is drawn all the way to t = 0.

In any simulator used for heat penetration data collection, the retort temperature does not immediately reach the designated processing temperature. The time from introduction of steam to when processing temperature ($T_r$) is reached is the retort come-up time, $t_{come\text{-}up}$. Sixty percent of the retort come-up time is assumed to have no heating value, therefore heating starts from a pseudo-initial time $t_{pi}$ which is $0.6t_{come\text{-}up}$. The pseudo-initial temperature, $T_{pi}$, is the intersection of the line drawn through the points and the line representing $t = t_{pi}$. $(T_r - T_{pi}) = jI$. The intercept index, j, is

$$j = \frac{T_r - T_{pi}}{T_r - T_0} = \frac{jI}{I} \tag{9.42}$$

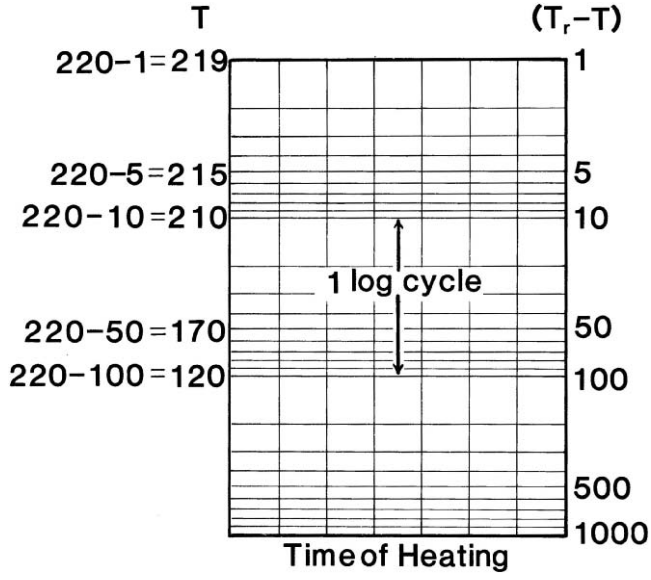



**Figure 9.14** Diagram showing how the axis of semi-logarithmic graphing paper is marked for plotting heat penetration data. Retort temperature = 220°F.

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The slope index, $f_h$, is the time for the linear section of the heating curve to traverse one log cycle on the graph.

#### *9.6.3.2 Determination of $f_c$ and $j_c$*

Using 180-degree rotated semi-log graphing paper, the cooling curve is plotted on the paper with the marked side labeled $(T - T_c)$ and the opposite side labeled the can temperature, T. The abscissa is the cooling time, $t_c$. At $t_c = 0$, steam is shut off and cooling water is introduced. The retort is assumed to reach cooling water temperature immediately, therefore the intercept of the cooling curve is evaluated at $t_c = 0$. $j_c I_c$ is the intercept of the line drawn between the data points and $t_c = 0$. $f_c$ is the slope index of the cooling curve and is the time for the linear section of the curve to traverse one log cycle. If the cooling data does not complete one log cycle within the graph, $f_c$ may be evaluated as the negative reciprocal of the slope of the line. Let $(T_1 - T_c)$ and $(T_2 - T_c)$ represent the unaccomplished temperature difference at $t_{c1}$ and $t_{c2}$, respectively:

$$f_c = -\frac{t_{c1} - t_{c2}}{\log(T_1 - T_c) - \log(T_2 - T_c)} \tag{9.43}$$

**Example 9.17.** Determine the heat penetration parameters, j, $f_h$, $j_c$, $f_c$ for a canned food that exhibited the following heating data when processed in a retort at 250°F. It took 3 minutes from introduction of steam to the time retort reached 250°F. Cooling water temperature is 60°F.

| Time (min) | Temp. (°F) | Time (min) | Temp. (°F) |
|---|---|---|---|
| 0 | 180 | 30 | 245 |
| 5 | 190 | 30 (cool) | 245 |
| 10 | 210 | 35 | 235 |
| 15 | 225 | 40 | 175 |
| 20 | 235 | 45 | 130 |
| 25 | 241 | 50 | 101 |

Calculate the temperature at various times during heating and cooling of this product processed at $T_r = 251°F$ if $T_0 = 160°F$, and t = 35 minutes from steam introduction. $T_c = 70°F$. Retort come-up time = 3 minutes. Calculate the $F_o$ of this process using the general method and Simpson's rule for graphical integration of the lethality.

**Solution:**

The heating and cooling curves are plotted in Figures 9.15 and 9.16. The value for $f_h = 22$ minutes and how it is determined is shown in Fig. 9.14. $T_{pi} = 152$ minutes is read from the intersection of the line through the data points and $t_{pi} = 0.6t_{come\text{-}up} = 1.8$ minutes. jI can be read by projecting the intersection to the axis labeled $(T_r - T)$. $jI = 98°F$, or by subtracting $T_{pi}$ from $T_r$. $I = (T_r - T_0) = 250 - 180 = 70°F$. $j = 98/70 = 1.40$.

The cooling curve is shown in Fig. 9.16. The intercept of the linear portion of the curve with $t_c = 0$ is projected to the side marked $(T - T_c)$ and $j_cI_c$ is read to be 333°F. The initial temperature difference for cooling, $I_c = 245 - 60 = 185°F$. Thus $j_c = j_cI_c/I_c = 333/185 = 1.8$. The slope index for the cooling curve is calculated from the points $(t_c = 0; (T - T_c) = 333)$ and $(t_c = 20; (T - T_c) = 41)$.

$$f_c = -\frac{0 - 20}{\log(333) - \log(41)} = 22\,\text{min}$$

The curved section of the cooling curve intersects the linear section at $t_c = 6$ minutes. Thus, $t_L = 6$ minutes, and for this cooling curve, k in Equation (9.41) is

$$k = \frac{j_c}{[10]^{t_L/f_c}} = \frac{1.8}{[10]^{6/22}} = 0.96$$

The temperature during heating and cooling at the same point within a similar-sized container can be determined for any retort temperature, initial can temperature, or cooling water temperature once the heating and cooling curve parameters are known. Equation (9.36) is used to determine the temperature during heating. The initial heating period is assumed to be constant at $T_0$ until calculated values for T exceeds $T_0$. This assumption dose not introduce any errors in the calculation of the lethality of heat received, since at this low temperature lethality is negligible. Exceptions are rare and apply to cases where a very high initial temperature exists.

As previously discussed, when heating is carried out under conditions where a come-up time exists, the first 60% of the come-up time is assumed to have no heating value; therefore, the time variable in Equation (9.36) should be zero when $t = t_{come\text{-}up}$. If t used in Equation (9.36) is based on the time after "steam on," then 60% of $t_{come\text{-}up}$ must be subtracted from it when used in Equation (9.36).

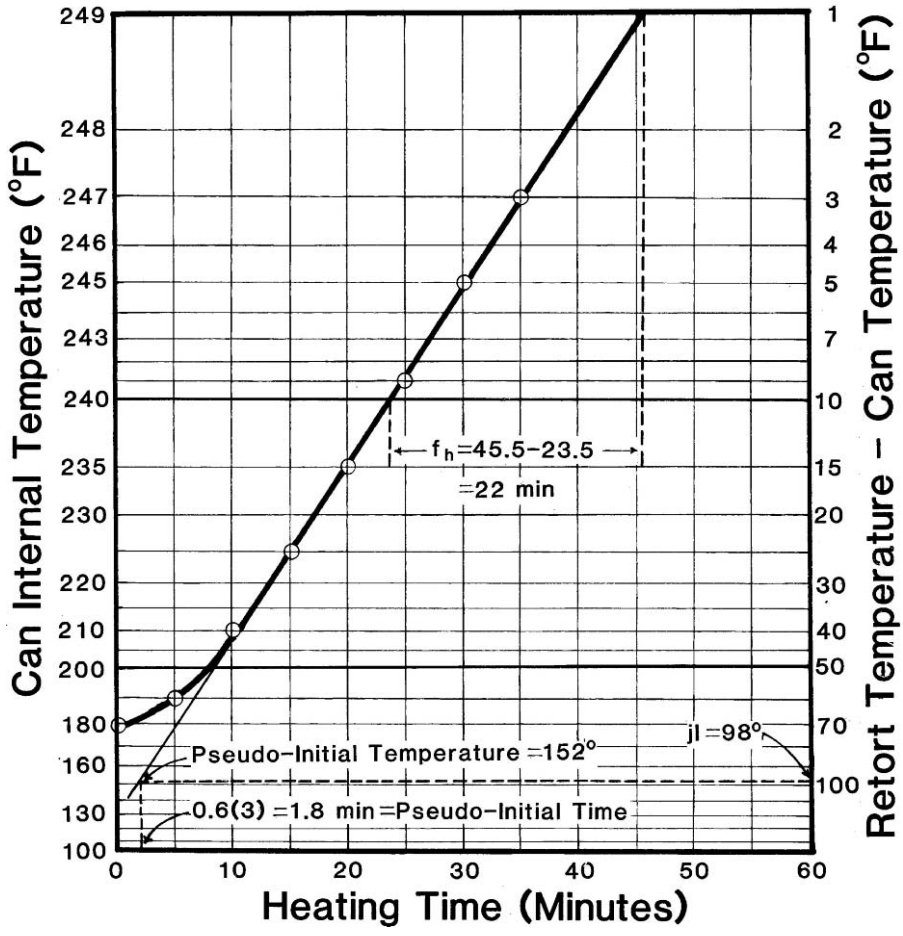


**Figure 9.15** A plot of the heating curve showing how the heating curve parameters $f_h$ and j are determined.

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Let the exponential term in Equation (9.36) = A.

$$A = 10^{-\{[t-0.6(3)]/fh\}} = 10^{-[(t-1.8)/22]}$$

$$T = Tr - jIA = 251 - 1.4(251 - 160)A$$

Calculated temperatures are shown in Table 9.11.

During cooling, the curved portion of the cooling curve is constructed with the temperatures calculated using Equations (9.39), (9.40), and (9.41). The time when the linear and curved portions of the cooling curve intersect is calculated using Equation (9.39) and the previously calculated value of k of 0.96.

$$t_L = 22 \log\left(\frac{1.8}{0.96}\right) = 6.1 \text{ min}$$

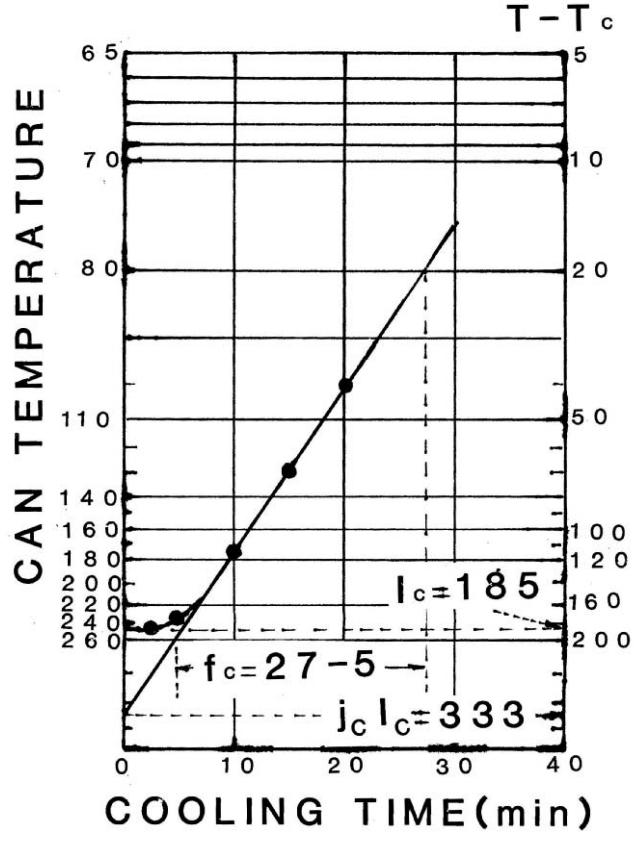


**Figure 9.16** A plot of the cooling curve showing how the cooling curve parameters $f_c$ and $j_c$ are obtained.

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Solving for parameter B in Equation (9.38):

$$B = \frac{1}{6.1}\left[\arccos\left[\frac{\ln(1.8)(174.3) - (6.1/22)}{\ln(174.3)}\right]\right]$$

$$= \frac{1}{6.1}\arccos(0.99018) = \frac{1}{6.1}\left[(8.034^\circ)\left[\frac{2\pi \text{ rad}}{360^\circ}\right]\right] = 0.02337$$

The temperature is then calculated using Equation (9.39):

$$T = 70 + (174.3)^{\cos[(0.02337)(tc)]}$$

Let: $E = \cos[(0.0296)(t_c)]$;

$$T = 70 + (174.3)^{E}$$

For the linear portion of the cooling curve, Equation (9.38) is used. The temperature calculated using Equation (9.30) will represent the actual can temperature only when $t_c > t_L$ because $t_L$ is the

**Table 9.11** Time and temperature during heating for Example 9.17

| *Time (min)* | *A* | $T_r - jla$ | *Temp (°F)* |
|---|---|---|---|
| 0 | 1.207 | (97) | 160 |
| 2 | 0.979 | (126) | 160 |
| 4 | 0.794 | (150) | 160 |
| 6 | 0.644 | 168 | 168 |
| 8 | 0.522 | 184 | 184 |
| 10 | 0.423 | 197 | 197 |
| 12 | 0.344 | 207 | 207 |
| 14 | 0.279 | 215.5 | 215.5 |
| 16 | 0.226 | 222 | 222 |
| 18 | 0.184 | 227.6 | 227.6 |
| 20 | 0.149 | 232 | 232 |
| 22 | 0.121 | 235.6 | 235.6 |
| 24 | 0.098 | 238.5 | 238.5 |
| 26 | 0.079 | 241.6 | 241.6 |
| 28 | 0.064 | 242.8 | 242.8 |
| 30 | 0.052 | 244.3 | 244.3 |

intersection of the curved and linear portions of the cooling curve.

Equation (9.38): $T = 70 + 1.8(174.3)(10)^{(-tc/22)}$

Let $A = 10^{(-tc/22)}$; $\quad T = 70 + (313.74)^A$

The calculated temperatures for cooling, and the lethality and area elements for area calculation using Simpson's rule, are shown in Tables 9.12 and 9.13, respectively.

$\text{Area} = F_0 = (2/3)(1.7904 + 5.5823 + 0.9698) = 5.6$ minutes

**Table 9.12** Time and temperature during cooling for Example 9.17

| | | | *(Temp °F)* | |
|---|---|---|---|---|
| *Time ($t_c$)* | *E* | *A* | $70 + 174.3^E$ | $70 + (313.74)^A$ |
| 0 | 1 | 1 | 244.3 | (383.7) |
| 2 | 0.998 | 0.811 | 243.3 | (324.5) |
| 4 | 0.993 | 0.658 | 240.4 | (276.4) |
| 6 | 0.984 | 0.534 | 235.7 | (237.3) |
| 8 | | 0.433 | | 199.4 |
| 10 | | 0.351 | | 180.2 |
| 12 | | 0.285 | | 159.4 |
| 14 | | 0.231 | | 142.5 |
| 16 | | 0.187 | | 128.8 |

**Table 9.13** Time, temperature, and Simpson's Rule factors for area calculations for Example 9.17

| *Time (min)* | *Temp (°F)* | *L* | *2L* | *4L* | *L* |
|---|---|---|---|---|---|
| Heating | | | | | |
| 0 | 160 | 0 | | | |
| 2 | 160 | 0 | | | 0 |
| 4 | 160 | 0 | | 0 | |
| 6 | 169 | 0 | 0 | | |
| 8 | 184 | 0.0002 | | 0.0008 | |
| 10 | 197 | 0.0011 | 0.0022 | | |
| 12 | 207 | 0.0042 | | 0.0168 | |
| 14 | 215.5 | 0.0121 | 0.0242 | | |
| 16 | 222.2 | 0.0284 | | 0.1136 | |
| 18 | 227.6 | 0.0571 | 0.114 | | |
| 20 | 232 | 0.1005 | | 0.402 | |
| 22 | 235.6 | 0.1588 | 0.3177 | | |
| 24 | 238.5 | 0.2304 | | 0.9215 | |
| 26 | 241.8 | 0.3414 | 0.6829 | | |
| 28 | 242.8 | 0.3977 | | 1.5908 | |
| 30 | 244.3 | 0.4899 | | | 0.4849 |
| Cooling | | | | | |
| 0 | 244.3 | 0.4849 | | | 0.4849 |
| 2 | 243.3 | 0.4244 | | 1.6976 | |
| 4 | 240.4 | 0.2929 | 0.5858 | | |
| 6 | 235.7 | 0.1605 | | 0.6421 | |
| 8 | 199 | 0.0015 | 0.0030 | | |
| 10 | 180 | 0.0001 | | 0.0004 | |
| 12 | 159 | 0 | 0 | | |
| 14 | 142 | 0 | | 0 | |
| 16 | 129 | 0 | | | 0 |
| Sums | | | 1.7297 | 5.3866 | 0.9698 |

The lethality of the process expressed as an equivalent heating time at 250°F is 5.3 minutes. The complete procedure used in the evaluation of the lethality of a heating process in this example is the general method. The general method may be used on data obtained experimentally or on time-temperature data reconstructed from values of heating and cooling curve parameters calculated from experimental data.

