STUDIES ON THE DYNAMICS OF CAKE-BAKING

II. The Interaction of Chlorine and Liquid in the Formation of Layer-Cake Structure[1]

J. T. WILSON AND D. H. DONELSON[2]

ABSTRACT

The quality of Kissell Research Formula layer cakes has been shown to be influenced among other things by chlorine dosage used on the flour, and by liquid level used in the batter. The present study is concerned with the interaction of these two factors. A response surface type of design was used, and cakes were assigned numerical scores for volume, structure, and contour. Volume and structure data indicated a simple relationship between independent variables, i.e., chlorine dosage and liquid level. When desirable contour was also required, complications arose. Acceptable cakes could be obtained: 1) with moderate chlorine dosage and rather high liquid levels, in which case contour was relatively insensitive to liquid level, or 2) with heavy chlorine dosage but moderate liquid levels, in which case contour was very sensitive to liquid level.

In a previous paper (1) the authors have shown that the amount of liquid used in preparing layer-cake batter has a marked effect on the structure of the cake produced from improved flour. As liquid level increases from suboptimum levels, there is a gradual change from coarse, open crumb, sunken contour, and low volume, through the ideal uniform cell structure, rounded contour, and large volume, to very small thin-walled cells, peaked contour, and reduced volume.

The use of chlorine-based mixtures as cake flour improvers is standard postmilling procedure. The treatment reduces flour pH, and dosage is usually regulated to attain a final reading of approximately pH 4.8. There are also noticeable effects on the quality of the baked product.

An unimproved cake flour, even at optimum liquid levels, produces a layer cake with thick-walled cells, soggy crumb, and extremely coarse appearance. The volume is small and the layer is flat-topped or fallen at the center. If chlorine is added in progressively increasing amounts the volume of the cake increases rapidly, the contour takes on the characteristics of a good cake, the crumb ceases to be soggy, the structure becomes much better, and the typical responses of the layer to liquid level in the batter appear. If excessive amounts of chlorine are added, the effects are less obvious, but volume of the cake decreases,

---

[1] Manuscript received March 16, 1964. Contribution from the Soft Wheat Quality Laboratory, Ohio Agricultural Experiment Station, Wooster, Ohio. A report of the NCM-28 research project of the North-Central States Soft Wheat Technical Committee.

[2] Research Staff, Department of Agronomy, Ohio Agricultural Experiment Station, Wooster, Ohio. J. T. Wilson presently at Dept. of Biochemistry, Purdue University, W. Lafayette, Indiana.

the crumb becomes dry, and the texture too fine. Thus there appears to be an optimum level for chlorine application to a given flour. Kissell (2) has reported changes in volume of layer cakes with various levels of chlorine dosage, and at a number of liquid levels.

In carrying out baking tests with the simplified formula (2) to determine the optimum level of chlorine and liquid to be used in variety evaluation and cake chemistry studies, a number of observations have been made.

The most striking aspect of treatment with chlorine was the effect on top contour of the cake. When unbleached or lightly bleached flours are baked into cakes they have flat or fallen tops, regardless of the liquid level in the batter. With increasing dosage, sunken, rounded or peaked contours appeared, depending on whether the liquid level was low, optimal, or high. Also with increasing dosage of chlorine, the optimum liquid level appeared to shift, and the contour became increasingly sensitive to the liquid level.

The present study was planned to measure and interpret the joint effect of improver and liquid level on cake flour response. This is illustrated by results obtained with a first-grade commercial cake flour.

Materials and Methods

Flour. A 48%-extraction, commercially milled soft red winter wheat flour was used. Protein content was 7.6% and ash 0.30% (14% m.b.). The flour had received no previous chlorine treatment.

Chlorine Treatment. Four aliquots of the flour were treated with appropriate quantities of chlorine gas in a Wallace & Tiernan laboratory bleaching apparatus.

