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RESEARCH ON THE PRODUCTION OF CURRENCY PAPER IN THE BUREAU OF STANDARDS EXPERIMENTAL PAPER MILL

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RESEARCH ON THE PRODUCTION OF CURRENCY PAPER IN THE BUREAU OF STANDARDS EXPERIMENTAL PAPER MILL

By Merle B. Shaw and George W. Bicking

ABSTRACT

The annual replacement of worn-out paper currency in the United States has become of such magnitude as to cause concern regarding the cost of redemption and the limited issue possible with the present printing facilities, which were becoming overtaxed. Increased rapidity of circulation and rougher trade usage are doubtless chiefly responsible for the decreased life of the paper money, but these conditions are unlikely to change in the future. An investigation was, therefore, made to determine the durability factors of paper suitable for currency use, with a view to increasing the wearing qualities and thereby prolonging the life of the paper money.

The experimental tests were made on a semicommercial scale under practical mill conditions. The paper-making fiber was obtained from new linen and cotton rags. Various proportions of these materials were employed, but the best results were obtained with a mixture of 75 per cent linen and 25 per cent cotton.

A solution of calcium oxide was used as the boiling liquor in preparing the fiber for the paper-making tests. Bleaching powder (calcium hypochlorite) was employed as the oxidizing agent to remove impurities and whiten the material. Very gradual application of the beater roll pressure reduced to a minimum the reduction in the length of the fibers and by brushing or fraying out their ends insured more and better contacts between adjacent fibers when they were felted in the sheet. The low concentration of pulp in the beater was also a contributing factor in increasing the strength of the paper. The concentration that proved most satisfactory was approximately 3.9 per cent; the beating interval that gave best results was approximately 12 hours.

The paper produced was of good printing quality and of much greater folding endurance than that in use at the time of the investigation. The results of the experimental tests have been applied in commercial production, and currency paper double the strength of that previously in use is now being received. It is believed that the data of the investigation will also be of value in the general technic of paper making.

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I. INTRODUCTION

The service records of the United States Treasury Department show that the useful life of United States paper currency, particularly the more commonly used denominations, has been continually decreasing during recent years. Increased rapidity of circulation and rougher trade usage are doubtless chiefly responsible for the decreased period of service, but are conditions unlikely to change in the future. Annual replacements of worn-out currency have become of such magnitude as to cause concern regarding the cost of redemption and the limited issue possible with the present printing facilities, which were becoming overtaxed. The Bureau of Standards was requested by the Treasury Department to undertake the investigation herein reported to determine the durability factors of paper suitable for currency use, with a view to increasing the wearing qualities and thereby prolonging the life of the paper money. The paper-making tests were a part of the general research on currency paper conducted in cooperation with the Bureau of Efficiency.

The kind of materials employed in the investigation and the methods of manufacture are essentially the same as those used in the production of high-grade bond papers. The strength of paper is, however, considerably influenced by modifications of the treatment in the various paper-making processes. The purpose in view was accomplished by the beating treatment of the fibers; therefore the effect of varying the other processes was not studied at this time. Detailed information of them is also given, however, as a matter of general information.

II. PAPER-MAKING FIBER USED

Since paper currency must withstand much folding and other severe usage, the paper employed in its manufacture needs to have toughness. It is commonly believed that the higher grades of rags furnish the most valuable material for the production of such papers. Linen rags with the addition of a small percentage of cotton are usually regarded as unequaled for the production of hard papers of maximum strength, but cotton rags have the preference if the printing qualities (softness and absorbency) of the paper are the principal consideration.

The paper-making fiber for the tests in the present investigation was obtained from new rags, graded as white and cream linen cuttings, brown and gray linen cuttings, white linen threads, gray linen threads, white cotton shirt cuttings, and cream cotton hosiery clippings. The difference in the characteristic physical properties of these raw materials make possible a wide range of papers, from soft, absorbent cotton blottings, to hard, resistant bonds.[1] The character of the rags was taken into account in the composition of the paper stock, and by blends or combinations of the materials intermediate qualities were obtained in the finished paper. The composition of the beater " furnish " (the various paper-making materials blended in the beater) is included in the description of each paper-machine run.

III. PAPER-MAKING EQUIPMENT

The paper section of the Bureau of Standards is equipped for making paper in a semicommercial way under practical mill conditions. The experimental equipment available for the work on currency paper was that in general use in the bureau mill and consisted of a rag duster, rag cutter, rotary boiler, 50-pound wood tub beater with manganese-bronze bars and plate and equipped with a washing cylinder, a drainer for bleached " half stuff," small Jordan with iron bars, a 4-plate screen, and a 29-inch Fourdrinier paper-making machine (with wire 33 feet long and having two presses, nine 15-inch dryers, a small machine stack of seven rolls, and a reel).[2]

IV. PREPARATION OF THE RAW MATERIAL

Plants consist of fibers and ligneous or incrusting nonfibrous materials. The former are cellulose and are the basis of paper but the latter are undesirable and must be eliminated. In the case of rags as paper-making material, the fibers have been isolated and much of the nonfibrous material removed by the textile processes. The nature of the subsequent treatment preliminary to converting the textile fiber into paper depends on the impurities introduced in the textile processes, the cleanliness and quality of the rags, and the grade of paper desired.

