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A Time-Temperature Model for Sensory Acceptance of a Military Ration

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ABSTRACT

Average consumer-acceptance scores on the military ration called the Meal, Ready-to-Eat, at four temperatures and storage times through 60 months fitted an Arrhenius-like mathematical model which estimated the dependence of average score on storage time and temperature as well as the effect of temperature on shelf life. Results are presented for individual items and for the most important classes of items.

INTRODUCTION

ROSS ET AL. (1983) have described sensory studies of the military ration called the Meal, Ready-To-Eat (MRE) after 24 months of storage. In that paper the objective was to estimate the shelf-life of an item at its storage temperature. This was done by fitting a mathematical model for time-dependence to the acceptance scores of the item at that temperature and solving the model for the time at which a critical, average score was reached. The statistical methods for doing this were regression and contingency-table analysis. These gave consistent and understandable results in most cases.

However, there are several reasons for trying to fit a more elaborate model in which both time and temperature, not merely time alone, are independent (predictor) variables. First, it provides mathematical formulas that enable one to predict shelf-life at any temperature, not solely at the test temperatures as in the earlier analyses. Secondly, if the model is well-chosen, it permits data at one temperature to assist in predicting results at all temperatures, and so combat the randomness that often afflicts the fitting of a model to data. Finally, it may furnish information about time-temperature relations that is less easily perceived from models of time-dependence only.

The score obtained from a sensory test of a stored food item is usually the result of an enormously complicated chain of events. These involve chemical and biological reactions that occur in the food, the processes of taste-sensation during eating and the eventual integration of these with the psychology of the test subject. Even if all these processes were perfectly understood and could be modelled in mathematical terms, their synthesis would still constitute a formidable task. The present effort undertakes no such ambitious project. The entire process is regarded as one reaction with (almost) Arrhenius kinetics, and the purpose is to see what information can be obtained from this coarse but relatively simple outlook.

The general status of efforts in mathematical modelling of food-deterioration is well-described in an article by Karel and Saguy (1980). Considerable information about parameters of chemical reactions occurring in foods is found in the work of Labuza (1980, 1982, 1984) and Labuza and Kamman (1983). Mathematical and statistical methods for estimating Arrhenius parameters have been discussed by Cohen and Saguy (1985) and Haralampu et al. (1985). These papers are all concerned primarily with estimation of reaction-parameters from physical or chemical measurements. In the present paper similar methods were used to estimate parameters based instead on sensory data for the MRE during 60 months storage.

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MATERIALS & METHODS

A THOROUGH ACCOUNT of the MRE storage test and statistical calculations with the data has been given by Ross et al. (1983). The MRE ration system consists of 12 meals or menus involving 51 separate food items. A food that is part of more than one menu is regarded as a different item in each menu. The items are classified into five main types: entrees, pastries, vegetables, fruits, and miscellaneous, of which the first four are thought to be the most important.

The meals were purchased through the military supply process, and some were tested immediately upon delivery. The others were stored at four temperatures, 4°, 21°, 30°, and 38°C, then withdrawn and tested at the times indicated in the following plan:

4° C:	0, 12, 30, 36, 48, 60 months
21° C:	12, 18, 24, 30, 36, 48, 60 months
30° C:	6, 12, 18, 24, 30, 36 months
38° C:	6, 12, 18, 24 months

In the tests, meals were served to panels of consumers drawn randomly from the work-force at the US Army Natick Research, Development and Engineering Center (NRDEC). Each item in the meal was rated by panelists on a nine-point hedonic scale (Peryam and Girardot, 1952), describing how much the item was liked. A score of 9 means "like extremely," 5 means "neither like nor dislike," 1 means "dislike extremely" and intermediate integer scores have graduated meanings. The panels always comprised 36 members, there were 23 combinations of time and temperature, and so the data for each item consisted of 828 scores.

A discussion about the proper statistical treatment (e.g., regression versus categorical methods) was presented by Ross et al. (1983). Both categorical methods and regression procedures were employed in that paper, and other categorical methods have been proposed (MacCullagh, 1980). In the present work nonlinear regression analysis was used exclusively and applied to the averages of the scores at each time and temperature. The basic model was that of a first order chemical reaction following Arrhenius kinetics. Although other choices were possible, this hypothesis allowed estimation of shelf-life at any temperature, had behavior that conformed with observations in many tests, and did not require excessive computation.

