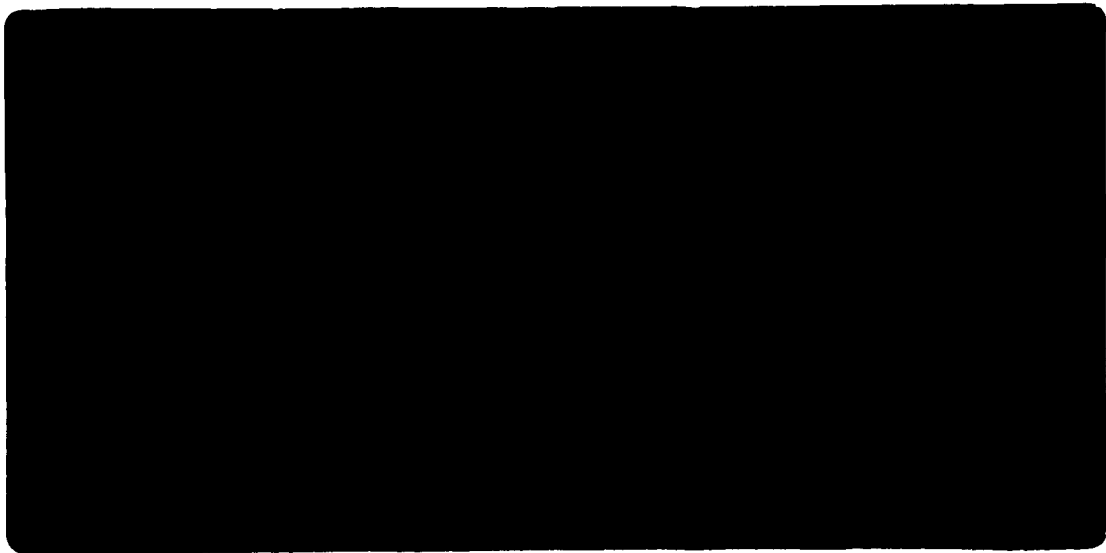*Institute of Paper Science and Technology*
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**IMAGING BLACK LIQUOR SPRAYS IN AN
OPERATING RECOVERY FURNACE**

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Imaging Black Liquor Sprays in an Operating Recovery Furnace

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IMAGING BLACK LIQUOR SPRAYS
IN AN OPERATING RECOVERY FURNACE

by

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Abstract

Images of black liquor sprays in an operating recovery furnace have been taken with high-speed video cameras in two trials. The sprays were imaged through the gunport in which a test nozzle had been installed. A B&W splashplate nozzle was used in both cases. In one trial, flow of the black liquor through the test nozzle was varied by changing the total number of nozzles in operation while the total firing rate of liquor was held constant. The images of sprays in the hot furnace environment are compared to images taken in a laboratory spray apparatus in order to show the similarities and differences in the initial break-up in the two environments. Due to the limited field of view and the modest quality of the video images, no conclusions can be drawn concerning the ultimate droplet size distribution. However, these trials illustrate the basic break-up pattern for black liquor sprays and also demonstrate the utility of high-speed video techniques for this application.

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Introduction

The economic manufacture of pulp and paper by the Kraft process depends on the efficient recovery and reuse of the pulping chemicals. This has led to extensive study of the safe and efficient operation of recovery boilers [1-4]. Central to the basic combustion process in these units is the break-up characteristics and ultimate droplet size distribution of black liquor sprays. Black liquor sprays have been the subject of past studies [5-10] and are currently under investigation at the Institute of Paper Science and Technology [11]. In the IPST investigation, black liquor is sprayed at typical mill operating conditions of liquor temperature, dry solids content, pressure, and flow rate. However, the environment surrounding the spray is air at room temperature rather than high temperature combustion gases. There has been some uncertainty about the impact of high gas temperature on black liquor spray break-up. Recently, an influence of gas temperature on black liquor jet break-up has been proposed [12]. In order to address this issue directly, field studies of black liquor spray break-up in operating recovery furnaces were conducted using high-speed video cameras.

There are a variety of high-speed video cameras now available. The Xybion Corp. model ISG-250 used in one of the field trials operates at the normal video camera framing rate of 30 frames per second, but is capable of very short exposure duration or "gating" times, ranging from 25 ns to 20 ms. This short exposure duration is necessary to freeze the motion of high velocity sprays. An ordinary video tube would not be able to respond to the meager light that could pass into the camera during such a short gating period. The Xybion camera, along with some other high speed cameras, uses an intensifier to enhance the light signal, producing clear video images from ordinary light levels at short gating periods. These images are recorded with a super VHS VCR for subsequent analysis.

During a typical laboratory spray trial, the high-speed camera is placed on the opposite side of the spray from a light source. The droplets and ligaments in the spray block a portion of the light emanating from the source and show up on the video images as dark spots on a light background. This is similar to the situation in an operating recovery furnace. Looking through a black liquor gunport, the droplets and ligaments appear as dark spots (or streaks) against the lighter background of the furnace volume. This similarity suggested the use of an intensified video camera to observe black liquor sprays in an operating recovery furnace in order to help resolve the issue of the effect of gas environment on black liquor spray break-up.

Initial trials designed to determine the feasibility of viewing black liquor sprays through a recovery boiler gunport were carried out on a Combustion Engineering (CE) recovery boiler at the Camas

mill of the James River Corporation [13]. Three liquor nozzles were investigated: a B&W splashplate, a CE swirlcone, and a Spraying System VEEJET. For each nozzle a range of liquor temperatures and flows was tested. High-speed video recordings were collected at each condition, along with other boiler operating data. Many difficulties were encountered which significantly reduced the clarity of the video images for the swirlcone and VEEJET nozzles. However, good images were obtained for the splashplate nozzle and these will be compared below to images taken in a laboratory environment.

Another study of black liquor sprays in an operating recovery furnace has been carried out by the Weyerhaeuser Technology Center. This study also examined the break-up of black liquor sprays from a B&W splashplate nozzle (the same one used in the IPST laboratory studies) in a CE furnace. In this preliminary investigation complete operating and liquor condition data were not recorded; however good images of spray break-up were obtained. The video camera used in these studies was an intensified Kodak EktaPro system. This camera is capable of both high gating rate and high framing rate. High gating rate produces individual frames which are free of motion blur. High framing rate produces a slow motion action which can reveal both the break-up mechanism and the motion of the ligaments and droplets of black liquor. At the lower framing rates of the Xybion camera only "snapshots" of the spray are obtained so information about the motion of the spray is lost.

A few of the video frames from the Weyerhaeuser study have been made available for comparison to the images obtained in the IPST study. These will be presented below along with the laboratory and field images from the IPST study to illustrate the similarities and differences between spray break-up in cold and hot environments.

