THE EFFECT OF TEMPERATURE ON DROP SIZE

OF

BLACK LIQUOR SPRAYS

by

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ABSTRACT

The effect of temperature on drop size of black liquor sprays produced by small grooved-core nozzles at near boiling point conditions was investigated. It was found that increasing temperature through the boiling point decreased the Sauter mean diameter in a smooth manner, by a magnitide accounted for by the viscosity decrease. In contrast, water sprayed through the same nozzle under similar conditions showed a near step increase in mean drop size for the same temperature increase through its boiling point.

The mass-weighted distributions of drop size for black liquor sprays were much broader than those of water, or glycerol/water solutions having the same viscosity as black liquor. Increasing the temperature through the boiling point of black liquor shifted its drop size distribution to smaller diameters.

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INTRODUCTION

The size of drops in a black liquor spray is an important parameter in the operation of a kraft recovery furnace. Though every spray contains a range of drop sizes, the upper and lower bounds of this range define limits within which furnace operation must be stable and controllable. When the drop size is too large, the liquor droplets do not dry sufficiently before they reach the char bed. This lowers the temperature in the char bed resulting in a poorer reduction efficiency, higher emission of H_2S, and could lead to a significant lowering of furnace temperature (a "brown out"). When the drop size is too small, droplets are entrained by the combustion gases and carried upwards in the furnace (carryover). In this case, smelt production decreases because insufficient liquor reaches the char bed, the upper furnace temperature increases, and the deposition of particulate matter on the boiler tubes causes heat transfer fouling. While increased fouling necessitates more frequent soot blowing, conditions could arise where soot blower resistant deposits form resulting in boiler passage plugging [1]. Increased carry over also increases the recycle of deadload chemicals through the recovery cycle (ash particles captured in the boiler and recycled with the incoming black liquor) and the emission of particulate matter from the boiler.

To avoid the foregoing problems, recovery boilers are operated with a "coarse" spray, that is, a spray which has a drop size distribution that maintains char bed temperature but minimizes

particulate carryover. Many variables affect this desired drop size distribution, for example: furnace operation, nozzle geometry, and black liquor properties. However, few of these variables can be changed during on-line operation. Furnace operation, for example, is largely determined by the installation. Nozzle geometry is usually fixed; liquor flow rate and solids content are determined by production rate. However, there is one easily-changed operational variable: the liquor temperature. This is commonly used to achieve on-line control of spray drop size.

It is well known from operational experience that black liquor temperature has a significant effect on furnace operation [2,3,4]. In practice the liquor firing temperature is carefully controlled by steam injection upstream of the boiler nozzles. Here slight temperature changes are used to control the quantity of material (inventory) in the furnace char bed. On occasion, very significant changes in recovery furnace operation can be made with relatively small changes in liquor temperature. For example, it has sometimes been observed in practical experience that a furnace brown out can be overcome by changing the liquor temperature only a few degrees.

While much is known from practical experience about the effect of liquor temperature on recovery boiler operation, very little specific detailed technical information on this subject has been published in the literature. There is, however, considerable published information on atomization theory, and a lesser but significant amount on black liquor properties to permit some prediction of the effect of temperature.

First, the drop size of any spray is known to be dependent on the viscosity of the liquid. Black liquor viscosity is known to be very temperature dependent. Second, flashing in or just after a nozzle can significantly affect spray characteristics. Black liquor is commonly sprayed at or near its boiling point. Thus, two factors, viscosity and flashing may individually or in combination significantly affect the sprayability of black liquor when temperature changes take place.

The objective of this thesis is to determine the effect of temperature on the drop size of black liquor sprays at near boiling point conditions. The specific aim is to determine whether small temperature changes can cause significant changes in drop size - changes large enough to be considered an instability. The investigation begins with a detailed search of the literature in the fields of recovery furnace operation, atomization theory, and black liquor properties.

2. LITERATURE REVIEW

2.1 Kraft Recovery Furnace Operation

There are two types of recovery furnaces common in North American kraft pulp mills: the Combustion Engineering (CE) furnace and the Babcock and Wilcox (B & W) furnace. While both perform the same recovery function, there are some key differences in operating strategy between them. One of these is the method used to fire black liquor in the furnace.

CE furnaces practice suspension firing in which the black liquor, atomized in grooved-core nozzles, evaporates and burns as it falls as droplets onto the char bed. The drop size distribution of the spray determines the degree of bed cooling and particulate carryover. Accordingly, CE furnace operation requires control on both the upper and lower limits of drop size. In contrast, B & W furnaces spray the liquor on the opposite furnace wall and rely upon wall drying for liquor evaporation. The B & W method of liquor firing is less sensitive to spray drop size since control is only required on the lower limit to ensure that the drops do not become too small. This thesis will concentrate on atomization in grooved-core nozzles characteristic of CE furnace firing because this method of furnace operation is likely to be more sensitive than the B & W furnace to changes in spray drop size.

The scientific literature pertaining to black liquor firing and recovery furnace operation recognizes the importance of black liquor

atomization on the control and efficiency of recovery furnaces [2,3,4].
However, despite this, there is little detailed information available on
black liquor atomization. In fact, the only work involving actual in
situ measurement of black liquor drop size has been done by Sandquist
[5]. In this work, motion pictures were taken of black liquor sprays
through an observation port at the firing gun level in the recovery
furnace. Black liquor droplets recorded on the film were then
measured. A typical black liquor spray produced by an impingement
nozzle for suspension firing (Scandanavian practice) gave an average
drop size of 2.1 mm for typical operating conditions.*

Other investigators have attempted to describe or estimate the
optimum size of a black liquor droplet required for efficient recovery
furnacy operation. The common reference to a "coarse" drop size is an
indication that fine spray formation and the problems associated with
particulate carryover are undesirable. Nelson [6] stated that the flash
dried liquor drop should be spherical and about 1/2 inch in diameter.
He used the "popped popcorn" analogy to describe the appearance of the
dried droplets upon reaching the char bed. V'yukov [7] stated that the
liquor droplet size must be such that droplets reaching the hearth
contain 8-10% moisture for optimum reduction efficiency. He presented a
system of equations to solve for this optimum size.

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*The test conditions were as follows: nozzle orifice diameter = 34 mm,
nozzle operating pressure = 18.9 psig, nozzle flow rate = 10.6 1/s,
black liquor solids content = 63%, black liquor firing temperature =
98°C, black liquor viscosity = 115 cp.

Modelling has also been attempted as a means of describing recovery furnace operation [3, 8, 9]. The most recent one, by Merrian [10], is a steady-state model of the entire kraft recovery furnace. It predicts that a drop size diameter close to 1.5 mm is required for stable firing in the CE furnace. However, the notion of a single optimum drop size can be misleading because, in actual fact, a distribution of drop sizes is produced by any spray nozzle.

The sensitivity of the black liquor spray to temperature is well known. Galtung and Williams [3] stated that "the drop size distribution is extremely sensitive to the liquor temperature as a few degrees will change a coarse spray into a fine mist." Jutila et al. [4] studied the actual effect of changes in firing variables on the temperature profile in a recovery furnace. They found that changing the liquor temperature by as little as 2°C introduced a noticable difference in the boiler temperature profile. They stated that liquor temperature control could be used to control the location of combustion and heat release in the furnace. They gave a narrow temperature range of 117 to 119°C for optimum liquor firing.

The mechanism by which temperature effects drop size is a question of contention. Viscosity is believed to be important by some investigators. For example, Kennedy [11] specified that black liquor should be sprayed at 125 cp, but did not give any indication of what would happen to the liquor drop size if the viscosity changed. Computer models, like Merriam's [10], used atomization models that allowed drop size to vary as a power of the viscosity. The other effect of

temperature - liquor flashing - is believed to be important by several investigators. Hochmuth [12] described the firing of black liquor as one of partial flashing of the liquor's water content. The liquor, heated above its atmospheric boiling point to 112 to 115°C is sprayed into the furnace. Upon leaving the nozzle, the liquor partially flashes, causing each droplet formed to expand to many times its original size, thereby increasing the available surface area for moisture removal. He suggested that changes in liquor temperature can be used to control the black liquor drop size. Reiche [13] also discussed flashing in the black liquor sprays in recovery furnaces. He cited two possibilities: droplets could either burst into smaller particles, or expand to larger ones due to the formation of a tough skin around their surface that traps the vaporizing moisture.

There is a third atomization phenomenon sometimes found in recovery furnaces - liquor roping [3]. This occurs when the liquor temperature is too low for spray formation. The resulting liquor flow can quickly quench the char bed and cause a black out. It is reportedly caused by high liquor viscosity.

It is apparent upon reviewing the literature that atomization of black liquor is a complex problem about which little is known. Temperature is known to be important in establishing the drop size of the liquor spray, but the independent effects of viscosity and liquid flashing, both of which are affected by liquor temperature, is not clear.

2.2 Physical Properties of Black Liquor

Black liquor is an aqueous mixture of dissolved lignin, hemicelluloses, and extractives from the pulped wood, and inorganic compounds formed from the cooking liquor of sodium hydroxide and sodium sulfide. The exact composition and physical properties of any given black liquor is determined by the particular wood species and the pulping conditions. Because black liquor properties change dramatically with liquor solids content (the gravimetrially determined solid material remaining after the liquor is dried under a fixed set of conditions, usually expressed as a percent (see appendix II)) and temperature, it is common to characterize a liquor by these variables. For safe firing in the recovery furnace liquor, solids content must be kept above 58% [14]. The usual practice is to fire the liquor at higher solids content, typically 62-68%.

The physical properties of interest in liquor firing are: boiling point rise, density, viscosity, and surface tension. The measurement of these properties at solids contents greater than 55% is difficult. Even the measurement of black liquor solids content can vary by as much as five percent, depending on the test procedure used. Nevertheless, values for these properties have been measured and reported in the literature. A detailed literature review of these properties is reported in appendix III. The findings are summarized below.

Boiling point rise: The boiling point rise of black liquor has been investigated by a number of researchers. A good summary is given by Clay and Grace [15]. Figure III-1 shows the boiling point rise as a

function of liquor solids content. At a typical firing solids content of 65%, most investigators report the boiling point rise to be 12 to 15°C above the water boiling point.

Density: The measurement of liquor density is straightforward. A number of correlations of density versus solids content are given in the literature (see appendix III-4).

Surface tension: Although attempts have been made to measure the surface tension of black liquor at typical solids contents used in firing (60-70%), most published data are for 50% solids content and lower. However, Soderjelm and Koivuniem [16] did report a value for black liquor at 61% solids, but suspected its accuracy because of experimental difficulties. The extrapolation of published data to liquor solids contents in the firing range suggest that surface tension is likely to be between 30 and 40 dynes/cm.

Viscosity: Black liquor viscosity is a strong function of solids content and temperature. The published data for viscosity at a typical solids content used in liquor firing (65%) are compared in figure III-2. The values in this figure vary widely, but appear to cluster about two levels which differ by a factor of more than ten. No indication of which level is appropriate for any given liquor is given in the literature. Thus the viscosity of an unfamiliar liquor must be measured.

2.3 Atomization

A vast body of literature exists on theoretical and experimental studies of atomization. Of this, only a small portion is directly

applicable to this study. A search of the appropriate literature was made and is described fully in appendix II. What follows is a summary of the pertinent parts of this search.

The first requirement of any atomization study is to choose a suitable method of characterizing the drop size in the spray. All sprays contain a distribution of drop sizes; thus, a statistic of the distribution is necessary to represent the spray. The selection of the statistic is dictated by the objective of the study. Black liquor is atomized for evaporation and combustion; accordingly, a mean diameter appropriate to these processes – the Sauter mean diameter – was chosen. The Sauter mean diameter, d_{32}, is the diameter of the droplet having the same ratio of volume to surface area as the entire spray. This diameter is commonly used in atomization studies, and therefore readily permits comparison with other investigations in the field.

Although some theoretical analyses have been made to predict the characteristics of sprays from hydrodynamic first principles [17], in practice the prediction of spray drop size is made from correlations. These are based on experimental data and the known dimensionless parameters that govern atomization. This holds true for the grooved-core nozzle of interest in this study.

Although spray correlations can take many forms, most can be rewritten in the following non-dimensional and dimensional forms.

$$\frac{d_{xx}}{D} = K \ Re^{\alpha} \ We^{\beta} \tag{1}$$

$$d_{xx} = K \ D^a \ U^b \ \rho^c \ \mu^d \ \sigma^e \tag{2}$$

For hydraulic swirl nozzles, of which the grooved-core nozzle is one type, the correlation given by Lappel, Henry and Blake [18] is the most general, encompassing the data published in the literature prior to 1967. This correlation is:

$$\frac{d_{32}}{D} = 5.5 \ Re^{-0.20} \ We^{-0.25} \tag{3}$$

As with most spray correlations published in the literature, limitations on the applicability of this equation are not readily apparent or clearly stated. Nevertheless, they exist and may be important, as shown below.

First, the above correlation was developed for a generic nozzle type - the hydraulic swirl nozzle. This generic category encompasses many specific types and geometries of nozzles. This wide application introduces an error, and may well account for some of the 50% error found in the use of equation (3). Second, limits on the range of values of the variables for which a correlation is applicable are usually not given, although it is well known in practice that practical operating limits exist. For any given nozzle and liquid there is a minimum operating pressure required to atomize the liquid. Just above this lower limit is an operating range over which only partial or incomplete atomization occurs. Eventually, an operating range is reached where the spray becomes fully developed [19]. The correlations usually apply to

this latter range. An upper limit is reached when further increases in atomizer pressure do not further decrease the spray drop size. This upper limit is evident in graphs supplied by makers of commercial nozzles, e.g. [20].

Despite the foregoing shortcomings, correlations provide the only quantitative method for predicting the drop size of sprays and the dependence of drop size on specific variables.

2.4 Liquid Flashing

As stated earlier, black liquor firing in recovery furnaces takes place at temperatures near the liquor boiling point. When heated liquids under pressure flow into a region of lower pressure in which the liquid is superheated, the liquid must partially vaporize (flash) to attain equilibrium with its surroundings. This sudden flashing may affect spray formation. Past studies have shown that a superheated water jet emerging from a plain circular orifice can be shattered to a sufficient extent to form a spray comparable to that created by other atomizing devices [21]. In other words, flashing alone can produce a spray.

When a grooved-core nozzle is used in place of a circular orifice, a spray is formed without superheat. The effect of liquid superheat in this case is unknown. No information could be found on this subject in the literature, nor is the effect obvious. On one hand, flashing could diminish the spray drop size by superimposing a spray

forming mechanism on the one already there. On the other hand, it could lead to two phase flow within the nozzle and disrupt the existing spray forming mechanism.

As is evident from the discussion thus far, temperature is known to effect spray drop size, but the mechanism by which it does so and the magnitude of the changes it introduces are not known.

An experimental program to measure the effect of liquor temperature on spray formation is described in the following section. A major objective is to determine the relative importance of liquor viscosity and liquor superheat (flashing).

3. EXPERIMENTAL WORK

3.1 Objectives

The objective of this thesis was to determine the effect of temperature on the drop size of black liquor sprays in grooved-core nozzles near boiling point conditions. This first required establishing the independent effect of viscosity and liquid temperature on drop size. The strong interdependence between temperature and viscosity in black liquor did not permit this, so glycerol/water solutions were used to measure the effect of viscosity change without temperature change. Heated water was used to study liquid superheat. The experimental apparatus and program are discussed below.

3.2 Apparatus

3.2.1 Spray Bomb

Sprays were produced in a desk top apparatus from which liquids could be atomized through various nozzles at pressures up to 600 psig. This 'spray bomb' is shown in Figure 1. It consists of a 1.6 l stainless steel insulated cylinder to hold the liquid at elevated temperature and pressure. The latter was controlled by an air or nitrogen gas pad over the liquid regulated by a valve from a gas cylinder. The liquid temperature was varied by adjusting the voltage supplied to an internal 600 watt heater, with uniformity maintained by an internal stirrer magnetically coupled to a variable speed drive.

Figure 1:   Schematic of Spray Bomb Apparatus.

1   Nitrogen or air cylinder
2   "Spray Bomb"
3   High pressure reduction valve
4   Bleed valve
5   Variable speed stirrer
6   Internal heater
7   Insulated & heated tube
8   Nozzle
9   Main Flow Valve

(P) Pressure Gauge
(T) Thermocouple
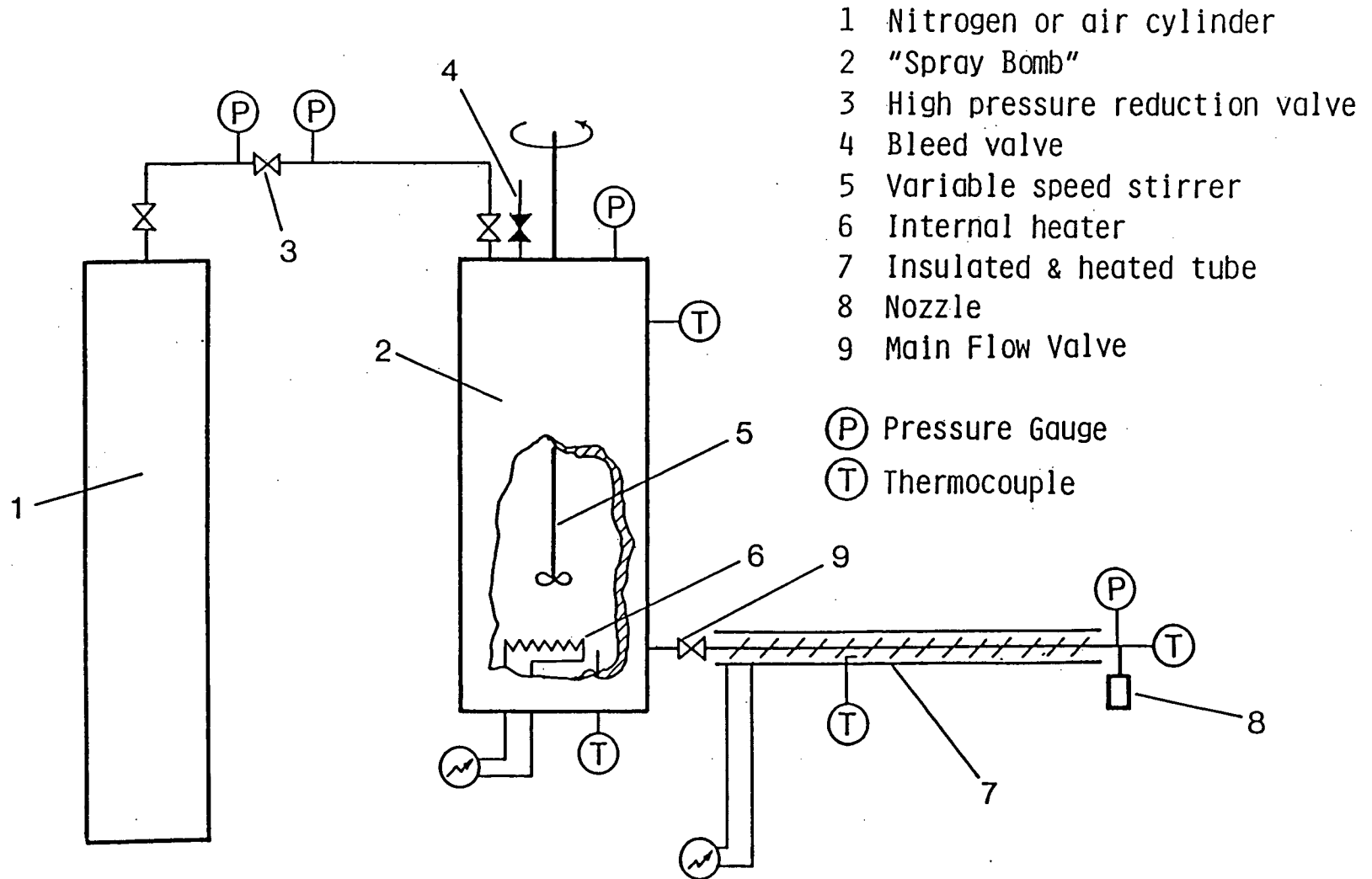
During spraying, the liquid was discharged through an insulated, heated tube to which various nozzles could be coupled. Temperatures and pressure were monitored inside the spray bomb and just upstream of the nozzle as shown in figure 1.

To contain the spray downstream of the nozzle, a spray curtain (76 cm x 46 cm ∅) of a 1/16" polycarbonate sheet was placed below the nozzle. A large plastic bag was fitted over the base of the spray curtain to collect the liquid for reuse. A blower was also fitted to the base to remove air entrained by the spray, thus preventing air currents from forming inside the curtain and carrying droplets back to the sample point. Two ports were cut into the spray curtain to hold and position the spray sampler.

Photographs of the spray apparatus are given in figure 2.

3.2.2 Sampling cell

The mean drop size of each spray was measured by capturing samples of the spray in a sample cell containing varsol. This capture technique, described by Rupe [22], permits the impinging droplets to retain their spherical shape by supporting them in an immisible fluid having a slightly lower specific gravity (varsol).

The sample cell consisted of a 9.6 mm diameter, 7 mm deep cylinder secured to a microscope slide. The slide surface, forming the bottom of the sample cell, had been previously coated with a silicone based surfactant to prevent the captured drops from wetting the glass surface.

Figure 2:   Layout of Spray Apparatus.
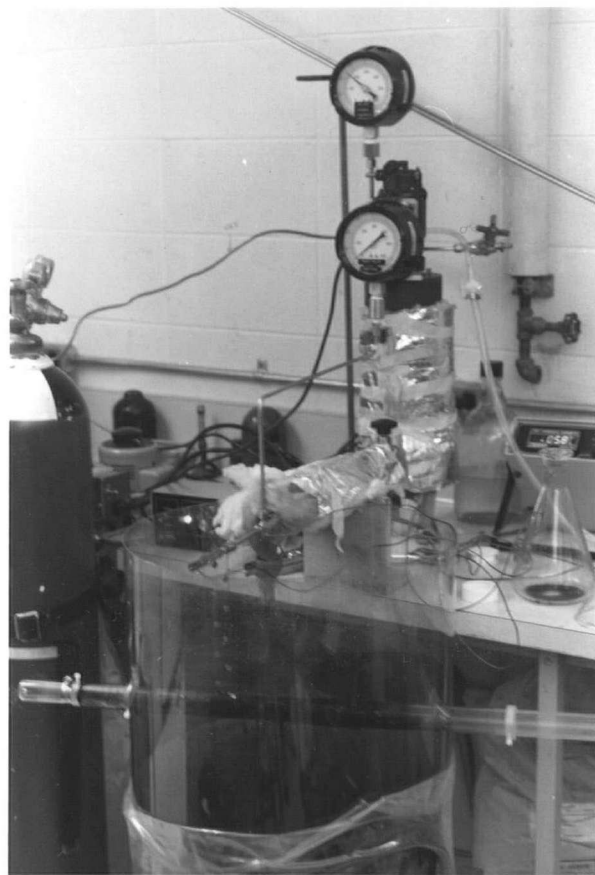
3.2.3 Sampler

The sampler consisted of a stationary plexiglass rod with a slot cut into its surface to hold the sample cell. A rotatable plexiglass tube having a "window" in line with the sample cell was fitted over the stationary rod. With the window closed, the sampler was positioned in the spray at the desired location. It was secured there by rings fitted to the outside of the spray curtain as shown in figure 3.

3.2.4 Nozzles Used

Commercial gooved-core nozzles manufactured by the Spraying Systems Company were chosen for this study. Five nozzles of the 1/4LNN series with orifice diameters of 0.0406 cm to 0.2184 cm were used [23]. Of available commercial small-scale nozzles these were the closest that could be found to the geometry of grooved-core nozzles used in recovery furnaces. Figure 4 shows a sketch of nozzle components and table 1 gives a list of important nozzle geometric parameters. While all the nozzles are grooved-core nozzles, they were not geometrically similar (having two, four, or six grooves, etc.). Nozzle parameter A, the ratio of the orifice area to the groove area, describes this difference to some extent.

3.3 Test Procedure

Each test run consisted of the following steps: sample preparation, liquid spraying, sampling, sample photography, and drop

Figure 3:   Spray Curtain and Sampler Details.

1 Spray Curtain
2 Nozzle
3 Sampling Device
4 Stationary Inner Rod
5 Rotatable Outer Cylinder
6 Adjustable Position Guides
7 Sample Cell
8 Window
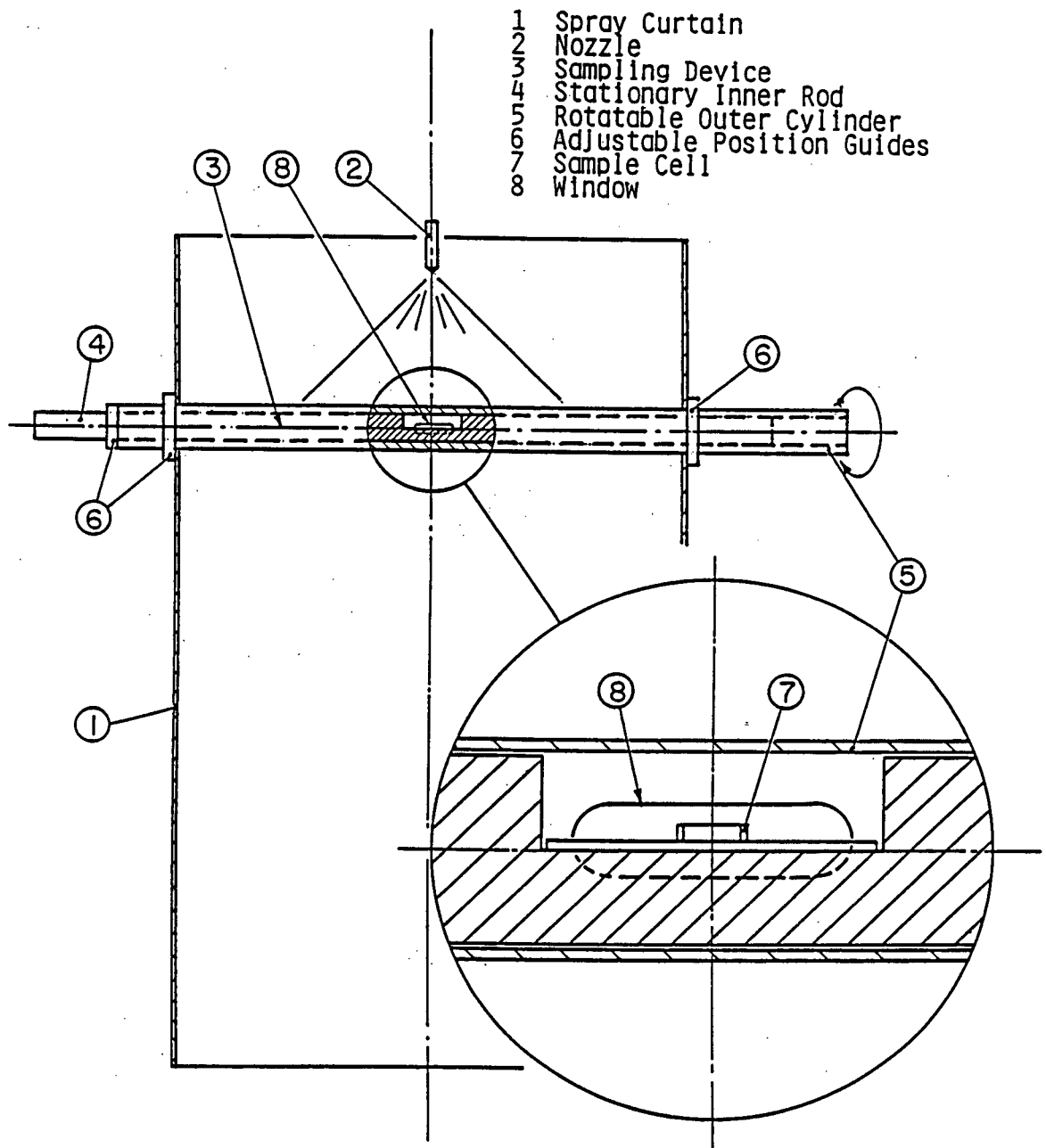
Figure 4: 1/4LNN Series Atomizing Nozzles Component Sketch.
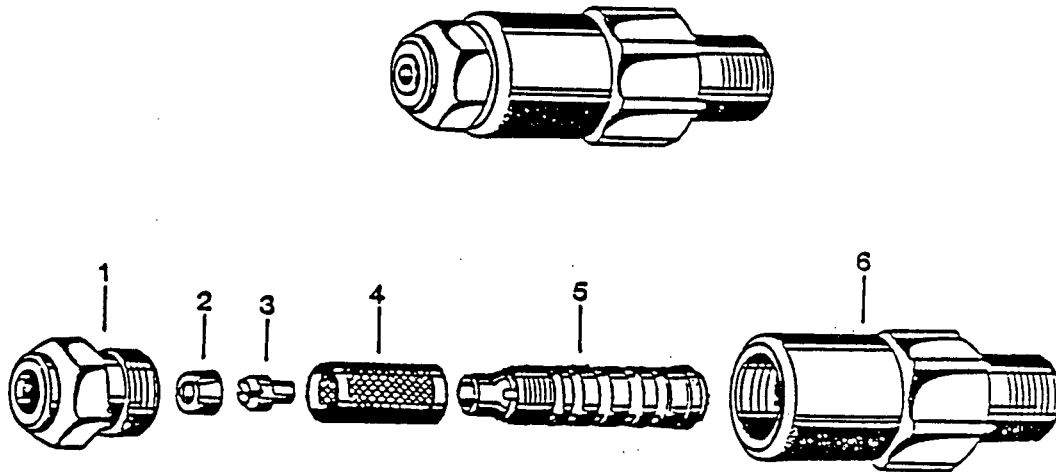
ITEM	PART NO.		DESCRIPTION
	BRASS	STAINLESS STEEL	
1	1206	1206-SS	Cap, Brass or Stainless Steel
2	1207-*-SS	1207-*-SS	Orifice Insert, Stainless Steel
3	1195-*-SS	1195-*-SS	Core Tip, Stainless Steel
4	2930-*-SS	2930-*-SS	Screen, Stainless Steel
5	1194-*	1194-*-SS	Core Tip Holder & Strainer Body Sub-Assembly, Brass or Stainless Steel
6	1210	1210-SS	Body, Brass or Stainless Steel, 1/4" NPT(M)

1/4LNN-- Atomizing Nozzle, Brass

1/4LNN-SS-- Atomizing Nozzle, Stainless Steel

*Specify Screen Mesh Size, Core Size or Insert Sizes

PARTS LIST		
1/4LNN-- AND 1/4LNN-SS-- ATOMIZING NOZZLES	**SPRAYING SYSTEMS CO.** *Engineers and Manufacturers*	
	NORTH AVENUE AT SCHMALE ROAD WHEATON, ILL.	
	DATE 2/13/81	NO. PL 1. 4LNN--

Table 1:   Summary of Grooved-Core Nozzle Dimensions

| Nozzle Designation | Orifice Diameter cm | Core Insert No. | Core | | | A |
			No. Grooves	Width cm	Height cm	
1/4LNN.6	.0406	206	2	.0152	.0254	1.6767
1/4LNN2	.0711	216	2	.0406	.0610	0.8016
1/4LNN8	.1524	225	2	.0635	.0940	1.5281
1/4LNN14	.1930	421	4	.0508	.1016	1.4170
1/4LNN26	.2184	625	6	.0635	.1219	0.8066

$$A = \frac{\text{Area of nozzle orifice}}{\text{Cross-sectional area of grooves upstream of nozzle orifice}}$$

size measurement. Each of these steps is described in detail in the following sections.

3.3.1 Sample Preparation and Liquid Spraying

Where necessary, liquids for spraying were prepared in advance. In the case of glycerol/water solutions, the correct proportions were mixed for the desired liquid viscosity. For black liquor, dilute black liquor from the mill had to be concentrated to the desired solids content. This was achieved by heating well-stirred weak black liquor ($\simeq$ 36% solids) on a hot plate while maintaining a nitrogen pad over the evaporating liquid.

The prepared liquids were then charged into the bomb. Where necessary, heating and stirring were used to maintain the desired test conditions. The liquid was then sprayed.

3.3.2 Spray Sampling and Sampling Location

All spray sampling was made at a fixed location. The vertical position was in a plane 14 cm below the nozzle, a distance at which all sprays were fully developed and the spray density was low enough for easy sampling. The horizontal position (measured from the nozzle centerline) was separately chosen for each test to be the location of greatest mass flow in the spray. This varied with the nozzle, liquid, and operating conditions. The means for determining this location is described in section 4.2.

Before sampling, the sample cell was prepared by half filling with varosol. It was then placed in the sampler. With the sampler

correctly positioned in the spray, droplets were captured by rotating the outer cylinder of the sampler to permit spray droplets to impinge on the cell. The exposure time of the cell was varied to obtain samples having an approximately equal droplet density.

3.3.3 Measurement of Drop Size

After sampling, the sample cell was completely filled with varosol and a standard microscope cover slip was placed over the cell to eliminate the miniscus. The cell was then photographed using a 35mm camera through a Wilde M20 microscope having an effective magnification of 13.6 times. The effective magnification of the microscope was determined by photographing a specially-constructed calibration cell containing a stage micrometer. This was photographed under identical conditions to those used for the test runs. The precise magnification factor determined from the image of the stage micrometer was recorded on the film. This permitted accurate measurement of droplet sizes.

To photograph the captured spray from a typical test run, the sample cell was divided into six to nine segments of equal area. Each segment was photographed onto one frame of a film. An identity number was assigned to each photograph, and a record was kept of each test condition (the liquid atomized, nozzle used, atomizer pressure and liquid temperature).

A number of photographs of tests made with water are shown in figure 5. These tests were made with the same nozzle but varying atomizer pressure.

