Thermal Processing

Advanced Food Process Engineering

(PFE-503)

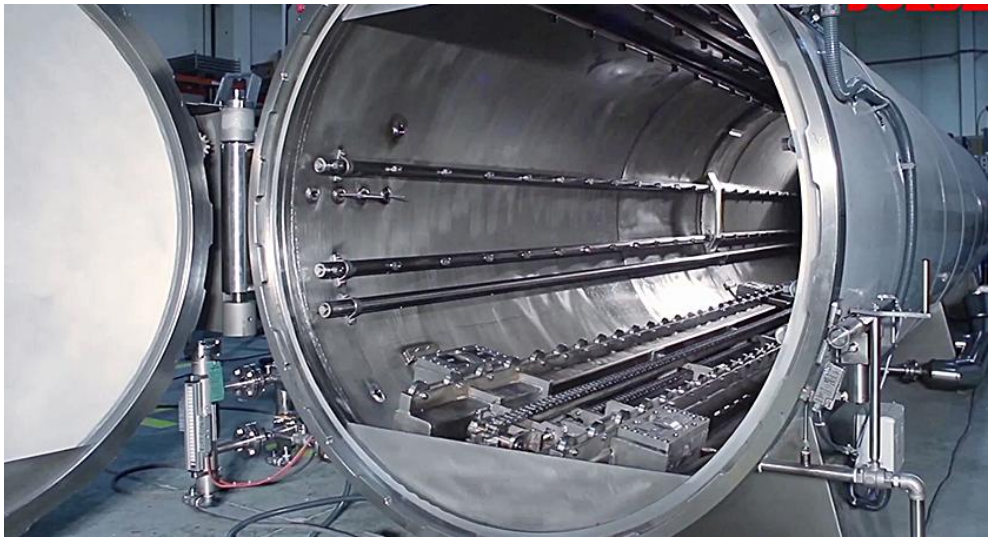
Lecture 1

Contents

- Thermal processing
- Death rate kinetics
- Thermal process calculations
- Methods of sterilization and equipments
- Latest trends in thermal processing

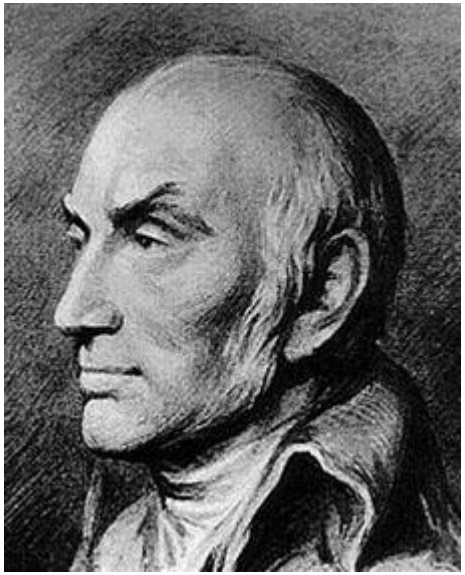
Thermal processing

- **Thermal processing** is defined as the combination of temperature and time required to eliminate a desired number of microorganisms from a food product.



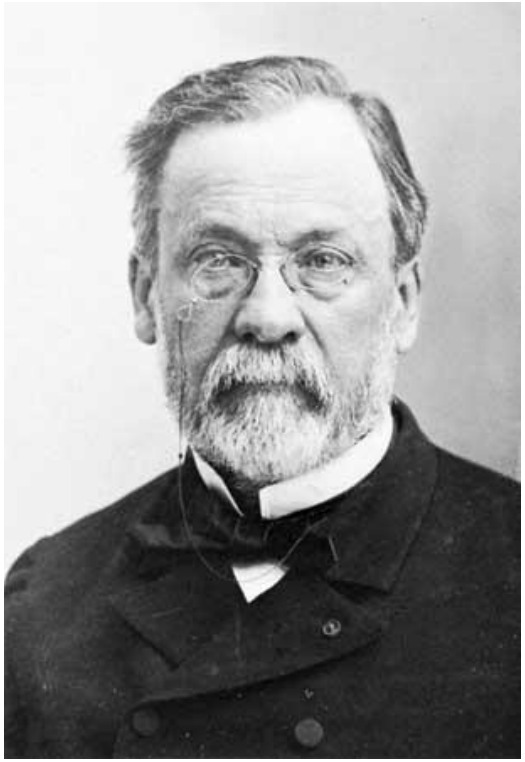
Thermal processing

- French inventor **Nicolas Appert** (1749–1841) who first demonstrated that long-term preservation of different kinds of foods can be achieved by heating the foods for a long time (many hours) in hermetically closed containers.



