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Manatū Ahu Matua

Standardising D and Z values for cooking raw meat

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Scientific Interpretative Summary

This SIS is prepared by MPI risk assessors to provide context to the following report for MPI risk managers and external readers.

Standardisation of parameters for pathogen control in food: *D* and *z* values for the heat inactivation of pathogens in raw meat

ESR Report FW 15001

Advice and requirements for thermal treatment times for raw meat are to be found in a number of MPI documents and have been based on the benchmark and universally accepted heat treatment parameters in a 1989 publication. This gives a 6D outcome at a core temperature of 70°C for 2 minutes for *L. monocytogenes,* derived from experiments with several matrices (chicken, beef steak and carrot).

This report analysed more recent data sets (1384 values) for raw meat with the intent of updating information for specific pathogen/meat combinations if appropriate. The analysis produced a higher 6D value at of 70°C of 2.4 minutes for *L. monocytogenes* for all meat types. For *Salmonella,* the 6D value range at 70°C is 1.8-2.2 minutes depending on meat types and values for *E.coli* are appreciably lower at 1.2 minutes for beef and 1.8 minutes for all meats. This confirms that a process that gives the required log reduction for *L. monocytogenes* will give at least the same log reduction for the other non-sporing pathogens.

At low temperatures the effects of the z value are very pronounced. Using the current MPI recommendations to achieve a 6D for *L. monocytogenes*, at 60°C and with z =7.5°C, the cooking time is 44 minutes. However when applying a z value of 6.25°C, the cook time is doubled to 91.2 minutes at 60°C.

While the study does not significantly challenge the 70°C for 2 minutes convention used to achieve a 6D reduction for *L. monocytogenes* in meat products, it is appropriate to extend the time to 2.4 minutes as the data used was all meat-based and should therefore be more relevant than values derived from a range of matrices.

For time/temperature combinations below 55°C, no recommendations can be made until further research is undertaken.

Where time/temperature combinations (and processing conditions e.g. vacuum packs) outside the range included in this report are intended to be taken up by by food processors or MPI, validation studies will need to be undertaken.

D and *z* values for the heat inactivation of pathogens in raw meat

December 2015

PREPARED FOR: Ministry for Primary Industries under project MFS/14/4 Microbiological Food Safety, as part of overall contract for scientific services

CLIENT REPORT No: FW15001

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	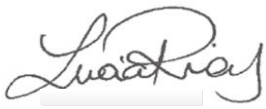	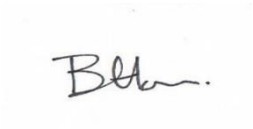
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DISCLAIMER

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EXECUTIVE SUMMARY

The objective of this project was to provide time-temperature combinations for industry, in the form of *D* and *z* values, for heat processing (cooking) of different meat types for inactivation of the pathogens: *Escherichia coli* including *E. coli* O157:H7 and other Shiga toxigenic *E. coli* serotypes, *Listeria monocytogenes*, *Salmonella* spp. and *Campylobacter jejuni/coli*.

Thermal inactivation data for pathogens in raw meat were located and compiled through searches of the scientific literature, up to and including October 2014. The *D* value database was initially filtered to extract the data which (i) had been determined by experiments specifically designed to estimate *D* values and (ii) were determined from the exponential inactivation phase.

Thermal inactivation can be affected by intrinsic properties of meat (e.g. meat type, fat, pH) as well as preliminary processing (which may include some heating). Consequently information on these factors was also collected alongside inactivation data when available. The proposed methodology, compiled data and supporting information (including that from a previous ESR project) were discussed with MPI in order to define the scope of meat types, intrinsic properties of the meat, preliminary and heating processes for which *D* and *z* values could be derived and that were supported by a substantial body of data. Finally the database was filtered to only include the data which fell within the agreed product scope, resulting in a data set of 1348 values.

For each pathogen-meat group combination, the reference *D* values are derived from a linear regression of the 95th percentile value of the available data at each temperature. This provides *D* values which take into account the variability of the heat resistance of pathogens due to the characteristics of the product and incorporates data from the most heat resistant strains of pathogens which are those most likely to survive cooking and present a risk of illness.

The scope of meat types for which D and z values were derived includes:

(i) Beef
(ii) Poultry
(iii) Pork
(iv) “All Meat”.

In addition to Beef, Poultry and Pork, the “All Meat” category also includes sheep meat, partially processed raw meat products such as sausages, and products containing a mix of meat types. Some exclusions to the scope (e.g. for high fat products) are described in Table 1.

The full dataset included *D* values ranging from 55°C to 74°C. Inspection of the data showed that for practical experimental reasons using a meat matrix, there were limited data above 70°C. Consequently *D* values in this report are given for meat types, pathogens and temperatures between 55°C and 70°C. Specifically, *D* and *z* values are given for; *E. coli* in Beef and “All Meat”, *L. monocytogenes* in “All Meat”, *Salmonella* spp. in Beef, Poultry and “All Meat”. There were insufficient data to provide Pork specific *D* values for any of the pathogens, but the Beef *D* values can be applied to this meat type.

The exception to the temperature range is *L. monocytogenes*, for which there were sufficient data from 70-74°C that a *D* value up to 75°C could be provided for "All Meat". As *L. monocytogenes* was consistently more heat resistant than the *E. coli* and *Salmonella* spp. across the meat types, this D_{75} value can also be applied to *E. coli* and *Salmonella* spp..

The other exception is for *C. jejuni/coli*, for which there were insufficient data to derive *D* and *z* values for any meat type. However, *C. jejuni/coli* are more sensitive to heat than the other pathogens. Consequently cooking processes that inactivate the other named pathogens (calculated from *D* values) will provide at least the same reduction in *C. jejuni/coli* concentration.

1. INTRODUCTION

Raw meat is frequently contaminated with pathogenic bacteria. Cooking the meat will reduce the risk of illness from pathogens in foods through the heat inactivation of pathogen cells present while at the same time increasing the palatability and shelf life of the meat. However the times and temperatures required to achieve these different outcomes may not be the same. Cooking at too low a temperature or for insufficient time may mean the meat remains unsafe to be eaten.

Reduction of the pathogen concentration during heating can be defined in terms of *D* and *z* values. Knowledge of *D* and *z* values combined with the appropriate target reduction in pathogen concentration, allows target time-temperature combinations to be defined for the cooking process.

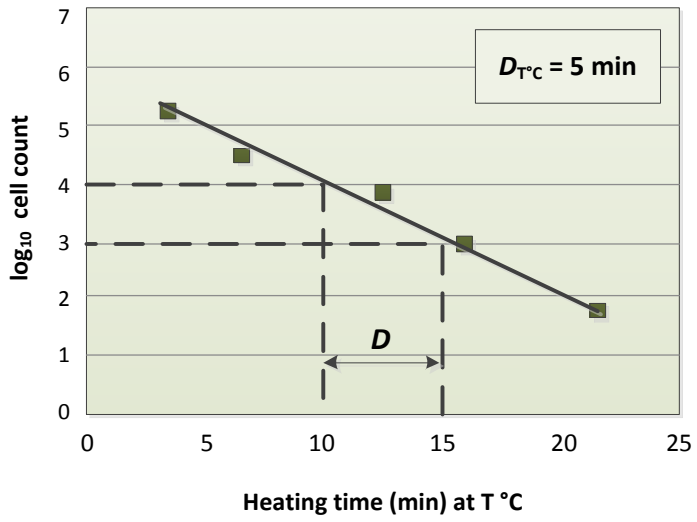
This report provides *D* and *z* values which can be applied to the heating of raw meat and the scope of the raw meat products the *D* and *z* values can be applied to.

1.1 *D* VALUE

1.1.1 Definition

In general terms, the *D* value is the time taken for a specific organism at a specified temperature and in a specified substrate to incur a 90% or 1 $\log_{10}$ reduction in its population as shown in Figure 1.

Figure 1: *D* value



1.1.2 Temperature

The specified temperature is the temperature that must be achieved and maintained at the slowest heating point of the product. The shape and size of the product will determine where in the product the temperature will need to be monitored. The temperature is given as a suffix to the *D* notation. For example D_{65} is the *D* value at 65°C.

1.1.3 Pathogens

For the purposes of this report, the *D* values stated are for the following pathogens;

- *Listeria monocytogenes,*
- *Salmonella* spp. and
- *Escherichia coli* including O157:H7 and other Shiga toxigenic *Escherichia coli* (STEC) serotypes
- *Campylobacter jejuni* and *coli*

These pathogens were chosen because of their public health significance in the New Zealand food safety context.

1.1.4 Raw meat products

The specified substrates are the raw meat products which fall within the scope of Table 1.