Baking Method. The simplified white layer cake developed by Kissell (2) was used. This was the same formula employed in the liquid-level study (1). A batter for the 103% liquid-level cakes made two 6-in. layers, each scaled to 240 g. In order that all layers would contain the same amount of flour, sugar, shortening, and leavening, scaling weights were adjusted when higher or lower liquid levels were used.

Measurements. As in the previous study, three numerical measures were used to describe the layer cakes; volume, crumb structure score, and top contour score. Volume was measured by seed displacement. Structure was rated on the system developed by Kissell (2), wherein total score was the sum of three individual scores for cell size, cell-wall thickness, and uniformity in distribution of cell size. Each individual score was rated from zero, extremely poor, to 5, excellent. Perfect total score was therefore 15. Top contour was given a numerical value on the scale described by Wilson and Donelson (1), with poor contour rated 1 and the ideal rounded contour, 7. In the present study the score zero was added to include the peculiar top contour of cakes obtained from flours which had little or no chlorine treatment. Cakes from unimproved flours were radically different; during baking they rose to large volumes, but collapsed in the oven. In contrast with improved flours, a sunken top contour was obtained from low-liquid batters, and the contour was not due to collapse but to failure of the batter at the center of the pan to rise as much as at the periphery.

An acceptable layer cake must possess a rounded top contour. In the normal course of baking tests, if such a contour was not obtained, conditions were altered to attain it, usually by adjusting liquid level. Quality was then evaluated by the volume and structure of the product. Admittedly, this neglects such quality factors as flavor, color, tenderness, and others, but these are not clearly defined, and are subject to modification by changes in flour treatment and formula. Because there are serious problems involved in establishing criteria for evaluating many aspects of flour quality, the present study is restricted to measures of volume, structure, and contour.

Response Surface Design. Baking experiments were set up with selected values for chlorine dosage of the flour and liquid level of the batter. The resulting cake volume, structure score, and contour score were considered as functions of these two variables. When an adequate number of experimental values were used, each function generated a series of points above the plane of the coordinate axes for chlorine and liquid. These points were considered as lying in a surface which represented the response of the flour to the joint treatment levels. A study of these surfaces permitted assessment of the effect on cake quality of various treatment levels and combinations.

The equations utilized in this study were set up in the following manner:

It was assumed that the two measures of quality — volume, Y_v, and structure score, Y_s — as well as the contour, Y_c, were each functions of the two independent variables, flour chlorine dosage, x_1, and liquid level of the batter, x_2. Hence, where the subscript i refers to the specific response,

$$Y_i = \phi\ (x_1, x_2) \tag{1}$$

and $\phi\ (x_1, x_2)$ is the functional relationship involved.

In earlier work (1) the authors had found that for the single variable, liquid level, a quadratic equation provided an adequate fit. Kissell (2) likewise had found that for chlorine dosage effect on cake volume the quadratic provided reasonably good fit. Thus it appeared likely that a second-order equation in the two independent variables would fit the experimental data. The function of equation 1 was assumed to exist, and was expanded as a Taylor series, combining all terms above the second degree. Whence, where

$$Y_i = B_{i0} + B_{i1}x_1 + B_{i2}x_2 + B_{i11}x_1^2 + B_{i22}x_2^2 + B_{i12}x_1x_2 + \xi_i \qquad (2)$$

the B_i's are the values of the coefficients to be estimated, and ξ_i is the remainder, and is also the deviation of the polynomial from the true relation which defines the surface.

The next consideration was selection of values to be assigned the independent variables. A central composite rotatable design in two independent variables with five levels of each variable, combined into nine experimental points, was chosen. The design and mathematics of the analysis are described by Cochran and Cox (3).

Ideally, one should use ranges of the variables broad enough to give an adequate picture of the surface. Both foreknowledge and some practice are required to locate and scale the design axes satisfactorily relative to the response surface. It frequently happens that not enough information is available to permit effective selection of points, but Box (4) has described methods for sequential trials to be used in exploratory work.