The proposed mathematical model for the behavior of y, the score, as a function of time in months, t, and temperature in °C, H, is

$$y = X_3 \qquad \text{if } t < X_4 \qquad (1)$$
$$= u + (X_3 - u)\exp-[K(t - X_4)] \qquad \text{if } t \geqslant X_4 \qquad (2)$$

X_3 is the score (assumed constant) prior to X_4, the time, in months, at which the score starts to change. K is a rate (dimension 1/months), with temperature dependence

$$K = K(H) = \exp[-X_1 + G(H)\,X_2] \qquad (3)$$

$$G(H) = m(H - H_c)/(H + H_0) \qquad (4)$$

$$H_0 = 273°\ C \qquad (5)$$

m is a dimensionless scaling constant, H_c (°C) is a constant temperature shift, X_2 is the dimensionless parameter specifying intensity of the temperature effect on K, and X_1 is another dimensionless parameter. Because u is the limiting value of y for long times, which is 1 on the nine-point hedonic scale, u = 1 is used in all calculations.

The shelf-life, L, defined as the time in months at which the score reaches a critical value, y_c (usually $y_c = 5$), is calculable from the above model by the formulas

$$L = X_4 + Q/K \qquad (6)$$
$$Q = \ln[(X_3 - u)/(y_c - u)]$$

The section on Theory of the model contains a discussion of the model and a brief description of the computations involved in fitting it to the data. The temperature-sensitivity parameter, A, takes the place of X_2 in the calculations. A and its standard error, S_A, play a major part in assessing the success of the fitting process.

THEORY

TO COMPARE Eq (1) to (5) with the usual Arrhenius behavior for first-order reactions, we write the latter as

$$C = C_0 \exp(-kt) \qquad (7)$$

$$k = k_o \exp[-E/(RT)] \qquad (8)$$

$$T = H + H_0 \qquad (9)$$

In the common, chemical context C is the concentration of a reacting substance, C_O its initial concentration, k_o the pre-exponential factor, E the activation energy and R the universal gas constant. Eq (1) and (2) differ from (7) primarily because of the time-shift, X_4, that is permitted in (1) and (2) but not in (7), and secondarily because of the presence of u in (2). The latter adjusts the model so that the lowest attainable score is not 0 but u = 1. If $X_4 = 0$ and u = 0, Eq (1) is unnecessary and (2) is the same as (7), provided y, X_3 and K are replaced by C, C_O and k, respectively.

The relation between Eq (3) and (8) can be seen if (4) is rewritten with the aid of (9) as

$$G(H) = [m(H + H_0 - H_c) - mH_0]/(H + H_0)$$
$$= m[T - (H_c + H_0)]/T$$
$$= m - m(H_c + H_0)/T$$

Then Eq. (3) becomes

$$K = \exp[-X_1 + mX_2 - X_2m(H_c + H_0)/T]$$
$$= \exp[-X_1 + mX_2] \exp[-X_2m(H_c + H_0)/T]$$

If in the last equation the definitions

$$k_o = \exp[-X_1 + mX_2] \qquad (10)$$

$$E/R = X_2m(H_c + H_0) \qquad (11)$$

are made, it is evident that (3) and (8) are mathematically equivalent. The present model, Eq (1) to (5), is, therefore, a modest generalization of the usual Arrhenius model, Eq (7) to (9).

The quantities m and H_c are introduced to improve the convergence of the iterative process involved in fitting the model to the data. The values m = 10 and H_c = 27°C are used throughout the calculations.

Eq (11) implies that, if this model were applied to a chemical process following Arrhenius kinetics,

$$E = Rm(H_c + H_0)\, X_2 \qquad (12)$$

Since R = 1.987 cal/deg/mol, this would lead to

$$E = (3000 \times 1.987/1000)\, X_2 = 5.961\, X_2 \text{ kcal/mol}$$

In the context of the present experiment there is no easily discernible component whose change determines the score, and so it is difficult to ascribe an activation energy, E, to the process. However, Eq (8) shows that E/R, which has the dimensions of temperature, can be viewed merely as a parameter specifying the effect of temperature on the process. If A is defined by

$$A = H_a r X_2$$
$$H_a = m(H_c + H_0)/1000 = 3$$
$$r = 1.987,$$

Eq (A6) states that A has the same numerical value as E, expressed in kcal/mol, for an Arrhenius process. A and r may be regarded as fictitious activation energy and gas constant, respectively, but it is probably more useful to think of A as an alternative parameter to X_2 (temperature sensitivity) on a scale determined by r so A has the same value as E in kcal/mol for a chemical process of Arrhenius type. In this paper A is used in that sense.

