

Survival curves of heated bacterial spores: effect of environmental factors on Weibull parameters

Olivier Couvert, Stéphane Gaillard, Nicolas Savy, Pierre Mafart, Ivan Leguérinel

► **To cite this version:**

Olivier Couvert, Stéphane Gaillard, Nicolas Savy, Pierre Mafart, Ivan Leguérinel. Survival curves of heated bacterial spores: effect of environmental factors on Weibull parameters. *International Journal of Food Microbiology*, Elsevier, 2005, 101 (1), pp.73-81. <10.1016/j.ijfoodmicro.2004.10.048>. <hal-00560873>

HAL Id: hal-00560873

<http://hal.univ-brest.fr/hal-00560873>

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.

Survival curves of heated bacterial spores:

Effect of environmental factors on Weibull parameters

Olivier Couvert¹, Stéphane Gaillard¹, Nicolas Savy², Pierre Mafart¹,

Ivan Leguérinel^{1*}

¹ Laboratoire Universitaire de Microbiologie Appliquée de Quimper 2 rue de l'Université

29334 Quimper cedex, France Tel 33 2.98.90.02.27 Fax 33.2.98.64.03.71

² Institut de Recherche Mathématique de Rennes, Université de Rennes 1,

35042 Rennes Cedex, France.

*corresponding author e mail: guerinel@univ-brest.fr

Abstract

The classical D value of first order kinetic is not suitable for quantifying bacterial heat resistance for non-log linear survival curves. One simple model derived from the Weibull cumulative function describes non-log linear kinetics of micro-organisms. The influences of environmental factors on Weibull model parameters, shape parameter “p” and scale parameter “ δ ”, were studied. This paper points out structural correlation between these two parameters. The environmental heating and recovery conditions do not present clear and regular influence on the shape parameter “p” and cannot be described by any model. On the opposite, the scale parameter “ δ ” depends on heating temperature and heating and recovery medium pH. The models established to quantify these influences on the classical “D” values could be applied to this parameter “ δ ”. The slight influence of the shape parameter p variation on the goodness of

- 23 fit of these models can be neglected and the simplified Weibull model with a constant p-value
- 24 for given microbial population can be applied for canning process calculations.
- 25 **Key words:**
- 26 Weibull distribution, Heat treatment pH, recovery medium pH

27 1. Introduction

28 The first order kinetic model describing inactivation of micro-organisms is generally
29 attributed to Madsen and Nyman (1907). The studies of Chick (1910), Esty and Meyer
30 (1922), Esty and Williams 1924 on vegetative cells had confirmed this equation:

$$31 \quad N = N_0 e^{-kt} \quad \text{Eq1}$$

32 where N_0 is the initial number of cells, N the number of surviving cells after a duration of heat
33 treatment t and k is the first order parameter .

34 In 1943 Katzin et al. defined the decimal reduction time that Ball and Olson (1957)
35 symbolized by the letter D . Thus the model appears on the familiar form:

$$36 \quad \log N = \log N_0 - \frac{t}{D} \quad \text{Eq2}$$

37 In this model the classical D value presents a simple biological significance: time that leads to
38 a ten fold reduction of surviving population, and is easily estimated from a simple linear
39 regression. This concept still governs canning process calculation.

40 However in many cases the survival curves of heated bacteria do not present a log linear
41 relation: a concave or upward concavity of curves was frequently observed (Cerf, 1977).

42 So the bacterial heat resistance cannot be evaluated from the classical D value. Consequently,
43 many authors proposed mechanistic or purely empirical models. (Kilsby et al., 2000;
44 Rodriguez et al., 1988; Sapru et al., 1993; Shull et al., 1963; Xiong et al., 1999; Buchanan et
45 al., 1997; Cole et al., 1993; Geeraerd et al., 2000; Linton et al., 1995; Whiting, 1993). These
46 models show good accuracy either over parameterized (mechanistic models) or have
47 parameters without any physical or biological significance (empirical models). Moreover the
48 complexity of these models hinder their application in heat treatment process calculation.

49 Other authors who considered the survival curve as a cumulative form of temporary
50 distribution of lethality event distribution, presented a probabilistic approach (Cunha et al.,

51 1998; Fernandez et al., 1999; Peleg and Cole, 1998 Peleg, 2000; Mafart et al., 2002). The
52 Weibull frequency distribution model (Eq3) involved to describe the time to failure in
53 mechanical system was applied to bacterial death time.

$$54 \quad f(t) = \frac{\beta}{\alpha} \left(\frac{t}{\alpha}\right)^{\beta-1} \times \exp\left(-\left(\frac{t}{\alpha}\right)^\beta\right) \text{ Eq3}$$

55 The β parameter has a marked effect on the failure rate of the Weibull distribution (Fig 1a).
56 According to the β value, the distribution corresponds to a normal law ($\beta = 2$), an exponential
57 law ($\beta = 1$) or an asymptotic law ($\beta < 1$).

58 A change of the scale parameter α , time unit, has the same effect on the distribution than a
59 change of the abscise scale (Fig 1b). If α increases, the distribution gets stretched out the right
60 and its height decreases while maintaining its shape.

61 The cumulative distribution Weibull function is

$$62 \quad F(t) = \exp\left(-\left(\frac{t}{\alpha}\right)^\beta\right) \text{ Eq 4}$$

63 or applied to survival kinetics curves

$$64 \quad \ln S(t) = -\left(\frac{t}{\alpha}\right)^\beta \text{ Eq5}$$

65 where $S(t)$ is the ratio N/N_0 at t time, α and β are the two parameters of the Weibull
66 probability density function.

