The Institute of Paper Chemistry

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Doctor's Dissertation

A Photographic Study of the Motion of Fibers and Water in Flowing Fiber Suspensions

by Lamar A. Moss

June, 1937

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A PHOTOGRAPHIC STUDY OF THE MOTION OF FIBERS AND WATER IN FLOWING FIBER SUSPENSIONS

A thesis submitted by

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TABLE OF CONTENTS

Chapter		Page
I.	INTRODUCTION	1
II.	LITERATURE SURVEY	
	A. Historical	3
	B. Patent Survey	
	1. Head Box Designs	20
	2. Agitators and Rectifiers	22
	3. Vertical Slices	23
	4. High Pressure Inlets	23
	5. Inlets without Slices	25
	6. Methods of Slowing Drainage on the Wire	25
	7. Treatment after the Slice	25
III.	PRESENTATION OF THE PROBLEM AND METHOD OF ATTACK	
	A. Scope of Usefulness and Development of Improvements	27
	B. Use of the Modified Technique in making a Study of Various Stock Flow Conditions	
	1. Conditions below a Single Vertical Slice	29
	2. Conditions around Various Slice Designs for Comparison	30
	3. Head Box Conditions	31
IV.	MATERIALS, EQUIPMENT, AND PROCEDURES	
	A. Materials	32

TABLE OF CONTENTS (Continued)

Chapter — Page

B. Equipment

1. Lighting System 33
2. Stock Circulation System 36
3. Camera 39
4. Slices, Inlets, Agitators, Vanes, Baffles, etc. 39

C. Procedures

1. Preparation of Stock in the Circulation System 49
2. Cleaning the Glass Surfaces in the Optic System 50
3. Insertion of the Slice 50
4. Alignment of the Optic System 51
5. Taking the Pictures 52
6. Developing Film and Prints 53
7. Photographing the Action of the Acceleration under the Slice on Breaking up of Fiber Bunches 53

V. DISCUSSION OF IMPROVED TECHNIQUES, PRESENTATION OF DATA, AND DISCUSSION OF RESULTS

A. Scope of Usefulness of the Technique and Modifications Consistent with Better Results

1. Lighting Theory 55
2. Thickness of the Stock Layer 58
3. Size of the Field 59
4. Dyed Fibers for Greater Contrast .. 59
5. Cleanliness and Evenness of Surfaces in the Optical System 60
6. Use of Pendulum Timer to Avoid Disadvantages of the Focal Plane Shutter 62

TABLE OF CONTENTS (Continued)

Chapter — Page

7. Use of Copper Slices with Rubber Gaskets to Avoid Time Losses in Sealing in Glass Slices 63
8. Blocking out Areas of the Light Beam not Important in the Picture . 63
9. Scope of Application 64

B. The Single Vertical Slice

1. General Considerations
   a. Stream Approaching the Slice. 65
   b. Under the Slice 71
   c. The Stream from the Slice ... 97
   d. Effect of Consistency and Beating 99

2. Effect of Rectifier Plates back of the Slice Lip 105
3. Effect of Relative Positions of the Slice and the End of the Apron 107

C. Slice and Inlet Designs

1. The Double Slice Inlet
   a. Conditions of Flow with the Slices 6 inches Apart 109
   b. The Effect of Distance between the Slices 116

2. The Slanting Surface Inlet
   a. The Effect of Angle 120
   b. The Effect of a Ridge in the Apron Cloth across the Machine 125
   c. Slanting Surface on the Bottom of a Vertical Slice 125

3. The Curved Slice 133
4. The Roll Inlet 133
5. The Dam-Type Inlet 135
6. Nozzle Inlets 135

TABLE OF CONTENTS (Continued)

Chapter — Page

D. Flow Conditions in the Head Box

1. Gough's Recirculation Design 140
2. A Four-Pass Head Box 142

VI. SUMMARY AND CONCLUSIONS 145

VII. LITERATURE CITED 155

TABLE OF ILLUSTRATIONS

Figure		Page
1.	Photograph Lighting Equipment	34
2.	Diagram of Pendulum Exposure Timer	34
3.	The Stock Circulating System with the Glass Trough	37
4.	Photograph of High Pressure Head Box	38
5.	Diagram of High Pressure Head Box	38
6.	Details of the Copper Slice Construction ...	40
7.	Details of Flow Control Devices	41-45
8.	Wire Hooks for Transferring Tiny Bunches of Fibers	48
9.	Alignment of the Optic System	51
10.	Comparison of Converging and Parallel Beams of Light	56
11.	Paths of Light Rays Forming the Images in Ordinary Photography Compared with those of Silhouette Images	56
12.	Fiber Behavior in a Free-Flowing Stream	67-68
13.	The Stream just back of the Slice	70
14.	The Effect of the Type of Lip on the Slice .	72-76
15.	Pressure Head Measurements	78
16.	The Stretching Action of Acceleration under the Slice	80
17.	The Stretching and Aligning Action of Acceleration under the Slice	81

TABLE OF ILLUSTRATIONS (Continued)

Figure		Page
18.	The Velocity Gradient between Layers in a High Speed Stream from the Slice with a 2-Foot Head	85
19.	The Curved Surface Inlet	88
20.	The Effect of the Head Back of the Slice	91-92
21.	Size of Slice Opening	95-96
22.	Fiber Behavior in the Stream at Various Distances from the Slice	98
23.	Effect of Consistency and Beating	100-102
24.	The Effect of Rectifier Plates back of the Slice Lip	104
25.	The Effect of Relative Positions of the Slice and the End of the Apron	106
26.	The Double Slice Inlet. Conditions of Flow with the Slices 6 Inches Apart	114-115
27.	The Double Slice Inlet. The Effect of Distance between the Slices	118-119
28.	The Slanting Surface Inlet. The Effect of the Angular Position of the Slice	122-124
29.	The Slanting Surface Inlet. The Effect of a Ridge in the Apron Cloth	126
30.	The Slanting Surface Inlet. A Slanting Surface on the Bottom of a Vertical Slice	130-132
31.	The Curved Surface Inlet. The Roll-Type Inlet	134
32.	The Dam-Type Inlet	136

TABLE OF ILLUSTRATIONS (Continued)

Figure		Page
33.	Nozzle Inlets	138-139
34.	The Head Box. Gough's Recirculation Design.	141
35.	The Head Box. A Four-Pass Head Box	143

CHAPTER I.

INTRODUCTION

Throughout the entire history of papermaking it has been the aim of investigators and designers to understand the behavior of paper fibers in the flow of the stock, and to use this knowledge in the design of equipment which would modify and control this flow of stock to the moving wire so that the desired formation and strength properties might be obtained.

Up to the present time this aim has not been satisfactorily realized, because no technique has been available for actually observing the fiber movements in the flow of stock. Each worker, therefore, has had to formulate his own theories by pure reasoning or by analogies, and the many conflicting views on the subject have led to slice and head box designs so inconsistent with each other that it would be of real value to establish fundamental knowledge of this flow and prove which points of the conflicting theories are correct.

Bryant (1) has recently developed a method for photographing the individual fibers in motion during stock

flow, and it is the purpose of this paper to describe the utilization of this technique in a study of the flow of stock and the movements of the individual fibers.

CHAPTER II

LITERATURE SURVEY

A. HISTORICAL.

Although this study deals primarily with the laws of hydrodynamics governing the movement of individual paper making fibers in dilute water suspension, it is made for the purpose of shedding new light on the motion of the fibers in paper stock during their flow through the head box and the slice opening or inlet and out upon the moving wire. Therefore, it is essential that the survey should cover, not only existing literature on the movements of the individual fibers in stock flow, but also that on head box and slice operation, theory, and design. This review also includes the American patent literature from 1918, and foreign patents as far as available.

The abundant literature on the subject of stock flow, sheet formation, and the action of the head box and slice shows the paper maker's intense interest in these subjects, and the number of current articles on the subject gives ample proof that the interest is still active and that the possibilities of the problem have not been exhausted. Most of the available information on the subject is of an empirical, rather than a fundamental nature, so that the

sheet formation in most mills is still an "art" rather than a "science". Although many of the factors involved in the initial deposition of the "mat" or "web" of fibers on the wire have been analyzed on a practical and semi-scientific basis, there is still need for fundamental information.

General discussions of the action of the head box and slice (2-8), as well as historical accounts dealing with their development to meet the increased speed requirements (9-12), have been published.

The first paper machine (9) to successfully use an endless wire web was made by Nicolas Louis Robert in Essonnes, France in 1799. The stock feed device for this machine consisted simply of a revolving fan for throwing the stock from the beater vat over the slowly moving wire and against a baffle plate which distributed it. This arrangement was not entirely satisfactory. Subsequently the patent rights were purchased by the Fourdrinier brotners in England, and with the assistance of Bryan Donkin they greatly improved the feed mechanism by replacing the Robert arrangement with a head box from which the stock flowed over a slide to the wire. This stock stream, however, was found to be disturbed by eddies, rivulets, and waves which caused uneven thickness and varied formation across the machine. Hence the slice was introduced; as the name implies, its purpose was

to slice off or smooth out the surface unevenness. As higher speed machines were developed it was found that a head box of this slice could be made to give the necessary acceleration to the stock stream to obtain a satisfactory formation for speeds up to about 400 feet per minute. There has been no really fundamental change in the wet end of the paper machine since that time (1803).

By 1867 presses, driers, and, finally, the calender stack had been added to the paper machine, thus making available all the mechanical parts necessary for high speed production. The maximum width and speed attained at that time were 60 inches and 100 feet per minute, respectively. In 1886 a machine was constructed with a 112 inch wire and a maximum speed of 250 feet per minute, and by 1896 a few machines were running at 450-500 feet per minute. A speed of 1000 feet per minute was not reached until 1921. These later speed increases were accompanied by further increases in width. In 1923 a 234-inch, and, later several 260-inch wires, were installed. A 320-inch machine recently installed in England is the widest one to date. This machine was designed for a maximum speed of 1400 feet per minute. A width of this magnitude would seem to be near the practical limit. Improved business conditions now make greater speeds desirable, but such speed increases must await further developments in the design of inlets, which, in turn,

must await further fundamental knowledge of stock flow. Drainage on the wire and drying also offer serious difficulties at higher speeds but they are not a part of the present problem.

The ordinary slice, which may be considered as an inverted weir (2), is still used today on many slow machines with no fundamental change from the design originally introduced. Two, or even three slices, rather than one, are used in most cases; but, according to Green (2), on machines equipped with more than one slice, it is not uncommon to have only the last one in contact with the stock. The object of the multiple slice is to obtain better agitation of the stock by giving it alternate periods of impetus and rest on its way to the wire. In any event, it is the last slice that imparts the final horizontal speed to the film and governs its thickness. An apron covers the wire from the lip of the head box to a point just short of the last slice, a point usually about coincident with the first table roll. This apron is supported by an apron board which spans the gap between the head box lip and the breast roll; its edges are bent upward and fastened to plates on either side to prevent loss of stock before the deckle mechanism is reached.

Such a simple slice is made of two plates which overlap at the center of the machine, and are clamped to-

gether to maintain a straight lower edge and to allow adjustment for the width of sheet to be made. Slices six to fifteen inches in height are common, the higher slices being used on the wider, faster machines. The double slice principle may be, and is, used as a type of high pressure inlet (2).

The slice is adjustable at its two ends as to distance above the apron or wire. In the two slice arrangement, the first slice is set higher than the second but low enough to make a difference in head between the main pond and the pond between the slices. This difference is said to give a measure of the agitation obtained. The height of the second slice, in conjunction with the hydrostatic head back of it and the stock consistency, determine the weight of the sheet produced (2).

A serious limitation to the straight or low-head slice (2) has always been that, regardless of the form of the lower edge, the top and bottom of the issuing stock stream receive widely different treatment. The top drags forth under the edge of the slice and emerges with its upper surface concave upward. Then it proceeds on its way, influenced only by the layers of stock under it. Meanwhile the bottom is sliding over the apron horizontally, with no change in direction. Then, just before it issues from the slice, it strikes the moving wire, either at wire speed, or

overrunning or lagging behind it, as the case may be. This difference in treatment between the upper and lower strata of the stock stream produces counter currents and eddies, causing the fibers to be deposited on the wire in various states of disorder, variously affecting the sheet formation. This condition can only be avoided by designing the inlet so that the same treatment is given to both the top and bottom of the stock stream. With increase in head back of the slice these differences, which are almost negligible at slow speeds, have been found to increase sharply (2, 28); this is supposed to be the reason that such slices do not give satisfaction at high speeds, even though they give fair results at low speeds and low heads.

The development of the high pressure inlet was necessary, therefore, as an approximate fulfillment of this requirement, before speeds of over about 400 feet per minute could be attained. Simplest and earliest of these inlets was a single high vertical slice, with a hinged lip at the bottom, slanting downward and forming a nozzle with the horizontal apron. An outgrowth of this type was the design which carried the nozzle construction back to the head box, by providing a continuous streamlined cover to guide the flow. Excellent illustrated discussions of the various inlets have been published (2, 3, 4, 10, 12). Most of these high pressure slices or inlets are of either the curved Van

de Carr type (63) or the straight Voith type (69), both of which have an adjustable, flexible upper lip set at an angle to form a nozzle with the apron or wire (9). The cast bronze originally used for this upper lip has been successfully replaced by flexible stainless steel which does not require frequent polishing of the nozzle surfaces to insure smooth flow. Chromium plating of both the upper and lower inlet surfaces has also proved effective. The nozzle principle has been carried still further in the Bell-Irving inlet, which has a cross section similar to that of a hydraulic nozzle; its lower lip slopes upward to make more similar the motions of the top and bottom layers of the stream (28).

In all of these inlets there are fine vertical adjustments at close intervals across the machine working on the flexible lip to give a precision method of equalizing the sheet weight over the entire machine width. These were the only adjustments on the earlier designs, but it was later found to be advantageous to adjust the height of the vertical slice as well, to permit control of the slope of the lip as well as the size of the opening. Further adjustment of this vertical wall made it possible to locate the nozzle tip as desired relative to the breast roll center line. Ordinarily the tip is located directly over the breast roll center line for high speed, but for very slow stock it is

said (2) to be better to move the tip about an inch forward with the apron still ending just over the center line.

All types of inlets are fitted with some means of evening the flow across the machine and of agitation for preventing, or breaking up, lumps of fiber. The head box plays a part by directing the flow over and under the baffles to give agitation by changes in direction and velocity of flow. A great number of mechanical agitators and flow evening devices have been designed, but their relative merits are a matter of controversy. A revolving cylinder of perforated sheet metal just before the inlet throat (Voith) is the most common type.

Investigation of the problem of what constitutes satisfactory stock delivery has not been very fruitful, but according to the literature it is desirable to have a jet with as little turbulence as possible and with a velocity very nearly equal to that of the wire. These conditions are what would be expected in view of the fact that they approximate the ideal conditions in a hand sheet mold where there is no relative horizontal motion between the stock and the wire. In approximating these ideal conditions the inlet is the most important single factor. Its best operation requires that stock passing under it from the head box be uniformly dispersed and free from all but very small eddies.

Gough (7) has described the functions of the head box and slice as follows:

"To receive, usually 3 or 4, localized, narrow and turbulent streams of stock from the screens and to deposit this stock and water on the rapidly moving Fourdrinier wire in one wide continuous, smooth, uniform, and well-mixed sheet, and ideally to do this at the speed of the wire and in such a manner that there will be no eddies or shock, so that the fibers will be quite uniformly distributed, both as to direction and quantity, lengthwise and crosswise of the wire. While it is true that the actual felting of fibres occurs subsequently on the wire, and that the quality of the felting is therefore dependent in a large measure upon conditions there, such as the number, diameter, spacing and condition of the tube rolls; length and slope of the wire; fibre quality and consistency; and the presence or absence of shake and dandy rolls, etc.; (and the position and intensity of suction application); nevertheless, this same quality of felting upon which formation and much of the finish and strength of the finished sheet depends, is also considerably affected by the conditions imposed by the flow box, slice, apron, and the relation of the slice and apron to the breast roll. ... No matter how perfect other machine conditions may be, incorrect setting of the relative location of slice, apron and breast roll, or of pond height, can ... cause serious imperfections in the sheet: up-ended fibres, so-called "rollies" or "worms", too much or too little directional or lengthwise strength, cloudy formation, and air bubbles."

Gough also emphasizes the fact that the two functions of the head box are mutually inconsistent, i.e., minimum turbulence and eddies, and, at the same time, minimum flocculation. The head box can accomplish one of these functions only at the expense of the other.

A host of head box designs have been introduced, but here again the merits of each are by no means agreed upon by paper makers. For a time the tendency was toward more and more baffles and passes, but now the tendency has

turned and many single pass head boxes are in use on the newer machines in order that the stock may be delivered from the screens, where it is in a perfectly dispersed condition, to the wire before enough time has elapsed to allow flocculation. Information on head box designs may be found in the following references: (2 - 8, 10 - 12).

To obtain satisfactory sheet formation, it has been found necessary to close up the sheet quickly and to slow up drainage of water immediately after the stock meets the wire. While the character of the stock is the most important single factor affecting this, the slice is the most critical machine factor. Strachan (13) states that the shake also plays an important part by aiding the fibers to work down into a compact mass which will slow up drainage and keep the upper layers of stock in a thin enough suspension so that the shake can play its part in aligning part of the fibers across the machine. Other investigators (22) question the action of shake for crossing fibers, however. Sufficient dilution of the stock and fewer table rolls are recommended (13) for obtaining slower drainage. Williamson (14) gives a further discussion of drainage control.

Like all colloidal materials in liquid suspension, the fibers in paper making stock tend to flocculate to a greater or less degree depending on conditions such as pH, the amount and type of sizing agent used, fillers, degree of

beating, consistency, and the presence or absence of frothing (15, 16). This flocculation is a process of aggregation of suspended solids, whereby the particles tend to gather together in little bunches or flocs with intervening spaces of clear liquid. Sheet formation involves both settling, or sedimentation action, and drainage, or filtration action; both processes are accelerated by flocculation. The shake, on the other hand tends to break up these flocs, close up the sheet, and slow up the drainage. Any flocs that form and are not broken up give a cloudy, spotty appearance to the sheet and also lower its strength; too rapid drainage resulting from flocculation decreases the effectiveness of the shake (14, 15). For further information on the effect of stock properties on sheet formation, the following references in the bibliography are cited: (17 - 20).

In this connection the strong dewatering action of the table rolls plays an important part. Campbell (21) has calculated that, on a news machine at 1200 feet per minute, the table roll suction effect would be equivalent to a vacuum of 20 inches of water. Lund (5) emphasizes the alternate pressure and suction caused by the table rolls as aids to the felting action. To obtain slower dewatering some of the table rolls may be removed or boards may be used as supports for the wire to retard the drainage on the wire area over the board surface.

The suction also has a very important influence on sheet formation. Strachan (13) states that improper application of suction at the first suction box may seriously injure what was a good sheet up to that point.

Robertson and Bailey (22) have found that the action of the presses and the stretching in driers increases the orientation of the fiber in the machine direction while the shake has little effect on orientation but does give more uniform distribution and felting together of the fibers, thereby increasing the strength of the sheet (see also 4 and 28). Venneman (33) proposes reciprocating air jets directed against the stock on the wire to aid the action of the shake.

Hydraulics of the Flow through the Slice: Although the literature abounds with general articles on the slice and head box, there is a pronounced scarcity of definite data as to the relation of the head to the jet speed and the wire speed: and only two or three papers have dealt with the actual fundamental hydrodynamics involved.

A number of authors have published articles concerning these speed relationships (5, 6, 23-27) giving the formula $v = \sqrt{2gh}$, or some variation thereof, for making calculations. While some of the authors use the formula as it stands, most of them apply certain corrections:

either a factor less than unity on the right side of the equation to correct for friction losses under the slice or a correction for the initial velocity of the stock as it approaches the slice. These two effects tend to counteract each other so that, in many cases, the uncorrected equation would be very nearly correct. In any event these equations can only be approximate and further minute adjustments of the head have to be made on the machine to obtain the best conditions on the wire.

No exact measurements of velocity versus head have been made, but it is undoubtedly true that this is affected by the form of the inlet or slice, and the agitators or flow evening devices used, as well as the stock characteristics to some extent. For any definite machine speed and sheet weight the head can only be adjusted by varying the amount of water used for dilution, and this adjustment is limited by the dewatering capacity of the machine. This may be expressed mathematically by the equation:

$$W = K\sqrt{2gh}\ AC$$

where W is the weight of dry stock delivered through the slice per second. If W is to be kept constant with a constant head h back of the slice, then AC (the area of the slice opening times the consistency) must be kept constant. Now if A is kept constant but h is varied to

change the velocity of the stream from the slice, then, according to the equation, the consistency C must also be adjusted if W is to be kept constant.

Lund's article (28) on "Hydraulics and Paper Machine Sheet Formation" seems to be the best discussion in the literature on the fundamentals of slice hydraulics and their effect on sheet formation. He emphasizes the necessity at high speeds for more uniform discharge velocities in different horizontal planes above the wire than can be obtained with a straight slice. When a flowing fluid changes its direction, the centrifugal force produces a pressure gradient along the radius of curvature of the streamlines at any point, in such direction that the pressure increases from the concave to the convex side of the stream. This increased pressure retards the flow so that the highest velocity is found at the place where the pressure is lowest, i.e., at the top of the stream from the slice. In the case of a vertical slice the turn is very sharp and the radius of curvature of the streamlines is small. This gives relatively large pressure and velocity gradients from top to bottom of the stream as is clearly shown by the following formulas:

$$(1)\ \underline{H} - \underline{h} = \frac{v^2}{2g}(1+\underline{k}); \quad (2)\ \underline{h} = \frac{1}{g}\int_{\underline{r_1}}^{\underline{r_2}} \frac{v^2 dr}{\underline{r}} \simeq \frac{v^2}{g}\int_{\underline{r_1}}^{\underline{r_2}} \frac{dr}{\underline{r}} = \frac{v^2}{g}\log\frac{\underline{r_2}}{\underline{r_1}}$$

where H is the head back of the slice, h is the head due to centripetal acceleration, k is the friction coefficient, r is the radius of curvature of the streamlines where dr is considered, and r_1 and r_2 are respectively the minimum and maximum radii of curvatures of the stream. If the velocity at the top of the stream is obtained from the formula, $H \quad v^2(1 \quad k)/2g$, that at the bottom of the stream is given approximately by the first formula above, and it is easily seen that the latter velocity is smaller than the former.

The high pressure inlets, on the other hand, avoid this sharp change in direction of flow and give much greater radii of curvatures for the streamlines and allow higher velocities before too high a velocity gradient is reached.

Lund (28) rejects the classical comparison with a log in a stream because the fiber has approximately the same specific gravity as the water and would therefore (he states) travel at the water speed. Furthermore, the flexible fiber would bend under the action of forces similar to those he pictures for the log. In place of this old theory to explain the universal tendency of fibers to form in the sheet in the machine direction, he advances one based on the rapidly decreasing velocity of layers from top to bottom of the jet from the slice as discussed above. He states: "It is obvious that any particle of significant dimensions (i.e.,

a fiber), which is sustained in such a current, will be in contact with two layers of water: those on the under and upper sides, which are moving at different velocities. The slower velocity (on the bottom) will produce a drag on one side of the fibre; the faster velocity will accelerate the other side of the fiber. The result will be to impart a whirling or rotating motion to the fiber. ... If the velocity on the surface of the stock mixture as it flows out on the wire is greater than the speed of the wire, it will tend to disturb the formation .... The best we can hope to obtain at this point is a speed equal to the wire speed. ... the velocity will decrease the closer we get to the wire, ... and ... as the first layer of fibers hits the wire the majority of them will hit with one end first. Not having obtained the same speed as the wire, most of them will be turned in the machine direction, and form a very dense sheet with the grain decidedly in this direction. This process will continue from plane to plane, and as the speed of the fibers in relation to the wire increases, the turning of the fibers will be less and less marked ... closer to the surface of the sheet."

Lund pictures shake as only effective on fibers not lined up in the machine direction, since fibers so lined up would simply follow an elliptical path about an axis parallel to the fiber length, while the lower ends of randomly oriented fibers would get entangled in the wire to be whipped down crosswise by the shake.

To sum up, Lund pictures random orientation of fibers in smooth flow, random orientation through the inlet with end over end rotation due to difference in velocity between layers of the jet, and preferential forming of the fibers in the machine direction due to differences in speed between the stock and the wire and between layers of the stock.

Illuminating and Photographing Liquid Currents.

Prandtl (29) has given an excellent resume, with references, of the techniques used for illuminating and photographing liquid currents. This seems to be fairly comprehensive up to the date of publication. Schmeischek (30) has given a method for preparing a fine suspension of metallic silver, and proposes its use, with lateral illumination, for photographing currents. However, it was not until Bryant (1) devised his technique for obtaining silhouette images of normal fibers that a study of fiber movements could be made. This technique will be considered in detail later in this paper. High tension electric sparks as sources of very high speed intermittent light for photographic purposes were in use in Germany prior to 1913 for studying ballistics at frequencies as high as 100,000 flashes per second (31); and Foley and Souder (32) in this country were using lower frequencies to photograph sound waves at about the same time; thus the use of this photographic light source is by no means new. However, Bryant seems to be the first investigator to apply it to the study of stock flow and to successfully photograph individual fibers during stock flow. The frequency used in his technique is 120 flashes per second or that normally resulting from a 60-cycle alternating current source. The duration of an individual discharge or flash is about 0.000,003 second.

B. PATENT SURVEY

A study of the patent literature on the design of inlets and headboxes shows clearly the wide differences of opinion on the subject of stock delivery to the wire. In the following survey these differences will be emphasized.

1. HEAD BOX DESIGNS

Berry (36) has patented a five pass head box with rounded corners and with one agitator in the second pass, one in the third and two in the last pass; and then thin rectifier plates just back of the inlet to insure uniform mixing and freedom from lumps. The agitators consist of driven paddle wheels extending across the machine with eight perforated blades arranged radially.

Lang (37) adapts the Voith inlet to slow machines by providing a trough across the machine back of the inlet to allow complete submergence of the perforated agitator and flow evener roll. An adjustable baffle over this roll causes all the flow to pass through this roll.

Wood (38) advocates a streamlined design in which the stock enters a compartment just back of the inlet, and flows from here over an adjustable dam back down, around and underneath this compartment and up to the inlet consisting of a long narrow nozzle adjustable across the machine.

Aldrich and Berry (39) admit the stock to the head box through a revolving perforated cylinder across the box width. In another design Berry (40) offers a somewhat similar device placed directly over the wire just in front of the breast roll and including a fiber crossing device consisting of reciprocating bars across the machine with fins to create gentle eddies. In still another design Berry (41) combines the head box and the screen to avoid the ordinary, comparatively small, fast streams of stock entering the head box from the screens.

Trimbey and Walker (42) recommend replacing the head box by a current and eddy baffling device consisting of a freely rotating shaft carrying six radially placed paddles along its length with edges sufficiently flexible to bend under their own weight as they dip into the stock trough just back of the slice.

Bucking (43) suggests admitting stock to the wire level back of the slice from below through vertical tubes fitted with spiral vanes to cause swirling and give random orientation.

A design by Mika (44) would place the breast roll in the lower front corner of the head box with a connection between the bottom of the box and the roll by means of a scraper engaging the roll. The design includes two distri-

buting rolls so made that a perforated shell revolves oppositely from a perforated blade paddle wheel inside the shell.

2. AGITATORS AND RECTIFIERS

Besides the agitators included in the head box designs above, Aldrich (45) proposes one similar to the paddle wheel used by Percy (36). Stewart (46) holds a patent on a distributing roll similar to the Voith roll (69). Other roll distributor designs have variously mounted discs: flat discs mounted perpendicular to the axis to merely act as rectifier plates (47), flat discs set at an angle from the perpendicular to induce swirling (48), and radially corrugated discs (49), while another design uses simplified propeller blades (50). Campbell (51) would use prongs or teeth dipping nearly to the bottom of the stock stream to give small eddies. Stationary thin plates in the stock throat back of the inlet are proposed by Mason and Wardle (52) to break up cross currents, and this idea is included in the Bell-Irving nozzle design (77). Aldrich (53, see also 40) has patented an agitator consisting of two bars across the head box just back of and above the slice opening with prongs projecting down across the opening. These bars are mechanically moved back and forth in opposite directions to each other.

Hyde (54) proposes an adjustable ridge across the machine in the apron cloth under the slanting inlet surface to break up localized streams. Corcoran (55) would fit the top and bottom surfaces of the inlet with raised ribs at forty-five degrees from the flow direction and oppositely directed on top and bottom to give interweaving.

3. VERTICAL SLICES

The many variations of the straight vertical slice that have been patented include angular adjustment to simulate an inlet (56), the use of flexible lips for finer adjustments (57, 58), and the use of a lip with semicircular gaps at short intervals (59) to give ridges of stock which should give interweaving of fibers as they spread and flatten out. Van Ornum (60) realizes the importance of the distance between the slices in a two-slice system for controlling formation and proposes a means for adjusting this distance. Lewthwaite (61) would use a curved extension on the lip of a vertical slice to restrain the surface of the stream and he also advocates blowing air along the top surface at wire speed. Leloff (62) proposes fastening a wooden strip to the back of a vertical slice in such a way as to form a slanting surface like the usual sloping inlet.

4. HIGH PRESSURE INLETS

Van de Carr (63) holds the earliest patent on a

high pressure inlet with the top surface curved to approximate streamlines and with a flexible lip adjustable over the machine width. Since his patent was issued, other curved inlets have been patented which differ only in mechanical details (64, 65). Lang (66) provides a means of varying the curvature and Valentine (67) suggests a straight slice back of the curved inlet. Clements (68) advocates the use of a rubber-covered roll capable of vertical and horizontal adjustment and also adjustment of diameter across the machine to get the same results as the common flexible lip. This roll is rotated slowly in the direction of flow with a doctor blade to take off any fibers that may adhere to the surface.

Voith (69) introduced the slanting inlet surface with a flexible adjustable lip; and, as in the case of the curved inlet, many modifications of it have been patented, differing principly in mechanical details to allow a greater range of adjustment (70 - 75). Aldrich (76) proposes an adjustable vertical slice back of the inlet.

The Bell-Irving (77) design carries the inlet idea still further by using a long narrow hydraulic nozzle with streamlined rectifier plates. Wood (38) includes a similar nozzle-like inlet in his head box design.

For still further adjustment of the inlet, Berry (78) and Valentine (79) recommend apron boards capable of adjust-

ment across the machine.

5. INLETS WITHOUT SLICES

Murray (80) and Kilberry (81) propose delivery of stock to the moving wire by means of an adjustable dam back of the breast roll with a streamlined spillway leading down to the wire. Kilberry advocates a waterproof belt under the first part of the wire to prevent drainage until the stock has reached quiescence.

