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Evaluating the Lethality of Heat Processes Using a Method Employing Hicks' Table

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SUMMARY

A method of calculating the lethality of heat processes is described and illustrated. This method can be used for z-values from 10 to 80°F; it allows the technologist to calculate directly the lethality of the heating and the cooling portion of the process.

METHOD

Hicks (1958) prepared a set of tables, where the term that we shall call H, which is a function of g and z, is tabulated; the term H in these tables is related to f_h, U_h, c, f_c, and U_c in the equation:

$$H = \frac{100\ U_h}{f_h} = \frac{1}{c}\ \frac{100\ U_c}{f_c}$$

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The function H is quite similar to the function f_h/U of Ball (1928). (We shall use the symbol B for Ball's function, $B = f_h/U$). The significant difference between the function B and the function H is that B relates U, the lethal effect of both the heating and cooling portions of the thermal process, with f_h, whereas H relates U_h, the lethal effect of the heating portion of the curve, with f_h, and through the use of c relates U_c, the lethal effect of the cool, with f_c ($c = U_c/U_h$). The potential use of Hicks table was recognized soon after it appeared in 1958; however, to bring the Hicks table (Table 1) into practical use it was necessary to develop the tables of c (Tables 2 and 3). The c tables were developed using the data in the cooling tables of the new calculation method in Ball *et al.* (1957). The variable c, in its most usable form, relates H, f_c and U_c in the equation.

$$U_c = \frac{cHf_c}{100}$$

This method of process evaluation, which is applicable for z values of 10 through 80 and for simple through very complex heating and cooling curves, is, in reality, a simplification of the new formula method of Ball *et al.* (1957). The method described here, using Hicks tables, was designed to solve less complicated problems than the new formula method of Ball *et al.* (1957).

In using the Hicks-tables method, the heating and cooling portions of the process are treated separately; in the case of the simple heating curve, the value of Hicks function is obtained directly from Table 1. When g is less

Table 1. Table of values of Hicks (1958) function "H" where $H = \frac{100U_h}{f_h}$. (From *Food Research* **23,** pages 396–400, 1958.)

g \ z	10	15	18	20	25	30	40	60	80
0.10	139.7	157.0	164.8	169.8	178.9	186.8	199.2	216.7	229.1
0.15	122.6	139.7	147.5	151.9	161.5	169.3	181.7	199.2	211.6
0.20	110.6	127.5	135.2	139.7	149.2	157.0	169.3	186.8	199.2
0.25	101.4	118.2	125.8	130.3	139.7	147.5	159.7	177.1	189.5
0.3	93.95	110.6	118.2	122.6	132.0	139.7	151.9	169.3	181.7
0.4	82.41	98.74	106.22	110.58	119.88	127.5	139.7	157.0	169.3
0.5	73.67	89.69	97.07	101.38	110.58	118.2	130.3	147.5	159.7
0.6	66.69	82.41	89.69	93.95	103.06	110.6	122.6	139.7	151.9
0.7	60.93	76.36	83.53	87.73	96.75	104.21	116.1	133.2	145.4
0.8	56.05	71.18	78.26	82.41	91.34	98.74	110.6	127.5	139.7
0.9	51.84	66.69	73.67	77.77	86.61	93.95	105.7	122.6	134.7
1.0	48.16	62.74	69.62	73.67	82.41	89.69	101.4	118.2	130.3
1.2	42.01	56.05	62.74	66.69	75.26	82.41	93.95	110.58	122.6
1.4	37.05	50.56	57.07	60.93	69.32	76.35	87.73	104.21	116.1
1.6	32.94	45.95	52.28	56.05	64.26	71.18	82.41	98.74	110.6
1.8	29.48	42.01	48.16	51.84	59.89	66.69	77.77	93.95	105.7
2.0	26.52	38.59	44.57	48.16	56.05	62.74	73.67	89.69	101.38
2.2	23.97	35.59	41.41	44.91	52.63	59.21	70.00	85.87	97.48
2.4	21.74	32.94	38.59	42.01	49.58	56.05	66.69	82.41	93.95
2.6	19.79	30.57	36.07	39.40	46.82	53.18	63.68	79.26	90.71
2.8	18.06	28.44	33.79	37.05	44.31	50.56	60.93	76.36	87.73
3.0	16.52	26.52	31.72	34.90	42.01	48.16	58.39	73.67	84.98
3.5	13.346	22.45	27.30	30.29	37.05	42.94	52.84	67.76	78.88
4.0	10.986	19.19	23.71	26.52	32.94	38.59	48.16	62.74	73.67
4.5	8.970	16.52	20.73	23.38	29.48	34.90	44.16	58.39	69.15
5.0	7.435	14.31	18.24	20.73	26.52	31.72	40.67	54.58	65.15
5.5	6.197	12.46	16.12	18.47	23.97	28.95	37.61	51.19	61.60
6.0	5.191	10.90	14.31	16.52	21.74	26.52	34.90	48.16	58.39
6.5	4.365	9.563	12.75	14.83	19.79	24.37	32.47	45.43	55.49
7.0	3.684	8.420	11.39	13.35	18.06	22.45	30.29	42.94	52.84
7.5	3.119	7.435	10.203	12.04	16.52	20.73	28.32	40.67	50.40
8.0	2.648	6.582	9.163	10.896	15.15	19.19	26.52	38.59	48.16
8.5	2.254	5.839	8.246	9.877	13.91	17.79	24.88	36.67	46.09
9.0	1.922	5.191	7.435	8.970	12.81	16.52	23.38	34.90	44.16
9.5	1.643	4.623	6.715	8.160	11.80	15.36	22.00	33.25	42.36
10.0	1.407	4.124	6.075	7.435	10.90	14.31	20.73	31.72	40.67
11.0	1.036	3.296	4.998	6.197	9.320	12.460	18.47	28.95	37.61
12.0	0.7678	2.648	4.124	5.191	8.009	10.896	16.52	26.52	34.90
13.0	0.5715	2.137	3.420	4.365	6.909	9.563	14.83	24.37	32.47
14.0	0.4272	1.731	2.847	3.684	5.979	8.420	13.35	22.45	30.29
15.0	0.3205	1.407	2.377	3.119	5.191	7.435	12.04	20.73	28.32
20.0	0.07948	0.5185	1.0019	1.407	2.648	4.124	7.435	14.311	20.73
30.0	0.005563	0.07948	0.1999	0.3205	0.7678	1.407	3.119	7.435	12.04
40.0	0.000429	0.01332	0.04347	0.07948	0.2412	0.5185	1.407	4.124	7.435

