THE UNIVERSITY OF MANITOBA

ENERGY LOSSES IN THE HYDRAULIC TRANSPORT OF SOLIDS AT THOMPSON MINES

by

JORGE LUIS POMALAZA-RAEZ

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements for the Degree of
Master of Science

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ABSTRACT

An experimental study of high concentration slurries in horizontal pipes was performed. The experiments were conducted in a test facility built for that purpose. Three different pipe diameters (3 in., 4 in., and 5 in.) were used to scale-up results to 6 inch pipe. The slurries consisted of two mixtures of tailings plus slag obtained from INCO's Thompson mine. The fluid was water. Tests of the mixtures were undertaken at 65% solids concentration by weight and at 55%. Velocity, temperature, and concentration of solids generally showed a direct relationship with energy loss, while pipe diameter was inversely related. Plastic behavior due to high solids concentration and colloidal dispersion increased the energy loss.

Statistical and theoretical models were examined for head-loss gradient prediction in a range of mean velocities from 6 f.p.s. to 20 f.p.s.

TO MY FRIENDS

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LIST OF SYMBOLS

C - Concentration of solids

C_v - Volume percent solids concentration

C_w - Weight percent solids concentration

D - Pipe Diameter

He - Hedstrom Number

H_s - Head-loss, feet of slurry

Hw - Head-loss, feet of water

$HL, \frac{h_f}{L}$ - Head-loss, feet per 100 feet of pipe

K - Constant of Power Law fluid

K' - $K \left(\frac{4n}{3n+1}\right)^n$

L - Length

R - Pipe radius

R_e - Reynolds number

R_m - Modified Reynolds number

$R_e{}^*$ - Generalized Reynolds Number

SG_m - Specific Gravity of the mixture

SG_s - Specific Gravity of the solids

SG_{MF} - Specific Gravity of the manometer liquid

T - Temperature

V - Mean velocity

ΔP - Pressure drop

f - Friction factor

n, n' - Power Law index

u - Point or instantaneous velocity

y - Radial distance

du/dy - Rate of shear or velocity gradient at radial distance y

α - $K' \, 8^{n'-1}$

β - Regression coefficient

μ - Dynamic viscosity

μ_a - Apparent viscosity

ν - Kinematic viscosity

ρ, ρ_1 - Density of the transporting medium

ρ_m - Density of the mixture

ρ_s - Density of solids

ϕ - Fluidity

τ - Shear stress

τ_w - Wall shear stress

τ_y - Yield value

ϵ_o - Total standard error of estimate

d_{50} - Particle mean diameter

η - Coefficient of rigidity

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CHAPTER I

1.1 INTRODUCTION

The economic transportation of bulk solids is a major transportation problem. Slurry pipelines containing a liquid-solid mixture are one of the more recent solutions. Slurry pipelines have received increasing attention since the 1950's, particularly in the mining industry. The development of new materials in pumping and pipelining systems has reduced the ton-mile cost of this method of transportation. Despite the existence of competitive land-based systems (such as roadways, railways and conveyor lines) the hydraulic transport of solids will consequently become one of the most suitable bulk solid transport alternatives in the near future, especially in remote areas.

The use of slurry pipelines is sometimes not considered in design of bulk transport systems because the knowledge available in technical literature typically refers to ideal slurries only. M. Sasic and P. Marjanovic (1978) have compared several methods to estimate the "deposition velocity", or the velocity at which a bed of particles begins to form, with different results for the same mixture. Furthermore, the values of primary parameters, such as solids, were mostly for sand with a smooth surface and uniform bulkiness. These results very often cannot be applied to material acquired by crumbling and grinding.

One method to lessen the gap between theory and practice is to use the bulk solid material being considered for transport in its anticipated granular form in a test facility. Although this action reduces the range of generalization for theory, it can give better results for specific practical applications.

At present, the University of Manitoba and INCO Mining Company are undertaking a research project to study the behavior of mining tailings at their Thompson Manitoba mines. The design and construction of the facilities required, data collection and the data analysis are presented in this work.

1.2 PROBLEM STATEMENT

The Manitoba Division of INCO (International Nickel Company) is located in Thompson, approximately 400 miles north of Winnipeg.

The Division currently operates two underground mines: Thompson Mine and Birchtree Mine, and an open pit at Pipe. Hydraulically placed sandfill recovered from the mill tailings is used for ground support in all stopes and pillars. Approximately 30% of the Thompson mine mill production is regained for backfill operations but the actual amount of fill required is 52%.

In order to make up this shortage, tailings from the Pipe open pit mill circuit must be used. However in one or two year's time a new auxiliary fill will be needed to sustain the mining cycle. For that reason, INCO's Thompson mine is considering the use of slag (a waste produced in the smelter) as a supplementary fill.

Since the backfill operation system primarily makes use of gravity forces to deliver the material, it is of crucial importance to study the behavior of the proposed mixture (i.e. slag plus tailings) and ensure that the energy losses all along the lines can be predicted. Main pipelines are six inch in diameter, while the auxiliary lines to individual working places are four inches in diameter.

1.3 SCOPE OF THIS WORK

This study encompasses the design and construction of a slurry test facility, and its use to derive predictive equations for unit head loss for a tailings-slag mix.

The concepts and principles governing solid-liquid systems are briefly presented in Chapter II. The non-Newtonian character and rheological effects are emphasized.

Physical properties of the experimental material are presented in Chapter III.

Chapter IV is devoted to a description of the facilities. For a better illustration the reader is referred to Appendix F and the blueprints at the end of the volume.

In Chapter V the procedures for a single experimental test are explained.

Data reduction and derivation of hydraulic variables are given in Chapter VI.

In Chapter VII the analysis and discussions of the experimental results are contemplated. Presentation of figures and discussions are arranged in historical sequence. Mathematical models to express the energy loss in the system are also introduced in Chapter VII. The use of English units in this study corresponds to the operative mining units required by INCO Mine Ltd.

Finally, the experimental conclusions and recommendations for further work are listed.

CHAPTER II

LITERATURE REVIEW

2.1 SLURRY VARIABLES

An extensive theory of solid-liquid systems requires a reasonable degree of knowledge of many variables and their relationships when they interact.

The major discrete variables are the following:

- Particle properties:	size, shape, size distribution, density, electro-chemistry, and attrition rate.
- Transporting medium:	viscosity, density, temperature, pH.
- Pipeline characteristics:	diameter, material, slope, length and roughness.

whereas the interaction is governed by:

- The forces that act between particles
- The hydrodynamic interactions between the particles and the fluid.

2.2 SLURRY PROPERTIES

2.2.1 Concentration and Density

Concentration and density in any solid-liquid system are proportionally related. They depend upon the amount of solids for a given volume of liquid and the densities of both phases.

Concentration of solids can be expressed in terms of weight or volume. However, it is more convenient in the industry to express solid concentrations as a percentage of weight to obtain capacities in tonnage throughput.

The density of a suspension in terms of its components is given by:

$$\rho_m = \frac{100}{\frac{Cw}{\rho_s} + \frac{100 - Cw}{\rho_1}} \qquad (2.1)$$

where:

ρ_m = density of the mixture (slurry)

ρ_s = density of solids

ρ_1 = density of the transporting medium

C_w = concentration of solids in weight percent

when dealing with Specific Gravity (SG) and water as the transporting medium:

$$SG_m = \frac{SG_s}{SG_s - \frac{Cw}{100}(SG_s - 1)} \qquad (2.2)$$

where:

SG_m = specific gravity of mixture

SG_s = specific gravity of solids

The relationship between specific gravity of the mixtures, specific gravity of solids, concentration by weight, and concentration by volume is as follows:

$$C_v = \frac{C_w \times SG_m}{SG_s} \qquad (2.3)$$

where C_v = concentration of solids by volume.

2.2.2 Viscosity

The coefficient of dynamic viscosity, which is generally called simply "viscosity", is the ratio of applied shearing stress to rate of shear (sometimes called velocity gradient) for ideal "viscous" bodies. (Bodies which exhibit flow as a function of the stress.)

The best known ideal viscous body is the Newtonian fluid, for which the viscosity μ is a constant.

The so-called kinematic viscosity ν is equal to μ divided by the density.

The reciprocal of viscosity called fluidity ϕ is also used in rheological discussion.

When the presence of particles and their hydrodynamic interactions affect the viscosity of the medium the behavior of the suspension becomes non-Newtonian. Then, an apparent viscosity, μ_a, rather than a constant viscosity, μ, can be defined. Apparent viscosity (μ_a) is the ratio of total shearing stress to total rate of shear. It is mainly employed for prediction and correlation of pipeline flow data:

$$\mu_a = \frac{\tau}{(du/dy)} \qquad (2.4)$$

where:

τ = shear stress

u = point velocity

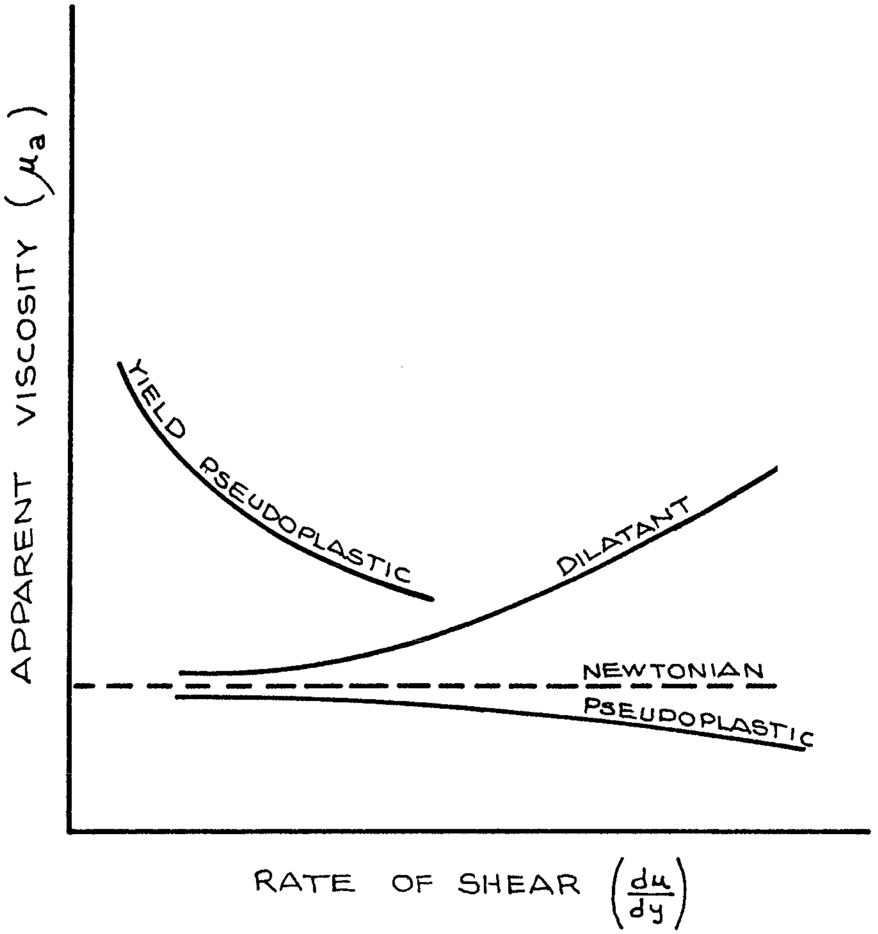
y = pipe radius

μ_a for a Newtonian fluid has a constant value and presents an horizontal straight line when plotted against rate of shear, (Figure II.1).

2.2.3 Rheology

Rheology is the science of the deformation and flow of matter. It is mainly concerned with the deformation of cohesive bodies, however,

FIGURE II.1



<u>APPARENT VISCOSITY VERSUS RATE OF SHEAR</u>

<u>FOR NON-NEWTONIAN FLUIDS</u>

it has been expanded to include solid friction and the flow of particulate substances.

Slurry rheology is mainly concerned with the viscosity of fluids. If a fluid exhibits a constant value of viscosity, the Newtonian methodology can be applied to solve many problems, but for several classes of fluids the viscosity is found to vary by many orders of magnitude with changing rate of shear (Van Wazer, Lyons, Kim, Colwell, 1963). Such materials are called non-Newtonian fluids and can be classified in two groups:

- time-independent fluids
- time-dependent fluids

2.2.3.1 Time-independent fluids

Typical flow curves are presented in Figure II.2. The straight line A represents Newtonian fluids in which μ is a constant,

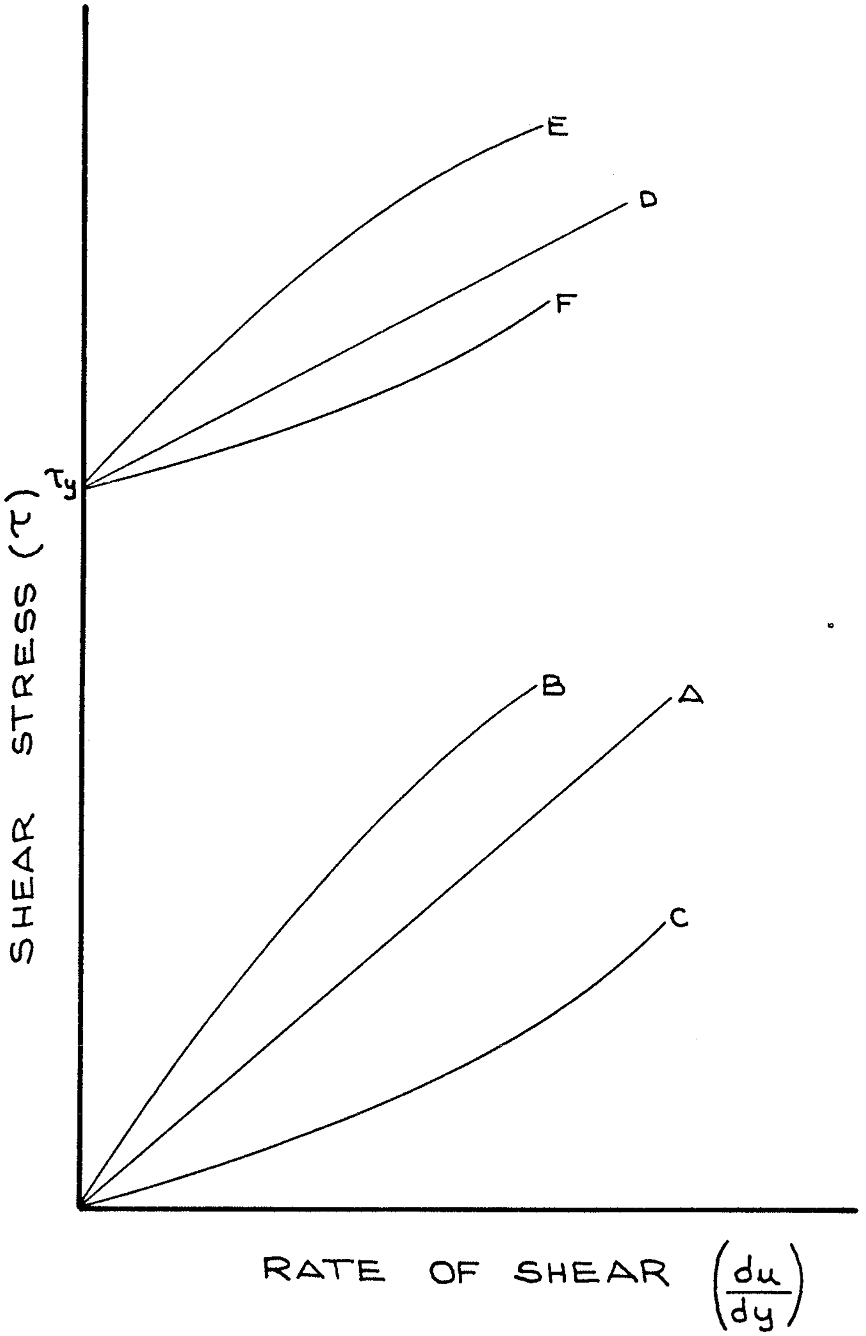
$$\mu = \frac{\tau}{(\frac{du}{dy})} = \text{constant}. \qquad (2.5)$$

When the rate of shear increases faster than the shearing stress (curve B) the fluid is called a pseudoplastic or shear-thinning liquid and the most common model to describe its behavior is the Ostwald de Waele or Power Law.

A fluid exhibiting a flow curve shaped like curve C is called dilatant or shear-thickening and it is roughly approximated by a power function.

Another important phenomenon connected with flow is the existence of a yield value. Several materials will not flow at all unless the shearing stress is increased beyond certain amounts called

FIGURE II.2



FLOW CURVES FOR VARIOUS RHEOLOGICAL FLUIDS

A - NEWTONIAN	D - BINGHAM
B - PSEUDOPLASTIC	E - YIELD PSEUDOPLASTIC
C - DILATANT	F - YIELD DILATANT

the yield value. Once this restriction has been exceeded, the rate of shear may be proportional to the stress. If that is the case, the material is called a plastic substance or a Bingham body (curve D).

Fluids exhibiting non-linearity of flow at stresses exceeding the yield value are called yield pseudoplastic (curve E) or yield-dilatant (curve F).

2.2.3.2 Time-dependent Fluids

The six curves presented above refer to equilibrium effects, however, it is found that many fluids exhibit time-dependent flow effects that can be either spontaneously reversible or irreversible.

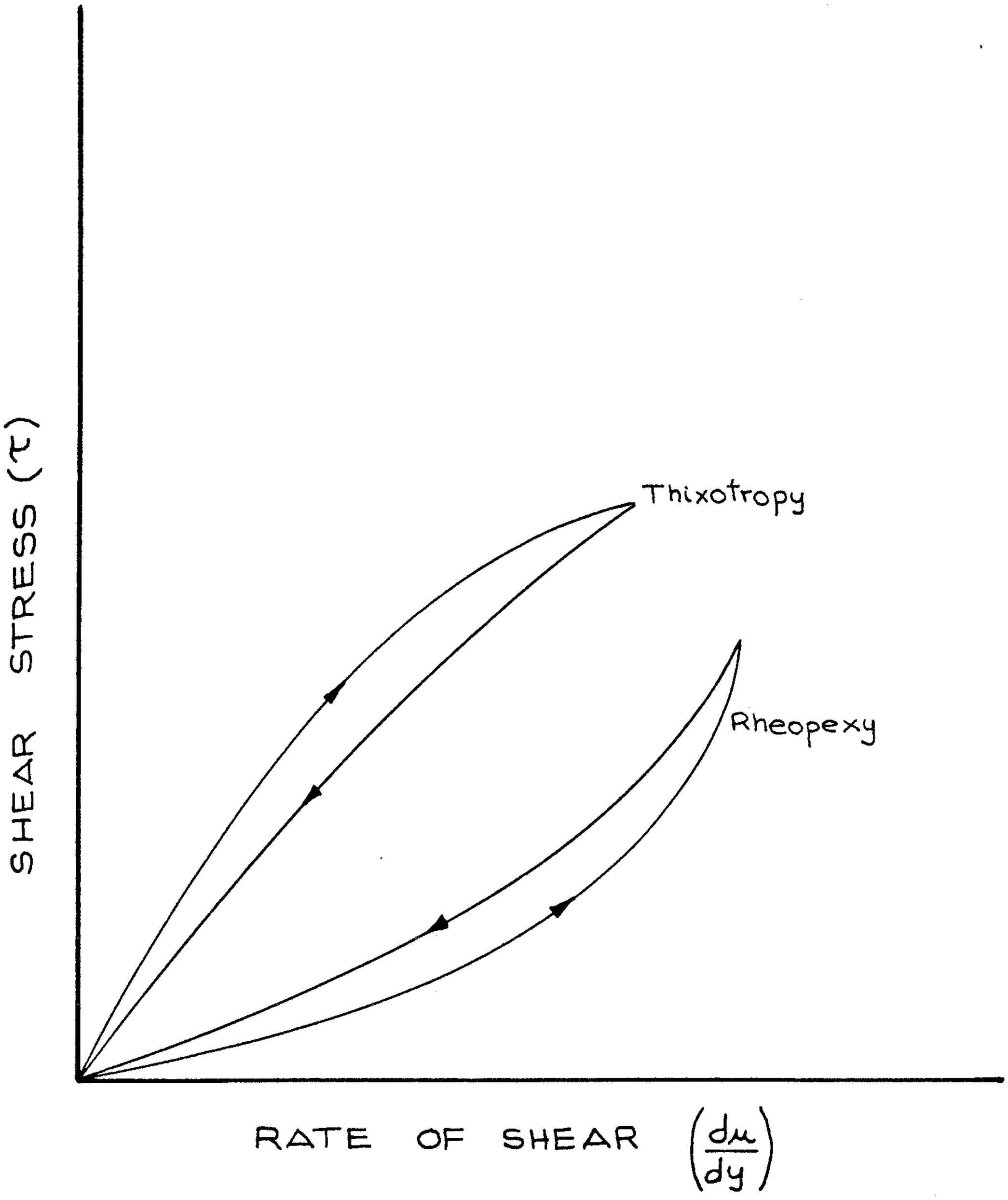
With respect to reversible behavior certain materials become more fluid with time under steady-state conditions, constant shear rate and temperature (Wasp, Kenny, Gandhi, 1977). Such materials are said to exhibit thixotropy, and are thixotropic. The opposite reversible effect, with the material exhibiting increased resistance to flow with time (while being subjected to steady-state shear) is called rheopexy.

Considerable emphasis has been placed on thixotropic changes upon going from one rate of shear to another when moderately long periods of time are involved. Under such conditions, hysteresis is observed in the flow curves (Figure II.3).

2.2.3.3 Factors Affecting Rheology

Generally, pure single-phase liquids will exhibit newtonian behavior, even at high flow rates.

FIGURE II.3



FLOW CURVES FOR THIXOTROPIC AND

RHEOPECTIC FLUIDS

A true yield value is always associated with emulsions or slurries, in which one or more phases are dispersed as particles or bubbles in a continuous phase. (Van Wazer, Lyons, Kim, Colwell, 1963.)

It is normally found that the flow characteristics of the continuous phase determines the type of flow observed when the yield value is exceeded. Thus a concentrated slurry in a Newtonian liquid may exhibit Bingam-body properties.

Dilatant flow behavior, either with or without a yield value, is associated with a suspension slurry, or perhaps an emulsion. It is found that deflocculating agents, such as the polyphosphates or highly charged organic polyelectrolytes, convert a slurry exhibiting the properties of a Bingham-body to a dilatant fluid. Such deflocculating agents act by plating out on the surface of the particles to give a uniform high surface charge, all of one sign, hence a dilatant fluid consists of a suspension of highly repellent particles (Van Wazer, Besmertnuk, 1950).

Non-Newtoni n flow is found in colloidal systems and colloids mixed with settling particles. The non-linear curves observed from colloidal and other dispersed systems can be explained by interaction between particles, interaction with the continuous phase, and particle deformation.

A natural force of attraction exists between any two masses (Van der Waals force). Random motion of colloids (Brownian movement), caused by bombardment of water molecules, tends to enhance this physical force of attraction in pulling the particles together. However a colloidal suspension will remain dispersed indefinitely if the forces of repulsion exceed those of attraction (Hammer, 1977). Both the forces of repulsion and attraction between particles depend upon the type of colloids in suspension, temperature, pH and chemical composition of the water.

2.2.3.4 Zeta Potential and pH Value Effects

Several researchers have pointed out that the electro-chemical nature of the particle surface is responsible for certain peculiarities in non-Newtonian behavior (Horsley, Reizes, 1980; Elliott, Gliddon, 1970; Friend, Hunter, 1971; Mishra, Severson, Owens, 1970, etc.). Colloidal particles can be classified as Hydrophobic or water repellant and Hydrophilic or water attracting. In either case the individual particles have a large surface area relative to their weight, thus gravity forces do not significantly influence their suspension.

Hydrophilic colloids are stable because of their attraction for dipole water molecules, rather than the slight charge that they possess. Hydrophobic particles, having no affinity for water, are dependent on electrical charge for their stability in suspension. Individual particles are held by electrostatic repulsion forces developed by positive ions adsorbed onto their surfaces from solution. The magnitude of the repulsive force developed by the charged double layer of ions attracted to a particle is referred to as zeta potential.

Horsley and Reizes (1980) have shown that the zeta potential was a major parameter influencing head-loss gradients. Horsley (1982) indicated that many slurries in industry consist of fine particles with a mean diameter of less than 50 μm. These slurries contain considerable quantities of colloidal particles, in which the repulsive forces are considered to be directly related to the zeta potential.

Elliott and Gliddon (1970) have also found that small changes in zeta potential affect the laminar head-loss gradient.

Friend, Hunter (1971) and Mishra (1970) have shown that the yield stress and the coefficient of rigidity of colloidal solutions depend, to some extent, on the zeta potential value.

Furthermore, it has been found that these electric charges are strongly related to the concentration of suspended solids. Charge strength can be explained by the fact that at higher concentrations the mean distance among particles is less than at lower concentrations with the result that higher repulsive forces are developed. Horsley (1982) reported that there was no time-dependant changes in zeta potential at solid concentrations below 28% by volume (known as low concentrations).

On the other hand, the pH (Negative Log H+ ion concentration) of water was also found responsible for changes in apparent viscosity of some gold mine tailings (Marsden, D., 1962). Elliott and Gliddon (1970) showed that pH changes substantially affected coal slurries in pipe loop tests when concentrated coal slurries were being pumped. This effect could be reversed by returning the pH to its original value. The small amount of data available for this topic thus show inconclusive and often contradictory results.

2.3 SLURRY FLOW CHARACTERISTICS

2.3.1 Homogeneous Flow

Homogeneous flow is encountered in slurries with high concentrations of solids and fine particle size. They are also called "non-settling" mixtures and frequently do not behave as Newtonian fluids but their homogeneity depends upon the velocity gradient. Slurries with a range of concentration from 50 to 70% by weight are normally homogeneous for small particle size or high velocity or both. The solid particles are uniformly distributed and particle inertial effects are negligible. Large particles may be suspended by the mass of smaller particles overcoming the gravitational pull.

2.3.2 Heterogeneous Flow

Heterogeneous flow is usually presented in slurries with low solid concentrations, low velocity; or coarse particle size. The effects of particle inertia are significant. The solid particles are not evenly distributed, hence these "settling" mixtures cannot be treated as a single phase system except under circumstances of high turbulence. Four different regimes are found in heterogeneous flow (Govier, Charles, 1961):

- Pseudo-homogeneous flow in which the particles are fully suspended.
- Saltating flow in which particles are transported by a leaping motion.
- Sliding or rolling bed motion of particles.
- Stationary bed of solid deposits.

2.3.3 Non-Newtonian flow

In Chapter II typical flow curves were presented in which non-Newtonian fluids were characterized by a non-linear relationship between shear stress and rate of shear. In order to define the non-Newtonian behavior the most acceptable approach is a power function, thus the following equation can be used to solve for τ in a Pseudoplastic fluid.

$$\tau = K \left(\frac{du}{dy}\right)^n \qquad (2.6)$$

where:

$n < 1.0$

K = constant

In the case of a Bingham fluid:

$$\tau = \tau_y + \eta \left(\frac{du}{dy}\right) \qquad (2.7)$$

where:

τ_y = yield value

η = coefficient of rigidity

Bingham fluids are normally ideal, so a combination of the two former equations can be used to describe the behavior of a material which exhibits non-linear flow.

$$\tau = \tau_y + K \left(\frac{du}{dy}\right)^n \qquad (2.8)$$

Non-Newtonian fluids can also be altered by two rheological complexities, thixotropy and rheopexy. Thixotropy does not present problems in pipe design, but the dilatant character of the rheopectic fluids has to be considered.

A dilatant fluid assumes a concave-upward curve described by the power function with the index $n > 1.0$ (Cheng, 1970).

$$\tau = K \left(\frac{du}{dy}\right)^n \qquad (2.6)$$

2.3.3.1 Prediction of Friction Losses

Since the non-Newtonian behavior cannot be expressed in terms of a characteristic "viscosity" the normal equations describing pipeline flow are often unsuitable. Many theoretical and empirical attempts to understand this matter have been undertaken in recent decades.

In laminar flow, Buckingham (1921) was the first to make a theoretical analysis for a Bingham plastic fluid. He derived the analogue of Poiseuille's equation:

$$\frac{8V}{D} = \frac{\tau_w}{\eta}\left[1 - \frac{4\,\tau_y}{3\,\tau_w} + \frac{1}{3}\left(\frac{\tau_y}{\tau_w}\right)^4\right] \qquad (2.9)$$

V = mean velocity of the suspension

D = diameter of the pipe

τ_w = wall shear stress

τ_y = yield value

η = coefficient of rigidity

If the fourth-power term is neglected, due to a small value of yield stress, the equation solve directly for τ_w:

$$\tau_w = \eta\left(\frac{8V}{D}\right) + \frac{4}{3}\tau_y \qquad (2.10)$$

The general equation can also be expressed in terms of friction factor (Hedstrom, 1952):

$$\frac{1}{R_m} = \frac{f}{16} - \frac{He}{6Rm^2} + \frac{(He)^4}{3f^3\ Rm^8}$$

where:

R_m = modified Reynolds number = $\dfrac{\rho VD}{\eta}$

He = Hedstrom Number = $\dfrac{D\ \tau_y}{V\eta}$

f = conventional Fanning friction factor = $\dfrac{D\ \ \Delta P}{2\ V^2\ L\rho}$

For pseudoplastic fluids, theoretical analysis and experimental data show that in a circular pipe:

$$\tau_w = K \left(\frac{8V}{D}\right)^n \left(\frac{4n}{3n+1}\right) \qquad (2.11)$$

where K and n are rheological constants (Govier, Charles, 1961).

