



Institute of Paper Science and Technology

KRAFT BLACK LIQUOR DELIVERY SYSTEMS

Contract No. DE-FC02-88CE40839

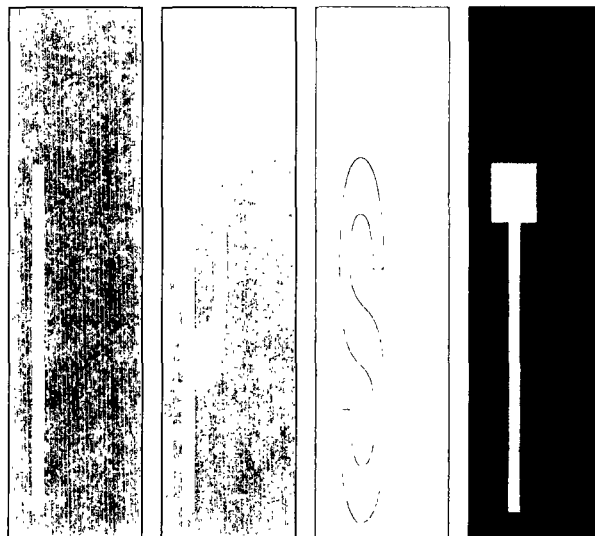
3657-2

REPORT TWO

to

U.S. DEPARTMENT OF ENERGY

December 1990



Atlanta, Georgia

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KRAFT BLACK LIQUOR DELIVERY SYSTEMS
(OCTOBER 1989 - OCTOBER 1990)

REPORT No. 2

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DECEMBER 1990

Work Performed Under Contract No. DE-FC02-88CE40839

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Table of Contents

	Page
Abstract	1
Acknowledgements	2
List of Tables	3
List of Figures	3
Executive Summary	5
1.0 Introduction	8
1.1 Objectives	8
1.2 Deliverables (summarized status)	9
1.3 Benefits	9
1.4 Organization	11
1.5 Schedule	11
1.6 Summary PR-1 (2/90)	11
2.0 BL Spray System Reconfiguration	12
2.1 System Overview	12
2.2 Black Liquor Spray Tank	13
2.3 Piping Arrangement	14
2.4 Offgas Clean-up	18
2.5 Liquor Handling	19
2.6 Waste Handling	21
2.7 Instrumentation	22
2.8 Video System	23
2.9 Black Liquor Viscosity Correlations	25
3.0 Spray Image Analysis	28
3.1 Introduction	28
3.2 Image Quality Problems	29
3.2.1 Still Images	29
3.2.2 Video Images	35
3.3 Image Math and Filters	38
3.4 High - Speed Video Images	51

	Page
4.0 Imaging Black Liquor Sprays in an Operating Recovery Furnace	62
4.1 Introduction	62
4.2 Field Setup and Operating Conditions	63
4.2.1 Boiler	63
4.2.2 Black Liquor	64
4.2.3 Operating Conditions	64
4.2.4 Video Location	66
4.2.5 Nozzle Setup	68
4.2.6 Video Camera and Lens Settings	68
4.3 Field Test Data for B&W Splashplate Nozzle	70
4.4 Laboratory Data for B&W Splashplate Nozzle	71
4.5 Discussion of Spray Breakup Images	77
4.6 Modifications for Improved Field Trials	77
4.6.1 Focus and Depth-of-Field	77
4.6.2 Electronic Gain and Aperture	80
4.6.3 Spray Field Size and Gun Port Dimension	81
References	84

ABSTRACT

Improvement of spray nozzles for black liquor injection into kraft recovery boilers is expected to result from obtaining a controlled, well-defined droplet size distribution. An environmentally sound spray facility capable of spraying black liquor at normal firing temperatures has been installed and is operational at the Institute of Paper Science and Technology. Image analysis techniques have been developed which give good two-dimensional representations of black liquor sprays from raw video images. Spraying trials were conducted at James River's Camas Mill to characterize black liquor sprays in an operating recovery furnace. Liquor sheet breakup by perforation was observed, in agreement with findings in the IPST spray facility. The video images were optically too dense to determine droplet size distribution by image analysis; however, differences in sheet breakup between nozzles were observed.

ACKNOWLEDGMENTS

The authors thank Stanley F. Sobczynski, Program Manager, Office of Industrial Programs, U.S. Department of Energy for providing guidance and critical support. The authors would like to acknowledge those who have provided invaluable input. Included are the support staff and students at IPST, along with industrial support from personnel at The Babcock & Wilcox Research Center at Alliance, OH; The Mead Corporation, Phenix City, AL; and James River Corporation, Camas, WA.

List of Tables

- 1.1 Benefits from Proposed Research.
- 2.1 Black Liquor Viscosity Data.
- 4.1 Conditions for Recovery Boiler Spray Trials.

List of Figures

- 2.1 Schematic of Black Liquor Spray System.
- 2.2 Black Liquor Spray Tank with Windows for Recording Droplet Formation.
- 2.3 Piping Arrangement Allows Liquor Temperature and Flow to be Adjusted as Needed.
- 2.4 Moyno Progressive Cavity Pump at the Outlet of the Spray Tank.
- 2.5 Spiral Heat Exchanger Provides Capacity to Heat 50 gpm of Black Liquor over 25°F.
- 2.6 Viscometer, Flowmeter, and Control Valve in the Line to the Spray Nozzle.
- 2.7 Carbon Adsorber and Fan for Gas Clean-up System.
- 2.8 Drum Handling Equipment for Transferring Black Liquor Feedstocks.
- 2.9 Black Liquor Storage Tanks for Waste Liquor.
- 2.10 Control Panel and Data Acquisition Setup for Black Liquor Spray System.
- 2.11 Tracor Northern Image Analyzer.
- 2.12 Viscosity Correlation for Black Liquor from Mead.

- 3.1 Screen Image of a Flash X-ray Spray Shadowgraph Displayed on the Tracor Northern Image Analyzer.
- 3.2 Screen Image of a Second Flash X-ray Spray Shadowgraph Displayed on the Tracor Northern Image Analyzer.
- 3.3 One Binary Cut of the Image in Figure 3.1.
- 3.4 A Second Binary Cut of the Image in Figure 3.1.
- 3.5 Image in Figure 3.2 along with a Histogram of the Gray Level Intensities Along the Line Shown on the Image.
- 3.6 Histogram of a Droplet in a Noisy Background Along with Two Binary Cuts.
- 3.7 Image Taken with the High Speed Video Camera Displayed on the Screen of the Image Analyzer.
- 3.8 Image Taken with the High Speed Video Camera Without the Spray.
- 3.9 Image Obtained by Subtracting the Background from the Original Spray Image.
- 3.10 Blown-Up View of a Portion of Figure 3.2.
- 3.11 Transfer Function for a Gauss Filter and an Average Filter.
- 3.12 Effect of the Averaging Filter on the Noisy Gray Level Histogram.
- 3.13 Binary of the Intensity Histogram after the Average Filter Has Been Applied.
- 3.14 Effect of an Average Filter and a Median Filter on a Histogram with Varying Background.
- 3.15 Droplet Profile After the Background Based on an Average Filter and a Median Filter Has Been Subtracted.

List of Figures (cont'd)

- 3.16 Image in Figure 3.2 After a 7x7 Average Filter Has Been Applied.
- 3.17 Image in Figure 3.16 After 16x16 Median Filter Has Been Applied.
- 3.18 Result of Subtracting the Image in Figure 3.16 from that in Figure 3.17.
- 3.19 Binary Produced from the Gray Intensity Image in Figure 3.18.
- 3.20 Image in Figure 3.16 after a 64x64 Median Filter Has Been Applied.
- 3.21 Result of Subtracting the Image in Figure 3.16 from that in Figure 3.20.
- 3.22 Binary Produced from the Gray Intensity Image in Figure 3.21.
- 3.23 Sum of the Binary Images in Figures 3.19 and 3.22.
- 3.24 Schematic Diagram of the Signal Flow Path Between the Light Source and the Image Analyzer.

- 4.1 Comparison of Predicted Versus Measured Viscosity for the Black Liquor Used in the High-Speed Video Spray Trials.
- 4.2 Photograph of the High-Speed Video Camera Setup Adjacent to the Recovery Boiler.
- 4.3 Schematic Diagram of the Camera and Spray Nozzle Setup for the Field Trials.
- 4.4 Twelve Images of the Spray from a B&W #22-35 Splashplate Nozzle Taken at a Flow of 25 GPM in an Operating Recovery Boiler.
- 4.5 Twelve Images of the Spray from a B&W #22-35 Splashplate Nozzle Taken at a Flow of 28 GPM in an Operating Recovery Boiler.
- 4.6 Twelve Images of the Spray from a B&W #22-35 Splashplate Nozzle Taken at a Flow of 32 GPM in an Operating Recovery Boiler.
- 4.7 Full-Scale Flash X-ray Image of a Black Liquor Spray From a B&W Splashplate Nozzle Operating at 220°F, 67% Solids, 56 cP, 21 psi.
- 4.8 Second Example of a Full-Scale Flash X-ray Image of a Black Liquor Spray from a B&W Splashplate Nozzle Operating at 220°F, 67% Solids, 56 cP, 21 psi.
- 4.9 Binary Image of the Flash X-ray Image of a Black Liquor Spray from a B&W Splashplate Nozzle Operating at 220°F, 67% Solids, 56 cP, 21 psi.
- 4.10 Second Example of a Binary Image of the Flash X-ray Image of a Black Liquor Spray from a B&W Splashplate Nozzle Operating at 220°F, 67% Solids, 56 cP, 21 psi.
- 4.11 Schematic Diagram of the Camera and Spray Nozzle Setup with Gooseneck Liquor Gun.

EXECUTIVE SUMMARY

The research work described in this report represents the results of the second year of a four-year project designed specifically to develop the optimum black liquor delivery system for the current kraft recovery boiler. Black liquor obtained from normal mill operation is being used in this development.

The primary objectives of the research program are:

- To develop laboratory equipment and methods for quantitatively studying commercial black liquor nozzle designs when spraying kraft liquors at typical operating conditions;
- To quantify droplet size distribution, velocity, and mass distribution for commercial nozzles spraying kraft liquors at typical boiler conditions;
- To develop techniques currently envisioned for improving the control of black liquor spray droplet size distribution with commercial nozzles;
- To extend current liquor spraying technology by testing several fundamentally different, but commercially viable, delivery systems.

Success with this program should yield benefits in increased thermal efficiency and process productivity, as well as have potential for improvements in equipment design and process control. Coupled with the fundamental combustion research currently in progress at IPST, the potential value of these programs to the industry is approximately \$125MM/year for increased thermal efficiency and \$200MM/year for increased productivity.

Assembly of the new black liquor spray facility has been completed, including installation of the spray tank, viscometer, all of the piping, waste liquor storage tanks, a gas scrubber system, and all of the electrical sensor and control wiring. A data acquisition system has also been connected so that information on liquor conditions is automatically recorded.

Windows on the front and back of the tank have been installed to allow the spray pattern to be videotaped. Lights and a translucent plexiglas screen are used to back-light the droplets. The high-speed videocamera has been tested and appears to provide an adequate recording for the image analyzer, even with water. Black liquor produces an excellent high-contrast image.

A series of spray tests was performed using black liquor from the Mead mill in Phenix City, Alabama. Two different nozzles were tested, a B&W 15/52 splashplate and a CE V-jet. The nozzles were tested at solids levels ranging from 50 to 65%, viscosities from 33 to 270 cP, temperatures from 77 to 110°C, and flowrates of 15 and 25 gpm.

Analysis of the data acquisition files has been completed and all of the sensors including the viscometer, appear to be working well. A correlation was developed to calculate the viscosity from the temperature and % solids for this black liquor.

There are still two issues to be resolved before droplet analysis is possible: completeness of droplet breakup; and out-of-focus droplets. Because of the width of the spray pattern, the depth of field has been too narrow to capture all of the drops in focus. The depth of field can be improved by reducing the aperture, but because of the requirement for a fast shutter speed, it has been necessary to increase the light intensity to the tank. The video data have also indicated that the droplet formation process is not completed within the length of the spray tank for all test conditions. This is especially true for the larger nozzles and at high viscosities. The length required for the drops to coalesce can be reduced by using smaller nozzles.

Image analysis techniques have been developed for generating good, clear, two-dimensional representations of black liquor sprays from the raw video images. The use of image math and filters to remove background variation and noise resulting in enhanced video image quality is detailed.

A series of trials was conducted at James River's Camas Mill to study black liquor sprays in a recovery furnace environment. This was a joint effort between the Institute of Paper Science and Technology and James River. High-speed video images of sprays were taken through a gun port on Camas #4 Recovery Boiler. Each of three different nozzles was operated at two levels of liquor flow and fired liquor temperature. The major conclusions from analysis of furnace response data and high-speed video images of the sprays are:

1. Changing one nozzle and/or firing conditions for a short period of time did not produce significant changes in furnace operation as indicated by particulate count or lower furnace temperatures.
2. Bed height was affected by transitory changes in fired liquor temperature and nozzle flow rate (pressure).
3. There is evidence of liquor sheet breakup by perforation which agrees with the findings in the IPST spray booth. There was not a lot of evidence of wave fronts and associated breakup in the liquor sprays studied.

4. Differences in breakup between nozzles were seen in the video images; however, it was not possible to detect variation due to firing conditions.
5. The video images were optically too dense to determine droplet size distribution by image analysis.
6. The video equipment may prove to be a valuable industrial tool for rapid evaluation of nozzle performance in the field and for optimization of firing conditions.

Major activities for the present year will involve acquiring additional nozzles from recovery boiler manufacturers and testing them in the spray tank. The characteristic nozzle dimension should be about 3/8 inch (e.g. #12 B&W nozzle). A companion spraying study at a mill site to examine spraying characteristics of black liquor in an operating recovery boiler will be conducted and should carefully monitor bed response to operational changes in order to determine the time required for combustion to stabilize after each change.

1.0 INTRODUCTION

1.1 OBJECTIVES

The research program detailed in this report represents an applied effort designed specifically to identify the optimum black liquor delivery system for the current kraft recovery boiler and to present it to the industry in a timely fashion. Only commercially viable (large capacity) delivery systems are being considered. Since the primary focus of this program is a system to deliver black liquor, a large number of experiments are to be conducted with actual (well-characterized) liquors. The program will answer the following specific questions:

- a. Exactly how good are the nozzles currently used for black liquor spraying?
- b. Do other commercially available (off the shelf) spraying systems exist which perform better than liquor nozzles now in use?
- c. Can vibratory assist or concepts from fluidics such as controlled vortex shedding be employed to develop significantly improved spraying systems?
- d. Are there more radically different delivery systems not involving the spraying of droplets which offer the opportunity for quantum improvements in recovery boiler operations?

In order to answer these questions, the research program has the following main objectives:

- a. To put in place a unique laboratory facility for the quantitative study of commercially viable black liquor nozzles which are tested with black liquors at typical operating conditions.
- b. To quantify the performance (droplet size distribution, velocity, and mass distribution) of commercially available nozzles when spraying kraft black liquors at typical boiler conditions.
- c. To test several potential techniques currently envisioned for improving the control of black liquor spray droplet size distribution with commercially viable nozzles.
- d. To proceed beyond current spray technology to test several fundamentally different, but commercially viable, delivery systems.

1.2 DELIVERABLES

This research effort will deliver the following:

- a. A test facility capable of quantitatively assessing the performance of commercially viable spray systems while spraying kraft black liquors at typical boiler feed conditions.
- b. The best commercial spray delivery system available with current technology.
- c. An appraisal of the commercial viability of several fundamentally different black liquor delivery systems.

This past year has seen the accomplishment of "a", with details contained in this report.

1.3 BENEFITS

To a large degree, the objective of this program can be viewed as delivering the tools required to realize the benefits of several other research activities in the black liquor area. Primary among these is the fundamental combustion and recovery boiler modeling research currently underway at IPST. This fundamental work will determine the optimum black liquor droplet size and velocity distribution to maximize effective use of the furnace volume. Development of a system to achieve this desired liquor distribution is the objective of the present program. As such, potential benefits from this applied study are essentially the same as projected for the fundamentals of combustion program. These are reproduced verbatim from a previous report by Clay et al. (1) in Table 1.1.

The increased thermal efficiency value for the industry is approximately \$125 million/year. The minimum process productivity value for the industry is estimated at \$200 million/year. Table 1.1 provides supporting detail. These costs reflect savings increments above the state-of-the-art recovery boiler technology available. Increments from industry average conditions to improved levels could approach 1.5 to 2.5 times the above values.

Table 1.1 Benefits from Proposed Research

- Goals:
1. Increased thermal efficiency
 2. Increased process productivity
 3. Improved equipment design potential
 4. Improved process control potential

Targets:

1. Increased thermal efficiency

Element	Improvement	Value	
		10 ⁵ Btu/adtp	\$/adt
Increased fired percent solids	70 to 75%	2.3	1.5
Reduced flue gas temperature	350 to 325°F	1.2	0.74
Reduced carbon in smelt	1.5 to 1.0%	0.86	0.54
Reduced sootblowing steam	3.0 to 2.5%	0.72	0.45
	(Total)	5.1	3.2

2. Increased process productivity

Incremental production	1% inc.	400 \$/adtp
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INDUSTRY VALUE

1. Increased thermal efficiency
 $5.1 \times 10^5 \text{ Btu/adtp} \times 50 \times 10^6 \text{ adtp/yr} = 2.5 \times 10^{13} \text{ Btu/yr}$
 $2.5 \times 10^{13} \text{ Btu/yr} \times \$5.0 \times 10^{-6}/\text{Btu} = \$125,000,000/\text{yr}$
2. Increased process productivity (1%)
 $0.01 \times \$400/\text{adtp} \times 50 \times 10^6 \text{ adtp/yr} = \$200,000,000/\text{yr}$

Thermal efficiency and process productivity goals are not independent. The recovery boiler is often found to be the bottleneck in the entire pulping process. Thermal efficiency is often sacrificed for high productivity. Thermal efficiency and productivity increases may not be realized simultaneously. On the other hand, the recovery boiler is the only pulp mill operation which can often claim that improved unit productivity will result in increased mill-wide productivity.

The in-place capital investment in recovery boiler technology is so large (\$10 billion) that radical changes, expansions, and replacements will be rare for the foreseeable future. Barring a significant departure from the kraft process in the near term, the industry will be firing black liquor in "Tomlinson-like" boilers through the year 2000.

1.4 ORGANIZATION

Organization of the project initially came from Dr. T.E. Farrington, Assistant Professor in the Engineering Division of IPST, and Dr. D.T. Clay, Associate Professor, and Dr. T.M. Grace, Professor, in the Chemical Sciences Division. With the move of IPST from Appleton to Atlanta, these individuals elected not to relocate. To maintain project continuity, IPST engaged consultant Dr. T.N. Adams on a part-time basis to assume primary technical responsibility. Subsequent to this, Dr. H.J. Empie was hired as Group Leader for Recovery and accepted organizational responsibility for the project. Mr. T.M. Spielbauer, a PhD candidate at IPST, elected to do his thesis research in the area of liquor droplet formation mechanisms, and is expected to contribute significantly to the success of the project. Mr. S.J. Lien, Research Engineer in the Chemical Recovery Group, was assigned responsibility for equipment reinstallation and operation.

1.5 SCHEDULE

The work reported here represents the second year of a 5-task project covering a total of 4 years. Successful completion should lead to a second phase involving implementation at some mill location.

1.6 SUMMARY OF PROGRESS REPORT No. 1

Early results were obtained on the performance of the three basic types of black liquor spray nozzles: the splashplate, the swirl cone, and the U- or V-type. Data were presented on the flow and pressure drop characteristics of two of these nozzle types which allow judgment of the sensitivity of the flow to normal mill variations in liquor properties. Data were also presented on several aspects of spray formation and droplet size distribution. Considerations of nozzle stability with respect to flashing ahead of the nozzle showed that the minimum nozzle operating pressure would have to be significantly increased to suppress flashing ahead of the nozzle when firing high solids, viscous liquors.

Flow coefficient correlations for hot and cold black liquor and corn syrup (a model comparison fluid) were developed for two types of black liquor nozzles: the B&W splashplate and the CE U- and V-type. The correlating parameter was Reynolds Number based upon the minimum flow diameter. Corn syrup was useful because its viscosity and density are similar to those for black liquor, and it was easier to handle.

The formation of droplets from a black liquor stream required the prior formation of a fluid sheet by the nozzle. The ultimate droplet size could be directly related to the initial sheet thickness and velocity. Sheet thickness, and therefore liquor droplet size, were found to increase with liquor

viscosity (and hence black liquor solids) for the B&W splashplate nozzle. This change in nozzle performance at high solids should be mild enough to allow routine mill optimization of existing B&W nozzles without replacing them with a new design when changing to high solids firing.

Data on droplet size distributions from a B&W splashplate nozzle and a CE swirl cone nozzle were obtained. Droplet size did vary with operating conditions; however, it showed a weak dependence on liquor velocity and fluid physical properties. Furthermore, the size distribution was almost the same for all nozzles when the size data were normalized by dividing the actual droplet size by the mass median diameter. Using this approach, there appeared to be very little impact of nozzle geometry, fluid properties, or operating conditions. This suggested the same mass median size also produced the same size distribution. When calculating normalized size distributions, use of a lower cutoff limit of one-third the observed median yielded the best results. For a 2mm mass median size typical of black liquor sprays, the lower cutoff limit would then be 0.66mm.

The Flash X-ray (FXR) shadowgraph technique originally proposed for this program was shown to be inferior to a high-speed video approach. This was because black liquor is a weak absorber of radiation resulting in poor image contrast for diameters under 0.5mm. The resolution of the high-speed video varied with the selected field-of-view, but appeared to be approximately 0.1mm. In addition, the number of FXR images per run was limited so that droplet history could not be recorded; such is not the case with the video approach.

2.0 BLACK LIQUOR SPRAY SYSTEM RECONFIGURATION

2.1 SYSTEM OVERVIEW

In conjunction with the move of the Institute from Appleton, Wisconsin to Atlanta, Georgia, a new black liquor spray facility was designed and constructed. This system was designed to allow observation and analysis of liquor spray patterns from a variety of black liquor nozzles over a wide range of flowrates and temperatures. The most important component in the system is the spray tank, which provides storage capacity for black liquor and to encloses the actual liquor spray (Figure 2.1).

A pump and stainless steel piping are connected to the tank outlet, allowing black liquor to be pumped from the tank outlet to the spray nozzle. The piping arrangement includes a heat exchanger and control valves to allow the temperature and flow rate of the liquor to be adjusted over a wide range (which includes conditions typical for operating recovery boilers).

A gas scrubber system was designed to prevent any odor from escaping the system. Additional equipment was also installed to allow black liquor to be easily added and removed from the tank; instrumentation was included to control and measure the test conditions in the spray booth; and a high speed video and image analysis system is used to collect data on the droplet size distribution.