Camera Set-up and Operating Conditions
For The IPST Field Study

Field tests of black liquor spray break-up were carried out in a CE recovery boiler rated at 2.4 MMlbm/day (18 kg/s) of black liquor solids. During normal operation of this unit the flow is 220 GPM (13.9 l/s) of black liquor at approximately 70% dry solids content producing approximately 440 Mlbm/hr of steam (55.5 kg/s). At this rate approximately 2.6 MMlbm/day (19.5 kg/s) of black liquor solids are processed.

The intention of the experimental plan was to video tape sprays at different conditions of nozzle flow rate and fired liquor temperature. The total firing rate and air flow to the furnace were held constant. Varying nozzle flow at constant total flow was achieved by changing the number of

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liquor nozzles in service. Eight Spraying Systems Company type U-501000 VEEJET nozzles are used in the normal operation of this boiler. During the trial periods between six and eight of these nozzles were used along with one of the test nozzles, a Babcock & Wilcox (B&W) #22-35 splashplate nozzle having a circular nozzle diameter of 22/32 in. (1.75 cm) and a splashplate angle of 35°. The flow of black liquor through this nozzle was estimated based on the total liquor flow to the boiler and the total number and size of the nozzles in service.

Samples of the black liquor were taken from the ring header periodically throughout the trials for subsequent laboratory analysis. Black liquor dry solids and viscosity characteristics were determined from these samples. Viscosity was measured with a laminar flow tube. For this type of viscometer the tube geometry along with measured flow and pressure drop are used to calculate viscosity. The shear rate for these measurements was between 370 s^{-1} to 1480 s^{-1}.

The viscosities of three large composite samples of black liquor taken during the trials were found to fit the expression:

$$\text{Log}\left[\frac{\mu}{\mu_w}\right] = \frac{1}{0.639\frac{T}{S} - 0.2213} \tag{1}$$

where

μ = black liquor viscosity, cP or mPa-s

μ_w = viscosity of water at temperature T, cP or mPa-s

T = temperature, °R

S = dry solids content, %

A comparison of the predicted values based on Equation (1) and the actual values is shown in Figure 1. A value of viscosity for this black liquor at the nominal dry solids content of 72% and nominal fired liquor temperature of 267°F (131°C) would be 45 cP (45 mPa-s).

Using the correlation of Equation (1) and the other data obtained during the spray trials the conditions for each test were compiled and are presented in Table 1:
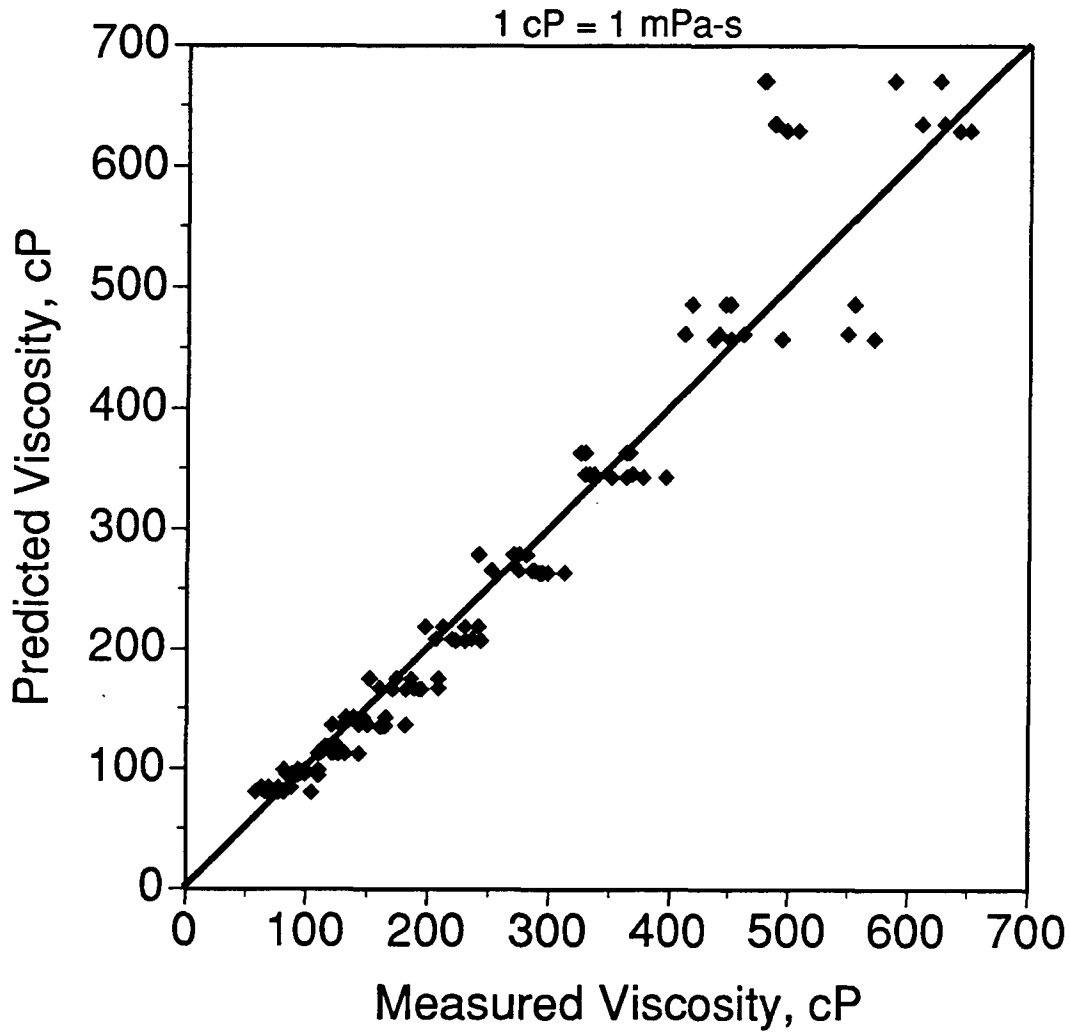
Figure 1—Comparison of the predicted and measured viscosity of the black liquor used in the high-speed video spray trial.