Figure 5:   Drop Size Photographs of Representative
Water Sprays.
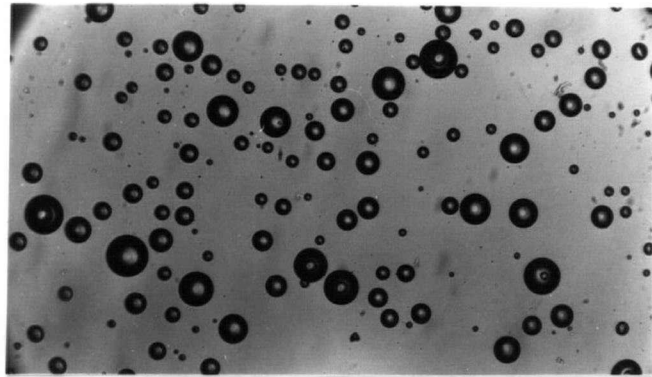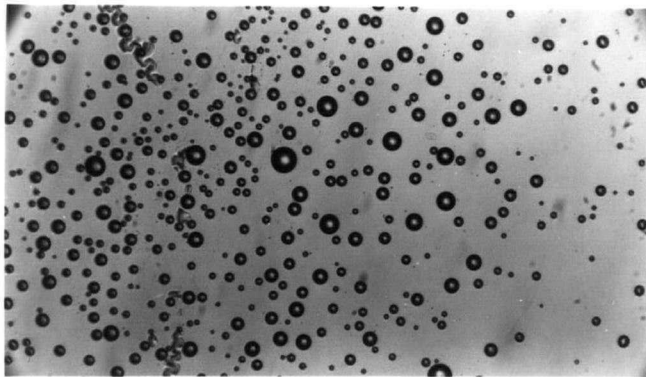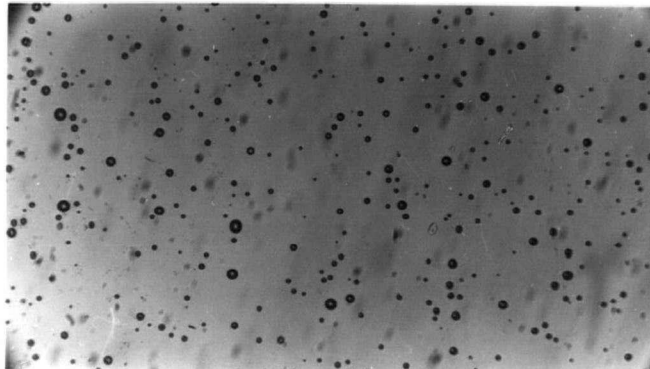
All tests made with the 1/4LNN2 grooved-core nozzle using water at 18°C sprayed into air. Samples taken from cone of spray. Magnification factor = 34.4X. Operating pressure:

(A)   50 psig
(B)   150 psig
(C)   200 psig

After use, the sample cell was flushed with water and dried with a gas stream (canned photographic propellant was used). Oven drying was used initially. However, the cell detached from the microscope slide after four or five cycles.

The diameters of the drops in the photographs were measured using a Zeiss MOP/40 Videoplan semi-automatic image analyser with video overlay. Constant magnification was used throughout these tests, permitting the measurements to be converted to their actual sizes by a single scale factor. The drop diameter measurements were stored on floppy disks in the Videoplan for later analysis. A schematic diagram of the image analyser components is given in figure 6.

This semi-automatic method of measurement proved to be very tedious: each of the 156 tests made required approximately two hours to complete. However, the procedure gave reliable measurements, even for the case of very dense sprays in which many droplets were touching.

3.4 Calculation of Spray Parameters

3.4.1 Mean Drop Size Diameter of Spray

As described earlier, the Sauter mean diameter, d_{32}, was used to characterize the sprays. This drop size was calculated from measured drop sizes by first transferring the data from the Videoplan's floppy disk files to the UBC central computer. Here, the program given in appendix IV was used to compute a number of statistical parameters, including the Sauter mean diameter, for each test.

Figure 6: Schematic Diagram of Videoplan Components.
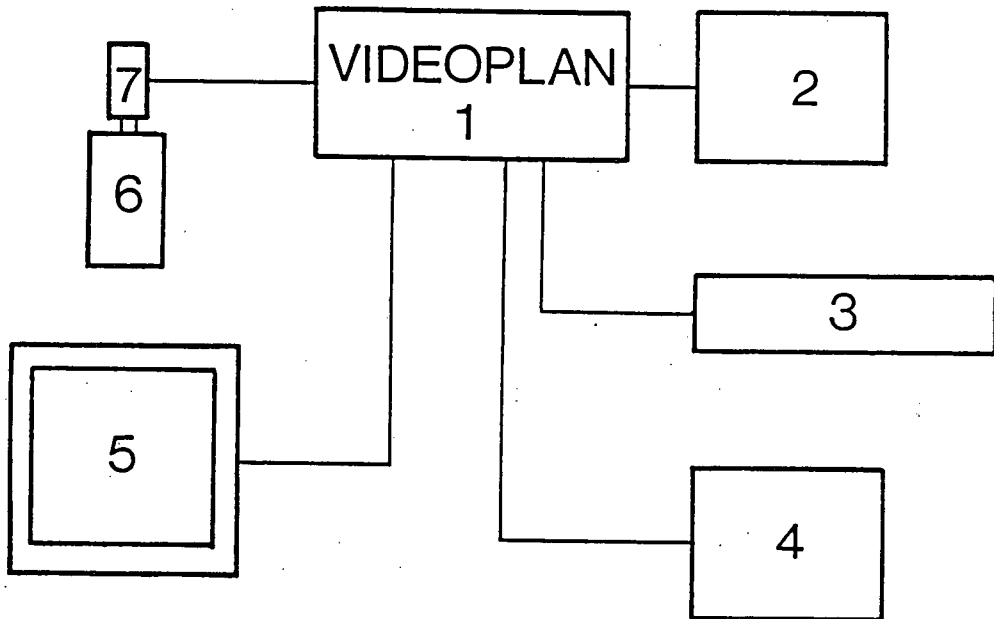
1. Videoplan: Main computer
2. Television Monitor
3. Computer Keyboard
4. Printer
5. Digitizer tablet
6. Microscope
7. High resolution television camera

3.4.2 Velocity

The velocity used throughout these tests was the superficial velocity at the nozzle orifice. This was calculated by dividing the known volumetric flow rate from the nozzle by the cross sectional area of the orifice. The volumetric flow rate was measured as a function of atomizer pressure for each of the liquids in the grooved-core nozzles studied, and is given in figure V-1.

Although the velocity determined by this method is not the velocity in the orifice (due to the presence of an air core and a tangential velocity component), it is the velocity commonly used by investigators in this field.

3.4.3 Orifice Diameter

The orifice diameter was obtained from the manufacturer's specifications for each nozzle [23]. These were listed previously in table 1.

3.4.4 Liquid Physical Properties

The physical properties of the liquids used in this study were obtained from standard reference tables or measured by standard procedures.

Water: The density, viscosity and surface tension of water were determined from tables published in the CRC handbook [24]. The viscosities of superheated water were estimated using a nomograph in Perry's handbook [25].

Glycerol/Water Solutions: Glycerol and water solutions were prepared to give the desired viscosity levels. The refractive index of samples taken from each test solution were made at 20°C using an Atago refractometer. This permitted a good estimate of the weight fraction of the solutions using tables in the CRC handbook [24]. The density was estimated using these same tables, while estimates of the surface tension were made using the International Critical Tables [26]. The viscosity of each solution was experimentally determined using a Haake RV 12 Rotovisco viscometer and the NV sensor system.

A summary of the properties for each glycerol/water solution is given in table V-2.

Black Liquor: One black liquor from a typical coastal kraft mill in British Columbia pulping a hemlock/balsam mixture was used in these tests. The liquor sample was obtained from the oxidized strong black liquor storage tank. It was diluted at the mill site from 50.5% to 35.6% solids content to maintain liquor homogeneity during transport and storage.

The physical properties of the liquor were estimated on the basis of liquor solids content. Density was determined using a correlation for the mill liquor tested. Surface tension was estimated to the best degree possible from findings reported in the literature (see appendix III). The viscosity of black liquor was measured as a function of liquor solids content and temperature, as described in the following section. Other properties of the liquor, including its chemical analysis, were also determined and are presented in appendix III.

3.5 Measurement of Black Liquor Viscosity

Black liquor viscosity was measured as a function of liquor solids content over the range of 38.2 to 68.8% solids and temperature over the range 26 to 127°C using a rotational viscometer (Haake RV12 Rotovisco). The sensor systems chosen for this analysis were the MV-400-I and the SV-400-II, details of which are given in table 2.

The viscosity measurements were made using the manufacturer's recommended procedures [27]. A nitrogen purge was maintained over the liquor sample to minimize oxidation. Viscosity was measured over the range of shear rates obtainable with the bob and cup used while maintaining test temperature to within ± 0.5°C.

3.6 Experimental Spray Tests

In total, 156 spray tests to determine spray drop sizes for various liquids under various conditions were carried out.

The first series consisted of 88 tests, using water and three glycerol/water solutions having viscosities of 14.7, 64.8 and 205 cp. These were atomized in the five 1/4LNN nozzles. The operating range for pressure was from 50 to 600 psig.

In the second test series, 42 tests were carried out using heated and superheated water. All five 1/4LNN series nozzles were used, and discharge velocity was maintained at 851 ± 43 cm/sec.

The final test series consisted of 26 tests using concentrated

Table 2:   Data for the Measuring Systems Used in Black Liquor Viscosity Work.

Sensor System	Temperature Range °C	Shear Rate Range S^{-1}	Sample Volume cm^3	Radius of Measuring Bob mm	Radius of Measuring Cup mm
MV-400-I	-60 to 300	2.34 to 1198	50	20.04	21
SV-400-II	-60 to 300	0.89 to 456	6	10.1	11.55

black liquor in one nozzle and at one fixed operating pressure. The

operating temperature was varied to pass through the estimated boiling

point of the liquor.

The conditions and results for all tests are given in Appendix V.

4. RESULTS AND DISCUSSION

4.1 Black Liquor Viscosity

The measured values for black liquor viscosity are presented in table V-1. Although the liquor did exhibit shear thinning during some tests as reported in the literature [28, 29], this effect was not observed for all tests. The reported viscosities were determined by plotting the shear stress against the shear rate and fitting a line by linear regression through the data points as shown in figure 7.

The viscosity values* were correlated with solids content and temperature using an equation similar to that suggested by Jagannath [30]. Agreement between this equation,

$$\mu(cp) = 0.0459 \exp\{1.22 \times 10^{-2} \; (\% \text{ solids}) + 4.20 \times 10^{-3} \; (\% \text{ solids})^2$$

$$+ \; 8.04 \times 10^{-2} \; (T°C) + 3.15 \times 10^{-4} \; (T°C)^2$$

$$- \; 3.25 \times 10^{-3} \; (\% \text{ solids}) \; (T°C)\} \qquad (4)$$

and the experimental data is shown in figure 8. This equation was used to extrapolate the measured data to determine the viscosity dependence of a 65% solids liquor as a function of temperature for comparison with the findings of other investigators. Agreement was good as shown in

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*Viscosity values of black liquor are "apparent viscosities" that do not take into account possible non-Newtonian behaviour at high solids content and high shear rates in nozzles.

Figure 7: Plots of Shear Stress Versus Shear Rate for Representative Black Liquor Tests.
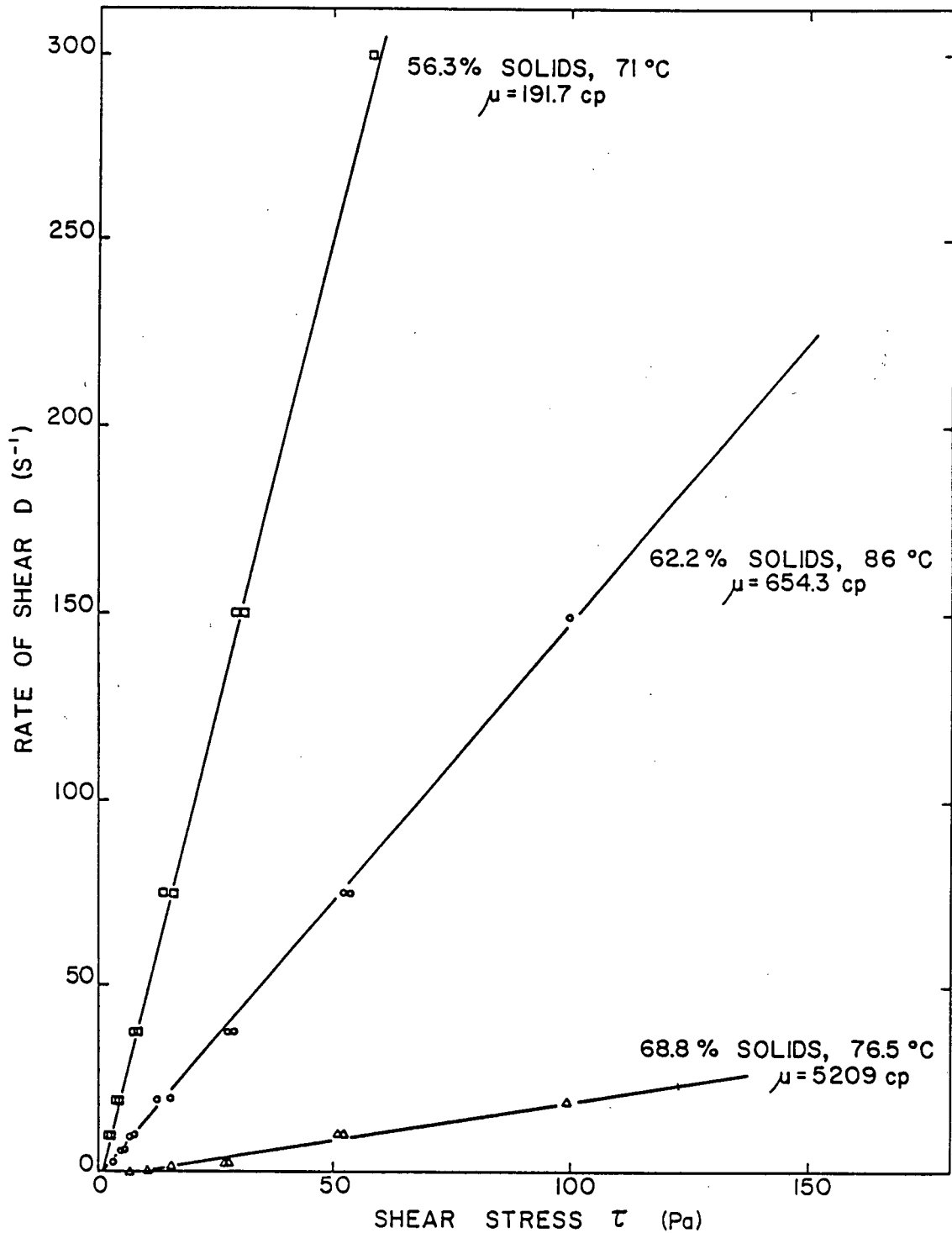
Figure 8:   Experimentally Determined Viscosities.
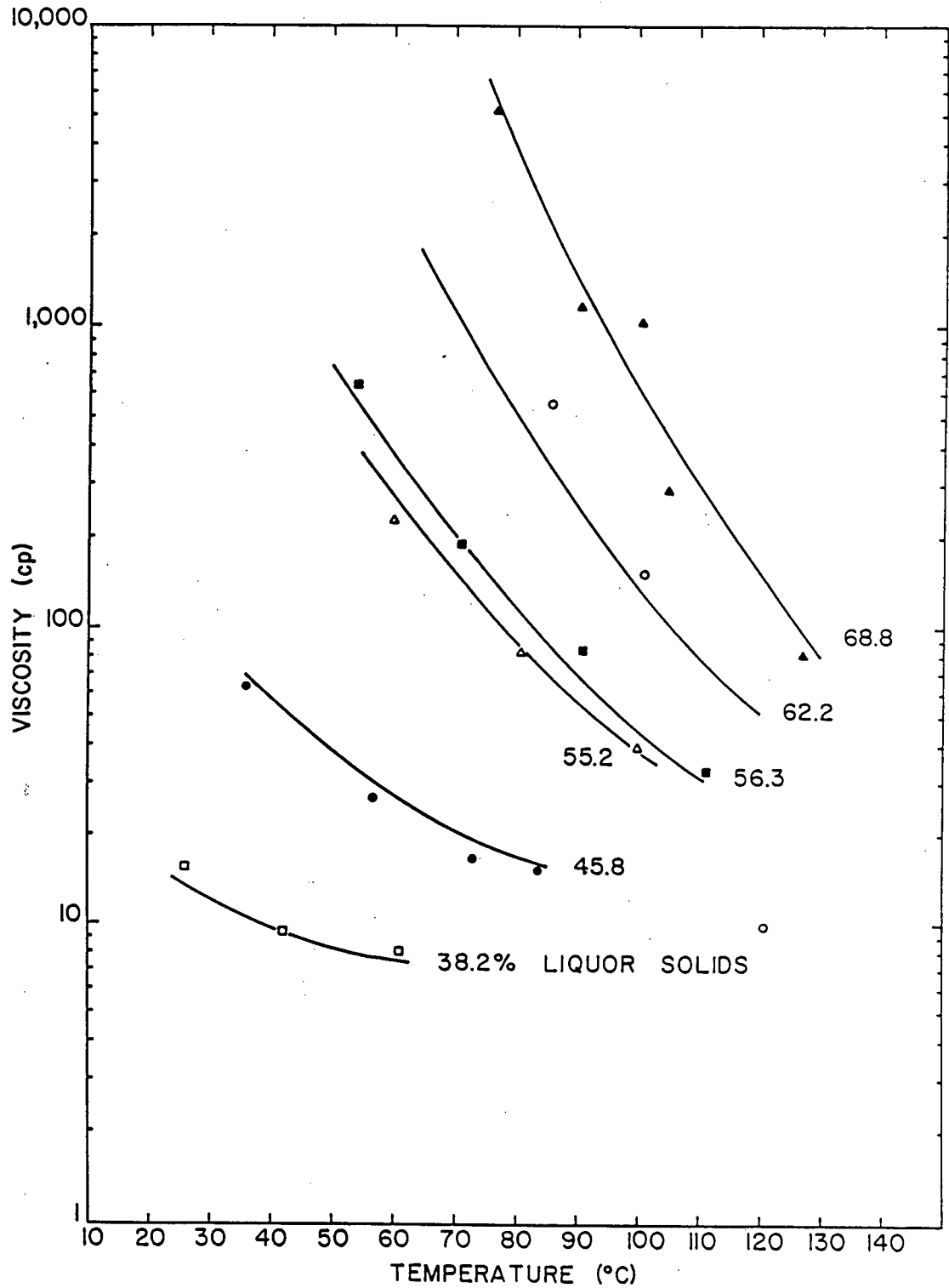
figure III-3. Thus, we may estimate the viscosity of the black liquor at the mill firing conditions (68% solids and 115°C) to be approximately 175 cp.

4.2 Spray Mass Distribution

A grooved-core nozzle produces a hollow cone spray with air in its core and the major part of the liquid mass flow concentrated in a conical ring about the nozzle axis. As described earlier (section 3.3.2), our horizontal location of sampling was in this conical ring. To determine its location, the mass flow profile was measured in 1 cm increments in a plane 13 cm below the nozzle. The mass profile for a typical operating condition (water at 18°C atomized through a 1/4LNN2 nozzle at 190-200 psig) is shown in figure 9. This distribution clearly shows the major mass flow to be centered in a cone approximately 7 cm from the nozzle. This corresponded to the visually observed center of mass flow and was the sampling position chosen for this test condition. The sample window indicated on figure 9 shows the size of the sample cell relative to the mass distribution in the spray.

Since a major objective of this thesis was to look for large changes in drop size caused by temperature change with other factors remaining constant, we only took samples from one position in the spray for each test. All sprays were sampled at a vertical location 14 cm below the nozzle and a radial distance corresponding to the major mass flow as determined by visual observation.

Figure 9: Spray Mass Flow Distribution.
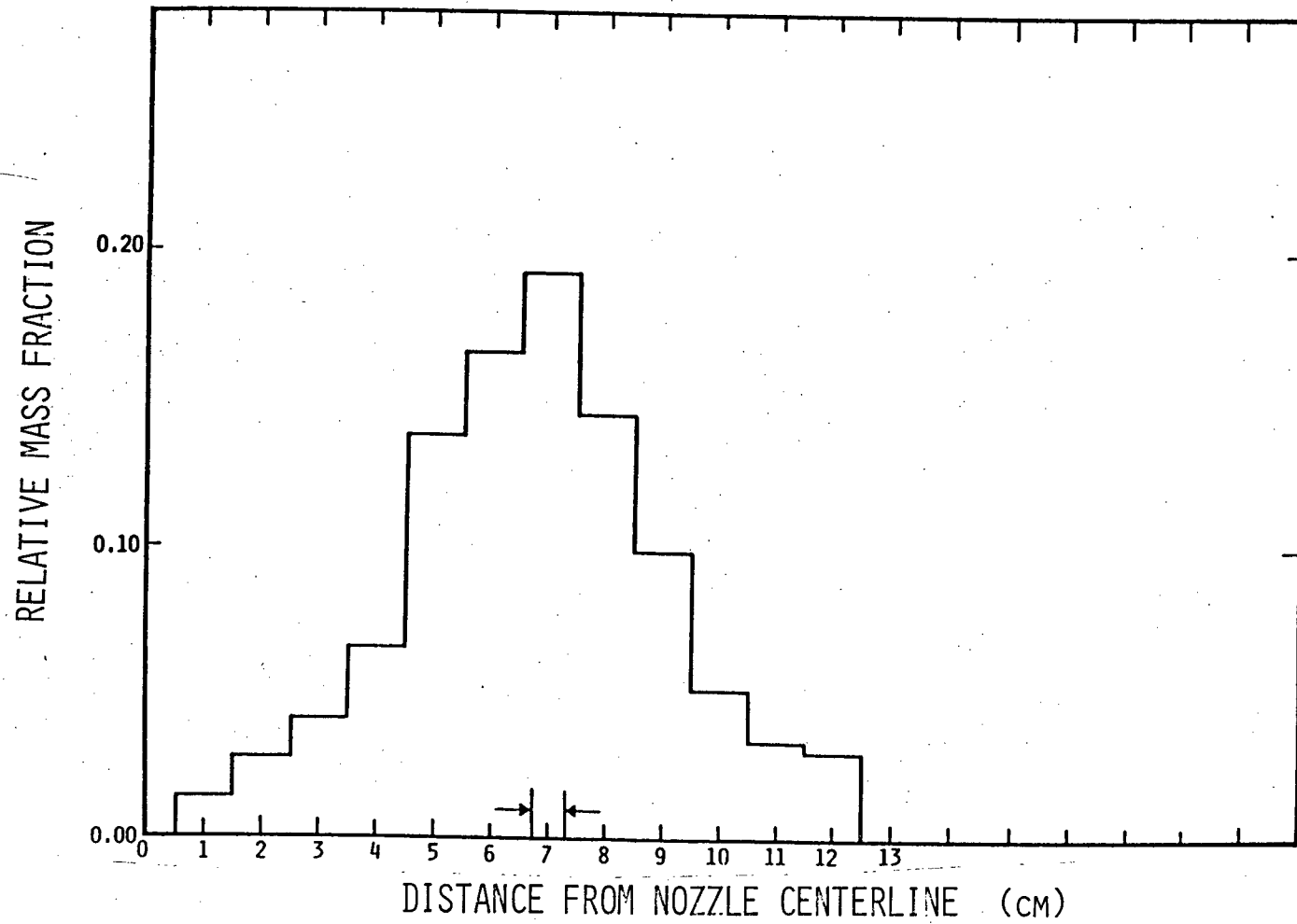
1/4LNN2 Nozzle, 190-200 psig, water at 18°C, sampled 13 cm below nozzle.

4.3 Analysis of Spray Drop Diameter Measurements

4.3.1 Mathematical Representation of Spray Drop Size Distribution

The drop size distribution of the test samples were found to be best described by the square-root normal distribution function given below:

$$f(x) = \frac{1}{s\sqrt{2\pi}} \exp\left\{\frac{-(x^{1/2} - \bar{x}^{1/2})^2}{2s^2}\right\} \tag{5}$$

The suitability of this equation is demonstrated by the goodness of a straight line fit to the plotted values of the square-root of the droplet diameter against its cumulative number fraction on probability paper. Such a fit for a number of tests is shown in figure 10. The appropriateness of the square-root normal distribution for characterizing spray drop size distributions is consistent with the findings of other investigators [31-34].

A commonly used alternative distribution, the log normal distribution [35], is plotted for the same tests in figure 11. It gives a poorer representation of the data, particularly at the ends of the distribution.

The Sauter mean diameter was estimated directly from the spray drop size data by the following equation:

Figure 10:   Square-Root Normal Representation of Drop Size Distributins.
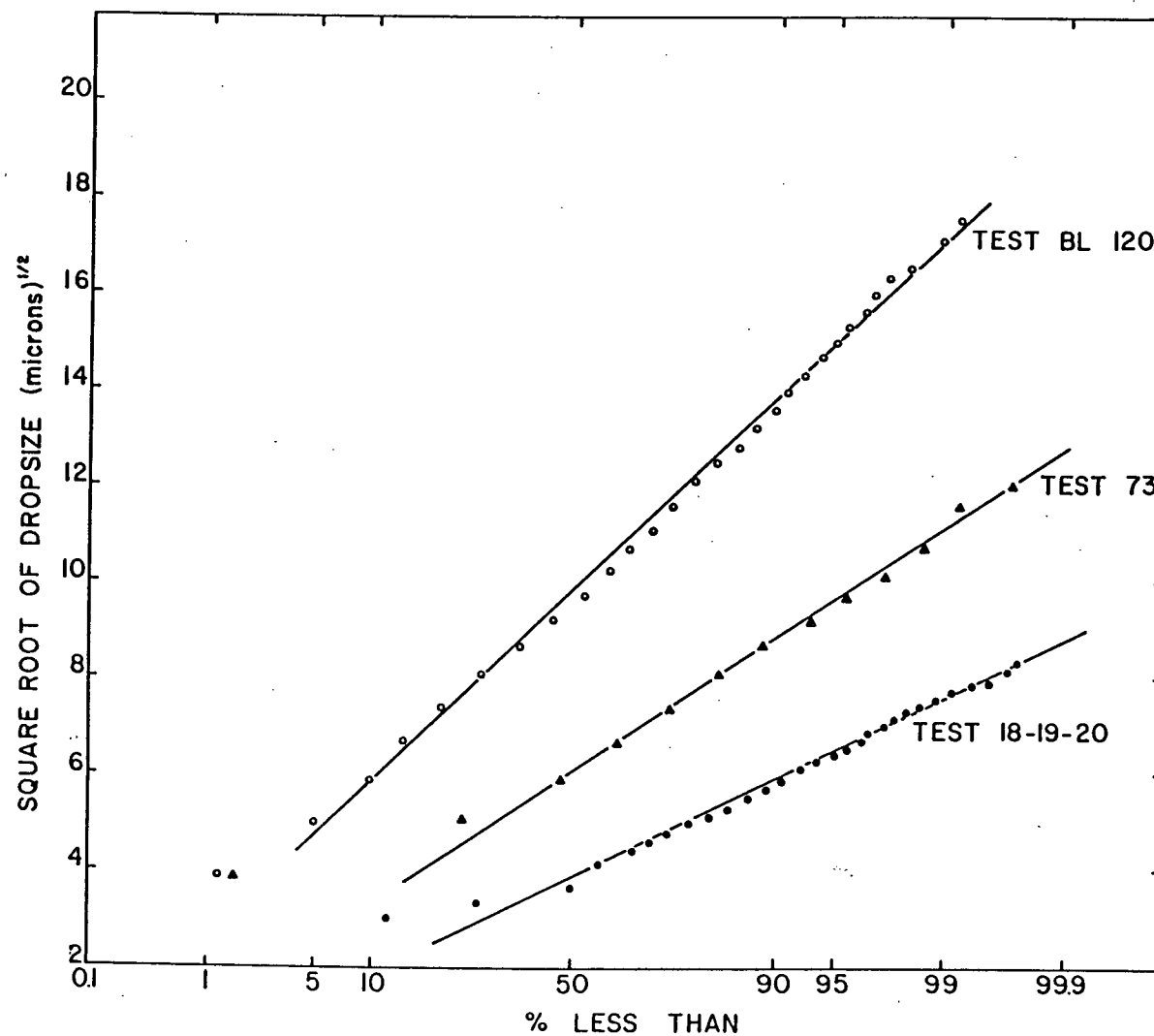
Figure 11: Log Normal Representation of Drop Size Distributions.
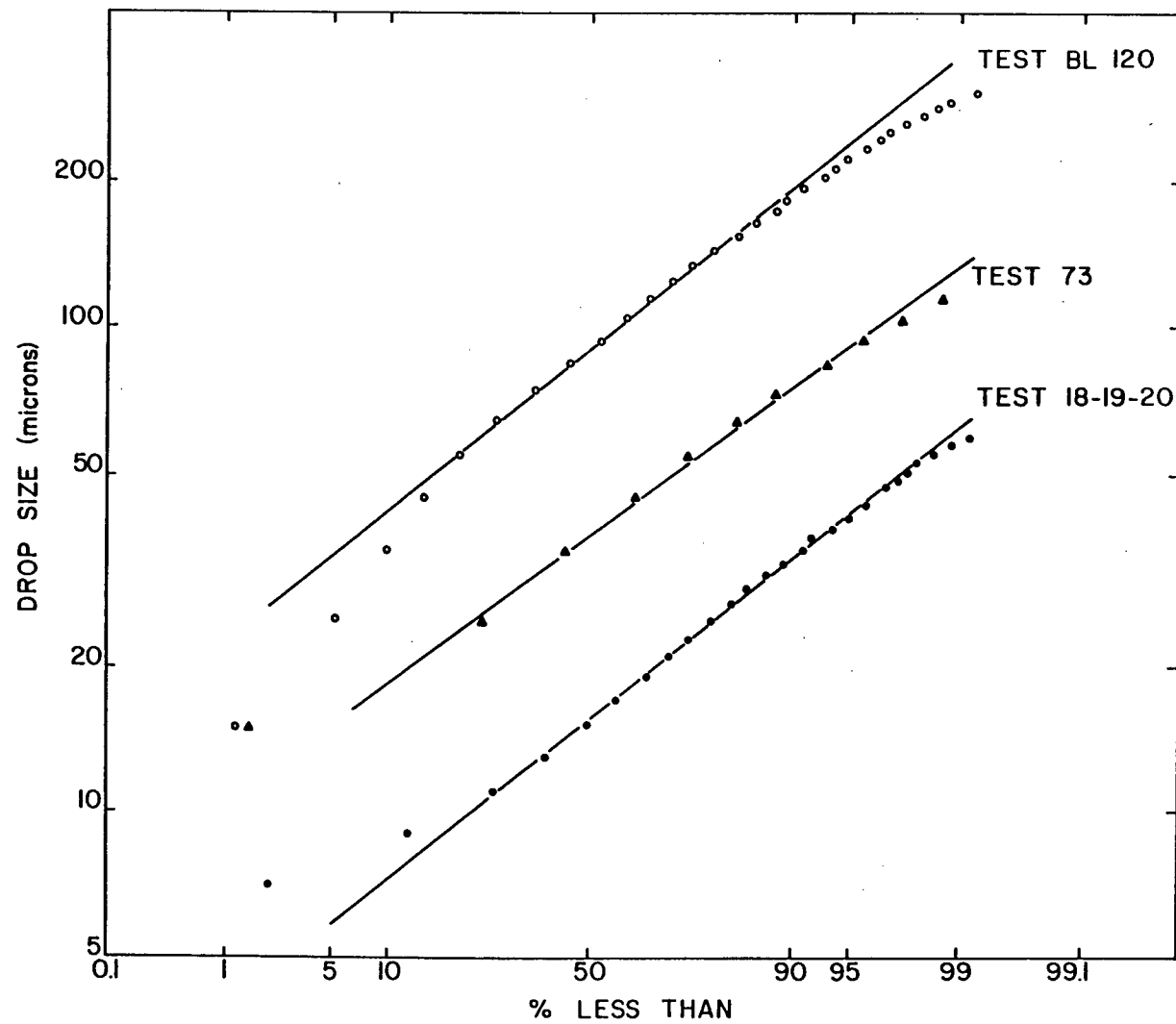
$$d_{32} = \frac{\sum\limits_{i=1}^{n} \phi_i \, d_i^3}{\sum\limits_{i=1}^{n} \phi_i \, d_i^2} \qquad\qquad (6)$$

This diameter is used to represent the mean drop size of the spray.

4.3.2 Determination of Parameters in Correlation Equations from Drop Size Measurements

Earlier in section 2.3, we described the use of correlation equations as the common means of predicting drop size in sprays. The suitability of these equations for this purpose was evaluated by fitting the equations to our data.

The mean diameters from tests conducted at room temperature (where little evaporation takes place (Series I, table V-3)), were fitted to the following two equations:

$$\frac{d_{xx}}{D} = K \; Re^{\alpha} \; We^{\beta} \qquad\qquad (1)$$

$$\frac{d_{xx}}{D} = K' \; Re^{\alpha'} \; We^{\beta'} \; A^{\gamma} \qquad\qquad (7)$$

Several mean diameters, d_{10}, d_{30} and d_{32} were used as the basis of these correlations. The curve fitting was achieved by a multiple regression program (UBC TRP [36]) after the equations had been linearized by taking logarithms. Each data point was weighted based on

an estimate of its error. This error estimate was based on the number
of droplets sampled in each test using a relationship developed by Bowen
and Davies [37] (see Appendix II).

Of these two equations, equation (1) proved to best represent the
data. The addition of the nozzle geometric parameter, A, to the
equation did not improve the fit of the data enough to warrant its
further use.

The power dependence of each spray variable was determined from
the fit obtained for the non-dimensional equation (1). By rewriting
this equation in its dimensional form (equation (2)), each exponent was
determined from the known values of α and β.

$$d_{xx} = K\ D^{(1+\alpha+\beta)}\ U^{(\alpha+2\beta)}\ \rho^{(\alpha+\beta)}\ \mu^{-\alpha}\ \sigma^{-\beta} \qquad (8)$$

Table 3 gives the values of the exponents so obtained. There is clearly
good agreement between the average power dependence found here and those
reported by Lappel et. al. [18]. In fact the measured values all lie
within the range reported by previous investigators (see Table II-3).

While the measured dependence of the powers of the various
variables agrees well with those reported in the literature, the
prediction of individual values of drop size is poor. For example, the
correlation determined for the Sauter mean diameter:

$$\frac{d_{32}}{D} = 1.56\ Re^{-.18}\ We^{-.18} \qquad (9)$$

Table 3: Power Dependence Found for Fundamental Spray Variables.

Variable	Mean Drop Size Correlated			Average	s	Recommended by Lappel et al. [18]
	d_{10}	d_{30}	d_{32}			
D	0.47	0.56	0.64	0.56	0.09	0.55
U	-0.86	-0.69	-0.53	-0.69	0.17	-0.70
ρ	-0.53	-0.44	-0.36	-0.44	0.09	-0.45
μ	0.19	0.19	0.18	0.19	0.01	0.20
σ	0.33	0.25	0.18	0.25	0.08	0.25

does not represent the data well, as is shown by the large scatter in figure 12. Thus, the precision for any individual point is low. The mean error for any single determination is approximately 50%. Such a large error may, however, be expected. When other investigators have specified confidence limits, they too report large errors of the order of 12% to 50% [18, 38].

There are a number of possible sources for the large error in equation (9). These are:

1. Nozzle geometry: Geometric dissimilarities between nozzles of one generic type (in this case the grooved-core nozzle) would change the atomization conditions (e.g., the axial and tangential velocity components) in ways that could not be accounted for by the simple equation forms. The geometric factor, A, did not account for these differences.

2. Sampling errors: The chosen sampling point, that is the cone of maximum liquid mass flow in the spray, may not be representative of the entire spray. Also, the sample may have been affected by the sampling technique.

3. Sample size: The number of droplets sampled in each test governs the accuracy with which the true population mean can be determined. For the majorty of tests the sample size was greater than 1000 drops, but in some cases sample sizes of less than 500 drops were obtained. For a test sample size of 500 drops, estimates by Bowen and Davies [37] place the error in estimating d_{32}, due to sample size alone, at 17.5%.