67 Figures 1c and 1d show the influence of these two parameters evolution on the cumulative
68 distribution Weibull function curves. $\beta < 1$ corresponds to concave upward survival curves,
69 $\beta > 1$ to concave downward curves and β equal 1 to a straight line. The evolution of α value
70 modifies the slope but does not affect the curve shapes. Different forms of this model were
71 presented in literature, however the decimal logarithm form (Eq 6) which is close to Eq 2,

72 seems more suitable to describe the non log linear survival curves (Mafart et al., 2002; Van
 73 Boekel, 2002)

$$74 \quad \log N = \log N_0 - \left(\frac{t}{\delta} \right)^p \quad (\text{Eq 6})$$

75 where δ is to the first reduction time that leads a ten fold reduction of survival population, and
 76 p the shape parameter β . For the traditional case where the survival curve, originated from a
 77 first order, is linear p equal 1 and the δ parameter correspond to the classical D value.

78

79 This simple and robust model can be regarded as an extension of the conventional first order
 80 equation. Like on D value, the influence of heating temperature on the δ value leads a log
 81 linear relationship. The classical z value can be evaluated (Mafart et al., 2002; Van Boekel,
 82 2002) and a modified Bigelow method can be used to optimize the heat treatment for a target
 83 reduction ratio (Mafart et al., 2002).

84 Among environmental factors other than heating temperature, which affect the heat resistance
 85 of bacteria, the pH of the heating medium and the pH of the recovery medium (pH') present a
 86 prominent importance. Couvert (1999) has developed an extended Bigelow model to describe
 87 both effects of heating and recovery medium pH on the apparent bacterial spore heat
 88 resistance.

$$\log D = \log D^* - \frac{T - T^*}{z_T} - \left| \frac{\text{pH} - \text{pH}^*}{z_{\text{pH}}} \right| - \left(\frac{\text{pH}' - \text{pH}'^*}{z'_{\text{pH}} 90} \right)^2 \quad \text{Eq 7}$$

91

92 Where pH^* and pH'^* are the reference heat treatment and recovery medium pH fixed to 7. z_{pH}
 93 is a distance of pH from pH^* , which leads to a ten fold reduction D-value. z_{pH} quantifies the
 94 heat medium pH influence on bacterial heat resistance. z'_{pH} is a distance of pH' from pH'^* ,
 95 which leads a ten fold reduction apparent D-value. z'_{pH} characterizes the influence of the pH

96 on the recovery of the micro-organism after a heat treatment. D^* is the calculated D value
97 corresponding to pH^* and pH'^* conditions. Like the Bigelow model, Couvert's model (Eq7)
98 was suitable for the calculation of δ values as well as for those of D values. However the
99 influence of heating temperature on the p value is not clear and variable according to several
100 authors (Fernandez et al., 1999; Peleg and Cole, 2000; Mafart et al., 2002; Van Boekel, 2002).
101 The aims of this paper are to bring arguments to estimate a single p value from a set of
102 survival kinetics, whatever the heating temperature or heating and recovery medium pH for
103 bacterial strain at a given physiology state.

104

105 **2. Material and methods**

106 *2.1. Microorganism and spore production*

107

108 *Bacillus pumilus* A40 was obtained and isolated from ingredient in a food canning industry.
109 Spores were kept in distilled water at 4°C.

110 Cells were pre-cultivated at 37°C for 24 hours in Brain Heart Infusion (Difco 0037). The pre-
111 culture was used to inoculate nutrient agar (Biokar Diagnostics, Beauvais / France)
112 supplemented with salt ($MnSO_4$ 40mg l⁻¹ and $CaCl_2$ 100 mg l⁻¹). Plates were incubated at 37°C
113 for 5 days. Spores were then collected by scrapping the surface of the agar, suspended in
114 sterile distilled water and washed three times by centrifugation (10000xg for 15 min)
115 (Bioblock Scientific, model Sigma 3K30). The pellet was resuspended in 5 ml distilled water
116 and 5 ml ethanol. The obtained suspension was kept at 4°C for 12 hours in order to reduce the
117 number of vegetative non sporulated bacteria, and washed again three times by centrifugation.
118 The final suspension (about 10¹⁰ spores ml⁻¹), containing more than 99% refractive spores and
119 no visible vegetative cells, was finally distributed in sterile Eppendorf microtubes and kept at
120 4°C.

121

122 *2.2. Thermal treatment of spore suspension and recovery conditions*

123

124 Heating media were tryptone salt broth (10g/l tryptone, 10g/l NaCl (Biokar)) for different pH
125 adjusted with addition of 1M H₂SO₄, media were sterilized by filtration through 0.22µm
126 porosity filter. 30µl of spore suspension was diluted in 3 ml of these media. Capillary tubes of
127 200 µl (vitrex) were filled with 100µl of sample and submitted to a thermal treatment in a
128 thermostated water bath. After heating, the tubes were cooled in water/ice bath. After rising,
129 the ends were flamed with ethanol. The capillary tubes were broken at both ends and their
130 contents poured into a tube containing 9 ml sterile tryptone salt broth (Biokar Diagnostics) by
131 rinsing with 1 ml tryptone salt broth.

132 Viable spores were counted by duplicate plating in nutrient agar for different pH (10g
133 tryptone, 5g meat extract, 5g sodium chloride, 15 g agar for 1000ml water)(Biokar
134 Diagnostic). The pH was adjusted with H₂SO₄ prior to autoclaving at 121°C for 15 min, the
135 pH value was controlled after autoclaving.

