U. S. Department of Commerce — National Bureau of Standards

RESEARCH PAPER RP1522

Part of Journal of Research of the National Bureau of Standards, Volume 30, February 1943

MEASURING THE DEGREE OF CURL OF PAPER

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ABSTRACT

In a method frequently used to determine the tendency of paper to curl, a measurement is made of the amount of curl of a small piece of the paper floating on water. The measurement is customarily made in terms of an arbitrarily chosen angle. The maximum curvature, however, is a more logical measure of curliness. An effort has been made to determine the maximum curvature of freely curling paper from measurements made of the curling of paper in contact with water, and the new apparatus devised for the purpose is described. Measurements were made of the relative curliness of a number of lithographic papers. The correlation of curl with other related properties is discussed. The results of the measurement of curl agree reasonably well with what is known about the behavior in use of the papers studied.

CONTENTS

I. INTRODUCTION

Trouble arising from the curling of sheets of paper during printing and some other converting processes can often be avoided if one knows beforehand what to expect of the behavior of the paper. A simple test now frequently used for predicting relative curling tendency is made with an instrument developed at the National Bureau of Standards, but which originally was intended for quite a different purpose. This instrument, known as the curl sizing tester, was designed to use the rate of curl of paper, when wet on one side, as a measure of the rate of penetration of water into the paper. In the extended use of the instrument the maximum angular displacement of the specimen is used as an indication of curling tendency. This new use of the instrument has been subject to some uncertainty, for reasons that will be discussed later. An appraisal of its value has therefore been attempted, and some suggestions have been made for improving the test for curling tendency.

The curl sizing tester[1] was devised several years ago to measure the "degree of sizing" of paper (resistance to permeation by water and aqueous solutions). The device contains a wax-coated aluminum

[1] Paper Trade J. 79, TS142 (1924).

float in which a rectangular aperture allows water to present a convex meniscus standing slightly above the bottom of the float. The principle of operation can be understood from figure 1, which represents a vertical section through the aperture. When a piece of paper is laid over this aperture it becomes wet on one side and curls up. The wet part over the aperture is curved, whereas the part extending beyond the aperture remains dry to serve as a pointer against the stippled background.[2] At the opposite side of the aperture a shorter, dry end of the specimen is held by a stop on the holder, *H*, and makes a fixed angle, *F*, with the plane of the float. In using the instrument as first intended one notes the time which elapses from the contact of the specimen with the water until the pointer attains its maximum sweep and reverses the direction of its movement. This time in-

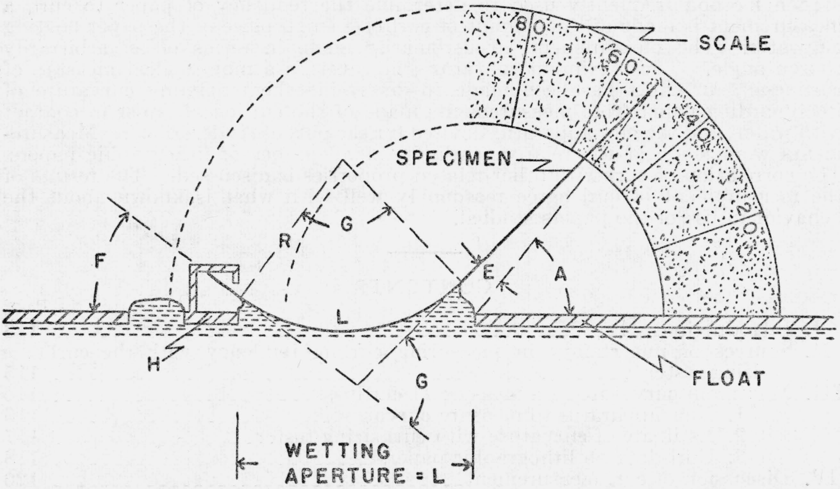

FIGURE 1.—*Sketch, vertical section, illustrating principle of curl sizing tester, and indicating how the apparatus has been adapted to measuring degree of curl.*

terval, interpreted as that required for the water to go halfway through the sheet, is taken as a measure of the relative resistance of papers to the passage of water through them. The wetting aperture is adjustable by means of the sliding holder, *H*, with which the length of the arc, *L*, in figure 1 can be increased or decreased, as required by the nature of the paper, so that the direction of movement of the pointer will be reversed at a convenient location for observation near the middle of the background. A very curly paper requires a narrow opening to prevent it from curling back upon itself, whereas a paper with little curl requires a wide opening to produce a substantial travel of the pointer.

