A STUDY OF COMMERCIAL DIAL MICROMETERS FOR MEASURING THE THICKNESS OF PAPER.

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ABSTRACT.

Disputes between the manufacturers and users with regard to the thickness of paper can usually be traced to a difference in readings of the instruments used to measure the thickness. To determine the magnitude of the difference that may result in the use of the types of dial micrometers commonly employed to measure paper, a number of instruments were calibrated against steel gauges and used to measure the thickness of several grades of paper. The micrometers were studied to ascertain the causes of the different readings on the same paper. The instruments were found to differ in form and area of contact, contact pressure, and in the amount of friction in the mechanism. To determine the effect of contact area and pressure, tests in measuring paper were made on commercial papers using contacts of different area and with varying contact pressures. These tests showed that the paper yielded to a greater extent with increase of pressure when the contact was large than when small. Under the same pressure per square inch, but different contact areas, different readings of thickness were obtained. The mechanisms of the instruments were studied to determine the effect of the various designs on the contact pressure, the variation in contact pressure, and the accuracy and variance of the instruments.

Specifications are given for a standard instrument. From a study of the mechanisms of instruments and the results of this investigation it is felt that two or more types of the mechanisms studied can be used in instruments that will meet the specifications. The paper also contains specifications for a standard procedure to determine the mean thickness of a sample of paper.

CONTENTS.

I. INTRODUCTION.

In the past a number of controversies have arisen over the results of the thickness test for paper. Often the manufacturer or jobber when filling an order for paper that required a certain thickness would claim that his paper met this requirement when it was tested at the mill or jobbing house. On the other hand, the consumer would claim that his micrometer showed that this paper did not meet the requirement. Upon investigation it was usually found that the maker and consumer were using micrometers of different makes, and since there was no standard micrometer each of the claims was reasonable and there seemed to be no means of settling the controversy. On account of these facts, the Bureau of Standards decided to carry on an investigation of the subject and determine, if possible, why different commercial micrometers give different results.

The work was carried on as a joint investigation by the paper section and the gauge section of the bureau.

1. STATEMENT OF PROBLEM.

In order to carry out this investigation it was decided to obtain a number of dial micrometers for measuring paper and to submit them to the following tests:

1. A calibration of the instruments.
2. A measurement of the area of the anvils and a determination of the parallelism of the contact surfaces.
3. A measurement of the static contact pressure for different readings of the instruments.
4. A performance test on commercial papers.
5. A measurement of the compressibility of paper; that is, a determination of the effect of different contact pressures and anvil areas on measurements of the thickness.

In addition, it was decided that a careful study should be made of the mechanism of the instruments to determine how the design and workmanship affect the performance and accuracy. Upon completion of the tests and study it was thought that reasons could be given for the variation in results obtained on different micrometers when the same paper was tested. It was also thought that recommendations could be made for a standard dial micrometer for the number of readings that are necessary for an accurate mean value for thickness and for the amount of tolerance to be allowed in interpreting this mean value.

II. DESCRIPTION OF INSTRUMENTS.

1. GENERAL.

Instruments used commercially for the measurement of paper are of the long-range type, measuring thicknesses up to 0.100 to 0.250 inch. Readings of the instruments are indicated by means of a pointer moving over a graduated dial. The pointer rotates one or more revolutions over the dial and a completely graduated dial is required.

The mechanism of these instruments is inclosed in a metal case with a glass front. Means are provided for raising the plunger for the insertion of the article to be measured between the foot of the plunger, which projects through the case, and the anvil. In some types the case containing the mechanism can be raised or lowered on a vertical post fastened to the base. In other types the case is permanently fastened to an arm in one piece with the base. The zero adjustment of the instruments of this type is obtained by raising or lowering the foot on the plunger or the anvil with respect to the plunger. Measuring instruments of this type are called dial gauges, dial micrometers, automatic gauges, or automatic micrometers. These instruments indicate readings automatically, but require an operator to raise the plunger and insert the paper. Furthermore, the terms "gauge" and "gauging" should be strictly limited to methods of determining whether or not an article is within two limiting dimensions, called the maximum and minimum dimensions, without determining the actual size. For these reasons "dial micrometer" is the preferred name for these instruments.

2. MECHANISM.

The nine dial micrometers obtained from the manufacturers were numbered 1 to 9 for identification purposes. Figure 1 shows the working parts of instrument No. 8. Figure 2 shows the mechanism in the instruments diagrammatically. In several cases one diagram represents the mechanism of more than one instrument. The figure also shows the mechanism of three other instruments—10 to 12. Instruments 10 and 11 are not regularly used for measuring paper and are not included in the test but might possibly be used for the purpose. Instrument 12 is a new type of instrument received after the completion of the tests.

In all of the instruments with the exceptions of 1 and 2 the plunger has two bearings, one above and one below the point of transfer of motion of plunger to next member in the train. To secure a pointer movement of over one revolution a small gear or pinion is carried on the pointer staff in all cases with the excep-

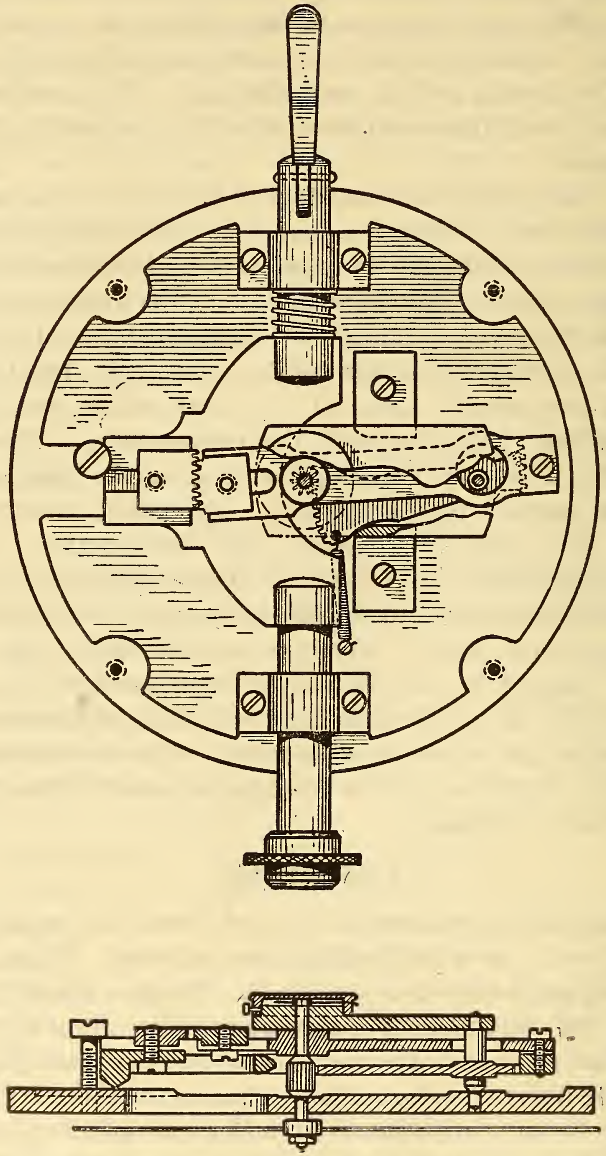

FIG. 1.—*Mechanism of micrometer 8, showing use of gear sectors transferring the movement from plunger to pointer.*

tion of micrometer 10. The instruments have at least two springs, one of which acts directly on the plunger, the other on the staff carrying the pointer or on the gear in mesh with the