Table 2. Table of values of c ($c = \frac{U_c}{U_h}$).

	z, °F						
	10	15	20	30	40	60	80
(T_1–T_2) = 125°F g, °F							
0.1	.0888	.0885	.0885	.0931	.0957	.1030	.1120
0.5	.1561	.1461	.1410	.1421	.1424	.1490	.1593
1.0	.2180	.1944	.1833	.1795	.1769	.1822	.1935
4.0	.5598	.4169	.3577	.3239	.3059	.3049	.3206
10.0	1.5565	.8293	.6337	.5213	.4774	.4735	.5102
30.0	10.7550	2.5164	1.4109	.9026	.8456	.9187	1.1148
(T_1–T_2) = 150°F g, °F							
0.1	.0823	.0822	.0826	.0876	.0892	.0960	.1049
0.5	.1452	.1360	.1313	.1320	.1321	.1387	.1491
1.0	.2035	.1817	.1708	.1672	.1641	.1699	.1807
4.0	.5277	.3882	.3339	.3006	.2849	.2838	.2990
10.0	1.4001	.7759	.5912	.4843	.4449	.4277	.4752
30.0	10.0665	2.3528	1.3123	.8884	.7879	.8464	1.0400
(T_1–T_2) = 175°F g, °F							
0.1	.0766	.0771	.0768	.0809	.0830	.0894	.0974
0.5	.1343	.1271	.1223	.1235	.1226	.1293	.1385
1.0	.1889	.1689	.1592	.1561	.1519	.1581	.1680
4.0	.4956	.3627	.3112	.2799	.2651	.2640	.2784
10.0	1.2793	.7202	.5487	.4507	.4150	.4127	.4425
30.0	8.9879	2.1389	1.2235	.8387	.7356	.7826	.9690
(T_1–T_2) = 200°F g, °F							
0.1	.0715	.0713	.0715	.0754	.0773	.0835	.0908
0.5	.1264	.1182	.1142	.1151	.1148	.1205	.1289
1.0	.1767	.1576	.1481	.1449	.1425	.1477	.1561
4.0	.4579	.3371	.2898	.2591	.2475	.2480	.2585
10.0	1.2153	.6717	.5104	.4172	.3852	.3848	.4122
30.0	8.9879	2.0131	1.1445	.7605	.6833	.7316	.9021

than 0.1°F (log g is less than −1.0) the value of H for g = 0.1°F is used but must be increased by a factor H_x obtained from Fig. 1 ($H = H_{g=0.1} + H_x$).