Use of a spreadsheet will greatly facilitate thermal process calculations using the general method. Time increments used in the lethality calculations can be made very small to increase the accuracy of calculated process lethality.

### 9.6.4 Formula Methods for Thermal Process Evaluation

Formula methods are based on tabulated values for lethality expressed as the parameter $f_h/U$, which have been previously calculated for various conditions of heating and cooling when unaccomplished temperature difference is expressed as the parameter "g." Two methods will be presented in this section:

Stumbo's (1973) and Hayakawa's (1970). The purpose of presenting both methods is not to compare their accuracy but to provide a means for selecting the most convenient method to use for certain conditions.

Stumbo's $f_h/U$ versus g tables combine lethalities of both heating and cooling. A major assumption used in the calculation of lethality is that $f_h = f_c$. When actual conditions do not meet this assumption, Stumbo recommends using the general method. Hayakawa (1970) presented lethality of the heating and cooling stages in the process in separate tables thus allowing the use of his method even under different rates for heating and cooling. Hayakawa's tabular values allow substitutions for different values of z, simplifying calculation of specific $F_0^z$ values for different z.

In this section, process calculations for products that exhibit simple heating curves will be discussed. Calculations for broken heating curves will be discussed in the section "Broken Heating Curves."

Both formula methods are based on the equation for the heating curve (Eq. 9.33). Let g = unaccomplished temperature difference, $(T_r - T)$ at the termination of the heating period; and $B_b$ = the heating time at that point. $B_b$ is the scheduled sterilization process. For products with simple heating curve, Equation (9.33) becomes:

$$B_b = f_h[\log(jI) - \log(g)] \tag{9.44}$$

$B_b = t - 0.6t_{come\text{-}up}$. t is time evaluated from steam introduction into the retort. In practice, $B_b$ is timed from the point where the retort temperature reaches the processing temperature to avoid the probability of errors arising from the operator having to correct for the come-up time.

g is obtained from the tables, using a specified $F_0$ and z value. Stumbo's tables are simpler to use for thermal process determinations. Hayakawa's tables will require an iterative procedure involving an assumption of the value of g, calculating the $F_0$, and calculations are repeated until the calculated matches the specified $F_0$.

The following parameters are used in the formula methods:

$$F_i = [10]^{250-T/z} \tag{9.45}$$

$U = F_0F_i$ = time at $T_r$ equivalent to $F_0$.

#### *9.6.4.1 Stumbo's Procedure*

Stumbo's tabulated $f_h/U$ versus g with $j_c$ as a parameter. $j_c$ strongly influences the contribution of the cooling part of the process to the total lethality as discussed in the section "Sterilizing Value of Processes Expressed as $F_0$." In general, $j_c$ values are higher than j. In the absence of $j_c$, j may be used and the error will be toward a longer process time or the safe side relative to spoilage. Condensed $f_h/U$ versus g tables for z values from 14 to 22 and for z from 30 to 45 are shown in Tables 9.14 and 9.15. Table 9.14 is used for microbial inactivation and Table 9.15 is used for nutrient degradation. It is possible to interpolate between values in the table for other z values. Thermal process determinations can easily be made from specified $F_0$ values and product heat penetration parameters by solving for $f_h/U$ determining the corresponding value for g and solving for $B_b$ using Equation (9.44).

#### *9.6.4.2 Hayakawa's Procedure*

Hayakawa's tables are shown in Table 9.16 for lethality of the heating part of the process and in Tables 9.17, 9.18, 9.19, 9.20, and 9.21 for lethality of the cooling part of the process. The tables are based on a z value of 20°F. The parameter $g/K_s$ with $K_s$ defined as $K_s = z/20$ is tabulated against $U/f_h$. The latter is the reciprocal of Stumbo's $f_h/U$.

**Table 9.14** $f_h$/U vs. g Table Used for Thermal Process Calculations by Stumbo's Procedure

| $f_h/U$ | $z=14$ | $\Delta g/\Delta j$ | $z=18$ | $\Delta g/\Delta j$ | $z=22$ | $\Delta g/\Delta j$ |
|---|---|---|---|---|---|---|
| **0.2** | **0.000091** | **0.0000118** | **0.0000509** | **0.0000168** | **0.0000616** | **0.0000226** |
| **0.3** | **0.00175** | **0.00059** | **0.0024** | **0.00066** | **0.00282** | **0.00106** |
| **0.4** | **0.0122** | **0.0038** | **0.0162** | **0.0047** | **0.020** | **0.0067** |
| **0.5** | **0.0396** | **0.0111** | **0.0506** | **0.0159** | **0.065** | **0.0197** |
| **0.6** | **0.0876** | **0.0224** | **0.109** | **0.036** | **0.143** | **0.040** |
| **0.7** | **0.155** | **0.036** | **0.189** | **0.066** | **0.25** | **0.069** |
| **0.8** | **0.238** | **0.053** | **0.287** | **0.103** | **0.38** | **0.105** |
| **0.9** | **0.334** | **0.07** | **0.400** | **0.145** | **0.527** | **0.147** |
| **1.0** | **0.438** | **0.009** | **0.523** | **0.192** | **0.685** | **0.196** |
| **2.0** | **1.56** | **0.37** | **1.93** | **0.68** | **2.41** | **0.83** |
| **3.0** | **2.53** | **0.70** | **3.26** | **1.05** | 3.98 | **1.44** |
| **4.0** | **3.33** | **1.03** | **4.41** | **1.34** | 5.33 | 1.97 |
| 5.0 | **4.02** | **1.32** | **5.40** | **1.59** | **6.51** | **2.39** |
| **6.0** | **4.63** | **1.56** | **6.25** | **1.82** | **7.53** | **2.75** |
| **7.0** | **5.17** | **1.77** | **7.00** | 2.05 | 8.44 | **3.06** |
| **8.0** | **5.67** | **1.95** | **7.66** | 2.27 | 9.26 | **3.32** |
| **9.0** | **6.13** | **2.09** | **8.25** | **2.48** | **10.00** | **3.55** |
| **10** | **6.55** | **2.22** | **8.78** | **2.69** | **10.67** | **3.77** |
| **15** | **8.29** | **2.68** | **10.88** | **3.57** | **13.40** | **4.60** |
| **20** | **9.63** | **2.96** | **12.40** | **4.28** | 15.30 | 5.50 |
| 25 | **10.7** | **3.18** | **13.60** | **4.80** | 16.9 | **6.10** |
| **30** | **11.6** | **3.37** | **14.60** | **5.30** | 18.2 | **6.70** |
| **35** | **12.4** | **3.50** | **15.50** | **5.70** | 19.3 | 7.20 |
| 40 | **13.1** | **3.70** | **16.30** | **6.00** | 20.3 | 7.60 |
| 45 | **13.7** | **3.80** | **17.00** | 6.20 | **21.1** | **8.0** |
| **50** | **14.2** | **4.00** | **17.7** | **6.40** | 21.9 | 8.3 |
| 60 | **15.1** | **4.3** | **18.9** | **6.80** | 23.2 | 9.0 |
| 70 | 15.9 | 4.5 | 19.9 | **7.10** | **24.3** | **9.5** |
| **80** | **16.5** | **4.8** | **20.8** | **7.30** | 25.3 | 9.8 |
| 90 | **17.1** | **5.0** | **21.6** | **7.60** | 26.2 | **10.1** |
| **100** | **17.6** | **5.2** | **22.3** | **7.80** | **27.0** | **10.4** |
| **150** | **19.5** | **6.1** | **25.2** | **8.40** | 30.3 | **11.4** |
| **200** | 20.8 | 6.7 | 27.1 | 9.10 | 32.7 | 12.1 |

*Source:* Based on $f_h/U$ *vs. g* tables in Stumbo, C. R. 1973. *Thermobacteriology in Food Processing,* 2nd ed. Academic Press, New York.
To use for values of $j$ other than l, solve for $g_j$ as follows:

$$g_j = g_{j-1} + (j-1)\left[\frac{\Delta g}{\Delta j}\right]$$

Example: $g$ for ( $f_h$/U) = 20 and j = 1.4 and z = 18: $g_{j=1.4} = 12.4 + (0.4)(4.28) = 14.11$.
Reprinted from: Toledo, R. T. 1980. Fundamentals of Food Process Engineering, ist ed. AVI Pub. Co. Westport, CT.

In the tables for lethality of the cooling part of the process, $j_c$ is used as a parameter. The tabular entry in the table for lethality of the cooling curve is $(T_g - T_c)/K_s = (T_r - g - T_c)/K_s = I_c/K_s$. U in the lethality table for the cooling curve is based on $T_g$, which must be converted to U at $T_r$ before adding to the U obtained from tabular values for heating. The conversion from U' which is the value of U at $T_g$ to the U at $T_r$ is done using Equation (9.46):

$$U = U = (10)^{-g/z} \tag{9.46}$$

**Table 9.15** $f_h$/U vs. $g$ Table Used for Thermal Process Calculation by Stumbo's Procedure

| | $z = 60$ | | $z = 70$ | | $z = 80$ | | $z = 90$ | |
|---|---|---|---|---|---|---|---|---|
| $f_h/U$ | $g_{j=1}$ | $\frac{\Delta g}{\Delta j}$ | $g_{j=1}$ | $\frac{\Delta g}{\Delta j}$ | $g_{j=1}$ | $\frac{\Delta g}{\Delta j}$ | $g_{j=1}$ | $\frac{\Delta g}{\Delta j}$ |
| 0.2 | 0.00018 | 0.00015 | 0.000218 | 0.000134 | 0.000253 | 0.00017 | 0.000289 | 0.000208 |
| 0.3 | 0.0085 | 0.000475 | 0.0101 | 0.0062 | 0.000253 | 0.00017 | 0.0134 | 0.0097 |
| 0.4 | 0.0583 | 0.032 | 0.0689 | 0.0421 | 0.0118 | 0.00775 | 0.0919 | 0.0661 |
| 0.5 | 0.185 | 0.1025 | 0.0219 | 0.0134 | 0.0802 | 0.0545 | 0.292 | 0.208 |
| 0.6 | 0.401 | 0.2225 | 0.474 | 0.292 | 0.255 | 0.17 | 0.632 | 0.452 |
| 0.7 | 0.699 | 0.3875 | 0.828 | 0.510 | 0.552 | 0.3675 | 0.101 | 0.791 |
| 0.8 | 0.064 | 0.595 | 0.263 | 0.777 | 0.963 | 0.6425 | 0.678 | 1.205 |
| 0.9 | 1.482 | 0.8325 | 1.76 | 1.08 | 1.469 | 0.9775 | 2.34 | 1.68 |
| 1.0 | 1.94 | 1.075 | 2.30 | 1.42 | 2.05 | 1.45 | 3.06 | 2.19 |
| 2.0 | 7.04 | 4.025 | 8.35 | 5.19 | 2.68 | 1.775 | 11.03 | 7.88 |
| 3.0 | 11.63 | 6.65 | 13.73 | 8.58 | 9.68 | 6.475 | 18.0 | 12.8 |
| 4.0 | 15.40 | 9.00 | 18.2 | 11.4 | 12.92 | 8.65 | 23.6 | 16.7 |
| 5.0 | 18.70 | 10.75 | 21.9 | 13.7 | 15.85 | 10.65 | 28.2 | 19.7 |
| 6.0 | 21.40 | 12.50 | 25.1 | 15.6 | 18.5 | 12.5 | | |
| 7.0 | 23.80 | 13.75 | 27.9 | 17.2 | 20.9 | 14.0 | | |
| 8.0 | 26.00 | 15.00 | 30.3 | 18.6 | 23.1 | 15.5 | | |
| 9.0 | 27.90 | 16.00 | 32.5 | 19.8 | 25.1 | 16.75 | | |

*Source:* Based on $f_h/U$ vs. $g$ tables in Stumbo, C.R. 1973. *Thermobacteriology in Food Processing*, 2nd ed. Academic Press, New York.

where U is the process $U = F_0F_i$ or the equivalent heating time at 250°F for the process at $T_r$. U = is U obtained from Tables 9.17 to 9.21, the equivalent heating time at $T_g$ for the lethality of the cooling part of the process.

**Example 9.18.** For the example in the previous section, which was evaluated using the general method, calculate $F_0$ using Stumbo's and Hayakawa's procedures and calculate a process time needed to obtain an $F_0$ of 8 minutes. The following heating and cooling curve parameters were previously determined: $f_h = f_c = 22$ minutes; $j = 1.4$; $j_c = 1.8$.

**Solution:**

The retort temperature, cooling water temperature, and process time are $T_r = 251°F$ ; $T_c = 70°F$; $t = 30 - 0.6(3) = 28.2$ minutes.