The computer program which fits the data to the model finds the parameters X_1, X_2, X_3, and X_4 so as to minimize the quantity SSQ, the sum of squares of differences between model predictions and average data scores at all combinations of time and temperature. The minimization is done by the nonlinear, least-squares algorithm NL2SOL, which improves initial parameter estimates until no significant reduction in SSQ is obtained. This also provides estimated variances and covariances of the parameters, from which the variances S_A and S_L of A and L, respectively, can be calculated approximately.

The results obtained from this calculation depend strongly on the data (average scores) that are entered. If the data are too inconsistent with each other, or with the model, NL2SOL may not converge or may converge to a meaningless solution. Although the form of G(H) in Eq (4) improves convergence by reducing the likelihood of certain common difficulties (scaling and collinearity) in calculations of this type, covergence could still fail and does so in a number of cases. Indeed, failure is almost certain when an item is very stable and undergoes no significant change at any temperature, for there is then no information in the data on which a significantly non-zero estimate of A or X_2 could be based.

RESULTS

THE MAIN RESULTS presented here for each food item are as follows: (1) At each test-temperature the estimated, lowest, average score during the time-period of the test, which, because of the model, is also the estimated, average score at the longest storage time; (2) the temperature-sensitivity parameter, A, and (3) the shelf-life, L, at each storage temperature. These results are calculated for each item, using the procedure described in the section on Theory of the model. Similar calculations are done on the scores obtained by averaging the data for all entrees at each time-temperature combination and likewise pooling the data for the other principal food-types: pas-

Table 1—Item names and indices[a]

Entrees	Vegetables
01 Pork Sausage	24,25,26 Beans
02 Ham-Chicken Loaf	27,28 Potato Patty
03 Beef Patty	
04 Barbequed Beef	**Fruit**
05 Beef Stew	29,30 Peaches
06 Frankfurters	31,32 Strawberries
07 Turkey	33 Applesauce
08 Beef in Gravy	34 Fruit Mix
09 Chicken	
10 Meatballs	**Miscellaneous**
11 Ham Slices	35[a] Cheese Spread
12 Beef in Sauce	36 Peanut Butter
	37 Jelly
Pastries	38,39,40 Cocoa
13[a],14[a] Brownies	41 Coffee
15,16,17 Cookies	42 Toffee
18 Pineapple Cake	43[a],44 Vanilla Candy
19 Cherry Cake	45,46[a] Catsup
20 Maple Cake	47,48 Crackers
21 Fruit Cake	49 Crackers & Peanut Butter
22 Chocolate Cake	50,51 Crackers & Cheese
23 Orange Cake	52 Crackers & Jelly

[a] Denotes items dropped from the test

Table 2—Estimates of average hedonic scores[a,b]

Avg. score	After 60 months at 4°C	After 60 months at 21°C	After 36 months at 30°C	After 24 months at 38°C
7.4	40			
7.3	15 33 38	33 40		17
7.2	39	15	15 17 33	15 39
7.1	16	17	39 40	
7.0	17 31	38 39	38	38
6.9	34 36 49			16
6.8	PP		16	33 36
6.7	11 32 37 FF	11 16 32 36	32 38	40
6.6	18 22 23 28 47 48	28 31 34 FF	11 28	24
6.5	19 21 26 51 AA	18 26 PP	19 24 26 PP	19 20 26 PP
6.4	05 09 20 27 52	05 19 22 24 49	05 20 22 FF	22
6.3	24 25 29 50 VV	20 25	18 25 34 VV	05 11 21 VV
6.2	04	37 47 VV AA	21 23 37 49	23 25
6.1		21 23 29 52	51 AA	01 37
6.0	01 10 30	30	01 30 47	18 28 34 49 AA
5.9	07 EE		29 31	07
5.8		01 09 10	07 09 51	30 47
5.7	08 12	07 08 12 EE	03 08 12 52 EE	03 08 09 EE
5.6	03 42	04 48 50	10	29 41 42
5.5	02	03 27	41	51
5.4	41	41	42 50	52
5.3			04 27	10 12
5.2		02		31 FF
5.1		42	02 48	50
5.0	06	06	06	04 27 32
4.9				06
4.8				02
4.7				
4.6				
4.5				48

[a] Numbers in columns refer to food items listed in Table 1.
[b] The symbols AA, EE, FF, PP and VV denote estimates for pooled data on all foods, entrees, fruits, pastries and vegetables, respectively.