At first there was no thought of any other use of the curl sizing tester, but in time technicians began to note the *amount* of travel of the pointer as a rough measure of the curliness of the paper. They requested the manufacturer of the instrument to add a scale in degrees to facilitate such a reading. A new use of the instrument

[2] To avoid confusion of the lines in figure 1, the left half of the background is not drawn in. There was no scale on the background of the original instrument.

thus arose, wherein the value of angle A, figure 1, at the instant the pointer reverses its direction of movement, is used as a measure of the relative curliness of papers.

II. SOURCES OF UNCERTAINTY IN MEASURING CURLING TENDENCY WITH THE CURL SIZING TESTER

There are some reasons for doubting the value of the scale reading alone (angle A, fig. 1) as a measure of curling tendency. This angle is not the one which the paper pointer (tangent to the arc) makes with the plane of the float (the plane of origin of the curling paper), because the stippled background of the curl sizing tester is symmetrical with respect to the fixed edge of the aperture, and the added scale radiates from this fixed edge. Therefore, the paper pointer does not lie on a radial line, and angle E must be subtracted from A to give the angular displacement of the pointer. Angle E varies with the position of the pointer and depends also on its length, which, for a specimen of fixed length, changes when the aperture is changed.

The scale angle, A, is only a part of the angle through which the specimen curls. The curling takes place in the part of the specimen that is wet, defined by the length of arc, L. The total angular displacement is $G=F+A-E$.

These factors are relatively unimportant in determining the time required to attain the maximum curl, for which the instrument was designed, but it seems necessary to consider them when a measurement of the amount of curl is the objective. Furthermore, the curl range is so great that it is not possible to obtain definite scale readings for all kinds of papers without changing the aperture setting. Unless the aperture setting is held constant, the scale angle alone is certainly not an acceptable measure of the relative degree of curl of different papers.

There are some other sources of uncertainty that have a tendency to make angle A (fig. 1) too small. The curling is retarded by the cohesion of the water and the wet paper. Both the weight of the water lifted by the curling paper and the surface tension of the increasing liquid surface contribute toward this restraint to curling. The weight of the overhanging paper that serves as a pointer contributes further toward making angle A smaller than it would be if the curling were unrestrained. The more pliable papers are more susceptible to these sources of error than the stiffer ones. Papers which curl slowly through a large angle may become partially dried out above the water line, a circumstance which contributes still further toward making the scale angle too small. Some of these limitations were discussed in a previous publication.[3]

The use of the flotation principle in determining the degree of curl of paper seems, nevertheless, not unreasonable. Since curling results from differential expansion, wetting one side intensifies the effect. The usual manner of making the test does, however, engender some doubt. It was thought possible to improve the test by modifying the procedure or by developing apparatus better adapted to the purpose, in order to minimize the various sources of uncertainty.

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[3] Paper Ind. & Paper World **22**, 246 (June 1940).

III. MAXIMUM CURVATURE AS A MEASURE OF CURLINESS

The curvature (reciprocal of radius of curvature), which takes into account the length of the wet portion of the paper, as well as the whole of the angle through which it curls, is a more comprehensive measure of the curl than is the scale angle. Therefore, if the maximum curvature of freely curling paper, unrestrained by the inhibiting influences that have been mentioned, could be determined, such a measure of relative curliness should be reasonably free of the uncertainties that characterize the present method. If proper allowance could be made for the restraining influences in the present method, one might make a fairly good estimate of the maximum curvature of freely curling paper from data obtained with the curl sizing tester. Both of these possibilities have been investigated.