Table 1

Operating Conditions for the IPST Spray Video Trials
of a B&W Splashplate Nozzle in a Recovery Boiler

| Total No. Guns	Ring Header Press. psi (kPa)	Test Nozzle Flow GPM (l/s)	Nozzle Vel. ft/s (m/s)	Liquor Dry Solids %	Black Liquor Temp. °F (°C)	Black Liquor Viscosity cP or mPa-s
9	15.2 (104)	23 (1.5)	20 (6.1)	73.5	267 (131)	58.0
7	15.5 (107)	24 (1.5)	21 (6.4)	72.5	267 (131)	52.1
6	17.6 (121)	25 (1.6)	21 (6.4)	72.5	271 (133)	48.7
8	16.5 (113)	26 (1.6)	22 (6.7)	73.5	267 (131)	58.1
7	18.4 (126)	29 (1.8)	25 (7.6)	73.5	267 (131)	58.1
5	20.2 (139)	34 (2.1)	29 (8.8)	72.5	267 (131)	52.1
5	21.9 (150)	34 (2.1)	29 (8.8)	72.5	271 (133)	48.8

The Xybion video camera was mounted on a tripod approximately 50 in. (1.14 m) in front of and slightly below the level of one of the black liquor gunports. A photograph of the arrangement is shown in Figure 2. A liquor gun mounted on a horizontal support bar located in front of the gunport is also shown. The gunport dimensions are 3 3/4 in. (9.5 cm) wide by 12 in. (30.5 cm) high. A 17.5 x 105 mm zoom lens was used with the Xybion camera. Setting the lens at 105 mm yielded a horizontal field-of-view of approximately 5.9 in. (15.0 cm) at the location of the spray.

The test nozzle was fitted to a liquor gun and this assembly was then inserted through the gunport. The gun was mounted so that the tip of the black liquor nozzle was approximately 1 ft (0.3 m) inside the furnace. The gun was oriented so that spray was as close as possible to being parallel with the boiler wall and directed downward. The general arrangement is shown in Figure 3. The spray orientation for this nozzle was nearly ideal for taking back-lighted video images.

During the IPST spray trials a gating rate of 5 μs was used. The black liquor leaving the guns had a velocity of approximately 20 to 29 ft/s (6.1 to 9.0 m/s). The amount of blur due to the motion of the spray can be calculated as the product of the gating duration and the droplet velocity. Motion blur for these trials ranged from 32 μm to 45 μm. The minimum feature dimension of interest in these black liquor spray studies is approximately 0.5 mm (500 μm) so the maximum level of

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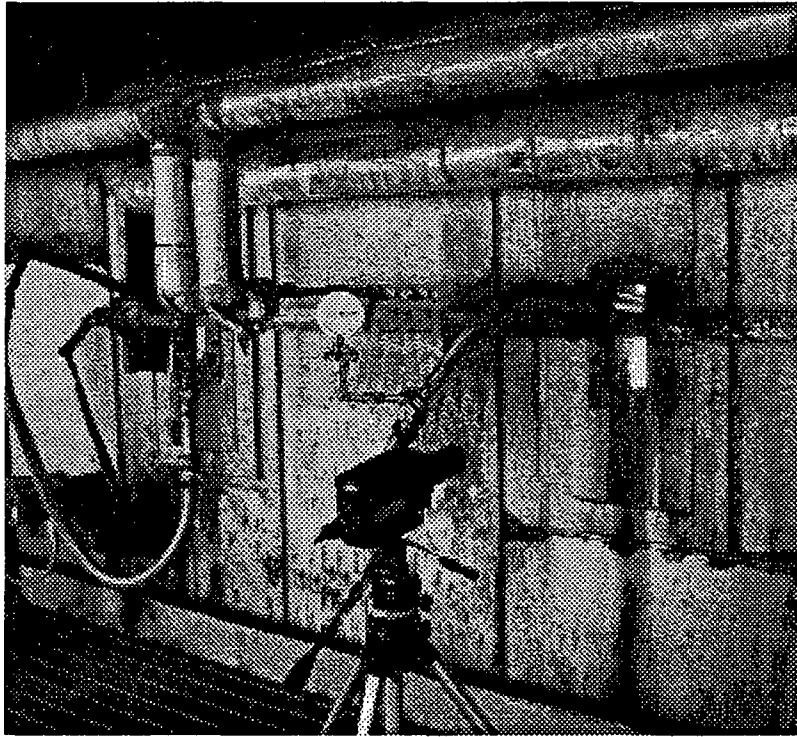
Figure 2—Photograph of the Xybion camera set up adjacent to the recovery boiler. The gun port, horizontal support bar, and part of the liquor gun are also shown.
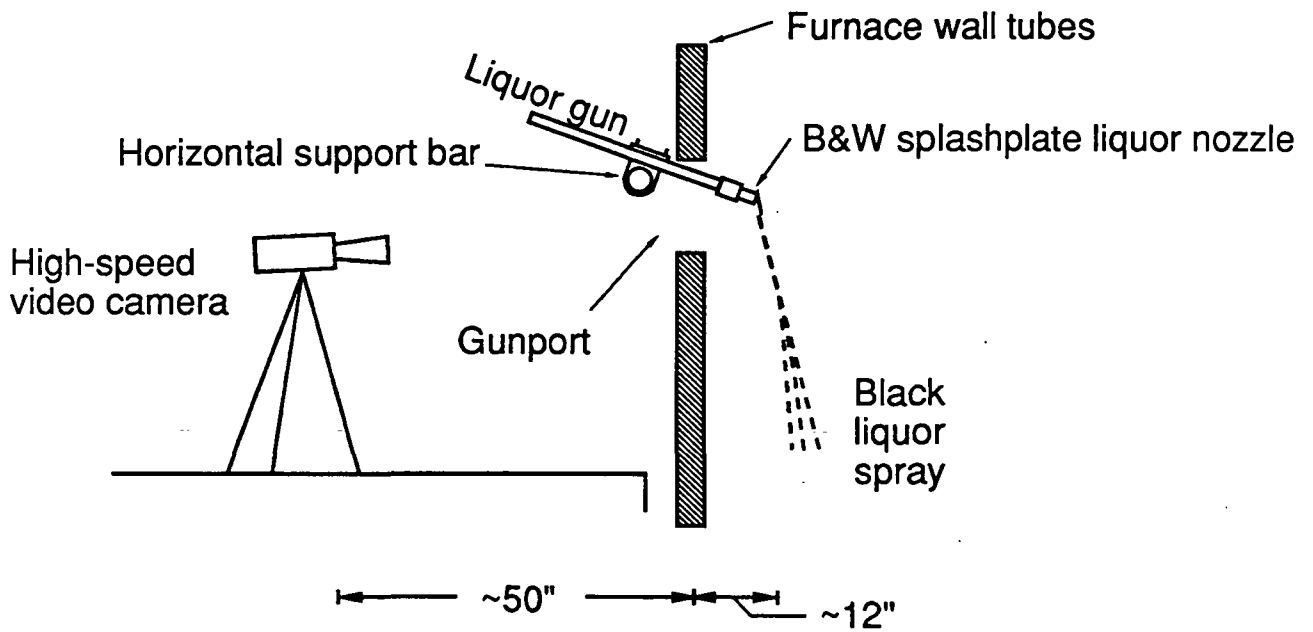
Figure 3–Schematic diagram of the camera and spray nozzle setup for the video spray trial.

motion blur is approximately 9%. This amount of feature distortion is acceptable for the present study.