Table 3—Temperature Sensitivity Parameter, A[a,b]

A	Items	
46-50	FF	
41-45		
36-40	33	
31-35		
26-30	31	
21-25	10 18 29 34 40 45	
16-20	02 04 47 48 50 51	
11-15	09 22 27 37 49 52 EE AA	
6-10	16 21 23 36 38 44 PP	
0- 5	07 20 39 42	
Indeterminate:	Entrees	01 03 05 06 08 11 12
	Pastries	15 17 19
	Vegetables	24 25 26 28 VV
	Fruits	30 32
	Miscellaneous	41

[a] Numbers under Items refer to food items listed in Table 1.
[b] The symbols AA, EE, FF, PP and PP denote estimates for pooled data on all foods, entrees, fruits, pastries and vegetables, respectively

tries, vegetables and fruits. Finally computations are done on the averages found by pooling all the foods in the system.

These calculations lead to an enormous amount of information, which must be condensed severely in this article. The main results are summarized in Tables 2, 3, and 4, dealing respectively with average score (y), temperature sensitivity (A), and shelf-life (L). In these charts the food items are represented by their indices, listed in Table 1, and the pooled results by the symbols EE (entrees), PP (pastries), VV (vegetables), FF (fruits) and AA (all items). The location at which the index or symbol is placed states the approximate value for each item or type.

More complete information is given by graphs of average score (y) versus storage time (t) at the four temperatures, H = 4, 21, 30 and 38°C. Figures 1 and 2 show two such graphs, for Items 4 (barbequed beef) and 8 (beef in gravy), chosen as typical of cases in which the calculation procedure worked well and poorly, respectively. Figures 3 and 4 show similar plots for pooled entree averages and for all foods. These figures also display time-dependent scores predicted by the model at the four temperatures.

The calculations furnish graphs of shelf life (L) as a function of temperature (H). Examples are shown for Item 4 and "all items pooled" in Fig. 5 and 6.

The following remarks are relevant to these results:

(1) Items 13, 14, 35, 43, and 46 were in the system originally but were removed early in the tests. No results are shown for these items.

(2) Several other items have small amounts of missing data, e.g., Items 31 and 32 lack data at the single point $t = 24$ months, $H = 38°C$. Items 44 and 45 have data missing at about half the test points in no discernible pattern. In these cases calculations were carried out on the remaining data.

(3) In Table 3 the indeterminate items are ones for which $S_A > A$, i.e., the computed standard error in A exceeds the estimate of A.

(4) All computations are done both with X_4 free and with X_4 fixed $= 0$. Usually the computations with X_4 free either fail or give results close to those for $X_4 = 0$, so only results for $X_4 = 0$ are shown. Also the estimates of L in Table 4 and Fig. 5 and 6 come from the choice $y_c = 5$.

DISCUSSION & CONCLUSIONS

THIS SECTION PRESENTS first conclusions about the storage characteristics of the ration system then discusses some aspects of the computational procedure. The results for the ration system may be summarized in a series of increasingly detailed statements as follows: (1) The results for "all items pooled," which characterize (coarsely) the entire ration system, show that $L > 70$ months for $H < 38°C$, average scores are approximately

$$\begin{aligned} y &= 6.5 \text{ after 60 months at 4°C} \\ &= 6.2 \text{ after 60 months at 21°C} \\ &= 6.1 \text{ after 36 months at 30°C} \\ &= 6.0 \text{ after 24 months at 38°C,} \end{aligned}$$

Table 4—Shelf-life, L, in months at test-temperatures[a,b,c,d]