Table 1: Scope of products applicable to *D* and *z* values given in this report

	Animal products and processing for which the *D* and z values in this report can be used	Animal products and processing for which the *D* and *z* values in this report cannot be used without further verification.
Meat Types	• Raw beef • Raw pork • Raw lamb / mutton • Raw poultry	• Fish (insufficient data) • Seafood (insufficient data)
Pre-heating processing or formulation	• Intact meat • Minced • Mechanically tenderised • Meat bonding • Brine injection	• Heat treatment applied during a fermentation process • Preparations which cause the water activity to go below 0.95 • Product with a fat content greater than 30% • Product in which the pH is less than 5 • Heat shocked or sub-lethal heat treatment before main heat treatment.
Heat Processing	Heat treatment using: • Water • Steam • Dry heat The temperature at the slowest heating point of the product is maintainable at a temperature of 55°C or above.	Processes which involve: • Microwave heating • Smoking • High pressure treatment • Vacuum packing • Anaerobic atmosphere The temperature at the slowest heating point of the product stays below 55°C.

D values vary depending on the characteristics of the food (Table 2) and how the food is processed prior to heating (Table 3). As a consequence, a set of cooking conditions for one food may not necessarily be applicable to another. Factors influencing *D* values are discussed in more detail by Gilbert et. al. (2011)[1]. The comments in Table 2 and Table 3 apply to *E. coli*, *L. monocytogenes* and *Salmonella* spp. unless indicated otherwise.

Table 1 above defined the scope of meat products and processes applicable to the *D* and *z* values presented in section 2. Meat products and heating treatments outside this scope may need less or extra heating time to ensure adequate pathogen reduction. **It is not appropriate to use the *D* and *z* values in this report to predict behaviour in food types other than meat**.

Table 2: How food characteristics can influence *D* values

Factor	Influence on *D* value
Additives	Can be utilised to decrease *D* values.
Atmosphere	Anaerobic conditions during heat treatment may increase *D* values.
Competition from other bacteria present	May increase *D* values by altering the atmosphere, however unlikely in meat unless spoilage has occurred.
Fat	Increasing fat concentration may increase thermal stability, but this may be via a reduction in water activity. Localised areas of fat may be more protective than product where fat is uniformly blended throughout product.
pH	Optimum survival of *Salmonella* spp. and *E. coli* in the pH range 5 to 7. *Listeria* optimum survival close to neural pH. Lower and higher pH result in decreased *D* values. Type of acidulant may not influence *D* value.
Water activity	Decreasing a_w tends to increase the *D* value.

[1] Gilbert S, et al. (2011) Background document on factors influencing the heat inactivation of bacteria in foods. ESR Report FW10045

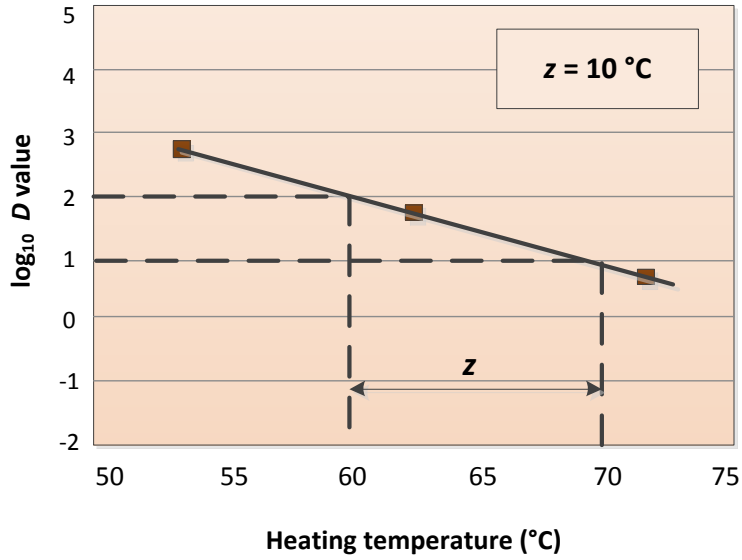
Table 3: Examples of how bacteria specific factors prior to cooking can influence *D* values

Factor	Influence on *D* value
Heat prior to cooking	Meat subjected to sub-lethal cooking temperatures prior to the main heating step increases *D* values.
Acid adaption	May increase *D* values. Acid adaption can occur with processing which increases the acidity of the meat product for a period of time before heating. E.g. using an acidic marinade.
Growth phase of cells	Heat resistance is greatest in stationary phase cells. Stationary cells exist in established populations which have a constant population density. Population density may be limited by depletion of key nutrients or the accumulation of metabolites. Pathogen cells may be in the stationary phase on the carcass, or pre-heating processing may allow enough cell growth for stationary phase to be reached.

1.2 *Z* VALUE

The *z* value is the increase in temperature needed to decrease the *D* value for a specific organism in a specific substrate by a factor of 10. A factor of 10 is equivalent to a one log reduction in the *D* value (Figure 2).

Figure 2: *z* value



1.3 MEAT TYPES

For the purposes of this report, meat satisfying the conditions in Table 1 have been separated into four different categories:

- Beef which is meat from cattle or calves.
- Poultry which is meat from chickens, ducks or turkeys.
- Pork which is meat from pigs.
- "All Meat" – this group includes meat in the beef, poultry and pork groups as well as other meat types and products which fit into the scope of Table 1. This includes types of sheep meat and raw products like sausages or products containing a mixture of meat types. This category incorporates the data from product – pathogen combinations with insufficient data to define product specific *D* and *z* values.

2. *D* VALUES

2.1 *D* VALUE REFERENCE TABLES

This section provides reference tables of D values in minutes by pathogen and meat type. A description of the method used to determine the D values is given in Appendix A and the experimental data used for the calculations is graphically presented in Appendix B.

There are insufficient data in the literature to define *D* values for *C. jejuni* or *C. coli* in meat. However, *Campylobacter* is more sensitive to heat than *L. monocytogenes, Salmonella* spp. and *E. coli.* Consequently, heat inactivation processes achieving a specified reduction in concentration for these three pathogens (calculated from *D* values) will provide at least the same reduction in *C. jejuni* or *C. coli* concentration.

A flowchart is given in Figure 3 to provide guidance on which D and z values should be used for different meat category / pathogen / target temperature combinations in order to calculate an appropriate heating process.

Figure 3: Flowchart for determining a *D* value for a given meat / pathogen / target temperature combination