1. NEW APPARATUS TO MEASURE CURVATURE

In view of the foregoing discussion, there appear to be two general ways in which the apparatus and procedure might be improved. The restraints to curling might be minimized so that moisture effects alone would be responsible for the curling. The measurement in terms of curvature could be facilitated. Several forms of apparatus were designed to achieve one or both of these ends. One of them is described below.

The restraints to curling can be greatly reduced by eliminating the paper pointer and by making the wetted length small so that the paper never lifts far from the general level of the water surface. The problem then is one of devising means sensitive enough to measure the curl with sufficient accuracy. Figure 2 is a sketch showing the principle of the method and of the apparatus used. The wetted length, L, is of course much exaggerated. One edge of the specimen is clamped at the water level, at K. A pivoted lever, having this clamping line as its axis of rotation, has an index registering on the scale and carries a hairline, Q, that is rotated, while the paper is curling, in such a manner as to keep it coincident with the chord of

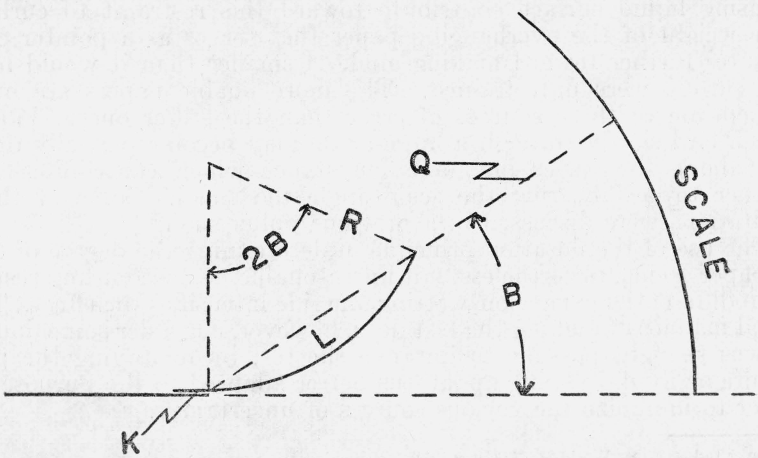

FIGURE 2.—*Sketch illustrating principle of optical apparatus devised to approximate free curling of paper when wet with water on one face.*