Preliminary baking tests were made to find values of the independent variables which produced rounded cake contour, with large volume

TABLE I

CHLORINE AND LIQUID-LEVEL TREATMENT COMBINATIONS, WITH CORRESPONDING CAKE DATA

TREATMENT				FLOUR pH	CAKE DATA[b]		
ACTUAL LEVEL		CODED LEVEL[a]					
Chlorine	Liquid Level	X_1 Chlorine	X_2 Liquid Level		Volume	Structure	Contour
cc.Cl$_2$/g. flour	*% flour wt.*				*cc.*	*units*	*units*
0.20	97.0	−1	−1	5.03	545	6.2	0.0
.40	97.0	+1	−1	4.66	578	9.7	3.7
.20	109.0	−1	+1	5.03	556	6.2	0.0
.40	109.0	+1	+1	4.66	599	10.7	9.7
.16	103.0	−1.414	0	5.15	515	5.2	0.0
.44	103.0	+1.414	0	4.56	588	11.8	7.3
.30	94.5	0	−1.414	4.80	562	8.0	3.0
.30	111.5	0	+1.414	4.80	563	11.3	8.7
0.30	103.0	0	0	4.80	583	11.1	7.3

[a] Code: $X_1 = \dfrac{\text{ml. Cl}_2\text{/g.} - 0.3}{0.1}$ $X_2 = \dfrac{\text{liquid level} - 103}{6}$

[b] Average of three bakes except last row, which is average of fifteen bakes.

and good crumb structure. This was attained with a chlorine treatment of 0.3 ml. per g. of flour (resulting pH 4.8), and a liquid level of 103%. These values were taken as the center point of the experimental design. Additional levels were selected to provide underbleached and overbleached flours, and batters with liquid levels below and above the optimum. The treatment combinations are shown in Table I. All values were coded to facilitate solving the matrices for computing the best-fitting coefficients of the response equation.

Figure 1 shows cross-sections of the layer cakes baked from the different treatments, arranged to correspond to their positions relative to the coordinate axes of the design. The chlorine dosage axis increased from left to right, and the liquid level axis increased from bottom to top of the photograph. Thus layer 7, for example, was the treatment (– 1, –1), or 0.2 ml. per g. chlorine and 97% liquid.

Estimates of the coefficients were obtained by the standard matrix method outlined by Cochran and Cox (3). Goodness of fit of the equations was tested by analysis of variance. The three polynomials were then converted to canonical form, by the method outlined by Davies

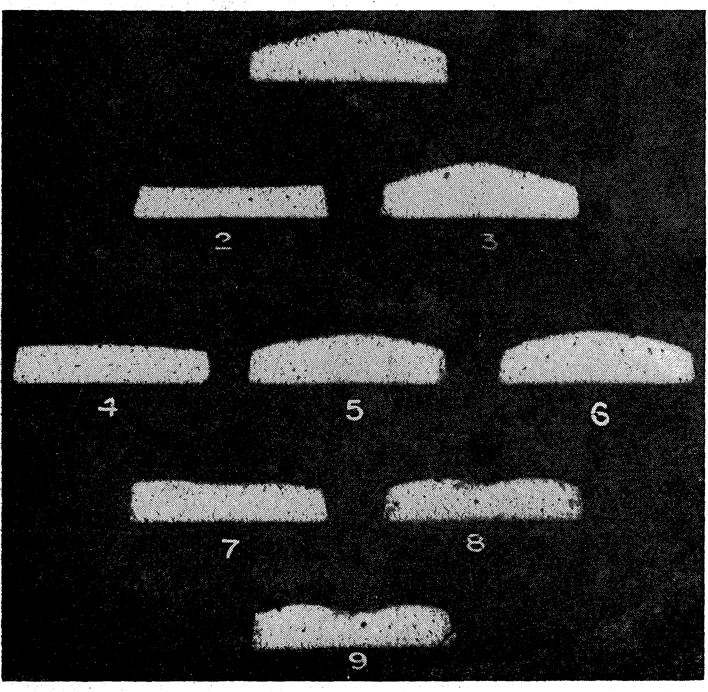

Fig. 1. Layer cake cross-sections showing cakes baked using the nine different treatment combinations. Chlorine dosage level increases from left to right, and liquid level increases from bottom to top of the photograph.