To use the formula methods to determine $F_0$, it is necessary to determine g from the process time and the heating curve parameters. The $f_h/U$ versus g table is then used to determine $f_h/U$, which corresponds to g, from which a value of U and $F_0$ can be calculated. Let $T_g$ = can temperature at the termination of heating. Solving for $T_g$ using Equation (9.36):

$$T_g = 251 - (251 - 160)(10)^{-28.2/22} = 244.3°F$$

$$g = T_r - T_g = 251 - 244.3 = 6.66°F.$$

**Table 9.16** $g/K_s$ *vs.* $U/f_h$ tables used for calculating the lethality of the heating part of a thermal process by Hayakawa's procedure

| $g/K_s$ (°F) | $U/f_h$ | $g/K_s$ (°F) | $U/f_h$ | $g/K_s$ (°F) | $U/f_h$ |
|---|---|---|---|---|---|
| 100.0000 | 0.4165(−06) | 33.0000 | 0.2095(−02) | 0.35000 | 0.1161(01) |
| 98.0000 | 0.5152(−06) | 32.0000 | 0.2413(−02) | 0.30000 | 0.1226(01) |
| 96.0000 | 0.6420(−06) | 31.0000 | 0.2780(−02) | 0.25000 | 0.1303(01) |
| 94.0000 | 0.8051(−06) | 30.0000 | 0.3205(−02) | 0.20000 | 0.1397(01) |
| 92.0000 | 0.1015(−05) | 29.0000 | 0.3699(−02) | 0.15000 | 0.1519(01) |
| 90.0000 | 0.1284(−05) | 28.0000 | 0.4272(−02) | 0.10000 | 0.1693(01) |
| 88.0000 | 0.1632(−05) | 27.0000 | 0.4939(−02) | 0.09000 | 0.1738(01) |
| 86.0000 | 0.2079(−05) | 26.0000 | 0.5715(−02) | 0.08000 | 0.1789(01) |
| 84.0000 | 0.2655(−05) | 25.0000 | 0.6620(−02) | 0.07000 | 0.1846(01) |
| 82.0000 | 0.3398(−05) | 24.0000 | 0.7677(−02) | 0.06000 | 0.1913(01) |
| 80.0000 | 0.4356(−05) | 23.0000 | 0.8914(−02) | 0.05000 | 0.1992(01) |
| 78.0000 | 0.5593(−05) | 22.0000 | 0.1036(−01) | 0.04000 | 0.2088(01) |
| 76.0000 | 0.7191(−05) | 21.0000 | 0.1206(−01) | 0.03500 | 0.2146(01) |
| 74.0000 | 0.9256(−05) | 20.0000 | 0.1407(−01) | 0.03000 | 0.2212(01) |
| 72.0000 | 0.1193(−04) | 19.0000 | 0.1643(−01) | 0.02500 | 0.2291(01) |
| 70.0000 | 0.1539(−04) | 18.0000 | 0.1922(−01) | 0.02000 | 0.2388(01) |
| 68.0000 | 0.1986(−04) | 17.0000 | 0.2254(−01) | 0.01500 | 0.2513(01) |
| 66.0000 | 0.2567(−04) | 16.0000 | 0.2648(−01) | 0.01000 | 0.2688(01) |
| 64.0000 | 0.3321(−04) | 15.0000 | 0.3119(−01) | 0.00900 | 0.2734(01) |
| 62.0000 | 0.4300(−04) | 14.0000 | 0.3684(−01) | 0.00800 | 0.2785(01) |
| 60.0000 | 0.5573(−04) | 13.0000 | 0.4365(−01) | 0.00700 | 0.2844(01) |
| 58.0000 | 0.7229(−04) | 12.0000 | 0.5191(−01) | 0.00600 | 0.2909(01) |
| 56.0000 | 0.9388(−04) | 11.0000 | 0.6198(−01) | 0.00500 | 0.2989(01) |
| 54.0000 | 0.1220(−03) | 10.0000 | 0.7435(−01) | 0.00400 | 0.3085(01) |
| 52.0000 | 0.1589(−03) | 9.0000 | 0.8970(−01) | 0.00350 | 0.3143(01) |
| 50.0000 | 0.2070(−03) | 8.0000 | 0.1090(00) | 0.00300 | 0.3210(01) |
| 49.0000 | 0.2364(−03) | 7.0000 | 0.1335(00) | 0.00250 | 0.3290(01) |
| 48.0000 | 0.2701(−03) | 6.0000 | 0.1652(00) | 0.00200 | 0.3384(01) |
| 47.0000 | 0.3087(−03) | 5.0000 | 0.2073(00) | 0.00150 | 0.3509(01) |
| 46.0000 | 0.3529(−03) | 4.0000 | 0.2652(00) | 0.00100 | 0.3685(01) |
| 45.0000 | 0.4036(−03) | 3.5000 | 0.3029(00) | 0.00090 | 0.3734(01) |
| 44.0000 | 0.4618(−03) | 3.0000 | 0.3490(00) | 0.00080 | 0.3780(01) |
| 43.0000 | 0.5286(−03) | 2.5000 | 0.4067(00) | 0.00070 | 0.3842(01) |
| 42.0000 | 0.6053(−03) | 2.0000 | 0.4816(00) | 0.00060 | 0.3903(01) |
| 41.0000 | 0.6934(−03) | 1.5000 | 0.5839(00) | 0.00050 | 0.3986(01) |
| 40.0000 | 0.7947(−03) | 1.0000 | 0.7367(00) | 0.00040 | 0.4073(01) |
| 39.0000 | 0.9113(−03) | 0.9000 | 0.7777(00) | 0.00035 | 0.4143(01) |
| 38.0000 | 0.1045(−02) | 0.8000 | 0.8241(00) | 0.00030 | 0.4204(01) |
| 37.0000 | 0.1200(−02) | 0.7000 | 0.8773(00) | 0.00025 | 0.4274(01) |
| 36.0000 | 0.1378(−02) | 0.6000 | 0.9395(00) | 0.00020 | 0.4358(01) |
| 35.0000 | 0.1584(−02) | 0.5000 | 0.1014(01) | 0.00015 | 0.4505(01) |
| 34.0000 | 0.1821(−02) | 0.4000 | 0.1106(01) | 0.00010 | 0.4659(01) |

Values in parentheses indicate powers of 10 by which tabulated values are to be multiplied; e.g., $U_{h/f}$ for $g/K_s = 40°$F is 0.0006646.

*Source:* Hayakawa, k., Food Technol. 24: 1407, 1970. Corrected table courtesy of K. Hayakawa.

**Table 9.17** $g/k_s$ vs. $U/f_c$ Tables used for Calculating the Lethality of the Cooling Part of a Thermal Process by Hayakawa's Procedure ($g/K_s \leq 200$)

| $I_c/K_s$ (°F) | $U'/f_c$ for $j_c = 0.40$ to 1.90 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *0.40* | *0.60* | *0.80* | *1.00* | *1.20* | *1.40* | *1.60* | *1.80* | *1.90* |
| 200.00 | 0.9339(−2) | 0.1086(−1) | 0.1220(−1) | 0.1976(−1) | 0.7021(−1) | 0.9440(−1) | 0.1112 | 0.1243 | 0.1300 |
| 195.00 | 0.9585(−2) | 0.1114(−1) | 0.1253(−1) | 0.2030(−1) | 0.7114(−1) | 0.9565(−1) | 0.1126 | 0.1260 | 0.1318 |
| 190.00 | 0.9844(−2) | 0.1145(−1) | 0.1288(−1) | 0.2086(−1) | 0.7211(−1) | 0.9695(−1) | 0.1142 | 0.1277 | 0.1335 |
| 185.00 | 0.1012(−1) | 0.1177(−1) | 0.1325(−1) | 0.2145(−1) | 0.7312(−1) | 0.9830(−1) | 0.1158 | 0.1295 | 0.1354 |
| 180.00 | 0.1041(−1) | 0.1212(−1) | 0.1364(−1) | 0.2208(−1) | 0.7418(−1) | 0.9972(−1) | 0.1174 | 0.1313 | 0.1373 |
| 175.00 | 0.1072(−1) | 0.1248(−1) | 0.1405(−1) | 0.2275(−1) | 0.7529(−1) | 0.1012 | 0.1192 | 0.1332 | 0.1394 |
| 170.00 | 0.1104(−1) | 0.1287(−1) | 0.1449(−1) | 0.2346(−1) | 0.7645(−1) | 0.1027 | 0.1210 | 0.1353 | 0.1415 |
| 165.00 | 0.1139(−1) | 0.1328(−1) | 0.1496(−1) | 0.2422(−1) | 0.7767(−1) | 0.1044 | 0.1229 | 0.1374 | 0.1437 |
| 160.00 | 0.1176(−1) | 0.1372(−1) | 0.1546(−1) | 0.2503(−1) | 0.7895(−1) | 0.1061 | 0.1249 | 0.1396 | 0.1460 |
| 155.00 | 0.1216(−1) | 0.1418(−1) | 0.1599(−1) | 0.2589(−1) | 0.8029(−1) | 0.1078 | 0.1270 | 0.1420 | 0.1485 |
| 150.00 | 0.1258(−1) | 0.1469(−1) | 0.1657(−1) | 0.2682(−1) | 0.8172(−1) | 0.1097 | 0.1292 | 0.1444 | 0.1510 |
| 145.00 | 0.1304(−1) | 0.1523(−1) | 0.1719(−1) | 0.2781(−1) | 0.8322(−1) | 0.1117 | 0.1315 | 0.1470 | 0.1538 |
| 140.00 | 0.1353(−1) | 0.1582(−1) | 0.1785(−1) | 0.2889(−1) | 0.8481(−1) | 0.1138 | 0.1340 | 0.1498 | 0.1566 |
| 135.00 | 0.1407(−1) | 0.1645(−1) | 0.1858(−1) | 0.3005(−1) | 0.8651(−1) | 0.1160 | 0.1366 | 0.1527 | 0.1597 |
| 130.00 | 0.1465(−1) | 0.1714(−1) | 0.1936(−1) | 0.3131(−1) | 0.8831(−1) | 0.1184 | 0.1393 | 0.1558 | 0.1629 |
| 125.00 | 0.1528(−1) | 0.1789(−1) | 0.2022(−1) | 0.3268(−1) | 0.9025(−1) | 0.1209 | 0.1423 | 0.1591 | 0.1663 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 120.00 | 0.1598(−1) | 0.1872(−1) | 0.2116(−1) | 0.3418(−1) | 0.9232(−1) | 0.1236 | 0.1454 | 0.1626 | 0.1700 |
| 115.00 | 0.!675(−1) | 0.1963(−1) | 0.2219(−1) | 0.3583(−1) | 0.9456(−1) | 0.1265 | 0.1488 | 0.1663 | 0.1739 |
| 110.00 | 0.1760(−1) | 0.2065(−1) | 0.2334(−1) | 0.3766(−1) | 0.9698(−1) | 0.1296 | 0.1524 | 0.1703 | 0.1781 |
| 105.00 | 0.1857(−1) | 0.2175(−1) | 0.2462(−1) | 0.3970(−1) | 0.9961(−1) | 0.1329 | 0.1563 | 0.1747 | 0.1826 |
| 100.00 | 0.1969(−1) | 0.2296(−1) | 0.2606(−1) | 0.4199(−1) | 0.1025 | 0.1366 | 0.1605 | 0.1794 | 0.1875 |
| 95.00 | 0.2104(−1) | 0.2433(−1) | 0.2769(−1) | 0.4463(−1) | 0.1057 | 0.1405 | 0.1651 | 0.1845 | 0.1929 |
| 90.00 | 0.2276(−1) | 0.2589(−1) | 0.2955(−1) | 0.4779(−1) | 0.1093 | 0.1449 | 0.1702 | 0.1901 | 0.1987 |
| 85.00 | 0.2414(−l) | 0.2768(−1) | 0.3170(−1) | 0.5103(−1) | 0.1132 | 0.1498 | 0.1757 | 0.1962 | 0.2051 |
| 80.00 | 0.2576(−1) | 0.2976(−1) | 0.3420(−1) | 0.5460(−1) | 0.1176 | 0.1552 | 0.1819 | 0.2031 | 0.2122 |
| 75.00 | 0.2768(−1) | 0.3221(−1) | 0.3715(−1) | 0.5878(−1) | 0.1227 | 0.1612 | 0.1888 | 0.2107 | 0.2202 |
| 70.00 | 0.2999(−1) | 0.3512(−1) | 0.4069(−1) | 0.6373(−1) | 0.1285 | 0.1682 | 0.1967 | 0.2193 | 0.2291 |
| 65.00 | 0.3280(−1) | 0.3865(−1) | 0.4499(−1) | 0.6967(−1) | 0.1353 | 0.1762 | 0.2057 | 0.2291 | 0.2394 |
| 60.00 | 0.3626(−1) | 0.4300(−1) | 0.5032(−1) | 0.7687(−1) | 0.1434 | 0.1855 | 0.2161 | 0.2405 | 0.2511 |
| 55.00 | 0.4061(−1) | 0.4846(−1) | 0.5703(−1) | 0.8575(−1) | 0.1532 | 0.1966 | 0.2284 | 0.2539 | 0.2650 |
| 50.00 | 0.4616(−1) | 0.5546(−1) | 0.6564(−l) | 0.9687(−1) | 0.1652 | 0.2101 | 0.2432 | 0.2698 | 0.2814 |
| 45.00 | 0.5340(−1) | 0.6462(−1) | 0.7692(−1) | 0.1111 | 0.1803 | 0.2268 | 0.2613 | 0.2892 | 0.3014 |
| 40.00 | 0.6302(−1) | 0.7688(−1) | 0.9197(−1) | 0.1295 | 0.1997 | 0.2478 | 0.2840 | 0.3132 | 0.3261 |
| 35.00 | 0.7607(−1) | 0.9362(−1) | 0.1124 | 0.1539 | 0.2251 | 0.2750 | 0.3129 | 0.3437 | 0.3573 |
| 30.00 | 0.9415(−1) | 0.1170 | 0.1408 | 0.1868 | 0.2591 | 0.3108 | 0.3507 | 0.3834 | 0.3978 |
| 25.00 | 0.1197 | 0.1501 | 0.1808 | 0.2322 | 0.3056 | 0.3593 | 0.4014 | 0.4361 | 0.4515 |

Values in parentheses are powers of 10 by which tabulated value should be multiplied.
*Source:* Hayakawa. K., *Food Technol.* 24:1407, 1970.

**Table 9.18** $g/K_s$ vs. $U/f_c$ Tables used for Calculating the Lethality of the Cooling Part of a Thermal Process by Hayakawa's Procedure ($g/K_s \leq 200$)