Figure 12: Comparison of Predicted and Measured Spray Drop Sizes.
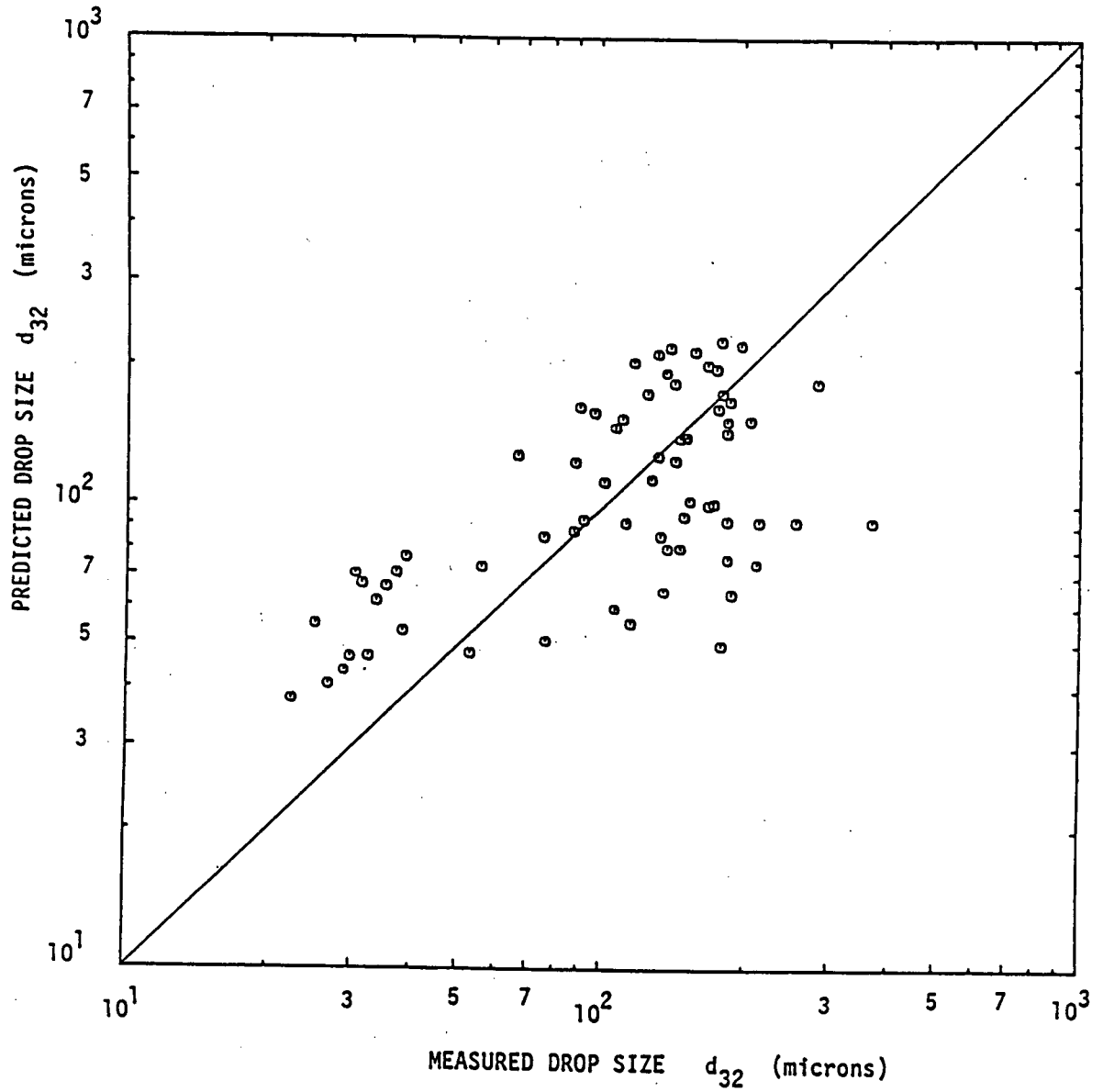
4. Limits on range of variables: All data obtained in test series I were used in evaluating the correlation, even data for the case where sprays had reached a limiting condition, i.e. where further changes in the independent variable did not further change the mean drop size. This factor was described in section 2.3, and is discussed in more detail in the following sections.

In summary, the correlation equation for Sauter mean diameter derived from these test data gives a power dependence of the spray variables in agreement with values published in the literature. However, the scatter of the data about the correlation equation is large. Therefore, there can be a large error when the equation is used to predict mean drop size for a given case. This error may be in part due to shortcomings in the measurements, but is also due in part to the inability of the correlation equation to adequately describe the atomization process. These factors limit the use of these equations for prediction of mean drop size.

4.3.3 Effect of Velocity on Mean Drop Size

As shown in the findings of the literature search (Section 2.2 and Appendix II), the flow velocity and nozzle orifice diameter are the two major variables that effect mean drop size. The effect of velocity on spray drop size, d_{32}, when atomizing water in the five grooved-core nozzles of this study is shown in figure 13.

As expected, there is considerable scatter in the data - a factor likely due to the errors discussed in the previous section. There is

Figure 13: Effect of Velocity on Mean Spray Drop Size.
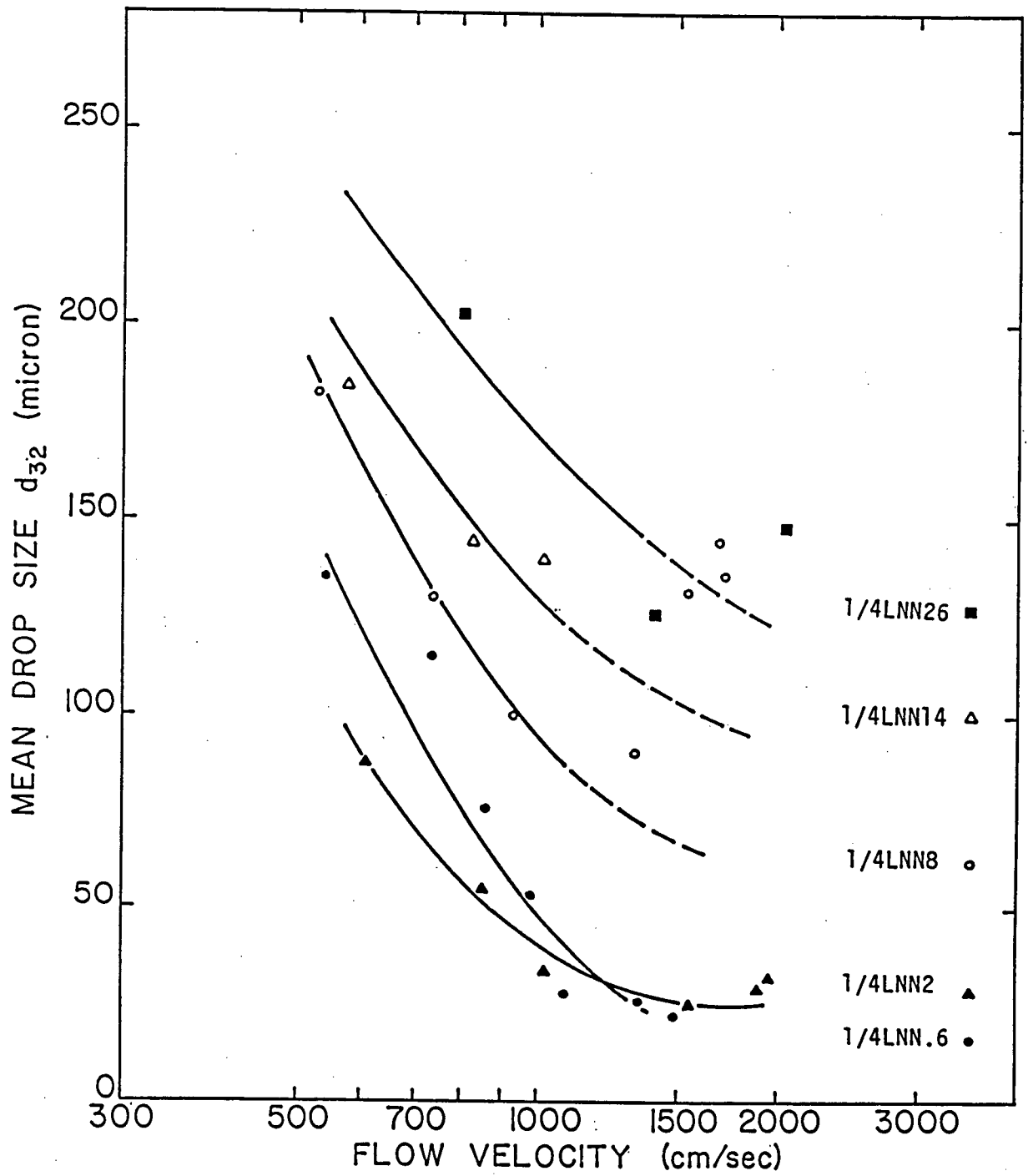
also an unexpected decrease in mean drop size produced when the nozzle orifice diameter is increased from 0.0406 cm to 0.0711 cm. This finding cannot be explained, even by geometric differences between the two nozzles.

The general finding of the data presented in figure 13 is that, for a given nozzle, the mean spray drop size decreases as velocity increases. This is consistent with the prediction of the correlation equations discussed earlier. In the case of the 1/4LNN2 nozzle, there is no further decrease in drop size above a flow velocity of approximately 1100 cm/sec. This finding, which agrees with the data supplied by the nozzle manufacturer [20], suggests a limiting drop size rather than an indefinitely decreasing drop size as the flow velocity is increased. This is an example of a limit on the applicability of the correlation equations that is found in practice but not always indicated in the literature.

4.3.4 Effect of Viscosity on Mean Drop Size

The effect of fluid viscosity on the drop size of sprays was evaluated in one nozzle, the 1/4LNN2 nozzle. The results are shown in figure 14. These findings show that, as the viscosity increases, the drop size of the spray increases (other factors remaining constant). This is predicted by the correlation equations. Here too there are limits of viscosity over which this effect takes place. Some viscous fluids could not be atomized even at the highest operating pressures attainable in the test apparatus (600 psig).

Figure 14: Effect of Viscosity on Mean Spray Drop Size.
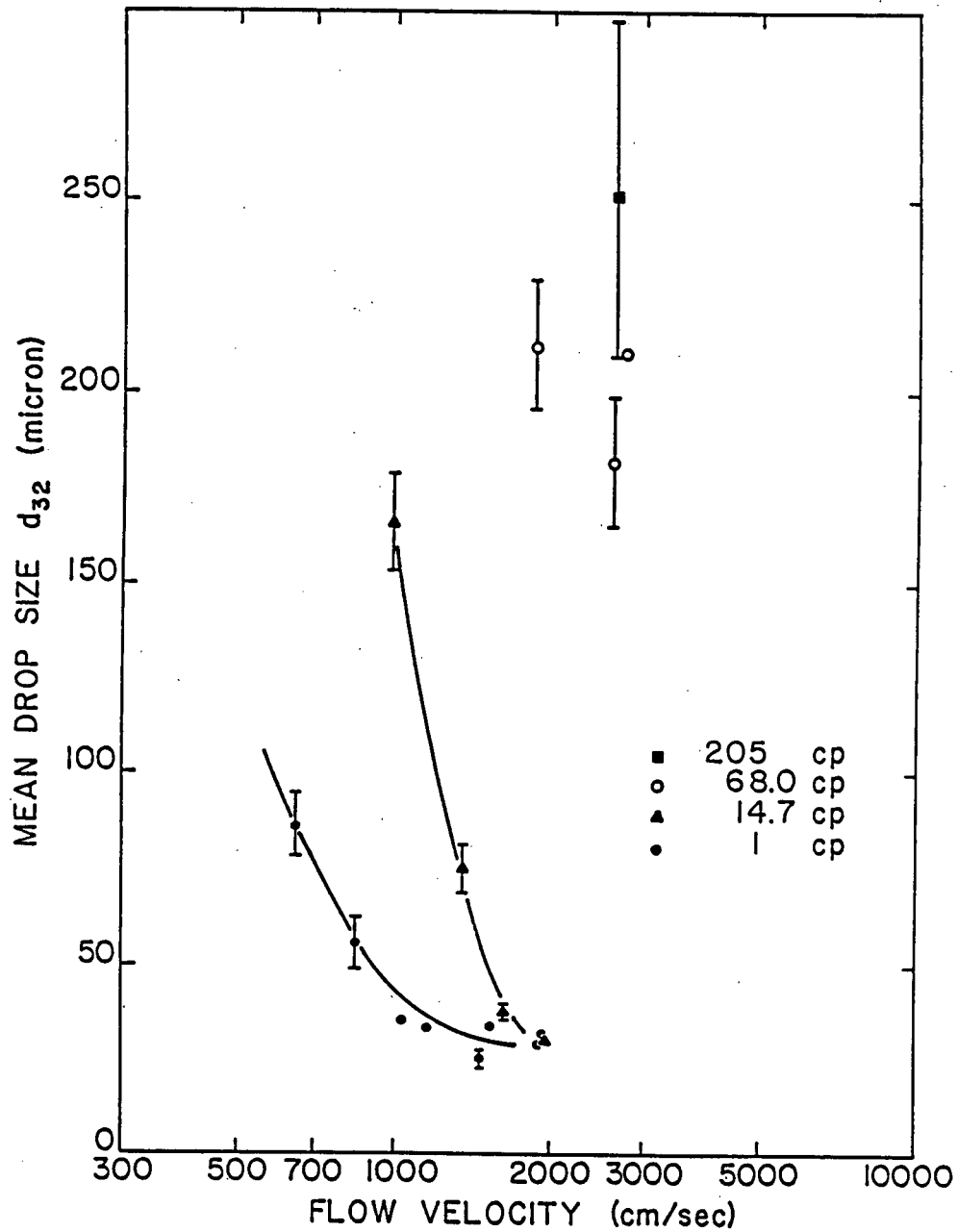
Spraying Systems Company 1/4LNN2 grooved-core nozzle.
Orifice diameter = 0.0711 cm.

4.4 Results of Spraying Superheated Water

As discussed in section 2.4, the sudden flashing (vapor generation) inside a superheated liquid jet can significantly affect atomization. In the case of a liquid jet issuing from a circular orifice, it can shatter the jet to form a spray.

A Spraying Systems Company 1/4TT000009 nozzle having an orifice diameter of 0.0203 cm was used to produce a solid liquid jet of water. As is shown in figure 15, this jet was almost completely shattered when the water temperature was increased to 140°C. This concurs with the findings of Brown and York [21], who found that 46°C of superheat was required to completely shatter a 0.0787 cm liquid jet.

Although the shattering of liquid jets has been reported in several occasions in the literature [21, 39-43], as described earlier we could find no reported observations on the effect of liquid superheat on sprays from grooved-core nozzles. To determine what may happen in this case, we sprayed water through the five 1/4LNN nozzles described in section 3.2.4 at temperatures above and below its boiling point. For each nozzle, the operating pressure was adjusted to make the flow velocity equal in all tests. A tabulation of the findings is given in appendix V. They are described in detail below.

As the water temperature was progressively increased through its boiling point, we observed the formation of a fine mist inside the hollow cone of the spray. As shown in figure 16, the size of this inner core of mist grew as water superheat was increased. We also measured drop sizes in these sprays by sampling at two locations: at the spray

Figure 15: Effect of Liquid Superheat on a Simple Water Jet.

A　　　　　B　　　　　C　　　　　D
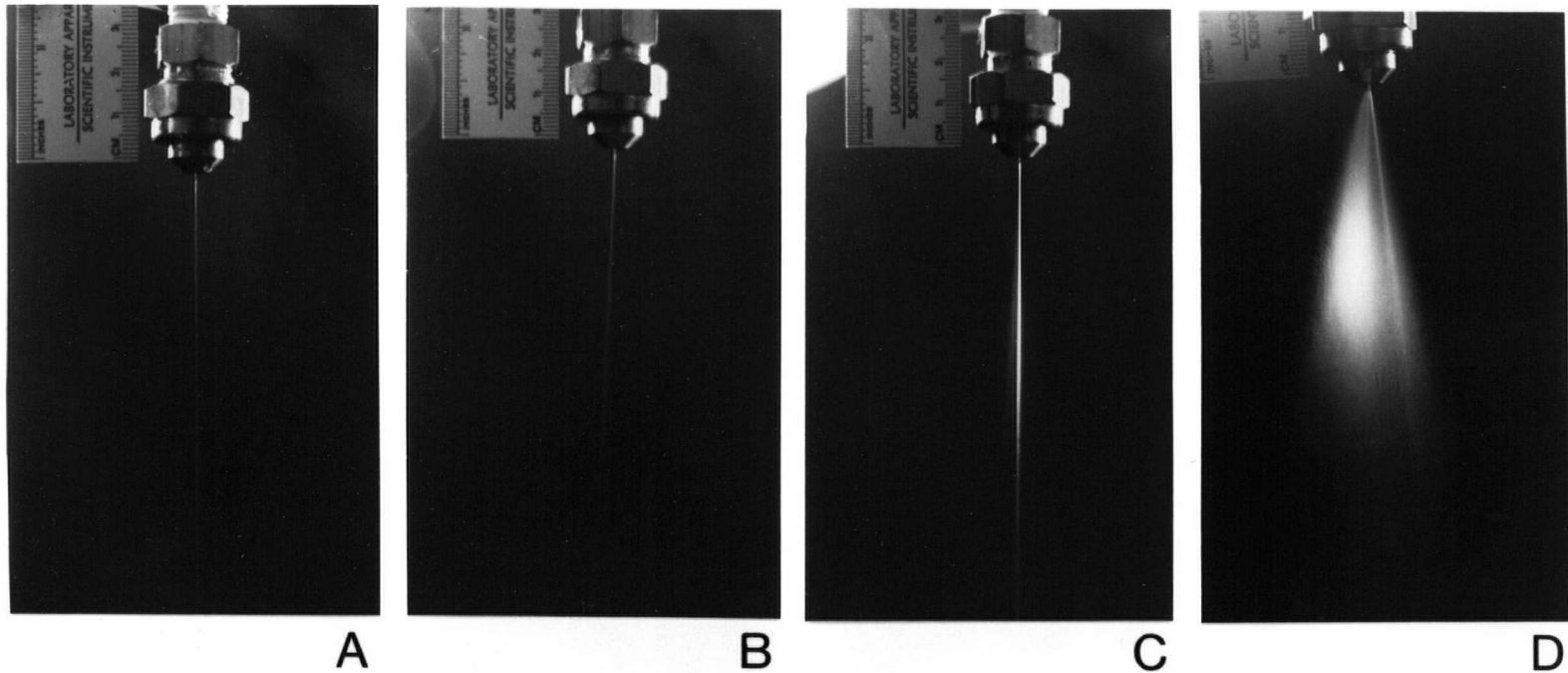
All water sprays made with a Spraying Systems Company 1/4TT000009 nozzle that produces a solid liquid stream. Tests made with water at 50 psig. Temperature: (A) 29°C, (B) 92°C (C) 118°C, (D) 140°C.

Figure 16: Effect of Liquid Superheat on Water Sprays
Produced from Grooved-Core Nozzles.

A   B   C

All water sprays are made with a Spraying System Company 1/4LNN2 nozzle operating at 100 psig.
Temperatures (A) 115°C, (B) 136°C, (C) 155°C.

cone (the normal sampling point), and at the centerline of the nozzle. The results for the 1/4LNN series nozzles, showing the Sauter mean diameter plotted against water temperature, are shown in figure 17.

The drop sizes measured in the cone (zone of major mass flow) of the spray are discussed first. For the 1/4LNN2 nozzle, the data show a near step increase in drop size when the water temperature is increased through its boiling point. This discontinuity is also present in the case of the 1/4LNN8 nozzle, though on a smaller scale. However, the two largest nozzles do not show any evidence of such a discontinuity.

The discontinuity in mean diameter size observed for the 1/4LNN2 nozzle is also apparent in the spray mass distribution. As shown in figure 18, when water is increased in temperature from 18°C to 85°C, there is a shift in the mass distribution of the spray towards smaller drop sizes. This trend of decreasing drop size with increasing temperature is reversed upon reaching 100°C. Here the distribution shifts to larger drop sizes. A further increase in temperature to 146°C does not drastically alter the mass distribution.

As shown in figure 17, the mean drop sizes measured on the spray centerline for the 1/4LNN2 and 1/4LNN8 nozzles are nearly the same at all temperatures (d_{32} = 25.0 ± 2.8 microns). For the two larger nozzles operating below the water boiling point, the drop sizes fall in this range. Above the boiling point, the measured drop size increases with temperature. However, for any given temperature, the drop size measured on the spray centerline is always less than that measured in the spray cone.

Figure 17:   Effect of Liquid Temperature on the Mean Drop
Size of Sprays Produced by Grooved-Core Nozzles
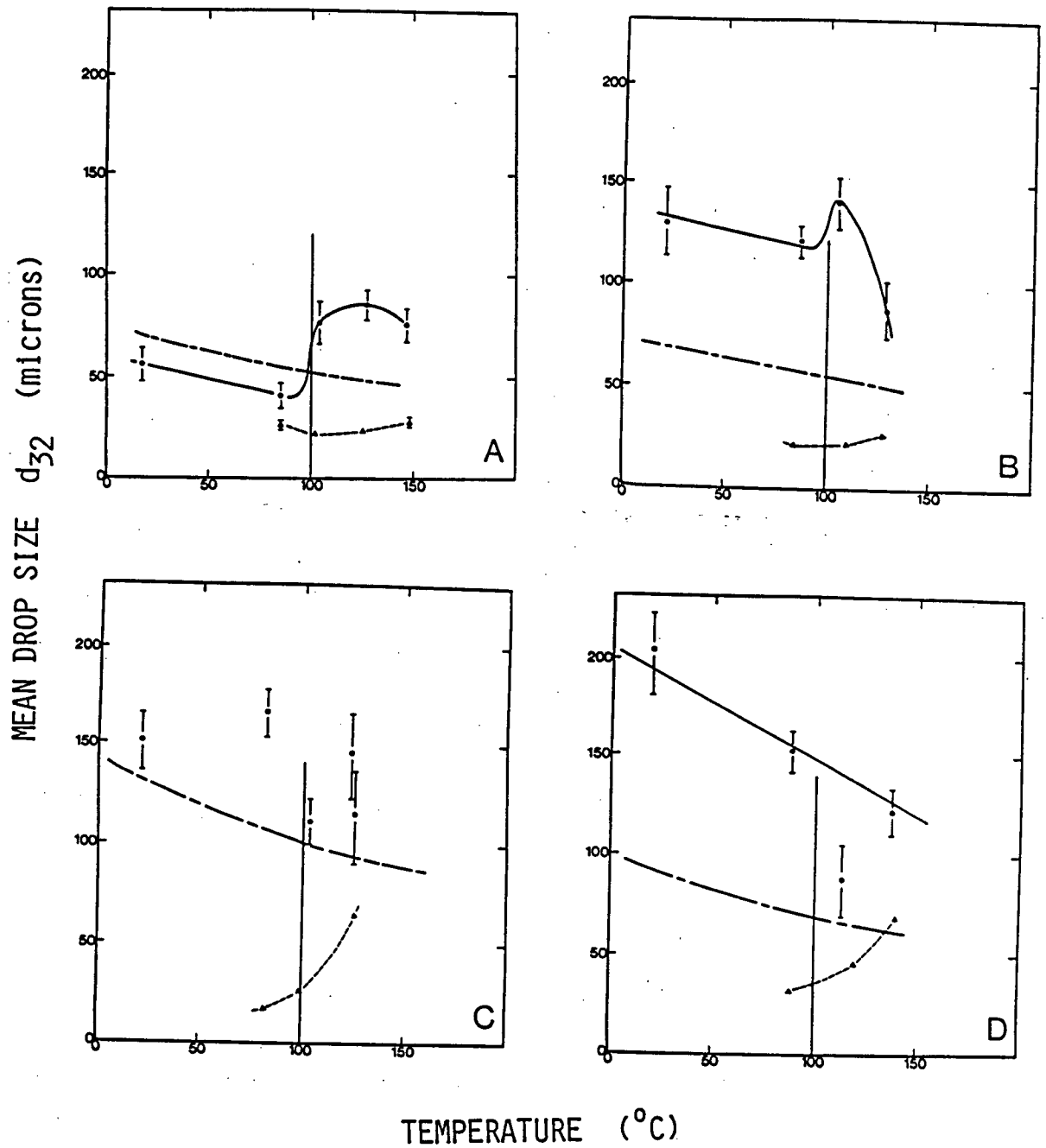
Flow velocity = 851 ± 43 cm/sec.
(A) 1/4LNN2, (B) 1/4LNN8, (C) 1/4LNN14, (D) 1/4LNN26.
● Sampled from cone of spray
▲ Sampled from center of spray
_____ Equation (9)

Figure 18: Effect of Water Temperature on the Mass
Distribution of Sprays Produced by
Grooved-Core Nozzles.
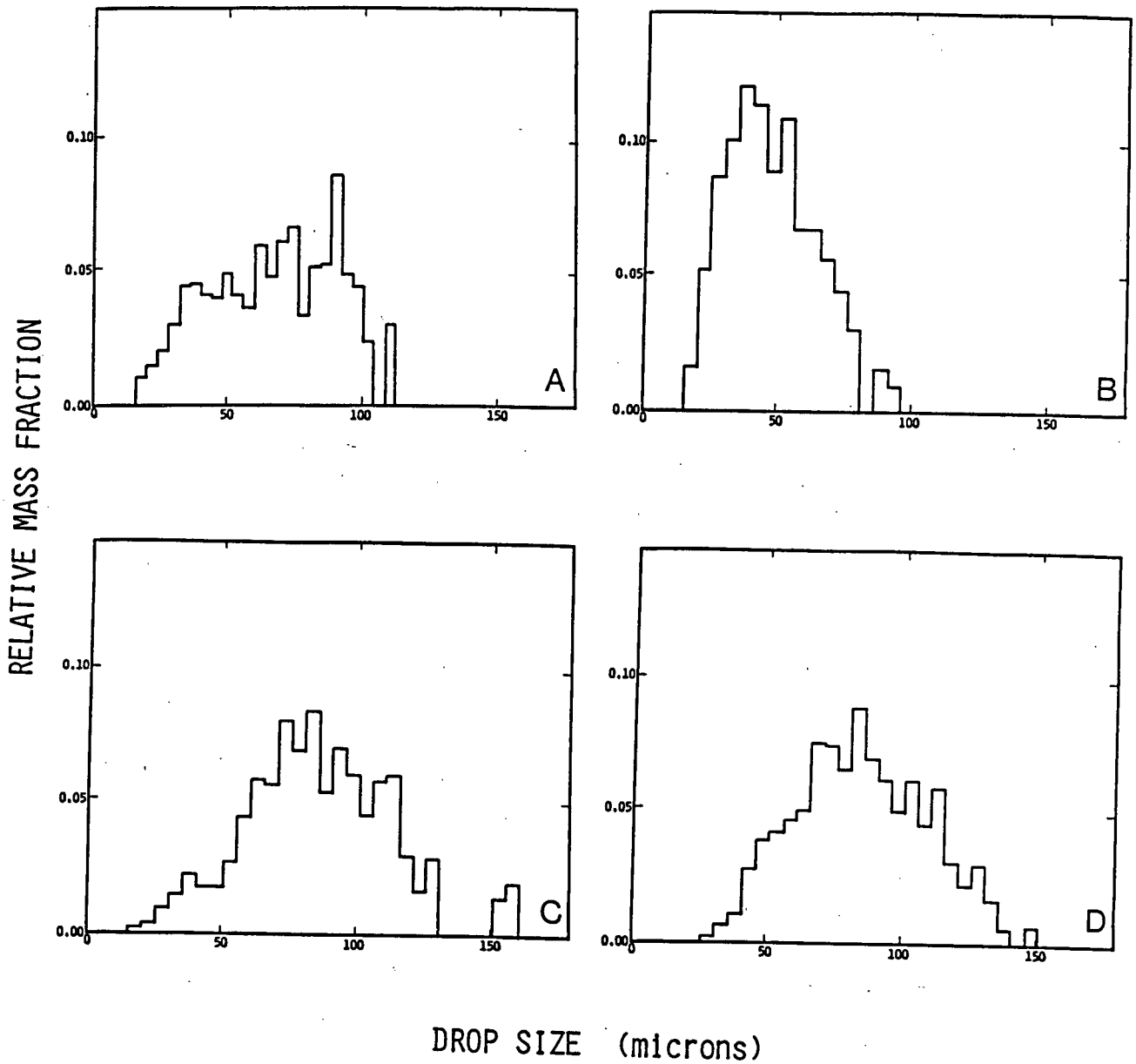
1/4LNN2 Nozzle, 100-110 psig, Samples taken from cone of spray.
Temperatures: (A) 18°C, (B) 85°C, (C) 100°C, (D) 146°C.

The small droplets described above are not always confined to the center of the spray. Figure 19 shows a drop size distribution sampled from the cone of a superheated water spray from the 1/4LNN2 nozzle. Here, the drop size distribution is clearly bimodal. This indicates that smaller drops may also be present in the cone of the spray.

It is not within the scope of this thesis to attempt a definitive explanation of these interesting observations. Our best hypothesis is that vaporization takes place in the grooves of the nozzle where the fluid flows at high velocity (and consequently low pressure). This vaporization may create a two phase flow in the nozzle that could disrupt the nozzle's normal atomization mechanism, thereby producing a coarser spray. Fine droplets may be produced by flashing of individual droplets. These remain largely in the central nozzle area and form the mist observed in the photographs.

From the spray tests using heated water, it is apparent that liquid superheat can introduce significant changes in the character of sprays produced by grooved-core nozzles. The largest effect was observed for the 1/4LNN2 nozzle. To determine if a similar effect may occur with black liquor, we carried out further spraying tests using black liquor and this particular nozzle.

4.5 Atomization of Black Liquor Above and Below its Boiling Point

The black liquor described earlier in section 3.4.4 was used in these spraying tests. A liquor solids content of approximately 56% was

Test run 93: 1/4LNN2 nozzle, 105 psig, 127°C, sample taken from cone of spray.

chosen because it was felt to be the most viscous liquid that could be atomized in the small nozzles. All tests were carried out using one nozzle (1/4LNN2) at one operating pressure (200 psig). The liquid temperature was varied from 100 to 136°C - a range which spanned the estimated liquor boiling point of 110°C (see figure III-1). Duplicate test runs were conducted on the same liquor at a solids content of 56%. The data for these test are tabulated in table V-6.

The black liquor spray was found in most respects to be similar in appearance to the hollow cone sprays of water and glycerol/water solutions. However, atomization did not appear to begin immediately at the orifice; rather a conical sheet formed, which then fragmented into droplets approximately 3 cm from the nozzle orifice. Such an extended sheet is common when viscous solutions are atomized. At the highest superheat used (136°C), a very small mist was observed inside the spray cone. Repeated attempts to sample from this mist failed, suggesting that the droplets were very small. Thus, all measurements of drop size in black liquor sprays were taken from the cone of the spray.

A comparison of droplet samples taken from sprays of (a) water, (b) 64.8% w/w glycerol/water, and (c) 56.3% solids black liquor at 120°C are shown in figure 20. These tests were all made using the 1/4LNN2 nozzle at the same flow velocity of approximately 1350 cm/sec.

Figure 21 compares the average Sauter mean diameter from the black liquor tests to the drop sizes of other liquids sprayed in the 1/4LNN2 nozzle. The expected trend of increasing drop size with increasing viscosity at a fixed velocity is evident, as shown in the

Figure 20:   Drop Size Photgraphs from Sprays of Water,
              Glycerol/Water and Black Liquor.
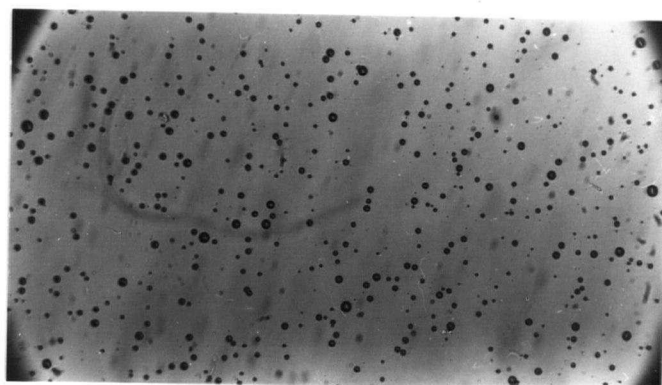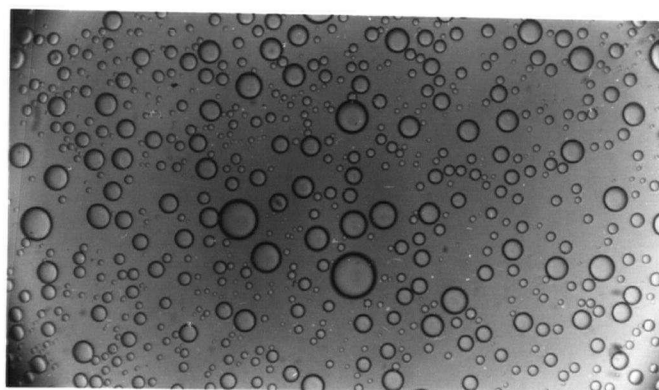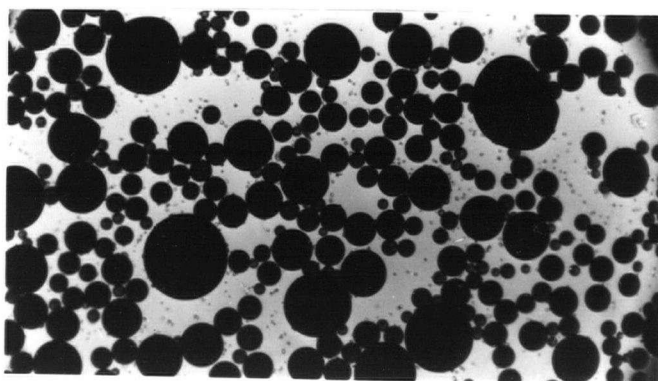
(A) Water, 200 psig, 18°C, μ = 1cp
(B) 64.8% w/w glycerol/water, 195 psig, 23°C, μ = 14.7cp
(C) 56.3% solids content West Coast Black Liquor, 210 psig, 120°C,
    μ = 18.9cp.
Magnification = 34.3X.