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[1] So called because originally designed for engraved bonds and certificates. Present uses, however, cover a much wider range.

[2] Photographs of the beater, Jordan, and Fourdrinier machine are shown in B. S. Tech. Paper No. 262, pp. 340–341.

1. CLEANING, SORTING, AND CUTTING

Rags are generally received at the mill in bales. The usual preliminary treatment is to put the rags through a dusting machine to loosen them and to eliminate such objectionable material as sand and dirt. The buttons, hooks and eyes, etc., are then removed and the rags sorted according to material, color, and degree of cleanliness.

Rags should be dry when dusted and, if for fine papers, left in the duster [3] sufficiently long to loosen up and remove any carbon or coal particles that may be adhering. These are not generally removed by boiling and washing and are very troublesome when present. In sorting, uniformity in quality of new as well as old rags should be maintained in order that each fiber may receive the treatment it requires and yet not be subjected to that of a, perhaps, much stouter neighbor.

After being sorted, the rags are cut into such size as will facilitate proper digestion in the boiler and separation in the beater.

The essentials of a rag cutter are a revolving knife cutting against a stationary bed knife and a means of feeding the rags to the cutter. In operation, the revolving knives are usually run at a constant speed but the speed with which the rags are fed varies with the size to which they are to be reduced. The more slowly the rags are fed in the longer they are exposed to the action of the knives and the shorter they will be cut. Also, when small pieces are desired, the rags may be passed two or three times through the cutter, or the machine may consist of two or more cutters in combination. If in the latter case the cutters are at right angles to each other, the second cut will be across the first and the size of the pieces will be reduced. The knives should be kept sharp in order to insure clean cutting without tearing the rags. If the rags are torn, some of the threads are unavoidably lost.

From the cutter the rags go again to the duster where the dust produced by the cutting operation is removed. The cleaned material is then ready to be boiled or digested.

Since the rags employed in the tests of this investigation were new and already graded as to material and color (uniform in quality), only dusting, cutting, and subsequently dusting again were necessary to prepare the material for the digestion process. In the cutting operation the rags were reduced to pieces averaging less than 16 square inches in area.

2. BOILING OR "COOKING"

The boiling or "cooking" process in paper making dissolves or softens the noncellulose material and permits the fiber to respond

[3] Descriptions of various dusting machines can be found in any of the standard books on paper making.

more readily to subsequent treatment. In the case of rags, cooking frees the fibers from such impurities as dyes, size, starch, dirt, grease, or other incrusting materials. Subsequent washing eliminates the noncellulose impurities contained in the cooking solution.

(*a*) Cooking Solution.—The cut and dusted rags were cooked in a solution of lime in a rotary boiler, under steam pressure. Solutions of soda ash (sodium carbonate) and caustic soda (sodium hydroxide) are also used in the cooking liquor for rags, but neither was included in the present tests. In the American paper mills lime is more generally used because, being a mild alkali, it attacks the various noncellulose materials with a minimum effect on the cellulose itself.

The solubility ratio for lime is 1:800 in cold water, 1:1500 in boiling water, and even less at the higher temperatures generally used in paper making. As soon as the effective lime in solution is used, by formation of compounds with noncellulose material, new quantities dissolve to take its place. This process of renewal is repeated so long as unused lime is present. The strength of the solution is therefore practically constant throughout the cooking and prevents injury to the fibers from too great concentration of alkali.

Either quicklime (calcium oxide) or hydrated lime (calcium hydroxide) may be used for cooking rags, but quicklime was used in the work herein reported. The lime should be free from dirt and gritty substances, such as sand or coal dust, because of the difficulty in removing these from the fiber. There should be a high percentage of available calcium oxide, and the color of the lime should be relatively white. Bureau of Standards Circular No. 96, Recommended Specifications for Quicklime and Hydrated Lime for Use in the Cooking of Rags for the Manufacture of Paper,[4] recommends the following composition:

Ingredients	Quicklime		Hydrated lime	
	Maximum	Minimum	Maximum	Minimum
	Per cent	*Per cent*	*Per cent*	*Per cent*
Calcium oxide		95		73
Magnesium oxide	2		1.6	
Oxides of silicon, iron, and aluminum, and other insoluble matter	2		1.6	
Carbon dioxide	2		1.6	

To meet these specifications the listed material must not exceed the maximum percentages or fall below the minimum.

[4] Price, 5 cents. Copies of Bureau of Standards publications may be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C., at the prices quoted.

(*b*) Cooking Procedure.—The following cooking constants show the proportions of the various constituents employed and the pressure, temperature, and duration of the cooking operation:

Weight of bone-dry fiber	pounds	106
Volume of water	gallons	52.5
Weight of lime, using 6 per cent	pounds	6.5
Weight of lime, using 12 per cent	do	13
Initial temperature	° F	70–80
Duration of initial temperature	hour	1
Time for raising to cooking temperature	do	1
Cooking temperature	° F	250–260
Duration of cooking temperatures	hours	5
Cooking pressure	pounds	30–40

In preparing the lime for use a small amount of the water was added for slaking and the remainder of the 52.5 gallons was later added to and thoroughly mixed with the slaked lime. The mixture was run into the boiler through a 60-mesh screen to remove sand, splinters of wood, coal particles, or other objectionable material. After the rags and lime, or cooking liquor, had been "furnished" the manhole cover was put on and the boiler was started rotating, the speed being one revolution per minute. The rotation was continued for one hour before the steam was turned on. This allowed the rags to become thoroughly wet and the dirt to be loosened before the temperature was raised. A rapid rise in temperature tends to set the color and render some of the impurities less soluble. Also more lime is in solution at the lower temperature.