L	At 21°C	At 30°C	At 38°C
>120	All (36) except:	All (26) except:	All (15) except:
111-120	04 09 41 45 50	03 07 41	01 41
101-110	02	37	
91-100	27 48	23 47 49 51	03 07 16
81-90		09 10 52	
71-80		31	15 18 EE AA
61-71			22 23 37
51-60	42 44	50	21
41-50		04 27 42	29 34 40 47 49 52
31-40		02 44 48	09 32 42 51 FF
21-30		45	04 05 10 27 31 44 50
11-20			02 45 48
0-10	06	06	06

[a] Numbers in columns refer to food items listed in Table 1.
[b] The symbols AA, EE, FF, PP and VV denote estimates for pooled data on all foods, entrees, fruits, pastries and vegetables, respectively.
[c] All items at 4°C had L > 120 months.
[d] The following items had L > 120 months at all H ≤ 38°C: 08 11 12; 17 19 20 PP; 24 25 26 28 VV; 30 33; 35 38 39

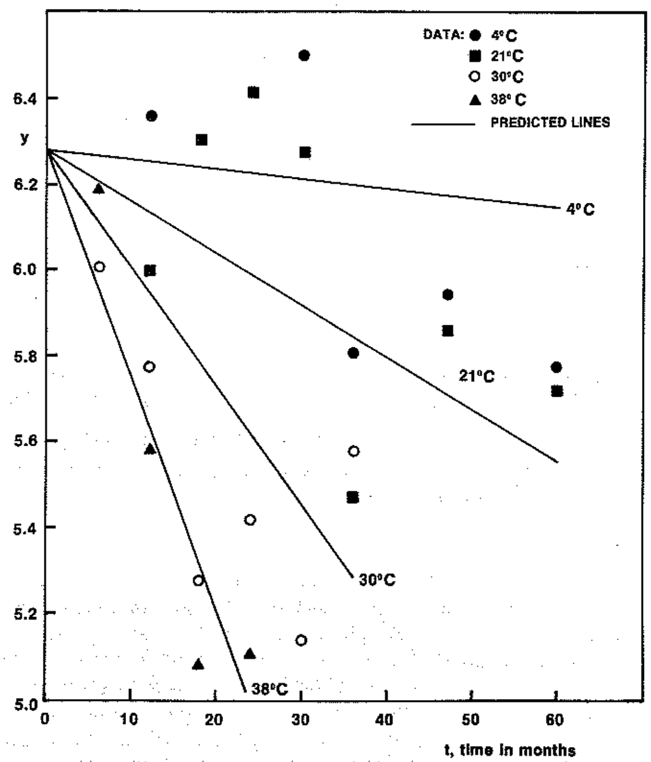

Fig. 1—Average scores, y, and predicted lines as functions of time for Item 4, Barbequed Beef.

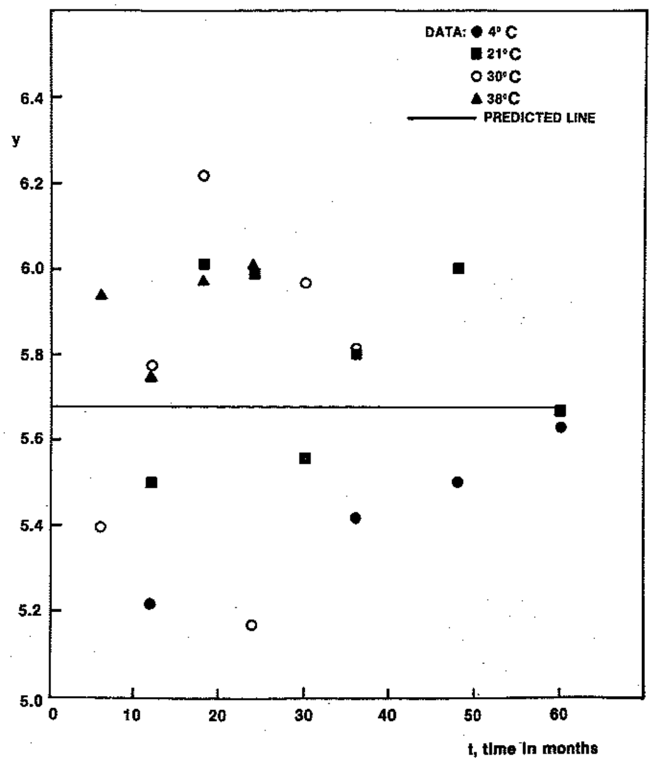

Fig. 2—Average Scores, y, and predicted line as functions of time for Item 8, Beef in Gravy.

