Thermal processing implies the controlled use of heat to increase, or reduce depending on circumstances, the rates of reactions in foods.

A common example is the retorting of canned foods to effect sterilization. The object of sterilization is to destroy all microorganisms, that is, bacteria, yeasts and moulds, in the food material to prevent decomposition of the food, which makes it unattractive or inedible. Also, sterilization prevents any pathogenic (disease-producing) organisms from surviving and being eaten with the food. Pathogenic toxins may be produced during storage of the food if certain organisms are still viable. Microorganisms are destroyed by heat, but the amount of heating required for the killing of different organisms varies. Also, many bacteria can exist in two forms, the vegetative or growing form and the spore or dormant form. The spores are much harder to destroy by heat treatment than are the vegetative forms.

Thermal Death Time

It has been found that microorganisms, including *C. botulinum*, are destroyed by heat at rates which depend on the temperature, higher temperatures killing spores more quickly. At any given temperature, the spores are killed at different times, some spores being apparently more resistant to heat than other spores. If a graph is drawn, the number of surviving spores against time of holding at any chosen temperature, it is found experimentally that the number of surviving spores fall asymptotically to zero. Methods of handling process kinetics are well developed and if the standard methods are applied to such results, it is found that thermal death of microorganisms follows, for practical purposes, what is called a first-order process at a constant temperature (see for example *Earle and Earle, 2003*).

This implies that the fractional destruction in any fixed time interval, is constant. It is thus not possible, in theory at least, to take the time when all of the organisms are actually destroyed. Instead it is practicable, and very useful, to consider the time needed for a particular fraction of the organisms to be killed.

The rates of destruction can in this way be related to:

1. The numbers of viable organisms in the initial container or batch of containers.
2. The number of viable organisms which can safely be allowed to survive.

Of course the surviving number must be small indeed, very much less than one, to ensure adequate safety. However, this concept, which includes the admissibility of survival numbers of much less than one per container, has been found to be very useful. From such considerations, the ratio of the initial to the final number of surviving organisms becomes the criterion that determines adequate treatment. A combination of historical
reasons and extensive practical experience has led to this number being set, for *C. botulinum*, at $10^{12}:1$. For other organisms, and under other circumstances, it may well be different.

The results of experiments to determine the times needed to reduce actual spore counts from $10^{12}$ to 1 (the lower, open, circles) or to 0 (the upper, closed, circles) are shown in Fig. 6.4.

![Figure 6.4. Thermal death time curve for Clostridium botulinum](image)

Based on research results from the *American Can Company*

In this graph, these times are plotted against the different temperatures and it shows that when the logarithms of these times are plotted against temperatures, the resulting graph is a straight line. The mean times on this graph are called thermal death times for the corresponding temperatures. Note that these thermal death times do not represent complete sterilization, but a mathematical concept which can be considered as effective sterilization, which is in fact a survival ratio of $1:10^{12}$, and which has been found adequate for safety.

Any canning process must be considered then from the standpoint of effective sterilization. This is done by combining the thermal death time data with the time-temperature relationships at the point in the can that heats slowest. Generally, this point is on the axis of the can and somewhere close to the geometric centre. Using either the unsteady-state heating curves or experimental measurements with a thermocouple at the slowest heating point in a can, the temperature-time graph for the can under the chosen conditions can be plotted. This curve has then to be evaluated in terms of its effectiveness in destroying *C. botulinum* or any other critical organism, such as thermophilic spore formers, which are important in industry. In this way the engineering data, which provides the temperatures within the container as the process is carried out, are combined with kinetic data to evaluate the effect of processing on the product.

Considering Fig. 6.4, the standard reference temperature is generally selected as 121.1°C (250 °F), and the relative time (in minutes) required to sterilize, effectively, any selected organism at 121°C is spoken of as the *F* value of that organism. In our example, reading from Fig. 6.4, the *F* value is about 2.8 min. For any process that is different from a steady holding at 121°C, our standard process, the actual attained *F* values can be worked out by stepwise integration. If the total *F* value so found is below 2.8 min, then sterilization is not sufficient; if above 2.8 min, the heat treatment is more drastic than it needs to be.

**Equivalent Killing Power at Other Temperatures**

The other factor that must be determined, so that the equivalent killing powers at temperatures different from 121°C can be evaluated, is the dependence of thermal death time on temperature. Experimentally, it has been...
found that if the logarithm of \( t \), the thermal death time, is plotted against the temperature, a straight-line relationship is obtained. This is shown in Fig. 6.4 and more explicitly in Fig. 6.5.

\[
\log t - \log F = m(121 - T) = \log t/F
\]

where \( t \) is the thermal death time at temperature \( T \), \( F \) is the thermal death time at temperature 121°C and \( m \) is the slope of the graph.