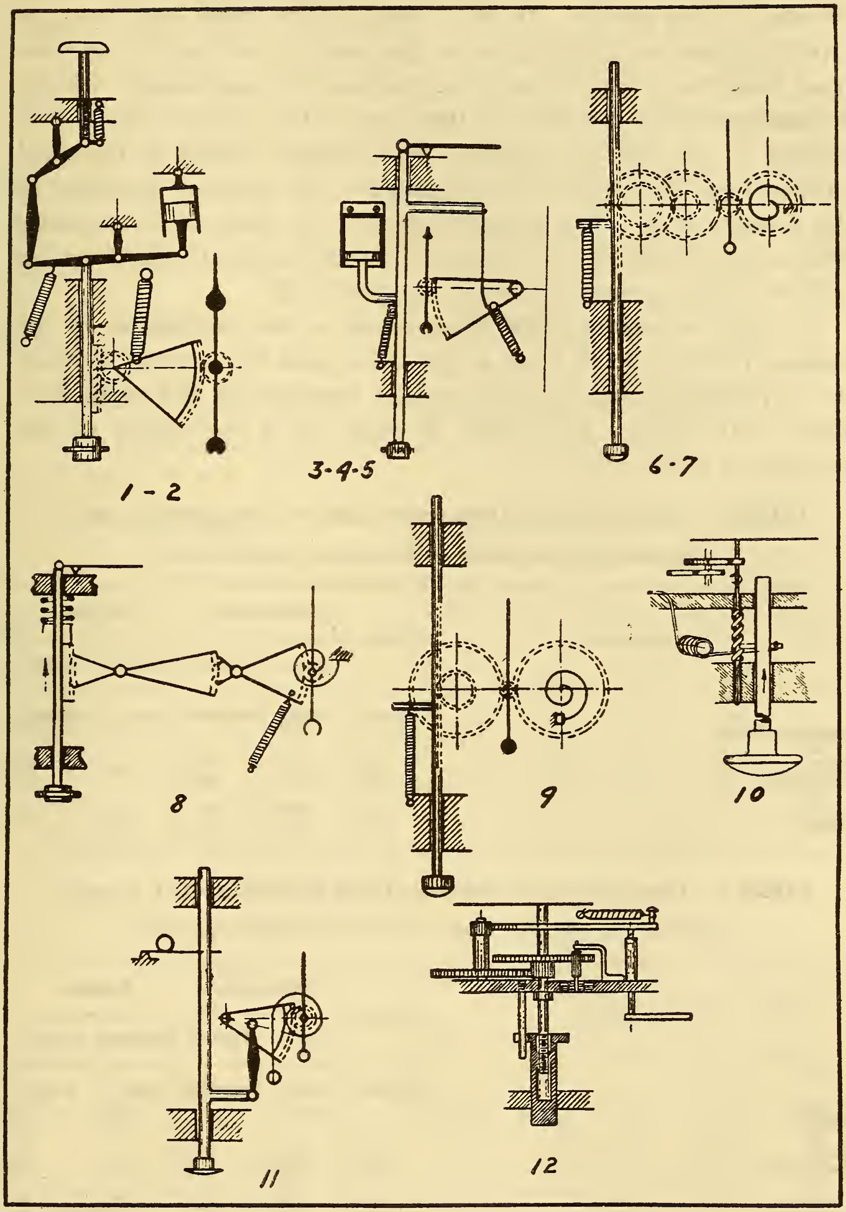

FIG. 2.—*Mechanisms of the instruments shown diagramatically.*

pinion on this staff. The spring acting on the pointer staff is intended to take up the backlash in the gears and overcome the friction in the pivots. If this spring exerts more than enough force to overcome the friction in the pivots it will add to or subtract from the plunger pressure produced by the plunger spring, depending on the direction of the force of the pointer spring with respect to the plunger spring. The plunger spring is intended to overcome the friction in the plunger and produce pressure at the plunger foot. The plunger spring may assist in overcoming friction and backlash in the rest of the mechanism if the direction of force of the pointer spring is opposed to it.

In order to facilitate the comparison of the mechanism of the various instruments a table is given for each instrument showing the approximate radii of the various members of the train with linear and angular movement of each for a movement of the plunger of 0.001 inch.

TABLE 1.—Dimensions and Displacement Data for Instruments 1 and 2.

[Instruments have three springs all adding to make plunger pressure.]

Train members.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inches.	Inch.	Deg. Min.	Inch.	Inches.
Plunger and rack	....	0.001	....	0.50	1.75
to					
Gear	0.318	.001	10.8	.31	.625
Gear sector	2.333	.0073	10.8		
to					
Gear	.350	.0073	1 12	.100	.100
Pointer	2.82	.0591	1 12		

TABLE 2.—Dimensions and Displacement Data for Instruments 3, 4, and 5.

[Instruments have two springs whose forces add to make plunger pressure.]

Train members.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inches.	Inch.	Deg. Min.	Inch.	Inch.
Plunger	....	0.001	....	0.50	0.62
Ribbon				.50	.62
to					
Pulley	0.782	.001	4.4	.31	.25
Gear sector	2.149	.0028	4.4		
to					
Pinion	.109	.0028	1 26.4	.125	.25
Pointer	2.31	.0581	1 26.4	.125	.19

TABLE 3.—Dimensions and Displacement Data for Instruments 6 and 7.

[Instruments have two springs whose forces are opposed.]

Train members.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inch.	Inch.	Deg. Min.	Inch.	Inches.
Plunger	....	0.001	....	0.14	0.05
Rack				.19	1.31
to					
Pinion	0.159	.001	21.6	.028	.03
Gear	.286	.0018	21.6	.028	.03
to					
Pinion	.114	.0018	54	.028	.03
Gear	.286	.0045	54	.028	.03
to					
Pinion	.072	.0045	3 36	.028	....
Pointer	.75	.0471	3 36	.028	....

TABLE 4.—Dimensions and Displacement Data for Instrument 8.

[Instrument has two springs whose forces add to make plunger pressure.]

Train member.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inches.	Inch.	Deg. Min.	Inch.	Inch.
Plunger	....	0.001	....	0.47	0.60
Rack				.47	.60
to					
Gear sector	1.05	.001	0.33	.28	.17
Gear sector	2.16	.0021	.33		
to					
Gear sector	.421	.0021	16.5	.10	.09
Gear sector	1.63	.0080	16.5	.10	.10
to					
Pinion	.100	.0080	4 34.3	.12	.46
Pointer	2.10	.167	4 34.3	.12	.12

TABLE 5.—Dimensions and Displacement Data for Instrument 9.

[Instrument has two springs whose forces are opposed.]

Train member.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inch.	Inch.	Deg. Min.	Inch.	Inch.
Plunger	....	0.001	....	0.20	0.50
Rack				.20	.50
to					
Pinion	0.080	.001	43.2	.03	.05
Gear	.430	.054	43.2	.03	.05
to					
Pinion	.043	.054	7 12	.03	.05
Pointer	.95	.120	7 12	.03	.05

TABLE 6.—Dimensions and Displacement Data for Instrument 10.

[Instrument has two springs whose forces add to make the plunger pressure.]

Train member.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inch.	Inch.	Deg. Min.	Inch.	Inch.
Plunger	}	0.001	....	{ 0.126	0.05
Pin to				.126	.13
Worm	0.031	[1].0022	3 36	.024	.03
Pointer	.60	.0367	3 36	.03	.03

[1] Linear displacement at pitch line of worm along the helix.

TABLE 7.—Dimensions and Displacement Data for Instrument 11.

[Instrument has two springs whose forces add to make the plunger pressure.]

Train member.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inch.	Inch.	Deg. Min.	Inch.	Inch.
Plunger to	}	0.001	....	{ 0.127	0.27
				.127	.42
Link to	} 0.240	.001	(1)	{ .067	.03
				.125	.03
Gear sector to	} .591	.0025	14.3	{ .040	.04
				.037	.04
Pinion	.051	.0025	2 46	.040	.04
Pointer	.75	.037	2 46	.040	.04

[1] Link has a slight variable angular movement.

TABLE 8.—Dimensions and Displacement Data for Instrument 12.

[Instrument has one spring to take up backlash and produce a pressure at plunger foot.]

Train member.	Radius.	Displacement.		Bearings.	
		Linear.	Angular.	Diameter.	Length.
	Inches.	Inch.	Deg. Min.	Inch.	Inch.
Plunger and nut to	....	0.001	....	0.530	0.50
Screw	0.142	[1].0009	3 36	} .246	.22
Pointer	1.90	.1193	3 36		

[1] Linear displacement at pitch line of screw along the helix.

III. TEST OF INSTRUMENTS.

1. A CALIBRATION OF THE INSTRUMENTS.

To determine the accuracy, a calibration of each micrometer against standard steel gauges was made for the full range of the instrument. Since the ranges of all the instruments were not the same, and the maximum thickness for paper (not including wall board) is about 0.125 of an inch, the tabulation of data (Table 9) shows corrections for readings within this range only. Micrometer No. 8 gave readings in millimeters, but these readings and their corrections have been converted into inches in this table for the purpose of comparison with the other micrometers. This is also the case in other tables where the readings of micrometer No. 8 occur.