136

137 *2.3. Experimental design*

138

139 To determine the thermal kinetic parameters at least ten samples were counted on nutrient
140 agar plates. For the longest heating time no colonies should be observed to detect possible
141 sigmoid curves.

142 Monofactorial designs were used to evaluate the influence of heating temperature, heating and
143 recovery medium pH. The heating temperatures investigated were 89, 92, 95, 98, 101 and
144 104°C (for heating and recovery media pH equal to 7), heating media pH were 7, 6.1, 5.8, 5.2,

145 5.15, 5.1, 4.7 and recovery media pH' were 7, 6.52, 6.26, 6.04, 5.82, 5.55 and 5.27 (for
146 temperature 95°C).

147

148 *2.4. Fitting parameters and region confidence determination*

149

150 To estimate Weibull parameters two fitting ways were realized. On the one hand, three
151 parameters $\log N_0$, δ and p were estimated from each kinetic. On the other hand, two
152 parameters $\log N_0$ and δ were estimated from each kinetic with only one p value evaluated
153 from the whole set of kinetics.

154 Couvert's model parameters (Eq 7) were estimated from these two sets of δ estimates. The
155 parameter values and their associated confidence interval were fitted by using a non-linear
156 module ("nlinfit" and "nlparci" Matlab 6.1, The Mathworks). "nlparci" function used to
157 evaluate confidence interval at 95% is based on the asymptotic normal distribution for the
158 parameter estimates (Bates and Watts. 1988) On the one hand, p value was estimated from
159 each set of data, and on the other hand, single p value was evaluated from the whole set of
160 curves. To appreciate the accuracy on the non linear models used in this study F test and
161 associated probability p were carried out.

162

163 **3 Results and discussion**

164

165 *3.1 Independence of Weibull model parameters*

166

167 One of the main questions to study in any regression is to check the independence of model
168 parameters. The shape of the joint confidence region determined by using Lobry et al. (1991)
169 method leads to detect possible structural correlation between model parameters. According

170 to Beale (1960), a vector of parameter model Θ is in the confidence regions if probability α
172 verifies the inequation:

$$174 \quad SSD_{\Theta} \leq SSD_{\min} \left(1 + \frac{p}{n-p} F_{p, n-p, \alpha} \right) \quad 175 \quad \text{Eq 8}$$

177 n number of data, p number of parameters, F Fisher value for α at p and n-p degrees of
178 freedom. 10 000 vectors Θ were calculated to define the joint confidence region where
179 dimension number is the parameter number. Figure 2 shows the projections of confidence
180 region projected on three orthogonal planes. The strength shape of the projections and the
181 high correlation coefficient associated characterize a structural correlation between model
182 parameters. Three Weibull model parameters were estimated from each kinetic data and
183 correlation coefficients were determined from the evaluated confidence region, for the 18
184 environmental conditions studied (Table 1) confirms this structural correlation between
185 parameters for all kinetics. Thus, Weibull model parameters ($\log N_0$, δ and p) are dependent:
186 an error on δ will be balanced by an error on p in the same way. Finally, a single p value
187 estimated from the whole set of kinetics eliminates the structural correlation between δ and p
188 parameters as well as $\log N$ and p parameters (Table 1) and decreases the structural correlation
189 between $\log N$ and δ . The Weibull model parameters become independent.

190

191 *3 2 Influence of environmental factors on p-value*

192

193 For each *Bacillus pumilus* survival curve, the shape parameter p values were estimated.
194 Figure 3 suggests that the environmental heating and recovery conditions slightly influence
195 the p values. This observation is in agreement with Fernandez et al. (2002) data concerning
196 the influence of heating temperature and heating pH medium on the p values for *Bacillus*
197 *cereus* spores. Van Boekel (2002) used bibliography data to study the influence of heating

198 temperature on the shape (p) and scale (δ) Weibull model parameter for different vegetative
199 bacteria and yeast species survival kinetics. In most cases the shape parameter is clearly
200 independent of heating temperature, however, in some cases, dependencies appear
201 significantly. Constant p value means that the Weibull probability density function curves
202 presents the same shape. Applied to the density probability distribution of inactivation death
203 time, a single p value leads us to consider that whatever the environmental condition, the least
204 resistant bacteria die first and the most resistant bacteria are the last to die while maintaining
205 proportion. For a given microbial population, at the same physiological state, if the population
206 proportion is independent of heating and recovery conditions, the Weibull model shape
207 parameter p value should be constant. To estimate a single p value, Fernandez et al. (2002)
208 determines average of shape parameter determined from the different kinetics. Then, for each
209 kinetic, the scale parameter was re-estimated from set of data with fixed p value. However, it
210 is preferable to evaluate both single shape and scale parameter by non linear least square
211 reduction for the whole set of data. Choosing the average value to evaluate a single p value is
212 not suitable because the number of data in each kinetic is not equal, each kinetic have not the
213 same weight on the p value evaluation. On the other hand, evaluating p value by estimating
214 process on the whole set of data consider that each data have the same weight in the p value
215 evaluation.

216

217 *3.3 Influence of environmental factors on δ -value*

218

219 To evaluate the influence of fixed / free p value on the scale parameter, the corresponding δ
220 values were compared. (Table 2). The results show clearly that the accuracy of the Weibull
221 model, characterized by F test and associated probability, is lower when a single p value is
222 evaluated. However the δ value confidence intervals were reduced, and δ parameter could be

223 described by the Bigelow model and the classical z_T value can be evaluated (Table 3) (z_T is
224 the distance of temperature from T^* which leads to a ten fold reduction of the first decimal
225 reduction time δ). Whatever the δ calculation procedure, no significant difference appears.
226 Van Boekel (2002) has alike applied the Bigelow model to assess the heating temperature
227 influence on the scale parameter values δ , however the Arrhenius model as well can be
228 applied (Fernandez et al., 2002).