| $I_c/K_s$ | $U'/f_c$ for $j_c = 2.0$ to 2.8 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (°F) | 2.00 | 2.10 | 2.20 | 2.30 | 2.40 | 2.50 | 2.60 | 2.70 | 2.80 |
| 200.00 | 0.1353 | 0.1403 | 0.1449 | 0.1492 | 0.1533 | 0.1572 | 0.1609 | 0.1645 | 0.1679 |
| 195.00 | 0.1371 | 0.1421 | 0.1468 | 0.1512 | 0.1553 | 0.1593 | 0.1630 | 0.1666 | 0.1700 |
| 190.00 | 0.1390 | 0.1440 | 0.1487 | 0.1532 | 0.1574 | 0.1614 | 0.1652 | 0.1689 | 0.1723 |
| 185.00 | 0.1409 | 0.1460 | 0.1508 | 0.1553 | 0.1596 | 0.1636 | 0.1675 | 0.1712 | 0.1747 |
| 180.00 | 0.1429 | 0.1481 | 0.1530 | 0.1575 | 0.1619 | 0.1660 | 0.1699 | 0.1736 | 0.1772 |
| 175.00 | 0.1450 | 0.1503 | 0.1552 | 0.1599 | 0.1643 | 0.1684 | 0.1724 | 0.1762 | 0.1798 |
| 170.00 | 0.1472 | 0.1526 | 0.1576 | 0.1623 | 0.1667 | 0.1710 | 0.1750 | 0.1788 | 0.1825 |
| 165.00 | 0.1495 | 0.1550 | 0.1600 | 0.1648 | 0.1693 | 0.1736 | 0.1177 | 0.1816 | 0.1853 |
| 160.00 | 0.1520 | 0.1575 | 0.1626 | 0.1675 | 0.1721 | 0.1764 | 0.1806 | 0.1845 | 0.1883 |
| 155.00 | 0.1545 | 0.1601 | 0.1653 | 0.1703 | 0.1749 | 0.1794 | 0.1836 | 0.1876 | 0.1914 |
| 150.00 | 0.1572 | 0.1629 | 0.1682 | 0.1732 | 0.1780 | 0.1825 | 0.1867 | 0.1908 | 0.1947 |
| 145.00 | 0.1600 | 0.1658 | 0.1712 | 0.1763 | 0.1811 | 0.1857 | 0.1901 | 0.1942 | 0.1982 |
| 140.00 | 0.1630 | 0.1689 | 0.1744 | 0.1796 | 0.1845 | 0.1891 | 0.1936 | 0.1978 | 0.2018 |
| 135.00 | 0.1661 | 0.1721 | 0.1777 | 0.1830 | 0.1880 | 0.1928 | 0.1973 | 0.2016 | 0.2057 |
| 130.00 | 0.1695 | 0.1756 | 0.1813 | 0.1867 | 0.1918 | 0.1966 | 0.2012 | 0.2056 | 0.2098 |
| 125.00 | 0.1730 | 0.1793 | 0.1851 | 0.1906 | 0.1958 | 0.2007 | 0.2054 | 0.2099 | 0.2142 |
| 120.00 | 0.1768 | 0.1832 | 0.1892 | 0.1948 | 0.2001 | 0.2051 | 0.2099 | 0.2145 | 0.2188 |
| 115.00 | 0.1809 | 0.1874 | 0.1935 | 0.1992 | 0.2046 | 0.2098 | 0.2147 | 0.2193 | 0.2238 |
| 110.00 | 0.1853 | 0.1919 | 0.1982 | 0.2040 | 0.2095 | 0.2148 | 0.2198 | 0.2246 | 0.2291 |
| 105.00 | 0.1900 | 0.1968 | 0.2032 | 0.2092 | 0.2148 | 0.2202 | 0.2253 | 0.2302 | 0.2349 |
| 100.00 | 0.1951 | 0.2021 | 0.2086 | 0.2148 | 0.2206 | 0.2261 | 0.2313 | 0.2363 | 0.2411 |
| 95.00 | 0.2006 | 0.2078 | 0.2146 | 0.2209 | 0.2268 | 0.2325 | 0.2378 | 0.2429 | 0.2478 |
| 90.00 | 0.2067 | 0.2141 | 0.2210 | 0.2275 | 0.2337 | 0.2395 | 0.2450 | 0.2502 | 0.2552 |
| 85.00 | 0.2134 | 0.2210 | 0.2281 | 0.2348 | 0.2412 | 0.2471 | 0.2528 | 0.2582 | 0.2634 |
| 80.00 | 0.2207 | 0.2286 | 0.2360 | 0.2429 | 0.2494 | 0.2556 | 0.2615 | 0.2670 | 0.2724 |
| 75.00 | 0.2290 | 0.2371 | 0.2447 | 0.2519 | 0.2587 | 0.2651 | 0.2711 | 0.2769 | 0.2824 |
| 70.00 | 0.2382 | 0.2467 | 0.2546 | 0.2620 | 0.2690 | 0.2757 | 0.2820 | 0.2879 | 0.2936 |
| 65.00 | 0.2488 | 0.2576 | 0.2658 | 0.2735 | 0.2808 | 0.2877 | 0.2943 | 0.3005 | 0.3064 |
| 60.00 | 0.2610 | 0.2701 | 0.2787 | 0.2868 | 0.2944 | 0.3015 | 0.3084 | 0.3149 | 0.3210 |
| 55.00 | 0.2752 | 0.2848 | 0.2937 | 0.3022 | 0.3101 | 0.3176 | 0.3248 | 0.3316 | 0.3380 |
| 50.00 | 0.2922 | 0.3022 | 0.3116 | 0.3204 | 0.3288 | 0.3367 | 0.3442 | 0.3513 | 0.3581 |
| 45.00 | 0.3127 | 0.3232 | 0.3331 | 0.3424 | 0.3512 | 0.3595 | 0.3674 | 0.3750 | 0.3821 |
| 40.00 | 0.3380 | 0.3491 | 0.3596 | 0.3694 | 0.3787 | 0.3876 | 0.3959 | 0.4039 | 0.4115 |
| 35.00 | 0.3700 | 0.3818 | 0.3929 | 0.4033 | 0.4132 | 0.4226 | 0.4315 | 0.4400 | 0.4480 |
| 30.00 | 0.4113 | 0.4239 | 0.4357 | 0.4468 | 0.4574 | 0.4674 | 0.4769 | 0.4860 | 0.4946 |
| 25.00 | 0.4659 | 0.4793 | 0.4920 | 0.5040 | 0.5153 | 0.5261 | 0.5363 | 0.5460 | 0.5553 |

*Source:* Hayakawa. K., *Food Technol.* 24:1407, 1970.

Determination of $F_0$ using Stumbo's procedure. Table 9.14 is used to determine a value of $f_h/U$ which corresponds to $g = 6.66$. Tabular parameters are for $z = 18$ and $j_c = 1.8$. It is necessary to interpolate. A value of $g = 6.66$ is not obtainable directly from Table 9.14, because a tabular entry for g is available only for a value of $j_c = 1$. Under the column "$z = 18$" in Table 9.14, a g value is an interpolating

**Table 9.19** $g/K_s$ vs. $U/f_c$ Tables used for Calculating the Lethality of the Cooling Part of a Thermal Process by Hayakawa's Procedure ($200 < g/K_s \leq 400$)

| $I_c/K_s$ | $U'/f_c$ for $j_c = 0.40$ to $1.90$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (°F) | *0.40* | *0.60* | *0.80* | *1.00* | *1.20* | *1.40* | *1.60* | *1.80* | *1.90* |
| 400.00 | 0.4642(−2) | 0.5348(−2) | 0.5964(−2) | 0.9644(−2) | 0.4919(−1) | 0.6616(−1) | 0.7794(−I) | 0.8721(−1) | 0.9124(−1) |
| 395.00 | 0.4700(−2) | 0.5416(−2) | 0.6041(−2) | 0.9769(−2) | 0.4951(−1) | 0.6658(−1) | 0.7844(−1) | 0.8777(−1) | 0.9182(−1) |
| 390.00 | 0.4760(−2) | 0.5486(−2) | 0.6120(−2) | 0.9897(−2) | 0.4983(−1) | 0.6702(−1) | 0.7895(−1) | 0.8833(−1) | 0.9241(−1) |
| 385.00 | 0.4822(−2) | 0.5558(−2) | 0.6201(−2) | 0.1003(−1) | 0.5016(−1) | 0.6746(−1) | 0.7947(−1) | 0.8892(−1) | 0.9302(−1) |
| 380.00 | 0.4886(−2) | 0.5632(−2) | 0.6284(−2) | O.1016(−1) | 0.5049(−1) | 0.6791(−1) | 0.8000(−1) | 0.8951(−I) | 0.9364(−1) |
| 375.00 | 0.4951(−2) | 0.5708(−2) | 0.6370(−2) | 0.1030(−1) | 0.5083(−1) | 0.6837(−1) | 0.8054(−1) | 0.9011(−1) | 0.9428(−1) |
| 370.00 | 0.5017(−2) | 0.5786(−2) | 0.6458(−2) | 0.1045(−1) | 0.5118(−1) | 0.6884(−1) | 0.8109(−1) | 0.9073(−I) | 0.9492(−I) |
| 365.00 | 0.5086(−2) | 0.5866(−2) | 0.6548(−2) | 0.1059(−1) | 0.5154(−1) | 0.6931(−1) | 0.8165(−1) | 0.9136(−1) | 0.9558(−1) |
| 360.00 | 0.5157(−2) | 0.5949(−2) | 0.6641(−2) | 0.1074(−1) | 0.5190(−1) | 0.6980(−1) | 0.8223(−1) | 0.9200(−1) | 0.9625(−1) |
| 355.00 | 0.5229(−2) | 0.6033(−2) | 0.6737(−2) | 0.1090(−1) | 0.5227(−1) | 0.7030(−1) | 0.8281(−1) | 0.9266(−1) | 0.9694(−1) |
| 350.00 | 0.5304(−2) | 0.6121(−2) | 0.6835(−2) | 0.1106(−1) | 0.5265(−1) | 0.7081(−I) | 0.8341(−1) | 0.9333(−1) | 0.9764(−1) |
| 345.00 | 0.5381(−2) | 0.6211(−2) | 0.6937(−2) | 0.1122(−1) | 0.5304(−1) | 0.7133(−1) | 0.8403(−1) | 0.9401(−1) | 0.9836(−1) |
| 340.00 | 0.5460(−2) | 0.6303(−2) | 0.7041(−2) | 0.1139(−1) | 0.5344(−1) | 0.7187(−1) | 0.8466(−1) | 0.9472(−1) | 0.9909(−1) |
| 335.00 | 0.5542(−2) | 0.6398(−2) | 0.7149(−2) | 0.1157(−1) | 0.5384(−1) | 0.7241(−1) | 0.8530(−1) | 0.9543(−1) | 0.9984(−1) |
| 330.00 | 0.5626(−2) | 0.6497(−2) | 0.7260(−2) | 0.1175(−1) | 0.5426(−1) | 0.7297(−1) | 0.8595(−1) | 0.9617(−1) | 0.1006 |
| 325.00 | 0.5713(−2) | 0.6598(−2) | 0.7374(−2) | 0,1193(−1) | 0.5468(−1) | 0.7354(−1) | 0.8663(−1) | 0.9692(−1) | 0.1014 |
| 320.00 | 0.5802(−2) | 0.6703(−2) | 0.7493(−2) | 0.1213(−1) | 0.5512(−1) | 0.7413(−1) | 0.8731(−1) | 0.9769(−1) | 0.1022 |
| 315.00 | 0.5895(−2) | 0.6811(−2) | 0.7615(−2) | 0.1232(−1) | 0.5556(−1) | 0.7472(−1) | 0.8802(−1) | 0.9847(−1) | 0.1030 |
| 310.00 | 0.5990(−2) | 0.6923(−2) | 0.7741(−2) | 0.1253(−1) | 0.5602(−1) | 0.7534(−1) | 0.8874(−1) | 0.9928(−1) | 0.1039 |
| 305.00 | 0.6089(−2) | 0.7038(−2) | 0.7871(−2) | 0.1274(−1) | 0.5648(−1) | 0.7597(−1) | 0.8948(−1) | 0.1001 | 0.1047 |
| 300.00 | 0.6191(−2) | 0.7157(−2) | 0.8006(−2) | 0.1296(−1) | 0.5696(−1) | 0.7661(−1) | 0.9024(−1) | 0.1010 | 0.1056 |
| 295.00 | 0.6297(−2) | 0.7281(−2) | 0.8146(−2) | 0.1319(−1) | 0.5746(−1) | 0.7727(−1) | 0.9102(−1) | 0.1018 | 0.1065 |

(*Cont.*)

**Table 9.19** (*Continued*)

| $I_c/K_s$ (°F) | $U'/f_c$ for $j_c = 0.40$ to 1.90 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *0.40* | *0.60* | *0.80* | *1.00* | *1.20* | *1.40* | *1.60* | *1.80* | *1.90* |
| 290.00 | 0.6406(−2) | 0.7409(−2) | 0.8291(−2) | 0.1342(−1) | 0.5796(−1) | 0.7795(−1) | 0.9182(−1) | 0.1027 | 0.1075 |
| 285.00 | 0.6519(−2) | 0.7541(−2) | 0.8441(−2) | 0.1367(−1) | 0.5848(−1) | 0.7865(−1) | 0.9264(−1) | 0.1036 | 0.1084 |
| 280.00 | 0.6636(−2) | 0.7679(−2) | 0.8596(−2) | 0.1392(−1) | 0.5901(−1) | 0.7937(−1) | 0.9348(−1) | 0.1046 | 0.1094 |
| 275.00 | 0.6758(−2) | 0.7821(−2) | 0.8758(−2) | 0.1418(−1) | 0.5956(−1) | 0.8010(−1) | 0.9435(−1) | 0.1055 | 0.1104 |
| 270.00 | 0.6884(−2) | 0.7969(−2) | 0.8925(−2) | 0.1445(−1) | 0.6012(−1) | 0.8086(−1) | 0.9524(−1) | 0.1065 | 0.1115 |
| 265.00 | 0.7015(−2) | 0.8123(−2) | 0.9099(−2) | 0.1473(−1) | 0.6070(−1) | 0.8164(−1) | 0.9616(−1) | 0.1076 | 0.1125 |
| 260.00 | 0.7152(−2) | 0.8283(−2) | 0.9281(−2) | 0.1503(−1) | 0.6130(−1) | 0.8244(−1) | 0.9710(−1) | 0.1086 | 0.1136 |
| 255.00 | 0.7293(−2) | 0.8449(−2) | 0.9469(−2) | 0.1533(−1) | 0.6192(−1) | 0.8327(−1) | 0.9807(−1) | 0.1097 | 0.1148 |
| 250.00 | 0.7441(−2) | 0.8623(−2) | 0.9666(−2) | 0.1565(−1) | 0.6255(−1) | 0.8412(−1) | 0.9908(−1) | 0.1108 | 0.1159 |
| 245.00 | 0.7595(−2) | 0.8803(−2) | 0.9870(−2) | 0.1599(−1) | 0.6320(−1) | 0.8500(−1) | 0.1001 | 0.1120 | 0.1171 |
| 240.00 | 0.7755(−2) | 0.8992(−2) | 0.1008(−1) | 0.1633(−1) | 0.6388(−1) | 0.8591(−1) | 0.1012 | 0.1132 | 0.1184 |
| 235.00 | 0.7923(−2) | 0.9188(−2) | 0.1031(−1) | 0.1669(−1) | 0.6458(−1) | 0.8685(−1) | 0.1023 | 0.1144 | 0.1197 |
| 230.00 | 0.8098(−2) | 0.9394(−2) | 0,1054(−1) | 0.1707(−1) | 0.6530(−1) | 0.8782(−1) | 0.1034 | 0.1157 | 0.1210 |
| 225.00 | 0.8281(−2) | 0.9609(−2) | 0.1079(−1) | 0.1747(−1) | 0.6604(−1) | 0.8882(−1) | 0.1046 | 0.1170 | 0.1224 |
| 220.00 | 0.8472(−2) | 0.9835(−2) | 0.1104(−1) | 0.1788(−1) | 0.6682(−1) | 0.8985(−1) | 0.1058 | 0.1184 | 0.1238 |
| 215.00 | 0.8673(−2) | 0.1007(−1) | 0.1131(−1) | 0.1832(−1) | 0.6762(−1) | 0.9093(−1) | 0.1071 | 0.1198 | 0.1253 |
| 210.00 | 0.8884(−2) | 0.1032(−1) | 0.1159(−1) | 0.1878(−1) | 0.6845(−1) | 0.9204(−1) | 0.1084 | 0.1212 | 0.1268 |
| 205.00 | 0.9106(−2) | 0.1058(−1) | 0.1189(−1) | 0.1926(−1) | 0.6931(−1) | 0.9320(−1) | 0.1097 | 0.1228 | 0.1284 |

Values in parentheses are powers of 10 hy which tabulated value should be multiplied.
*Source:* Hayakawa, K., *Food Technol.* 24:1407, 1970.

