

Quantifying the effects of heating temperature, and combined effects of heating medium pH and recovery medium pH on the heat resistance of *Salmonella typhimurium*

Ivan Leguérinel, Isabelle Spegagne, Olivier Couvert, Louis Coroller, Pierre Mafart

► **To cite this version:**

Ivan Leguérinel, Isabelle Spegagne, Olivier Couvert, Louis Coroller, Pierre Mafart. Quantifying the effects of heating temperature, and combined effects of heating medium pH and recovery medium pH on the heat resistance of *Salmonella typhimurium*. *International Journal of Food Microbiology*, Elsevier, 2007, 116 (1), pp.88-95. <10.1016/j.ijfoodmicro.2006.12.016>. <hal-00553560>

HAL Id: hal-00553560

<https://hal.univ-brest.fr/hal-00553560>

Submitted on 9 Jan 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 09/01/12 13:01:40

2 **Quantifying the effects of heating temperature, and combined effects of heating medium**
3 **pH and recovery medium pH on the heat resistance of *Salmonella typhimurium***

4

5 I. Leguérinel^{1*}, I. Spegagne¹, O. Couvert², L. Coroller¹, P. Mafart¹

6

7 ¹ Laboratoire Universitaire de Microbiologie Appliquée de Quimper, Quimper, France

8 ² Adria Développement, Z.A. de Creac'h Gwen, 29196 Quimper France

9 *Corresponding author: LUMAQ, 6 rue de l'Université, F29334, Quimper cedex, France

10 Tel +33 02 98 90 02 27, Fax +33 02 98 90 85 44

11 E mail address: guerinel@univ-brest.fr

12 Abstract

13 The influence of heating treatment temperature, pH of heating and recovery medium on the
14 survival kinetics of *Salmonella typhimurium* ATCC 13311 are studied and quantified. From
15 each non log linear survival curve, Weibull model parameters were estimated. An average
16 shape parameter value of 1.67 was found, which is characteristic of downward concavity
17 curves and is in agreement with values estimated from other *Salmonella typhimurium* strains.
18 Bigelow type models quantifying the heating temperature, heating and recovery medium pH
19 influences, are fitted on scale parameter δ data, (time of first decimal reduction), which
20 reflects the bacterial heat resistance. The estimate of z_T (4.64°C) is in the range of values
21 given in literature for this species. The influence of pH of the heating medium on the scale
22 parameter (z_{pH} : 8.25) is lower than that of the recovery pH medium influence (z'_{pH} : 3.65)

23 **Key words:** Weibull, heating medium, recovery medium, pH, *Salmonella typhimurium*

24 **Nomenclature**

25 N_0 : initial number of cells .

26 N : number of surviving cells after the heating time t .

27 δ : scale parameter : first decimal reduction of surviving spores or cells from N_0 to $N_0/10$.

28 p : shape parameter.

29 T : heating temperature.

30 pH : heating medium pH.

31 pH' : recovery medium pH.

32 T^* : reference temperature fixed at 60°C.

33 pH^* : reference pH of the heating medium fixed to 7 .

34 pH'_{opt} : recovery medium:pH corresponding to the maximal apparent bacterial heat resistance.

35 z_T : distance of T from T^* which leads to a ten fold reduction in δ -value z_T quantifies the
36 influence of the heating temperature on the bacterial heat resistance.

37 z_{pH} : distance of pH from pH^* which leads to a ten fold reduction in δ -value z_{pH} quantifies the
38 influence of the pH of the heating medium on the bacterial heat resistance.

39 z'_{pH} : distance of pH' from pH'_{opt} , which leads a ten fold reduction in apparent δ -value. z'_{pH}
40 characterises the influence of the pH on the recovery of the micro-organism after a heat
41 treatment .

42 δ^* :estimated δ value corresponding to T^* , pH^* and pH'_{opt} conditions.

43

44

45 **Introduction**

46 Salmonellae continue to be a major public health setting a great problem to the food industry.
47 These bacterial species appear in a wide variety of foods and food ingredients. Various heat
48 treatments implemented by the food processing industry are generally effective for destroying
49 the vegetative bacteria. Taking into account not only temperature but other environmental
50 factors is likely to allow significant reduction of heat treatment intensity with the same
51 microbial safety and minimize damage of heat sensitive food. It is commonly agreed that the
52 pH decrease of the heating medium is the main environmental factor after temperature, which
53 reduces the bacterial heat resistance of spores (Bigelow and Esty, 1920) or vegetative form
54 (White, 1963; Blackbrun, Curtis, Humpheson, Billon & McClure, 1997). The same effect was
55 observed for *Salmonella enteritidis*, (Casadei, Ingram, Hitchings, Archer & Gaze, 2001) and
56 for *Salmonella typhimurium* (Mazzotta, 2001).

57 Moreover the pH of the recovery medium highly influences the apparent heat resistance of
58 bacterial spores for the same heat treatment condition. The *D* values decrease when pH values
59 shift from an optimum (Cook and Brown, 1965). However, as far as we know, the influence
60 of the recovery medium pH on the apparent heat resistance of *Salmonella* species has never
61 been described. A decrease of pH of the heating medium or of the recovery medium both
62 reduces the bacterial heat resistance (Couvert, Leguérinel & Mafart, 1999). Theses influences
63 can be taken into account for reducing heat treatments. Such a cumulative effect is more or
64 less specific of pH and is not observed for water activity where, oppositely, the protective
65 effect of a low water activity of the heating medium tends to be balanced by the selectivity of
66 a low water activity of the recovery medium towards injured cells (Coroller, Leguérinel &
67 Mafart, 2001).

68 The aim of this study was to quantitatively characterise the impact of heating temperature, pH
69 of the heating medium and pH of the recovery medium on the heat resistance of *Salmonella*
70 *typhimurium* from relevant parameters of appropriated primary and secondary models

71

72 **Materials and methods**

73 *Strain and culturing conditions*

74 The studied strain was *Salmonella typhimurium* ATCC 13311 (NCTC 74). Cultures were
75 stored in cryotube in mixing nutrient broth 50% glycerol 50% at -70°C.