Figure 21: Effect of Viscosity on the Mean Drop Size of Black Liquor Sprays.
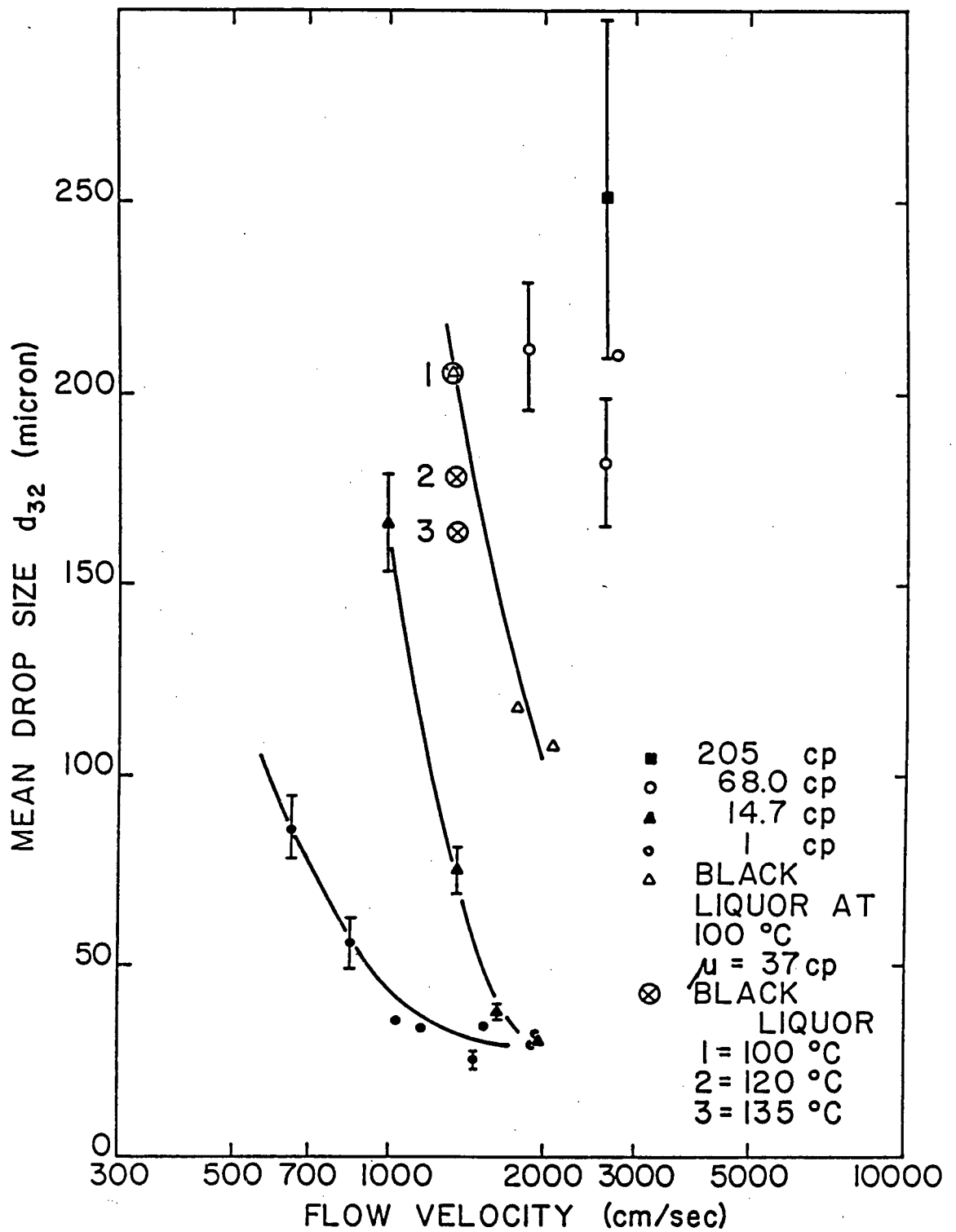
previous photographs. As expected, the mean drop size of the black liquor sprays decrease as their velocity increases.

In some of the black liquor sprays, the captured drops were not spherical, but rather appeared as deformed spheres and ligaments or cylinders. This phenomenon did not seem to occur for any particular operating condition. An example of this 'poor atomization' is shown in figure 22. While these particles were clearly not spherical, there was no noticable effect on the appearance of the spray.

A possible explanation for this phenomenon is that during the initial stages of sheet formation, where the sheet thins to the point of ligament formation, the liquor is cooled to a high viscosity such that the surface tension forces cannot pull the ligaments into spheres. The resulting sample then consists of ligaments formed in the early stages of spray formation. It is not clear why this effect was only observed in some cases. The samples that exhibited this 'poor atomization' were not analysed.

Most of the black liquor tests yielded spherical droplets, with the Sauter mean diameters from the tests showing a large amount of scatter. As described earlier, such large scatter is expected in spraying studies, and can be attributed to the difficulties involved in spraying and spray sampling. In our case, an additional source of error was the relatively small number of droplets sampled for some test conditions (see figure II-2). To increase the sample size, the two test runs made under similar conditions were combined to obtain a weighted average of the drop size for three temperature levels: 100°C, 120°C and

Figure 22:   Example of 'Poor Atomization' Found for Some
             Black Liquor Sprays.
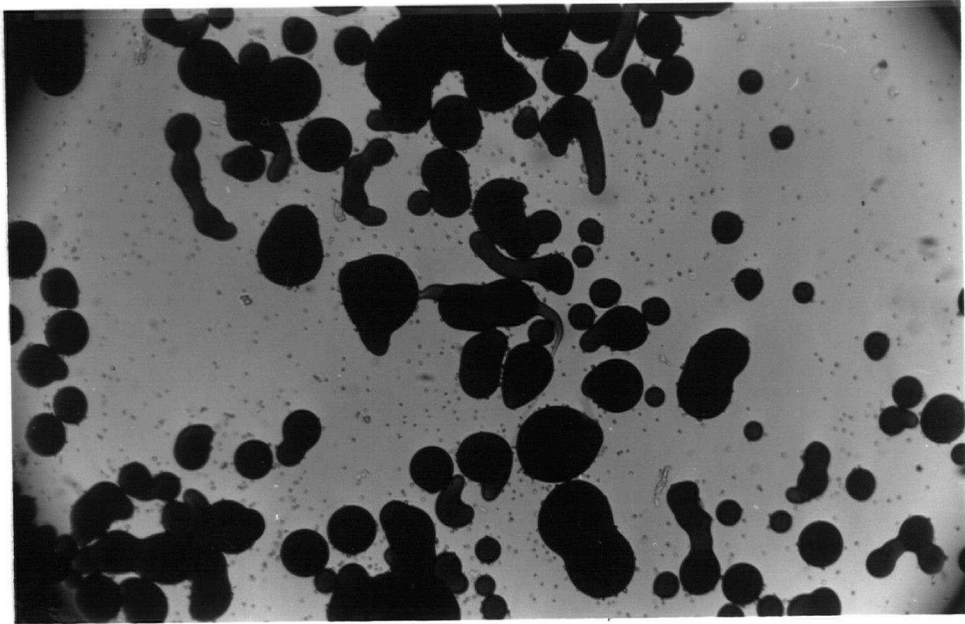
Test run 154: Black liquor at 55.2% solids content, Spraying Systems
Company 1/4LNN2 groved-core nozzle, orifice diameter = 0.0711 cm, liquor
temperature = 133°C, operating pressure = 205 psig.

135°C. The lower value is estimated to be approximately 10 degrees below the liquor boiling point (110°C), while the latter is 25°C above.

The measured mean diameters for the black liquor sprays are shown in figure 23. An estimate of the error associated with these averaged values was based on the standard deviation of the mean obtained by averaging the individual test points. This error is represented by error bars in figure 23. For comparison, the drop size predicted from correlation equation (9) using the measured properties of black liquor at the test conditions is also shown in the figure.

The data curves of figure 23 show several interesting findings. These are summarized in point form below:

1. The measured mean drop size of black liquor sprays are much larger than those predicted by correlation equation (9).

2. Although larger in absolute size than predicted, the dependence of drop size change on temperature change appears to be similar to that predicted by the correlation equation, i.e. lines through the measured and predicted drop sizes have similar slopes.

3. The drop size of black liquor does not show a discontinuous change through the boiling point as did water when sprayed through this nozzle.

It is not clear why the measured black liquor drop sizes are so much larger than those predicted by the correlation equation, although it may be noted that such is also the case for water sprayed through

Figure 23: Temperature Dependence of Black Liquor Sprays.

EXPERIMENTAL DATA

FROM CORRELATION EQUATION

$$\frac{d_{32}}{D} = 1.56\,Re^{-.18}\cdot We^{-.18}$$

MEAN DROP SIZE (microns)

LIQUOR TEMPERATURE (°C)
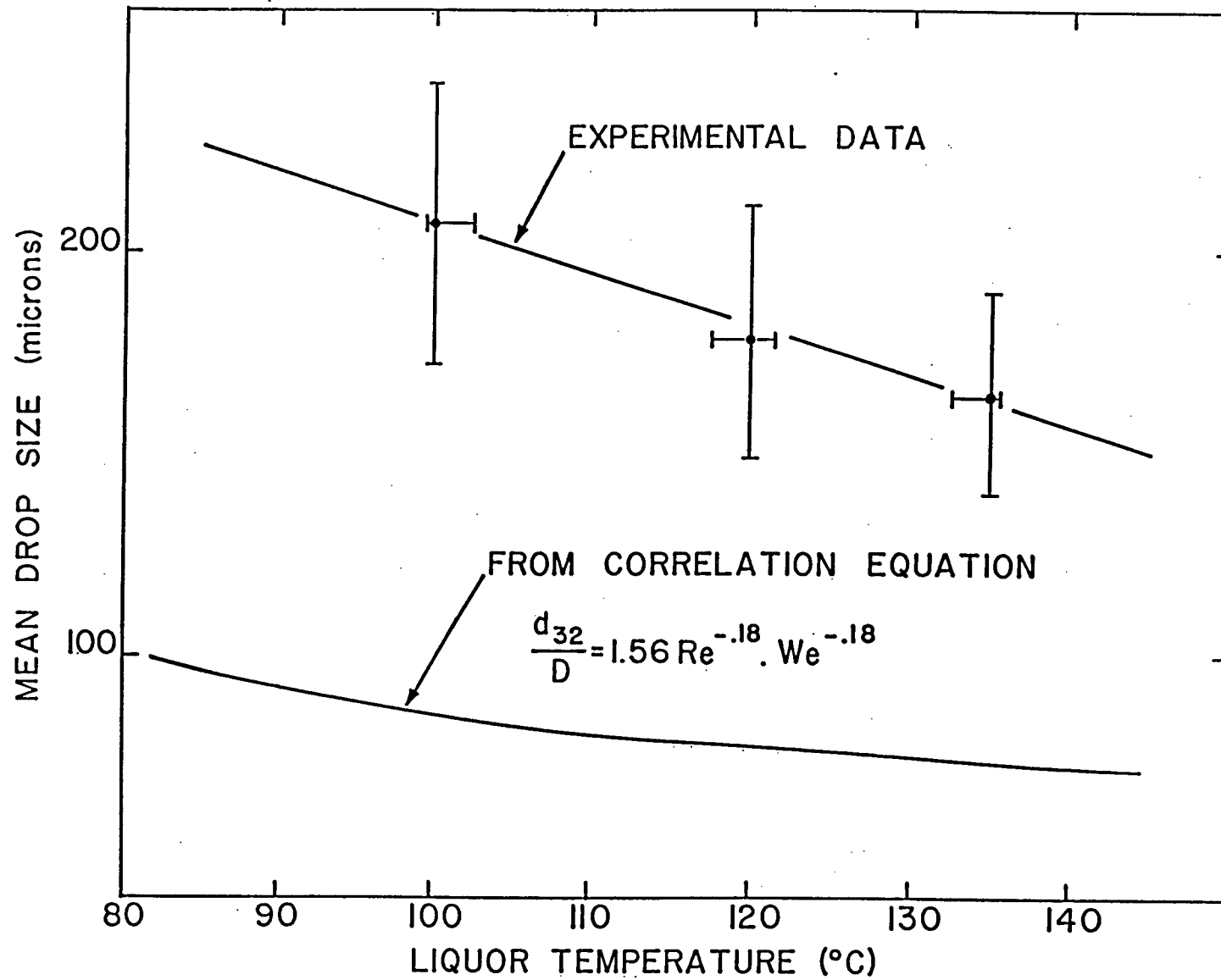
larger nozzles. For black liquor, a possible reason for the observed larger drop size may be the rapid cooling of the liquor when it is sprayed into a 23°C environment. The liquor cooling increases the liquor viscosity and, as a result, it is atomized as a more viscous liquid than is thought to be the case. However, extrapolation of the theoretical curve to the level of lower temperature required to produce the measured drop size suggests that the liquor temperature would have to fall below room temperature for it to account for this effect. Thus rapid cooling does not appear to account for the large drop sizes measured in black liquor sprays.

While the cause of the larger than predicted size is not clear, it is evident that the change in drop size with temperature through the boiling point is not discontinuous. Rather, it is a smooth change, having a slope similar to the slope of the correlation equation. This suggests that the change in drop size with change in temperature can be accounted for by change in viscosity - the only property in the correlation equation to vary significantly with temperature.

The nature of the change in drop size with temperature is further illustrated by the mass-weighted distribution of drop sizes of the black liquor sprays. These are shown in figure 24. It is evident that as the black liquor temperature increases, there is a shift in the distribution to smaller drops. Thus, under the conditions of these tests, it appears that increasing temperature of black liquor through its boiling point does not radically change the Sauter mean diameter of the spray. Rather, it shifts the drop size distribution slightly towards smaller droplets.

Figure 24: Mass Distribution of Black Liquor Sprays.

RELATIVE MASS FRACTION

DROP SIZE (microns)
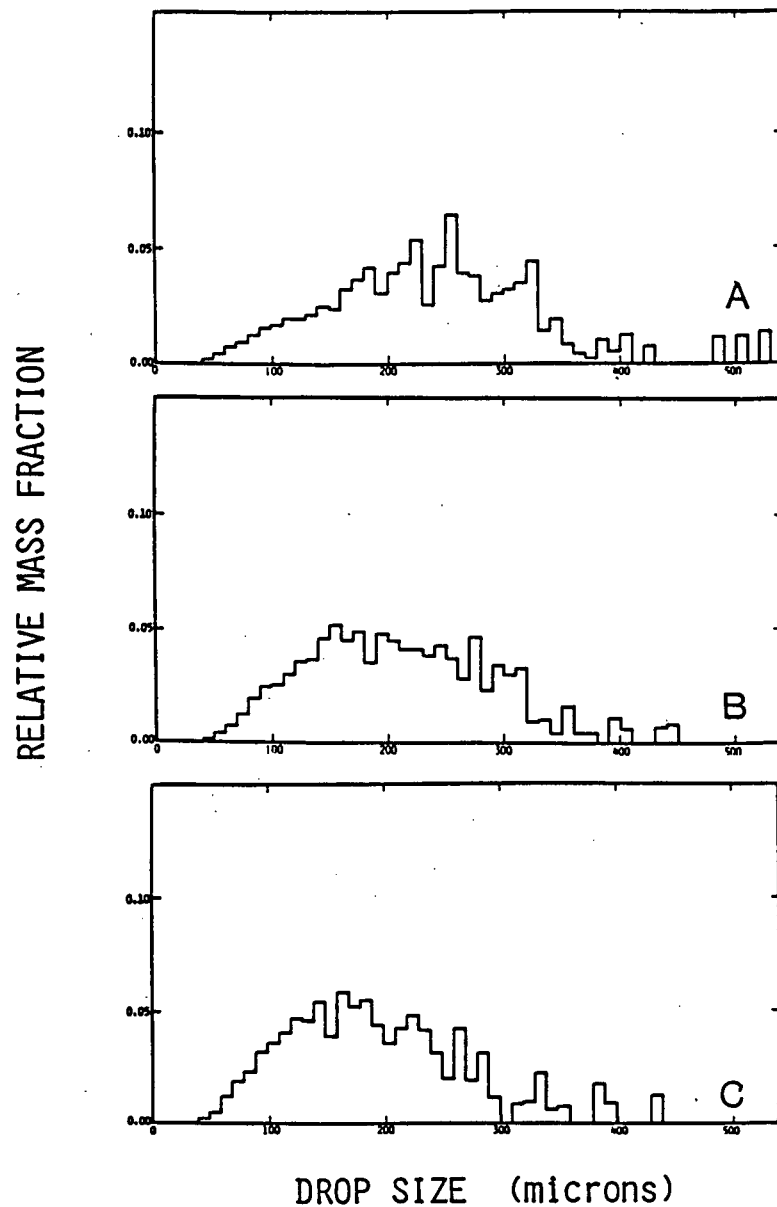
All distributions are from tests made with the 1/4LNN2 nozzle at
approximately 200 psig. Liquor temperature is given below. All samples
taken from cone of spray.

(A) 100°C
(B) 120°C
(C) 135°C

On figure 25, the mass drop size distributions for water, 64.8% w/w glycerol/water solution and 56.3% solids black liquor at 120°C are compared. It is apparent that the mass distributions of the black liquor and glycerol/water solutions differ markedly, even though both have viscosities of approximately 15 cp. Black liquor has a much greater size distribution, further suggesting that black liquor sprays in a different manner than glycerol/water solution of similar viscosity.

Figure 25:   Mass Distribution of Selected Water, Glycerol/
              Water and Black Liquor Sprays.
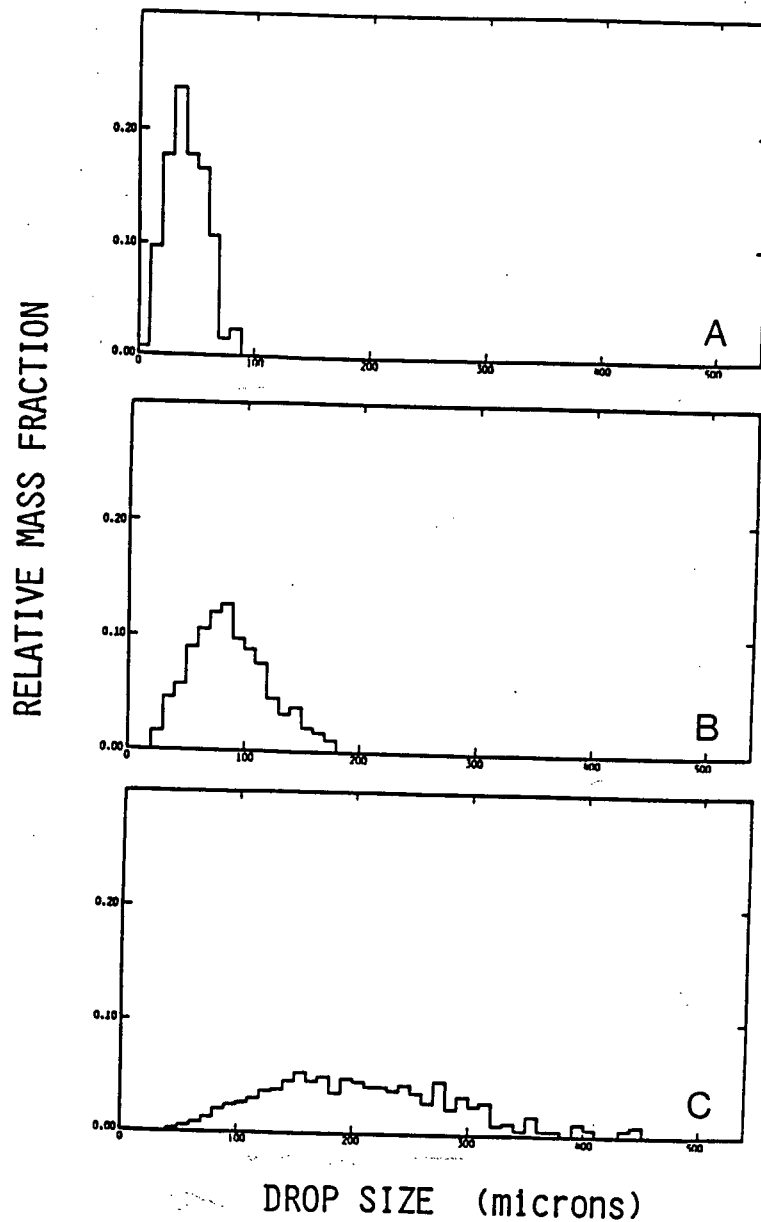
All distributions are from tests made with the 1/4LNN2 nozzle at
approximately 200 psig.

(A) Water, 18°C, $\mu = 1$ cp
(B) 64.8% w/w glycerol/water solution, 23°C, $\mu = 14.7$ cp
(C) 56.3% solids content West-Coast Black Liquor 120°C,
    $\mu = 18.9$ cp.

5. SUMMARY AND CONCLUSIONS

The results of this study are summarized below.

1. Prediction of the Sauter mean diameter from correlations published in the literature is subject to large error, as much as 50%. This error is due largely to the difficulty in obtaining accurate measurements of spray drop size, specifically in sampling. Other factors may also be important in certain circumstances: differences in nozzle geometry not accounted for by the correlations and limits in the range of applicability of the correlations not specified.

2. Increasing the temperature of water through its boiling point was found to drastically change the atomization characteristics of some grooved-core nozzles. In the case of smaller nozzles, this change produced a near step increase in the Sauter mean diameter, as well as a shift in the mass distribution to larger drop sizes. The larger nozzles did not exhibit this drastic change. However, all nozzles showed the presence of an inner core of fine mist located on the nozzle centerline when the temperature was increased above 120°C.

3. When the temperature of black liquor was increased through its boiling point, the resulting sprays did not show a near step change in Sauter mean diameter for the nozzle and flow

velocity where water exhibited this effect.

4. The measured value of mean drop size of black liquor sprays were much larger than those predicted by the correlation equation (9). However, the change in mean drop size with temperature change was similar to that predicted by the correlation equation for the corresponding viscosity change, i.e. the slopes of the experimental and predicted lines were similar.

5. For the black liquor sprays, the mass-weighted drop size distribution was found to be much broader than that found for a glycerol/water solution of corresponding viscosity, sprayed in the same nozzle, at the same velocity.

6. Increased temperature in the black liquor sprays shifted the drop size distribution of the spray towards smaller drop sizes.

In conclusion, the findings of these tests indicate that raising of the temperature of black liquor through its boiling point does not introduce a discontinuous change in drop size. Rather, the mean drop size decreases in the manner predicted by the correlation equations for the corresponding viscosity change. The distribution of drop sizes is shifted to smaller diameters.

6. RECOMMENDATIONS FOR FURTHER WORK

Further work on this topic is necessary to fully understand black liquor spraying as it occurs in a pulp mill recovery furnace. The recomendations listed below aim to do this. They fall into two general categories: suggestions to make the conditions of the spraying closer to those used in industrial practice and improvements upon the techniques used to measure drop size.

1. Further experiments should be made with black liquors using a higher liquor solids content more typical of recovery furnace operation i.e. 60-70%. In addition, a better simulation of the liquor firing conditions, e.g. atomizing the liquor into heated chamber and/or the use of large industrial scale grooved-core nozzles.

2. The major shortcoming of the drop size measurement technique was the extremely long time required to measure the drop sizes. In future, a fully automatic image analysis technique should be employed for this purpose.

3. If extensive further tests are to be carried on, a reappraisal of the drop size measuring techniques should be made. Recent developments in this field may be adapted to the present problem and improve the representativeness of the spray data obtained.

NOMENCLATURE

Unless otherwise indicated here or in the text, cgs units are used thoughout.

A   nozzle parameter, the ratio of the flow area in the nozzle orifice to the flow area of the nozzle grooves.

D, Do   nozzle orifice diameter.

Di   inlet diameter of swirl chamber for a swirl hydraulic nozzle.

K   constant.

P   differential pressure across nozzle, psig.

Q   volumetric flow rate.

Re   Reynolds number $= \dfrac{UD\rho}{\mu}$.

T   temperature.

U, Uo   superficial flow velocity through the nozzle orifice.

V_t tangential velocity component.

Va, Vv   vertical or axial velocity component.

We   Weber number $= \dfrac{U^2 D\rho}{\sigma}$.

X, Y, Z   parameters of equations II-11 and II-19.

a,b,c,d,e   exponents of equation (2).

d   droplet size.

d_{xx} unspecified mean drop size (see Table II-1).

d_{32} sauter mean drop size, the drop diameter having the same ratio of volume to surface area as the entire spray.

$D_{N,0.5}$ number mean diameter.

$d_{V,0.5}$	volume mean diameter.
p, q	parameters in equation II-4.
s	square-root normal standard distribution.
w	mass flow rate.
x	size, or droplet size.
$\bar{x}$	mean size or mean droplet size.
α	exponent on Reynolds number.
β	exponent on Weber number equations.
γ	exponent on nozzle parameter A, equation (7).
θ	spray angle.
θ_m	maximum spray angle.
μ, μ_ℓ	liquid viscosity. ("Apparent viscosity" for black liquor as described on page 32.)
μ_g	viscosity of gas phase.
ρ, ρ_ℓ	liquid density.
ρ_g	density of gas phase.
σ	surface tension.
ϕ, Ψ	indicates functionality.

subscripts

i	denotes size or class increment.

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APPENDIX I   KRAFT PROCESS AND RECOVERY FURNACE OVERVIEW

1. The Kraft Process

The kraft process is an important chemical pulping process that produces a strong pulp with minimum damage to the pulp fibers. In the kraft process, the desired cellulose and hemicellulose wood components making up the wood fibers are chemically separated from the undesired lignins and other extraneous wood components. A typical kraft pulping process will remove about 50% of the wood mass. The spent materials – the dissolved wood and exhausted cooking chemicals – are recovered and processed through a recovery cycle that regenerates the cooking chemicals and recovers the energy value of the wood components. This cyclical and interrelated process is illustrated in figure I-1.

A brief description of the chemical reactions and process steps involved in the kraft cycle is presented below. Although the kraft process is an intricate chemical process that varies from mill to mill, the overall process steps remain the same. More detailed information about the kraft process can be found in the following reference texts [44-47].

The kraft cycle begins with the cook or digestion process. Wood chips are reacted with an aqueous cooking liquor composed of NaOH and Na_2S under high temperature and pressure. This reaction takes place in batch or continuous mode in reactors called digesters. The cooking solution (white liquor) selectively reacts with the lignin, making it

Figure I-1: Diagram of the Kraft Process.

MUD WASHER

MUD THICKENER

WHITE LIQUOR
Na$_2$S, NaOH

CLARIFIER

LIMESTONE
CaCO$_3$

WOOD
CHIPS

DIGESTER

1
LIME KILN

2,3
CAUSTICIZER

BLOWTANK

GREEN LIQUOR
STORAGE

GREEN LIQUOR
CLARIFIER

PULP WASHER

DREGS WASHER

17 - 20 %
WBL

PULP

EVAPORATOR

4
DISSOLVING TANK

45 - 55 % SBL
STORAGE

4
RECOVERY
FURNACE
60 - 70 %

WEAK-WASH
STORAGE

WBL = Weak Black Liquor
SBL = Strong Black Liquor
% = Black Liquor Solids

Na$_2$SO$_4$

1 CaCO$_3$ → CaO + CO$_2$

2 CaO + H$_2$O → Ca(OH)$_2$

3 Ca(OH)$_2$ + Na$_2$CO$_3$ → 2NaOH + CaCO$_3$

4

Table 1. Basic recovery-boiler reactions are shown in
simplified equations

Reducing zone

Na$_2$SO$_4$ + 2C → Na$_2$S + 2CO$_2$
Na$_2$SO$_4$ + 4C → Na$_2$S + 4CO
Na$_2$SO$_4$ + C → Na$_2$O + SO$_2$ + CO
2C + O$_2$ → 2CO
2CO + O$_2$ → 2CO$_2$
CO$_2$ + C → 2CO
C + H$_2$O → CO + H$_2$
C + 2H$_2$ → CH$_4$
2H$_2$ + O$_2$ → 2H$_2$O

Drying zone

Na$_2$S + CO$_2$ + H$_2$O → Na$_2$CO$_3$ + H$_2$S
Na$_2$O + CO$_2$ → Na$_2$CO$_3$
CH$_4$ + H$_2$O → CO + 3H$_2$

Oxidizing zone
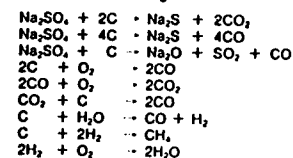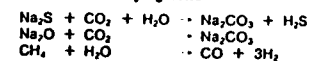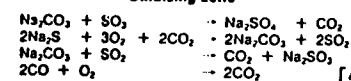
Na$_2$CO$_3$ + SO$_3$ → Na$_2$SO$_4$ + CO$_2$
2Na$_2$S + 3O$_2$ + 2CO$_2$ → 2Na$_2$CO$_3$ + 2SO$_2$
Na$_2$CO$_3$ + SO$_2$ → CO$_2$ + Na$_2$SO$_3$
2CO + O$_2$ → 2CO$_2$
[4]

soluble in the cooking liquor. After the cook, the cooking liquor, spent of its active components, is black in color due to the dissolved wood components. This black liquor is separated from the pulp in a counter current washing cycle. The washed pulp, a light brown in color, is then ready for further processing, depending on its end use.

After the washing cycle, the black liquor has been diluted to 16-18% solids content (see definition in section III-3). It is then concentrated to 60 to 70% in two stages. It is first concentrated to 45-55% solids in multiple effect evaporators, and then to 60-70% solids using sensible heat from the recovery boiler flue gases.

The black liquor is then sprayed into a recovery furnace where further evaporation and combustion of the dissolved wood components takes place. The heat recovered from the liquor combustion is used to generate steam for the mill. The spent cooking chemicals are reduced in the furnace by a complex set of reactions, which may be simplistically expressed by:

$$Na_2SO_4 + 2C \rightarrow Na_2S + 2CO_2 \qquad (I-1)$$
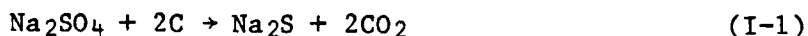
As a result of these reactions, a molten smelt consisting of Na_2S and Na_2CO_3 is produced in the base of the furnace. This smelt is removed from the furnace and dissolved in water to form a solution of Na_2CO_3 and Na_2S (green liquor). In the subsequent recausticization step of the kraft process, the Na_2CO_3 is converted to the desired NaOH by reaction with $Ca(OH)_2$ as follows:

$$Na_2CO_3 + Ca(OH)_2 \rightleftharpoons 2NaOH + CaCO_3 \qquad (I-2)$$
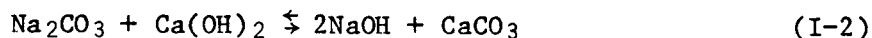
The $CaCO_3$ formed in this reaction is removed from the liquor by clarification and is burned in a lime kiln to regenerate CaO used to make more $Ca(OH)_2$ (Slaking). The clarified liquor, containing NaOH and Na_2S, is now the white liquor used to pulp wood. Here the cycle starts again.

2. The Recovery Furnace

2.1 Introduction

The recovery furnace is the largest single piece of equipment in the kraft mill. It fulfills the important roles of producing pulping chemicals and process steam by the combustion of black liquor. These along with other important objectives of recovery furnace operation are described below:

Recovery of Pulping Chemicals: As described earlier, the kraft process uses a cooking liquor composed of NaOH and Na_2S. In the recovery furnace the first step in recovering these chemicals from a completed cook occurs - the regeneration of the sulfur compounds in the black liquor as Na_2S. These reactions (represented by equation I-1) takes place largely in the char bed of the furnace in a reducing atmosphere. The efficiency of the conversion is measured by the reduction ratio:

$$\text{Reduction ratio} = \frac{Na_2S}{Na_2S + Na_2SO_4} \qquad (I-3)$$

where the chemical quantities are represented on a molar basis. From the operational standpoint, it is desirable to have as large a reduction ratio as possible, i.e. a minimum of Na_2SO_4. The Na_2SO_4 does not contribute to the pulping and is therefore considered a "dead load" that is carried around the chemical cycle. Typical reduction ratios are around 0.90 to 0.95.

Production of Steam: The combustion of the organic solids present in the liquor releases a large quantity of heat. This heat is used in the furnace to further evaporate the black liquor and to generate process steam. The amount of steam generated makes an important contribution to the overall mill energy balance. High steam production requires efficient liquor combustion and clean heat transfer surfaces in the boiler heat exchanger.

Minimization of Particulate and Gaseous Emissions: In the recovery furnace, particulate and gaseous compounds that can escape with the flue gases are formed. The particulates are primarily Na_2SO_4 and Na_2CO_3. The gaseous compounds include CO, SO_2, H_2S and small quantities of highly odiferous sulfur compounds. From the environmental standpoint it is desired to reduce these emmissions as much as possible, which can be done to some extent by manipulation of certain furnace operating variables, e.g. the coarseness of the liquor spray.

Safety: In the process of chemical recovery a smelt bed is

generated in the base of the recovery furnace. If water or dilute liquor comes in contact with this molten smelt, violent generation of steam, referred to as smelt/water explosions, can occur. Such an explosion can extensively damage the furnace and poses a threat to the safety of operating personnel. This fact necessitates close monitoring of the furnace operation, in particular the spray liquor solids content.

2.2 Recovery Furnace Operation

One of the more important steps involved in recovery furnace operation is the spraying of black liquor into the furnace. This aspect of recovery furnace operation is the topic of this thesis and is therefore discussed in detail below. Discussion of other aspects of furnace operation may be found in a number of texts and publications, for example see [2, 47-49].

In North America today there are two major types of recovery furnaces in use - the Combustion Engineering Furnace and the Babcock and Wilcox furnace. Major differences between these furnace designs include the manner in which liquor and air are introduced to the furnace and are discussed below.

2.2.1 Combustion Engineering (CE) Furnaces

In the CE furnace, black liquor is evaporated and burned in suspension. To achieve this the liquor is first atomized using

grooved-core nozzles (illustrated in figure I-2) and introduced to the
furnace at the firing gun level (shown in figure I-3) using oscillating
liquor guns. Combustion air is introduced in the CE furnace in two
zones: - the primary zone just above the char bed where approximately
65% of the total air is added; and the secondary zone, above the liquor
guns where the remaining air is added in a tangential manner to promote
intense mixing of the gases, thus completing the combustion process.

Although recovery furnaces differ in design from installation to
installation, the one shown in figure I-3 is typical of a number of
recovery units. In figure I-3 the major pieces of operating equipment
have been identified.

2.2.2 Babcock and Wilcox (B & W) Furnaces

In the B & W furnaces, black liquor is sprayed on to the furnace
walls by an impringment (splash plate) nozzle, see figure I-2. Liquor
evaporation occurs on the furnace walls, with the dried liquor sloughing
off and falling to the char bed. Air is introduced in three areas in
the B & W furnace. Approximately 45-55% of the total air is added in
the primary zone just above the char bed and is used to control the
shape of the bed. A further 20-35% of the total air is introduced
between the primary zone and the liquor gun level, creating a secondary
zone to control the wall drying and further adjust the char bed height
and shape. The remaining air is added above the liquor nozzles in a
tertiary zone to complete the combustion process.