229 Like the classical D value, the scale parameter δ decreases with heating and recovery medium
230 pH (Mafart et al., 1998; Couvert et al., 1999; Couvert ,2002). Couvert's model, (Eq 7)
231 including the dependence temperature and heating and recovery medium pH, was fitted on the
232 δ values evaluated with the two calculation methods. Table 3 presents the parameter estimated
233 and Figures 4 a & b compares observed and calculated values, and show a slight higher
234 accuracy of Couvert's model when the δ values were evaluated with single p value.

235 For the *Bacillus cereus* strain, Fernandez et al. (2002), following a full factorial design, four
236 levels of heating temperature and pH medium, evaluated Weibull scale parameter δ . The
237 goodness of fit of Couvert's model on these data (Figure 5 & Table 4) confirms the adequacy
238 of this model on the scale parameter estimated with a single shape parameter value p.

239 These results confirm that single p value evaluated from a set of survival kinetics is sufficient
240 to describe the survival kinetics and the effect of external factors on bacterial heat resistance.
241 Furthermore, the evolution of p values, determined for each kinetics according to
242 environmental conditions, are too irregular to be described by any constant model (Van
243 Boekell 2002)

244 The Weibull model is suitable for describing log linear, or not, heat survival curves. However,
245 a simplification of this model consisting in getting a single overall estimation of p-value per
246 strain, regardless of environmental conditions of heat treatment and recovery, seems to be
247 enough for bacterial food predictive modeling and canning process calculation (Mafart et al.,

248 2002). Moreover, despite a slight loss of goodness of fit, this modification leads to an
249 improvement of the robustness of the model. However the cell physiology states seem to
250 influence the density function; as a result, the p values are likely to change. Further works
251 should be realized to assess the influence of spore age and environmental sporulation or
252 germination conditions on the Weibull shape parameter value.

253 As expected, the secondary model developed to describe the heating and recovery
254 environmental influence on the classical D values remains suitable for δ value estimates.

255 .

256

257

258 Bibliography

259

260 Ball, C. O., and Olson, F. C. W., 1957. "Sterilization in food technology Theory, practice and
261 calculation." McGraw-Hill Book Compagny, inc.

262 Bates, D.M. and Watts, D.G., 1988 "Nonlinear Regression Analysis and Its Applications".
263 John Wiley & Sons, NY.

264 Beale, E.M., 1960 Confidence region in non-linear estimation. Journal of Royal Statistic
265 Society B22, 41-88.

266 Buchanan, R. L., Golden, M. A., and Phillips, J. G., 1997. Expanded models for the non-
267 thermal inactivation of *Listeria monocytogenes*. Journal of Applied Microbiology 82, 567-
268 577.

269 Cerf, O., 1977. Tailing of survival curves of bacterial spores, a review. Journal of Applied
270 Bacteriology 42, 1-19

271 Chick, H., 1910. The process of disinfection by chemical agencies and hot water. Journal of
272 Hygiene, Cambridge 10, 237-286.

273 Cole, M. B., Davies, K. W., Munro, G., Holyoak, C. D., and Kilsby, D. C., 1993. A vitalistic
274 model to describe the thermal inactivation of *Listeria monocytogenes*. Journal of Industrial
275 Microbiology 12, 232-239.

276 Couvert, O., Leguérinel, I., and Mafart, P., 1999. Modelling the overall effect of pH on the
277 apparent heat resistance of *Bacillus cereus* spores. International Journal of Food Microbiology
278 49, 57-62.

279 Couvert, O., 2002. Prise en compte de l'influence du pH dans l'optimisation des traitements
280 thermiques. These de l'Université de Bretagne Occidentale.

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

284 Esty, J. R., and Meyer, K. F., 1922. The heat resistance of spores of *B. botulinus* and allied
285 anaerobes. *Journal of Infectious Diseases* 31, 650-663.

286 Esty, J. R., and Williams, C. C., 1924. Heat resistance studies. A new method for
287 determination of heat resistance of bacterial spores. *Journal of Infectious Diseases* 34, 516-
288 528.

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

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

296 Geeraerd, A. H., Herremans, C. H., and Impe, J. F. V., 2000. Structural model requirements to
297 describe microbial inactivation during a mild heat treatment. *International Journal of Food*
298 *Microbiology* 59, 185-209.

299 Katzin, L. I., Sandholzer, L. A., and Strong, M. E., 1943. Application of the decimal reduction
300 time principle to a study of the resistance of coliform bacteria to pasteurization. *Journal of*
301 *Bacteriology* 45, 256-272.

302 Kilsby, D. C., Davies, K. W., McClure, P. J., Adair, C., and Anderson, W. A., 2000. Bacterial
303 thermal death kinetics based on probability distributions: the heat destruction of *Clostridium*
304 *botulinum* and *Salmonella* bedford. *Journal of Food Protection* 63, 1197-1203.

305 Linton, R. H., Carter, W. H., Pierson, M. D., and Hackney, C. R., 1995. Use of modified
306 Gompertz equation to model nonlinear survival curves for *Listeria monocytogenes* Scott A.
307 Journal of Food Protection 58, 946-954.

308 Lobry, J.R., Rosso, L., Flandrois, J.P., 1991. A FORTRAN subroutine for the determination of
309 parameter confidence limits in non-linear model. Binary 3, 86-93.