76 The basic heating medium was tryptone salt broth (10g/l tryptone USP (Biokar Diagnostics,
77 A1401HA) and 10g/l NaCl). The pH was adjusted with addition of H₂SO₄ and sterilised by
78 filtration through 0.22µm porosity filter.

79 The recovery medium was nutrient agar (Biokar Diagnostics, BK021HA). The pH were
80 adjusted with H₂SO₄ prior autoclaving at 121°C for 15 minutes. The pH values were checked
81 after autoclaving.

82 *Preparation of cells suspension*

83 Nutrient broth (Biokar Diagnostics, BK003HA) in 200ml flask was inoculated with
84 *Salmonella typhimurium* and incubated at 37°C for 24 hours under agitation (150 rpm). The
85 culture (40ml) was centrifuged (2000g 15min at 20°C) and re-suspended in 3 ml of heating
86 medium.

87 *Thermal treatment of bacterial suspension and recovery conditions*

88 Capillary tubes of 200 µl (Ringcaps® Duran®) were filled with 100µl of sample and
89 submitted to a thermal treatment in a thermostated water bath. After heating, the tubes were
90 cooled in water/ice bath. After rinsing, the ends were flamed with ethanol. The capillary tubes
91 were broken at both ends and their contents poured into a tube containing 9 ml sterile tryptone
92 salt broth (Biokar Diagnostics, BK014HA) by rinsing with 0.9 ml tryptone salt broth.

93 Viable cells were counted by duplicate plating in adjusted pH nutrient agar (Biokar
94 Diagnostics, BK021HA) and incubated at 37°C for 48h.

95 *Experimental design*

96 To determine survival kinetic parameters, bacteria, for each sample corresponding to different
97 heating times, were counted on nutrient agar plates.

98 Heating temperatures applied were 53, 55, 57 and 59°C (heating and recovery media pH equal
99 7). For studying the effect of pH, a complete factorial design was implemented according to
100 the following levels of pH of the heating medium: (7, 6.5, 6, 5.3, 5, 4.4 and 3.8) and to the
101 following levels of pH of the recovery medium (denoted pH'): 7, 6.5, 6, 5.5 and 5 (controlled
102 pH values are given table3) at 55°C.

103 *Data from literature*

104 Data taken from figures in literature were scanned and digitized using the software program
105 DigXY 1.2 (Thunderhead Engineering, Manhattan, USA).

106 *Primary and secondary models*

107 Different authors considered the survival curve as a cumulative form of temporary
108 distribution of lethality event frequency (Cunhan, Oliveira & Oliveira, 1998; Peleg & Cole,
109 1998; Fernandez, Salmeron, Fernandez & Martinez, 1999). In 2002, Mafart, Couvert,
110 Gaillard, and Leguerinel proposed a new presentation of the Weibull frequency distribution
111 model.

$$112 \log N = \log N_0 - \left(\frac{t}{\delta} \right)^p \text{ Eq1}$$

113 Parameter p characterises the shape of the curve: concave curves $p < 1$, convex curves $p > 1$ and
114 linear curves $p = 1$, in this case δ value corresponds to classical D value. This equation was
115 taken up during the IFT summit in January 2003 (Heldman and Newsome, 2003), was used
116 by different authors (Mafart et al., 2002; Gómez, García, Álvarez, Raso & Condón, 2005;

117 Geeraerd, Valdramidis & Van Impe, 2005; Virto, Sanz, Álvarez, Condón & Raso, 2005;
118 Carlin et al., 2006) and was implemented in this work as primary model.

119 The influences of environmental factors on the Weibull model parameter estimated from
120 survival kinetics related to bacterial spores or vegetative cells, were studied (Fernandez et al.,
121 1999; Fernandez, Collado, Cunhan, Ocio & Martinez, 2002; van Boekel, 2002; Couvert,
122 Gaillard, Savy, Mafart & Leguerinel 2005). These studies showed that the shape parameter
123 was practically independent of the heating temperature and the pH of the heating medium.
124 The conclusion of these studies leads us to determine a single average shape parameter value
125 for a set of kinetics.

126 The δ value, first decimal reduction time, is highly influenced by heating temperature. The
127 classical Bigelow model was used to describe the influence of heating temperature on the δ
128 with the conventional z_T value.

129 The effect of the pH of the heating medium and the pH' of the recovery medium on the heat
130 resistance was described according to the following equation (Leguérinel, Spegagne, Couvert,
131 Gaillard & Mafart, 2005) :

$$132 \log \delta = \log \delta^* - \left| \frac{pH - pH^*}{z_{pH}} \right| - \left(\frac{pH' - pH'_{opt}}{z'_{pH}} \right)^2 \text{ Eq 2}$$

133 *Curve fitting.*

134 In a first time, N_0 , δ and p values are estimated from each survival curve to assess the
135 influence of environmental factors on these parameters.

136 In a second time a single shape parameter p value was estimated from the corresponding
137 whole set of experimental kinetics and from set of kinetics taken from the literature. Scale
138 parameter δ values and $\log N_0$ values were determined for each curve.

139

140 Bigelow parameter z_T was estimated from scale parameter δ values obtained from the
141 temperature mono factorial design. Equation 2 parameter values: z_{pH} and z'_{pH} were estimated
142 from scale parameter δ values obtained from pH factorial design.

143 The parameter values and their associated confidence interval were estimated by using a non-
144 linear module (nlinfit and nlparci Matlab 6.1, Statistical Toolbox, The Mathworks).

145

146 **Results and discussion**

147 Survival kinetics curves of *Salmonella typhimurium* showed a clear downward concavity. The
148 same pattern of curves was elsewhere observed for different *Salmonella typhimurium* strains
149 (Garibaldi, Ljichi & Bayne, 1969; Mackey and Derrick, 1986; Jäckle, Geiges & Schmidt-
150 Lorenz, 1987). Such non linear curves were fitted according to the Weibull model.