(5), to eliminate first-order and cross-product terms. In effect, this operation was a translation and rotation of the coordinate axes of the system.

The principal axes, the directions of most rapid response of each variable, and the center point of the surface did not coincide with the design coordinate axes and the design center point. In the analysis, this led to significant first-order terms in the independent variables. As pointed out by Box (4), to reveal the degree of dependence of cross-product terms, the fitted equation should be transformed to canonical form, and the directions of the principal axes of the surface relative to the design axes should be determined. The angle of rotation required to map the experimental axes into the principal axes is the true measure of interaction.

Results

Table I gives the levels of chlorine and of liquid application, and the resulting flour pH used for each design point. It also shows average values for cake volume, structure, and contour scores for the three replications of the experiment.

The results for the analyses of variance for each set of cake-baking data are given in Table II. Each polynomial accounted for over 90% of the total variation. The very high significance of first-order terms indicates that the design centers were considerably displaced from the centers of the surfaces, and that in the regions covered, the surfaces rose rapidly. Significance of the second-order term indicated that the surfaces not only rose, but displayed marked curvature.

TABLE II

ANALYSIS OF VARIANCE FOR CAKE-BAKING DATA FOR JOINT CHLORINE AND LIQUID-LEVEL EXPERIMENT

SOURCE	D.F.	MEAN SQUARES		
		Volume	Structure	Contour
Total	12			
Due to regression				
First order				
Cl_2	1	4025.23**	37.96**	70.23**
HOH	1	134.71**	4.08*	24.05**
Second order	3	450.12**	6.99**	15.68**
Lack of fit	3	172.62**	1.22	2.21**
Error	4	3.01	0.21	0.055
s	. .	1.74	0.46	0.24
$R^2 \times 100$	. .	91.2%	93.3%	95.7%

Calculated estimates of the coefficients of the response equations and their standard errors are given in Table III. The relatively small

TABLE III

VALUES OF COEFFICIENTS AND THEIR STANDARD ERRORS (±) FOR CAKE-BAKING DATA

(Fitted equations: $Y_i = b_{i0} + b_{i1}X_1 + b_{i2}X_2 + b_{i11}X_1^2 + b_{i22}X_2^2 + b_{i21}X_1X_2$)

COEFFICIENT	VOLUME	STRUCTURE	CONTOUR
b_{i0}	583.0467	11.1333	7.3333
b_{i1}	22.4311**	2.1783	2.9628**
	0.62	0.16	0.083
b_{i2}	4.1035	0.7142	1.7156*
	0.62	0.16	0.083
b_{i11}	−12.7025*	−1.5458*	−2.1875**
	0.66	0.18	0.090
b_{i22}	−6.9775*	−0.9625	−1.1042*
	0.66	0.18	0.090
b_{i12}	2.6250	0.2500	1.5000*
	0.87	0.23	0.120

values of most of the standard errors indicated that the polynomial for each parameter approximated its surface closely enough to serve as a usable description of the characteristics and orientation of the surface.

Table IV gives the results obtained from the canonical transformations of the fitted equations. The second-order coefficients for volume, contour, and structure score were negative and unequal, and the coefficients for chlorine dosage had a much smaller value than those for liquid level. Results indicated each surface was a mound possessing elliptical contours. The constant terms are the maximum values in each surface. The coordinates (X_{1m}, X_{2m}) show the location of the maximum in the surface in relation to the design axes. The angle of rotation of the principal axes indicated how each surface was oriented with respect to the design axes.