and A lies in the range $10 < A \leq 15$. These results suggest that the ration is fairly stable and well-liked under typical storage conditions. (2) A closer view is afforded by the predictions for the four principal item-types displayed in Tables 2 to 4. It is clear and not surprising that pastries receive the best scores (6.5–6.8). Fruits score well at moderate temperatures but drop abruptly at H = 38°C. Vegetables and entrees are stable with scores in the ranges (6.2–6.3) and (5.7–5.9), respectively. Temperature sensitivity is highest for fruits ($46 \leq A \leq 50$), moderate for entrees and pastries ($6 < A < 15$) and zero for vegetables. For H ≤ 30°C all types have L > 120 months, but at H = 38°C fruits drop to $31 \leq L \leq 40$ and entrees to $71 \leq L \leq 80$. (3) The individual items show much larger differences than the type-averages, as expected. Most of the items that obtain high scores are fruit, pastry or miscellaneous. Among the entrees Items 5 and 11 appear the best and 2 and 6 the worst. Items 10, 2, 4, and 9 display the greatest temperature-sensitivity, and Items 6, 2, 4, 5, 10, and 9 have the shortest shelf-lives. In particular, Item 6, frankfurters, receive average initial scores below 5, so L = 0 for that item. (4) Table 4 contains a list of 15 items that have shelf-lives exceeding 120 months at H ≤ 38°C. Entree items 8, 11, and 12 are in this group and appear to be the most stable entrees although 8 and 12 receive scores no better than the entree average.

Although the ration system as a whole is reasonably acceptable and stable, some of its most important items, entrees, are not regarded highly, and there are serious questions about Items 2, 4, and 6. Apart from these there is reason to believe that the meals can be stored up to (and often much beyond) 24 months at temperatures below 38°C without important loss of quality. At 30°C and 21°C almost all items are acceptable after 40 and 90 months of storage, respectively, and shelf-lives are estimated to exceed 120 months for all items at 4°C.

However, it is important to be cautious in applying these estimates. Since the data extend only up to t = 60 months, and shorter times at higher temperatures, predictions about shelf-lives exceeding 60 months represent significant extrapolations from the data. These become increasingly erratic as the predicted L becomes larger. For that reason, no results

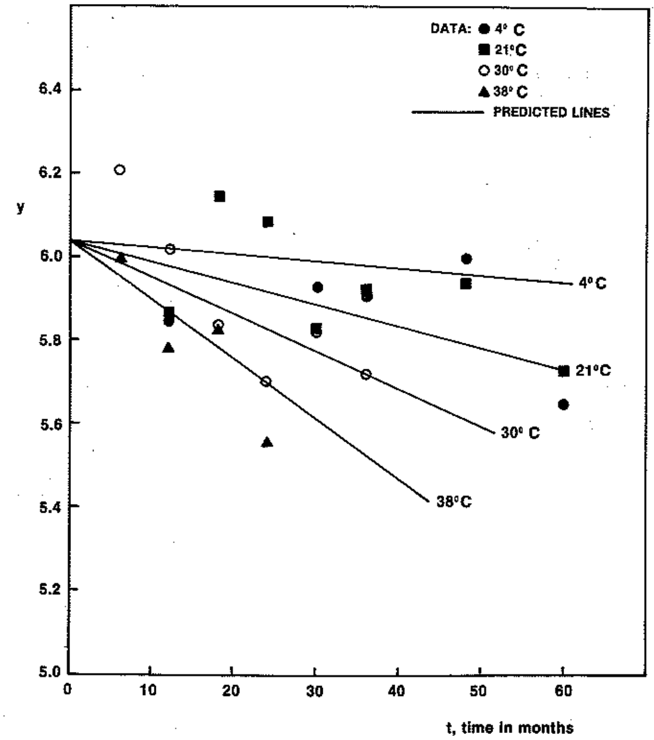

Fig. 3—Average Scores, y, and predicted lines as functions of time for all entrees pooled.