The lethal effect of the cool $U_c = cU_h$; values of c are tabulated in Table 2. When g is greater than 0.1°F the cooling lethality is found by determining H as a function of g and z, c as a function of g, ($T_1 - T_2$) and z after which the value U_c can be found using the equation

$$U_c = \frac{cHf_c}{100}$$

The lethality of heating plus cooling is found using the equation

$$U = U_h + U_c = \frac{Hf_h}{100} + \frac{cHf_c}{100}$$

It is assumed that there is no difference in the lethal effect of the cool when g = 0.1°F and when g = 0°F; therefore, for all values of g equal to or less than 0.1°F, the value of the function cH/100 for g = 0.1°F the

Table 3. Values of $\frac{cH}{100}$ for g = 0.1°F for use in calculating the cooling curve lethality when g is less than 0.1°F; lethality of the cool $U_c = \frac{cH}{100} f_c$.

	$\frac{cH}{100}$			
z, °F	$(T_1-T_2) = 125°F$	$(T_1-T_2) = 150°F$	$(T_1-T_2) = 175°F$	$(T_1-T_2) = 200°F$
10	0.124	0.115	0.107	0.100
15	0.139	0.129	0.121	0.112
20	0.150	0.140	0.130	0.121
30	0.174	0.162	0.151	0.141
40	0.191	0.178	0.165	0.154
60	0.223	0.208	0.194	0.181
80	0.257	0.240	0.223	0.208

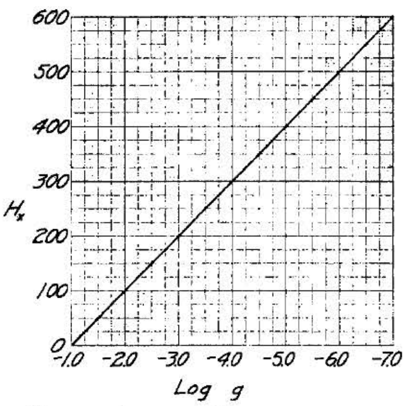
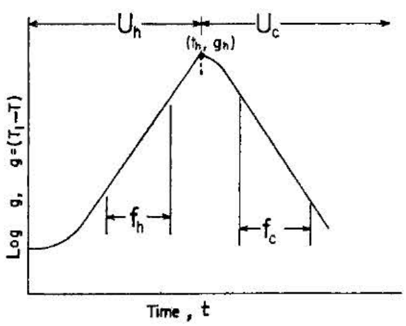


Fig. 1. Values of H_x vs log g. In table 1 H is tabulated for log g values down to −1.0 (g = 0.1°F), when log g is less than −1.0 (g is less than 0.1°F) H must be corrected ($H = H_{g=0.1} + H_x$).



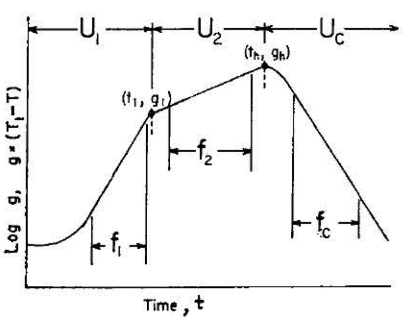


Fig. 2. Diagram of heating curves and symbols (A) simple Heating curve, (B) complex heating curve.

particular z and $(T_1 - T_2)$ is used. Values of cH/100 for g equal to or less than 0.1°F as a function of z and $(T_1 - T_2)$ are tabulated in Table 3.

In general, heat processing conditions may be thought of as either having simple heating curves with $f_h = f_c$, simple heating curves with f_h not equal to f_c, or complex heating curves consisting of f_1, f_2, and f_c. The procedure using Hicks tables may be used equally well to analyze data from all three process situations. Symbols for use with a simple heating curve are diagrammed in Fig. 2A and for a complex heating curve in Fig. 2B.