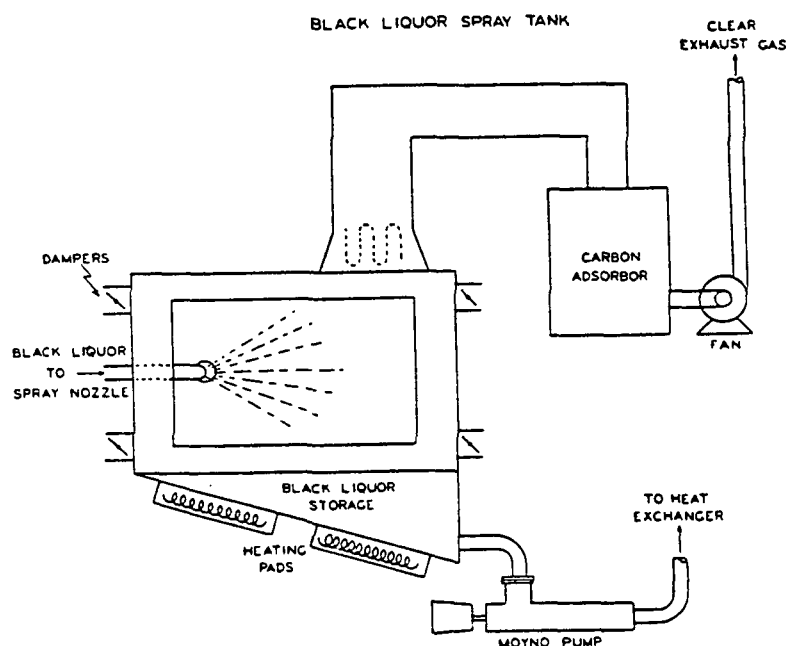


Figure 2.1 Schematic of Black Liquor Spray System

2.2 BLACK LIQUOR SPRAY TANK

The spray tank was fabricated from stainless steel by an outside company and then installed in the industrial research bay at IPST (Figure 2.2). The nominal dimensions of the tank are 7 ft long (in the direction of the liquor spray), 6 ft wide and 10 ft high. The volume available for the spray pattern is approximately 6 ft X 7 ft X 7 ft.

The tank has large 5 ft by 4 ft windows on the front and back to allow video-taping the black liquor spray pattern. The tempered glass windows are installed in hinged frames to provide access to the tank and the inside of the windows. At the side of the tank is an opening for the spray nozzle. The liquor spray will travel primarily in a horizontal direction and parallel to the windows.

In order to obtain a good video recording of the spray pattern, baffles are used to restrict the spray pattern to a narrow path parallel to the windows at the center of the tank and prevent black liquor from collecting on the windows. Another set of baffles at the end of the tank opposite the spray nozzle is used to reduce the splash-back of liquor off the wall on to the window.

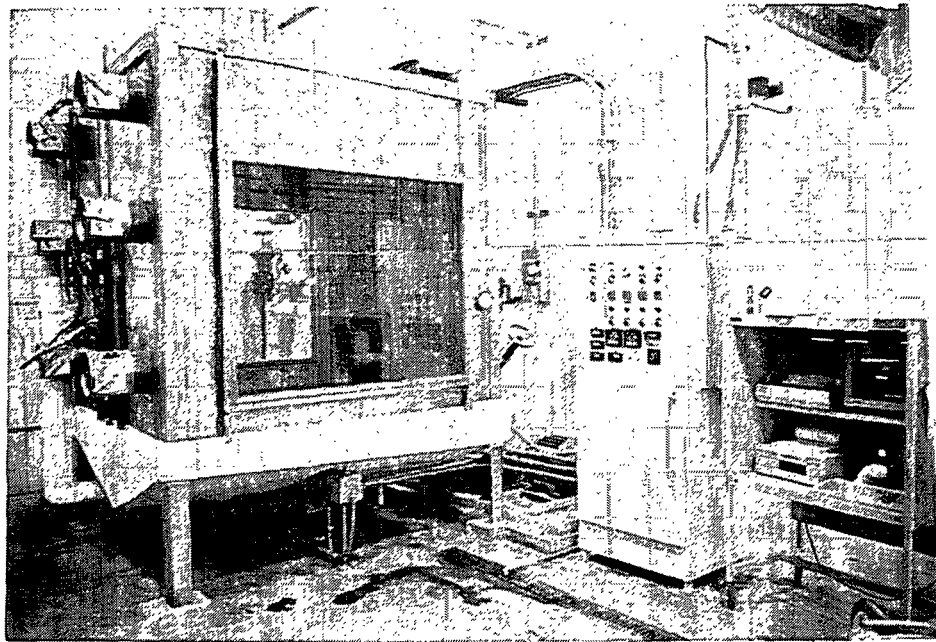


Figure 2.2 Black Liquor Spray Tank with Windows for Recording Droplet Formation

The bottom of the tank is V-shaped to provide storage capacity for up to 300 gallons of liquor (during normal operation we expect to use 150 to 200 gallons of black liquor). Large flexible heating pads were installed on the bottom surface of the storage tank and then covered with insulation. These will heat the liquor to approximately 200 F, reducing the viscosity enough to allow the high solids liquor to be pumped from the tank.

2.3 PIPING ARRANGEMENT

The piping was designed to maximize flexibility in the operation of the system, to prevent unnecessary shut-downs due to plugging and other problems, and to prevent black liquor spills and discharges to the sewer system (see piping schematic Figure 2.3).

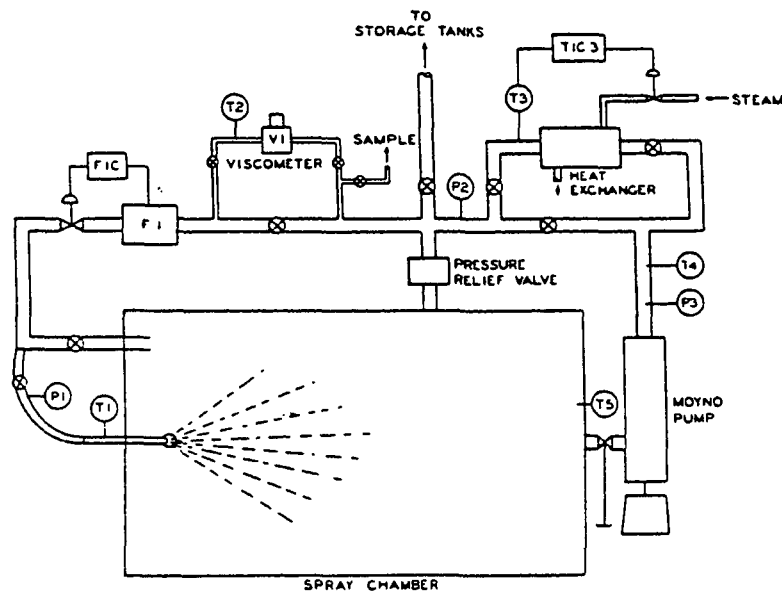


Figure 2.3 Piping Arrangement Allows Liquor Temperature and Flow to be Adjusted as Needed.

At start-up, a knife-gate valve at the tank outlet is opened allowing warm liquor to flow to the inlet of the Moyno pump. Liquor is then pumped through a bypass loop back into the spray tank. This short pipe run allows the high viscosity fluid to be pumped more easily and the mixing action insures that the liquor is at a uniform temperature and consistency before the actual testing begins.

The pump is a two-stage Moyno progressive cavity type pump (Figure 2.4). Running at 470 RPM it has a volumetric capacity of about 60 gpm at 150 psi. The pump output is a non-pulsating flow and has the ability to handle high viscosity fluids.

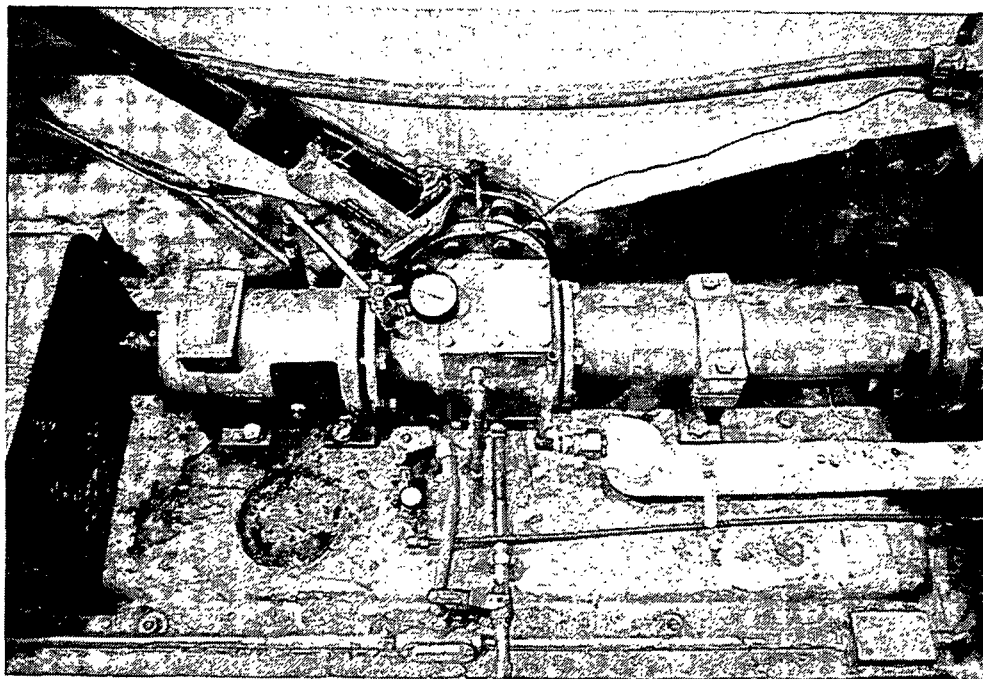


Figure 2.4 The Moyno Progressive Cavity Pump at the Outlet of the Spray Tank.

When the liquor is at the desired temperature, it is diverted through a second loop where a pressure relief valve is installed to maintain a constant pressure, regardless of the flow rate to the nozzle and also to insure that the constant volume Moyno pump is not operating against a closed valve. To prevent black liquor from solidifying in the pipe, the entire piping loop is wound with electrical heating cable and insulated to maintain a minimum temperature of 200 F.

When additional heat is required, an Alfa-Laval spiral heat exchanger can be used (Figure 2.5). This unit has the capacity to heat 50 gpm of black liquor about 25 F. This allows single pass heating of the liquor in order to perform tests above the boiling point. This system includes a DeZurik steam control valve (with an actuator, a positioner and a PID controller) to provide accurate adjustment of the outlet liquor temperature.

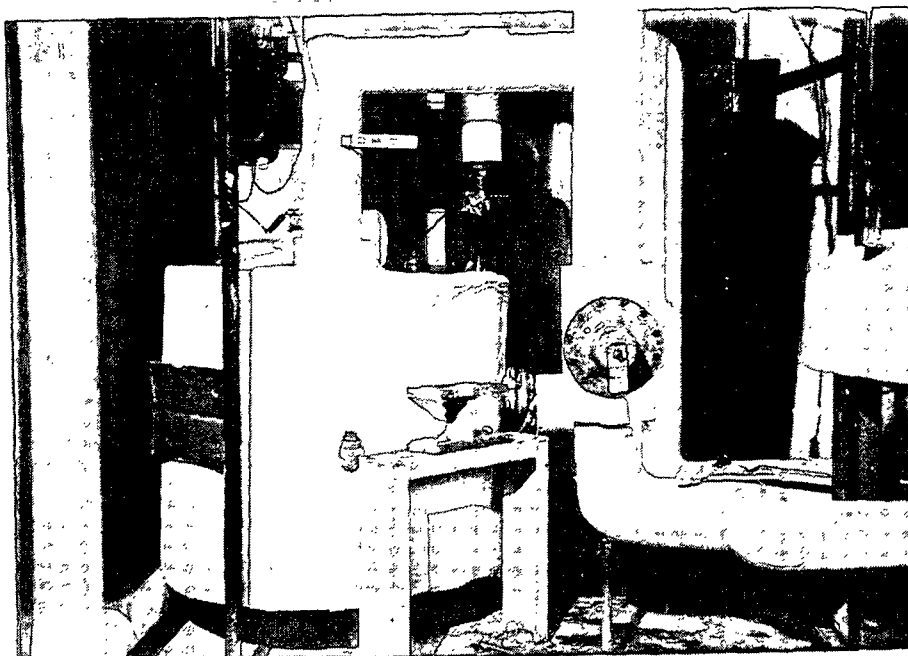


Figure 2.5 Spiral Heat Exchanger Provides Capacity to Heat 50 gpm of Black Liquor over 25 F.

When the liquor is at the correct conditions for the test, the black liquor flow is directed through the spray nozzle. A DeZurik V-port control valve is used (also with an actuator, a positioner and a PID controller) to achieve a precise flowrate. Because of the pressure drop through the piping and the heat exchanger, the full capacity of the Moyno pump is not available at the nozzle. Under normal conditions, the system has the capacity to deliver up to 40 gpm at 80 psi to the nozzle. Another by-pass is provided just before the spray nozzle so that modifications can be made at the nozzle by temporarily diverting the flow without upsetting the test conditions.

The temperature of the liquor is measured at the nozzle and at several other locations in the pipe loop. Pressure transducers are also used to monitor the pressure at the pump outlet, the pipe loop, and the nozzle. Stainless steel diaphragms have been used to isolate the transducers from the black liquor, resulting in more accurate pressure measurements. The flow rate of black liquor to the nozzle is measured with a Foxboro magnetic flowmeter. The viscosity of the black liquor in the flow loop is monitored on a continuous basis with a Brookfield viscometer (Figure 2.5). This unit will measure viscosities from 0 to 1000 cp based on the torque required to continuously rotate a coaxial cylinder.

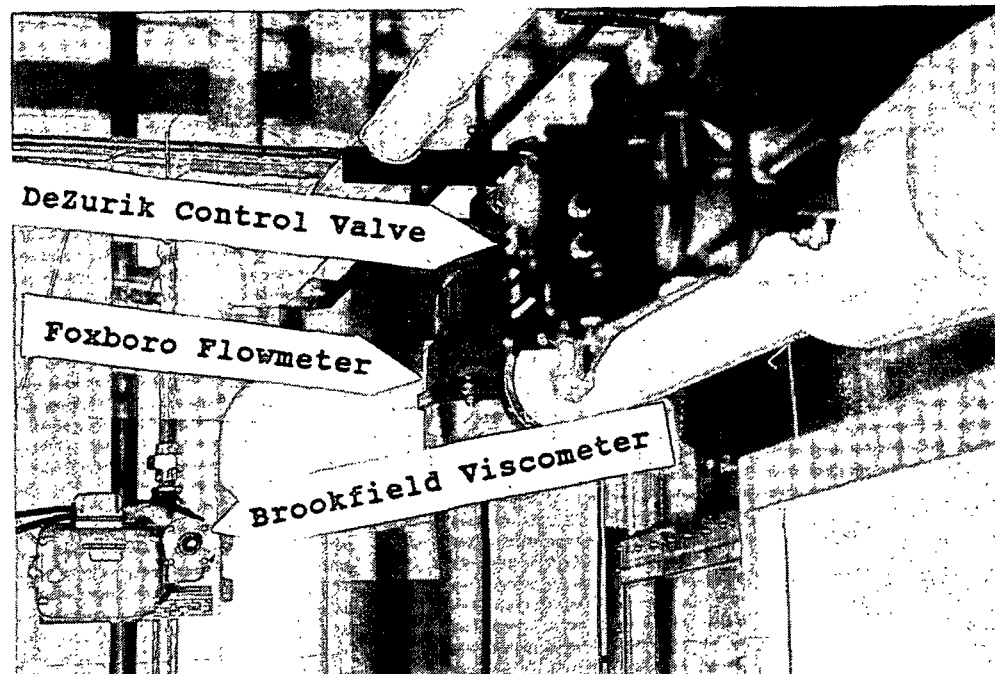


Figure 2.6 The Viscometer, Flowmeter and the Control Valve Installed in the Line to the Spray Nozzle.

A hot water supply is maintained to flush out the piping in order to prevent the black liquor from solidifying and plugging the pipe. For example, if liquor is diverted from the nozzle for several minutes, it will be necessary to rinse out the nozzle in order to prevent plugging. The hot water will also be used to clean all of the piping at the end of a run and to clean out the liquor tank when the supply is being changed.

2.4 Offgas Clean-Up

In order for the black liquor spray system to be useful, it was necessary to contain the odor caused by the release of sulfur compounds from warm black liquor. In order to do this, a fan is used to draw air from the spray tank and through activated carbon for odor removal. Clean air is exhausted outside (Figure 2.7).

Because even tiny amounts of these sulfur compounds can create a serious odor problem, it was necessary to design the gas handling system to insure that the entire system operated under a vacuum so that no gas could escape. A fan was selected that draws 2000 ft³/min (scfm) of gas through the spray tank. The average retention time for the gas in the tank is less than 15 seconds. Eight dampers are installed on the spray tank to allow for adjustment of the vacuum and the air flow patterns. The dampers are set to insure odor containment and to minimize the effect of gas flow on the black liquor spray pattern.



Figure 2.7 Carbon Adsorber and Fan for the Gas Clean-up System.

A large carbon adsorber was donated by Westvaco Corporation, which removes all of the odor from the gas before discharge. Because it is impossible to estimate the concentration of mercaptan and other gases in the spray tank, it is not known how long the carbon will remain effective.

The spray of hot black liquor will produce large amounts of water vapor which will add to the loading on the scrubber system. In addition, this water vapor will result in a gradual increase in the solids level of the black liquor. In order to reduce this problem, a condenser can be installed in the duct at the outlet of the spray tank. This will reduce the gas flow through the carbon adsorber and also return most of the water to the spray tank. Although this has not been done, the configuration of the outlet duct has been designed so that a condenser can be easily added in the future. For the time being, a flowmeter has been added to the pump inlet so that water can be added to make up for the evaporative loss.

2.5 LIQUOR HANDLING

In order to collect useful data on spray nozzle performance it will be necessary to test black liquor from several sources. Therefore, a system for transferring black liquor to the spray tank was needed. The system has been designed so that black liquor can be added to the tank as a liquid, solid or semi-solid.

Normally the liquor will be delivered in 55-gallon drums. A lift mechanism has been purchased which will allow drums to be easily lifted and tilted using a small fork-lift (Figure 2.8). If the liquor is hot, it can be poured directly into the tank. More often the black liquor has cooled and solidified in the drums. Because it is a slow and time consuming process to reheat the drums, the system has been designed so that solidified liquor can be placed directly in the tank and then heated with electrical heaters.

In order to ship black liquor, Department of Transportation (DOT) regulations require drums meet DOT Specification 5B for re-usable steel drums. Seven 5B drums were purchased with an added epoxy-phenolic coating to help prevent black liquor from sticking to the walls. Disposable plastic liners are also available to help remove liquor from the drums. A small electric drum heater has been purchased to melt a thin outer layer of the solidified black liquor to help in removing the liquor.

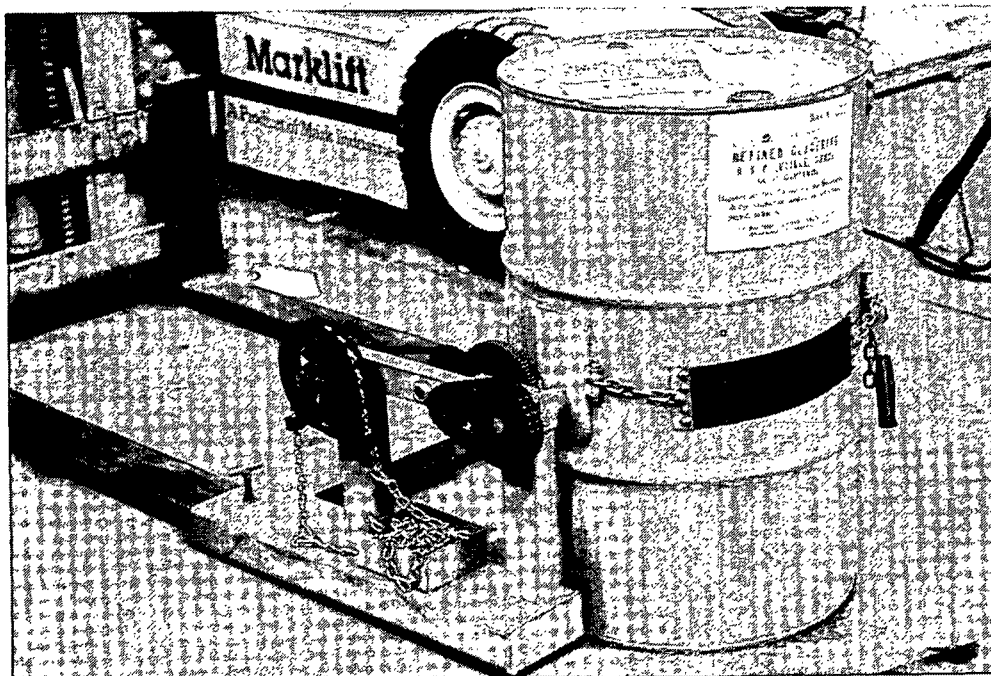


Figure 2.8 Drum Handling Equipment for Transferring Black Liquor Feedstocks.

2.6 WASTE HANDLING

It will also be necessary to dispose of the old black liquor. Heating and pumping tends to modify the viscosity and other properties of black liquor, so that even for studies of a single liquor supply it may be necessary to change the liquor frequently. In order to efficiently dispose of the liquor, two large 5000-gallon tanks (Figure 2.9) have been installed outside of the Industrial Research Facility (IRF). These tanks are connected to the spray loop piping so that liquor can easily be transferred to these tanks. When a large amount of waste liquor has been accumulated, it can be loaded into a tank truck and transported to a nearby kraft mill for disposal in their liquor cycle.

During shut-down and liquor transfer procedures it is necessary to rinse out the piping and storage tanks. Most of this rinse water is transferred to the waste storage tank, but a small amount is disposed of down the drains. Additional water from pump seals is also sent to the sewer system. Permits have been obtained for the disposal of this limited amount of dilute black liquor ($< 1\%$ solids). The trench drains in the floor of the IRF were extended to reach the spray booth area.



Figure 2.9 Black Liquor Storage Tanks for Waste Liquor.

2.7 INSTRUMENTATION

The control panel has been setup just in front of the spray tank so that the system can be easily monitored and controlled during the operation of the spray system (Figure 2.10). Push button starters for the exhaust fan and the liquor pump are located at the control panel. Selector switches and relays are used to turn the heaters on and off as needed. PID controllers and digital readouts provide a continuous indication of the status of the system.

The tank heaters are controlled in three separate banks so that the heating rate can be adjusted to the amount of liquor in the tank. When the heaters are on, they are controlled by two separate control loops; the main controller adjusts the liquor temperature to the desired set point, and secondary controllers are used to prevent the silicone rubber heaters from exceeding their operating limit. The water heater and the heat tracing on the pipe can also be turned on, when needed, with selector switches.

The temperature of the liquor is measured by thermocouples located at several points in the system. These temperatures are displayed on individual controllers and on a switchable digital display. Three digital instruments provide pressure readings from transducers located at the outlet of the pump, in the pipe loop, and at the spray nozzle. The flowrate of the black liquor to the spray nozzle is measured with a Foxboro magnetic flowmeter.

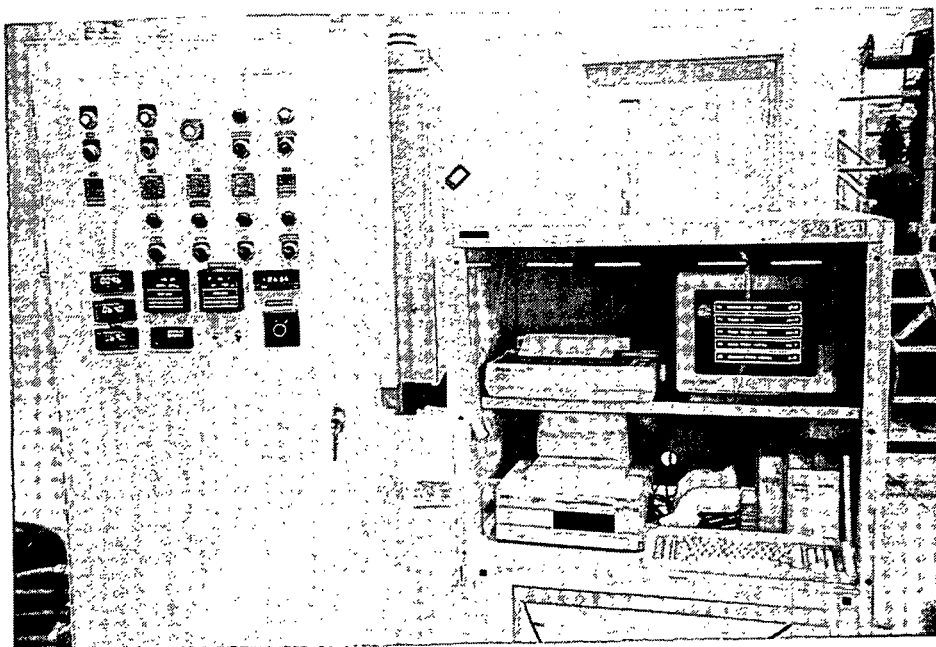


Figure 2.10 Control Panel and Data Acquisition Setup for Black Liquor Spray System.