Thermal processing

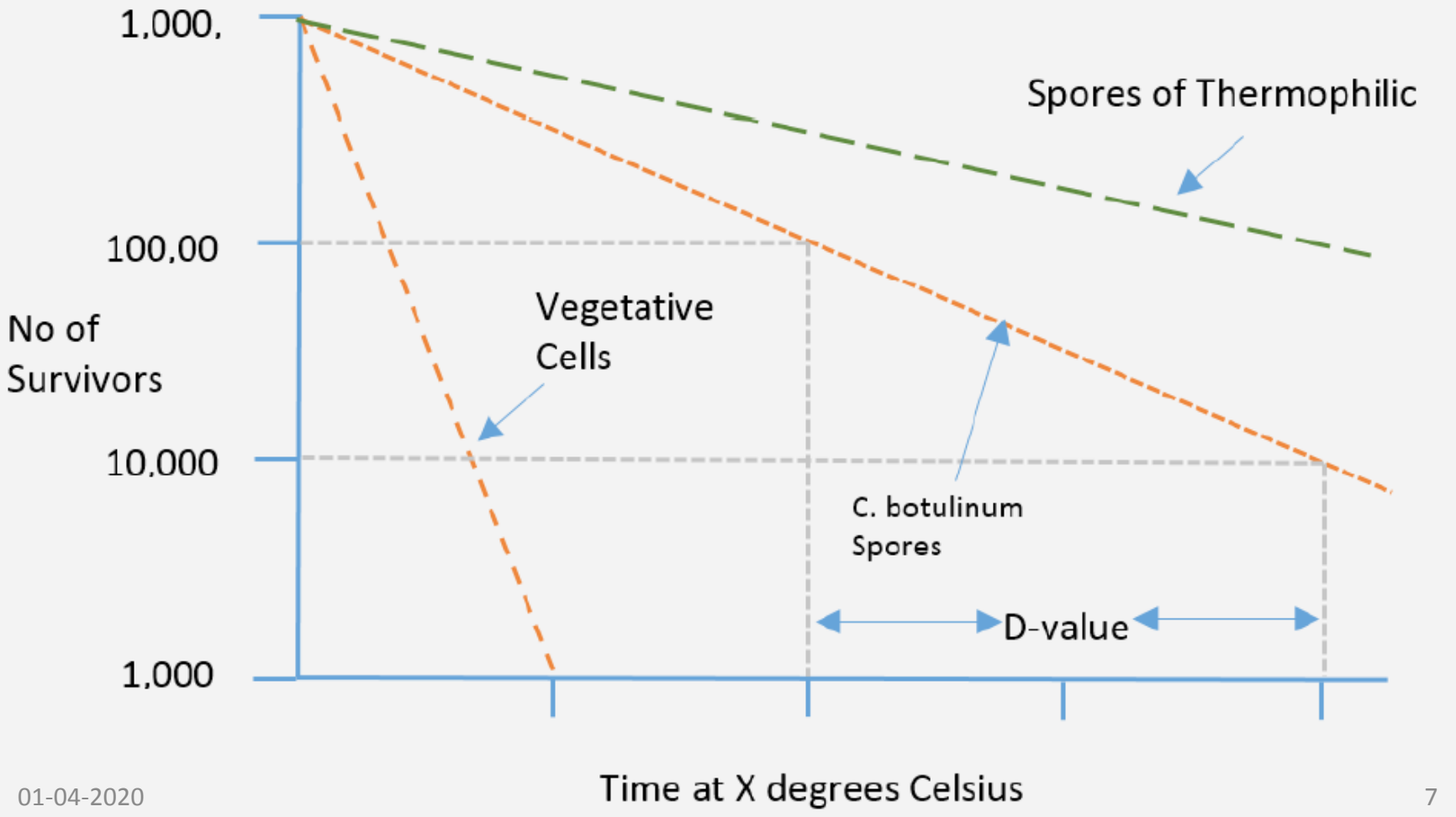
- The microbial origin of food spoilage and the relationship between thermal destruction of microorganism and food preservation were demonstrated only later by **Louis Pasteur** (French chemist and biologist, 1822–1895).