Many workers prefer to generalize this approach assuming a relationship similar to that of the power Law (Wasp, 1977)

$$\tau_w = K' \left(\frac{8V}{D}\right)^{n'} \qquad (2.12)$$

where K' and n' are not necessarily constants

$$K' = K \left(\frac{4n}{3n+1}\right)^n$$

Fanning friction factor can also be expressed as:

$$f = \frac{K' \left(\frac{8V}{D}\right)^{n'}}{\rho \frac{V^2}{2}} = \frac{16\,\alpha}{D^{n'}\, V^{2-n'} \rho} \qquad (2.13)$$

where:

$$\alpha = K'\, 8^{n'-1}$$

Metzner and Reed (1955) defined a "generalized Reynolds Number" as

$$R_e{*} = \frac{D^{n'}\, V^{2-n'} \rho}{\alpha} \qquad (2.14)$$

Hence, for all time-independent fluids

$$f = \frac{16}{Re*} \qquad (2.15)$$

In turbulent non-Newtonian flow there are no comparable theoretical equations but extensive experiments indicate that for smooth pipes the friction factor is a function of the modified and/or generalized Reynolds Number.

2.3.4 Deposition Velocity

The deposition velocity of a solid-liquid system is the velocity at which particles begin to settle. Solids tend to accumulate in the pipe reducing the cross section available for liquid flow until, ultimately, they will block the pipe. A range of velocities from 4 to 5 fps is often used in the industry as the deposition velocity value.

Despite the fact that blockage of the pipe is predicted to occur at mixture velocities below 4.6 fps (Govier, Charles, 1961) several workers have obtained pressure drop data for mixture velocities as low as 2.5 fps for certain concentrations. Bonnington (1959) has observed that substantial depositon of sand took place at velocities only below 3.5 fps.

The deposition velocity is related to the fall velocity of particles, the degree of turbulence, concentration of solids and fines, electro-chemical interaction between particles and liquid, and finally pipe diameter.

Backfill systems for mines depend on keeping velocities above the deposition velocity. At INCO's Thompson mine the deposition velocity was found at about 6.0 fps. (Stewart, G. personal comm.)

CHAPTER III

HYDRAULIC BACKFILL

3.1 HYDRAULIC BACKFILL OPERATION

Hydraulically placed mill tailings have been used as backfill at a few mines for several decades. The increased costs of labor and materials in mining and the necessity for increasing the efficiency of mining cycles have resulted in an expansion of the use of the "hydraulic fill" method. This process is applied to fine-grained material suspended in water and carried through pipes to the point where it is discharged to fill a mined-out area to provide support for unmined portions of an ore body. This technique permits nearly complete recovery of the ore body in contrast to lower recovery for stope or room and pillar methods.

The deficit of mill tailings for the hydraulic fill process is normally made up by:

Alluvial sand along with any ground rock available.

Ground slag (silt size) has been used in many mines as a pozzolan with good results.

Granulated slag (sand size) which is also mixed with tailings.

3.1.1 Advantages and Disadvantages of Hydraulic Fill

Advantages

The immediate use of waste material from mills and the elimination of surface environmental impact make hydraulic fill an attractive solution for mine tailings allocation. The cost of material is usually less than the cost of filling with waste rock.

Sand and fine material form a tight filling, flowing into cracks and irregularities in the wall rock. The hydraulic fill is a very rapid process. Where gravity flow is used energy costs are minimal.

Disadvantages

The water used to transport the fill must be pumped out again at an additional cost. If the tailings contain a large proportion of slimes, both the draining and the fill solidification become difficult after they are run into the mined-out area. If the wall or roof rocks are argillaceous the introduction of water in the workings may cause softening of these rocks with consequent support difficulties.

3.2 BASIC CHARACTERISTICS OF THE PROPOSED INCO SLURRIES

3.2.1 Constituent Materials

Tailings are the waste product of mine mills. They consist of ground-up rock that remain after the mineral value has been removed from the ore. The disposal of tailings is an additional cost for the industry, consequently, the obejctive of all mine operators is to dispose of the tailings as cheaply as possible, or preferably, to find a better use for them.

The Thompson slag consists of melted silicates produced during the smelting process. Extraction slags are formed from the oxides among the gangue minerals which can be made fluid at a reasonable temperature.

The addition of cement to backfill process began in 1967. The cemented mixture is mainly used for floors, pillars and sills, and is thus only occasionally added to the slurry.

A flocculant agent was introduced to the fill process in 1972 (Alchem 85030), a high molecular weight anionic polymer in liquid form. It supplies negative ions that attract the small slimes particles to form large flocculated masses which settle rapidly and are more readily retained in the fill mass.

3.2.2 Concentration

The concentration of solids plays an important role in the hydraulic backfill. The backfill process requires a mixture with the highest possible concentration of solids without losing its fluidity. At INCO's mine, the operative concentration of 60 to 65% by weight reduces the considerable volume of water to be pumped out after the fill. It accelerates the filling time and prevents excessive migration of cement and slimes over the surface of the load. In addition, the compressive strength of the mixture when dry depends upon this high range of concentrations. Studies made regarding this matter have shown that a drop in densities from 65% to 60% by weight results in a decrease of 50% in compressive strength of the mortar. (Ashton, Haskins, 1980). For the purposes of this work the concentrations to be studied are 55 and 65% by weight (approximately 30 and 40% by volume).

The quantity of slag in both concentrations is in the order of 10% and 20% of the total weight of solids.

The use of slag as a supplementary fill is not a new idea. Different mines throughout the world use ground slag to make up for deficits. However, the benefits of using ground slag as a pozzolan do not help at Thompson mine because its mining methods require high early strengths of cemented fill, hence, the lower cost use of granulated slag in the mixture was proposed.

In general, the addition of granulated slag to cemented mill tailings results in an increase in compressive strength, but an excess of 50% of the tailings will result in lower strengths than the normal cemented mixture. The optimal value was found at around 25% of slag (Ashton, Haskins, 1980).

3.2.3 Particle Size Distribution

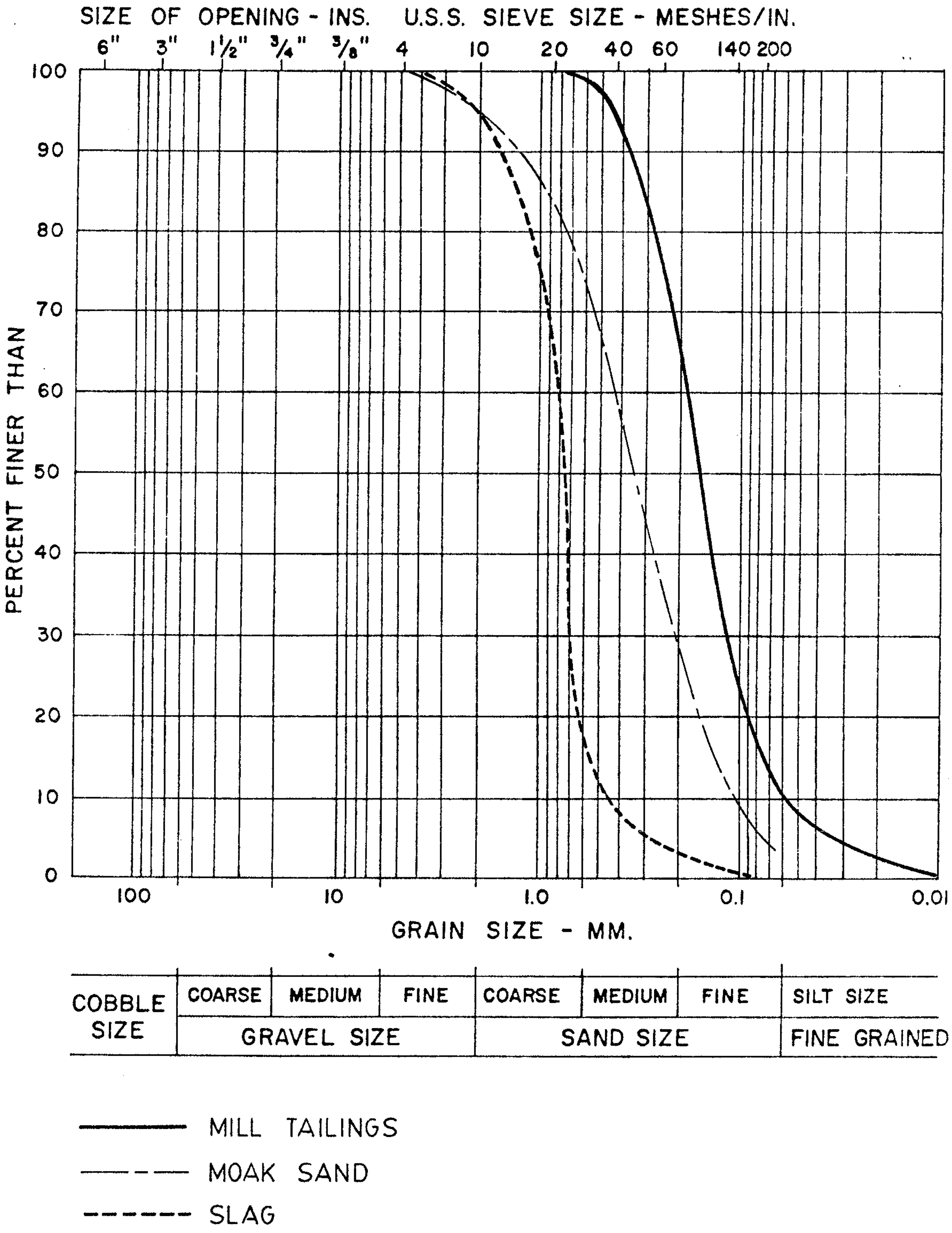
The grain size distribution of tailings depends upon the characteristics of the ore and the mill processes used to concentrate and extract the metal values (Figure III.1). The size reduction of the slag was obtained from "quenching" water poured on hot slag to crack it by thermal shock.

3.2.4 Basic Chemistry (Mineralogy)

Table III.1 lists the chemical analysis of the fill sample used in this work indicating a pyrrhotite content of 16%.

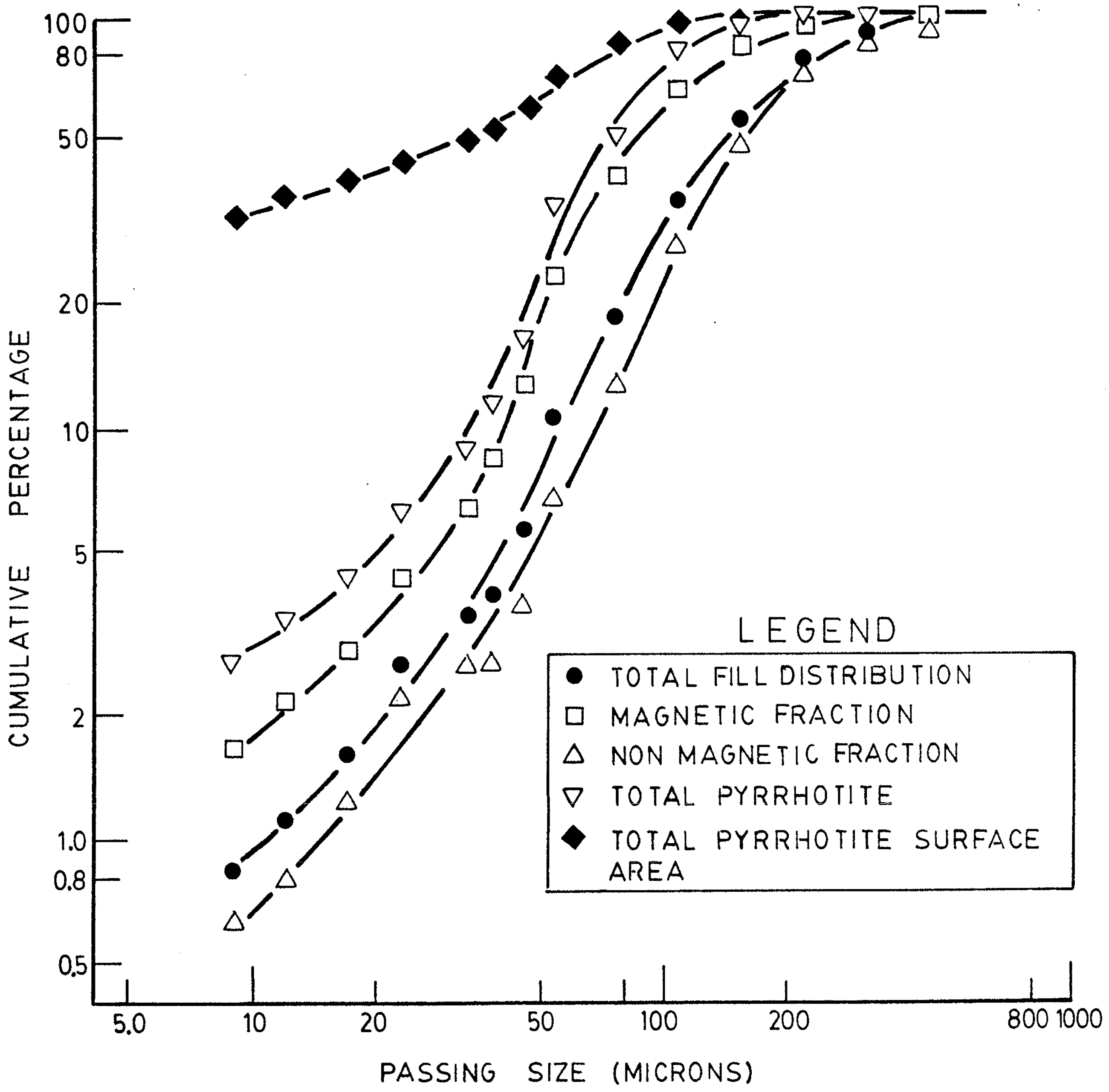
Distributions of weight, pyrrhotite and pyrrhotite surface area for the total fill, magnetic fraction and non-magnetic fraction are presented in Figure III.2. Although the -38 micron fraction makes up only 4% of the total weight of fill, it contains over 12% of the pyrrhotite and accounts for 54% of the total pyrrhotite surface area.

FIGURE III.1



TYPICAL SIZE ANALYSES

FIGURE III.2



DISTRIBUTION OF WEIGHT, PYRRHOTITE AND PYRRHOTITE SURFACE AREA.

Table III.1 CHEMICAL ANALYSIS OF THOMPSON BACKFILL SAMPLE

% Fe_{total}	13.00
% Ni	0.195
% CU	0.012
% S	6.46
% Pyrrhotite	16.00

3.2.5 Densities

Densities of the solids are presented in the following Table:

Table III.2 DENSITIES OF FILL MATERIALS

	Mill Tailings	Moak Sand	Slag
Specific gravity	3.0	2.7	3.5
Specific weight (lb/ft^3)	187	168	218
Bulk density-dry (lb/ft^3)	93	87-90	102

3.3 PILOT PLANT DESIGN FOR SLURRIES TEST

Most of the facilities to test slurries are based upon a recirculating pipeline system. The creation of the suspension takes place in a tank where the solid particles and the continuous medium are mixed. The pump, used to circulate the slurry is normally below the tank. An apparatus to test slurries will be described in greater detail in the next chapter.

CHAPTER IV

DESCRIPTION OF THE RESEARCH APPARATUS

4.1 INITIAL STUDIES

In 1981, the University of Manitoba and INCO Mining Company signed an agreement to initiate studies of slurry transport. The major concern was to examine unit headlosses for proposed tailing mixes in the mine pipelines. For that purpose, the construction of a pilot plant was contemplated.

The system lay-out and instrumentation began the same year based upon the experience of the Saskatchewan Research Council. Since then, many changes have taken place due to the geometric limitations in the Hydraulic Lab and as experience was gained.

Originally, a set of pipes, 2, 3 and 4 inches in diameter was proposed, but the need to extrapolate to larger pipe diameters suggested a replacement of the 2 inch for a 5 inch pipeline. This was necessary as relative Reynolds Number effects would produce faulty data in a 2 inch line (W. Schriek, pers. comm.) An open recirculating loop was initially built, however, it provided inadequate head for mixing the discharge jet. The "closing" of the system plus the contraction at the exit nozzle solved the problem.

The high rate of temperature-rise caused by the pipe wall friction was controlled after the installation of a cooling-jacket.

The high concentration of solids in the pump scroll-case proved to be a problem in its performance. The pressure inside the casing forced the particles to enter the stuffing-box throat. The abrasive action of the material resulted in heavy leakage through the pump throat, eroding seal rings, shaft packings and bushings. A pressurized flushing arrangement in the stuffing-box eliminated the problem. This arrangement required the use of a booster pump, a pressurized storage tank and a differential pressure relief valve. Photos of the existing system are presented in Appendix F (Plates 12, 13).

4.2 RECIRCULATING PIPELINE

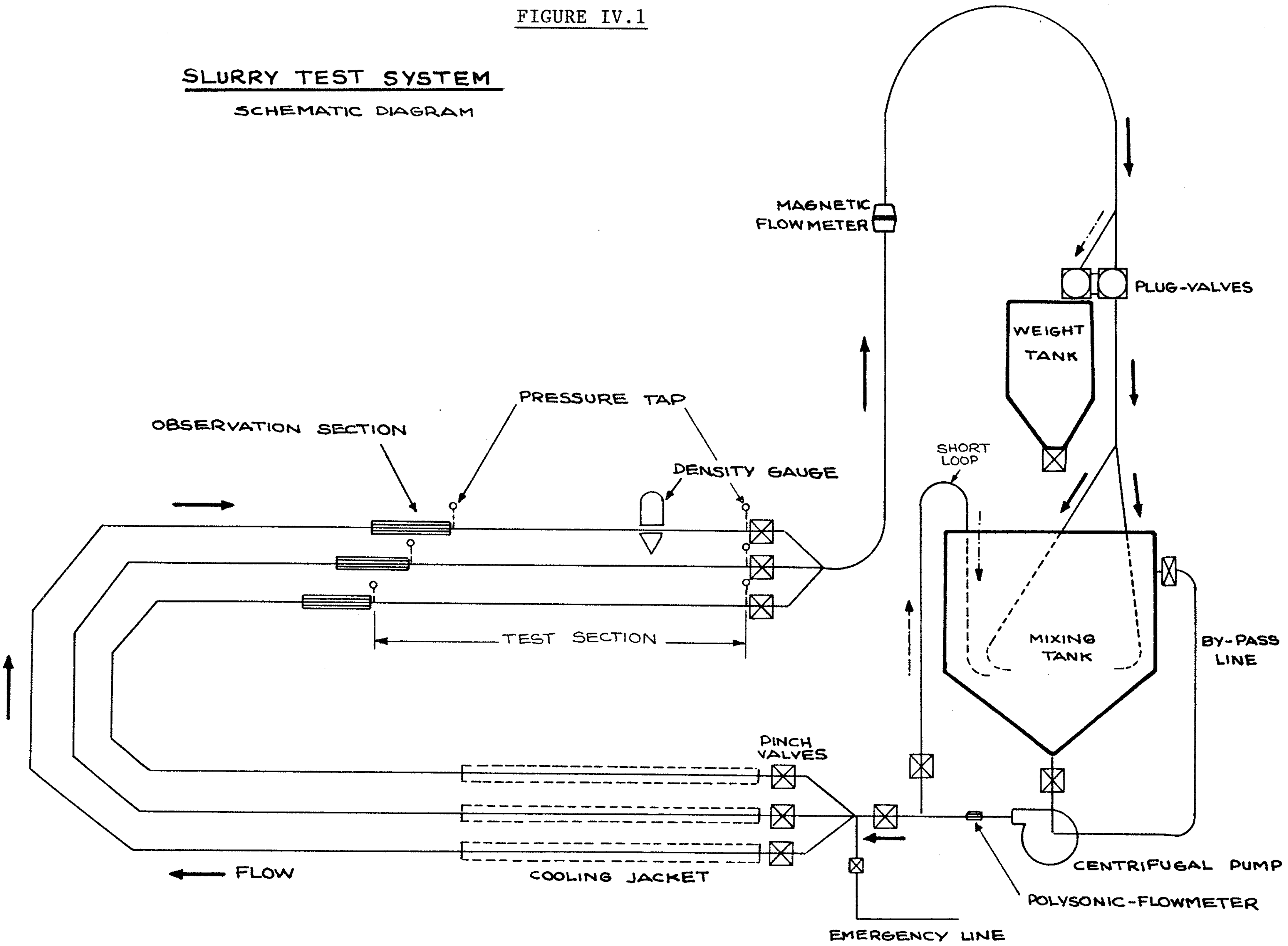
4.2.1 Principle

In a recirculating scheme, a booster pump forces the material to flow through a pipeline circuit. The inlet of the pump is immediately below the mixing tank and its discharge nozzle is connected to the circuit. In an "open" system the free-extremity of the line ends in a deflector box with a free air surface. A hinged plate inside the box deviates the flow either to the sampler or to the mixing tank, whereas in a "closed" system no free air surface occurs before the free-extremity is submerged in the mixing tank.

4.2.2 Main-line

The main line consists of a steel pipe network where all testing and measurement devices are installed. The single 3 inch pipe discharging from the pump (Fig. IV.I) is divided into three independent lines of 3, 4 and 5 inches in diameter. These lines run horizontally away from the pump, ascend to a second level and make their way back ending in a single 4 inch pipe in which two plug valves are mounted to obtain external samples. Finally, a Y-connection bifurcates the return line with both branches submerged in the mixing

FIGURE IV.1



SLURRY TEST SYSTEM

SCHEMATIC DIAGRAM

tank.

The nozzles attached to the free-ends, are circumferentially tangential to the tank wall, and discharge clockwise jets on opposite sides of the tank to produce the rotational agitation.

A 4 inch vertical pipeline outside the building has been built for future studies. This loop rises approximately 47 feet above the pump level.

The test section is encountered in the returning level of the main line. Devices such as density gauge, thermo-couples, and pressure taps are found in this segment. The length of each test section was limited by the geometry of the Lab and the requirements for "fully developed flow" in which the boundary layer has grown to fill the whole pipe. In this region the velocity profile is constant. (Wasp, et al. 1977). Lengths for the 3, 4 and 5 inch pipe are 21.30, 16.90 and 13.80 feet respectively.

Each branch of the main line has a 5 foot-long pipe made of transparent plexiglass located immediately before the test section. Through it, suspended material and particle motion can be observed. The diameter is identical to the steel pipe and aligned with it by flanges.

4.3 SHORT LOOP AND BY-PASS LINE

The short loop is a 3 inch pipe branched off the pump discharge. It rises from the pump into the mixing tank and has its discharge submerged. Its purpose is to suspend the material in the mixing tank prior to start-up. The by-pass line, a 4 inch pipe, connects the upper half of the mixing tank to the pump suction line.

It serves to withdraw clear water from above the settled solids. Both the short loop and the by-pass line are required for a safe starting of the system.

4.4 PUMPS

4.4.1 Centrifugal Pump

Centrifugal pumps accomplish the generation of pressure by the conversion of velocity head into static head. The rotary motion of the impeller adds energy to the fluid in the form of a velocity increase. This velocity increase is converted into static head in the discharge section of the casing.

The unit used in the apparatus is a centrifugal rubber lined pump Worthington model # 3R111 with a single end-suction (lateral inlet) 4 inches in diameter and a discharge nozzle (outlet) 3 inches in diameter. The casing is made of cast iron fitted with an abrasion resistant rubber liner. The impeller is also manufactured in resistant rubber which has a steel support skeleton.

The pump is driven by a Brown-Bovari D.C. electric motor with variable speed. The pressure inside the scroll-case can reach 56 p.s.i. at 100% pump power.

4.4.2 Emergency Pump

The emergency pump consists of a vertical 4 inch submersible pump (1½ HP). It is installed inside the small sump near the apparatus. A hermetically sealed motor, in line with the pump, drives a series of impellers made of fibre glass. The shutoff head reaches 131 p.s.i. The entrance in the slurry system is located two feet away from the centrifugal pump discharge. The emergency pump performs three tasks: it injects pressurized water to prevent clogging along the lines. It serves to dilute the mixture when necessary. It flushes the pipe network for a new test program.

4.5 TANKS

4.5.1 Weighing Tank

The weighing tank is also a volumetric device to obtain an external sample of the slurry flow. It consists of a cylindrical container with conical shape at the bottom plus a valve at the end (Plate 10). The whole unit hangs by three cables strung from load cells. The slurry sample is put back into the mixing tank after measuring its weight and volume.

4.5.2 Mixing Tank

This steel tank is also circular having 6 feet as a maximum diameter (Plate 8). The solids loading and the mixing process take place in this unit. The cylindrical wall has two outlets; an aperture to the by-pass line and a drain for excess water. A vertical shaft is centred inside the tank and holds circular gratings which eliminate the vortex produced by rotational motion.

4.6 VALVES AND SAND-TRAPS

The system has a set of pinch-valves installed in the main line and in the short loop. Pinch-valves are suitable for slurry handling as they cannot be jammed by solids and abrasion is a minimal problem (Plate 6). Butter-fly valves are used in the by-pass line and main drain (Plate 14).

A couple of plug-valves are mounted in the returning pipe. Only one of them must be open at a time. When an external sample is to be collected these valves shift the normal flow to the sampler tank (Figure IV.2, Plate 11).

The sand-traps are small cylinders connected to the pressure taps. Their purpose is to "catch" the solid particles in still water thus preventing any contact between the manometer-liquid and the solids (Plate 15).

Flushing water connections are also provided in these units, so that the lines to the manometer can be cleared of solid particles (Figure IV.3).

4.7 MEASUREMENT DEVICES

Different devices to measure flow rate, velocity, pressure drop, density and temperature are installed in the system. The function of each piece of equipment is presented in this section.

4.7.1 Magnetic-Flowmeter

A magnetic Flowmeter is installed in the vertical section of the apparatus (Plate 9). This unit consists of a tube with an electrically insulated metal liner. The tube has an opposed pair of metal electrodes. Electromagnetic coils are mounted external to the metering tube in a protective casing.