Two controllers are used to regulate the liquor flowrate and temperature as needed. The flowmeter provides a signal to a PID controller which adjusts the flow control valve to maintain the desired flow rate. A second PID controller is used to adjust the steam to the heat exchanger to produce the correct liquor temperature.

A data acquisition system is used to record all of the measured values from the system sensors. This includes temperatures, pressures, flow rate and viscosity. The hardware is a Metra-byte system with a plug-in PC board. The software is Labtech Notebook, a menu-driven package which is easy to set up and modify. An Epson 286 IBM compatible computer is used as the basis of the data acquisition.

The program is set up to collect data slowly (each sensor is sampled every 30 seconds) until the system is operating at the desired conditions. Then, when the videocamera is recording the spray pattern, the data are collected rapidly (one sample per second), so that a good average of the sampled values can be determined for the test conditions. The data are stored in an ASCII format file which can easily be imported into a Lotus 123 file for data analysis. While the data are being collected, some of the critical values are graphed on the PC.

2.8 VIDEO SYSTEM

Images of the black liquor spray pattern are collected using a high-speed video camera developed by Xybion Electronics Systems (XES). The model ISG-250 camera has an adjustable image capture gate range (shutter speed) of 25 nanoseconds to 20 milliseconds. By using a Micro Channel Plate Intensifier and a charge coupled device (CCD) image array, the camera is able to operate at light levels down to 1 millionth foot-candle. This camera has a resolution of 768 x 493 pixels.

The rear window of the spray tank is lighted using three 1000-watt quartz lights behind a translucent Plexiglas screen. The camera is positioned in front of the tank to record the high-contrast image of the black liquor drops against a white background. A JVC Super VHS recorder is used to collect and store high-quality video images with a 525 x 400 line resolution. This unit has digital tracking to allow clear analysis of individual frames.

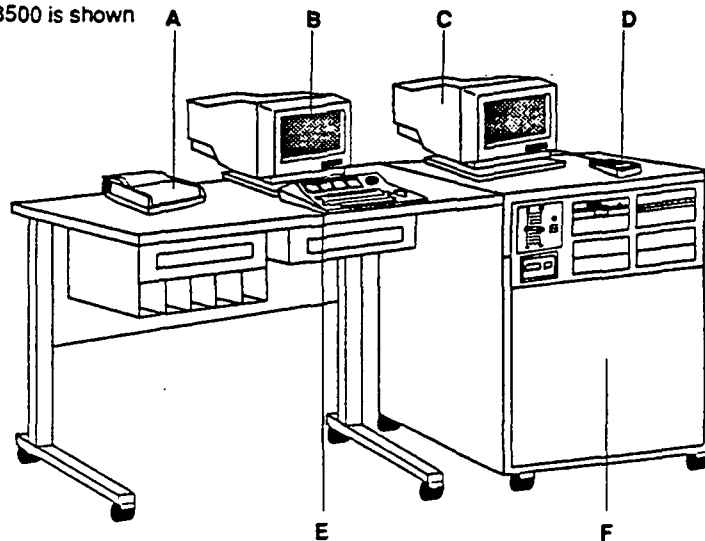
The key to the data analysis for the black liquor spray system is the image analyzer, which will automate the analysis of video images of spray patterns to determine the droplet size distribution and other important variables. The image analyzer is the TN-8500 manufactured by Tracor Northern. This system includes the main computer, image monitor, control monitor, operator's console, mouse, and printer (Figure 2.11).

System Configuration

The hardware configuration for your TN-8500 is shown here.

Components

- A - Printer (optional)
- B - Control monitor
- C - Image monitor
- D - Mouse
- E - Operator's Console
- F - Mainframe



(System shown with large table. A smaller table is also available.)

Figure 2.11 Tracor Northern Image Analyzer

The system is connected to the Super-VHS recorder allowing images to be acquired by the computer directly from the VCR. The original gray level image can be processed to improve the image and reduce the background to a more uniform gray level, and then is converted to a binary image. The binary image is then filtered to further enhance the image, and finally, the computer analyzes the image to measure the number and sizes of the drops. This data can be transferred to another computer for further statistical analysis.

2.9 VISCOSITY BLACK LIQUOR CORRELATIONS

In a study of black liquor break-up and droplet formation from spray nozzles, the most important liquor variable is the viscosity. In addition to being a function of the specific liquor, viscosity is very closely tied to the solids concentration and the temperature of the liquor. Using black liquor from the Mead Mill in Phenix City, Alabama, data collected with the Brookfield Viscometer were analyzed to determine a correlation for predicting viscosity as a function of percent solids and liquor temperature.

The solids concentration of the liquor changed rapidly during the tests, so the only useful data were those collected at the same time that a liquor sample was taken for solids analysis. Liquor samples were taken at 18 times during the two days of testing. The viscosity and the temperature of the liquor at the same time was extracted from the data acquisition file. These data are listed below in Table 2.1:

Table 2.1 - Black Liquor Viscosity Data

Sample	Viscosity			Temp K	Solids %	S%T*/T
	BL cP	H2O cP	Reduced Log(Vr)			
1	90	0.370	2.39	349	56.3	60.1
2	80	0.322	2.66	361	60.9	63.0
3	67	0.337	2.30	357	57.3	59.9
4	93	0.318	2.47	362	58.9	60.8
5	59	0.311	2.28	363	57.3	58.8
6	36	0.293	2.09	369	57.3	57.9
7	58	0.303	2.29	366	58.4	59.5
8	189	0.303	2.80	366	61.7	62.9
9	37	0.431	1.93	339	50.4	55.4
10	47	0.446	2.02	337	50.4	55.8
11	43	0.269	2.21	377	59.3	58.7
12	137	0.301	2.66	366	61.6	62.7
13	290	0.278	3.02	374	66.6	66.4
14	94	0.312	2.48	363	59.2	60.8
15	193	0.316	2.79	362	60.6	62.4
16	54	0.275	2.29	375	60.5	60.2
17	45	0.254	2.25	383	61.3	59.7
18	106	0.267	2.60	378	63.8	63.02

Viscosity Correlation

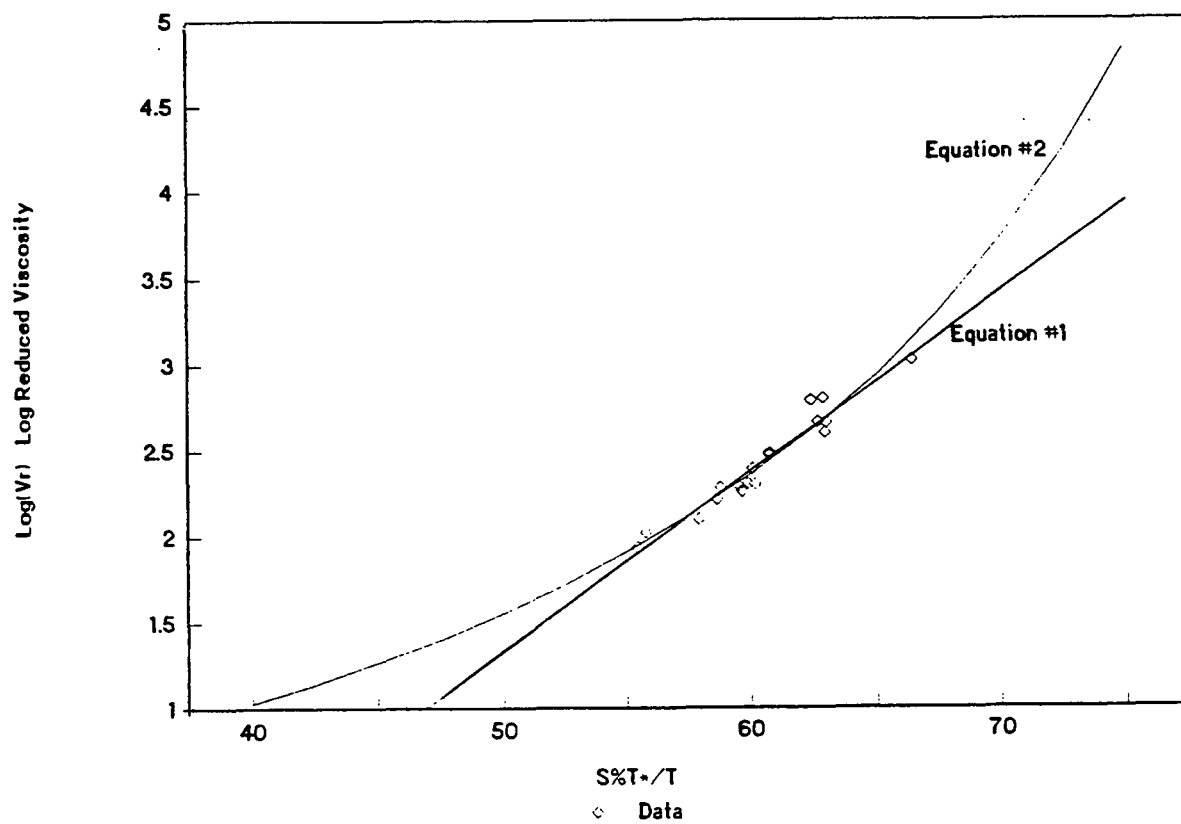


Figure 2.12 Viscosity Correlation for Black Liquor from Mead Corporation.

Two different types of correlation were tested. Both of these models are calculated based on the reduced viscosity, that is, the ratio of the black liquor viscosity to the viscosity of water at the same temperature. This type of correlation is useful for polymer solutions.

The first is a simple Arrhenius-type correlation where the logarithm of the reduced viscosity is a linear function of the % solids divided by the temperature. The R-squared value for this correlation is 0.94.

$$\text{Log } (u/u_w) = 0.1042 (S\% \times T^*/T) - 3.883 \quad (2.1)$$

where u = liquor viscosity (cP)
 u_w = water viscosity at T (cP)
 = $1000 / (36.6 \times T - 10090)$
 $S\%$ = solids percent (%)
 T = liquor temperature (K)
 T^* = reference temperature = 373 (K)

The second correlation uses the inverse of both the $\text{Log } (u/u_w)$ and the $(S\% \times T^*/T)$ values, as shown below. The R-squared value of 0.95 is only slightly better than the previous equation.

$$\text{Log } (u/u_w) = 1 / (65.62T / (S\% \times T^*) - 0.6682) \quad (2.2)$$

These two correlations are plotted below as a function of $(S\% \times T^*/T)$, along with the experimental data (Figure 2.12). For the range of data measured there is no significant difference between these two models (as expected from the equivalent R-squared values). However, for values of $(S\% \times T^*/T)$ above and below this range, there is a large variation in the predicted value. Based on other published black liquor viscosity data (2), the second correlation will be much more accurate at high and low viscosities.

In addition to providing good viscosity data, these correlations will be useful for operation of the spray system. The current analytical method for solids requires 24 hours to complete. The correlation will allow the on-line calculation of the solids concentration from the liquor temperature and viscosity, which are continuously monitored.

3.0 SPRAY IMAGE ANALYSIS

3.1 INTRODUCTION

The raw data obtained in the black liquor spray experiments are photographic, flash x-ray, or video images. These images are two-dimensional representations of the three-dimensional objects in the spray: droplets, ligaments or strands, and liquid sheets. In most circumstances the images consist of dark objects against a lighter background. Image analysis is used to determine the size and shape of each object in the image.

Droplet size information obtained from the basic images will always be affected by uncertainties resulting from object overlap and three-dimensional object geometry. As well, because high aspect ratio strands always break up, assumptions about the ultimate distribution of droplet sizes must be made. Overshadowing these concerns is the technical challenge of obtaining good, clear, two-dimensional representations of the spray from the raw images, and that is the subject of this chapter.

Presented below are some of the techniques developed at the Institute for analyzing black liquor spray images. The field of image analysis is broad and well developed. The material presented below represents a narrow slice of this field, specific to the task at hand. Though much of the material will be of general use for spray image analysis, some of it is necessarily specific to the video camera, video recording equipment, flash x-ray system, and image analyzer used at the Institute. The camera is a Xybion Corporation model ISG-250 high-speed video camera operating at 30 frames per second. The exposure time per frame, or gating duration, can be varied from 25 ns to 20 ms. The flash x-ray system used at the Institute has been described previously [3,4]. It produces shadowgraphs of a spray using a 70 ns x-ray flash. The image analyzer is a Tracor Northern Corporation model TN-8502.

Four subjects are discussed in this chapter. In the first section, the wide range of image quality problems encountered in spray image analysis is demonstrated. Next, the rudiments of image math and filters are presented. The third section, techniques for obtaining good representations from still images such as flash x-ray shadowgraphs are discussed. Finally, similar techniques are presented for processing video images.

3.2 IMAGE QUALITY PROBLEMS

In this section image quality problems and defects will be discussed for both still and video images. Methods for obtaining these images and for improving their quality during acquisition will be discussed in later sections.

3.2.1. STILL IMAGES

Two typical spray images taken by the flash x-ray technique are shown in Figures 3.1 and 3.2. To clarify the origin of these two figures, the basic layout and steps for producing the figures will be described briefly.

To obtain the raw data images for the two figures, the flash x-ray system was set up on one side of a black liquor spray. The x-ray path was through and perpendicular to the flat spray sheet. An 8 1/2 x 11 in. Kodak DEF x-ray film was positioned on the other side of the spray. An x-ray flash was triggered which briefly exposed the spray and film to the x-ray source. In areas where there was no black liquor in the path of the x-rays, the film was exposed more than in areas where liquor absorbed some of the x-ray energy. This produced a shadowgraph negative image on the x-ray film. The negative was processed by normal photographic techniques to produce a positive print. The print was then placed on a light table in the field of view of an ordinary video camera which serves as the electronic input device for the Tracor Northern image analyzer. The CRT screen of the image analyzer was then photographed to produce the prints used in preparing this report.

The two images in Figures 3.1 and 3.2 are typical of the images obtained with the flash x-ray technique. Careful inspection of the figures will reveal the most common defect in such images;--variation in the gray level of the background.

A human observer is able to identify all the droplets in these figures. Though tedious, it would be possible to draw an outline and fill in each droplet so that it appears as a "black" object on a "white" background. This is the important task of making a "binary" or two-intensity-level image from the original gray scale image. All subsequent size analysis depends on first having a binary which correctly represents the size and shape of the objects in the gray-level image.

A simplistic approach to making a binary is to assign all parts of the image which are darker than a specified value to the category of black objects. All other parts lighter than the specified value are assigned to the background.



Figure 3.1-Screen Image of a Flash X-ray Spray Shadowgraph
Displayed on the Tracor Northern Image Analyzer.



Figure 3.2-Screen Image of a Second Flash X-ray Spray Shadowgraph
Displayed on the Tracor Northern Image Analyzer.

Unfortunately, this simplistic approach to making a binary from a gray image rarely yields an accurate depiction of the spray. The background intensity varies so that some of the smaller droplets in the lighter background areas are lighter than the background in the darker areas. This is demonstrated in Figures 3.3 and 3.4 where two different binary cuts have been specified for the image shown in Figure 3.2. Neither is a very good representation of the original gray-level image, and, in fact, no simple binary cut would be acceptable.

Figure 3.5 demonstrates more clearly why the simple binary cut doesn't work. Shown in Figure 3.5 is a histogram of the gray-level intensities along a line running diagonally downward from left to right on the original image shown in Figure 3.2. The gray-level intensity at each point or pixel along the line is shown in the histogram. The background is lighter and, therefore, higher in the histogram. The droplets are darker than the background and show up as narrow valleys in the histogram. It can be seen in Figure 3.5 that the variation in the background is substantial. It should also be noted that the minimum of some of the valleys is above, or lighter than, some of the darker background regions. As is, a simple binary cut would never work on this image. Most of the effort in image analysis of the spray images is directed at removing the background variation.

Background variation is not the only quality problem with these images. Figure 3.5 also shows a fairly high level of background noise, i.e., random fluctuations in background intensity over a relatively short length scale. This is referred to as high-frequency noise, whereas the background variation discussed above is low-frequency noise. In general, the variation in gray level associated when the objects of interest in these images corresponds to frequencies between the two extremes of noise. Most techniques for enhancing the raw gray-level images exploit this difference in frequency between the objects and the noise.

Typically, image analyzers suitable for spray image analysis work with 256 levels of gray. Initially, this would appear to lend itself to relatively easy separation between the objects and the background. However, Figure 3.5 shows that the actual difference between clearly identifiable objects and the background can be quite small. To put this on a scale independent of the number of gray levels available, let the range be 0% for black to 100% for white. On this basis some of the smaller objects are only 2% different from the background. Image acquisition and subsequent processing all affect the absolute and relative gray levels for both the objects and the background. Only rarely will the objects and background be well separated in gray level.



Figure 3.3-One Binary Cut of the Image in Figure 3.1.



Figure 3.4-Second Binary Cut of the Image in Figure 3.1.

Part of the problem with a small gray-level difference is that the objects don't have well-defined edges. The objects are usually darkest near their centers with their gray level tapering off to the background value at their edges. There are several reasons for this. With the flash x-ray technique, the amount of x-ray energy absorbed is proportional to the thickness of the droplet. The edges of the droplets are necessarily thinner and therefore produce exposures on the film less different from the background than the thicker centers. For photographs or video images, poor focus and limited depth-of-field also produce droplets with fuzzy edges.

The problem with poorly defined edges is that even a relatively clean binary cut can produce images with black objects smaller than the original gray-level objects. A binary cut just darker than the background gives the most representative image, but may also pick up minor variations in the background as objects. A binary cut significantly darker than the background avoids the extraneous background fluctuations but cuts the object part way down the valley. As a result, the object size is smaller than the original object. This is demonstrated in one dimension in Figure 3.6.

Finally, defects in the film, the developing process, or subsequent improper handling can produce spots and scratches in the final image. Examples of these can be seen in Figure 3.2. Because they are much lighter than either the background or the objects, they are easy to spot and identify with the image analyzer. However, they complicate manipulation of the image gray levels because they bias any averaging technique and often appear to cut droplets in half.

3.2.2 Video Images

To digitize and store the still image in the image analyzer, an ordinary video camera connected to the analyzer is focused on the still image. Either a black-lighted negative or a front-lighted print may be used. Because these usually have solid reflective surfaces, extraneous signals may enter the video camera. As well, the lights themselves, if incandescent, can produce a bright spot in the image.

Video cameras are sensitive to a range of wavelengths of light, which can include some wavelengths in the near infrared. The lens used with these cameras focuses the various wavelengths at different focal points. Most of the wavelengths in the visible spectrum are focused relatively close together, but the infrared wavelengths are not focused at the same location. Incandescent lighting produces significant intensity in the near infrared. In combination with a video camera with near infrared sensitivity, this produces a bright spot in the image. A bright spot would be

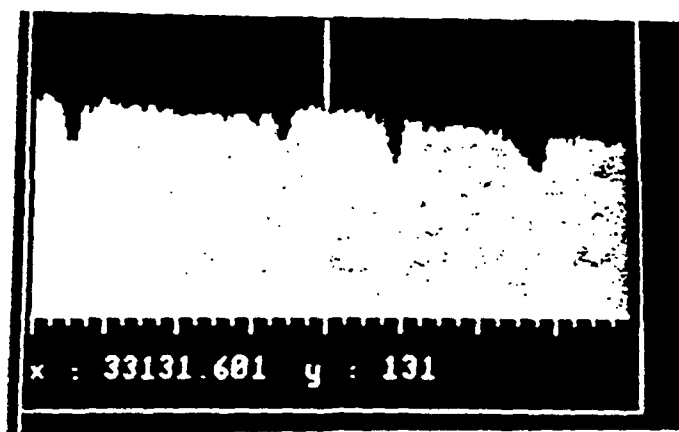
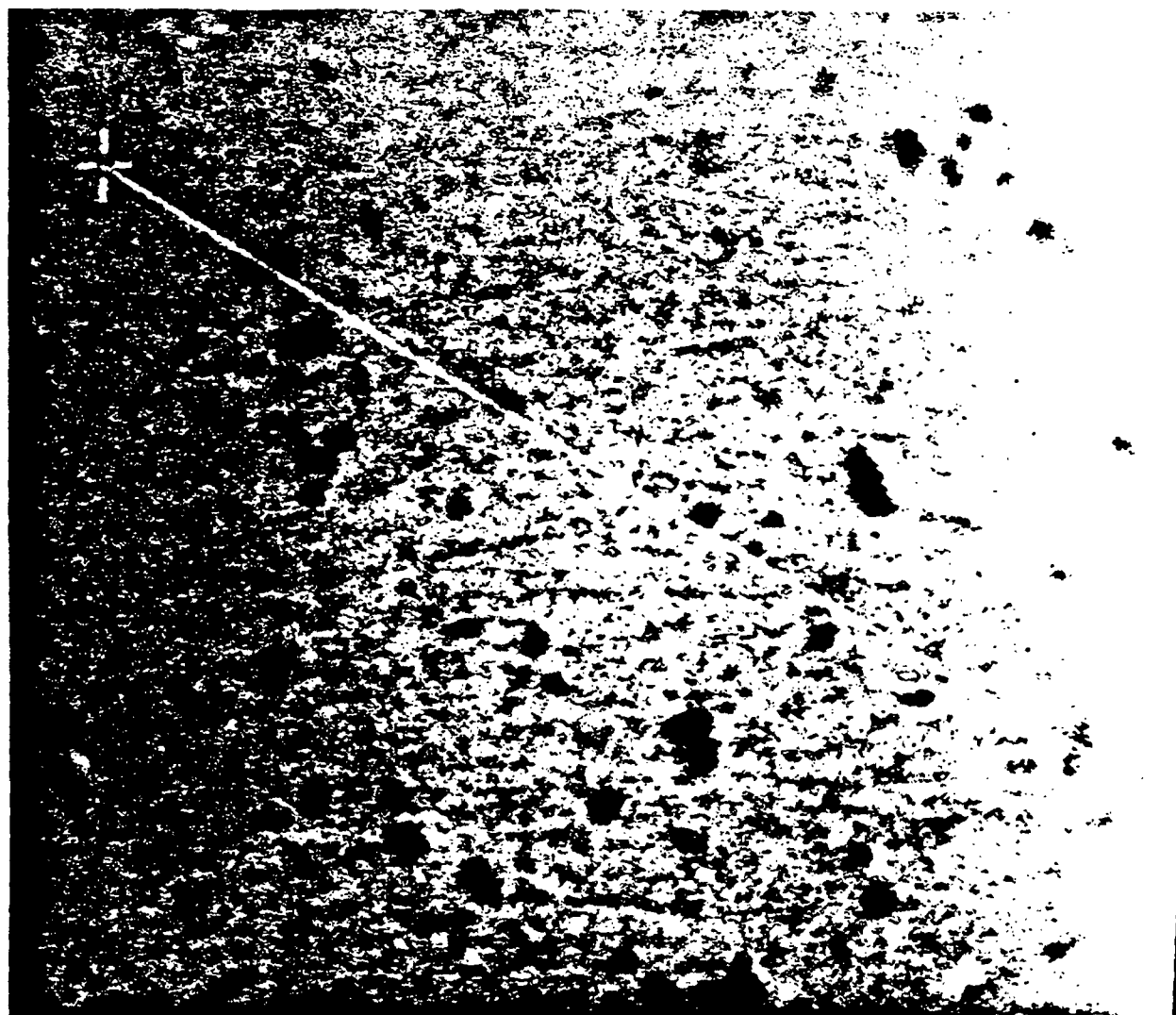


Figure 3.5-Image in Figure 3.2 along with a Histogram of the Gray Level Intensities along the Line Shown on the Image.