Thermal Processing - Classification

- ***Pasteurization :*** *heat processing at relatively mild temperature (say 70–100°C).*
  - Pasteurization destroys vegetative cells of microorganisms but has almost no effect on spores.
- ***Sterilization :*** *heat processing at high temperature (above 100°C) with the* objective of destroying all forms of microorganisms, including spores.
  - Sterilization alone provides long-term preservation of foods, on the condition that recontamination is prevented by proper packaging

Thermal Processing - Classification



Pasteurization

- The process objective is to destroy non-spore-forming pathogens (e.g. *Mycobacterium tuberculosis , Salmonella, Listeria etc. in milk, Salmonella in* liquid egg)
- The product is intended for consumption within a short time after production and is distributed under refrigeration (pasteurized dairy products, ready-to-eat meals prepared by cook–chill technologies)
- The acidity of the product is high enough (pH 4.6) to prevent growth of spore-forming pathogens, particularly *Clostridium botulinum (fruit juices,* canned fruit, pickles)
- The process objective is to prevent ‘ wild ’ fermentation and/or to stop fermentation (wine, beer).

Blanching

- The primary purpose of blanching is to destroy enzyme activity in fruit and vegetables. It is not intended as a sole method of preservation, but as a pre-treatment prior to freezing, drying and canning. Other functions of blanching include:
- Reducing surface microbial contamination
- Softening vegetable tissues to facilitate filling into containers
- Removing air from intercellular spaces prior to canning
- Methods of Blanching
- Blanching is carried out at up to 100°C using hot water or steam at or near atmospheric pressure.

Sterilization

- The aim of sterilization is the destruction of all bacteria including their spores.
- Heat treatment of such products must be severe enough to inactivate/kill the most heat resistant bacterial microorganisms, which are the spores of Bacillus and Clostridium.
- Food products filled in sealed containers are exposed to temperatures above 100°C in pressure cookers.
- Temperatures above 100°C, usually ranging from 110-121°C depending on the type of product, must be reached inside the product.

The Kinetics of Thermal Inactivation of Microorganisms and Enzymes

- **The concept of decimal reduction time**

  If a suspension of cells (vegetative cells or spores) of a certain microorganism is heated above a certain temperature, death of the microorganism occurs, i.e. the number of living cells is gradually reduced. Temperatures at which such destruction occurs are named **'lethal temperatures'** .
- Experience shows that when a homogeneous suspension of cells is held at a constant lethal temperature, the decrease in the number of living cells with time **is nearly logarithmic**.