When the coils are excited by an electrical current they generate a magnetic field at right angles to the axis of the fluid

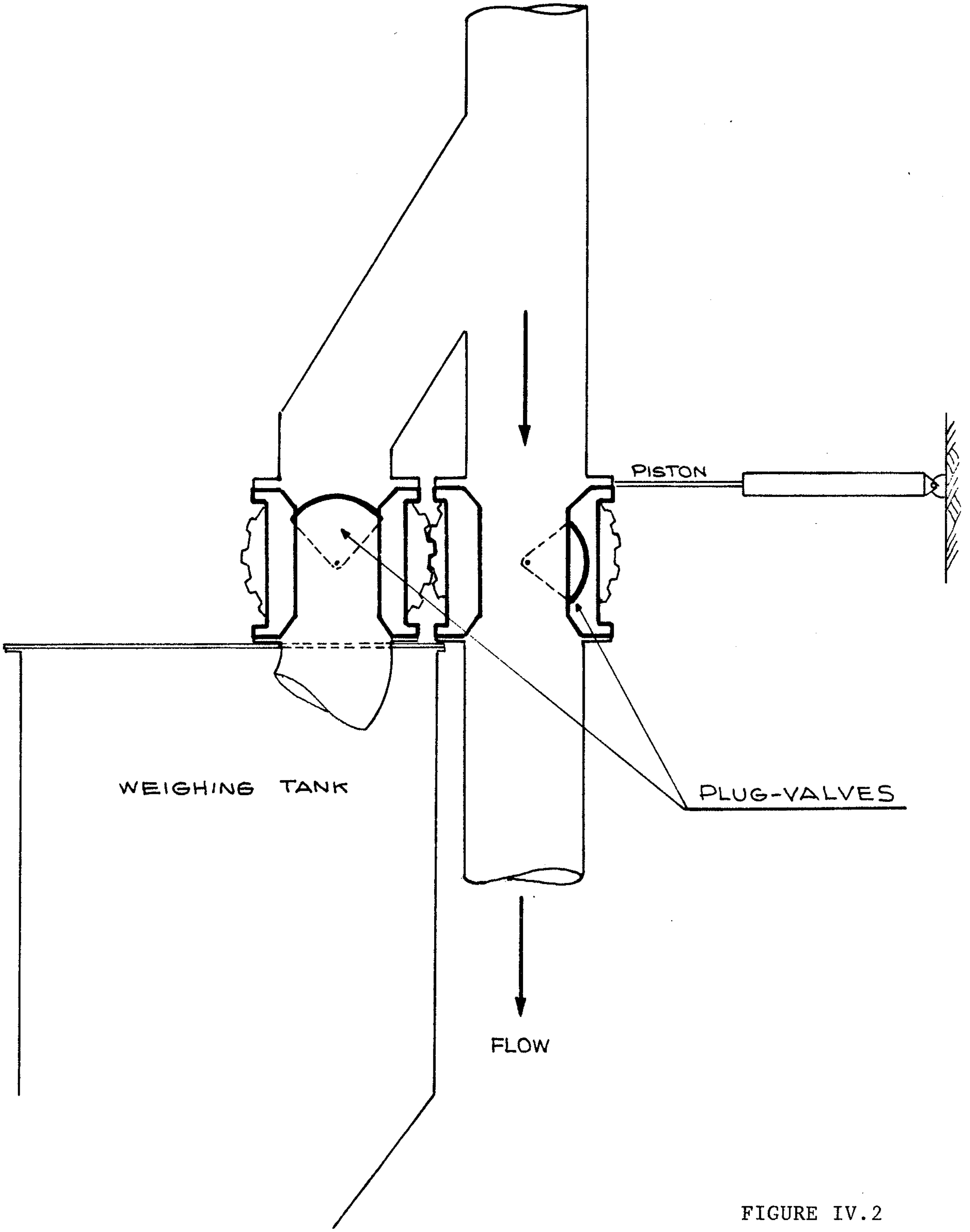
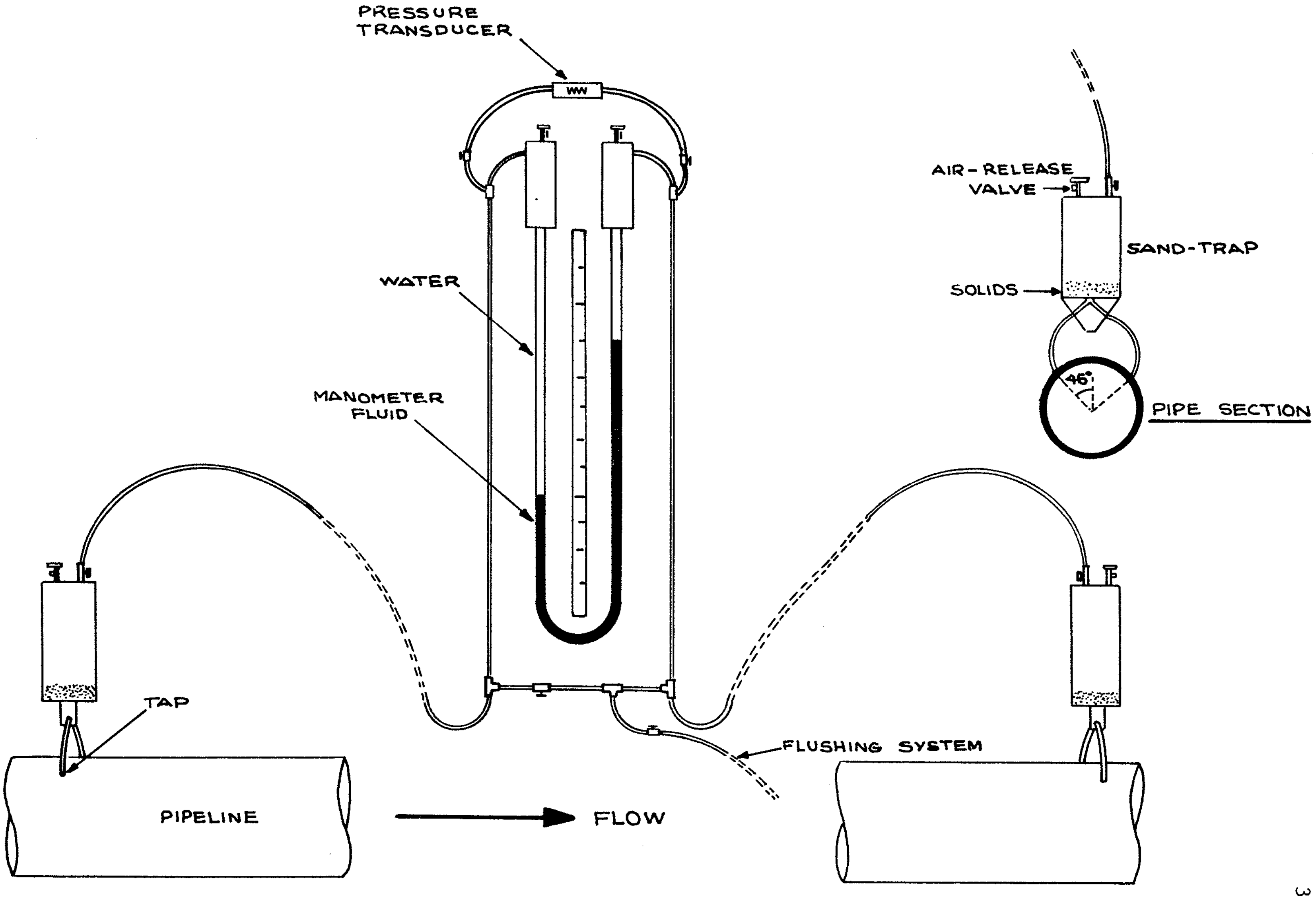


FIGURE IV.2



PRESSURE DROP MEASUREMENT FIGURE IV.3

passing through the tube. As the fluid passes across the magnetic field an electrical potential develops around the electrodes which is proportional to the volumetric flow rate. The voltage signal generated is converted, in the magnetic flow transmitter, to either a standardized current signal or an output cue. The flowmeter does not present any restriction to the fluid flow.

4.7.2 Polysonic-Flowmeter

The polysonic flowmeter makes use of the Doppler frequency shift of an ultrasonic signal reflected from discontinuities in a fluid stream to obtain flow measurements. These discontinuities can be suspended solids, bubbles or interfaces generated by turbulent eddies in the flow.

The sensor is mounted on the ouside of the 3 inch pipe near the pump (Plate 12). An ultrasonic beam from a piezoelectric crystal is transmitted through the pipe wall into the fluid. Signals reflected from flow disturbances are detected by a second piezoelectric crystal located in the same sensor. Transmitted and reflected signals are compared in an electrical circuit. The corresponding frequency shift is proportional to the flow velocity.

4.7.3 Volumetric Sampler (i.e. mixing tank)

In the research apparatus provision has been made to obtain flow rate measurements volumetrically (Plate 10). A temporary slurry mass is diverted from the main line and collected in the weighing tank. The shifting process takes place during 0.2 seconds, with sample times up to 30 seconds.

The volumetric sampler or weighing tank provides the volume and weight of a momentary sample, hence the density and concentration of solids are easily obtained.

4.7.4 U-Tube Manometers

A U-Tube manometer is provided for each test section to measure the pressure drop exerted on the interior wall over the entire length of pipe (Figure IV.3). The manometer liquid used (either mercury or meriam fluid) depends upon the amount of pressure drop and the accuracy required for calculation.

4.7.5 Pressure Transducers

Another way to obtain the pressure drop is from miniature pressure sensors. They consist of strain gages which combine a fully active Wheatstone bridge with state of the art transducer design. The semiconductor elements are bonded directly to the stainless steel diaphragm thereby providing high frequency response coupled with low sensitivity to extraneous vibrations. The semiconductor circuitry is fully compensated for temperature changes in the environment. The output is given in P.S.I. with a range of ± 5 psi.

4.7.6 Nuclear Density Gauge (Gamma-logger detector)

Measurements of specific gravity are obtained by a nuclear gauge which makes use of a gamma radiation beam across the pipe. This device consists of a source housing opposed to a detector case (Plate 15). As the material flowing in the pipe section becomes denser, more and more of the radiation beam is being absorbed. The detector converts the remaining radiation field into a proportional electric current.

4.7.7 Cooling Jacket

Since the solid-liquid mixture is constantly recirculated its temperature rises, mainly due to the friction against the internal pipe wall. This effect is controlled by enclosing a section of each line in a larger diameter concentric pipe (cooling jacket). A cold water flow passes through the cooling jacket, with flow rate regulated by an automatic valve responding to a thermo-couple (Plate 7).

4.7.8 Heating Elements

In order to accelerate the rate of temperature-rise when needed, two heating elements are installed in the mixing tank and provide 6,000 watts of heating. An example of the temperature-rise is shown in Figure IV.4.

4.7.9 Thermo-Couples

The thermo-couples are probes attached externally to the pipe wall. They transmit the pipe temperature to an electronic recorder and computer.

The Temperature Control System monitors the temperature of the slurry mixture. It compares temperature to temperature setting and regulates flow through the cooling jacket if necessary.

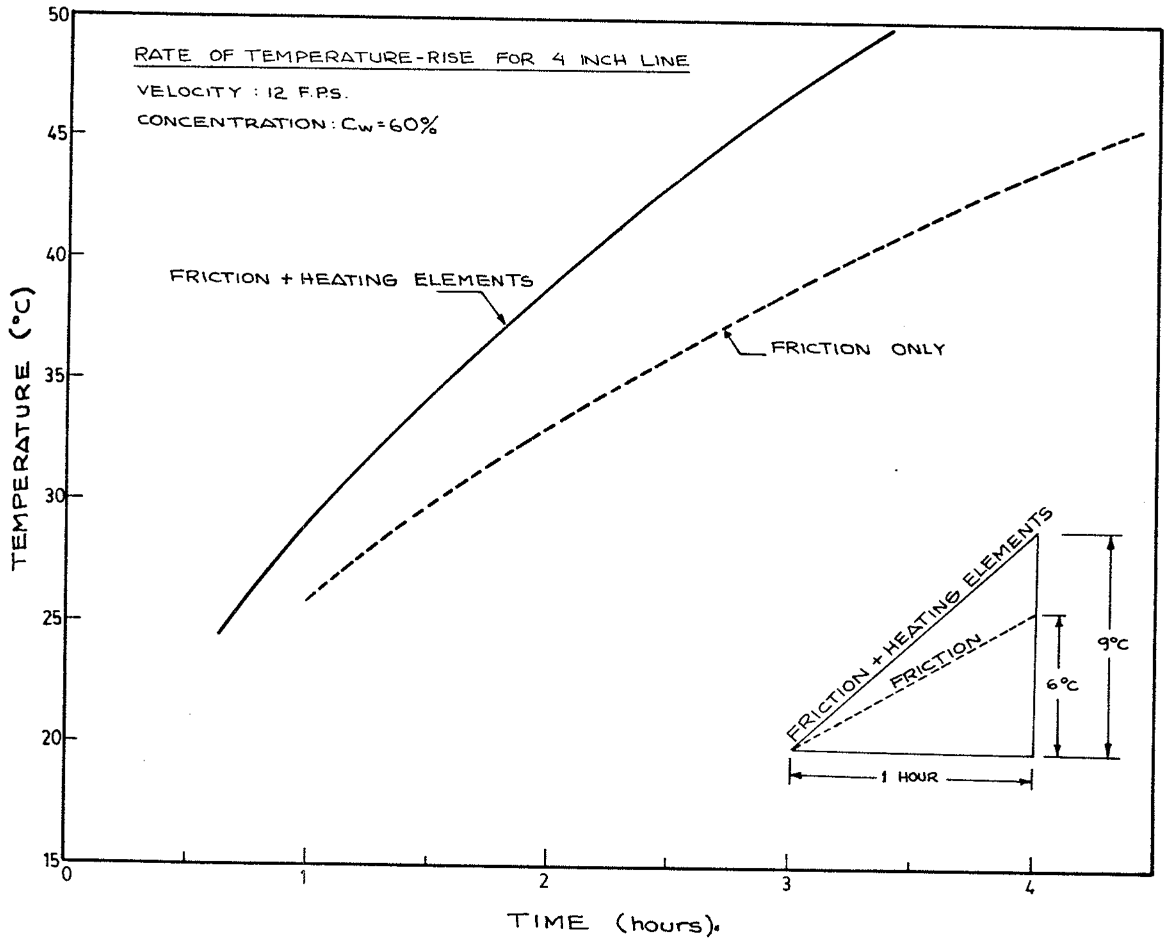

RATE OF TEMPERATURE-RISE FOR 4 INCH LINE
VELOCITY : 12 F.P.S.
CONCENTRATION : Cw = 60%
FRICTION + HEATING ELEMENTS
FRICTION ONLY
FRICTION + HEATING ELEMENTS
FRICTION
6°C
9°C
1 HOUR
TEMPERATURE (°C)
TIME (hours).
50
45
40
35
30
25
20
15
0
1
2
3
4

FIGURE IV.4

CHAPTER V

DATA COLLECTION PROCEDURES

5.1 STEPS TO INITIATE A SINGLE RUN

The methods of testing slurries in recirculating pipelines and in mines are similar in principle. Solid particles and liquid are loaded into the mixing tank to reach the effective concentration. At this point, all valves are closed, the pump is off, and there is no circulation through the pipe network. To initiate a run, a flushing arrangement on the pump gland has to be opened. Flushing can be defined as the introduction of liquid into the stuffing box of the pump at a higher pressure than the stuffing box pressure. The liquid being injected must flow into the box at a rate that is sufficiently high to prevent any solid particles behind the impeller from entering the stuffing box. The box also must have an outlet to drain the external flush liquid, so that the amount of dilution will depend only upon the restricted pressure differential between the flush liquid and the product behind the impeller.

With the valve at the bottom of the mixing tank closed, the by-pass line is opened, withdrawing clear water from above the settled solids. This procedure will prevent clogging of the pump. Then, the short loop is opened and the pump started with a small rate of discharge. As mentioned earlier, the mixing process will take place by rotational agitation which is the result of a jet discharging from the nozzle at the free-end of the line.

When the mixture becomes fully suspended the valve at the bottom of the tank is gradually opened. At the same time the by-pass line is closed. The flow rate is adjusted to obtain a better mixing.

While the circulation in the short loop is maintained, one of the branches in the main line (previously primed) is set for testing procedures. Finally, the circulation is shifted from the short loop to the main line. Up to this step no measurements have been taken.

5.2 DATA ACQUISITION (MANUALLY)

Collection of data in each branch uses the same procedure. A typical test begins once the temperature needed has been reached and controlled. With the pump at its maximum power the highest flow rate is procured.

The density of the mixture is then verified with the nuclear gauge. Adjustments can be done by adding more solids or liquid, or, by shutting the entire system down to decant some water.

Flow velocities are recorded at one second intervals through the sonic-meter and magnetic-flow meter in which 50 readings are averaged with the assistance of the computer.

The pressure drop along the test section is measured in the U-tube manometer.

Once the above readings are completed the velocity is reduced in steps until the deposition velocity is reached. In each step new data are obtained.

There are two methods of reducing velocity: either lessening the pump power or opening the short loop gradually. The latter provides an additional mixing energy in the tank. Another way of obtaining the flowrate, density and velocity of the mixture is carried out using the volumetric tank. The plug-valves momentarily divert the flow into the sampler. The time of collection, weight, and volume of the sample are recorded, then the material is allowed to return to the system. Data reading and computations are tabulated for further analysis and comparisons.

5.3 DATA ACQUISITION (ELECTRONICALLY)

A computer program similar to the one shown in Appendix D has been prepared, which does not require a manual input of data. The program is written to obtain the data via various interfaced input devices. However, due to a recent recalibration of the instruments the program is waiting to be updated. It will provide automatic results and graphic representations.

5.4 SHUT-DOWN PROCEDURES

Shutting the system down is the reverse of the starting process. Before shifting the flow from the main line to the short loop the velocity of the suspension, which has normally reached the critical value of the deposition velocity, has to be increased. The danger of plugging the line will be thus eliminated. Two pinch-valves are used to shift the circulation from the main line to the short loop. Then the by-pass line is opened while the valve in the tank is gradually closed, finally the pump and its flushing arrangement are shut down.

CHAPTER VI

DATA REDUCTION

6.1 RAW DATA AND MANIPULATIONS

Raw data are usually expressed in base units. A typical array of data collection can be observed in the left side of the computer print-out, Table VI.1.

- The electric power to drive the pump is given in percentage of its maximum.
- The polysonic-flowmeter provides readings in litres per second.
- The Gamma-logger density gauge displays the specific gravity of the suspension.
- Pressure drop is measured in inches of manometer fluid.
- Collecting and shifting time for an external sample are given in seconds.
- Volume of the sample in U.S. gallons.
- Weight of the sample in pounds.
- The averaging scheme in the computer converts the Mag-meter readings to feet per second.
- Temperature is measured in degrees centigrade.

Once the raw data are obtained, derived and basic slurry variables can be calculated either manually or by computer. The data are stored in Flexy-disks. The units used reflect the units used by the sponsor, INCO Ltd.

THE UNIVERSITY OF MANITOBA
DEPT. OF CIVIL ENGINEERING
INCO SLURRY PROJECT

DATA COLLECTED BY: JORGE
DATE: MARCH 02/83
TIME: 8
ACTIVE LOOP: 4 INCH
X-SECTIONAL AREA: .0873 SQ. FEET
TEST LENGTH: 16.9 FEET
SLURRY TYPE: TAILINGS 90% SLAG 10%

	:	LINE								: MIXTURE	:	DISCHARGE		:	VELOCITY		:	LINE			:	
ROW	PUMP POWER (%)	SONIC RDG. L/S	GAMMA LOGGER	PRESS. (INCH)	C&S TIME SEC.	VOL. U.S. GAL.	WT. LB.	MAG. METR RDG.	TEMP (C)	S.G. (S)	CONC (WT) (%)	WT. TANK GPM	WT. TANK CFS	MAG. METR CFS	WT. TANK F/S	MAG. METR F/S	SONIC F/S	PRESS. FT-S	PRESS. FT-W	HEAD LOSS /100	SHEAR STRESS PSI	VEL. GRAD /SEC
PR#1																						
1	100	36.3	1.61	26.9	6.159	50.0	584	7.7	24.3	1.61	0.00	487.09	1.08	1.02	12.43	11.73	0.00	2.72	4.38	25.94	0.009383	281.62
2	88	34.5	1.62	26.0	6.156	49.4	576	7.5	24.5	1.62	0.00	481.48	1.07	0.98	12.28	11.29	0.00	2.61	4.23	25.07	0.009069	271.19
3	82	33.4	1.60	23.5	6.269	46.3	531	7.3	25.0	1.60	0.00	443.13	0.98	0.94	11.30	10.86	0.00	2.39	3.83	22.66	0.008197	260.76
4	78	32.0	1.61	21.3	6.300	43.3	472	7.1	25.2	1.61	0.00	412.38	0.91	0.91	10.52	10.43	0.00	2.15	3.47	20.54	0.007429	250.32
5	74	30.5	1.63	19.3	6.145	41.2	448	6.8	25.0	1.63	0.00	402.27	0.89	0.85	10.26	9.77	0.00	1.93	3.14	18.61	0.006732	234.68
6	70	29.0	1.63	17.2	8.139	52.5	552	6.5	24.8	1.63	0.00	387.02	0.86	0.79	9.87	9.12	0.00	1.72	2.80	16.58	0.005999	219.03
7	65	27.0	1.62	15.1	8.153	47.2	517	6.2	24.7	1.62	0.00	347.35	0.77	0.73	8.86	8.47	0.00	1.51	2.46	14.56	0.005267	203.39
8	60	24.8	1.61	11.8	9.228	47.0	515	5.8	24.5	1.61	0.00	305.59	C.68	0.66	7.79	7.60	0.00	1.19	1.92	11.38	0.004116	182.53
9	55	22.7	1.60	10.2	9.162	42.2	450	5.5	24.4	1.60	0.00	276.35	0.61	0.60	7.05	6.95	0.00	1.03	1.66	9.83	0.003557	166.88
10	50	20.0	1.60	7.6	9.133	35.6	373	5.1	24.0	1.60	0.00	233.87	0.52	0.53	5.96	6.08	0.00	0.77	1.23	7.32	0.002651	146.02
11	46	18.0	1.63	6.2	12.146	39.5	420	4.7	23.5	1.63	0.00	195.12	0.43	0.45	4.97	5.21	0.00	0.62	1.01	5.97	0.002162	125.16

REF: D4-0302

TABLE VI.1

6.2 CALCULATION OF DERIVED VARIABLES

The derived variables are the result of converting the raw inputs to hydraulic terms such as discharge, velocity and head-loss. The right side of the computer print-out (Table VI.1) shows the results.

Despite the fact that the velocity is obtained directly from electronic devices, it is considered a derived variable because its value can be computed from the volumetric sampler. As soon as the volume is collected the discharge is calculated as follows:

$$Q = \frac{60}{\text{collecting time (sec.)}} \text{ x volume (U.S. gal.)}$$

where Q = Discharge G.P.M.

also

$$q = \text{G.P.M. } (0.002228)$$

where q = Discharge c.f.s.

Velocity in each line is derived from the continuity equation.

Thus $V = \frac{q}{A}$

where:

A = cross section area of the testing pipe in ft^2

V = velocity, F.P.S.

The head-losses are expressed in feet of slurry, feet of water and feet of water per 100 feet of pipe. The following equations are used when the carrier fluid is water.

- Feet of slurry:

$$H_S = \frac{H_{MF}}{SG_m} (SG_{MF} - 1) \qquad (6.1)$$

- Feet of water:

$$H_W = H_{MF} (SG_{MF} - 1) \qquad (6.2)$$

- Feet of water per 100 feet of pipe

$$HL = H_w \times \frac{100}{L} \qquad (6.3)$$

where:

H_s = Head-loss, feet of slurry

H_w = Head-loss, feet of water

HL = Head-loss, feet/100 feet of pipe

H_{MF} = pressure drop in U-manometer, feet.

SG_m = specific gravity of the mixture (slurry)

SG_{MF} = specific gravity of the manometer liquid.

L = length of pipe test section, feet

6.3 BASIC SLURRY VARIABLES

6.3.1 Concentration (C)

Concentration of solids is expressed in percentage by weight. In practice, a specific gravity curve is used to determine the concentration (Figure VI.2). The range of curves is based on the solid components used for each sample.

The experiment contemplates two mixtures.

MIXTURE I: 90% tailings + 10% slag

Concentrations:

55% by weight (29% by volume)

65% by weight (38% by volume)

MIXTURE II: 80% tailings + 20% slag

Concentrations:

55% by weight (28% by volume)

65% by weight (37% by volume)

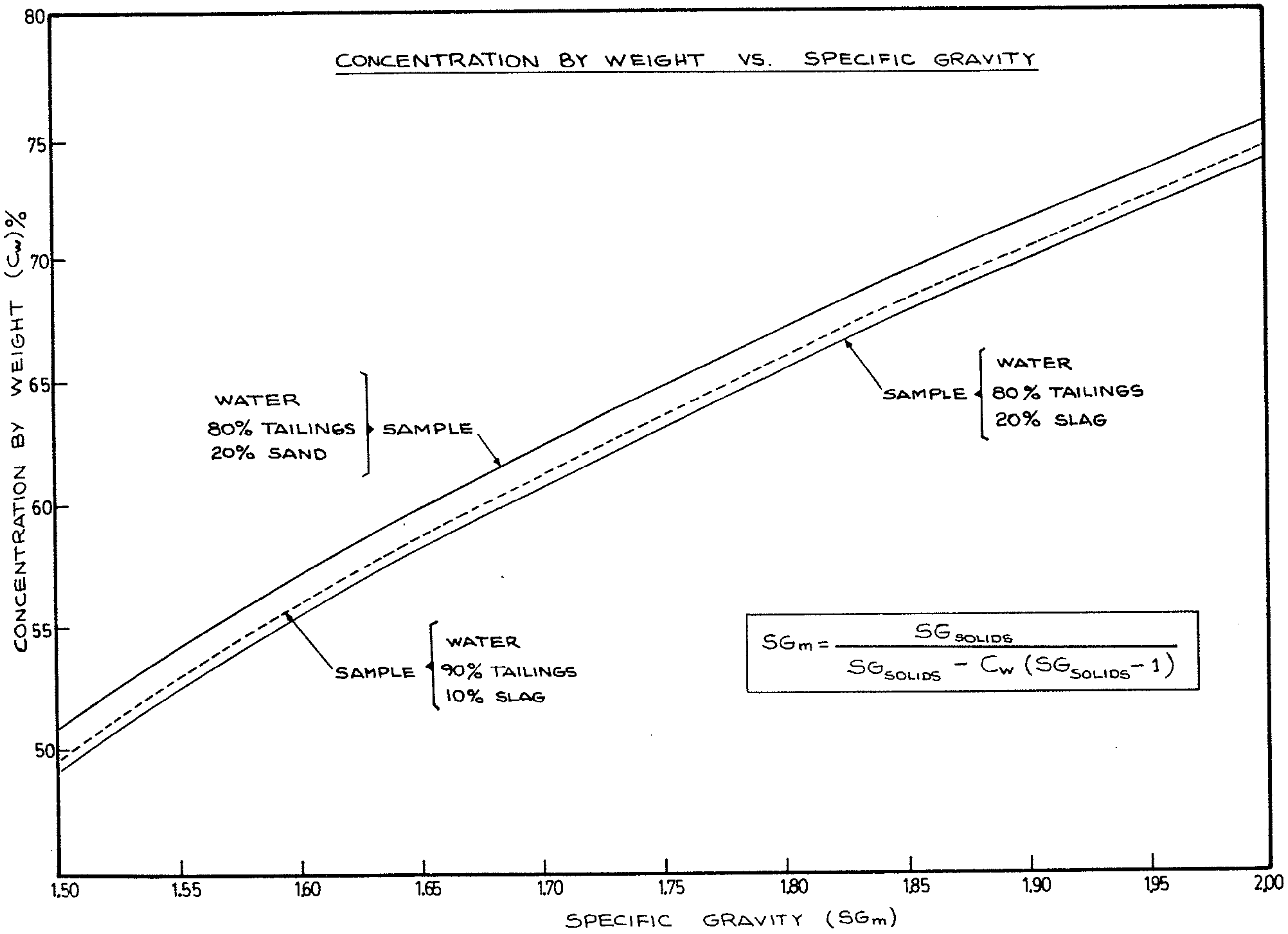

CONCENTRATION BY WEIGHT VS. SPECIFIC GRAVITY
CONCENTRATION BY WEIGHT (C_w)%
80
75
70
65
60
55
50
1.50
1.55
1.60
1.65
1.70
1.75
1.80
1.85
1.90
1.95
2.00
SPECIFIC GRAVITY (SG_m)
WATER
80% TAILINGS
20% SAND
SAMPLE
SAMPLE
WATER
80% TAILINGS
20% SLAG
SAMPLE
WATER
90% TAILINGS
10% SLAG
$SG_m = \frac{SG_{SOLIDS}}{SG_{SOLIDS} - C_w (SG_{SOLIDS} - 1)}$

FIGURE VI.2

6.3.2 Shear Stress (τ)

The low range of velocities and the highly concentrated slurries allow use of the formulation for laminar flow. Pipe roughness is not usually important in this region (Harris, Quader, 1971).

Wall shear stress is:

$$\tau_w = \frac{D\,\Delta P}{4L} \qquad (6.4)$$

where:

τ_w = wall shear stress, p.s.i.

D = pipe diameter, feet

ΔP = pressure difference, p.s.i.

L = length of pipe test section, feet.

(For derivation see Appendix C.)

6.3.3 Rate of Shear (du/dy) or velocity gradient

Rate of shear for laminar flow in a circular pipe is given by the following equation (for derivation see Appendix C):

$$\frac{du}{dy} = \frac{8V}{D} \qquad (6.5)$$

where:

V = velocity, F.P.S.

D = pipe diameter, feet

(du/dy) = rate of shear, $\sec^{-1}$

Due to the complexity of the velocity profile, laminar flow is assumed for the purpose of obtaining an "apparent viscosity".

6.3.4 Apparent Viscosity (μ_a)

$$\mu_a = \frac{\tau}{du/dy} \times 144 \qquad (6.6)$$

where:

τ = shear stress, p.s.i.

du/dy = rate of shear, sec^{-1}

μ_a = apparent viscosity, $\frac{\text{lb.sec}}{\text{ft}^2}$

A computer algorithm was developed to calculate most of the derived and basic slurry variables based on these formulas.

6.4 COMPUTER PROGRAM AID

The program algorithm, written in BASIC language, is listed in Appendix D. The "user friendly" program facilitates the loading process. Raw data and pipe diameter are the inputs. Calculations and printouts are immediately obtained (e.g. Table VI.1). A software package (Visical) for the Apple computer was used to present the data and calculate the slurry variables (see Appendix A).

6.5 PLOTTING TECHNIQUE

Figures B.1 to B.41 in Appendix B show the plotted points. Since the energy consumption expressed in head-loss per pipe length was the main concern, the plotting technique has concentrated on head-loss as the major independent variable. The effects of the dependent variables are discussed in the next chapter.

Connecting points one by one following the trends as possible, permitted generation of interpolated values. Some extrapolation was also obtained (dotted line in graphs).

Apparent viscosity versus rate of shear was plotted to identify the rheological behavior of the mixture (Figures B.18-B.27).

The sequence of figures permits the time-dependency of the mixture to be distinguished. Consistency of X-Y scales permits rapid comparison.

CHAPTER VII

DATA ANALYSIS

7.1 PRESENTATION OF DATA PLOTS

7.1.1 Head-Loss vs. Velocity (Figures B.1 to B.17, Appendix B)

Figures B.1 to B.8 show the experimental results for the 90/10 (90% tailings + 10% slag) mix. Figures B.9 to B.17 present the experimental results for the 80/20 mix. Figures B.1 and B.2 present the early data obtained at 55% concentration for 90/10 in March, 1983.

Figures B.3 to B.5 present the data at 65% concentration by weight for the 90/10 mix. These data were obtained in September. However, during the period from March to September the mixture remained in the system. Deficiencies in the apparatus such as poor mixing energy, and errors in the density gauge did not provide reliability for higher concentrations as the density measurements were in error due to a leaking argon gas chamber in the detector. Finally a concentration of 65% in 3" and 4" lines was reached. The maximum for the 5" line was 63%. A jellied appearance was noticed in the mixture with a very slow settling velocity. The results of these runs produced extremely high head-losses. An attempt to reproduce the data of March was then undertaken.

The mixture was diluted until the concentration reached 55%. Figures B.6 to B.8 show the attempted reproduction of the 55% data in Figures B.1 and B.2. The result was a clear difference between the fresh material in March and the old material run later in October. High head-losses and different curve shape indicated that something took place in the slurry over this period of time.