TABLE IV

VALUES FOR CANONICAL EQUATION COEFFICIENTS AND LOCATION OF MAXIMUM RESPONSE ON ORIGINAL COORDINATES

(Canonical equations: $Y_i = Y_{is} + B_{i11}\Theta_1^2 + B_{i22}\Theta_2^2$)

RESPONSE Y_i	CANONICAL EQUATION			ORIGINAL EQUATION		
	Max. Value for Response Y_{is}	Coefficients		Values of Coded Variables at Max. Response		Angle of Rotation [a]
		B_{i11}	B_{i22}	X_{1m}	X_{2m}	
Volume	594.456	−12.989	−6.691	0.931	0.469	−12° 18′
Structure	12.109	−1.572	−0.937	0.742	0.467	−11° 37′
Contour	10.608	−2.571	−0.721	1.237	1.634	−27° 5′

[a] Negative rotation signifies rotation of axes in clockwise direction.

The surfaces for volume, internal score, and contour score were graphed as contour maps, and these are presented in Figs. 2, 3, and 4. In each case the experimental values are indicated at the appropriate

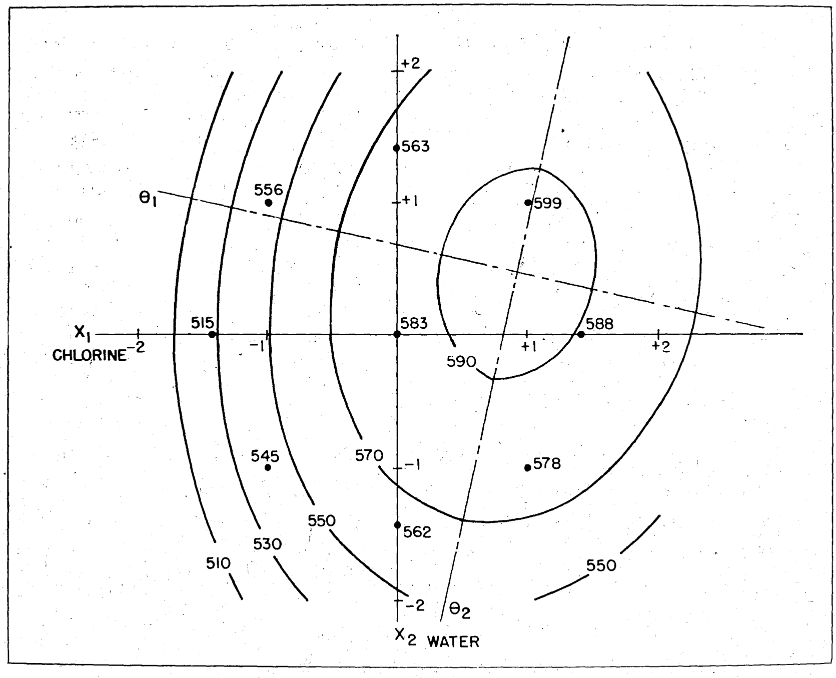

Fig. 2. Contour diagram for cake volume showing location of principal axes relation to design axes (X_1,X_2). Experimental values are indicated at the coordinates of the design plane.

coordinates of the design plane, and enough contour lines are drawn to indicate the shapes of the surfaces above the plane. The principal axes of each surface, which are the gradients of response to each variable, are shown by dashed lines, Θ_1 for chlorine dosage and Θ_2 for liquid level. The point of intersection of the principal axes is the location of the maximum value. With the scaling used for the axes of the independent variables, the major axis of each hemiellipsoidal surface was in the direction of the liquid level axis.

The volume and structure score surfaces, Figs. 2 and 3, had elliptical contour, with the maxima located close together in the first quadrant of the design and the principal axes of each surface oriented in nearly the same directions. The two surfaces were thus similar in shape, location, and orientation. This might be expected, because crumb structure is intimately related to cake volume.