310 Madsen, T., and Nyman, M. 1907. Zur theorie der desinfektion. Zeitschrift für Hygiene und
311 Infektionskrankheiten 57, 388-404.

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

315 Peleg, M., and Cole, M. B., 1998. Reinterpretation of microbial survival curves. Critical
316 Reviews in Food Science 38, 353-380.

317 Peleg, M., and Cole, M. B., 2000. Estimating the survival of *Clostridium botulinum* spores
318 during heat treatment. Journal of Food Protection 63, 190-195.

319 Rodriguez, A. C., Smerage, G. H., Teixeira, A. A., and Busta, F. F., 1988. Kinetic effect of
320 lethal temperature on population dynamics of bacterial spores. Transaction of the American
321 Society of Agricultural Engineers 31, 1594-1601, 1606.

322 Sapru, V., Smerage, G. H., Teixeira, A. A., and Lindsay, J. A., 1993. Comparaison of
323 predictive model for bacterial spore population resources to sterilization temperature. Journal
324 of Food Science 58, 223-228.

325 Shull, J. J., Cargo, G. T., and Ernst, R. R., 1963. Kinetics of heat activation and of thermal
326 death of bacterial spores. Applied Microbiology, 485-487.

327 van Boekel, M. A. J. S., 2002. On the use of the Weibull model to describe thermal
328 inactivation of microbial vegetative cells. International Journal of Food Microbiology 74,
329 139-159.

- 330 Whiting, R. C., 1993. Modeling bacterial survival in unfavorable environments. *Journal of*
331 *Industrial Microbiology* 12, 240-246.
- 332 Xiong, R., Xie, G., Edmondson, A. E., and Sheard, M. A., 1999. A mathematical model for
333 bacterial inactivation. *International Journal of Food Microbiology* 49, 45-55.

334 Table legend

335

336 Table 1: Correlation coefficients between Weibull model parameters evaluated from the
337 evaluated joint confidence for the 18 environmental studied conditions.

338

339

340 Table 2:

341 Weibull model parameters definite with associated p value determined for each kinetic for
342 one part, for the other with single p value evaluated for the whole set of kinetics for *Bacillus*
343 *pumilus* A40

344

345 Table 3

346 Couvert's model parameters fitted on log δ values evaluated with multiple p values on the one
347 hand, with single p values for *Bacillus pumilus* A40 on the other. The method used to
348 compute the 95% confidence intervals is based on an "asymptotic normal distribution for the
349 parameter estimate". (Bates and Watts 1988)

350

351 Table 4

352 Couvert's model parameters fitted on log δ values for *Bacillus cereus* INRA TZ 415
353 (Fernandez et al., 2002)

354

355

356 Figure legends

357

358 Figure 1

359 Simulated frequency distribution of critical inactivation time (Figures a and b) and microbial
360 survival curves (Figures c and d) generated with the assumption that the heat resistance has a
361 Weibull distribution.

362 Figures a and c: α : 5, β : 3 (—), 1(---), 0.5(⋯⋯) , Figures b and d: α : 3 (—), 6(---), 9(⋯⋯) , β : 3

363

364 Figure 2

365 Projection of the confident region on three orthogonal planes, from *Bacillus pumilus* A40 data
366 (heating temperature : 95°C, heating and recovery medium pH : 7)

367

368 Figure 3

369 Graph of the shape parameter p and 95% confidence interval associated as function of heating
370 temperature, treatment and recovery medium pH for *Bacillus pumilus* A40

371

372 Figures 4 a&b

373 Comparison of calculated and observed $\log \delta$ values evaluated with multiple p values on the
374 one hand (Figure a : \square), with single p values on the other (Figure b: \circ)

375

376 Figure 5

377 Comparison of calculated and observed $\log \delta$ values. Couvert's model fitted from Fernandez
378 et al. (2002) data

379

380

			p values estimated from each set of data			Overall p value estimated from the gathered sets of data		
T°	pH	pH'	LogNo vs δ	logN ₀ vs p	δ vs p	LogNo vs δ	logN ₀ vs p	δ vs p
89	7	7	-0.78	-0.62	0.92	-0.71	0.15	-0.06
92	7	7	-0.81	-0.63	0.89	-0.74	0.12	-0.06
95	7	7	-0.75	-0.59	0.93	-0.67	0.35	-0.12
98	7	7	-0.81	-0.64	0.9	-0.74	0.17	-0.08
101	7	7	-0.84	-0.67	0.89	-0.73	0.12	-0.06
104	7	7	-0.82	-0.67	0.93	-0.71	0.26	-0.09
95	4.7	7	-0.84	-0.59	0.73	-0.71	0.09	-0.06
95	5.1	7	-0.9	-0.74	0.88	-0.77	0.15	-0.08
95	5.15	7	-0.64	-0.11	0.65	-0.55	0.03	-0.06
95	5.2	7	-0.86	-0.7	0.92	-0.65	0.21	-0.08
95	5.8	7	-0.81	-0.66	0.93	-0.71	0.22	-0.09
95	6.1	7	-0.82	-0.52	0.77	-0.82	0.12	-0.05
95	7	5.27	-0.81	-0.632	0.92	-0.75	0.2	-0.11
95	7	5.55	-0.85	-0.71	0.91	-0.77	0.16	-0.06
95	7	5.82	-0.82	-0.66	0.91	-0.73	0.19	-0.09
95	7	6.04	-0.87	-0.74	0.9	-0.74	0.15	-0.10
95	7	6.26	-0.89	-0.73	0.91	-0.79	0.17	-0.08
95	7	6.52	-0.86	-0.72	0.89	-0.72	0.10	-0.07