The deposition velocity was also different, being lower for the old material. The fall velocity of particles, mainly for fines, was far slower than before. These findings suggested an unmeasured variable was affecting head-losses as the variable caused "ageing". To explain the time-dependency in the mixture a closer study was required. Factors which cause particles to remain stable despite passage of time are sometimes explained by the phenomenon of the electrical double layer consisting of the charged-particle surface and a surrounding sheath of ions of charge opposite to that of the particle surface. A consequence of the electrical double layer around each particle in water is to create regions of electrical potential in a bulk mixture that nominally has a zero potential.

The system was emptied and a new slurry mix, 80/20, was tested. Figures B.9 to B.17 show the experimental results. Figures B.9 - B.11 represent the 55% concentration. If they are compared with the results of the 90/10 mix in March the variability in head-loss is almost similar. The deposition velocity was found at about 5 F.P.S. A noticeable sliding bed at 6 F.P.S. was observed usually in the 3 inch line. Lower velocities than 5 F.P.S. could be run but were normally affected by a "queuing" problem at the foot of the vertical pipe resulting in a bed formation which extended upstream as a test proceeded. This problem was detected by an increase in slurry density. The physical appearance of the mixture after the runs remained constant.

Before the addition of solids to reach the 65% concentration some points were reproduced for the 55% 80/20 runs with negligible discrepancies. The 65% runs are shown in figures B.12 to B.14. High head-losses are observed. Most of the curves are concave downwards denoting plasticity at low velocities. The deposition velocity was reduced to 3.5 F.P.S. It was impossible to distinguish any bed formation in the solids. The mixture exhibited a different appearance after the experiment. Fine particles were totally dispersed with a longer settling time. However, several points were reproduced without discordance.

Figures B.15 to B.17 were obtained from the plots for the 80/20 mix. The results are separated by pipe diameter. From these figures it is clear that temperature has an effect on head-loss. This effect is more evident in smaller pipes. The importance of concentration is also demonstrated by these figures.

7.1.2 Apparent Viscosity vs. Rate of Shear (Figures B.18 to B.27, Appendix B)

To assist in design of predictive equations for headloss, plots of apparent viscosity vs. rate of shear were made. Since the behavior of the slurry cannot be expressed in terms of a "viscosity", apparent viscosity has been used as an indicator of "thickness" between mixtures.

It can be seen from Figure II.1, in Chapter II, that the values of apparent viscosity for a yield-pseudoplastic fluid decreases with increase of applied shear rate. In the experiment, at 65% solids concentration by weight the yield-pseudoplastic pattern is observed in all plots. At 55% concentration the plots suggest the existence of a plastic material with nearly constant apparent viscosity. However, once the material is affected by the "ageing" process the apparent viscosity increases with a decrease in shear rate.

7.2 BIVARIATE PLOTS

To assist in model design bivariate plots of the independant variables with unit head-loss were generated.

7.2.1 Head-Loss vs. Pipe Diameter (Figures B.28 to B.31, Appendix B)

From interpolated and extrapolated points, curves of head-loss vs. pipe diameter were generated. Figure B.28 clearly shows that the data are in error for the 4" line for the 90/10 mix. The exponential variability of head-loss is reversed due to a high value in the 4 inch line. Once the source of error (a leak in a manometer fitting) was eliminated the expected variation took place, Figure B.29, B.30, B.31. A family of curves for different velocities was then plotted. High velocity information in the 5 inch line was derived from an extrapolation for a velocity of 12 F.P.S. The variation of clear water at 7 F.P.S. serves for comparison.

7.2.2 Head-Loss vs. Temperature (Figures B.32 to B.35, Appendix B)

Temperature was normally controlled by the cooling jacket. Values of 25, 35 and 45 degrees centigrade were used in the experiment. Unfortunately, lower temperatures were impossible to reach. Figures B.32, B.33 are obtained from data for the 90/10 mix. An inverse relationship between head-loss and temperature is noticed in most cases. Only in the 3 inch line is the variation direct. For the 80/20 mix, which is considered more reliable, the direct relationship is shown in all cases. Some discrepancies in Figures B.35.a and B.35.b are referred to Fig. B.15 and B.16 respectively. The discrepancies are likely produced by partial blockage of the poly-lines to the sand-traps by solids.

7.2.3 Head-Loss vs. Concentration (Figures B.36 to B.41, Appendix B)

These figures show the effect of solids concentration. Points for equal velocities were joined with a straight line. However, the actual relationship may be nonlinear and discontinuous at a weight concentration of 60%. Concentration effect was more noticeable in smaller pipes. The bigger the pipe the less the variation. Figure B.38 presents extrapolated values for 65% concentration. A certain degree of divergence toward high concentrations is noted in the 5 inch line for both samples.

With all the data plots presented, discussion of the slurry behavior shall be now undertaken.

7.3 DISCUSSIONS

7.3.1 Discussion of Data

Theoretical fluid curves were presented in Chapter II in which a non-Newtonian fluid can be identified in a plot of apparent viscosity vs. rate of shear (Fig. B.1). If we observe the actual curves obtained in Figures B.18 to B.25 it is clear that the slurry behavior is non-Newtonian within the range of our major variables. The plasticity at 65% concentration by weight is consistent in every plot. It resembles the behavior of a yield-pseudoplastic fluid. On the other hand, at 55% concentration the plasticity is neither persistent nor clear. It can be related to a pseudoplastic fluid or to a fluid nearly Newtonian. However, the plasticity increases with slurry ageing as continuous bombardment of particles either in the mixing tank or in the centrifugal pump occurs. It seems that what was a pseudoplastic fluid has turned into a yield-pseudoplastic fluid (Figs. B.19, B.23, B.26).

Another important finding is that the apparent viscosity tends toward a constant value at high rates of shear (e.g. 350 sec^{-1}) regardless of concentration and time-dependency. It appears that high shear disrupts the electro-chemical bonds generated by a high zeta-potential. Plasticity is thus to be considered only at low range of velocities (e.g. 4 to 12 F.P.S.). The concave downward shape in a plot of Head-loss vs. Velocity may also indicate the presence of a plastic fluid. Most of the figures at 65% concentration by weight show this peculiarity.

Zeta potential may also play a role in changing HL for the 55% concentration after an extended time period. The most likely phenomenon is a change in zeta-potential of the colloidal matter. In 1982 an Australian researcher (Horsley) concluded that in laminar slurry flow a change in head-loss gradient at constant concentration of solids and constant velocity and temperature can be explained in terms of zeta potential. Furthermore he pointed out that for solid concentrations exceeding a minimum value of 28% by volume the yield stress and the plastic viscosity are a function of zeta potential. In the turbulent flow regime the zeta potential had no detectable effect on the head-loss gradient.

Considering the present slurry tests, at a 55% concentration by weight (29% by volume), the mixture was in the upper limit of what is Horsley's low solid concentration slurry. Additionally, the percentage of fine particles ($d_{50} < 50$ µm) was high (Fig. III.1).

The percent fines slightly increased after continuous recirculation through the system. Hence the surface/volume ratio of the fines was increased. But what really became the major component in this change was the fact that after the first run of 55% in March there were many attempts to obtain a value of 65% concentration due to the faulty gamma-logger. More solids were added and mixed. Not until the month of September was the 65% concentration reached after the gamma logger was fixed. By the time this occurred the effects of zeta potential were already in the mixture. The collodial matter remained dispersed even when the slurry was diluted below a 55% concentration by weight. Therefore, the entire set of data for the 90/10 mix taken in September/October were affected by these electrical repulsive forces. Although somewhat conjectural as a zeta probe was not available, this scenario appears likely.

There are still two questions to be answered. The first is how rapidly the zeta potential affects the head-loss gradient in a recirculating system. Or at least, how long does it take to become a significant parameter. The second is where do the electric charges increase, in the line, in the pump, in the mixing tank, or throughout the system. The increase could be the result of continuous friction between particles and the internal pipe wall, or friction between particles exerted by the pump and mixers. To answer these questions an experiment will be undertaken in the Hydraulics Lab. It will consist of constant measurement of zeta potential for different samples. In the meantime, the results will be correlated with the response in the fluid viscosity. This experiment is described in Appendix E.

As a result of this discussion, and in line with the interests of INCO Ltd., model building will concentrate on the 80/20 mix.

Considering the effect of pipe diameter, figures B.9 to B.17 show that the slopes of the curves become steeper with a reduction in pipe diameter. Friction is high in smaller pipes. Fig. B.30 and B.31 provide a closer view of this non-linear relationship. Another factor in this variation may be the ratio d_{50}/D (particle size/pipe diameter) in which d_{50} becomes more important in small pipes.

The temperature effect can be observed in Figs. B.34 and B.35. There is a slight but definite increment of head-loss when temperature rises. To explain this phenomenon in a high concentration slurry, consider that the higher the temperature the less viscous the carrier fluid, therefore, fall velocity of particles increases with a resulting reduction in homogeneity of the suspension. Friction and colision between solids occurs more often. This effect is more evident in smaller pipes where particle size plays an important role (Figs. B.34, B.35). Figures B.15 to B.17 show that temperature has a smaller effect on the head-loss in bigger pipes.

The effect of concentration is obvious. An increase in concentration will result in higher head-losses. Apparent viscosity thus increases. Pipe diameter interacts with solids concentration to make the variation in headloss more pronounced in small pipes (Figs. B.39, B.40, B.41).

The deposition velocity was found to be lower for the 65% concentration, as the increase in viscosity with a larger concentration reduced fall velocity. This effect was even more remarkable after the dispersion of fines due to zeta potential.

A persistent irregularity noted as a "lump" in curves head-loss vs. velocity (Figs. B.12, B.13, B.14) has also been observed by Shook, Schriek, Smith, Haas, Husband (1973). Several explanations for this anomaly in high concentration slurries exist. As velocity decreases an interface between suspended and bedload solids is developed increasing the roughness between the two layers. Saltation or repetitive leaping motion may occur in the interface. Another reason might be that the percentage of cross-section area with low concentration decreases with an increase in velocity gradient. The momentum transfer from the slow velocity region may produce asymmetric distribution of velocity in the entire pipe cross section and higher head-losses.

Given these discussions and findings, prediction of the variability in head-loss for a 6-inch pipe become feasible within the range of variables used. Figures B.30 and B.31 clearly indicate that the use of a 5" line rather than a 2" line produced better information for a scale-up extrapolation. However, the 5" pipe velocities could only reach 8 fps. It was impossible to obtain higher velocities due to the restricted power of the pump.

Anomalies and systematic errors will be discussed in the next section.

7.3.2 Discussion of Errors

The errors observed in the data may be the result of bias in the apparatus, systematic errors, un-reliability of devices and the limited knowledge of slurries.

The density measurements from the nuclear density gauge, if the concentration is low, can always be verified in the weight tank. But for high concentrations (greater than 55% by weight) the presence of a "queuing" phenomenon along the pipe produced erroneous concentrations as determined by the weight tank for the same mixture. This discrepancy required reliance on the nuclear gauge only for high concentrations. The zeta-potential effect was a systematic error impossible to control. Partially plugged lines or leakage in connections and sand-traps can also be sources of error.

Figure B.1 to B.5 show a systematic error in the 4 inch line, caused by a leak in the U-Manometer. Figure B.28 presents the same defect. Changes in zeta-potential affected the 90/10 mix as previously noted (Figs. B.3 to B.8).

Figure B.12 shows a discrepancy in the trend of 3 and 4 inch line losses. Figure B.16 more clearly shows this anomaly. Since the U-Manometers were thoroughly examined for the 80/20 mix, the only explanation for this error seems to be a leak in the air-release valve of the upstream sand-trap in which low pressure was exerted at high velocities of the slurry.

It is evident that after this assessment the only data to statistically examine is that for the 80/20 mix.

7.4 STATISTICAL MODEL BUILDING AND ALTERNATIVES

7.4.1 Choice of Bivariate Models

For dealing with plastic or pseudoplastic fluids, theory and practice (Chapter II) suggest the use of a power model to explain the non-Newtonian behavior. An alternative approach using non-dimensional parameters, which would not require the assumption of symmetrical flow, has not been used here but should be tried in future work.

The power model requires the relation between shear stress and velocity gradient in the form:

$$\tau = K \left(\frac{8V}{D}\right)^n$$

Nevertheless, in practical application the energy loss, which dictates pump sizes, is normally expressed in head-loss gradient. To study this parameter the following mathematical models will consider head-loss as the only dependent variable.

Substituting $\tau = \frac{D\Delta P}{4L} = \frac{Dg\rho hf}{4L}$

we obtain: $\frac{h_f}{L} = K \left(\frac{4}{Dg\rho}\right) \left(\frac{8V}{D}\right)^n$

where: $\frac{h_f}{L}$ = Head-loss (%) or gradient

K = constant

D = diameter, feet

V = mean velocity, F.P.S.

n = exponent

g = gravity force

ρ = density

Based on the last formula a bivariate model was built for the 80/20 mix at 65% concentration. To apply the Multiple Regression technique on head-loss the logarithm of variables was used.

Model-a:

$$\mathrm{Ln}\left(\frac{h_f}{L}\right) = \beta_0 + \beta_1 \,\mathrm{Ln}\left(\frac{4}{Dgp}\right) + \beta_2 \,\mathrm{Ln}\left(\frac{8V}{D}\right) + \epsilon_0$$

The statistical results of the regression are shown in Table VII.1

The final equation for Model-a was:

$$\mathrm{Ln}\left(\frac{h_f}{L}\right) = 2.138 + 0.523 \,\mathrm{Ln}\left(\frac{4}{Dg}\right) + 0.441 \,\mathrm{Ln}\left(\frac{8V}{D}\right) \qquad (1)$$

However, in this work the carrier fluid is water with a negligible change in specific weight in the range of temperatures used. The

Head-loss can also be expressed by simplifying the right-side of Model-a. Then:

$$\frac{h_f}{L} = f(D,V)$$

The next section will elaborate this approach.

7.9.2 Presentation of Bivariate Models

An analogue of Model-a was run for variables D (diameter) and V (velocity).

The 80/20 mix equation for 65% concentration by weight is given by Model-b:

$$\text{Ln}\left(\frac{h_f}{L}\right) = \beta_o + \beta_1 \text{ Ln }(D) + \beta_2 \text{ Ln }(V) + \epsilon_o$$

The log equation is:

$$\text{Ln}\left(\frac{h_f}{L}\right) = 1.620 - 0.961 \text{ Ln}(D) + 0.440 \text{ LN}(V) \qquad (2)$$

The exponential Eq. $\frac{h_f}{L} = 5.053 \frac{V^{0.44}}{D^{0.961}}$ (2')

Results of the regression are presented in Table VII.2. Figure VII.1 shows a family of curves for equation (2). Evidently, curves for model-a are equal to model-b.

The same approach for determination of head-loss was used for the mixture at a 55% concentration resulting in the following log equation (Table VII.3)

$$\text{Ln}\left(\frac{h_f}{L}\right) = -0.272 - 0.790 \text{ Ln}(D) + 1.037 \text{ Ln}(V) \qquad (3)$$

Exponentially expressed

$$\frac{h_f}{L} = 0.762 \frac{V^{1.037}}{D^{0.79}} \qquad (3')$$

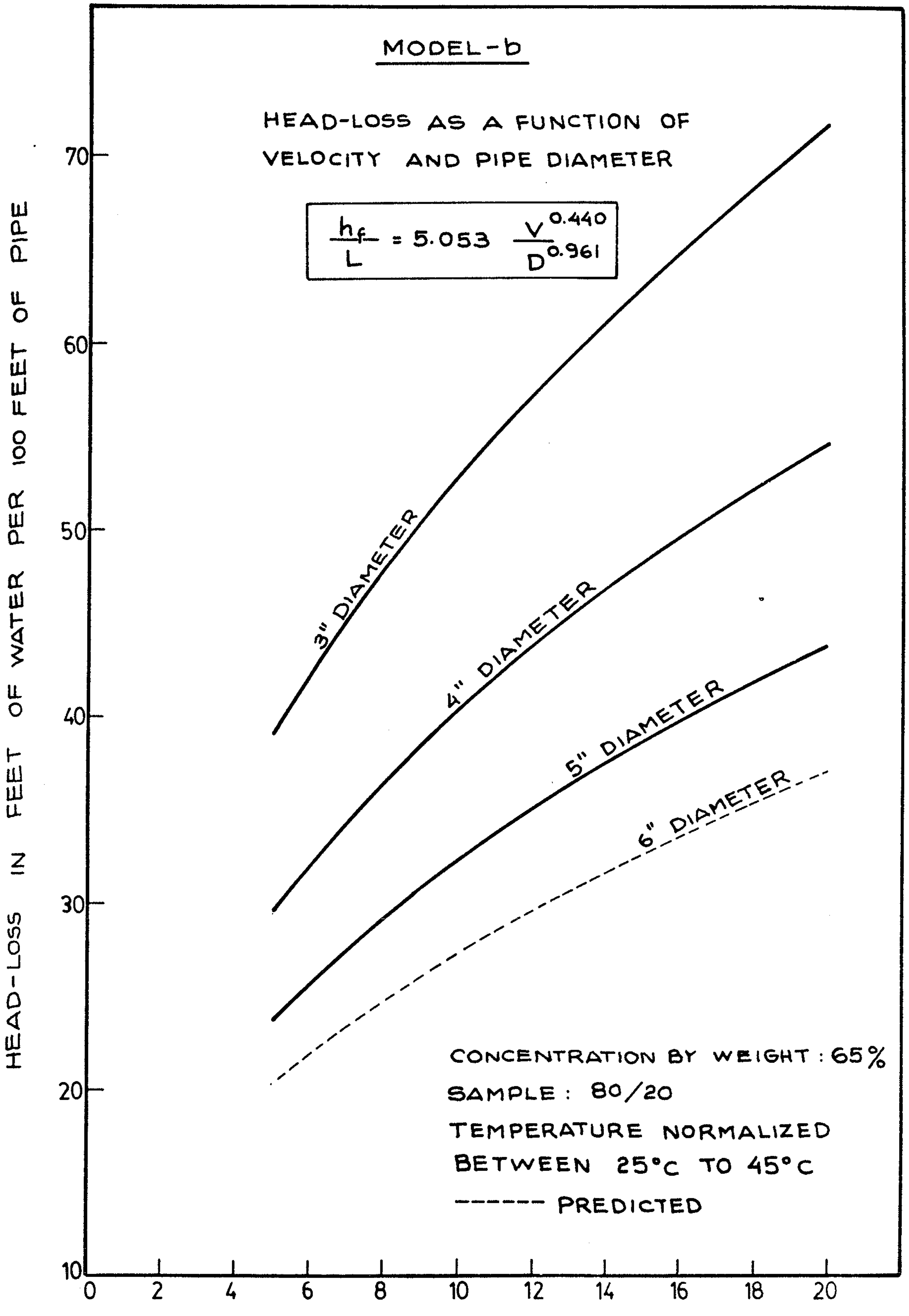

MODEL-b
HEAD-LOSS AS A FUNCTION OF VELOCITY AND PIPE DIAMETER
$\frac{h_f}{L} = 5.053 \frac{V^{0.440}}{D^{0.961}}$
3" DIAMETER
4" DIAMETER
5" DIAMETER
6" DIAMETER
CONCENTRATION BY WEIGHT : 65%
SAMPLE : 80/20
TEMPERATURE NORMALIZED BETWEEN 25°C TO 45°C
------ PREDICTED
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.

FIGURE VII.1

Figure VII.2 shows the curves for equation (3).

In models "a" and "b" temperature includes the range from 25°C to 45°C. The regression techniques have normalized this range to a value which tends toward 35°C. However, it was noted in the data discussion section that changes in temperature affected the head-loss variability. For that reason a three-variable model was built.

7.4.3 Presentation of Trivariate Model

The variables to be considered are: D (diameter), V (velocity) and T (Temperature).

Model-c

The 3 independent variable equation is:

$$\mathrm{Ln}\ (\frac{h_f}{L}) = \beta_o + \beta_1\ \mathrm{Ln}\ (D) + \beta_2\ \mathrm{Ln}\ (V) + \beta_3\ \mathrm{Ln}\ (T) + \epsilon_o$$

The 80/20 mix at Cw = 65% results in the multiple regression equation shown on Table VII.4.

The log equation is defined by

$$\mathrm{Ln}\ (\frac{h_f}{L}) = 1.051 - 0.967\ \mathrm{Ln}(D) + 0.428\ \mathrm{Ln}(V) + 0.166\ \mathrm{Ln}(T) \qquad (4)$$

or

$$\frac{h_f}{L} = 2.861\ \frac{V^{0.428}\ T^{0.166}}{D^{0.967}} \qquad (4')$$

For 55% concentration the statistical results are in Table VII.5.

A log equation is:

$$\mathrm{Ln}\ (\frac{h_f}{L}) = -1.549 - 0.817\ \mathrm{Ln}(D) + 1.018\ \mathrm{Ln}(V) + 0.366\ \mathrm{Ln}(T) \qquad (5)$$

or the exponential expression is:

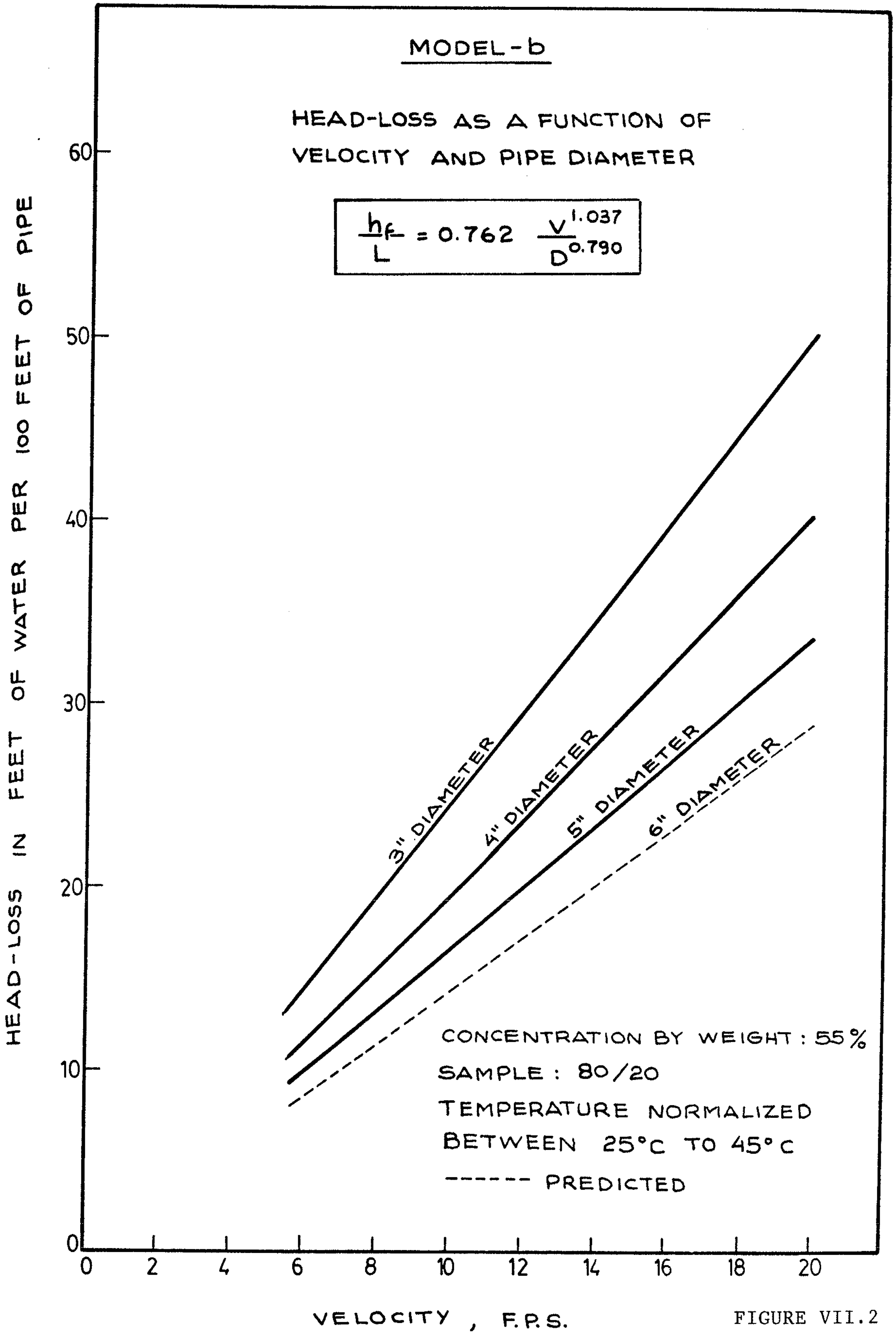

MODEL-b
HEAD-LOSS AS A FUNCTION OF VELOCITY AND PIPE DIAMETER
$\frac{h_f}{L} = 0.762 \frac{V^{1.037}}{D^{0.790}}$
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
VELOCITY, F.P.S.
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
3" DIAMETER
4" DIAMETER
5" DIAMETER
6" DIAMETER
CONCENTRATION BY WEIGHT : 55%
SAMPLE : 80/20
TEMPERATURE NORMALIZED BETWEEN 25°C TO 45°C
------ PREDICTED

FIGURE VII.2

$$\frac{h_f}{L} = 0.212 \frac{V^{1.018} T^{0.366}}{D^{0.817}} \qquad (5')$$

Curves in Figures VII.3, VII.4 and VII.5 represent the changes of head-loss explained by the three observed variables. Figure VII.6 shows a prediction of head-loss for a 6 inch pipeline based on equations (4) and (5).

Despite the lack of information for intermediate values of concentration an attempt to include concentration in the model was also considered.

7.4.4 Multivariate Model

Assuming that concentration effects might be an additional factor, affected by an exponent, the following model was proposed:

Model-d:

$$\mathrm{Ln}\left(\frac{h_f}{L}\right) = \beta_0 + \beta_1 \mathrm{Ln}(D) + \beta_2 \mathrm{Ln}(V) + \beta_3 \mathrm{Ln}(T) + \beta_4 \mathrm{Ln}(C) + \epsilon_0$$

The regression results for all data for the 80/20 mix are shown in Table VII.6. These data result in the following log equation:

$$\mathrm{Ln}\left(\frac{h_f}{L}\right) = -20.426 - 1.043 \mathrm{Ln}(D) + 0.643 \mathrm{Ln}(V) + 0.258 \mathrm{Ln}(T) + 4.944 \mathrm{Ln}(C) \qquad (6)$$

Figure VII.7 and VII.8 show the curves of Head-loss vs. velocity, based on Eq. (6), with concentration held at 65% and 55% respectively. The temperature is assumed to be 25°C in both cases. Curves and statistic results are compared and discussed in the next section.

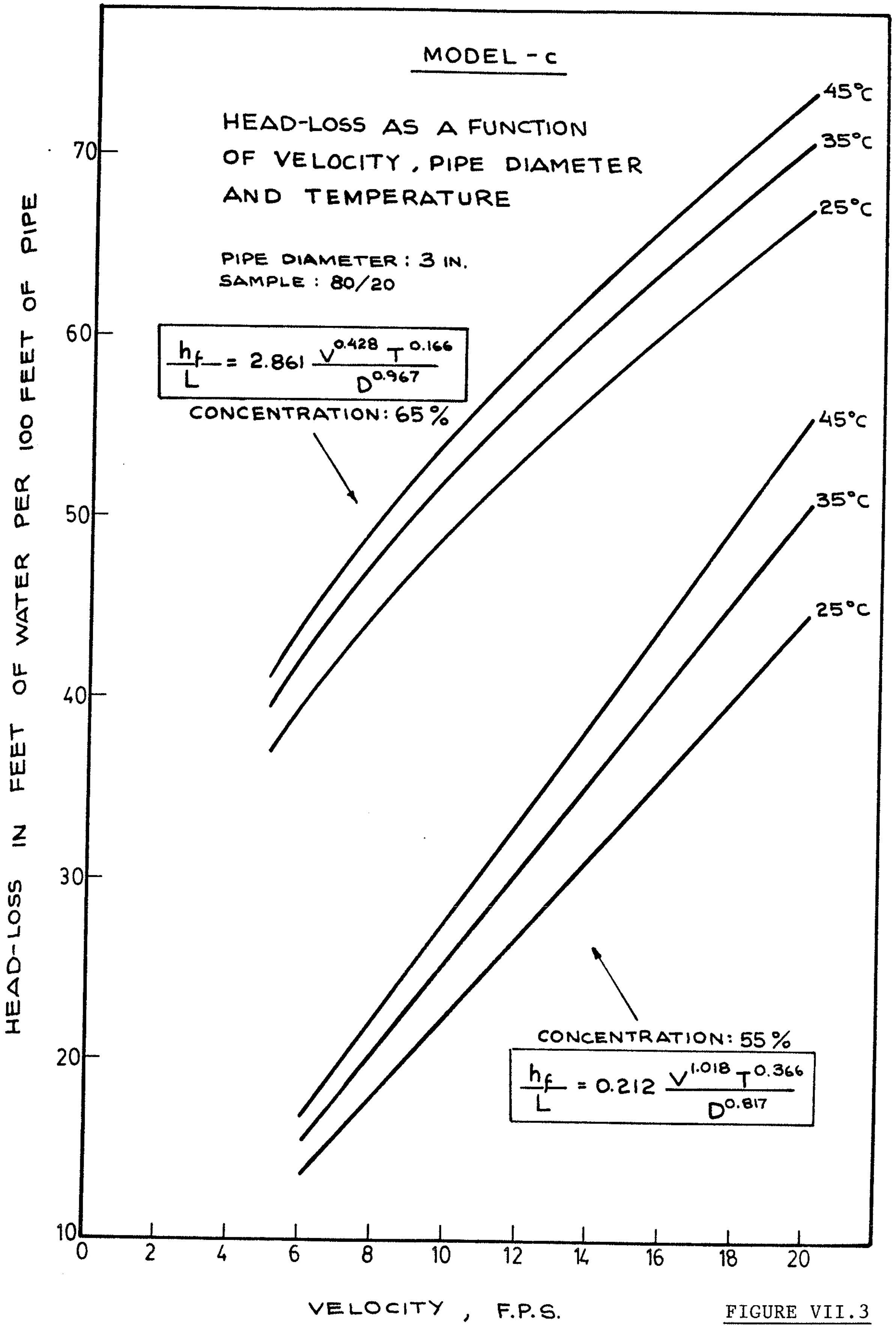

MODEL - c
HEAD-LOSS AS A FUNCTION OF VELOCITY, PIPE DIAMETER AND TEMPERATURE
PIPE DIAMETER : 3 IN.
SAMPLE : 80/20
$\frac{h_f}{L} = 2.861 \frac{V^{0.428} T^{0.166}}{D^{0.967}}$
CONCENTRATION: 65 %
$\frac{h_f}{L} = 0.212 \frac{V^{1.018} T^{0.366}}{D^{0.817}}$
CONCENTRATION: 55 %
45°C
35°C
25°C
45°C
35°C
25°C
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.