The rotation of the principal axes relative to the design axes showed that response as liquid level was changed depended to some extent on the chlorine dosage used, and vice versa. Location of the

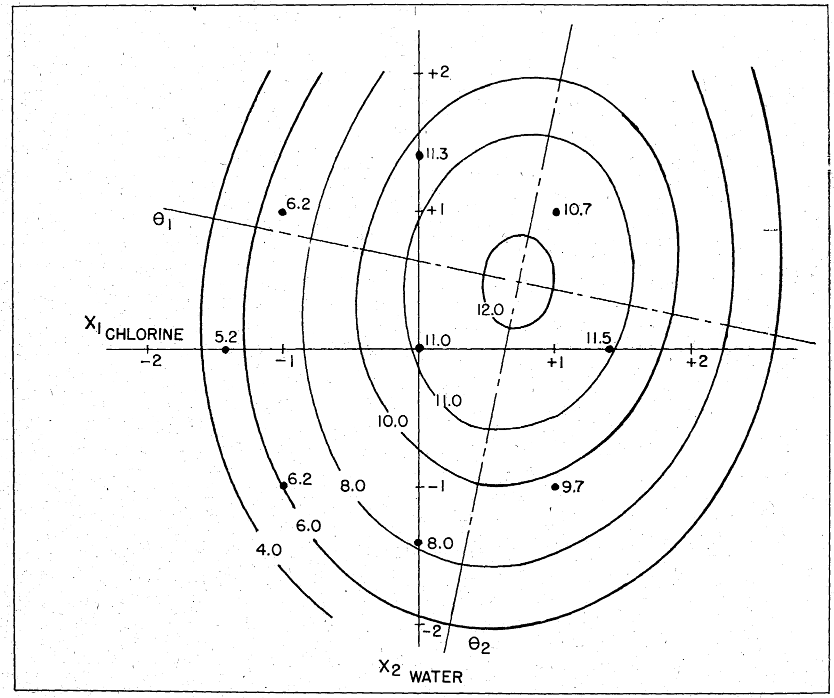

Fig. 3. Contour diagram for cake internal structure showing location of principal axes relation to design axes (X_1,X_2). Experimental values are indicated at the coordinates of the design plane.

surfaces implied that the largest cakes and best crumb structures would have been obtained at higher chlorine dosage than that required to attain pH 4.8; the apparent optimum for this flour was in the neighborhood of pH 4.6, which would have required a treatment of about 0.4 ml. per g. The response to increasing chlorine application at any particular liquid level was rapid improvement of cake volume and crumb quality; but beyond pH 4.8, response was less pronounced as the maxima on the Θ_2 principal axis were approached. The positions of the maxima, however, depended on the liquid level. The amount of chlorine needed to reach maximum response increased with higher liquid levels. Thus the Θ_2 axis was skewed relative to the liquid level axis, and these shifts measured the interaction.

If the over-all response of a flour were determined solely by structure and volume measurements, it would be a simple matter to locate the area of optimum cake quality, and the interaction between liquid level and chlorine dosage could be dismissed as of minor importance.