Correctly adjusting the focus of the camera on the fast moving spray proved to be difficult and reduced the quality of many of the images. An aperture of f/1.8 was used for these trials. With this f/number and lens, the depth-of-field is only a few inches. This means that obtaining a proper focus on the spray is critical to overall image quality. Droplets more than 2 or 3 in. (5 to 7 cm) away from the focal plane were out of focus in the image.

Field Data With The Xybion High-Gating-Rate Video Camera

Only a few of the video recordings of the B&W splashplate nozzle sprays provided images of high enough quality for comparison to images taken under laboratory conditions. Some of these images will be presented below for two different operating conditions. All of the images were taken at a liquor temperature (measured at the ring header) of 267°F (131°C), a liquor dry solids content of 73.5%, and a calculated viscosity of 63 cP (63 mPa-s). The two conditions differed in the value of their nominal liquor flow rate: 25 GPM (1.6 l/s) and 34 GPM (2.2 l/s). The corresponding nozzle discharge velocities were 21 and 29 ft/s (6.4 and 8.8 m/s), respectively.

For all video cameras the horizontal-to-vertical aspect ratio of the image has a value of approximately 4:3. The gunport is only 3 3/4 in. (10 cm) wide so the vertical dimension of an image which just fits the width of the gunport is only 2 7/8 in. (7.1 cm); therefore, the full height of the gunport could not be covered by a single image. For this reason, images were taken at two or three elevations: at the top (just below the downward directed splashplate tip), at the bottom of the gunport, and approximately half way in-between. The height of the port which is unobstructed by either the horizontal mounting bar or the liquor gun is only about 8 in. (20 cm) so there is some overlap in the images at the three elevations.

One image from each of two or three elevations has been combined to form a composite image of the spray. This gives a better visual impression of the development of the spray for comparison to images taken in the laboratory. It must be kept in mind that these images do overlap and that they were taken a different times so should not be expected to match at their boundaries. Each image of a set is merely typical of that elevation. Also, the total recording time for images of this B&W nozzle was approximately 8 minutes. At 30 frames per second, this results in 14,400 individual images of the black liquor spray under various operating conditions. The 10 images presented below represent only a very small fraction of the available data from this part of the field trial.

Shown in Figures 4 and 5 are ten images of two sprays from the B&W #22-35 nozzle operating at low and high flow rates. To facilitate comparison of these images with those from the laboratory and the other field trial, the image closest to the nozzle is on the bottom and the image furthest from the nozzle is on the top. Comparison of the images at each vertical position shows the type of variation observed with time. Comparison from bottom to top shows the variation in spray development with distance from the nozzle. Because the maximum distance displayed in these images is only 8 in. (20 cm), spray break-up into droplets is not very advanced.

The general pattern shown in these images is of a sheet of black liquor extending from the tip of the plate with very few holes or perforations. Further away there are more perforations along with a few large drops and strands. At the furthest distance there are many perforations, along with strands or ligaments of various sizes, droplets, and large globs often connected to strands. Within the range of conditions covered and the field of view of the spray, there appears to be very little effect of firing rate on the pattern of spray break-up.

Laboratory Data For a B&W Splashplate Nozzle

Images of the break-up of the spray from a B&W splashplate nozzle have been taken in the laboratory at IPST. Hot, concentrated black liquor has been used in these trials. Shown in Figure 6 is a typical spray of liquor at 220°F (104°C), 67% dry solids, and about 8 psi (55 kPa). Note the difference in scale in this image compared to that for Figures 4 and 5. An outline of the spray nozzle has been sketched onto the image for visual reference. The perspective is from above the nozzle looking down nearly normal to the plane of the splashplate and spray.

The general pattern of this black liquor spray break-up is similar to that shown in the furnace images. A sheet of liquid is formed on the splashplate. It rapidly thins as it moves out from the nozzle and begins to perforate within inches. The liquor accumulates in thick rims around the perforation. As the number and size of the perforations grow with distance from the nozzle, the liquor in the rims forms a lace-like structure. This initial structure subsequently breaks into individual ligaments or strands. These then break down into the ultimate droplets of the black liquor spray.