6. METHODS OF SLOWING DRAINAGE ON THE WIRE

Kutter's (82) formation table provides a plate under the wire just after the breast roll to slow up drainage and allow improved formation. Liebach's (83) design supports the wire between table rolls on boards which slow up drainage and prevent splashing of water against the under side of the wire. Danninger (84) proposes the use of an additional wire around the breast roll and the first few table rolls to slow up drainage. Provision is made for lowering this wire to allow faster drainage. Monaghan (85) recommends having the apron extend beyond the slice to hold the pool longer. The design includes a curved front edge on the apron with the center extending considerably further than the sides.

7. TREATMENT AFTER THE SLICE

In direct contradiction to the accepted views

that table rolls should be both statically and dynamically balanced, Aldrich (86) recommends off-center table rolls to give vibration to aid felting. Putnam (87) uses a surface held to the front of the slice by means of hinges and floating on the stock stream to dampen ripples and allow the separation of air bubles. Vitham (88) uses air jets to puddle the stock on the wire and then a roll driven at wire speed to smooth out the surface and give improved formation. Valentine (89) recommends a roll with thin longitudinal fins dipping into the stock on the wire. This roll is driven slightly slower than the wire and the fins wipe off bubbles and is said to improve formation. Cofrin's (90) patent simply provides a smooth roll driven at a slightly different speed from the stock to smooth the surface. In another patent Vitham (91) proposes variable speed and elevation wire stirrers in the stock on the wire in front of the slice to give random fiber orientation. Hurrey (92) advocates the use of high velocity sprays on the stock to disrupt flow lines as it leaves the inlet.

CHAPTER III

PRESENTATION OF THE PROBLEM AND METHOD OF ATTACK

The purpose of this study is to obtain fundamental knowledge of the hydrodynamic phenomena occurring in the flow of a liquid through paper machine flow control devices, such as the head box and slice or inlet, and to definitely show the movements of individual paper making fibers carried along in dilute suspension by this flow. A further purpose is to show that the tendencies observed at the very dilute suspension also are active at commercial consistencies; and, finally, another purpose is to show the effects produced by various patented devices.

The subjects covered in this study are: 1. The scope of usefulness of Bryant's high speed photographic technique in studying stock flow and the development of modifications in the technique consistent with improved results; 2. The use of the modified techniques in making a detailed study of the flow conditions around a single vertical slice, around various other slice and inlet designs for comparison, and around the baffles in a head box.

A. SCOPE OF USEFULNESS AND DEVELOPMENT OF IMPROVEMENTS

After a series of experiments with various methods

of lighting, Bryant (1) found that silhouette images of individual paper making fibers, flowing in very dilute water suspensions, could be obtained photographically by passing a beam of intermittent light through the stock and then into an ordinary camera which was lined up with the light beam and focused on the stock suspension. He made use of a high tension electric spark as a light source to give 120 flashes per second. By means of a focal plane shutter in the camera, he timed the exposures to catch three flashes and thus obtain three successive images of each fiber in the field at intervals of 1/120 second to show not only the lateral motion of the fibers and their orientation distribution, but also any rotation or change in position of an individual fiber in relation to the direction of flow. He successfully used this method to obtain side and top views of the flow conditions around glass slices, sealed into the glass trough shown in Figure 1. The details of the method will be given later in this paper.

Preliminary work in mastering Bryant's technique clearly showed its limitations: 1. The amount of stock through which the light beam passes must not be high enough to greatly decrease the intensity, and any fibers in the beam, but outside the camera's depth of focus, decrease the definition of fibers within the depth of focus. 2. Sealing each slice design into the trough and waiting for it to set consumes much time. 3. Using ordinary fibers with low

opacity, the contrast obtainable is somewhat limited. 4. All surfaces in the optical system must be scrupulously clean and free from scratches and unevennesses which would cause refraction and blot out part of the beam. 5. The size of the field can be only as large as the light beam striking the stream and the larger the beam, the more the distortion in the outer slices. 6. Use of the focal plane shutter gives a banded exposure because it is impossible to synchronize the shutter with the spark frequency.

Improvements made in the technique are: the use of copper slices with built in rubber gaskets, so that they could simply be slipped into place anywhere in the trough without any other seal or support; the use of heavily dyed black fibers to obtain better contrast; the use of a viewing box to avoid surface ripples in the top views; the blocking out of areas of the beam not important to the picture; and the use of a pendulum timer system of exposure in place of the focal plane shutter.

B. USE OF THE [illegible] TECHNIQUE IN MAKING A STUDY OF VARIOUS STOCK FLOW CONDITIONS

1. CONDITIONS BEHIND A SINGLE VERTICAL SLICE

From five types of slice edges a round-lipped one was selected for the use in this study. Top and side views were taken to show the conditions in the stream back of the slice, in the zone of acceleration around the slice, and in

the stream from the slice. Similar studies were made of the effects of head, width of the slice opening, vanes back of the slice, consistency, beating, and relative positions of the apron and slice; and, finally, the action of acceleration under the slice for pulling apart or breaking up fiber bunches or clots was observed by specially designed equipment, whereby the interval between successive images was increased.

2. CONDITIONS AROUND VARIOUS SLICE DESIGNS FOR COMPARISON

A thorough investigation of the common system of two vertical slices was carried out to show the situation around each slice and in the pond between, and to show the effect of a control rack in the pond, of a stirrer in the pond, of a stirrer in the stream from the second slice (91), and of the effect of distance between the slices. Then studies were made of the conditions under a slice sloping at various angles; under a vertical slice having a sloping surface attached to its lower edge like the Voith design and the effect of having just back of this inlet a vertical slice and then a control rack; under a similar inlet having a vertically set lip at the lower edge of the sloping surface, around a curved slice or inlet similar to the Van de Carr design; under Clement's roll slice; under Leloff's modification of the straight

slice to obtain an inlet, on a streamlined spillway of a dam-type of inlet (Murray and Kilberry), and in nozzle inlets of Bell-Irving and of Lund designs.

3. HEAD BOX CONDITIONS

Finally, the conditions of stock flow and fiber movements around ordinary head box baffles, and also the recirculation design proposed by Gough (8) for evening up the flow across the machine, were investigated.

CHAPTER IV

MATERIALS, EQUIPMENT, AND PROCEDURES

A. MATERIALS

Eastman Safety Panchromatic Process film in (5 x 7 inch sheets cut to 3½ x 5 inch sheets) was used in this study. Both Super Sensitive Panchromatic and Commercial Ortho films were tried where more speed was desired, but neither gave sufficient contrast.

Eastman Azo sensitized paper of F 4 grade was used to obtain sufficient contrast for the prints of the fiber pictures where three spark exposures were used. F 2 and F 3 grades were found satisfactory for one and two flash exposures, respectively.

A very high contrast developer for both negatives and prints was necessary and the Eastman D-11 (33) formula was found to give satisfactory results.

The regular acid harlener fixing bath (Eastman F-5 (33) was found to give very satisfactory fixing.

The pulp used for all the studies, except those on beaten stock and high consistency, was fractionated long unbleached western hemlock sulphite pulp dyed black by a

heavy dying with direct dyes salted out at boiling temperature with sodium sulphate.

The beaten stock used was unbleached Jack pine kraft pulp beaten to a freeness of 300 C. S.

For the higher consistencies undyed and unbleached western hemlock sulphite pulp was used.

A commercial caulking compound similar to common putty was used to seal up seams in the trough and, when necessary, to seal the various flow control devices into the trough. Strips of cellulose acetate, softened with acetone to make them provide their own cementing agent, were used to furnish both a seal and support for glass slices and spillways which were used when it was desired to photograph through these surfaces.

Twenty gauge sheet copper was used for the construction of the various slices, etc.

B. EQUIPMENT

1. LIGHTING SYSTEM

The lighting system (Figure 1) used was the same as that described by Bryant (1) except that for the latter part of this work a pendulum flash timer was devised and constructed. Figure 2 shows the details of this device. With the power turned on, the pendulum was released from an

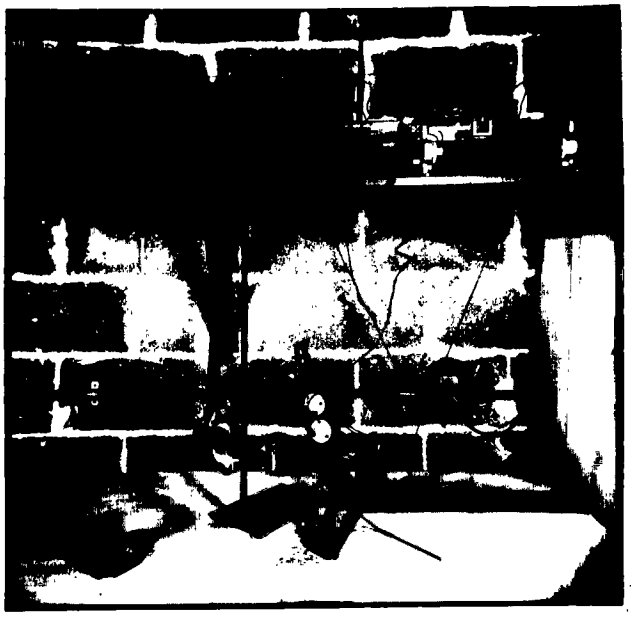


Figure 1. LIGHTING EQUIPMENT

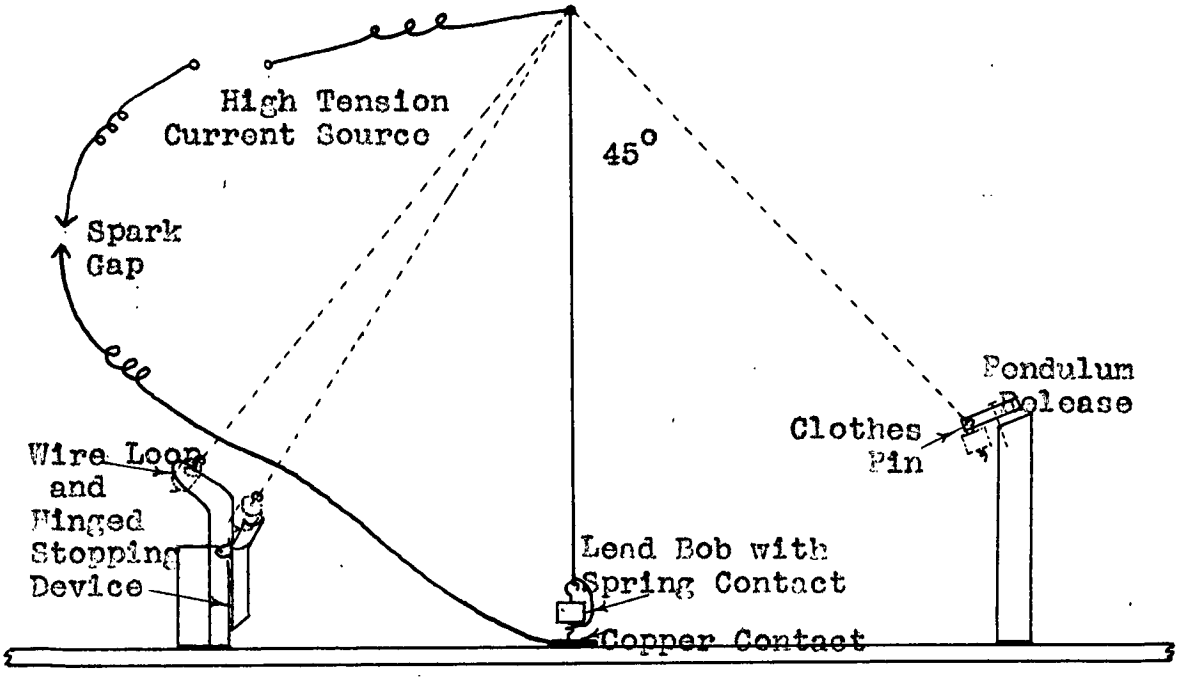


Figure 2. PENDULUM EXPOSURE TIMER

ordinary clothes pin release mechanism to swing down and close the high tension circuit to the spark gap during that period of the swing when the spring contact on the bottom of the bob was in contact with the copper strip connected to the spark gap. To avoid loss of power, the pendulum was suspended by a heavy 10-strand copper wire extending around the bob, with its lower end protruding just below the end of the spring to make the contact with the copper strip. A strip width of 0.25 inch just caught one flash, 0.90 inch caught two and 1.5 inch caught three. The effective width of the contact was slightly greater than that of the strip, due to the size of the contact tip on the pendulum and due to the distance over which a spark jumped between the contacts. The pendulum speed at the bottom of its swing was calculated to be 75.7 inches per second or 0.63 inch between flashes. At the end of its swing the pendulum was caught by the hinged stopping device, so that it would not swing back to cause further sparks (Figure 2).

The viewing box used to smooth out ripples on the surface of the stock stream and thus permit uniform lighting of the whole field on the film consisted of a box with copper sides and a glass bottom. This box was mounted on an iron rod by which it could be supported in the desired position by clamping it to a ringstand or to the camera tripod post. The glass bottom was 2 inches wide and 3.6 inches long (see Figure 1).

2. STOCK CIRCULATION SYSTEM

The stock circulation system as described by Bryant (1) (Figure 3) was used, except for the following modifications: For side views at high consistencies the normal trough width of 2.25 inches was too great, hence a glass wall was provided inside the trough to leave a passage 0.5 inch wide between it and the front wall of the trough. The remaining trough width was dammed off to keep it empty. A motor driven stirrer was provided at the entrance of the narrow passage to partially overcome the tendency of the unbeaten fiber to flocculate.

For the study of high pressure back of the slice and high velocity in the stream from the slice, a narrow head box, 26 inches high, was constructed as shown in Figures 4 and 5. Figure 4 shows the general arrangement of the head box in relation to the rest of the system, and Figure 5 shows the details of its construction. Figure 5 (a) shows the full size details of the seams. The glass sides were sealed to the wooden frame with caulking compound and held tightly in place by sheet iron channel strips shaped to cover the entire length of each side. Drawings (b) and (c) show the front and side views, respectively, at a scale of one to eight. The glass walls consisted of two sections of 1/8 inch thick window glass: the lower one 8 by 14 inches and the upper one 18 inches high and 9 inches

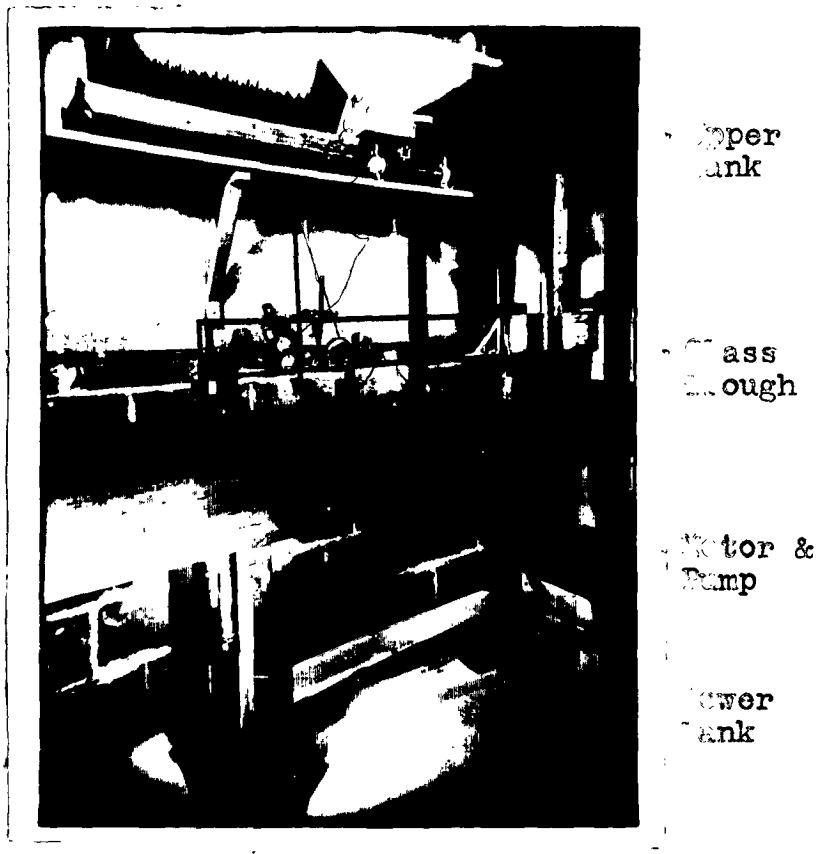


Figure 3.

THE STOCK CIRCULATING SYSTEM

WITH THE GLASS TROUGH

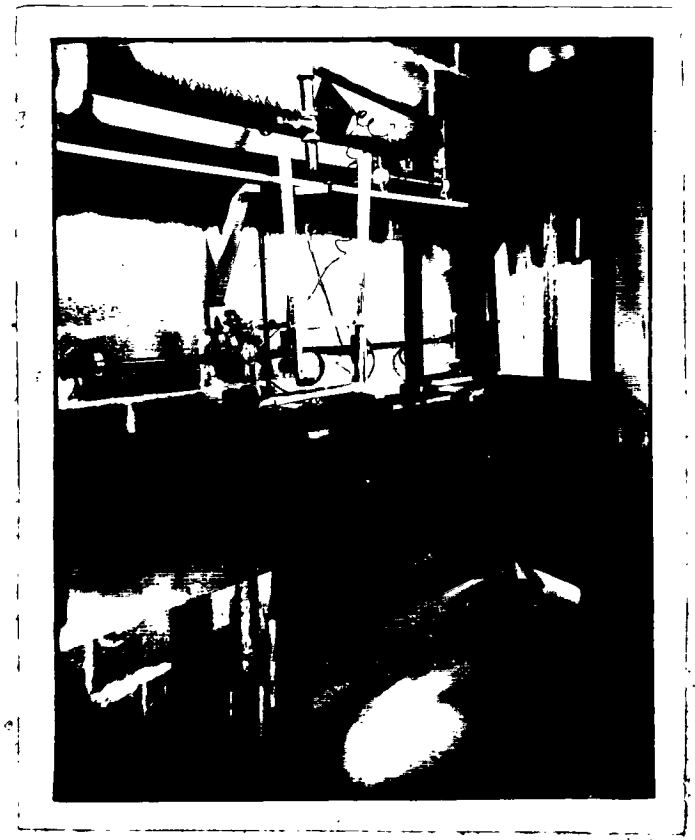


Figure 4.

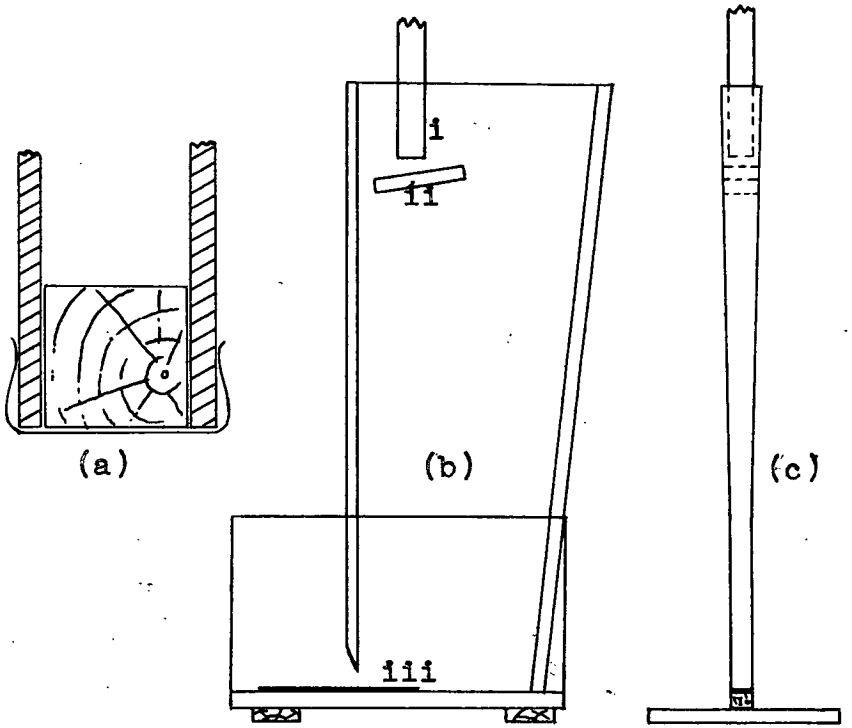


Figure 5.

THE HIGH PRESSURE HEAD BOX

wide at the bottom spreading to 11 inches wide at the top. The wooden baffle (ii), shown under the inlet pipe (i), was used to break up the stream of stock entering the head box. The glass plate (iii), shown on the wooden bottom of the head box (b), was used to give a smooth surface under the slice. Screw clamps with metal braces were used to hold the lower sections of the glass walls snugly against the wooden wall just above the slice opening. The head box was fitted with a sharp edged slice.

3. CAMERA

The camera and camera adjustments described by Bryant (1) were used for this work.

4. SLICES, INLETS, AGITATORS, VANES, BAFFLES, ETC.

Figure 6 shows the construction of the rubber gasket for the copper slices. The edges of the copper strip were folded over as shown to form a crimp along either edge to receive a quarter inch wide strip of rubber. The crimp was then hammered down to hold the rubber tightly in place. The slice edge or lip was filed straight and square with the sides, and the surfaces were smoothed by filing, followed by polishing with emery and finally with fine steel wool.

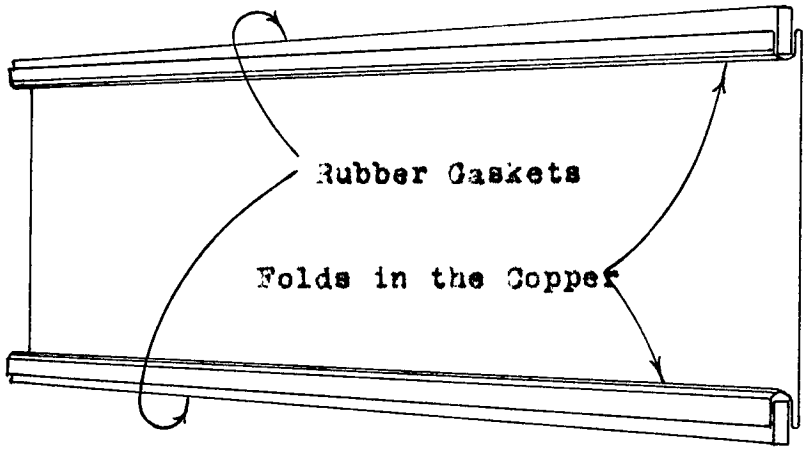


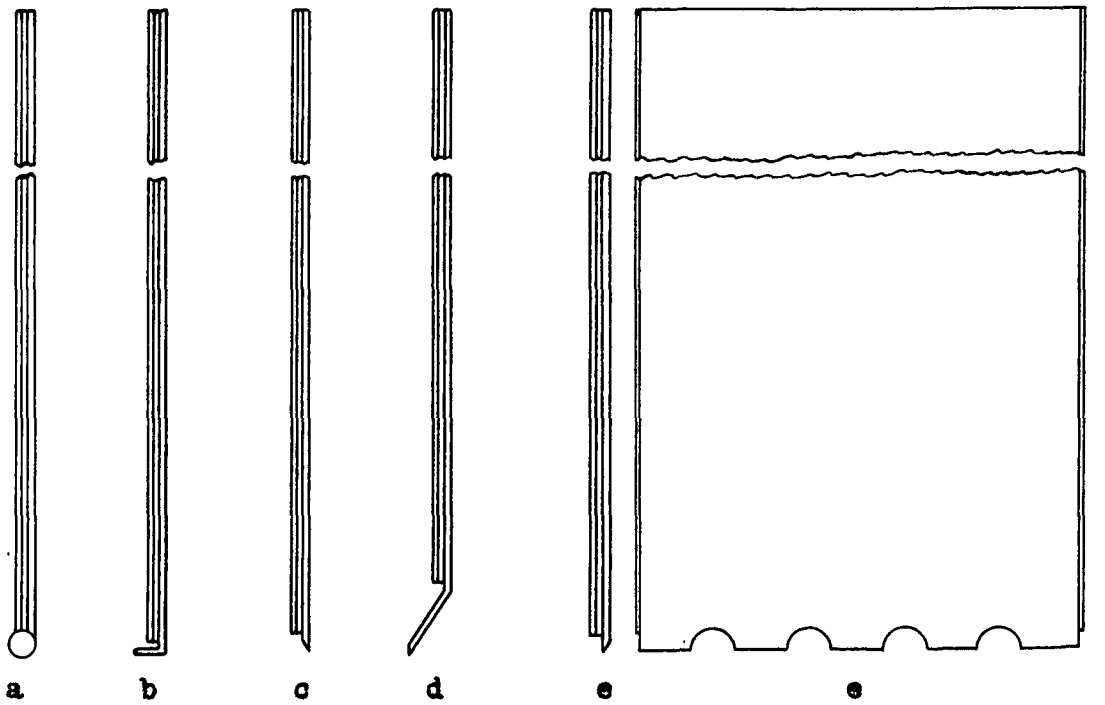
Figure 6.

The drawings in Figure 7 show the actual size and the important details of the various devices used in the trough to obtain the desired flow conditions. In all cases the flow direction, with respect to the drawings, is from right to left. Only side views are shown, except for variations from the details shown in Figure 6.

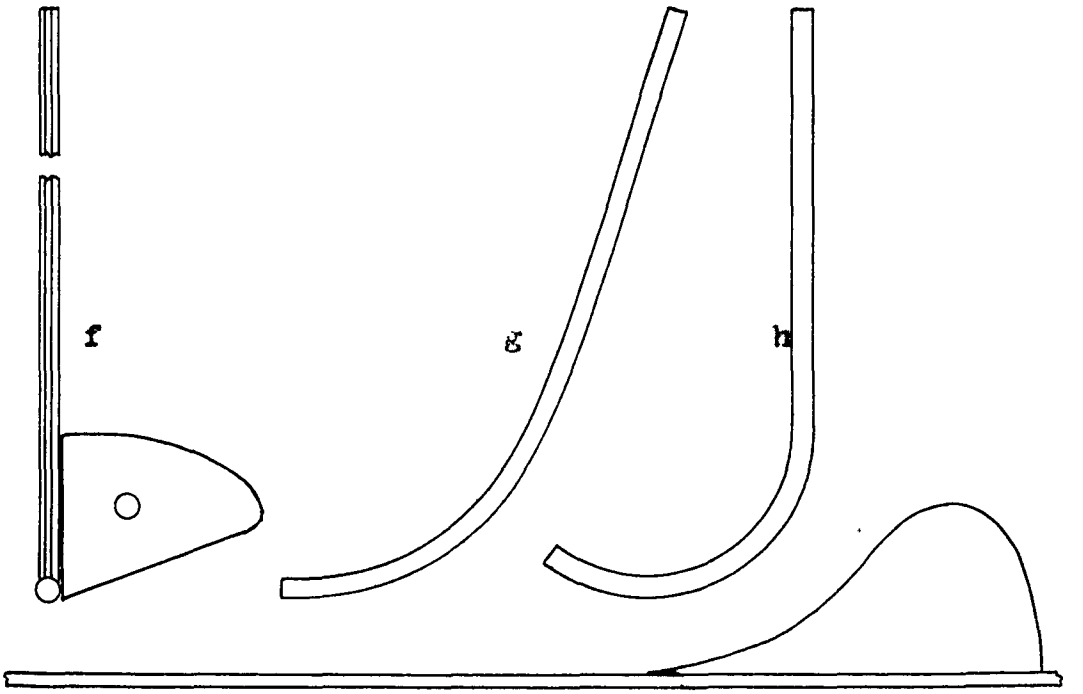
Referring to Figure 7, drawings (a), (b), (c), and (d) show the round-lipped, the square-lipped, and the knife-edged vertical slices. Drawing (e) shows both front and side views of the slice with semicircular gaps in its edge according to the patent of Davies and Thomas (59). In (f) is shown the model of Neloff's (62) modification of a vertical slice to obtain a high pressure inlet. The vane used in this model was made of wood, carefully shaped and smoothed with file and fine sandpaper.