While the determination of the maximum variance of each instrument from the hysteresis loop, as suggested by Schlink, Scientific Papers of Bureau of Standards No. 328, "Variance of Measuring Instruments," would be of some interest, in the present study we are more interested in the variation in the readings of the instruments on various grades of commercial paper of uniform thickness.

Variation in readings on paper will arise from three causes:

1. Instrumental variations due to friction and backlash in the instruments.

2. Inevitable variation in actual thickness of the paper.

3. Variable reductions in the thickness of the paper due to variable plunger pressure and to variation in the area of the plunger foot in contact with the paper.

TABLE 9.—Results of Calibrations Showing the Corrections for Dial Readings within the Range of 0 and 0.125 of an Inch.

[A plus (+) correction means that the instrument reads too low. A minus (—) correction means that the instrument reads too high.]

Value of standard.	Corrections for dial readings.								
	Micrometer No. 1.	Micrometer No. 2.	Micrometer No. 3.	Micrometer No. 4.	Micrometer No. 5.	Mircometer No. 6.	Micrometer No. 7.	Micrometer No. 8.	Micrometer No. 9.
	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
.0010	+.0003	+.0002	.0000	.0000	—.0001	+.0001	+.0001	.0000	.0000
.0020	+.0002	+.0001	+.0001	+.0001	.0000	.0000	—.0001	.0000	.0000
.0030	+.0001	.0000	.0000	.0000	—.0001	.0000	.0000	—.0001	—.0001
.0040	.0000	—.0003	—.0002	—.0002	—.0002	+.0002	+.0002	—.0001	—.0002
.0050	.0000	—.0003	—.0004	.0000	.0000	+.0002	+.0001	—.0001	.0000
.0060	.0000	—.0002	—.0004	.0000	.0000	+.0002	+.0001	—.0002	.0000
.0070	.0000	.0000	—.0006	—.0003	—.0003	+.0003	+.0002	—.0001	—.0001
.0080	—.0003	—.0002	—.0004	—.0003	—.0003	+.0003	+.0002	.0000	—.0001
.0090	—.0001	—.0001	—.0005	.0000	—.0001	+.0003	+.0002	.0000	.0000
.0100	—.0003	—.0003	—.0004	.0000	—.0003	+.0001	—.0001	—.0001	—.0003
.0200	—.0003	.0000	—.0002	.0000	—.0002	+.0001	—.0002	—.0002	+.0006
.0300	—.0003	—.0002	—.0002	—.0003	.0000	—.0001	—.0003	—.0003	+.0013
.0400	—.0003	—.0004	—.0002	—.0003	.0000	+.0001	—.0007	—.0003	+.0017
.0500	—.0003	—.0003	—.0006	—.0005	+.0003	+.0001	—.0003	—.0004	+.0014
.0600	.0000	—.0002	—.0003	—.0001	+.0003	+.0003	—.0003	—.0004	+.0003
.0700	—.0003	—.0003	—.0006	—.0001	+.0003	+.0002	—.0004	—.0004	—.0012
.0800	—.0003	—.0001	—.0005	—.0007	+.0002	.0000	—.0003	—.0008	+.0017
.0900	—.0003	+.0002	—.0003	—.0005	+.0001	+.0002	—.0003	....	+.0013
.1000	—.0004	+.0002	—.0001	—.0003	+.0003	.0000	—.0003	....	+.0005
.1250	.0000	+.0002	—.0002	—.0007	.0000	+.0002	—.0002	....	+.0021

Variations due to the first cause were determined by noting the variations in the readings on steel gauges when the instruments were operated in the manner in which they should be used to obtain the best results in measuring paper. Micrometers 4 and 8 repeated their readings on steel gauges to 0.0001 inch when care was taken to lower the plunger at a slow and uniform rate. The other micrometers tested repeated their readings to 0.0002 inch under the same conditions.

Variations due to the second cause can not be determined without a perfect instrument, which is not available. Variations from the third cause can not be separated from those due to the second cause. However, the area and form of contacts and the friction and plunger pressure for each instrument can be determined. Then by comparing these quantities with the results of a determination of the compressibility of commercial papers with plunger feet of various areas, the magnitude of the variations due to the third cause can be estimated.

2. AREA OF ANVILS OR CONTACT SURFACES, AND PARALLELISM OF CONTACT SURFACES.

In Table 10 the areas of the anvil or contact surfaces and the parallelism of these surfaces are given.

TABLE 10.—Results of Area and Parallelism Determinations of Contact Surfaces.

Micrometer identification numbers.	Area.	Maximum distance between contact surfaces when in metallic contact.
	Inch.²	Inch.
1	0.319	0.0005
2	.316	.0030
3	.259	.0005
4	.259	.0005
5	.273	.0010
6	.119	.0030
7	.029	.0002
8	.250	.0008
9	.046	.0005

In the case of micrometers numbered 8 and 9, the contacts were slightly convex. In all other cases the contacts were plane to approximately 0.0001 inch, but not parallel. All of these instruments will make contact at a point or over a very much smaller area than nominal area of contact.

3. STATIC CONTACT PRESSURE FOR DIFFERENT READINGS OF THE INSTRUMENTS.

The forces required to move the mechanism of each instrument from rest at various readings toward increased readings were measured and are presented in Figure 3. The forces required to just prevent movement toward decreased readings were measured and are presented in the same curves. It is evident that the difference between the two curves for any reading on an instrument is approximately twice the static friction of the whole mechanism in that position. The actual contact pressure, when the instruments are properly used—that is, when the contact position is approached at a slow and uniform rate—will lie between the average static pressure and the minimum static pressure. The average static pressure in pounds per square inch of nominal contact area obtained from the above static-pressure curves is shown for each micrometer in Figure 3. In Figure 4 is shown the total average for each instrument. It should be noted that the instruments fall into two groups, instruments 6, 7, and 9, which have a low plunger pressure, low friction, and an area of contact of approximately 0.1 $in.^2$ or less, and instruments 1, 2, 3, 4, 5, and 8, which have a high plunger pressure, high friction, and an area of contact 0.25 $in.^2$ or over. In Figure 5 is shown the average contact pressure in pounds per square inch for each instrument.

4. PERFORMANCE OF INSTRUMENTS.

A performance test was made on the nine micrometers to determine whether or not the different contact areas and different contact pressures of the micrometers had any effect on the results obtained. This performance test was made in the following manner: 14 different papers were obtained, and from each a test sample was cut. Each test sample comprised 10 separate sheets. Ordinarily one reading is taken on each sheet in testing paper for thickness and an average of the 10 readings is taken as a final result. However, in order to eliminate as far as possible any variation in the final results obtained on any one paper by the different micrometers, which variation might be due to variations in thickness of that paper, three sets of readings were taken on each sheet and an average of the 30 readings was taken as a final result. In this way the average reading of each micrometer for each paper was obtained, and these averages were arranged in order and the corrections in Table 9 were applied to them. The average thick-