**Table 9.20** $g/K_s$ vs. $U/f_c$ Tables used for Calculating the Lethality of the Cooling Part of a Thermal Process by Hayakawa's Procedure ($200 < g/K_s \leq 400$)

| $I_c/K_s$ | $U'/f_c$ for $j_c = 2.00$ to $2.80$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (°F) | 2.00 | 2.10 | 2.20 | 2.30 | 2.40 | 2.50 | 2.60 | 2.70 | 2.80 |
| 400.00 | 0.9497(−1) | 0.9844(−1) | 0.1017 | 0.1048 | 0.1077 | 0.1105 | 0.1131 | 0.1156 | 0.1180 |
| 395.00 | 0.9557(−1) | 0.9907(−1) | 0.1024 | 0.1054 | 0.1084 | 0.1112 | 0.1138 | 0.1164 | 0.1188 |
| 390.00 | 0.9619(−1) | 0.9971(−1) | 0.1030 | 0.1061 | 0.1091 | 0.1119 | 0.1145 | 0.1171 | 0.1195 |
| 385.00 | 0.9682(−1) | 0.1004 | 0.1037 | 0.1068 | 0.1098 | 0.1126 | 0.1153 | 0.1179 | 0.1203 |
| 380.00 | 0.9747(−1) | 0.1010 | 0.1044 | 0.1075 | 0.1105 | 0.1134 | 0.1161 | 0.1186 | 0.1211 |
| 375.00 | 0.9813(−1) | 0.1017 | 0.1051 | 0.1083 | 0.1113 | 0.1141 | 0.1168 | 0.1194 | 0.1219 |
| 370.00 | 0.9880(−1) | 0.1024 | 0.1058 | 0.1090 | 0.1120 | 0.1149 | 0.1176 | 0.1203 | 0.1228 |
| 365.00 | 0.9948(−1) | 0.1031 | 0.1065 | 0.1097 | 0.1128 | 0.1157 | 0.1184 | 0.1211 | 0.1236 |
| 360.00 | 0.1002 | 0.1038 | 0.1073 | 0.1105 | 0.1136 | 0.1165 | 0.1193 | 0.1219 | 0.1245 |
| 355.00 | 0.1009 | 0.1046 | 0.1080 | 0.1113 | 0.1144 | 0.1173 | 0.1201 | 0.1228 | 0.1254 |
| 350.00 | 0.1016 | 0.1053 | 0.1088 | 0.1121 | 0.1152 | 0.1182 | 0.1210 | 0.1237 | 0.1263 |
| 345.00 | 0.1024 | 0.1061 | 0.1096 | 0.1129 | 0.1161 | 0.1190 | 0.1219 | 0.1246 | 0.1272 |
| 340.00 | 0.1031 | 0.1069 | 0.1104 | 0.1138 | 0.1169 | 0.1199 | 0.1228 | 0.1255 | 0.1281 |
| 335.00 | 0.1039 | 0.1077 | 0.1113 | 0.1146 | 0.1178 | 0.1208 | 0.1237 | 0.1265 | 0.1291 |
| 330.00 | 0.1047 | 0.1085 | 0.1121 | 0.1155 | 0.1187 | 0.1217 | 0.1246 | 0.1274 | 0.1301 |
| 325.00 | 0.1055 | 0.1094 | 0.1130 | 0.1164 | 0.1196 | 0.1227 | 0.1256 | 0.1284 | 0.1311 |
| 320.00 | 0.1064 | 0.1102 | 0.1139 | 0.1173 | 0.1206 | 0.1237 | 0.1266 | 0.1294 | 0.1321 |
| 315.00 | 0.1072 | 0.1111 | 0.1148 | 0.1183 | 0.1215 | 0.1247 | 0.1276 | 0.1305 | 0.1332 |
| 310.00 | 0.1081 | 0.1120 | 0.1157 | 0.1192 | 0.1225 | 0.1257 | 0.1287 | 0.1315 | 0.1343 |
| 305.00 | 0.1090 | 0.1130 | 0.1167 | 0.1202 | 0.1236 | 0.1267 | 0.1297 | 0.1326 | 0.1354 |
| 300.00 | 0.1099 | 0.1139 | 0.1177 | 0.1212 | 0.1246 | 0.1278 | 0.1308 | 0.1337 | 0.1365 |
| 295.00 | 0.1109 | 0.1149 | 0.1187 | 0.1223 | 0.1257 | 0.1289 | 0.1319 | 0.1349 | 0.1377 |
| 290.00 | 0.1118 | 0.1159 | 0.1197 | 0.1234 | 0.1268 | 0.1300 | 0.1331 | 0.1360 | 0.1389 |
| 285.00 | 0.1128 | 0.1170 | 0.1208 | 0.1244 | 0.1279 | 0.1312 | 0.1343 | 0.1373 | 0.1401 |
| 280.00 | 0.1139 | 0.1180 | 0.1219 | 0.1256 | 0.1290 | 0.1323 | 0.1355 | 0.1385 | 0.1414 |
| 275.00 | 0.1149 | 0.1191 | 0.1230 | 0.1267 | 0.1302 | 0.1336 | 0.1367 | 0.1398 | 0.1427 |
| 270.00 | 0.1160 | 0.1202 | 0.1242 | 0.1279 | 0.1315 | 0.1348 | 0.1380 | 0.1411 | 0.1440 |
| 265.00 | 0.1171 | 0.1214 | 0.1254 | 0.1292 | 0.1327 | 0.1361 | 0.1393 | 0.1424 | 0.1454 |
| 260.00 | 0.1183 | 0.1226 | 0.1266 | 0.1304 | 0.1340 | 0.1374 | 0.1407 | 0.1438 | 0.1468 |
| 255.00 | 0.1194 | 0.1238 | 0.1279 | 0.1317 | 0.1354 | 0.1388 | 0.1421 | 0.1452 | 0.1483 |
| 250.00 | 0.1207 | 0.1251 | 0.1292 | 0.1331 | 0.1367 | 0.1402 | 0.1435 | 0.1467 | 0.1498 |
| 245.00 | 0.1219 | 0.1264 | 0.1305 | 0.1344 | 0.1381 | 0.1417 | 0.1450 | 0.1482 | 0.1513 |
| 240.00 | 0.1232 | 0.1277 | 0.1319 | 0.1359 | 0.1396 | 0.1432 | 0.1466 | 0.1498 | 0.1529 |
| 235.00 | 0.1245 | 0.1291 | 0.1333 | 0.1373 | 0.1411 | 0.1447 | 0.1482 | 0.1514 | 0.1546 |
| 230.00 | 0.1259 | 0.1305 | 0.1348 | 0.1389 | 0.1427 | 0.1463 | 0.1498 | 0.1531 | 0.1563 |
| 225.00 | 0.1274 | 0.1320 | 0.1363 | 0.1404 | 0.1443 | 0.1480 | 0.1515 | 0.1548 | 0.1580 |
| 220.00 | 0.1288 | 0.1335 | 0.1379 | 0.1421 | 0.1460 | 0.1497 | 0.1532 | 0.1566 | 0.1599 |
| 215.00 | 0.1301 | 0.1351 | 0.1396 | 0.1438 | 0.1477 | 0.1515 | 0.1551 | 0.1585 | 0.1617 |
| 210.00 | 0.1320 | 0.1368 | 0.1413 | 0.1455 | 0.1495 | 0.1533 | 0.1569 | 0.1604 | 0.1637 |
| 205.00 | 0.1336 | 0.1385 | 0.1430 | 0.1473 | 0.1514 | 0.1552 | 0.1589 | 0.1624 | 0.1657 |

Values in parentheses an powers of 10 by which tabulated value should be multiplied.
*Source:* Hayakawa, K., *Food Technol.* 24:1407, 1970.

**Table 9.21** $g/K_s$ vs. $U/f_c$ Tables used for Calculating the Lethality of the Cooling Part of a Thermal Process by Hayakawa's Procedure ($g/K_s \leq 400$)

| $I_c/K_s$ (°F) | $U'/f_c$ for $j_c = 2.90$ | $U'/f_c$ for $j_c = 3.00$ | $I_c/K_s$ (°F) | $U'/f_c$ for $j_c = 2.90$ | $U'/f_c$ for $j_c = 3.00$ |
|---|---|---|---|---|---|
| 400.00 | 0.1204 | 0.1226 | 200.00 | 0.1711 | 0.1742 |
| 395.00 | 0.1211 | 0.1234 | 195.00 | 0.1733 | 0.1765 |
| 390.00 | 0.1219 | 0.1242 | 190.00 | 0.1757 | 0.1789 |
| 385.00 | 0.1227 | 0.1250 | 185.00 | 0.1781 | 0.1813 |
| 380.00 | 0.1235 | 0.1258 | 180.00 | 0.1806 | 0.1839 |
| 375.00 | 0.1243 | 0.1266 | 175.00 | 0.1833 | 0.1866 |
| 370.00 | 0.1252 | 0.1275 | 170.00 | 0.1860 | 0.1894 |
| 365.00 | 0.1260 | 0.1284 | 165.00 | 0.1889 | 0.1923 |
| 360.00 | 0.1269 | 0.1293 | 160.00 | 0.1919 | 0.1954 |
| 355.00 | 0.1278 | 0.1302 | 155.00 | 0.1951 | 0.1986 |
| 350.00 | 0.1287 | 0.1311 | 150.00 | 0.1985 | 0.2020 |
| 345.00 | 0.1297 | 0.1321 | 145.00 | 0.2020 | 0.2056 |
| 340.00 | 0.1306 | 0.1331 | 140.00 | 0.2057 | 0.2094 |
| 335.00 | 0.1316 | 0.1341 | 135.00 | 0.2096 | 0.2134 |
| 330.00 | 0.1326 | 0.1351 | 130.00 | 0.2138 | 0.2177 |
| 325.00 | 0.1337 | 0.1361 | 125.00 | 0.2183 | 0.2222 |
| 320.00 | 0.1347 | 0.1372 | 120.00 | 0.2230 | 0.2270 |
| 315.00 | 0.1358 | 0.1383 | 115.00 | 0.2281 | 0.2321 |
| 310.00 | 0.1369 | 0.1394 | 110.00 | 0.2335 | 0.2377 |
| 305.00 | 0.1380 | 0.1406 | 105.00 | 0.2393 | 0.2436 |
| 300.00 | 0.1392 | 0.1417 | 100.00 | 0.2456 | 0.2500 |
| 295.00 | 0.1404 | 0.1430 | 95.00 | 0.2525 | 0.2570 |
| 290.00 | 0.1416 | 0.1442 | 90.00 | 0.2600 | 0.2646 |
| 285.00 | 0.1428 | 0.1455 | 85.00 | 0.2683 | 0.2730 |
| 280.00 | 0.1441 | 0.1468 | 80.00 | 0.2774 | 0.2823 |
| 275.00 | 0.1455 | 0.1481 | 75.00 | 0.2876 | 0.2926 |
| 270.00 | 0.1468 | 0.1495 | 70.00 | 0.2991 | 0.3043 |
| 265.00 | 0.1482 | 0.1509 | 65.00 | 0.3120 | 0.3174 |
| 260.00 | 0.1497 | 0.1524 | 60.00 | 0.3269 | 0.3325 |
| 255.00 | 0.1511 | 0.1539 | 55.00 | 0.3442 | 0.3501 |
| 250.00 | 0.1527 | 0.1555 | 50.00 | 0.3645 | 0.3707 |
| 245.00 | 0.1543 | 0.1571 | 45.00 | 0.3889 | 0.3954 |
| 240.00 | 0.1559 | 0.1587 | 40.00 | 0.4187 | 0.4256 |
| 235.00 | 0.1576 | 0.1604 | 35.00 | 0.4557 | 0.4631 |
| 230.00 | 0.1593 | 0.1622 | 30.00 | 0.5028 | 0.5107 |
| 225.00 | 0.1611 | 0.1640 | 25.00 | 0.5641 | 0.5725 |
| 220.00 | 0.1630 | 0.1659 | | | |
| 215.00 | 0.1649 | 0.1679 | | | |
| 210.00 | 0.1669 | 0.1699 | | | |
| 205.00 | 0.1689 | 0.1720 | | | |

*Source:* Hayakawa, K., *Food Technol.* 24:1407, 1970.

factor, $\Delta g/\Delta j = 1.59$. The value of g for $f_h/U = 5$ and for $j = 1.8$ is

$$g_{j=1.8} = 5.4 + 0.8(1.59) = 6.672$$

The value $g = 6.672$ exceeds 6.66, the specified g; therefore, a lower value of $f_h/U = 4$ is chosen, a corresponding g value for $j_c = 1.8$ is calculated, and by interpolation, a value of $f_h/U$ which corresponds to $g = 6.66$ is calculated. For $f_h/U = 4$, $g_{j=1} = 4.41$; $\Delta g/\Delta j = 1.34$; and $g_{j=1.8} = 4.41 + 0.8(1.34) = 5.482$. Interpolating:

$$\left(\frac{f_h}{U}\right)_{g=6.66} = 4 + \left(\frac{1}{6.672 - 5.482}\right)(6.66 - 5.482) = 4.99$$

$$U = \frac{f_h}{(f_h/U)_{g=6.66}} = \frac{22}{4.99} = 4.41$$

At 251°F, $F_i = (10)^{-1/18} = 0.8799$

$$F_0 = U/F_i = 4.41/0.8799 = 5.01$$

This value compares with 5.6 minutes calculated using the general method in the previous section. Stumbo's procedure for determining the process time $B_b$ can be done directly without the need for iteration. To obtain an $F_0$ of 8.0 minutes a value of g is now required, and this value is obtained from Table 9.14 to correspond to a value of $f_h/U$. U is calculated as :

$$U = F_0 Fi = 8(0.8799) = 7.0392$$
$$f_h/U = 22/7.0392 = 3.1253$$

From Table 9.14, for $z = 18$, $j_c = 1.8$, and $f_h/U = 3$:

$$g_{j=1} = 3.26; \Delta g/\Delta j = 1.05; g_{j=1.8} = 3.26 + 0.8(1.05) = 4.10$$

For $f_h/U = 4$:

$$g_{j=1} = 4.41; \quad \Delta g/\Delta j = 1.34; \quad g_{j=1.8} = 4.41 + 0.8(1.34) = 5.482$$

Interpolating to obtain g for $f_h/U = 3.1253$:

$$g = 4.10 + \left(\frac{5.482 - 4.10}{1}\right)(3.1253 - 3.0) = 4.273$$

$B_b$ is calculated using Equation (9.44):

$$B_b = 22[\log(1.4)(251 - 160) - \log(4.273)] = 32.4 \text{ minutes}$$

Determination of $F_0$ using Hayakawa's procedure: For $g = 6.658$; $K_s = 18/20 = 0.900$; $g/K_s = 7.398$.

From Table 9.16:

$$g/K_s = 7; \qquad U/f_h = 0.1252$$
$$g/K_s = 8; \qquad U/f_h = 0.1020$$

Interpolating to obtain $U/f_h$ for $g/K_s = 7.398$ :

$$U/f_h = 0.1252 - [(0.1252 - 0.1020)/1][7.398 - 7] = 0.1159$$
$$U = 22(0.1159) = 2.551$$

For the cooling curve, use Table 9.17 to 9.21. $T_g = 251 - 6.658 = 244.3$; $I_c = 244.3 - 70 = 174.3$: $I_c/K_s = 174.3/0.900 = 193.71$. The appropriate table is Table 9.17, because $I_c/K_s < 200$ and $j_c < 1.9$. Values of $I_c/K_s = 190$ and 195 can be read in Table 9.17. A value for $U/f_c$ corresponding to $I_c/K_s = 193.71$ is obtained by interpolation. For $j_c = 1.8$, $I_c/K_s = 190$, $U = /f_c = 0.1277$; $I_c/K_s = 195$ and $U = /f_c = 0.1260$. Interpolating:

$$\frac{U'}{f_c} = 0.1277 - \left(\frac{0.1277 - 0.1260}{5}\right)(193.71 - 190) = 0.1264$$

Solving for U = for the cooling part of the process:

$$U = 22(0.1264) = 2.7816.$$

U = is converted to U using Equation (9.46): $U = 2.7816(10)^{-6.66/18} = 1.187$ for the cooling part of the process. Total U is the sum of U for heating and U for cooling.

$$U = 2.551 + 1.187 = 3.738$$

The process $F_0$ is then determined using $U = F_0F_i$.

$F_i$ was previously calculated at 251°F to be 0.8799. Therefore, $F_0 = U/F_i = 3.738/0.8799 = 4.248$ minutes.

Determination of $B_b$ using Hayakawa's procedure. A value of g is first assumed. Let g = 3.7°F. Because $K_s = 18/20 = 0.9$, $g/K_s = 3.7/0.9 = 4.111$°F. For the heating part of the process, Table 9.16 is used. The value of $U/f_h$ corresponding to $g/K_s = 4.111$ will be obtained by interpolation.

From Table 9.16, for $g/K_s = 4$ and $U_h/f_h = 0.2514$; for $g/K_S = 5$ and $U_h/f_h = 0.1958$:

$$\frac{U}{f_h} = 0.2514 - \left(\frac{0.2514 - 0.1958}{1}\right)(4.1111 - 4) = 0.2452$$

Solving for U, $U = 0.2452(22) = 5.39$ for the heating portion of the process.