After one hour of digesting at from 70 to 80° F. the steam was turned on and the temperature raised to 250–260°. This temperature was maintained for five hours, at the end of which time the cook was completed. The steam was then blown off and the boiler allowed to drain overnight. The cooked rags were removed the following morning and were ready for washing.

The white and cream linens were kept separate from the gray and brown in cooking and the cotton rags were cooked alone. Six per cent of lime was used for the cotton and the white and cream linens, but 12 per cent was employed for the colored linens.

3. WASHING

After the boiling the rags were washed to remove the cooking liquor and the loosened impurities. A 50-pound beater having a washing drum was used for washing. One-half of a cook (approximately 50 pounds) constituted a charge. The rags by being drawn in between the revolving roll and the stationary bedplate of the beater were partially disintegrated and the impurities were mixed with the water and later removed with it.

Before the stock was added to the beater (used as a washer at this stage) the beater roll was raised by a definite number of turns of the adjusting handwheel. The cooked rags were then added and the washing begun, fresh water being added continuously during this operation. After the washing had continued for one-half hour the roll was partially lowered (by a definite number of turns of the adjusting wheel) and the pressure was gradually increased thereafter throughout the washing process. Putting the roll down too soon would tend to rub the dirt into the fibers and cause the stock to be of poor color. Care must also be taken not to cut the fibers, which should be comparatively long in the "half stuff" and shortened as desired in the beating operation proper. (See V, 1.)

The rags were washed until the effluent was clear, the time required being about two and one-half hours. One thousand five hundred gallons of water, or 30 gallons per pound of rags, were used in each washing operation.

The beating action of the washer was continued further to brush the rags out of weave. The cotton and uncolored linens responded somewhat more readily to this treatment than the gray or brown linens. The former required six and one-half hours, the latter seven hours for conversion into the partially prepared pulp, commonly termed "half stuff."

4. BLEACHING

The washed half stuff at this stage usually contains some noncellulose materials. Bleaching is a treatment with oxidizing agents to remove these impurities and whiten the half stuff.

Bleaching powder, calcium hypochlorite, was the oxidizing agent used. It was thoroughly mixed with water and after being agitated for some time left to settle. The clear liquor was then drawn off, analyzed, and subsequently used as the bleaching agent.

The bleaching operation was begun in the washer (beater used as washer) and completed in the drainer. Before the bleach liquor was added to the half stuff in the washer the excess water was removed and the beater roll was adjusted so as to circulate the pulp during the bleaching process. The bleach liquor was then slowly added and the stock circulated for three-quarters of an hour. The temperature in the beater during this interval was from 90 to 105° F. The contents were then discharged into the drainer, as was also the fresh water subsequently used in washing out the beater, and left for one-half hour before the valve was opened and the water permitted to drain off. The half stuff was allowed to remain in the drainer 24 hours, during which time the bleach slowly acted upon it until finally exhausted. No acid or other material was added to accelerate the bleaching operation.

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The bleaching was followed by washing to remove residual chemicals. The half stuff in the drainer was covered with fresh water and allowed to stand for one hour before the drainer valve was opened. The process was repeated and the stock left 24 hours to drain. The use of an "antichlor" to neutralize the excess of bleach was found unnecessary.

The division of the rags into cotton, uncolored linens, and colored linens had been maintained throughout the foregoing processes. Therefore, three corresponding lots of half stuff were made available for the following paper-making processes:

V. PAPER-MAKING PROCESSES

1. BEATING

(*a*) General Description.—Beating is the term applied to the mechanical treatment given the half stuff, suspended in water, to prepare it for forming a sheet on the paper machine. The manner and duration of the beating operation determines to a great extent the characteristics of the finished paper.

The beater, or beating engine, is an oblong, shallow tub with rounded ends and with a partition dividing it at the center but not extending to the ends, thus providing a continuous channel for the circulation of the pulp. Extending from the center partition to the edge is a horizontal revolving roll, fitted around its surface with knives called fly bars. Underneath the roll and fixed in the bottom of the beater are a number of parallel bars fastened together and called the bedplate. The function of the roll and bedplate is to separate, shorten, and brush or fray-out the fibers so that they will interlace more effectively in the final paper-making processes. The roll can be raised or lowered on the plate so as to diminish or increase the cutting and brushing action as desired. By its paddle-like action the roll also effects the circulation of the pulp in the beater.

The beater employed in the present work is part of the general equipment of the bureau paper mill. For the information of those interested in its design and construction the following data are included: Hollander type, 50-pound capacity, manganese-bronze fly bars and bedplate; weight of roll and spindle, 700 to 750 pounds; fly bars (number, spacing, and thickness), 36, $1\frac{6}{8}$ to $1\frac{7}{8}$ inches, and $\frac{1}{4}$ inch, respectively; plate bars (number, spacing, and thickness), 11, $\frac{1}{4}$ inch, and $\frac{1}{4}$ inch, respectively; peripheral speed of roll, 1,250 to 1,300 feet per minute (200 to 210 revolutions per minute); vertical adjustment of roll, 15 turns of handwheel raises or lowers the roll one-eighth of an inch (one turn, 0.008 inch).