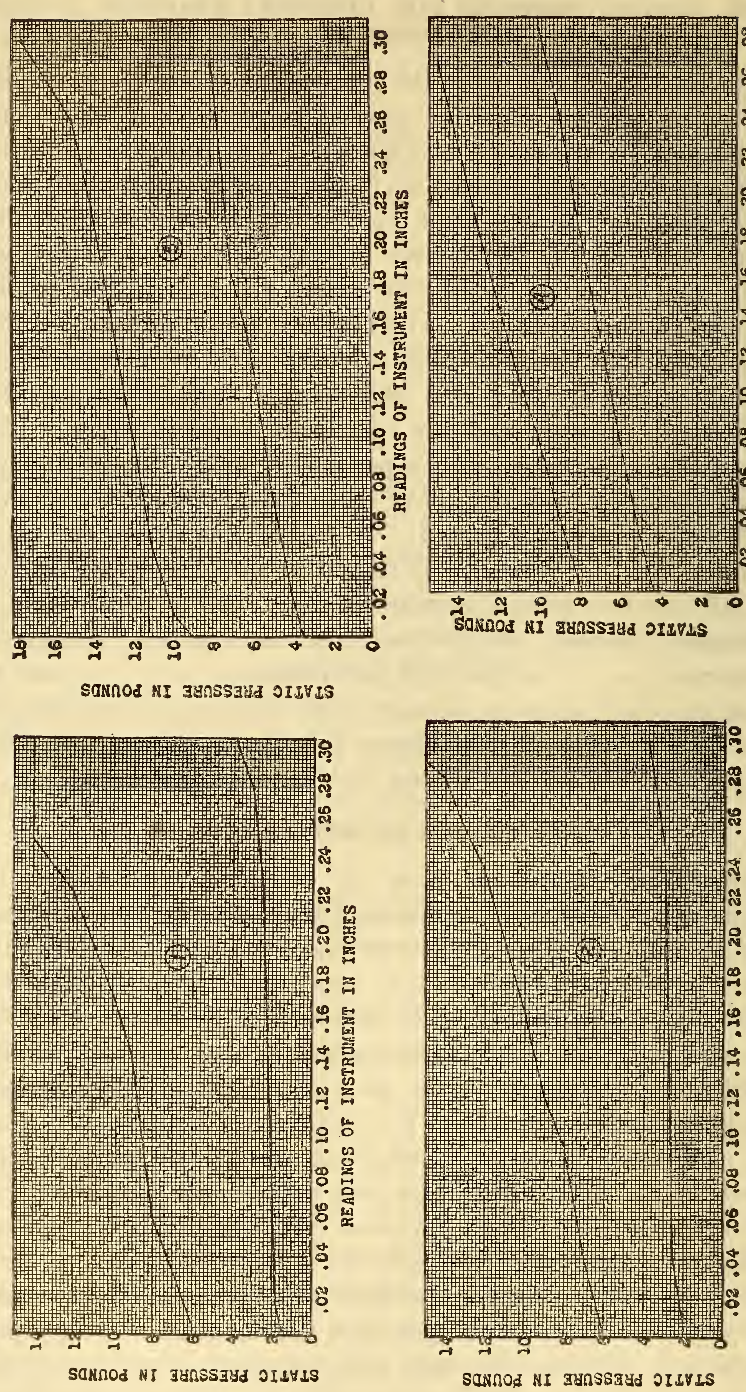

FIG. 3.—*Diagrams showing the maximum and minimum static pressures for the different dial readings of micrometers 1 to 4, inclusive.*

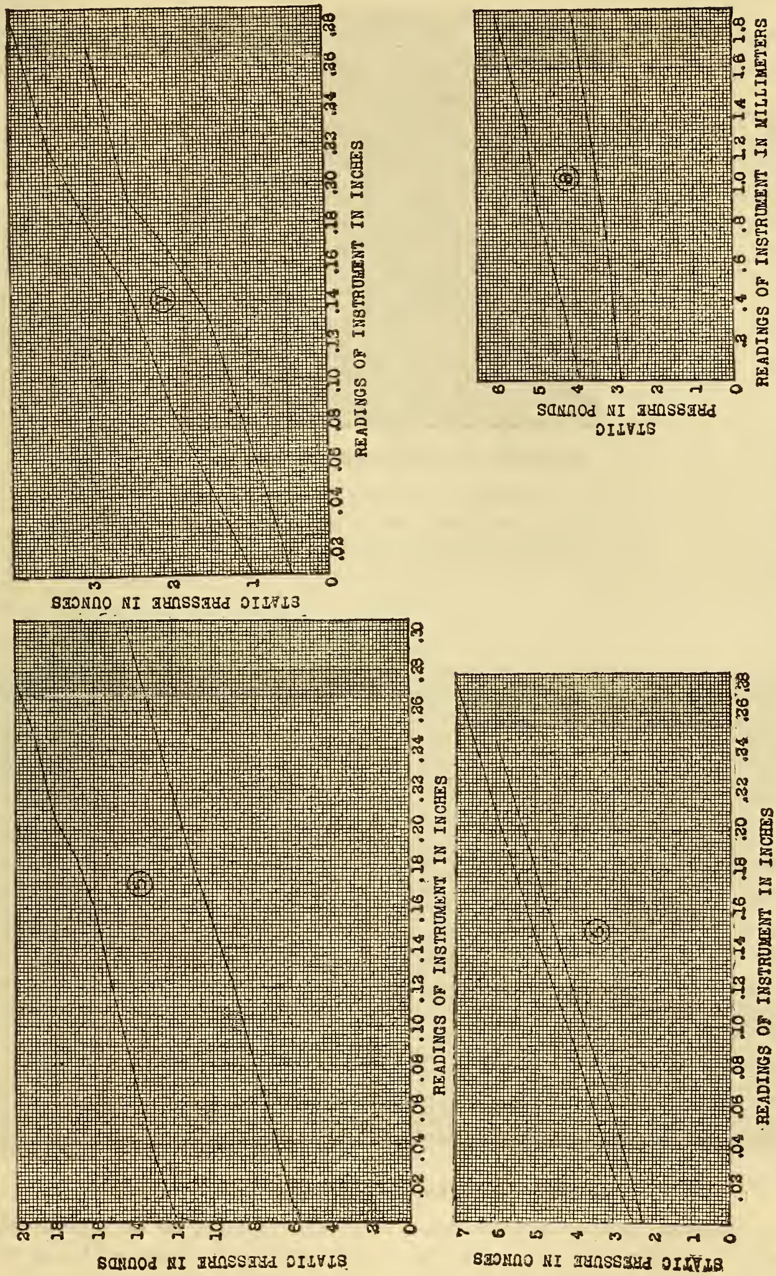

FIG. 3. (Continued).—*Diagrams showing the maximum and minimum static pressures for the different dial readings of micrometers 5 to 8, inclusive.*

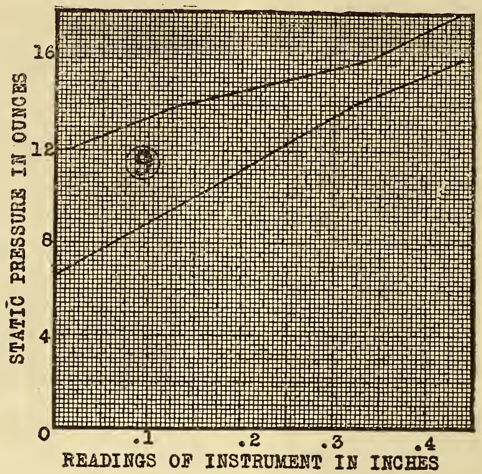

FIG. 3. (Continued).—*Diagram showing the maximum and minimum static pressures for the different dial readings of micrometer 9.*

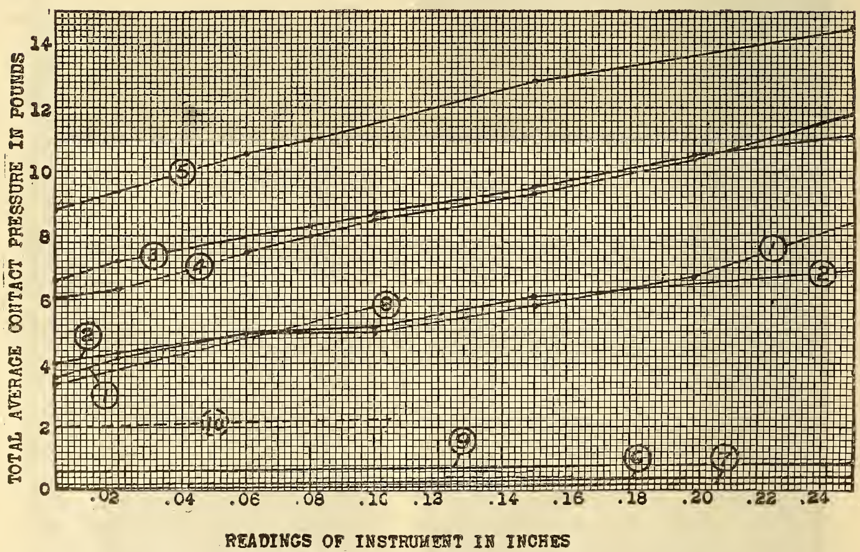

FIG. 4.—*Diagram showing the total contact or plunger pressures for the different dial readings of micrometers 1 to 9, inclusive, as compared with the recommended total contact or plunger pressures for the different dial readings of a new standard micrometer.*

ness of each paper as determined by each micrometer is given in Table 11. The mean average of the nine micrometers was then determined for each paper, and the variation of each micrometer average from this mean average was found for each paper and