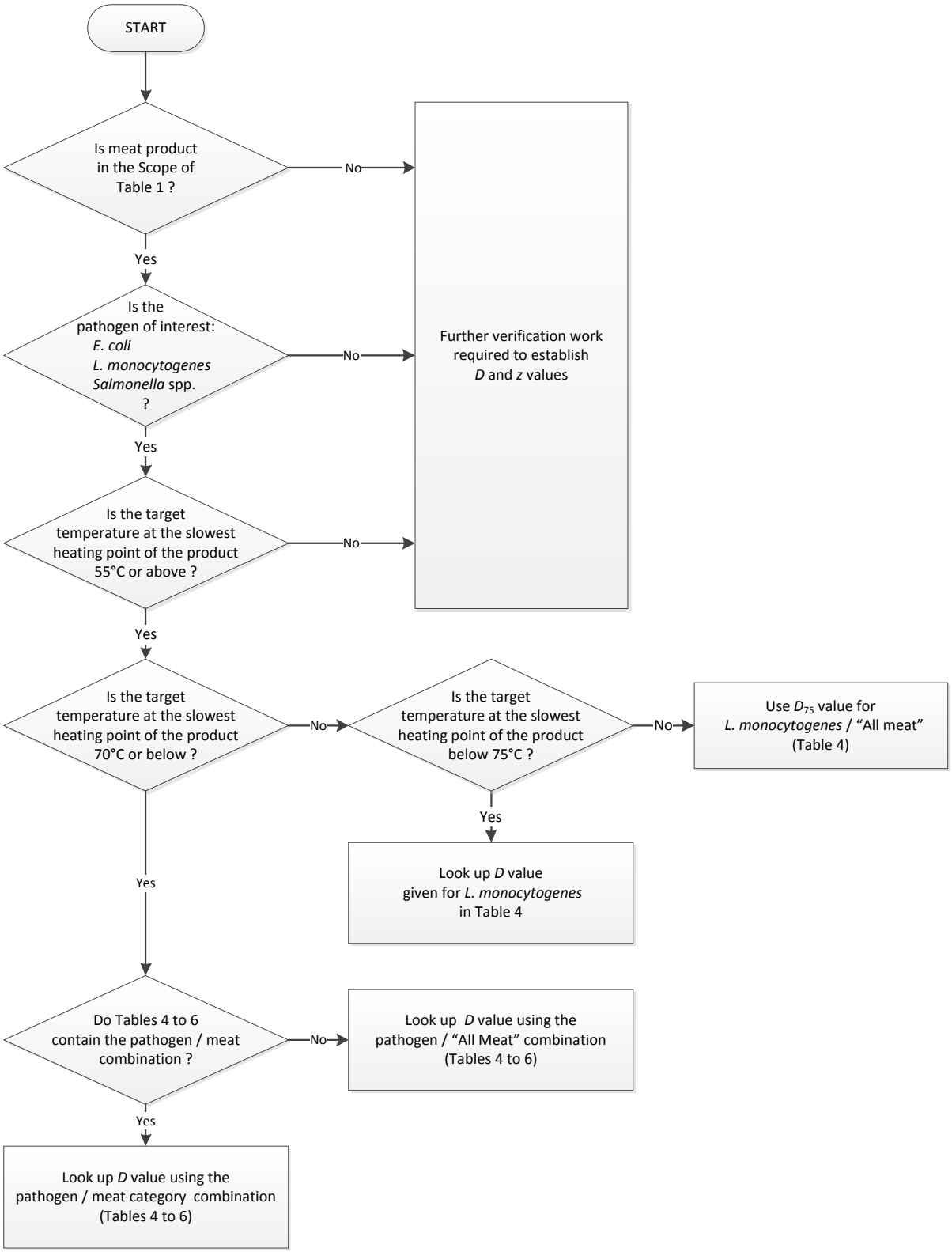


Table 4 *D* values for the inactivation of *L. monocytogenes*

Temperature (°C)	*D* value (minutes)[a]
	"All Meat"
55	95.6
56	66.2
57	45.8
58	31.7
59	21.9
60	15.2
61	10.5
62	7.3
63	5.1
64	3.5
65	2.4
66	1.7
67	1.2
68	0.8
69	0.6
70	0.4
71	0.3
72	0.2
73	0.2
74	0.1
75	0.1

a: D values rounded up to 1 decimal place

Table 5 *D* values for the inactivation of *Salmonella* spp.

Temperature (°C)	*D* value (minutes)[a]		
	Poultry	Beef / Pork	"All Meat"
55	47.4	49.2	69.9
56	34.2	34.7	49.3
57	24.7	24.5	34.7
58	17.8	17.3	24.5
59	12.9	12.2	17.2
60	9.3	8.6	12.2
61	6.7	6.1	8.6
62	4.9	4.3	6.1
63	3.5	3.1	4.3
64	2.5	2.2	3.0
65	1.8	1.5	2.1
66	1.3	1.1	1.5
67	1.0	0.8	1.1
68	0.7	0.6	0.8
69	0.5	0.4	0.6
70	0.4	0.3	0.4

a: D values rounded up to 1 decimal place

Table 6 *D* values for the inactivation of *E. coli* including O157:H7 and other STEC serotypes

Temperature (°C)	*D* value (minutes)[a]	
	Beef / Pork	"All Meat"
55	33.6	36.3
56	23.9	26.0
57	17.0	18.7
58	12.1	13.4
59	8.6	9.6
60	6.1	6.9
61	4.4	5.0
62	3.1	3.6
63	2.2	2.6
64	1.6	1.9
65	1.1	1.3
66	0.8	1.0
67	0.6	0.7
68	0.4	0.5
69	0.3	0.4
70	0.2	0.3

a: D values rounded up to 1 decimal place

2.2 HEAT INACTIVATION TIME-TEMPERATURE COMBINATIONS

2.2.1 Factors in setting a time-temperature combination

To decide on the appropriate time-temperature combination, the following must be considered:

- The relevant pathogens for the specific meat type as determined by hazard analysis
- The prevalence (frequency and numbers) of the pathogen in the meat.
- The reduction in pathogen concentration that is required. This will depend on factors such as;
    - initial pathogen concentration on the raw product ,
    - intended purpose, e.g. immediate consumption, extended shelf life chilled product , ready to eat product and,
    - the final concentration of pathogens required to meet regulatory or operator defined limits.
- Potential adverse effects on food quality brought about by the heat treatment.

The *D* value provides the target time at a specific temperature to ensure a 1 $\log_{10}$ reduction in pathogen cells. If a particular log reduction is required, the required time at the target temperature is calculated by multiplying the *D* value by the $\log_{10}$ reduction required.

2.2.2 Example

Table 7 outlines the time-temperature combinations required to ensure a 6 $\log_{10}$ reduction in pathogen cell count. A 6 $\log_{10}$ reduction is given as an example only, however reductions of 5-7 $\log_{10}$ are commonly applied. The desired pathogen reduction will depend on the factors given above.

Table 7: Time – temperature requirements to ensure a 6 $\log_{10}$ reduction in pathogen concentration is achieved

Pathogen	Meat	Time required to achieve 6 $\log_{10}$ pathogen reduction at given temperature (minutes)			
		60°C	65°C	70°C	75°C
E.coli	Beef / Pork	36.6	6.6	1.2	
	"All Meat"	41.4	7.8	1.8	
L. monocytogenes	"All Meat"	91.2	14.4	2.4	0.6
Salmonella spp.	Beef / Pork	51.6	9.0	1.8	
	Poultry	55.8	10.8	2.4	
	"All Meat"	73.2	12.6	2.4	

2.3 DISCUSSION

The quantity and type of experimental data available from the literature determined which combinations of meat and pathogen type are able to have specified *D* and *z* values. Where there was insufficient data to provide clear evidence for the *D* and *z* values for the specific meat group no values are given in the tables. In total, 1348 data points defined the *D* and *z* values given in the tables, which represent data across a range of pathogen strains, cooking methods and meat preparations.

D values are not given for target temperatures below 55°C. There are not enough data to define a *D* and *z* relationship and the data that are available do not show the linear relationship, observed at temperatures of 55°C and above, between $\log_{10} D$ and the target temperature. This may be due to temperatures below 55°C being close to the maximum observed growth temperatures for the pathogens (45°C for *L. monocytogenes* to 49°C for *Salmonella* spp.[2]).

There is also very limited data for temperatures above 70°C. The inactivation rate of the considered pathogens at temperatures above 70°C is high, resulting in *D* values which are numbers of seconds. This makes it practically difficult to accurately calculate *D* values in the meat food matrix.

The *D* values listed for *L. monocytogenes* are higher than the *D* values given for *Salmonella* spp. and *E. coli*. This may be due to differences in heat resistance of the varieties of pathogen strains that were available from the literature or due to differences in cell type. In general Gram-positive cells (*L. monocytogenes*) are more heat resistant than Gram-negative (*Salmonella* spp. and *E. coli)* due to differences in the cell construction[3].

[2] http://www.foodsafety.govt.nz/science-risk/hazard-data-sheets/pathogen-data-sheets.htm
[3] Adams MR and Moss MO (2000) Food Microbiology: Chapter 4. The Royal Society of Chemistry. ISBN 0-85404-611-9.

3. CONCLUSIONS

This report presents *D* and *z* values that can be applied to heating meat products in which *E. coli*, *L. monocytogenes*, *Salmonella* spp. and *Campylobacter jejuni/coli* may be present. The characteristics of meat products, e.g. fat content and processing of the product prior to heating, may influence the thermal inactivation of these pathogens. Hence the *D* and *z* values in this report may only be appropriate, without further verification, to products identified within the scope of Table 1.

Using data from the literature up to and including October 2014, thermal inactivation data relating to meat have been extracted. From these data, 1348 points were found to fit the scope of Table 1 as well as the experimental procedure being appropriate for calculating *D* values. The *D* values for a given temperature were highly variable due to the intrinsic properties of meat, pathogen strains, cooking and experimental processes.

For each pathogen-meat group combination, the presented *D* values were derived from a linear regression of the 95th percentile value of the available data at each temperature. This approach takes into account the most heat resistant strains which are those most likely to survive cooking and present a risk of illness.

Where there is insufficient data to perform a linear regression for a given meat type, the “All Meat” regression line for the pathogen is used.

APPENDIX A: METHOD

A.1 DATA COLLECTION AND EXPLORATORY DATA ANALYSIS

Thermal inactivation data of pathogens in meat were collected from the scientific published literature up to October 2014. When review papers were located, the data were not considered unless the primary publications containing the relevant data for meat could be obtained. The references are included in Appendix C.

Only data meeting the conditions below were included in the project:

- Raw meat products defined in the scope for this report as given in Table 1.
- Test product was of a form that allowed rapid heating throughout the sample to the target temperature, such as thin patties or in small glass tubes.
- Test product was held at a constant internal temperature once at the target temperature.
- Test product that was rapidly cooled after the designated heating time to prevent further decline in viable cell concentrations.
- A linear relationship existed between the base 10 logarithm of the cell count and the time at temperature.

The resulting dataset contained 1348 *D* values. There were 526 *E. coli D* values including 418 relating to beef, 448 *L. monocytogenes D* values and 374 *Salmonella* spp. *D* values including 94 relating to beef and 212 relating to poultry.