Figure 7

DETAILS OF FLOW CONTROL DEVICES



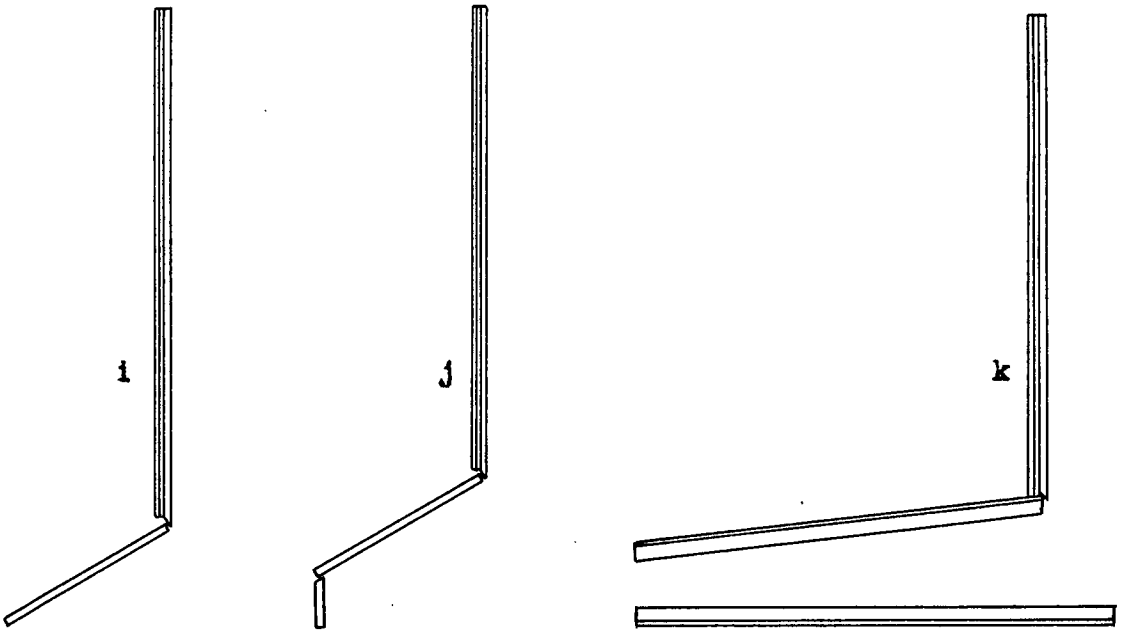
Types of Lips on Vertical Slices



Inlets

Figure 7 (Continued)

DETAILS OF FLOW CONTROL DEVICES



Inlets

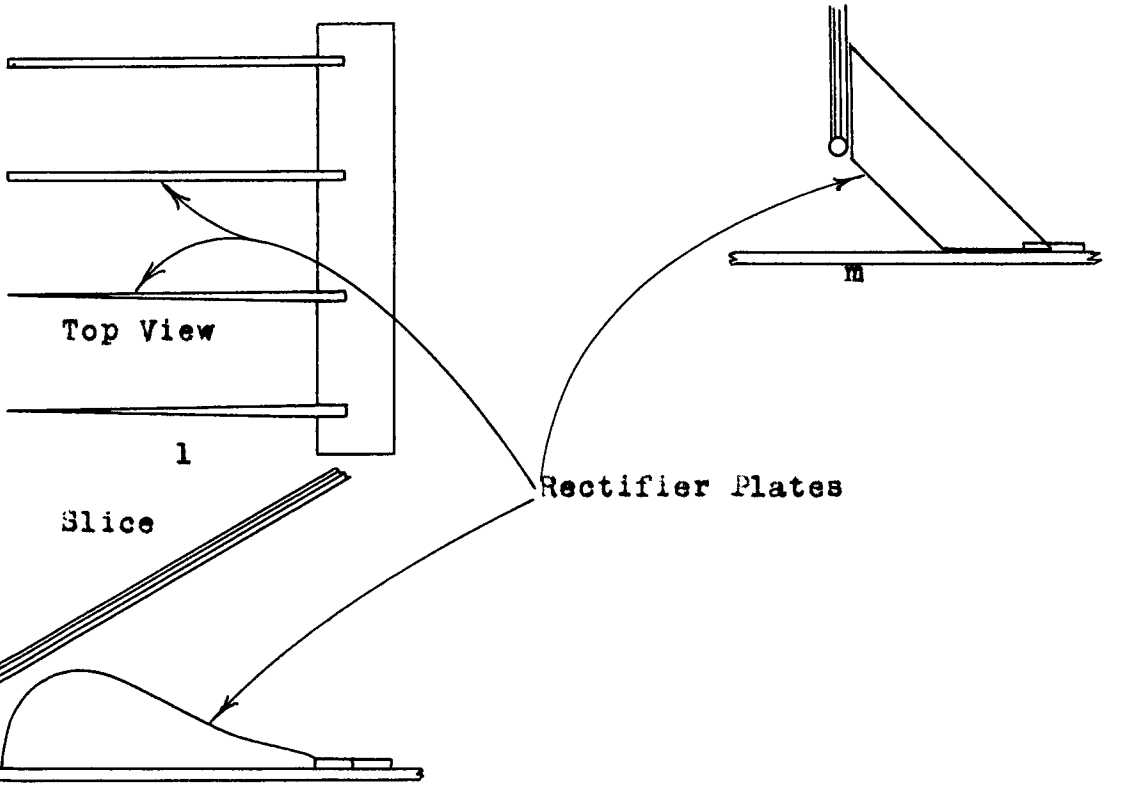
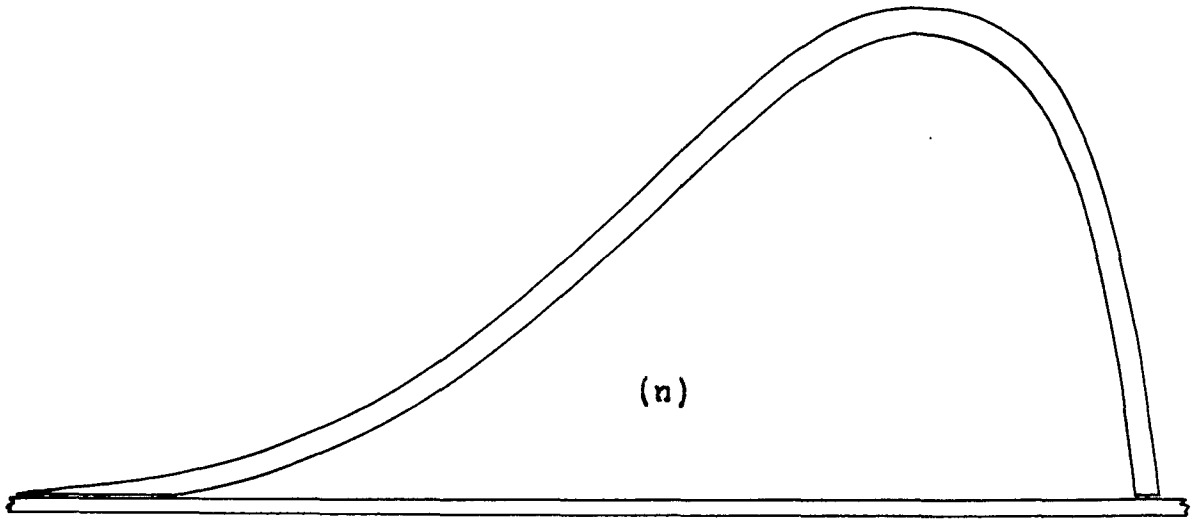


Figure 7 (Continued)

DETAILS OF FLOW CONTROL DEVICES



Dam-Type of Inlet

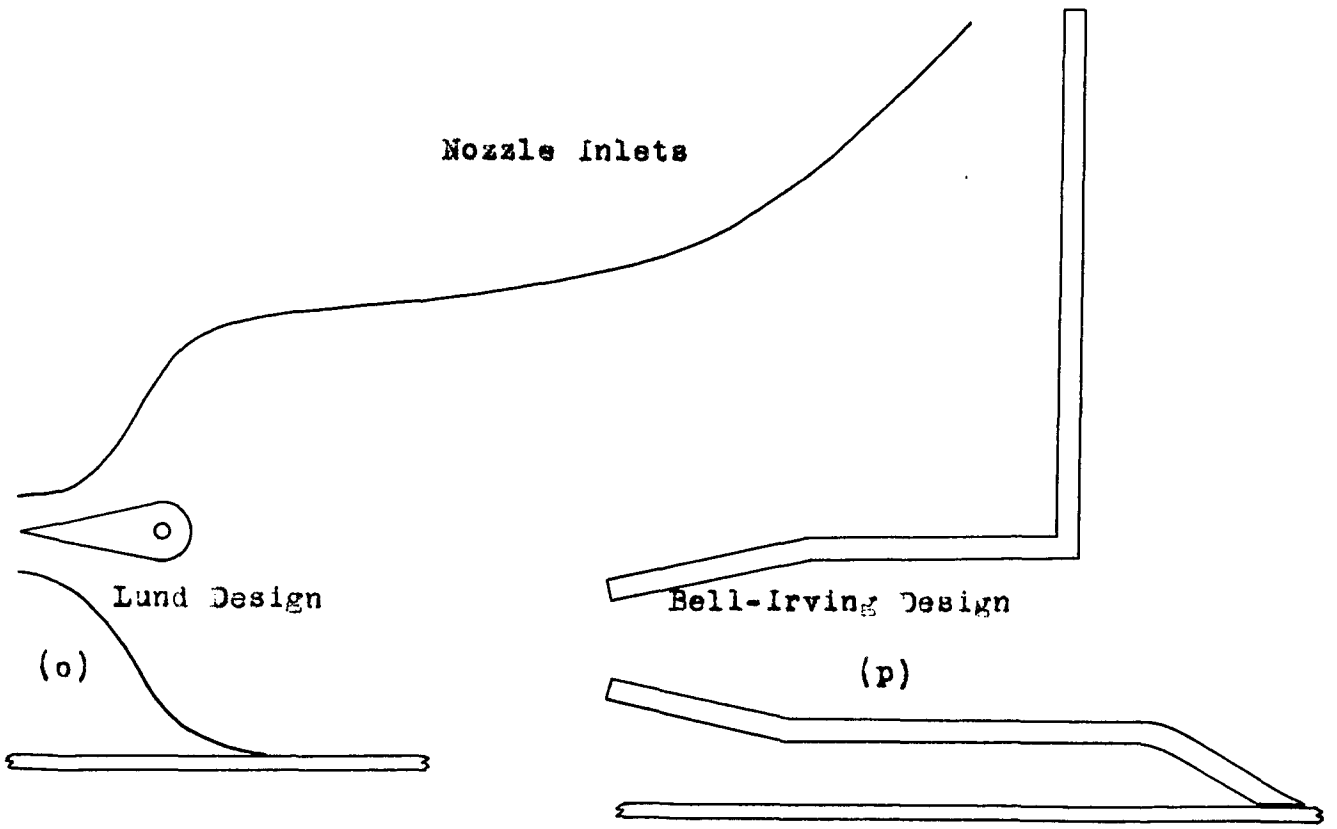
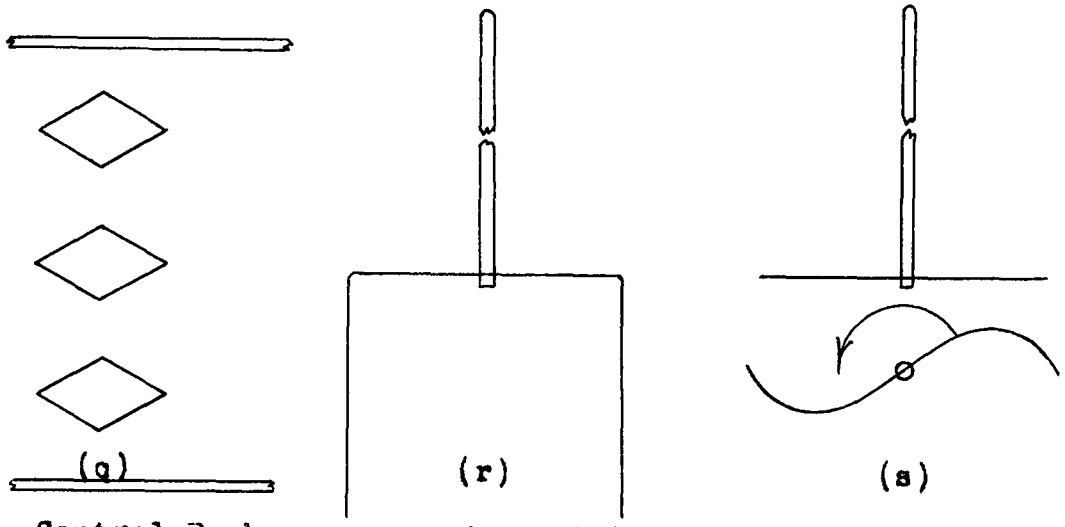


Figure 7 (Continued)

DETAILS OF FLOW CONTROL DEVICES



Control Rack

Motor Driven Wire Stirrers

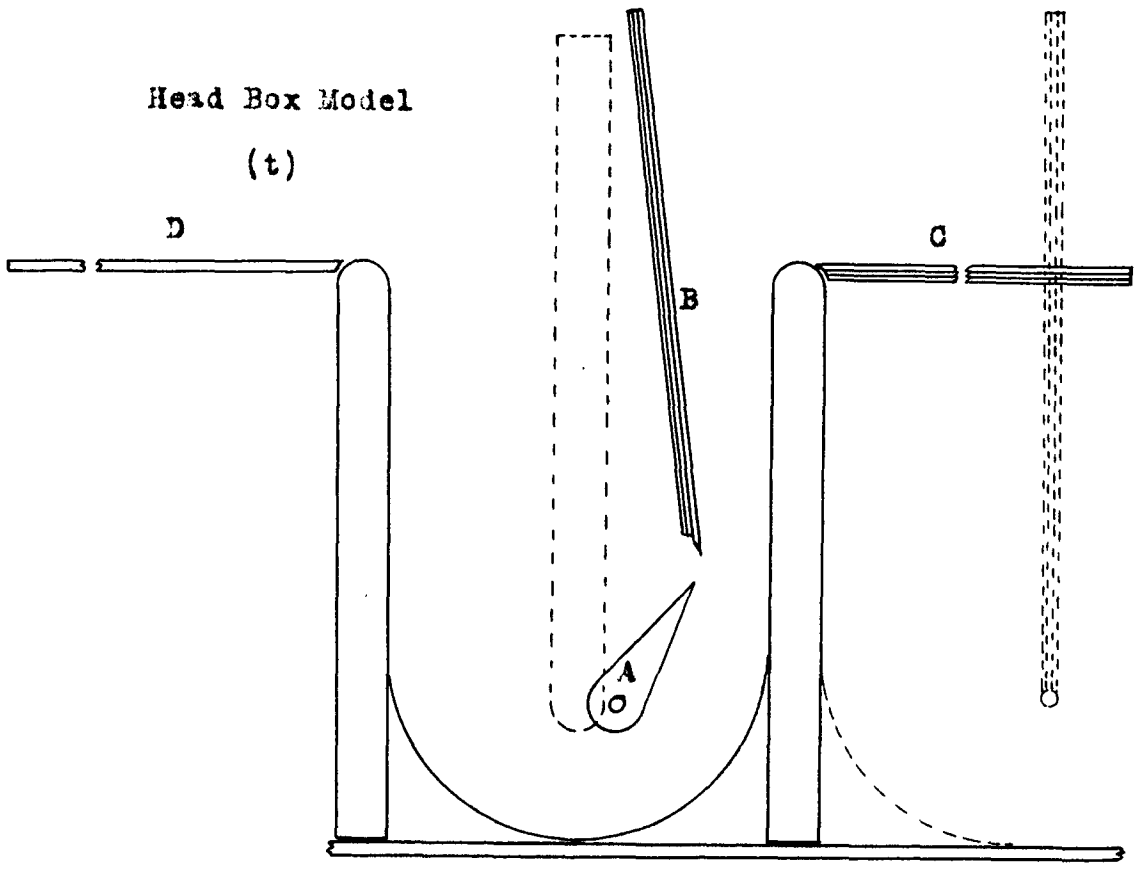
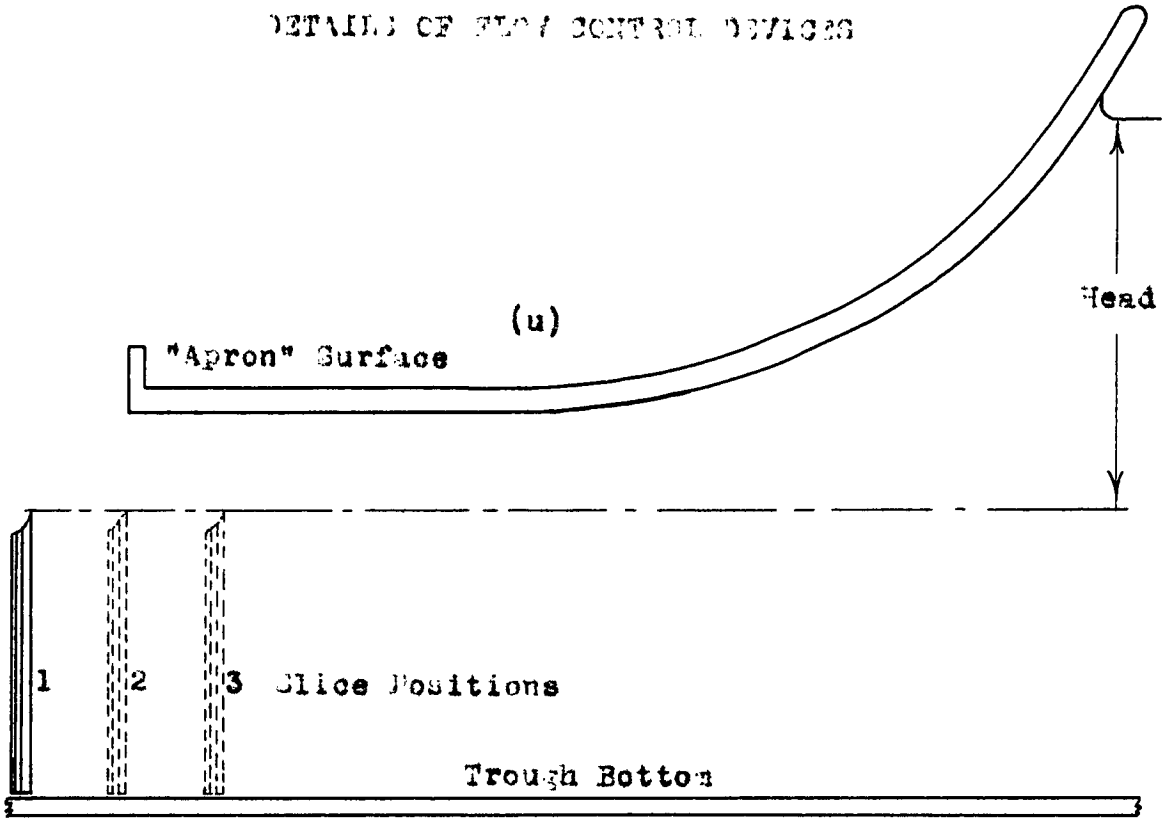


Figure 7 (Continued)

DETAILS OF FLOW CONTROL DEVICES



Device to Show the Effect of the Relative Slice and Apron Positions

Drawing (g) shows a model of the Van de Carr (63) curved inlet and (n) is a design to demonstrate the action of a roll-type slice with a dam back of it, as proposed by Clements (68). Models of various slanting surface inlets are shown in (i), (j), (k), and (l). In (k) the inlet surfaces had ridges (55) at thirty degrees from the flow direction, those on top being oppositely directed from those on the bottom. These ridges, consisting of folds in the sheet copper, were spaced at half inch intervals and were three thirty-seconds inch high.

The vanes or rectifier plates in (l) and (m) were patterned after the patent of Mason and Wardle (52). As shown in (l) two plates were streamlined and two were not, to demonstrate any resulting differences. Rectifier plates for use with a vertical slice, together with the relative position of the trough bottom, are shown in (m). Two sets of these plates were constructed, one set streamlined and the other not. They were mounted in the same manner as shown in (l).

Models of the dam-type of inlet (80, 81) and the Lund (28) and Bell-Irving (77) nozzle inlets are shown in (n), (o), and (p) respectively. The usual rubber gasket support and seal were used in the models of these designs but are not shown in detail in the figure. Drawing (q) shows a cross section of the diamond-shaped wooden prongs (51) of the so-called "control rack" (15) together with their position relative to the glass side walls of the trough. These prongs are arranged to extend through the stock stream and rest on the bottom of the trough. The motor driven wire stirrers are shown in (r) and (s). The stirrer in (r) was used back of the slice, while that in (s) was used in the stream from the slice (91). The end view of this stirrer shows the curvature which has been given it to reduce the amount of fiber collected.

The models of head box designs used are shown in

(t). The drawing as shown without the members in dotted lines represents a model to demonstrate the recirculation of stock about the vane A (9) to even the flow across the machine. With members A, B, and C removed and the dotted line members in place as shown, a four pass head box was obtained. The vane A and the thick baffles were made of wood, while the streamlining surfaces at the bottom were of sheet copper, fitted snugly in place without the rubber gasket construction. The glass plate D was used like an apron to support the issuing stock stream and also to permit top views to be taken with lighting from below through an area of the trough from which the usual glass bottom had been removed. Top views of the stream from the Lund and Bell-Irving inlets were handled similarly.

Drawing (u) shows the device used to demonstrate the effect of the relative positions of the apron and slice. The curved "apron" surface, shown at the top of the drawing, was held in place as usual by rubber gaskets. The upturned lip on the end over the inverted slice was provided to prevent the stock from running back over the top of this surface. The slice was then inserted in position 1, 2, or 3 to show the conditions of flow with the end of the apron back of the slice, even with it, or extending beyond the slice, respectively. The apron surface was made horizontal near the slice position to duplicate the usual machine conditions and was curved upward further back to allow a pressure head

back of the slice.

Figure 8 shows the wire hooks used to introduce fiber bunches into the stream back of the slice to show the action of acceleration in pulling them apart. Five small wires, 2.25 inches long with tiny hooks (a) bent in their lower ends, are fastened at one inch intervals to the strip of wood (b) four inches long, which has a wire handle attached.

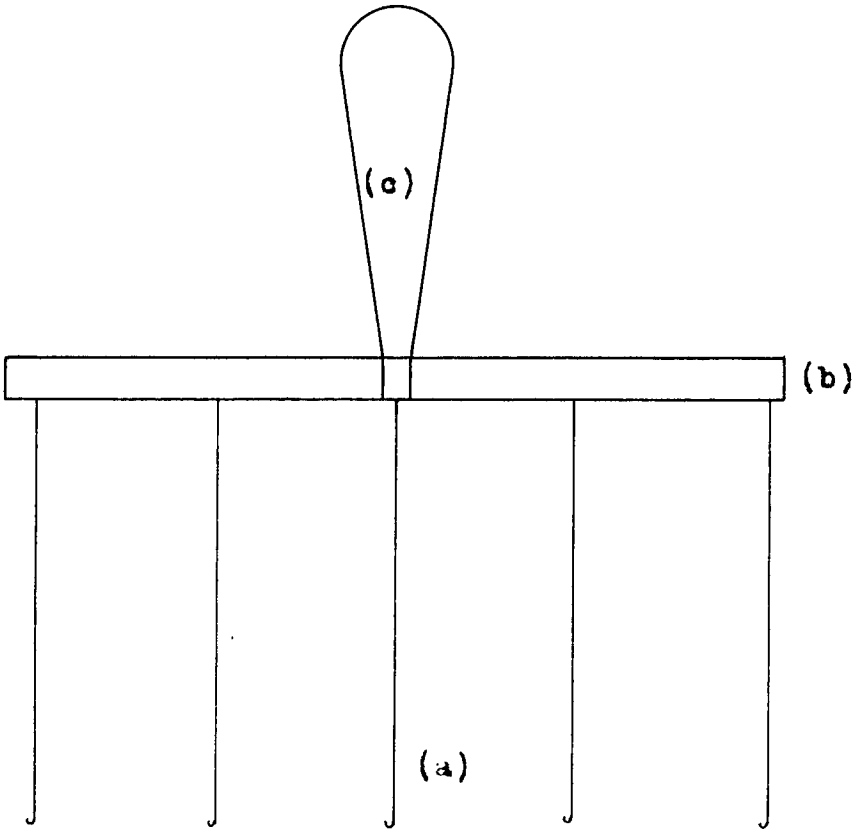


Figure 8

C. PROCEDURES

1. PREPARATION OF STOCK IN THE CIRCULATION SYSTEM

Water at 20° C. was run into the upper tank to a depth of 8.5 inches, and the necessary weight of dyed fiber to give the desired consistency was added. For the side views 0.1 gram, and for the top views 0.5 gram, of fiber were dispersed in water by means of a stirrer and added to the water in the tank. The consistencies, then, were 0.0002 and 0.001 per cent, respectively.

Circulation was started, and the rate of flow was adjusted by means of a valve in the pipe line leading from the upper tank to the trough. The pump was started after the lower tank began to fill, to return the stock to the upper tank, and the valve in the pump line was adjusted to balance the rate of pumping with the rate of flow into the lower tank.

With the high pressure head box, the upper tank was not used; therefore the stock was prepared in the lower tank by adding 0.05 gram of fiber to 16 liters of water. The slice opening was adjusted to just take the entire output from the circulating pump when a head of two feet was maintained in the head box. To allow entrained air bubbles to escape, a baffle was used to divide the lower taken into two compartments. The stock returning from the head box

entered one and flowed over the baffle to the other and then was pumped back to the head box. The air bubbles escaped during the passage over the baffle.

2. CLEANING THE GLASS SURFACES IN THE OPTIC SYSTEM

In most cases water with a little acid was sufficient to loosen the dirt and allow the glass surfaces to be rubbed clean. Gardinol gave excellent results in removing grease and other foreign matter with very little rubbing, but organic solvents were not satisfactory, because they caused smearing of the caulking compound used in sealing the seams of the trough.

3. INSERTION OF THE SLICE

After preparing the stock and thoroughly cleaning the part of the trough to be used, the slice, or other device, was dipped into water to wet the rubber gaskets, which made them slip more easily on the glass surfaces of the trough. It was then slipped into place, with a metal strip of the proper thickness on the bottom of the trough to gauge accurately the desired width of the slice opening. When a glass slice or spillway was used, the position desired was marked with crayon on the outside surfaces of the trough walls. A strip of cellulose acetate, one quarter inch wide, was then sealed to the inside surface of each wall along the crayon line by means of acetone; and, finally, the

glass plate was cemented to the acetate strips by the addition of more acetone. This glass plate was prepared by cutting accurately to size and then truing its edges by grinding on emery cloth moistened with a solution of camphor in turpentine.

4. ALIGNMENT OF OPTIC SYSTEM

The light beam from the spark and lens was focused to a point 4 feet from the lens. This placed the lens 9.5 inches from the spark gap. The plane of the lens was adjusted perpendicular to the optic axis, which was made horizontal. For side views the lens was placed against the back wall of the trough, and the optic axis was adjusted to be perpendicular to this wall. The camera, with its lens aperture set at f. 3.5, and the bellows extended to place the lens 12.5 inches from the focal plane, was put into place with the focal plane 25 inches from the field desired and lined up with the optic axis. This adjustment made the size of the images the same as that of the objects. This is shown diagramatically in Figure 9.

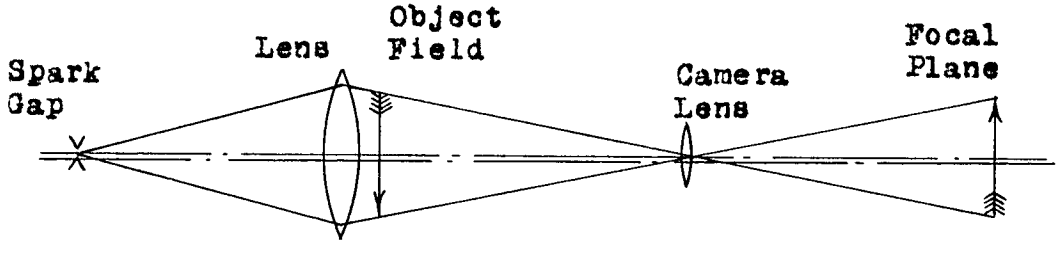


Figure 9.

For the top views the spark and lens assembly were lowered just below the trough bottom and the mirror, at 45 degrees with the horizontal, was placed under the trough to throw the horizontal beam vertically through the desired field in the trough. The camera was then put into place over the trough at the proper distance with its axis vertical and directly through the field to be photographed. The viewing box was next put into place and adjusted to smooth the top surface of the stream. By adjusting the mirror the light beam was directed squarely into the camera. A second mirror, mounted over the camera in such a position as to allow the operator to observe the field on the ground glass focusing screen, facilitated this adjustment.

5. TAKING THE PICTURES

All exposures were made with the room in darkness. When using the focal plane shutter, the shutter was set to give the desired timing, the cover was removed from the film holder in the camera, the spark was turned on and the shutter was released. When the pendulum timing mechanism was used, the pendulum was fastened in the starting position, the current was turned on, the camera shutter was opened, the pendulum was released to give the desired number of sparks, and then the shutter was closed and the current shut off.

6. DEVELOPING FILM AND PRINTS

The negatives were developed for 4 minutes at 25° C., or 7 minutes at 20° C., in Eastman D-11 developing solution (33) to obtain high contrast. To avoid stains from this developer the negatives were washed thoroughly in running water before fixing. Fixing for 10 to 20 minutes in the usual acid hardner fixing bath, followed by washing and drying, finished the operation.

Normal print developer failed to give sufficient contrast even on F 5 contact printing paper, hence D-11 was also used in for the prints. They were developed for 1 to 3 minutes at 20° C. in this solution, dipped into an acid "quick stop", fixed in an acid hardener fixing bath, washed in running water, and dried on a ferrotype plate.

7. PHOTOGRAPHING THE ACTION OF THE AGGLOMERATION UNDER THE SLICE ON THE BREAKING UP OF FIBER BUNCHES

For this study fresh water was run into the upper tank continuously at the desire rate; and, after flowing through the trough and under the slice, it was pumped to the sewer. Tiny fiber bunches were picked from a 2 per cent consistency unbeaten sulphite stock and transferred, five at a time, to the stream back of the slice by means of the 5-pronged hook (Figure 8). The exposure was timed with a triple contact under the pendulum, calculated to catch

three single sparks separated by 1/40 second to allow a greater interval between successive images of each fiber bunch, thereby avoiding overlapping of the images. The passage of the group of fiber bunches under the slice and the timing of the pendulum were synchronized by hand by trial and error until satisfactory pictures were obtained, showing three successive images of bunches during their passage through the zone of acceleration.

CHAPTER V

DISCUSSION OF IMPROVED TECHNIQUES, PRESENTATION OF DATA AND DISCUSSION OF RESULTS

A. SCOPE OF USEFULNESS OF THE TECHNIQUE AND MODIFICATIONS CONSISTENT WITH BETTER RESULTS

1. LIGHTING THEORY

Bryant's (1) technique obtained silhouette images of individual papermaking fibers on photographic film by passing a converging beam of intermittent light through the stock and then by way of a camera lens to the film. The intermittent light source consisted of a high-tension electric spark operating on a 60- cycle line to give normally 120 flashes per second, the duration of an individual flash being about 0.000003 second, so that the fiber movement was entirely "stopped." Any desired number of sparks was admitted to the film either by means of the camera shutter or, as developed in the course of this work, by means of a pendulum timer in the high tension circuit to give only the desired number of sparks.

To catch the entire area illuminated by the beam it was necessary to use a converging beam as illustrated in Figure 10. As shown in (a) only an area the size of the camera lens would be imaged on the film by a parallel beam,

while with a converging beam, as shown in (b), the light from the entire illuminated area enters the lens, to be focused on the film.

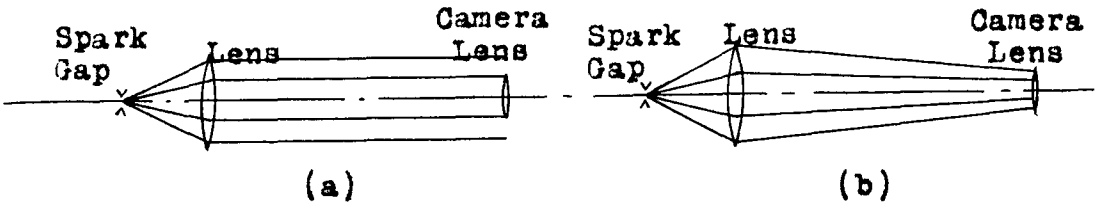


Figure 10

Since the images were silhouettes, the focusing may be considered as being on the fiber edges. Due to the finite size of the spark gap light source and to the aberrations of the uncorrected simple lens used, each point on the fiber was actually imaged through light in a narrow cone of rays localized in one particular part of the beam, and the camera lens focused this cone back to a point on the film. In ordinary photographic work a cone of light from each point in the object fills the entire lens and all this light is focused back to a point in the image as shown in Figure 11 (a). Most of this light passes through the highly-corrected portion of the lens, while that passing

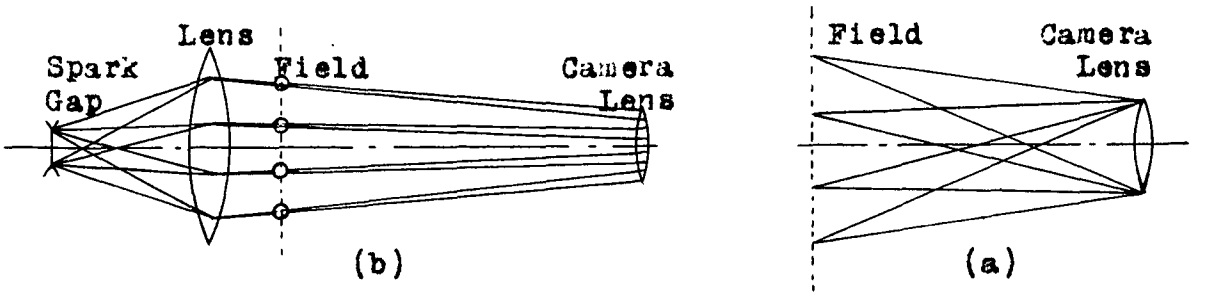


Figure 11

through the less-corrected edges is negligible. In this technique, however, where each tiny cone was localized to a small part of the beam and therefore a small part of the lens, as shown in Figure 11 (b), those cones entering the highly-corrected portions of the lens were focused sharply, while those entering the less corrected edges were more or less blurred. Stopping down the camera lens was found to shut out these areas but a more convergent beam of light was then necessary to obtain the same field and this brought in more distortion from the uncorrected simple lens. It was found advisable to mask out the extreme edges of this lens and to use a diameter of 2.5 inches instead of the full 4 inches.