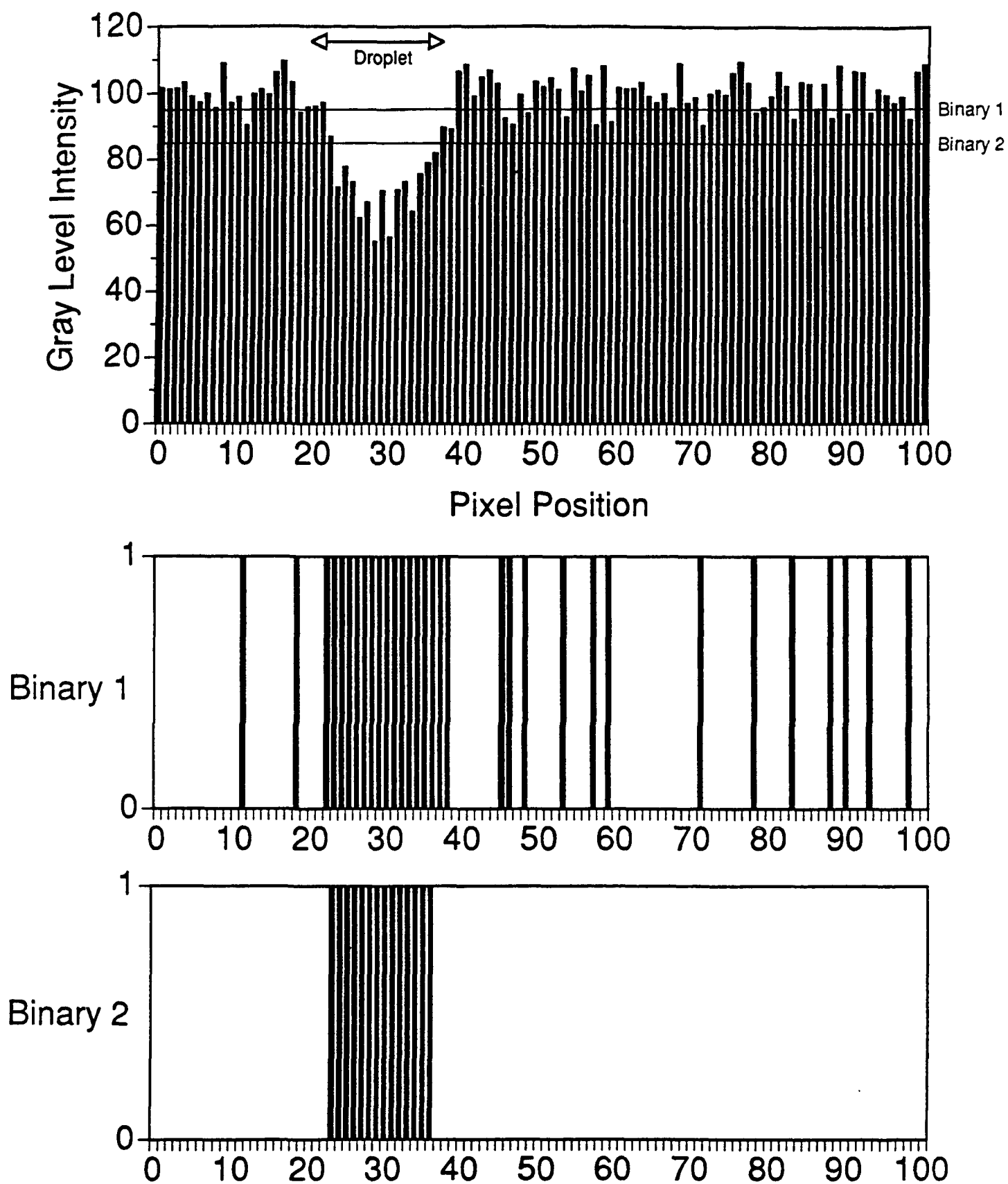


Figure 3.6-Histogram of a Droplet in a Noisy Background along with Two Binary Cuts.

a difficult background variation to remove in subsequent analysis. Fortunately, this problem can be eliminated at the source by using either an IR filter on the lens or by using fluorescent lighting.

Extraneous dark spots can also diminish the video image quality. These spots can be due to dust, grit, and blemishes on the vidicon or other video tube, the camera lenses, or on any windows ahead of or behind the spray. These spots are more difficult to detect because they are very similar in appearance to the spray droplets. Figure 3.7 shows a video image from a spray booth. Figure 3.8 shows an image without the spray. Smudges, spots, and background non-uniformity are apparent in this image.

An image of the area of interest without the spray present, but still containing the smudges, spots, and lighting non-uniformities is called a background image. There are two easy methods for obtaining a background image with the high-speed video camera. Recording the scene with the spray turned off is the most straightforward method. Alternatively, after the spray has been recorded, the image analyzer can be used to average any number of video frames. Averaging approximately 100 video frames removes the droplets because they don't frequently occur in the same location. The stationary spots and smudges are always present, so averaging many frames leaves them unchanged. At 30 frames per second, 100 frames can be acquired in about 3 seconds, so little change occurs in the stationary background elements.

Having a background image available allows the original image to be improved greatly. The background can be subtracted from the original to produce an image of just the spray. This is shown in Figure 3.9. It is obvious that cleaning the camera, lens, and windows is an effective way of improving image quality, but this is not always possible.

3.3 IMAGE MATH AND FILTERS

Image math consists of changing the gray-level of individual pixels in the image. The simplest use of image math is in subtracting the background from the original image as was done with Figures 3.7 and 3.8 to produce Figure 3.9. The gray-level intensity of each pixel in the background image is subtracted from the gray-level intensity of the corresponding pixel in the original. There are two important features here: (1) gray-level intensities are manipulated with simple math functions, and (2) the math is applied to each individual pixel, one at a time.

It is important to focus down at the individual pixel level to understand some of the complicating factors of image analysis, particularly for the high-frequency noise. The background in



Figure 3.7-Image Taken with the High-Speed Video Camera
Displayed on the Screen of the Image Analyzer.



**Figure 3.8-Image Taken with the High-Speed Video Camera
without the Spray.**

any small area of Figure 3.2 appears uniformly gray to the eye. A blow up of a small area of Figure 3.2 is shown in Figure 3.10. The pixel-to-pixel variation is now more obvious. The small darker object near the center is a droplet. The noise in this area makes some of the background pixels darker than some of the droplet pixels. It would be difficult to choose a binary cut here that would produce an accurate representation of even this small section of an image.

Filters allow the values of gray intensities of surrounding pixels to modify the value of a central pixel. Both one-dimensional and two-dimensional filters can be used. One-dimensional filters consist of a length of pixels one pixel wide, while two-dimensional filters have both length and width. A simple filter that could be applied to a 3 x 3 group of pixels would multiply the gray-level intensity of each pixel by one-ninth and place the sum in the central pixel. This is a two-dimensional averaging filter. Both the size of the filter (i.e., the number of pixels used) and the type of filter can vary. Many filters are available, including several averaging and several edge enhancement filters.

One key feature of the spray images is that the droplets only occupy a relatively small portion of the image. Considerably more than 50% of the image is background. Our eyes easily detect the individual droplets, even very faint ones, for two reasons: (1) the droplets are always in the context of their local background, and (2) our eyes average the gray level intensities of both the background and the droplet. The two types of noise which complicate image analysis are high frequency noise and low frequency background variation; our eyes neatly take care of both. This suggests that averaging filters, properly selected, should help produce good binary images for subsequent size analysis.

Several averaging methods are available. Simple averaging was described above. Two additional averaging filters that have proven useful are Gauss filters and Median filters. A Gauss filter uses a block of pixels surrounding a central pixel, but instead of weighing each gray-level intensity equally, it increases the weight of pixels close to the center and decreases the weight of those away from it. A diagram of the transfer functions for a one-dimensional simple average filter and a Gauss filter are shown in Figure 3.11.

In Figure 3.12 are two gray-level intensity histograms. The first is the original histogram showing both significant background noise and a droplet near the left side. The second shows the result of applying an average filter. Both the simple average filter and the Gauss filter work well to suppress background noise. They both affect the shape of the droplet in approximately the same way. Because the Gauss filter emphasizes the central pixels, it changes the droplet



Figure 3.10-Blown-up View of a Portion of Figure 3.2.

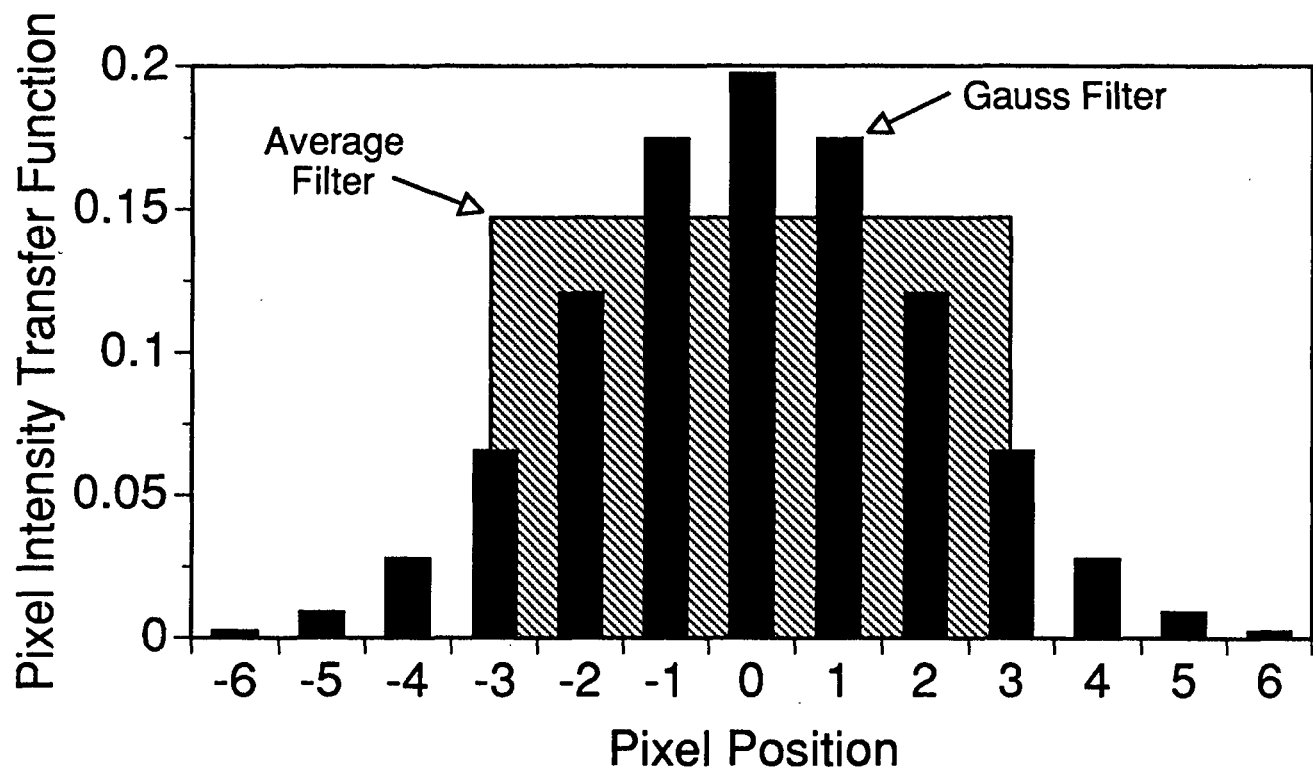


Figure 3.11-Transfer Function for a Gauss Filter and an Average Filter.

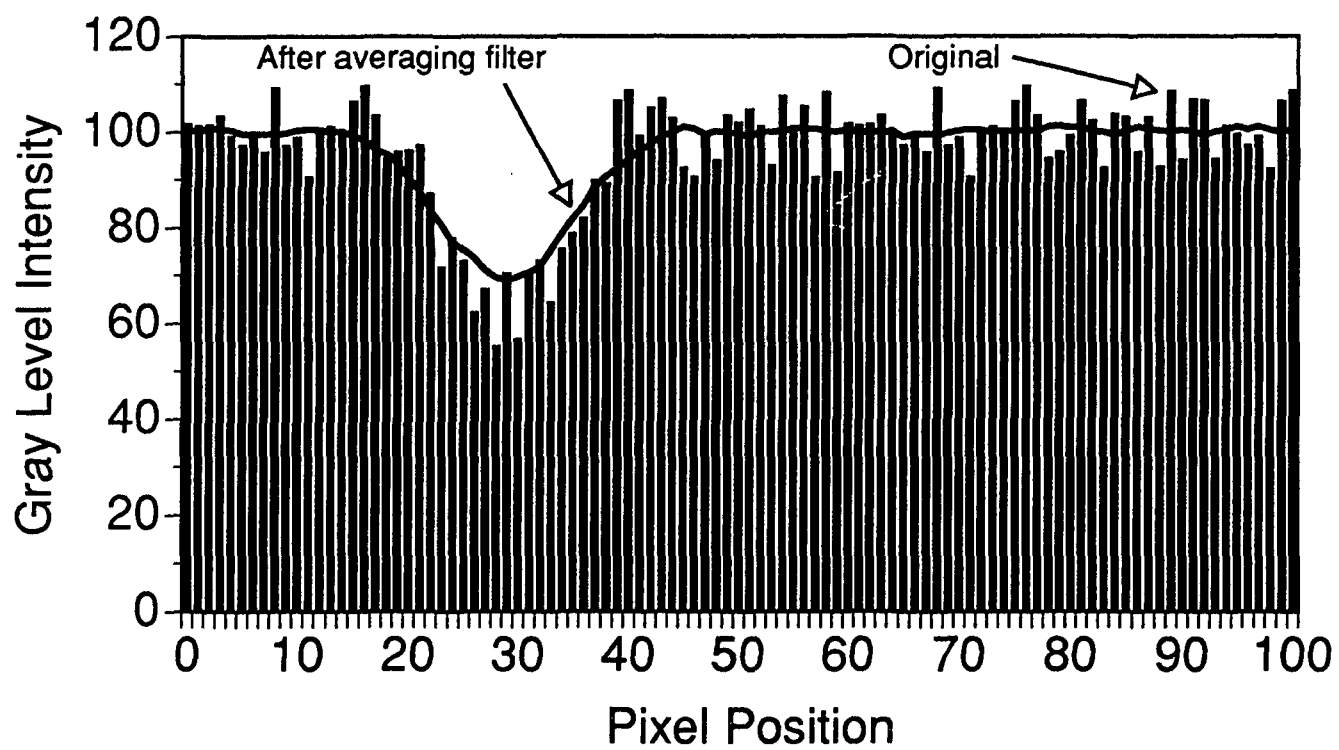


Figure 3.12-Effect of the Averaging Filter on the noisy Gray-Level Histogram.

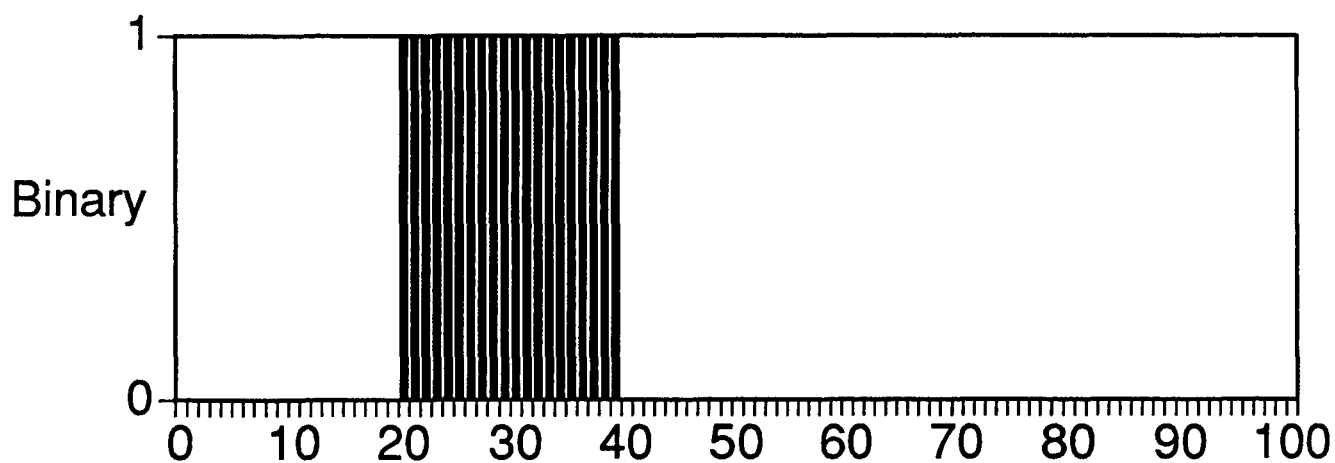
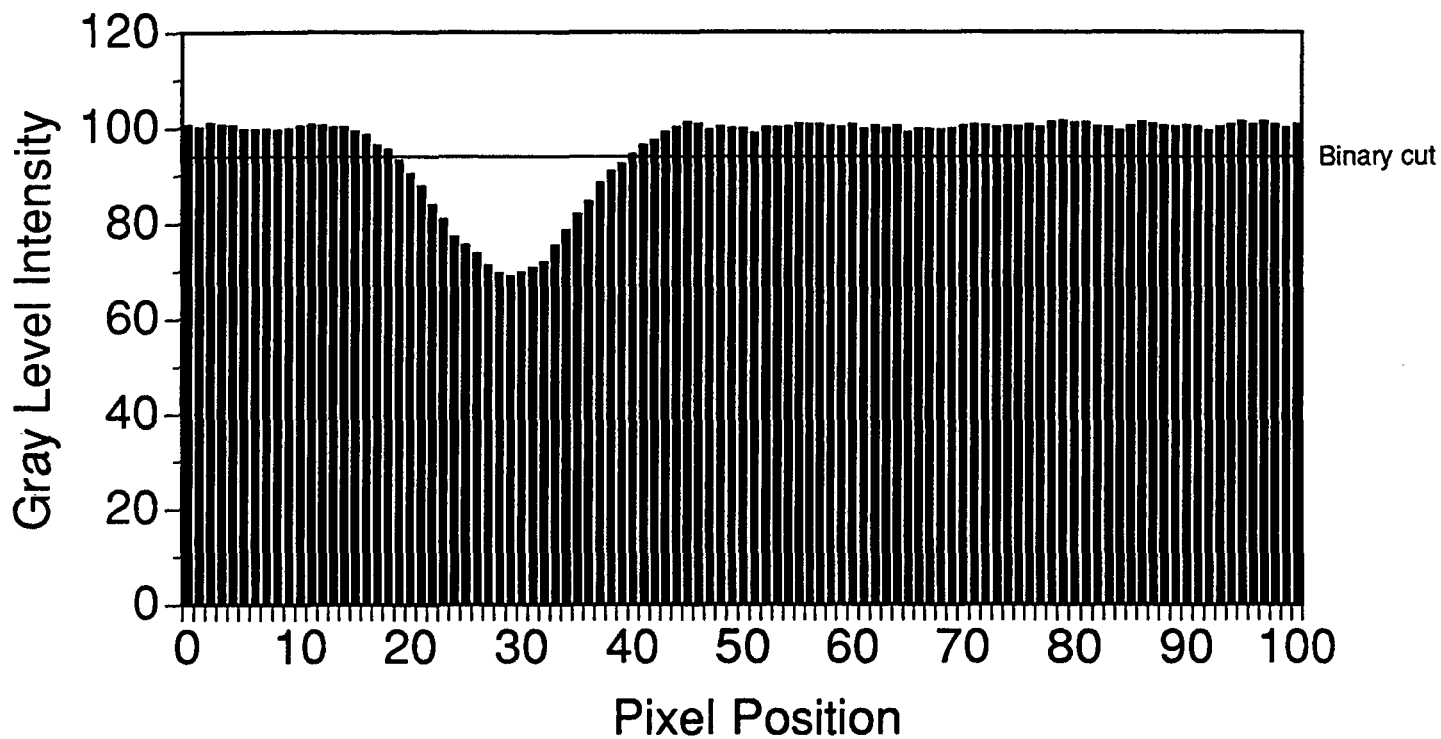


Figure 3.13-Binary of the Intensity Histogram after the Average Filter Has Been Applied.

shape slightly less than the average filter. However, the Gauss filter has the disadvantage of being larger than the simple average filter for the same level of noise suppression. The two filters shown in Figure 3.11 perform approximately the same, but the Gauss filter involves twice as many pixels (four times as many for a 2-D filter). The Gauss filter is based on the normal curve and so is specified in terms of a standard deviation. The total length of a simple average filter with the equivalent noise suppression is approximately 3.5 times the Gauss filter standard deviation.

The purpose of applying these filters is to allow an accurate binary image to be obtained. Figure 3.6 showed two binary cuts of one original histogram. Horizontal lines on the original show the two binary cut levels. Everything above the lines becomes "white," or 1, and everything below the lines becomes "black," or 0. The binary cut at the highest gray level in Figure 3.6 gives the best representation of the droplet size but adds many additional fictitious "droplets" due to noise. The binary from the lowest gray level eliminates the extraneous drops, but doesn't correctly represent the real droplet. Improvement in this situation is obtained by using an average or a Gauss filter as shown in Figure 3.13. Only one binary cut is shown, but the significantly better representation of the droplet and elimination of most of the fictitious "droplets" is obvious.

Selecting the filter size is important. A very small filter would not provide sufficient smoothing of the noise. A very large filter works better to eliminate the noise, but if it is much larger than the droplet, the droplet will also be eliminated. In general, the filter size should be no larger than the dimension of the smallest feature of interest.

A common method for dealing with the low-frequency noise on the variation in the background of a still image again involves the use of averaging-type filters. The background occupies most of the field of view for spray images. Taking the average gray-level intensity of a large region of an image produces a value which is near, but slightly below, the background level of the central pixel. It is below because the droplets are included in the average and they are necessarily darker than the background. Most spray images have smoothly varying backgrounds as long as the region considered is not too large. The largest diameters of the droplets are ten times the size of the smallest and occupy one hundred times the area. To ensure that region includes mainly background pixels, the region must be two or three times larger than the largest droplet. Thus, using the simple approach of averaging to obtain a background will not portray the smallest droplets within the context of their local background. An approach to analyze each droplet within the context of its local background has been developed which relies on multiple application of median filters.

The size of the region to be analyzed must be large when using an average filter because the droplets affect the average. A Gauss filter would be worse in this situation because it emphasizes the gray-level intensity of the central pixels of the filter region. A median filter has been found to be better for finding the local background. The median value of a region is the gray-level intensity for which half of the pixels in the region have a higher value and half have a lower value. As long as more than 50% of the region in the filter area is background, then the median value will be from the background. The median would be at the low end of the background gray levels if the background occupies only just more than 50%. However, this is a significant improvement over the average filter. A comparison of an average filter and a median filter is shown in Figures 3.14 and 3.15. In Figure 3.14 an original gray-level intensity line histogram is shown, along with the results of applying an averaging filter and a median filter of the same size. In Figure 3.15 the original droplet profile is compared to the profile obtained by subtracting the background obtained from the average and median filter. The median filter produces a better background, particularly in the region surrounding the droplet. This is always the case.