The data were collated for each combination of pathogen and meat category and plotted for visual inspection. Any outlying values were first checked for transcription errors and then checked to determine possible reasons for the data being inconsistent with other collected data. Possible reasons include strain-to-strain variability in heat resistance, heating methodology, cell history prior to heating or choice of enumeration method for the cells which could be damaged/changed by the heat treatment. No reason was found to exclude any data in the dataset of 1348 values.

A.2 CALCULATION OF *D* AND *z* VALUES

For each combination of pathogen and meat type, the following process was used to calculate the associated reference *D* and *z* value:

1. For each temperature greater or equal to 55°C, which had more than 10 data points, the 95th percentile of the experimental *D* values was calculated (blue diamonds in Figure 4).
2. A linear regression of the logarithm of the 95th percentile *D* values against temperature was then conducted using least squares fitting in Excel (solid line in Figure 4).
3. *z* was calculated to two decimal places from the inverse of the slope of the regression function.
4. A reference *D* value at 65 °C was calculated (rounding up to one decimal place) from the linear regression function.

The resulting *D* and *z* values are given in Table 8, Table 9 and Table 10

Figure 4 Data analysis example

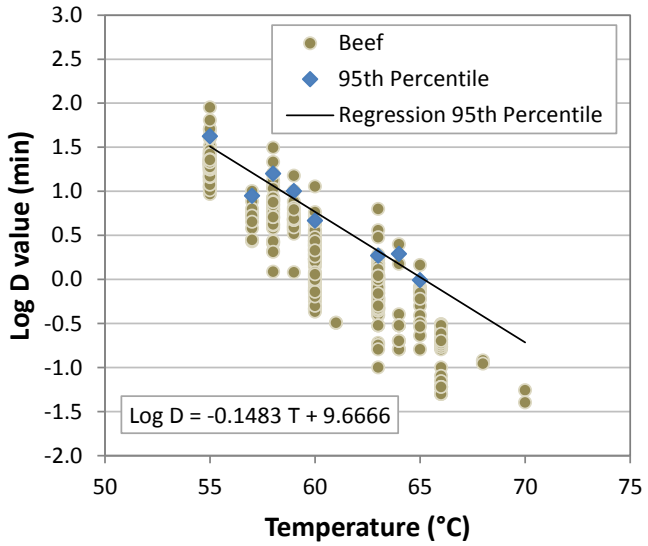


Table 8: *D* and *z* values for the inactivation of *E. coli* including O157:H7 and other STEC serotypes

Meat Category	Number of Data Points	Temperature Range (°C)	*z* (°C)	D_{65} (minutes)
Beef	418	55-70	6.74	1.1
"All Meat"	526	55-70	6.92	1.3

Table 9: *D* and *z* values for the inactivation of *L. monocytogenes*

Meat Category	Number of Data Points	Temperature Range (°C)	*z* (°C)	D_{65} (minutes)
"All Meat"	448	55-74	6.25	2.4

Table 10: *D* and *z* values for the inactivation of *Salmonella* spp.

Meat Category	Number of Data Points	Temperature Range (°C)	*z* (°C)	D_{65} (minutes)
Beef	94	55-70	6.60	1.5
Poultry	212	55-70	7.04	1.8
"All Meat"	374	55-70	6.57	2.1

A.3 CALCULATION OF NON-REFERENCE *D* VALUES.

A.3.1 Formula

Once a *D* value at a specific temperature (D_{ref}) and a *z* value have been established, a *D* value at any temperature (*T*) in the experimental data range can be calculated using the following relationship.

$$\log_{10}(D) = \log_{10}(D_{ref}) - \frac{T - T_{ref}}{z} \qquad \text{(Equation 1)}$$

This relationship should not be extended beyond the range of the experimental data used to calculate the *z* value.

In this report, all *D* values were calculated using a single reference temperature of 65°C. This temperature was chosen as 65°C is always within the temperature range of the 95th percentile data used to calculate the *z* values. A single reference temperature was chosen through the report to ensure consistency in the calculation of *D* values at given temperatures.

A.3.2 Example

To calculate the *D* value to reduce *Salmonella* spp. on poultry using a target temperature of 68°C:

i. From Table 10 extract the reference *D* value and the *z* value. D_{65} in poultry is 1.8 minutes and the *z* value is 7.04°C.

ii. Use Equation 1 to calculate the logarithm of the *D* value,

$$\log_{10}(D_{68}) = \log_{10}(1.8) - \frac{68 - 65}{7.04} = -0.171 .$$

iii. Calculate the *D* value by taking the inverse of the base 10 logarithm,

$$D_{68} = 10^{-0.171} = 0.7 \text{ minutes} = 42 \text{ seconds.}$$

A.4 VARIABILITY AND METHOD SELECTION

For each pathogen and meat category combination, plots of $\log_{10}$ *D* value against temperature are given in Appendix B. The variability observed in these plots for the *D* values at a given temperature are due to differences in the design of the studies from which the data was obtained and include differences in; pathogen strains, meat samples properties, cooking process and experimental design.

While, processors may be able to reduce the variability in thermal inactivation due to cooking processes and the characteristics of the meat in their products. The strains of the pathogens presenting on the raw meat are unlikely to be known before heat treatment commences. Therefore, it is important to heat products to time temperature combinations which will take into account the possible variation in *D* values.

The *D* and *z* values in this report take into account the likely variability of pathogen thermal inactivation in meat products by using data which includes a range of pathogen strains and meat sources for each of the pathogens. The variability is incorporated into the calculation methodology to ensure safety in two ways:

1. For each pathogen/ meat category/ temperature combination the 95th percentile *D* value was calculated. This approach takes into account the most heat resistant strains which are those most likely to survive cooking and present a risk of illness.

2. The number of data points for each pathogen/ meat group/ temperature combination was determined. Only combinations with ten or more data points were used in further calculations. Ten was chosen to ensure incorporation of data from a range of studies and from the visual inspection of 95th percentile points at each temperature compared to the overall dataset. This approach avoids biasing the regression line towards data points which do not represent the variability seen in the dataset overall.

APPENDIX B: DATA PLOTS

This appendix provides plots of the data used to generate the *D* values in this report for the meat categories; “All Meat”, Beef, Poultry and Pork. Where appropriate the plot also indicates the 95th percentile points (solid diamond) at temperatures where there are more than 10 data points and the points are used in the regression analysis.

The solid line is the linear regression line through the 95th percentile points when there is sufficient data to perform the regression. To explore the possibility of having a red meat category, the pork data is compared to the beef regression line for *Escherichia coli* and *Salmonella* spp.. For other meat categories which did not have sufficient data, *D* values are based on the “All Meat” category and the “All Meat” regression line is plotted.

Figure 5: *Escherichia coli* – Experimental *D* value data by meat type with the appropriate 95th percentile linear regression lines.

