

Principles of Integrated Time-Temperature Processing

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Introduction

For the next few minutes we are going to talk about integrated time-temperature processing. We will discuss how integrated time-temperature processing can be used to achieve some of the performance standards that USDA has proposed. We will also discuss what is needed to determine a such a process for cooked meat and poultry products and why we would want to do this.

The principles of integrated time-temperature processing have been around for about 75 years, so we are not going to be talking about a new concept. In 1920, this concept was presented by W. D. Bigelow of the National Canners Association as a scientific way of establishing thermal processes for low-acid canned foods. Refinements were made over the years, but the concept is still applied each and every day in the canned food industry. More recently the concept has been used for pre-cooked foods such as cook-chill products for foodservice and retail.

Most thermal processes are designed to destroy microorganisms. To do this with heat, we must transfer heat from a heating source or medium, such as hot water, air or steam, into the product. Thus, to comprehend the concept of integrated time-temperature processing one must be aware of two vastly different sciences: 1) the kinetics of microbial destruction and 2) the mechanism of heat transfer into products. Discussions of kinetics and heat transfer almost sound like an engineering course, but don't worry, we will not be conducting an engineering workshop here today. Once the concept is understood, determining an integrated time-temperature process is not that difficult. In fact a document published by the former American Can Company states – "For one having a reasonable faculty for handling algebra and logarithms, it will not be difficult to carry out the necessary calculations." And remember, these methods were developed before we had hand-held calculators and personal computers!

While we don't have time today to delve into great detail on the subjects of microbial destruction and heat transfer into products, we do need to review these topics prior to approaching the task of integrated time-temperature processing so we have a basic understanding of the subjects.

Thermobacteriology

The science of thermobacteriology has shown us that microorganisms can be destroyed in predictable manners. The goal of the thermobacteriologist is to determine the amount of time at a specific temperature that is required to inactivate the microorganism of concern. The microorganism can be a pathogen or a heat-resistant spoilage organism. The performance standards proposed by FSIS generally are concerned with a specific pathogen such as *Salmonella* or *E. coli* O157:H7. If another test organism is chosen for process development, it should have a greater heat resistance than the most heat resistant pathogen expected to survive and grow in the product.

Why choose a non-pathogen? There are a number of reasons, which I won't dwell on. For some products it is necessary to target a more heat resistant non-pathogen to achieve the appropriate stability and shelf life for the product. Another major reason is that we do not want to take pathogens into a food plant, so a simulator organism must be used when processes are validated in a plant rather than in a laboratory or pilot facility.

Once we have identified our target microorganism, we must define its heat resistance in the product of concern. Thermal death time or TDT studies are conducted in a laboratory to determine the heat resistance of microorganisms. The thermobacteriologist will need to consider several factors which may affect the heat resistance of the organism. Generally the most conservative approach is taken to accommodate variations encountered every day. The factors which affect the heat resistance of a microorganism include

- 1) the species and strain,
- 2) how it is grown,
- 3) the medium in which it is heated (food vs. buffer), and
- 4) the environment in which it will recover after heating.

TDT studies involve inoculating the product (generally in a comminuted form) or phosphate buffer with a known amount of the test organism. The inoculated product is placed in TDT tubes, a 3-neck flask or capillary tubes – there are several methods – and heated for varying lengths of time at a series of different temperatures. The goal of the TDT tests is to find the breaking point or time between destruction and survival of the organism at each of the different temperatures and to calculate survivor curves.

Many studies of the heat resistance of organisms have shown scientists that the death of microorganisms is based on both temperature and time and that death generally occurs logarithmically, meaning that a semi-logarithmic plot of the number of survivors versus heating time will give us a straight line. A 90% reduction in population occurs in a constant time interval, regardless of the initial population. This 90% reduction is called a logarithmic or log reduction or D value (for decimal reduction). Performance standards which refer to a 5-D reduction in a pathogen or a 5-D lethality are referring to this concept.