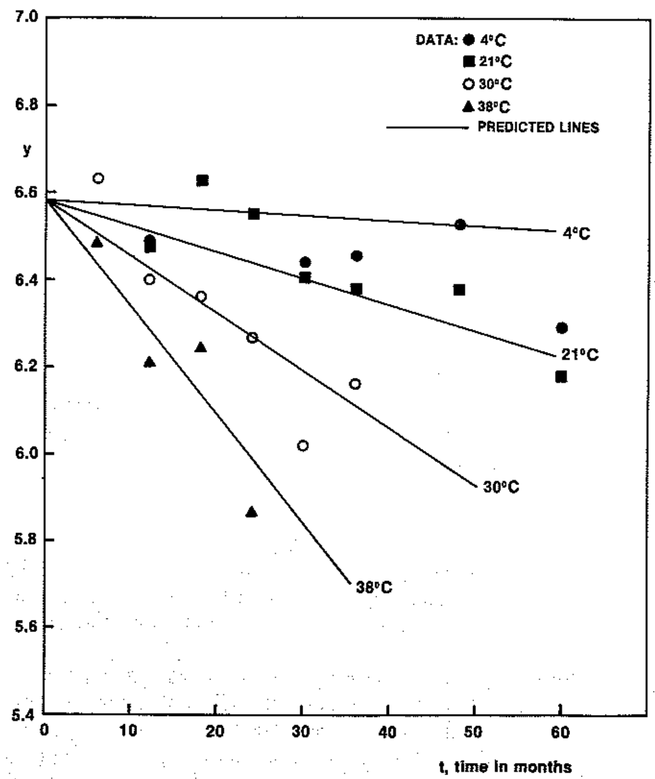

Fig. 4—Average Scores, y, and predicted lines as functions of time for all items pooled.

having L > 120 are stated, and predictions in the range 60 < L < 120 should be viewed with skepticism. Moreover, the results given in Tables 2 to 4 are all merely averages. Although the computations always furnish the corresponding standard errors, there is no concise way to present these, so they have been omitted. No gross misstatements result from this omission, but there are sizeable standard errors in some of the predictions.

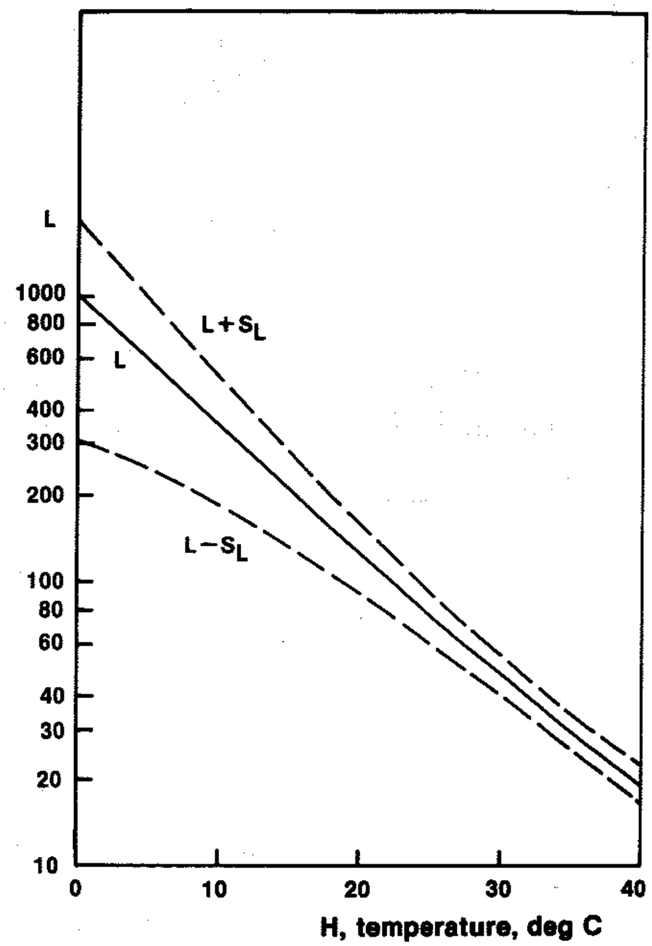

Fig. 5—Shelf-Life, L, in months as a function of temperature, H, for Item 4, Barbequed Beef.