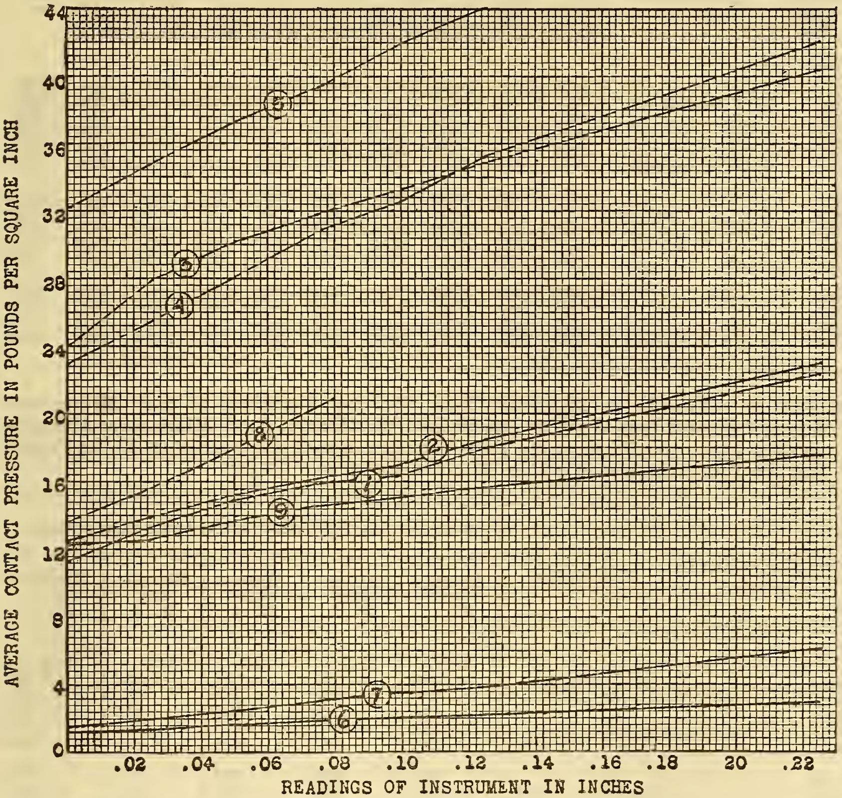

FIG. 5.—*Diagram showing the average static pressures for the different dial readings of micrometers 1 to 9, inclusive.*

recorded in Table 12 with its corresponding positive or negative sign depending on its relation to the mean average.

Also it was thought that the relative accuracy of each instrument would be indicated by obtaining the total variation of each micrometer on all the papers. This was done and the results are shown in Table 12, where the total variation of all the micrometers on each paper is also given.

TABLE 11.—Results of Thickness Test, Showing Averages of 30 Readings from each One of the 9 Micrometers on each One of the 14 Papers and Showing the Mean of the 9 Micrometer Averages on each Paper.

Paper identification number.	Kind of paper.	Average results of 30 readings.									Mean average.
		Micrometer No. 1.	Micrometer No. 2.	Micrometer No. 3.	Micrometer No. 4.	Micrometer No. 5.	Micrometer No. 6.	Micrometer No. 7.	Micrometer No. 8.	Micrometer No. 9.	
		Inch.	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.
4952....	M. F. printing........	0.0040	0.0045	0.0042	0.0041	0.0046	0.0042	0.0049	0.0044	0.0041	0.0043
4953....	.....do...............	.0029	.0029	.0030	.0026	.0027	.0024	.0028	.0026	.0024	.0027
4954....	.....do...............	.0038	.0037	.0037	.0036	.0038	.0036	.0042	.0036	.0034	.0037
4955....	.....do...............	.0046	.0044	.0045	.0044	.0046	.0046	.0050	.0044	.0043	.0045
4956....	S. & S. C. printing...	.0030	.0030	.0029	.0029	.0027	.0028	.0030	.0026	.0026	.0029
4957....	.....do...............	.0031	.0030	.0031	.0029	.0030	.0029	.0031	.0029	.0027	.0030
4958....	High M. F. writing..	.0035	.0033	.0035	.0032	.0035	.0034	.0036	.0033	.0032	.0034
4959....	.....do...............	.0025	.0025	.0025	.0025	.0026	.0024	.0025	.0024	.0023	.0025
4960....	S. & S. C. writing...	.0051	.0052	.0048	.0050	.0054	.0051	.0053	.0051	.0050	.0051
4961....	.....do...............	.0058	.0058	.0055	.0056	.0060	.0057	.0059	.0056	.0057	.0057
4962....	.....do...............	.0023	.0022	.0023	.0022	.0023	.0021	.0023	.0022	.0022	.0022
4963....	.....do...............	.0045	.0044	.0043	.0043	.0049	.0043	.0044	.0045	.0043	.0044
4964....	.....do...............	.0035	.0036	.0036	.0035	.0036	.0033	.0037	.0037	.0033	.0035
4965....	S. & S. C. ledger....	.0068	.0066	.0062	.0062	.0065	.0065	.0072	.0063	.0064	.0065

TABLE 12.—Results of Thickness Test, Showing Variations of each Micrometer Average on each One of the 14 Papers from the Mean of the 9 Micrometer Averages on each Paper and Showing the Total Variation of each Micrometer on all the Papers and the Total Variation of all the Micrometers on each Paper.

Paper identification number.	Kind of paper.	Variation of each micrometer average from mean average.				
		Micrometer No. 1.	Micrometer No. 2.	Micrometer No. 3.	Micrometer No. 4.	Micrometer No. 5.
		Inch.	Inch.	Inch.	Inch.	Inch.
4952..................	M. F. printing.....	−0.0003	+0.0002	−0.0001	−0.0002	+0.0003
4953..................	.....do............	+ .0002	+ .0002	+ .0003	− .0001	.0000
4954..................	.....do............	+ .0001	.0000	.0000	− .0001	+ .0001
4955..................	.....do............	+ .0001	− .0001	.0000	− .0001	+ .0001
4956..................	S. & S. C. printing.	+ .0001	+ .0001	.0000	.0000	− .0002
4957..................	.....do............	+ .0001	.0000	+ .0001	− .0001	.0000
4958..................	High M.F. writing.	+ .0001	− .0001	+ .0001	− .0002	+ .0001
4959..................	.....do............	.0000	.0000	.0000	.0000	+ .0001
4960..................	S. & S. C. writing..	.0000	+ .0001	− .0003	− .0001	+ .0003
4961..................	.....do............	+ .0001	+ .0001	− .0002	− .0001	+ .0003
4962..................	.....do............	+ .0001	.0000	+ .0001	.0000	+ .0001
4963..................	.....do............	+ .0001	.0000	− .0001	− .0001	+ .0005
4964..................	.....do............	.0000	+ .0001	+ .0001	.0000	+ .0001
4965..................	S. & S. C. ledger..	+ .0003	+ .0001	− .0003	− .0003	.0000
Total variations..	....	.0006	.0003	.0006	.0003	.0007

TABLE 12—Continued.