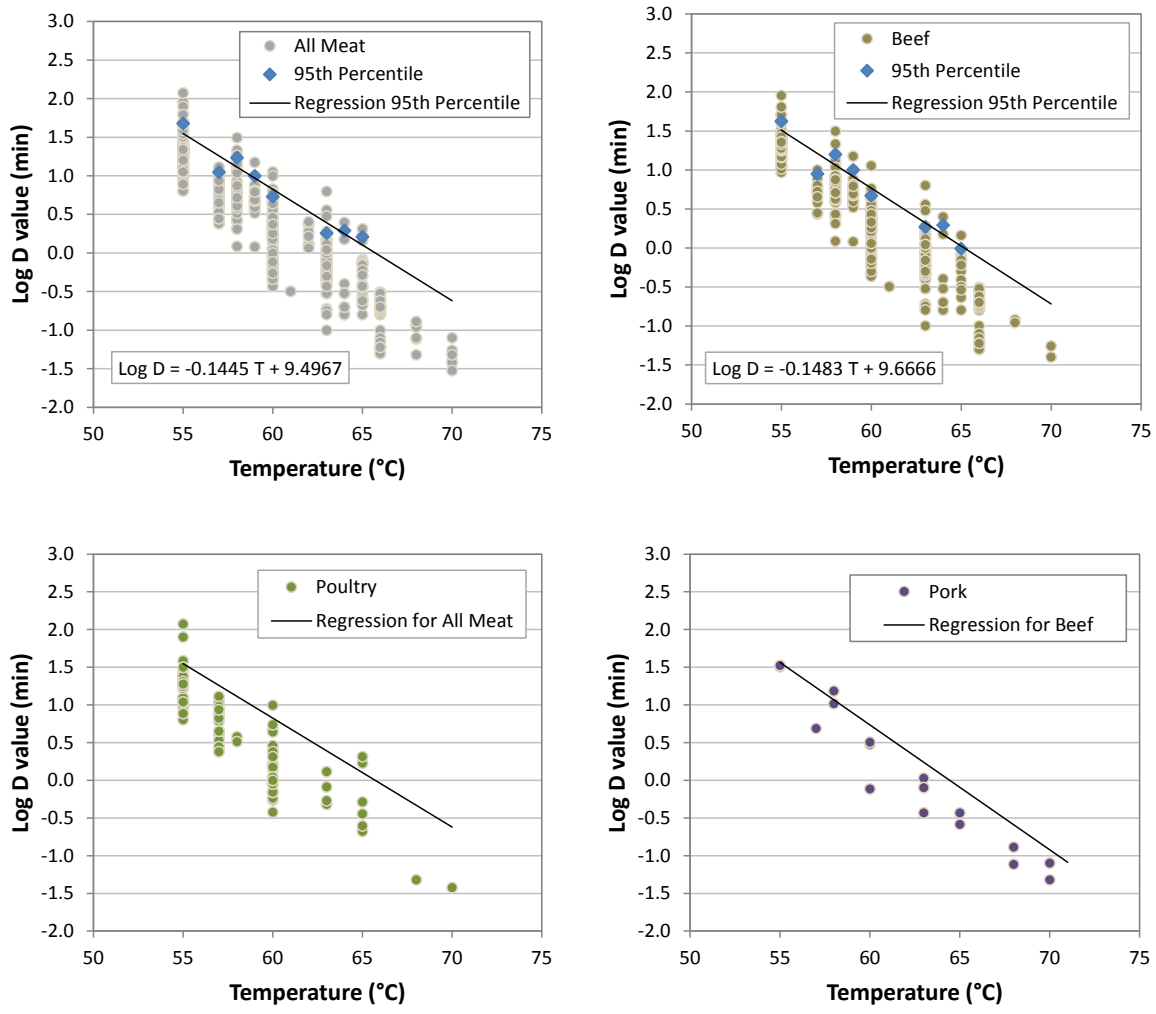
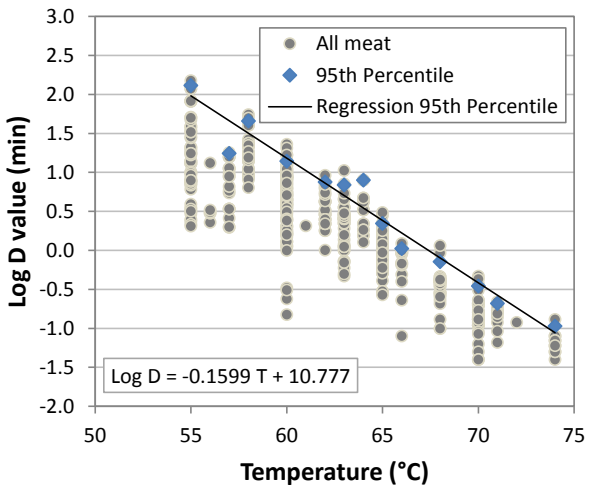
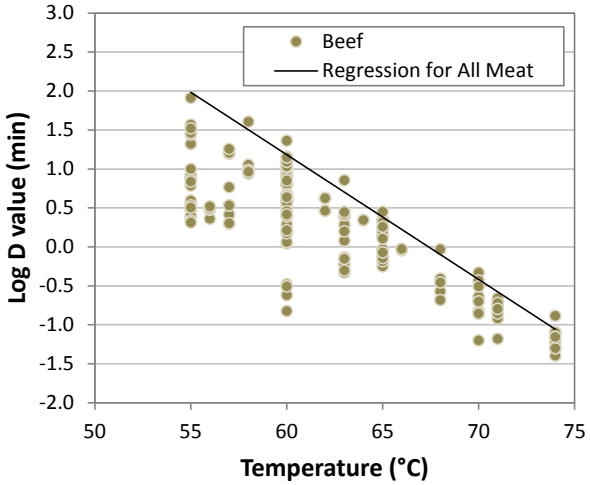
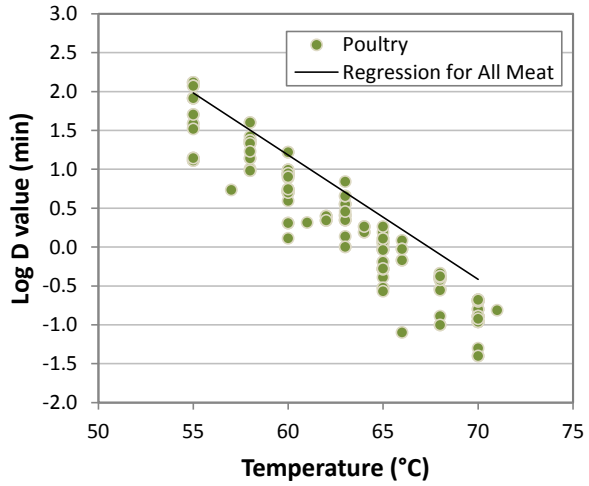


Figure 6: *Listeria monocytogenes* – Experimental *D* value data by meat type with the appropriate 95th percentile linear regression lines.


All meat
95th Percentile
Regression 95th Percentile
Log D = -0.1599 T + 10.777
Log D value (min)
Temperature (°C)


Beef
Regression for All Meat
Log D value (min)
Temperature (°C)


Poultry
Regression for All Meat
Log D value (min)
Temperature (°C)

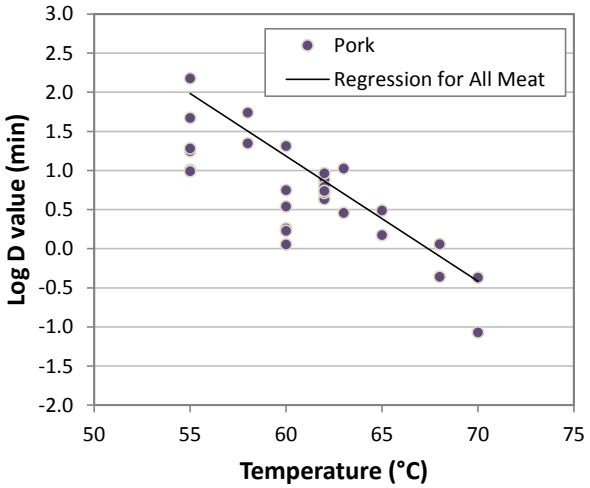
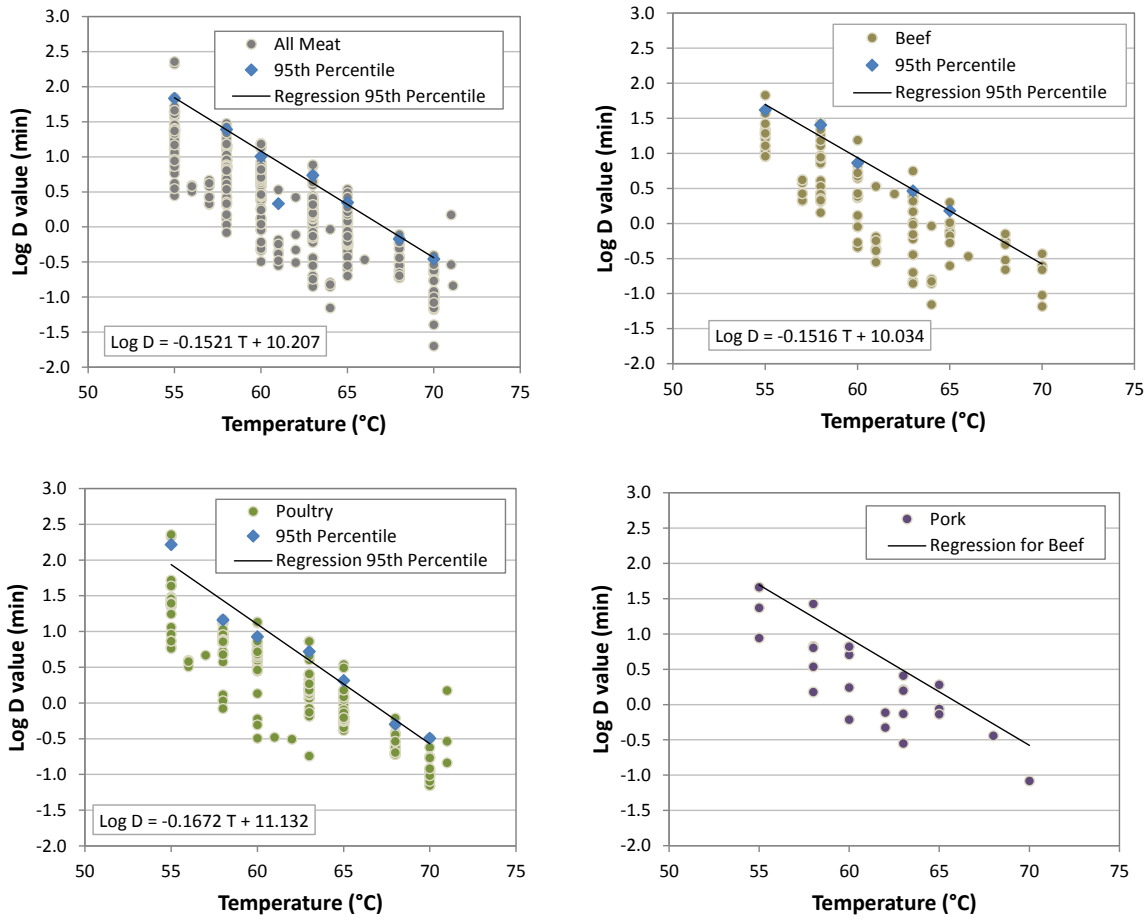

Pork
Regression for All Meat
Log D value (min)
Temperature (°C)

Figure 7: *Salmonella* spp. – Experimental *D* value data by meat type with the appropriate 95th percentile linear regression lines.



