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HEAT PROCESSING OF BEEF. PART VII. RESIDUAL HEATING EFFECTS IN BEEF PROCESSED AT HIGH RETORT TEMPERATURES[a]

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The lag in cooling observed immediately after the end of the heating phase has been long recognized in the studies of heat penetration into cylindrical containers undergoing a thermal process. Most research workers investigated the center of the can, and several attempts were made *(1, 2)* to find a mathematical formula expressing the time-temperature relationship in the early stages of cooling. The formulae derived assumed this relationship to be (in terms of degrees above the cooling water temperature) a monotonic nonincreasing function from the beginning of cooling, or time when cooling water was started and steam cut off. This assumption might have been justified for all practical purposes for low-temperature, long-time heating processes; however, it has been observed by Hicks *(3)* and by the present authors in the past in *(4)* and *(5)* that for relatively short processes and especially for high temperatures, this assumption is not justified by the experimental facts. Furthermore, the theoretical relationship (eq. 1 *(5)*) in its series expansion indicates that for small values of $(t-t_1)$ a certain amount of residual heating is to be expected in the central region of the can. In the expression $(t-t_1)$ t_1 is the designated process time; t is any time after the beginning of process.

The experimental procedure and design of this investigation have been described in detail in previous papers *(5, 8)*. The nomenclature used in this work is consistent throughout with the same references. New symbols introduced for the first time are explained in Table 1.

Intermediate cooling period. The intermediate cooling was defined by the authors *(5)* as the period occurring immediately after the steam is shut off and cooling started, and before the time-temperature relationship is approximated by a linear function in semi-log coordinates. This period corresponds to the introductory phase of heating but assumes a more important role in process lethality calculation because of high temperatures involved. Experimental evidence from the investigation used for derivation of a time-temperature relationship during the intermediate cooling showed that more than one term in the series expansion of Equation 1 *(5)* should be retained to approximate the actual thermal history in the can, and that some rise in the temperature for small $(t-t_1)$ occurred. Therefore, the function to be derived should not be monotonically decreasing. The occurrence of residual heating affects significantly the

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TABLE 1

Effects (min.) of residual heating at the point of greatest heating lag for six retort temperatures (RT)

RT=225°F. t_2(a) = 103 min.			
(b) t_1	(c) Δt	(d) $\Delta t'$	(d) $\Delta t/\Delta t'$
10	12.00	93	0.129
20	6.00	83	0.072
30	3.72	73	0.051
40	3.00	63	0.048
50	1.66	53	0.031
60	2.44	43	0.057
70	0.33	33	0.010
80	0.33	23	0.014
90	0.00	13	0.000
100	0.00	3	0.000
110	1.00	----	....
120	0.00	----	....
Average			0.041

RT=243°F. t_2=88 min.			
t_1	Δt	$\Delta t'$	$\Delta t/\Delta t'$
8	14.00	80	0.175
17	6.56	71	0.092
25	4.44	63	0.070
34	2.11	54	0.039
42	1.66	46	0.036
50	1.11	38	0.029
59	2.00	29	0.067
67	1.33	21	0.063
76	0.00	12	0.000
84	1.22	4	0.030
93	0.00	----	....
101	0.66	----	....
Average			0.060

RT=261°F. t_2=74 min.			
t_1	Δt	$\Delta t'$	$\Delta t/\Delta t'$
7	13.28	67	0.198
14	7.78	60	0.130
21	8.06	53	0.152
27	4.44	47	0.094
34	3.89	40	0.097
41	4.00	33	0.121
48	2.00	26	0.077
54	4.00	20	0.200
61	0.78	13	0.060
68	1.11	6	0.185
75	0.00	----	....
87	0.33	----	....
Average			0.131

RT=279°F. t_2=59 min.			
t_1	Δt	$\Delta t'$	$\Delta t/\Delta t'$
5	12.66	54	0.234
10	10.00	49	0.204
16	8.00	43	0.186
21	5.33	38	0.140
26	5.17	33	0.157
31	2.78	28	0.092
36	1.89	23	0.080
42	3.00	17	0.176
47	0.00	12	0.000
52	1.55	7	0.221
57	0.33	2	0.165
62	0.33	----	....
Average			0.150