381

382

383 T1

384

			p values estimated from each set of data							Single p value for the whole set of kinetics						
T°	pHt	pHr	log No	CI 95%	delta	CI 95%	p	CI 95%	SSD	log No	CI 95%	delta	CI 95%	p	CI 95%	SSD
89	7	7	4.09	0.18	49.14	4.83	2.87	0.76	0.012	4.27	0.18	42.01	3.23	1.96	0.14	0.172
92	7	7	3.83	0.18	18.74	1.97	2.50	0.67	0.028	3.93	0.18	17.04	1.32	1.96	0.14	0.097
95	7	7	4.20	0.12	9.25	0.86	2.03	0.32	0.149	4.22	0.12	9.06	0.51	1.96	0.14	0.153
98	7	7	4.04	0.16	3.88	0.40	2.26	0.51	0.103	4.10	0.16	3.64	0.25	1.96	0.14	0.138
101	7	7	3.93	0.18	1.51	0.18	2.19	0.62	0.070	3.98	0.16	1.44	0.11	1.96	0.14	0.084
104	7	7	4.04	0.21	0.57	0.08	2.16	0.49	0.094	4.10	0.20	0.53	0.04	1.96	0.14	0.109
95	4.7	7	3.66	0.26	1.91	0.56	1.10	0.36	0.543	3.35	0.17	2.70	0.23	1.96	0.14	0.689
95	5.1	7	3.61	0.20	3.77	0.57	1.75	0.44	0.727	3.54	0.16	4.00	0.28	1.96	0.14	0.737
95	5.15	7	4.20	0.29	1.66	1.19	0.59	0.46	0.008	3.84	0.28	3.22	0.47	1.96	0.14	0.352
95	5.2	7	3.95	0.25	1.73	0.50	1.08	0.26	0.151	3.54	0.17	2.85	0.21	1.96	0.14	0.544
95	5.8	7	4.03	0.22	3.67	0.61	1.78	0.42	0.051	3.96	0.18	3.90	0.28	1.96	0.14	0.066
95	6.1	7	4.13	0.28	5.54	0.95	1.99	0.62	0.115	4.14	0.26	5.50	0.49	1.96	0.14	0.115
95	7	5.27	3.89	0.24	1.12	0.25	1.32	0.32	0.280	3.60	0.17	1.48	0.11	1.96	0.14	0.563
95	7	5.55	4.05	0.24	2.62	0.43	1.95	0.55	0.052	4.05	0.22	2.63	0.20	1.96	0.14	0.052
95	7	5.82	3.79	0.16	3.72	0.35	2.60	0.61	0.084	3.93	0.16	3.28	0.23	1.96	0.14	0.209
95	7	6.04	3.99	0.17	6.00	0.63	2.33	0.55	0.017	4.09	0.15	5.57	0.41	1.96	0.14	0.063
95	7	6.26	3.83	0.20	4.54	0.60	1.95	0.45	0.177	3.82	0.17	4.55	0.31	1.96	0.14	0.177
95	7	6.52	3.98	0.18	6.12	0.78	2.09	0.62	0.033	4.01	0.16	5.96	0.48	1.96	0.14	0.037

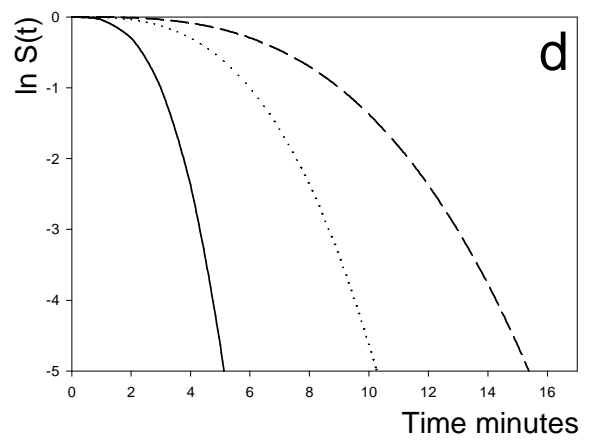
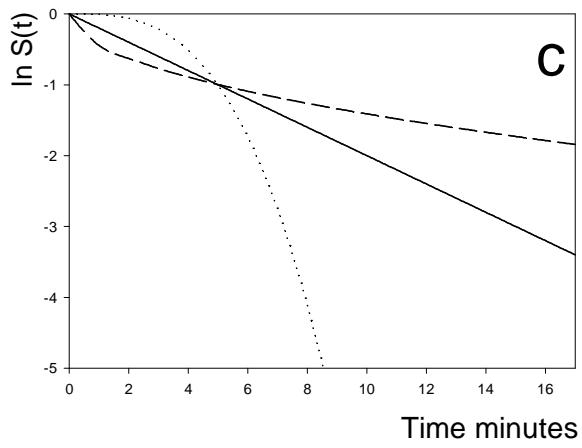
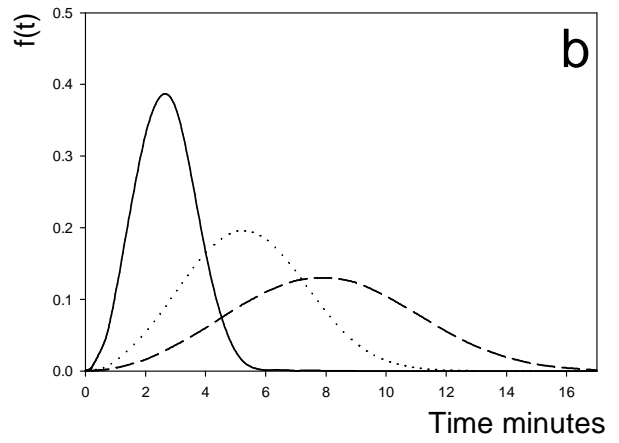
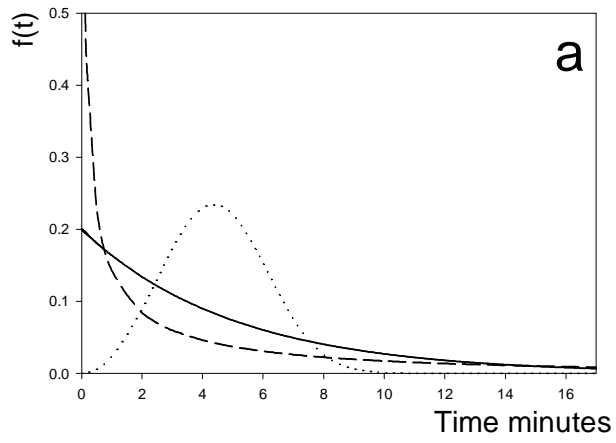
T2