Note: For the "All Meat" category, the regression of 95th percentile points did not include the data point at 61°C. Temperatures above and below this value suggested the 95th percentile value at 61°C was not consistent with the general trend and so the data point was removed to avoid biasing the regression line to shorter *D* times.

APPENDIX C: BIBLIOGRAPHY

ACMSF. (2007) Ad hoc group on safe cooking of burgers. Advisory Committee on the Microbiological Safety of Food. Food Standards Agency, London, United Kingdom.

Aguilar C, Valencia V, Ochoa O et al. (2013) Improving food thermal processing: a death-time study on processed meat products. Journal of Food Processing and Preservation 37 (3): 189-97

Ahmed NM, Conner DE, Huffman DL. (1995) Heat resistance of *Escherichia coli* O157:H7 in meat and poultry as affected by product composition. Journal of Food Science; 60:606-610.

Amalaradjou MAR, Baskaran SA, Ramanathan R et al. (2010) Enhancing the thermal destruction of *Escherichia coli* O157:H7 in ground beef patties by trans-cinnamaldehyde. Food Microbiology 27 (6): 841-4

Anonymous (1998) Lethality and stabilization performance standards for certain meat and poultry products: Technical paper December 31 1998; USDA, FSIS, USA. http://www.fsis.usda.gov/oa/fr/95033F-a.htm.

Anonymous (1999) Appendix A, Compliance guidelines for meeting lethality performance standards for certain meat and poultry products. Federal Register January 6, 1999; volume 64, FR, page 732-749. USDA/FSIS.

Baker RC, Poon W, Vadehra DV. (1983) Destruction of *Salmonella typhimurium* and *Staphylococcus aureus* in poultry products cooked in a conventional and microwave oven. Poultry Science; 62: 805-810.

Bearns RE, Girard KF. (1958) The effect of pasteurization on *Listeria monocytogenes.* Canadian Journal of Microbiology; 4: 55-61.

Benito A, Ventoura G, Casedei M, Robinson T, Mackey B. (1999) Variation in resistance of natural isolates of *Escherichia coli* O157 to high hydrostatic pressure, mild heat, and other stresses. Applied and Environmental Microbiology; 65: 1564-1569

Blackman IC, Park YW, Harrison MA. (2005) Effects of oxidative compounds on thermotolerance in *Escherichia coli* O157:H7 strains EO139 and 380-94. Journal of Food Protection; 68: 2443-2446.

Blankenship LC. (1978) Survival of a *Salmonella typhimurium* experimental contaminant during cooking of beef roasts. Applied and Environmental Microbiology; 35: 1160-1165.

Byrne CM, Bolton DJ, Sheridan JJ, Blair IS, McDowell DA. (2002) The effect of commercial production and product formulation stresses on the heat resistance of *Escherichia coli* O157:H7 (NCTC 12900) in beef burgers. International Journal of Food Microbiology; 79: 183-192.

Carlier V, Augustin JC, Rozier J. (1996) Destruction of *Listeria monocytogenes* during a ham cooking process. Journal of Food Protection; 59: 592-595.

Cassin MH, Lammerding AM, Todd ECD, Ross W, McColl RS. (1998) Quantitative risk assessment for *Escherichia coli* O157:H7 in ground beef hamburgers. International Journal of Food Microbiology; 41: 21-44.

Cotterill OJ, Glauert HP, Russell WD. (1977) Microbial counts and thermal resistance of *Salmonella oranienburg* in ground turkey meat. Poultry Science; 56:1889-1892.

Cygnarowicz-Provost M, Whiting RC, Craig JC Jr. (1994) Steam surface pasteurization of beef frankfurters. Journal of Food Science; 59: 1-5.

Davidson CM, Boothroyd M, Georgala DL. (1966) Thermal resistance of Salmonella senftenberg. Nature; 212:1060-1061.

Edelson-Mammel SG, Whiting RC, Joseph SW, Buchanan RL. (2005) Effect of prior growth conditions on the thermal inactivation of 13 strains of *Listeria monocytogenes* in two heating menstrua. Journal of Food Protection; 68: 168-172

Elliker PR, Frazier WC. (1938) Influence of time and temperature of incubation on heat resistance of *Escherichia coli*. Journal of Bacteriology; 36, 83-98.

Evans DA, Hankinson DJ, Litsky W. (1970) Heat resistance of certain pathogenic bacteria in milk using a commercial plate heat exchanger. Journal of Dairy Science; 53:1659-1665.

Farber JM, Pagotto F. (1992) The effect of acid shock on the heat resistance of *Listeria monocytogenes*. Letters in Applied Microbiology; 15:197-201.

Farber JM, Peterkin PI. (1991) *Listeria monocytogenes*, a foodborne pathogen. Microbiological Reviews; 55: 476-511.

Fedio WM, Jackson H. (1989) Effect of tempering on the heat resistance of *Listeria monocytogenes.* Letters in Applied Microbiology; 9:157-160.

Felicio MTS, Ramalheira R, Ferreira V et al. (2011) Thermal inactivation of *Listeria monocytogenes* from alheiras, traditional Portuguese sausage during cooking. Food Control 22 (12): 1960-4

Gadzella TA, Ingham SC. (1994) Heat shock, anaerobic jar incubation and fluid thioglycollate medium have contrasting effects on D-values of *Escherichia coli*. Journal of Food Protection; 57: 671-673.

Gaze, J, Hooper G and Burling S (2007) Determination of the appropriate cooking regimes for recommendations for the safe roasting/cooking of poultry including turkey, chicken, goose and duck. Report No. B13R007 for the UK FSA.

George SM, Peck MW. (1998) Redox potential affects the measured heat resistance of *Escherichia coli* O157:H7 independently of oxygen concentration. Letters in Applied Microbiology; 27: 313-317.

George SM, Richardson LCC, Pol IE, MW Peck. (1998) Effect of oxygen concentration and redox potential on recovery of sublethally heat-damaged cells of *Escherichia coli* O157:H7, *Salmonella enteritidis* and *Listeria monocytogenes*. Journal of Applied Microbiology; 84: 903-909.

Gilbert S, McIntyre L, Lake R, Wong T L and Hudson J A (2011) Background document on factors influencing the heat inactivation of bacteria in foods. ESR. FW10045

Glass KA, Doyle MP. (1989) Fate and thermal inactivation of *Listeria monocytogenes* in beaker sausage and pepperoni. Journal of Food Protection; 52: 226-231.

Goodfellow SJ, Brown WL. (1978) Fate of *Salmonella* inoculated into beef for cooking. Journal of Food Protection; 41: 598-605.

Huang L. (2013) Determination of thermal inactivation kinetics of *Listeria monocytogenes* in chicken meats by isothermal and dynamic methods. Food Control 33 (2): 484-8

Huang L. (2004) Thermal resistance of *Listeria monocytogenes, Salmonella Heidelberg*, and *Escherichia coli* O157:H7 at elevated temperatures. Journal of Food Protection; 67: 1666-1670.

Humphrey TJ, Wallis M, Hoad M, Richardson NP, Rowbury RJ. (1993) Factors influencing alkali-induced heat resistance in *Salmonella enteritidis* phage type 4. Letters in Applied Microbiology; 16: 147-149.

Humphrey TJ. (1990) Heat resistance in *Salmonella enteritidis* phage type 4: the influence of storage temperatures before heating. Journal of Applied Bacteriology; 69: 493-497.

Jackson TC, Hardin MD, Acuff GR. (1996) Heat resistance of *Escherichia coli* O157:H7 in a nutrient medium and in ground beef patties as influenced by storage and holding temperatures. Journal of Food Protection; 59: 230-237.