Figure I-2: Nozzles Used for Black Liquor Firing in North American Recovery Furnaces.
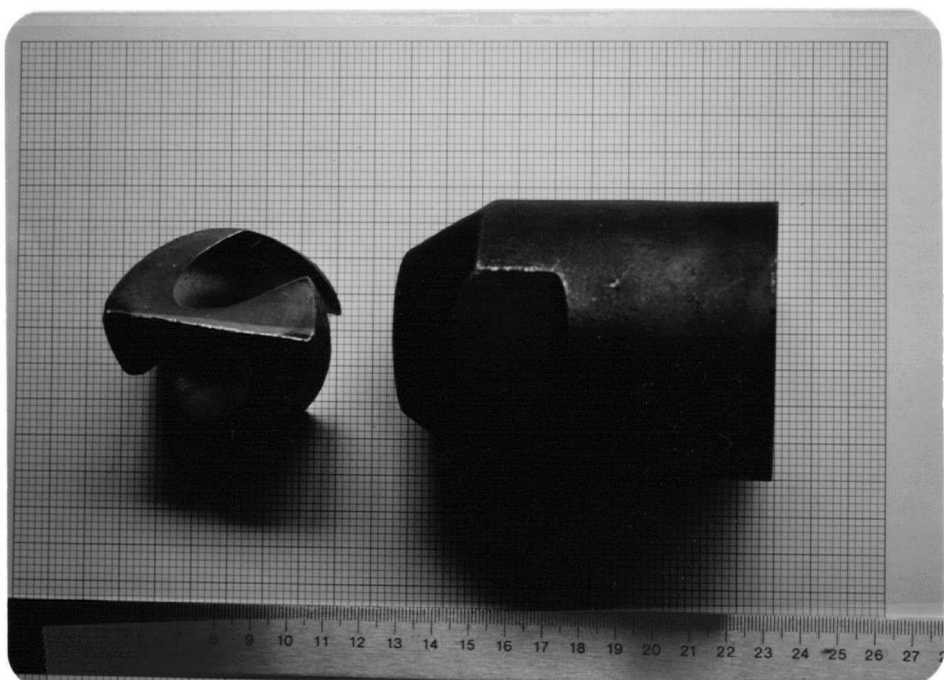
(A)
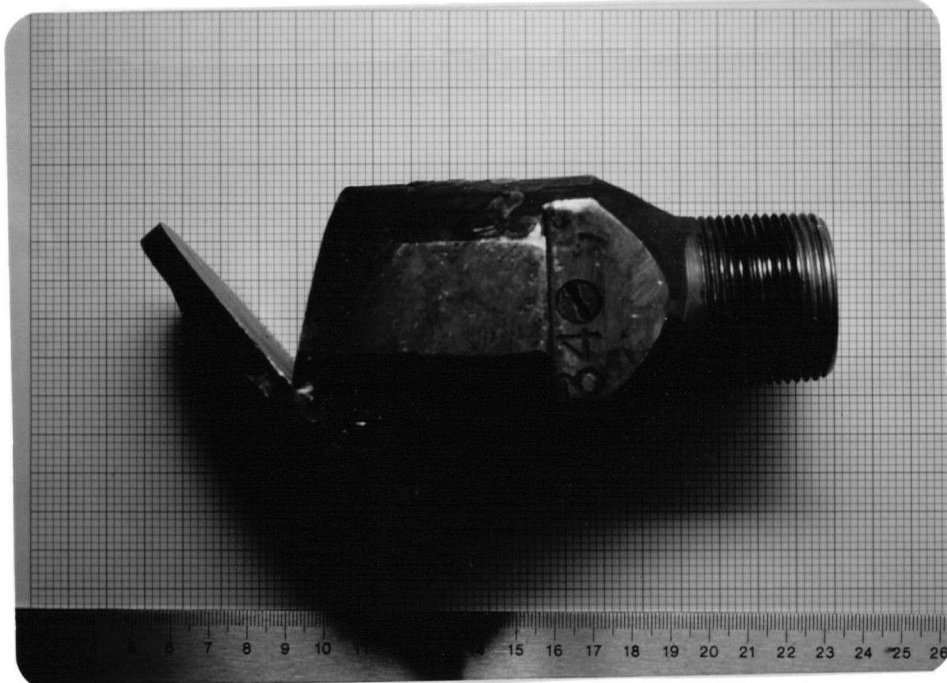
(B)

(A) CE furnace nozzle
(B) B & W furnace nozzle

Scales in centimeters.

Figure   I-3:   Schematic of a Combustion Engineering
Recovery Furnace.

SUPERHEATER SECTION

BOILER BANK

SOOT BLOWER

ECONOMIZER SECTION

SECONDARY AIR LEVEL

FIRING GUN LEVEL

PRIMARY AIR LEVEL

DISSOLVING TANK
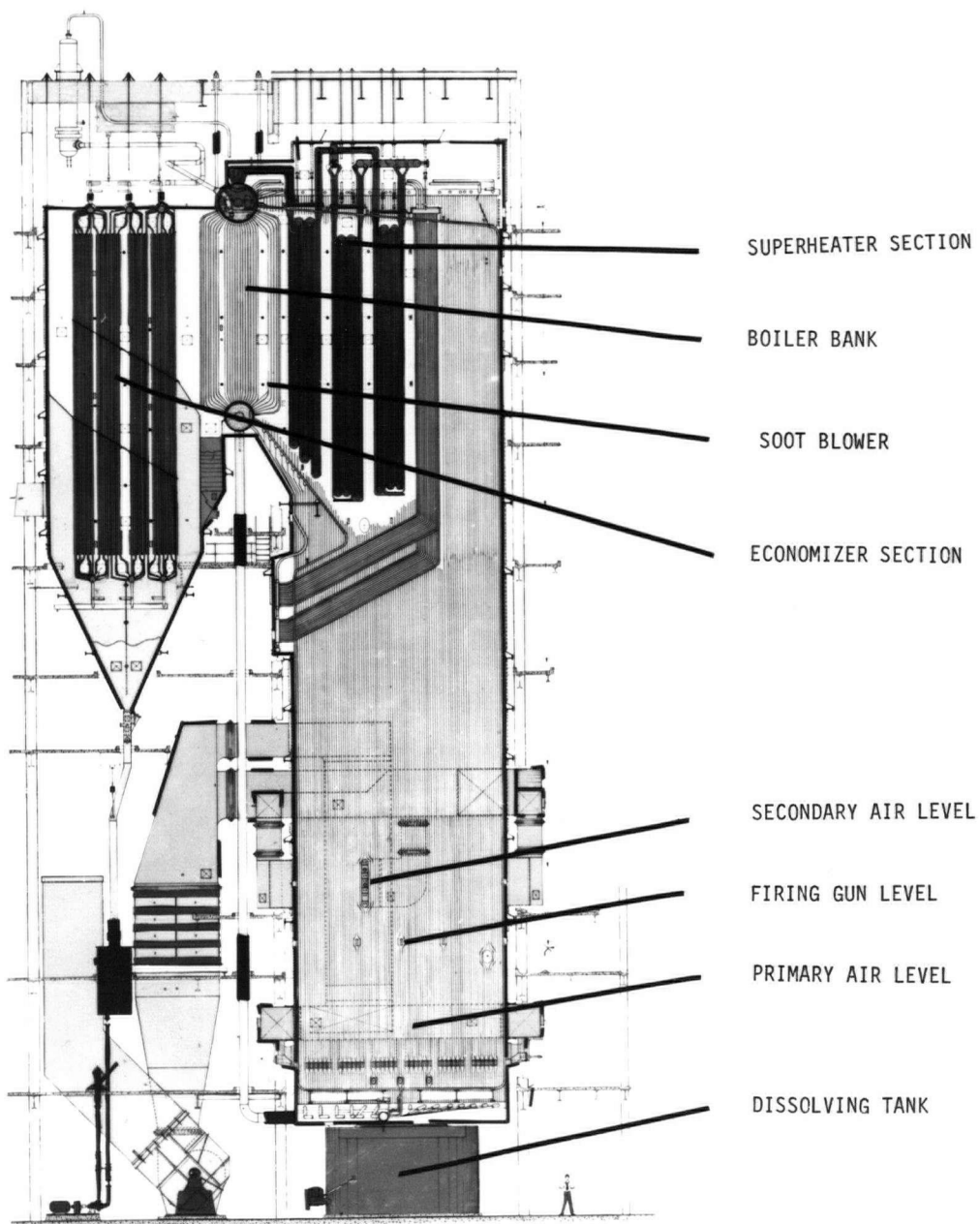
2.2.3 Black Liquor Firing

The spraying of black liquor is of fundamental importance to the operation and control of a recovery furnace. If the size of the liquor droplets in the spray is too small, they will be entrained by the combustion gases and carried upwards in the furnace. If this size is too large the droplets will have too small a surface/volume ratio and will fail to sufficiently evaporate before reaching the char bed. This latter factor is of particular importance to a CE furnace which relys upon suspension firing of the liquor. The B & W furnace operation is not as sensitive to variation in spray drop size; the strategy of wall drying requires only that control on the small end of the drop size distribution be maintained - to prevent carry over. This review will concentrate on suspension drying and burning of black liquor; however, many of the points to be discussed are equally valid for wall drying operation.

There are two extreme conditions of black liquor sprays: fine sprays and coarse sprays. These are examined below along with the problems in furnace operation that result.

Fine Spraying of Black Liquor

CE furnaces are sometimes operated using a fine black liquor spray (less than 1/4 inch expanded particle diameter) caused by either too high a liquor temperature and/or pressure [6]. This results in a number of problems. First, there is increased carryover of particulate matter which leads to increased fouling of heat exchange surfaces and

places a greater load on the electrostatic precipitator. The former necessitates increased soot blowing and/or more frequent outages for thorough cleaning of the critical ash-accumulating sites in the boiler. The latter increases the recycle of dead load chemicals through the recovery cycle.* Secondly, fine spraying reduces the amount of liquor brought to the char bed, which can result in formation of a shallow char bed. These conditions decrease reduction efficiency, and increase the deadload Na_2SO_4 recycled through the kraft process. Thirdly, fine spraying causes the upper areas in the boiler to heat up [4] which can lead to conditions where soot blower resistent deposits are formed [1].

Other problems are encountered with fine liquor spraying, including increased H_2S, mercaptan and SO_2 emission, decreased liquor burning stability and increased fireside corrosion of waterwall tubes have been documented by Nelson [6].

Very Coarse Spraying of Black Liquor

Although the correct drop size for black liquor sprays is commonly described as being coarse [6], eventually a point occurs when the droplets become so large that insufficient evaporation takes place before the liquor droplets reach the char bed. This excess moisture must be evaporated, which removes heat from the char bed. The resulting decrease in bed temperature adversly affects the reduction efficiency and can result in a condition known as a "brown out," a localized cooling of the char bed. If the bed temperature falls too far,

---

*Captured particulate matter is returned to the black liquor and is therefore fired again.

insufficient heat is present to maintain combustion. The heat present continues the evolution of pyrolysis gases which may form pockets in the furnace. If one should suddenly ignite, the resulting explosion could rupture a wall tube and result in a second more violent smelt/water explosion.

While the above discussion has been concerned with a single drop size, any spray produced by a nozzle has a distribution of drop sizes. Thus any spray is likely to have extremes which fall into the categories of "coarse" or "fine" sprays as described above. Therefore, a desirable operating point is one where stable operation with a maximum of steam production and reduction efficiency and a minimum of particulate carryover is achieved.

APPENDIX II   LITERATURE REVIEW OF ATOMIZATION IN

GROOVED-CORE NOZZLES

1. Introduction

Atomization is the subdivision of a continuous liquid jet into a
spray consisting of a large number of droplets. This subdivision
produces a considerable increase in surface are of the liquid, and
therefore is an important means for obtaining high mass and/or heat
transfer between liquids and gases. For this reason atomization is
commonly used in drying, evaporation, and combustion processes.

Atomizers are usually classified by two criteria: the energy
source used to atomize the liquid and the shape of the resulting spray.
Most atomization techniques use hydraulic, pneumatic, or centrifugal
energy sources to produce sprays with a hollow cone, full cone, or flat
spatial configuration. The liquid to be atomized and the
characteristics required of the spray will determine which atomizer is
best suited for the task.

The performance of atomization devices are described by four key
parameters:

1. mean size and size distribution of the droplets in the spray,

2. energy required for atomization,

3. volumetric flow capacity of the device, and

4. special operational considerations, such as erosion and

clogging.

While all of these are important, the mean drop size and drop size distribution is most important in light of the objective of atomization.

This review examines the published literature of one type of atomizer - the gooved-core hydraulic nozzle. Emphasis is placed on published findings of drop sizes produced in sprays from these nozzles and the dependence of this drop size on key liquid properties. For a general overview of atomization and spraying processes, a number of references can be consulted [18, 19, 50-52].

2 Mechanism of Jet Breakup

All atomization techniques involve the disruption of the stabilizing forces within the liquid by the application of internal or external forces. These forces initate instabilities which result in fragmentation of the liquid. After dissipation of the disruptive forces, the liquid fragments form spheres under influence of surface tension forces.

The detailed steps in the atomization process have been summarized by Lappel et. al. [18] as:

1. The extension of the bulk liquid into sheets, jets, films or streams by acceleration of the liquid.

2. The initiation of small disturbances in the liquid in the form of ripples, proturbances, or waves.

3. The formation of short ligaments on the liquid surface as a result of fluid pressure or shear forces.

4.   The collapse of the ligaments into drops as the result of

surface tension.

5.   The further breakup of drops as they move through the gaseous

medium by the action of fluid pressure or shear forces.

Some or all of the above steps may be important in a given atomization

process. For atomization by grooved-core nozzles, distrubances are

initated by the imposition of directional changes on the fluid as it

moves through the nozzle. The liquid emerges from the nozzle as

ligaments or sheets which rapidly collapse into droplets. This process

is extremely rapid, so much so that in many cases the spray forms

immediately at the orifice.

Several theoretical analysis have been attempted to explain the

atomization process by rigorous hydrodynamic analysis [17]. While these

theoretical studies have improved our understanding of the atomization

processes, they apply to circumstances far to idealized to be used for

quantitative prediction of spray drop size in commonly used nozzles.

Most equations in the literature which yield this type of quantitative

prediction have been derived from experimental data, and are presented

in the form of correlations of dropsize with nozzle geometry, operating

conditions and liquid properties. Often the variables in these

correlations are grouped as dimensionless parameters.

3.0 Dimensional Analysis of Atomization Phenomenon

A number of dimensional analyses of atomization phenomenon are

given in the literature [18, 50]. The use of this approach greatly
simplifies the development of experimental correlations for predictive
purposes. In the case of liquid atomization, the many variables which
govern this process may be grouped into three categories:

1. The nozzle type and the nature of the flow at the orifice,

2. The physical properties of the discharging fluid, and

3. The properties of the medium into which the fluid is
   discharged.

While dimensional analyses can be applied with equal validity to
any number of atomization processes, the solution presented here is
developed for atomization in grooved-core nozzles under the experimental
conditions studied in this thesis. For other situations some of the
simplifying assumptions made may not be valid.

The mean drop size diameter can be expressed as a function of
many variables,

$$d_{xx} = \Psi \ (D, \ U, \ \rho_\ell, \ \rho_g, \ \sigma, \ \mu_\ell, \ \mu_g, \ \theta) \qquad \qquad \text{(II-1)}$$

where D is a characteristic dimension of the nozzle, usually the orifice
diameter, and U is a characteristic of the jet velocity, more properly
the relative velocity between the liquid and gas phases, but usually
for simplicity the superficial discharge velocity.

By applying the principles of dimensional analysis, one solution
of equation (II-1) is:

$$\frac{d_{xx}}{D} = \Psi'(Re, \ We, \ \rho_{\ell}/\rho_g, \ \mu_{\ell}/\mu_g, \ \theta) \qquad (II\text{-}2)$$

For the atomization of liquids into ambient air, the gaseous properties ρ_g and μ_g will be constant, and the terms ρ_{ℓ}/ρ_g and μ_{ℓ}/μ_g drop from equation (II-2). The spray angle, θ, can be treated in a number of ways. Some authors use it to describe the radial and axial components of the liquid velocity at the orifice, while others did not observe any dependence of the spray angle on the drop size and do not include it in their correlations. If the spray drop size is independent of θ, equation (II-2) can be further simplified to:

$$\frac{d_{xx}}{D} = K \ Re^{\alpha} \ We^{\beta} \qquad (II\text{-}3)$$

4. Drop Size Distributions in Sprays

4.1 Characterization of Sprays

All nozzles yield sprays having a distribution of drop sizes. To characterize the spray drop size, it is necessary to choose appropriate statistical parameters to represent the mean drop size as well as its distribution. The major requirement, however, is to define some form of mean drop size.

There are a number of ways of defining the mean drop size of a

spray. The specific mean chosen in any particular case is determined by
application. Some possible mean diameters are listed in table II-1
along with a brief description of their usual application. These
statistics are computed from the spray distribution using the equation
given below:

$$d_{qp} = \left\{ \frac{\sum\limits_{i=1}^{n} \phi_i \, d_i^2}{\sum\limits_{i=1}^{n} \phi_i \, d_i^p} \right\}^{\frac{1}{q-p}}$$

where ϕ_i is the fraction (weight or number) of particles in the ith
size interval having mean diameter d_i.

One cannot directly compare size distributions described by
different mean diameters. This fact is shown in figure II-1 where the
different mean diameters calculated for a spray drop size distribution
are shown along with the original number distribution.

A complete description of a spray is given when the distribution
as well as the mean drop size is specified. To achieve this, some
investigators have chosen empirical distribution functions that require
estimation of two or three parameters from experimental data. Others
have used standard distributions such as the log normal or square-root
normal functions. The square-root normal distribution has been found to
describe spray drop size data well [31-34]. This distribution is given
below:

Table II-1   Mean Diameters Used to Describe Sprays

Mean Diameter	Symbol	Field of Application
Linear or arithmetic	d_{10}	evaporation, comparisons
Surface	d_{20}	adsorption, or other processes where the surface area is controlling
Volume	d_{30}	comparison of the mass distribution of a spray
Surface diameter	d_{21}	adsorption
Volume diameter	d_{31}	evaporation, molecular diffusion
Volume-surface or Sauter mean	d_{32}	efficiency studies, mass transfer, reaction

Figure II-1: Comparison of the Number Distribution and Mean Diameters of a Typical Spray.

1 $d_{N,0.5}$ NUMBER MEAN
2 d_g GEOMETRIC MEAN
3 d_{10} ARITHMETIC MEAN
4 d_{20} SURFACE MEAN
5 d_{30} VOLUME MEAN
6 d_{32} SAUTER MEAN
7 $d_{V,0.5}$ MASS MEAN

NUMBER OF DROPS

DROP SIZE (microns)
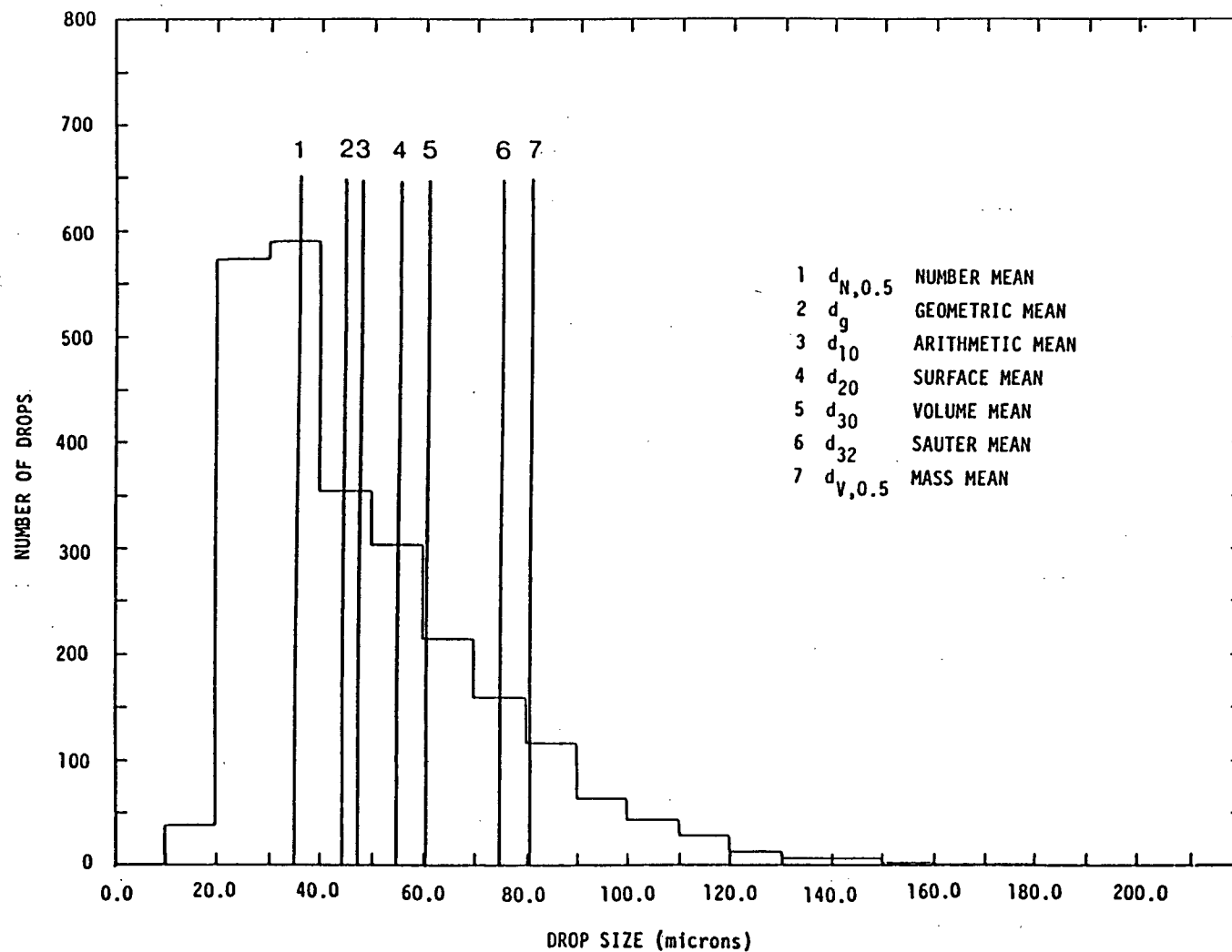
$$f(x) = \frac{1}{s\sqrt{2\pi}} \exp\left\{\frac{-(x^{1/2} - \bar{x}^{1/2})^2}{2s^2}\right\} \qquad (II-5)$$

4.2 Measurement of Spray Drop Size

As described earlier, most of our fundamental knowledge of spray drop size has been obtained by experiment. Accordingly, much effort has been spent developing suitable techniques for measuring drop sizes in sprays. Many techniques have been developed; each has advantages and disadvantages, and none is completely satisfactory.

There are two basic approaches for obtaining drop size information from a spray: (1) measurement of the droplets that pass through a plane during a given time interval (temporal sampling); and (2) measurement of the droplets present in a volume of space in a given instant (spatial sampling). Excepting the special case where all droplets have the same velocity and direction, the two methods give different results.

Another factor involved in measuring the spray is the technique used to sample the droplets. Direct sampling, i.e. where the spray droplets are physicaly captured, poses problems of withdrawing a representative, unaltered sample from the spray. Indirect sampling, where the spray drops are photographed or measured by optical methods, can introduce other errors such as spatial resolution. In addition, different sampling methods can yield a number or weight distribution of

the drop sizes in the spray. A extensive discussion of the many spray measuring techniques available is beyond the scope of this thesis. Such information can be found in a number of sources in the literature, for example references [53-56].

The main point to be noted from this discussion is that many different measuring techniques, mean diameters, and distribution functions have been used by workers in the past to describe sprays. This makes comparison of findings reported in the literature very difficult, if not impossible.

4.3 Problems Involved With Accurate Determination of Spray Drop Size

There are a number of problems associated with the accurate determination of spray drop size distributions. One discussed previously is the sampling technique. Other problems involve sampling procedures, including incorrect sampling location, and the instrumentation used. These are summarized and discussed in an article by Tate [57].

One major problem in sampling is to ensure that enough droplets are measured that a meaningful mean droplet size is obtained. This problem was addressed by Bowen and Davies [37] who experimentally measured the error of estimating the Sauter mean diameter from a known population of drops when various sample sizes were taken. Their results indicated that 5500 drops had to be measured to obtain a sample mean accurate to within five percent of the population mean, while 35,000

drops were required to be within two percent. Their findings are shown in figure II-2. Bowen and Davies commented that these values were likely maximum error limits and that actual measurements would give a better representation of the true mean drop size.

5. Studies of Grooved-Core Nozzles

As reported earlier, the grooved-core nozzle is of special interest in this study. It is therefore discussed in some detail below.

The grooved-core nozzle takes its name from the helically-grooved insert that imparts a swirl notion to the liquid upstream of the nozzle orifice. This swirl motion produces a spray with a characteristic hollow cone. The main mass flow of the liquid is within this outer conical ring, but the mass distribution becomes more uniform as the distance from the nozzle is increased [50].

Previous investions of grooved-core nozzles have produced a number of correlations for mean drop size. Some of these applied to specific nozzles, while others were intended to apply to the generic class of nozzle of which the grooved-core nozzle is a member. The various correlation equations presented in the literature for grooved-core nozzles are discussed below.

5.1 Turner and Moulton (1953)

Turner and Moulton [35] studied commercial grooved-core nozzles (Spraying Systems Company 1/4LN and 1/8A) spraying organic materials

Figure II-2:   Estimated Error of Sauter Mean Diameter Based
on Sample Size.
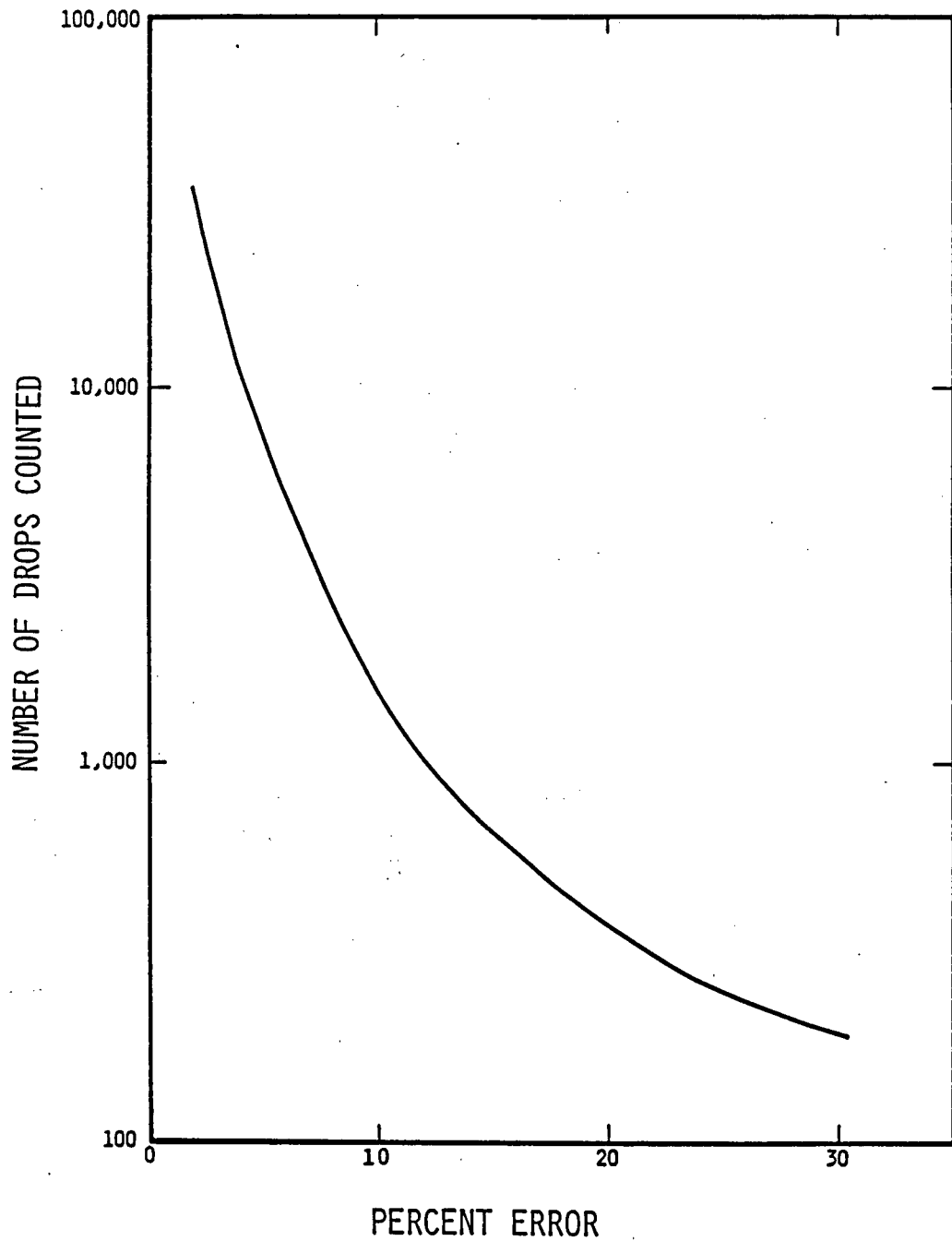
After Bowen and Davies [37].

that solidified well above room temperature. The material was liquidified by heating and sprayed. The atomized droplets solidified as cooling occurred, and were then collected and measured. A characteristic mean size defined by:

$$\log \overline{x} = \frac{\Sigma \, n \, x^3 \, \log x}{\Sigma \, n \, x^3} \tag{II-6}$$

was used to describe the spray distribution. The findings gave the following correlation for the 1/4LN nozzle:

$$\overline{x} \text{ (microns)} = 16.56 \, D^{1.520} \, w^{-.444} \, \sigma^{0.713} \, \mu^{0.159} \tag{II-7}$$

where w is the flow rate in g/s and the other quantities are in cgs units.

For our purposes, equation (II-7) can be rewritten as:

$$\overline{x} = 0.127 \, D^{0.632} \, U^{0.444} \, \rho^{0.444} \, \mu^{0.159} \, \sigma^{0.713} \tag{II-8}$$

The large exponent for surface tension (0.713) shows strong dependence of mean drop size on this liquid property, in contrast to the weaker dependence found by other investigators (typically 0.2 to 0.3).

Turner and Moulton fitted their data to the log normal distribution function and used an adjustment factor to account for the

sampling losses of small drops. To facilitate correlation of the data, the nozzle orifice diameter alone was used to describe the nozzles even though other geometric differences existed among them. This practice is commonly used by investigators in this field.

5.2 Tate and Marshall (1953)

Tate and Marshall [31] studied the atomization of water in Spraying Systems Company grooved-core nozzles. They sampled drops in an immisible liquid collector. The drops were then photographed and measured.

In deriving their correlation, Tate and Marshall concentrated on three variables they felt to be of fundamental importance: the nozzle orifice diameter, and the axial and tangential velocity components of the liquid emerging from the orifice. The liquid velocity components were calculated from knowledge of the nozzle geometry and the assumption that the orifice ran full. The correlation they obtained is:

$$d_{32}(\text{microns}) = 286(0.394D + 0.17) \exp\left\{\frac{396.2}{V_v} - 3.08 \times 10^{-4} Vt\right\} \quad (\text{II-9})$$

where D, the orifice diameter is in cm, and V_v and Vt, the liquid velocity components are in cm/sec. While only water was used to obtain this correlation, trial runs with viscous liquids demonstrated that increased liquid viscosity produced a sharp increase in the drop size as

well as a decrease in spray uniformity.

5.3 Mugele (1960)

Mugele [58] analyzed atomization in hydraulic nozzles using data available in the literature supplemented with photographic measurements of some sprays. He rationalized that every nozzle produces a maximum drop size, and fitted the observed spray distributions to an empirical function requiring the specification of three parameters: the mean drop size, the variance of the distribution, and the upper size limit of the drops.

He recommended the following correlation for the grooved-core nozzle:

$$\frac{d_{32}}{D} = 5.0 \ Re^{-0.35} \ (\frac{\mu U}{\sigma})^{-0.20} \qquad\qquad (II-10)$$

It is interesting to note that Mugele recommends this correlation for other atomization devices in addition to the hydraulic swirl nozzle.

5.4 Nelson and Stevens (1961)

Nelson and Stevens [32] studied the atomization of water and organic liquids in Spraying Systems Company type SL spray drying nozzles. The spray was sampled by freezing the droplets in liquid

nitrogen. They then screened and weighed the size fractions and correlated their data using the square-root normal distribution. They found their water data to be correlated by:

$$Y = -0.144 \ Z^2 + 0.702 \ Z - 1.260 \qquad \text{(II-11a)}$$

where

$$Y = \log_{10} \frac{d_{V,0.5}}{D} \qquad \text{(II-11b)}$$

and

$$Z = \log_{10}[\text{Re} \left(\frac{We}{Re}\right)^{0.20} \left(\frac{Vt}{Va}\right)^{1.20}] \qquad \text{(II-11c)}$$

Lappel [18] has shown that this can be correlated as:

$$d_{V,0.5} = \frac{23.0 \ D^{0.47} \ \mu^{0.42} \ \sigma^{0.11}}{\left(\tan \frac{\theta m}{2}\right)^{0.64} \ U^{0.60} \ \rho^{0.53}} \qquad \text{(II-12)}$$

where $d_{V,0.5}$ is the volume mean diameter.

Nelson and Stevens also present a graph for obtaining the Sauter mean diameter from the volume mean diameter and square-root normal standard distribution of the spray.

The authors developed two separate correlations – one for water and another for organic liquids. They offered no explanation for this.

It is possible that factors other than the physical differences between water and the organic liquids may have accounted for this.

5.5 Lappel, Henry and Blake (1967)

This study critically reviewed and evaluated published findings in the field of atomization prior to 1966 [18]. Their literature review covering 955 pertinent references is the most comprehensive summary of atomization work to date.

For hydraulic swirl nozzles, these authors derived a correlation which gave best agreement between the data (weighted average) of various investigators. This correlation is given below:

$$\frac{d_{32}}{D} = 5.5 \ Re^{-0.20} \ We^{-0.25} \qquad (II-13)$$

The authors found the error of the above correlation to be large: ±50%. They attributed most of this to differences among the drop size analysis techniques used by different investigators, particularly spray sampling.

5.6 Kim and Saunders (1971)

Kim and Saunders [33] carried out an experimental investigation of swirl nozzles with orifice diameters up to 3.96 mm. They used a sampling technique in which a representative sample of spray was captured, frozen in chilled petroleum ether, and then screened.

They found the drop size distribution of these sprays to be square-root normal, and presented two correlations for the mass median diameter. The first was based on the axial and tangential velocities (in ft/sec):

$$d_{V,0.5}(\text{microns}) = 7670 \frac{D_o^{0.33}}{V_a^{0.11} V_t^{0.40}} \qquad (\text{II-14})$$

with D_o (the orifice diameter) expressed in inches. The second equation was based on the nozzle geometry:

$$d_{V,0.5}(\text{microns}) = 16900 \frac{D_o^{0.95} D_i^{0.80}}{Q^{0.51}} \qquad (\text{II-15})$$

where D_i is the diameter of the nozzle swirl chamber inlet, in inches, and Q is the volumetric flow rate, USGPM.

Kim and Saunders found that other investigators' data could be correlated by these equations if the constant was changed. They concluded that this constant depended on nozzle geometry. However, it could also depend on differences in spray sampling among investigators.