For the cooling curve: $I_c = 251 - 3.7 - 70 = 177.3$. $I_c/K_s = 177.3/0.9 = 197$. The appropriate table to be used is Table 9.17, because $I_c/K_s < 200$ and $j_c < 1.9$. From Table 9.17, for $j_c = 1.8$, U=/$f_c$; for $I_c/K_s = 197$ will be obtained by interpolation.

$$\frac{I_c}{K_s} = 195; \frac{U_g}{f_c} = 0.1260 = 200; = 0.1243$$

$$\frac{U'}{f_c} = 0.1260 - \left(\frac{0.1260 - 0.1243}{5}\right)(197 - 195) = 0.1253$$

Because $f_c = 22$ minutes, $U = 0.1243(22) = 2.756$. U = is converted to U using Equation (9.46): $U = 2.756(10)^{-3.7/18} = 1.716$ for the cooling portion of the process. The total U is the sum of U for the heating portion and U for the cooling portion.

$$U = 5.394 + 1.716 = 7.11 \text{ min} = F_0F_i$$

$F_i$ was previously determined to be 0.8799. $F_0 = U/F_i = 7.11/0.8799 = 8.08$ minutes. This is close to the specified $F_0$ value of 8.0 min; therefore required value of g is 3.7°F. If the calculated $F_0$ for the assumed g is not close enough to the specified $F_0$, it will be necessary to assume another value of g and to repeat the calculations. When selecting another value of g, keep in mind that a smaller g will result in a larger calculated $F_0$ value.

The selected g of 37°F, which resulted in an $F_0$ value close to the specified $F_0$ of 8.0 minutes, is used to solve for the process time. Solving for $B_b$ using Equation (9.44):

$$B_b = 22[\log(1.4)(251 - 160) - \log(3.7)] = 33.8 \text{ minutes}$$

### 9.6.5 Evaluation of Probability of Spoilage from a Given Process

This procedure is used to determine if a process that deviated from specifications will give a safe product. The procedures discussed in this section will also be useful in cases of spoilage outbreaks where a spoilage organism is isolated, its heat resistance determined, and it is desired to determine if process schedule adjustment is necessary to prevent future occurrences of spoilage. Another useful application of these procedures is the conversion of standard $F_0$ values to $F_0^z$ values for specific microorganisms.

#### *9.6.5.1 Constant Temperature Processes*

A process time at a constant retort temperature and an initial temperature are given. The procedure is similar to example. A g value is calculated using Equation (9.33). Tables 9.14 or 9.16 to 9.20 are then used to determine U at a specified z value, from which $F_0^z$ is calculated. The probability of spoilage is then calculated by substituting $F_0^z$ for t in Equation (9.11).

**Example 9.19.** The following data represents the heating characteristics of a canned product. $f_h = f_c = 22.5$ minutes; $j = j_c = 1.4$. If this product is processed for 25 minutes at 252°F from an initial temperature of 100°F, calculate (a) the $F_0$ and (b) the probability of spoilage if an organism with a $D_0$ value of 0.5 minutes and a z value of 14 is present at an initial spore load of 10/can.

**Solution:**

g is determined from the process time, using Equation (9.33):

$$g = [10]^{\log(jI) - t/f_h}$$
$$= [10]^{[\log[(1.4)(252-100)] - 25/22.5]}$$
$$= [10]^{1.2168} = 16.5°F$$

(a) Because $f_h = f_c$, Stumbo's procedure is used. The $F_0$ is determined using Table 9.14 for $z = 18°F$ and $j_c = 1.4$. Inspection of Table 9.14 reveals that to obtain $g = 16.5$ when $j = 1$, $f_h/U$ has to be between 40 and 45. However, the interpolation factor $\Delta g/\Delta j$ is about 6; therefore, because $j_c = 1.4$, g in the table will increase by 0.4(6) or 2.4. Thus, the entry for $f_h/U = 30$ will be considered, and after calculating g at $j_c = 1.4$, the other entry to be used in the interpolation will be selected.

$$\frac{f_h}{U} = 30; \quad g_{j=1.4} = 14.60 + 0.4(5.3) = 16.72$$

The value of g is greater than 16.5; therefore, the next lower value of $f_h/U$ in the tables will be used to obtain the other value of g to use in the interpolation.

$$\frac{f_h}{U} = 25; \quad g_{j=1.4} = 13.6 + 0.4(4.8) = 15.52$$

Interpolating between g = 16.72 and g = 15.52 to obtain $f_h/U$ corresponding to g = 16.5:

$$\frac{f_h}{U} = \frac{25 + 5(16.5 - 15.52)}{(16.72 - 15.52)} = 29.1$$

$$U = \frac{f_h}{(\frac{f_h}{U})_{g=16.5}} = \frac{22.5}{29.1} = 0.7736 = F_0F_i$$

$$F_i = (10)^{-2/18} = 0.774$$

$$F_0 = \frac{0.773}{0.774} = 0.999\,\text{min}$$

(b) To evaluate lethality to the organism with z = 14°F, $F_0^{14}$ must be determined. Using Table 9.14 for z = 14°F:

$$\frac{f_h}{U} = 50;\ g_{j=1.4} = 14.2 + 0.4(4.00) = 15.8$$

For g = 16.5:

$$\frac{f_h}{U} = 60;\ g_{j=1.4} = 15.1 + 0.4(4.3) = 16.82$$

$$\frac{f_h}{U} = \frac{50 + 10(16.5 - 15.8)}{(16.82 - 15.8)} = 56.9$$

$$U = \frac{f_h}{(f_h/U)_{g=16.5}} = \frac{22.5}{56.9} = 0.395 = F_0F_i$$

$$f_i = (10)^{-2/14} = 0.7197$$

$$F_0^{14} = \frac{U}{F_i} = \frac{0.395}{0.7197} = 0.549\,\text{min}$$

The number of survivors will be

$$N = 10[10]^{-F_0/D_0} = 10(10)^{0.549/0.5} = 0.798$$

The probability of spoilage is 79.80%.

#### *9.6.5.2 Process Temperature Change*

When the process temperature changes, errors in the formula method are magnified because evaluation of $f_h$ and j is based on an original uniform initial temperature, while the starting temperature distribution with in-process temperature deviations is no longer uniform. The most accurate method for evaluating the effect of process temperature changes is by using finite difference methods for evaluation of temperature at the critical point and using the general method for determining process lethality. If process deviation occurs before the temperature at the critical point exceeds 200°F, and the deviation simply involves a step change in processing temperature at $t = t_1$ from $T_{r1}$ to $T_{r2}$ and remains constant for the rest of the process, lethality may be approximated by the formula methods. The part of the process before the step temperature change is considered to have negligible lethality (if the temperature at the critical point did not exceed 200°F), and the temperature at $t_1$ is considered the initial temperature for a process at $T_{r2.}$ Procedures for evaluation will be the same as in example 9.19.

## 9.7 BROKEN HEATING CURVES

Broken heating curves are those that exhibit a break in continuity of the heating rate at some point in the heating process. Thus, two or more line segments will be formed when the heat penetration data are plotted on semi-logarithmic graphing paper. This type of heating behavior will occur when the product inside the can undergoes a physical change that changes the heat transfer characteristics. A typical broken heating curve is shown in Figure 9.17. The slope indices of the curve are designated as

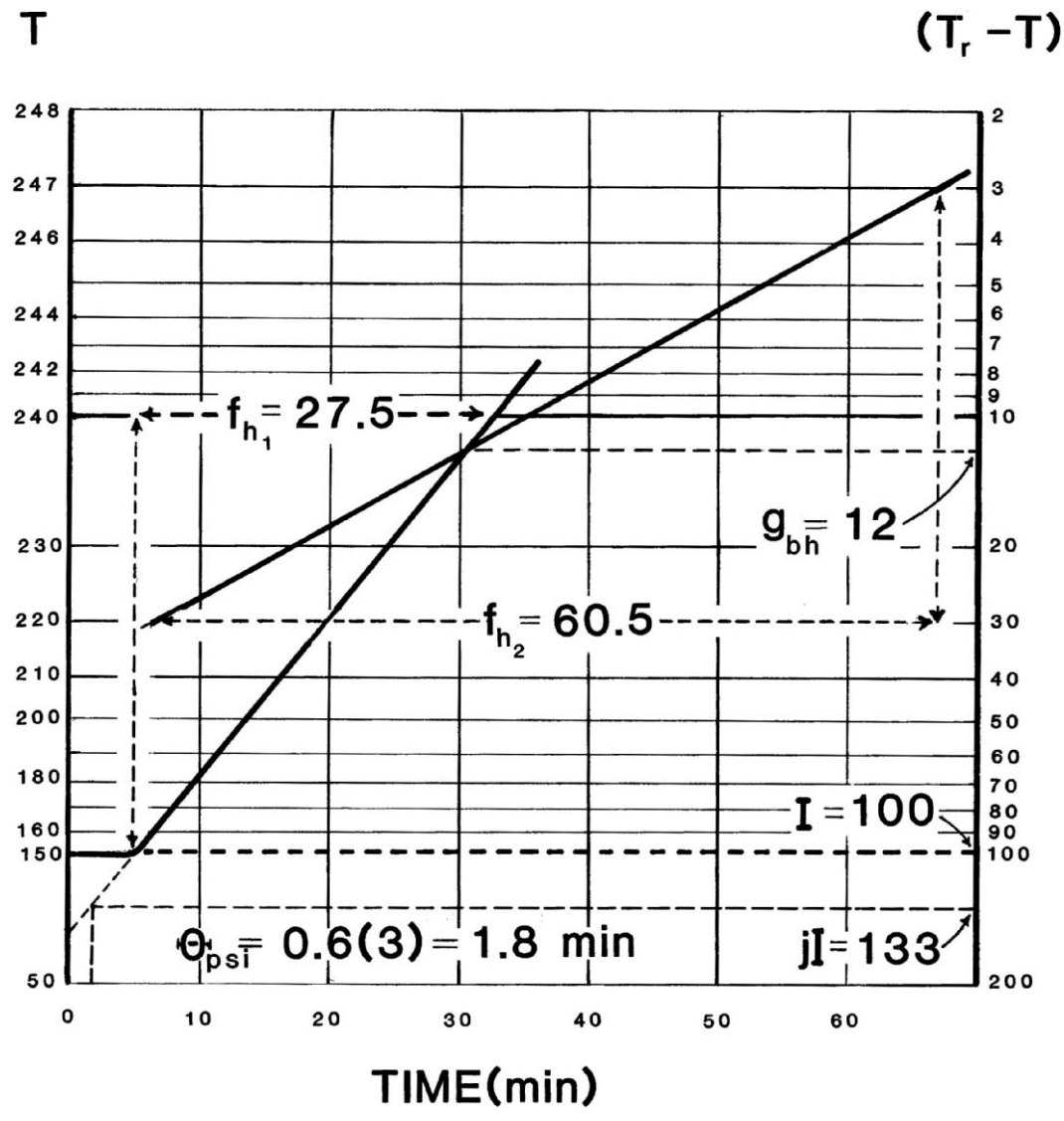


**Figure 9.17** Diagram of a broken heating curve showing the heating curve parameters.

$f_{h1}$ for the first line segment and $f_{h2}$ for the second line segment. The retort-can temperature difference at the point of intersection of the first and second line segments is designated gbh. The rest of the parameters of the heating curve is the same as for a simple heating curve.
The equation of the first line segment is

$$\log\left(\frac{jI}{g_{bh}}\right) = \frac{t_{bh}}{f_{h1}} \tag{9.47}$$

The equation of the second line segment is

$$\log\left(\frac{g_{bh}}{g}\right) = \frac{t - t_{bh}}{f_{h2}} \tag{9.48}$$

Combining Equations (9.46) and (9.47):

$$t = f_{h1}\log\left(\frac{jI}{g_{bh}}\right) + f_{h2}\log\left(\frac{g_{bh}}{g}\right) \tag{9.49}$$

Equation (9.49) is used to calculate a process time to obtain g. An expression for g can be obtained by rearranging Equation (9.49).

$$g = [10]^{1/f_{h2}[f_{h1}\log(jI) - (f_{h1} - f_{h2})\log(g_{bh}) - t]} \tag{9.50}$$

Hayakawa's procedure involves using the lethality tables to determine U for each segment of the heating curve. However, because integration of the lethality in the U-tables is carried from the start of the process, the lethality under the second and succeeding line segments must be corrected by subtracting lethality up to times preceding the shift to the current line segment under consideration.

If there is one break in the heating curve, the following parameters define the line segments: j, I, $f_{h1}$, $g_{bh}$, $f_{h2}$, and g. Tabular values are obtained for $U/f_h$ from Table 9.16 for $g_{bh}/K_S$ and for $g/K_s$.

$$U = f_{h1}\left[\frac{U}{f_h}\right]_{g_{bh}} + f_{h2}\left[\left[\frac{U}{f_h}\right]_{g} - \left[\frac{U}{f_h}\right]_{g_{bh}}\right] \tag{9.51}$$

If there are two breaks in the heating curve, the following parameters define the line segments: j, I, $f_{h1}$, $g_{bh1}$, $f_{h2}$, $g_{bh2}$, $f_{h3}$, and g. Tabular values from Table 9.15 can be obtained for $U/f_h$ at $g_{bh1}/K_s$, $g_{bh2}/K_S$, and $g/K_S$.

$$U = f_{h1}\left[\frac{U}{f_h}\right]_{g_{bh1}} + f_{h2}\left[\left[\frac{U}{f_h}\right]_{g_{bh2}} - \left[\frac{U}{f_h}\right]_{g_{bh1}}\right] + f_{h3}\left[\left[\frac{U}{f_h}\right]_{g} - \left[\frac{U}{f_h}\right]_{g_{bh2}}\right] \tag{9.52}$$

Evaluation of lethality under the cooling curve is the same as in the section "Formula Methods for Thermal Process Evaluation."

Stumbo's procedure involves evaluation of lethality of individual segments of the heating curve. Because the $f_h/U$ versus g tables were developed to include the lethality of the cooling part of the process, a correction needs to be made for the lethality of cooling attributable to the first line segment of the heating curve, which does not exist. The "r" parameter was used to express the fraction of the total process lethality attributed to the heating part of the process.

For the first line segment which ends when $(T_r - T) = g_{bh}$:

$$U_1 = r\frac{f_{h1}}{[f_h/U]_{g_{bh}}} \tag{9.53}$$

The second line segment begins when $(T_r - T) = g_{bh}$ and ends when $(T_r - T) = g$. The lethality from the $f_h/U$ tables considers the heating process with the same $f_h$ value starting from time zero, therefore the effective lethality up to $(T_r - T) = g_{bh}$ must be subtracted from the total.

$$U_2 = \frac{f_{h2}}{(f_h/U)_g} - r\frac{f_{h2}}{(f_h/U)_{g_{bh}}} \tag{9.54}$$

Thus, the total U for the process is

$$U = \frac{f_{h2}}{(f_h/U)_g} + \frac{r(f_{h1} - f_{h2})}{(f_h/U)_{g_{bh}}} \tag{9.55}$$

The denominator, $(f_h/U)_g$ or $(f_h/U)_{g\,b\,h}$ in Equations (9.52) to (9.55) represent tabular values for $f_h/U$ corresponding to g or $g_{\ bh}$. The parameter "r" is a function of g. Figure 9.18 can be used to obtain r corresponding to g.

**Example 9.20.** For the product that exhibited the heating curve shown in Fig. 9.17, assume $f_c = f_{h2}$ and $j_c = j$. This product is processed for 50 minutes at 248°F, from an initial temperature of 140°F. Calculate $F_0$ and the probability of spoilage from an organism having a $D_0$ value of 1.5 minutes and a z value of 16°F in cans given this process. The initial spore load is 100/can. The cooling water temperature is 60°F.