By shortening the spark gap from one-eighth inch to three thirty-seconds inch, the size of the light source was reduced to give sharper images without reducing the amount of light obtained. Since the lighting system used gave barely enough light for good exposure, the use of a lens system consisting of two simple four inch convex lenses was tried in an attempt to obtain a larger solid angle of light from the spark, but the aberration of the lens pair was found to be undesirably great.

The forming of the image in this technique is comparable to that in a microscope, since it depends on the absorption and scattering of light by the fibers. Ab-

sorption due to the opacity of the dyed fiber is the principle factor in producing the silhouette images but scattering must also play an important part.

2. THICKNESS OF THE STOCK LAYER

The amount of stock through which the light beam passed was a very important factor governing definition of the fiber images and ease of tracing successive images. Fibers in the light beam, but not within the half-inch depth of focus of the camera, did not give clear images but did cause scattering of light to reduce the intensity and at the same time the contrast of the fibers that were in focus. This is clearly illustrated by the vastly better contrast and sharpness shown in top views, where the entire half-inch or so of the stream was in sharp focus, than in the side views, where about 1.75 inches thickness of the stock was not in focus. For side views in the 2.25 inch trough, therefore, a consistency of about 0.0002 per cent had to be used. This did not give very many fibers in focus but a higher consistency gave so many fibers in the layers out of focus that the images of those in focus were indistinct.

All fibers within the camera's depth of focus gave sharp images; but if the stock consistency was too high, the fibers overlapped to such an extent that it was difficult to trace out whole individual fibers and to follow them in successive positions in multiple spark exposures.

It is to be remembered in connection with multiple spark exposures that they showed this same multiple of images of the actual number of fibers present. For this reason high consistencies could only be shown by single spark exposures, and a narrower trough had to be used for the side views.

3. SIZE OF THE FIELD

The size of the field that could be photographed was limited to the area illuminated by the light beam as it passed through the stream. Masking out the uncorrected edges of the lens to avoid distortion reduced the size of the field accordingly. Thus when a 2.5 inch opening was used in the mask, the field illuminated was slightly less due to convergence of the beam. The lens was placed as near to the field as possible to get the maximum size of field.

4. DYED FIBERS FOR GREATER CONTRAST

Normal fibers are of rather low opacity in water suspension and the contrast obtained in their silhouette images was correspondingly low. To improve this condition the fiber used was dyed black with a heavy dyeing of direct dyes. Twenty-five grams of the long, unbleached western hemlock sulphite pulp were thoroughly broken up and heated just to boiling in two liters of water. Two grams of Du-Pont Black E Double, and one gram each of Pontamine Green and DuPont Purpurine were added and thoroughly mixed. After

ten minutes ten grams of sodium sulphate were added and the mixture was allowed to cool to room temperature. The fiber was then washed repeatedly in a sheet mold until the effluent was clear. These fibers gave a considerable improvement in contrast in the photographs.

It will be recalled that where two- or three-flash exposures were used the contrast was reduced to a half and a third, respectively, by flashes which occurred before or after any particular image of the moving fiber was made, hence the actual contrast for single spark exposures was relatively high. It was still necessary, however, to increase it by the use of high contrast film, paper, and developer.

5. CLEANLINESS AND EVENNESS OF SURFACES IN THE OPTICAL SYSTEM

Any scratches or smears on the glass surfaces in the optical system were exaggerated in multiple spark exposures because they held their same position for all the sparks to build up more contrast for each successive spark, while the contrast for the moving fibers was reduced successively as explained above. Therefore, cleanliness of these surfaces was of the utmost importance for clear pictures, since smears that were almost invisible to the eye could blot out a part of the picture. It was extremely difficult to get the side walls of the trough perfectly clean right down to the seam where they make contact with

the trough bottom so, after cleaning them as far down as possible, a glass plate cut the width of the trough was slipped in to raise the flow above these obstructions. Tiny air bubbles collecting on the trough walls in contact with the flow and droplets of water or any other moisture on any free glass surface in the light beam blotted out part of the field and had to be painstakingly avoided. Surface unevennesses caused scattering of rays in the light beam to blot out or distort the image; to avoid this the ripples on the free stock surfaces were ironed out by means of a glass-bottomed viewing box to show the field uniformly in top views, and to permit a greater thickness of the stream to be shown in the side views. In all cases the box was adjusted to just make contact with the stock surface and to conform as closely as possible to the slope of this surface. Such adjustment caused little or no change in the head back of the slice, showing that it caused very little change in flow resistance. No turbulence in the flow along this surface was evident.

Attempts were made to show top views of flow through curved inlets and over the streamlined spillway of a dam-type inlet where these surfaces were made of transparent cellulose acetate, but they were unsuccessful, due to distortion of the field by the curved surfaces.

6. USE OF PENDULUM TIMER TO AVOID DISADVANTAGES OF THE FOCAL PLANE SHUTTER

It was not found possible to synchronize perfectly the camera focal plane shutter with the spark frequency, and the resulting pictures showed correctly exposed bands separated by bands having received one spark more or less than normal. The difference in density between these bands made it impossible to show any detail in either the under- or overexposed bands at the optimum printing conditions for the normally exposed areas. These bands were sometimes as much as a quarter of an inch wide and often blotted out the most interesting part of the picture. The speed of the focal plane shutter was not perfectly uniform, so that the bands varied in width and position. Furthermore, the sparks causing the exposure in one normally exposed band were not the same sparks that formed the images in the adjacent normally exposed bands. This any irregularity in spark intensity caused even the bands receiving the same number of sparks to vary in density, so that both areas could not be shown clearly in the same print. The picture of the stirrer in Figure 26 (d) will illustrate this.

The lens diaphragm shutter gave no better results, because the spark showed the shutter in process of opening and closing and again part of the field was blotted out. The speed of this shutter was less uniform than that of the focal plane shutter. It seemed necessary, therefore, to

leave the camera wide open and produce only the desired number of sparks. This was accomplished by means of the pendulum timing device already described. This device allowed perfectly uniform lighting over the entire field, but had the disadvantage that the number of sparks could not be controlled perfectly every time. An optimum setting gave the desired number of sparks at least nine times out of ten, but it could give one spark more or less when the pendulum reached the contact at one certain point in the half cycle of the current supply. But even then the field was uniformly lighted so that, except for showing one image more or less than planned a perfectly good clear picture resulted.

7. USE OF COPPER SLICES WITH RUBBER GASKETS TO AVOID TIME LOSSES IN SEALING IN GLASS SLICES

Sealing a glass slice into place in the trough and waiting for it to set took from one to two hours, hence this procedure was impractical where a large number of changes were desired in a short period of time. The copper slices as described above were capable of instantaneous insertion, removal, or adjustment, and permitted a great saving in time.

8. BLOCKING OUT AREAS OF THE LIGHT BEAM NOT IMPORTANT IN THE PICTURE

Very painstaking care was required to keep clean

all the glass surfaces that were in the light beam but not important to the picture. Besides, these areas detracted from the main area of interest; hence they were blocked out by pieces of blotting paper cut to the proper shape and fixed to the front wall of the trough.

9. SCOPE OF APPLICATION

From the above discussion it is concluded that the usefulness of this technique at its present stage of development is restricted to studies of fundamental hydrodynamics under carefully controlled laboratory conditions. A study of conditions on a moving machine wire would seem to be impossible because the wire itself would blot out too much of the picture in the top views; and while a very narrow stream may possible be segregated for side views, this would require a consistency much below those commercially used. Furthermore, it would be difficult to keep the lighting system dry and prevent leakage of current, and spray getting on the glass surfaces would interfere. While these difficulties can probably be surmounted, it seems much more feasible to study certain aspects of the action on the wire in the laboratory.

B. THE SINGLE VERTICAL SLICE

The larger photographs in the following illustrations have been enlarged two diameters, while the small

pictures have been printed by contact to show the true size of the field and the fibers.

The top views show the full 2.25 inch width of the trough, except for the edges which were masked off by the iron frame of the trough. Some of the field length was usually sacrificed to place the most interesting area in the central part of the field for sharp definition.

If the exposure was timed by the focal plane shutter, dark and light bands will be seen in the pictures. In all cases where the focal plane shutter was used an exposure of 1/30 second was used to catch three successive sparks. Unless otherwise specified the exposures timed by the pendulum were also 3-spark exposures. In all cases the direction of flow, as shown in the pictures, was from right to left. Where it is not otherwise specified, the round lip vertical slice was used in the following studies.

The hydraulic head back of the slice was measured as the distance between the slice lip and the free surface of the pond.

1. GENERAL CONSIDERATIONS

a. Stream Approaching the Slice

The top views [Figure 12 (a-d)] were taken of a half-inch thick stream flowing normally along the bottom of

the trough with no agitation or obstruction to alter the normal conditions of flow. The viewing box (Figure 1 and page 35) was used to iron out any surface unevennesses. In (a) a single spark exposure shows that the orientation of the fibers was perfectly random. A 2-spark exposure made under exactly the same flow conditions is shown in (b) and gives the impression that most of the fibers are across the flow direction. This is an optical illusion, however, since actual count shows the following angular distribution for (a) and (b) of Table I.

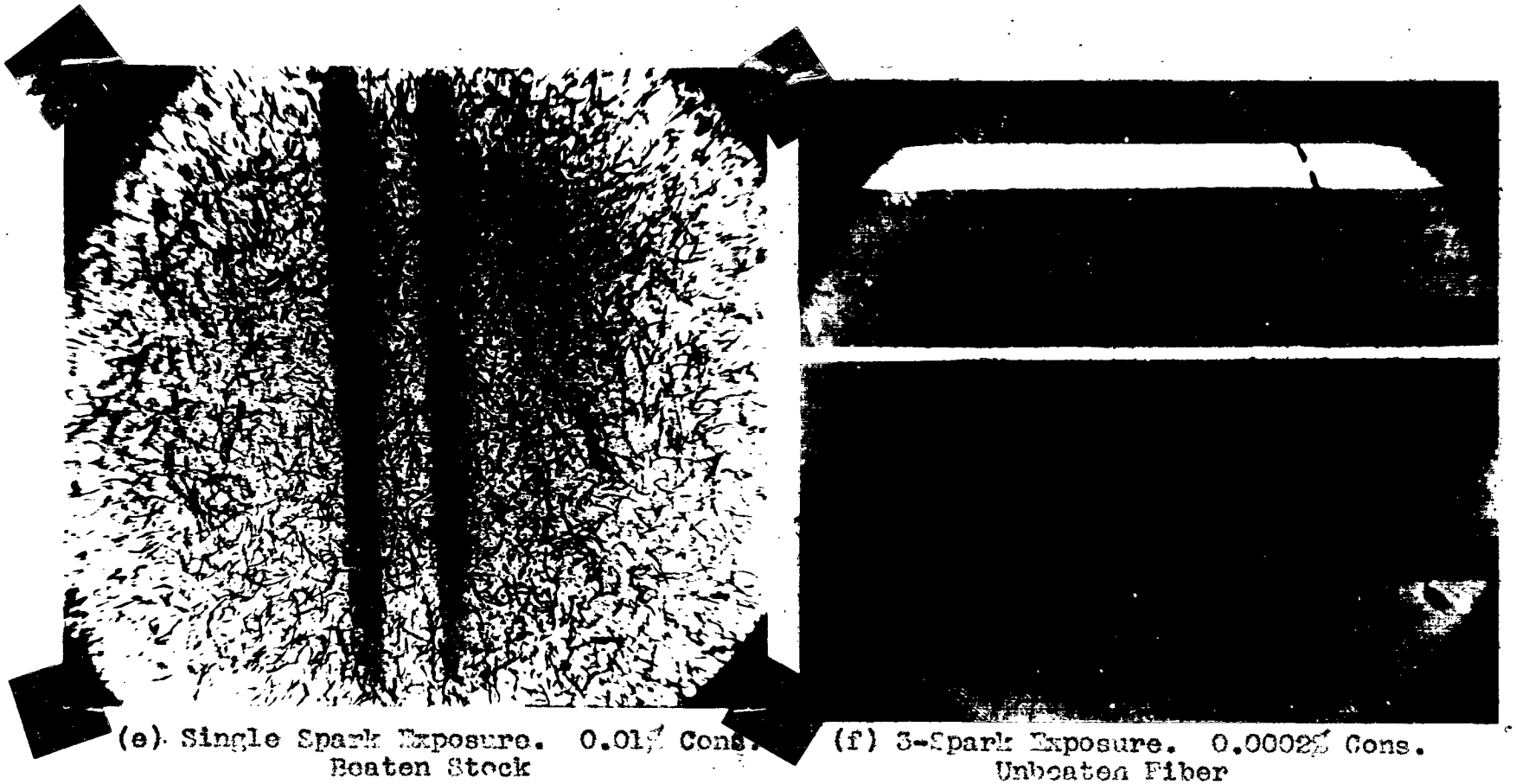
TABLE I

ANGULAR DISTRIBUTION OF FIBERS IN NORMAL FLOW

Angle between Fiber and Flow	Number of Fibers	
	(a)	(b)
0°	46	98
30°	49	104
60°	53	92
90°	45	96

Each fiber was counted under the nearest 30° grouping.

When the exposure was timed to catch successive images at a greater interval (skipping two sparks), as shown in (c), the parallel images were no longer close enough together to give the illusion. (d) is a 3-flash exposure with one spark skipped between the second and third. The speed of flow, as calculated from the interval between images and the spark frequency was 75 feet per minute.



(e) Single Spark Exposure. 0.01% Cons. Beaten Stock

(f) 3-Spark Exposure. 0.0002% Cons. Unbeaten Fiber

Side Views

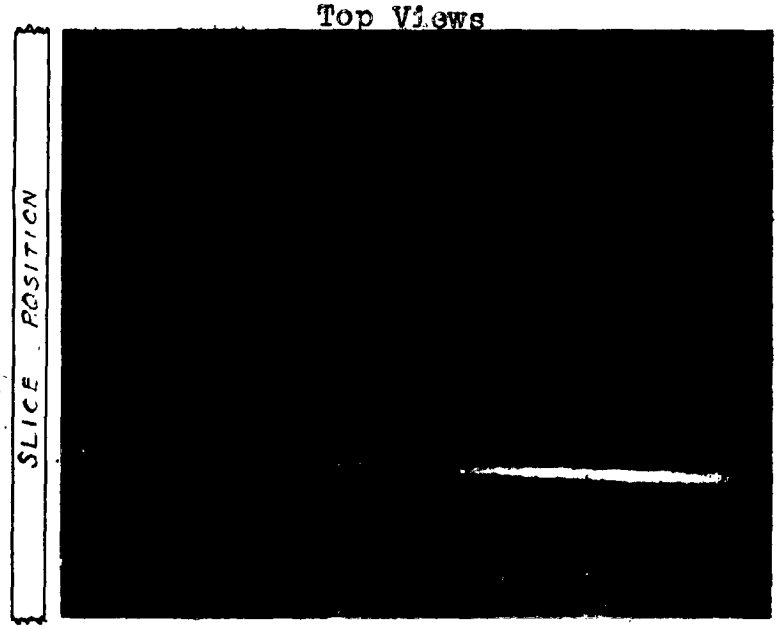
Figure 12 (Cont.) FIBER BEHAVIOR IN A FREE-FLOWING STREAM

Side views of normal flow in the stream back of the slice are shown by (e) and (f). (e) shows a single spark exposure of a half-inch thick stream at a consistency of 0.01 per cent, while (f) shows a 3-spark exposure in the normal trough with a consistency of 0.0002 per cent as usual for side views.

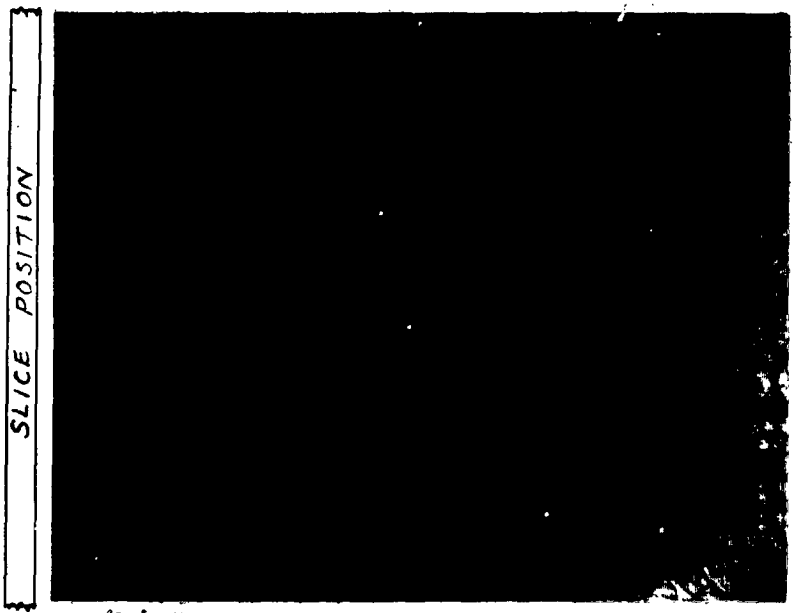
These pictures show that the orientation of fibers in normal flow is random. The classic comparison of a fiber with a log in a stream is, therefore, not valid for it is not even true that the lower specific gravity of the log makes it flow more slowly than the stream [as stated by Lund (28)]. With no retarding force, the log would quickly come to equilibrium at the same speed as the water flow. This would be true to a much greater degree for the fiber, due to its small mass and relatively large surface in contact with the water in which it is completely submerged. There is, therefore, no relative motion between the fiber and the water in normal flow and, hence, no tendency toward alignment.

Figure 13 (a) and (b) show top views of the conditions just back of a round lip vertical slice [Figure 7 (a)] with a head of 1½ inches. For (a) the camera was focused one inch above the trough bottom and the short interval between some images in the left side of the picture indicates that most of their motion was downward toward the

Top Views



(a) Focused One Inch above the Trough Bottom



(b) Focused at the Bottom of the Stream in the Trough

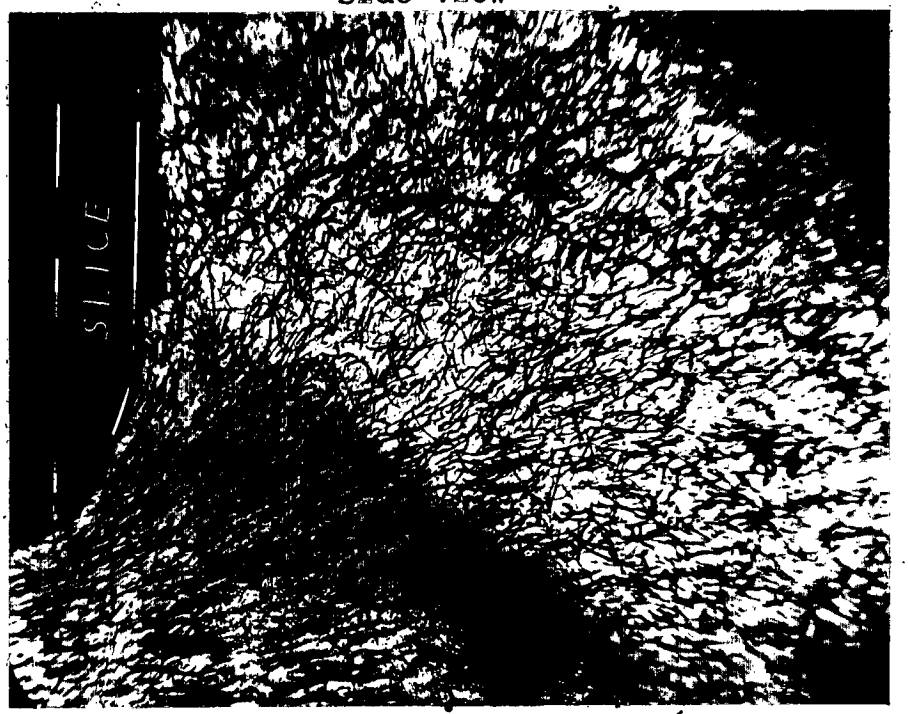
Figure 13. THE STREAM JUST BACK OF THE SLICE (3-Spark Exposures)

Top View



(c) Focused at the Bottom of the Trough and Showing the Stream from the Slice

Side View



(d) Single Spark Exposure. 0.01% Beaten Stock

Figure 13. THE STREAM JUST BACK OF THE SLICE
(3-Spark Exposures).

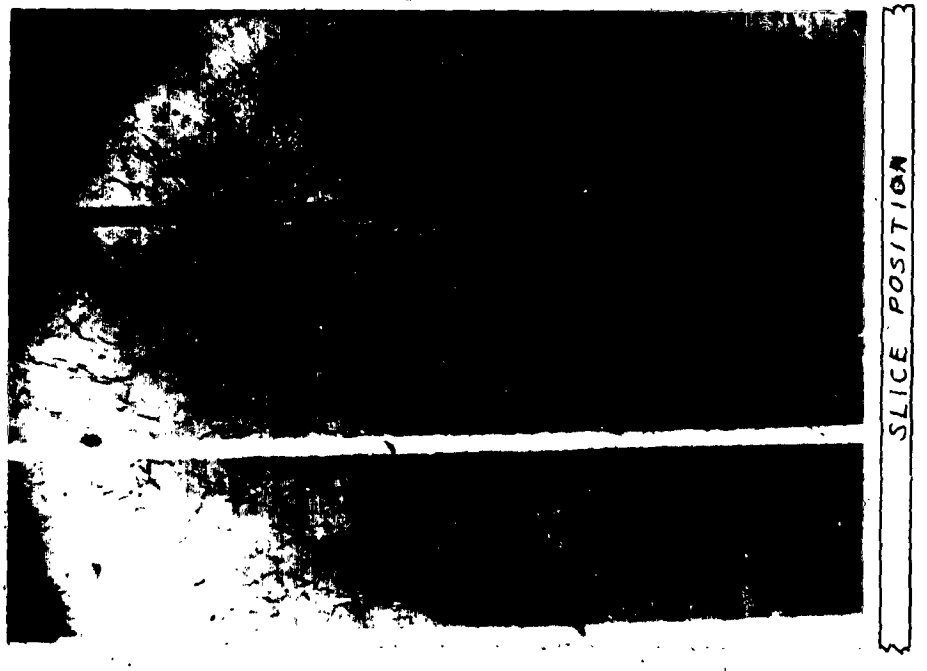
slice opening showing the conditions at the bottom of the trough. In (b) some tendency toward alignment is evident near the slice (the left edge of the picture). (c) shows a similar view of the condition back of the slice and also the stream from the slice, showing the alignment of fibers in the flow direction, and also ripples in the top surface. The side view (d) shows the fibers lining up as they approached the slice opening at the lower left of the picture (beaten fiber at 0.01 per cent consistency in the half-inch trough described on Page 36)

b. Under the Slice

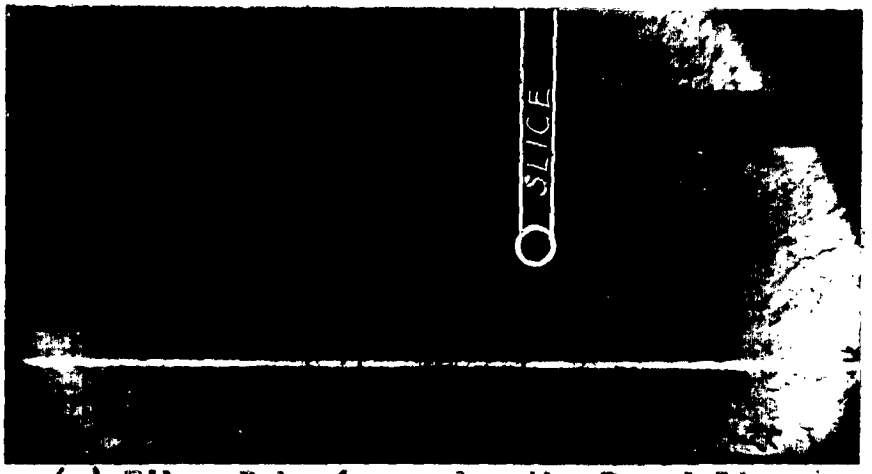
i. Effect of the Type of Lip on the Vertical Slice

Figure 14 shows side views of the flow under vertical slices with various types of lips and corresponding top views of the streams from these slices. The round lip, slanting knife edge, sharp knife edge, square lip, and gapped lip slices (Figure 7 a - e) are shown in (a), (b), (c), (d) and (e), respectively. A slice opening of half an inch was used in all cases, and the head back of the slice was allowed to adjust itself while the rate of flow was kept constant. Calculation of the stream velocities from the maximum interval between fiber images in the photographs and the spark frequency showed the following results as compared with the velocities predicted by hydraulic calculations from the head back of the slice (Table II).

Top View

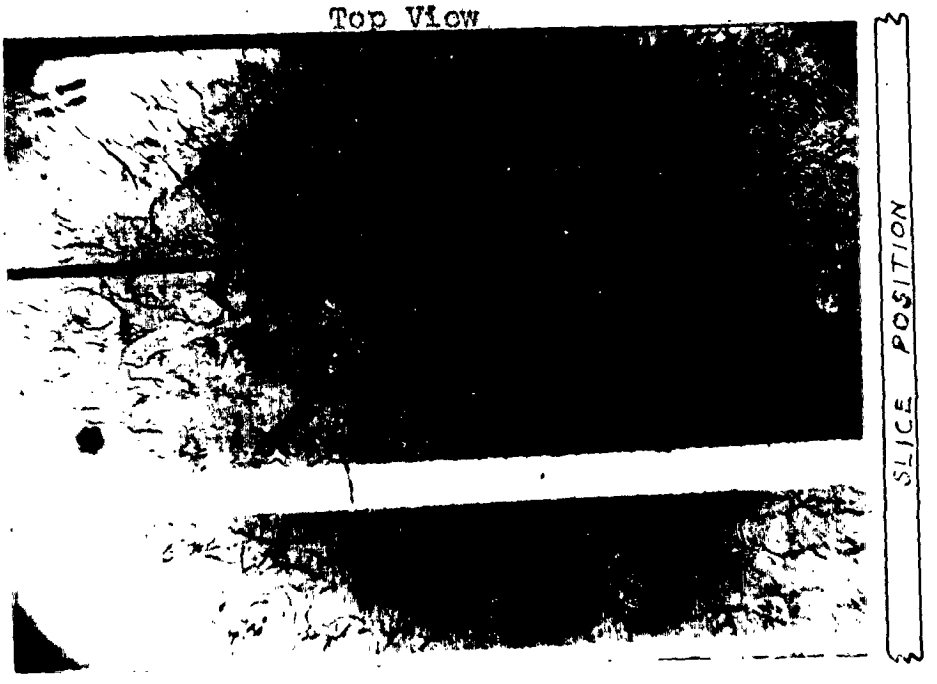


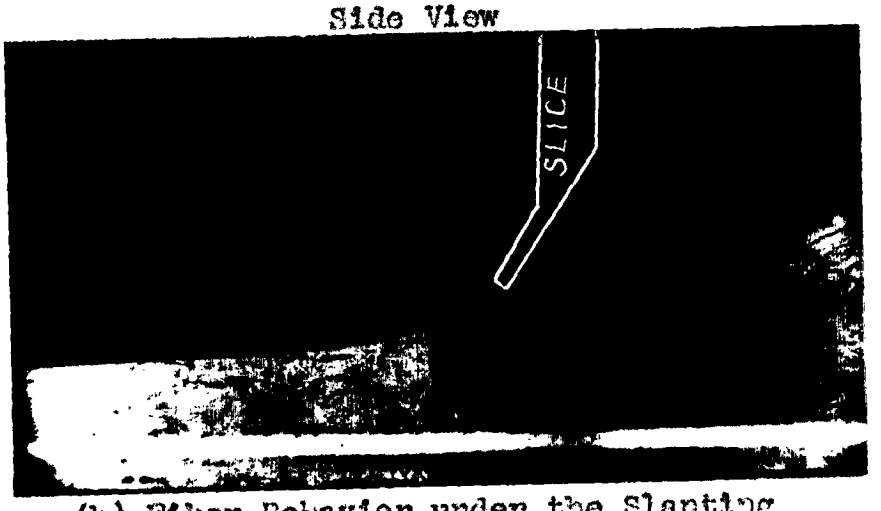
Side View



(a) Fiber Behavior under the Round Lip Vertical Slice

Figure 14. THE EFFECT OF SLIT TYPE OF LIP ON THE SLICE (3-Spark Exposures)





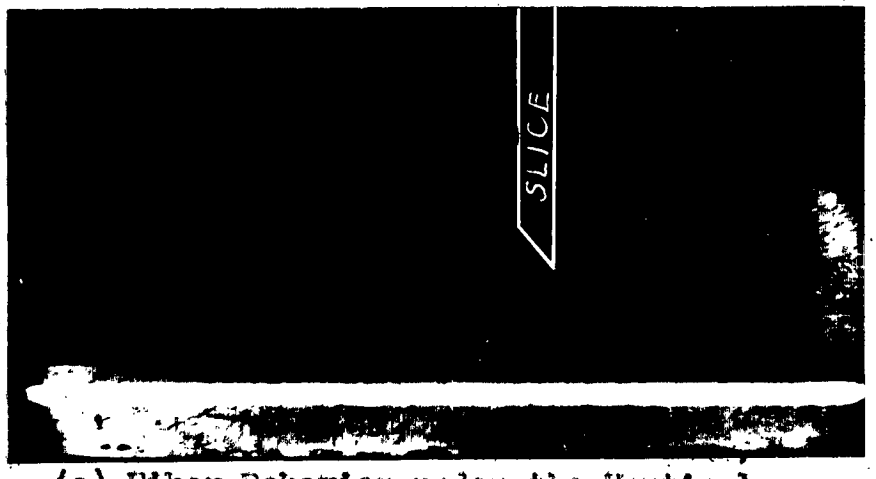
(b) Fiber Behavior under the Slanting Knife Edge Slice