151 The influences of the heating temperature, the pH of the heating and of the recovery medium
152 on the shape parameter p are shown Figure 1. p values appear to be not clearly influenced by
153 these environmental factors. This observation is in agreement with those of Fernandez *et al.*
154 (2002), Collado, Fernandez, Rodrigo, Camats and Martinez Lopez. (2003) regarding *Bacillus*
155 *cereus*, Couvert *et al.* (2005) ,and *Bacillus pumilus* and van Boekel's (2002). These authors
156 did not observe any significant influence of the temperature on the shape parameter p . The
157 presented results (Figure 1) show no clear influence of the heating medium or the recovery pH
158 on estimates of p for the lower pH. However structural correlation between parameters p and
159 δ could explain the variability of p values (Couvert *et al.*, 2005).

160 Then, a single average p value was estimated, regardless of the heating temperature, the pH of
161 the heating and of the recovery medium. The three parameters (N_0 , δ and p) were globally
162 estimated from the whole set of data by using the least square regression method (nlinfit
163 Matlab 6.1). The single p value estimated from our set of data (1.677 ± 0.065) is close to the p
164 value estimated from other sets of data from literature for the same *Salmonellae* species:

165 1.648 ± 0.313 (Jäckle *et al.*,1987), 1.538 ± 0.187 (Garibaldi *et al.*, 1969), 1.429 ± 0.295
166 (Mackey & Derrick, 1986). $\log N_0$, the scale parameters δ and their confidence interval
167 coefficients as functions of different pH and temperature conditions, are presented in Table 1
168 and 2. The scale parameter δ values are influenced by environmental factors: heating
169 temperature, pH of the heating and the recovery medium. Within the investigated temperature
170 range (53°C -59°C) the classical Bigelow relationship was kept to quantify the effect of
171 temperature on δ value. The corresponding z_T value 4.64°C (Table 3) is lower than z_T values
172 determined from Jäckle *et al.* (1987) data for the same bacterial strain but are in agreement
173 with z_T value estimated from Mackey and Derrick data (1986) and with other values found in
174 literature. Doyle and Mazzotta (2000) reviewed z_T values concerning different *Salmonella*
175 *typhimurium* strains heated in different media. These z_T values, ranging from 3.24°C to 9.5°C
176 with a mean of 5.56°C, illustrates the large variability of z_T values reported in literature. For
177 the same *Salmonella typhimurium* strain ATCC13311 Casadei *et al.* (2001) reported a z_T -
178 value of 4.6°C (Table 4).

179 Both the pH of the heating and the recovery medium affect the heat resistance of *Salmonella*
180 *typhimurium* as shown Figure 2. A decrease of the pH of the heating medium reduces the
181 salmonella heat resistance. This observation has been reported by Blackburn *et al.* (1997) and
182 Casadei *et al.* (2001). Concerning the influence of the recovery medium, low pH reduces heat
183 resistance parameter value δ of *Salmonella typhimurium*. A similar effect was observed for
184 the thermal inactivation of bacterial spore (Cook and Brown, 1965; Lopez, Gonzalez, Mazas,
185 Gonzalez, Martin & Bernardo, 1997) but never for vegetative bacteria cells.

186 Equation 2 was used to describe the effect of the heating medium pH and the recovery
187 medium pH on δ values. This model does not take interactions between these two
188 environmental factors into account. To estimate the weight of the possible interaction, a
189 variance analysis was performed. For the studied pH range, the weight of heating and

190 recovery medium pH represent 62.9% and 34.7% respectively, while the unexplained
 191 variance comprising interactions represented only 2.4% of the total variability. This
 192 observation concerning *Salmonella typhimurium* is in agreement with Couvert et al. (1999)
 193 results related to *Bacillus cereus* spores. Such observations led us to neglect interactions and
 194 to retain the simple Equation 2 without crossed term. Model parameters (Eq 2) determined for
 195 *Salmonella typhimurium* (Table 5) were estimated from the whole set of δ values, according
 196 to factorial design.

197 The determination coefficient between experimental and calculated values (R^2 :0.958) and
 198 Figures 3a and 3b illustrate the goodness of fit of the model. The high z_{pH} parameter value
 199 8.25, indicates a poor influence of the heating medium pH on the heat resistance for this
 200 *Salmonella* strain. For other salmonella strains few data allow to evaluate this z_{pH} parameter.
 201 From Blackburn et al. (1997), Casadei et al. (2001) and Mañas, Pagán, Raso and Condón
 202 (2003) data, an optimal pH value appears to be variable and often lower than 7. This
 203 observation leads to replace a fixed reference pH^* , equal to 7, by a variable optimal pH
 204 parameter (pH_{opt}) to be estimated Eq 3.

$$205 \quad \log \delta = \log \delta_{opt} - \left(\frac{T - T^*}{z_T} \right) - \left| \frac{pH - pH_{opt}}{z_{pH}} \right| \text{ Eq 3}$$

206 Parameters z_{pH} , pH_{opt} and z_T estimated from published values are shown Table 4. Regarding
 207 the studied bacterial strain and different bacterial species, z_{pH} values estimated from data of
 208 literature and our own data are lower than z_{pH} obtained in this work, even for the same
 209 *Salmonella typhimurium* strain ATCC 11331. This difference could be explained by errors on
 210 D value estimates due to the fitting of concave curves by linear regressions or growth
 211 condition and physiology state of bacteria which can have produced stress protein.
 212 Concerning the effect of the pH of the recovery medium, the z'_{pH} value (3.6) indicates a
 213 higher influence of this factor than that of the heating medium pH. It is generally accepted

214 that the pH of the recovery medium exerts a large influence on the apparent heat resistance of
215 spores: D -values decrease as pH is reduced (Cook and Brown, 1965; Yokoya and York, 1965;
216 Cook and Gilbert, 1968; Mallidis and Scholefield, 1986; Santos and Zarzo, 1996; Lopez et al.,
217 1997). Observed z'_{pH} values, which characterized the influence of the recovery medium pH,
218 for *Salmonella typhimurium* cannot be compared with values regarding other *Salmonella*
219 strains or species. As far as we know, no data which could be compared to our results, are
220 available from literature.