Any attempt to fit a mathematical model to data will fail if either the model is inappropriate or the date are excessively irregular (random or noisy). Sensory tests of food present a severe challenge to fitting procedures on both counts. The complexity of the physical, chemical and psychological reactions almost ensures that the present, simple model will be deficient in some respects. Data from these tests are noisy for many reasons: the raw food is highly variable, the processing difficult to control, and the human subjects even more so. The problems are compounded by the fact that it is often impossible to distinguish model errors from unavoidable randomness.

These effects are abundantly evident in the results of Fig. 1 to 4, where the data are plotted along with the model predictions. Although the calculations are successful in Fig. 1, 3, and 4, many discrepancies between model and data are visible. For example, in Fig. 1 at 18 months the data point for 21°C lies above the prediction for 4°C while at 30°C the data point is below the prediction for 38°C. Several such anomalies can be found in Fig. 1, 3, and 4. It is unclear whether these anomalies are model defects or random fluctuations.

Figure 2 shows the result of an unsuccessful calculation in which $S_A > A$, the estimate of A is, therefore, worthless, and Item 8 is classified as having indeterminate A in Table 3. The computation found good estimates only of the parameter X_1. The prediction is unaffected by t and H and consists merely of the average of all data, a result supported by visual examination of Fig. 2.

It is important to notice that, if we fit lines to the data for each temperature separately, as was done in earlier analyses (Ross et al., 1983), the results need not be very close to those obtained here. In extreme cases it is even possible that L at some temperature may be indeterminate in the previous analy-

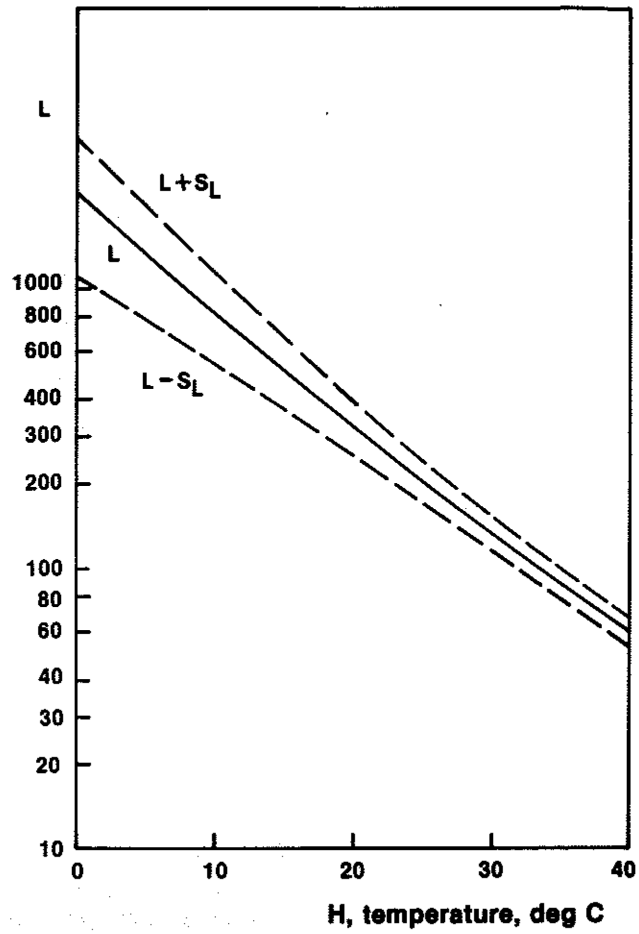

Fig. 6—Shelf-Life, L, in months as a function of temperature, H, for all items pooled.

sis but determinate according to the present computation, or vice versa. Item 2 has this behavior in these calculations; it is caused by a few, highly irregular points at one temperature, whose effect is offset to some extent by many points that conform to the model at other temperatures.

The model and computational procedure described here are not free of difficulties but seem to offer promise as a mathematical framework for analyzing storage tests. They are capable of refinement and extension in several directions. For example, it is thought that a meal is judged primarily by its entree, but it would be useful to compare scores for an entire meal with those of the items in the meal and obtain a relation between item and meal scores. This was done by Moskowitz and Rogozenski (1975) for a different system of rations. If it could be done for this system, it would provide a way to estimate the relative importance of each type of item and enable us to get a clearer picture of ration acceptability and stability.

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