Jenkins DE, Schultz JE, Matin A. (1988) Starvation-induced cross protection against heat or H_2O_2 challenge in *Escherichia coli.*

Jørgensen F, Panaretou B, Stephens PJ, Knøchel S. (1996) Effect of pre- and post-heat shock temperature on the persistance of thermotolerance and heat shock-induced proteins in *Listeria monocytogenes*. Journal of Applied Bacteriology; 80: 216-224

Juneja VK, Gonzales-Barron U, Butler F et al. (2013) Predictive thermal inactivation model for the combined effect of temperature, cinnamaldehyde and carvacrol on starvation-stressed multiple *Salmonella* serotypes in ground chicken. International Journal of Food Microbiology 165 (2): 184-99

Juneja VK, Altuntas EG, Ayhan K et al. (2013) Predictive model for the reduction of heat resistance *of Listeria monocytogenes* in ground beef by the combined effect of sodium chloride and apple polyphenols. International Journal of Food Microbiology 164 (1): 54-9

Juneja VK, Yadav AS, Hwang C-A et al. (2012) Kinetics of thermal destruction of *Salmonella* in ground chicken containing trans-cinnamaldehyde and carvacrol. Journal of Food Protection 75 (2): 289-96

Juneja VK, Friedman M. (2008) Carvacrol and cinnamaldehyde facilitate thermal destruction of *Escherichia coli* O157:H7 in raw ground beef. Journal of Food Protection; vol. 71, no. 8: 1604-1611.

Juneja VK. (2007) Thermal inactivation of *Salmonella* spp. in ground chicken breast or thigh meat. International Journal of Food Science and Technology; 42: 1443-1448.

Juneja VK, Marks HM. (2005) Heat resistance kinetics variation among various isolates of *Escherichia coli*. Innovative Food Science and Emerging Technologies; 6: 155-161.

Juneja VK, Marks HM, Mohr T. (2003) Predictive thermal inactivation model for effects of temperature, sodium lactate, NaCl, and sodium pyrophosphate on *Salmonella* serotypes in ground beef. Applied and Environmental Microbiology; 69: 5138-5156.

Juneja VK. (2003) Predictive model for the combined effect of temperature, sodium lactate, and sodium diacetate on the heat resistance of *Listeria monocytogenes* in beef. Journal of Food Protection; 66: 804-811.

Juneja VK. (2003) A comparative heat inactivation study of indigenous microflora in beef with that of *Listeria monocytogenes*, *Salmonella* serotypes and *Escherichia coli* O157:H7. Letters in Applied Microbiology; 37: 292-298.

Juneja VK, Marks HM. (2003) Characterizing asymptotic D-values for *Salmonella* spp. subjected to different heating rates in sous-vide cooked beef. Innovative Food Science and Emerging Technologies; 4: 395-402.

Juneja VK, Novak JS. (2003) Heat resistance of *Escherichia coli* O157:H7 in cook-in-bag ground beef as affected by pH and acidulant. International Journal of Food Science and Technology; 38: 297-304

Juneja VK, Eblen BS, Marks HM. (2001) Modeling non-linear survival curves to calculate thermal inactivation of *Salmonella* in poultry of different fat levels. International Journal of Food Microbiology; 70: 37-51.

Juneja VK, Eblen BS, Ransom GM. (2001) Thermal inactivation of *Salmonella* spp. in chicken broth, beef, pork, turkey, and chicken: Determination of D- and z- values. Journal of Food Science; 66: 146-152.

Juneja VK, Synder OP Jr., Marmer BS. (1997) Potential for growth from spores of *Bacillus cereus* and *Clostridium botulinum* and vegetative cells of *Staphylococcus aureus*, *Listeria monocytogenes*, and *Salmonella* Serotypes in cooked ground beef during cooling. Journal of Food Protection; 60: 272-275.

Juneja VK, Snyder OP Jr, Marmer BS. (1997) Thermal destruction of *Escherichia coli* O157:H7 in beef and chicken: determination of D- and z- values. International Journal of Food Microbiology; 35: 231-237.

Juneja VK, Snyder OP Jr., Williams AC, Marmer BS. (1997) Thermal destruction of *Escherichia coli* O157:H7 in hamburger. Journal of Food Protection; 60: 1163-1166.

Kamau DN, Doores S, Pruitt KM. (1990) Enhanced thermal destruction of *Listeria monocytogenes* and *Staphylococcus aureus* by the lactoperoxidase system. Applied and Environmental Microbiology; 56: 2711-2716.

Katsui N, Tsuchido T, Takano M, Shibasaki I. (1981) Effect of preincubation temperature on the heat resistance of *Escherichia coli* having different fatty acid compositions. Journal of General Microbiology; 122: 357-361.

Kaur J, Ledward DA, Park RWA, Robson RL. (1998) Factors affecting the heat resistance of *Escherichia coli* O157:H7. Letters in Applied Microbiology; 26: 325-330.

Kim Y-H, Kim S-A, Chung H-J. (2014) Synergistic effect of propolis and heat treatment leading to increased injury to *Escherichia coli* O157:H7 in ground pork. Journal of Food Safety 34 (1): 1-8

Kotrola JS, Conner DE. (1997) Heat inactivation of *Escherichia coli* O157:H7 in turkey meat as affected by sodium chloride, sodium lactate, polyphosphate, and fat content. Journal of Food Protection; 60:898-902.

Kotrola JS, Conner DE, Mikel WB. (1997) Thermal inactivation of *Escherichia coli* O157:H7 in cooked turkey products. Journal of Food Science; 62: 875-905.

Linton RH, Pierson MD, Bishop JR. (1990) Increase in heat resistance of *Listeria monocytogenes* Scott A by sublethal heat shock. Journal of Food Protection; 53:924-927.

Lou Y, Yousef AE. (1996) Resistance of *Listeria monocytogenes* to heat after adaptation to environmental stresses. Journal of Food Protection; 59: 465-471.

Lovett J, Wesley IV, Vandermaaten MJ, Bradshaw JG, Francis DW, Crawford RG, Donnelly CW, Messer JW. (1990) High-temperature short-time pasteurization inactivates *Listeria monocytogenes*. Journal of Food Protection; 734-738.

Luchansky JB, Porto-Fett ACS, Shoyer BA et al. (2013) Thermal inactivation of a single strain each of serotype O26:H11, O45:H2, O103:H2, O104:H4, O111:H-, O121:H19, O145:NM, and O157:H7 cells of shiga toxin-producing *Escherichia coli* in wafers of ground beef. Journal of Food Protection 76 (8): 1434-7

Mackey BM, Derrick CM. (1986) Elevation of the heat resistance of *Salmonella typhimurium* by sublethal heat shock. Journal of Applied Bacteriology; 61: 389-393.

Mackey BM, Derrick CM. (1987) Changes in the heat resistance of *Salmonella typhimurium* during heating at rising temperatures. Letters in Applied Microbiology; 4:13-16.

Mattick KL, Bailey RA, Jørgensen F, Humphrey TJ. (2002) The prevalence and number of *Salmonella* in sausages and their destruction by frying, grilling or barbecuing. Journal of Applied Microbiology; 93: 541-547.

Mazzotta AS. (2000) D- and z- values of *Salmonella* in ground chicken breast meat. Journal of Food Safety; 20: 217-223.

Mazzotta AS, Gombas DE. (2001) Heat resistance of an outbreak strain of *Listeria monocytogenes* in hot dog batter. Journal of Food Protection; 64: 321-324.

McCormick K, Han IY, Acton JC, Sheldon BW, Daawson PL. (2003) D- and z-values for *Listeria monocytogenes* and *Salmonella* Typhimurium in packaged low-fat ready-to-eat turkey bologna subjected to a surface pasteurization treatment. Poultry Science; 82: 1337-1342.

Membré J-M, Bassett J, Gorris LGM. (2007) Applying the Food Safety Objective and related standards to thermal inactivation of *Salmonella* in poultry meat. Journal of Food Protection; 70: 22036-2044.

Mukherjee A, Yoon Y, Belk K, Scanga JA, Smith GC, Sofos JN. (2008) Thermal inactivation of *Escherichia coli* O157:H7 in beef treated with marination and tenderization ingredients. Journal of Food Protection; 71: 1349-1356.

Murano EE, Pierson MD. (1992) Effect of heat shock and growth atmosphere on the heat resistance of *Escherichia coli* O157:H7. Journal of Food Protection; 55: 171-175.

Murphy RY, Driscoll KH, Duncan LK, Osaili T, Marcy JA. (2004) Thermal lethality of *Salmonella* in chicken leg quarters processed via an air/steam impingement oven. Journal of Food Protection; 67: 493-498.

Murphy RY, Beard BL, Martin EM, Duncan LK, Marcy JA. (2004) Comparative study of thermal inactivation of *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in ground pork. Journal of Food Science; 69: 97-101.

Murphy RY, Martin EM, Duncan LK, Beard BL, Marcy JA. (2004) Thermal process validation for *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in ground turkey and beef products. Journal of Food Protection; 67: 1394-1402.