The Hicks-table method of analysis of heat processes where the heating curve is complex is carried out by dividing the process into sections analyzing each section separately and summing up the parts to complete the solution. The process is divided at the time point when the semi-logarithmic heating curve changes slope. The subscripts used in the equations below correspond to those used in Fig. 2. The significance of the subscripts is to relate the value of g used in arriving at H and the value of f used with H to arrive at the U_h. In general, when the term U is used, without subscript, it implies that it is the total lethal effect of both heating and cooling for the entire process. The subscripts refer to the sections of the process and may be either heating or cooling according to the respective subscripts as shown below:

$$U = U_1 + U_2 + U_c$$

$$U_1 = U_{g_1}$$

$$U_2 = U_{g_h f_2} - U_{g_1 f_2}$$

$$U_c = cU_{g_h f_c}$$

Evaluation of thermal process using Hicks tables when heating curve is a single straightline:

1. Assemble data, values are needed for T_1, T_o, T_2, f_h, j, z, t_h (or t_B, t_{CUT}). If f_c is not given we will assume that $f_c = f_h$; j_c must be known or assumed to be 1.41.
2. Calculate log g using the equation $\log g = -t_h/f_h + \log j\ (T_1 - T_o)$.
3. Using the data in Table 1 determine H for the particular value of log g and z.
4. Using Table 2 determine the value c as a function of log g, z, and $(T_1 - T_2)$.
5. Calculate U using the equation

$$U_h = \frac{Hf_h}{100}$$

$$U_c = \frac{cHf_c}{100}$$

$$U = \frac{f_h H}{100} + \frac{cHf_c}{100}$$

6. Calculate F_{250} using the equation

$$F_{250} = U\ 10^{\frac{T_1-250}{z}}$$

Example: Simple heating, g is greater than 0.1°F (log g greater than −1.0).

1. Data:
   - $T_1 = 245°F$ $\quad j = 1.5$
   - $T_o = 160°F$ $\quad z = 18°F$
   - $T_2 = 65°$ $\quad f_h = f_c$
   - $t_h = 80.0$ min $\quad j_c = 1.41$
   - $f_h = 48.0$ min
2. $\log g = -t_h/f_h + \log j\ (T_1 - T_o) = -80/48 + \log 1.5\ (245-160) = 0.441.$
3. From Table 1, H = 35.
4. From Table 2, c = 0.27.
5. $U = \frac{Hf_h}{100} + \frac{cHf_c}{100} = \frac{35 \times 48}{100} + \frac{0.27 \times 35 \times 48}{100} = 21.3.$
6. F_{250} = (U × lethality ratio 245°F, z = 18) = 21.3 × 0.527 = 11.2 min.

Example: Simple heating, g is less than 0.1°F (log g less than −1.0).

1. Data:
   - $T_1 = 250°F$
   - $T_o = 140°F$
   - $T_2 = 75°F$
   - $(T_1 - T_2) = 175°F$
   - $t_h = 35$ min
   - $f_h = 8$ min
   - $j = 1.2$
   - $z = 35°F$
   - $f_c = 12$ min
   - j_c assume 1.41

2. $\log g = -t_h/f_h + \log j\ (T_1 - T_o)$
$\log g = -35/8 + \log 1.2\ (110) = -4.375 + 2.121 = -2.254$
$g = 0.00557°F$

3. g is less than 0.1°F therefore
$H = H_{g=0.1°F} + H_x$
from Table 1, $H_{g=0.1} = 193.4$
from Fig. 1, $H_x = 125$
$H = 193.4 + 125 = 318.4$

4. From Table 3 cH /100 = 0.158.

5. $$F = U = \frac{Hf_h}{100} + \frac{cHf_c}{100} = \frac{318.4 \times 8}{100} + 0.158 \times 12 = 27.4 \text{ min}$$

Evaluation of thermal process for complex heating curve using Hicks tables. The evaluation of heating processes where the heating curve consists of more than one straight line is carried out on a straight forward divide and conquer basis. The steps required to arrive at the solution of a complex heating curve with two slopes are outlined below. From this general solution, heating curves with more than two slopes may be solved by simply extending the procedure:

1. Assembling the data. Values are needed for T_1, T_o, T_2, f_1, f_2 f_c, j, t_1, t_h, z and it must be known or assumed that $j_c = 1.41$.
2. Develop values for g_1, g_h. In some cases they may be determined graphically; in other cases they may be calculated:
$\log g_1 = -t_1/f_1 + \log j\ (T_1 - T_o)$
$$\log g_h = \frac{-(t_h - t_1)}{f_2} + \log g_1$$
3. Determine H_1, H_2 from Table 1.
4. Determine c for g_h, z and $(T_1 - T_2)$ from Table 2.
5. Calculate U using the relationships:
$$U = U_1 + U_2 + U_c$$
$$U_1 = H_{g_1}\frac{f_1}{100}$$
$$U_2 = H_{g_h}\frac{f_2}{100} - H_{g_1}\frac{f_2}{100} = (H_{g_h} - H_{g_1})\frac{f_2}{100}$$
$$U_c = \frac{cH_{g_h} f_c}{100}$$

6. Calculate F_{250} using the equation:
$$F_{250} = U\ 10^{\frac{T_1 - 250}{z}}$$

Example: Complex heating curve (two-slope type)

1. Data:
$T_1 = 245°F$
$T_o = 140°F$
$T_2 = 65°F$
$z = 18°F$
$j = 1.73$
$f_1 = 12.1$ min
$t_1 = 20.1$ min
$f_2 = 46.4$ min
$t_h = 40$ min
$f_c = 23.7$ min
assume j_c is 1.41
2. Calculation of g_1 and g_h
$\log g_1 = -t_1/f_1 + \log j\ (T_1 - T_o)$
$\log g_1 = -1.661 + 2.259 = 0.598$
$$\log g_h = \frac{-(t_h - t_1)}{f_2} + \log g_1$$
$\log g_h = -0.428 + 0.598 = 0.170$
3. Determine H from Table 1
$H_{g_1} = 24.1$
$H_{g_h} = 55.0$
4. From Table 2, c = 0.196.
5. Calculate U where $U = U_1 + U_2 + U_c$
$$U_1 = \frac{24.1 \times 12.1}{100} = 2.92 \text{ min.}$$
$$U_2 = (55.0 - 24.1)\frac{46.4}{100} = 14.34 \text{ min.}$$
$$U_c = \frac{0.196 \times 55.0 \times 23.7}{100} = 2.55 \text{ min.}$$
$$U = 2.92 + 14.34 + 2.55 = 19.81 \text{ min.}$$
6. $$F^{18}_{250} = 19.81 \cdot 10^{\frac{245-250}{18}} = 10.44 \text{ min.}$$

ADVANTAGES OF THE METHOD

1. This method makes it possible for the food technologist or microbiologist to calculate the lethality of heat processes for z-values from 10 to 80°F.
2. It makes possible the use of the data in the tables of Ball *et al.* (1957) with their improved accuracy for solving both simple and complex heat processing problems.
3. It allows the technologist to directly calculate the lethality of the heating and cooling portion of the process.

NOMENCLATURE

B, symbol for Ball (1923) function, $B = \frac{f}{U}$

c, ratio of heating lethality to cooling lethality, $c = \frac{U_c}{U_h}$

F^z_T the equivalent time of a heat process at temperature T for a temperature coefficient value z

f, the temperature response parameter, the time for the straight line asymptote of the semilogarithmic heating or cooling curve to traverse one log cycle, f_h for heating, f_c for cooling, f_1, f_2, f_3 . . . respective temperature response parameters for complex heating curves.

g, degrees F below medium temperature $g = (T_1 - T)$

H, symbol for Hicks (1958) function $H = \frac{100\ U_h}{f_h} = \frac{100\ U_c}{c\ f_c}$

j, the lag factor of the heating curve, $j = (T_1 - T_a)/(T_1 - T_o)$

L, symbol for the lethal rate (min at 250 F/min at T) $= 10^{\frac{T-250}{z}}$

t, symbol for time, t_h heating time measured from steam on to steam off assuming retort or heating bath instantly reaches heating medium temperature (T_1), t_{CUT} is the time for the retort or bath to reach T_1, t_B is the canning industry process time measured from the time the retort or bath reaches temperature to steam off ($t_B + 0.42\ t_{CUT} = t_h$), t_1, t_2 times at which the slope of the heating curve changes.

U, the equivalent time at heating medium temperature: $U = F_{T_1}$ and is the sum of the heating and cooling lethality $U = U_h + U_c$, U_h for heating only, U_c for cooling only, U_1, U_2, U_3 are lethality values used in analysis of complex heating curves.

z, a measure of the effect of temperature on the heat destruction rate of a microorganisms (a type of temperature coefficient). Numerically z is the °F for the thermal destruction curve to traverse one log cycle (the °F for the thermal destruction rate to change by a factor of 10).

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