RT=297°F. t_2=44 min.			
t_1	Δt	$\Delta t'$	$\Delta t/\Delta t'$
3	9.89	41	0.241
7	8.22	37	0.222
11	8.44	33	0.256
14	7.66	30	0.255
18	5.66	26	0.218
21	4.66	23	0.203
25	5.00	19	0.263
29	4.11	15	0.274
32	3.22	12	0.268
36	3.33	8	0.416
40	0.00	4	0.000
43	0.50	1	0.500
Average			0.260

RT=315°F. t_2=29 min.			
t_1	Δt	$\Delta t'$	$\Delta t/\Delta t'$
2	13.77	27	0.510
4	10.50	25	0.420
6	9.89	23	0.430
8	9.66	21	0.460
10	10.50	19	0.553
12	9.33	17	0.549
14	5.33	15	0.355
16	8.17	13	0.628
18	4.00	11	0.333
20	4.33	9	0.481
22	2.17	7	0.310
24	3.76	5	0.752
Average			0.482

(a) t_2 is the time when $\Delta t = 0$.
(b) t_1 is the designated processing time.
(c) $\Delta t = t'_t - t_1$ = (effective processing time) − (designated processing time).
(d) $\Delta t' = t_2 - t_1$.

sterilizing effect (lethality) of the process, and thus is of great importance in canning process evaluation. These effects have been evaluated and will be discussed at length.

In the attempt at the determination of functional relationship of time, temperature, and space during the intermediate cooling, average thermal histories at 12 locations chosen at random from the central, intermediate, and outside regions of the can were compared with the theoretically expected temperatures at these locations. Fifteen terms ($i = \ldots, 5$ and $m = 1, \ldots, 5$) of Equation 1 given in *(5)* were calculated for retort temperatures 243, 279, and 315°F. and for 4 values of $(t - t_1)$ ranging from 2 to 14 minutes. For each of the locations temperatures were calculated for cooling curves starting at 3 values of $(RT - CT)_{t_1}$ (difference between retort temperature and can temperature at a given location at time t_1 – equivalent to Ball's g) to estimate the influence of $(RT - CT)_{t_1}$ on the necessary number of terms to be retained in the expansion without affecting significantly the accuracy of the prediction. Since the design of this experiment *(5)* did not have as a main objective the derivation of prediction equations for the intermediate cooling phase, only approximate comparisons could be made and only tentative conclusions may be drawn. These comparisons were made only by inspection of the corresponding experimental and theoretically computed data.

From inspection of the experimental data certain trends were observed. For the locations tested it appeared from the computed data that for values of $(t - t_1) > 10$ minutes the inclusion of more than one term of the series did not change the values of temperatures by more than 1°F. Furthermore, for the values of $(t - t_1)$ of 2-3 minutes the series was observed to converge to the limit after 12 terms were computed; for $(t - t_1)$ of 5-7 minutes the limit was reached with approximately 7-8 terms computed, and only 4 terms were necessary for $(t - t_1) = 10$ minutes. The number of terms required for attaining the limit was not influenced by the retort temperature but fewer terms had to be used on the average when the value of $(RT - CT)_{t_1}$ decreased. Since $(RT - CT)_{t_1}$ was smaller for outside locations, fewer terms are required in this region than in the interior part of the container. Direct comparison of computed and experimentally observed temperatures indicated overestimate of the temperature by the theoretical equation for $(t - t_1) < 3$ minutes and underestimate thereafter. Thus, the observed rise in temperature after cooling water was started was not reflected properly by the theoretical estimates.