Murphy RY, Osaili T, Duncan LK, Marcy JA. (2004) Thermal inactivation of *Salmonella* and *Listeria monocytogenes* in ground chicken thigh / leg meat and skin. Poultry Science; 83: 1218-1225.

Murphy RY, Osaili T, Duncan LK, Marcy JA. (2004) Effect of sodium lactate on thermal inactivation of *Listeria monocytogenes* and *Salmonella* in ground chicken thigh and leg meat. Journal of Food Protection; 67: 1403-1407.

Murphy RY, Beard BL, Martin EM, Keener AE, Osaili T. (2004) Predicting process lethality of *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in ground, formulated, and formed beef/turkey links cooked in an air impingement oven. Food Microbiology; 21: 493-499.

Murphy RY, Duncan LK, Driscoll KH, Beard BL, Berrang MB, Marcy JA. (2003) Determination of thermal lethality of *Listeria monocytogenes* in fully cooked chicken breast fillets and strips during postcook in-package pasteurization. Journal of Food Protection; 66: 578-583.

Murphy RY, Duncan LK, Driscoll KH, Marcy JA. (2003) Lethality of *Salmonella* and *Listeria innocua* in fully cooked chicken breast meat products during postcook in-package pasteurization. Journal of Food Protection; 66: 242-248.

Murphy RY, Driscoll KH, Arnold ME, Marcy JA, Wolfe RE. (2003) Lethality of *Listeria monocytogenes* in full cooked and vacuum packaged chicken leg quarters during steam pasteurization. Journal of Food Science; 68: 2780-2783.

Murphy RY, Duncan LK, Johnson ER, Davis MD, Smith JN. (2002) Thermal inactivation D- and z-values of *Salmonella* serotypes and *Listeria innocua* in chicken patties, chicken tenders, franks, beef patties, and blended beef and turkey patties. Journal of Food Protection; 65: 53-60.

Murphy RY, Duncan LK, Berrang ME, Marcy JA, Wolfe RE. (2002) Thermal inactivation D- and Z-values of *Salmonella* and *Listeria innocua* in fully cooked and vacuum packaged chicken breast meat during postcook heat treatment. Poultry Science; 81: 1578-1583.

Murphy RY, Duncan LK, Johnson ER, Davis MD, Marcy JA. (2002) Thermal inactivation of *Salmonella* Senftenberg and *Listeria innocua* in beef/turkey blended patties cooked via fryer and/or air convection oven. Journal of Food Science; 67: 1879-1885.

Murphy RY, Johnson ER, Marks BP, Johnson MG, Marcy JA. (2001) Thermal inactivation of *Salmonella Senftenberg* and *Listeria innocua* in ground chicken breast patties processed in an air convection oven. Poultry Science; 80: 515-521.

Murphy RY, Johnson ER, Duncan LK, Davis MD, Johnson MG, Marcy JA. (2001) Thermal inactivation of *Salmonella* spp. and *Listeria innocua* in chicken breast patties processed in a pilot-scale air-convection oven. Journal of Food Science; 66: 734-741.

Murphy RY, Duncan LK, Johnson ER, Davis MD, Wolfe RE, Brown HG. (2001) Thermal lethality of *Salmonella* Senftenberg and *Listeria innocua* in fully cooked and packaged chicken breast strips via steam pasteurisation. Journal of Food Protection; 64; 2083-2087.

Murphy RY, Marks BP, Johnson ER, Johnson MG. (2000) Thermal inactivation kinetics of *Salmonella* and *Listeria* in ground chicken breast meat and liquid medium. Journal of Food Science; 65: 706-710.

Nguyen HTT, Corry JEL, Miles CA. (2005) Heat resistance and mechanism of heat inactivation in thermophilic Campylobacters. Applied and Environmental Microbiology; 72: 908-913.

Novak JS, Yuan JTC. (2003) Viability of *Clostridium perfringens*, *Escherichia coli*, and *Listeria monocytogenes* surviving mild heat or aqueous ozone treatment on beef followed by heat, alkali, or salt stress. Journal of Food Protection; 66: 382-389.

O'Bryan CA, Crandall PG, Martin EM, Griffis CL, Johnson MG. (2006) Heat resistance of *Salmonella* spp., *Listeria monocytogenes*, *Escherichia coli* O157:H7, and *Listeria innocua* M1, a potential surrogate for *Listeria monocytogenes*, in meat and poultry: A review. Journal of Food Science; 71: R23-R30.

Osaili TM, Al-Nabulsi AA, Shaker RR et al. (2013) Thermal inactivation of *Salmonella Typhimurium* in chicken shawirma (gyro). International Journal of Food Microbiology 166 (1): 15-20

Osaili T, Griffis CL, Martin EM, Beard BL, Keener AE, Marcy JA. (2007) Thermal inactivation of *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in breaded pork patties. Journal of Food Science; 72: M56-M61.

Osaili T, Griffis CL, Martin EM, Beard BL, Keener A, Marcy JA. (2006) Thermal inactivation studies of *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in ready-to-eat chicken fried beef patties. Journal of Food Protection; 69: 1080-1086.

Pradhan AK, Li Y, Marcy JA, Johnson MG, Tamplin ML. (2007) Pathogen kinetics and heat and mass transfer-based predictive model for *Listeria innocua* in irregular-shaped poultry products during thermal processing. Journal of Food Protection; 70: 607-615.

Rocelle M, Clavero S, Beuchat LR. (1996) Survival of *Escherichia coli* O157:H7 in broth and processed salami influenced by pH, water activity, and temperature and suitability of media for its recovery. Applied and Environment Microbiology; 62:2735-2740.

Sallami L, Marcotte M, Naim F, Ouattara B, Leblanc C, Saucier L. (2006) Heat inactivation of *Listeria monocytogenes* and *Salmonella enterica* serovar Typhi in a typical bologna matrix during an industrial cooking-cooling cycle. Journal of Food Protection; 69: 3025-3030.

Shipp DK, Rehberger TG, Hand LW. (1992) Thermal inactivation of *Escherichia coli* O157:H7 in ground beef patties. Animal Research Report MP136, p56-60. Oklahoma Agricultural Experiment Station, Oklahoma State University, Stillwater.

van Asselt ED and Zwietering, MH. (2006) A systematic approach to determine global thermal inactivation parameters for various food pathogens. International Journal of Food Microbiology; 107: 73-82.

Vasan A, Geier R, Ingham SC et al. (2014) Thermal tolerance of O157 and non-O157 shiga toxigenic strains of *Escherichia coli, Salmonella*, and potential pathogen surrogates, in frankfurter batter and ground beef of varying fat levels. Journal of Food Protection 77 (9): 1501-11

Veeramuthu GJ, Price JF, Davis CE, Booren AM, Smith DM. (1998) Thermal inactivation of *Escherichia coli* O157:H7, *Salmonella senftenberg*, and enzymes with potential as time-temperature indicators in ground turkey thigh meat. Journal of Food Protection; 61: 171-175.

Velasquez A, Breslin TJ, Marks BP et al. (2010) Enhanced thermal resistance of *Salmonella* in marinated whole muscle compared with ground pork. *Journal of Food Protection* 73 (2): 372-5

Walsh D, Sheridan JJ, Duffy G, Blair IS, McDowell DA, Harrington D. (2001) Thermal resistance of wild-type and antibiotic-resistant *Listeria monocytogenes* in meat and potato substrates. Journal of Applied Microbiology; 90: 555-590.

Wiegand KM, Ingham SC, Ingham BH. (2012) Evaluating lethality of beef roast cooking treatments against *Escherichia coli* O157:H7. Journal of Food Protection 75 (1): 48-61

Williams NC, Ingham SC. (1997) Changes in heat resistance of *Escherichia coli* O157:H7 following heat shock. Journal of Food Protection; 60: 1128-1131.

Williams NC, Ingham SC. (1998) Thermotolerance of *Escherichia coli* ATCC 43894, *Escherichia coli* B, and an rpoS-deficient mutant of *Escherichia coli* O157:H7 ATCC 43895 following exposure to 1.5% acetic acid. Journal of Food Protection; 61: 1184-1186.

Xavier IJ, Ingham S. (1993) Increased D-values for *Salmonella enteritidis* resulting from the use of anaerobic enumeration methods. Food Microbiology:10: 223-228.

Yen LC, Sofos JN, Schmidt GR. (1992) Destruction of *Listeria monocytogenes* by heat in ground pork formulated with kappa-carrageenan, sodium lactate and the algin-calcium meat binder.

Zhao T, Doyle MP, Kemp MC, Howell RS, Zhao P. (2004) Influence of freezing and freezing plus acidic calcium sulfate and lactic acid addition on thermal inactivation of *Escherichia coli* O157:H7 in ground beef. Journal of Food Protection; 67: 1760-1764.

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