221 The primary model derived from the Weibull distribution and describing non linear survival
222 kinetics associated with Bigelow type secondary models, can be easily used to optimise heat
223 treatment process calculations taking the heating and recovery pH influences into account. For
224 example, compared to a heat treatment in food at pH 7, a heat treatment for *Salmonella*
225 *typhimurium* in food at pH 5, could reduce the heating time to a 3.5 ratio, or, with the same
226 heating time, could reduce the heating temperature of 2.25°C with the same lethal efficiency.

227 In practice, to ensure safety of acid foods, heating pH is the pH of food before heat treatment.
228 Because foods represent both the heating and the recovery medium, the input recovery pH is
229 likely to keep the value of the heating pH. However, it frequently occurs that a decrease of
230 food pH is observed during the heat treatment. In this case, for safety reasons, it is
231 recommended to retain the value of the pH which is measured immediately after the heat
232 treatment.

233 This work confirms the impact of low recovery medium pH on the apparent heat resistance.
234 This influence allows reducing heat treatments with the same safety objective to keep better
235 nutritional and sensory quality of foods. This approach could be extended to other vegetative
236 strains and species which would require further data: p and z parameter values, related to
237 heating temperatures and heating and recovery medium pH. From these data, standard values
238 of z_{pH} and z'_{pH} could be defined according to a similar approach to the one that was

239 implemented for the standard z_T value equal to 7°C for most resistant vegetative cells and
240 input in pasteurisation process calculations.

241 **Bibliography**

- 242 Bigelow, W. D., Esty, J. R., 1920. The thermal death point in relation to time of typical
243 thermophilic organisms. *Journal of Infectious Diseases* 27, 602- 617
- 244 Blackbrun, C. W., Curtis, L. M., Humpheson, L., Billon, C., McClure, P. J., 1997.
245 Development of thermal inactivation models for *Salmonella enteritidis* and *Escherichia coli*
246 0157:H7 with temperature, pH and NaCl as controlling factors. *International Journal of Food*
247 *Microbiology* 38, 31-44.
- 248 Carlin, F., Fricker, M., Pielaat, A., Heisterkamp, S., Shaheen, R., Salonen, M. S., Svensson,
249 B., Nguyen-the, C., Ehling-Schulz, M., 2006. Emetic toxin-producing strains of *Bacillus*
250 *cereus* show distinct characteristics within the *Bacillus cereus* group. *International Journal of*
251 *Food Microbiology* 109, 132-138.
- 252 Casadei, M. A., Ingram, R., Hitchings, E., Archer, J., Gaze, J. E., 2001. Heat resistance of
253 *Bacillus cereus*, *Salmonella typhimurium* and *Lactobacillus delbrueckii* in relation to pH and
254 ethanol. *International Journal of Food Microbiology* 63, 125-134.
- 255 Collado, J., Fernandez, A., Rodrigo, M., Camats, J., Martinez Lopez, A., 2003. Kinetics of
256 deactivation of *Bacillus cereus* spores. *Food Microbiology* 20, 545-548.
- 257 Cook, A. M., Brown, M. R. W., 1965. Relationship between heat activation and percentage
258 colony formation for *Bacillus stearothermophilus* spores: effects of storage and pH on the
259 recovery medium. *Journal of Applied Bacteriology* 28, 361-364.
- 260 Cook, A. M., Gilbert, R. J. 1968. Factors affecting the heat resistance of *Bacillus*
261 *stearothermophilus* spores I. The effect of recovery condition on colony count of unheated
262 and heated spores. *Journal of Food technology* 3, 285-293.
- 263 Coroller L., Leguérinel I., Mafart P., 2001. Effect of the water activities of the heating and of
264 the recovery media on the apparent heat resistance of *Bacillus cereus* spores. *Journal of*
265 *Applied and Environmental Microbiology* 67, 317-322

266 Couvert O., Leguérinel I., Mafart P., 1999. Modelling the overall effect of pH on the apparent
267 heat resistance of *Bacillus cereus* spores. International Journal of Food Microbiology 49, 57-
268 62.

269 Couvert O., Gaillard S., Savy N., Mafart P., Leguerinel I., 2005. Survival curves of heated
270 bacteria: effect of environmental factors on Weibull parameters. International Journal of Food
271 Microbiology 101, 73-81.

272 Cunhan, L. M., Oliveira, F. A. R., Oliveira, J. C., 1998. Optimal experimental design for
273 estimating the kinetic parameters of processes described by the Weibull probability
274 distribution function. Journal of Food Engineering 37, 175-191.

275 Doyle M.E., Mazzotta A.S., 2000. Review of studies on the thermal resistance of
276 Salmonellae. Journal of Food Protection 63, 779-795.

277 Fernandez, A., Salmeron, C., Fernandez, P. S., Martinez, A., 1999. Application of a frequency
278 distribution model to describe the thermal inactivation of two strains of *Bacillus cereus*. Food
279 Science and Technology 10, 158-162.

280 Fernandez, A., Collado, J., Cunhan, L. M., Ocio, M. J., Martinez, A., 2002. Empirical model
281 building based on Weibull distribution to describe the joint effect of pH and temperature on
282 the thermal resistance of *Bacillus cereus* in vegetable substrate. International Journal of Food
283 Microbiology 77, 147-153.

284 Garibaldi, J. A., Ljichi, K., Bayne, H. G., 1969. Effect of pH and chelating agent on the heat
285 resistance and viability of *Salmonella typhimurium tm-1* and *Salmonella senftenberg*. Applied
286 Microbiology 18, 318-332.

287 Geeraerd, A. H., Valdramidis, V. P., Van Impe, J. F., 2005. GIInaFiT, a freeware tool to assess
288 non-log-linear microbial survivor curves. International Journal of Food Microbiology. 102,
289 95-105.

290 Gómez, N., García, D., Álvarez, I., Raso, J., Condón, S., 2005. A model describing the
291 kinetics of inactivation of *Lactobacillus plantarum* in a buffer system of different pH and in
292 orange and apple juice. *Journal of Food Engineering* 70, 7-14.