A D value is defined as the time in minutes at a constant temperature necessary to destroy 90% or 1 log of the organisms present. This is sometimes referred to as the “death rate” of an organism. D values are determined from survivor curves at different temperatures; a semi-log plot of these D values against temperature allows us to calculate a z value from the slope of the line.

A z value is defined as the number of degrees between a 10-fold change (or 1 log cycle) in an organism’s heat resistance. In other words, the D value will be 1 log higher or lower when it is heated z °F lower or higher, respectively. If the D value is 5 minutes at 130°F and the z is 10°F, at 140°F the D will be 0.5 minutes and at 120°F it will be 50 minutes.

The z value is considered to be constant for a given strain of microorganisms in a given product. A D value at one temperature, along with a z value, are used to define the heat resistance of a microorganism, and can be used to calculate the D value at any other temperature.

Determining the heat resistance of a microorganism is not difficult, but it’s also not routine microbiology. Not every micro lab is set up to do this work. And it takes time, and money. However, basic thermobacteriologic research has been conducted and published for many microorganisms, including pathogens, therefore establishments may find that they do not need to conduct TDT studies for their products.

Product heating rate

The study of heat transfer into a product is something that each processor may find the need to perform. The goal is to define or map the heating and cooling profile of the product by observing the temperature characteristics of the product during heating and cooling. A product will not reach a minimum internal temperature instantaneously; as heat is transferred into the product most products will only gradually heat up. To define the heating styles of products, heat penetration studies will need to be conducted.

The classic method of determining the heating rate of a product is to measure the temperature in the slowest heating portion of the product. In many thick or dense products this is likely to be the geometric center of the product. Temperatures can be monitored with a thermometer, an RTD or a thermocouple – any device which will provide accurate and quick responses to changes in temperatures. Traditionally thermocouples have been used to collect heat penetration data and they work quite well for a batch type process, such as occurs in a stationary smoke house or oven.

A thermocouple is a simple device made by joining two wires made from different metals – e.g., copper and constantan. The different metals will react to changing temperatures in different manners. The metals will develop low voltages which are dependent on the temperature. Instruments such as potentiometers or dataloggers have been designed to convert the voltages into temperature readings.

Because thermocouples involve directly linking product to the potentiometer with wires, this temperature measuring system may not be suitable for some continuous systems. There are self-contained, computerized temperature measuring systems which are designed to travel with the product through a processing system. The temperature profile of the product is captured in memory to be “down-loaded” after the process. These instruments are quite expensive, but they are reusable. One popular brand is Mesa Lab’s DATATRACE unit.

Regardless of the temperature monitoring system, the end product is the same – a time-temperature map of the product as it heats and cools. An example heating profile of a meat patty is shown in this table.

Elapsed Time (minutes)	Center patty temperature (°F)	Elapsed Time (minutes)	Center patty temperature (°F)
0	40	5.0	145
0.5	64	5.5	140
1.0	82	6.0	137
1.5	97	6.5	136
2.0	113	7.0	135
2.5	128	7.5	134
3.0	138	8.0	133
3.5	142	8.5	129
4.0	145	9.0	120
4.5	148	9.5	112
		10.0	104

The goal of the heat penetration study is to map the coldest or slowest heating portion of the product under normal processing conditions. Remember the samples selected for testing should represent the worst case scenario for the product. Multiple samples should be tested to allow for the generation of reliable and reproducible data.

Many factors of the product and cooking equipment will influence the heating rate of the product and these should be considered when designing the studies. Product factors which influence the heating rate may include weight, shape, fat content, moisture content, density, and the raw product temperature. Factors to consider with the cooking equipment include temperature, heat variability, relative humidity, belt speed (if a continuous cook), and arrangement of product in the cooker. There are probably many more factors to consider. Again the product tested should represent the slowest heating product.

Generally each product produced will need to be tested to determine the heating rate. Slight variations in seasonings may not affect the heating rate of the product but significant variations will. If there is a question about whether or not a change in

formulation is significant, it is always safe to conduct a test to determine the impact of the change.