The more difficult case involves a region with both large and small droplets. The "background" obtained with a small median filter is not accurate for the large droplet and vice-versa. However, if a background from a small median is subtracted from the original, a binary can be made which correctly shows the small droplets. The same procedure with a large median yields a good binary for large droplets. These binaries can then be added to produce a binary containing droplets of all sizes. A very acceptable portrayal of the size of the original droplets is thus achieved. This approach seems to be very effective for most spray images where background variation cannot be eliminated in any other way.

The actual math step in "subtracting the background" is to subtract the original from the background to produce a negative droplet image. This technique also helps eliminate most of the defects due to white spots and scratches. These defects are relatively small compared to the region size to which the median filter is applied. As a result, the median value is only very slightly affected by these defects. When the original is subtracted from the background obtained from the median filter, the white defects would mathematically produce negative gray-level intensities. These negative values are automatically set to zero, thus eliminating these defects. This same restriction of only non-negative gray-level intensities also results in the elimination of about half of the high-frequency noise when the original is subtracted from the background.

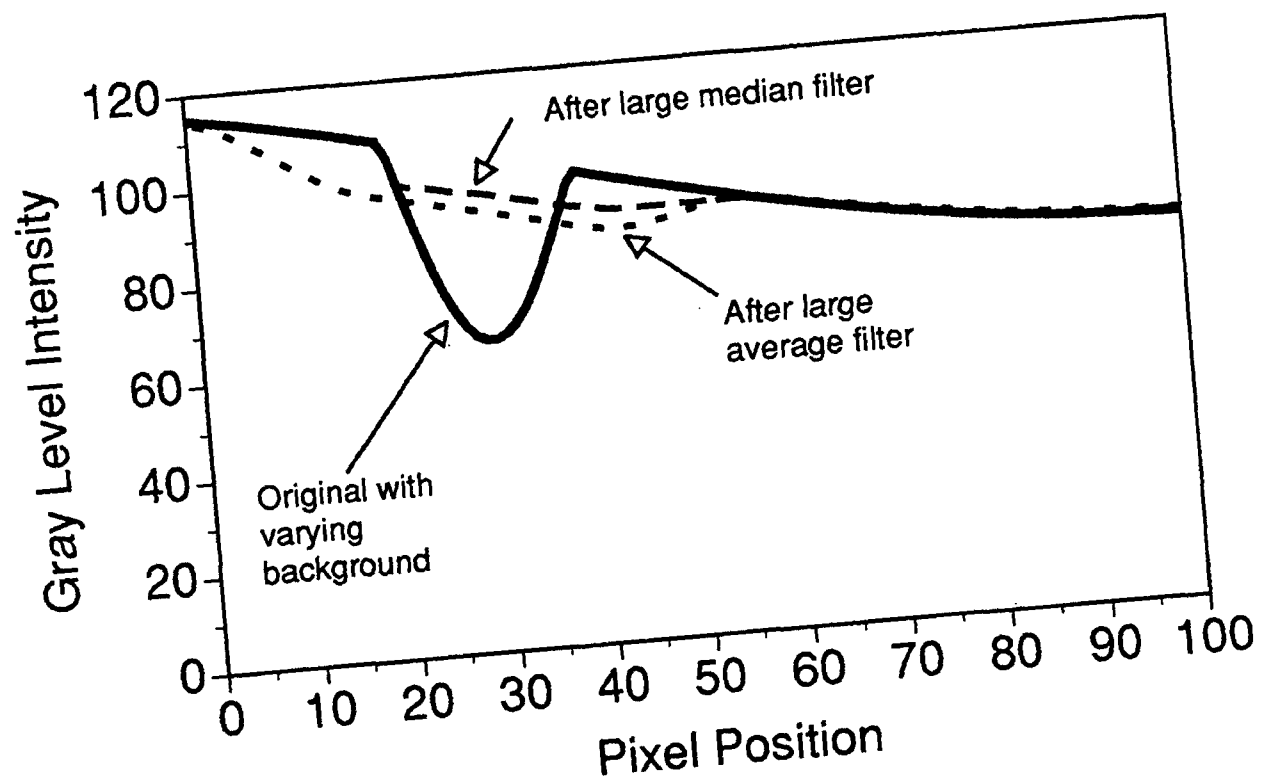


Figure 3.14-Effect of an Average Filter and a Median Filter on a Histogram with Varying Background.

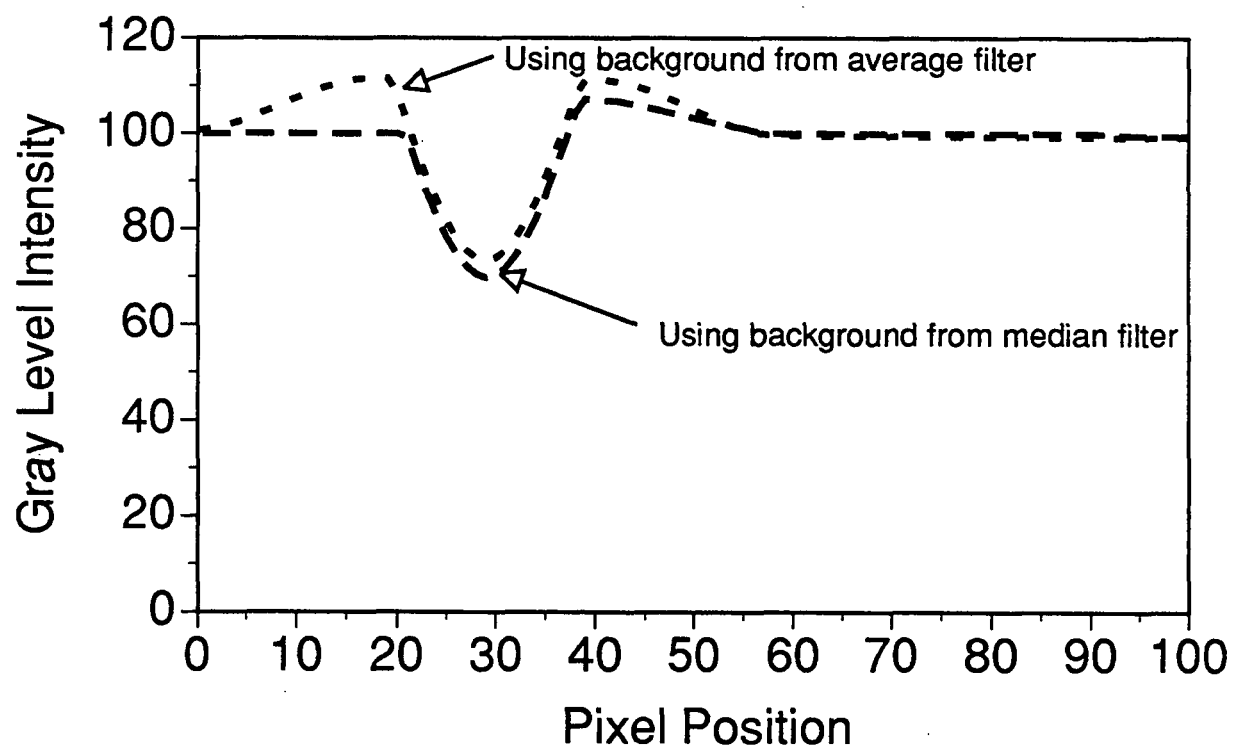


Figure 3.15-Droplet Profile after the Background Based on an Average Filter and a Median Filter Has Been Subtracted.

A complete sequence for producing a binary image of the gray-level image in Figure 3.2 is shown in Figures 3.16 through 3.23. Figure 3.16 shows the image after a 7x7 average filter has been applied. Figure 3.17 shows the image after a 16x16 median is applied. Figure 18 shows the difference between Figure 3.16 and 3.17, and Figure 3.19 is the binary from Figure 3.18. Figures 3.20 through 3.22 show the same sequence for a 64x64 median filter. Figure 3.23 shows the final binary image which is the sum of Figures 3.19 and 3.22.

3.4 HIGH-SPEED VIDEO IMAGES

The techniques for obtaining a background image and for improving the video stills were discussed above. This section discusses the steps which can be taken to improve the video image quality during acquisition. To fully understand the effect of lens and video camera settings on image quality, it is necessary to describe the signal path from the spray to the final gray level image. A schematic of this is shown in Figure 3.24. Light from the light source passes through the spray. It is focused on the face of the video tube by the camera lens. The video tube converts the incoming light intensity signal to an electronic video output signal. This signal is stored on a super VHS video recorder. This electronic signal is converted to a digital gray-level image by the image analyzer and, during playback, displayed on the output screen.

Along this flow path the absolute and relative levels of the signal for the droplets and the background can be changed in a number of ways. The light source, the droplet size and opacity, the lens focus, and the lens aperture all affect the light intensity reaching the video tube face. Brighter background lighting and lower f/numbers (i.e., more open aperture) will result in higher levels of light intensity on the video tube face. More opaque droplets will increase the difference in light intensity between the background and the droplets. For this reason, black liquor is a better test fluid for spray characterization than water, glycerol, or corn syrup because it is more opaque.

In addition, two adjustments of the video camera and its electronics can affect the conversion of this incoming light intensity signal to an electronic signal, the gating rate and the gain. The high-speed camera uses gating to effectively limit the duration of the incoming light signal. Gating performs the same function as the shutter in an ordinary camera. The longer the gate is open, the greater the light intensity signal received by the video tube during each exposure. The video tube and its electronics convert the light intensity signal to an electronic signal. The gain setting of the camera is usually selected so that the light

signal is converted to an electronic signal within the normal range of video outputs. Higher gain settings must be used either when the light source brightness is low or the gating duration is short. Automatic gain is often used with ordinary video cameras in order to produce good screen images with either bright or dark scenes. The image analyzer can also accomplish this function of producing an acceptable viewing image from a weak signal. With the image analyzer this is accomplished by multiplying the gray levels of a dark image by an appropriate factor.

Thus, there are three areas where the absolute and relative values of the ultimate gray-level image can be manipulated: where it is a light intensity signal, where it is an gray-level signal, and where it is an electronic signal. The first two areas are better than the third.

The camera gating duration must be short enough to avoid motion blur of the spray image. The proper gating duration can be calculated from the droplet size and velocity. Longer gating times result in more light to the video tube but poorer overall image quality due to motion blur.

Under most circumstances the camera gain can be adjusted to produce an acceptable screen image of a spray. However, the high frequency noise signal of an analog circuit increases with the gain. This increased noise produces a "grainy" screen image which complicates image analysis. In addition, high electronic noise levels and grainy images can also complicate the adjustment of focus of the camera on the spray image. The need to use higher camera gain can be avoided by increasing the incoming light intensity. This can be done by increasing the brightness of the light source, by decreasing the attenuation of the light due to intervening windows, and by increasing the aperture opening (i.e., using lower f/numbers).

Amplification of a weak signal can be accomplished, within reason, by the image analyzer. Multiplication of the digital gray-level image amplifies the "signal" without disproportionately amplifying the noise. In general, the electronic gain of the camera should be adjusted to its lowest setting as long as the output video signal from the camera is at least 10% of its usual maximum level. The actual gray level of the acquired image can be used to judge this.

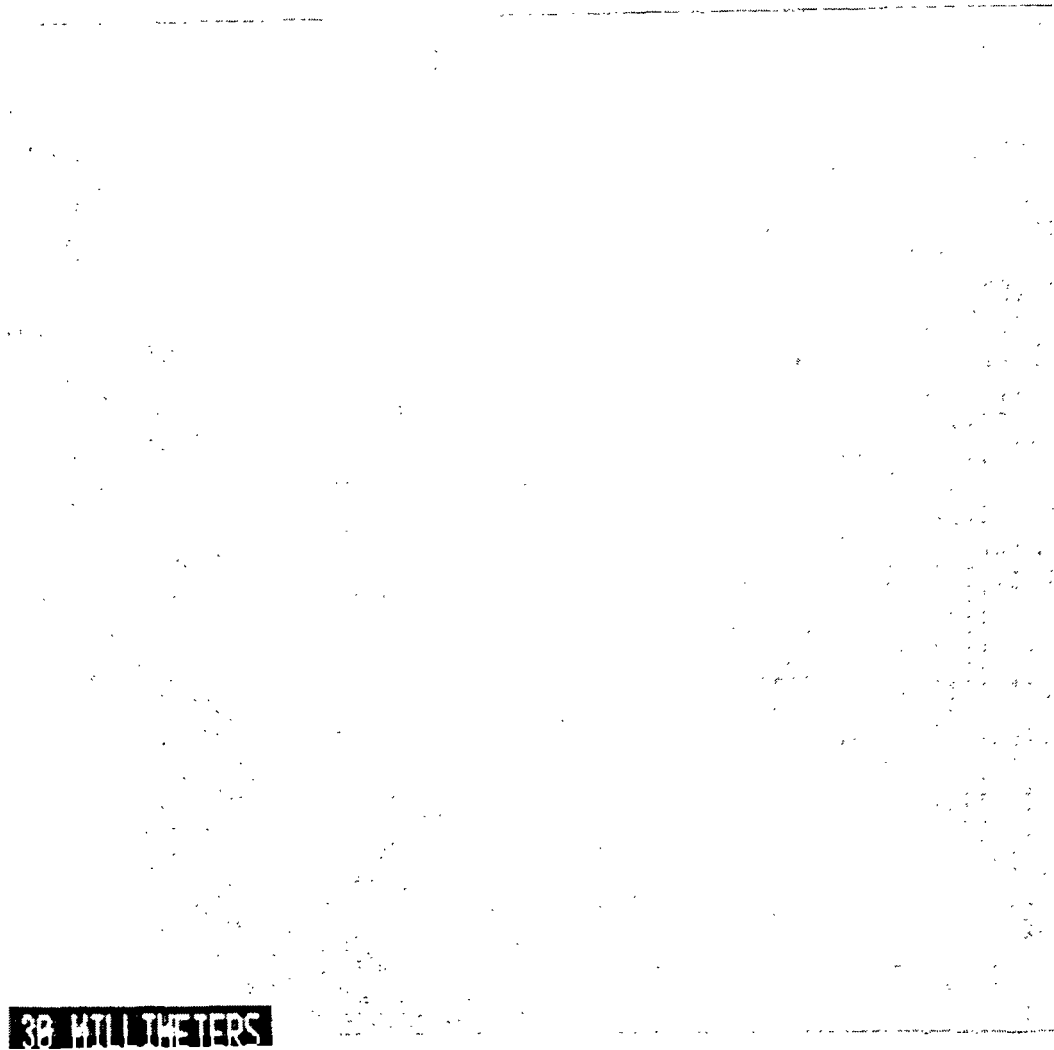


Figure 3.16-Image in Figure 3.2 after a 7x7 Average Filter Has Been Applied.

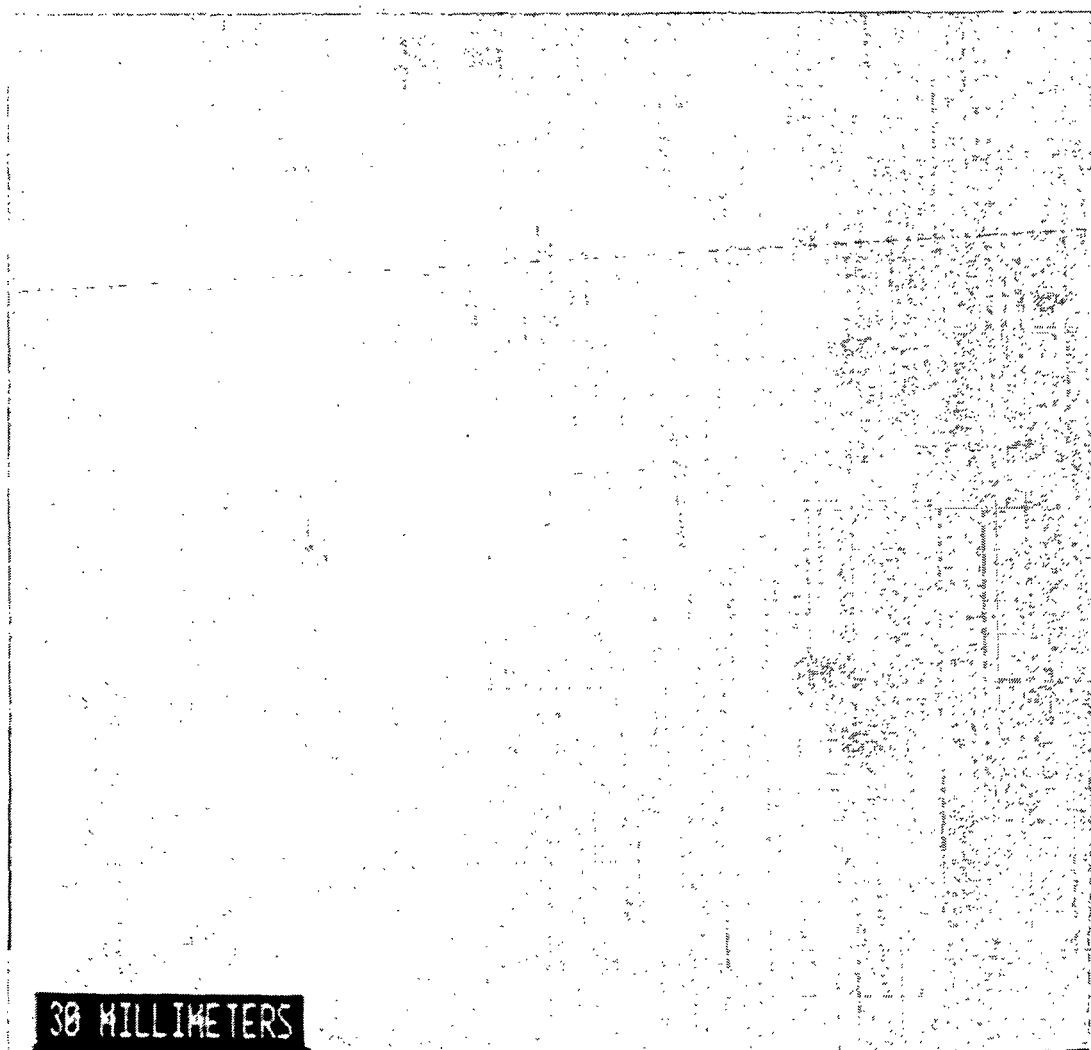


Figure 3.17-Image in Figure 3.16 after a 16x16 Median Filter Has Been Applied.

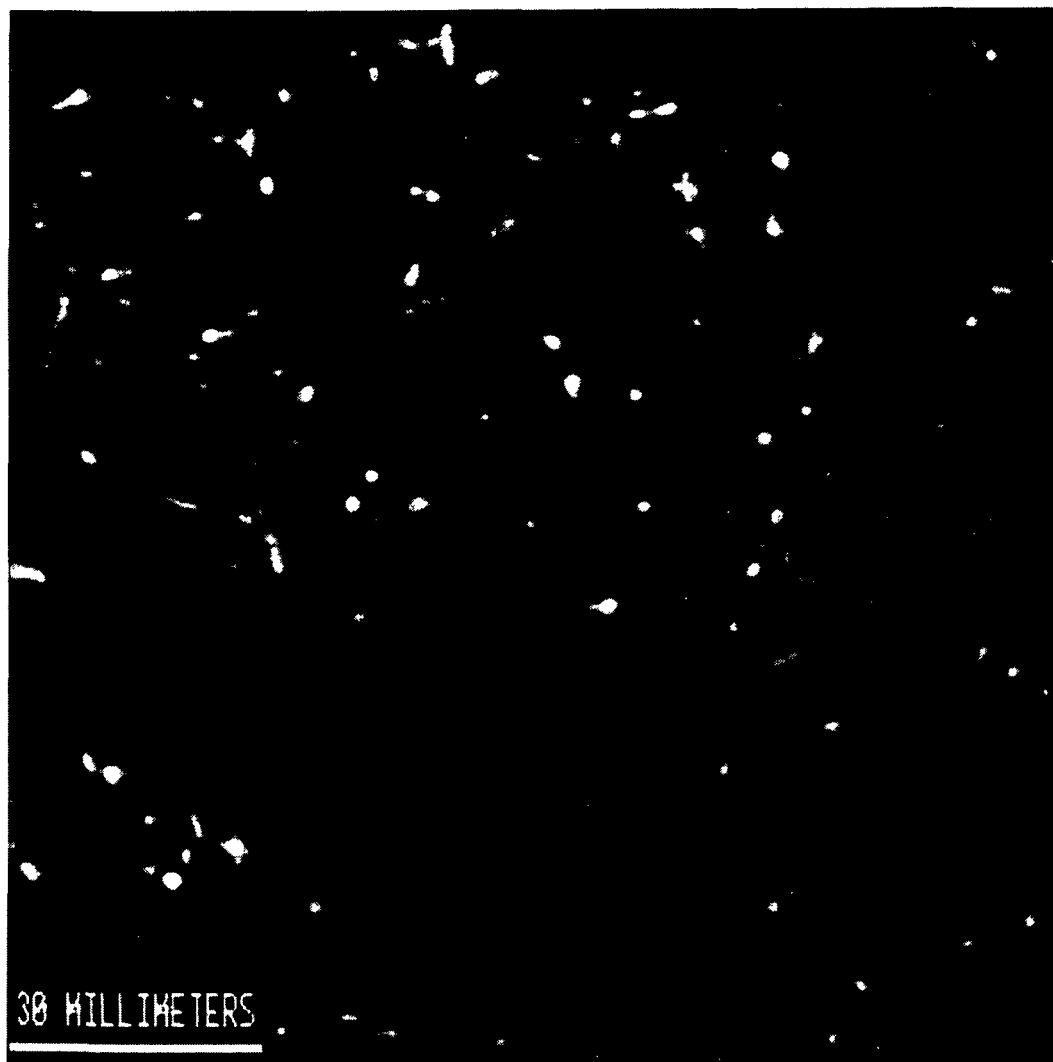


Figure 3.18-Result of Subtracting the Image in Figure 3.16 From That in Figure 3.17.