293 Heldman, D. R., Nennsone, R.L., 2003. Kinetic models for microbial survival during
294 processing. *Food Technology* 57, 40-46.

295 Jäckle, M., Geiges, O., Schmidt-Lorenz, W., 1987. Thermal inactivation of Alpha amylase,
296 *Salmonella typhimurium*, *Salmonella senftenberg* 775 W, *Pseudomonas aeruginosa* and
297 *Staphylococcus aureus* in whole egg. *Mitteilungen aus dem Gebiete Lebensmitteltechnologie*
298 *und Hygiene* 79, 69-89.

299 Leguérinel I., Spegagne I., Couvert O., Gaillard S., Mafart P., 2005. Validation of an overall
300 model describing the effect of three environmental factors on the apparent D-value of
301 bacterial spores. *International Journal of Food Microbiology* 100, 223-229.

302 Lopez, M., Gonzalez, I., Mazas, M., Gonzalez, J., Martin, R., Bernardo, A., 1997. Influence
303 of recovery condition on apparent heat resistance of *Bacillus stearothermophilus* spores.
304 *International Journal of Food Science and Technology* 32, 305-311.

305 Mackey, B. M., Derrick, C. M., 1986. Elevation of heat resistance of *Salmolnella*
306 *typhimurium* by sublethal heat shock. *Journal of Applied Bacteriology* 61, 389-393.

307 Mafart, P., Couvert, O., Gaillard, S., Leguerinel, I., 2002. On calculating sterility in thermal
308 preservation methods: application of Weibull frequency distribution model. *International*
309 *Journal of Food Microbiology* 72, 107-113.

310 Mallidis, C. G., Scholefield, J., 1986. Evaluation of recovery media for heated spores of
311 *Bacillus stearothermophilus*. *Journal of Applied Bacteriology* 61, 517-523.

312 Mañas, P., Pagán, R., Raso, J., Condón, S., 2003. Predicting thermal inactivation in media of
313 different pH of *Salmonella* grown at different temperatures. *International Journal of Food*
314 *Microbiology* 87, 45-53.

315 Mazzotta, A. S., 2001. Thermal inactivation of stationary-phase and acid adapted *Escherichia*
316 *coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in fruit juices. *Journal of Food*
317 *Protection* 64, 315-320.

318 Peleg, M., Cole, M. B., 1998. Reinterpretation of microbial survival curves. *Critical Reviews*
319 *in Food Science* 38, 353-380.

320 Santos, M. H. S., Zarzo, J. T., 1996. Evaluation of citric and GDL in the recovery at different
321 level of *Clostridium sporogenes* P A 3679 spores subjected to HTST treatment conditions.
322 *International Journal of Food Microbiology* 29, 241-254.

323 van Boekel, M. A. J. S., 2002. On the use of the Weibull model to describe thermal
324 inactivation of microbial vegetative cells. *International Journal of Food Microbiology* 74,
325 139-159.

326 Virto, R., Sanz, D., Álvarez, I., Condón, S., Raso, J., 2005. Inactivation kinetics of *Yersinia*
327 *enterocolitica* by citric and lactic acid at different temperatures. *International Journal of Food*
328 *Microbiology* 103, 251-257.

329 White, H. R., 1963. The effect of variation in pH on the heat resistance of cultures of
330 *Streptococcus faecalis*. *Journal of Applied Bacteriology* 26, 91-99.

331 Yokoya, F., York, G. K., 1965. Effect of several environmental conditions on the "thermal
332 death rate" of endospores of aerobic, thermophilic bacteria. *Applied Microbiololy* 13, 993-
333 999.

334

335

336

337

338

339 **Table legends**

340 Table 1

341 $\log N_0$ and δ estimates and their confidence interval coefficients as functions of the heating
342 temperature.

343

344 Table 2

345 $\log N_0$ and δ estimates and their confidence interval coefficients as functions of the heating
346 and the recovery medium pH.

347

348 Table 3

349 Parameters z_T estimated (from $\log \delta$ values determined) from our own (data) and published
350 data for different *Salmonella* strains

351

352 Table 4

353 z_T , z_{pH} and pH_{opt} estimates from published classical D values for different *Salmonella* species

354

355 Table 5

356 z_{pH} , z'_{pH} , pH'_{opt} estimates for *Salmonella Typhimurium* ATCC 13311 ($\log \delta$ values)

357

358 **Figure legends**

359 Figure 1

360 Weibull shape parameter values and their confidence interval 95% evaluated for each kinetic
361 of heating temperature, and heating and recovery medium pH

362

363 Figure 2

364 Survival kinetics experimental data and fitted curves, with p-value equal 1.67, at different
365 heating medium pH for different recovery pH (pH 7 ●, pH 6.5 □, pH 6 ▲, pH 5.5 ▽, pH 5 ◆)
366 and at different temperatures (59°C ●, 57°C □, 55°C ▲, 53°C ▽) heating and recovery pH
367 fixed at 7