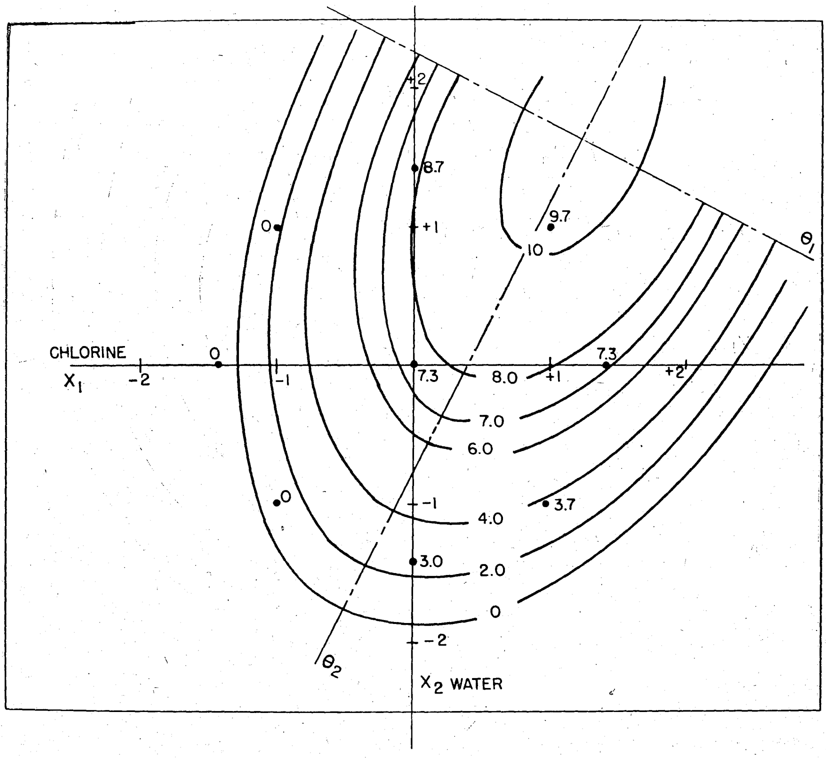

Fig. 4. Contour diagram for cake contour score showing location of principal axes relation to design axes (X_1,X_2). Experimental values are indicated at the coordinates of the design plane.

However, when cake contour is considered, the interrelations become more complex.

Top contour of layer cakes was the constraining factor, as is evident from consideration of Fig. 4. The center point of response was found at very high chlorine and liquid levels, actually outside the range of the design. The surface was, in effect, one of parabolic contours, and responses to chlorine and liquid occurred on a rising ridge. Increasing values of the parameter signified progressive changes in cake top shape from deeply sunken (zero score) through flat and rounded, to greater and greater degrees of peakedness. The maximum value of 10 denotes a very peaked cake, obtained at very high liquid and chlorine levels. Figure 1 shows the trend clearly. At the opposite end of the contour scale, interpretation is not straightforward. For moderate chlorine dosages, low values of contour score clearly denote sunken layers, for example layer No. 9 in Fig. 1. Low chlorine treatments, 0.14 and 0.2 ml. per g., gave cakes with essentially no contour response at all three liquid levels used (layers 2, 4, and 7). But with chlorine dosage of 0.3 ml. per g., varying liquid level resulted in definite contour response (layers 1, 5, and 9). The correspondence of the contours of the various treatments as shown in Fig. 1 with the contour map, Fig. 4, suggested that the response pattern of the contour map was valid.

Only rounded top contour is acceptable. If a score of 6 to 8 is selected as the limit of acceptibility, the range of experimental error for this parameter was closed, and located far enough from the region of hazy definition to be unaffected by it.

The principal axes of the contour surface, Fig. 4, were rotated 27.5 degrees clockwise from the design axes. An angle as large as this suggested a very strong interaction between chlorine dosage and liquid level in their effect on cake contour. The surface was oriented in such a way that its level lines in the second quadrant were nearly parallel to the liquid axis X_2, and the level lines in the third quadrant were roughly parallel to the chlorine axis X_1. Thus for low chlorine dosages top contour changed very little over a broad range of liquid level. This relationship gradually changed with increasing chlorine until, at high levels, the top contour was very sensitive to liquid level. On the other hand, at any liquid level, there was marked response in top contour to chlorine dosage level. However, at high liquid levels, if chlorine was restricted to a moderate amount, the top contour was rounded, and became peaked only when chlorine dosage was raised.

Thus the required rounded contour may be obtained in either of two ways: 1) A moderate chlorine application, in conjunction with moderate to high liquid level. The shape of the cake in this case would be relatively insensitive to liquid level; the flour would display a considerable tolerance to liquid as well as a high capacity for it. 2) A heavy dosage of chlorine should lead to full expression of the contour potential, but to maintain a rounded shape, liquid would have to be restricted to a moderate level. In this case, contour is sensitive to liquid level, which must be kept within a narrow range.