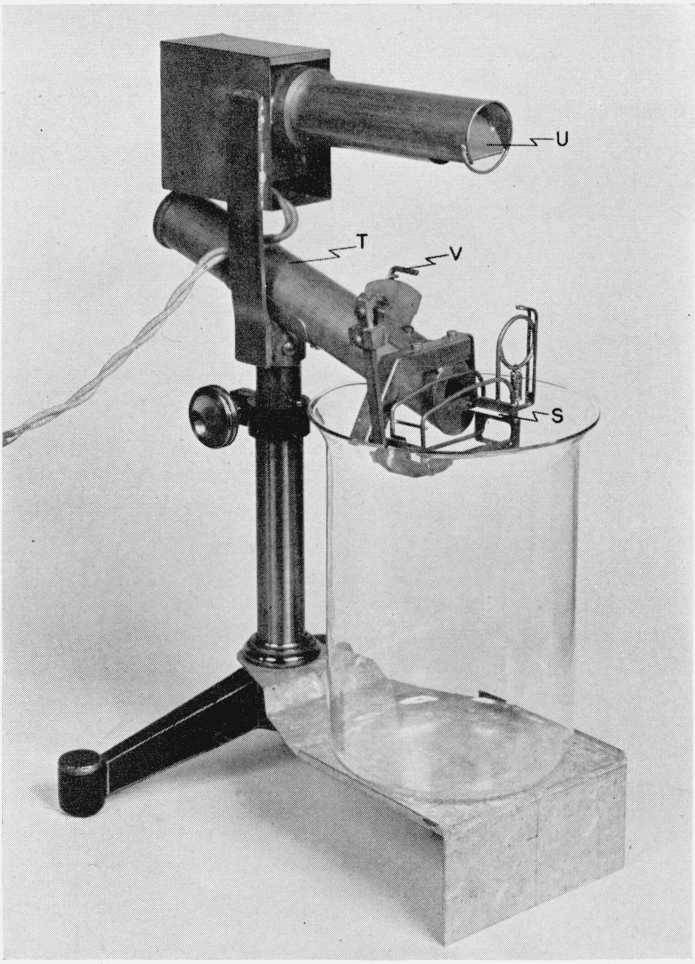

FIGURE 3.—*Optical apparatus for measuring degree of curl.*

arc L. The profile of the specimen is magnified to facilitate this adjustment. When the specimen has attained its maximum curl, the angle B is read on the scale. The curvature is $2B/L$.

Figure 3 shows the apparatus, with which it is possible to measure B when L is only 3 or 4 mm in length. The narrow specimen, S, is seen through a low-power microscope, T. Light from the lamp-house above passes through a slit and is reflected from a mirror in the end of the tube, U, producing a sharp slit image across the specimen perpendicular to the axis of curl. A hairline (Q, fig. 2) in the microscope is rotated by the lever, V, (fig. 3) about the pivotal point, which appears to coincide with the point of intersection of an edge of the light slit with the clamping line (at K, fig. 2). As the paper curls, the image of the slit delineates the vertical profile of the specimen, and appears in the microscope as an upcurling arc. The hairline is rotated (in a plane parallel to that of the slit-image profile) by means of the lever, V, so that it appears as the chord of this arc. Hence, the position of the lever on the scale indicates angle B of figure 2.

This optical apparatus, with the chief sources of uncertainty removed or considerably minimized, seems to give very good results, although they are not entirely independent of the arc length. The smaller lengths yield somewhat greater values of curvature. Of the several new instruments devised, the optical apparatus is the most complicated, and is perhaps the least convenient to use. Its continued use is rather fatiguing to the operator. Nevertheless, the tests made with various devices developed for applying the flotation principle to measuring degree of curl indicate that the optical apparatus gives the most reliable and reasonable results. It can therefore serve as a means of evaluating the curl sizing tester when used to determine the relative curling tendency of papers.

2. ESTIMATE OF CURVATURE WITH CURL SIZING TESTER

If tests made with the curl sizing tester in terms of the scale angle, A (fig. 1), have been found useful in predicting curling tendency, an evaluation of curvature from similar data should be more valuable. If found to agree, or if they could be made to agree, with corresponding determinations made with the optical apparatus, such data should lend substantial support to the use of the curl sizing tester for determining the curling tendency of paper.

Although angle A is not sufficient to determine the curvature of the curled specimen, an approximate value of curvature can be obtained if the wetted length, L, is also known. Arc L is assumed to be the arc of a circle, since the expansion of the paper is substantially uniform. From the geometry of figure 1 it is apparent that the actual curvature of the specimen is given by the expression $G/L=(F+A-E)/L$. Since angle A is read in degrees on the scale, it is convenient to express the curvature as degrees per centimeter of arc. Angle F is a fixed angle of about 30 degrees. Angle E is variable, but never large. An average value of 5 degrees could be assigned to it without introducing much error. Hence, the actual curvature, G/L, in degrees per unit length of arc, is approximately $(A°+25°)/L$.