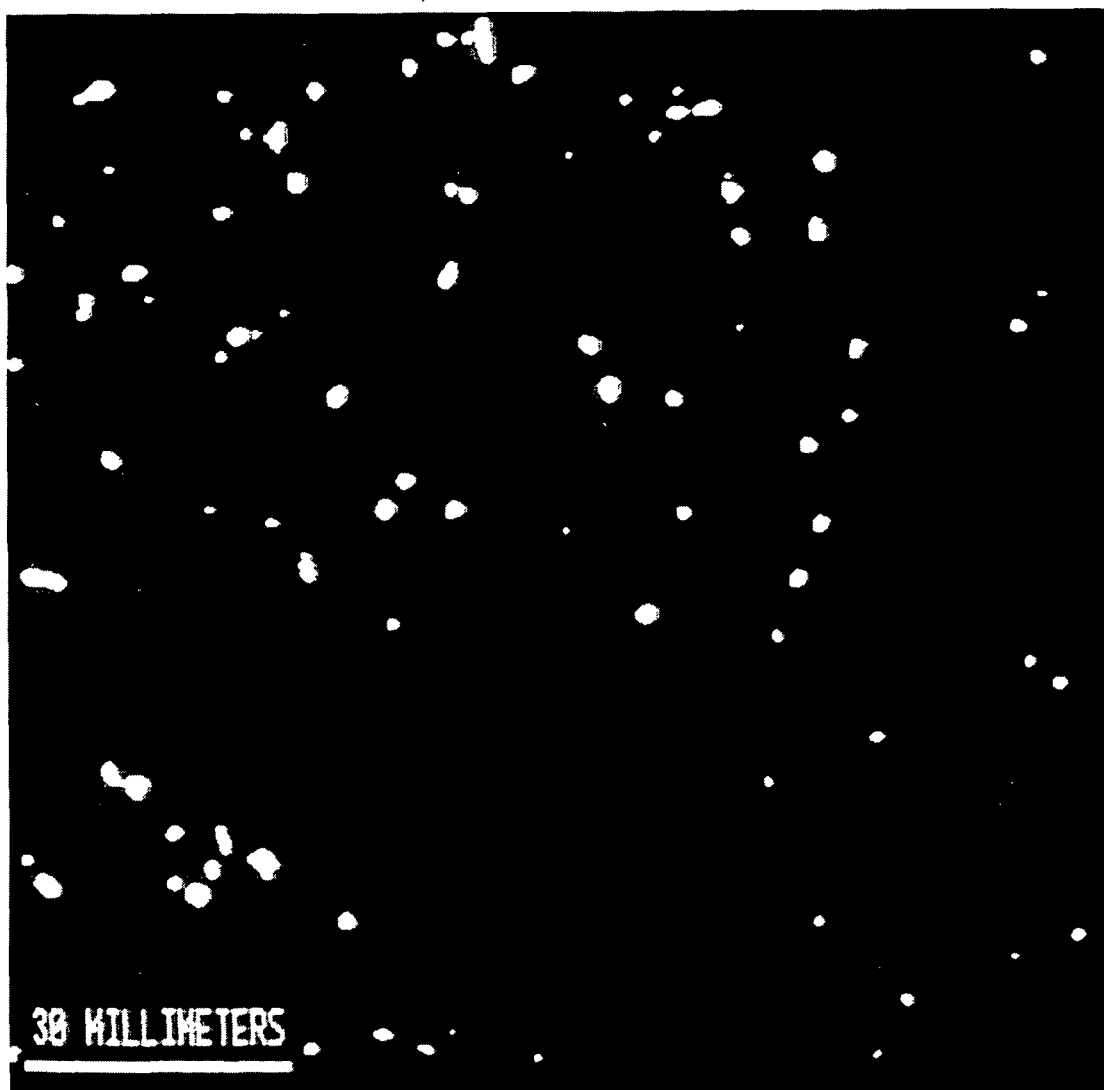


Figure 3.19-Binary Produced From the Gray Intensity
Image in Figure 3.18.

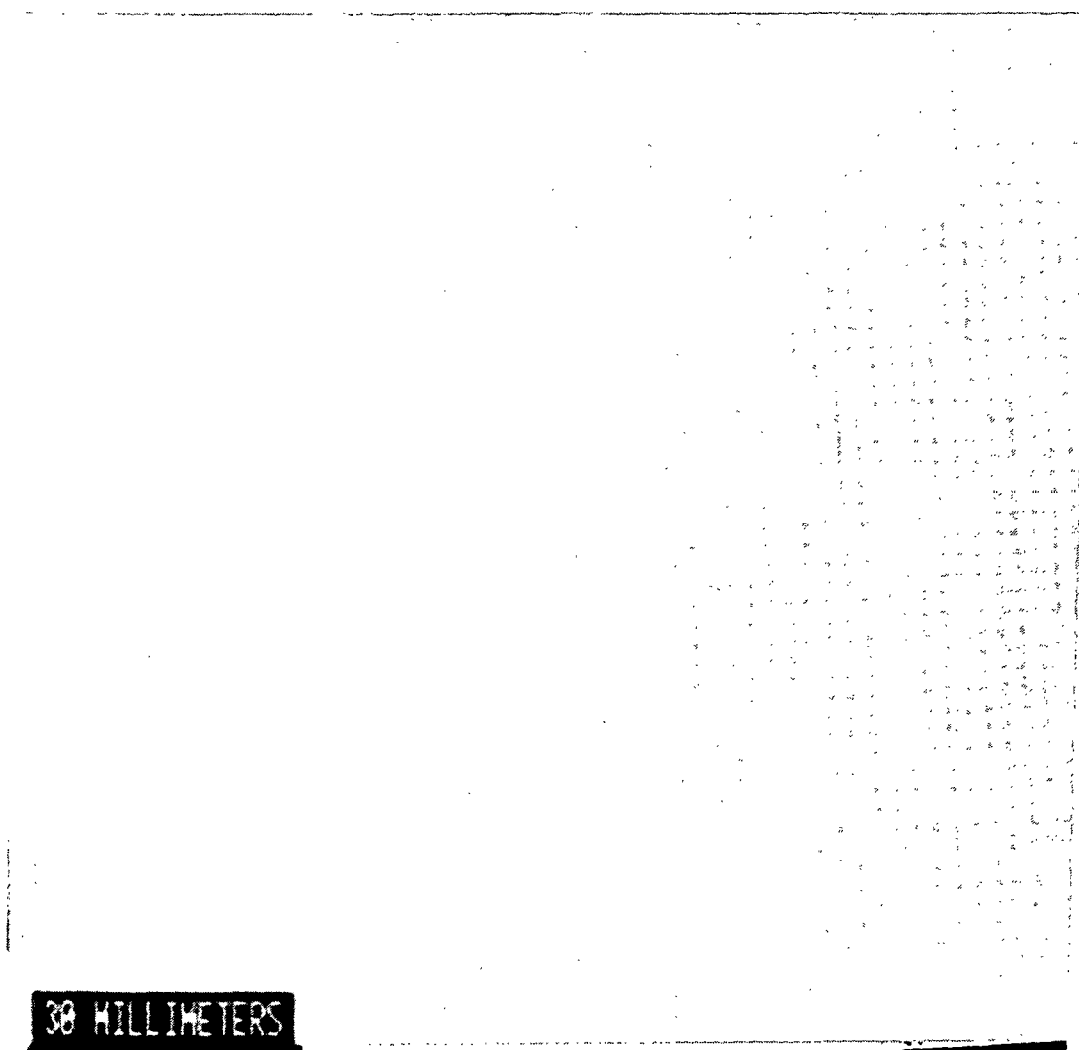


Figure 3.20-Image in Figure 3.16 after a 64x64 Median Filter Has Been Applied.

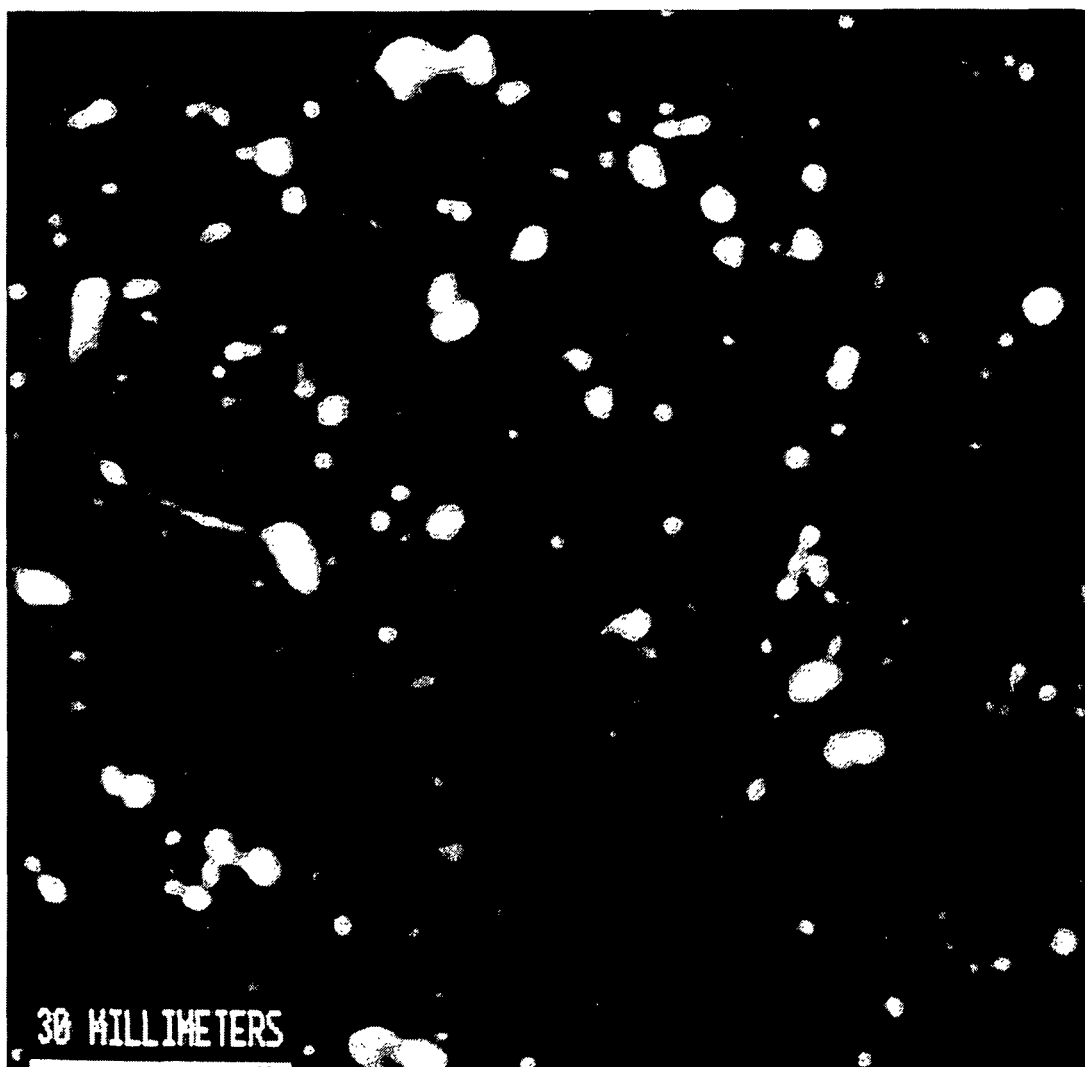


Figure 3.21-Result of Subtracting the Image in Figure 3.16
From That in Figure 3.20.

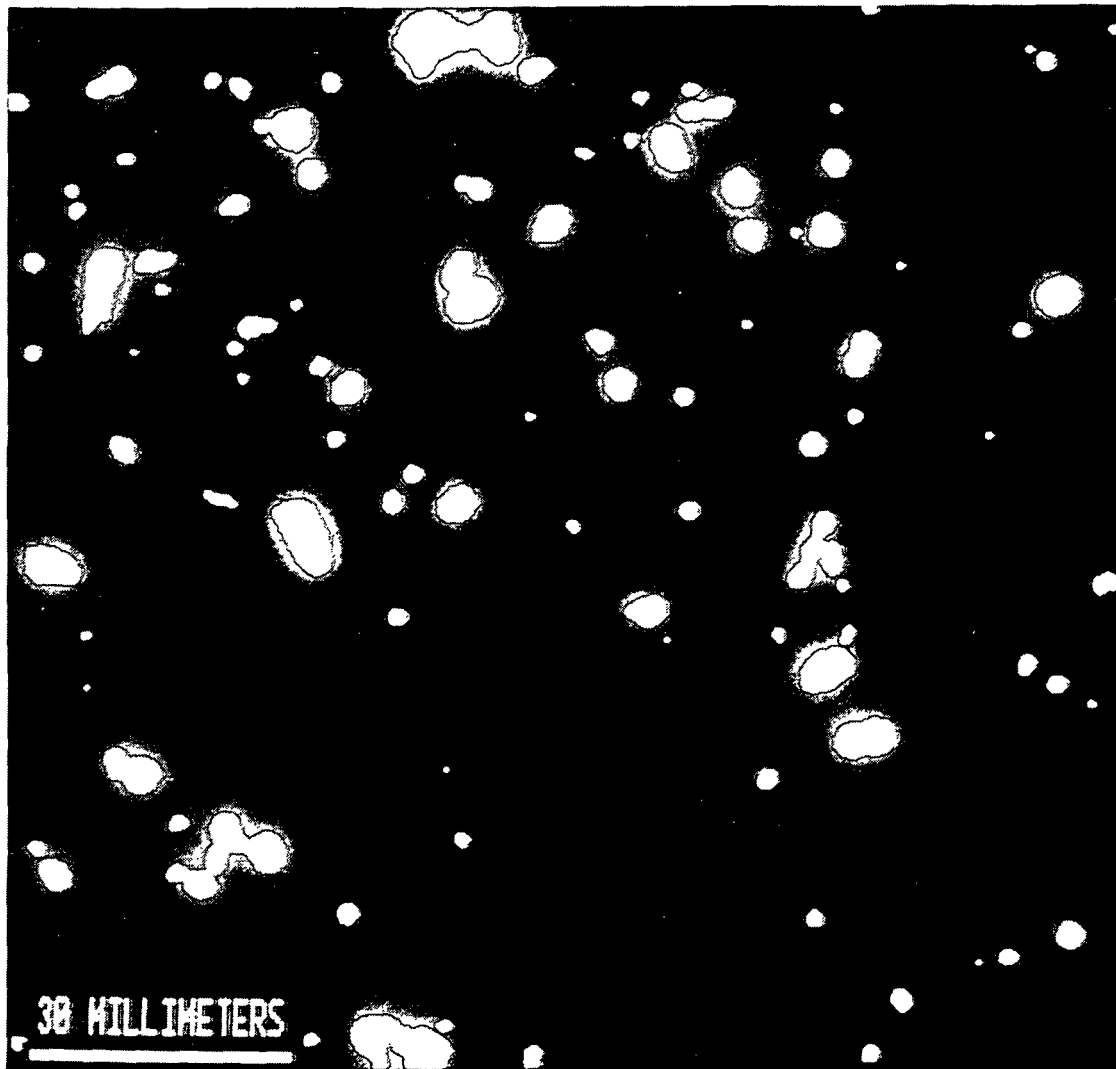


Figure 3.22-Binary Produced From the Gray Intensity Image in Figure 3.21.

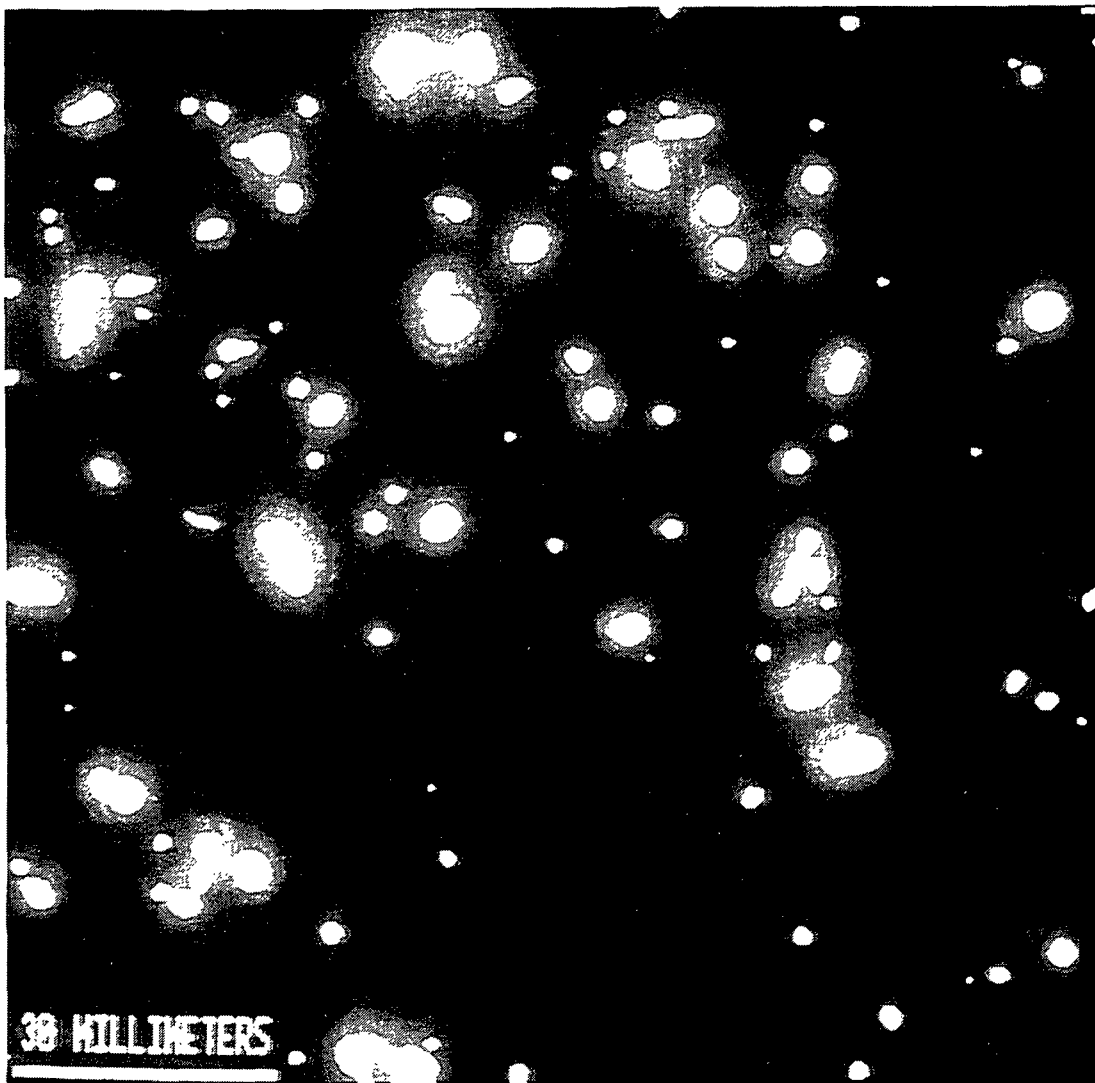


Figure 3.23-The Sum of the Binary Images in
Figures 3.19 and 3.22.

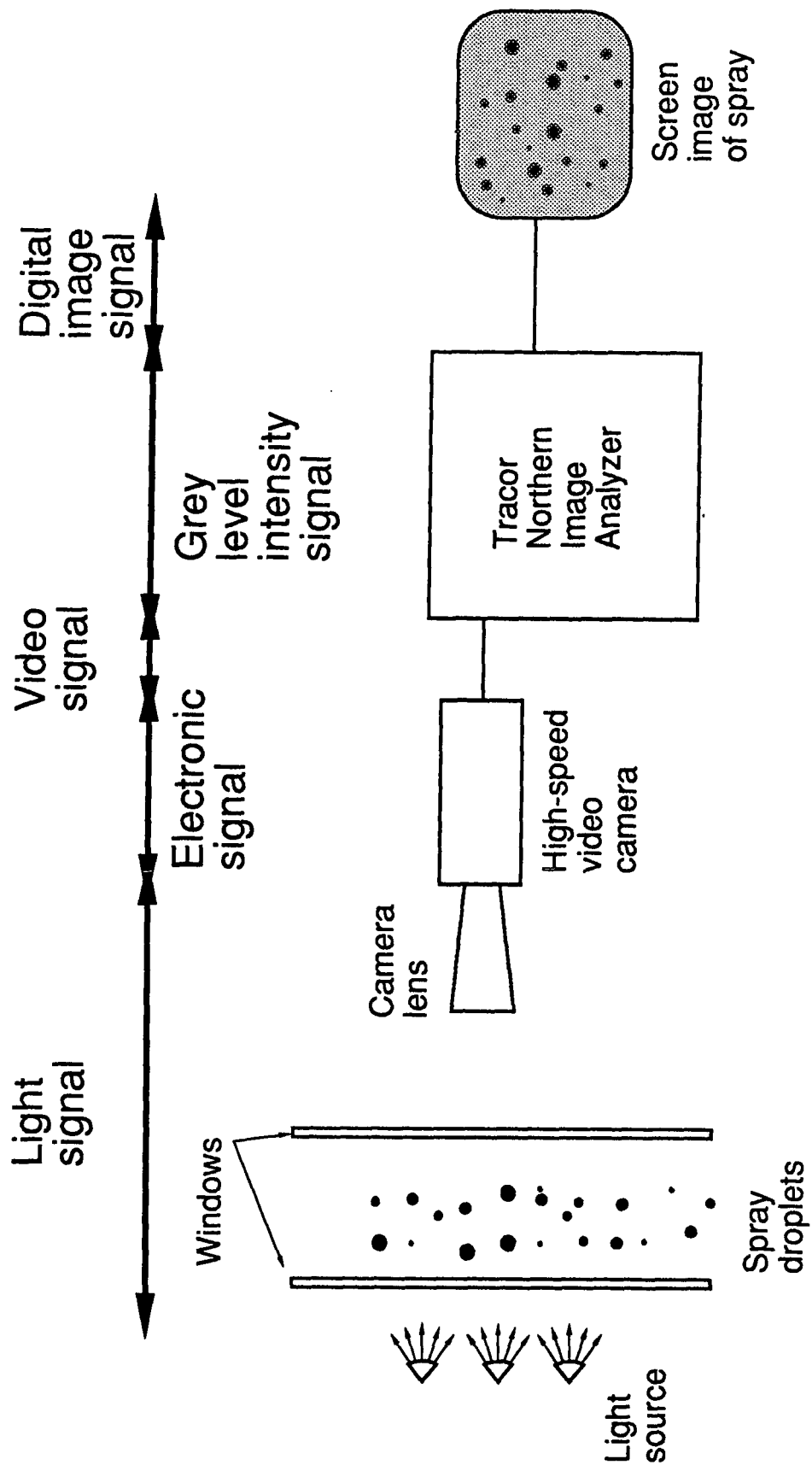


Figure 3.24 - Schematic Diagram of the Signal Flow Path Between the Light Source and the Image Analyzer.

4.0 IMAGING BLACK LIQUOR SPRAYS IN AN OPERATING RECOVERY FURNACE

4.1 INTRODUCTION

One objective of the Kraft Black Liquor Delivery Systems project is to determine the breakup characteristics and ultimate droplet size distribution of black liquor sprays. In the IPST experimental spraying facility, black liquor is sprayed at typical mill operating conditions of liquor temperature, dry solids content, pressure, and flow. However, by necessity, the environment surrounding the spray is room temperature air rather than high temperature combustion gases. There has been some uncertainty about the impact of high gas temperature on black liquor spray breakup. Recently, an influence of gas temperature on jet breakup has been proposed based on data in a related DOE project [5]. In order to address this issue directly, a field study of black liquor spray breakup in an operating recovery furnace was conducted using a high-speed video camera.

The Xybion Corp. Model ISG-250 described earlier was used in this investigation. In this study the exposure duration was usually about 5 μ s. This short "gating" duration produces the stop-action necessary to freeze the motion of the high-speed sprays. An ordinary video tube would not be able to respond to the meager light that would 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 from the source and show up on the video images as dark spots on a light background. This is quite similar to the situation in the operating recovery furnace. Looking through a black liquor gun port, the droplets and ligaments appear as dark spots (or streaks) against the lighter background of the general furnace volume. This similarity suggested the use of the Xybion camera to observe black liquor sprays in a operating recovery furnace in order to help resolve the issue of the effect of gas environment on black liquor spray breakup.

Initial trials to determine the feasibility of viewing black liquor sprays through a recovery boiler gun port were carried out on the #4 Combustion Engineering recovery boiler at the Camas mill of the James River Corporation [6]. These trials covered a range of liquor nozzle types: a B&W splashplate, a

CE swirl cone, and a Spraying Systems VEEJET nozzle. For each, a range of liquor temperatures and flows were 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, but some good images were obtained and these will be compared to images taken in a laboratory environment. The sources of difficulties and methods to correct them in future field studies are also presented.

4.2 FIELD SETUP AND OPERATING CONDITIONS

4.2.1 Boiler

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

Nozzles

The intention of the experimental plan was to videotape sprays at different conditions of: 1) spray nozzle type; 2) nozzle flow rate; and 3) fired liquor temperature, while maintaining constant total firing rate and air flow to the furnace. Varying nozzle flow at constant total flow was achieved by varying the number of liquor nozzles in service. Eight Spraying Systems Company type U-501000 VEEJET nozzles are used in normal operation for this boiler. During the trial periods, between six and eight of these nozzles were used along with one of the test nozzles:

- a) 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°.
- b) a Combustion Engineering (CE) #5 swirl cone nozzle having a minimum flow area at the swirl block equivalent to a 11/16 in. (1.75 cm) diameter and an exit orifice diameter of 15/16 in. (2.38 cm).
- c) a Spraying Systems U-501000 VEE JET having an exit orifice with an equivalent circular diameter of 23/32 in. (1.83 cm).