Also, if we define the \( z \) value as the number of degrees below 121°C at which \( t \) increases by a factor of 10, that is by one cycle on a logarithmic graph,

\[
F = 10^z \quad \text{when} \quad T = (121 - z)
\]

so that,

\[
\log 10F - \log F = \log (10F/F) = 1 = m[121 - (121 - z)]
\]

and so

\[
z = 1/m
\]

Therefore

\[
\log (t/F) = (121 - T)/z
\]

or

\[
t = F \times 10^{(121-T)/z} \quad (6.3)
\]

Now, the fraction of the process towards reaching thermal death, \( dS \), accomplished in time \( dt \) is given by \( (1/t_1) dt \), where \( t_1 \) is the thermal death time at temperature \( T_1 \), assuming that the destruction is additive.

That is

\[
dS = (1/t_1) \cdot dt
\]

or

\[
= (1/F) 10^{(121-T)/z} \cdot dt
\]

When the thermal death time has been reached, that is when effective sterilization has been achieved,

\[
\int dS = 1
\]

that is

\[
\int (1/F) 10^{(121-T)/z} \cdot dt = 1
\]

or

\[
\int 10^{(121-T)/z} \cdot dt = F \quad (6.4)
\]

This implies that the sterilization process is complete, that the necessary fraction of the bacteria/spores have been destroyed, when the integral is equal to \( F \). In this way, the factors \( F \) and \( z \) can be combined with the time-temperature curve and integrated to evaluate a sterilizing process. The integral can be evaluated graphically or by stepwise numerical integration. In this latter case the contribution towards \( F \) of a period of \( t \) min at a temperature \( T \) is given by \( t \times 10^{(121-T)/z} \). Breaking up the temperature-time curve into \( t_1 \) min at \( T_1 \), \( t_2 \) min at \( T_2 \), etc., the total \( F \) is given by

\[
F = t_1 \times 10^{(121-T)/z} + t_2 \times 10^{(121-T)/z} + \ldots
\]

This value of \( F \) is then compared with the standard value of \( F \) for the organism, for example 2.8 min for \( C. \) botulinum in our example, to decide whether the sterilizing procedure is adequate.

\(--\text{EXAMPLE 6.5. Time/Temperature in a can during sterilisation}\)--
In a retort, the temperatures in the slowest heating region of a can of food were measured and were found to be shown as in Fig. 6.6. Is the retorting adequate, if $F$ for the process is 2.8 min and $z$ is 10°C?

![Figure 6.6 Time/Temperature curve for can processing](image)

Approximate stepped temperature increments are drawn on the curve giving the equivalent holding times and temperatures as shown in Table 6.2. The corresponding $F$ values are calculated for each temperature step.

<table>
<thead>
<tr>
<th>Temperature $T$ (°C)</th>
<th>Time $t$ (min)</th>
<th>$(121 - T)$</th>
<th>$10^{(121-T)/10}$</th>
<th>$t \times 10^{(121-T)/10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>11</td>
<td>41</td>
<td>$7.9 \times 10^5$</td>
<td>0.00087</td>
</tr>
<tr>
<td>90</td>
<td>8</td>
<td>31</td>
<td>$7.9 \times 10^4$</td>
<td>0.0063</td>
</tr>
<tr>
<td>95</td>
<td>6</td>
<td>26</td>
<td>$2.5 \times 10^3$</td>
<td>0.015</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>21</td>
<td>$7.9 \times 10^3$</td>
<td>0.079</td>
</tr>
<tr>
<td>105</td>
<td>12</td>
<td>16</td>
<td>$2.5 \times 10^2$</td>
<td>0.30</td>
</tr>
<tr>
<td>108</td>
<td>6</td>
<td>13</td>
<td>$5.0 \times 10^2$</td>
<td>0.30</td>
</tr>
<tr>
<td>109</td>
<td>8</td>
<td>12</td>
<td>$6.3 \times 10^2$</td>
<td>0.50</td>
</tr>
<tr>
<td>110</td>
<td>17</td>
<td>11</td>
<td>$7.9 \times 10^2$</td>
<td>1.34</td>
</tr>
<tr>
<td>107</td>
<td>2</td>
<td>14</td>
<td>$4.0 \times 10^2$</td>
<td>0.08</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>21</td>
<td>$7.9 \times 10^3$</td>
<td>0.016</td>
</tr>
<tr>
<td>90</td>
<td>2</td>
<td>31</td>
<td>$7.9 \times 10^4$</td>
<td>0.0016</td>
</tr>
<tr>
<td>80</td>
<td>8</td>
<td>41</td>
<td>$7.9 \times 10^5$</td>
<td>0.00005</td>
</tr>
<tr>
<td>70</td>
<td>6</td>
<td>51</td>
<td>$7.9 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Total 2.64</strong></td>
</tr>
</tbody>
</table>

The above results show that the $F$ value for the process = 2.64 so that the retorting time is not quite adequate. This could be corrected by a further 2 min at 110°C (and proceeding as above, this would add $2 \times 10^{121-110}/10 = 0.16$, making 2.8).