Figure 14.(Cont.). THE EFFECT OF THE TYPE OF LIP ON THE SLICE (3-Spark Exposures)

Top View



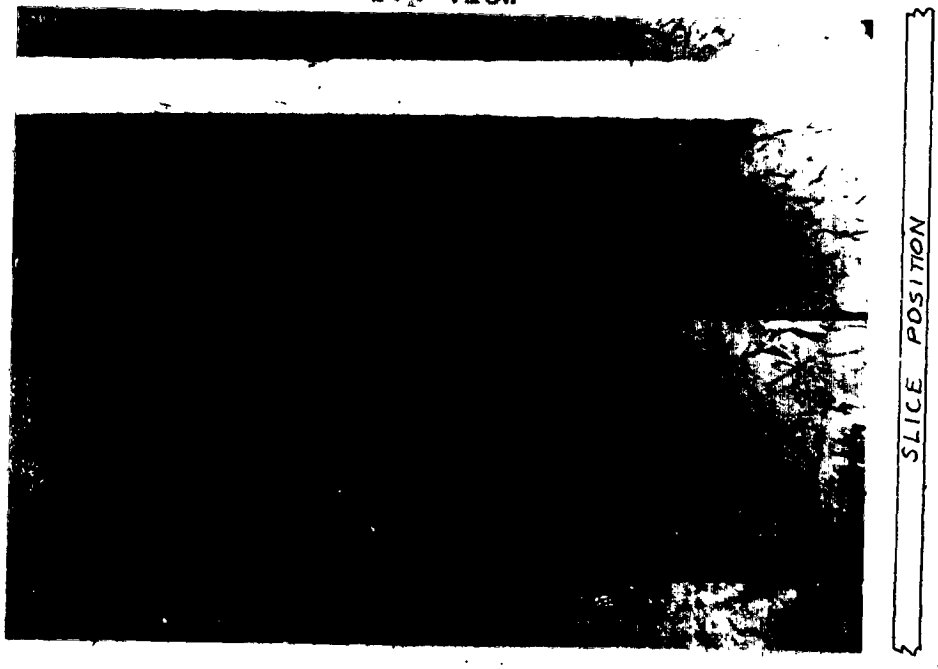
Side View



(c) Fiber Behavior under the Vertical Knife Edge Slice

Figure 14 (Cont.) THE EFFECT OF CUT TYPE ON LIP ON THE SLICE (3-Spark Exposures)

Top View

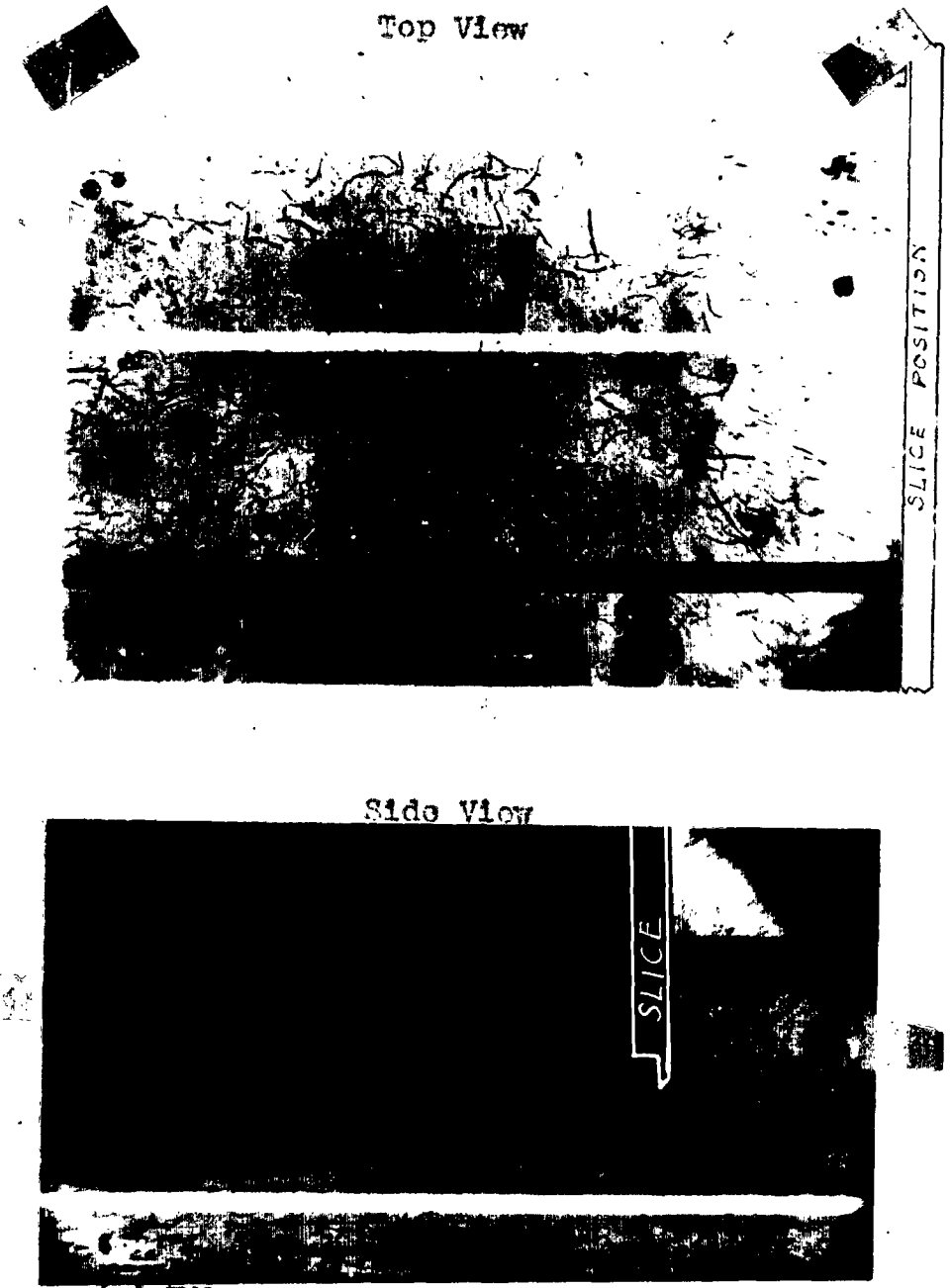


Side View



(d) Fiber Behavior under the Square Lip Slice

Figure 14 (Cont.) THE EFFECT OF SLICE TYPE OF LIP ON THE SLICE (3-Spark Exposures)



(e) Fiber Behavior under the Gapped Lip Slice

Figure 14 (Cont.) THE EFFECT OF THE TYPE OF LIP ON SIDE SLICE (3-Spark Exposures)

TABLE II

THE RELATION BETWEEN THE HEAD BACK OF THE SLICE AND THE STREAM VELOCITY FOR VARIOUS TYPES OF SLICE

Type of Lip	Head in Feet h	Interval Between Images in Inches d	Velocity in Feet per Minute	
			Calculated from Image Intervals v	Predicted Value v'
Round	0.125	0.0508	183	176
Slanting Knife Edge	0.125	0.0508	183	176
Vertical Knife Edge	0.172	0.0573	204	204
Square	0.151	0.0535	192	192
Gapped	0.146	0.0535	192	190

The equation, $v = \frac{d}{2 \times 12} \times 120 \times 60$ feet per minute, was employed for calculating the stream velocity v from the interval d in inches between the successive fiber images on the enlargements. The predicted velocities v' were calculated from the equation:

$$v' = \sqrt{2g}\,\frac{h + h'}{\sqrt{h + 2h'}}$$

This equation has been derived from Bernoulli's theorem, and it takes into account the velocity of approach of the stream back of the slice.

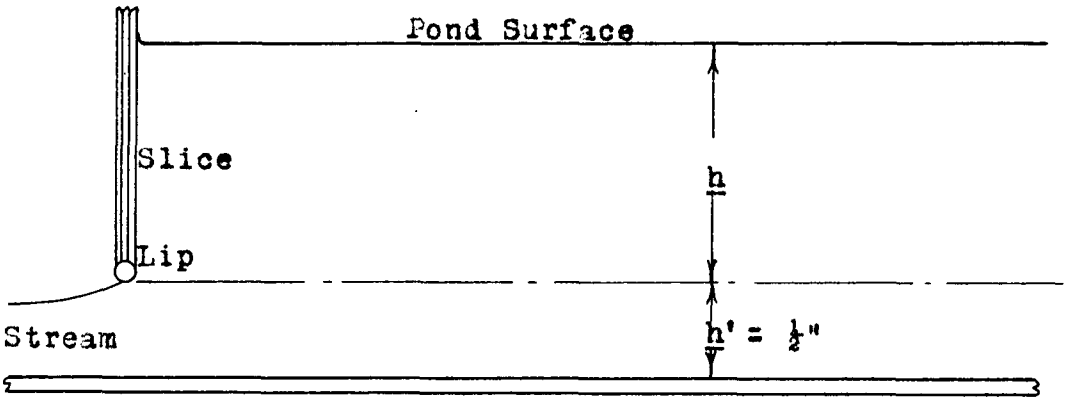


Figure 15

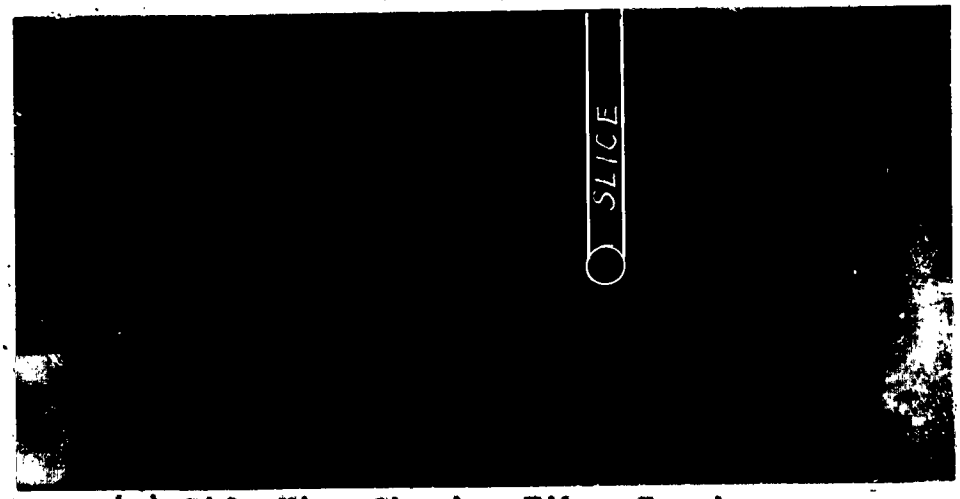
Figure 15 shows diagramatically the significance of h and h'. h is the head measured above the slice lip and h' is the height of the slice lip above the bottom of the trough.

These results show a very close agreement between the stream velocities as measured from the photographs and those predicted by hydraulic calculations. The variations undoubtedly resulted from experimental error in measuring the intervals between images or from slight irregularities in the time interval between the sparks which made the exposure.

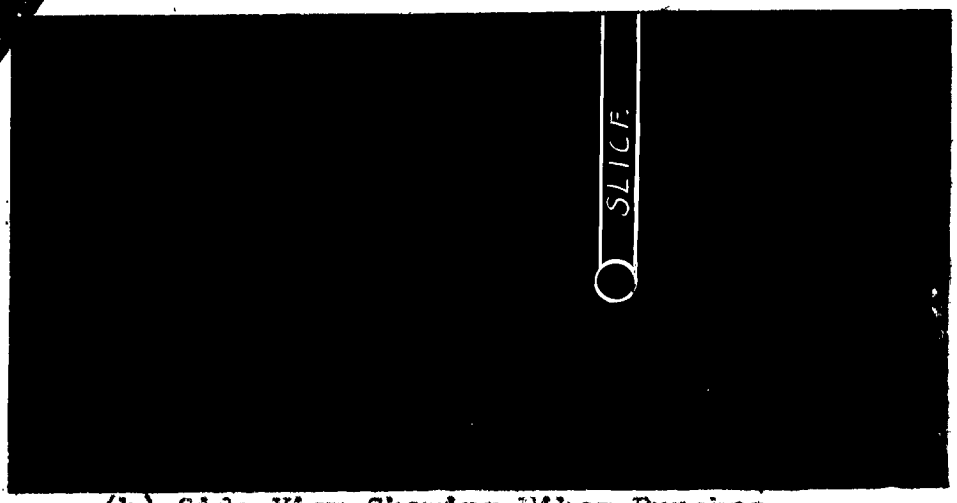
All these side views show a pronounced alignment of the fibers as they passed under the slice. Straight fibers are seen to be perfectly aligned with the streamlines, while curved fibers were as well aligned as their

shape would permit. Successive images of individual fibers show that the streamlines of flow progressed so that the fibers gave no rotation or change in position relative to the flow direction. Likewise in the top views the fiber images show definite alignment but not as complete as in the side views.

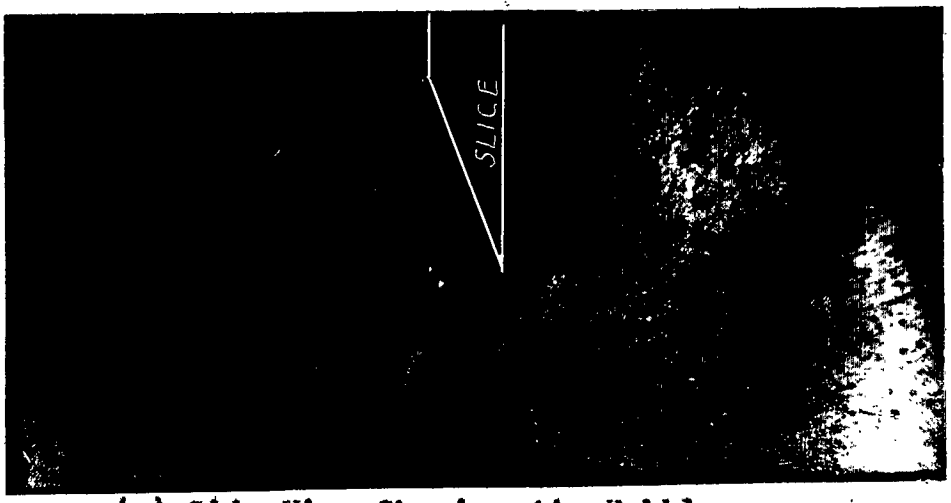
ii. Stretching Action of the Acceleration Under the Slice. The aligning action is seen to have begun just back of the slice where the accelerating action began. The leading point of each fiber entering this zone was acted upon first to speed it up and make it tend to pull away from the rest of the fiber, thereby increasing its length along the line of the accelerating force. The velocity of motion of the individual fiber might be considered as being equal to that of the water at its midpoint. During acceleration, any part of the fiber that was ahead of its midpoint would be in faster moving water and any part back of the center would be in slower moving water, so that the fiber would be stretched out in the flow direction. This pulling out action was demonstrated by means of fiber bunches photographed in passage under the slice to show that they were stretched and pulled apart. Figure 16 (a) and (b) show this action clearly by three successive images of each bunch as it passed through the zone of acceleration. It will be seen that the length of each bunch and the in-



(a) Side View Showing Fiber Bunches



(b) Side View Showing Fiber Bunches



(c) Side View Showing Air Bubbles

Figure 16. THE STRETCHING ACTION OF ACCELERATION UPON THE SLICE (3 Sparks at 1/40 Sec. Intervals)

terval between images increased as it progressed through this zone. (a) shows the movements of three such bunches and (b) shows those of two more over the entire acceleration zone. Two images of a third bunch that had already passed the zone of acceleration are shown in (b). In (c) is shown a relatively large air bubble just as it passed under the slice lip. It was pulled out to an elliptical shape by the accelerating action under the slice of the high pressure head box (Figure 3 and 5). Surface tension undoubtedly prevented any noticeable elongation of the small bubbles.

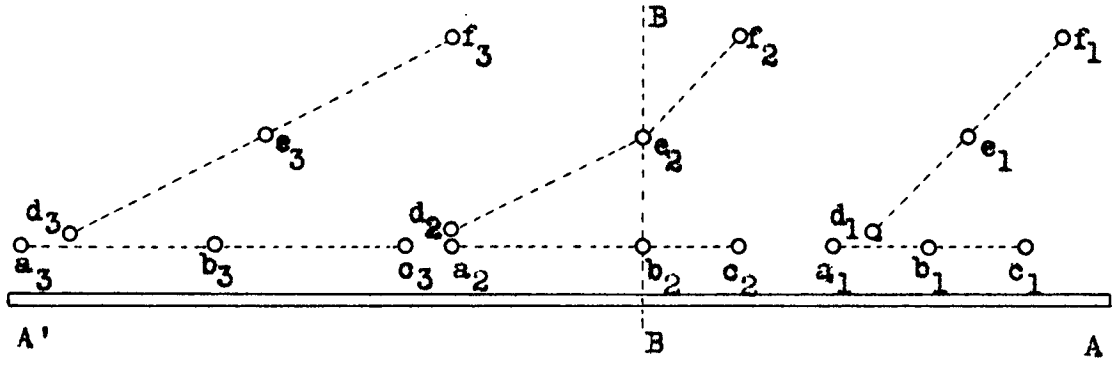


Figure 17

This action of acceleration may be further demonstrated by the accompanying diagram (Figure 17). Considering the flow of a fluid from right to left in a trough with bottom AA', it may be assumed that the flow is uniform at x feet per second up to a point B where it is suddenly accelerated to 2x feet per second. Now if three particles

(a, b and c), suspended in this fluid are aligned in the direction of flow and spaced at intervals of y feet (a_1, b_1 and c_1), a will reach the point of sudden acceleration at a time interval of y/x seconds ahead of b. After being accelerated to a velocity of 2x feet per second, it will move a distance of 2xy/x or 2y feet in the time required for b to reach the point of acceleration, and the positions will be as shown by a_2, b_2 and c_2. Similarly, when c reaches the point of acceleration, a and b will both have moved 2y feet further so that the positions after acceleration will be as shown by a_3, b_3 and c_3. This illustrates the pulling out effect.

Now if three other particles (d, e and f) are along a line at 45° from horizontal, for example, as shown by d_1, e_1 and f_1, the same increase in interval between particles occurs without any vertical displacement (d_3, e_3 and f_3). However, if these points or particles represent the ends and center of a fiber, this interval is fixed by the length of the fiber so that no increase can occur. Instead, the forces tending to cause this elongation act as a couple to gradually rotate the fiber until it is aligned with the streamlines of flow.

Under actual flow conditions, these actions take place more gradually since acceleration is never instantaneous as pictured here; this example merely serves to il-

lustrate the effects.

This stretching action might also be illustrated by considering a more concentrated stock suspension as one large fiber bunch which was stretched out to many times its original length as it passed under the slice. Under the influence of this stretching force, the fibers would tend to line up exactly like the threads of loosely woven cloth when it is pulled on the bias. A practical advantage of this phenomenon is the fact that flocculation of the stock in the head box is broken up, at least in part, by this action.

iii. Velocity Gradient Between Layers in the Stream from the Slice. In all cases, acceleration at the slice was accompanied by a more or less sharp change in the direction of flow. Lund (28) has shown, on the basis of hydraulic theory, that this change in direction at the slice causes a velocity gradient between layers of the stream from the slice, the highest velocity being at the top, and the lowest at the bottom (see page 16). He states that this difference in velocity between layers causes end-over-end rotation of the fibers as they pass through the slice opening. However, these pictures show definitely that no such rotation was found to occur under the slice. This indicates that the strong aligning action of the acceleration

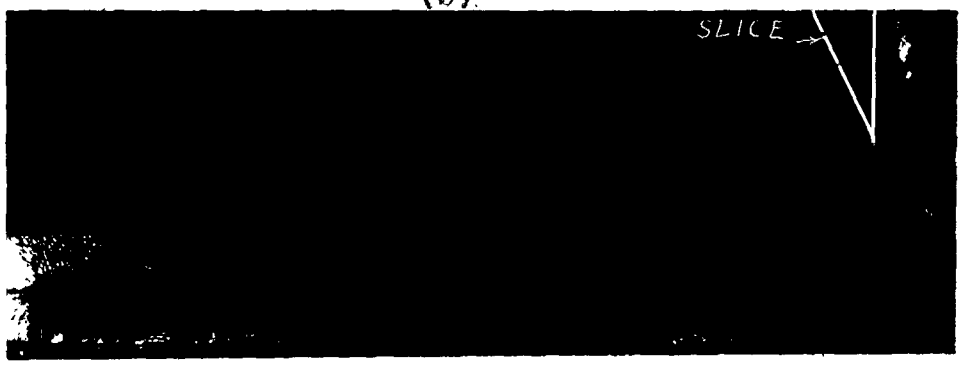
was sufficient to mask any tendency toward rotation of fibers that would be caused by differences in layer velocities. With the low heads used for most of this work, the difference in head made by the width of the slice opening tended to make the bottom layer faster, thus counteracting Lund's effect to some extent; but the same alignment of fibers was found (Figure 18) when a head of 2 feet was used back of the slice. Exposures of two, rather than three, sparks were used for photographing these high speed conditions in order to obtain better contrast and definition. With this high velocity, the interval between images was so great that it was found difficult to follow successive images of individual fibers in the turbulent stream from the slice, but careful examination did disclose a number of pairs of images approximately 1 11/16 to 1 13/16 inches apart in the enlargements, indicating velocities of 507 to 543 feet per minute. In (a) pairs of fiber images are pointed out, 1 11/16 inches apart near the top of the stream and only 1 5/8 inches apart near the bottom, to indicate a greater speed in the top layers. This speed difference would probably be much more noticeable if the measurements were made over a wider interval, and still higher velocities of flow would probably give greater differences according to Lund's formulas (page 16). A pair of images of an air bubble in the stream is also indicated in (a). It is to



(a)



(b)



(c)



(d)

FIGURE 10. THE VELOCITY GRADIENT [illegible] IN A HIGH SPEED STREAM FROM THE SLICE WITH A 2-FOOT HEAD
(2-Spark Exposures)

be noted that the interval between these images is the same as that between fiber images. In (b) two pairs of air bubble images and one pair of fiber images, all 1 13/16 inches apart, are pointed out. These measurements were made far enough down the stream to be outside the zone of acceleration.

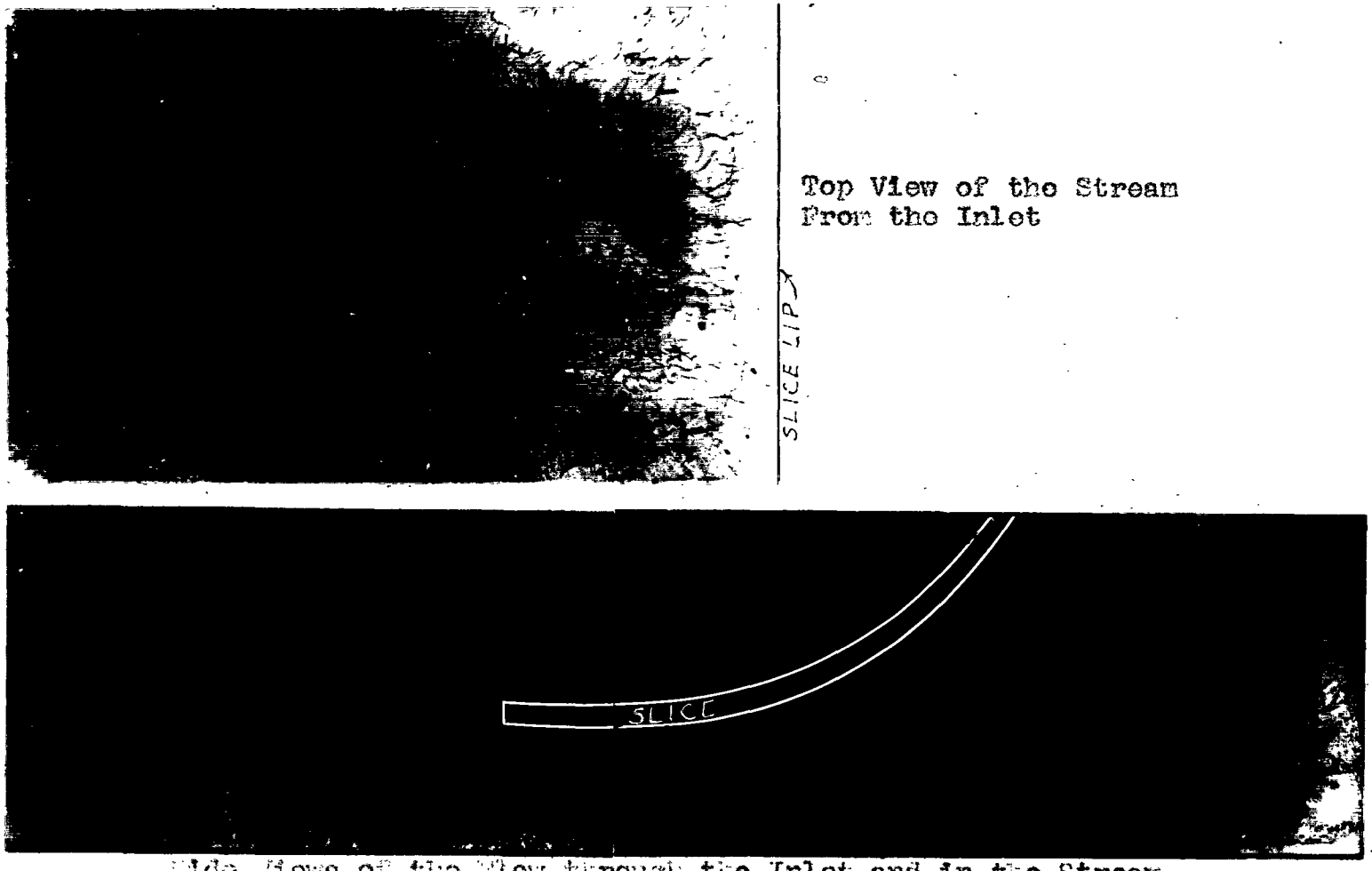
iv. Fiber Alignment by Change in Flow Direction Under the Slice. The flow direction change at the slice was found to have another important function: Most of the volume of stock passing under a vertical slice came, not horizontally along the trough bottom, but from above at a greater or less angle; and under these conditions it had to make a sharp turn around the slice lip at the same time that the strong accelerating action exerted its effect. As a result, the forward ends of the fibers were suddenly seized by the accelerating forces and, not only pulled out by them, but also whipped around the slice lip to make the trailing ends line up behind in the streamline planes of flow. Therefore, the change in direction of flow would increase the tendency for fiber alignment, especially that shown in the side views; and this would explain the more perfect alignment observed in these views.

In general, however, the fibers, as seen in these top views, were either lined up parallel to the flow or were

almost perpendicular to it. The reason for this seems to be that while fibers at an angle less than 90° from the flow direction were stretched out by the acceleration under the slice, those at almost exactly 90° from the flow direction were unaffected, because the water had the same speed along their entire lengths. They did not extend far enough in the flow direction to allow the flow at their front ends to be appreciably faster than the flow at their trailing ends. Differences in layer speeds and the change in direction effects did not permit a similar condition for fibers seen in the side views, therefore their alignment was more complete.

This would indicate that better alignment could be expected for sharp edged slices than for other types of inlets which do not give such sharp changes in the direction of flow. A comparison of the alignment shown for various types of vertical slices in Figure 14 with that for a curved surface inlet in Figure 19, or for the slanting surface inlets in Figure 28, will show that this was found to be the case. This relative effect is especially noticeable in the alignment shown in the top views.

v. Relative Fiber-Water Velocity. It has already been shown that, in smooth normal flow, there is no relative motion between the submerged fibers and the water surrounding



Side View of the Flow through the Inlet and in the Stream

Figure 19. THE CURVED SURFACE INLET (3-Spark Exposures)

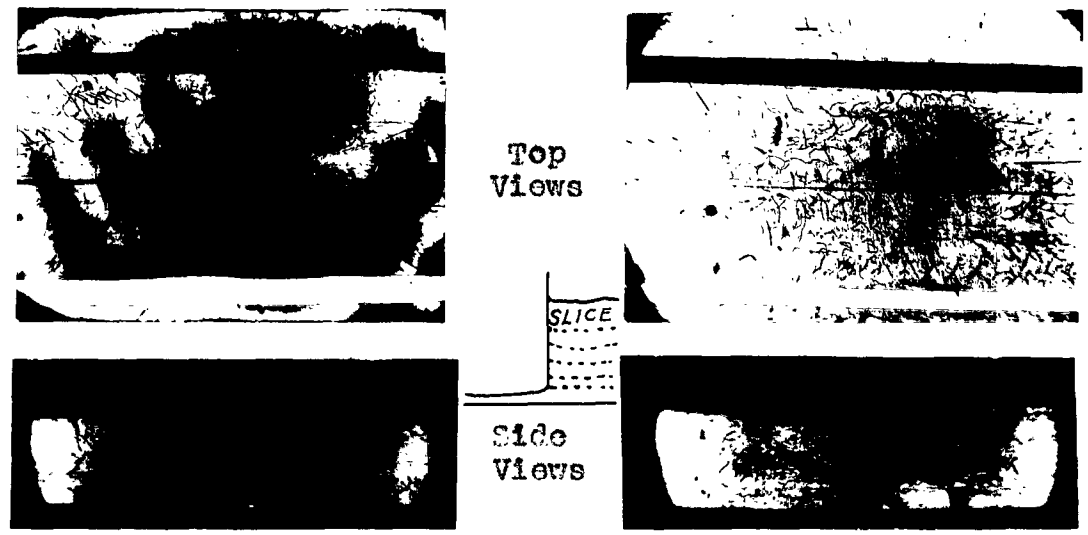
them. It was thought that, even under the influence of the acceleration at the slice, fibers, having small mass and relatively large surface area would still show no lag behind the water. Under such conditions it can be shown mathematically (34) that, for a sphere with a diameter of the same magnitude as a fiber, the retarding effect of inertia would be negligible as compared to the viscous force tending to cause acceleration. If this is true with a spherical body, which has the minimum surface for its mass, then a fiber, with its greater surface area, would tend still better to keep up with the stream during acceleration. It is obvious that a smaller particle offers more surface in proportion to its mass than a larger one. Therefore, successively smaller particles should show less and less lag during acceleration, and comparison of the relative speeds of various sized fiber particles in the acceleration zone under the slice should be enlightening. The fiber movements under the curved surface inlet as shown in Figure 19 were selected to demonstrate this, because this inlet gave a longer zone of acceleration and a larger area for study.