In addition to the mechanical reduction of the fibers mentioned above, beating also produces another very important change in the physical state of the fibers. Cellulose imbibes water readily, but the capacity of the fibers in the beater for absorbing moisture is greatly increased by the continual friction of the beater roll. The process of imbibition is commonly spoken of as "hydration," but the union is generally considered a physical one, rather than a chemical one, as the term hydration implies. The flexible and gelatinous condition of so-called "hydrated" pulp tends to increase the strength of paper up to a certain point. The soft and plastic fibers interlace better than free stiff fibers and give better formation in the sheet on the paper machine.

It is in the beater that nonfibrous materials are added as required; for example, dye to impart color, loading or filler material to increase opacity or produce certain surface characteristics, and sizing[5] agent to render the sheet resistant or partially resistant to the penetration of ink and aqueous liquids. The mixture of the various materials, the chief constituent, of course, being the fibers, is called the beater furnish.

Before the furnish is added to the beater the roll is raised off the plate by turns of the handwheel in order to give clearance to the lumps of pulp. The beater is partly filled with water and the pulp (in these tests, half stuff from drainers) is added. Additional water is run in until the desired concentration is obtained. After sufficient circulation of the stock the roll is gradually lowered on the plate to brush out the fibers and reduce them to optimum length.

The beater furnish for most of the tests of this investigation consisted of the half stuff only, varying in composition from 100 per cent linen to 100 per cent cotton. Measurement of the half stuff and the water added to the beater permitted the concentration to be kept as nearly constant as possible throughout the tests. The manner and duration of the beating depended on the fiber composition of the furnish. Table 1 gives the composition and the beating interval for the beater of each paper-machine run.

During the beating the roll was very gradually lowered by definite amounts and at fixed intervals. The following shows the various positions of the roll and the time interval for each during the beating of one furnish and is representative of the beating conditions of these tests. The change in distance between the roll and the plate is expressed in turns of the handwheel, 15 turns, as stated above, changing this distance by one-eighth inch.

[5] Papers made without any sizing are termed waterleaf.

Log of 50-pound beater[1]

[Beater record No. 776 (furnish: 25 per cent cotton; 75 per cent linen)]

Clock time	Time interval	Position of roll[2]	Temperature	Speed of roll	Circulation of pulp	Remarks
Oct. 19:	*H. m.*		° *F.*	*R. p. m.*	*Ft./min.*	
8.55	0 00	+10				Lighter-bar[3] up; started furnishing.
9.05	0 10	+10				Furnished; lighter-bar down.
9.10	0 15	+5	68			
9.55	1 00	+4	74			
10.25	1 30	+3	78			
10.55	2 00	+2	82	214	25	
11.55	3 00	+2	92			
12.25	3 30	+1½	96			
1.25	4 30	+1	104			
1.55	5 00	+1	108	214	8.2	
2.25	5 30	+½	111			
3.25	6 30	+½	113	214	6.3	
4.25	7 30	+½	116			Lighter-bar up; shut down.
Oct. 20:						
8.30	7 30	0	90			Started up; added water; lighter-bar down.
9.00	8 00	0	91	210	9.2	
10.00	9 00	0	95			
11.00	10 00	−½	98			
12.00	11 00	−½	102			
12.30	11 30	−½	104	210	9.0	
1.00	12 00	−½	106			Lighter-bar up; dropped to chest and shut down.

[1] Only data of interest at this point are included here.
[2] From zero setting. Indicated as turns of the handwheel.
[3] A lever device enabling the weight of the roll to be relieved at will. Additional space is required at time of furnishing, discharging, or discontinuing operation of the beater.

(*b*) Technical Control.—It is not yet possible to determine the proper control of the beating operation by numerical expression. It might seem that by computing the pressure between the beater roll and the bedplate the manipulation of the roll for effecting the desired results could be determined mathematically. Numerous other factors, however, also enter into the mechanics of beating and the theory of the operation presents a number of problems yet unsettled. Definite comparison of beating processes is limited to beaters of identical construction employing similar material that has undergone the same preliminary preparation. Differences in the condition of the fly bars and bedplate would even then make direct comparison difficult. Even differences in the textile processes employed earlier in the preparation of the rags would prevent uniformity of results. General mathematical control will doubtless be satisfactorily developed, but at present the experience of the paper maker is essential in the production of stock suitable for high-grade papers, such as currency. There are, however, well-established requirements relating to the desired condition of the paper-making fiber that need to be met in the beating operation. A discussion of these requirements follows.

The determining factors of strength of the finished paper are length and separation of the fiber bundles, condition of the fiber ends, and the degree of imbibition of moisture. The corresponding preparation of the fibers in the beater consists of division transversely (reduction in length), division longitudinally (separation into fiber bundles, later into individual fibers, and finally into partial fibers—fibrillas), and absorption or imbibition of water.