FIGURE VII.3

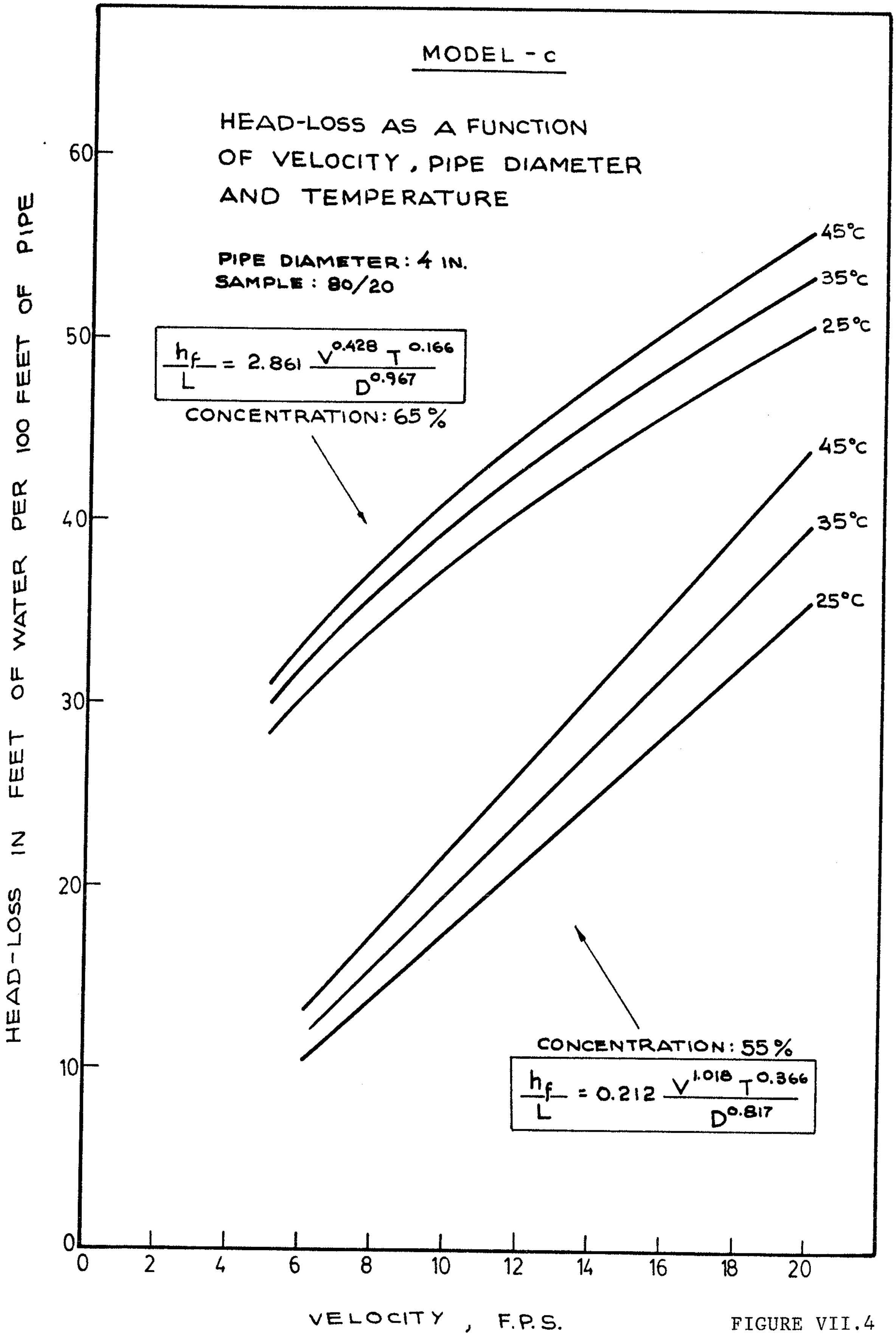

MODEL - c
HEAD-LOSS AS A FUNCTION OF VELOCITY, PIPE DIAMETER AND TEMPERATURE
PIPE DIAMETER: 4 IN.
SAMPLE: 80/20
$\frac{h_f}{L} = 2.861 \frac{V^{0.428} T^{0.166}}{D^{0.967}}$
CONCENTRATION: 65 %
45°C
35°C
25°C
45°C
35°C
25°C
CONCENTRATION: 55 %
$\frac{h_f}{L} = 0.212 \frac{V^{1.018} T^{0.366}}{D^{0.817}}$
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
VELOCITY, F.P.S.

FIGURE VII.4

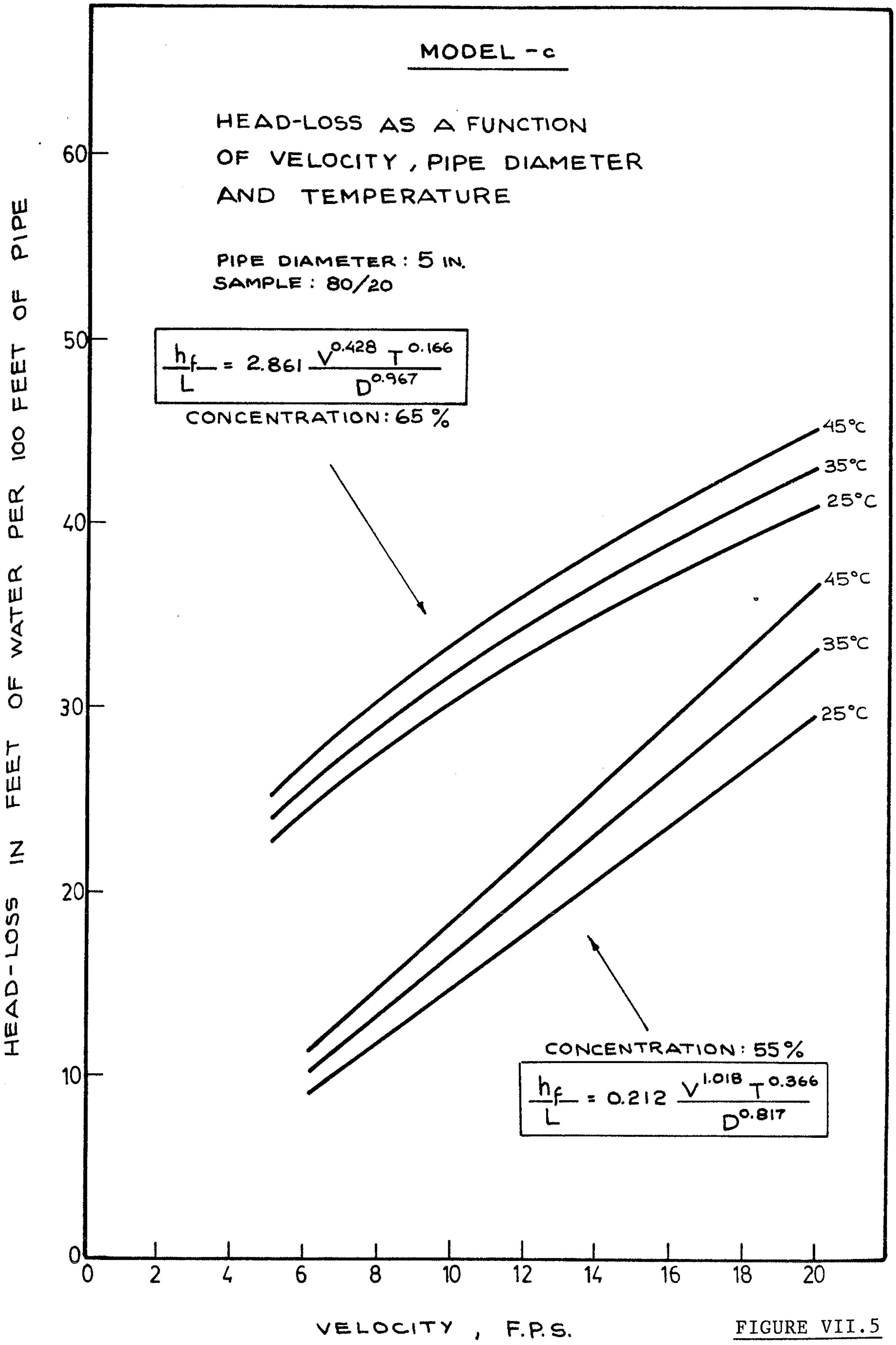

MODEL - c
HEAD-LOSS AS A FUNCTION OF VELOCITY, PIPE DIAMETER AND TEMPERATURE
PIPE DIAMETER : 5 IN.
SAMPLE : 80/20
$\frac{h_f}{L} = 2.861 \frac{V^{0.428} T^{0.166}}{D^{0.967}}$
CONCENTRATION : 65 %
45°C
35°C
25°C
45°C
35°C
25°C
CONCENTRATION : 55 %
$\frac{h_f}{L} = 0.212 \frac{V^{1.018} T^{0.366}}{D^{0.817}}$
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.

FIGURE VII.5

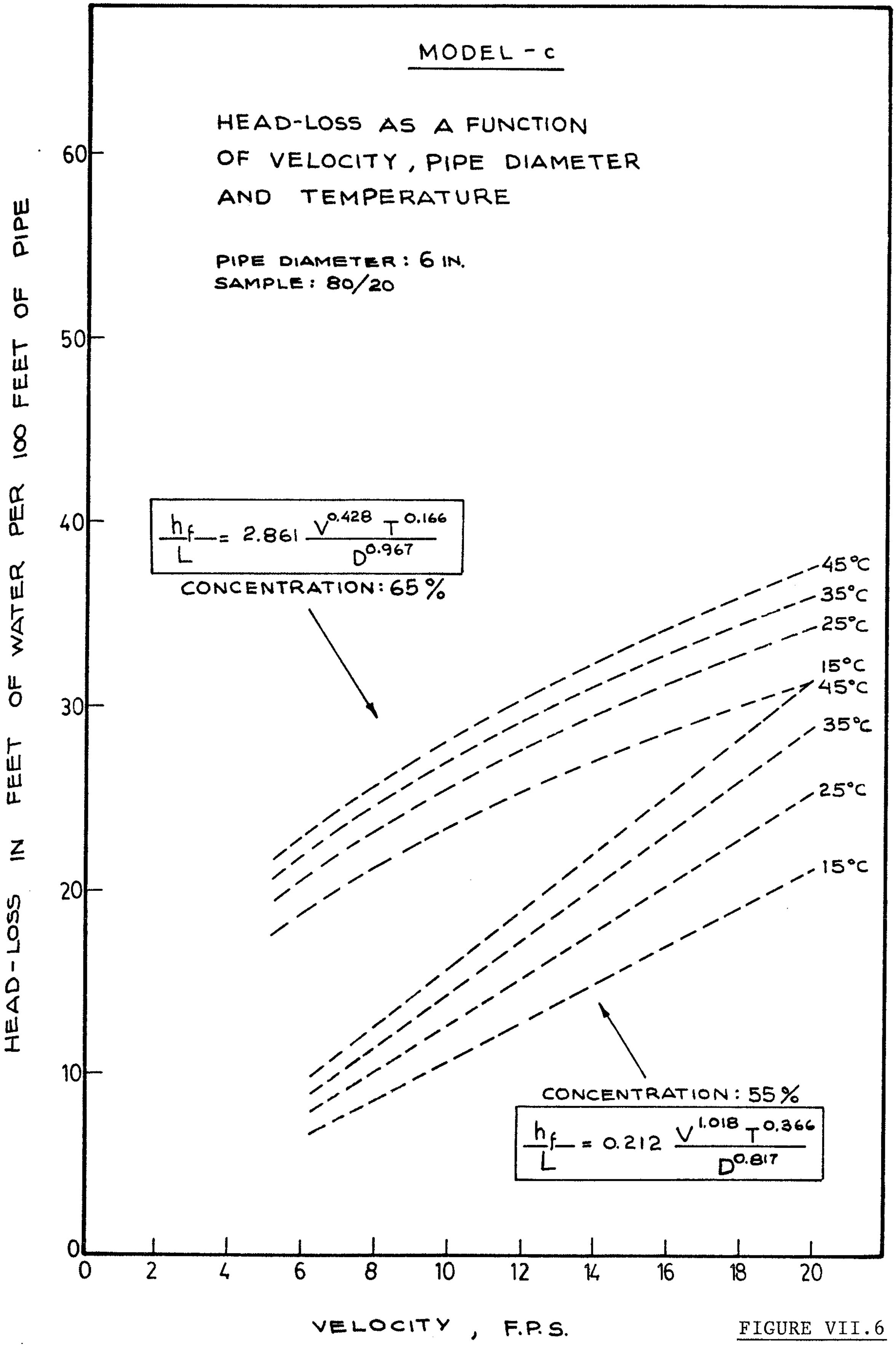

MODEL - c
HEAD-LOSS AS A FUNCTION OF VELOCITY, PIPE DIAMETER AND TEMPERATURE
PIPE DIAMETER: 6 IN.
SAMPLE: 80/20
$\frac{h_f}{L} = 2.861 \frac{V^{0.428}\ T^{0.166}}{D^{0.967}}$
CONCENTRATION: 65 %
CONCENTRATION: 55 %
$\frac{h_f}{L} = 0.212 \frac{V^{1.018}\ T^{0.366}}{D^{0.817}}$
45°C
35°C
25°C
15°C
45°C
35°C
25°C
15°C
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
VELOCITY, F.P.S.
0
2
4
6
8
10
12
14
16
18
20

FIGURE VII.6

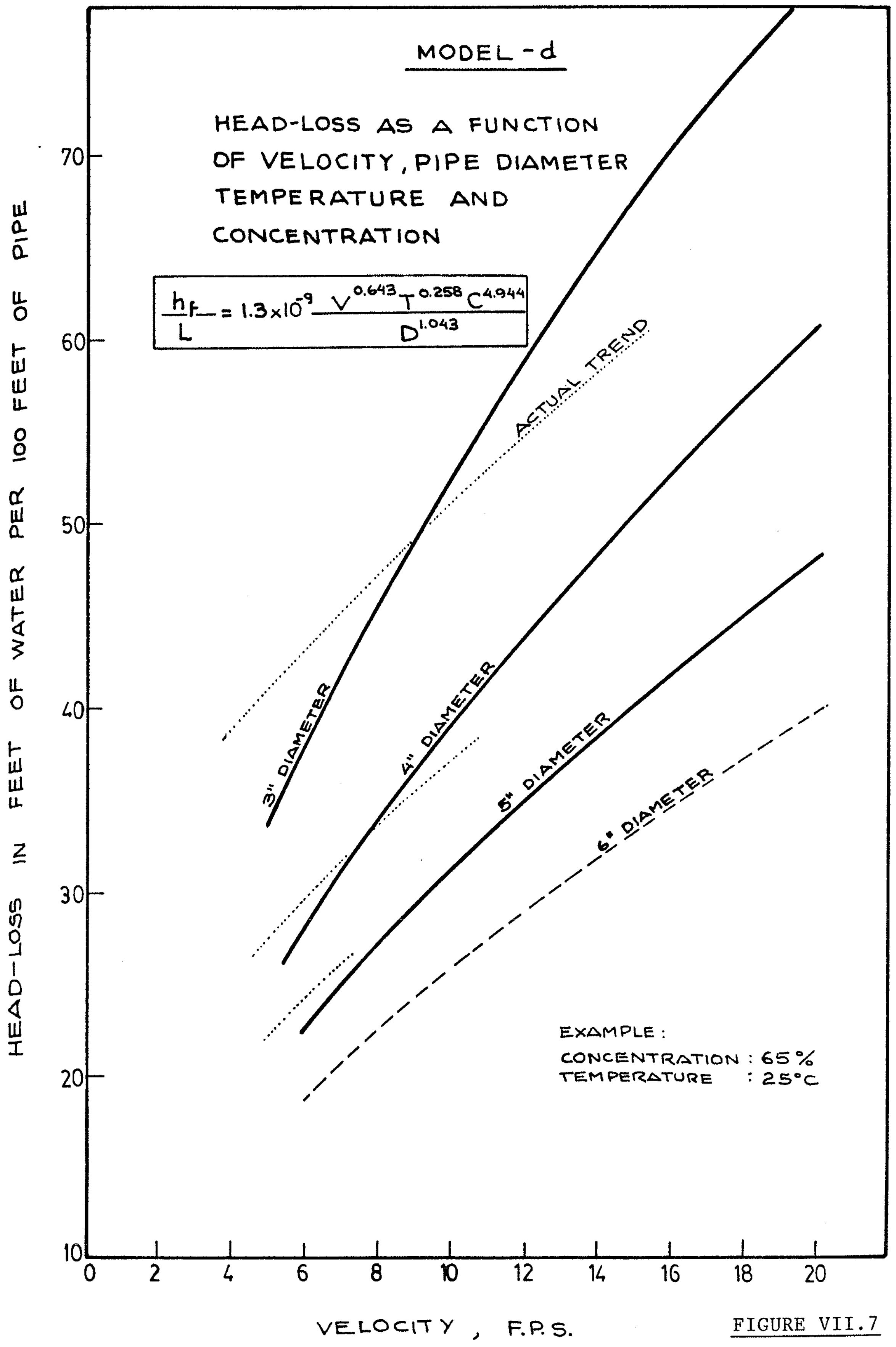

MODEL - d
HEAD-LOSS AS A FUNCTION OF VELOCITY, PIPE DIAMETER TEMPERATURE AND CONCENTRATION
$\frac{h_f}{L} = 1.3\times10^{-9}\frac{V^{0.643}T^{0.258}C^{4.944}}{D^{1.043}}$
ACTUAL TREND
3" DIAMETER
4" DIAMETER
5" DIAMETER
6" DIAMETER
EXAMPLE :
CONCENTRATION : 65 %
TEMPERATURE : 25°C
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
VELOCITY , F.P.S.
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20

FIGURE VII.7

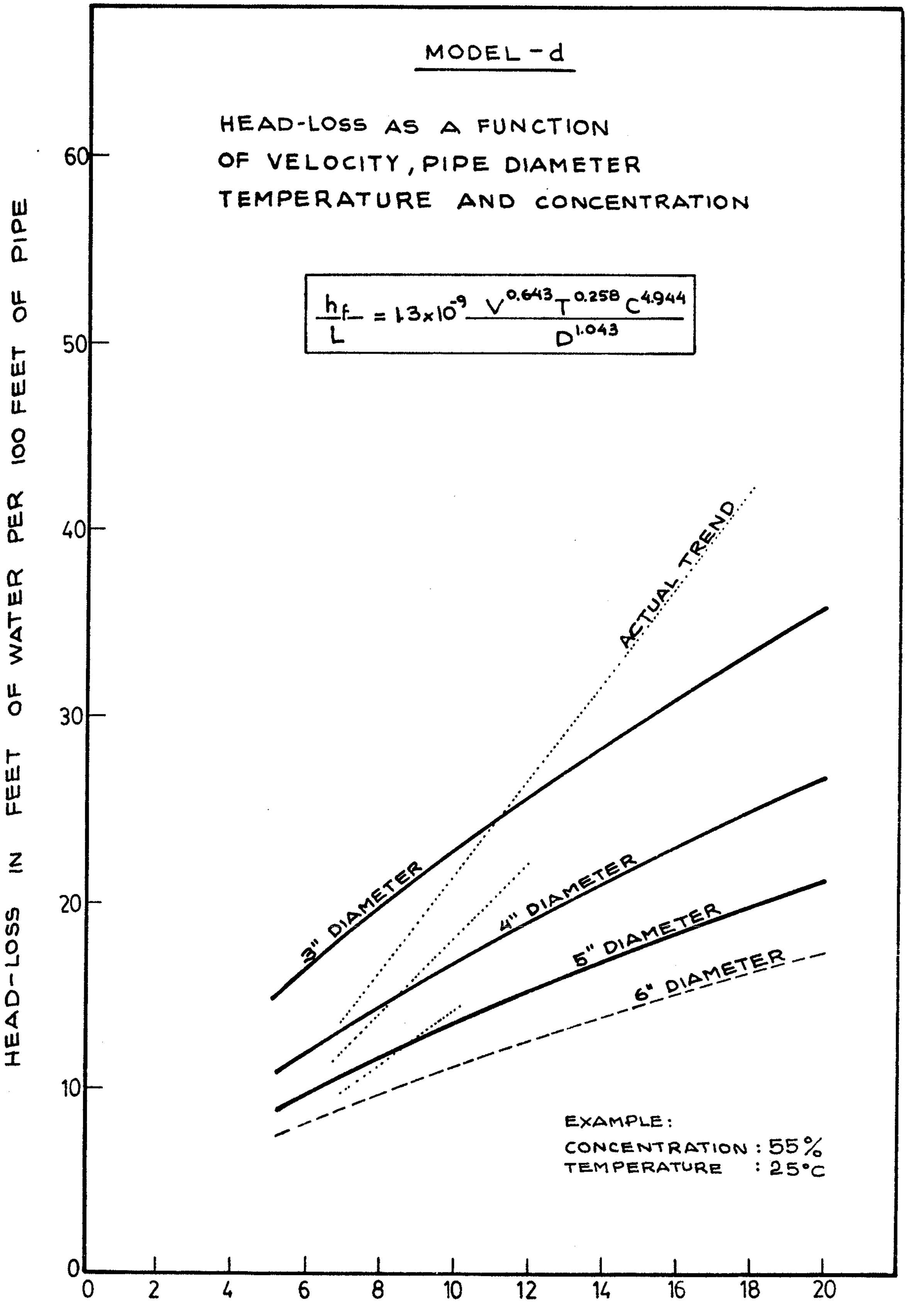

MODEL - d
HEAD-LOSS AS A FUNCTION OF VELOCITY, PIPE DIAMETER TEMPERATURE AND CONCENTRATION
$\frac{h_f}{L} = 1.3 \times 10^{-9} \frac{V^{0.643} T^{0.258} C^{4.944}}{D^{1.043}}$
ACTUAL TREND
3" DIAMETER
4" DIAMETER
5" DIAMETER
6" DIAMETER
EXAMPLE:
CONCENTRATION : 55%
TEMPERATURE : 25°C
HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.

FIGURE VII.8

7.4.5 Discussion of Models

Summary of Models

Model-a: $\frac{h_f}{L} = f\left[\frac{4}{Dgp}, \frac{8V}{D}\right]$

Cw = 65% Eq: $\frac{h_f}{L} = 2.138 \left(\frac{4}{Dgp}\right)^{0.523} \left(\frac{8V}{D}\right)^{0.441}$

Model-b: $\frac{h_f}{L} = f(D,V)$

Cw = 65% Eq: $\frac{h_f}{L} = 5.053 \frac{V^{0.44}}{D^{0.961}}$

Cw = 55% Eq: $\frac{h_f}{L} = 0.762 \frac{V^{1.037}}{D^{0.79}}$

Model-c: $\frac{h_f}{L} = f(D, V, T)$

Cw = 65% Eq. $\frac{h_f}{L} = 2.861 \frac{V^{0.428}\ T^{0.166}}{D^{0.967}}$

Cw = 55% Eq. $\frac{h_f}{L} = 0.212 \frac{V^{1.018}\ T^{0.366}}{D^{0.817}}$

Model-d: $\frac{h_f}{L} = f(D, V, T, C)$

Eq. $\frac{h_f}{L} = 1.3 \times 10^{-9} \frac{V^{0.643}\ T^{0.258}\ C^{4.944}}{D^{1.043}}$

On comparing the predicted curves for each model with the actual plotted data it appears that Model-d does not follow the trend of points. At a 65% concentration by weight the curve has been twisted giving higher values of head-loss at high velocities and lower values at low velocities. The reverse of this effect is presented at the 55% concentration. Despite the fact that concentration is highly significant for prediction of head-loss as shown in the statistical results (Table VII.6), with F value = 1663, the sequential sum of squares (Type I SS) does not present an incremental improvement in error. Additionally, the variance in the residual plot is not constant but increases with head-loss. It appears that Model-d needs extra linear terms. Therefore Model-d is inadequate.

Model-b and Model-c show a good correlation with actual data. The residuals are evenly scattered. Errors are random. Residuals in Model-c are reduced with less deviation from the zero line than Model-b. The total F-values are highly significant. The R-square is slightly higher in Model-c than Model-b. The effect of temperature considered in the models proved that within the range of variables used in the experiment, Model-c is the best predictive one. Curves and actual data have the same trend. Figures VII.9 and VII.10 show plotted points of total actual data for the 80/20 mix in which the two concentrations are compared. The points are represented by a number which indicate the diameter, in inches, of the pipe used. The concave-downwards shape at 65% concentration denotes plasticity while at 55% concentration the trend is almost linear passing through the origin. An imaginary extrapolation toward the Y-axis suggests the existence of a "yield value" in the mixture at 65% concentration by weight.

The multiple regression technique used in the model building has been applied only with head-loss as a dependant variable, therefore caution is to be taken with regard to algebraic solution for the rest of the variables.

TABLE VII.1

```
                                                 SAS                    13:19 SUNDAY, FEBRUARY 5, 1984 •  3

                                      GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: LHL

SOURCE                  DF        SUM OF SQUARES          MEAN SQUARE       F VALUE         PR > F      R-SQUARE          C.V.

MODEL                    2           10.41831733           5.20915866       1073.25         0.0001      0.961048        1.9423

ERROR                   87            0.42226634           0.00485364                     ROOT MSE                    LHL MEAN

CORRECTED TOTAL         89           10.84058367                                         0.06966804                 3.58687408

SOURCE                  DF             TYPE I SS    F VALUE    PR > F          DF          TYPE III SS    F VALUE    PR > F

LDIA                     1            8.11723468    1672.40    0.0001           1           0.43613390      89.86    0.0001
LRS                      1            2.30108265     474.09    0.0001           1           2.30108265     474.09    0.0001

                                      T FOR HO:     PR > |T|          STD ERROR OF
PARAMETER                ESTIMATE    PARAMETER=0                          ESTIMATE

INTERCEPT              2.13817258          11.66      0.0001            0.18334785
LDIA                   0.52306097           9.48      0.0001            0.05517928
LRS                    0.44067443          21.77      0.0001            0.02023883
```

$$\mathrm{LDIA} = \mathrm{Ln}\left(\frac{4}{Dg}\right)$$

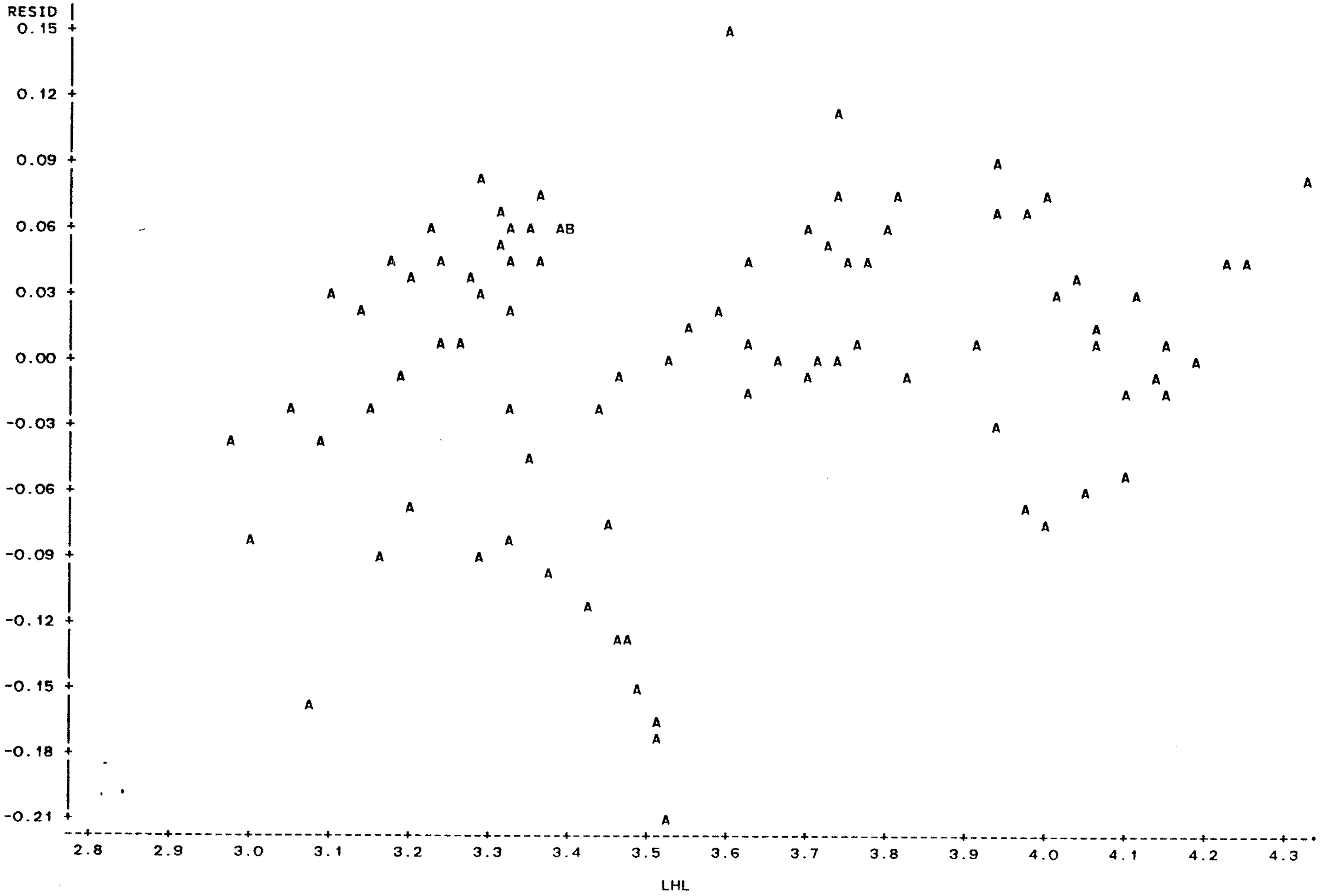
$$\mathrm{LRS} = \mathrm{LN}\left(\frac{8V}{D}\right)$$

Equation (1):

$$\mathrm{Ln}\left(\frac{hf}{L}\right) = 2.138 + 0.523\ \mathrm{Ln}\left(\frac{4}{Dg}\right) + 0.441\ \mathrm{Ln}\left(\frac{8V}{D}\right) + \in_o$$

SAS 13:19 SUNDAY, FEBRUARY 5, 1984 • 5

PLOT OF RESID*LHL LEGEND: A = 1 OBS, B = 2 OBS, ETC.