	p values determined for each kinetic		Single p value for the whole set of kinetics	
	Values	CI 95%	Values	CI 95%
$\text{Log}\delta_{121.1}^*$	-2.38	0.44	-2.36	0.26
z_T	7.90	1.08	8.06	0.66
z_{pH}	3.37	0.77	5.09	1.03
z'_{pH}	1.92	0.23	2.06	0.17
F test	5.42		5.57	
p value	0.0084		0.0076	

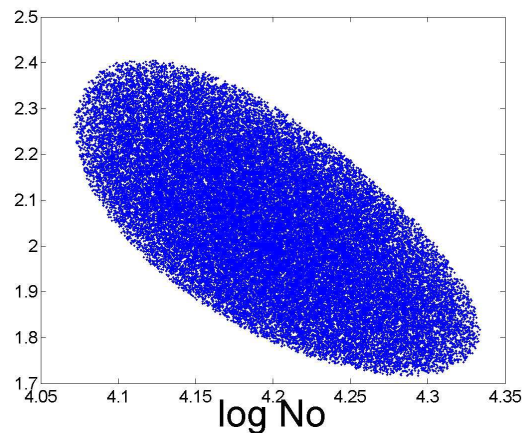
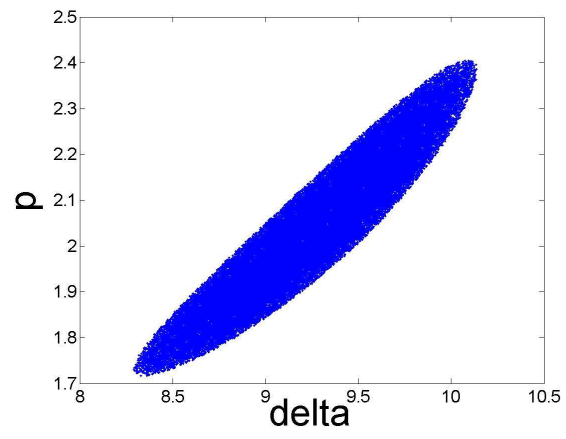
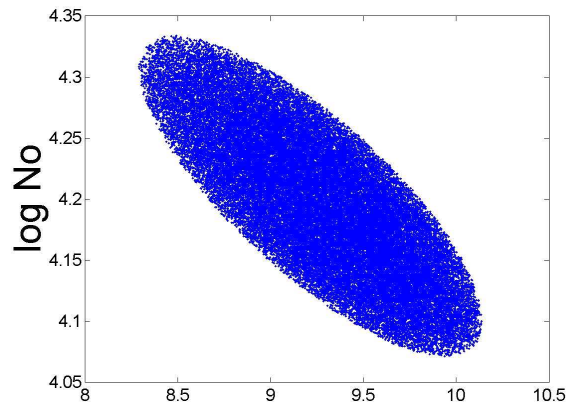
T3

	Values	CI 95%
$\log \delta_{121.1^{\circ}\text{C}^*}$	-3.48	0.21
z_T	7.71	0.34
z_{pH}	3.26	0.59
F test	7.46	
p value	0.0021	