The Kinetics of Thermal Inactivation of Microorganisms and Enzymes

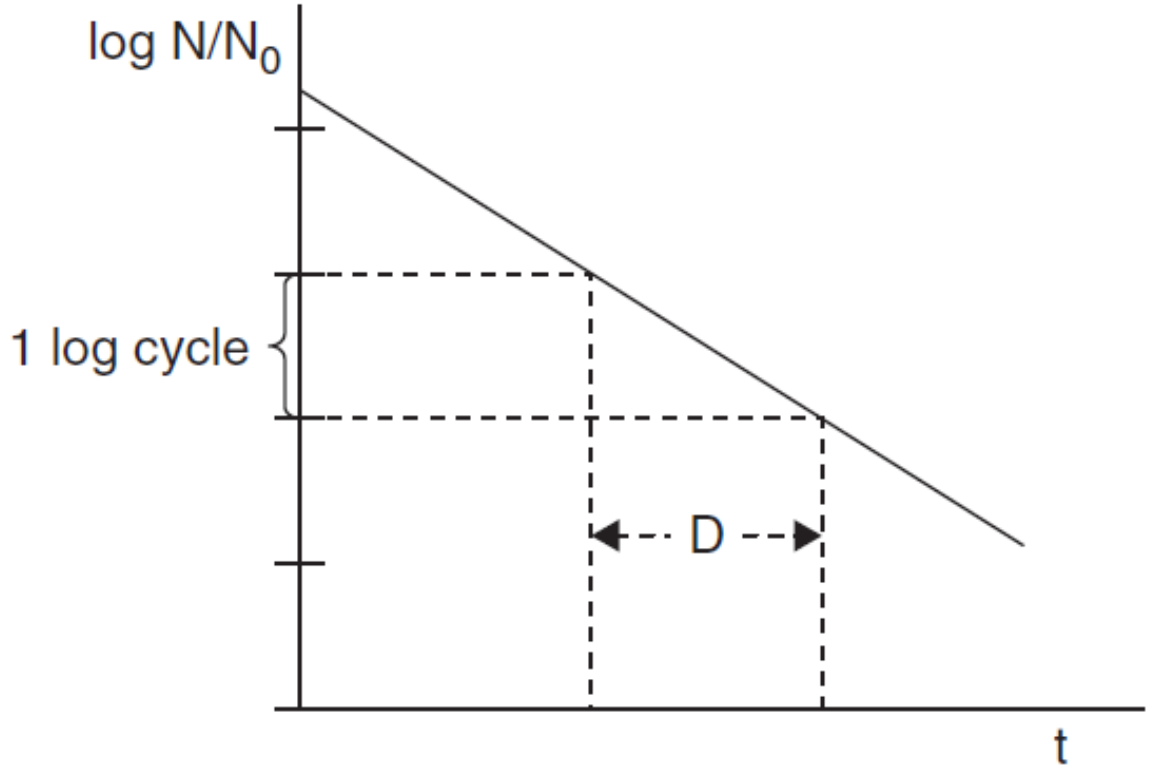
- This relationship was first demonstrated by Viljoen (1926) in a now classical experiment with bacterial spores. If N is the number of surviving cells at time t, the first order model is written as follows:

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

Integration gives:

$$\log \frac{N}{N_0} = -kt$$

The Kinetics of Thermal Inactivation of Microorganisms and Enzymes



The log-linear model of thermal reduction of microorganisms

Decimal reduction time

- *Decimal reduction time D is defined as the duration (usually in minutes) of heating* time at a constant lethal temperature required for the reduction of the number of living cells by a factor of 10 (i.e. by one log factor).

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

Decimal reduction time

- Decimal reduction time depends on the microorganism, the temperature and the medium (pH, composition.)
- According to the first order destruction model, complete sterility (N= 0) can never be achieved. A concept of ‘ commercial sterility ’ is therefore conventionally defined as the objective of practical thermal sterilization.

Decimal reduction time

- Peleg (2006) proposes the following expression as a possible (Weibullean) kinetics model, requiring two parameters a and b, and eliminating the concept of ‘ decimal reduction time ’:

$$\log \frac{N}{N_0} = -\frac{at}{b - t}$$

EXAMPLE 17.1

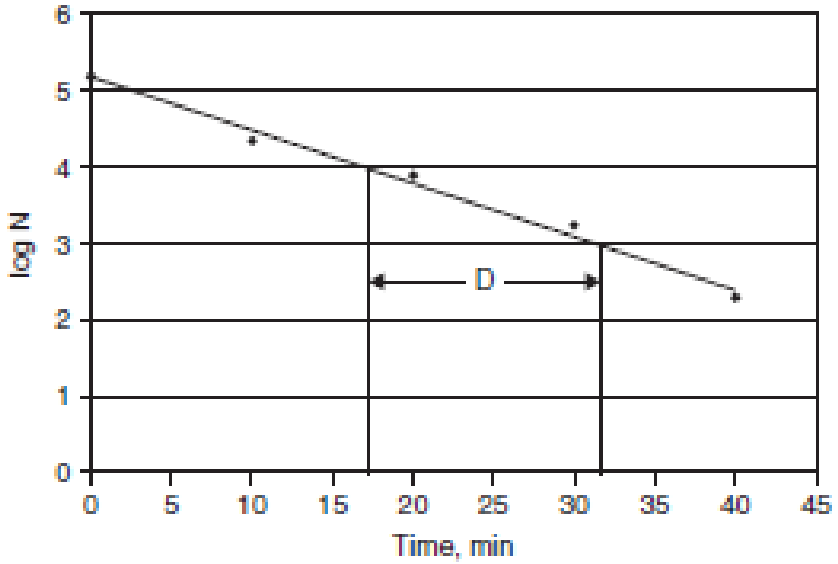
A suspension of bacterial spores containing 160 000 spores per ml is heated at 110°C. The number of survivors is determined in samples withdrawn every 10 minutes. The results are:

Heating time	N, survivors per ml
0	160 000
10	25 000
20	8000
30	1600
40	200

Assuming 'first order' kinetics, calculate the decimal reduction time.

Solution:

Log N is plotted against the heating time t. Good agreement with the first order theory is observed, within the range of the data. The decimal reduction time is determined from the curve (Figure 17.2). The result is: D = 13.4 min.



Effect of the temperature on the rate of thermal destruction/inactivation

- the rate of destruction is accelerated (D is shortened) by increasing the temperature.
- Experiments show a nearly linear relationship between the logarithm of D and the temperature

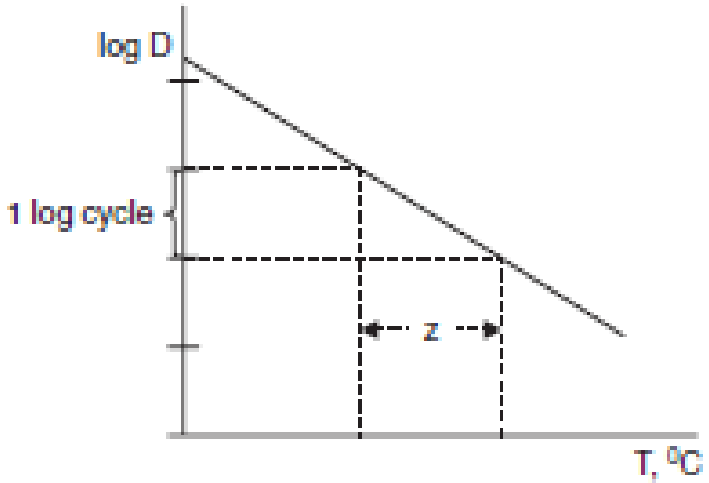


Figure 17.3 Effect of the temperature on D

Z - value

$$\log \frac{D_1}{D_2} = \frac{T_2 - T_1}{z} \qquad (17.5)$$

where D_1 and D_2 are the decimal reduction time at temperatures T_1 and T_2 respectively.

The *z value* is defined as the temperature increment needed for a ten-fold acceleration of the rate of thermal destruction (i.e. for shortening D by a factor of 10). For many spore-forming bacteria of interest in food processing, z = 8–12°C.

The logarithmic relationship between the rate of thermal inactivation and the temperature is in agreement with the Arrhenius model for the effect of temperature on the rate of chemical reactions, expressed as the following equation:

$$\log \frac{k_1}{k_2} = \frac{-E}{2.3R}\left(\frac{T_2 - T_1}{T_1 T_2}\right) \qquad (17.6)$$

where:

k_1, k_2 = rate constants at absolute temperatures T_1 and T_2 respectively

E = energy of activation

R = universal gas constant = 8.31 J mol^{-1} K^{-1}.

Activation energy

The activation energy E represents the sensitivity of the reaction rate to temperature, just as the z value indicates the sensitivity of the rate of thermal inactivation to temperature. The quantitative relationship between E and z is given by:

$$E = \frac{2.3RT_1T_2}{z} \qquad (17.7)$$

If the absolute temperatures are not too far apart, one can write:

$$E \cong \frac{2.3RT_m^2}{z} \qquad (17.8)$$

T_m is the average *absolute* temperature.

It is again important to emphasize that the ‘ energy of activation ’ for thermal destruction of cells has no molecular significance. With this warning in mind, it is interesting to note the z value and the corresponding ‘ energy of activation ’ of different thermal effects.