RESIDUALS FOR EQUATION (1)

TABLE VII.2

```
                                          SAS                        12:03.SATURDAY, FEBRUARY 18, 1984     3

                               GENERAL LINEAR MODELS PROCEDURE
DEPENDENT VARIABLE: LHL

SOURCE                  DF     SUM OF SQUARES        MEAN SQUARE      F VALUE        PR > F      R-SQUARE          C.V.

MODEL                    2        10.40531209         5.20265604      1062.79        0.0001      0.960679        1.9507

ERROR                   87         0.42588992         0.00489529                   ROOT MSE                    LHL MEAN

CORRECTED TOTAL         89        10.83120201                                     0.06996632                 3.58673622


SOURCE                  DF        TYPE I SS     F VALUE      PR > F        DF      TYPE III SS       F VALUE      PR > F

LDIA                     1       8.10285841     1655.24      0.0001         1       2.58096899        527.24      0.0001
LVEL                     1       2.30245367      470.34      0.0001         1       2.30245367        470.34      0.0001


                                       T FOR HO:      PR > |T|        STD ERROR OF
PARAMETER               ESTIMATE     PARAMETER=0                       ESTIMATE

INTERCEPT             1.61974898           37.16      0.0001           0.04359120
LDIA                 -0.96121127          -22.96      0.0001           0.04186167
LVEL                  0.44084252           21.69      0.0001           0.02032718
```

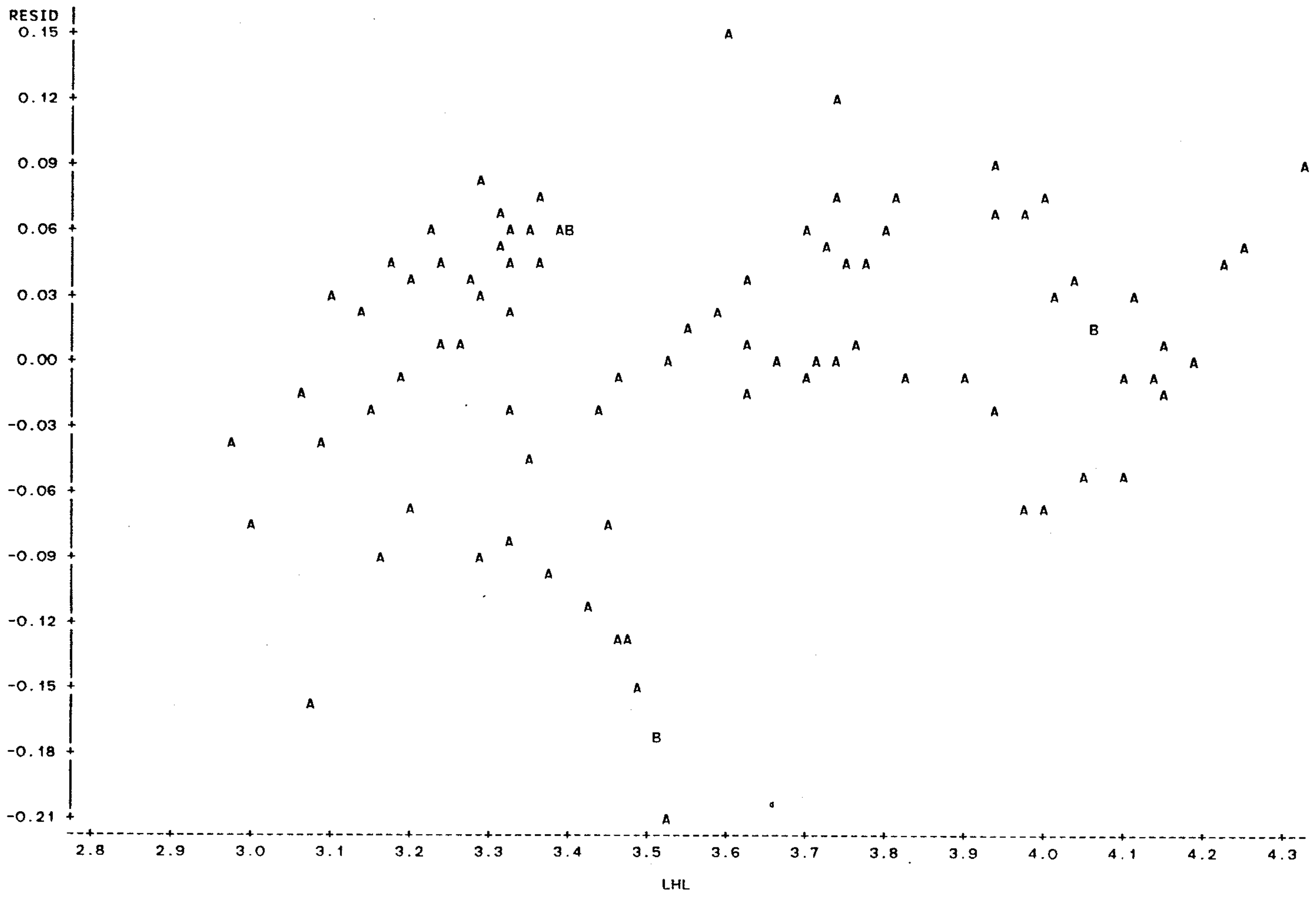
LDIA = Ln (D)

LVEL = Ln (V)

Equation (2)

$$\ln\left(\frac{hf}{L}\right) = 1.620 - 0.961 \ln(D) + 0.440 \ln(V) + \epsilon_o$$

```
                                SAS                  12:03.SATURDAY, FEBRUARY 18, 1984    4
              PLOT OF RESID*LHL    LEGEND: A = 1 OBS, B = 2 OBS, ETC.
```



RESIDUALS FOR EQUATION (2)

TABLE VII.3

```
                                              SAS                     11:43 SATURDAY, FEBRUARY 18, 1984    3

                                 GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: LHL

SOURCE              DF      SUM OF SQUARES         MEAN SQUARE      F VALUE        PR > F      R-SQUARE          C.V.

MODEL                2         26.92780991         13.46390496       904.13        0.0001      0.951085        4.2806

ERROR               93          1.38490768          0.01489148                   ROOT MSE                    LHL MEAN

CORRECTED TOTAL     95         28.31271760                                      0.12203065                2.85075429

SOURCE              DF             TYPE I SS     F VALUE     PR > F        DF      TYPE III SS       F VALUE      PR > F

LDIA                 1           20.57339398     1381.55     0.0001         1       1.08260552         72.70      0.0001
LVEL                 1            6.35441594      426.71     0.0001         1       6.35441594        426.71      0.0001

                                        T FOR HO:     PR > |T|           STD ERROR OF
PARAMETER                 ESTIMATE   PARAMETER=0                            ESTIMATE

INTERCEPT              -0.27216794         -3.63       0.0005              0.07487879
LDIA                   -0.79041164         -8.53       0.0001              0.09270158
LVEL                    1.03751084         20.66       0.0001              0.05022544
```

LDIA = Ln (D)

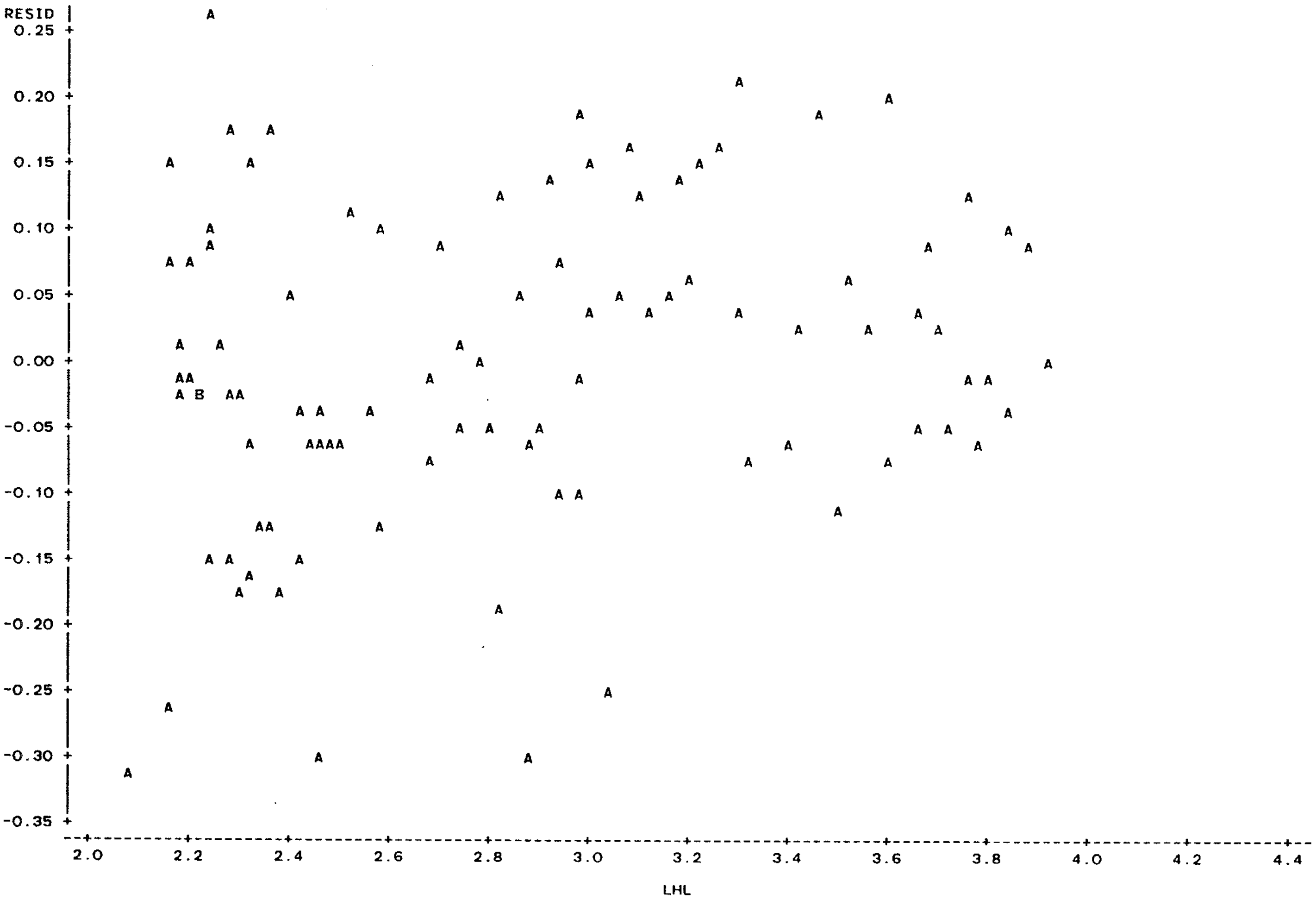
LVEL = Ln (V)

Equation (3):

$$\mathrm{Ln}\ \left(\frac{hf}{L}\right) = -0.272 - 0.790\ \mathrm{Ln}\ (D) + 1.037\ \mathrm{Ln}\ (V) + \epsilon_o$$

```
                                  SAS                   11:43 SATURDAY, FEBRUARY 18, 1984    4

             PLOT OF RESID*LHL    LEGEND: A = 1 OBS, B = 2 OBS, ETC.
```



RESIDUALS FOR EQUATION (3)

TABLE VII.4

```
                                                    SAS                          12:43.SATURDAY, FEBRUARY 18, 1984    3

                                         GENERAL LINEAR MODELS PROCEDURE
DEPENDENT VARIABLE: LHL

SOURCE                  DF      SUM OF SQUARES       MEAN SQUARE      F VALUE       PR > F        R-SQUARE           C.V.

MODEL                    3         10.54425968        3.51475323      1053.41       0.0001        0.973508         1.6105

ERROR                   86          0.28694232        0.00333654                  ROOT MSE                       LHL MEAN

CORRECTED TOTAL         89         10.83120201                                  0.05776278                     3.58673622

SOURCE                  DF           TYPE I SS     F VALUE     PR > F        DF      TYPE III SS     F VALUE     PR > F

LDIA                     1          8.10285841     2428.52     0.0001         1       2.61326391      783.23     0.0001
LVEL                     1          2.30245367      690.07     0.0001         1       2.15085671      644.64     0.0001
LTEM                     1          0.13894760       41.64     0.0001         1       0.13894760       41.64     0.0001

                                           T FOR HO:     PR > |T|         STD ERROR OF
PARAMETER                  ESTIMATE     PARAMETER=0                         ESTIMATE

INTERCEPT                1.05131722           11.05      0.0001           0.09515286
LDIA                    -0.96760344          -27.99      0.0001           0.03457434
LVEL                     0.42873649           25.39      0.0001           0.01688623
LTEM                     0.16581698            6.45      0.0001           0.02569517
```

L DIA = Ln (D)

L VEL = Ln (V)

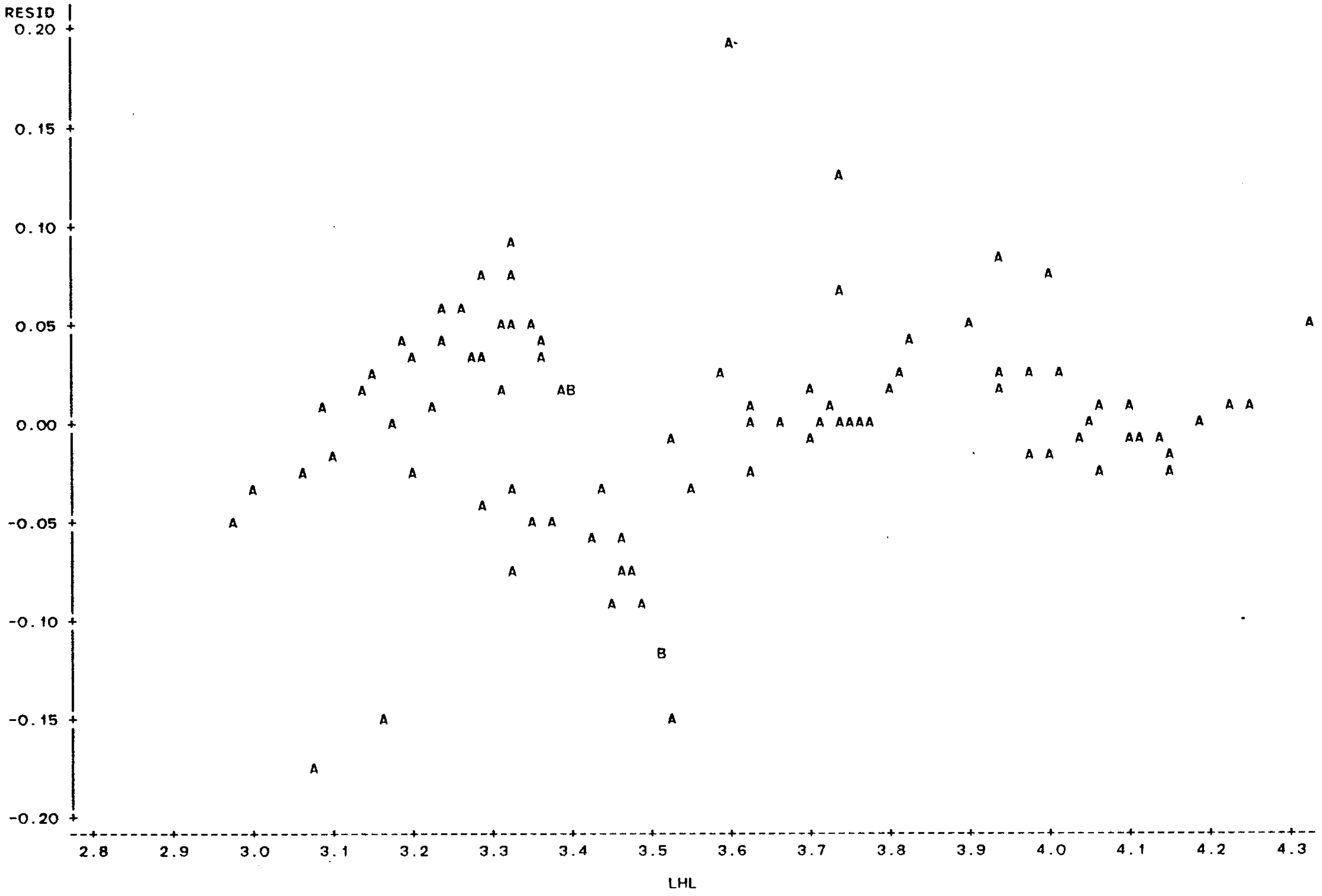
L TEM = Ln (T)

Equation (4)

$$\text{Ln}\left(\frac{hf}{L}\right) = 1.051 - 0.967\ \text{Ln}\ (D) + 0.428\ \text{Ln}\ (V) + 0.166\ \text{Ln}\ (T) + \epsilon_o$$

SAS 12:43.SATURDAY, FEBRUARY 18, 1984 4

PLOT OF RESID*LHL LEGEND: A = 1 OBS, B = 2 OBS, ETC.



RESIDUALS FOR EQUATION (4)

TABLE VII.5

```
                                                     SAS                             12:26 SATURDAY, FEBRUARY 18, 1984    3
                                       GENERAL LINEAR MODELS PROCEDURE
DEPENDENT VARIABLE: LHL
SOURCE                   DF         SUM OF SQUARES          MEAN SQUARE       F VALUE        PR > F        R-SQUARE           C.V.
MODEL                     3            27.65381451           9.21793817       1287.06        0.0001        0.976728         2.9686
ERROR                    92             0.65890309           0.00716199                    ROOT MSE                       LHL MEAN
CORRECTED TOTAL          95            28.31271760                                       0.08462854                     2.85075429

SOURCE                   DF              TYPE I SS      F VALUE      PR > F        DF       TYPE III SS       F VALUE        PR > F
LDIA                      1            20.57339398      2872.58      0.0001         1        1.15600846        161.41        0.0001
LVEL                      1             6.35441594       887.24      0.0001         1        6.09464966        850.97        0.0001
LTEM                      1             0.72600459       101.37      0.0001         1        0.72600459        101.37        0.0001

                                       T FOR HO:       PR > |T|          STD ERROR OF
PARAMETER                ESTIMATE    PARAMETER=0                           ESTIMATE
INTERCEPT             -1.54917570         -11.30         0.0001          0.13705407
LDIA                  -0.81748199         -12.70         0.0001          0.06434496
LVEL                   1.01770258          29.17         0.0001          0.03488698
LTEM                   0.36670941          10.07         0.0001          0.03642246
```

L DIA = Ln (D)

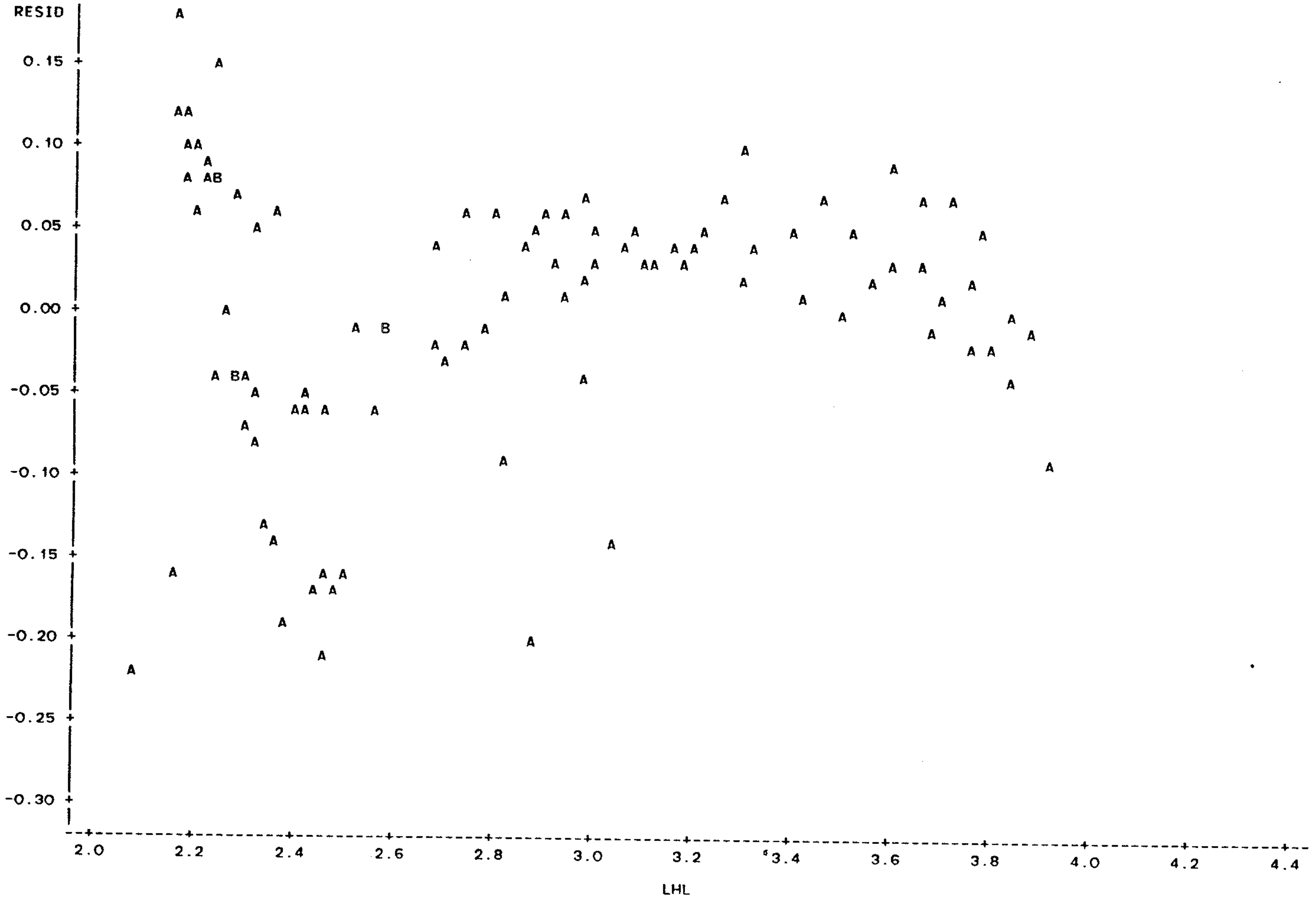
L VEL = Ln (V)

L TEM = Ln (T)

Equation (5)

$$\mathrm{Ln}\ \left(\frac{hf}{L}\right) = -\ 1.549 - 0.817\ \mathrm{Ln}\ (D) + 1.018\ \mathrm{Ln}\ (V) + 0.366\ \mathrm{Ln}\ (T) + \epsilon_o$$

```
                                   SAS                    12:26 SATURDAY, FEBRUARY 18, 1984    4
                    PLOT OF RESID*LHL     LEGEND: A = 1 OBS, B = 2 OBS, ETC.
```



RESIDUALS FOR EQUATION (5)

```
                                              SAS                   11:35 MONDAY, FEBRUARY 6, 1984 •  7

                                       GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: LHL

SOURCE                 DF      SUM OF SQUARES        MEAN SQUARE      F VALUE        PR > F      R-SQUARE          C.V.

MODEL                   4         61.07014849        15.26753712       854.18        0.0001      0.949690        4.1690

ERROR                 181          3.23518832         0.01787397                   ROOT MSE                    LHL MEAN

CORRECTED TOTAL       185         64.30533681                                    0.13369356                  3.20687458


SOURCE                 DF         TYPE I SS    F VALUE      PR > F        DF       TYPE III SS    F VALUE      PR > F

LDIA                    1       27.84227325    1557.70      0.0001         1        5.11220709     286.01      0.0001
LVEL                    1        2.25506736     126.16      0.0001         1        7.36864775     412.26      0.0001
LTEM                    1        1.24570499      69.69      0.0001         1        0.69776754      39.04      0.0001
LCON                    1       29.72710289    1663.15      0.0001         1       29.72710289    1663.15      0.0001


                                      T FOR HO:     PR > |T|          STD ERROR OF
PARAMETER              ESTIMATE     PARAMETER=0                         ESTIMATE

INTERCEPT          -20.42654960          -39.55       0.0001            0.51652755
LDIA                -1.04333088          -16.91       0.0001            0.06169193
LVEL                 0.64320068           20.30       0.0001            0.03167839
LTEM                 0.25826952            6.25       0.0001            0.04133598
LCON                 4.94365473           40.78       0.0001            0.12122225
```

L DIA = Ln (D)

Equation (6)

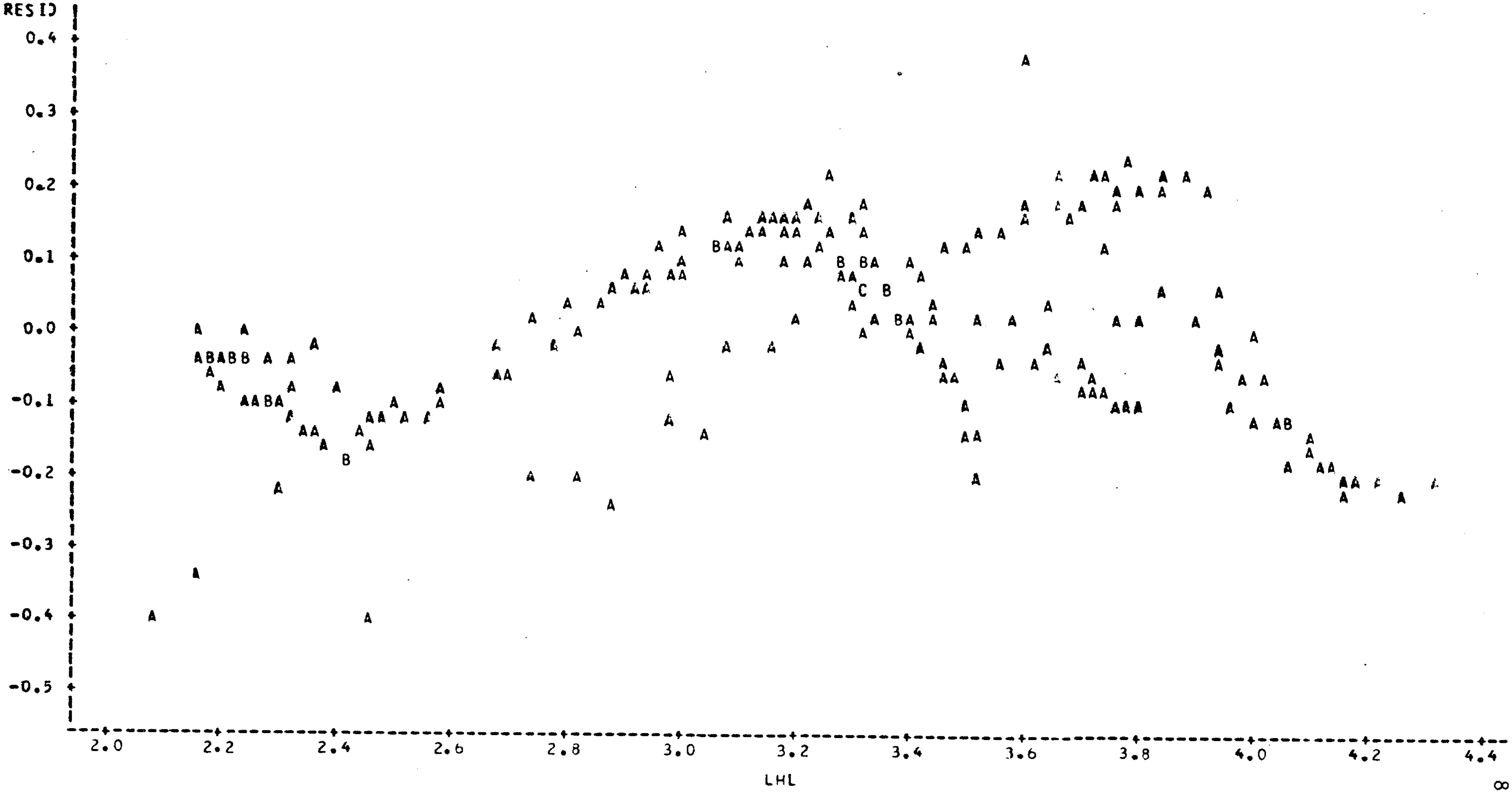
L VEL = Ln (V)