5.7 Dombrowski and Wolfshon (1972)

Dombrowski and Wolfshon [38] carried out investigations on a series of commercial swirl spray nozzles, some of which were of the

grooved-core type. Atomizing water over the range of 1 to 725 US gal/hr

and at pressures ranging from 50 to 500 psig, they found the drop sizes

to be smaller than those reported by other investigators, and

independent of nozzle design. Their data were correlated well (+14% to

-12.5%) by the following equation:

$$d_{32} (\text{microns}) = 3305 \frac{Q^{1/3}}{Uo} \qquad (II-16)$$

where Q is in US gal/hr and Uo in ft/sec. No dependence of the drop

size on spray angle was found. Their data were also correlated well by:

$$d_{32} (\text{microns}) = 332 \frac{Q^{1/3}}{P^{1/2}} \qquad (II-17)$$

where P is the pressure drop across the nozzle, psig.

These correlations were derived from drop sizes measured by the

Sauter light absorption technique which only gives the Sauter mean

diameter of the spray. To obtain size distributions they supplemented

this study by photographing sprays from selected nozzles. The

distributions were found to be best described by the square-root normal

distribution. A correlation for the square-root standard deviation was

also given.

5.8 Wang and Tien (1972)

Wang and Tien [34] studied the atomization of non-Newtonian fluids in grooved-core nozzles. The drops were frozen, then collected and seived. They proposed a correlation of the form:

$$\frac{d_{xx}}{D} = \Psi(\text{Re, We, A}) \tag{II-18}$$

where A is the ratio of the orifice area to that of the grooved slots. Their study showed that the correlation was valid if the viscosity used was the liquid viscosity at the shear rate in the nozzle.

Their correlation, based on 210 sets of data (their own combined with Nelson and Stevens' data for organic fluids) is given below

$$Y = -0.60 \ X + 1.40 \tag{II-19a}$$

where

$$Y = \log_{10} \left(\frac{d_{V,0.5}}{D} \right) \tag{II-19b}$$

and

$$X = \log_{10}(\text{Re}^{0.40} \ \text{We}^{0.52} \ A^{0.30}) \tag{II-19c}$$

This correlation can be rewritten to:

$$\frac{d_{V,0.5}}{D} = 25.1 \ Re^{-0.240} \ We^{-.312} \ A^{-0.180}$$ (II-20)

6. Comparison of Grooved-Core Nozzle Studies

The published findings on atomization from grooved-core nozzles described thus far show the following:

1. Different mean drop sizes are used by different investigators,

2. A wide range of correlations are used to predict spray drop size,

3. The dependence of mean drop size on nozzle geometry, operating conditions, and liquid properties differs among the various investigators.

Thus, the current state of knowledge does not definitively indicate which correlation, if any, can accurately, or even adequately, represent the process of atomization in grooved-core nozzles. It is likely that each of the correlations is suitable in the particular experimental conditions under which it was investigated. Nevertheless, to obtain some form of general picture of the dependence of spray drop size on key spray variables, we attempted to compare all the published correlations on a common basis. This was achieved in two ways. First, a comparison was based on rearranging each investigators' correlation in the following form:

$$d_{xx} = K \; D^a \; U^b \; \rho^c \; \mu^d \; \sigma^e \qquad\qquad (II\text{-}21)$$

Table II-2 gives the dependence of the mean drop size found by each investigator on the fundamental spray properties given in equation (II-21). Here most investigators found similar magnitude for the powers a,b,c... representing the powers of the individual variables affecting the spray. The values suggested by Lappel et. al. [18] are average values based on those reported in the literature prior to 1966, and give a good indication of the likely dependence of mean drop size on each variable. The nozzle orifice diameter and flow velocity clearly have the largest effect on spray drop size, while the other variables have lesser effects. The dependence reported for surface tension varies widely among authors. This is likely due to the limited range over which it can be varied experimentally.

A second comparison was made and is shown in figure II-3. Here, the correlations found in the literature predicting the Sauter mean diameter of grooved-core nozzles are compared using one particular nozzle as a basis. The correlations were evaluated for water atomization into air at 23°C using the Spraying Systems Company 1/4LNN2 grooved-core nozzle (described in section 3.2.4). In making this comparison, the limits for each correlation specified by the author were taken into account. Where no limits were specified, the range of velocity over which this nozzle was found to operate in our experiments was used.

TABLE II-2

SUMMARY OF DEPENDENCE OF VARIABLES ON THE MEAN DROP SIZE PRODUCED
BY SWIRL JET NOZZLES

Year	Investigator(s) and Reference	Power Dependence of Mean Dropsize on Indicated Variable					Comments
		Nozzle Orifice Diameter	Velocity	Liquid Density ρ	Liquid Viscosity μ	Surface Tension σ	
1943	Longwell [18]	1.00	-0.75	-0.375			
1949 1953	Joyce [18]	0.50	-0.8	-0.6	0.2		
1953	Turner & Moulton [35]	0.632 0.515	-0.444 -0.537	-0.444 -0.537	0.159 0.220	0.713 0.594	-Grooved Core Nozzles -Tangential Nozzles
1954 1955	Radcliffe [18]	0.50 to 0.636	-0.55 to -0.742	-0.15 to -0.212			
1955	Knight [18]	0.418	-0.707	-0.464	0.215		
1955	Tanasawa & Kobayasai [18]	0.75	-0.50	-0.25		0.25	
1957	McIrvine [18]	1.28	-0.66	-0.33	0.19	0.24	
1960	Mugele [58]	0.65	-0.55	-0.35	0.15	0.20	
1961	Nelson & Stevens [32]	0.47 0.47	-0.82 -0.64	-0.53 -0.53	0.24 0.42	0.29 0.11	-Organic liquids -Water
1964	Il'yashenko & Talantov [18]	1.00	-0.817			0.77	
1967	Lappel, Henry & Blake [18]	0.55	-0.70	-0.45	0.20	0.25	Dependence based on values reported in the literature prior to 1967.
1968	Kim & Saunders [33]	0.73	-0.51				
1972	Dombrowski & Wolfshon [38]	0.67	-0.67				
1972	Wang & Tien [34]	0.44	-0.86	-0.55	0.24	0.31	

Figure II-3: Comparison of Drop Size Correlations.
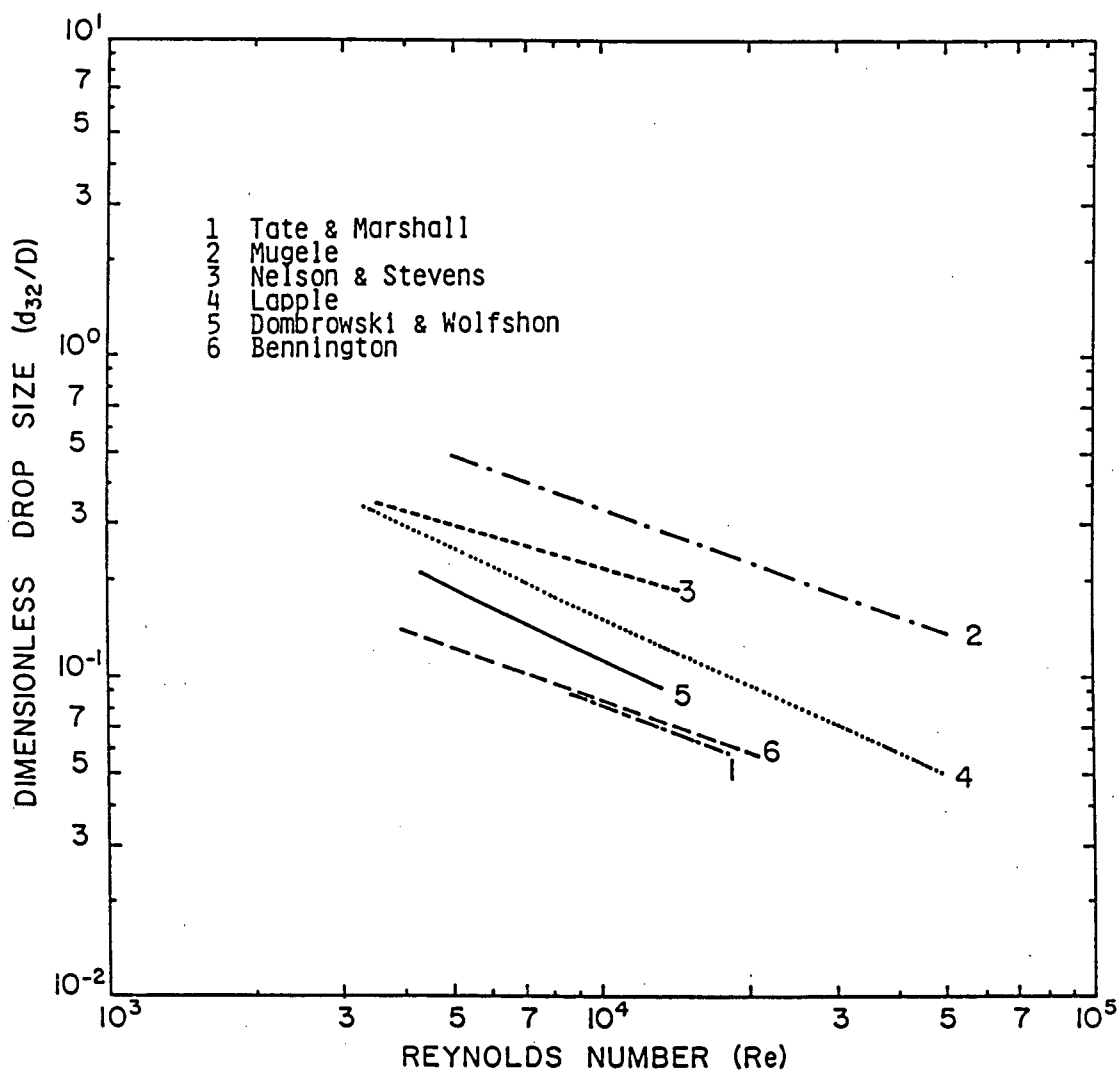
Spraying Systems Company 1/4LNN2 nozzle atomizing water into air at room temperature. Correlations used are given in text.

Examination of figure II-3 shows that the absolute drop size predicted by the various correlations varies over a wide range, almost by a factor of ten at any given Reynolds number. However, the dependence of the mean drop size on flow velocity is similar as is indicated by the similar slopes of the two correlations.

Only one orifice diameter was used to prepare this figure. Thus, although the graph as presented is dimensionless, scale up on the basis of orifice diameter should not be attempted.

7. Atomization by Liquid Flashing

When a liquid at high temperature suddenly moves into a zone of reduced pressure it becomes superheated. The liquid must partially vaporize (flash) to attain equilibrium with its surroundings, by removing sensible heat from the liquid through the latent heat of vaporization. Vaporization continues until the remaining liquid is cooled to the saturation temperature. This generation of vapor can occur at any suitable nucleus in the liquid. Once a bubble is formed, the bubble provides a site where further vaporization can easily occur, promoting rapid bubble growth. This may create a major instability in the liquid.

The rapid growth of bubbles caused by flashing may be sufficient to shatter a liquid jet to the extent that it is atomized. Atomization produced by this means may not require other sources of instabilities as are commonly introduced in spraying nozzles, eg. the tangential swirl

induced by a grooved core nozzle. Brown and York [21] showed this - that flashing alone, caused by superheating a liquid jet issuing form an orifice, is sufficient to produce sprays having a drop size distribution similar to that produced by other techniques. However, they found that complete jet breakup occurred only when the water temperature was typically 40°C or more above its saturation point. In addition they found that the temperature below which no effect was shown on the liquid jet and above which the jet was shattered was only 3°C, with the actual jet shattering temperature determined by the liquid flow rate through the orifice. They correlated their data with water temperature and Weber number as follows:

$$d_{10}(microns) = \frac{1840 - 5.18\ T(°F)}{We} \qquad (II-22)$$

Brown and York also commented that more rapid disintegration of the liquid mass would be expected for water than for organic fluids due to the much larger rate of bubble growth in water. Also, they suggested that flashing may occur with smaller superheat in larger nozzles.

Lienhard [40] examined superheated water jets issuing from 1/8" ID glass tubes. His observations showed that superheats of only 2.5°C could disrupt a turbulent liquid jet and that as the amount of superheat was increased the divergence of the issuing jet increased.

Gooderum and Bushnell [42] studied the mean drop size produced from the atomization of superheated water jets. They found that when

liquid temperature was above that required to shatter the liquid jet that the drop size was only a function of liquid temperature and nozzle diameters.

8. Summary and Conclusions

Although there have been many theoretical and experimental studies of all aspects of the atomization process, prediction of spray drop size is still best made from correlations of experimental results. Some major considerations to take into account when using these correlations are given below:

1. The correlations available in the literature should be used cautiously. Ideally they should be used for the particular nozzle or nozzles for which they were developed, and then only over the range of conditions for which the correlation is valid. Under favorable conditions the mean drops could probably be estimated to within 15 to 25 percent. For the more general correlations, such as the one suggested by Lappel et. al. (See equation II-13), prediction to within ±50% would be considered good.

2. The relationship between the mean dropsize and the fundamental spray properties as determined by various investigators can vary widely as shown in Table II-2. While the magnitude of the dependence differs from investigator to investigator, a trend is clearly evident: jet velocity has

the largest influence on the spray drop size, while the fluid properties of viscosity and surface tension have smaller influences.

3. It has been observed that factors that hinder atomization - low discharge velocity and high liquid viscosity - increase spray nonuniformity.

4. The calculation of mean diameters from the spray distribution should be carried out cautiously. Large errors can result if the actual drop size distribution does not closely follow the one chosen to represent the distribution. Estimation of mean drop size is best made from the original data using equation II-4.

5. The extrapolation of drop size correlations to conditions beyond which they were developed should be done with extreme caution. For the particular case of the orifice diameter, most studies were made with small scale nozzles having orifice diameters less than four millimeters. While the influence of orifice diameter on spray drop size is anticipated to be similar for larger nozzles, there is no experimental confirmation of this in the literature. It has been noted that when existing correlations are extended beyond their applicable range for orifice diameter that the mean drop size is overestimated.

6. It is possible to completely atomize a fluid jet using liquid superheat alone, but the amount of superheat required

to achieve this is generally large. The drop size
distributions produced by this method are comparable to those
produced using conventional hydraulic nozzles. The effect of
atomizing superheated liquids in other nozzles, where a spray
forming mechanism is already present, is not known.

APPENDIX III   REVIEW OF THE PHYSICAL PROPERTIES

OF BLACK LIQUOR

1. Introduction

Black liquor is the spent cooking liquid after the kraft pulping process. It is an aqueous solution containing material dissolved from the wood and inorganic chemicals. Black liquor composition depends on the mixture of wood species pulped and the operating conditions of the cook. However, all black liquors share certain general characteristics in their physical and chemical properties.

2. Chemical Composition

The organic components of black liquor are primarily lignin compounds (largely aromatic in nature), carbohydrates, fatty acids and resins. Most of the lignin is solubilized as large colloidal macromolecules with molecular weights ranging from 500 to 1800. The organic fraction exists largely as sodium salts, while the inorganic part of the liquor contains Na_2CO_3, Na_2SO_4, Na_2S, $Na_2S_2O_3$, NaOH and NaCl. Depending on the degree of closure of the recovery system, quantities of other chemicals can also build up to significant levels. A description of the full range of the components present in black liquor may be found in standard pulp and paper handbooks [47, 59]. The following is a brief description of the physical properties of black liquor that are important to its spraying.

3. Liquor Solids Content

The solids content is defined as the total dissolved and suspended solids remaining after the evaporation of water from the liquor sample. In practice, because other non aqueous volatile materials are also removed during the evaporation, the solids content is affected by the analytical procedure used. Accordingly the industry definition is defined by a standard test (TAPPI T 650 su [60]). In essence, this is a gravimetric determination of the solids remaining after a sample of black liquor is evaporated to dryness under controlled conditions.* Because the TAPPI test is rather lengthy, other analytical techniques that correlate with the TAPPI test have been developed. Nevertheless, values of liquor solids content in the literature are usually reported as TAPPI solids.

There are a number of analytical techniques used to measure black liquor solids content. These include evaporation (various oven drying and microwave drying procedures), distillation, and chemical methods. It is not possible to compare the absolute accuracy of each technique because there is no way to determine exactly how much water is present as H_2O in the liquor. Wagoner and Veeci [61] compared several techniques used for liquor solids determination and found as much as

---

*Black liquor samples are dried at 105°C for a minimum of 6 hours with an inert surface extender and a controlled flow of dried air to increase drying rate and eliminate moisture entrapment. Strong black liquors are diluted to allow volumetric handling and to reduce scum formation.

five percent difference in reported solids content between them. These
differences were attributed to the different temperature maxima reached
by the liquor sample during testing. Tests that reached higher liquor
temperatures resulted in lower reported solids content. Wagoner and
Veeci identified the potential problems affecting the solids content
determination as:

1. formation of a surface film,

2. loss or retention of water of hydration from organic salts,

3. loss or retention of volatile matter,

4. oxidation of liquor constituents,

5. water produced by reaction of NaOH with organic liquor
   constuents,

6. water produced by degradation of organic liquor
   constituents, and

7. detection of other liquor constituents and water of hydration
   as free water.

In our study, we determined black liquor solids content using the
filter paper procedure developed by McDonald [62]. This procedure
requires less time to complete than the TAPPI standard procedure and
correlates well with it. This correlation is given below:

$$\text{TAPPI (\% solids)} = 1.018 \times \text{Filter Paper (\% solids)} - 0.4 \qquad \text{(III-1)}$$

All solids contents reported in this thesis are TAPPI solids.

4. Boiling Point Rise

The boiling point rise of a black liquor is the difference between the boiling point of the liquor and that of pure water at a given pressure. Its value is primarily effected by the liquor solids content, and to a lesser extent by liquor composition, in particular the ratio of organic to inorganic material in the liquor. Clay and Grace [15] have summarized the investigations made of the the boiling point rise of kraft black liquor. These findings are shown in figure III-1. Most investigations place the boiling point rise of a kraft black liquor with 65% solids content between 12-15°C.

5. Liquor Density

The density of black liquor is influenced primarily by its solids content and to a lesser degree by liquor temperature and composition. The density of various black liquors have been reported by a number of investigators including Hultin [63], Koorse and Veeramani [64], and Laurola and Wallendahl [65]. A correlation for liquor specific gravity as a function of solids content and liquor temperature was given by Jagannath [66]. Most investigators report liquor densities of approximately 1.35 g/cm^3 for liquor with 65% solids content.

6. Surface Tension

There have been few investigations of black liquor surface

Figure III-1: Kraft Liquor Boiling Point Rise Data from Several Sources.
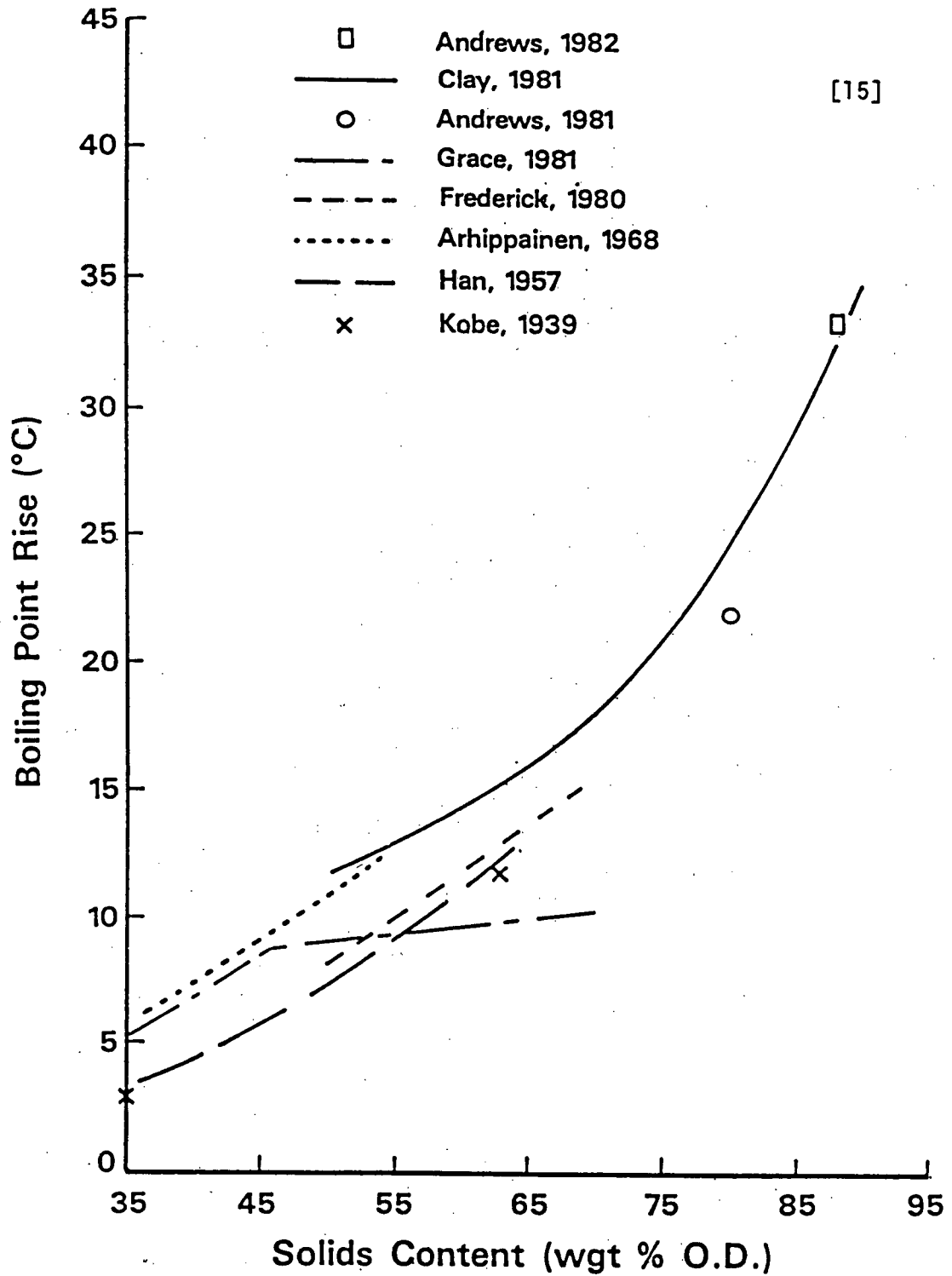
tension, and only one where a value is reported for a liquor having a solids content greater than 50%. Surface tension measurements are difficult to obtain for concentrated liquors due to the tendency of the liquor to form a surface film.

One of the earliest measurements of surface tension was made by Maksimov et. al. [67]. They correlated the surface tension of white and black liquor with alkali content and temperature. This correlation was used to predict liquor surface tension in Merriam's computer model of a recovery furnace [10]. Mehrotra and Veeramani [68] measured the surface tension of bamboo and bagasse black liquors at low solids content using the capillary rise method. Beckwith et. al. [69] used a Du Nouy ring tensiometer for surface tension measurements of softwood black liquors up to 45% solids content. Surface tensions for liquors of greater solids contents could not be determined because a tube of liquor was pulled from the surface. Söderhjelm and Koivuniem [16] obtained a value of approximately 34 dynes/cm for a 61% solids content liquor using a method that involved droplet formation at a capillary. They commented that this determination was likely inaccurate due to high liquor viscosity and poor drop formation.

The consensus among the reviewed articles is that surface tension decreases with increasing temperature. From Söderhjelm and Koivuniem's work it appears that as liquor solid content is increased surface tension first decreases, reaches a plateau and then increases again. The reviewed literature is summarized in table III-1. Most researchers report typical values of black liquor surface tension of 30-40 dynes/cm.

TABLE III-1
SUMMARY OF LITERATURE WORK ON BLACK LIQUOR SURFACE TENSION

Year	Investigator(s) and Reference	Method Used	Liquor Tested	Comments
1966	Maksimov, Bushmelev, Vol'f & Isaeva [67] [Russ.]	not given	kraft white & black	Institute of Paper Chemistery Abstract. Equation given to correlate surface tension with alkali content, C (g/l) and temperature, t (°C): $$\sigma = 76.2 + 0.0805C - 0.167t$$ Surface tension is affected by composition, with organic components reducing σ and inorganic components increasing σ.
1966	Volkov, Khim. Pererabotka Drevesiny, Ref. Inform. no. 4:8-9(1966). [Russ.]; Ref. Zh., Khim. no 13:AS335 (July 10,1966).	not given	kraft	Institute of Paper Chemistery Abstract. Surface tension increased with solids content but not effected by sulfate soap concentration.
1968	Hultin [63]	Tensio-meter	Sulfite	Sulfite liquor was tested from 11 to 57 percent solids and from 20 to 90°C. Values for σ ranged from 50 to 37 dynes/cm.
1970	Volkov & Grigor'ev, Lesnaya Promyshlennost', Moscow, (1970). [Russ.]	not given	kraft & sulfite	Institute of Paper Chemistery Abstract. Other physical properties of spent liquors are given as well.
1970	Polyakov & Marshak, Tr. Leningrad. Tekhnol. Inst. Tsellyul.-Bumazh. Prom. no. 27:21-7(1970). [Russ.]	not given	soda & kraft	Institute of Paper Chemistery Abstract. Noted gradual decrease of surface tension as organic content increased.
1976	Foliadova & Kiprianov, Izv. VUZ, Lesnoi Zh. 19, no.5:91-93 (1976). [Russ.]	not given	hardwood kraft	Institute of Paper Chemistery Abstract. Surface tension of hardwood liquor decreased linearly with increasing temperature.
1977	Mehrotra & Veeramani [68]	Capillary rise	Bamboo, Bagasse & mixed kraft	Surface tensions measured at low liquor solids content, 10-35%, and from 27-95°C. The surface tension ranged from 15 to 45 dynes/cm.
1981	Beckwith, Small & Wood [69]	Du Nouy ring tensio-meter	kraft	Surface tension measured for southern kraft liquors gave values of surface tension of 31-35 dynes/cm up to 45% solids.
1982	Soderhjelm & Koivuniemi [16]	Capillary drop method	kraft	Values of surface tension are given for various solids content up to 61% solids. The authors commented on the probable inaccuracy of values obtained at the higher solids content due to high liquor viscosity and poor drop formation. The data show an initial decrease in σ as liquor solids are increased and postulated an increase in σ after approximately 40% solids.

7.0 Viscosity

The viscosity of black liquor has been measured in a number of investigations. The aim of the review is restricted to data and means of predicting the viscosity of black liquor at high temperatures and high solids content.

The first study of black liquor viscosity was made in 1949 by Kobe and McCormarck [70]. They studied three different pulping liquors: soda, sulfite and sulfate over a range of 14-48% liquor solids content and up to 97°C using Ostwald viscometry. They developed a nomograph for spent liquors based on all data and made no distinction between liquor types. Hedlund [71] reported viscosities for sulfate liquors with different inorganic contents at the same solids level. Han [72] was the first to report a non-Newtonian behaviour for neutral sulfite spent liquor - a thixotropic behaviour at high solids content. In 1977, Oye et. al. [73] reported the viscosity of black liquors from various tropical woods. Although liquor analyses were made, no attempt was made to correlate these with liquor viscosity. Stenuf and Agrawal [74] measured the viscosity of several black liquors with three different types of viscometers. The viscosities they measured using an Ostwald viscometer and a flow tube viscometer of their own design were markedly different than those determined using a rotational viscometer. They dismissed the results of the rotational viscometer, but gave no sound reason for this decision. Kim et. al. [29] studied kraft softwood liquors at high solids contents of 54-69%, up to 90°C, using a wide

range of shear rates. They concluded that the liquors exhibited shear thinning and found the departure from Newtonian behaviour marked at lower temperatures and higher solids contents. They also noted that both liquor viscosity and shear rate behaviour varied significantly with liquor source.

The general findings of this literature search is summarized in Table III-2. Figure III-2 compares the available viscosity data found for black liquors having solids contents ranging from 65 to 67%. Here, viscosity is plotted against liquor temperature.

Figure III-2 shows that reported liquor viscosities vary by almost two orders of magnitude at conditions typical of liquor firing in a recovery furnace (65% solids and 110-115°C).

In view of this wide variation and no obvious way of reconciling it, we decided that it was necessary to measure the viscosity of any specific liquor used in our atomization tests.

8. Characterization of Black Liquor Used in this Study

The liquor chosen for study was from a typical coastal kraft mill in British Columbia pulping a wood mixture of Hemlock and Balsam fir. The liquor was obtained from the oxidized strong black liquor storage tank and diluted to maintain its homogeneity during transportation and storage. Prior to the spray tests the liquor was concentrated to the desired solids content by evaporation over a hot plate. A nitrogen purge was kept over the liquor surface during evaporation to minimize oxidation.

TABLE III-2
SUMMARY OF LITERATURE WORK ON BLACK LIQUOR VISCOSITY

Year	Investigator(s) and Reference	Viscometer Used	Liquor Tested	Solids Range %	Temp. Range °C	Data Given	Comments
1949	Kobe & McCormack [70]	Ostwald	Sulfate	14-48	0-97	yes	Nomograph for soda, sulfate & sulfite liquor. No distinction between liquor types.
1951	Hedlund [71]	Hoppler	Sulfate	0-65	20-200	yes	
1954	Kennedy [11]	not given	Sulfate	55-68	10-148	no	
1955	Davis [75]	not given	not given	45-70	6-204	no	Nomograph, no data or information given
1955	Harvin [76]	Ostwald	Sulfate	13-53	38-93	yes	Used Cannon-Fenske-Ostwald type viscometer
1957	Han [72]	Brookfield & Ostwald	Sulfite	10-47	25-100	yes	Non-Newtonian
1967	Reiche [13]	Hoppler & Engler	Sulfate	0-60	30-110	no	
1968	Hultin [63]	Hoppler	Sulfate	0-65	20-150	no	Extrapolation above 100°C
1968	Lengyel [77]	not given	Straw Sulfate	10-50	20-140	no	
1969	Lankenau & Flores [78]	not given	Sulfate	60-67	50-175	no	Graphs for various liquors
1977	Oye et al. [73]	Epprecht	Hardwood Eucalpt Sulfate	9-70	20-60	yes	For liquors studied, viscosity increased with increasing organic matter
1980	Jagannath [30]	not given	Sulfate	<40 >40		no	Two correlations are given. No data or limits are given for the equations.
1980	Moser [79]	Haake SV	Sulfate	51-67	12-69	yes	Difficulty with skimming
1980	Stenuf & Agrawal [74]	Flow tube, Ostwald & Brookfield	Softwood Hardwood Sulfate	15-65	12-69	yes	Compared various types of viscometers. They noted large differences with viscosities determined with the Brookfield viscometer.
1981	Karoly [80]	not given	Sulfate	67-77	58-90	yes	Varied shear rate. Non-Newtonian
1981	Kim, Co & Fricke [29]	Capillary	Softwood Sulfate	54-69	30-90	yes	Varied shear rate from 10 to 5000s⁻¹
1981	Sandquist [28]	Contraves Rheomat 15	Sulfate	63-73	110&115	yes	Varied shear rate. Non-Newtonian
1982	Korpio & Virkola [81]	not given	Sulfate	55	90	yes	Data as part of study of black liquors
1982	Liem [82]	Flow tube	Sulfate	44-67	89-105	yes	Poiselle flow, non-Newtonian
1982	Sadawarte et.al. [83]	Capillary	Sulfate	10-60	90	yes	Bagasse & bamboo liquors

Figure III-2: Temperature Dependence of 65% Solids Content Black Liquors.

1 Hedlund
2 Kennedy
3 Davis
4 Reiche
5 Hultin
6 Lankenau & Flores
7 Jagannath
8 Moser (65.2%)
9 Stenuf & Agrawal
10 Kim, Co & Fricke (66.8%)
11 Sandquist (66.7%)
12 Liem (66.5%)
13 Bennington
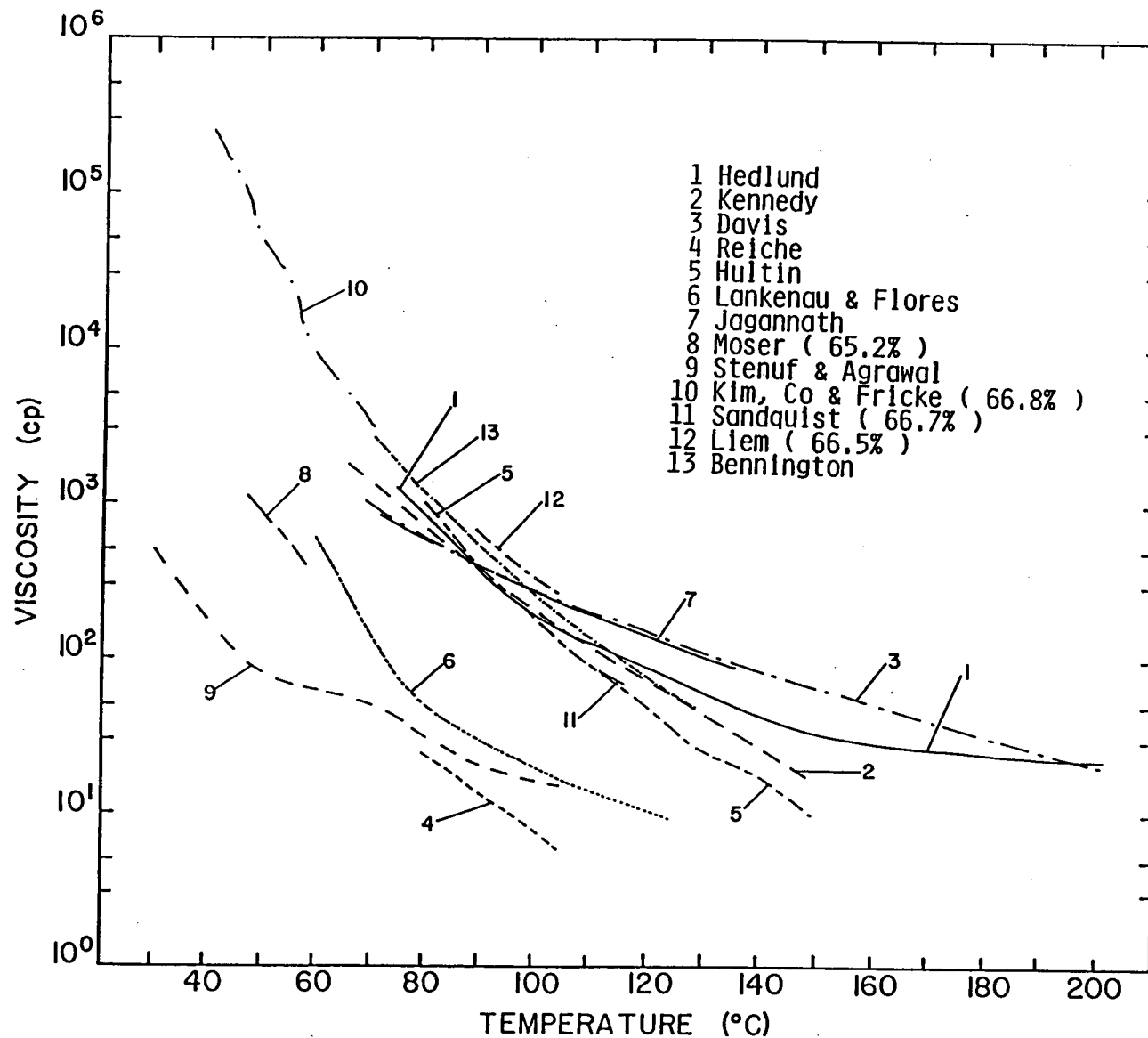
The following figures and tables characterize the liquor chemical composition, density as a function of solids content, and viscosity as a function of both temperature and solids content. The liquor surface tension and boiling point rise were not measured, but were estimated using information available in the literature as discussed in the previous sections.