## Field Tests With the Kodak High-Framing-Rate Video Camera

The objective of the Weyerhaeuser field study of black liquor sprays was, like the IPST study, only to obtain preliminary information regarding the usefulness of high speed video techniques in this application. Video images of a spray were taken through a gunport of an operating boiler. The
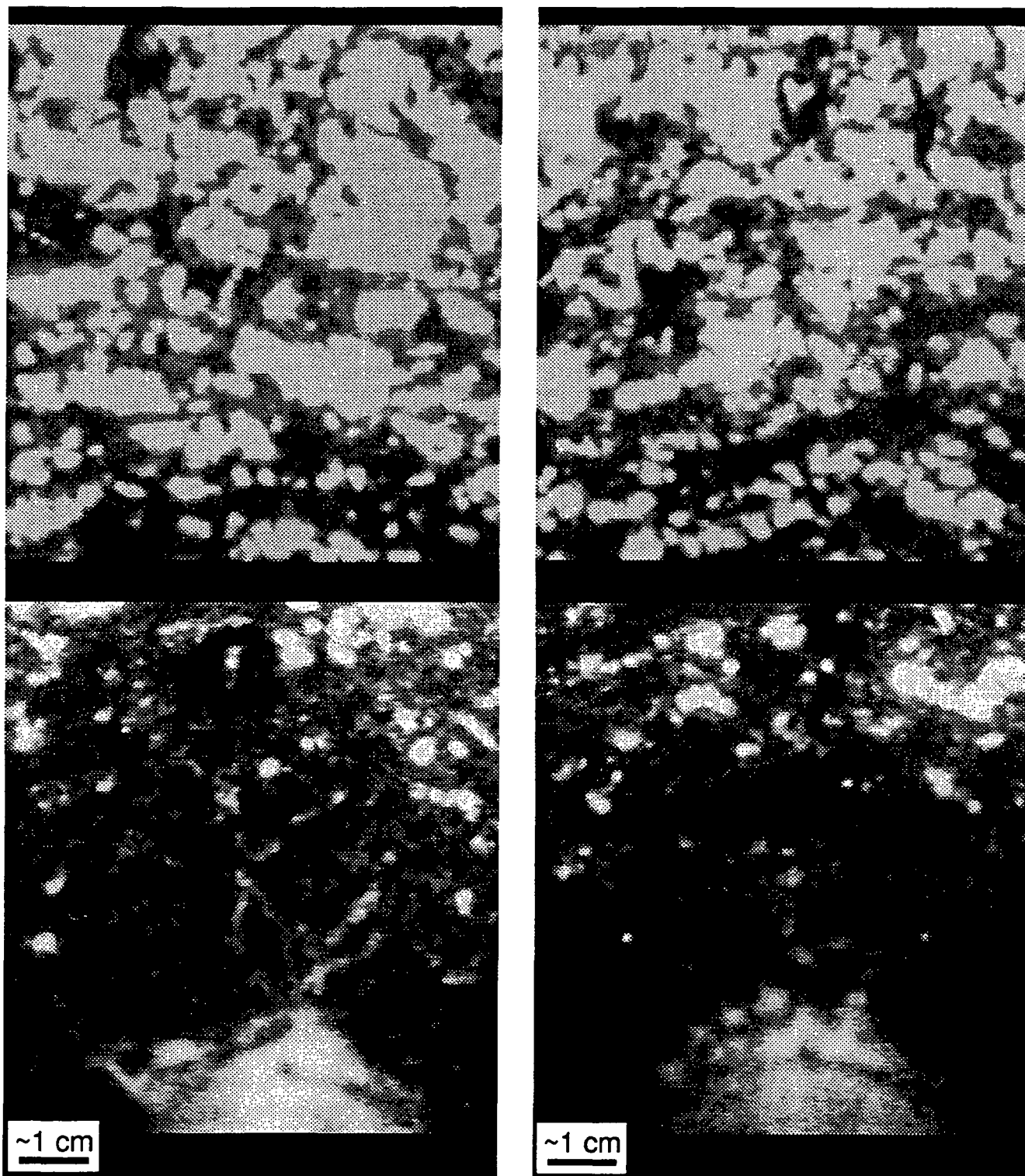
Figure 4—Two composite images of a black liquor spray in a recovery furnace. The nozzle is a B&W #22-35 splashplate operated at a flow of 25 GPM.
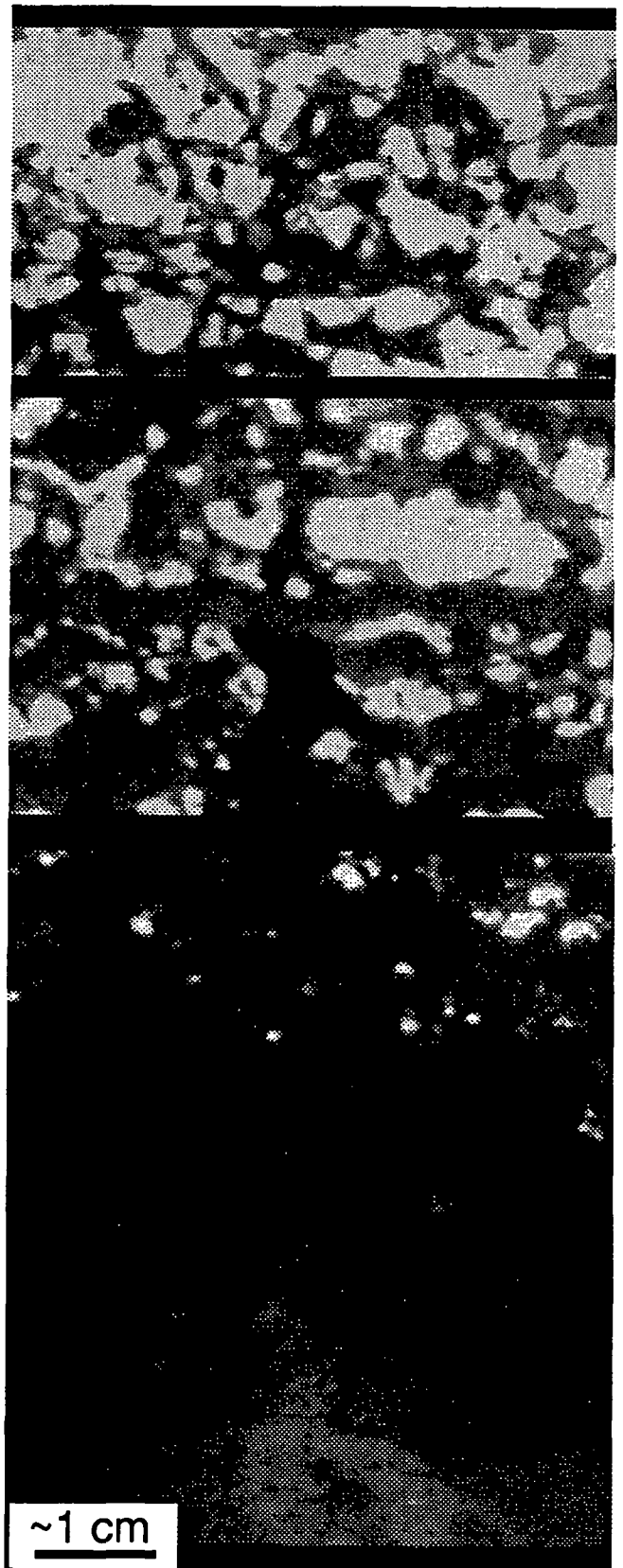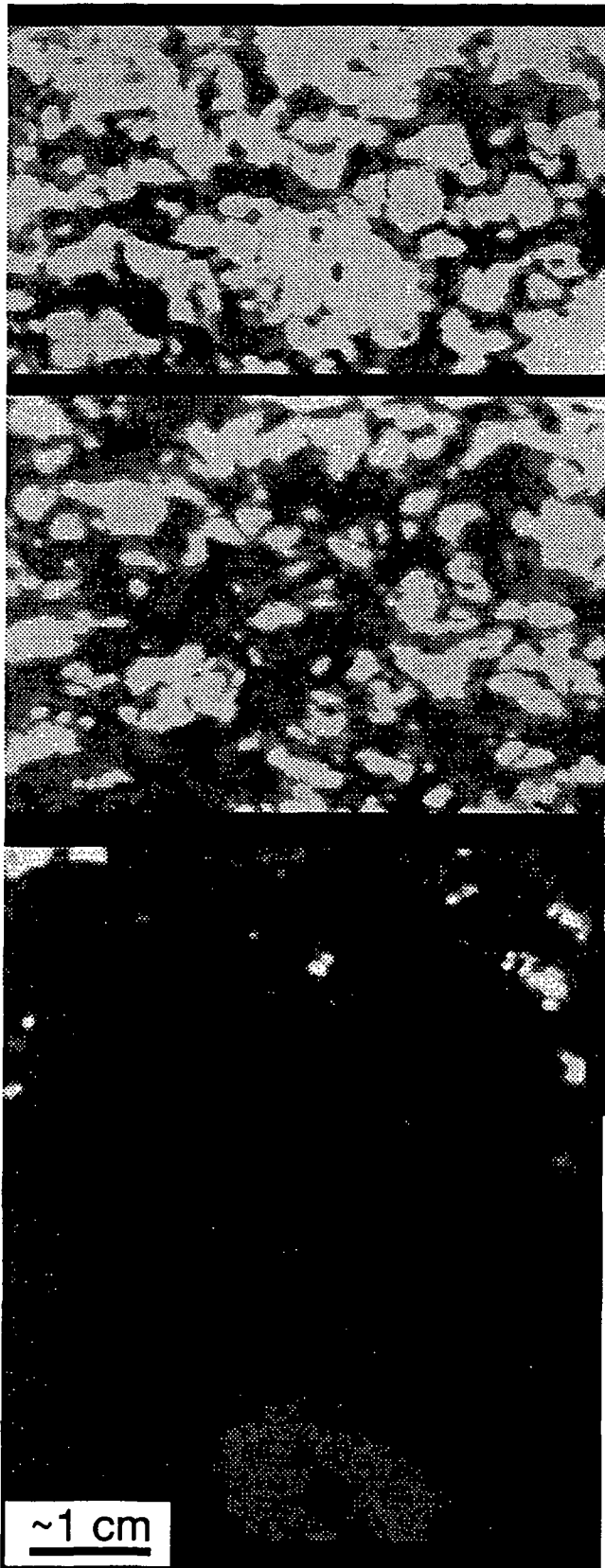
Figure 5—Two composite images of a black liquor spray in a recovery furnace. The nozzle is a B&W #22-35 splashplate operated at a flow of 34 GPM.
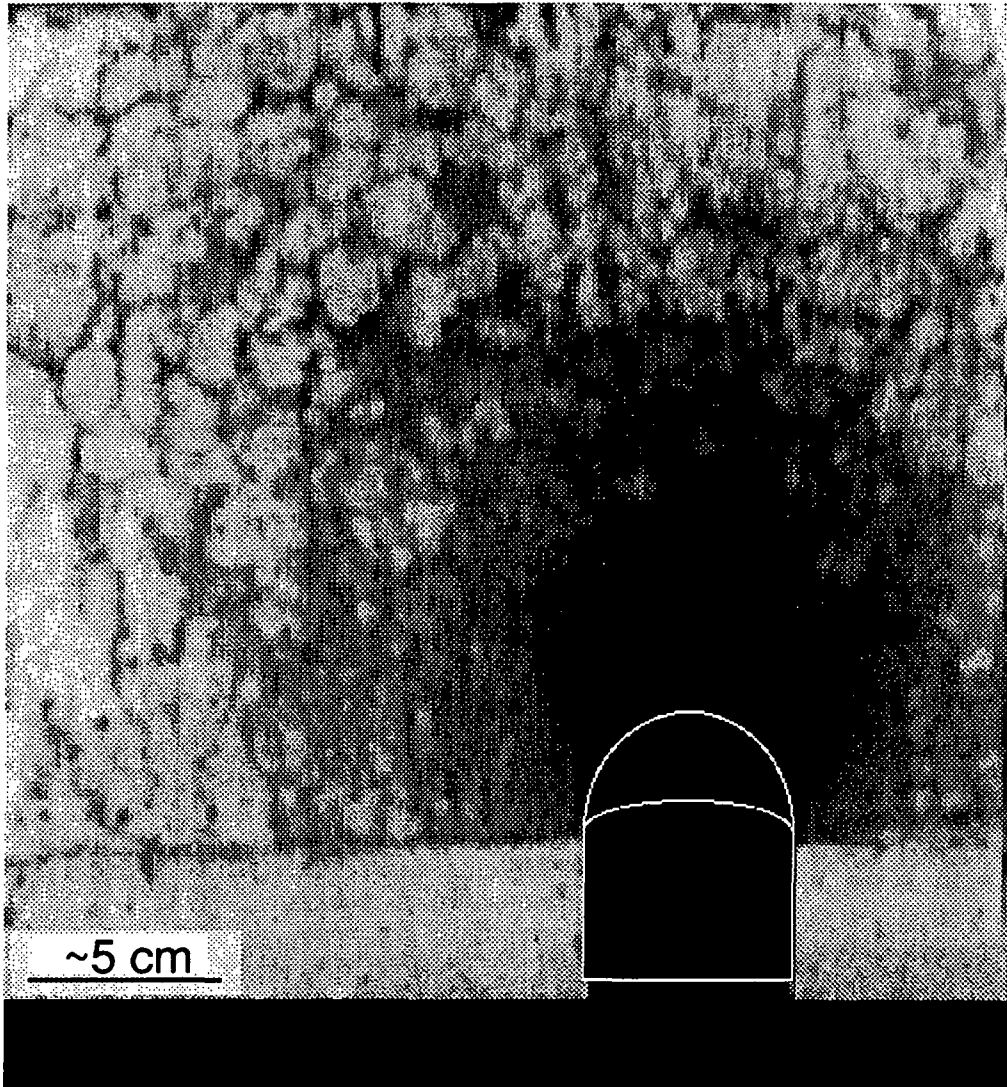
Figure 6—Image of a black liquor spray in a laboratory spray chamber. The nozzle is a B&W #12-49 splashplate.