L TEM = Ln (T)

$$\mathrm{Ln}\left(\frac{h_f}{L}\right) = -20.426 - 1.043\ \mathrm{Ln}(D) + 0.643\ \mathrm{Ln}(V) + 0.258\ \mathrm{Ln}(T) + 4.944\ \mathrm{Ln}(C) + \epsilon_o$$

L CON = Ln (C)

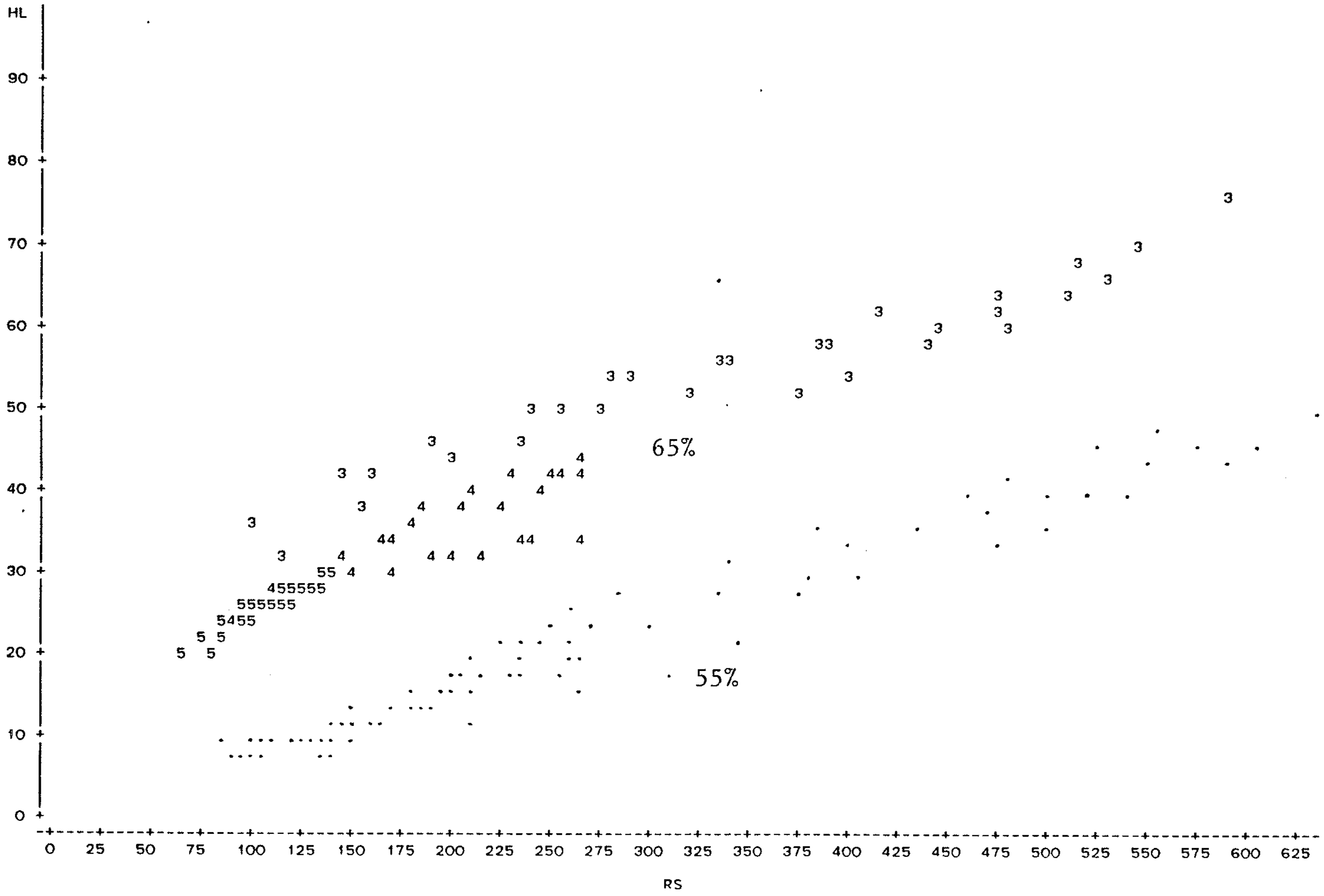
```
                              SAS                          21:10 MONDAY, FEBRUARY 6, 1984    8
          PLOT OF RESID*LHL    LEGEND: A = 1 OBS, B = 2 OBS, ETC.
```



RESIDUALS FOR EQUATION (6)

```
                         SAS                    11:35 MONDAY, FEBRUARY 6, 1984   2

             PLOT OF HL*RS    SYMBOL IS VALUE OF Z
```



```
NOTE:      35 OBS HIDDEN
```

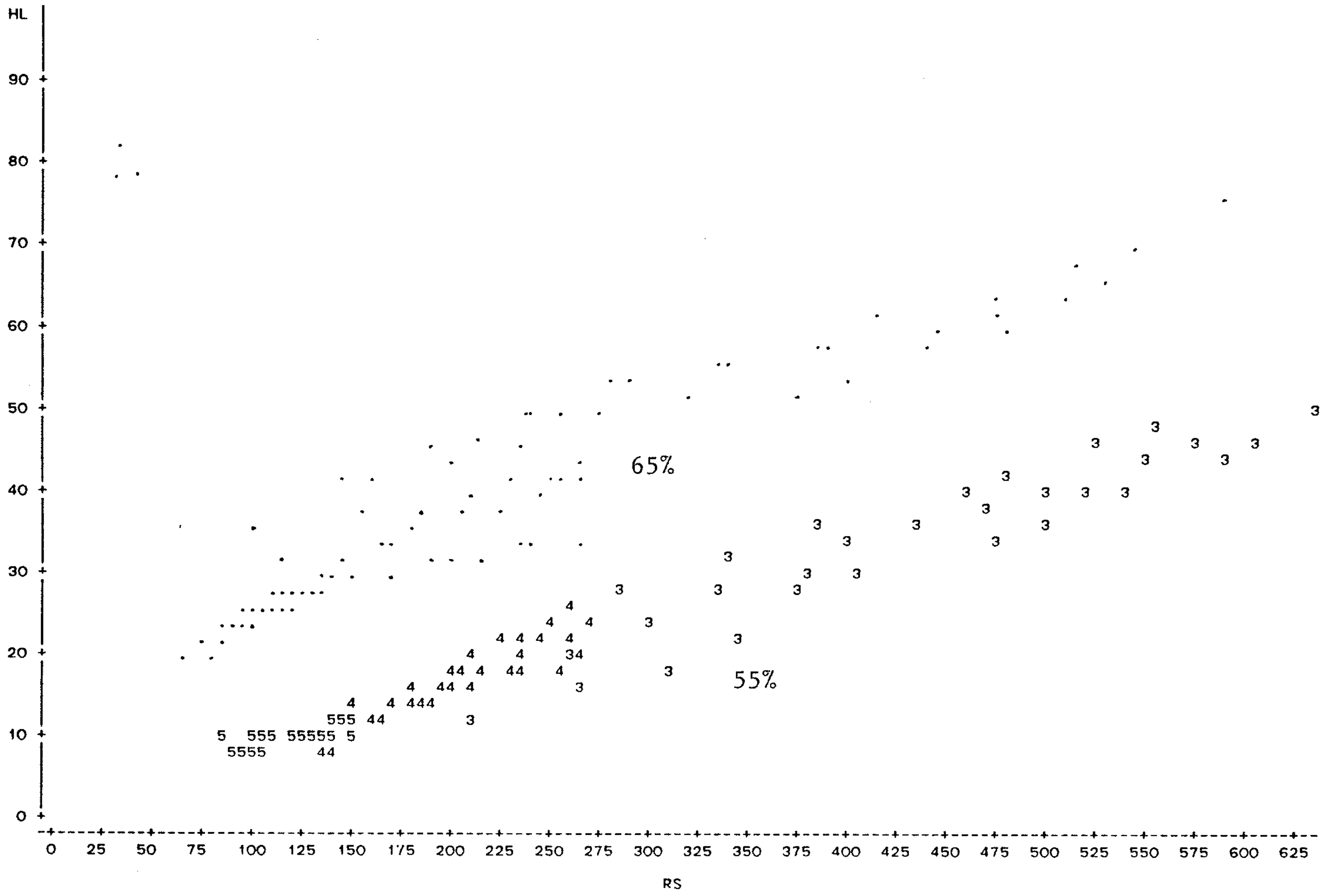
Head-Loss vs. Rate of Shear

for 80/20 Mix at 65% Concentration

Figure VII.9

SAS 11:35 MONDAY, FEBRUARY 6, 1984 1

PLOT OF HL*RS SYMBOL IS VALUE OF Y



NOTE: 35 OBS HIDDEN

Head-Loss vs. Rate of Shear

Figure VII.10

for 80/20 Mix at 55% Concentration

CHAPTER VIII

CONCLUSIONS & RECOMMENDATIONS

8.1 CONCLUSIONS

- The solid-liquid mixture at 65% concentration by weight exhibits a yield-pseudoplastic behavior when velocity varies from 4 to 20 F.P.S.
- The mixture at 55% concentration of solids behaves like a pseudoplastic or nearly-Newtonian fluid.
- Plasticity of the mixture, hence the head-loss gradient, is affected by the electrokinetic potential (zeta-potential) between the solid surface and the free liquid.
- The zeta-potential effect does not alter the mixture behavior at low concentrations ($C_w < 55\%$).
- The apparent viscosity of the suspension tends toward a constant value at high rate of shear (350 sec^{-1}) regardless of the concentration of solids tested and the zeta potential effect.
- The deposition velocity has been found at about 4.0 F.P.S. in the 65% mixture and 5.0 F.P.S. in the 55% mixture in the slurry facility. Values even lower than those were observed after the fines dispersion due to changes in zeta-potential. Mine values may be higher.
- Head-loss gradient varies proportionally with concentration of solids. This effect is more noticeable in small pipes where the particle size becomes significant.
- Head-loss is directly proportional to temperature-rise, being more remarkable in small pipes. With increasing temperature

the Brownian motion and particles colision increase. In small diameter pipes fall velocity phenomenon dominates concentration gradient.

- Once fines are completely dispersed, an increase in zeta potential no longer increases head-loss. Once the limit is reached head-loss varies inversely with temperature.
- Pipe diameter has an inverse relationship with Head-loss gradient.
- The statistical trivariate model (Model-C) in which Head-loss is explained by pipe diameter, velocity and temperature is the best predictive model based on the range of variables used in the experiment.

8.2 RECOMMENDATIONS

8.2.1 Research Apparatus

1. Circuit modifications and lay-out improvements are recommended. Inclined pipes, longer test sections, elimination of "queuing" phenomenon near the test section, an increase in pumping capacity and the use of a timer to record pump operation are specifically recommended.
2. Calibration and recalilbration of the facilities including measurement devices must be a constant task.

8.2.2 Slurries

1. Studies of particle degradation and particle size distribution should be analyzed for future experiments.
2. Deposition velocities and bed formation may be examined

for slurries with different concentration of solids.

3. Runs at low temperatures (e.g. 10-15°C) should be undertaken to verify the effects on Head-loss gradient found in this work.

4. The abrasive action of solid-liquid mixture exerted on pipes and bends should also be studied.

5. The time-dependancy of the mixture found in this work has proved that for a new slurry the rheological behavior has to be examined before any transportation test.

6. Slurries with different concentration of solids should be studied to find the optimal composition of the mixture.

7. Since measurements of the zeta-potential (electro-kinetic potential) are normally difficult to evaluate maximum and minimum values should be studied (zeta-potential is very sensitive to concentrations and valence of the ions in solution).

8. The stability of particles based on zeta-potential suggests an examination of the time required for development of an adverse zeta potential be determined.

9. The use of an appropriate flocculant to avoid fine particle dispersion should be considered.

10. The zeta-potential value is found to respond to the pH value of water, mainly in flotation and magnetic separations (Metallurgical process), therefore water quality is another item suggested for further studies. The use of an ion exchange water softener might be considered.

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APPENDIX - A

CALCULATED DATA

* Bed formation

3" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:APRIL 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	16.22	0.79	39.71	519.32	.01076	.00298359393	.02428511676
2	15.45	0.75	37.75	494.59	.01023	.00297846701	.02544873347
3	14.29	0.70	33.83	457.49	.00916	.00288321056	.02663658369
4	13.52	0.66	31.38	432.76	.00850	.00282835752	.02761296545
5	13.13	0.64	28.93	420.40	.00784	.00268544244	.02700437421
6	11.59	0.56	25.49	370.94	.00691	.00268248234	.03054630491
7	10.43	0.51	21.57	333.84	.00584	.00251905104	.03197804925
8	10.04	0.49	18.14	321.48	.00492	.00220380739	.02898312328
9	9.27	0.45	15.20	296.75	.00411	.00199440607	.02840075338
10	8.11	0.39	11.27	259.66	.00305	.00169144266	.02753630335
11	7.34	0.36	8.33	234.93	.00226	.00138526370	.02490943210
12	6.95	0.34	5.88	222.56	.00159	.00102875629	.01954677097

3" PIPE　CONCENTRATION:55%　TEMPERATURE:30 C

SAMPLE:TAIL 90% SLAG 10%　SPECIFIC GRAV:1.58　DATE:APRIL 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	14.68	0.72	40.70	469.86	.01102	.00337734644	.03036525904
2	14.29	0.70	39.22	457.49	.01063	.00334590920	.03091123195
3	13.91	0.68	37.26	445.13	.01009	.00326412509	.03096595036
4	13.52	0.66	35.30	432.76	.00956	.00318107034	.03105646467
5	12.75	0.62	33.34	408.03	.00903	.00318682450	.03298487843
6	12.36	0.60	30.89	395.67	.00837	.00304617484	.03253389221
7	11.59	0.56	28.44	370.94	.00770	.00298916267	.03403857421
8	11.20	0.55	26.47	358.57	.00717	.00287943777	.03394146763
9	10.81	0.53	24.02	346.21	.00651	.00270772075	.03308098410
10	10.04	0.49	20.10	321.48	.00545	.00244120941	.03210528900
11	9.27	0.45	16.67	296.75	.00452	.00219336142	.03123391856
12	8.50	0.41	13.23	272.02	.00359	.00190044850	.02950557647
13	7.34	0.36	9.80	234.93	.00266	.00163044311	.02931916114
14	6.56	0.32	6.37	210.20	.00173	.00118515699	.02387184200

3" PIPE CONCENTRATION:55% TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:APRIL 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	16.22	0.79	49.03	519.32	.01328	.00368235385	.02997394336
2	15.45	0.75	45.11	494.59	.01222	.00355785600	.03039917135
3	14.68	0.72	42.17	469.86	.01142	.00349993615	.03146744630
4	14.29	0.70	39.22	457.49	.01063	.00334590920	.03091123195
5	13.52	0.66	36.28	432.76	.00983	.00327091228	.03193358240
6	13.13	0.64	33.34	420.40	.00903	.00309305423	.03110325244
7	12.36	0.60	30.40	395.67	.00823	.00299522329	.03198971720
8	11.20	0.55	26.47	358.57	.00717	.00287943777	.03394146763
9	10.43	0.51	23.04	333.84	.00624	.00269153879	.03406147728
10	9.66	0.47	19.12	309.12	.00518	.00241304348	.03256271792
11	8.88	0.43	15.20	284.39	.00412	.00208614930	.03102550016
12	8.11	0.39	12.25	259.66	.00332	.00184117692	.02997394336
13	7.34	0.36	9.80	234.93	.00266	.00163044311	.02931818114
14	6.56	0.32	7.35	210.20	.00199	.00136327307	.02748951768
15	5.40	0.26	5.39	173.10	.00146	.00121455806	.02973122771
16	4.25	0.20	4.41	136.01	.00119	.00125990736	.03912160000

3" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:OCTOB 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	20.49	1.00	59.82	655.68	.01621	.00356002928	.02292696696
2	18.06	0.88	51.48	577.92	.01395	.00347591362	.02539722244
3	16.87	0.82	48.54	539.84	.01315	.00350770599	.02743740834
4	15.24	0.74	45.11	487.68	.01222	.00360826772	.03124271585
5	12.72	0.62	40.70	407.04	.01102	.00389858491	.04044407238
6	10.95	0.53	40.20	350.40	.01089	.00447534247	.05393207731
7	7.58	0.37	38.24	242.56	.01036	.00615039578	.10707025949
8	7.26	0.35	36.28	232.32	.00983	.00609297521	.11074593228
9	5.23	0.25	35.79	167.36	.00969	.00832747610	.21036229796
10	4.93	0.24	34.81	157.76	.00943	.00860750507	.23039092117
11	3.86	0.18	34.81	123.52	.00943	.01099352332	.37582406910

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3" PIPE                          CONCENTRATION:55%                 TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10%         SPECIFIC GRAV:1.58                DATE:OCT08 83

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              VELOCITY  DISCHARGE  HEAD LOSS  RATE OF SH  SHEAR STR.   APP.VISC.  FRIC.FACTOR

NO.           (FT/SEC)      (CFS)  FT/100 FT       1/SEC       (PSI)  LB.SEC/FT2

-----------------------------------------------------------------------------------------

1                20.56       1.00      62.27      657.92      .01687 .00369236381 .02369825504

2                19.64       0.96      59.82      628.48      .01621 .00371410387 .02495442429

3                18.83       0.92      58.84      602.56      .01594 .00380934679 .02669532325

4                16.98       0.83      54.43      543.36      .01475 .00390901060 .03037834818

5                14.66       0.71      50.99      469.12      .01382 .00424215553 .03818454407

6                13.11       0.64      47.56      419.52      .01288 .00442105263 .04449979258

7                11.31       0.55      44.62      361.92      .01209 .00481034483 .05612399768

8                 8.84       0.43      41.68      282.88      .01129 .00574717195 .09579004960

9                 5.96       0.29      42.66      190.72      .01155 .00872063758 .19307985845

10                5.84       0.28      40.20      186.68      .01189 .00916181507 .20701598302

11                5.80       0.28      39.22      185.60      .01063 .00824741379 .19763972354

12 *              2.83       0.13      35.79       90.69      .00959 .01538604006 .71845308344
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3" PIPE                     CONCENTRATION:55%                  TEMPERATURE:45 C

SAMPLE:TAIL 90% SLAG 10%    SPECIFIC GRAV:1.58                 DATE:OCTOB 83

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           VELOCITY   DISCHARGE   HEAD LOSS  RATE OF SH  SHEAR STR.   APP.VISC.  FRIC.FACTOR

NO.        (FT/SEC)       (CFS)   FT/100 FT      1/SEC       (PSI)  LB.SEC/FT2

-----------------------------------------------------------------------------------------

1             21.20        1.04       62.76     678.40      .01700 .00360849057 .02246077341

2             20.87        1.02       61.78     667.84      .01674 .00360948730 .02282222920

3             19.45        0.95       57.86     622.40      .01567 .00362544987 .02459672537

4             17.78        0.87       53.94     568.96      .01461 .00369769404 .02744316581

5             16.74        0.82       51.97     535.68      .01408 .00378494624 .02983590767

6             15.16        0.74       50.50     485.12      .01368 .00406068602 .03534558726

7             13.59        0.66       49.03     434.88      .01328 .00439735099 .04269791503

8             12.92        0.63       48.54     413.44      .01315 .00458010836 .04677870906

9             11.75        0.57       48.05     376.00      .01302 .00498638298 .05599932060

10             9.93        0.48       46.09     317.76      .01249 .00566012095 .07521621035

11             8.28        0.40       43.64     264.96      .01182 .00642391304 .10237745047

12             6.94        0.34       41.68     222.08      .01129 .00732660519 .13919463869

13             4.93        0.24       37.75     157.76      .01023 .00933772819 .24993629034

14             3.99        0.19       36.77     127.68      .00996 .01123308271 .37150191268

15 *           2.83        0.13       29.42      90.56      .00797 .01267314488 .59092580754
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3" PIPE                          CONCENTRATION:65%              TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10%         SPECIFIC GRAV:1.77             DATE:SEPT  83
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              VELOCITY   DISCHARGE   HEAD LOSS  RATE OF SH  SHEAR STR.    APP.VISC.  FRIC.FACTOR

NO.           (FT/SEC)       (CFS)   FT/100 FT       1/SEC       (PSI)  LB.SEC/FT2
----------------------------------------------------------------------------------------

1                18.00        0.88       71.59      576.00      .01939 .00484750000 .03553696265

2                16.74        0.82       71.10      535.68      .01926 .00517741935 .04081247029

3                15.05        0.73       69.63      481.60      .01886 .00563920266 .04944429576

4                12.74        0.62       66.68      407.68      .01807 .00638265306 .06610994618

5                11.19        0.54       63.74      358.08      .01727 .00694504021 .08189920226

6                10.39        0.51       64.72      332.48      .01754 .00759672762 .09648193412

7                10.08        0.49       63.25      322.56      .01714 .00765178571 .10016990465

8                 8.86        0.43       62.76      283.52      .01700 .00863431151 .12859645145

9                 7.15        0.35       60.80      228.80      .01647 .01036573427 .19130619003

10                6.81        0.33       59.82      217.92      .01621 .01071145374  .2075564806

11                6.72        0.32       59.82      215.04      .01621 .01085491071 .21315325831

12                4.01        0.19       55.90      128.32      .01614 .01811221945 .59602200235

13 *              3.50        0.17       53.94      112.00      .01461 .01878428571 .70820931429
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3" PIPE CONCENTRATION:65% TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.77 DATE:SEPT 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	17.64	0.86	78.45	564.49	.02125	.00542091837	.04055172003
2	16.87	0.82	76.49	539.84	.02072	.00552697095	.04323217575
3	14.29	0.70	73.06	457.28	.01979	.00623198041	.05754781564
4	12.86	0.63	72.08	411.52	.01953	.00683398134	.07012418279
5	11.03	0.54	69.63	352.96	.01886	.00769446953	.09205304745
6	9.08	0.44	67.67	290.56	.01833	.00908425110	.13201955916
7	8.12	0.39	66.68	259.84	.01807	.01001416256	.16273973374
8	7.02	0.34	66.19	224.64	.01793	.01149358974	.21604965260
9	6.68	0.32	65.70	213.76	.01780	.01199101796	.23687246764
10	5.91	0.29	65.70	189.12	.01780	.01355329949	.30261546067
11	5.00	0.24	61.78	160.00	.01674	.01506600000	.39751517600
12	3.74	0.18	56.88	119.68	.01541	.01854144385	.65419457948

3" PIPE CONCENTRATION:65% TEMPERATURE:45 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.77 DATE:SEPT 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	17.41	0.85	83.36	557.12	.02258	.00583630098	.04423580168
2	17.16	0.84	80.41	549.12	.02178	.00571153846	.04392085799
3	14.94	0.73	79.43	478.08	.02152	.00648192771	.05725172533
4	12.92	0.63	74.53	413.44	.02019	.00703212074	.07182221566
5	11.71	0.57	71.10	374.72	.01926	.00740136635	.08340459919
6	10.90	0.53	70.61	348.80	.01913	.00789770642	.09551135677
7	10.06	0.49	70.12	321.92	.01899	.00849453280	.11142342664
8	8.53	0.41	69.63	272.96	.01886	.00994958968	.15391861013
9	7.57	0.37	66.68	242.24	.01806	.01073579921	.18714295985
10	7.38	0.36	65.65	236.16	.01860	.01134146341	.20279055677
11	5.78	0.28	67.67	184.96	.01833	.01427076125	.32580241197
12	5.73	0.28	66.69	183.36	.01806	.01418324607	.32652995349
13	5.38	0.26	67.67	172.16	.01833	.01533178439	.37604985075
14	3.50	0.17	62.27	112.00	.01697	.02169000000	.81776120000

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3" PIPE                      CONCENTRATION:55%            TEMPERATURE:25 C

SAMPLE:TAIL 80% SLAG 20%     SPECIFIC GRAV:1.59           DATE:NOVEM 83

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          VELOCITY  DISCHARGE  HEAD LOSS  RATE OF SH  SHEAR STR.  APP.VISC.  FRIC.FACTOR

NO.       (FT/SEC)      (CFS)  FT/100 FT       1/SEC       (PSI)  LB.SEC/FT2

-------------------------------------------------------------------------------

1            18.38       0.90      43.64      588.16      .01182 .00289390642 .02077657564

2            16.95       0.83      40.94      542.40      .01109 .00294424779 .02292132126

3            16.21       0.79      39.22      518.72      .01063 .00295095620 .02402230260

4            15.55       0.76      36.28      497.60      .00983 .00284469453 .02414016522

5            14.80       0.72      33.34      473.60      .00903 .00274560611 .02448002328

6            12.73       0.62      30.15      407.36      .00817 .00288805970 .02993730874

7            11.78       0.57      27.46      376.96      .00744 .00284210526 .03153683317

8            10.81       0.53      21.08      345.92      .00571 .00237696577 .02901564488

9             9.64       0.47      17.65      308.48      .00478 .00223132780 .03054367823

10            8.22       0.40      16.71      263.04      .00398 .00217883212 .03497735332

11            6.53       0.32      11.76      208.96      .00319 .00219831547 .04442340335