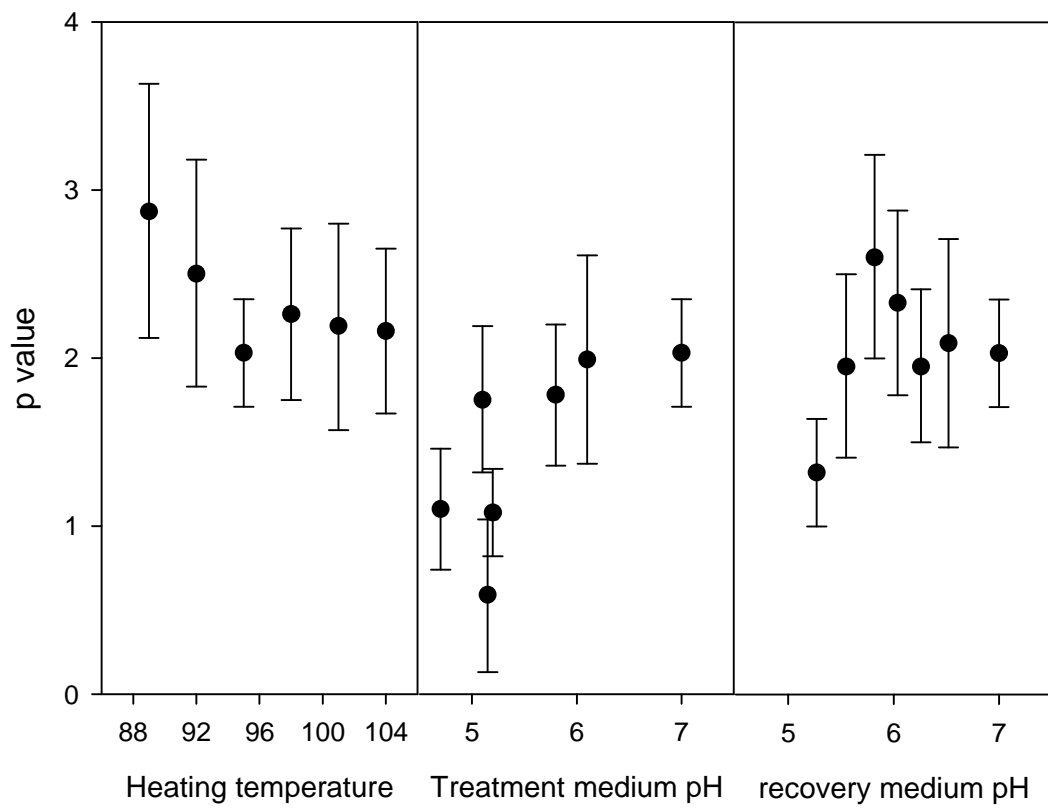
T4



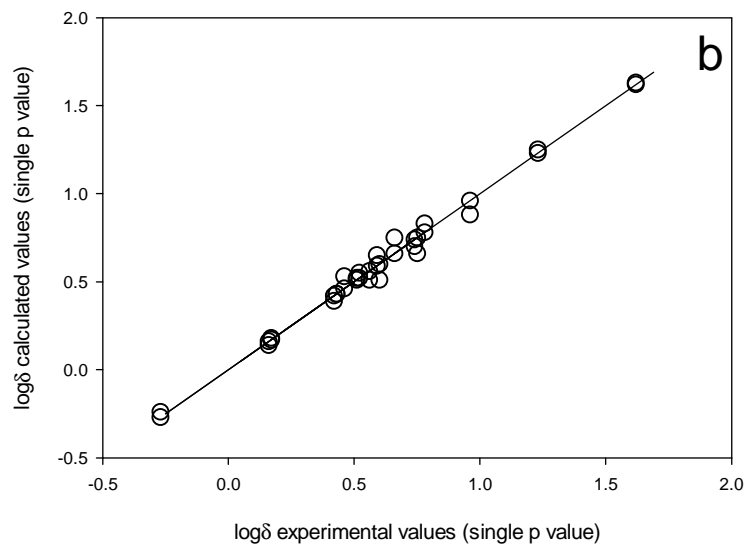
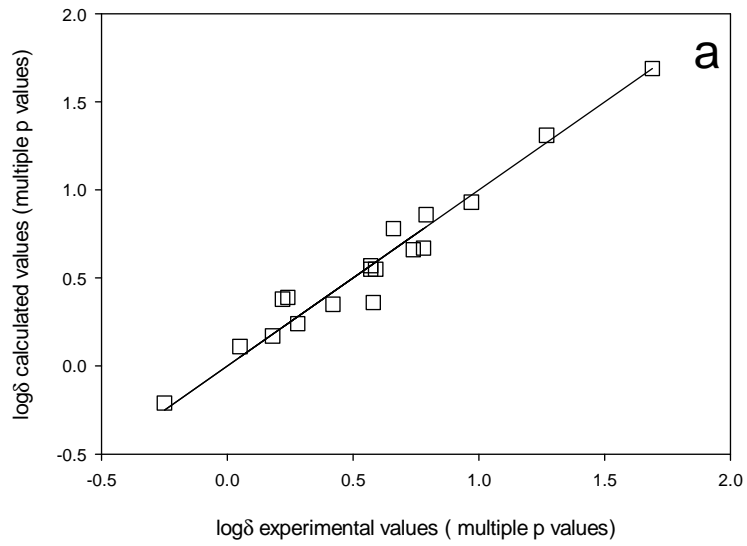
F1



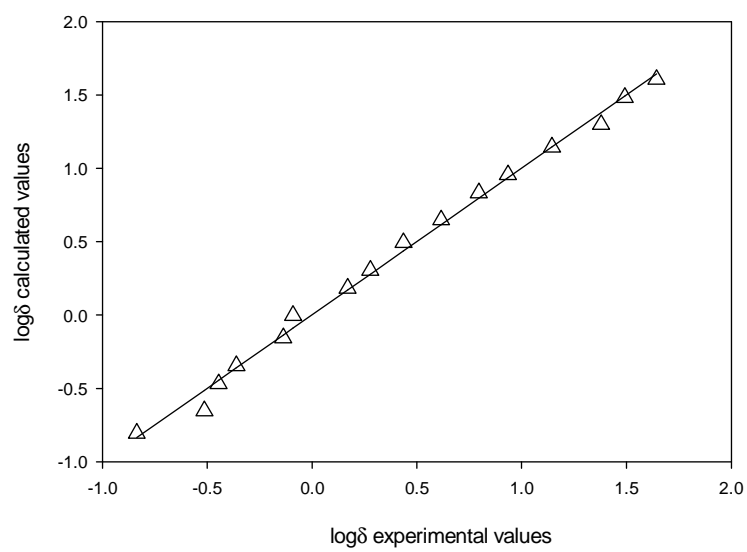
F2



F3



F4 a&b



F5