368

369 Figure 3a 3b

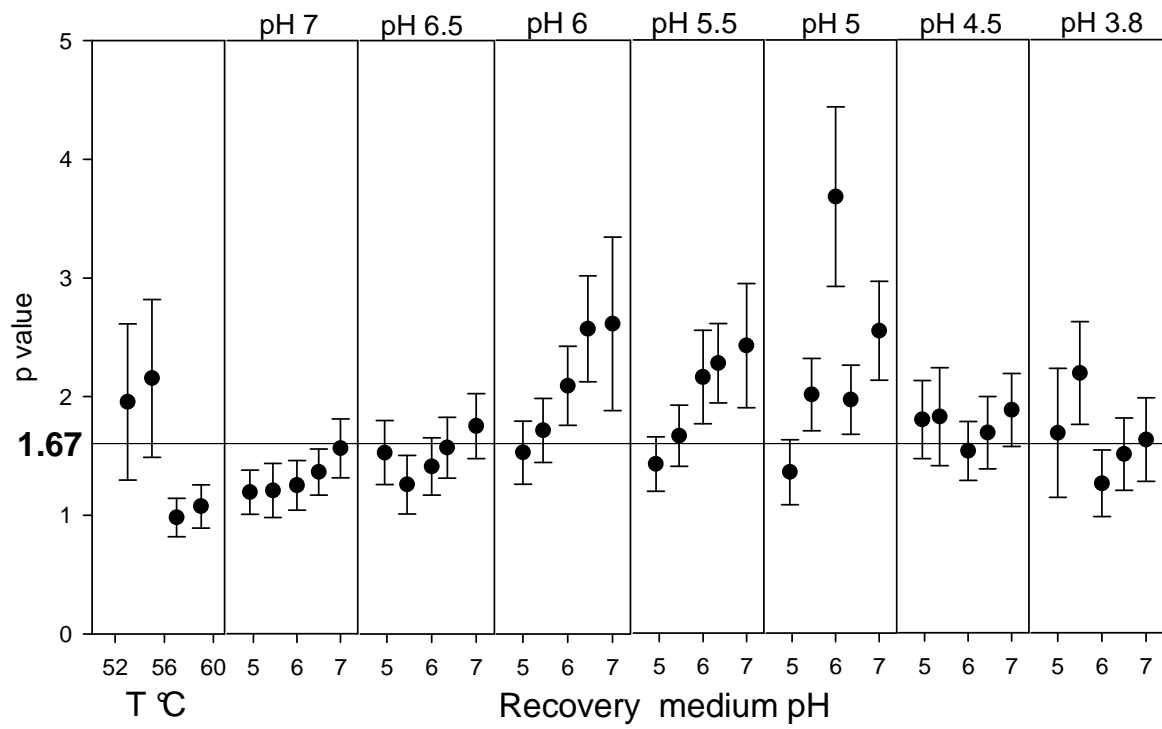
370 Observed and calculated $\log \delta$ values for different conditions of heating and recovery medium
371 pH