nozzle used was a B&W #12-49 splashplate, the same nozzle used in many of the IPST laboratory tests.

There were two significant differences between the Weyerhaeuser tests and the IPST tests. First, the camera used by Weyerhaeuser was capable of high framing rates, up to 1000 frames/second. Slow motion videos of the sprays were obtained so that the development of the spray and the motion of the droplets could be studied directly. This dramatically enhanced the clarity of the physical processes occurring during black liquor spray break-up. Second, during the Weyerhaeuser tests the boiler was operated mainly on fossil fuel rather than black liquor. Black liquor only entered the boiler through the single (rather small) nozzle being tested. This removed a great deal of the fume and entrained liquor droplets characteristic of furnace flows under normal black liquor firing conditions. This improved the clarity of the images and eliminated any uncertainty about the source of the liquor droplets viewed in the images.

During these preliminary tests no information was gathered on the liquor characteristics or flows; as a result, only very limited conclusions can be drawn. However, the results of the trials served to highlight some basic differences between field and laboratory spray tests, as well as confirm some basic black liquor break-up phenomena.

A set of images from the Weyerhaeuser trials are shown in Figure 7. Again, the view is down, approximately normal to the splashplate and spray. The edges of the gunport are visible along the sides of the images. Note the approximate scale for these images in comparison to that for the IPST images. The scale in these images was estimated from the known dimensions of the splashplate nozzle just visible at the bottom of each image.