**Solution:**

Note that the conditions under which the product is processed are different from those under which the heat penetration parameters were derived. Figure 9.17 is simply used to determine the heat penetration parameters, and these parameters are utilized in the specific process to evaluate the process lethality. From Fig. 9.17: $f_{h1} = 27.5$ minutes; $f_{h2} = 60.5$ minutes; $g_{bh} = 12$°F; $I = 248 - 140 = 108$°F; $j = j_c = 1.33$. Solving for g using Equation (9.50):

The exponent is:

$$g = [10]^{\left(\frac{1}{f_{h1}}\log(jI) - (f_{h1} - f_{h2})\log(g_{bh}) - t\right)}$$

$$\text{Exponent} = \frac{27.5\log(1.33)(108) - (27.5 - 60.5)\log(12) - 50}{60.5}$$

$$\text{Exponent} = \frac{[27.5(2.157) + 33(1.0792) - 50]}{60.5} = 0.743$$

$$g = (10)^{0.743} = 5.53°\text{F}$$

Using Stumbo's procedure: The $F_0$ value for the process is determined using Table 9.14 for $z = 18$°F and $j_c = 1.33$. The value of $f_h/U$ corresponding to $g = 5.53$°F and that corresponding to $g_{bh} = 12$°F will have to be determined by interpolation. Inspection of Table 9.12 shows that for $j_c = 1$, $g = 5.40$ corresponds to $f_h/U$ and the interpolating factor $\Delta g/\Delta j = 1.59$. Thus:

$$\frac{f_h}{U} = 5; g_{j=1.33} = 5.40 + 1.59(0.33) = 5.925$$

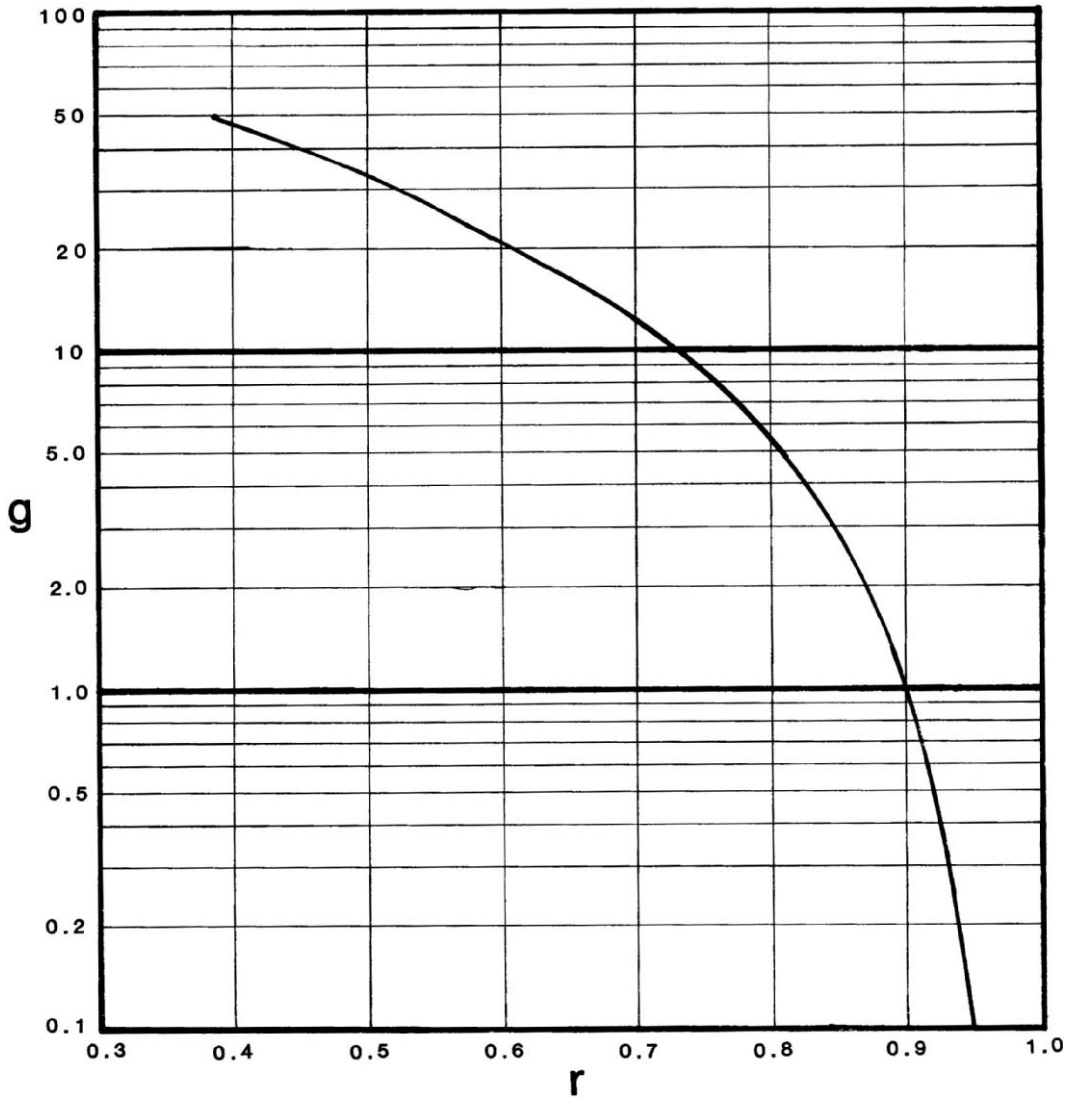


**Figure 9.18** Values of the parameter r corresponding to the value of g. (Source: Anonymous. 1952. Calculation of process for canned food. American Can Company, Technical Services Division, Maywood, IL.)

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This value is higher than 5.53; therefore, a lower value of $f_h/U$ is picked for the second set of values to use in the interpolation. Thus:

$$\frac{f_h}{U} = 4; g_{j=1.33} = 4.41 + 1.34(0.33) = 4.852$$

The value of $f_h/U$ corresponding to $g = 5.53$ is calculated by interpolating between the above two

tabular values of g:

$$\left(\frac{f_h}{U}\right)_{g=5.53} = 4 + \frac{(5-4)(5.53-4.852)}{(5.925-4.852)} = 4.632$$

Next, the value of $f_h/U$ corresponding to $g_{bh}$ needs to be evaluated. $g_{bh}$ is entered into Table 9.14 as a value of g, and the corresponding $f_h/U$ is determined.

Inspection of Table 9.14 shows that for $j_c = 1$, $z = 18$, and $f_h/U = 15$ corresponds to $g = 10.88$ with the interpolating factor $\Delta g/\Delta j = 3.57$. Thus:

$$\frac{f_h}{U} = 15; \quad g_{j=1.33} = 10.88 + 0.33(3.57) = 12.058$$

The value of g is greater than 12; therefore, the next lower tabular entry is selected as the other set of values used in the interpolation.

$$\frac{f_h}{U} = 10; \quad g_{j=1.33} = 8.78 + 0.33(2.69) = 9.668$$

Interpolating between these two values to obtain $f_h/U$ corresponding to $g = 12$:

$$\left(\frac{f_h}{U}\right)_{g_{bh}} = \left(\frac{f_h}{U}\right)_{g=12} = 10 + 5(12 - 9.668)/(12.058 - 9.668) = 14.88$$

Equation (9.55) is used to determine U from values of $(f_h/U)_g$ and $(f_h/U)_{g\,bh}$. r needs to be evaluated from Fig. 9.18 to correspond to $g_{bh} = 12$. From Fig. 9.18, $r = 0.71$. Using Equation (9.55):

$$U = \frac{60.5}{4.622} + \frac{0.71(27.5 - 60.5)}{14.88} = 13.08 - 1.574 = 11.51$$

Using Equation (9.45):

$$F_i = (10)^{2/18} = 1.291$$

$$F_0 = U/F_i = 11.51/1.291 = 8.91 \text{ minutes}$$

The probability of spoilage: Because the organism has a z value of 16°F, $F_0$ cannot be used in Equation (9.11) to determine the probability of spoilage. It is necessary to calculate $F_0^{16}$ for the conditions used in the process. Because the process is the same, g calculated in the first part of this problem is the same; $g = 5.53$. Evaluating $f_h/U$ corresponding to this value of g, however, should be done using $z = 16$°F in Table 9.14. A double interpolation needs to be done. Values for $f_h/U$ corresponding to $g = 5.53$ are determined for $z = 14$ and $z = 18$; and the two values are interpolated to obtain $f_h/U$ at $z = 14$.

$f_h/U = 6$; $g_{j=1.33,z=14} = 4.63 + 0.33(1.56) = 5.145$
$g_{j=1.33,z=18} = 6.5 + 0.33(1.82) = 6.850$
$f_h/U = 6$; $g_{j=1.33,z=16} = 5.145 + [(18 - 16)(6.850 - 5.145)]/(18 - 14) = 5.997$
$f_h/U = 5$; $g_{j=1.33,z=14} = 4.02 + 0.33(1.32) = 4.455$
$f_h/U = 5$; $g_{j=1.33,z=18} = 5.40 + 0.33(1.59) = 0.925$
$f_h/U = 5$; $g_{j=1.33,z=16} = 4.455 + (18 - 16)(5.925 - 4.455)/(18 - 14) = 5.190$

Interpolating between the two values of $f_h/U$ at $z = 16$, which straddles $g = 5.53$:

$$(f_h/U)_{g=5.53,z=16} = 5 + (6 - 5)(5.53 - 5.190)/(5.997 - 5.190) = 5.42$$

The same procedure is used to determine $f_h/U$ corresponding to $g_{bh} = 12$

$f_h/U = 20$; $g_{j=1.33,z=14} = 9.63 + 0.33(2.96) = 10.61$
$f_h/U = 20$; $g_{j=1.33,z=18} = 12.4 + 0.33(4.28) = 13.81$
$f_h/U = 20$; $g_{j=1.33,z=16} = 10.61 + (16 - 14)(13.81 - 10.61)/(18 - 14) = 12.21$
$f_h/U = 15$; $g_{j=1.33,z=18} = 10.88 + 0.33(3.57) = 12.06$
$f_h/U = 15$; $g_{j=1.33,z=14} = 8.29 + 0.33(2.68) = 9.17$
$f_h/U = 15$; $g_{j=1.33,z=16} = 9.7 + (16 - 14)(12.06 - 9.17)/(18 - 14) = 11.14$

Interpolating between the two values of $f_h/U$ at $z = 16$, which correspond to values of g, which straddle $g_{bh} = 12$:

$$(fh/U)_{g\ b\ h} = 15 + (12 - 11.14)(20 - 15)/(12.21 - 11.14) = 19.02$$

Because r is dependent only on $g_{bh}$, the same value as before is obtained from Fig. 9.18. For $g_{bh} = 12$, $r = 0.71$. Using Equation (9.55):

$$U = \frac{60.5}{5.41} + \frac{0.71(27.5 - 60.5)}{19.02} = 11.182 - 1.232 = 9.95$$
$$F_i = (10)^{2/16} = 1.333$$
$$F_0^{16} = U/F_i = 9.95/1.333 = 7.465$$

The number of survivors can now be calculated by substituting $F_0^{16}$ for t in Equation (9.11). Using Equation (9.11):

$$\log(N/100) = -F_0/D_0 = -7.465/1.5 = -4.977$$
$$N = 10^{-4.977} = 0.0011$$

The probability of spoilage is 11 in 10,000.

Hayakawa's procedure: The solution for $F_o$ will not be presented here. The procedure will the same as for the determination of $F_0^z$, which is shown below. As an exercise, the reader can determine $F_0$. The calculated value is 8.16 minutes. The probability of spoilage is determined by calculating $F_0^{16}$.

For the heating part of the process, U is calculated using Table 9.16 to obtain $(f_h/U)_{gbh}$, which is substituted in Equation (9.51). The parameter for the table entry in Table 9.16 is $g/K_s = 5.53/0.8 = 6.91$. g was previously calculated for this problem to be 5.53°F and $K_s = 16/20 = 0.8$. $g_{bh}/K_s = 12/0.8 = 15.00$.

From Table 9.16: $(f_h/U)_{g/Ks=6} = 0.1555$ and $(f_h/U)_{g/Ks=7} = 0.1252$. $f_h/U$ for $g/K_s = 6.91$ is obtained by interpolating between the above values.

$$(f_h/U)_g = 0.1555 - (0.1555 - 0.1252)(6.91 - 6)/(7 - 6) = 0.1279$$

From Table 9.16, for $g_{bh}/K_s = 15.00$:

$$(f_h/U)_{gbh} = 0.02706$$

There is only one break in the heating curve; therefore, Equation (9.51) is used to determine U for the heating portion of the process.

$$U = 27.5(0.02706) + 60.5(0.1279 - 0.02706) = 6.84 \text{ minutes}$$

The lethality of the cooling curve is determined using Tables 9.17 to 9.21. Tabular entry is done using $I_c/K_s$. Because g = 5.53°F, $T_g = 248 - 5.53 = 242.47$. $I_c = 242.47 - 60 = 182.47$;

$I_c/K_s = 182.47/0.8 = 228$. Table 9.19 is the appropriate table to use, because $I_c/K_s > 200$ and $j_c < 1.9$. From Table 9.19:

$$(U = /f_c)_{Ic/Ks=225,jc=1.2} = 0.06604$$
$$(U = /f_c)_{Ic/Ks=225,jc=1.4} = 0.08862$$

Interpolating for $j_c = 1.33$:

$$(U = /f_c) = 0.06604 + [(0.08862 - 0.06604)(1.22 - 1.2)]/0.2 = 0.8072$$

From Table 9.19:

$$(U = /f_c)_{Ic/Ks\,=\,230,jc\,=\,1.2} = 0.06530$$
$$(U = /f_c)_{Ic/Ks\,=\,230,jc\,=\,1.4} = 0.08782$$

Interpolating for $j_c = 1.33$:

$$(U = /fc) = 0.06530 + [(0.08782 - 0.06530)(1.33 - 1.2)]/0.2 = 0.07994$$

Solving for $(U = /f_h)_{Ic/Ks=228,jc=1.33} = 0.07994 + [(0.08782 - 0.07994) \times (230 - 228)]/5 = 0.0831$

$$U = f_c(U/f_c)_{Ic/Ks\,=\,228,\,jc\,=\,1.33} = 60.5(0.0831) = 5.027$$

$U =$ is then converted to U of the cooling part of the process using Equation (9.46).

$$U = 5.027|10|^{-5.53/16} = 5.027(0.452) = 2.27 \text{ minutes}$$

The total U is the sum of U for heating and U for cooling.

$$U = 2.27 + 6.86 = 9.13 \text{ minutes}$$
$$F_0^{16} = 9.13|10|^{248-250/16} = 6.85 \text{ minutes}$$

The number of survivors is calculated using Equation (9.11) by substituting $F_0^{16}$ for t:

$$\text{Log } (N/100) = -6.85/1.5 = -4.567$$

$$N = 100(10)^{-4.567} = 0.0027$$

The probability of spoilage = 27/10,000.

Hayakawa's procedure results in a higher probability of spoilage than Stumbo's procedure. $F_0$ calculated using Hayakawa's procedure is lower than that calculated using Stumbo's procedure, which in turn is lower than that calculated using the general method, as shown in the examples in the section "Determination of $f_c$ and $j_c$" and "Formula Method for Thermal Process Evaluation." The safety factor built unto the formula methods is primarily responsible for the success with which these thermal process calculation techniques have served the food industry over the years in eliminating the botulism hazard from commercially processed canned foods.

## 9.8 QUALITY FACTOR DEGRADATION

Quality factor degradation has to be evaluated on the basis of integrated lethality throughout the container. Unlike microbial inactivation, which leaves practically zero survivors at regions in the can near the surface, there is substantial nutrient retention in the same regions. Quality factor degradation

can be determined by separating the container into incremental cylindrical shells, calculating the temperature at each shell at designated time increments, determining the extent of degradation, and summing the extent of degradation at each incremental shell throughout the process. At the termination of the process, the residual concentration is calculated by integrating the residual concentration at each incremental cylindrical shell throughout the container. The procedure is relatively easy to perform using a computer, but the calculations can be onerous if done by hand.

For cylindrical containers, Stumbo (1973) derived an equation for the integrated residual nutrient based on the following observations on the temperature profiles for conduction heat transfer in cylinders.

(a) In a container, an isotherm exists where the j value at that point, designated $j_v$, is 0.5 j. The g at that point at any time, designated $g_v$, is 0.5 g, and the volume enclosed by that isotherm is 19% of the total volume.
(b) If v is the volume enclosed by the isotherm, and if the F value at the isotherm and at the critical point are $F_v$ and F, respectively, then the difference, $(F_v - F)$, is proportional to $\ln(1 - v)$.