Paper identification number.	Kind of paper.	Variation of each micrometer average from mean average.				Total variation.
		Micrometer No. 6.	Micrometer No. 7.	Micrometer No. 8.	Micrometer No. 9.	
		Inch.	Inch.	Inch.	Inch.	Inch.
4952	M. F. printing	−0.0001	+0.0006	+0.0001	−0.0002	0.0009
4953	do	− .0003	+ .0001	− .0001	− .0003	.0006
4954	do	− .0001	+ .0005	− .0001	− .0003	.0008
4955	do	+ .0001	+ .0005	− .0001	− .0002	.0007
4956	S. & S. C. printing.	− .0001	+ .0001	− .0003	− .0003	.0004
4957	do	− .0001	+ .0001	− .0001	− .0003	.0004
4958	High M.F.writing.	.0000	+ .0002	− .0001	− .0002	.0004
4959	do	− .0001	.0000	− .0001	− .0002	.0003
4960	S. & S. C. writing	.0000	+ .0002	.0000	− .0001	.0006
4961	do	.0000	+ .0002	− .0001	.0000	.0005
4962	do	− .0001	+ .0001	.0000	.0000	.0002
4963	do	− .0001	.0000	+ .0001	− .0001	.0006
4964	do	− .0002	+ .0002	+ .0002	− .0002	.0004
4965	S. & S. C. ledger	.0000	+ .0007	− .0002	− .0001	.0010
Total variations		.0004	.0007	.0005	.0003	

Frequently the total permissible variation in the thickness of paper is 0.001 inch, and it is seen from the results in Table 12 that the values on most papers obtained with different instruments may differ by half this amount, 0.0005 inch, even after the readings of the instruments are corrected for errors found by the steel gauge test. It will be noted that 7 out of the 14 papers show a total variation of over 0.0005 inch when the values obtained with all 9 instruments are considered. In some cases an instrument reads high on nearly all papers while others read low. It will be seen, however, from Table 12 that the instruments are not very consistent in this respect; only four micrometers (2, 4, 6, and 8) showed a total variation less than 0.0005 inch in the variation of reading from the average thickness of the papers.

The variation in the contact pressure and shape of contact may account for the instruments reading high or low, while the variations in the variations from the average thickness of the papers may be accounted for by varying compressibility of the papers, the finish of the papers, and the shape of instrument contacts.

IV. COMPRESSIBILITY OF COMMERCIAL PAPERS.

In order to determine definitely whether different contact areas and different contact pressures do affect the results of thickness tests, or, in other words, in order to determine whether paper is compressible under different pressures applied to contacts of different areas, a special micrometer was constructed as follows: An ordinary commercial micrometer with a different base was employed for this purpose. A small upright post was erected at the side of the micrometer gauge in such a way that the post could be raised and lowered with as little friction as possible. A small arm projected at right angles from this post, so that the pressure foot of the micrometer rested on the end of the arm, and the pressure foot of the micrometer was raised or lowered accordingly as the post was raised or lowered. The post was so constructed that weights could be placed on it and pressure feet of different areas could be fastened to its base. Each pressure foot of this instrument, representing the upper contact, rested upon a surface which was always parallel to it, because the position of the lower contact could be changed with respect to the base of the instrument, since the lower contact rested in a socket in the base, the ball and socket principle being applied. Three pressure feet or upper contacts of different areas were used. The area of the first was twice that of the second, and the area of the second was twice that of the third. Their areas were 0.314, 0.157, and 0.0785 in.^{2} Three 24-ounce weights were used, and the weight of the post together with the spring tension of the micrometer was found with a spring balance to be about 200 g or 7 ounces. (The change in spring tension for different readings of this gauge was so small that there was no indication of it on the spring balance and it was felt that it was not worth consideration in a study of compressibility, where it was desired to show the effect of large changes in contact pressures.) A gauge, similar in construction to number 6, was used for this work. (Note below in Fig. 4 the small change in spring tension or total contact pressure for different readings of this gauge.) The same papers were used in measuring compressibility as were used in the performance test, and the test samples were prepared in the same manner. The samples were tested in the following manner: Each sheet of each test sample was tested for thickness in one spot by using the different weights on the upright post. Readings were taken of the increasing and decreasing loads of units of 24 ounces. The total number of readings for each test sample for each operation was 10. Each 10 readings were totaled and averaged, and the results were plotted in the form of curves.

V. STUDY OF RESULTS.

1. PRESSURE AND CONTACT AREA.

On examination of the above curves (Fig. 6) it is possible to state definitely that different contact areas and different contact pressures do affect the results of thickness tests, or in other words, that paper is compressible under different pressures applied to contacts of different areas. The curves also show that some papers are more compressible than others. For instance, the M. F. (machine finished) printings numbered 4952, 4953, 4954, and 4955 are more compressible than the S+S. C. (sized and supercalendered) printings numbered 4956 and 4957. In general, this would be true because a machine-finished paper is usually softer and bulkier than a supercalendered paper. This, however, is not so noticeable in the case of the high machine-finished writings numbered 4958 and 4959 and the supercalendered writings numbered 4960, 4961, 4962, 4963, and 4964, because the pressure that is applied to the paper machine calender rolls in order to make the paper high machine finished is also apt to make the paper as hard as, and no bulkier than, the supercalendered paper. (A machine-finished paper is a paper that has received its finish or surface polish from the stack of steel calender rolls which is a part of the paper machine, while a supercalendered paper is a paper that has received its finish or surface polish from a stack of rolls called a supercalender, which is a machine separate from the paper machine and which is made up of a combination of steel rolls and compressed paper rolls or steel rolls and compressed cotton rolls.)

It is interesting to note from the curves that in most cases there seems to be a greater compressibility of the paper when the large pressure foot is used than when the medium and small pressure feet are used. This is undoubtedly due to the fact that the larger contact touches on a large number of high points which resist compression at a light plunger pressure but which gradually yields as the pressure is increased, whereas the small contact touches on a few points which yield at once under the light plunger pressure. It is readily seen that large contacts and high-plunger pressure give results entirely different from small contacts and low pressures. It has been suggested that a standard pressure per square inch be adopted for dial micrometers. A study of the performance and compressibility tests show that this suggestion is not a complete solution. For instance, referring to Figure

5, it will be seen that micrometers 1 and 9 have practically the same pressure per square inch; then referring to Table 12 it will be seen that micrometer 9 always reads less than the mean thick-

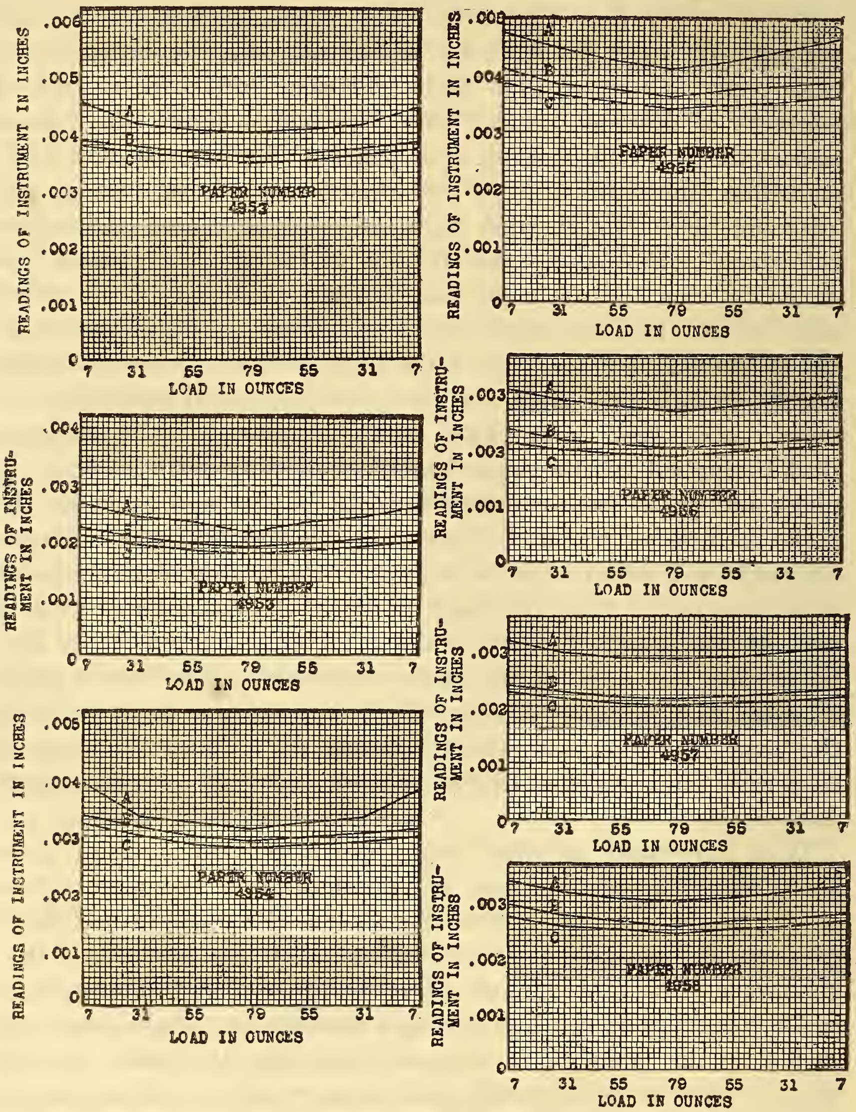

FIG. 6.—*Diagrams showing the compressibility of a series of writing papers when A (a large size), B (a medium size), and C (a small size), pressure foot is used and when different loads apply different pressures to these pressure feet.*

ness of the paper, while micrometer 1, with one exception, reads greater than the mean thickness. Of course, some of this effect may be due to the convexity of the contact of micrometer 9, but