In order to produce a sheet of maximum strength, the fibers must be long. If the beater roll is lowered rapidly onto the pulp, the fibers may be so reduced in length and have such clean-cut ends that proper felting can not be secured in the final process. Very gradual application of the pressure of the roll " draws out " the fibers with a minimum of cutting action and the more brushed or frayed out ends insure more and better contacts between adjacent fibers when interlaced on the paper-machine wire. Theoretically the beating should be accomplished without bringing the fly bars into actual contact with the bedplate, although the space between these parts may be no greater at the end of the beating than the thickness of the fibers.

The brushing action of the beater separates the half stuff into fiber bundles. The disintegration of the fiber bundles greatly increases the surface of the cellulose and increases the degree of imbibition accordingly. It is believed that if the mechanical friction due to beating is continued the pressure exerted by the imbibed water causes the fibers to split longitudinally into smaller units, called fibrillas, and the surfaces become of gelatinous nature. Owing to these changes in physical characteristics, water drains from the pulp less readily and the pulp is said to be " slow " or " wet." Pulp receiving more vigorous and rapid beating for a shorter interval has its fibers transversely reduced but less finely divided longitudinally and, therefore, permits water to drain from it more quickly. Such pulp is said to be " free." In order that the stuff in the beater be suitable for the manufacture of strong, high-grade paper, it must possess a certain degree of wetness. Different degrees of wetness lead to different properties in the finished paper. The characteristics of the finished product are largely dependent on the treatment accorded the fibers in the beater.

Fibrillation and resultant wetness increase the binding quality of the materials, due to the cementing action of the gelatinized surfaces and the flexible condition and tendril-like ends of the fibers. The two factors affecting strength of paper are the strength and flexibility of the fibers themselves and their binding action with reference to one another. Maximum strength is obtained when the two are balanced so that a portion of the fibers pull apart and the other portion break. Too much gelatinous material, resulting from too long beating, tends to increase the brittleness of the dried paper and, hence, decreases the strength. With insufficient beating, however, there is too little fraying and splitting of the fiber ends for good interlacing and the lack of the "gel" formation to aid in the binding process also prevents the paper from being of maximum strength.

The wetness of the fibers is controlled not only by manipulation of the roll, but by the dilution of the half stuff as well. If too much half stuff is added in furnishing the beater, especially with large proportions of linen, the pulp circulates slowly, the time required for beating (division and reduction) is increased, and the resultant mass is too "slow" or "wet." The concentration that proved most satisfactory in the currency tests was approximately 3.9 per cent. The speed of circulation of the pulp was from 20 to 27 feet per minute at the beginning of the beating (shortly after the beater was furnished) and from 4 to 12 feet per minute at the end. Since linen becomes "wet" more rapidly than cotton, the exact speed of circulation was partly dependent on the proportion of linen in the beater furnish.

(*c*) Measurement of "Freeness."—Comparison of the stuff (beaten half stuff) of different furnishes can be made to some extent by comparing the rates at which water drains from samples taken from the beaters. Measurements indicating relatively the rate of drainage for the different beaters were made during the currency tests. The measurements on this property of the stuff are termed "freeness."

If the "drainability" of the stuff is considered as dependent on the fibrillation and plasticity of the fibers, the progress of the heating operation could be followed by freeness measurements on samples taken at different stages of the beating. The readings obtained could then be used as a measure of the degree of beating and a means of beater control. Fibrillation causes a slowing of the rate of drainage, but it should be kept in mind that some kinds of fibers by nature drain more slowly than others and that freeness is, therefore, not necessarily a measure of the degree of reduction. The freeness measurements of the currency stuff were used only for comparison of the beaten pulp of the different furnishes. The beating was controlled by manipulation of the roll and was independent of the results of the freeness tests.

The apparatus used in the freeness determinations consisted of a receiver and a conical funnel suspended below it. A wire cloth forms the bottom of the receiver, and the valve, which can be opened or closed as desired, is fastened beneath it. In addition to the usual opening in the tip, the funnel is also provided with a second opening for the discharge of the water received. The second opening is a short distance above the tip and extends downward as a side arm. The water issuing from the side outlet flows into a cylindrical graduate and the measurement recorded indicates relatively the rate of drainage of the stock. If the stock is free the water drains from the receiver readily, the rate of flow exceeds the capacity of the outlet in the tip of the funnel, and the excess is discharged through the side outlet into the graduate. As the stock becomes slower the rate of draining decreases and the amount issuing through the side outlet becomes less. When the rate of flow falls below the capacity of the lower opening, there ceases to be an outflow from the side arm. The amount of water in the graduate indicates relatively, therefore, the " freeness " of the stock.

Samples of constant volume were taken from the beater at the time of completion of the beating operation. Four samples were taken for each furnish. By the addition of different amounts of water to three of these, four different concentrations were obtained. The testing instrument was washed out to wet the sides (insure uniform conditions), the valve below the receiver was closed, and 500 cm^3 of one of the diluted samples, well mixed and cooled or warmed to the desired temperature, were poured into the container. The lid was opened, and after the completion of the discharge from the side arm the volume of the water that had been delivered from the side outlet was read and recorded. The process was repeated for two other concentrations. The three measurements were used later to define a curve for comparative use. The fourth sample was put into an oven to dry and the solid content subsequently determined. Without this latter determination the exact concentration of the samples of the freeness tests could not accurately be ascertained. The curve of the freeness data, however, made it possible for comparisons to be made later at the desired concentration.