Process calculations

Before we start talking about determining an integrated time-temperature process, let's revisit the concept of performance standards. Proposed performance standards set out quantifiable microbial pathogen reduction requirements for cooked meat and poultry products. They define the amount of microbial lethality that is required. For example, the performance standard for cooked meat patties is a 5-D or 5-log reduction in *Salmonella*, i.e., a reduction in *Salmonella* organisms by 5 logs or 10^5 organisms per gram.

Knowing the D value of the organism of concern in the product allows us to calculate the number of minutes at a particular temperature to achieve this log reduction.

We have 3 vastly different ways to show we are meeting the performance standards.

1. We can monitor the levels of microorganisms in the product, both before and after cooking, to see if we have achieved the proper pathogen reduction.
2. We can determine the minimum temperature and minimum hold time needed to result in the required reduction.
3. We can determine how the product heats during specific processing conditions, establish a process based on integrated time-temperature processing designed to achieve the required performance standard, and monitor the process parameters rather than the product.

Obviously the first method – microbial sampling – will not be a very efficient or effective means of monitoring a operation to ensure that a performance standard is met. We are all aware of the limitations with sampling plans and testing to ensure compliance with a standard.

With the second method, during production we would need to monitor the temperature reached inside the product and start timing the hold period once the product reached minimum temperature to ensure minimum time. This method ignores the effects of the increases in temperature that occur in reaching the minimum internal temperature. Products do not heat and cool instantaneously. As we saw with the TDT data, there is not just one temperature that will destroy the organism; any temperature that is lethal to the organism will be effective as long as enough time is also applied. Additionally, monitoring the temperature inside the product during production has its limitations. Monitoring frequencies need to be established to ensure that all variations in the application of the process are accounted for.

The traditional cooking guidelines for fully cooked patties provided in USDA's regulations are based on the second option. Let's revisit the requirements briefly. The current regulations for uncured meat patties require the product be cooked to specific

temperatures for specific periods of time (9CFR 318.23). These time/temperature combinations achieve a 5-D performance standard for *Salmonella*.

Minimum internal temperature at the center of each patty	Minimum holding time after minimum temperature is reached	
	Minutes	Seconds
Degrees Fahrenheit		
151	.686	41
152	.54	32
153	.43	26
154	.34	20
155	.27	16
156	.22	13
157 +	.17	10

The third method – integrated time-temperature processing – takes credit for all of the heat seen by the product – the increase in temperatures in the product as the product heats up and the temperatures seen as the product cools down. Remember microbial destruction takes place during the entire heating and cooling – not just at the minimum internal temperature.

The USDA cooking guidelines for patties are based on the knowledge that it takes 10.3 seconds to destroy 1 log of *Salmonella* at 150°F. The same level of destruction (1 log) will be achieved at 140°F for 103 seconds or at 160°F for 1.03 seconds because the z value is 10°F. Of course these are only 3 examples; microbial destruction will occur at other temperatures as well, provided the time component is maintained. Another useful characteristic of microbial destruction is that we can have partial log reductions if the entire time requirement is not met. For example, after 5 seconds at 150°F there is about a half log reduction.

A final basic assumption regarding microbial destruction is that the lethal effect obtained at different temperatures is additive. We don't need to ignore the lethal effects as the product increases in temperature during heating and decreases in temperature during cooling.

Process calculations using integrated time-temperature processing combine the thermobacteriology time temperature data with the product heating time-temperature data. These data are combined to form a lethal rate curve.

Let's walk through an example to see how this is done. Our product heating data for patties was represented earlier. The lethal effect of each temperature can be calculated based on a reference temperature. The formula for calculating lethal rates is as follows:

Lethal rate = 10^A , where $A=(T-T_r)/z$
 and T_r is the reference temperature,
 T is the temperature we are determining the lethal rate for and
 z is the z-value for the organism of concern.