In each case the orifice dimension of the test nozzle is similar to that of the other nozzles used on the boiler. As a result, the liquor flow per nozzle can be estimated from the total flow of 220 GPM (13.9 l/s) and the total number of

nozzles in service. With seven nozzles the calculated flow per nozzle would be 32 GPM (2.0 l/s), with eight it would be 28 GPM (1.8 l/s), and with nine it would be 25 GPM (1.6 l/s).

4.2.2 Black Liquor

Samples of the black liquor were periodically taken from the ring header during the trials for subsequent laboratory analysis. Black liquor dry solids, viscosity, and boiling point characteristics were determined. Viscosity was measured with a laminar flow tube. For this device the tube geometry along with measured flow and pressure drop were used to calculate viscosity. The shear rate range for these measurements was 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 an expression similar to Eq. (2.2):

$$\text{Log} \left[\frac{\mu}{\mu_w} \right] = \frac{1}{0.0639 \frac{T}{S} - 0.2213} \quad (4.1)$$

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 (4.1) and the actual values is shown in Figure 4.1. 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).

4.2.3 Operating Conditions

Using the correlation of Equation (4.1) and the other data obtained during the spray trials, the conditions for each test were compiled and are presented in Table 4.1:

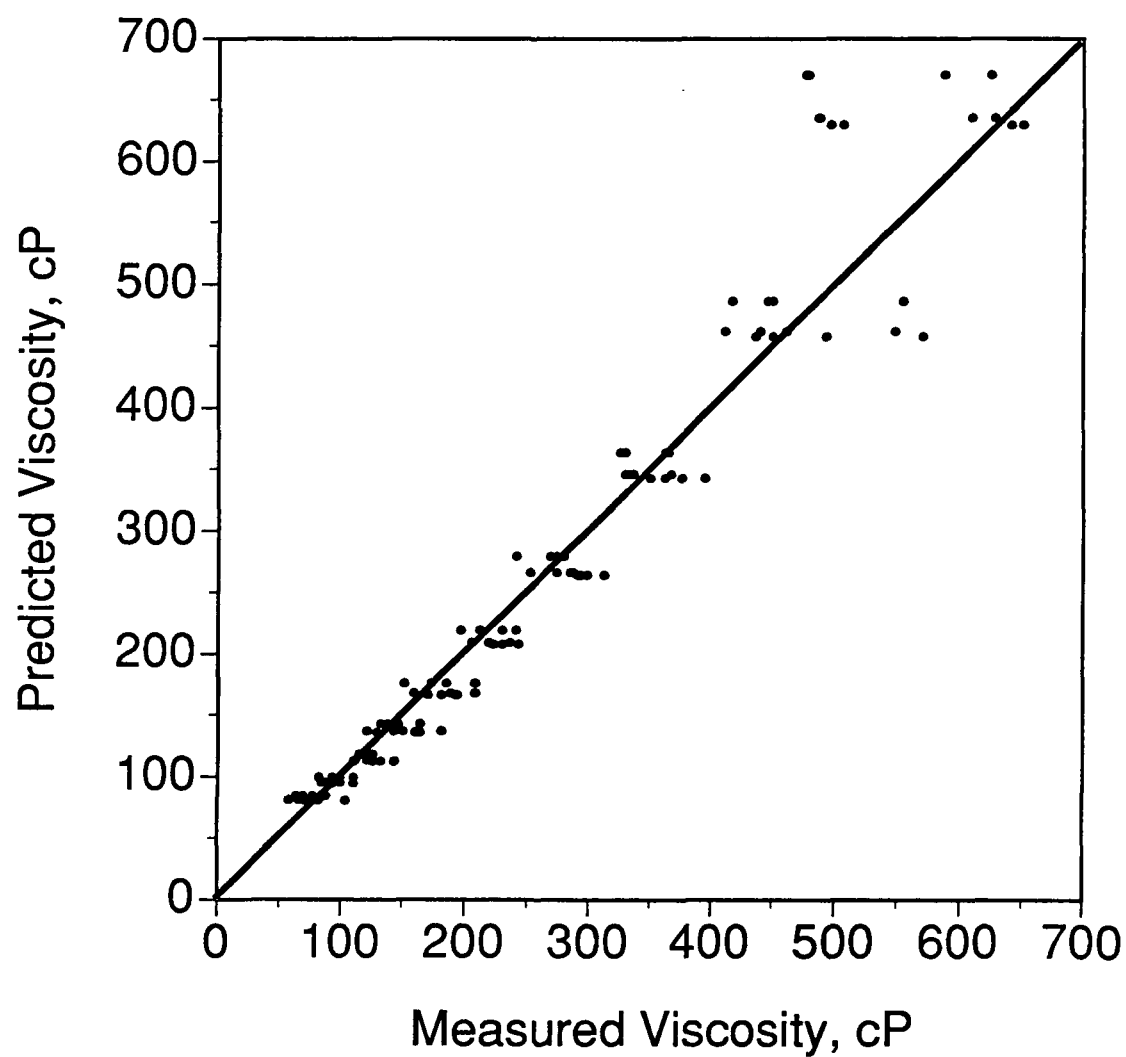


Figure 4.1 - Comparison of Predicted Versus Measured Viscosity for the Black Liquor Used in the High-Speed Video Spray Trails.

Table 4.1. Operating Conditions for Recovery Boiler Spray Trails.

Nozzle type	Nozzle Size, in.	Total Number of Guns	Total	Ring	Test	Nozzle Velocity, ft/s	Liquor	Black	Black
			Liquor Flow, GPM	Header Press. psi	Nozzle Flow GPM		Dry Solids %	Liquor Temp., °F	Liquor Viscosity cP
B&W splashplate	0.688	9	223	15.2	23	20	73.5	267	58.0
B&W splashplate	0.688	7	182	15.5	24	21	72.5	267	52.1
B&W splashplate	0.688	6	161	17.6	25	21	72.5	271	48.7
B&W splashplate	0.688	8	223	16.5	26	22	73.5	267	58.1
B&W splashplate	0.688	7	223	18.4	29	25	73.5	267	58.1
B&W splashplate	0.688	5	181	20.2	34	29	72.5	267	52.1
B&W splashplate	0.688	5	182	21.9	34	29	72.5	271	48.8
CE swirlcone	0.688	9	223	14.9	23	20	73.0	266	55.4
CE swirlcone	0.688	9	223	16.4	23	20	73.0	271	51.9
CE swirlcone	0.688	8	200	14.3	23	20	73.9	265	63.1
CE swirlcone	0.688	9	231	17.6	24	20	72.8	271	50.4
CE swirlcone	0.688	6	161	15.9	25	21	72.8	266	54.3
CE swirlcone	0.688	7	223	19.3	29	25	73.0	271	51.8
CE swirlcone	0.688	7	223	17.9	30	25	73.0	266	55.4
CE swirlcone	0.688	7	232	20.9	31	27	72.8	271	50.4
CE swirlcone	0.688	7	232	19.5	31	27	72.8	268	52.8
CE swirlcone	0.688	6	200	18.6	31	27	73.9	266	61.5
Vjet	0.719	9	223	14.9	25	20	73.8	266	60.8
Vjet	0.719	9	223	16.4	25	20	73.8	270	57.8
Vjet	0.719	7	223	19.3	32	25	73.8	271	56.7
Vjet	0.719	7	223	17.9	32	25	73.8	266	62.2

4.2.4 Video Location

The Xyblon 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 gun ports. A photograph of the arrangement is shown in Figure 4.2. This photograph also shows a liquor gun mounted on a horizontal support bar located in front of the gun port. The gun port dimensions are 3 3/4 in. (9.5 cm) wide by 12 in. (30.5 cm) high. The mounting bar and gun blocked most of the upper half of the port.



Figure 4.2 - Photograph of the High-Speed Video Camera Set Up Adjacent to the Recovery Boiler. Gun Port, Horizontal Support Bar, and Part of a Liquor Gun Are Also Shown.

4.2.5 Nozzle Setup

The individual nozzles were fitted to a liquor gun and this assembly was then inserted through the gun port. The gun was mounted so that the tip of the black liquor nozzle was approximately 1 ft (0.3 m) inside the furnace. In each case 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 for each nozzle is shown in Figure 4.3. For the B&W splashplate nozzle the spray orientation was nearly ideal for taking back-lighted video images. The other two nozzles were less ideally oriented, which resulted in significantly poorer images. In the case of the VEEJET nozzle the line of sight of the camera was 45° off the direction of the spray so that very poor separation of the droplets was observed. The orientation of the CE swirlcone nozzle was better, but its size and position blocked more of the gun port. This significantly reduced the region of the spray which could be imaged.

4.2.6 Video Camera and Lens Settings

During the spray trials a gating rate of 5 μ s 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) in these trials. The amount of blur due to the motion of droplets can be calculated as the product of the gating duration and the droplet velocity. Motion blur for these trials ranged from 32 μ m to 45 μ m. The minimum droplet dimension of interest in black liquor droplet studies is approximately 0.25 mm (250 μ m) so this level of motion blur is acceptable in this situation.

A 17.5 x 105 mm zoom lens was used with the Xybion camera during these trials. It was located approximately 60 in. (1.5 m) from the spray. Setting the lens at 105 mm yielded a horizontal field-of-view of approximately 5.9 in. (15.0 cm). The gun port located 45 in. (1.14 m) from the camera was 3 3/4 in. (9.5 cm) wide so it just filled the field of view. This will be the case for all the high-speed video images presented below.

Correctly adjusting the focus of the camera on the fast moving spray proved to be another difficulty which 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 inches (5 to 7 cm) away from the focal plane would be out of focus in the image.

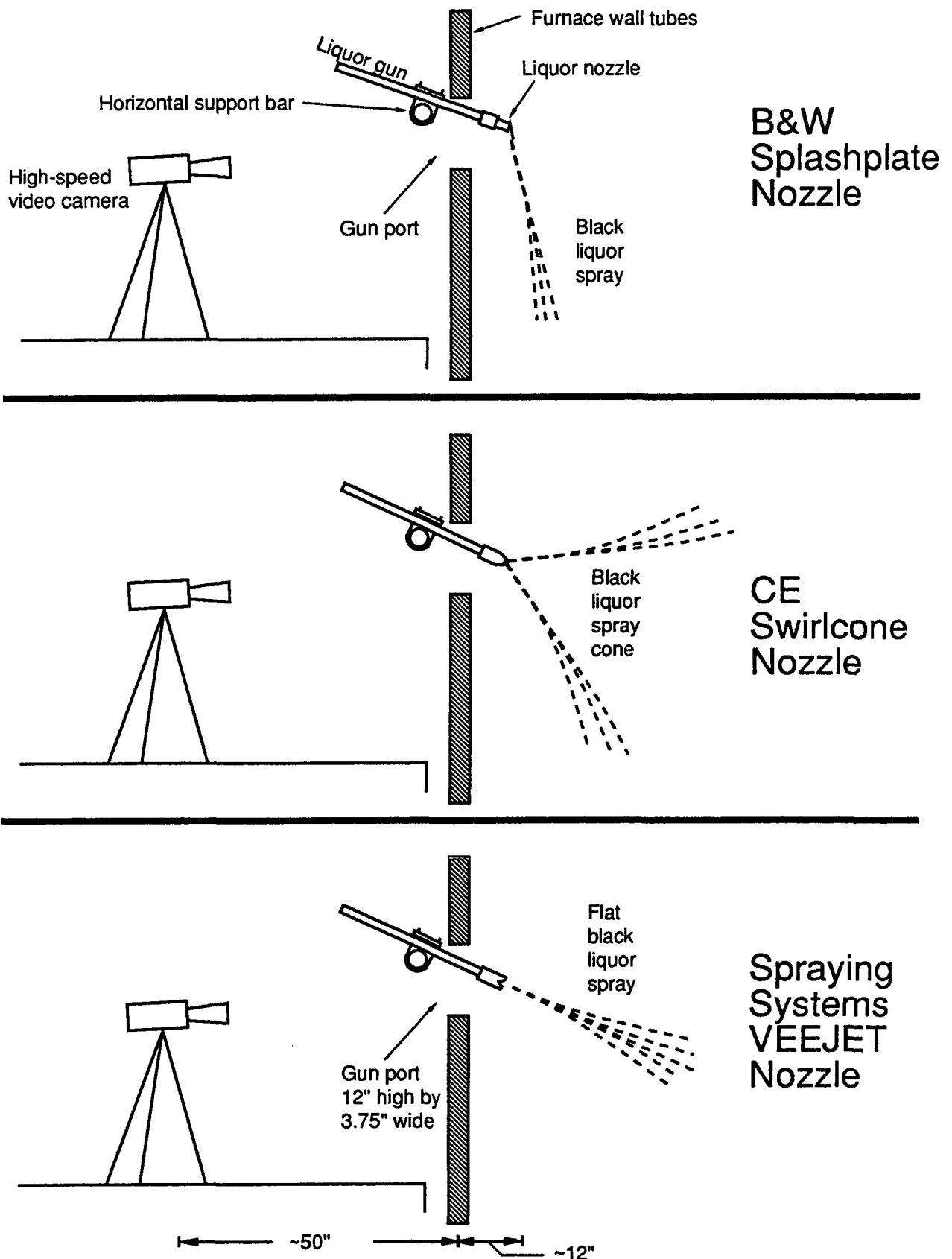


Figure 4.3 - Schematic Diagram of the Camera and Spray Nozzle Setup for the Field Trials.

4.3 FIELD TEST DATA FOR THE B&W SPLASHPLATE NOZZLE

Only the video recordings for the B&W splashplate nozzle provided images of high enough quality for comparison to images taken under laboratory conditions. Some of these images will be presented below for three different operating conditions. All of these images were taken at an as-fired 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 three conditions differed in the value of their nominal liquor flow rate. The three rates were: 25 GPM (1.6 l/s), 28 GPM (1.8 l/s), and 32 GPM (2.0 l/s). The corresponding nozzle discharge velocity for each was: 21.3, 24.3, and 27.4 ft/s (6.6, 7.4, and 8.4 m/s), respectively.

For all video cameras, including the Xybion ISG-250, the aspect ratio of the image (i.e., the horizontal to vertical dimension) has a value of approximately 4:3. The gun port is only 3 3/4 inches (10 cm) wide so the vertical dimension is only about 2 7/8 inches (7.1 cm). Therefore, the full height of the gun port could not be covered by a single image. For this reason images were taken at three elevations: at the top (just below the downward directed splashplate tip), at the bottom of the gun port, 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 inches (20 cm), so there is some overlap in the images at the three elevations.

One image from each of the three elevations is presented one above the other. This gives a better visual impression of the development of the spray for comparison to images taken in the laboratory. However, it must be kept in mind that these images do overlap and that they were taken at different times. They 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 36 images presented below represent only a very small fraction of the available data from this part of the field trial.

Shown in Figures 4.4 - 4.6 are twelve images of each of the sprays from the B&W #22-35 under low, medium, and high flow rates taken during the field trials. The image closest to the nozzle is on top and the image farthest from the nozzle is on the bottom. Comparison of the images at each elevation shows the variation in spray development with distance from the nozzle. Because the maximum distance displayed in these images is only 8 inches (20 cm), which corresponds to only about 30 ms, spray breakup is not very advanced.

The general pattern of these images near the nozzle is of a sheet of black liquor with very few holes or perforations. Further away there are more perforations along with a few large drops and strands. At the farthest 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 breakup.

4.4 LABORATORY DATA FOR A B&W SPLASHPLATE NOZZLE

Previously, images of spray breakup for a B&W splashplate nozzle have been taken at IPST [7,8]. Due to the relocation of the Institute from Appleton, WI to Atlanta, GA only limited high-speed video data have been taken of hot, concentrated black liquor. However, numerous images of the spray from a B&W splashplate nozzle were taken with the flash x-ray technique [8,9]. Two of these images are shown in Figures 4.7 and 4.8 for a B&W #17-49 nozzle operating at 220°F, 67% dry solids and 21 psi nozzle pressure. At these conditions the liquor viscosity is 56 cP (56 mPa-s).

Flash x-ray images are somewhat different from the video images in that the black liquor partially transmits the x-rays. This produces an image with a range of gray shades where, typically, the largest drops and strands are darker while the smaller ones are lighter. This can be seen in Figures 4.7 and 4.8, as can the excellent stop action provided by the 70 ns x-ray flash.

In order to present images for visual comparison to the high-speed video images, the flash x-ray images were processed using a Tracor Northern Inc. image analyzer located at IPST. Portions of each of the two x-ray images were input to the analyzer by means of an ordinary video camera. These portions correspond approximately to the dimensions used in the high-speed video field trial. The distances were shortened for the flash x-ray, and the field of view decreased approximately in proportion to the ratio of the diameters of the B&W nozzles used in the two experiments, 22/32 inches and 17/32 inches (1.75 cm and 1.35 cm).

The gray-level images stored in the image analyzer were then processed to remove the uneven background and to convert all the gray-level droplets into black images. The results are shown in Figures 4.9 and 4.10. The liquid sheet, strands, and droplets now appear as black images on a white background similar to the high-speed video images taken from the field trials.

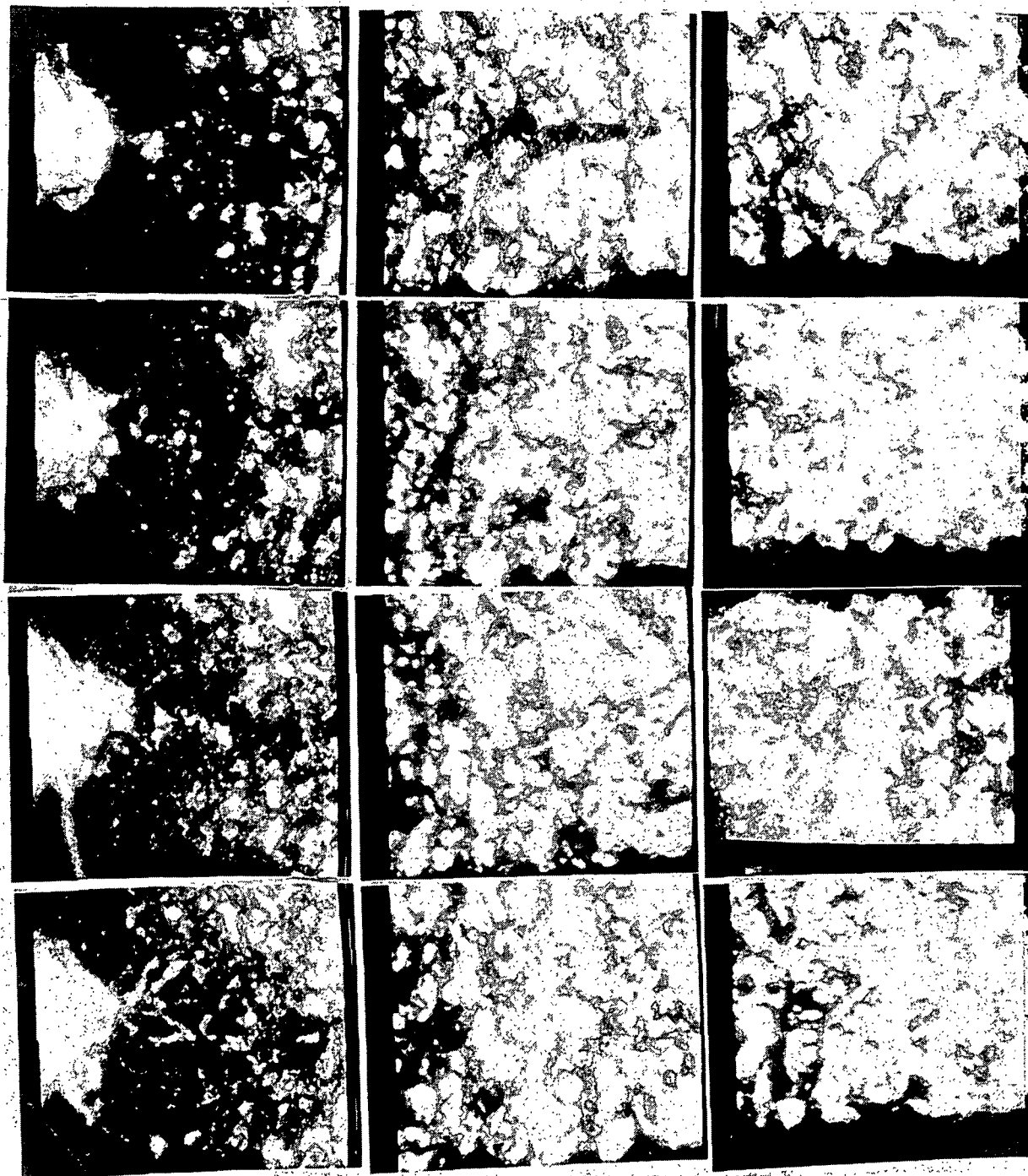


Figure 4.4 - Twelve Images of the Spray from a B&W #22-35 Splashplate
Nozzle Taken at a Flow of 25 GPM in an Operating Recovery Boiler.

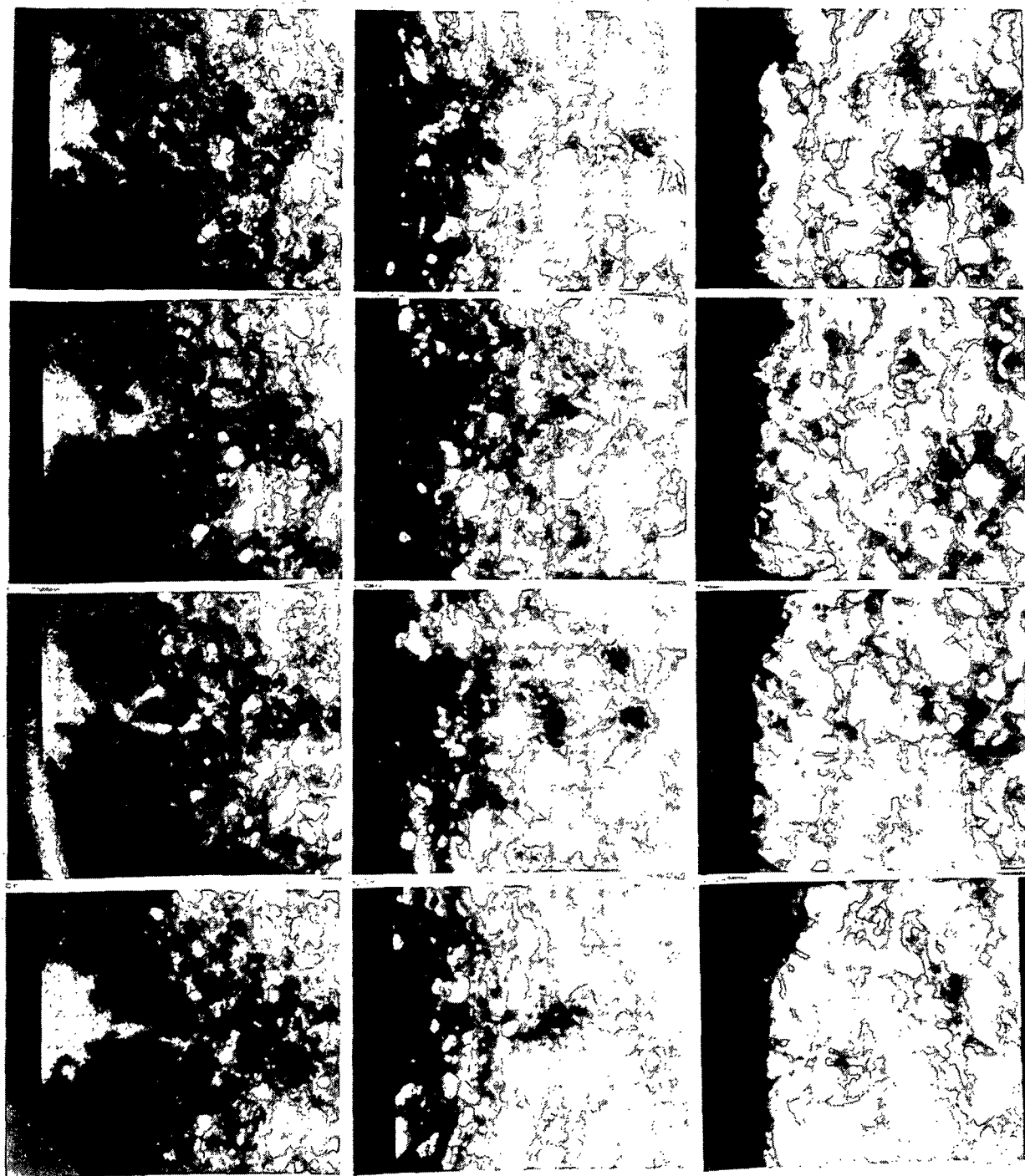


Figure 4.5 - Twelve Images of the Spray from a B&W #22-35 Splashplate
Nozzle Taken at a Flow of 28 GPM in an Operating Recovery Boiler.