Chemical Composition: Results of a chemical analysis made on the liquor is sumarized in table III-3. For details regarding the testing procedures the reader should consult the TAPPI standard procedures [60]. The high NaCl content reported in table III-3 is typical for coastal mills pulping ocean-borne logs.

Black Liquor Density: To estimate the black liquor density at any given solids content, a correlation was developed based on information supplied by the mill [84]. 167 individual density measurements spanning a range of solids content from 10 to 67% were used in developing this correlation, given below:

$$\rho(g/cm^3) = 0.950 + 6.503 \times 10^{-3} \ (\% \ solids)$$

Figure III-3 shows the agreement between this equation and the data. Because the data and equation are for liquor at 90°C, density corrections for temperature were estimated based on Hultin's results [63].

Table III-3 Chemical Analysis of West Coast Black Liquor Tested.

Dilution factor	1.419
Total solids - diluted black liquor	35.6% w/w
Total solids - original black liquor	50.5% w/w

Chemical Analysis*	% w/w ODS**
"NaOH"	5.03
Na_2S	0.21
Na_2CO_3	8.55
$Na_2S_2O_3$	4.90
Na_2SO_4	1.04
NaCl	15.2
Total Na	20.9
Total S	3.23
TOC	31.4
Ash	50.7

Calorific Value	5189 BTU/lb ODS
Density	1.212 g/ml

*for testing procedure see TAPPI TIS sheets [60].
**ODS = Oven dried solids.

Figure III-3: West Coast Black Liquor Density (90°C).
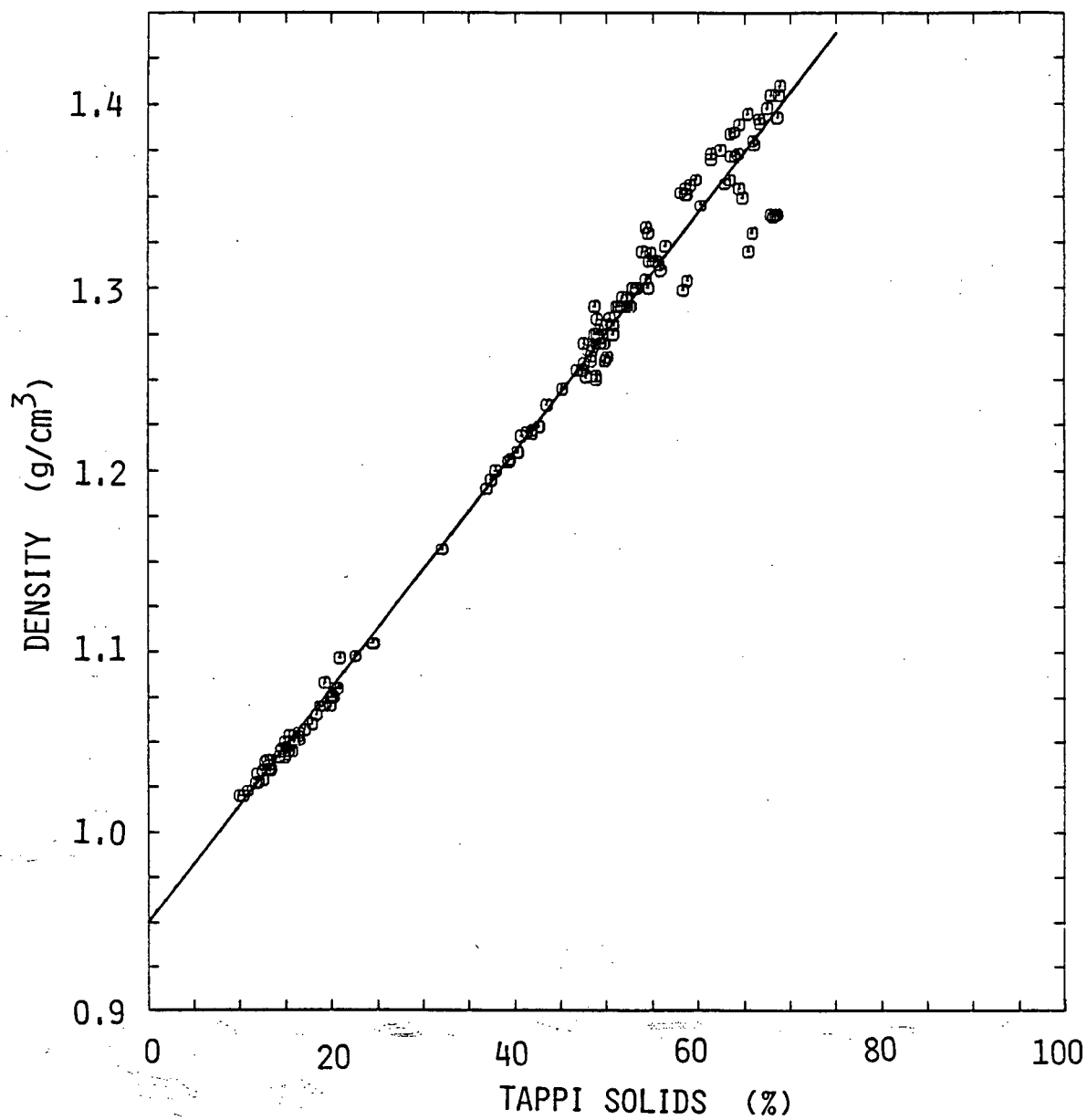
Liquor Viscosity: The liquor viscosity is the most important liquor variable in atomization. Consequently much detail has been given about this subject (see sections 3.5, 4.1 and III-7). The correlation developed for this liquor (equation (4)) is used in figure III-4 to predict the liquor viscosity between 35 and 70% solids content from 20 to 130°C.

Figure III-4: West Coast Black Liquor Viscosity.
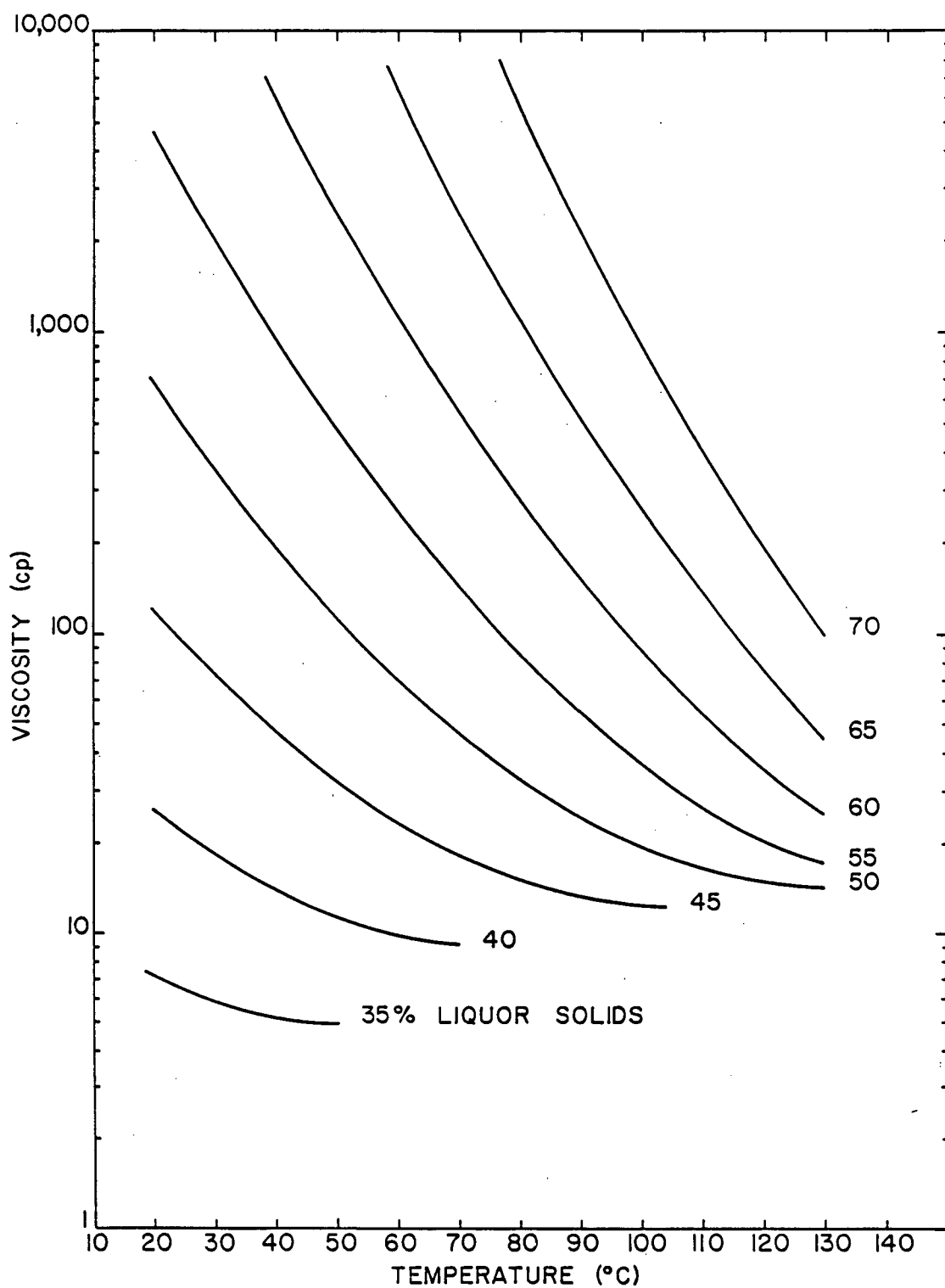
APPENDIX IV: COMPUTER PROGRAM FOR SPRAY DROP SIZE DISTRIBUTION ANALYSIS

```
1    C  DROP SIZE DISTRIBUTION ANALYSIS ROUTINE
2    C
3    C
4    C     This program takes the information from a drop size distribution
5    C  presented as the number of discrete occurences in classes of
6    C  known size, and computes the following properties of the distribution:
7    C
8    C              (1) Linear Mean Diameter
9    C              (2) Surface Mean Diameter
10   C              (3) Volume Mean Diameter
11   C              (4) Sauter Mean Diameter
12   C              (5) Geometric Mean Diameter
13   C              (6) Square Root Mean Diameter
14   C              (7) Normal Standard Dviation
15   C              (8) Log Normal Standard Deviation, and
16   C              (9) Square-Root Normal Deviation.
17   C
18   C     The data deck for this program may be set up in two ways. The size of
19   C  each class may be calculated from appropriate information, or read in
20   C  from a file. (The latter will allow the use of non-uniformly sized
21   C  intervals)
22   C
23   C
24   C  (A) Calculated Class Increments
25   C
26   C     The card deck (in input unit 5) must be structured as follows:
27   C  (The appropriate format is given in braces)
28   C
29   C              (1) N, The number of classes, (I2)
30   C              (2) The number '1', indicating that the information for the
31   C                  class sizes is to be calculated, (I1)
32   C              (3) The starting position of the first increment, (F5.1)
33   C              (4) The incremental step for each class, (F5.1)
34   C              (5) Five cards giving information about the spray from
35   C                  which the distribution was produced, including the:
36   C                     - Data set ID number
37   C                     - Fluid atomized
38   C                     - Nozzle used
39   C                     - Atomizer pressure
40   C                     - Liquid temperature
41   C              (6) The number of drops in each class. There must be N
42   C                  data sets.
43   C
44   C
45   C  (B) Class Sizes Read in from Files
46   C
47   C     The card deck is in input unit 5, structured as before, with the
48   C  following exceptions:
49   C
50   C              (1) Card 2 is '0',
51   C              (2) Cards 3 & 4 are eliminated.
52   C
53   C     The class sizes are read from input unit 7, structured in the following
54   C  way:
55   C
56   C         FROM    TO    MEAN
57   C
58   C  The format is (3F7.3). There must be N entries.
59   C
60   C                                                          cpjb
```

```
61
62
63             IMPLICIT REAL*4 (A-H, O-Z)
64             DIMENSION M(150), L(150), SCALE(150,3), DROP(150,5)
65             REAL*4 MEAN, SURF, VOLUME, SAUTER, CHECK
66             REAL*4 LOWER, DINCR, STDEV
67             REAL*4 GEO, LSD
68             REAL*4 SRN, SRDEV
69             INTEGER COUNT, N, INPUT
70             INTEGER CHAR(5,80)
71
72             DATA   COUNT, MEAN, SURF / 0, 0.0, 0.0 /
73             DATA VOLUME, SAUTER, CHECK / 0.0, 0.0, 0.0 /
74             DATA STDEV / 0.0 /
75             DATA GEO, LSD / 0.0, 0.0 /
76             DATA SRN, SRDEV / 0.0, 0.0 /
77
78             READ(5,4) N
79      4      FORMAT(I2)
80             READ(5,5) INPUT
81      5      FORMAT(I1)
82
83      C   Input of Class Sizes
84
85             IF (INPUT.EQ.1) GO TO 20
86              DO 15 IROW=1,N
87              READ(7,10) (SCALE(IROW,ICOL), ICOL=1,3,1)
88      10      FORMAT (3F7.3)
89      15      CONTINUE
90             GO TO 40
91      20     CONTINUE
92             READ(5,21) LOWER
93             READ(5,21) DINCR
94      21     FORMAT (F5.1)
95             SCALE(1,1)=LOWER
96             SCALE(1,2)=LOWER+DINCR
97             SCALE(1,3)=(LOWER+SCALE(1,2))/2
98             DO 25 IROW=2,N
99             SCALE(IROW,1)=SCALE(IROW-1,1)+DINCR
100            SCALE(IROW,2)=SCALE(IROW-1,2)+DINCR
101            SCALE(IROW,3)=SCALE(IROW-1,3)+DINCR
102      25    CONTINUE
103      40    CONTINUE
104
105      C  Reading of Spray Data Information
106
107             DO 50 I=1,5
108             READ (5,45) (CHAR(I,J), J=1,80,1)
109      45     FORMAT (80A1)
110      50     CONTINUE
111
112      C  Input of Drop-size Distribution
113
114             DO 70 IROW=1,N
115             M(IROW)=IROW
116             READ(5,60) L(IROW)
117      60     FORMAT (I4)
118             COUNT=COUNT+L(IROW)
119      70     CONTINUE
120
```

```
121      C  Calculation of Mean Diameters
122
123              DO 100 IROW=1,N
124              DROP(IROW,1)=FLOAT(L(IROW))/FLOAT(COUNT)
125              DROP(IROW,2)=DROP(IROW,1)*SCALE(IROW,3)
126              DROP(IROW,3)=DROP(IROW,1)*SCALE(IROW,3)**2
127              DROP(IROW,4)=DROP(IROW,1)*SCALE(IROW,3)**3
128      100     CONTINUE
129              DROP(1,5)=DROP(1,1)
130              DO 120 IROW=2,N
131              DROP(IROW,5)=DROP(IROW-1,5)+DROP(IROW,1)
132      120     CONTINUE
133              DO 150 IROW=1,N
134              CHECK=CHECK+DROP(IROW,1)
135              MEAN=MEAN+DROP(IROW,2)
136              SURF=SURF+DROP(IROW,3)
137              VOLUME=VOLUME+DROP(IROW,4)
138              IF (L(IROW).EQ.0) GO TO 140
139              GEO=GEO+DROP(IROW,1)*ALOG(SCALE(IROW,3))
140              SRN=SRN+L(IROW)*SQRT(SCALE(IROW,3))
141      140     CONTINUE
142      150     CONTINUE
143              SAUTER=VOLUME/SURF
144              SURF=SQRT(SURF)
145              VOLUME=(ALOG(VOLUME))/3
146              VOLUME=EXP(VOLUME)
147              GEO=EXP(GEO)
148              SRN=(SRN/COUNT)
149
150      C  Calculation of Standard Deviations
151
152              DO 200 IROW=1,N
153              IF (L(IROW).EQ.0) GO TO 190
154              STDEV=STDEV+L(IROW)*(SCALE(IROW,3)-MEAN)**2
155              LSD=LSD+L(IROW)*((ALOG(SCALE(IROW,3))-ALOG(GEO))**2)
156              SRDEV=SRDEV+L(IROW)*(SQRT(SCALE(IROW,3))-SQRT(SRN)**2)**2
157      190     CONTINUE
158      200     CONTINUE
159              STDEV=SQRT(STDEV/(COUNT-1))
160              LSD=SQRT(LSD/COUNT)
161              LSD=EXP(LSD)
162              SRDEV=(SRDEV/COUNT)
163
164      C  Output of Data
165
166              WRITE (6,225)
167      225     FORMAT ('1',/)
168              WRITE (6,240)
169      240     FORMAT (' SPRAYABILITY OF CONCENTRATED ')
170              WRITE (6,245)
171      245     FORMAT ( ' BLACK LIQUOR - MASc THESIS')
172              WRITE (6,247)
173      247     FORMAT (' ',/)
174              WRITE (6,250) (CHAR(1,J), J=1,80,1)
175      250     FORMAT ('   ','Identification Number: ',80A1)
176              WRITE (6,260) (CHAR(2,J), J=1,80,1)
177      260     FORMAT ('   ','Fluid Atomized:        ',80A1)
178              WRITE (6,270) (CHAR(3,J), J=1,80,1)
179      270     FORMAT ('   ','Nozzle Used:           ',80A1)
180              WRITE (6,280) (CHAR(4,J), J=1,80,1)
```

```
181    280    FORMAT (' ','Atomizer Pressure:        ',80A1)
182           WRITE (6,290) (CHAR(5,J), J=1,80,1)
183    290    FORMAT (' ','Temperature:             ',80A1)
184           WRITE (6,295) COUNT
185    295    FORMAT (' ','Drops Counted:         ',I4)
186           WRITE (6,247)
187           WRITE (6,300)
188    300    FORMAT ( ' CLASS      FROM     TO      MEAN     COUNTS    RELATIVE
189          1 FRACTION    CUMULATIVE')
190           DO 400 IROW=1,N
191    400    WRITE (6,410) M(IROW), (SCALE(IROW,J), J=1,3,1),
192          1 L(IROW), DROP(IROW,1), DROP(IROW,5)
193           WRITE (6,247)
194    410    FORMAT (3X,I2,5X,F6.2,2X,F6.2,3X,F6.2,5X,I4,10X,F6.4,12X,F6.4)
195           WRITE (6,247)
196           WRITE (6,420) COUNT, CHECK
197    420    FORMAT ( ' Sum=                                  ',I4,
198          1 '                 ',F6.4)
199           WRITE (6,247)
200           WRITE (6,225)
201           WRITE (6,240)
202           WRITE (6,245)
203           WRITE (6,247)
204           WRITE (6,250) (CHAR(1,J), J=1,80,1)
205           WRITE (6,247)
206           WRITE (6,247)
207           WRITE (6,440)
208    440    FORMAT ( ' CALCULATED DROPSIZE DIAMETERS FROM DISTRIBUTION')
209           WRITE (6,247)
210           WRITE (6,450) MEAN
211    450    FORMAT (' Linear Mean:       ',F8.3)
212           WRITE (6,460) SURF
213    460    FORMAT (' Surface Mean:      ',F8.3)
214           WRITE (6,470) VOLUME
215    470    FORMAT (' Volume Mean:       ',F8.3)
216           WRITE (6,480) SAUTER
217    480    FORMAT (' Sauter Mean:       ',F8.3)
218           WRITE (6,490) GEO
219    490    FORMAT (' Geometric Mean:    ',F8.3)
220           WRITE (6,495) SRN
221    495    FORMAT (' Square Root Mean:',F8.3)
222           WRITE (6,247)
223           WRITE (6,500)
224    500    FORMAT ('CALCULATED STANDARD DEVIATIONS ')
225           WRITE (6,247)
226           WRITE (6,550) STDEV
227    550    FORMAT (' Normal Standard Deviation:              ',F8.3)
228           WRITE (6,600) LSD
229    600    FORMAT (' Log Normal Standard Deviation:          ',F8.3)
230           WRITE (6,650) SRDEV
231    650    FORMAT (' Square-root Normal Standard Deviation:',F8.3)
232           WRITE (6,700)
233    700    FORMAT (' ',//////)
234           STOP
235           END
End of file
```

SPRAYABILITY OF CONCENTRATED
BLACK LIQUOR - MASc THESIS

Identification Number: RUN 73
Fluid Atomized: 64.8% Glycerol/Water
Nozzle Used: 1/4LNN2
Atomizer Pressure: 195 psig
Temperature: 23 C
Drops Counted: 2516

CLASS	FROM	TO	MEAN	COUNTS	RELATIVE FRACTION	CUMULATIVE
1	0.0	10.00	5.00	1	0.0004	0.0004
2	10.00	20.00	15.00	38	0.0151	0.0155
3	20.00	30.00	25.00	573	0.2277	0.2432
4	30.00	40.00	35.00	590	0.2345	0.4777
5	40.00	50.00	45.00	353	0.1403	0.6180
6	50.00	60.00	55.00	303	0.1204	0.7385
7	60.00	70.00	65.00	214	0.0851	0.8235
8	70.00	80.00	75.00	159	0.0632	0.8867
9	80.00	90.00	85.00	116	0.0461	0.9328
10	90.00	100.00	95.00	64	0.0254	0.9583
11	100.00	110.00	105.00	43	0.0171	0.9754
12	110.00	120.00	115.00	28	0.0111	0.9865
13	120.00	130.00	125.00	13	0.0052	0.9917
14	130.00	140.00	135.00	7	0.0028	0.9944
15	140.00	150.00	145.00	7	0.0028	0.9972
16	150.00	160.00	155.00	3	0.0012	0.9984
17	160.00	170.00	165.00	2	0.0008	0.9992
18	170.00	180.00	175.00	1	0.0004	0.9996
19	180.00	190.00	185.00	0	0.0	0.9996
20	190.00	200.00	195.00	0	0.0	0.9996
21	200.00	210.00	205.00	0	0.0	0.9996
22	210.00	220.00	215.00	1	0.0004	1.0000

Sum=   2516   1.0000

SPRAYABILITY OF CONCENTRATED
BLACK LIQUOR - MASc THESIS

Identification Number: RUN 73

CALCULATED DROPSIZE DIAMETERS FROM DISTRIBUTION

Linear Mean: 48.641
Surface Mean: 54.455
Volume Mean: 60.627
Sauter Mean: 75.152
Geometric Mean: 43.494
Square Root Mean: 6.780

CALCULATED STANDARD DEVIATIONS

Normal Standard Deviation: 24.487
Log Normal Standard Deviation: 1.594
Square-root Normal Standard Deviation: 2.673

APPENDIX V: DATA

Figure V-I: Flow Rate Data for 1/4LNN Series Nozzles.
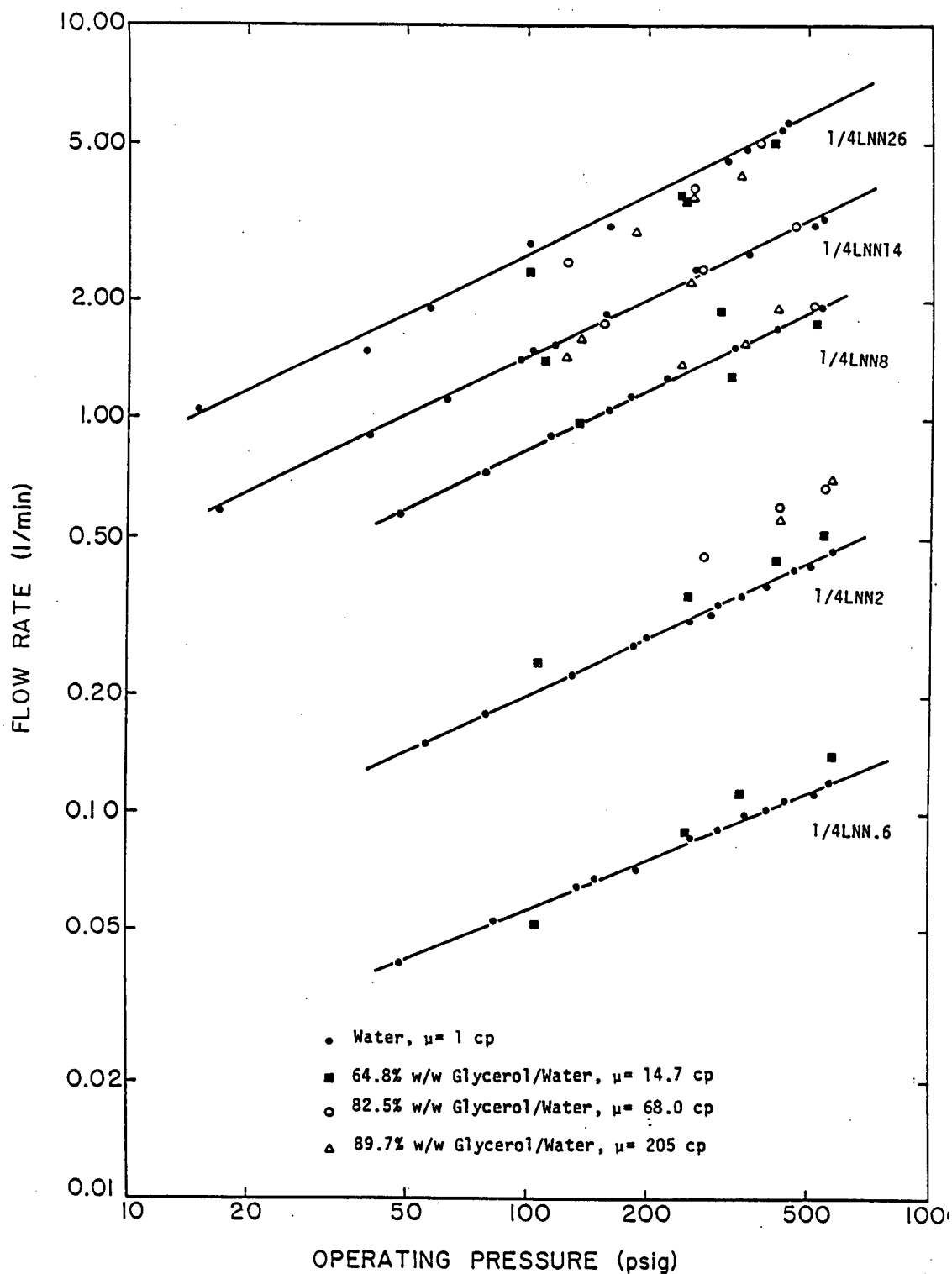
Table V-1   Tabulation of Experimental Measurements of West Coast
            Black Liquor Viscosity.

Tappi Percent Solids	Temperature °C	Viscosity cp	Comments
68.8	76.5	5209	
68.8	90.5	1178	
68.8	100.5	1031	
68.8	107.0	290.3	
68.8	127.0	83.0	
62.2	86.0	654.3	
62.2	101.0	150.4	
62.2	121.5	9.8	Liquor Boiling in cell
56.3	71.0	191.7	
56.3	91.0	85.5	
56.3	111.0	33.6	
55.2	60.0	231.3	
55.2	81.0	81.0	
55.2	100.0	39.0	
45.8	36.0	62.6	
45.8	57.0	26.9	
45.8	73.5	16.7	
45.8	84.0	15.1	
38.2	26.0	15.4	
38.2	42.0	9.4	
38.2	61.0	8.2	

TABLE V-2

PHYSICAL PROPERTIES OF GLYCEROL/WATER SOLUTIONS AT 23°C
DETERMINED FROM REFRACTIVE INDICES

Glycerol Sample Identification:	Refractive Index at 20°C	Glycerol Percent w/w	Density ρ g/cm³	Surface Tension σ dynes/cm	Viscosity[1] ν cp	Viscosity[2] ν cp
Stock Glycerol (99.5%)	1.4715	98.6				
Glycerol dilution #1, before tests	1.4579	89.7	1.2323	64.3	222.9	
after tests	1.4579	89.7	1.2323	64.3	222.9	
average		89.7	1.2323	64.3	222.9	205.0
Glycerol dilution #2, before tests	1.4472	82.69	1.2137		75.24	
after tests	1.4467	82.36	1.2128		73.15	
average		82.5	1.2132	65.2	74.2	68.0
Glycerol dilution #3, before tests	1.4190	64.07	1.1634		13.70	
after tests	1.4212	65.53	1.1673		15.30	
average		64.8	1.1654	67.5	14.5	14.7

[1] Viscosities determined at 20°C from refractive index measurements
[2] Viscosities determined at 23°C using Haake RV12 Rotovisco

4. Introduction to Spray Analysis Data Tables

The following sections give the data for each individual test made in the course of this study. The tabulated spray parameters were determined as described in section 3.4 and require no further comment here. In table V-7 the following abbreviations are used:

Poor Atom = the atomization produced by the nozzle was judged to be poor.

Some Flash = the presence of a mist in the center region of the spray.

% S BL = black liquor solids content

TABLE V-3
SUMMARY OF EXPERIMENTAL RESULTS: Part I
Atomization of Water and Glycerol/Water Mixtures

Test No.	Nozzle	Glycerol Water Weight Percent	Fluid Temp °C	Atom. Pres. psig	Orifice Diameter cm	Uo cm/s	ρ Density g/cm³	σ Surface Tension dynes/cm	μ Visc. cp	Re	We	Drops Counted	Mean Diameter d_{10} μm
1	1/4LNN.6	0.0	17	50	0.0406	547.1	0.9989	73.20	1.081	2053	165.8	384	69.9
2	1/4LNN.6	0.0	17	50	0.0406	547.1	0.9989	73.20	1.081	2053	165.8	1178	56.7
3	1/4LNN.6	0.0	17	100	0.0406	733.8	0.9989	73.20	1.081	2753	298.3	1061	60.0
4	1/4LNN.6	0.0	17	100	0.0406	733.8	0.9989	73.20	1.081	2753	298.3	3199	47.4
5	1/4LNN.6	0.0	17	150	0.0406	869.0	0.9989	73.20	1.081	3260	418.4	2436	39.1
6	1/4LNN.6	0.0	17	200	0.0406	978.4	0.9989	73.20	1.081	3671	530.4	4282	28.8
7	1/4LNN.6	0.0	17	200	0.0406	978.4	0.9989	73.20	1.081	3671	530.4	2017	22.6
8	1/4LNN.6	0.0	17	300	0.0406	1159	0.9989	73.20	1.081	4348	744.2	3536	19.5
9	1/4LNN.6	0.0	18	400	0.0406	1300	0.9986	73.04	1.053	5005	938.4	1588	13.9
10	1/4LNN.6	0.0	18	400	0.0406	1300	0.9986	73.04	1.053	5005	938.1	2869	17.7
11	1/4LNN.6	0.0	18	550	0.0406	1493	0.9986	73.04	1.053	5748	1237	243	15.5
12	1/4LNN.6	0.0	18	550	0.0406	1493	0.9986	73.04	1.053	5748	1237	3196	13.5
13	1/4LNN2	0.0	18	50	0.0711	608.7	0.9986	73.04	1.053	4104	360.2	872	35.5
14	1/4LNN2	0.0	18	50	0.0711	608.7	0.9986	73.04	1.053	4104	360.2	790	49.0
15	1/4LNN2	0.0	18	100	0.0711	852.1	0.9986	73.04	1.053	5745	705.8	1076	32.1
16	1/4LNN2	0.0	18	150	0.0711	1028	0.9986	73.04	1.053	6932	1027	1650	23.3
17	1/4LNN2	0.0	18	150	0.0711	1028	0.9986	73.04	1.053	6932	1027	753	25.3
18	1/4LNN2	0.0	18	200	0.0711	1175	0.9986	73.04	1.053	7922	1342	2096	15.5
19	1/4LNN2	0.0	18	200	0.0711	1175	0.9986	73.04	1.053	7922	1342	606	24.0
20	1/4LNN2	0.0	18	200	0.0711	1175	0.9986	73.04	1.053	7922	1342	502	32.4
21	1/4LNN2	0.0	18	300	0.0711	1457	0.9986	73.04	1.053	9824	2064	4342	15.8
22	1/4LNN2	0.0	18	400	0.0711	1547	0.9986	73.04	1.053	10430	2326	3341	20.1
23	1/4LNN2	0.0	19	400	0.0711	1547	0.9984	72.89	1.027	10690	2331	1279	20.9
24	1/4LNN2	0.0	24	550	0.0711	1889	0.9973	72.13	0.911	14700	3502	916	20.3
25	1/4LNN2	0.0	23	550	0.0711	1889	0.9975	72.28	0.9325	14370	3501	931	16.6

Atomization of Water and Glycerol/Water Mixtures

Test No.	Nozzle	Glycerol Water Weight Percent	Fluid Temp °C	Atom. Pres. psig	Orifice Diameter cm	Uo cm/s	ρ Density g/cm³	σ Surface Tension dynes/cm	μ Visc. cp	Re	We	Drops Counted	Mean Diameter d_{10} μm
26	1/4LNN2	0.0	21	560	0.0711	1910	0.9980	72.59	0.978	13860	3566	3766	18.1
27	1/4LNN8	0.0	21	50	0.1524	529.9	0.9980	72.59	0.978	8241	588.3	498	77.8
28	1/4LNN8	0.0	21	50	0.1524	529.9	0.9980	72.59	0.978	8241	588.3	212	71.8
29	1/4LNN8	0.0	21	50	0.1524	529.9	0.9980	72.59	0.978	8241	588.3	282	68.4
30	1/4LNN8	0.0	21	100	0.1524	733.8	0.9980	72.59	0.978	11410	1128	942	72.2
31	1/4LNN8	0.0	21	150	0.1524	931.9	0.9980	72.59	0.978	14490	1820	1367	57.9
32	1/4LNN8	0.0	21	300	0.1524	1334	0.9980	72.59	0.978	20750	3729	565	58.7
33	1/4LNN8	0.0	21	300	0.1524	1334	0.9980	72.59	0.978	20750	3729	1002	68.2
34	1/4LNN8	0.0	21	510	0.1524	1736	0.9980	72.59	0.978	27000	6315	1096	44.8
35	1/4LNN8	0.0	21	500	0.1524	1727	0.9980	72.59	0.978	26860	6249	1382	53.1
36	1/4LNN8	0.0	21	400	0.1524	1544	0.9980	72.59	0.978	24010	4995	2074	54.3
37	1/4LNN14	0.0	21	50	0.1930	581.1	0.9980	72.59	0.978	11440	896.0	789	60.6
38	1/4LNN14	0.0	21	50	0.1930	581.1	0.9980	72.59	0.978	11440	896.0	1020	62.1
39	1/4LNN14	0.0	21	100	0.1930	826.1	0.9980	72.59	0.978	16270	1811	1520	39.0
40	1/4LNN14	0.0	21	150	0.1930	1014	0.9980	72.59	0.978	19970	2728	4065	41.4
41	1/4LNN26	0.0	21	50	0.2184	805.3	0.9980	72.59	0.978	17950	1947	1373	46.6
42	1/4LNN26	0.0	21	150	0.2184	1401	0.9980	72.59	0.978	31230	5894	3506	30.4
43	1/4LNN26	0.0	20	305	0.2184	2002	0.9982	72.74	1.002	43560	12010	3431	28.3
44	1/4LNN26	0.0	20	310	0.2184	2010	0.9982	72.74	1.002	43730	12110	3704	29.1
45	1/4LNN14	0.0	20	340	0.1930	1532	0.9982	72.74	1.002	29460	6216	6700	32.1
46	1/4LNN14	0.0	19	325	0.1930	1504	0.9984	72.89	1.027	28220	5980	3001	43.2
47	1/4LNN14	0.0	20	500	0.1930	1834	0.9982	72.74	1.002	35270	8908	1210	39.9
48	1/4LNN14	0.0	20	475	0.1930	1800	0.9982	72.74	1.002	34610	8581	1349	42.1
49	1/4LNN14	0.0	20	475	0.1930	1800	0.9982	72.74	1.002	34610	8581	2222	54.3
50	1/4LNN2	89.7	23	500	0.0711	2687	1.232	64.3	205	114.8	9836	507	53.3