Wherever a large fiber and a small fiber appeared together, they were traced through their successive images to see whether or not they retained their relative positions. Due to the fact that the picture showed a field that was

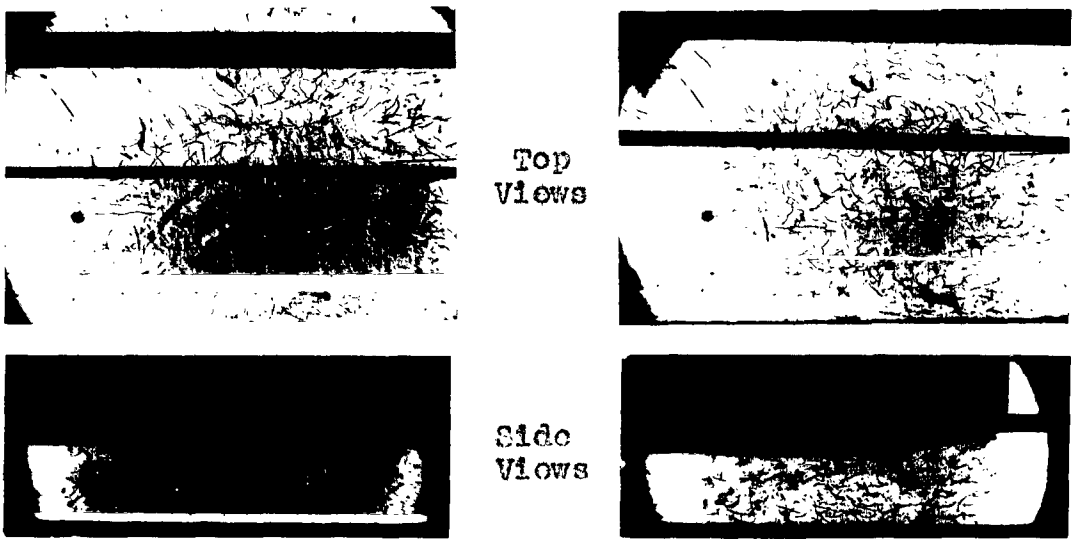
approximately half an inch thick, the two fibers being compared might not have been right together and any lack of uniformity of flow across the stream would have interfered. Any such difference in the narrow trough used would have been so small as to be negligible, however. A large number of comparisons were found to show equal speeds and accelerations regardless of the size of the fiber particles, hence it was assumed that there was no appreciable lag between the fibers and the stream. Examination of the side view in Figure 19 will show numerous examples for comparison, and similar additional evidence may be obtained from the side views of the conditions under the vertical slices (Figure 14) and under slanting slices (Figure 28).

vi. Effect of Head Back of the Slice. A series of pictures were taken to show the effect of the head back of the slice on the aligning action and on the velocity of the stream from the slice. Figure 18 shows top and side views of conditions at heads of 0, 1/8, 1/4, 1/2, 1, 1 5/8, and 23 1/2 inches above the slice lip with a slice opening of half an inch. The head above the trough bottom was, therefore, half an inch greater in each case.

In Figure 20, (a) shows that no tendency for alignment was evident in the stream with a zero head above the slice lip. The top view of this condition was taken without



(a) Zero Head over Lip (b) One Eighth Inch Head



(c) One Quarter Inch Head (d) One Half Inch Head

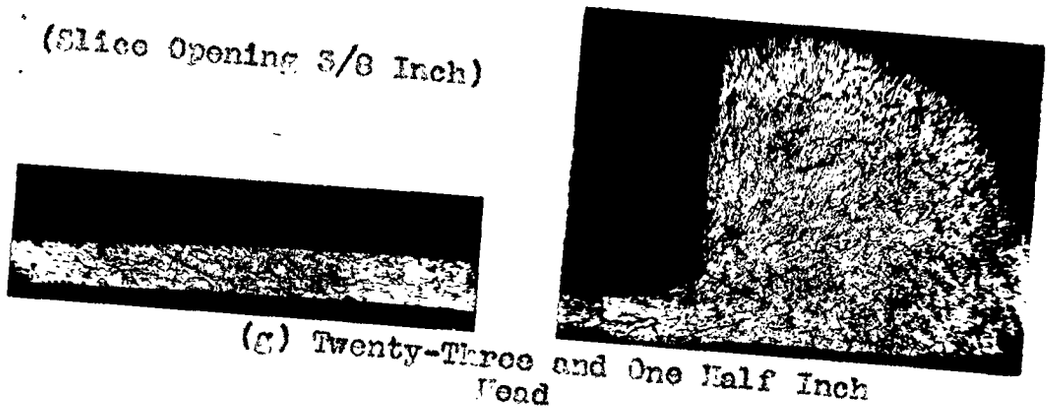
Figure 20. THE EFFECT OF THE HEAD BACK OF THE SLICE
(Slice Opening $\frac{1}{8}$ Inch)
(3-Spark Exposures)



(e) One Inch Head

(f) One and Five Eighths Inch Head

(Slice Opening 3/8 Inch)



(g) Twenty-Three and One Half Inch Head

Figure 20 (Cont.) THE EFFECT OF THE HEAD BACK OF THE SLICE
(Slice Opening $\frac{1}{2}$ Inch)
(3-Spark Exposures)

the viewing box and thus slight surface unevennesses are shown in the picture. In (b) it is shown that an eighth-inch head produced little or no change; but with a quarter inch head, the alignment as shown in the side view of (c) was almost complete, and that in the top view is quite distinct. Further increase in alignment is shown in (d) and (e) for heads of a half and one inch, respectively. No further increase is shown in (f) for a head of 1 5/8 inches. With a 23 1/2 inch head and a 3/8 inch slice opening, side views of the zone of acceleration and the stream three inches beyond the slice were taken to show that the same aligning phenomena occurred at high speeds. It will be observed that the alignment in the stream below the slice was rapidly breaking up.

The velocities of flow for the various heads have been calculated according to the equations given on pages 77 and 78 and are shown in Table III.

The velocities as calculated from the image intervals and the predicted values are all within the limits of experimental error for the low heads back of the round lip slice in the 2.25-inch trough, but for the 23 1/2 inch head back of a sharp edge slice the retarding action of friction was sufficient to make the observed stream velocity considerably less than that calculated for this pressure head. This increase in friction resulted partly from the greatly

TABLE III

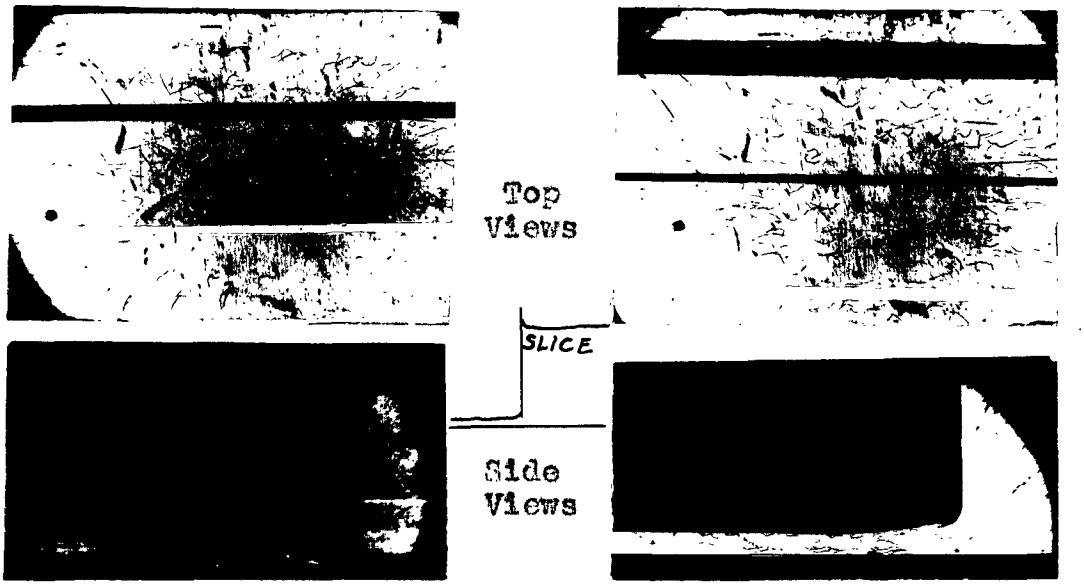
THE EFFECT OF HEAD ON THE VELOCITY OF THE STREAM

Head Above Slice Lip Feet	Image Interval Inches #	Velocity in Feet per Minute	
		Calculated from Image Intervals	Predicted Value
0.0000	0.110	66	70
0.0104	0.141	85	82
0.0208	0.172	103	93
0.0417	0.188	113	114
0.0833	0.234	141	148
0.1355	0.313	188	183
1.9580	0.905	543	675

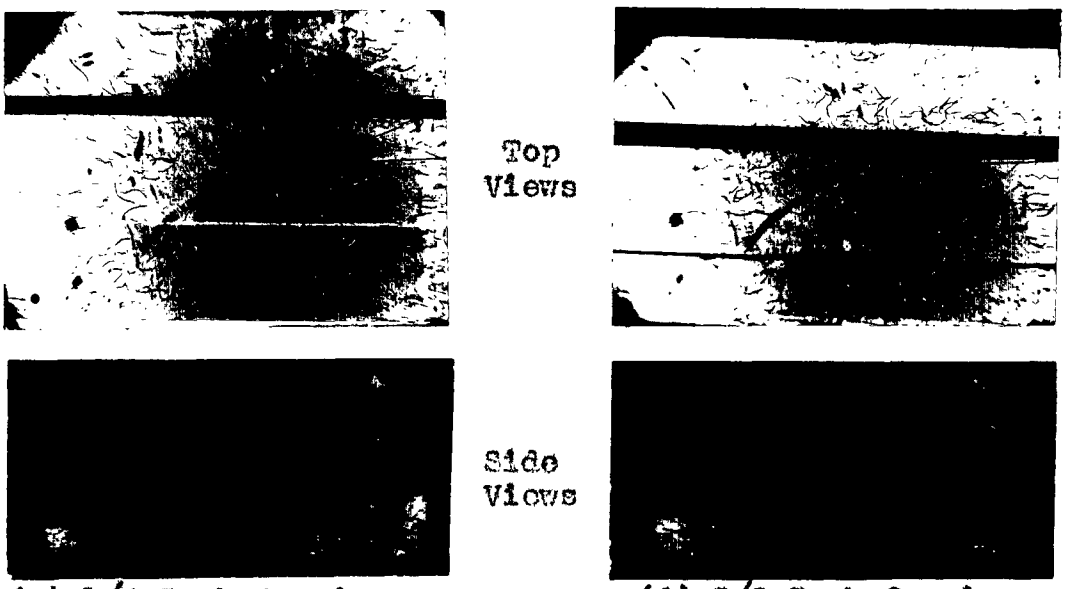
The image intervals listed in this table were measured on unenlarged prints.

increased velocity and partly from the fact that a sharp edge slice in a 3/4 inch wide trough was used.

vii. Effect of the Size of the Slice Opening. Another series of pictures was taken to show the effect of varying the width of the slice opening when the head back of the slice was kept constant. These pictures are shown in Figure 31 with (a), (b), (c), (d), and (e) showing the conditions for 1/8, 3/16, 1/4, 3/8, and 1/2 inch openings, respectively. No difference was noted in the resulting alignment of the fibers. The water level back of the slice was kept constant for all these studies, so that the effective head, as



(a) 1/8 Inch Opening (b) 3/16 Inch Opening



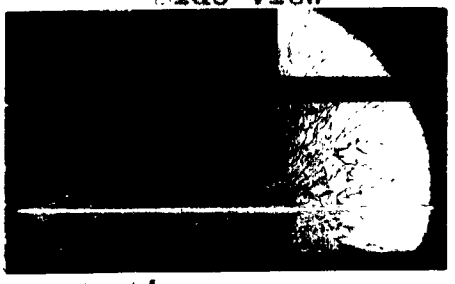
(c) 1/4 Inch Opening (d) 3/8 Inch Opening

Figure 21. SIZE OF THE SLICE OPENING
(Head 2 Inches)
(3-Spark Exposures)

Top View



Side View



(e) 1/2 Inch Opening

Figure 21 (Cont.) SIZE OF THE SLICE OPENING
(Head 2 Inches)
(3-Spark Exposures)

measured above the midpoint of the slice opening, increased slightly with the decrease in the size of the opening. After correction was made for this difference, the volume of flow was found to be closely proportional to the width of the opening.

c. The Stream from the Slice.

To determine the behavior of the fibers in the stream at various distances beyond the slice, a group of top and side views were taken with and without the viewing box in contact with the top surface. These pictures were taken with a 2-inch head back of the slice and a half inch opening for all views except the side views of the conditions at the slice as shown in Figure 22 (a). For these views a 3/8 inch opening was used. In Figure 19, (a) shows the conditions at the slice and (b), (c), and (d) show the conditions at distances of 4, 6, and 12 inches beyond the slice, respectively.

It is apparent from Figure 22 (a) that the presence of the viewing box on the surface of the stream just after the slice caused no change in the flow conditions at that point, but it did greatly improve the top view. It also permitted the showing of a slightly greater thickness of the stream in the side view. In all cases the normal fiber alignment was evident.

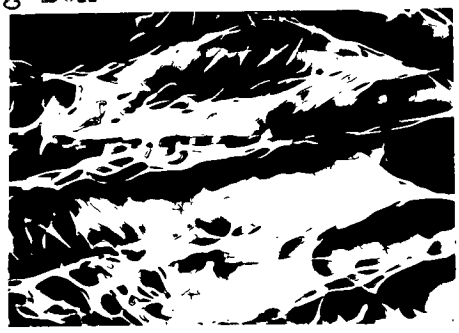
With the Viewing Box



Top Views

(d) (e)

Without the Viewing Box



Top View

(e)

With the Viewing Box



Side Views

(d) (e)

Without the Viewing Box



Side Views

(d) 12 Inches from Slice (e) 6 Inches from Slice

Figure 22. FIBER BEHAVIOR IN THE STREAM AT VARIOUS DISTANCES FROM THE SLICE. (3-Spark Exposures)

With the Viewing Box



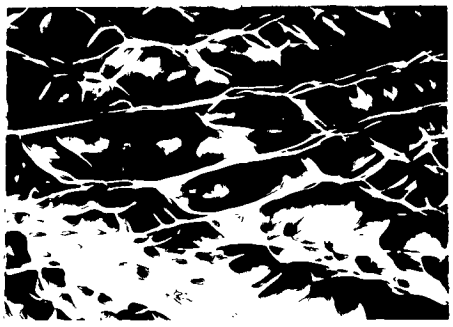
(b)

Top Views



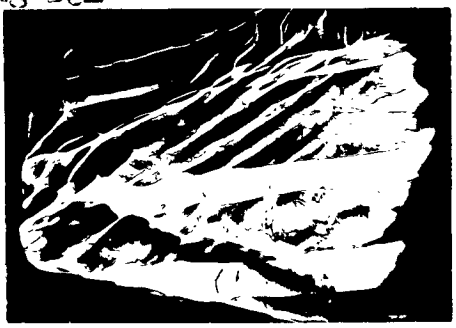
(a)

Without the Viewing Box



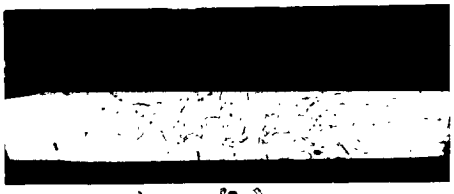
(b)

Top Views



(a)

With the Viewing Box



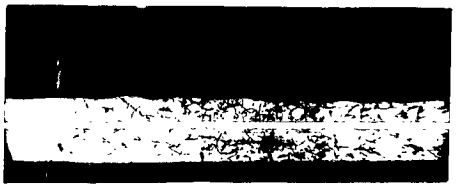
(b)

Side Views



(a)

Without the Viewing Box



(b) 4 Inches from Slice

Side Views



(a) Stream at the Slice

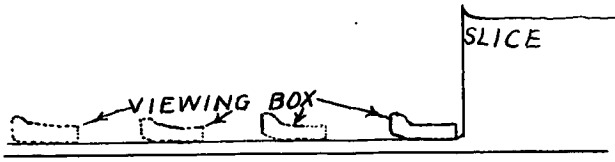
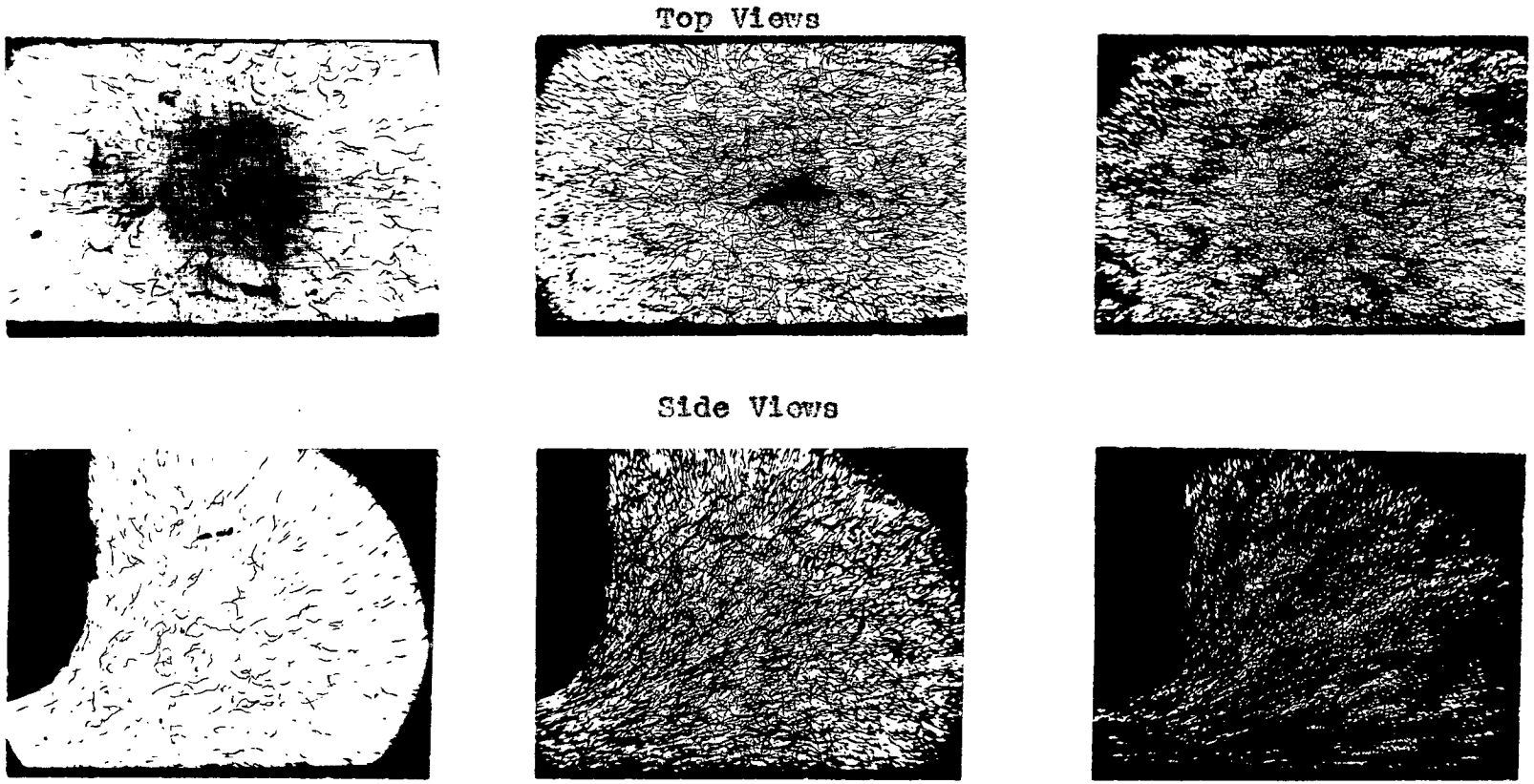


Figure 22. FIBER BEHAVIOR IN THE STREAM AT VARIOUS DISTANCES FROM THE SLICE. (3-Spark Exposures).

At a distance of 4 inches from the slice, the alignment had begun to break up as shown in (b). Here ripples in the top view, where the viewing box was not used, blotted out nearly all the fiber images. The fibers that are visible in (b), however, show that the alignment was more completely broken up than when the viewing box was used. The alignment became progressively less at 6 and 12 inches from the slice as shown in (c) and (d), but still it seems that the presence of the viewing box exaggerated the alignment. The ripples on the stream at 12 inches from the slice blotted out the fiber images completely, so this picture is not shown. The side views show almost random orientation 6 inches from the slice, and they do not show any change due to the presence of the viewing box. That the breaking up of the alignment was very gradual is indicated by the fact that no rotation of individual fibers can be detected in the short interval between successive fiber images in either the top or the side views. Apparently the slight drag exerted by the viewing box on the top surface tended to equalize the drag of the trough bottom reducing the rolling turbulent motion and thereby helping to preserve the alignment as seen in the top views.

d. Effect of Consistency and Beating.

To show that the phenomena observed in very dilute suspensions of unbeaten fiber also occurred at the consis-



(a) Unbeaten Fiber
0.001% Cons.

(b) Unbeaten Fiber
0.01% Cons.

(c) Unbeaten Fiber
0.05% Cons.

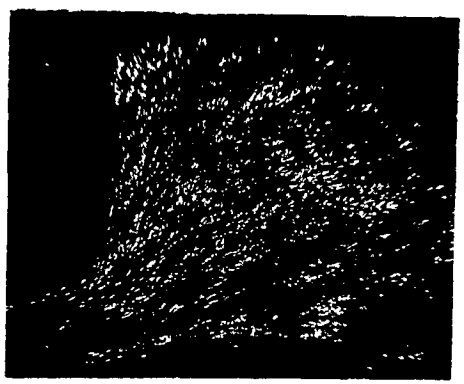
Figure 23. EFFECT OF CONSISTENCY AND BEATING
(Single Spark Exposures)

Top Views

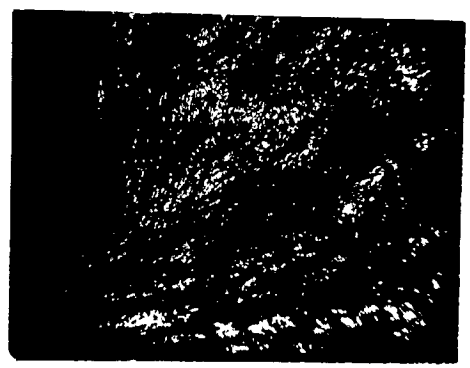




Side Views



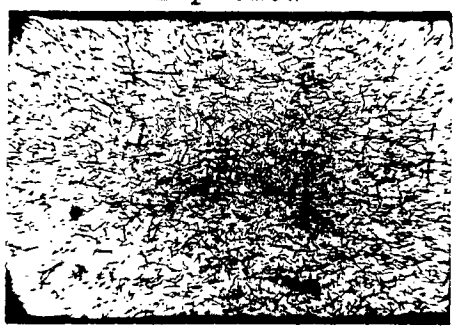
(d) Unbeaten Fiber
0.1% Cons.



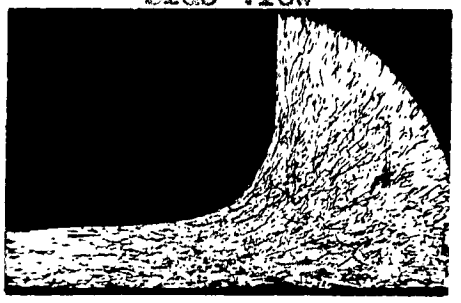
(e) Unbeaten Fiber
0.25% Cons.

Figure 25 (Cont.) EFFECT OF CONSISTENCY AND BEATING
(Single Spark Exposures)

Top View



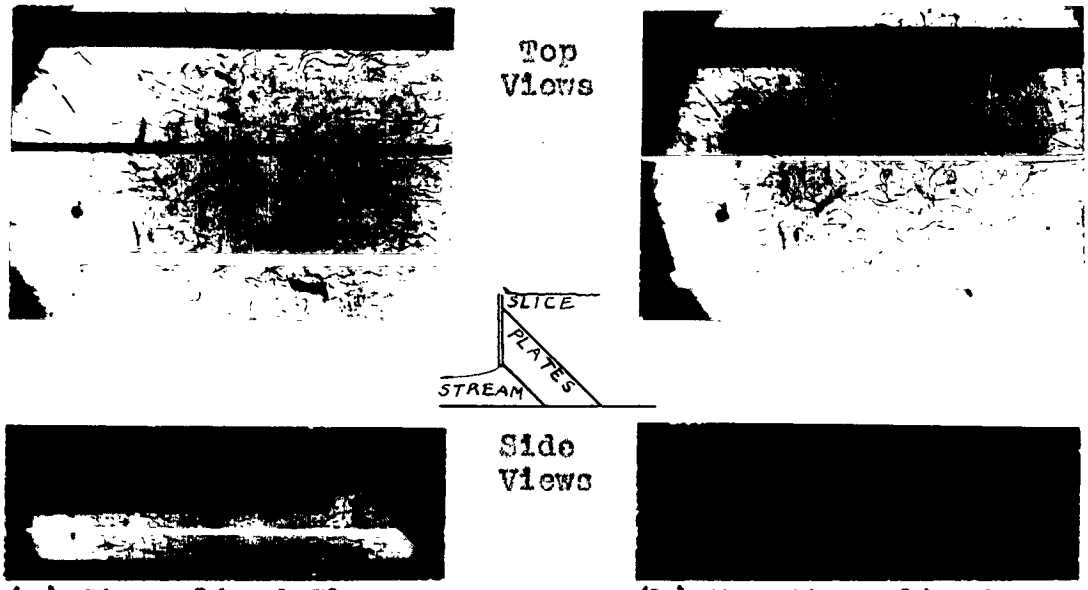
Side View



(f) Beaten Stock
810 S. R. 0.01% Cons.

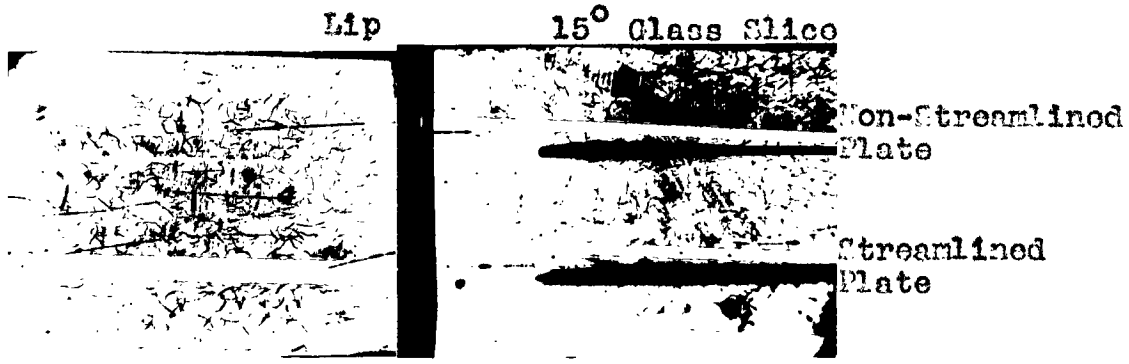
Figure 23.(Cont.) EFFECT OF CONSISTENCY AND BEATING
(Single Spark Exposures)

tencies used on the paper machine, a series of pictures were taken at various consistencies, using beaten stock. The effect of consistency is shown in Figure 23 with (a), (b), (c), (d), and (e) showing top and side views of 0.001, 0.01, 0.05, 0.1, and 0.25 per cent consistencies, respectively. (f) shows the top and side views of the behavior of beaten stock. Single spark exposures were used throughout this study so that the number of fiber images at the high consistencies would be at a minimum. The half-inch wide trough described on page 36 was employed for the side views. With increasing consistency the side views show individual fibers less distinctly but the pulling out and aligning action under the slice is obvious in all cases. The top views also show the preferential alignment in the direction of flow. The long unbeaten fiber used in the stock for these pictures showed a strong tendency to flocculate at the higher consistencies. Consequently, clumps of fibers appeared in pictures (b - e). It is interesting to note that all of these fiber clumps were aligned in the flow direction under the slice and in the stream from the slice, and that stretching of these clumps in the passage through the zone of acceleration would necessarily cause the fibers in the clumps to be strongly aligned in the same direction. Beaten stock, as shown in Figure 23 (b), exhibited the normal fiber alignment at the slice but did not show any tendency toward floc-



(a) Streamlined Plates

(b) Non-Streamlined Plates



(c) Streamlined and Non-Streamlined Rectifier Plates under a Sloping Slice

Figure 34. THE EFFECT OF RECTIFIER PLATES BACK OF THE SLICE LIP (3-Spark Exposures)

culation at consistencies as high as 0.1 per cent. The presence of size and alum in the stock showed no effect on these phenomena, but did smear up the glass walls of the trough and make the water cloudy, so that it was impossible to get clear pictures.

2. EFFECT OF RECTIFIER PLATES BACK OF THE SLICE LIP

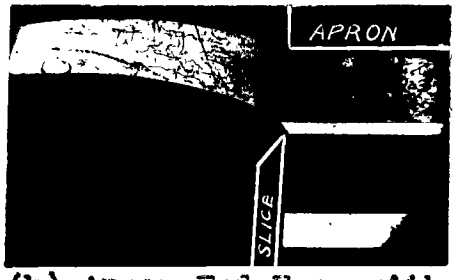
With rectifier plates back of the slice lip, pictures were taken to show their effect on the conditions of flow. In Figure 24 (a) and (b) show, respectively, the conditions of flow after streamlined and non-streamlined plates back of the round lip vertical slice [Figure 7(m)]. In Figure 24 (c), the picture on the right shows the flow past rectifier plates [Figure 7 (l)] under a glass slice at 15° from horizontal. This view was taken through the glass slice. Besides the plates shown in this picture, another non-streamlined plate was just outside the field at the top of the picture and a second streamlined one was just outside at the bottom. The picture at the left in (c) shows the resulting conditions in the stream from the slice.