The problem thus became one of selecting chlorine dosage and liquid-level treatments within the range that produced satisfactory rounded cake contour. Figure 5 combines values, in a single map, for the volume and structure which meet the conditions of satisfactory contour. Acceptable values lay in the hatched, crescent-shaped area. Within this area, contour ranged from rounded with flat center (score 6), to rounded but slightly peaked (score 8). The lower limits for internal score and volume, shown in Fig. 5, for acceptable cakes were those used in variety evaluation, where the purpose is to eliminate low-quality wheats.

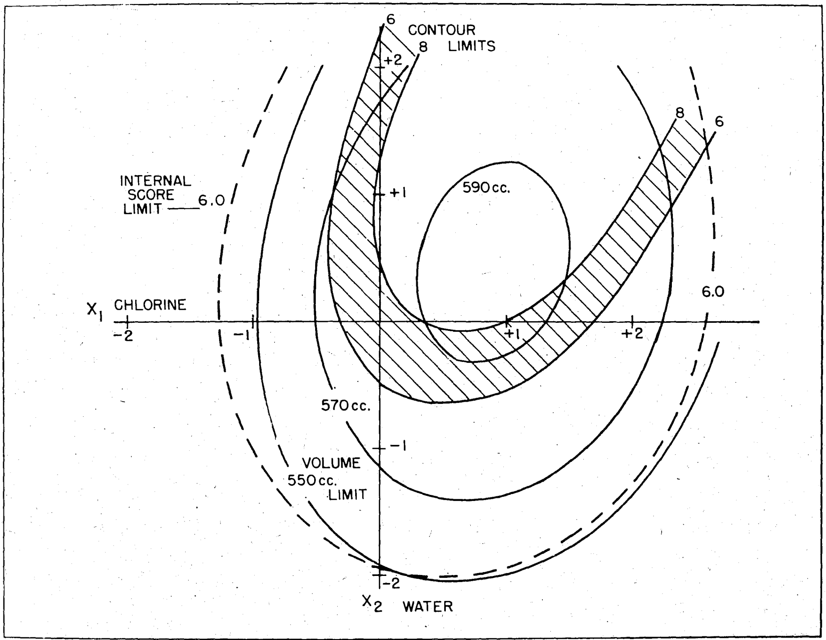

Fig. 5. Contour map showing area of acceptable cake quality. Hatched section indicates chlorine and water level combinations that produce cakes with acceptable cake volume, internal score, and contour.

If Fig. 5 is compared with the more detailed response surfaces mapped in Figs. 2, 3, and 4, several observations may be made: 1) Use of moderate chlorine dosage to obtain high liquid-carrying capacity resulted in reduced volume and suboptimum crumb structure. 2) Largest volume and highest structure score obtainable with acceptable top contour was attained at relatively high chlorine dosage. The penalty in this case was reduced liquid-carrying capacity and extreme sensitivity to liquid level. 3) As chlorine dosage was further increased, liquid capacity of the batter increased, and also tolerance to liquid level became greater.

Sensitivity of flours to liquid level has been shown to be much reduced when a complete layer-cake formula is used instead of the lean formula (2). It is believed that the lean formula gave a truer picture of inherent flour response than a complete formula would have done.

Literature Cited

1. Wilson, J. T., and Donelson, D. H. Studies on the dynamics of cake-baking. I. The role of water in formation of layer cake structure. Cereal Chem. **40**: 466–481 (1963).

2. Kissell, L. T. A lean-formula cake method for varietal evaluation and research. Cereal Chem. **36:** 168–175 (1959).
3. Cochran, W. G., and Cox, Gertrude M. Experimental designs (2nd ed.), chap. 8A. Wiley: New York (1957).
4. Box, G. E. P. The exploration and exploitation of response surfaces: some general considerations and examples. Biometrics **10:** 16–60 (1954).
5. Davies, O. L. The design and analysis of industrial experiments (2nd ed., rev.), chap. XI. Hafner Pub. Co.: New York (1956).