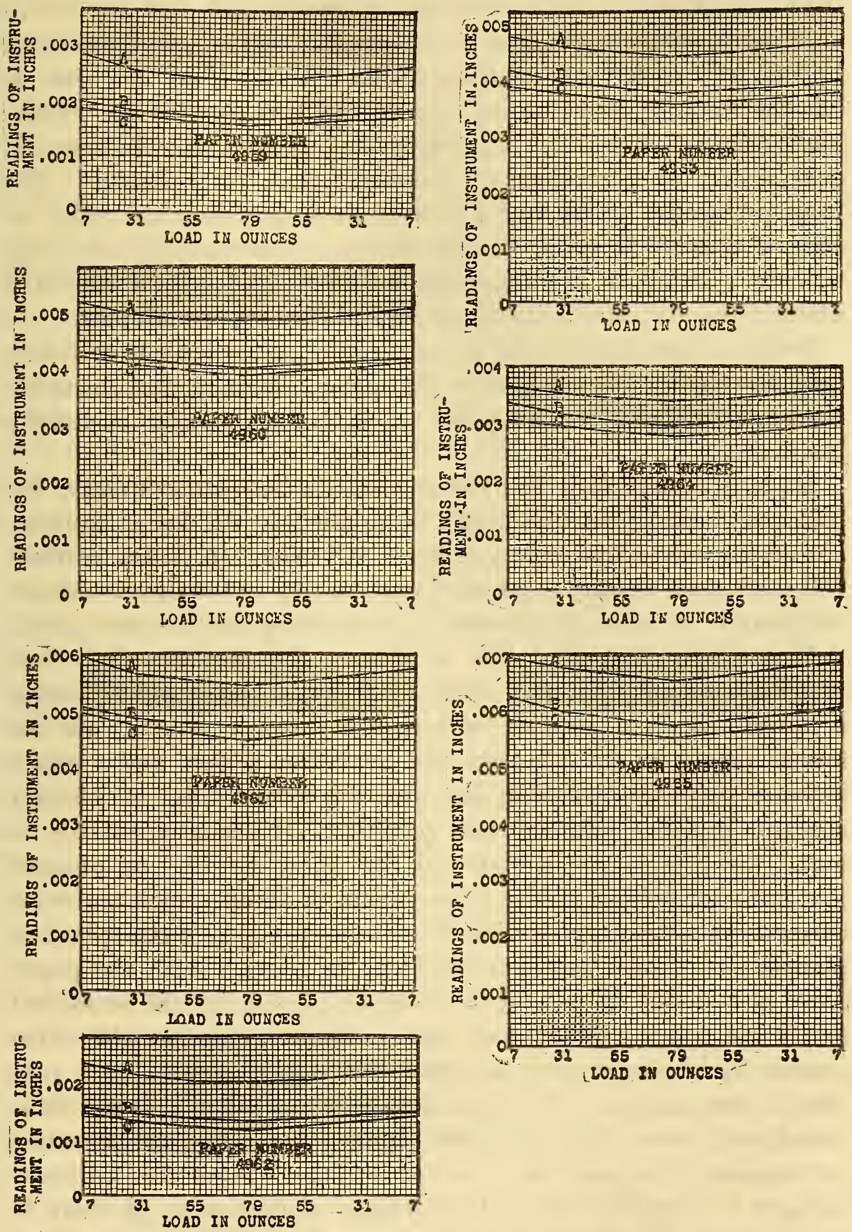

Fig. 6.—*Diagrams showing the compressibility of a series of writing papers when different pressure feet are used, A (a large size), B (a medium size), and C (a smzll size), and when different loads are applied.*

consider the compressibility curves. Figure 6, paper 4954, has a thickness of 0.0032 inch under the large contact *A*, 0.314 in.^{2} in area, at a contact pressure of 67 ounces, which is equivalent to 13 lbs./in.^{2}; under the medium contact *B*, 0.157 in.^{2} in area, it has the same thickness at 29 ounces, which is 11.5 lbs./in.^{2}; while under the small contact *C*, 0.0785 in.^{2} in area, its thickness is 0.0032 inch at a pressure of 9 ounces; that is, 7 lbs./in.^{2} For large pressures, 12 lbs./in.^{2} and over, it is true that the effect of area of contact is small, but in general the results indicate that uniform readings of thickness can not be secured until a standard plunger pressure and a standard area of contact are adopted.

Sufficient pressure should be used in the measurement of thickness to flatten or straighten the paper between the contacts. Pressure sufficient to compress or indent the paper is hardly justifiable.

Since it is necessary to have parallelism between contacts, the ball and socket principle might be applied to the lower contact. However, unless the socket is kept well oiled the lower contact will stick and assume a position not parallel to the upper contact and may be a cause of variance in the readings of the instrument.

It has been suggested that a plunger contact of a slight but definite convexity be used with a flat anvil and a light plunger pressure. Such a contact will assure positive contact at the lowest point on the plunger foot with the paper, and contact between paper and anvil in line with the lowest point on plunger contact, under a light contact pressure. It seems advisable to make the lower contact flat and the upper contact or plunger foot spherical with a radius of curvature of about 1 inch and with diameter of at least one-half inch. Then the edges of the spherical plunger foot which would never come in contact with the paper could be rounded off so that test samples of paper could be pushed under the upper contact; this would eliminate any possible error caused by the operator's lowering this upper contact at a rate that is not uniform. The question of parrallelism is also eliminated in the case of the spherical plunger foot, since the pressures are applied to a point in a curved surface. Since the spherical plunger foot would have a large radius of curvature, if there is any increase in compressibility obtained by this plunger foot over that obtained by a flat plunger foot, the increase is small. Of course, the area of contact will change a little in the case of the spherical plunger foot because of compressibility, but the area of contact will probably never be as large as that of the smallest pressure foot used in the compressibility test, and since all micrometers should be constructed to give practically the same total plunger pressures for the same readings on the dial, and since the readings of the dial or test results are in fractions of an inch and have no relation to the area of contact, it would seem that area of contact in this case is not worth consideration. Such contacts would be suitable for an instrument intended to determine the hardness or compressibility of papers, since all end effect which might be noticeable with small flat contacts with more or less sharp edges is eliminated. Weights to determine compressibility could be added to the plunger. Also the convex contact would be suitable for determining the stacking thickness of a number of sheets under light pressure. It will be noticed in Table 10 that two micrometers tested have convex plunger feet, and that the contacts of most of the other instruments are so much out of parallel that in effect they are equivalent to convex contacts.

A study of the pressure curves Figures 3, 4, and 5 shows that it would be impossible to adapt all of these types of instruments to both a standard area of contact and a standard contact pressure without radical changes in design. To secure lighter plunger pressures the spring tension must be reduced, and this can not be done without a considerable reduction in the static friction in many cases. The static friction can be reduced by reducing the weight of the moving parts, their number if possible, and the size of their bearings, also by improvement in the quality of the bearings. The plunger pressure can also be reduced by using the principle of opposed springs. This principle is used in the three instruments showing the lowest plunger pressures—6, 7, and 9. The advantages of opposed springs are best shown by study of the following algebraic formulas:

Let A and B be the forces transmitted to the plunger by the pointer and plunger springs, respectively, neglecting friction, and let F_M and F_P be the friction in the mechanism and in the plunger bearings, respectively. Then if A and B are in the same direction,

$$\text{plunger pressure} = (B \pm F_P) + (A \pm F_M) \qquad (1)$$

The sign of F_P will always be plus when the sign of F_M is plus, so the formula may be written:

$$\text{plunger pressure} = B + A \pm (F_P + F_M)$$

If A and B are opposed,

$$\text{plunger pressure} = (B \pm F_P) - (A \pm F_M) \qquad (2)$$

$$\text{or} = B - A \pm (F_P + F_M)$$

To secure positive pressure the first term in formula (2) must be greater than the second term. To take up all backlash B must be greater than F_P and A greater than F_M. The average plunger pressure for an instrument with the spring forces adding is evidently $B + A$, while for opposed springs the average plunger pressure is $B - A$.