The results of these evaluations of the trends during the intermediate cooling phase do not warrant a recommendation of the prediction equation for the time-temperature relationship in the can. It may be concluded, however, that the theoretical equation does not approximate well the thermal history in the can as assumed by Hicks *(3)* since the series converges to a temperature value not in agreement with the experimental data. The temperatures observed indicate definitely that the temperature-time relationship is not a monotonic function as assumed by Ball *(1)*. This is especially true for large values of $(RT - CT)_{t_1}$ and thus for the high-temperature, short-time process. It would seem that a separate investigation of the above functional relationship may be warranted by the importance of the intermediate cooling phase for canning process determination.

Residual heating effect. In the discussion of time-temperature relationships during the intermediate cooling phase, attention was drawn to the effects of residual heating resulting in increase in temperature at locations in the can at the beginning of the cooling phase of the process. Since no prediction equation was derived to represent the functional relationship for that period, some of the effects of residual heating are discussed and illustrated graphically in the following section.

The end of the heating phase determines the processing time equal to t_1; the residual heating extends the effective processing time by an interval Δt to t'_1. Processing time requirement calculated from the thermal history at the center of the can (or point of greatest heating lag *(6)*) by methods which neglect the effect of residual heating at this location *(1)* specifies actually t'_1 and not the t_1. Thus a calculated process requirement is an overestimate of the retort holding time. In view of the above the determination of $\Delta t = t'_1 - t_1$ becomes of interest as it may lead to shorter safe processing times, and thus improve the palatability of the canned product.

In an attempt to determine the effective heating time (t'_1), Δt was measured at the location of greatest heating lag in the container for several processing times (t_1) at each of the 6 processing temperatures. The results were tabulated (Table 1) and the average of 3 determinations of Δt for each processing time (t_1) was plotted against t_1. The plot of Δt for each temperature resulted in an approximately straight line relationship. The intercept of the line yielded values of time (t_2) necessary to achieve a state when $\Delta t = 0$ or $t'_1 = t_1$. In other words a processing time was determined when no residual heating took place after the steam was shut off. The values of t_2 thus obtained were plotted (Figure 1) against temperature (RT) giving an excellent fit as a straight line of the form, $t_2 = a - b(RT)$. Since it was noticed that Δt decreases with the increase in t_1, a new variable was introduced, $\Delta t' = t_2 - t_1$ (the time remaining to the moment when $\Delta t = 0$) which also decreased with the increase in t_1. The values of t_2 used in computation of $\Delta t'$ were taken from Figure 1. Next the ratio of $\Delta t/\Delta t'$ was computed for each processing time and found substantially constant for each of the 6 temperatures used in this investigation. The plot of $\Delta t/\Delta t'$ against RT (Fig. 1) was found to be a curvilinear function of second degree increasing with the increase in retort temperature.

The meaning of the increase of $\Delta t/\Delta t'$ with processing temperature may reflect two occurrences: first and more significant, the effect of residual heating becomes larger as the retort temperature becomes higher for the same value of $\Delta t'$; second, for the same residual heating effect (in terms of time) less time is necessary to reach the point when $\Delta t = 0$. From Table 2 one can readily see that t_2, as determined previously for the increasing temperatures, corresponds to rapidly increasing sterilizing values. This table also shows that for processes equivalent in terms of lethality, $\Delta t' = t_2 - t_1$, when computed for $F_o = 2$, increases from 1 minute at 225°F. to about 36 minutes at 261°F. and then decreases to 12 minutes at 315°F. This trend is in agreement with trends observed by Hurwicz and Tischer in *(6)* and *(7)* for other thermal properties of beef. The respective values for Δt are 0.04, 4.68, and 5.76 minutes, which indicates the larger and larger effect of residual heating, for processing times com-