The set of four images in Figure 7 does not represent a sequence of frames, but simply four snapshots of the spray. Several observations can be made based on these images. First, the basic mechanism for black liquor spray break-up appears to be the same as that observed in the IPST field and laboratory tests. Perforations in the black liquor fluid sheet form and expand with distance from the nozzle. A laced pattern of interconnected ligaments initially forms and then breaks into individual strands. Strand break-up is not very advanced in the short distance captured in these frames, but will be shown in other images.

An outline of a splashplate was given in Figure 6. The solid-looking section in the plane of the splashplate in Figure 7 extends beyond the location of the splashplate itself. In these still images the initial visual impression is that a sheet of fluid has formed on the splashplate that extends out

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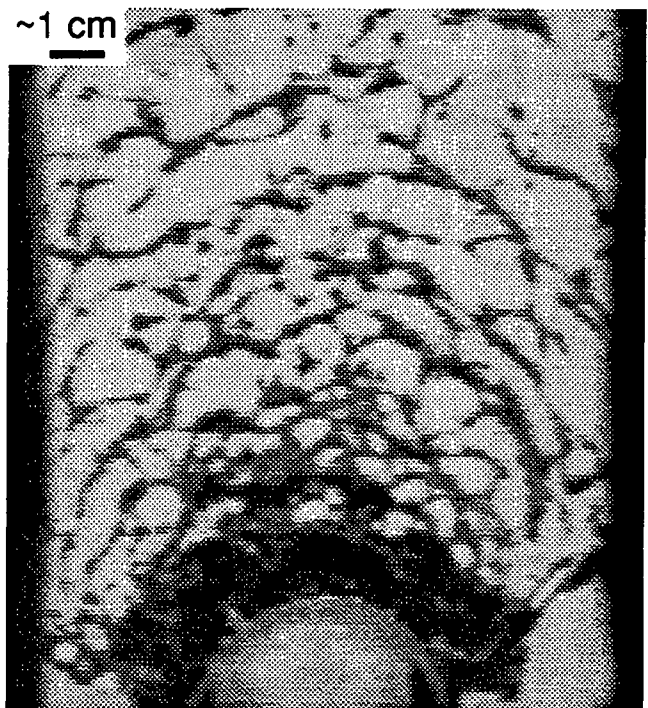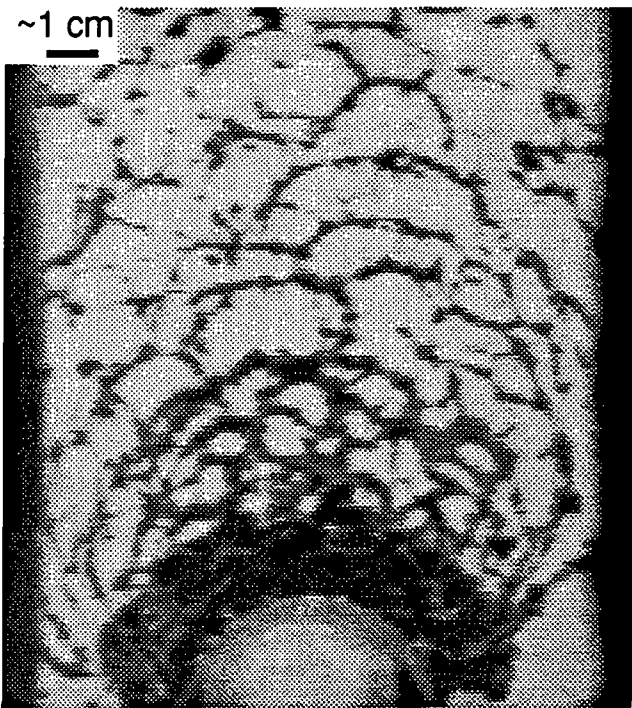
Figure 7—Four images of a black liquor spray near a B&W #12-49 splashplate nozzle. The view is down approximately normal to the plane of the spray sheet looking through a recovery boiler gunport.

beyond it to the initial perforation region located a centimeter or two beyond the splashplate lip. However, what is obvious from the actual video presentation of this sequence, and can be discerned by careful examination of these stills is that this "sheet" is stationary. The "sheet" is actually comprised of solid deposits attached to the splashplate and extending outward from it. Initial break-up of the liquid sheet occurs before it has passed beyond these deposits, less than a centimeter from the nozzle. A similar observation can be made from the "still" images obtained with the Xybion camera presented in Figures 4 and 5. Initial perforation occurred very close to the nozzle in both field trials. This is in contrast to the laboratory tests where "clean" nozzles usually produce continuous liquid sheets with dimensions from a few centimeters to over a meter from the nozzle. Solid deposits on the nozzles in furnace operation may play an important role in the initiation of sheet break-up.

Shown in Figure 8 is a sequence of two images taken a short time apart. These images were taken with higher magnification at a location near the extreme upper limit of the images in Figure 7. The scale for the images in Figure 8 were estimated from comparison of the ligament sizes in Figures 7 and 8. Because the two images in Figure 8 have been taken only 4 ms apart, the ligaments have not had time to move out of the field-of-view. For reference, two ligament structures have been identified in the images of Figure 8. One has a generally triangular shape while the other looks something like a running panther. These features have been identified in both images.