372

373

374

375

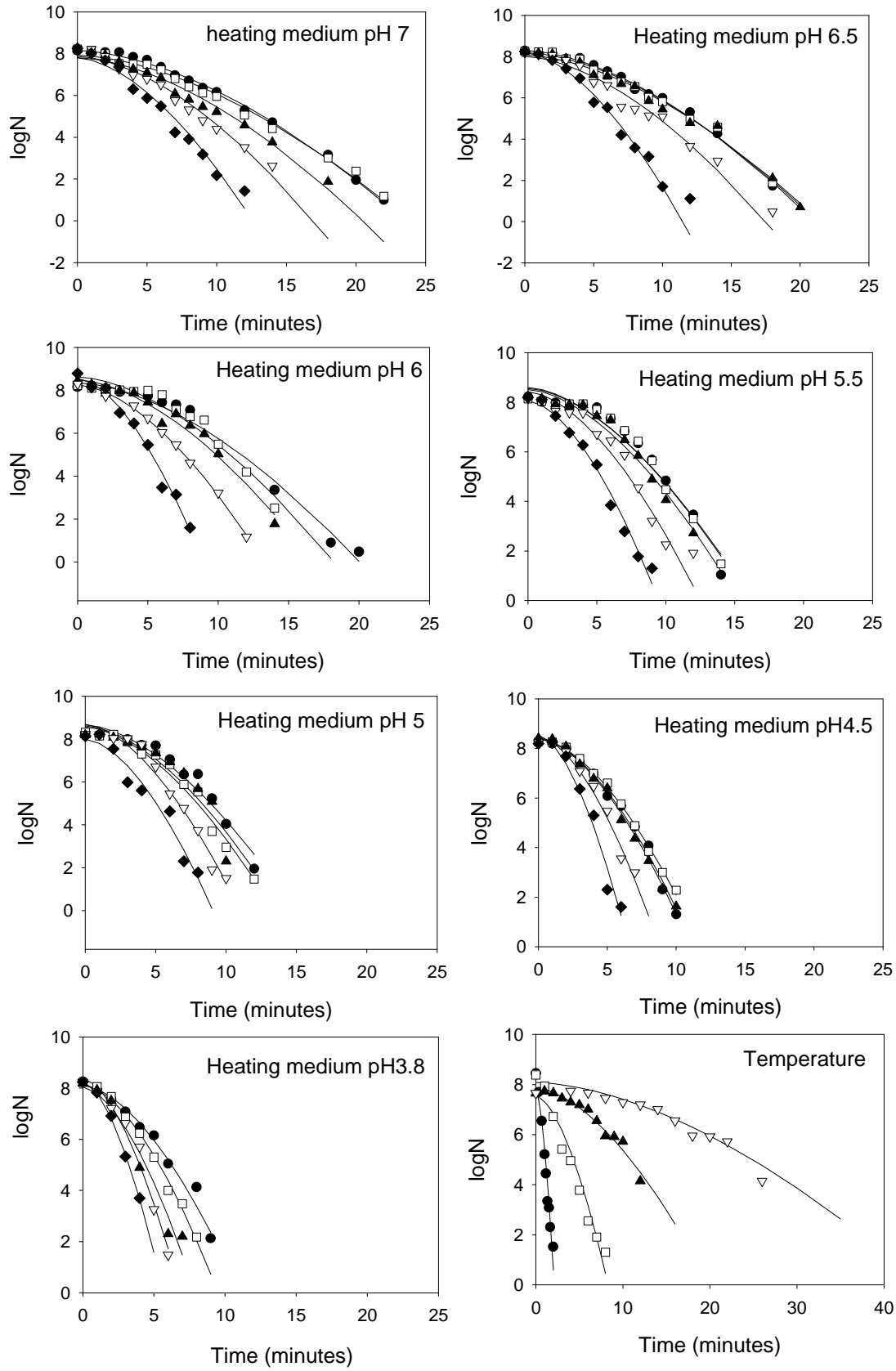


376

377

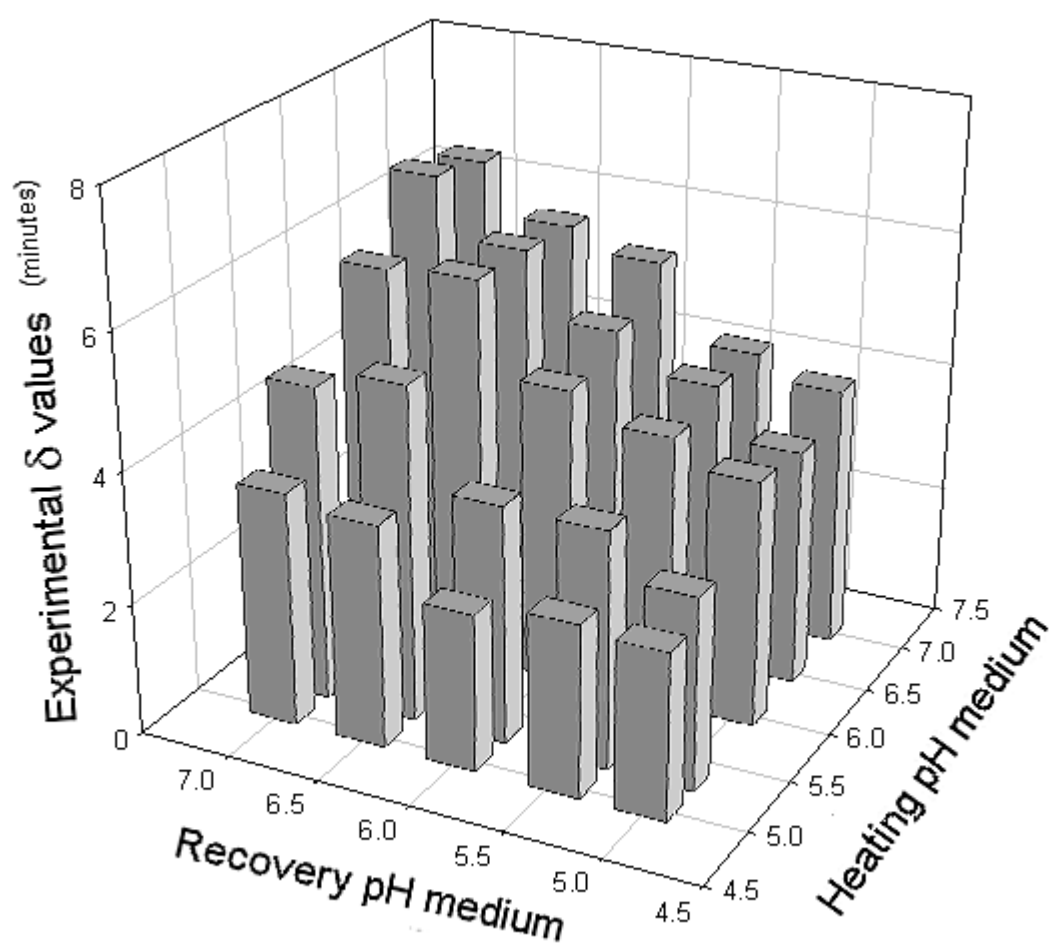
378 Figure 1

379

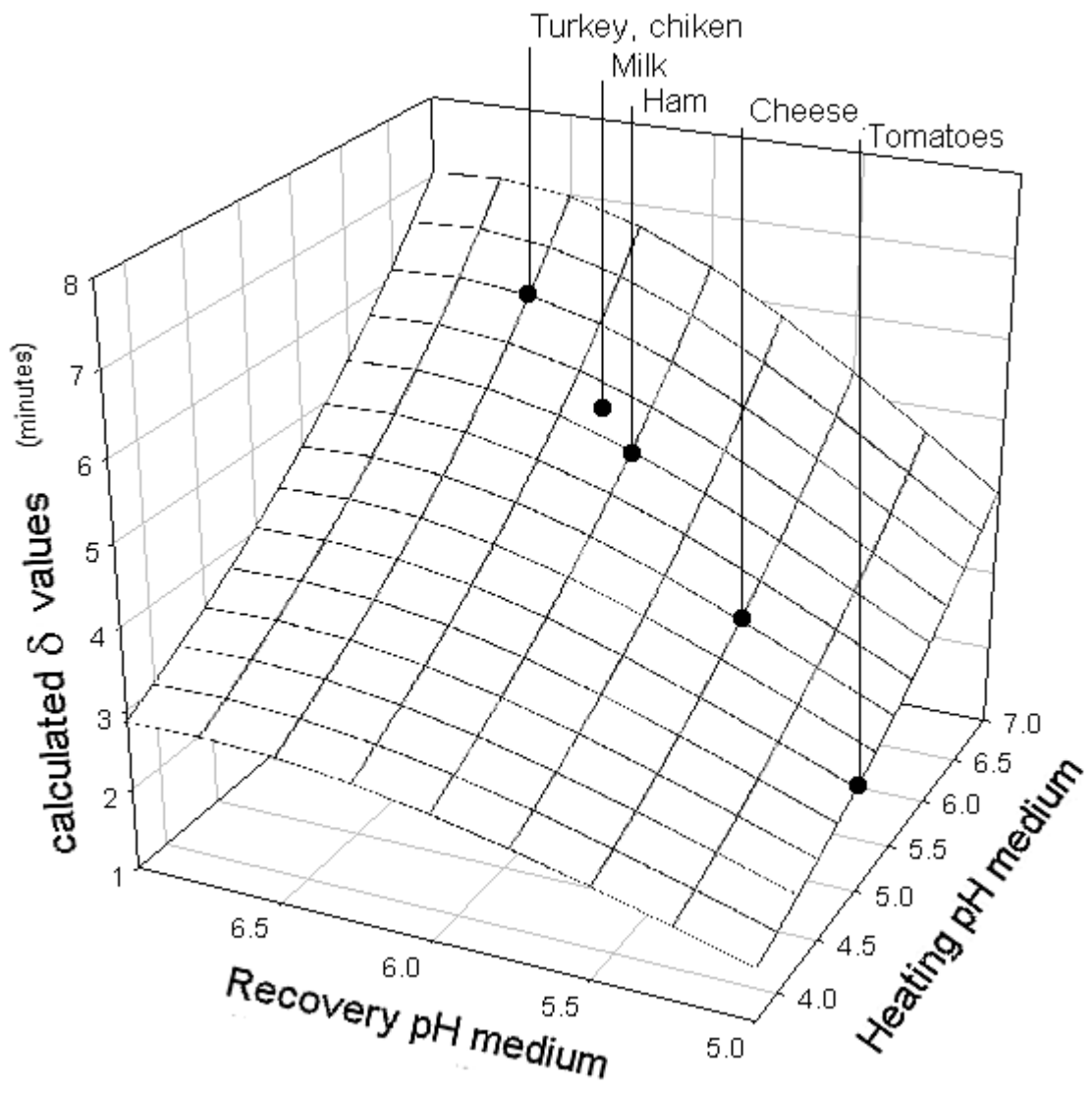


380

381 Figure2



382
 383 figure 3a
 384



385
 386
 387 Figure 3 b
 388

389
390
391

Heating temperature °C	$\log N_0$	CI _{95%}	δ minutes	CI _{95%}
59	7.730	± 0.385	0.619	± 0.047
57	7.522	± 0.352	2.495	± 0.182
55	7.837	± 0.297	5.846	± 0.690
53	8.077	± 0.315	12.741	± 1.547

392 Table 1

393
394
395
396
397

Heating pH	Recovery pH	Global p value		1.677 \pm 0.065	
		$\log N_0$	CI _{95%}	δ minutes	CI _{95%}
7.02	7	8.155	\pm 0.244	6.734	\pm 0.475
7.02	6.5	7.925	\pm 0.244	6.922	\pm 0.499
7.02	6	7.812	\pm 0.257	6.010	\pm 0.447
7.02	5.45	7.872	\pm 0.281	4.949	\pm 0.380
7.02	4.92	7.808	\pm 0.302	3.696	\pm 0.258
6.5	7	8.295	\pm 0.257	5.956	\pm 0.440
6.5	6.35	8.197	\pm 0.257	6.059	\pm 0.454
6.5	6	8.067	\pm 0.257	6.178	\pm 0.472
6.5	5.45	7.998	\pm 0.281	5.063	\pm 0.397
6.5	4.95	8.191	\pm 0.321	3.276	\pm 0.236
6	7	8.356	\pm 0.270	5.657	\pm 0.370
6	6.45	8.626	\pm 0.281	5.041	\pm 0.394
6	6	8.489	\pm 0.284	4.683	\pm 0.367
6	5.45	8.261	\pm 0.323	3.760	\pm 0.277
6	5	8.570	\pm 0.352	2.483	\pm 0.181
5.3	7	8.599	\pm 0.283	4.458	\pm 0.314
5.3	6.35	8.559	\pm 0.282	4.506	\pm 0.319
5.3	6	8.514	\pm 0.299	4.273	\pm 0.335
5.3	5.45	8.425	\pm 0.320	3.513	\pm 0.268
5.3	4.92	8.066	\pm 0.336	2.731	\pm 0.191
5	7	8.659	\pm 0.300	4.107	\pm 0.310
5	6.35	8.568	\pm 0.302	3.728	\pm 0.261
5	6	8.613	\pm 0.319	3.857	\pm 0.324
5	5.45	8.684	\pm 0.322	3.047	\pm 0.209
5	4.95	7.990	\pm 0.356	2.628	\pm 0.201
4.4	7	8.414	\pm 0.321	3.171	\pm 0.223