The top views in (a) and (b) indicate that somewhat better alignment resulted in the stream from the streamlined plates in (a). No difference could be noted from the side views. The stream from the 15° glass slice with the plates

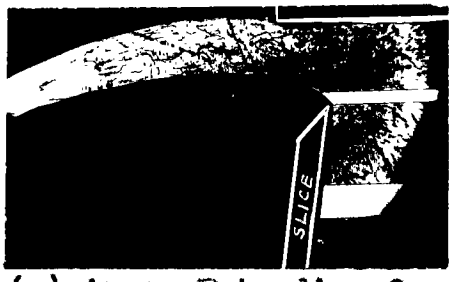
Side Views



(a) Apron End 1/2 Inch Back of the Slice



(b) Apron End Even with The Slice



(c) Apron Extending One Half Inch beyond the Slice

Figure 25. THE EFFECT OF RELATIVE POSITIONS OF THE SLICE AND THE END OF THE APRON. (3-Spark Exposures)

back of its lip seemed to show slightly better alignment on the side having the streamlined plates. A comparison of the top views shows that the fiber alignment from this sloping slice was much less pronounced than that from the vertical slice. The difference between the effects of the streamlined and non-streamlined plates would undoubtedly be greater at higher speeds, under which conditions the latter would tend to cause streaks in the resulting sheet on the paper machine. Streamlined plates would give smoother flow and less tendency to break up the alignment.

Rectifier plates are used in paper machine inlets chiefly to break up cross currents. In the narrow trough used here, no such currents existed, hence this action was not demonstrated.

3. EFFECT OF RELATIVE POSITIONS OF THE SLICE AND THE END OF THE APRON

A number of investigators (2, 3, 8) have stressed the importance of the relative positions of the slice and the end of the apron on the wire. This adjustment has been found to be a very important factor in the control of sheet formation; and therefore, it seemed desirable to obtain photographs showing the effect of this adjustment on the velocity and the flow direction of the stock as it emerged from the slice opening. The apparatus available was not

readily adaptable to showing these effects with the slice in its normal position so an inverted arrangement was devised for this study as shown in Figure 7 (a). The conditions resulting from terminating the upper surface or "apron" half an inch behind the inverted slice, from having it end even with the slice, and from allowing it to extend half an inch beyond the slice, are shown in (a), (b), and (c) of Figure 25, respectively. With the surface terminating back of the slice, the fiber alignment in the stream through the opening was fairly complete as shown in (a). If a wire were in place along the line of the apron surface, as would be the case on the paper machine, the vertical component of this stream against the wire, assisted by gravity, would make the stream tend to pass through the wire. The aligned fibers would hit the wire end first and tend to pass through. Not having attained wire speed at such a point back of the slice, however, their ends would be pulled forward by the faster moving wire to lay down the fibers in the machine direction in the first layers to form on the wire.

When the apron end was even with the slice as shown in (b), the stream still had a component upward. On the machine, this again would direct the stream downward against the wire, but here the stream would have attained its full acceleration, and, therefore, should be moving at wire speed. With little or no relative motion between the

stock and the wire to cause the fibers to lie flat on the wire, a considerable amount of fiber would be expected to pass through.

With the apron extending beyond the slice as shown in (c) there was no longer an upward component. Hence the stream would be traveling horizontally at its maximum speed when it hit the wire. Under these conditions the fibers would lie parallel to the wire surface and have little or no chance to pass through unless they were very short.

C. SLICE AND INLET DESIGNS

1. THE DOUBLE SLICE INLET

The use of the 2-slice inlet is almost as old as the Fourdrinier paper machine. Paper makers were quick to realize the effectiveness of this arrangement for evening the flow across the machine and for giving agitation to break up fiber flocs in the stock just before it was admitted to the wire. The following investigations of this inlet were made to show the conditions responsible for its effectiveness.

a. Conditions of Flow with the Slices 6 Inches Apart

For this study of the flow conditions in a 2-slice inlet, two round lip vertical slices [Figure 7 (a)] were inserted in the trough 6 inches apart, with slice openings of 5/8 and 3/8 inches, respectively, for the first and second

slices. With heads of 3 1/8 inches back of the first and 2 inches back of the second slice, side views were taken of the flow under the first slice, through the middle of the pond between the slices, and under the second slice. These pictures are shown in Figure 26 (a) from right to left in the order given above. The conditions in the stream from the second slice are shown by the top and side views in Figure 27 (c). From these pictures, it is apparent that, although the fibers were strongly aligned directly under the slice, this alignment was broken up immediately thereafter. Evidently enough eddies carried from the turbulent pond through the slice to the stream beyond to break up the fiber alignment as soon as the zone of acceleration was passed. The turbulence in this stream was so great that it was difficult to follow successive images of fibers in the pictures. It is apparent from Figure 26 (a) that the fibers were aligned normally in passage under the first slice and that this accelerated stream flowed along the trough bottom and underneath the water of the pond straight to the second slice. Friction with this mass of water in the pond, however, gradually broke up this stream by the formation of eddies whose random movements are shown by the successive images of fibers in the upper layers of the pond. This action was accompanied by a spreading of the stream to a greater thickness so that most of it finally hit the second

slice above the slice opening and caused strong turbulence in this area as shown in the photograph.

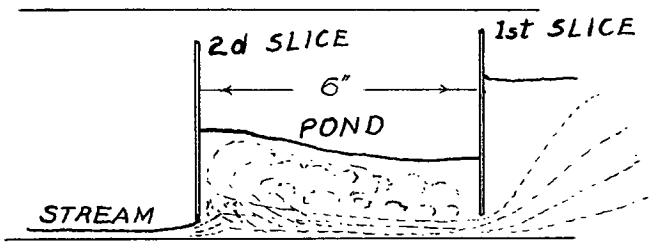
It was found that the movements of the dyed fibers in the pond could be followed visually when viewed against a well-lighted white background. This method was used, together with the photographs, to further elucidate the behavior of the fibers and confirm the observations described above.

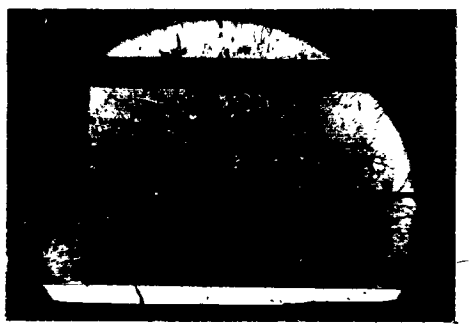
The lack of fiber alignment in the stream from this type of inlet seemed to indicate that ample agitation was obtained in the pond between the slices. However, additional agitation in the pond has often been recommended; and therefore, Williamson's control rack (5) [Campbell (51) has patented a similar device] and a motor-driven wire stirrer in the pond were investigated, to determine the effect of such agitation on the stream from the second slice.

i. The Effect of a Control Rack in the Pond. With the slices arranged as described above, the control rack [Figure 7 (q)] was placed in the pond midway between the slices, with its prongs extending to the bottom of the trough. It was found by visual observation that this control rack acted as a multiple nozzle, which retarded flow and caused the fast stream from the first slice to spread much higher into the upper layers of the pond. As the streams from the sev-

eral nozzles flowed back together beyond the rack, they produced considerable turbulence, but the movement of the eddies was then largely about vertical axes instead of the rolling action in the normal pond. The pictures of the stream from the second slice show that this agitation was very effective for causing random fiber orientation in the stream from the slice [Figure 26 (b)]. The viewing box was in contact with the surface of the stream for the side view to permit the showing of a larger area. Without the viewing box in place, ripples caused by the turbulence in the stream would blot out much of the view, as is the case in (c).

ii. The Effect of a Motor Driven Wire Stirrer in the Pond. With the same arrangement of slices as before, the motor-driven wire stirrer [Figure 7 (r)] was placed in the center of the pond and started rotating. It caused no change in the heads back of the slices, but did collect fibers rapidly from the stock as shown by Figure 26 (d), which was taken just after inserting the stirrer. It may be seen from this picture that the rapidly moving (800 R.P.M.) stirrer blades were completely "stopped" in the three different positions in each exposure band. In the right part of this picture, aligned fibers in the stream from the first slice may be seen approaching the stirrer, which broke up this alignment, spread the fast stream, and broke up eddies

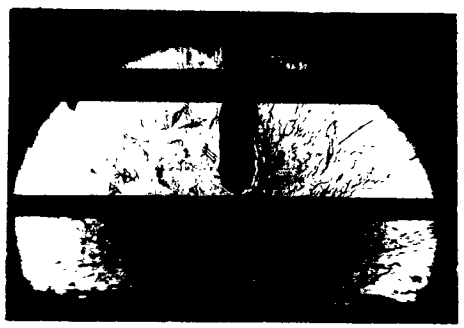




At the Second Slice
3/8 Inch Opening



In the Middle of the
Pond



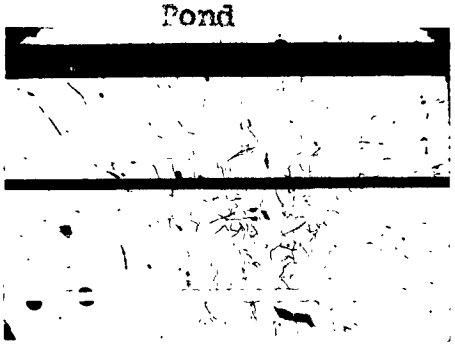
At the First Slice
5/8 Inch Opening

(a) Normal Conditions of Flow under the Slices and in the Pond

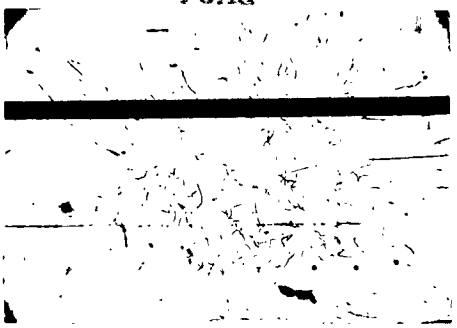
Figure 26. THE DOUBLE SLICE INLET. CONDITIONS OF FLOW WITH THE SLICES 6 INCHES APART. (3-Spark Exposures)

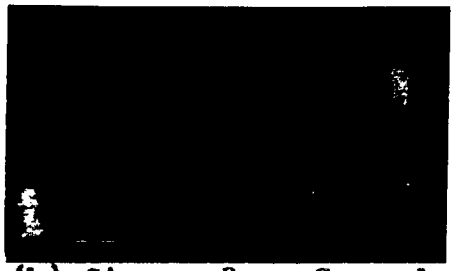
Control Rack in the Pond

Stirrer in the Pond

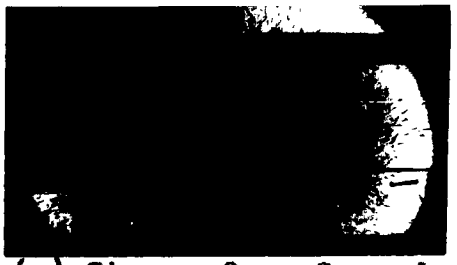


Top Views



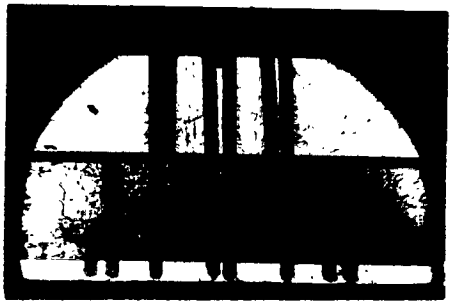


Side Views



(b) Stream from Second Slice

(c) Stream from Second Slice



Side Views



(d) Stirrer in Action in the Pond

(e) Stirrer in Action In the Stream from A Single Slice

Figure 20. THE DOUBLE SLICE INLET. CONDITIONS OF FLOW WITH THE SLICES 6 INCHES APART. (3-Spark Exposures)

in the pond. This was confirmed by visual observation. The top and side views of the stream from the second slice (c) show random fiber orientation.

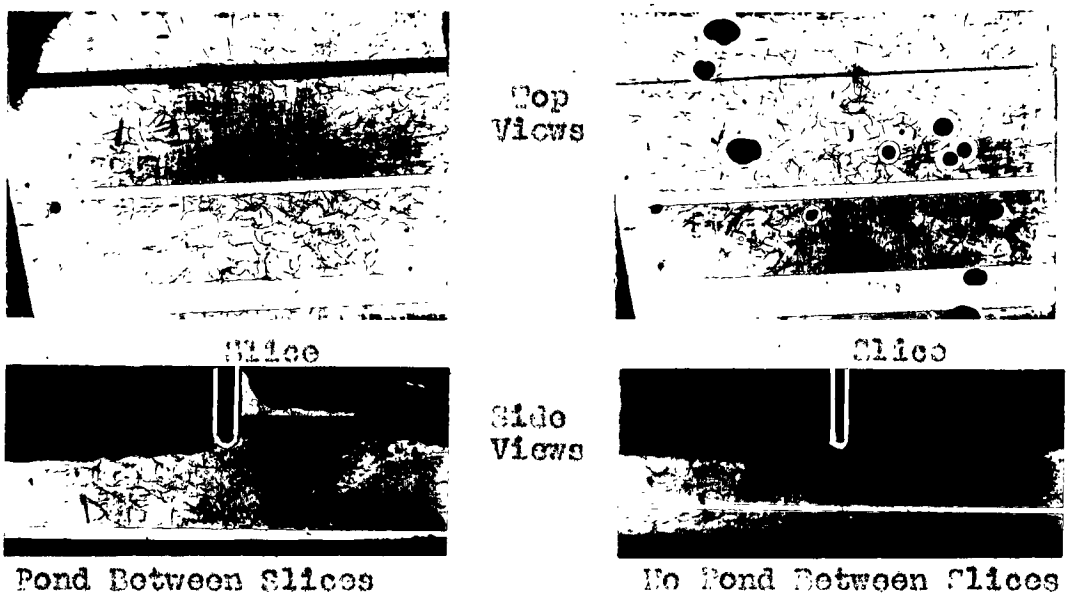
Figure 26 (e) was taken to show the action of a stirrer [Figure 7 (s)] in the stream from a single slice (91). This stirrer was found to cause entrainment of air and surface agitation which entirely blotted out the picture until a sheet of cellulose acetate, with a hole to admit the stirrer shaft, was placed in contact with the stream surface. This picture shows that the stirrer did break up the alignment, but it is doubtful if such a device would be desirable on the paper machine because of its tendency to entrain air. Furthermore, a series of stirrers could not give uniform action across the machine and streaks would likely result.

b. The Effect of Distance Between the Slices.

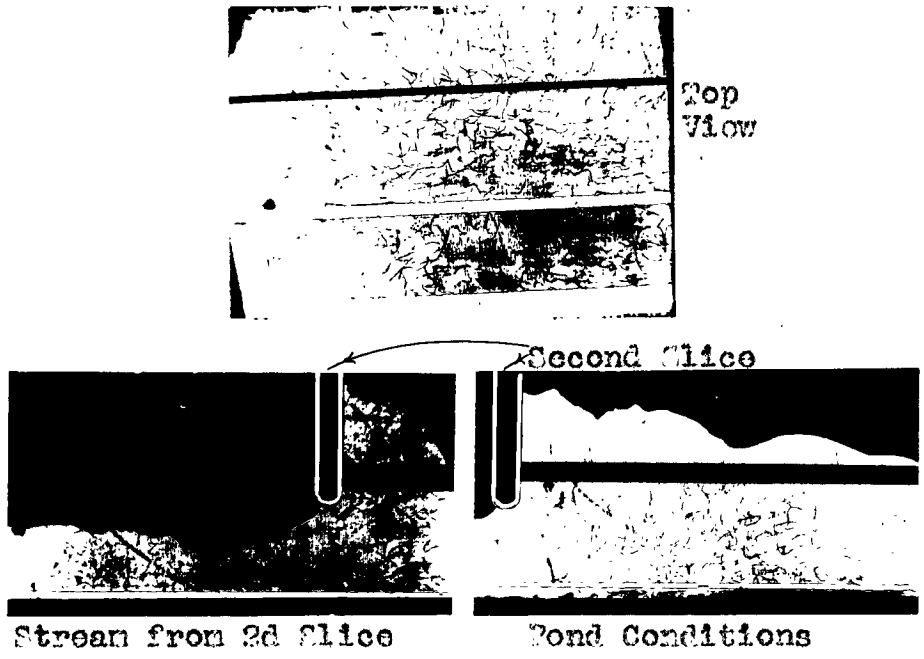
Papermakers realize that the action of a 2-slice inlet is dependent to a large extent on the distance between the slices, and the adjustment of this distance has been proposed as an aid to controlling sheet formation.(60). Pictures were taken to show the conditions existing when the slices were 1½, 3, 6, and 12 inches apart, and Figure 27 shows these conditions in (a), (b), (c) and (d), respectively. The slice openings used were the same as stated above.

With 1½ inches between the slices the flow, once started, would continue either with or without a pond in between, as shown in the pictures on the right and left, respectively (a). In either case there was little or no agitation between the slices and the fibers were aligned in both cases. Air bubbles under the viewing box caused the black spots in the top view of the conditions without a pond. There was more agitation in the 3-inch pond, and, as a result, the alignment in the stream was to a large extent broken up (b). A maximum degree of agitation seemed to be reached with the slices 6 inches apart (c), while at 12 inches the amount of stock in the pond seemed to be too great to be thoroughly agitated by the stream from the first slice, and this stream was almost completely broken up before reaching the second slice. It is apparent from the side view (d) that the strong alignment under the second slice extended on down the stream for an inch or so beyond the zone of acceleration before being broken up. The fibers shown in the top view also show more tendency toward alignment.

The mass of stock in the 6-inch pond seemed to be small enough to allow thorough agitation by the stream from the first slice and, at the same time was large enough to resist the flow of this stream and keep it from rushing directly to the second slice opening. Longer or shorter ponds seemed less effective. Changing the relative sizes

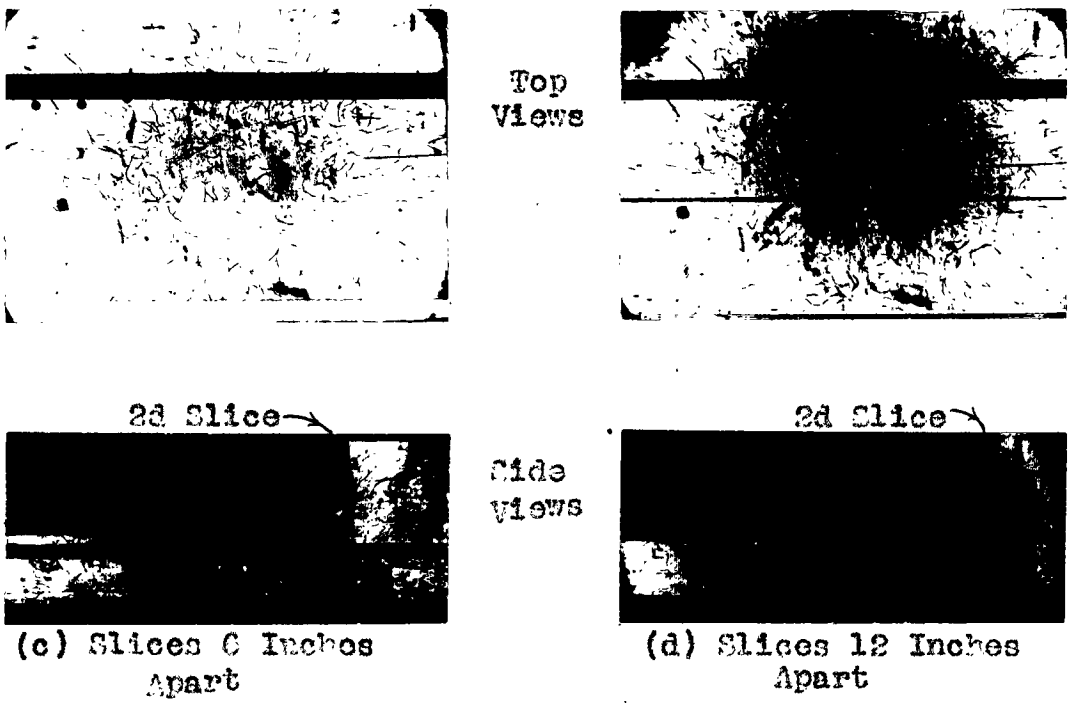


(a) Slices 1½ Inches Apart



(b) Slices 3 Inches Apart

Figure 27. THE DOUBLE SLICE JET. THE EFFECT OF DISTANCE BETWEEN THE SLICES. (3-Spark Exposures)



(c) Slices 6 Inches Apart

(d) Slices 12 Inches Apart

Figure 27.(Cont.) THE DOUBLE SLICE INLET. THE EFFECT OF DISTANCE BETWEEN THE SLICES. (3-Spark Exposures)

of the slice openings affected the height of this pond, hence this variable would also influence the amount of agitation.

Where there was enough agitation in the stream from the second slice to break the alignment quickly, the individual fibers were twisted and turned about so much that it was almost impossible to trace their successive images.

2. THE SLANTING SURFACE INLET

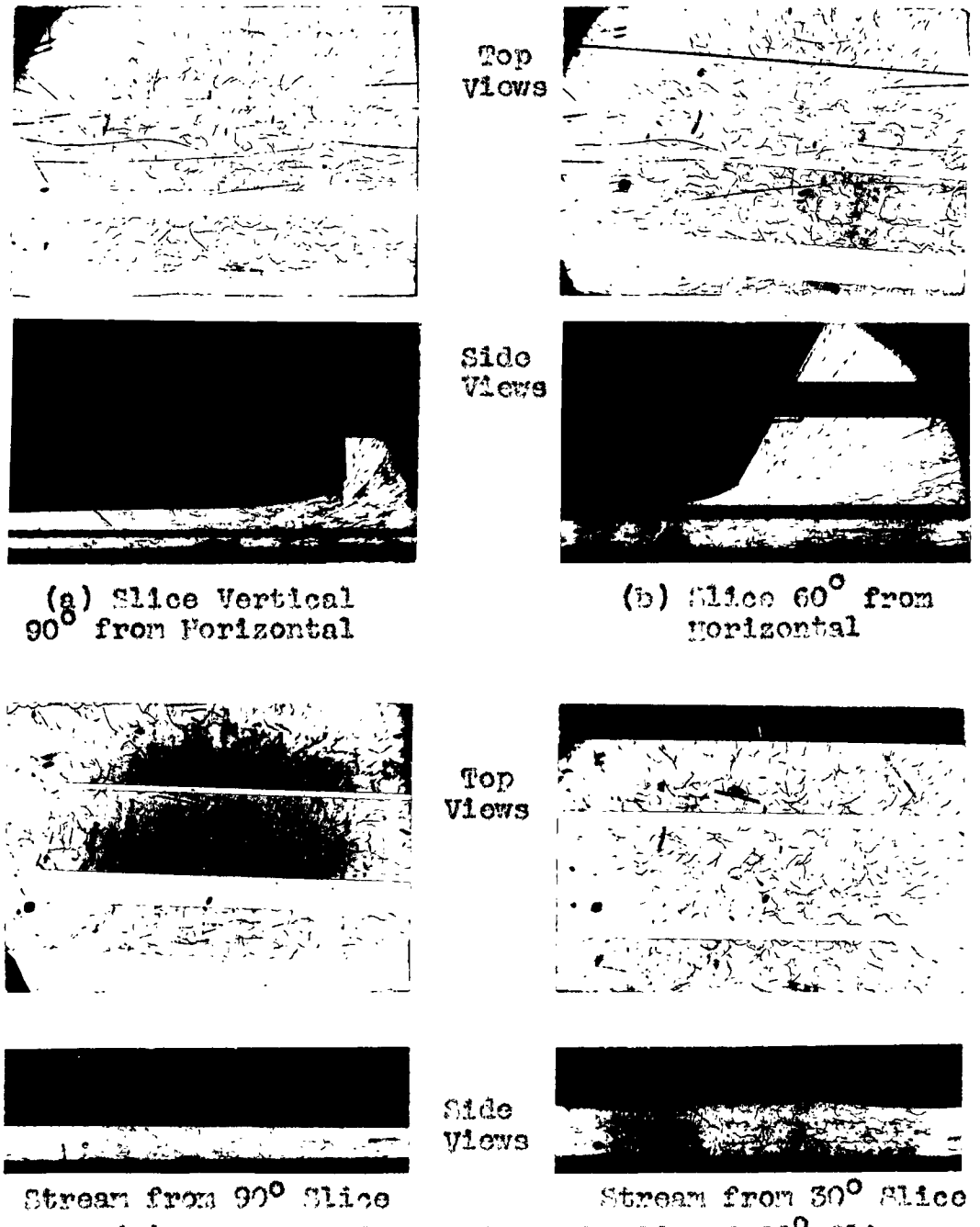
a. The Effect of Angle.

In many patented inlets, a slanting top surface is used to give a more gradual acceleration and change in the direction of flow through the inlet (69 - 75, 77), and ordinary straight slices have been modified to permit angular adjustment from the vertical (50). To show the effect of the angular position of a straight slice, photographs were taken of the flow conditions under a glass slice at angles of 90, 60, 30 and 15° from the horizontal; these pictures are shown in (a), (c), (d) and (e) of Figure 28. The heads required back of the slice in these various positions for the same volume of flow were 3 1/8, 2 7/8, 2 1/4 and 1 7/8 inches, respectively. A glass slice was used to permit the taking of top views of the flow under the slice in the 15° position. Top and side views of the stream 6

inches beyond the slice lip were taken for the 90 and 30° positions to show any difference in the rate of breaking of the alignment.

Under the slice in the vertical (90°) position, the usual pronounced fiber alignment was observed, as shown in (a). A slight decrease in the alignment, as seen in the top views, was noticed with the slice in the 60° position (c), and still more with the slice in the 30 and 15° positions, as shown in (d) and (e), respectively. The angular position of the slice seemed to have little effect on the alignment, as seen in the side views. A study of the side views of the flow under the 30 and 15° slices (d and e) will show the gradual change from random orientation of the fibers, as the stock reached the slice, to complete alignment in the stream issuing from the slice opening. The top views of the acceleration zone under the 15° slice (e) also show how the alignment increased over this zone.

A comparison of the alignment of fibers in the streams at a distance of 6 inches from the 90° slice and from the 30° slice, as pictured in (b), showed that the alignment was still quite strong in the side view of the stream from the 30° slice, while that in the side view of the stream from the 90° slice was almost completely broken. The top views indicate that the alignment, as seen from that angle, was also



(a) Slice Vertical 90° from Horizontal

(b) Slice 60° from Horizontal

Stream from 90° Slice

Stream from 30° Slice

(c) Streams 6 Inches from the 90 and 30° Slices

Figure 28. THE PLANTING SURFACE ITSELF. THE EFFECT OF THE ANGULAR POSITION OF THE SLICE. (3-Spark Exposures)



Top View
of Stream

Side Views



(d) Slices 30° from Horizontal

Figure 28 (Cont.) THE SLANTING SURFACE RULER. THE EFFECT OF THE ANGULAR POSITION OF THE SLICE. (3-Spark Exposures)



Top Views of Flow Under the Slice and Stream from the Slice

Side Views



(c) Slice 15° from Horizontal

Figure 23 (Cont.) THE SLANTING SURFACE INLET. THE EFFECT OF THE ANGULAR POSITION OF THE SLICE. (3-Spark Exposures)

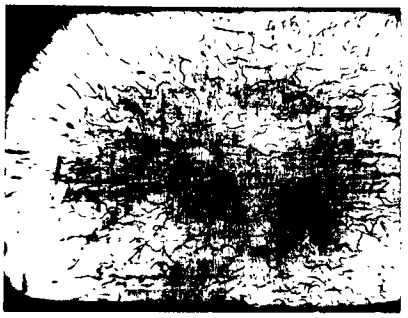
better preserved in the stream from the 30° slice. These observations seem to indicate that the flow in the stream from the 30° slice was smoother than that from the 90° one.

b. The Effect of a Ridge in the Apron Cloth across the Machine

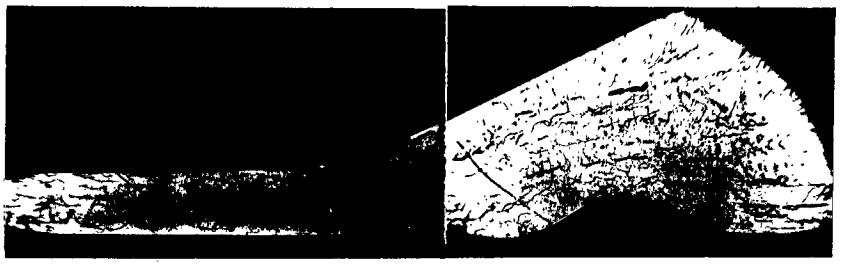
Hyde (54) has patented a device for producing a ridge of adjustable height in the apron cloth under a slanting inlet surface and extending across the width of the machine. He claimed that this ridge, or hump, would cause a swirling in the stream over it, and that this would break up localized streams and give a uniform velocity across the machine. Figure 29 shows pictures taken of the flow through a model of his device. The surface of the hump in this model was made from polished sheet copper, and a copper slice at 20° from horizontal was used for the top surface of the inlet. The side views show that the flow over this hump was along smooth streamlines without any swirling. Its only effect, therefore, was to act as an additional constriction in the passage under the slice. Very appreciable alignment resulted in the stream from the slice (Figure 29).

c. Slanting Surface on the Bottom of a Vertical Slice

The Voith inlet (69) and its various modifications (70 - 75) consist of a slanting upper inlet surface attached to the bottom of a vertical slice which serves as the front wall of the head box. Figure 30 (a) shows pictures taken of



Top View of Stream



Side Views of Flow under the Slice and in the Stream

Figure 29. THE SLANTING SURFACE INLET. THE EFFECT OF A RIDGE IN THE AERON CLOTH. (3-Spark Exposures).

the flow under a model of this inlet [Figure 7 (i)]. It will be seen from these pictures that the flow was closely similar to the flow already observed under a slanting slice (Figure 28), but the alignment, as seen in the top view, was somewhat better, probably due to the sharp turn the stock had to make on entering the passage under the sloping surface. This sharp change in direction was accompanied by rapid acceleration and this combination would be expected to produce strong alignment.

Figure 30 (b) shows the conditions of flow under a model of Leloff's (62) proposed modification of a vertical slice described on page 23 [Figure 7 (f)]. The acceleration of the stock on entering the passage under this device is seen to have caused very complete alignment (side view). Very pronounced alignment is also shown in the stream from this slice. It is obvious that this device gave flow conditions similar to those under the model of the Voith inlet (a).

Valentine (67) and Aldrich (76) both propose the use of a vertical slice just back of the inlet to give gentle agitation and to even the flow across the machine. Using the round lip vertical slice right against the vertical member of the Voith inlet model, top and side views were taken to show the flow conditions under this arrangement [Figure 30 (c)]. The flow is seen to have been much the

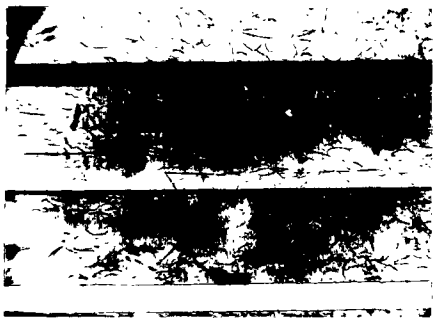
same as for the 2-slice inlet with 1½ inches between the slices. In spite of the small size of the pond between the vertical slice and the inlet lip, it caused a marked decrease in the fiber alignment in the stream, as may be seen by comparison with (a). But this model did not show machine conditions accurately, because a full size inlet would have a proportionally longer slanting surface, so that the vertical slice would be further behind the inlet lip, thereby allowing a larger pond and more thorough agitation to insure random orientation of fibers in the stream from the slice.