From the example, it may be seen that the very sharp decrease of thermal death times with higher temperatures means that holding times at the lower temperatures contribute little to the sterilization. Very long times at temperatures below 90°C would be needed to make any appreciable difference to $F$, and in fact it can often be the holding time at the highest temperature which virtually determines the $F$ value of the whole process. Calculations can be shortened by neglecting those temperatures that make no significant contribution, although, in each case, both the number of steps taken and also their relative contributions should be checked to ensure accuracy in the overall integration.

It is possible to choose values of $F$ and of $z$ to suit specific requirements and organisms that may be suspected of giving trouble. The choice and specification of these is a whole subject in itself and will not be further
discussed. From an engineering viewpoint a specification is set, as indicated above, with an $F$ value and a $z$ value, and then the process conditions are designed to accomplish this.

The discussion on sterilization is designed to show, in an elementary way, how heat-transfer calculations can be applied and not as a detailed treatment of the topic. This can be found in appropriate books such as Stumbo (1973), Earle and Earle (2003).

### Pasteurization

Pasteurization is a heat treatment applied to foods, which is less drastic than sterilization, but which is sufficient to inactivate particular disease-producing organisms of importance in a specific foodstuff. Pasteurization inactivates most viable vegetative forms of microorganisms but not heat-resistant spores. Originally, pasteurization was evolved to inactivate bovine tuberculosis in milk. Numbers of viable organisms are reduced by ratios of the order of $10^{15}:1$. As well as the application to inactivate bacteria, pasteurization may be considered in relation to enzymes present in the food, which can be inactivated by heat. The same general relationships as were discussed under sterilization apply to pasteurization. A combination of temperature and time must be used that is sufficient to inactivate the particular species of bacteria or enzyme under consideration. Fortunately, most of the pathogenic organisms, which can be transmitted from food to the person who eats it, are not very resistant to heat.

The most common application is pasteurization of liquid milk. In the case of milk, the pathogenic organism that is of classical importance is *Mycobacterium tuberculosis*, and the time/temperature curve for the inactivation of this bacillus is shown in Fig. 6.7.

![Figure 6.7 Pasteurization curves for milk](image)

This curve can be applied to determine the necessary holding time and temperature in the same way as with the sterilization thermal death curves. However, the times involved are very much shorter, and controlled rapid heating in continuous heat exchangers simplifies the calculations so that only the holding period is really important. For example, 30 min at 62.8°C in the older pasteurizing plants and 15 sec at 71.7°C in the so-called high temperature/short time (HTST) process are sufficient. An even faster process using a temperature of 126.7°C for 4 sec is claimed to be sufficient. The most generally used equipment is the plate heat exchanger and rates of heat transfer to accomplish this pasteurization can be calculated by the methods explained previously.

An enzyme present in milk, phosphatase, is destroyed under somewhat the same time-temperature conditions as the *M. tuberculosis* and, since chemical tests for the enzyme can be carried out simply, its presence is used as an indicator of inadequate heat treatment. In this case, the presence or absence of phosphatase is of no significance so far as the storage properties or suitability for human consumption are concerned.
Enzymes are of importance in deterioration processes of fruit juices, fruits and vegetables. If time-temperature relationships, such as those that are shown in Fig. 6.7 for phosphatase, can be determined for these enzymes, heat processes to destroy them can be designed. Most often this is done by steam heating, indirectly for fruit juices and directly for vegetables when the process is known as blanching.

The processes for sterilization and pasteurization illustrate very well the application of heat transfer as a unit operation in food processing. The temperatures and times required are determined and then the heat transfer equipment is designed using the equations developed for heat-transfer operations.

**EXAMPLE 6.6. Pasteurisation of milk**

A pasteurization heating process for milk was found, taking measurements and times, to consist essentially of three heating stages being 2 min at 64°C, 3 min at 65°C and 2 min at 66°C. Does this process meet the standard pasteurization requirements for the milk, as indicated in Fig. 6.7, and if not what adjustment needs to be made to the period of holding at 66°C?

From Fig. 6.7, pasteurization times \( t \) can be read off the UK pasteurisation standard, and from these and the given times, rates and fractional extents of pasteurization can be calculated:

- **At 64°C**, \( t_{64} = 15.7 \) min
  - so 2 min is \( \frac{2}{15.7} = 0.13 \)
- **At 65°C**, \( t_{65} = 9.2 \) min
  - so 3 min is \( \frac{3}{9.2} = 0.33 \)
- **At 66°C**, \( t_{66} = 5.4 \) min
  - so 2 min is \( \frac{2}{5.4} = 0.37 \)

Total pasteurization extent = \( (0.13 + 0.33 + 0.37) = 0.83 \).

Pasteurization remaining to be accomplished = \( 1 - 0.83 = 0.17 \).
At 66°C this would be obtained from \((0.17 \times 5.4) \) min holding = 0.92 min.
So an additional 0.92 min (or approximately 1 min) at 66°C would be needed to meet the specification.