4.4	6.45	8.392	\pm 0.321	3.338	\pm 0.244
4.4	6	8.400	\pm 0.322	3.114	\pm 0.217
4.4	5.35	8.488	\pm 0.352	2.458	\pm 0.178
4.4	4.95	8.548	\pm 0.394	1.836	\pm 0.141
3.8	7	8.117	\pm 0.322	3.170	\pm 0.226
3.8	6.5	8.152	\pm 0.351	2.722	\pm 0.214
3.8	6	8.045	\pm 0.398	2.281	\pm 0.182
3.8	5.5	8.402	\pm 0.394	1.935	\pm 0.155
3.8	5	8.264	\pm 0.455	1.611	\pm 0.183

399

400

401 Table2

Bacterial strain		Heating medium	n*	T°C range	z_T °C	CI95 %	R ²
<i>Salmonella typhimurium</i> ATCC13311		Tryptone salt broth	4	51-59	4.64	±0.877	0.989
<i>Salmonella typhimurium</i> ATCC13311	Jäckle <i>et al.</i> 1987	Tryptone salt broth	3	58.5-61.5	8.55	±1.796	1.000
<i>Salmonella typhimurium</i> NCBI 10248	Mackey & Derrick 1986	Tryptone salt broth	5	50-59	3.44	±0.510	0.994

403 * n: data number

404 Table3

405

406

407

408

409

410

412
413

Bacterial strain		Heating medium	n	T°C range	$z_T^{\circ\text{C}}$	CI 95%	pH range	z_{pH}	CI 95%	pH_{opt}	R ²
<i>Salmonella typhimurium</i> ATCC13311	Manas <i>et al.</i> 2003	Citrate buffer	8				4-7.7	3.27	0.969	5.75	0.939
<i>Salmonella enteritidis</i> P167807	Blackburn <i>et al.</i> 1997	Tryptone salt broth + HCl /NaOH	8				4.3-9.5	3.92	2.261	6.00	0.724
<i>Salmonella typhimurium</i> NCTC 74	Casadei <i>et al.</i> 2001	Nutrient broth + Citric acid	8	48-54	4.61	1.204	7 & 3	2.17	0.203	ND Fixed at 7	0.994

414 * n: data number

415

416

417 Table 4

418

419

420
421
422
423

	Parameter values	CI 95%
$\log \delta^*_{55^\circ\text{C}, \text{pH}7, \text{pH}'_{\text{opt}}}$	0.851	± 0.053
z_{pH}	8.254	± 1.572
z'_{pH}	3.655	± 1.349
pH'_{opt}	6.805	± 0.656
R^2	0.958	

424
425
426
427
428
429
430
431
432

Table 5