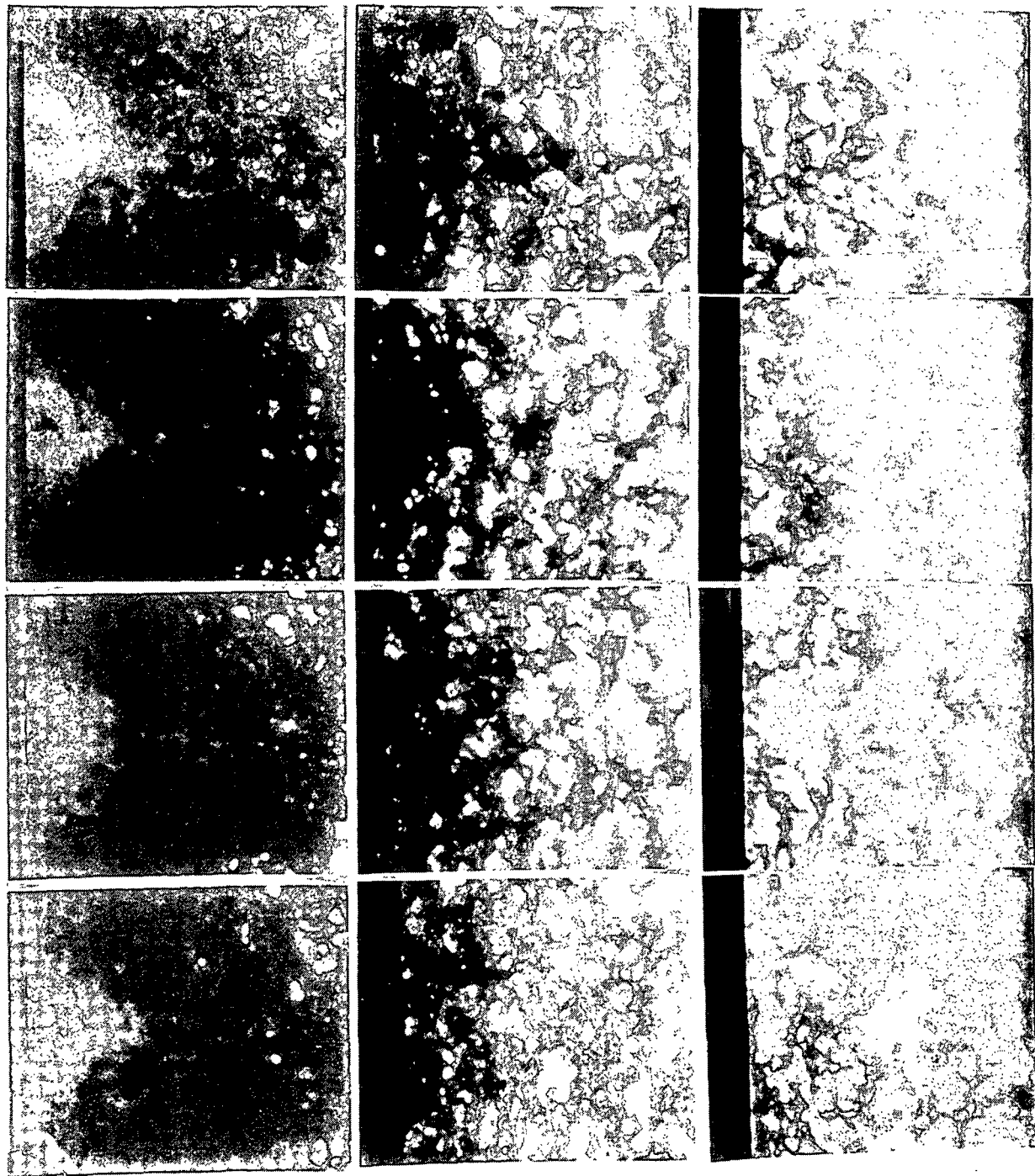


Figure 4.6 - Twelve Images of the Spray from a B&W #22-35 Splashplate
Nozzle Taken at a Flow of 32 GPM in an Operating Recovery Boiler.

Approximate nozzle
location



**Figure 4.7 - Full-Scale Flash X-ray Image of a Black Liquor
Spray from a B&W Splashplate Nozzle Operating at
220 F, 67% Solids, 56 cP, and 21 psi.**

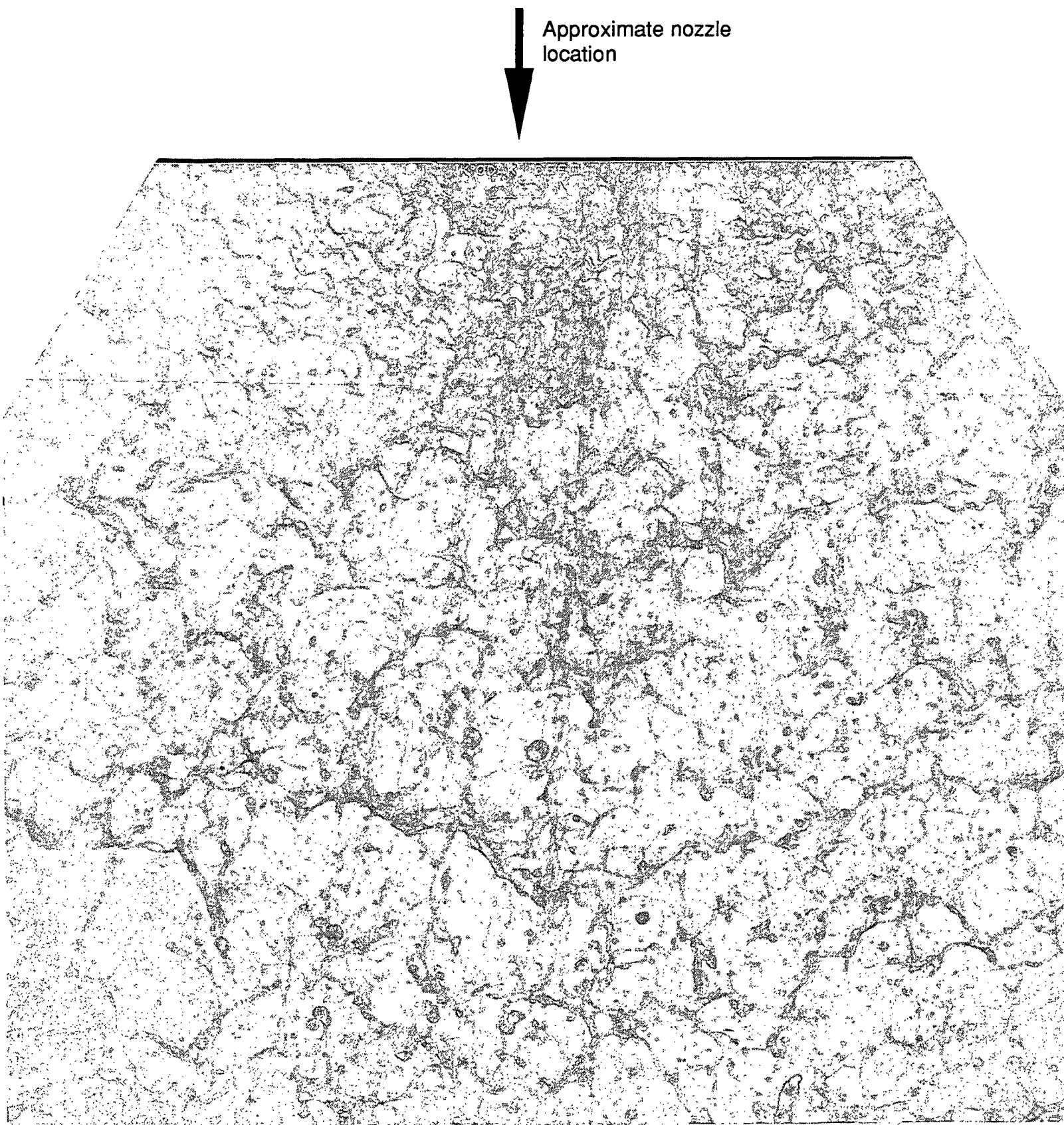


Figure 4.8 - Second Example of a Full-Scale Flash X-ray Image of a Black Liquor Spray from a B&W Splashplate Nozzle Operating at 220 F, 67% Solids, 56 cP, and 21 psi.

4.5 DISCUSSION OF SPRAY BREAKUP IMAGES

Comparing the images from the field trial to the images from the laboratory experiments, there are detailed differences, but the general pattern of spray breakup is quite similar. There are enough operating differences between the two experiments (nozzle size, liquor characteristics, operating conditions, and imaging technique) so that a detailed comparison of the two is not warranted. However, within the fairly narrow field-of-view investigated, the general similarity of spray breakup is encouraging. The relatively good image quality for a first use of the high-speed video camera for field trials of black liquor spray breakup is also encouraging.

The general spray breakup for both the field and lab experiments is the increasingly familiar pattern of the formation of a liquid sheet, the development of perforations, the growth of perforations resulting in a web of strands [10], and the subsequent breakdown of strands into droplets. For black liquor sprayed with commercial black liquor nozzles this is the nearly universally observed mode of breakup rather than the commonly described wave breakup mechanism [11,12].

Both the development of perforations and the location of the start of spray breakup appear to be quite similar in the field trials and laboratory experiments. However, the portion of the spray investigated is quite small, corresponding to only the first 30 ms of spray breakup. Further field trials of a greater portion of the spray breakup, including ultimate droplet size distribution, will be required to confirm the impact of gaseous environment on black liquor spray breakup.

4.6 MODIFICATIONS FOR IMPROVED FIELD TRIALS

Several aspects of the field trials significantly reduced the utility of the data obtained. They were: focus and depth-of-field, electronic gain and aperture, and spray field size and gun port dimensions.

4.6.1 Focus and Depth-of-Field

As with all experiments, something is learned about experimenting as well as about the phenomenon being investigated. The most important observation about these experiments is that it is much easier to focus on a stationary object than on a moving one. In this field trial on black liquor sprays, the focus for each experiment was adjusted based on the visual clarity of the live image on a video monitor. Far better results could be obtained by placing a stationary object in the spray, such as a rod, obtaining a proper focus and then removing the rod for video recording of

Approximate nozzle
location

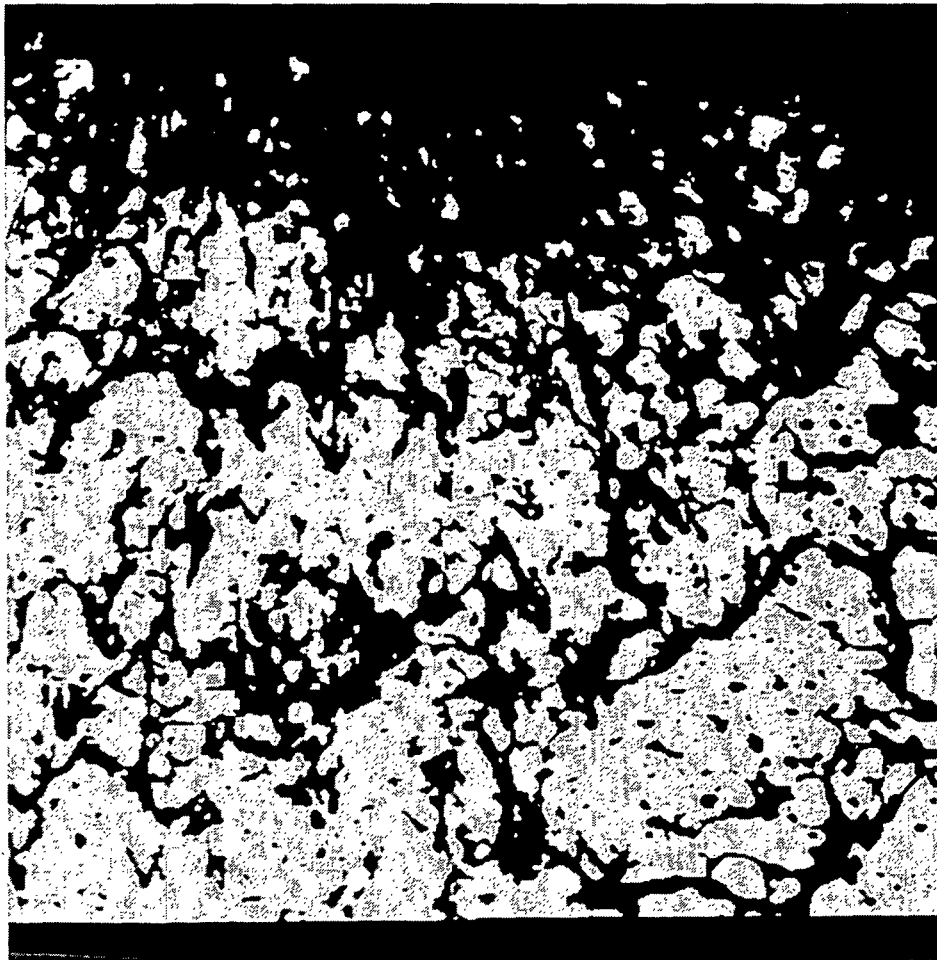



Figure 4.9 - Binary Image of the Flash X-ray Image of a Black Liquor Spray from a B&W Splashplate Nozzle Operating at 220 F, 67% Solids, 56 cP, and 21 psi.



Figure 4.10 - Second Example of a Binary Image of the Flash X-ray Image of a Black Liquor Spray from a B&W Splashplate Nozzle Operating at 220 F, 67% Solids, 56 cP, and 21 psi.

the spray. This technique and similar ones are currently being used in the IPST Black Liquor Spray Facility. Use of a rod or other object for a few seconds at the start of a video sequence also provides a length scale calibration for use in subsequent droplet size analysis.

Accurate focus is important for in-furnace trials because the depth-of-field is typically quite narrow. In the trials reported here, the depth-of-field was only a few inches. Focusing the camera only two or three inches away from the spray would severely degrade the video image for subsequent image analysis. Changing the lens and camera setup could result in a greater depth-of-field, but this is undesirable for in-furnace trials. Though the liquor spray is the largest source of droplets near the gun port, casual observation of operating recovery boiler furnaces reveals that the combustion gases carry around a significant number of large, partially burned black liquor droplets. By focusing the video camera beyond the spray in the current trials these could be seen. When the camera is focused on the spray, a narrow depth-of-field helps reduce the interference of these extraneous particles.

4.6.2 Electronic Gain and Aperture

The lens aperture setting affects both the depth-of-field and the amount of light reaching the video sensing element. Smaller apertures (i.e., higher f/numbers) increase the depth-of-field and decrease the amount of light. With high-speed gating of the camera, in this case 5 μ s, the sensing element receives only a small amount of light. For this reason relatively large aperture openings must be used to obtain a reasonable image. An f/number of 1.8 was used in this study.

To a certain extent the automatic electronic gain of the camera can compensate for poor light levels, but at the cost of additional noise in the signal. This was a problem, particularly with the CE swirlcone nozzle trials. The swirlcone nozzle occupied more of the gun port than the B&W splashplate. This left only 4 to 5 inches (10 to 13 cm) of open space between the CE nozzle tip and the bottom of the gun port. Spray breakup was not well advanced in this distance, so few perforations had formed within the field-of-view. As a result, the amount of light from the furnace passing through the spray to the camera was very low. The automatic gain of the camera compensated for this by increasing the gain so that an image could be obtained. However, with the gain set high, the image was very grainy due to high electronic noise level. This made adjusting the focus even more difficult because the image was fuzzy even with the correct focus setting. The overall image quality for the CE nozzles was quite poor as a result.

The three parameters--aperture, gain, and gating rate--work together in a complex way to determine the overall brightness of the image. To avoid motion blur, the gate duration must be set to a low value. This can be calculated with reasonable accuracy from the object speed and size. Motion blur of approximately one-tenth of the smallest object size is satisfactory for droplet image analysis. The proper gate duration would then be one-tenth of the smallest object size divided by the object velocity.

Larger apertures allow more light to reach the camera and result in a narrower depth-of-field. At locations near the nozzle the liquid sheet thickness is fairly narrow, less than a few inches, so a small depth-of-field provides good images of spray breakup while de-emphasizing extraneous out-of-plane droplets and particles. For this circumstance, large apertures (small f/numbers) satisfy the need for both good light levels and narrow depth-of-field. Farther away from the nozzle the spray trajectory widens and a greater depth-of-field is more advantageous. Under these conditions a compromise between light level reaching the sensing element and depth-of-field is necessary.

A very bright image background would also be a problem. High background brightness could be reduced by closing the aperture. However, this would increase the depth-of-field, bringing into better focus extraneous objects outside the spray trajectory. In this case, a low f/number in combination with a neutral density filter would be better to control light level and depth-of-field.

It is always more advantageous to have low gain for the camera because this reduces noise and graininess. The higher the light level from the object and background, the lower the gain can be adjusted. Certain portions of the spray will always be more difficult to image because they inherently let less background light through to the camera. The liquid sheet near the nozzle will be the most difficult to image. Further away from the nozzle as breakup progresses, more background light will pass through the spray allowing easier camera adjustment. Even further out the individual droplets will block little of the background. Very high light levels will then require adjustment of the gating or aperture, with aperture adjustment affecting depth-of-field. In this region, a neutral density filter may help optimize the image by controlling light levels at low f/numbers.

4.6.3 Spray Field Size and Gun Port Dimension

Commercial black liquor sprays are large. The spray from a B&W splashplate spreads out through an angle of nearly 180° and covers more than 20 sq.ft (2 sq.m). The gun port dimensions will always be much smaller. There are then two

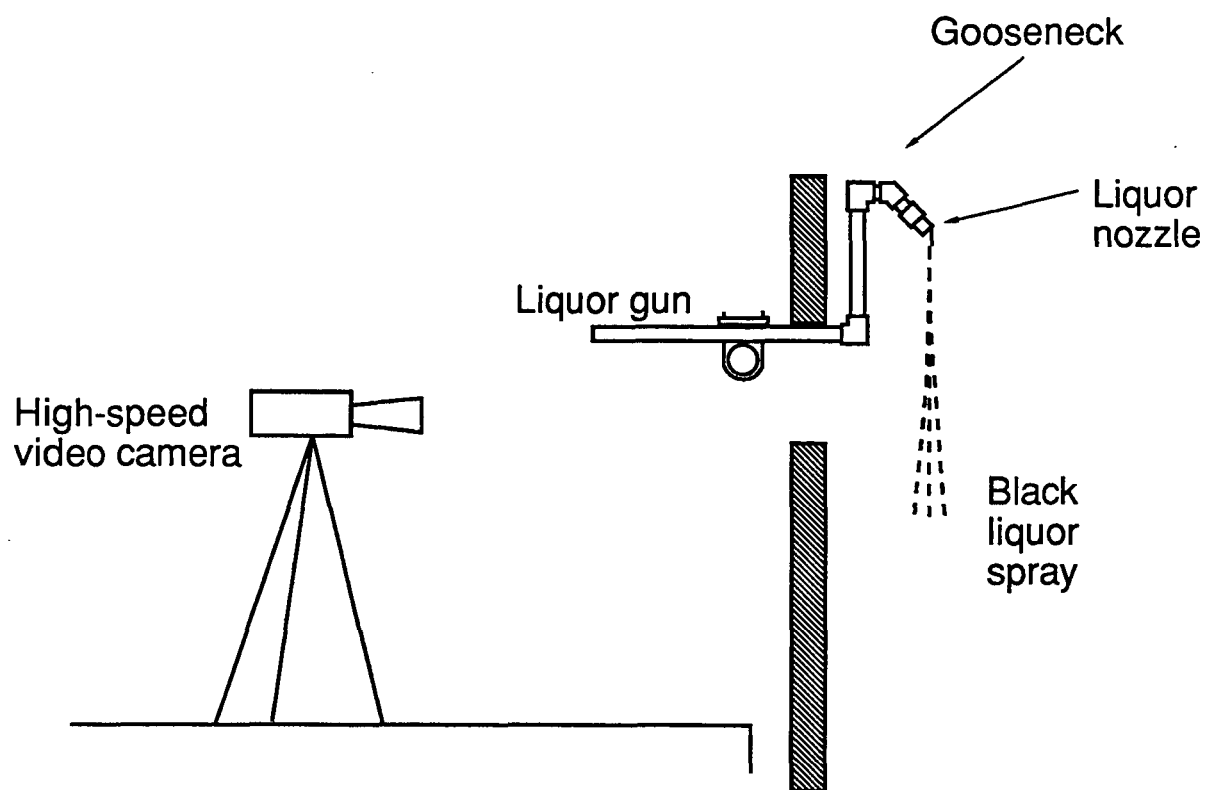


Figure 4.11 - Schematic Diagram of the Camera and Spray Nozzle Setup with Gooseneck Liquor Gun.

options for video recording a black liquor spray from outside the furnace. The first is to use a larger opening, such as a man-door, as an observation port so that more of the spray breakup can be viewed at one time. The second is to locate the nozzle inside the furnace at a distance from the gun port so that a small portion of different parts of the spray can be observed. Considering the unsteady puffing of most recovery boilers, the first option would appear to be unsafe. The second option would require fabrication of a liquor gun in the shape of a gooseneck, as depicted in Figure 4.11. The gooseneck and nozzle fastener would allow the nozzle to be situated some distance above the gun port, but oriented to give a spray back down in front of the gun port, parallel to the wall. Different rotations of the gooseneck would allow different parts of the spray to be recorded. Different gooseneck guns would be required to vary the distance between the gun and the port.

Design of these gooseneck guns would require careful attention to safety and maneuverability. Black liquor guns burn out in ordinary service if extended too far into the furnace. Careful metal selection, inspection in service, and continuous liquor flow would be required to insure the safety of these guns even for short-duration trials.

These guns must be designed to go through an approximately 4 inch-by-12-inch (10 cm by 30 cm) gun port. In addition, the gooseneck will produce a significant torque in two directions which will hamper installation and removal unless they are equipped with appropriate handles and fittings. Such design considerations will be part of future field trial work.

ACKNOWLEDGEMENTS

The assistance of Bob Damon and the operating staff of the Camas #4 recovery boiler are greatly appreciated. The participation of Chris Verrill at IPST both in facilitating the mill trials and preparing the report for James River Corporation is also appreciated. The high-speed video trials could not have been carried out without their help.

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