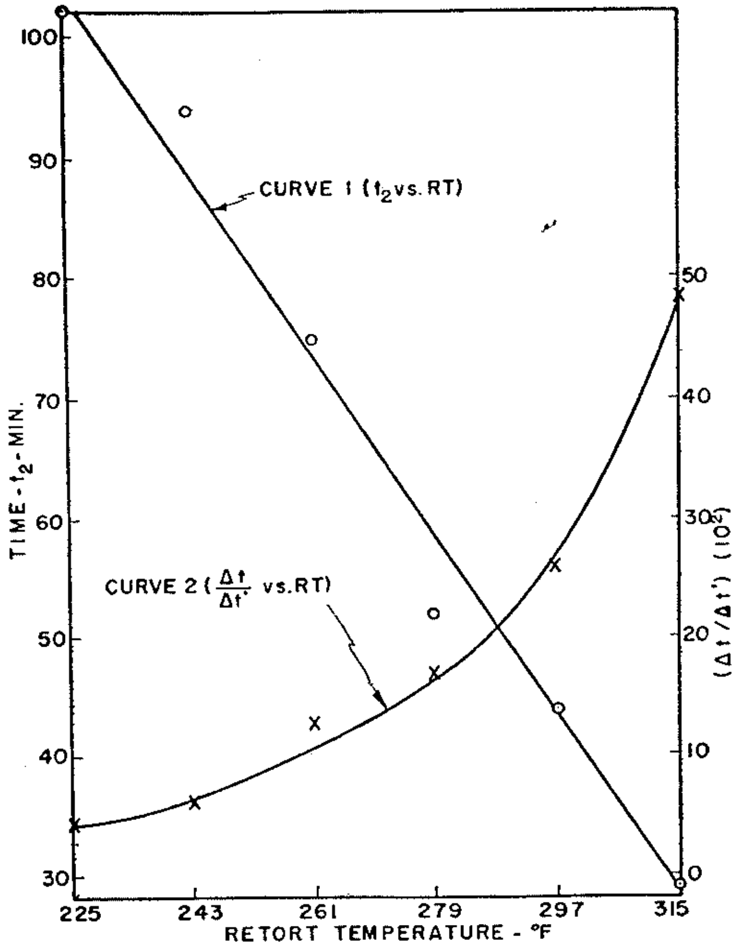

Figure I. Residual Heating Effects.
(For use in determination of the effective heating time — t'_1)

TABLE 2
Mean values of processing times t_1 (min.) for five F_o values[1]

RT (°F.)	t_2 (min.)	F_o				
		1	2	3	4	5
225	103	74.0	102.0	119.5	....	....
243	88	49.0	55.0	58.0	61.5	63.0
261	74	34.0	37.5	39.5	41.0	42.0
279	59	23.0	26.0	27.5	22.5	29.5
297	44	21.0	24.0	25.0	26.0	26.5
315	29	16.5	17.8	18.0	18.5	18.7

[1] Based on (8) Table 9.

monly used in canning, as the temperature increases. This effect is augmented by the fact that at higher temperatures the F_o values increase with time faster than at low temperatures.

The usefulness of the computed ratio $\Delta t/\Delta t'$ lies not only in facilitation of interpretation of effects of residual heating, but also gives means, with the help of Figure 1 to determine the effective heating time (t'_1) for a given process (t_1) or vice versa. The ratio $(\Delta t/\Delta t') = (t'_1 - t_1)/(t_2 - t_1)$ may be found for retort temperatures in the range 225-315°F. from Curve 2, and t_2 from Curve 1 (Fig. 1). Thus the effect of residual heating may be approximately assessed and corrections to the estimated process time by the "formula method" may be made.

The fitting of the curves by statistical methods would give means of evaluation of the precision of these results. It would seem unnecessary, however, to evaluate the precision of a procedure to be used in connection with the "formula method," since that method does not afford an estimate of precision itself, and because of large variations in F_o determinations.

SUMMARY AND CONCLUSIONS

In the course of the investigation of the intermediate cooling period and residual heating effects a method has been developed to determine effective retort holding times. This method may result in shorter but safe processing times and may increase the palatability of canned beef and other products.

On the basis of the experimental results the following conclusions may be drawn:

Neither the theoretical solution of the heat conduction equation nor a monotonic function approximate the experimental results for the intermediate cooling phase.

The residual heating at the beginning of the cooling phase increases the effective processing time. This increase is most pronounced for short time, high temperature processes. The contribution of residual heating to the sterilizing effect displays the same trend and possibly reaches maximum at 297°F. retort temperature.

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