SUMMARY OF EXPERIMENTAL RESULTS: Part I (cont)
Atomization of Water and Glycerol/Water Mixtures

Test No.	Nozzle	Glycerol Water Weight Percent	Fluid Temp °C	Atom. Pres. psig	Orifice Diameter cm	Uo cm/s	ρ Density g/cm³	σ Surface Tension dynes/cm	μ Visc. cp	Re	We	Drops Counted	Mean Diameter d₁.₀ μm
51	1/4LNN2	89.7	23	500	0.0711	2687	1.232	64.3	205	114.8	9836	1300	37.8
52	1/4LNN8	89.7	23	460	0.1524	1827	1.232	64.3	205	167.3	9747	3286	56.2
53	1/4LNN14	89.7	23	460	0.1930	1709	1.232	64.3	205	198.2	10800	1491	58.9
54	1/4LNN26	89.7	23	350	0.2184	1913	1.232	64.3	205	251.1	15310	82	56.2
55	1/4LNN26	82.5	23	350	0.2184	2091	1.213	65.3	68.0	814.6	17740	668	50.2
56	1/4LNN8	82.5	22	325	0.1524	1407	1.214	65.2	68.0	382.8	5618	1635	62.3
57	1/4LNN8	82.5	22	430	0.1524	1608	1.214	65.2	68.0	437.5	7337	631	53.5
58	1/4LNN8	82.5	22	475	0.1524	1690	1.214	65.2	68.0	459.8	8105	611	68.7
59	1/4LNN2	82.5	22	275	0.0711	1889	1.214	65.2	68.0	239.8	4724	2534	49.0
60	1/4LNN2	82.5	22	475	0.0711	2645	1.214	65.2	68.0	335.7	9262	1710	55.5
61	1/4LNN2	82.5	22	550	0.0711	2771	1.214	65.2	68.0	351.7	10170	1906	47.1
62	1/4LNN14	82.5	22	230	0.1930	1231	1.214	65.2	68.0	424.2	5446	777	64.7
63	1/4LNN14	82.5	22	350	0.1930	1493	1.214	65.2	68.0	514.4	8010	1938	53.0
64	1/4LNN14	82.5	22	525	0.1930	1874	1.214	65.2	68.0	645.7	12620	2734	44.9
65	1/4LNN14	82.5	22	525	0.1930	1874	1.214	65.2	68.0	645.7	12620	990	40.7
66	1/4LNN26	82.5	22	210	0.2184	1513	1.214	65.2	68.0	589.9	9309	1171	52.1
67	1/4LNN26	82.5	22	300	0.2184	1980	1.214	65.2	68.0	772.0	15940	1003	58.2
68	1/4LNN26	82.5	22	450	0.2184	2491	1.214	65.2	68.0	971.3	25230	2956	48.4
69	1/4LNN.6	82.5	22	625	0.0406	1867	1.214	65.2	68.0	135.3	2635	1784	33.9
70	1/4LNN.6	64.8	23	570	0.0406	1892	1.165	67.5	14.7	608.8	2508	2403	55.6
71	1/4LNN.6	64.8	23	350	0.0406	1339	1.165	67.5	14.7	430.8	1256	2590	52.5
72	1/4LNN2	64.8	23	100	0.0711	1007	1.165	67.5	14.7	567.4	1244	2430	67.6
73	1/4LNN2	64.8	23	195	0.0711	1352	1.165	67.5	14.7	761.8	2243	2516	48.6
74	1/4LNN2	64.8	23	310	0.0711	1637	1.165	67.5	14.7	922.4	3288	4151	27.1
75	1/4LNN2	64.8	23	450	0.0711	1931	1.165	67.5	14.7	1088	4576	1233	18.9

SUMMARY OF EXPERIMENTAL RESULTS: Part I (cont)
Atomization of Water and Glycerol/Water Mixtures

Test No.	Nozzle	Glycerol Water Weight Percent	Fluid Temp °C	Atom. Pres. psig	Orifice Diameter cm	Uo cm/s	ρ Density g/cm^3	σ Surface Tension dynes/cm	μ Visc. cp	Re	We	Drops Counted	Mean Diameter d_{10} μm
76	1/4LNN2	64.8	23	435	0.0711	1910	1.165	67.5	14.7	1076	4477	3733	26.5
77	1/4LNN2	64.8	23	575	0.0711	2120	1.165	67.5	14.7	1195	5515	3969	24.7
78	1/4LNN8	64.8	23	95	0.1524	731	1.165	67.5	14.7	882.9	1405	1867	30.2
79	1/4LNN8	64.8	23	300	0.1524	1270	1.165	67.5	14.7	1534	4242	2809	49.2
80	1/4LNN8	64.8	23	300	0.1524	1270	1.165	67.5	14.7	1534	4242	1350	38.0
81	1/4LNN8	64.8	23	575	0.1524	1681	1.165	67.5	14.7	2030	7433	3307	42.8
82	1/4LNN14	64.8	23	95	0.1930	798	1.165	67.5	14.7	1221	2121	1652	58.1
83	1/4LNN14	64.8	23	320	0.1930	1481	1.165	67.5	14.7	2265	7306	2042	46.5
84	1/4LNN14	64.8	23	500	0.1930	1766	1.165	67.5	14.7	2701	10390	3385	54.3
85	1/4LNN26	64.8	23	100	0.2184	1023	1.165	67.5	14.7	1771	3945	233	57.7
86	1/4LNN26	64.8	23	110	0.2184	1045	1.165	67.5	14.7	1809	4116	2902	37.7
87	1/4LNN26	64.8	23	300	0.2184	1869	1.165	67.5	14.7	3235	13170	2196	59.8
88	1/4LNN26	64.8	23	470	0.2184	2447	1.165	67.5	14.7	4235	22570	1658	47.6

TABLE V-4
SUMMARY OF EXPERIMENTAL RESULTS: Part II
Atomization of Water and Superheated Water

Test No.	Nozzle	Water Temp °C	Atom. Pres. psig	Orifice Diameter cm	Sample Locat'n	Uo cm/s	ρ Density g/cm³	σ Surface Tension dynes/cm	μ Visc. cp	Re	We	Drops Counted	Mean Diameter d_{10} μm
89	1/4LNN.6	86	153	0.0406	center	875	0.968	61.5	0.33	10420	489	4207	24.9
90	1/4LNN.6	100	150	0.0406	center	870	0.958	58.9	0.25	13520	500	2803	27.7
91	1/4LNN.6	120	154	0.0406	center	875	0.944	55.2	0.19	17650	532	2941	16.6
92	1/4LNN.6	149	155	0.0406	center	875	0.926	49.9	0.125	26320	576	1016	16.2
93	1/4LNN2	127	105	0.0711	cone	877	0.940	54.0	0.17	34580	952	958	57.8
94	1/4LNN2	146	105	0.0711	cone	877	0.926	50.5	0.13	44420	1003	1384	57.7
95	1/4LNN2	148	110	0.0711	center	882	0.925	50.1	0.13	44620	1021	6410	17.8
96	1/4LNN2	85	107	0.0711	center	879	0.969	61.7	0.32	18730	863	3425	17.2
97	1/4LNN2	85	105	0.0711	cone	877	0.969	61.7	0.32	18880	859	1692	30.4
98	1/4LNN2	102	105	0.0711	center	877	0.957	58.6	0.25	23870	893	2737	16.1
99	1/4LNN2	104	107	0.0711	cone	879	0.956	58.2	0.24	24890	902	894	49.1
100	1/4LNN2	126	110	0.0711	center	882	0.940	54.1	0.18	32820	961	1689	16.8
101	1/4LNN2	126	110	0.0711	cone	882	0.940	54.1	0.18	32820	961	1016	86.0
102	1/4LNN8	84	130	0.1524	center	861	0.969	61.8	0.32	39720	1770	2145	15.8
103	1/4LNN8	87	134	0.1524	cone	886	0.967	61.3	0.33	39580	1890	3444	44.5
104	1/4LNN8	105	125	0.1524	cone	850	0.955	58.0	0.25	49480	1813	2027	51.1
105	1/4LNN8	127	109	0.1524	center	804	0.940	54.0	0.17	67750	1715	1432	15.2
106	1/4LNN8	130	127	0.1524	center	859	0.938	53.4	0.17	72220	1975	1142	20.8
107	1/4LNN8	130	129	0.1524	cone	859	0.938	53.4	0.17	72220	1975	578	33.4
108	1/4LNN14	120	99	0.1930	center	820	0.944	55.2	0.19	78670	2219	1341	13.2
109	1/4LNN14	120	103	0.1930	cone	843	0.944	55.2	0.19	80840	2346	1292	42.3
110	1/4LNN14	120	82	0.1930	center	740	0.944	55.2	0.19	70960	1807	1108	13.9
111	1/4LNN14	116	82	0.1930	cone	740	0.948	56.0	0.20	67600	1789	2422	40.5
112	1/4LNN14	116	125	0.1930	center	911	0.948	56.0	0.20	83340	2711	1038	40.2
113	1/4LNN14	116	125	0.1930	cone	911	0.948	56.0	0.20	83340	2711	336	83.4
114	1/4LNN14	116	123	0.1930	cone	911	0.948	56.0	0.20	83340	2711	663	75.0

SUMMARY OF EXPERIMENTAL RESULTS: Part II (cont)
Atomization of Water and Superheated Water

Test No.	Nozzle	Water Temp °C	Atom. Pres. psig	Orifice Diameter cm	Sample Locat'n	Uo cm/s	ρ Density g/cm³	σ Surface Tension dynes/cm	μ Visc. cp	Re	We	Drops Counted	Mean Diameter d_{10} μm
115	1/4LNN26	88	50	0.2184	center	805	0.967	61.1	0.31	54840	2240	1062	16.4
116	1/4LNN26	88	50	0.2184	cone	805	0.967	61.1	0.31	54840	2240	3163	45.9
117	1/4LNN26	119	55	0.2184	cone	850	0.946	55.4	0.19	92430	2690	353	44.0
118	1/4LNN26	119	55	0.2184	center	850	0.946	55.4	0.19	92430	2690	1134	30.4
119	1/4LNN26	121	55	0.2184	cone	850	0.944	55.1	0.18	97360	2700	2126	52.2
120	1/4LNN26	138	48	0.2184	center	796	0.933	51.9	0.15	108100	2490	2158	29.9
121	1/4LNN26	135	48	0.2184	center	796	0.935	52.5	0.15	108100	2460	1367	30.6
122	1/4LNN26	136	48	0.2184	cone	796	0.934	52.3	0.15	108100	2470	589	72.5
123	1/4LNN26	136	53	0.2184	cone	832	0.934	52.3	0.15	113100	2700	1213	73.8
124	1/4LNN2	96	50	0.0711	center	609	0.961	59.6	0.27	15410	425	2062	38.0
125	1/4LNN2	96	50	0.0711	cone	609	0.961	59.6	0.27	15410	425	847	85.3
126	1/4LNN2	97	150	0.0711	center	1028	0.961	59.6	0.27	26020	1218	1260	25.6
127	1/4LNN2	98	150	0.0711	cone	1028	0.960	59.3	0.27	16020	1218	498	71.8
128	1/4LNN2	98	380	0.0711	center	1595	0.960	59.3	0.27	40320	2930	1081	13.0
129	1/4LNN2	98	380	0.0711	cone	1595	0.960	59.3	0.27	40320	2930	653	50.8
130	1/4LNN2	98	385	0.0711	cone	1595	0.960	59.3	0.27	40320	2930	635	62.7

TABLE V-5
SUMMARY OF EXPERIMENTAL RESULTS: Part III
Atomization of Concentrated Black Liquor in Spraying Systems 1/4LNN2 Grooved-Core Nozzle

Test No.	Black Liquor Solids %	Liquor Temp °C	Atom. Pres. psig	Uo cm/s	ρ Density g/cm³	σ Surface Tension dynes/cm	μ Visc. cp	Re	We	Drops Counted	Mean Diameter d₁₀ μm	Comments
131	56.3	102	185	1322	1.31	35	46.0	268	4650	2729	60.3	
132	56.3	108	175	1280	1.31	35	37.0	332	4360	782	113.8	
133	56.3	135	170	1257	1.31	35	8.5	1377	4210	364	126.7	
134	56.3	112	195	1343	1.31	35	27.3	458	4800	1589	95.8	
135	56.3	134	205									Poor Atom.
136	56.3	136	195									Poor Atom.
137	56.3	110	180									Poor Atom.
138	56.3	121	380									Poor Atom.
139	56.3	121	210	1393	1.31	35	17.5	741	5160	1408	84.2	
140	56.3	120	210	1393	1.31	35	18.9	720	5160	245	65.1	
141	56.3	102	410	1721	1.31	35	46.0	348	7880	871	90.6	
142	56.3	101	520	2057	1.31	35	48.0	399	11260	1320	83.5	
143	55.2	100	195	1343	1.31	35	37.0	338	4800	904	105.0	
144	55.2	102	190	1339	1.31	35	34.0	367	4800	97	166.9	
145	55.2	100	190	1339	1.31	35	37.0	337	4800	1811	117.4	
146	55.2	134	190	1339	1.31	35	7.8	1560	4800	385	128.2	Some flash.
147	55.2	135	200	1364	1.31	35	7.5	1694	4950	1504	91.2	
148	55.2	133	190	1339	1.31	35	8.3	1503	6700	418	134.3	Some flash.
149	55.2	119	195	1343	1.31	35	15.5	807	4800	648	144.3	
150	55.2	120	195	1343	1.31	35	15.0	833	4800	368	133.0	
151	55.2	118	200	1364	1.31	35	16.2	784	4950	626	128.4	
152	55.2	135	200									Poor Atom.
153	55.2	136	200									Poor Atom.
154	55.2	133	205									Poor Atom.
155	55.2	120	200	1364	1.31	35	15.0	847	4950	604	114.8	
156	55.2	115	200	1364	1.31	35	18.6	683	4950	1611	97.4	

TABLE V-6
SUMMARY OF EXPERIMENTAL RESULTS: Part IV
Mean Diameters Determined from Experimental Data

Test No.	Nozzle	Liquid Used	Liquid Temp. °C	Atom. Pres. psig	Sample Locat'n	Mean Diameters (microns)						Deviations	
						d_{10}	d_{20}	d_{30}	d_{32}	d geom	d sqrt	Geo.	Sq.Rt.
1&2	1/4LNN.6	water	17	50	center	59.9	76.7	92.6	135.2	45.2	7.20	2.12	7.76
3&4	1/4LNN.6	water	17	100	center	50.5	65.9	79.3	115.0	33.5	6.50	2.73	8.45
5	1/4LNN.6	water	17	150	center	39.1	48.3	56.3	76.3	29.6	5.85	2.16	4.83
6&7	1/4LNN.6	water	17	200	center	26.8	32.3	38.1	53.0	22.4	4.95	1.80	2.39
8	1/4LNN.6	water	17	300	center	19.5	21.6	23.8	28.9	17.7	4.31	1.54	0.94
9&10	1/4LNN.6	water	18	400	center	16.4	18.6	21.0	26.7	14.2	3.91	1.72	1.08
11&12	1/4LNN.6	water	18	550	center	13.3	15.1	17.2	22.4	11.9	3.55	1.58	0.74
13&14	1/4LNN2	water	18	50	cone	41.9	52.1	61.7	86.8	32.9	6.09	2.01	4.77
15	1/4LNN2	water	18	100	cone	32.1	37.3	42.7	55.7	27.6	5.45	1.73	2.39
16&17	1/4LNN2	water	18	150	cone	23.9	26.5	29.2	35.3	21.5	4.77	1.59	1.24
18-20	1/4LNN2	water	18	200	cone	19.7	22.6	25.8	33.6	17.3	4.29	1.64	1.28
21	1/4LNN2	water	18	300	cone	15.8	17.5	19.7	25.0	14.4	3.88	1.52	0.75
22&23	1/4LNN2	water	18	400	cone	20.3	23.2	27.4	38.2	18.3	4.38	1.54	1.10
24&25	1/4LNN2	water	23	550	cone	18.4	20.5	23.2	29.6	16.9	4.20	1.48	0.81
26	1/4LNN2	water	21	560	cone	18.1	20.3	23.8	32.4	16.6	4.16	1.47	0.82
27-29	1/4LNN8	water	21	50	cone	73.9	98.1	120.6	182.5	48.5	7.82	2.74	12.77
30	1/4LNN8	water	21	100	cone	72.2	87.4	100.0	130.9	53.3	7.95	2.40	8.97
31	1/4LNN8	water	21	150	cone	57.9	69.2	78.4	100.4	44.0	7.16	2.28	6.67
32&33	1/4LNN8	water	21	300	cone	64.8	71.5	77.5	91.1	56.2	7.80	1.82	3.95
34	1/4LNN8	water	21	510	cone	44.8	59.1	78.1	136.7	31.7	6.18	2.46	6.59
35	1/4LNN8	water	21	500	cone	53.1	71.7	90.8	145.6	35.0	6.24	2.69	9.19
36	1/4LNN8	water	21	400	cone	54.3	70.0	86.6	132.6	39.0	6.82	2.38	7.53
37&38	1/4LNN14	water	21	50	cone	61.5	85.8	110.8	184.9	41.3	7.11	2.47	10.89

Mean Diameters Determined from Experimental Data

Test No.	Nozzle	Liquid Used	Liquid Temp. °C	Atom. Pres. psig	Sample Locat'n	Mean Diameters (microns)						Deviations	
						d_{10}	d_{20}	d_{30}	d_{32}	d geom	d sqrt	Geo.	Sq.Rt.
39	1/4LNN14	water	21	100	cone	39.0	56.6	77.6	145.7	26.3	5.65	2.39	7.00
40	1/4LNN14	water	21	150	cone	41.4	60.0	80.0	142.2	27.2	5.79	2.48	7.80
41	1/4LNN26	water	21	50	cone	46.6	70.7	100.6	203.6	29.5	6.10	2.62	9.49
42	1/4LNN26	water	21	150	cone	30.4	45.1	63.7	126.7	20.4	4.93	2.41	5.61
43&44	1/4LNN26	water	20	305	cone	28.7	44.1	66.0	148.0	19.6	4.85	2.32	5.20
45	1/4LNN14	water	20	340	cone	32.1	48.0	73.3	170.6	23.8	5.22	2.04	4.78
46	1/4LNN14	water	19	325	cone	43.2	61.0	82.7	152.1	31.8	6.06	2.06	6.50
47	1/4LNN14	water	20	500	cone	39.9	50.9	66.2	111.7	32.6	5.99	1.81	4.04
48&49	1/4LNN14	water	20	475	cone	49.7	70.3	96.5	181.9	37.0	6.52	2.02	7.28
50	1/4LNN2	89.7% g/w	23	500	cone	53.3	81.6	119.2	253.9	36.8	6.62	2.22	9.59
51	1/4LNN2	89.7% g/w	23	500	cone	37.8	62.8	113.1	366.4	29.7	5.72	1.79	5.09
52	1/4LNN8	89.7% g/w	23	460	cone	56.2	83.0	124.6	281.1	42.3	6.93	1.97	8.10
53	1/4LNN14	89.7% g/w	23	460	cone	58.9	82.7	110.1	194.9	42.2	7.04	2.18	9.34
54&55	1/4LNN26	82.5% g/w	23	350	cone	50.9	75.3	100.2	177.0	29.6	6.29	3.03	11.29
56	1/4LNN8	82.5% g/w	22	325	cone	62.3	75.7	89.3	124.1	50.4	7.49	1.93	6.23
57	1/4LNN8	82.5% g/w	22	430	cone	53.5	61.2	69.4	89.4	46.6	7.07	1.69	3.53
58	1/4LNN8	82.5% g/w	22	475	cone	68.7	75.0	81.4	95.8	62.6	8.10	1.56	3.08
59	1/4LNN2	82.5% g/w	22	275	cone	49.0	70.8	102.1	212.7	36.9	6.48	1.99	7.01
60	1/4LNN2	82.5% g/w	22	475	cone	55.5	76.5	102.3	182.6	41.3	6.89	2.08	7.91
61	1/4LNN2	82.5% g/w	22	550	cone	47.1	70.4	101.4	210.1	34.3	6.29	2.05	7.50
62	1/4LNN14	82.5% g/w	22	230	cone	64.7	79.0	95.3	138.6	52.3	7.64	1.95	6.44
63	1/4LNN14	82.5% g/w	22	350	cone	53.0	74.2	98.3	172.7	38.1	6.68	2.17	8.36
64&65	1/4LNN14	82.5% g/w	22	525	cone	43.8	62.4	88.5	178.0	32.3	6.10	2.06	6.57

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Mean Diameters Determined from Experimental Data

Test No.	Nozzle	Liquid Used	Liquid Temp. °C	Atom. Pres. psig	Sample Locat'n	Mean Diameters (microns)						Deviations	
						d_{10}	d_{10}	d_{10}	d_{11}	d geom	d sqrt	Geo.	Sq.Rt.
66	1/4LNN26	82.5% g/w	22	210	cone	52.1	69.6	85.9	130.8	36.4	6.61	2.34	8.42
67	1/4LNN26	82.5% g/w	22	300	cone	58.2	76.5	93.9	141.3	41.2	7.02	2.33	8.96
68	1/4LNN26	82.5% g/w	22	450	cone	48.1	69.4	94.4	174.4	34.5	6.35	2.14	7.81
69	1/4LNN.6	82.5% g/w	23	625	center	33.9	51.0	78.5	186.4	26.0	5.40	1.88	4.76
70	1/4LNN.6	64.8% g/w	23	570	center	55.6	76.8	101.6	178.0	41.3	6.89	2.05	8.09
71	1/4LNN.6	64.8% g/w	23	350	center	52.5	63.5	75.3	106.1	43.4	6.90	1.82	4.82
72	1/4LNN2	64.8% g/w	23	100	cone	67.6	87.3	108.3	166.7	51.6	7.68	2.06	8.62
73	1/4LNN2	64.8% g/w	23	195	cone	48.6	54.5	60.6	75.2	43.5	6.78	1.59	2.67
74	1/4LNN2	64.8% g/w	23	310	cone	27.1	29.5	32.3	38.7	25.0	5.10	1.47	1.08
75	1/4LNN2	64.8% g/w	23	450	cone	18.9	20.6	23.4	30.4	17.6	4.27	1.42	0.66
76	1/4LNN2	64.8% g/w	23	435	cone	26.5	28.7	31.2	37.0	24.5	5.05	1.47	1.01
77	1/4LNN2	64.8% g/w	23	575	cone	24.7	26.0	27.7	31.4	23.6	4.91	1.33	.56
78	1/4LNN8	64.8% g/w	23	95	cone	30.2	44.8	64.8	135.9	22.4	5.05	1.98	4.63
79&80	1/4LNN8	64.8% g/w	23	300	cone	45.6	65.3	92.0	182.3	34.2	6.24	1.99	6.61
81	1/4LNN8	64.8% g/w	23	575	cone	42.8	51.5	61.4	87.2	35.8	6.25	1.79	3.73
82	1/4LNN14	64.8% g/w	23	95	cone	58.1	76.7	97.2	156.3	44.3	7.11	2.03	7.62
83	1/4LNN14	64.8% g/w	23	320	cone	46.5	58.7	72.3	109.7	36.9	6.43	1.94	5.16
84	1/4LNN14	64.8% g/w	23	500	cone	54.3	70.9	91.0	150.0	42.5	6.91	1.94	6.49
85	1/4LNN26	64.8% g/w	23	100	cone	57.7	68.7	81.9	116.1	49.1	7.29	1.73	4.59
86	1/4LNN26	64.8% g/w	23	110	cone	37.7	52.2	76.7	165.8	30.8	5.80	1.75	4.01
87	1/4LNN26	64.8% g/w	23	300	cone	59.8	69.2	79.9	106.5	51.1	7.44	1.79	4.42
88	1/4LNN26	64.8% g/w	23	470	cone	47.6	52.3	56.6	66.3	42.5	6.72	1.65	2.51
89	1/4LNN.6	water	86	153	center	24.9	29.8	35.9	52.1	21.1	4.79	1.76	2.04

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SUMMARY OF EXPERIMENTAL RESULTS: Part IV (cont)
Mean Diameters Determined from Experimental Data

Test No.	Nozzle	Liquid Used	Liquid Temp. °C	Atom. Pres. psig	Sample Locat'n	Mean Diameters (microns)						Deviations	
						d_{10}	d_{20}	d_{30}	d_{32}	d geom	d sqrt	Geo.	Sq.Rt.
90	1/4LNN.6	water	100	150	center	27.7	31.4	35.4	44.9	24.5	5.11	1.64	1.69
91	1/4LNN.6	water	120	154	center	16.6	17.4	18.3	20.2	15.8	4.02	1.37	0.387
92	1/4LNN.6	water	146	155	center	16.2	16.7	17.1	17.9	15.8	4.01	1.25	0.20
93	1/4LNN2	water	127	105	cone	57.8	63.6	71.5	90.2	51.0	7.40	1.78	3.09
94	1/4LNN2	water	146	105	cone	57.7	62.3	66.5	76.0	52.8	7.44	1.56	2.41
95	1/4LNN2	water	148	110	center	17.8	19.7	22.3	28.4	16.3	4.13	1.53	0.81
96	1/4LNN2	water	85	107	center	17.2	18.9	21.2	26.7	15.9	4.06	1.48	0.70
97	1/4LNN2	water	85	105	cone	30.4	32.8	35.4	41.1	28.2	5.41	1.48	1.15
98	1/4LNN2	water	102	105	center	16.1	17.3	18.6	21.5	15.0	3.94	1.47	0.57
99	1/4LNN2	water	104	107	cone	49.1	55.7	62.0	76.8	42.5	6.77	1.73	3.34
100	1/4LNN2	water	125	110	center	16.8	18.4	20.0	23.6	15.3	4.01	1.55	0.76
101	1/4LNN2	water	126	110	cone	86.6	112.2	135.2	196.5	62.2	8.59	2.30	12.79
102	1/4LNN8	water	84	130	center	15.8	16.9	18.7	23.0	15.0	3.92	1.37	0.43
103	1/4LNN8	water	87	134	cone	44.5	59.5	75.6	122.0	33.5	6.20	2.05	6.09
104	1/4LNN8	water	105	125	cone	51.1	69.5	88.2	141.9	36.9	6.58	2.17	7.82
105	1/4LNN8	water	109	127	center	15.2	16.6	18.7	23.5	14.1	3.83	1.50	0.59
106	1/4LNN8	water	127	130	center	20.8	22.4	24.2	28.3	19.4	4.48	1.44	0.73
107	1/4LNN8	water	129	130	cone	33.7	46.6	57.7	88.2	23.2	5.28	2.27	5.90
108	1/4LNN14	water	99	120	center	14.7	16.4	19.0	25.6	13.2	3.73	1.56	0.734
109	1/4LNN14	water	103	120	cone	42.3	57.5	71.5	110.4	29.1	5.93	2.40	7.11
110	1/4LNN14	water	82	120	center	13.9	14.8	15.7	17.9	13.1	3.67	1.41	0.41
111	1/4LNN14	water	82	116	cone	40.5	58.5	82.8	165.9	28.5	5.81	2.25	6.68
112	1/4LNN14	water	125	116	center	40.2	44.7	49.5	60.5	36.0	6.17	1.59	2.15

SUMMARY OF EXPERIMENTAL RESULTS: Part IV (cont)
Mean Diameters Determined from Experimental Data

Test No.	Nozzle	Liquid Used	Liquid Temp. °C	Atom. Pres. psig	Sample Locat'n	Mean Diameters (microns)						Deviations	
						d_{10}	d_{20}	d_{30}	d_{32}	d geom	d sqrt	Geo.	Sq.Rt.
113	1/4LNN14	water	125	116	cone	83.4	91.6	98.3	113.3	72.3	8.85	1.83	5.04
114	1/4LNN14	water	123	116	cone	75.0	90.7	105.8	144.0	59.0	8.18	2.08	8.03
115	1/4LNN26	water	88	50	center	16.4	19.4	23.1	33.0	13.9	3.89	1.82	1.30
116	1/4LNN2G	water	88	50	cone	45.9	63.8	85.3	152.1	33.8	6.26	2.10	6.74
117	1/4LNN26	water	113	55	cone	44.0	52.6	62.3	87.6	37.4	6.36	1.74	3.58
118	1/4LNN26	water	119	55	center	30.4	33.7	37.2	45.3	27.7	5.39	1.53	1.45
119	1/4LNN26	water	121	55	cone	52.2	64.3	77.0	110.2	42.2	6.85	1.89	5.35
120	1/4LNN26	water	138	48	center	29.8	37.1	45.7	69.4	24.9	5.20	1.75	2.77
121	1/4LNN26	water	135	48	center	30.6	35.6	41.4	55.9	26.4	5.32	1.70	2.21
122	1/4LNN26	water	136	53	cone	72.5	85.6	96.9	124.0	57.7	8.08	2.06	7.27
123	1/4LNN26	water	136	53	cone	73.8	86.0	96.2	120.5	59.7	8.18	2.02	6.89
124	1/4LNN2	water	96	50	center	38.0	43.3	49.1	63.4	33.6	5.97	1.63	3.31
125	1/4LNN2	water	96	50	cone	85.3	93.0	100.3	116.6	76.6	9.00	1.63	4.21
126	1/4LNN2	water	97	150	center	25.6	27.9	30.3	35.6	23.6	4.96	1.49	1.05
127	1/4LNN2	water	98	150	cone	71.8	78.6	84.7	98.4	63.8	8.24	1.68	3.82
128	1/4LNN2	water	97	380	center	13.0	13.8	14.8	16.9	12.3	3.55	1.42	0.38
129	1/4LNN2	water	98	380	cone	50.8	57.2	63.3	77.6	44.1	6.89	1.74	3.31
130	1/4LNN2	water	98	385	cone	62.7	73.7	84.7	111.6	51.8	7.56	1.90	5.50
131	1/4LNN2	56.3%S BL	102	185	cone	60.3	69.3	78.6	101.1	52.0	7.49	1.74	4.24
132	1/4LNN2	56.3%S BL	108	175	cone	113.8	128.1	143.6	180.3	100.3	10.34	1.87	6.79
133	1/4LNN2	56.3%S BL	135	170	cone	126.7	140.7	155.5	189.8	114.0	10.96	1.58	6.52
139	1/4LNN2	56.3%S BL	121	210	cone	84.2	98.7	114.0	152.3	70.8	8.80	1.83	6.86
140	1/4LNN2	56.3%S BL	120	210	cone	65.1	77.4	89.5	119.8	53.6	7.70	1.89	5.92

SUMMARY OF EXPERIMENTAL RESULTS: Part IV (cont)
Mean Diameters Determined from Experimental Data

Test No.	Nozzle	Liquid Used	Liquid Temp. °C	Atom. Pres. psig	Sample Locat'n	Mean Diameters (microns)						Deviations	
						d_{10}	d_{20}	d_{30}	d_{32}	d geom	d sqrt	Geo.	Sq.Rt.
141	1/4LNN2	56.3%S BL	103	410	cone	90.6	97.1	103.8	118.6	84.3	9.35	1.46	3.16
142	1/4LNN2	56.3%S BL	101	520	cone	83.5	89.1	95.0	108.1	78.3	8.99	1.43	2.65
143	1/4LNN2	55.2%S BL	100	195	cone	105.0	132.2	157.3	223.0	80.6	9.60	2.07	12.88
144	1/4LNN2	55.2%S BL	102	190	cone	166.8	195.9	215.7	261.5	121.9	12.11	2.56	20.15
145	1/4LNN2	55.2%S BL	100	190	cone	117.4	134.0	151.6	193.9	102.5	10.48	1.69	7.69
146	1/4LNN2	55.2%S BL	134	190	cone	128.2	139.1	150.7	176.8	117.4	11.09	1.54	5.37
147	1/4LNN2	55.2%S BL	135	200	cone	91.2	100.6	111.1	135.5	82.9	9.33	1.55	4.25
148	1/4LNN2	55.2%S BL	133	195	cone	134.3	145.5	156.7	182.0	123.1	11.34	1.55	5.53
149	1/4LNN2	55.2%S BL	119	195	cone	144.3	159.6	174.3	207.9	127.7	11.67	1.70	8.05
150	1/4LNN2	55.2%S BL	120	195	cone	133.0	146.2	159.6	190.2	119.6	11.24	1.62	6.64
151	1/4LNN2	55.2%S BL	118	200	cone	128.4	142.2	156.3	188.2	114.8	11.03	1.62	6.85
155	1/4LNN2	55.2%S BL	120	200	cone	114.7	124.4	134.4	156.5	105.8	10.50	1.49	4.60
156	1/4LNN2	55.2%S BL	115	200	cone	97.4	105.4	113.6	131.9	89.8	9.67	1.50	3.84

TABLE V-7
SUMMARY OF EXPERIMENTAL RESULTS: Part V
Mean Diameters of Averaged Black Liquor Tests

Test No.	Nozzle	Liquid Used	Liquid Temp. °C	Atom. Pres. psig	Sample Locat'n	Mean Diameters (microns)						Deviations	
						d_{10}	d_{20}	d_{30}	d_{32}	d geom	d sqrt	Geo.	Sq.Rt.
BL100'	1/4LNN2	56% S BL	100	190	cone	115.1	136.0	156.6	207.6	95.4	10.25	1.87	10.08
BL120'	1/4LNN2	56% S BL	120	200	cone	109.4	125.7	141.5	179.3	92.7	10.06	1.61	8.30
BL135'	1/4LNN2	56% S BL	135	190	cone	108.1	120.4	133.5	164.1	96.8	10.11	1.61	5.74

' Weighted average of tests 143,144,145
' Weighted average of tests 139,140,149,150,151,155
' Weighted average of tests 133,146,147,148