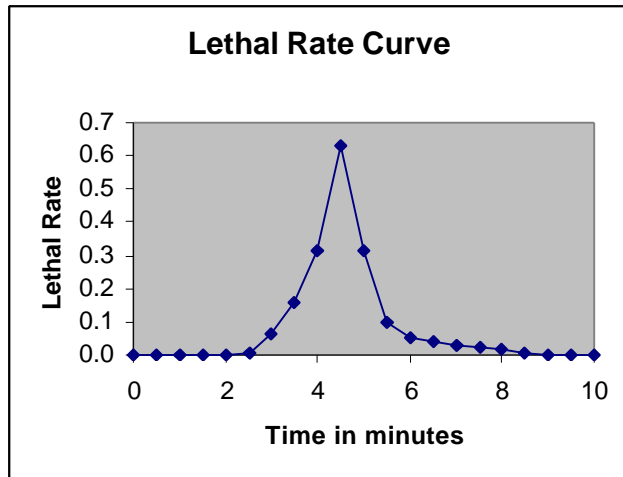
While the formula for calculating lethal rates seems a bit daunting, the use of a PC spreadsheet program makes this quite easy. Additionally some dataloggers can be programmed to calculate lethal rates automatically.

The next table shows the calculated lethal rates for a portion of our temperatures. Using this table, we can also demonstrate visually the impact of lethal rates for comparison purposes. Because we selected a reference temperature of 150°F, all other temperatures will be compared to 150°F. The lethal rate at the reference temperature is set at 1.0. We can see that 1 minute at 140°F has one-tenth (0.10) the effect of 1 minute at 150°F. Remember from our previous discussions of the z-values, it would take 10 minutes at 140°F to have the same lethal effect as 1 minute at 150°F. As the product temperature increases closer to 150°F, the lethal rate also increases. One minute at 148°F has the same lethal effect as 0.63 minutes at 150°F.

Lethal Rate
 ($T_r = 150^\circ\text{F}$, $z = 10^\circ\text{F}$)

Elapsed Time (minutes)	Center Patty Temperature (°F)	Lethal Rate Per Minute
0	40	0.000
2.5	128	0.006
3.0	138	0.063
3.5	142	0.158
4.0	145	0.316
4.5	148	0.631
5.0	145	0.316
5.5	140	0.100
6.0	137	0.050
6.5	136	0.040
10.0	104	0.000

To determine the integrated lethal effect of our process, we need to determine the area under the lethal rate curve. The graph below shows a plot of our time-temperature data converted to lethal rates. This plot show the time intervals on the X axis and the lethal rates plotted on the Y axis.



Because, in our example we selected 150°F to be the reference temperature, the area under the curve represents the total lethal effect of the process equivalent to 150°F. In our example, the lethality of the process is 0.884 minutes. What this represents is an “equivalent” time. So even though the product never reached 150°F, our total process of 10 minutes heating and cooling has the same or equivalent lethal effect as instantaneously heating the product to 150°F and holding it at 150°F for 0.884 minutes.

Now this integration will give us an equivalent time at a specific temperature, but how does it relate to the D-value? Remember the D_{150} for *Salmonella* is 0.172 minutes (10.3 seconds). If our process is equivalent to 0.884 minutes at 150°F, the process has achieved 5.15 D’s. This is calculated by dividing the lethal effect by the D value. Therefore, a product processed with the same or more conservative processing parameters – product initial temperature, cook temperature, cook time etc. – will always achieve at least a 5-D process.

Now figuring the area under a curve brings back memories of calculus and counting squares on graph paper. However, we are fortunate that several different summation techniques have been established to make this task quite simple; in fact we don’t even need to draw a graph. Again the use of a PC spreadsheet program eases the task.

The table below adds a fourth column to our heating data. This column is the lethality or lethal effect for the time period the product was at that temperature. The lethal rate which we calculated earlier showed the lethal rate at a specific temperature for a 1 minute time period. Because the product was at the temperatures for only one-half of a minute we can only take credit for one-half of the lethal rate. Therefore the lethality or lethal effect is simply calculated by multiplying the lethal rate by the time interval.