It is essential that all freeness measurements be made at the same temperature. The viscosity of water decreases with rise in temperature and the rate of drainage, therefore, increases. Due to the heat generated by the friction of the beating operation, the temperature in the beater increases with longer beating intervals. A difference in the fiber material may also cause a variation. For the currency tests the temperature of the pulp in the beater varied from 70 to 80° F. at the beginning of the beating and from 110 to 125° at the end. The temperature was largely determined by the kind of fiber and the length of time it was in the beater.

When the beating was completed, the stuff (beaten half stuff) was run into a chest on the floor below. The freeness data of Table 1 are on the mixture at the time of running into the stuff chest. The concentration of the test samples was 0.2 per cent and the temperature 80° F.

2. PAPER-MACHINE OPERATION

From the stuff chest the beaten material was pumped in a continuous stream through the stuff box to the Jordan and thence to the paper machine. Jordanning the stock directly to the paper machine is considered better practice than discharging it into a machine chest and subsequently withdrawing it as needed. The former method enables better control of the conditions affecting the stock. An ampere-meter recorder enabled close control of the Jordanning process during the tests.

The following brief description of the paper-machine equipment and processes is included for the reader not familiar with paper manufacture:

The function of the stuff box is to regulate the rate of flow of the stock going to the machine and, by controlling the amount of water added for dilution, regulate the consistency also. The Jordan is a refining engine, named after its inventor, and serves to smooth out the lumps of pulp and brush out the fibers so that they will flow independently in the watery medium. The Jordan is not necessarily an essential part of paper-making equipment, but is very useful in preparing stock for uniform formation on the machine. It consists of a horizontal, conical plug free to rotate inside a conical shell to which it is fitted. Both plug and shell are provided with bars running the length of them and having their edges parallel. The distance between the revolving and stationary bars can be regulated by moving the conical plug, in line with the axis, in the direction desired. The stuff is fed in at the narrow end of the Jordan and by the rotation of the plug it is centrifugally propelled to the wider end, being thereby refined and freed from lumps.

From the Jordan the diluted stuff, now called "stock," passed to a flat 4-plate screen. The screen consists of four strong bronze plates full of narrow slits, 0.024 inch wide, which serve to keep back all unrefined material or foreign particles that may have escaped previous treatment. Only individual or separated fibers are allowed to pass through. The stock passing through the screen was warmed by steam to make it freer and more easily handled on the paper machine. The temperature for the 100 per cent linen furnish was 115 to 125° F.; for the 100 per cent cotton, 95 to 105° F.

The screened stock flowed forward onto a traveling endless wire cloth, containing approximately 70 meshes to the inch. The supporting frame is so arranged that the wire is given a sidewise reciprocating motion, called the "shake." This motion throws the fibers from their position of being parallel to the direction of flow and causes them to interweave in all directions. A better felted and consequently stronger sheet is thereby produced. A rubber strap, called a deckle strap, placed at either edge of the wire prevents the stock from overflowing sidewise.

The bulk of the water drains through the wire mesh as it moves forward and the fibers settle down into a continuous web of paper. As much as possible of the remaining water is removed by passing over suction boxes (placed beneath the wire and maintaining a partial vacuum), under a woolen-covered couch roll, and onto an endless woolen "felt." The sheet is then conveyed through a series of press rolls, where it is squeezed as dry as possible, and over iron drying cylinders heated by steam, where most of the remaining water is evaporated. When the paper comes off the last drying roll it passes between a number of highly polished metal calendering rolls, which impart a polish to the sheet. The paper is then wound on spindles and taken from the machine for test or use.

A dandy roll, a hollow cylindrical roll covered with wire cloth, is sometimes used on the wet end of the paper machine to give the upper surface of the sheet the same appearance as the side in contact with the traveling wire of the machine. If it is desired to watermark the paper, such is usually effected by a pattern in relief on the surface of the dandy roll. When the roll revolves the pattern is impressed in the wet pulp and a thinning in the sheet, corresponding to the design, results.

The operation of the paper machine was very carefully controlled during the tests. The speed was approximately 30 feet per minute and the shake was three-sixteenths inch and 232 revolutions per minute. Two suction boxes were used before the dandy roll and one after. The stock carried considerable water up to the dandy roll, thus permitting the roll to break down high places, close up depressions, and smooth out the sheet. The suction box following the dandy roll permitted the withdrawal of sufficient water to "set" the sheet before going through the couch and off the wire.

Some attempt was made to watermark the paper, but the results obtained were unsatisfactory. A clear watermark is not feasible with long-fibered or slow stock. Moreover, for currency purposes, the watermark is of no particular value since it can be easily duplicated and would doubtless be somewhat obliterated by the wetting process to which the paper is subjected preparatory to the intaglio printing (printing from engraved metal plates).