The curvature of a freely curling specimen would be greater, however. Since angle G is too small, because of the influences tending to restrain the curling, an increment, D, must be added. This increment may be different for different papers. The curvature of a freely curling specimen therefore becomes $(G+D)/L$. An independent method of determining the curvature of freely curling paper, such as is afforded by the optical apparatus, would allow one to evaluate D for various papers, and to formulate a provisional expression that could be used in calculating curvature from data obtained with the curl sizing tester, provided that D does not vary too much. A modified procedure for the use of the curl sizing tester will materially facilitate the formulation. This special procedure is designed to make the wetted length small enough to reduce to some extent the restraints to curling on water, and yet yield a scale reading large enough to be read with sufficient accuracy. In this special procedure the aperture length[4] is made 1.2 cm, except that when the scale reading falls below 25 degrees the aperture length, L, is increased to a value such that angle A (fig. 1) at maximum curl lies between 25 and 35 degrees. This procedure has the effect also of reducing the range over which G (and presumably also that of D) will vary.

3. CURL DATA ON LITHOGRAPHIC PAPERS

Measurements of curl were made on a number of papers by means of the optical apparatus and the curl sizing tester, the special procedure being used. These measurements were made on 54 lithographic paperes which had been used in a research project[5] to improve the performance of lithographic papers in the printing process. These papers were made in the Bureau's experimental paper mill with variations in the beating treatment, which produced papers differing greatly in degree of curl.

The value of the increment, D, can be evaluated for each paper by setting the best available value of curvature, K_0, obtained with the optical apparatus, equal to $(G+D)/L$, the curvature formulated for the curl sizing tester, and solving for D. This was done for the 54 lithographic papers. An average value of 40 was thus found for D. A trial formula for the curvature, K_s, of freely curling paper, determined by means of the curl sizing tester, is therefore obtained by substituting 40 for D. That is, $K_s=(G+40)/L$, in which G is approximately $A°+25°$. Values of K_s were obtained for all of the 54 lithographic papers, and were compared with the corresponding values of K_0. All K_s values were within 10 percent of the K_0 values, except for a very few that differed by 15 to 20 percent. The average difference was 6 percent. Table 1 is a condensation of typical data on approximately one-fourth of the papers, covering the range of curliness shown by these papers. In addition to the two sets of values of curvature, K_s and K_0, the table also shows under A_2 the values obtained for the scale angle when a constant aperture length of a little more than 2 cm was used. These A_2 values represent the customary measure of relative curling tendency obtained with the curl sizing tester. The values for all three sets of measurements are plotted in figure 4. Data for some other pertinent properties[6] are also shown.

[4] The shorter, adjustable dimension of the aperture is designated in this paper as the length of the aperture, because it corresponds in direction to the length of the specimen, and is the length of the arc of the curved specimen in an apparatus such as that illustrated by figure 1.

[5] J. Research NBS 28, 241 (1942) RP1455.

[6] The values for expansivity, sheet shrinkage, and density were made available by C. G. Weber, of the Bureau staff, whose many helpful suggestions during the investigation and in the preparation of the report the authors gratefully acknowledge. The values for curl time represent the data which the curl sizing tester was originally designed to obtain.

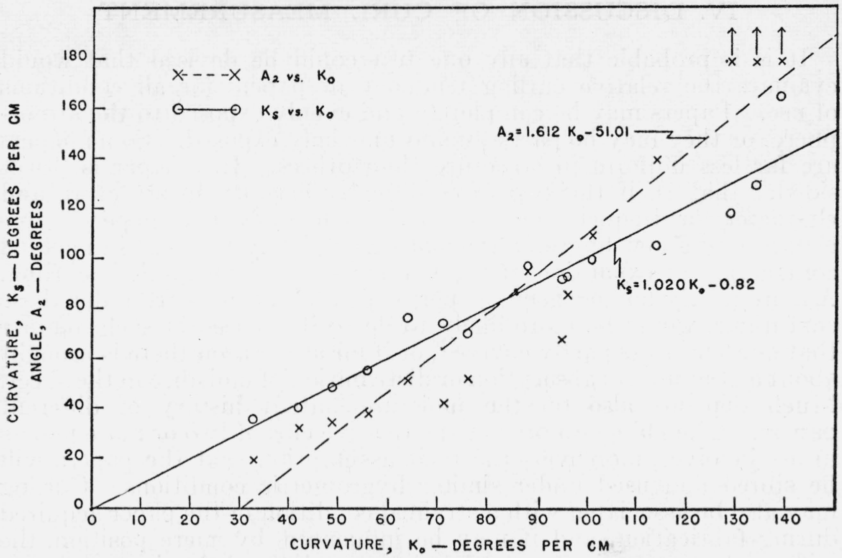

FIGURE 4.—*Degree of curl determined with the curl sizing tester in comparison with that determined with the optical apparatus.*

For meaning of symbols, see table 1, note 1. The equations of the best fitting straight lines were determined by the method of least squares.