Comparison of the "triangle" and "panther" as well as other elements in the images gives a sense of the stretching, collecting, and initial breakdown of the ligaments into droplets. The estimated scale of the images and the known elapse time can be used to estimate the velocity of the spray at this location. Because the scale of these images was based on a comparison with the images in Figure 7, the accuracy is expected to be no better than ±20%. The same level of uncertainty would apply to the estimate of velocity. Recognizing this limitation, the velocity estimated from Figure 8 is 6.5 m/s (21 ft/s).
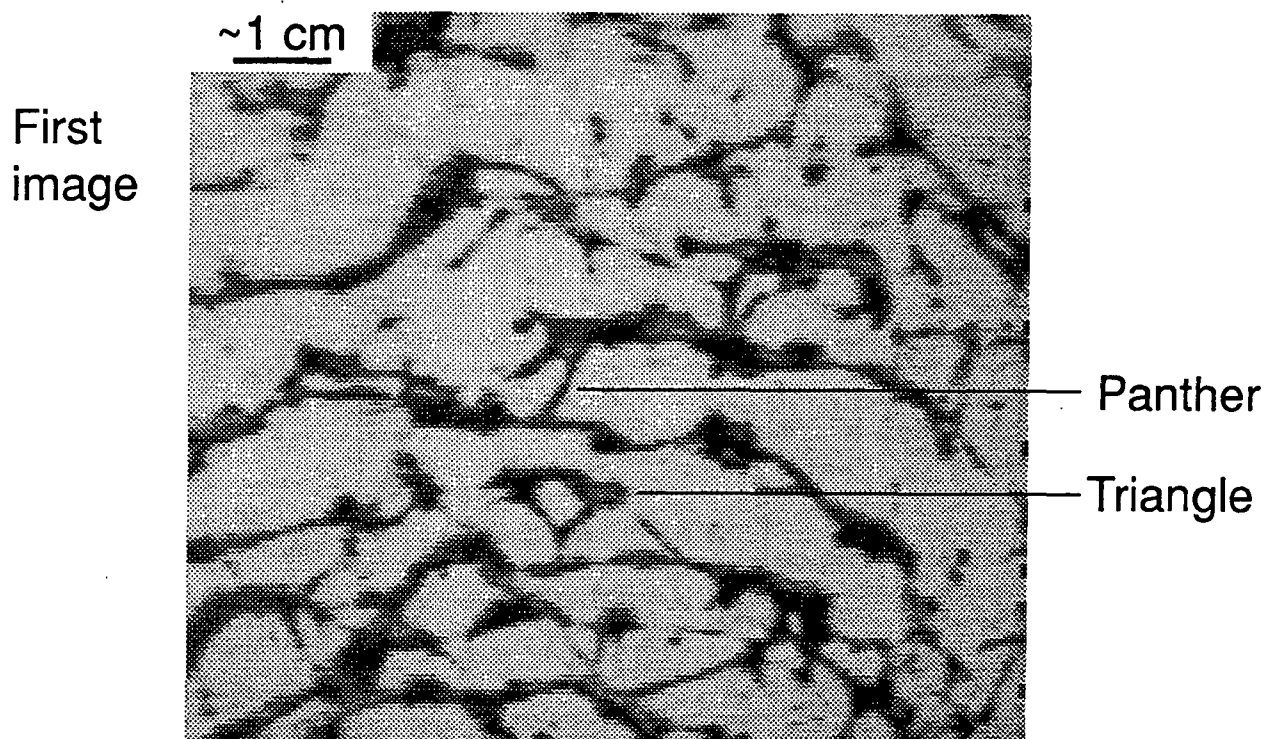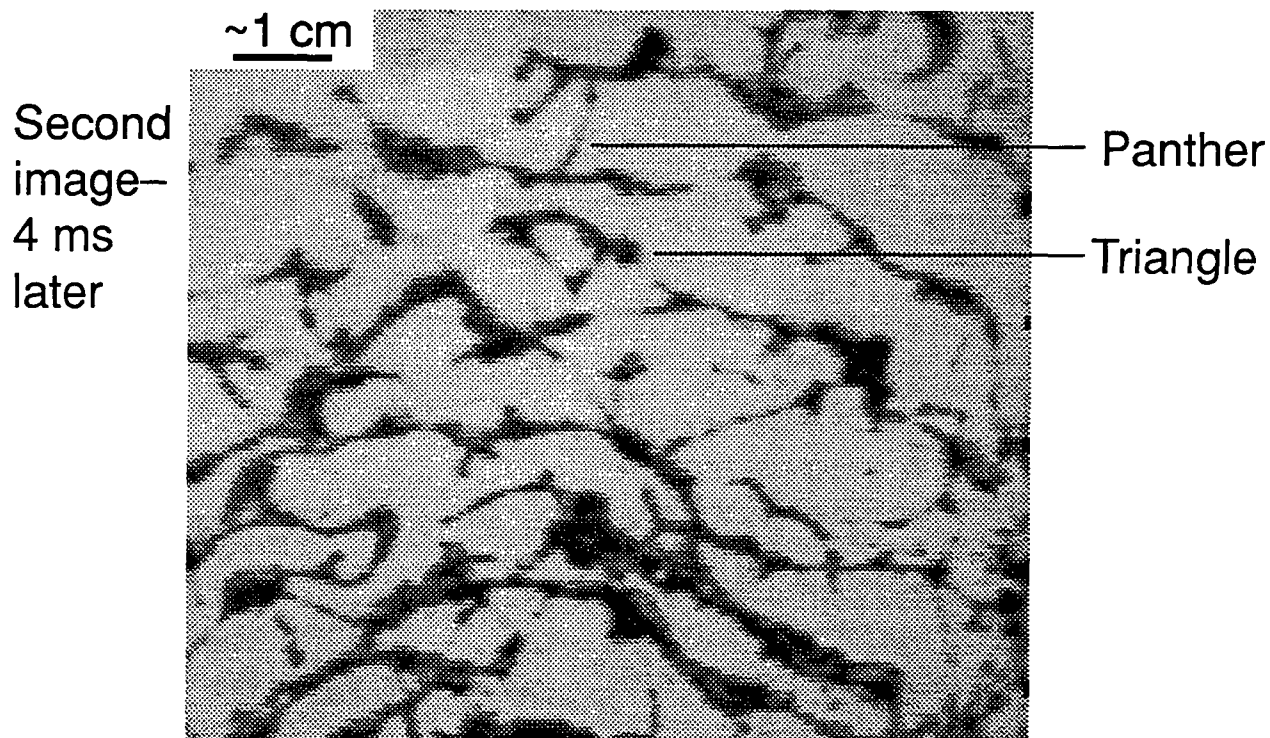
Figure 8—Two images of the black liquor spray at higher magnification. The top image was taken 4 ms after the bottom one. Based on the approximate dimensions, the "triangle" moved 2.6 cm at an approximate speed of 6.5 m/s (21 ft/s).

Conclusions

Two field trials of black liquor sprays produced by commercial nozzles have been conducted. High speed video images from these two trials have been compared to images obtained in a laboratory spray apparatus. These images all show the same characteristic break-up mechanism for the B&W splashplate nozzle. The black liquor issuing from the nozzle forms a flat liquid sheet. Perforations form in the sheet at or near the nozzle. These perforation grow in number and size as the liquor is projected out from the splashplate. The thick rims of the perforations form interconnected ligaments which initially appear as a lace-like structure. This structure breaks down into individual strands which subsequently break into droplets.

Though the basic mechanism appears to be the same, there are some differences between the sprays observed in a hot furnace environment and one observed with hot, concentrated liquor in a cold laboratory spray chamber. The main differences appear to be the formation of solid deposits on the splashplate and the more immediate perforation of the sheet in the hot environment. These phenomena may be related.

There is not sufficient data from these studies to determine the ultimate droplet size distribution of the black liquor sprays. However, these preliminary studies reveal a general image quality which should result in such data with improved calibration and filming techniques.

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