Table 17.1 Representative approximate values of E, z for different thermal effects

Thermal effect	z (°C)	E (10^3 kJ/kmol at T_m = 393 K (120°C))
Cell death (spores)	9–10	300–330
Enzyme inactivation	15–20	150–200
Chemical reactions (not enzyme-catalyzed)	30–40	75–100

EXAMPLE 17.2

In a laboratory experiment it was found that heating a suspension of spores at 120°C for 100 seconds results in a 9-log killing of the spores. To achieve the same reduction at 110°C, 27.5 seconds are needed. Calculate the decimal reduction time at the two temperatures, the z value, the energy of activation and the Q_{10} of the thermal inactivation process at these temperatures.

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Solution:

The decimal reduction time at the two temperatures:

$$D_{120} = \frac{100}{9} = 11.1 \text{ seconds} \quad D_{110} = \frac{27.7 \times 60}{9} = 183.3 \text{ seconds}$$

The z value is calculated from Eq. (17.5):

$$\log \frac{D_1}{D_2} = \frac{T_2 - T_1}{z} \quad \log \frac{183.3}{11.1} = \frac{120 - 110}{z} \quad \Rightarrow \quad z = 8.21°C$$

The activation energy E is calculated from Eq. (17.7):

$$E = \frac{2.3RT_1T_2}{z} \quad E = \frac{2.3 \times 8.314 \times 393 \times 383}{8.21} = 350.6 \times 10^3 \text{ kJ/kmol·K}$$

The Q_{10} value is found applying Eq. (4.13) (Chapter 4):

$$Q_{10} = \frac{10E}{RT(T + 10)} = \frac{10 \times 350.6 \times 10^3}{8.314 \times 393 \times 383} = 2.8$$

Lethality of Thermal Processes

- The same reduction in the number of microorganisms can be achieved under different time–temperature combinations.
- F value is *the duration (in minutes) required to achieve a given reduction ratio in the number of microorganism at a given constant temperature.*

$$F = D \log\left(\frac{N_0}{N}\right)$$

- *log (N_0 /N) 12 is specified, then F 12D. For commercial sterility in low-acid foods*

12 D Process

- The practical consequence of a 12-log reduction process is that if the food contains originally 10^3 spores of the target microorganism per gram, it will contain 10^{-9} spores per gram after processing.
- If the food is packed in units containing 500 g each, then one in two million cans will contain one viable spore.

F_0 value

- If the temperature T of the product varies according to a known time–temperature profile, T=f(t)
- The equivalent process at a given *constant temperature* (reference temperature R)

$$F_R^z = \int_0^t 10^{\frac{T-R}{z}} dt$$

- For thermal sterilization R=121°C and Z value = 10°C

$$F_{121}^{10} \equiv F_0 = \int_0^t 10^{\frac{T-121}{10}} dt$$

- ***The F_0 value of any thermal sterilization process is the number of minutes of heating at 121°C required to achieve the same thermal destruction ratio of a specified target microorganism .***

EXAMPLE 17.3

For the flash sterilization of milk, a thermal treatment of 2 seconds at 131°C is recommended. Calculate the F_0 value of the process.

Solution:

Equation (17.11) is applied:

$$F_{121}^{10} \equiv F_0 = \int_0^t 10^{\frac{T-121}{10}}\, dt \quad F_0 = t \times 10^{\frac{T-121}{10}} = 2 \times 10^{\frac{131-121}{10}} = 20\,\text{sec}$$

EXAMPLE 17.4

For the evaluation of *pasteurization* processes, it is recommended to utilize an F value based on a reference temperature of 70°C and a *z* value of 7°C (Bimbenet et al., 2002). For the evaluation of cooking processes and other chemical changes that occur during thermal processing (e.g. destruction of vitamins), the recommended reference temperature is 100°C and $z = 30$°C. Calculate the 'pasteurization value' and the 'cooking value' of the following constant temperature processes:

Process	Temp.°C	Time (s)
A	74	15
B	92	6
C	65	150
D	105	220

Solution:

For processes at constant temperature Eq. (17.10) reduces to:

$$F_R^z = t \times 10^{\frac{T-R}{z}}$$

Substitution of the data gives:

A: $F_{70}^{7} = 15 \times 10^{\frac{74-70}{7}} = 55.9\,\text{s}.$ $\quad F_{100}^{30} = 15 \times 10^{\frac{74-100}{30}} = 2.04\,\text{s}.$

B: $F_{70}^{7} = 6 \times 10^{\frac{92-70}{7}} = 8337\,\text{s}.$ $\quad F_{100}^{30} = 6 \times 10^{\frac{92-100}{30}} = 3.25\,\text{s}.$

C: $F_{70}^{7} = 150 \times 10^{\frac{65-70}{7}} = 29.0\,\text{s}.$ $\quad F_{100}^{30} = 150 \times 10^{\frac{65-100}{30}} = 10.2\,\text{s}.$

D: $F_{70}^{7} = 220 \times 10^{\frac{105-70}{7}} = 22 \times 10^{6}\,\text{s}.$ $\quad F_{100}^{30} = 220 \times 10^{\frac{105-100}{30}} = 322.9\,\text{s}.$

Optimization of Thermal Processes with Respect to Quality

- Required preservation, with the least amount of damage to the organoleptic and nutritional quality of the product
- Other thermal effects except preservation
  - **Inactivation of enzymes**: this is desirable and essential for long-term stability
  - **Cooking :** a large number of different chemical reactions that affect the quality of the product – changes in texture, flavor, color, appearance. Such changes are usually desirable up to a certain extent but objectionable beyond
  - **Destruction of nutritionally significant components**, such as heat sensitive vitamins.

Kinetics of destruction and deterioration

- The kinetic parameters of these effects are different from those of the thermal destruction of microorganisms. The z value of ordinary chemical reactions is larger than that of thermal death of microorganisms.
- *For an equal F_0, processing at higher temperature for a shorter time results in less thermal damage to quality . This is the theoretical background of the High temperature Short time (HTST) concept.*

Practical limitations of HTST approach

- The z value for enzyme inactivation is also higher than that of sterilization. Therefore, for an equal F_0 value, enzyme inactivation will be **less extensive** if the process is carried out at higher temperature. The highest permissible process temperature of an HTST process is, therefore, that at which the residual enzyme activity of the product will not endanger long-range stability.
- If cooking is one of the objectives of thermal processing, then an HTST process may result in less than desirable cooking (**undercooking**)
- For safety reasons, thermal processes are designed to achieve the desired F_0 *at the coldest point of the product (e.g. at the geometric center of a can* heated by conduction, the central axis of a tube in continuous processing in a tubular heat exchanger). Consequently, a considerable portion of the food is over-processed. At higher processing temperatures, over-processing of the food outside the coldest region and therefore **thermal damage to the average quality is more extensive**, particularly if resistance to heat transfer is high (solid foods).

EXAMPLE 17.5

A liquid food is processed at a constant temperature of 110°C for 30 seconds. The process results in a 25% loss of a vitamin present in the food. It is desired to change the constant temperature so that the same destruction of microorganisms is achieved with only 10% loss of the vitamin. Calculate the new constant temperature and the new processing time.

The z value of the thermal destruction of microorganisms is 10°C.

The Q_{10} value of the thermal destruction of the vitamin is 2.

Solution:

For the inactivation of microorganisms:

$$\frac{t_1}{t_2} = 10^{\frac{T_2 - T_1}{z}} \qquad \frac{30}{t_2} = 10^{\frac{T_2 - 110}{10}} \qquad \textit{(Equation A)}$$

For the thermal destruction of the vitamin (with C = the vitamin content):

$$\log \frac{C}{C_0} = -kt \qquad \log(0.75) = -k_1 \times 30 \qquad \log(0.90) = -k_2 t_2$$

$$\frac{k_2}{k} = \frac{\log(0.90)}{\frac{\log(0.75)}{30} \times t_2} = 2^{\frac{T_2 - 110}{10}} \qquad \textit{(Equation B)}$$

Solving Equation A and Equation B for t_2 and T_2 we find:

$$T_2 = 117°C$$
$$t_2 = 5.9\,s.$$

The result confirms the validity of the HTST approach.