Elapsed Time (minutes)	Center Patty Temperature (°F)	Lethal Rate Per Minute	Lethality Per Time Interval
0	40	0.000	0.000
2.5	128	0.006	0.003
3.0	138	0.063	0.032
3.5	142	0.158	0.079
4.0	145	0.316	0.158
4.5	148	0.631	0.315
5.0	145	0.316	0.158
5.5	140	0.100	0.050
6.0	137	0.050	0.025
6.5	136	0.040	0.020
10.0	104	0.000	0.000

Now we can simply add up the lethality values for each time interval to calculate a good approximation of the area under our lethal rate curve.

This is represented in the final column of the table below and is sometimes referred to as the “cumulative process lethality”. Again the calculation results in an equivalent lethality at 150°F of 0.884 minutes. **[the table does not show all the data so if someone tries to add the numbers in the final column they may get a slightly smaller number]**

Elapsed Time (in minutes)	Center Patty Temperature (°F)	Lethal Rate Per Minute	Lethality Per Time Interval	Cumulative Process Lethality
0	40	0.000	0.000	0.000
0.5	64	0.000	0.000	0.000
1.0	82	0.000	0.000	0.000
1.5	97	0.000	0.000	0.000
2.0	113	0.000	0.000	0.000
2.5	128	0.006	0.003	0.003
3.0	138	0.063	0.032	0.035
3.5	142	0.158	0.079	0.114
4.0	145	0.316	0.158	0.272
4.5	148	0.631	0.315	0.588
5.0	145	0.316	0.158	0.746
5.5	140	0.100	0.050	0.796
6.0	137	0.050	0.025	0.821
6.5	136	0.040	0.020	0.841
7.0	135	0.032	0.016	0.857
7.5	134	0.025	0.013	0.869
8.0	133	0.020	0.010	0.879
8.5	129	0.008	0.004	0.883
9.0	120	0.001	0.001	0.884
9.5	112	0.000	0.000	0.884
10.0	104	0.000	0.000	0.884

Benefits of integrated time-temperature processing

We have to admit, establishing or confirming a process using the principles of integrated time-temperature processing sounds a bit more complicated than simply monitoring the minimum internal temperature of the product after a cook. But there are several benefits to establishing a process in this manner.

The main benefit is that we are able to optimize the process. By taking credit for the lethal effects of the temperature achieved during heating and cooling, we can obtain the desired performance standard with less time. As seen with our example for heating patties, a 5D process can be achieved with 4.5 minutes of cooking and an additional 5.5 minutes of cooling. To meet the requirement of maintaining a minimum internal patty temperature of 151°F for 41 seconds may require at least 5.5 minutes of cooking, because of the additional come-up time to reach 151°F, which results in an 11 D process. And since the product continues to accumulate lethality as it cools, the final process is equivalent to a 14.9 D process – almost 3 times the process required to meet a 5D performance standard. The differences are even more dramatic with large products such as sausages, roast beef, etc.

A second benefit is evidenced by the monitoring techniques. A process established with integrated time-temperature processing requires limited, if any, product sampling and monitoring. Instead of monitoring the product temperature, the process itself is monitored. The process parameters established during the heat penetration test are what is monitored – temperature of oven, time product is in oven, size and composition of product, for example. These are factors which probably already being monitored to ensure that the minimum temperature requirements are always met. An occasional product temperature can be obtained to verify the process. While similar monitoring techniques can be established when cooking to a final internal temperature, the process is not necessarily optimized for product quality.

Even if an establishment does not want to establish a process based on integrated time-temperature processing, the concepts are good to know and understand. This method of process establishment proves quite useful in evaluating processes for products involved in a deviation situation.

Conclusion

In the short time we had today, we tried to present the concept of integrated time-temperature processing. While the calculation methods may seem a bit confusing at first glance, further study into the subject may prove to be quite beneficial. All signs in the regulatory environment point to performance standards as the means to ensuring the safety of our products. Integrated time-temperature processing may be a very beneficial tool to ensure compliance with the new standards and optimize product quality at the same time.