The agitation caused in the stream by the control rack [Figure 7 (q)] behind the Voith inlet model was more effective for such a small scale model [Figure 30 (d)], for it gave almost random fiber alignment in the stream. On a full size inlet, however, where the rack would be proportionally further from the inlet lip, it would probably be less effective.

The effect of a vertically-set lip on the lower end of the sloping surface of a Voith type of inlet [Figure 7 (j)] is shown in (e). This device is a model of an inlet design patented by Niks (48). The flow through this inlet is seen to have been along smooth stream lines, leaving a small dead space in the corner between the sloping surface

and the vertical lip. The fiber alignment in the stream from this inlet is seen to have been even stronger than with the sloping surface alone. This greater alignment probably resulted from the change in direction of flow and the sharp acceleration in the constriction under the vertical lip.

To demonstrate the effect of ridges on the upper and lower inlet surfaces as proposed by Corcoran (55) the pictures shown in Figure 30 (f) were taken of stock flow through a model of his design [Figure 7 (k)]. It will be seen that the fibers lined up as usual on entering the inlet passage, but the alignment was broken almost immediately by the agitation caused by the oppositely directed ridges, and random orientation resulted in the stream from the inlet. The turbulence of this stream is evidenced by the unevenness of the top surface as seen in the side view. This device unquestionably gave random fiber orientation, and it is quite possible that the number and size of the ridges could be selected to give the desired amount of agitation for a given set of machine conditions, but its action would be dependent to a large extent on the machine speed and little or no adjustment would be possible for control of sheet formation.



Top View



Stream from Slice

Side Views



Flow under the Slice

(a)
The Voith Inlet



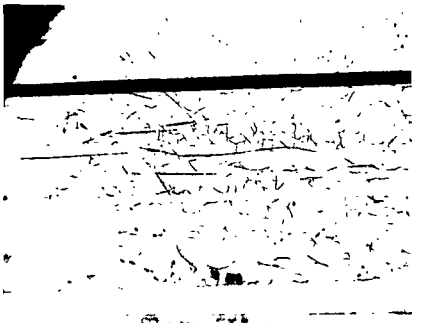
Top View of Stream



Flow through the Inlet

(b) Leloff's Inlet

Figure 30. THE SLANTING SURFACE INLET. SLANTING SURFACE ON THE BOTTOM OF A VERTICAL SLICE.
(3-Spark Exposures)



Top View



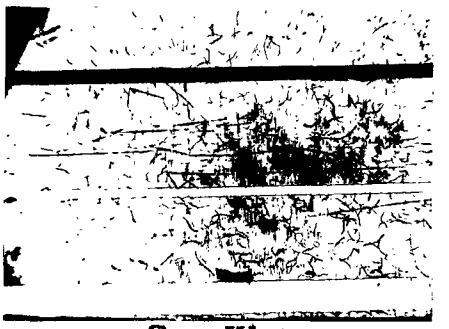
Side Views



Stream from Slice

Flow under the Slice

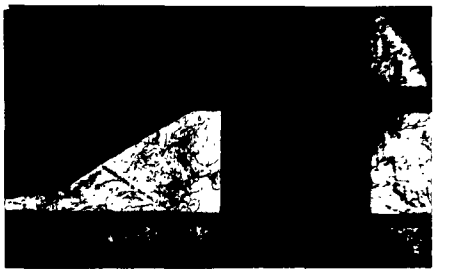
(c) Vertical Slice Back of the Inlet



Top View



Side Views



Stream from Slice

Flow under the Slice

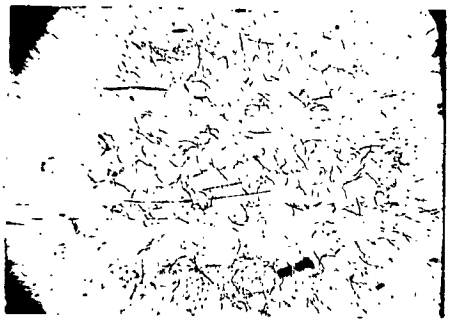
(d) Control Rack back of the Inlet

Figure 30 (Cont.) THE SLANTING SURFACE INLET. SLANTING SURFACE OF THE BOTTOM OF A VERTICAL SLICE (3-Spark Exposures)



Top View of Stream Side View

(e) Effect of a Vertically Set Lip on the Slanting Surface



Top View

Side Views



Stream beyond the Slice Flow through the Inlet

(f) Effect of Oblique Ridges on the Inlet Surfaces

Figure 30 (Cont.) SIDE SLANTING SURFACE INLET. SLANTING SURFACE ON THE BOTTOM OF A VERTICAL SLICE (3-Spark Exposures)

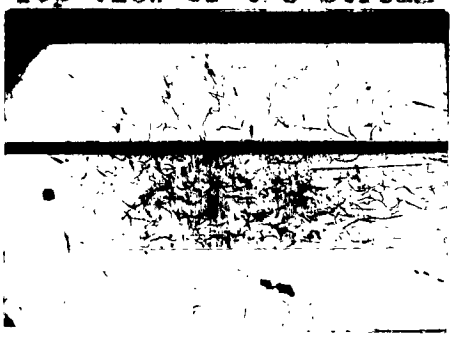
3. THE CURVED SLICE

The Van de Carr inlet (63) and its modifications (64 - 68) use an inlet surface curved to conform approximately to the streamlines of flow in the stock passing through the inlet. Pictures showing the flow conditions under a model of this type of inlet [Figure 7 (g)] have already been shown in Figure 19. The side views in this figure show the fibers lining up in the streamlines of flow under the slice to give the usual strong alignment in the stream. As noted earlier (page87), the alignment, as seen in the top view, was not as complete as that from a vertical slice. It was, however, about the same as the alignment resulting from the 30° sloping slice Figure 29 (c) .

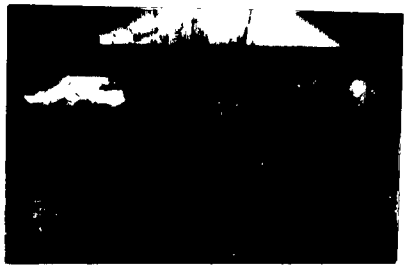
4. THE ROLL INLET

Clements' roll inlet (68) is really a modification of the Van de Carr type (See page 23-24 for description) in which he uses a dam just back of the slice with a streamlined spillway extending under the slice to give the passage the general shape of a curved nozzle, as shown in the sketch of the model used in this study [Figure 7 (h)]. Photographs of the flow conditions through this model are shown in Figure 31. The fiber alignment through this inlet and in the resulting stream is seen to differ little from that through the curved surface inlet (Figure 19).

Top View of the Stream



Side Views



Stream from Inlet



Flow through Inlet

Figure 31. THE CURVED SURFACE INLET. THE ROLL-TYPE INLET. (3-Spark Exposures).

5. THE DAM-TYPE INLET

A description of the dam-type of inlet, as proposed by Murray (80) and Kilberry (81), has been given on page 25. With this inlet the acceleration of the stock is obtained by allowing it to flow down the streamlined spillway from the dam and no slice is used. Figure 32 shows the flow conditions along the spillway of a model of this inlet [Figure 7 (n)] and also the fiber orientation in the stock stream on the bottom of this device. Here the fibers were aligned by the acceleration of the stream as it flowed down the spillway without having passed under a slice at all. This showed that the particular set of conditions existing under a slice was not necessary for fiber alignment by the action of acceleration. The fiber alignment in the stream off the bottom of the dam was not complete but this was not surprising when it is considered that friction between the free flowing stream and the surface of the dam would cause a certain amount of turbulence, which would tend to break the alignment.

6. NOZZLE INLETS

Models of the Lund (28) and Bell-Irving (77) inlets are shown in (o) and (p) of Figure 7, respectively. In Figure 33, (a) and (b) show the fiber behavior in the flow through the Lund nozzle with and without the streamlined vane

Top View of Stream



Side Views of the Stream over the Spillway

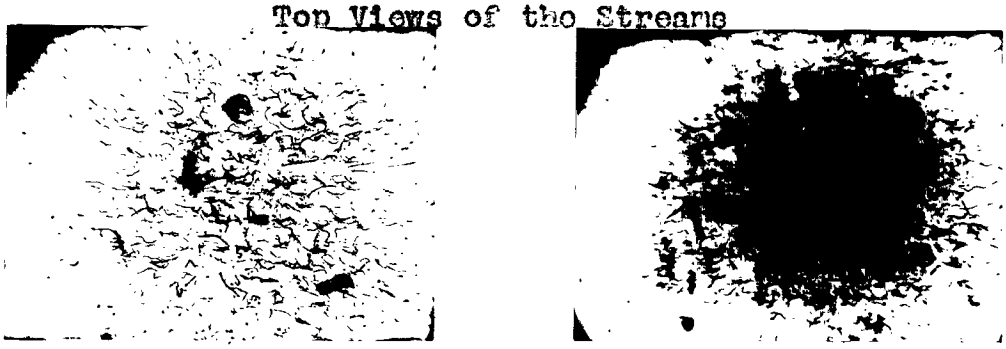
Figure 32. THE DAM-TYPE INLET
(3-Spark Exposures)

in place. In both cases the usual aligning process was active. The top views indicate that the alignment was slightly better for the inlet with the vane (a). This vane divided the full nozzle opening into two smaller openings and also made all the stock enter the inlet at an angle, either from above or from below. Both these changes would tend to strengthen the alignment.

The flow conditions through the Bell-Irving inlet model are shown in (c). On entering the nozzle from the pond back of it, the stock was accelerated and the fibers were strongly aligned. Passage through the constriction at the lip gave further acceleration, and, therefore, good alignment resulted in the stream.

In conclusion, it has been shown that all the inlet devices used on paper machines to accelerate the stock to approximately wire speed cause, at the same time, a strong alignment of the fibers in the machine direction. Suitable agitation back of the inlet to break the fiber alignment in the stream immediately after it leaves the inlet may be obtained by the use of a vertical slice or a control rack back of the inlet. The double slice inlet with a pond between the slices seems to be particularly effective in this respect.

Top Views of the Streams



Side Views of the Flow



(a) With the Stream-Lined Vane in Place

(b) Without the Vane

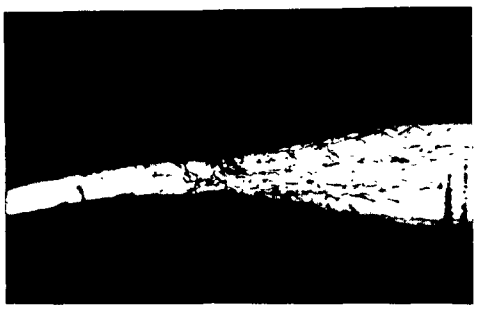
The Lund Inlet

Figure 33. NOZZLE INLETS
(3-Spark Exposures)

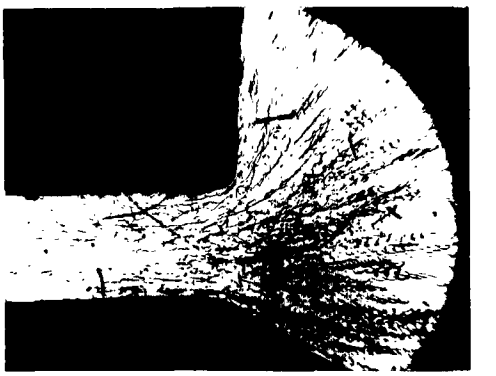
Top View of Stream



Side Views of Flow



Stream from the Lip



Flow into the Nozzle

(c) The Bell-Irving Inlet

Figure 33 (Cont.) NOZZLE INLETS
(3-Spark Exposures)

D. FLOW CONDITIONS IN THE HEAD BOX

The flow of stock through the head box was studied only in a general way to indicate the nature of this flow.

1. GOUGH'S RECIRCULATION DESIGN

Gough (9) considers eddies to be the most effective agents in breaking up localized fast streams in the head box, but these eddies are sometimes difficult to control and are not uniform in their action. To correct these difficulties, he claims to have designed a recirculation device for a head box to give an effective eddy which can be controlled, and he has given a detailed description of the operation of this device (9). Figure 7 (t) shows a sketch of a model of his design, and Figure 34 shows the conditions of flow and the behavior of the fibers through this head box model. Upon entering the narrow passage to the right of the baffle (B) [Figure 7 (t)], the stock was accelerated and fiber alignment resulted, but after passing the constriction in this passage, the alignment was quickly broken up. At the bottom of this pass, centrifugal force made this stream hug the streamlined surface under the vane (C). In the wide passage to the left of (B) and (C), the stream flowed upward along the left side of the passage but was retarded and broken up by friction with the body of stock lying between it and (B) and (C), exactly as the fast stream from the first

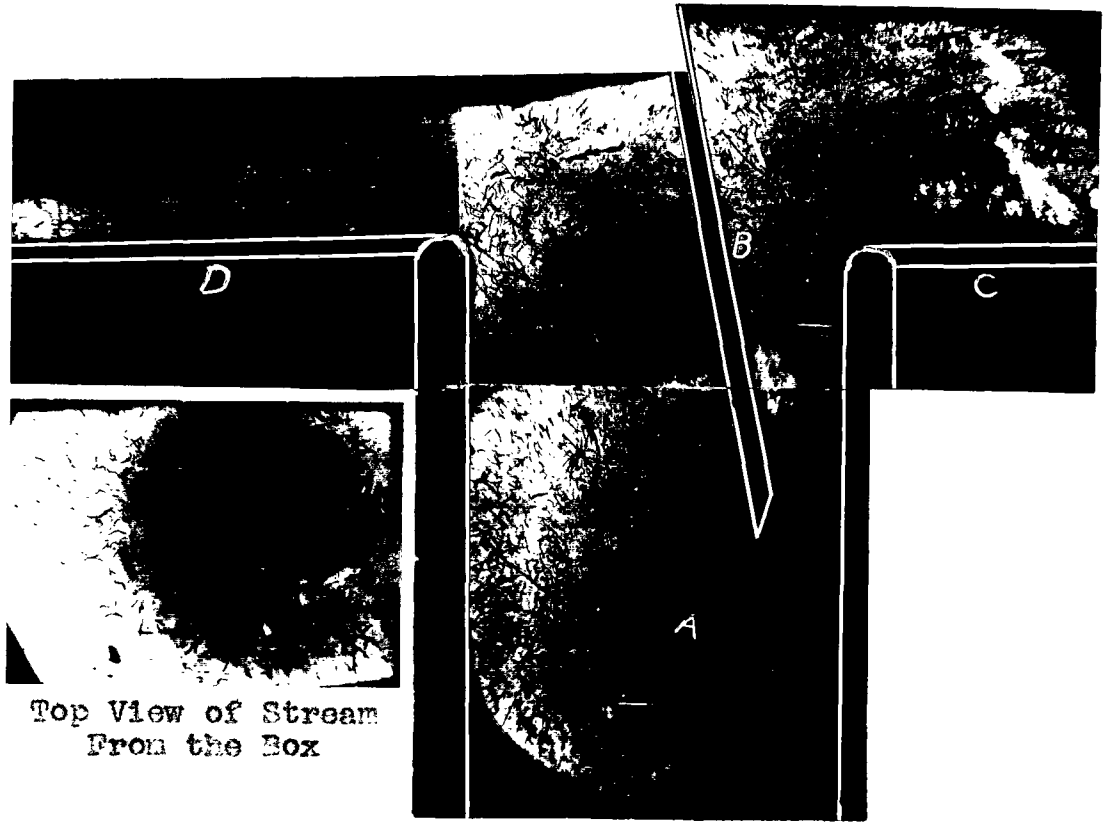


Figure 34. THE HEAD BOX. GOUGE'S RECIRCULATION DESIGN
(3-Spark Exposures)
(The letters indicate the same parts as designated in Figure 7 u).

slice of a 2-slice inlet was broken up by the stock in the pond. This turbulence insured random fiber orientation in the stream from the head box. Difference in pressure between the fast stream to the right of (B) and (C) and the slow turbulent stock to the left caused stock to flow through the slit between (B) and (C) to give the recirculation as claimed by Gough. The sucking action of the fast moving stream at the constriction is explained by the Bernoulli theorem. This action is indicated by the picture (Figure 34) and was definitely observed by visual observation of the stock movement.

Although the effectiveness of this device could not be demonstrated in the narrow trough used, it would undoubtedly have an evening effect across a machine, because the pressure drop at the constriction is proportional to the square of the velocity of the stream at that point and hence a fast localized stream would cause more recirculation and friction at that point to retard the stream, thereby making the flow more uniform.

2. A FOUR-PASS HEAD BOX

The flow of stock through a model of a 4-pass head box [Figure 7 (t)] was photographed to show the flow conditions in a normal head box designed (Figure 35). On passing under the baffle to the right, the stock was accel-

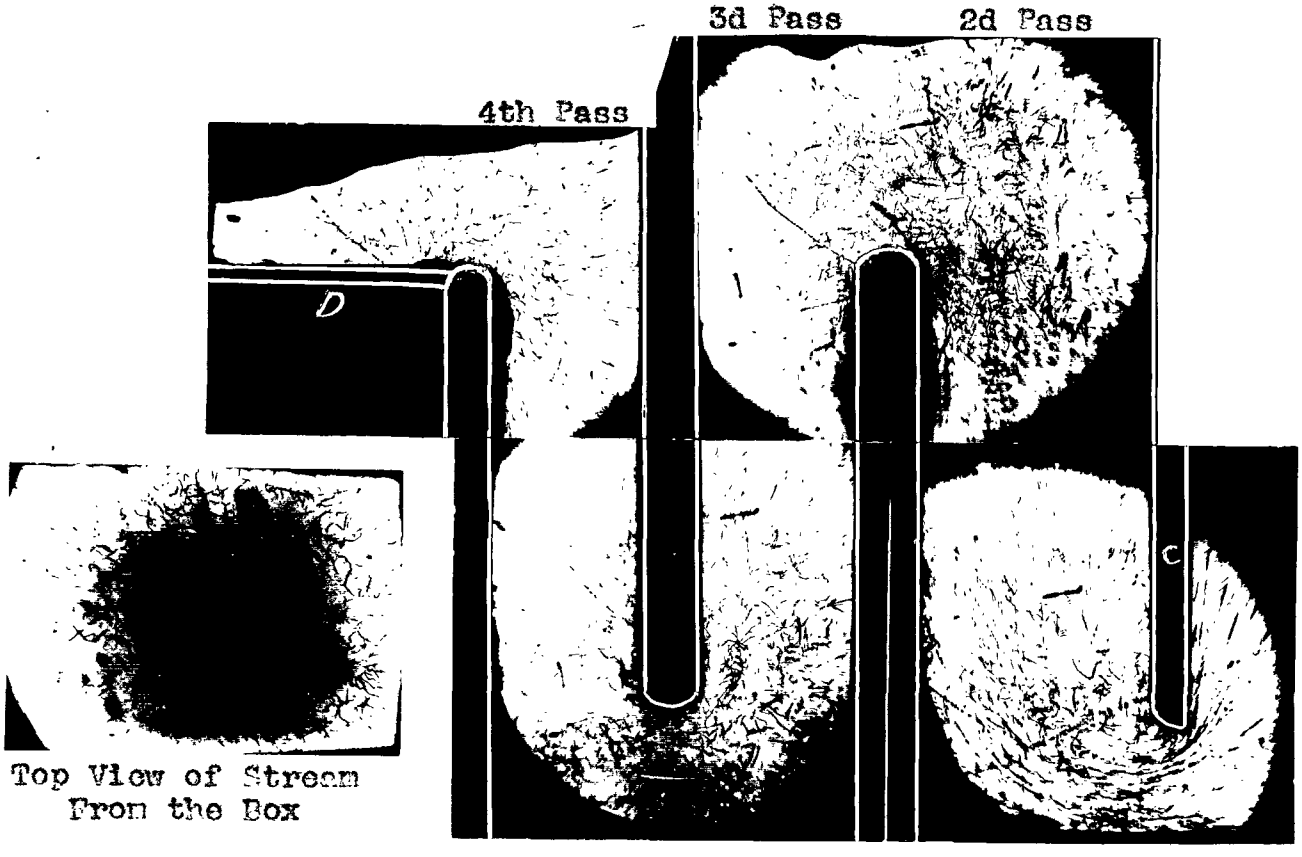


Figure 35. THE HEAD BOX. A FOUR-PASS HEAD BOX
(3-Spark Exposures)

erated and alignment resulted exactly as under a slice. Turbulence in the passage above this point, however, quickly broke up this alignment by an action comparable to that in the pond of a 2-slice inlet (Figure 26). In passing over the second baffle, the top surface of the stock was free, and, therefore, strong turbulence resulted in this area as the stream coming up through the second pass turned and started down again. There was no appreciable constriction under the next baffle, hence no alignment of fibers took place. Strong turbulence was again evident as the stock reached the top of the last pass and flowed out on the horizontal spillway, and the fiber orientation was random in this stream.

These photographs of the flow of stock through the head box models show several examples of change in direction of flow which was not accompanied by any constriction of the passage which would cause acceleration. Under these conditions no tendency toward fiber alignment could be detected. Apparently the action of the acceleration was the factor of prime importance in causing fiber alignment and was only modified to a certain extent by accompanying changes in the flow direction, which alone could not cause alignment.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A critical study was made of Bryant's technique to show that its scope of application is limited to controlled laboratory conditions. Through 2.5 inches of stock at consistencies up to about 0.0003 per cent three successive images of individual fibers were obtained without too much distortion from fibers not in focus. Through half an inch or less, images were shown obtained at consistencies up to 0.25 per cent with single spark exposures; but where it was desired to show three successive images, a consistency of 0.001 - 0.002 per cent had to be used.

A field 2.5 inches in diameter was shown without excessive distortion in the edges. The contrast obtained was improved by dyeing the fibers. Cleanliness and evenness of all surfaces in the optical system was essential. A glass-bottomed viewing box was used to smooth out ripples on the stock surface to obtain a uniform field in top views. A pendulum timer was found to be an effective means for catching the desired number of flashes and avoiding the banded exposure resulting with the focal plane shutter. Copper

slices fitted with rubber gaskets saved the time and trouble necessary for sealing in glass slices. Areas of the light beam not important to the picture were masked out.

Fiber orientation in free flow of stock was shown to be random but alignment began as soon as the fibers entered the zone of acceleration just back of, and under, the slice. In all cases studied the acceleration action under the slice or through the inlet pulled out each individual fiber and lined it up in the machine direction. Fibers nearly perpendicular to the direction of flow were not always acted upon, however. This pulling-out action was definitely demonstrated in pictures showing bunches of fibers and air bubbles being elongated in passage under the slice. The alignment as shown in the side views was much more complete than that shown in the top views, and in top views the alignment was stronger for sharp edged vertical slices than for inlets having sloping or curved inlets.

Comparison of the velocity at the top and bottom of the stream from a vertical slice, especially one having a sharp edge facing the flow, showed an appreciably greater velocity at the top of the stream in agreement with the theory postulated by Lund (28).

It was shown by comparison of velocities of large and small particles that in smooth flow the fibers move at the same speed as the stream and that even during acceleration there is little or no lag.

A head of about a quarter inch back of a vertical slice was found to give good alignment in side views, but the alignment as shown in the top views continued to increase with increased head up to about half an inch. Similar alignment at a head of two feet showed that this same phenomenon was in evidence at high speeds. As computed from the spark frequency and the interval between images, the jet velocity resulting from the 2-foot head was 540 feet per minute.

The width of the slice opening had no effect on the velocity of the stream or the alignment of the fibers with a constant head back of the slice, indicating that the volume of delivery was approximately proportional to the width of the opening.

The alignment in the stream from the slice broke up gradually to become almost random again six inches from the slice. The use of a viewing box over the stream had no noticeable effect near the slice but seemed to exaggerate the alignment when used further down the stream.

Consistencies from 0.001 to 0.25 per cent were studied to show that the fiber aligning action of the acceleration under the slice was independent of consistency over this range. Pulp beaten to a freeness of 310 S. R. exhibited the same phenomena as the unbeaten stock.

Exposures of one, two, and three sparks as well as sparks timed at certain intervals by the pendulum timer were compared.

It was shown that having the apron end directly under the slice or back of it would direct the jet against the wire, tending to cause the aligned fibers to hit the wire end first and pass through. Having the apron extend beyond the slice gave a horizontal stream.

In a two-slice inlet system the stream from the first slice tended to flow underneath the pond directly to the second slice, but friction with the pond caused strong turbulence agitation which tended to break up the stream. In spite of this strong agitation the fibers lined up as usual in their passage under the second slice, only to have the alignment quickly broken up after the slice by residual turbulence in the stream. This agitation in the pond was so great that a control rack or a motor-driven wire stirrer in the pond had no appreciable effect on the fiber behavior in the stream from the front slice. A stirrer in the stream

from a single slice gave good agitation and broke up the alignment, but it also caused serious entrainment of air. A series of these stirrers could hardly give unifrom action across a paper machine and streaks would probably result in the sheet.

The angular position of a sloping slice did not noticeably affect the alignment of fibers as seen in the side views. In the top views, however, the fiber alignment decreased as the slice was turned further from the vertical. The flatter the slice, the less difference existed between the velocities of the top and bottom layers of the issuing stream and the more slowly was the alignment of fibers broken in this stream. A ridge in the apron cloth under a sloping slice had no effect on the stream conditions. A slanting surface on the bottom of a vertical slice gave flow conditions similar to those under a slanting slice. A similar inlet having obliquely ridged top and bottom surfaces gave strong agitation and broke the alignment entirely.

The curved and the roll-type inlets produced conditions similar to those with the sloping slices but gave somewhat less alignment in top views, because they did not give sharp changes in flow direction to assist in aligning the fibers.

The stream over the streamlined spillway of a dam-type inlet showed the usual aligning phenomena in the zone of acceleration, and the stream off the bottom still exhibited strong fiber alignment. Models of the Bell-Irving and Lund nozzle inlets showed similar lining up of the fibers along streamlines in the zone of acceleration, and the fibers in the issuing streams were well oriented in the direction of flow.

Gough's proposed head box design was found to give recirculation which would tend to even up the flow, although the width of the trough used for these experiments was not sufficient to demonstrate this effect. In this design, and also in the 4-pass head box, the flow around the underpass baffles was found to be along streamlines with no tendency for alignment in the direction of flow, unless the change in direction was accompanied by acceleration at a constriction in the passage. Around overpass baffles, where the upper surface of the stock was free, strong turbulence resulted and insured random orientation.

The results of this investigation show that, regardless of what type of inlet is used, the accelerating action through the inlet causes strong alignment of the fibers in the direction of flow. If this stream simply flows smoothly out upon the wire, the alignment will not be broken up and

and the resulting sheet will be very strongly grained in the machine direction. Even under the ideal conditions in a hand sheet mold, it is necessary to agitate the stock suspension thoroughly, but gently, to obtain good sheet formation; on the moving machine wire, proper agitation of the stock to break up alignment and to cause uniform dispersion is even more important. But this agitation must be very gentle, so as not to disturb the bottom layers of the sheet as they form on the wire.

This need for just the right amount of agitation on the wire is undoubtedly responsible for many of the conflicting theories on inlet design. With no fundamental basis of fact some designers have realized the need for agitation and put oblique ridges in the inlet surfaces (56), semicircular gaps in the lip (59) to provide this agitation, or provided agitators on the wire (86, 88 - 92). Others have made every effort to admit the stock to the wire in a perfectly smooth stream to avoid the difficulties thought to result from agitation.

The two-slice inlet has long been giving satisfactory service at slower speeds, though the reasons for its effectiveness have not been completely understood. The results of this investigation show that its action is not simply to provide agitation for uniform dispersion and to even up the flow across the machine, but also to extend its

agitating effect to the stock on the wire by means of gentle eddies still remaining in the stream after the slice.

Information obtained from practical papermakers indicates that, at speeds above 500 feet or so per minute, no advantage is derived from the use of two slices. Their explanation for this is that, at these higher speeds, the passage of the stock from the screens through the slice is too rapid to allow time for flocculation, hence no agitation is necessary.

However, it seems more likely from the results of this investigation that some other type of agitation comes into play at that speed, i.e., the agitation resulting from difference in speed between layers of the stock stream from the slice.

On the wire moving at approximately the same speed as the stream from the slice, there is no appreciable retarding action comparable to that caused by the glass bottom of the trough to exaggerate the velocity difference between the top and bottom layers of the stream from the slice, hence this effect is not great until high speeds are reached where the velocity gradient is steep in accordance with the equations of Lund (28) (see page 16 of this paper). At speeds of 500 feet or more per minute this action seems to give sufficient agitation on the wire, and too little time is

allowed between the screens and the slice to permit flocculation of these speeds; therefore, two slices are not necessary. At still higher speeds, however, this agitation will become excessive and disturb the formation of the first layers of the sheet to form on the wire. A cloudy formation in the sheet will then result. At high speeds the high pressure inlet is therefore necessary to reduce this effect and at the same time to accomplish two other important functions: (1). to give the desired stock speed with less head back of the slice, due to the lower resistance of the more streamlined passage, and (2). to allow finer adjustments of thickness of the sheet across the machine. With a vertical slice the issuing stream undergoes strong contraction in thickness at high speeds; and with no means to control this contraction across the machine, the uniformity of sheet thickness suffers. The high pressure inlet, however, causes much less contraction so that the control should be much more effective.

It is obvious that the rod-like shape of paper-making fibers would allow them to fit together most compactly when they are laid parallel. Therefore, when quick sheet closure is desired, the first thin film of fiber on the wire would theoretically be best laid down parallel; and, in view of the greater ease of causing fiber alignment

in the machine direction, it would be best to provide for parallel alignment in this direction. Having the apron stop a little short of the slice would ideally accomplish this purpose since the stock would hit the wire just before being accelerated to wire speed by the slice. The faster moving wire would then assist the accelerating action under the slice to line up the fibers for the first thin film on the wire.

For breaking up the fiber alignment on the wire, the action of the turbulence in the pond of a two-slice inlet is to be recommended, rather than the rolling action of the stock which takes place on the wire as a result of the greater velocity in the top layers of the stream. The action of the former is uniform across the machine, its action on the wire is not violent enough to disturb the bottom layers of the sheet as they form on the wire, and it is much less dependent upon changes in speed; hence it would seem that a flow evening and agitating device designed to obtain similar conditions in a high pressure inlet would offer the best possibilities for high speed operation.

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