TABLE 1.—*Curling and expansion data for a number of typical papers*

Paper	Degree of curl [1] K_s	Degree of curl [1] K_0	Degree of curl [1] A_2	Expansivity [2] cross direction	Sheet shrinkage, cross direction	Density	Air permeability [3]	Curl time
	deg/cm	*deg/cm*	*deg*	*Percent*	*Percent*	*g/cm³*	*csm*	*sec*
1	35	33	19	0.13	0.9	0.60	4,010	23
2	40	42	32	.14	1.3	.63	2,260	20
3	48	49	35	.15	1.6	.70	1,440	15
4	55	56	38	.16	1.6	.71	935	14
5	70	76	52	.17	1.9	.76	1,240	13
6	74	71	42	.22	2.2	.71	1,000	11
7	76	64	51	.18	1.9	.71	845	16
8	92	95	68	.18	2.2	.87	76	5
9	93	96	86	.21	3.4	.85	119	17
10	97	88	96	.26	3.1	.79	232	30
11	100	101	110	.24	3.8	.82	67	23
12	106	114	140	.29	3.4	.81	134	17
13	119	129	180+	.31	4.4	.80	39	28
14	130	134	180+	.31	3.8	.87	99	17
15	166	139	180+	.32	5.6	.85	25	34
CORRELATION [4]								
r		0.97	0.9	0.91	0.95	0.85	−0.77	0.45
k		.90	.9	.92	.92	.70	−.79	.30

[1] K_s=curvature from data obtained with curl sizing tester and special procedure; K_0=curvature from data obtained with optical curl tester; A_2=scale reading (angle) on curl sizing tester with fixed aperture length of about 2.2 cm.

[2] For a change of 15 percent in relative humidity.

[3] The unit csm = cubic centimeters of air flowing per second through a square meter of paper under unit-pressure difference (1 g/cm²).

[4] The Pearson correlation coefficient, r, is calculated as $\Sigma xy/\sqrt{\Sigma x^2 \Sigma y^2}$, in which x is the difference between the mean value and any value of K_s in the table, and y is the difference between the mean value and any value of the property whose correlation with K_s is being determined.

The Kendall (Biometrika **30**, 81 (1938)) coefficient of rank correlation, k, with K_s is determined by arranging the papers in the order of increasing values of K_s and calculating k for each of the other properties as $1-4\Sigma s/[n(n-1)]$, in which n is the number of items (papers), s is the number of items following a given item which have values *smaller* than the given item, and Σs is the sum of the s values for all of the n items.

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IV. DISCUSSION OF CURL MEASUREMENT

It is improbable that any one test could be devised that would evaluate the relative curling tendency of papers for all conditions of use. Papers may be completely and evenly exposed to the atmosphere, or they may be partially and unevenly exposed. Some papers are far less uniform in structure than others. If a paper is "two-sided," that is, if the two faces differ sufficiently in structure and character (a frequent occurrence in machine-made papers), free exposure to a new hygrometric condition is likely to result in unequal contraction or expansion of the two surfaces. The result is curling. A more nearly homogeneous paper, which might not curl under these conditions, would be more likely to do so if exposed in such manner that one surface is partly covered, or if for any reason there is brought about a nonuniform absorption or distribution of moisture in the sheet. Much depends also on the moisture-content history of different papers. The ability to predict the relative curl of two or more papers in use involves, moreover, the tacit assumption that the papers will be stored and used under similar hygrometric conditions. Curling may also be associated with a strained condition in the paper acquired during fabrication, and it may be influenced by mere position, the stiffness having an important bearing on relative behavior.