The pressure curves for some of the instruments, notably 6, 7, and 9, are more nearly horizontal than for the remaining instruments. This means that the plunger pressure is nearly constant over the full range of the instruments and is secured by using long helical springs for the plunger and long spiral springs of a large number of turns for the pointer. Such springs give a minimum change in tension for a given movement of pointer and plunger.

Some of the instruments are provided with an air dashpot for regulating the velocity with which the plunger can move. They appear to function as intended and prevent the plunger from striking the paper with an excessive impact or blow. However, the piston of an air dashpot must be tight fitting, and this adds to the friction of the instrument. Instrument 12, recently introduced, contains a friction governor which, however, does not add to the static friction of the bearings when the plunger is at rest.

It is important in all types of instruments to keep down the weight of the rotating parts; otherwise, if the angular velocity is high, considerable kinetic energy may be developed, a large part of which must be absorbed by the paper when contact is made. This may prove to be an important factor in an instrument with a governor type of plunger speed regulator.

It is interesting to note that the motion of instrument 12 is irreversible; that is, the plunger can not be raised by applying force directly to the foot. This is because the helix angle of the screw that engages with the threads of the plunger is less than the friction angle of repose. The plunger can only be raised by applying a torque to the screw, which is done by moving the handle attached to the gear sector engaged with the pointer pinion. Instrument 10, which is somewhat similar in principle, has a screw or worm with a helix angle of about 27°, much larger than the angle of repose. The only possible advantage to an irreversible motion is that the plunger can not rebound from its lowest position, so that one source of variation in contact pressure is eliminated.

2. ACCURACY AND VARIANCE OF INSTRUMENTS.

It is desirable that a paper micrometer be accurate to 0.0001 inch at all points and that it repeat its readings within 0.0001 inch when in use. It will be noted in Table 9 that the majority of the instruments calibrated have inaccuracies so large that corrections must be applied to secure an accurate determination of the thickness of paper. Probably one of the chief sources of inaccuracy in the instruments with a rack cut on the plunger that engages with the first gear in the train, is irregular spacing or inaccuracies in the form of the teeth of both rack and gear. These teeth must be accurate to 0.0001, or better, if the instrument is to be accurate to 0.0001 inch. Inaccuracies in the teeth of other gears in the train are not multiplied at the pointer to the extent that errors in the rack and its gear are. Also the play in the bearings of the staff of the gear engaged with the rack may cause considerable variance in the readings of the instrument. If the staff takes up varying positions in its bearings varying angular displacements of the gear will occur for equal angular displacements of the plunger. This statement also applies to the play in the bearings of other gears, but the resulting variations at the pointer are small in comparison. If contact is made at varying rates the staff tends to assume different positions in its bearing, due to the varying recoil of the plunger.

In instruments 3, 4, and 5 a design is used intended to overcome the difficulties of securing accurate toothed racks and gears. In these instruments a flexible connector is used to convert the linear motion of the plunger into rotary motion of the gear engaged with the pointer pinion. This flexible connector is a brass or bronze ribbon about 0.003 inch thick. The pulley or drum on which the ribbon winds can be accurately turned or ground so that the ratio of linear displacement of plunge to angular displacement of drum will be quite constant. A brass or bronze ribbon is probably used because of the noncorrosive qualities of these materials; a steel ribbon would be preferable from the standpoint of flexibility and strength. Unfortunately the workmanship in the instruments employing the flexible connectors is not as high grade as other instruments tested, so that the tests do not show any decided advantage in this design.

In instruments 10 and 12, Figure 2, the parts transferring linear motion of plunger to rotary motion of pointer are reduced to a minimum. The sources of inaccuracy in these instruments include the progressive and periodic errors in the screw or worm and errors in the thrust bearings of the screw or worm. The latter will appear as periodic errors. Any rotary motion of the plunger will cause either an inaccuracy or variance in the readings of the instrument.

Instrument 8, Figure 1, is arranged so that the multiplication of the instrument can be adjusted. This is done by moving the gear sector engaged with the rack toward or away from its center of rotation. After the completion of the tests of this instrument it was adjusted so that the maximum error in reading on steel gauges was not over ±0.0001 inch.

VI. SPECIFICATIONS.

1. FOR DIAL MICROMETERS FOR MEASURING PAPER.

The following specifications are intended to provide instruments whose readings on commercial paper corrected for any errors found by calibration against steel gauges will agree within 0.0002 inch.

1. Any type or design of instrument that will meet the balance of these specifications can be used.

2. The instrument shall be provided with a spherical plunger foot with 1 inch ±0.1 inch radius of curvature and at least one-half inch diameter.

3. (*a*) The pressure required to move the mechanism from zero reading toward a higher reading shall not exceed 2 pounds, 6 ounces, and the pressure required to just prevent the mechanism from moving from zero to a lower reading shall not be less than 1 pound, 10 ounces. (*b*) The pressure required to just move the mechanism from a reading of 0.1 inch toward higher readings shall not exceed 2 pounds, 8 ounces, and a pressure that will just prevent the movement of the mechanism from a reading of 0.1 inch to a lower reading shall not be less than 1 pound, 12 ounces. (*c*) If the instrument is provided with a device for regulating the speed of the plunger, the plunger must not strike the paper with an impact greater than the maximum pressure specified above.

4. One division on dial shall be read as 0.001 inch and shall be at least one-eighth inch wide.

5. Accuracy of dial readings of micrometer shall be within the following tolerances:

Intervals:	Maximum permissible error, inch.
0 to 0.01 inch	±0.0001
0.01 inch to 0.04 inch	± .0002
0.04 inch to 0.12 inch	± .0004

6. Means shall be provided for adjusting or setting the zero reading on the micrometer.

7. Micrometer must be of such a construction and workmanship that it will not easily get out of adjustment.

2. SPECIFICATIONS FOR PROCEDURE IN DETERMINING MEAN THICKNESS OF A SAMPLE OF PAPER.

By taking a large number of readings, errors due to variance in the instrument and variation in the paper can practically be eliminated. Errors due to inaccuracies in the instrument or incorrect contacts and contact pressure can not be eliminated.

It is recommended that the test be made on 10 sheets taken from the lot at such intervals as to represent an average. One reading shall be taken on each sheet and the readings averaged. The result shall be rounded off to the nearest 0.0005 inch. For example, if the average result of 10 tests on a paper is 0.0041, or 0.0042, then report as 0.004. If the average result of 10 tests is 0.0043, 0.0044, 0.0046, or 0.0047, then report as 0.0045. If the average result of 10 tests is 0.0048, 0.0049, 0.0051, or 0.0052, then report as 0.005. It seems advisable to interpret final results in this way, since there is apt to be an error in estimating the fourth decimal place when the 10 readings are taken from the micrometer dial.

VII. SUMMARY.

A number of dial micrometers were calibrated against steel gauges and used to measure the thickness of several grades of paper. The micrometers were studied to ascertain the causes of the different readings on the same paper. The instruments were found to differ in form and area of contact, contact pressure, and in the amount of friction in the mechanism. To determine the effect of contact area and pressure, tests in measuring paper were made on commercial papers using contacts of different area and with varying contact pressures. These tests showed that the paper yielded to a greater extent with increase of pressure when the contact was large than when small. Under the same pressure per square inch but different contact areas different readings of thickness were obtained. The mechanism of the instruments was studied to determine the effect of the various designs on the contact pressure, the variation in contact pressure, and the accuracy and variance of the instruments. Specifications were drawn up for a standard instrument and for a standard procedure in determining the mean thickness of a sample of paper.

WASHINGTON, June 22, 1922.