VI. TEST DATA ON FINISHED PAPER

1. WATERLEAF

Table 1 gives data relative to the furnish and operation of the beater for each machine run and various measurements on the finished waterleaf or unsized paper. The purpose of the tests and the apparatus and methods employed in obtaining the measurements are either described herein or are available in other publications.[6]

TABLE 1.—*Test data on finished (waterleaf) paper*

Machine run No.	Fiber composition		Beating		Physical tests			
	Linen	Cotton	Time interval	Freeness reading	Weight, 25 by 40—500	Bursting strength	Ratio of bursting strength to weight, 25 by 40—500	Thickness
	Per cent	*Per cent*	*Hr. Min.*		*Pounds*	*Points*	*Per cent*	*Inch*
547	100		12 00	25	64.1	52.9	82.5	0.0040
548	100		14 30	27	61.4	49.1	81.4	.0040
534	75	25	13 15	(1)	63.9	47.1	73.4	.0036
535	75	25	11 50	(1)	57.2	44.5	77.8	.0032
538	75	25	9 30	(1)	64.3	47.5	73.9	.0036
539	75	25	11 30	60	63.0	48.5	77.0	.0037
542	75	25	12 00	42	64.2	49.5	77.1	.0039
540	50	50	10 30	74	59.5	39.6	66.6	.0034
541	50	50	14 00	55	61.5	46.6	75.8	.0037
543	25	75	14 0	75	60.6	39.4	65.0	.0037
544	25	75	16 0	74	63.1	42.8	67.8	.0042
545		100	14 30	100	60.8	37.5	61.7	.0042
546		100	18 00	102	61.9	35.3	57.1	.0043

Machine run No.	Physical tests							
	Folding endurance		Tensile strength		Tearing strength		Opacity	Finish (gloss)
	Machine direction	Across machine direction	Machine direction	Across machine direction	Machine direction	Across machine direction		
	Double folds	*Double folds*	*kg*	*kg*	*g*	*g*		*Per cent*
547	3,947	6,116	10.55	5.56	151.2	145.6	0.880	28.7
548	4,460	3,955	9.62	4.79	178.4	151.2	.886	26.6
534	5,330	3,615	9.97	4.71	161.6	157.6	.900	32.5
535	5,145	5,665	8.38	4.57	161.2	146.4	.871	29.5
538	5,370	6,235	9.57	5.27	175.2	170.4	.896	27.5
539	5,430	6,880	9.36	5.16	169.6	170.8	.883	25.8
542	5,760	4,995	10.61	5.34	149.6	148.8	.882	29.0
540	4,910	3,780	8.36	4.54	158.0	142.4	.872	29.0
541	5,730	5,025	8.97	4.66	156.0	148.0	.894	24.8
543	3,685	2,985	8.16	4.56	160.0	154.4	.876	27.0
544	4,120	3,656	8.68	4.72	154.0	155.2	.871	27.2
545	4,462	1,548	7.63	3.99	157.2	159.6	.885	28.5
546	2,667	1,436	6.78	4.17	161.2	160.0	.864	29.7

[1] Runs Nos. 534, 535, and 538 were made before freeness tests were begun.

[6] The Testing of Paper, B. S. Cir. No. 107, price 10 cents. More recent information is given in Paper Testing Methods, published by the Technical Association of the Pulp and Paper Industry, 18 East Forty-first Street, New York, N. Y. Specifications of the Transparency of Paper and Tracing Cloth, B. S. Cir. No. 63, price 5 cents. "The Glarimeter and the measurement of the finish of paper," R. E. Lofton, Paper Trade J., 80, No. 7, pp. 47–49 (Feb. 12, 1925). See footnote 4, p. 93.

Strength tests on paper show, in general, the resistance of the paper to a rupturing force. Variation in the method of application of the force permits measurement of the different qualities reported in Table 1 as bursting, folding, tensile, and tearing strengths. Bursting strength shows how well the fibers are felted together; that is, their adhesion. Folding endurance shows the flexibility of the fibers and their resistance to breaking due to folding. Tensile and tearing measurements indicate the load required to break and pull apart a strip of definite width.

The suitability of paper for currency use depends not only upon its strength and durability but also upon its ability to meet the printing requirements. Although the waterleaf paper is tub-sized (dried and passed through a bath of glue and hung over poles to dry) before being submitted to the printing operation, the uniformity and surface of the waterleaf sheet are factors in the results obtained. These qualities can not be reported numerically, but consideration of them should supplement the other physical qualities in the final evaluation of the paper.

The results of measurements on the finished paper of the above tests indicate the following:

As to fiber composition, the mixture of 75 per cent of linen and 25 per cent of cotton gave the best results. This composition gave the best folding quality and was as good as the other compositions in other respects. The formation and surface of the sheet were better than for the 100 per cent linen. The papers containing larger amounts of cotton were, in general, weaker in folding endurance and, being softer in texture, the surface of the paper was more likely to fuzz when in actual service.

The beating interval that seemed to give the best results was, for the 75–25 mixture, approximately 12 hours. The results, as shown in Table 1, were equally as good as for the other intervals and the formation was much better. The strength of the finished paper was largely attributable to the fibers being long and well brushed out at the completion of the beating.

The freeness readings were dependent on the kind of fiber (linen is much slower than cotton) as well as the duration of the beating. The results of tests herein given on this property are not sufficient to permit definite statement as to the effect of freeness on the quality of the paper. The fibers must be beaten long enough to produce smoothness, but not so long as to produce weakness.