Considering the complexity of factors entering into the curling of paper, the data presented indicate that the curl sizing tester affords a measure of curliness that is probably good enough for most practical requirements, particularly if the procedure here recommended is used. If one is interested only in the relative rank of a set of papers, the customary measurement of the angle alone (A_2 of table 1) on the scale of the curl sizing tester, when a given aperture setting is used, may serve the purpose. The scale of values, however, will be distorted. If the group of papers includes extremes, such that the very curly ones go beyond the limit of the scale (as in the case of the last three values under A_2 of table 1), this measure will not be adequate even for ranking. A better balanced and more useful measure can be obtained with little additional effort, however, in terms of the maximum curvature. The data in table 1 and figure 4 indicate that the curvature values obtained with the curl sizing tester, used according to the special procedure, agree well with those obtained with the optical apparatus, which gives the nearest approach to freely curling paper that we have been able to achieve in a flotation test.

The investigation began with the assumption that the curl sizing tester would prove to be so poorly adapted to measuring degree of curl that a better instrument could easily be devised. But, on the basis of the data obtained, the best apparatus we were able to devise to apply the flotation principle is so little superior to the curl sizing tester, when used according to the recommended procedure, that its use to displace the curl sizing tester as a means of measuring degree of curl does not seem to be justified. The curl sizing tester, moreover, is a simpler and more practical instrument, and is already widely available.

Since the curling of paper is the result of differential expansion, and since there is usually some degree of "two-sidedness," either in the paper or in the conditions of exposure, a paper that is susceptible to expansion is more likely to curl than one which suffers little dimensional change with changes in moisture conditions. One is therefore led to expect some correlation of the test with expansivity and with other properties associated with expansivity. Table 1 shows fairly good correlation of the degree of curl with expansivity, shrinkage during fabrication, density, and air permeability. Density and air permeability are related to expansivity, in that a dense, relatively impermeable sheet usually means "hydration" and bonding of contiguous fibers that make the sheet expand or contract as a unit, whereas in a bulky, loosely bonded, permeable sheet the fibers move more with respect to one another when they swell or shrink, and less sheet movement results.

No evidence has been presented so far to show that the tests made are actually useful in predicting the curling tendency of paper under service conditions. Data of this character are hard to obtain, but such comparisons as it has been possible to make between the curvature determined in the flotation test and curling tendency in use, or under simulated service conditions, have been very gratifying.

The papers listed in table 1 were observed under a condition favorable to curling that is frequently encountered in use—sudden exposure to dry air. The papers were first conditioned at 50-percent relative humidity and then transferred to a dry atmosphere (about 12-percent relative humidity). Except for two papers, 11 and 14, the departure from flatness of the horizontally supported sheets correlated very well with the curvature, K_s, determined with the curl sizing tester, the rank correlation, k, for the others being 0.85 to 0.90.

A similar comparison was made of independent measurements on 11 papers submitted by a commercial firm. This firm first ranked the papers according to their observation of the behavior of the papers when transferred from an atmosphere of 35-percent relative humidity to very dry air, giving values for change in curvature. The same papers were tested at the Bureau with the curl sizing tester, values of K_s being obtained for the comparison. The correlation was again satisfactory, the Pearson correlation coefficient being 0.8.

An opportunity was had to observe the curling of six of the papers listed in table 1 (papers 1, 5, 6, 10, 14, and 15) while being printed in five colors by the offset process under identical conditions and with like moisture conditioning. Paper 1, with the lowest degree of curl, measured with the curl sizing tester (table 1), remained flat at all times. Papers 5 and 6 curled slightly during the first printing. Number 10 showed a definite tendency to curl. Numbers 14 and 15 curled so much that they interfered with the operation of the automatic feeders.

WASHINGTON, November 19, 1942.