The following expression was then derived:

$$\overline{F} = F + D \log\left(\frac{D + 10.92(F_v - F)}{D}\right) \tag{9.56}$$

Equation (9.56) is an expression for the integrated lethal effect of the heating process ($\overline{F}$) on nutrients based on the lethality at a the critical point, F, and the lethality $F_v$ evaluated at a point where $g_v = 0.5$ g and $j_v = 0.5$ j. Equation (9.54) has been found to be adequate for estimating nutrient retention in cylindrical containers containing foods that heat by conduction.

**Example 9.21.** A food product has a j value of 1.2, a $j_c$ value of 1.4, and $f_h = f_c = 35$ minutes. This product is processed at 255°F from an initial temperature of 130°F to an $F_0$ of 5.5. Calculate the residual ascorbic acid remaining in this product after the process if the initial concentration was 22 Φg/g. The $D_0$ value for ascorbic acid in the product is 248 minutes, and the z value is 91°F.

**Solution:**

Stumbo's procedure will be used. The $F_0$ value is used to determine a value of g using the $f_h/U$ tables for $z = 18$ and $j_c = 1.4$. From this value of g, a new $f_h/U$ is determined for a z value of 91°F. The $F_0^{91}$ obtained is the value of F in Equation (9.56). $F_v$ is determined from $f_h/U$, which corresponds to $g_v = 0.5g$ and $j_v = 0.5j_c$.

$$U = F_0 F_i = 5.5(10)^{-5/18} = 2.901 \text{ minutes}$$
$$f_h/U = 35/2.901 = 12.06$$

From Table 9.14, for $z = 18$:

$$\frac{f_h}{U} = 10;\ g_{jc=1.4} = 8.78 + 2.69(0.4) = 9.956$$
$$\frac{f_h}{U} = 15;\ g_{jc=1.4} = 10.88 + 3.57(0.4) = 12.308$$

For $f_h/U = 12.06$:

$$g = 9.936 + (12.308 - 9.956)(12.06 - 10)/(15 - 10) = 10.925$$

For g = 10.925, using Table 9.15 , z = 90°F:

$$\frac{f_h}{U} = 1; g_{jc=1.4} = 3.06 + 0.4(2.19) = 3.936$$

$f_h/U$ for g = 10.925:

$$\frac{f_h}{U} = 2;\ g_{jc=1.4} = 11.03 + 0.4(7.88) = 14.182 = 1 + \frac{(2-1)(10.925 - 3.936)}{(14.182 - 3.936)} = 1.682$$

U at the geometric center = 35 / 1.682 = 20.81 minutes.
$F_i = 10^{-5/90} = 0.8799$.
F at the geometric center = $U/F_i$ = 23.65 minutes.
At a point where $g_v = 0.5$ g and $j_{vc} = 0.5j_c$, $g = 0.5(10.925) = 5.463$; $j_{vc} = 0.5(1.4) = 0.7$.
Using Table 9.15, z = 90°F:

$$\frac{f_h}{U} = 1;\ g_{jc=0.7} = 3.06 - 0.3(2.19) = 2.403$$

$f_h/U$ for $g_v = 5.463$:

$$\frac{f_h}{U} = 2;\ g_{jc=0.7} = 11.03 - 0.3(7.88) = 8.666 = 1 + \frac{(2-1)(5.463 - 2.403)}{(8.666 - 2.403)} = 1.488$$

U at point where $g_v = 0.5$ g = 35 /1.488 = 23.52 minutes.
$F_v = U/F_I = 23.52 / 0.8799 = 26.73$ minutes.
Substituting in Equation (9.56):

$$\overline{F} = 23.65 + 248 \log\left[\frac{248 + 10.92(26.73 - 23.65)}{248}\right]$$

$$= 23.65 + 248(0.055233) = 37.348$$

$$\log\left(\frac{C}{C_0}\right) = -\frac{F}{D} = \frac{-37.348}{248} = -0.1506$$

$$\frac{C}{C_0} = (10)^{-0.1506} = 70.6$$

The percent retention of ascorbic acid is 70.6%.
The residual ascorbic acid content is 0.706(22) = 15.55 Φg/g.

Hayakawa's tables may also be used to determine F and $F_v$ to use in Equation (9.56). U for the heating and cooling portions of the process has to be evaluated separately, as was done for microbial inactivation. When values of z are not the same as the tabulated values in Table 9.16, use of Hayakawa's tables is recommended because interpolation across large values of z in Table 9.16 may introduce too much of an error.

## PROBLEMS

9.1. Calculate the D value of an organism that shows 30 survivors from an initial inoculum of $5 \times 10^6$ spores after 10 minutes at 250°F.

9.2. What level of inoculation of PA 3679 ($D_0 = 1.2$ minutes) is required such that a probability of spoilage of 1 in 100 attributed to PA 3679 would be equivalent to 12D inactivation of *C. botulinum*? Assume the same temperature process and the same z values for both organisms. The $D_0$ value of *C. botulinum* is 0.22 minutes.

9.3. Calculate the length of a holding tube in high-temperature processing in an aseptic packaging system that would be necessary to provide a 5D reduction of spores of PA 3679 ($D_{250} = 1.2$ minutes) at 280°F. Use a z value of 20°F. The rate of flow is 30 gal/min, density is 65 lb/ft$^3$, and viscosity is 10 cp. The tube has 1.5-in. outside diameter and has a wall thickness of 0.064 in.

9.4. If the same system were used on another fluid having a density of 65 lb/ft$^3$ and a viscosity of 100 cp, calculate the probability of spoilage when the process is carried out at 280°F (z = 20). The initial inoculum is 100 spores/can ($D_{250} = 1.2$ minutes). The rate of flow is 30 gal/min on a 1.5-in. outside diameter tube (wall thickness 0.064 in.).

9.5. If an initial inoculum of 10 spores/g of produce ($D_{250} = 1.2$ minutes) and a spoilage rate of 1 can in 100,000 is desired, calculate an F value for the process that would give the desired level of inactivation. Calculate the $F_{280}$ for a z value of 18°F.

9.6. If an organism has a D value of 1.5 at 250°F and a z value of 15°F, calculate the $F_{240}$ for a probability of spoilage of 1 in 10,000 from an initial inoculum of 100 spores/can.

9.7. Figure 9.19 shows an air sterilization system that supplies sterile air to a process. Calculate the length of the holding tube necessary to sterilize the air. The most heat resistant organism that must be avoided requires 60 minutes of heating at 150°C sterilization and has a z value of 70°C. The inside diameter of the holding tube is 0.695 in. Assume plug flow ($V_{max} = V_{avg}$).

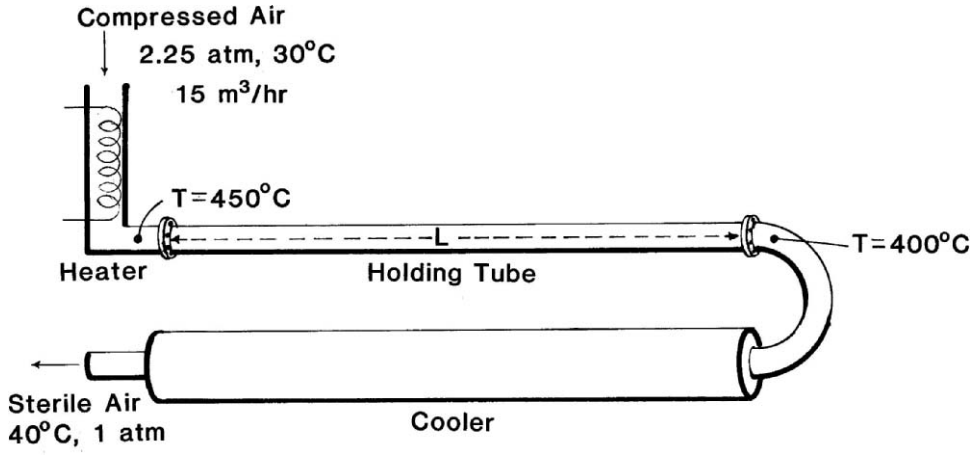


**Figure 9.19** Diagram of an air sterilization system by heat (for Problem 7 ).

9.8. (a) A food product in a 303 × 407 can has an $f_h = 5$ and a $j = j_c = 0.8$. For an initial temperature of 80°F and a retort temperature of 250°F, calculate the process time $B_b$. Use an $F_0 = 4$ minutes and $z = 18$°F.

(b) The product in part (a) is processed in a stationary retort and it takes 4 minutes for the retort to reach 250°F from the time the steam was turned on. How many minutes after turning the steam on should the steam be turned off?

(c) In one of the retorts where the cans were processed, there was a mis-process and the record on the retort temperature chart showed the following:

| *Time (min)* | *Retort temperature °F* |
|---|---|
| 0 | 70 |
| 3 | 210 |
| 10 | 210 |
| Sudden jump from 210°FE to 250°F at 10 minutes | |
| 15 | 250 |
| 16 | Steam off, cooling water on |

What is the $F_0$ of this process. The can temperature at time 0 was 80°F.

9.9. In a given product, PA 3679 has a D value of 3 minutes at 250°F and a z value of 20°F. If the process was calculated at 280°F for a z value of 18°F, how many minutes of heating is required for a 5D process? What would be the actual probability of spoilage of PA 3679 if $N_0$ is 100 spores/can?

9.10. The following heat penetration data were obtained on Chili Con Carne processed at 250°F in a retort having a come-up time of 3 minutes. Assume $j = j_c$.

(a) Calculate the $f_h$ and j values and processes at:

250°F, $z = 18$, $F_0 = 8$ (initial temperature = 120°F)
240°F, $z = 18$, $F_0 = 8$ (initial temperature = 120°F)
260°F, $z = 18$, $F_0 = 8$ (initial temperature = 120°F)

(b) Calculate the probability if spoilage from FS 1518 that might occur from the process calculated at 240°F, $z = 18$, $F_0 = 8$ if FS 1518 has a D value at 250 of 4 minutes and a z value of 22°F for an initial spore load of 50/can.

Heat penetration data

| *Time (min)* | *Temp. (°F)* | *Time (min)* | *Temp. (°F)* |
|---|---|---|---|
| 0 | 170 | 35 | 223 |
| 5 | 170 | 40 | 228 |
| 10 | 180 | 45 | 235 |
| 15 | 187 | 50 | 236 |
| 20 | 200 | | |
| 25 | 209 | | |
| 30 | 216 | | |

9.11. A canned food having an $f_h$ of 30 and a $j = j_c$ of 1.07 contains a spore load of 56 organisms per can and this organism had a $D_{250}$ value of 1.2 minutes. A process with an $_0$ of 6 minutes was calculated for this product at a retort temperature of 250°F and an initial temperature of

150°F. Subsequent analysis revealed that the spores actually have a z value of 14°F instead of 18°F. If the same time as the above process was used at a retort temperature of 248°F, calculate the probability of spoilage.

9.12. A process for a pack of sliced mushrooms in 303 × 404 cans on file with the FDA specifies a processing time at 252°F for 26 minutes from an initial temperature of 110°F. A spoiled can from one pack was analyzed microbiologically and was found to contain spore-forming organisms. Data on file for similar products show j values ranging from 0.98 to 1.15 and $f_h$ values ranging from 14 to 18 minutes.
   (a) Would the filed process be adequate to provide at least a 12D reduction in spores of *C. botulinum* (D = 0.25 min; z = 14°F)?
   (b) If the spores of the spoilage organism have $D_0$ of 1.1 minutes and z of 16°F, what would have been the initial number of organisms in the can to result in a probability of spoilage of 1 in 10,000 after the process.
   (c) If you were evaluating the process, would you recommend a recall of the pack for inadequate processing? Would you be calling for additional technical data on the process before you made a recommendation? Explain your action and provide as much detail to convince a non- technical person (i.e., lawyers and judges) that your action is the correct way to proceed.

9.13. The following data were collected in a heat penetration test on a canned food for thermal process determination.

| *Time (min)* | *Temp. (°F)* | *Time (min)* | *Temp. (°F)* |
|---|---|---|---|
| 0 | 128 | 35 (cool) | 245 |
| 3 | 128 | 40 | 243 |
| 5 | 139 | 45 | 240 |
| 10 | 188 | 50 | 235 |
| 15 | 209 | 55 | 185 |
| 20 | 229 | 60 | 145 |
| 25 | 238 | 65 | 120 |
| 30 | 242 | 70 | 104 |

The processing temperature was 250°F and the retort come-up time was 2 minutes. Cooling water temperature was 60°F.
Calculate:
   (a) The values of $f_h$, $f_c$, $j_h$, and $j_c$.
   (b) If this product is processed from an initial temperature of 150°F at 248°F, how long after retort temperature reaches 248°F must the process be carried out before the cooling water is turned on if the final can temperature at the time of cooling must reach to within 2 degrees of the retort temperature.
   (c) If the process is to be carried out at 252°F from an initial temperature of 120°F, calculate a process time such that an organism with a $D_0$ value of 1.2 minutes and a z of 18°F will have a probability of spoilage of 1 in 10,000 from an initial spore load of 100/can.

9.14. Beef stew is being formulated for canning. The marketing department of the company wants large chunks of meat in the can and they stipulate that the meat should be 5-cm cubes.
The current product utilizes 2-cm cubes of all vegetables (carrots and potatoes) and meat, and the process time used is 50 minutes at 250°F from an initial temperature of 150°F.

Marketing thinks that the change can be made without major alteration of the current process.

Heat penetration data for the current product obtained from the files did not specify if the thermocouple was embedded in a particle during the heating process. The $f_h$ value was reported to be 35 minutes and j of heating was 1.55. There was no data available on j of cooling. There was, however, an inoculated pack done where an inoculum of 1000 spores of an organism having a $D_0$ value of 1.2 minutes and a z value of 18°F injected into a single meat particle in each can resulted in a spoilage rate of 3 cans in 1000.

(a) Calculate the $F_0$ of the process used on the current product based on the heat penetration data available.
(b) Calculate the $F_0$ of the process based on the survivors from the inoculated microorganisms. Does the inoculated pack data justify the assumption of a safe process on the current product?
(c) Is it likely that the heat penetration data was obtained with the thermocouple inside a particle or was it simply located in the fluid inside the can? Explain your answer.
(d) Calculate the most likely value for the $f_h$ if the thermocouple was located in the center of a particle, based on the inoculated pack data, assuming that the j value would be the theoretical j for a cube of 2.02.
(e) If the$f_h$ varies in direct proportion to the square of the cube size, and j remains the same at 2.02, estimate the process time for the 5-cm size cube such that the $F_0$ value for the process will be similar to that based on the inoculated pack data on the present product.

9.15. A biological indicator unit (BIU), which consists of a vial containing a spore suspension and installed at the geometric center of a can, was installed to check the validity of a thermal process given a canned food. The canned food has an $f_h$ value of 30 minutes and a j value of 1.8. Of the 1000 spores originally in the BIU, an analysis after the process showed a survivor of 12 spores. The spores in the BIU has a $D_0$ of 2.3 min and a z value of 16°F. The process was carried out at 248°F from an initial temperature of 140°F. Calculate:
(a) The $F_0$ value received by the geometric center of the can.
(b) The process time.
(c) The sterilizing value of the process expressed as a number of decimal reductions [(log $N_0/N$) of *C. botulinum* having a $D_0$ value of 0.21 minutes and a z value of 18°F].

9.16. A canned food with an $f_h$ of 30 minutes and j of 1.2 is to be given a process at 250°F with an $F_0$ of 8 minutes and a z of 18°F. In order to verify the adequacy of the process, an inoculated pack is to be performed using an organism with a $D_0$ of 1.5 minutes and a z of 22°F. If the process to be used on the inoculated pack is at 250°F from an initial temperature of 130°F, calculate the number of spores that must be inoculated per can such that a spoilage rate of 10 in 100 will be equivalent in lethality to the process $F_0$ desired. Assume j of heating and cooling are the same.

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