The use to which paper is to be put determines the kind of test to evaluate its quality. Currency paper should have a high resistance to repeated folding (which is dependent on the strength and durability of the paper) and must meet the printing requirements. At the time of the beginning the tests reported herein, the folding of the tub-sized[7] currency paper then in use was approximately 2,000 double folds. The folding endurance of the waterleaf paper of the experimental tests greatly exceeded this amount. As the result of modifications in the commercial production processes in accordance with the results of the investigation, the currency paper now being supplied has at least double the strength of that formerly in use.

2. SPECIAL PAPERS

In addition to the tests already described, five machine runs were made from stock containing size or filler mixed with the pulp in the beating operation. It was desired to compare the strength of papers containing these materials with the corresponding property of the sheet containing fiber only. As shown in Table 2, the fiber composition of three of the runs was 75 per cent linen and 25 per cent cotton. The other materials added to the beater furnish for these runs were 1 per cent of rosin size (based on weight of dry fiber), 2 per cent of glue size, and 1 per cent of rosin size with 5 per cent of clay, respectively. The fiber content of the fourth and fifth runs was 100 per cent cotton, the textile material being white canvas ducking. The first of these latter runs was similar to the regular currency run of this composition and permits comparison of the paper-making value of the cotton materials employed; the second differed only in the addition of 1 per cent of rosin size.

In comparing the unsized papers of Table 1 with the papers of Table 2 it will be noted that the unsized sheet has higher resistance to tear, greater tensile strength, and better folding endurance. This indicates, at least within certain limits, that strength is attributable to the flexibility and softness of the fibers as well as to their length. When paper is engine sized (size added in beater furnish) the sizing material is precipitated upon the fibers. The fibers of unsized paper (waterleaf) are not so coated and retain their natural elasticity and strength. Under the action of the shake on the machine the unsized fibers also felt more closely than the fibers stiffened by the coating material. The run on 100 per cent cotton (canvas ducking) without size compares favorably with the 100 per cent cotton paper of Table 1, but the addition of rosin seems to have considerably weakened it.

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[7] In addition to improving the regularity of the surface for printing purposes, tub-sizing also increases the endurance of paper against folding and continual rough handling.

TABLE 2.—*Test data on finished paper of special runs*

Machine run No.	Beater furnish				Beating		Acidity of machine water	Physical tests		
	Fiber composition		Size	Clay	Time interval	Freeness reading		Weight, 25 by 40 −500	Bursting strength	Ratio of bursting strength to weight, 25 by 40 −500
	Linen	Cotton								
	Per cent	*Per cent*	*Per cent* [1]	*Per cent* [1]	*Hr.-Min.*		pH	*Pounds*	*Points*	*Per cent*
549	75	25	1, rosin		12 00	42	5.4	63.0	38.5	61.1
550	75	25	2, glue		12 00	43	4.4	62.7	42.9	68.4
551	75	25	1, rosin	5.0	12 00	47	4.4	61.5	33.2	54.0
552		100			16 00	116		60.3	36.1	59.9
553		100	1, rosin		16 00	124	4.3	61.6	34.4	55.8

Machine run No.	Physical tests									Chemical tests	
	Thickness	Folding endurance		Tensile strength		Tearing strength		Opacity	Finish (gloss)	Ash	Size
		Machine direction	Across machine direction	Machine direction	Across machine direction	Machine direction	Across machine direction				
	Inch	*Double folds*	*Double folds*	*kg*	*kg*	*g*	*g*		*Per cent*	*Per cent*	*Per cent*
549	0.0041	3,355	2,055	8.23	4.04	152.0	152.8	0.881	29.1	0.7	0.8
550	.0041	2,300	3,145	9.05	4.83	154.8	144.8	.895	31.3	.6	[2] 1.3
551	.0040	1,540	1,020	7.84	3.73	151.6	146.4	.905	29.7	4.9	.96
552	.0042	4,320	1,920	7.89	4.00	200.0	188.0	.865	25.0	.13	[3] .35
553	.0044	3,190	445	6.89	3.58	189.6	180.8	.892	25.7	.41	1.09

[1] Based on weight of fiber.
[2] Glue was added as sizing agent, but finished sheet was waterleaf.
[3] Size not removed from textile material by paper-making process.

In run No. 550 glue was added as the sizing material, but the finished sheet was waterleaf. No improvement except in the feel was noted in the paper. Filler produces a more even or smoother surface but separates the fibers and, as shown in the table, weakens the paper.

The measurements indicate that beater furnish consisting of fibers only is more satisfactory for currency use than furnish to which sizing or filler material is added. In either case the paper would later be tub-sized in order to afford protection to the sheet and improve the printing quality. The purpose of the foregoing tests was for the improvement of the paper-machine product only.

VII. CONCLUSIONS

The very satisfactory quality of the paper made in the experimental tests was attributable chiefly to the manner and duration of the beating treatment of the fibers. The principal contributing factors in increasing the strength of the paper were the very gradual application of the beater-roll pressure and the low concentration of pulp during the beating process. The concentration employed was approximately 3.9 per cent; the beating interval that gave best results was 12 hours (fiber composition, 75 per cent linen and 25 per cent cotton).

The paper produced was of much greater folding endurance than that in use at the time of the investigation. The results of the experimental tests have been applied in commercial production, and paper of 100 per cent greater folding endurance than the paper previously supplied is now being received for currency use.

WASHINGTON, June 15, 1926.