12 *          5.04       0.24      10.29      161.28      .00279 .00249107143 .06522147917
```

3" PIPE　CONCENTRATION:55%　TEMPERATURE:35 C

SAMPLE:TAIL 80% SLAG 20%　SPECIFIC GRAV:1.59　DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	18.92	0.92	46.58	605.44	.01262	.00300158562	.02093459665
2	18.04	0.88	45.11	577.28	.01222	.00304822616	.02229695958
3	17.19	0.84	43.15	550.08	.01169	.00306020942	.02349147383
4	15.68	0.76	40.45	501.76	.01096	.00314540816	.02647073160
5	14.65	0.71	38.49	468.80	.01043	.00320375427	.02885735792
6	13.65	0.67	35.30	436.80	.00956	.00315164835	.03046772968
7	12.55	0.61	33.58	401.60	.00910	.00326294821	.03430847764
8	11.80	0.57	30.40	377.60	.00824	.00314237288	.03514072393
9	10.50	0.51	27.70	336.00	.00751	.00321957143	.04044909841
10	9.34	0.45	24.70	296.88	.00664	.00319914347	.04519827226
11	8.08	0.39	19.61	258.56	.00531	.00295730198	.04929690563
12	6.25	0.30	15.44	200.00	.00418	.00300960000	.06354242043
13*	5.00	0.24	13.23	160.00	.00359	.00322200000	.08503359200

3" PIPE CONCENTRATION:55% TEMPERATURE:45 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.59 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	19.81	0.97	50.75	633.92	.01375	.00312342251	.02080564836
2	17.36	0.85	48.05	555.52	.01302	.00337500000	.02565423387
3	16.47	0.80	46.09	527.04	.01249	.00341256831	.02734152582
4	15.00	0.73	42.66	480.00	.01156	.00346800000	.03050863922
5	14.41	0.70	39.71	461.12	.01076	.00336016655	.03077030611
6	12.01	0.58	36.53	384.32	.00990	.00370940883	.04075648173
7	10.65	0.52	31.87	340.80	.00863	.00364647887	.04518133792
8	8.87	0.43	27.21	283.84	.00737	.00373900789	.05562470941
9	6.64	0.32	19.61	212.48	.00531	.00359864458	.07151643698
10 *	3.17	0.15	13.48	101.44	.00365	.00518138801	.21568594573

3" PIPE

CONCENTRATION:65%

TEMPERATURE:25 C

SAMPLE:TAIL 80% SLAG 20%

SPECIFIC GRAV:1.79

DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	15.06	0.73	60.06	481.92	.01627	.00486155378	.04259759854
2	13.80	0.67	57.61	441.60	.01561	.00509021739	.04867346198
3	12.55	0.61	54.43	401.60	.01475	.00528884462	.05560989508
4	11.76	0.57	52.95	376.32	.01435	.00549107143	.06161476049
5	9.99	0.49	51.48	319.68	.01395	.00628378378	.08300241693
6	8.58	0.42	49.77	274.56	.01348	.00706993007	.10873336376
7	7.41	0.36	46.09	237.12	.01249	.00758502024	.13507455002
8	5.04	0.24	42.17	161.28	.01142	.01019642857	.26696389991
9	3.10	0.15	36.77	99.20	.00996	.01445806452	.61543679501
10 *	2.81	0.13	29.42	89.92	.00797	.01276334520	.59936749788

3" PIPE CONCENTRATION:65% TEMPERATURE:35 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	16.63	0.81	65.95	532.16	.01786	.00483283223	.03834815403
2	15.90	0.78	63.74	508.90	.01727	.00488773585	.04056445038
3	14.81	0.72	62.27	473.92	.01687	.00512592843	.04567225687
4	13.83	0.67	60.31	442.56	.01634	.00531670282	.05072857124
5	12.19	0.59	58.35	390.08	.01581	.00583634126	.06317898626
6	10.40	0.51	55.41	332.80	.01501	.00649471154	.0824065098
7	9.02	0.44	54.43	288.64	.01474	.00735365854	.10758009302
8	7.52	0.36	50.99	240.64	.01382	.00826994681	.14511752702
9	6.23	0.30	43.15	199.36	.01169	.00844382022	.17884875647
10	4.84	0.23	37.75	154.88	.01023	.00951136364	.25931785312
11	3.64	0.17	31.38	116.49	.00850	.01050824176	.38094621724
12 *	1.85	0.09	24.02	59.20	.00651	.01583513514	1.1294969882

3" PIPE CONCENTRATION:65% TEMPERATURE:45 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	18.45	0.90	75.51	590.40	.02046	.00499024390	.03569113799
2	17.00	0.83	70.12	544.00	.01899	.00502676471	.03901886471
3	16.11	0.79	68.16	515.20	.01846	.00515962733	.04223651949
4	14.92	0.73	63.74	477.44	.01727	.00520878016	.04606830127
5	13.00	0.63	61.05	416.00	.01654	.00572538462	.05811607929
6	11.98	0.58	58.10	383.36	.01574	.00591235392	.06512362961
7	10.66	0.52	56.39	341.12	.01527	.00644606004	.07979434878
8	8.75	0.42	53.44	280.00	.01448	.00744685714	.11230822514
9	7.92	0.38	50.99	253.44	.01382	.00785227273	.13082935096
10	5.92	0.29	45.11	189.44	.01222	.00928885135	.20705003082
11	4.60	0.22	42.17	147.20	.01142	.01117173913	.32047779773
12 *	3.81	0.18	34.32	121.92	.00930	.01098425197	.38043503420

4" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:MARCH 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.73	1.02	25.94	281.62	.00938	.00479625027	.04048126792
2	11.29	0.98	25.08	271.19	.00907	.00481610679	.04225391071
3	10.86	0.94	22.66	260.76	.0082	.00452830189	.04128589549
4	10.43	0.91	20.54	250.32	.00743	.00427420901	.04055717567
5	9.77	0.85	18.61	234.68	.00673	.00412953809	.04186715438
6	9.12	0.79	16.58	219.03	.00601	.00395123956	.04290741021
7	8.47	0.73	14.56	203.39	.00527	.00373115689	.04362056651
8	7.60	0.66	11.38	182.53	.00412	.00325031502	.04235625346
9	6.95	0.60	9.83	166.88	.00356	.00307190796	.04376509704
10	6.08	0.53	7.32	146.09	.00265	.00261208844	.04256829175
11 *	5.21	0.45	5.97	125.16	.00216	.00248513902	.04725261106

4" PIPE CONCENTRATION:55% TEMPERATURE:30 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:MARCH 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.29	0.98	25.17	271.19	.00910	.00483203658	.04239367306
2	10.64	0.92	19.28	255.54	.00698	.00393331768	.03661168134
3	9.56	0.83	15.04	229.46	.00544	.00341392835	.03534521454
4	8.90	0.77	13.30	213.82	.00481	.00323936021	.03605890797
5	8.25	0.72	11.76	198.17	.00425	.00308825756	.03707904500
6	7.38	0.64	10.41	177.31	.00377	.00306175625	.04110324726
7	6.73	0.58	9.25	161.67	.00335	.00298385600	.04391998525
8	6.08	0.53	7.90	146.02	.00286	.00282043556	.04594162807
9	5.21	0.45	6.75	125.16	.00244	.00280728667	.05337794954
10 *	4.56	0.39	5.90	109.51	.00206	.00270879372	.05880912981

4" PIPE CONCENTRATION:55% TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:MARCH 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	10.86	0.94	31.82	260.76	.01151	.00635618960	.05795129965
2	10.21	0.89	28.35	245.11	.01025	.00602178614	.05838750107
3	9.56	0.83	25.75	229.46	.00931	.00584258694	.06048969622
4	8.47	0.73	22.08	203.39	.00799	.00565691529	.06613440729
5	7.82	0.68	19.96	187.74	.00722	.00553787152	.07010658445
6	7.38	0.64	17.16	177.31	.00621	.00504337037	.06770587944
7	6.51	0.56	14.75	156.45	.00534	.00491505273	.07482156484
8	5.86	0.51	12.17	140.81	.0044	.00449968042	.07608603478
9	4.99	0.43	9.35	119.94	.00338	.00405802901	.08060521042

4" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:OCTOB 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	13.18	1.15	36.82	316.32	.01332	.00606373293	.04553243867
2	12.90	1.12	36.82	309.60	.01332	.00619534854	.04753049216
3	12.66	1.10	34.96	303.84	.01264	.00599052133	.04683032477
4	11.43	0.99	34.96	274.32	.01264	.00663517060	.05745159895
5	10.43	0.91	34.04	250.32	.01231	.00708149569	.06719499765
6	9.47	0.82	33.11	227.28	.01197	.00758394931	.07925774273
7	8.11	0.70	32.49	194.64	.01175	.00869297164	.10608248026
8	7.59	0.66	31.25	182.16	.01130	.00893280632	.11647759603
9	7.38	0.64	31.56	177.12	.01141	.00927642276	.12440001359
10	6.57	0.57	30.01	157.12	.01085	.00994399185	.14926105470
11	4.88	0.42	26.92	117.12	.00974	.01197540984	.24286605583
12	4.20	0.36	26.61	100.80	.00962	.01374285714	.32363515873
13	4.13	0.36	25.06	99.12	.00906	.01316222760	.31541010383
14	3.25	0.28	24.44	78.00	.00884	.01632000000	.49697329231
15	3.10	0.27	23.82	74.40	.00862	.01668387097	.53263706556

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4" PIPE                        CONCENTRATION:55%             TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10%       SPECIFIC GRAV:1.58            DATE:OCTOB 83

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           VELOCITY  DISCHARGE  HEAD LOSS  RATE OF SH  SHEAR STR.   APP.VISC.  FRIC.FACTOR

NO.        (FT/SEC)      (CFS)  FT/100 FT       1/SEC       (PSI)  LB.SEC/FT2

----------------------------------------------------------------------------

1             13.74       1.19      34.96      329.76      .01265 .00552401747 .03978914134

2             12.63       1.10      34.34      303.12      .01242 .00590023753 .04623409932

3             11.51       1.00      34.04      276.24      .01231 .00641702867 .05517659709

4             10.59       0.92      33.42      254.16      .01209 .00684985836 .06401502032

5              9.55       0.83      32.80      229.20      .01185 .00745130890 .07721922754

6              8.39       0.73      31.56      201.36      .01142 .00816686532 .09633623944

7              7.27       0.63      31.25      174.48      .01130 .00932599725 .12695713953

8              7.00       0.61      30.94      168.00      .01119 .00959142857 .13560681429

9              5.99       0.52      30.01      143.76      .01086 .01087813022 .17973128937

10             5.06       0.44      28.16      121.44      .01018 .01207114625 .23609905638

11             4.08       0.35      25.68       97.92      .00929 .01366176471 .33139266748

12             3.85       0.33      24.75       92.40      .00895 .01394805195 .35854946571

13             3.29       0.28      21.97       78.96      .00795 .01449848024 .43613690746
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4" PIPE CONCENTRATION:55% TEMPERATURE:45 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:OCTOB 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	13.79	1.20	34.04	330.96	.01231	.00535605511	.03843943783
2	12.85	1.12	33.11	308.40	.01197	.00558910506	.04304625778
3	11.68	1.01	32.80	280.32	.01186	.00609246575	.05162338883
4	10.69	0.93	31.25	256.56	.01141	.00640411600	.05928949360
5	9.58	0.83	31.25	229.92	.01130	.00707724426	.07311305521
6	8.96	0.78	29.70	215.04	.01074	.00719196429	.07943936593
7	7.92	0.69	27.85	190.08	.01007	.00762878788	.09532934619
8	6.99	0.61	27.54	167.76	.00996	.00854935622	.12104657174
9	5.48	0.47	25.68	131.52	.00929	.01017153285	.18369701702
10	4.87	0.42	23.82	116.88	.00862	.01062012320	.21582256534
11	4.26	0.37	22.28	102.24	.00806	.01135211268	.26373231722
12	3.77	0.32	19.49	90.48	.00705	.01122015915	.29454653871
13	3.31	0.28	17.32	79.44	.00627	.01136555891	.33992792234

4" PIPE CONCENTRATION:65% TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.77 DATE:SEPT 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.17	0.97	69.93	268.08	.02529	.01358460161	.12036216477
2	11.14	0.97	71.17	267.36	.02574	.01386355476	.12316453397
3	9.96	0.86	68.69	239.04	.02485	.01496987952	.14874940021
4	8.50	0.74	67.46	204.00	.0244	.01722352941	.20053929412
5	7.40	0.64	66.22	177.60	.02395	.01941891892	.25971054602
6	5.81	0.50	62.51	139.44	.02261	.02334939759	.39773692683
7	5.08	0.44	56.32	121.92	.02037	.02405905512	.46871743931
8	4.83	0.42	56.32	115.92	.02037	.02530434783	.51849464398
9	4.42	0.38	55.08	106.08	.01992	.02704072398	.60546954403
10	4.07	0.35	53.84	97.68	.01947	.02870270270	.69775052792
11 *	3.40	0.29	56.94	81.60	.02059	.03633529412	1.0576598529

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4" PIPE                             CONCENTRATION:65%                TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10%            SPECIFIC GRAV:1.77               DATE:SEPT  83

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                VELOCITY   DISCHARGE   HEAD LOSS  RATE OF SH  SHEAR STR.    APP.VISC.  FRIC.FACTOR

NO.             (FT/SEC)       (CFS)   FT/100 FT      1/SEC       (PSI)  LB.SEC/FT2

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1                  11.25        0.98       74.27     270.00      .02686 .01432533333 .12602261017

2                  11.07        0.96       71.17     265.68      .02574 .01395121951 .12472709513

3                   9.85        0.85       67.46     236.40      .02440 .01486294416 .14933612306

4                   8.17        0.71       64.36     196.40      .02328 .01706883910 .20710299046

5                   7.26        0.63       60.03     174.24      .02171 .01794214876 .24458740495

6                   6.15        0.53       56.94     147.60      .02059 .02008780488 .32326123075

7                   6.02        0.52       56.32     144.48      .02037 .02030232558 .33376865873

8                   5.03        0.43       53.84     120.72      .01947 .02322465209 .45695926627

9                   4.50        0.39       51.98     108.00      .01880 .02506666667 .55129027160

10                  3.75        0.32       53.22      90.00      .01925 .03080000000 .81285991111

11 *                2.72        0.23       56.32      65.28      .02037 .04493382353 1.6349358915
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4" PIPE CONCENTRATION:65% TEMPERATURE:45 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.77 DATE:SEPT 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.89	1.03	70.55	285.36	.02552	.01287804878	.10719251677
2	11.47	1.00	72.41	275.28	.02619	.01370008718	.11821053140
3	10.70	0.93	70.55	256.80	.02552	.01431028037	.13236117740
4	9.54	0.83	61.89	228.96	.02238	.01407547170	.14601949422
5	8.35	0.72	56.94	200.40	.02059	.01479520958	.17536014773
6	7.67	0.66	55.08	184.08	.01992	.01558279009	.20106946076
7	6.62	0.57	51.98	158.88	.01880	.01703927492	.25473544418
8	6.00	0.52	50.75	144.00	.01836	.01836000000	.30284331000
9	5.08	0.44	48.27	121.92	.01746	.02062204724	.40175780427
10	4.36	0.38	49.51	104.64	.01791	.02464678899	.55946138267
11	3.77	0.32	53.22	90.48	.01925	.03063660477	.80425827945
12	3.48	0.30	54.46	83.52	.01970	.03396551724	.96593133109

4" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.59 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	10.95	0.95	19.80	262.80	.00716	.00392328767	.03545947416
2	10.57	0.92	18.87	253.68	.00683	.00387701041	.03630097051
3	9.72	0.84	18.25	233.28	.00660	.00407407407	.04148192603
4	9.63	0.83	17.94	231.12	.00649	.00404361371	.04155656378
5	8.73	0.76	16.40	209.52	.00593	.00407560137	.04620337633
6	8.29	0.72	15.47	198.96	.00560	.00405307600	.04838675225
7	7.94	0.69	14.54	190.56	.00526	.00397481108	.04954413454
8	7.66	0.66	13.30	183.84	.00481	.00376762402	.04867825979
9	6.66	0.58	11.14	159.84	.00403	.00363063063	.05395157094
10	5.81	0.50	8.66	139.44	.00313	.00323235800	.05506042760
11	5.69	0.49	8.04	136.56	.00291	.00306854130	.05337230550
12 *	5.20	0.45	6.49	124.80	.00235	.00271153846	.05169700614

4" PIPE CONCENTRATION:55% TEMPERATURE:35 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.59 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.26	0.98	23.51	270.24	.00851	.00453463598	.03985660348
2	10.89	0.95	22.59	261.36	.00817	.00450137741	.04090952342
3	10.26	0.89	21.35	246.24	.00772	.00451461988	.04354818767
4	9.73	0.84	20.11	233.52	.00727	.00448304214	.04559909647
5	8.92	0.77	18.87	214.08	.00683	.00459417040	.05097280133
6	8.50	0.74	17.63	204.00	.00638	.00450352941	.05243609412
7	8.15	0.71	16.09	195.60	.00582	.00428466258	.05293017351
8	7.48	0.65	14.54	179.52	.00526	.00421925134	.05582517615
9	6.90	0.60	12.99	165.60	.00470	.00408695652	.05862018484
10	6.30	0.54	11.75	151.20	.00425	.00404761905	.06358509700
11	5.95	0.51	11.14	142.80	.00403	.00406386555	.06759563025
12	5.22	0.45	9.90	125.28	.00358	.00411494253	.07501705054

4" PIPE CONCENTRATION:55% TEMPERATURE:45 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.59 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.07	0.96	25.99	265.68	.00940	.00509485095	.04554913742
2	10.89	0.95	25.06	261.36	.00906	.00499173554	.04536489967
3	10.51	0.91	23.82	252.24	.00862	.00492102759	.04633928631
4	9.88	0.86	22.28	237.12	.00806	.00489473684	.04903076390
5	9.37	0.81	21.66	224.88	.00783	.00501387407	.05295781856
6	8.77	0.76	20.11	210.48	.00727	.00497377423	.05612840889
7	8.23	0.71	18.56	197.52	.00672	.00489914945	.05851380998
8	7.54	0.65	16.71	180.96	.00604	.00480636605	.06308727283
9	7.00	0.61	14.85	168.00	.00537	.00460285714	.06507672857
10	6.17	0.53	13.30	148.08	.00481	.00467747164	.07502780748
11	5.73	0.50	12.37	137.52	.00447	.00468062927	.08094762636

4" PIPE CONCENTRATION:65% TEMPERATURE:25 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.06	0.96	34.04	265.44	.01231	.00667811935	.05975789709
2	9.91	0.86	33.73	237.84	.01220	.00738647830	.07376664450
3	9.74	0.85	33.42	233.76	.01208	.00744147844	.07561301013
4	8.89	0.77	32.80	213.36	.01186	.00800449944	.08911045765
5	8.30	0.72	32.49	199.20	.01175	.00849397590	.10128128175
6	7.88	0.68	31.87	189.12	.01153	.00877918782	.11026162263
7	7.00	0.61	30.63	168.00	.01108	.00949714286	.13427377143
8	6.17	0.53	29.39	148.08	.01063	.01033711507	.16580929469
9	5.29	0.46	27.85	126.96	.01007	.01142155009	.21368086521
10	4.81	0.41	26.61	115.44	.00963	.01201247401	.24716310441
11	3.78	0.32	24.44	90.72	.00884	.01403174603	.36738056045
12 *	2.86	0.24	20.42	68.64	.00739	.01550349650	.53648783559

4" PIPE CONCENTRATION:65% TEMPERATURE:35 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.09	0.96	42.08	266.16	.01522	.00823444545	.07348506238
2	10.58	0.92	41.15	253.92	.01488	.00843856333	.07893672478
3	10.25	0.89	40.22	246.00	.01455	.00851707317	.08223614991
4	9.38	0.81	38.99	225.12	.01410	.00901918977	.09516142634
5	8.58	0.74	37.75	205.92	.01365	.00954545455	.11010463022
6	7.49	0.65	36.20	179.76	.01309	.01048598131	.13855541969
7	6.89	0.60	34.04	165.36	.01231	.01071988389	.15398099305
8	6.00	0.52	31.25	144.00	.01130	.01130000000	.18639036111
9	5.09	0.44	28.47	122.16	.01030	.01214145383	.23607454811
10	3.55	0.30	21.66	85.20	.00783	.01323380282	.36893729516
11 *	2.45	0.21	20.73	58.80	.00750	.01836734694	.74195335277

4" PIPE CONCENTRATION:65% TEMPERATURE:45 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	11.13	0.97	44.56	267.12	.01612	.00869002695	.07727201117
2	10.95	0.95	43.63	262.80	.01578	.00864657534	.07814951148
3	10.45	0.91	42.70	250.80	.01544	.00886507177	.08395802660
4	9.56	0.83	41.46	229.44	.01499	.00940794979	.09739425846
5	8.81	0.76	40.22	211.44	.01455	.00990919410	.11131627974
6	7.79	0.68	37.44	186.96	.01354	.01042875481	.13249248915
7	7.13	0.62	34.96	171.12	.01265	.01064516129	.14776071122
8	6.05	0.52	31.87	145.20	.01153	.01143471074	.16705359743
9	4.62	0.40	27.85	110.88	.01007	.01307792208	.28015154795
10	3.67	0.32	23.51	88.08	.00871	.01423978202	.38400204174
11 *	2.40	0.20	21.66	57.60	.00783	.01957500000	.80721046875

5" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:MARCH 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	8.34	1.15	6.39	160.24	.00238	.00258811782	.02458713317
2	7.65	1.12	6.02	146.88	.00272	.00266666667	.02759901235
3	7.23	1.08	5.52	138.87	.00249	.00258198315	.02828591679
4	6.81	1.03	5.02	130.86	.00227	.00249793673	.02906558962
5	6.25	0.90	4.47	120.18	.00202	.00242036945	.03070710272
6	5.84	0.82	4.10	112.17	.00185	.00237496657	.03221020888
7	5.14	0.70	3.69	98.81	.00167	.00243376177	.03753511408
8 *	4.45	0.60	3.33	85.46	.00150	.00252749824	.04497992675

5" PIPE CONCENTRATION:55% TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:MARCH 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	8.20	1.11	10.40	157.57	.00470	.00429523386	.04150664783
2	7.51	1.02	10.31	144.21	.00466	.00465321406	.04906293783
3	7.23	0.98	9.54	138.87	.00431	.00446921581	.04896076361
4	6.53	0.88	8.71	125.52	.00393	.00450860421	.05472851886
5	5.98	0.81	7.76	114.84	.00350	.00438871473	.05811833760
6	5.84	0.79	7.34	112.17	.00332	.00426210217	.05780426675
7	5.42	0.73	6.75	104.15	.00305	.00421699472	.06165222764
8	4.72	0.64	6.07	90.80	.00274	.00434537445	.07303214773
9	4.31	0.58	5.43	82.79	.00245	.00426138423	.07831754243
10	4.03	0.54	5.29	77.45	.00239	.00444364106	.08738468511

5" PIPE CONCENTRATION:55% TEMPERATURE:40 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:MARCH 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	8.20	1.11	15.57	157.57	.00713	.00651596116	.06296646788
2	7.51	1.02	14.97	144.21	.00676	.00675015602	.07117284544
3	7.23	0.98	14.24	138.87	.00643	.00666753078	.07304355220
4	6.95	0.94	13.46	133.53	.00608	.00655672882	.07474488484
5	6.67	0.90	12.78	128.19	.00577	.00648162883	.07701434965
6	6.25	0.85	12.59	120.18	.00569	.00691777334	.08649673984
7	5.98	0.81	12.14	114.84	.00548	.00687147335	.09099671145
8	5.84	0.79	11.32	112.17	.00511	.00636004279	.08896982021
9	5.42	0.73	10.68	104.15	.00482	.00666423428	.09743073351
10	5.28	0.71	10.08	101.48	.00455	.00645644462	.09691501306
11	5.00	0.68	9.49	96.14	.00428	.00641065113	.10166027200
12	4.72	0.64	9.12	90.80	.00412	.00653392070	.10981476228
13	4.31	0.58	8.81	82.79	.00398	.00692257519	.12722604852
14	4.03	0.54	8.39	77.45	.00379	.00704661072	.13857236360
15	3.89	0.52	7.94	74.78	.00358	.00689382188	.14048544485

5" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:OCTOB 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	8.67	1.17	25.27	166.46	.01141	.00987047939	.09013530995
2	8.10	1.10	25.15	155.52	.01135	.01050925926	.10272433318
3	7.34	0.99	24.92	140.92	.01125	.01149598419	.12399606687
4	6.75	0.91	24.09	129.60	.01087	.01207777778	.14166726365
5	6.04	0.82	23.74	115.96	.01071	.01329975854	.17432637549
6	5.34	0.72	22.91	102.52	.01034	.01452360515	.21532057540
7	4.62	0.62	22.67	88.70	.01023	.01660789177	.28460281385
8	4.46	0.60	22.91	85.63	.01034	.01738829849	.30867277645
9	4.34	0.59	21.85	83.32	.00986	.01704080653	.31084577077
10	4.11	0.55	21.61	78.91	.00975	.01779242175	.34274290941
11	3.82	0.51	20.43	73.34	.00922	.01810308154	.37519038678

5" PIPE CONCENTRATION:55% TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.58 DATE:OCTOB 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	9.10	1.23	24.98	174.72	.01127	.00928846154	.08081437870
2	7.86	1.06	24.80	150.91	.01119	.01067762242	.10755546977
3	7.33	0.99	24.68	140.73	.01113	.01138861650	.12300838655
4	6.45	0.87	24.03	123.84	.01085	.01261627907	.15486661859
5	5.77	0.78	23.50	110.78	.01061	.01379165914	.18923927023
6	5.22	0.70	22.55	100.22	.01018	.01462702055	.22184736718
7	4.76	0.64	22.20	91.39	.01002	.01578816063	.26260399160
8	4.48	0.60	21.43	86.01	.00967	.01618974538	.28610006278
9	4.04	0.54	20.31	77.56	.00917	.01702527076	.33362156284
10	3.98	0.54	19.96	76.41	.00900	.01696113074	.33738352567
11	3.52	0.47	18.54	67.58	.00837	.01783486239	.40113230404

5" PIPE | CONCENTRATION:55% | TEMPERATURE:45 C

SAMPLE:TAIL 90% SLAG 10% | SPECIFIC GRAV:1.58 | DATE:OCTOB 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	9.26	1.25	25.15	177.79	.01135	.00919286799	.07859979171
2	8.94	1.21	24.68	171.64	.01114	.00934607318	.08276708507
3	7.86	1.06	24.33	150.91	.01098	.01047723809	.10553700251
4	7.31	0.99	23.50	140.35	.01061	.01088592804	.11790389082
5	6.63	0.90	23.03	127.29	.01039	.01175394768	.14035762076
6	5.96	0.81	21.96	114.43	.00991	.01247085554	.16566419024
7	5.32	0.72	21.25	102.14	.00959	.01352026630	.20120689058
8	4.69	0.63	19.96	90.04	.00901	.01440959574	.24323530535
9	4.09	0.55	18.18	78.52	.00821	.01505654610	.2914365708
10	3.68	0.50	16.41	70.65	.00741	.01510318471	.32491523659
11	3.23	0.43	14.76	62.01	.00666	.01546589260	.37906762262

5" PIPE CONCENTRATION:63% TEMPERTAURE:25 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.73 DATE:SEPTE 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	8.06	1.09	45.59	154.75	.02057	.01914106624	.18802331921
2	7.63	1.03	40.86	146.49	.01844	.01812656154	.18809724614
3	6.89	0.93	36.02	132.28	.01626	.01770063502	.20339000381
4	6.14	0.83	31.18	117.88	.01407	.01718764845	.22161791372
5	5.39	0.73	28.46	103.48	.01284	.01786780054	.26244300412
6	4.78	0.65	26.92	91.77	.01215	.01906505394	.31576790935
7	4.60	0.62	25.86	88.32	.01167	.01902717391	.32749351134
8	4.14	0.56	25.39	79.48	.01146	.02076295924	.39703742211
9	4.02	0.54	23.85	77.18	.01077	.02009432495	.39574105229
10	3.76	0.51	18.89	72.19	.00853	.01701509904	.35827858335
11	3.31	0.45	18.54	63.55	.00837	.01896585366	.45364588677

5" PIPE CONCENTRATION:63% TEMPERATURE:35 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.73 DATE:SEPTE 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	8.10	1.10	47.83	155.52	.02158	.01998148148	.19531199207
2	7.23	0.98	40.74	138.81	.01839	.01907758807	.20890683126
3	6.68	0.90	34.25	128.25	.01546	.01735859649	.20573305335
4	5.84	0.79	28.46	112.12	.01284	.01649090260	.22355626056
5	5.15	0.70	25.62	98.88	.01157	.01684951456	.25903974739
6	4.45	0.60	21.61	85.44	.00975	.01643258427	.29236952405
7	4.03	0.54	21.02	77.37	.00949	.01766265995	.34697934944
8	3.75	0.51	20.55	72.00	.00927	.01854000000	.39143955200
9	3.75	0.51	20.55	72.00	.00927	.01854000000	.39143955200
10 *	3.50	0.47	21.85	67.20	.00986	.02112857143	.47795645714

5" PIPE CONCENTRATION:63% TEMPERATURE:45 C

SAMPLE:TAIL 90% SLAG 10% SPECIFIC GRAV:1.73 DATE:SEPTE 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	8.40	1.14	46.88	161.28	.02116	.01889285714	.17807567460
2	8.23	1.11	46.06	158.01	.02078	.01893753560	.18217693027
3	7.60	1.03	37.08	145.92	.01674	.01651973684	.17209758130
4	7.41	1.00	38.03	142.27	.01716	.01736866521	.18557880531
5	6.76	0.91	34.84	129.79	.01572	.01744109716	.20427097266
6	6.67	0.90	30.47	128.06	.01375	.01546150242	.18352639647
7	6.09	0.82	26.57	116.92	.01199	.01476702018	.19196944303
8	5.15	0.70	23.14	98.88	.01044	.01520388350	.23374027335
9	4.74	0.64	21.02	91.00	.00949	.01501714286	.25081703876
10	4.57	0.62	21.02	87.74	.00949	.01557510827	.26982446169
11	4.07	0.55	19.25	78.14	.00869	.01601433325	.31151464241

5" PIPE CONCENTRATION:55% TEMPERATURE:25 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.59 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	7.40	1.00	10.27	142.08	.00464	.00470270270	.05031552958
2	7.31	0.99	10.03	140.35	.00453	.00464780905	.05033973849
3	6.94	0.94	9.74	133.24	.00440	.00475532873	.05424768913
4	6.69	0.90	9.44	128.44	.00426	.00477608222	.05652035365
5	5.85	0.79	9.27	112.32	.00418	.00535897436	.07252906129
6	5.80	0.78	9.21	111.36	.00415	.00536637931	.07325539536
7	5.66	0.76	9.09	108.67	.00410	.00543296218	.07599735919
8	5.59	0.76	8.85	107.32	.00399	.00535370854	.07582227079
9	5.50	0.74	8.85	105.60	.00399	.00544090909	.07832402975
10	5.33	0.72	8.79	102.33	.00397	.00558663149	.08298194228
11	4.93	0.67	8.62	94.65	.00389	.00591822504	.09503930895

5" PIPE CONCENTRATION:55% TEMPERATURE:35 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.59 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	7.80	1.06	10.74	149.76	.00485	.00466346154	.04733692472
2	7.34	0.99	10.62	140.92	.00480	.00490491059	.05290498853
3	7.16	0.97	10.39	137.47	.00469	.00491278097	.05432432079
4	6.60	0.89	10.09	126.72	.00456	.00518181818	.06216192837
5	6.19	0.84	9.86	118.84	.00445	.00539212386	.06896459974
6	5.82	0.79	9.56	111.74	.00432	.00556720959	.07573302158
7	5.31	0.72	9.44	101.95	.00426	.00601706719	.08971562025
8	5.21	0.70	9.33	100.03	.00421	.00606058183	.09209883916
9	5.15	0.70	8.97	98.88	.00405	.00589805825	.09067510604
10	4.63	0.62	8.62	88.89	.00389	.00630172123	.10775442811

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5" PIPE                          CONCENTRATION:55%                TEMPERATURE:45 C

SAMPLE:TAIL 80% SLAG 20%         SPECIFIC GRAV:1.59               DATE:NOVEM 83

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             VELOCITY   DISCHARGE   HEAD LOSS   RATE OF SH   SHEAR STR.    APP.VISC.  FRIC.FACTOR

NO.          (FT/SEC)       (CFS)   FT/100 FT        1/SEC        (PSI)  LB.SEC/FT2

------------------------------------------------------------------------------------

1                7.94        1.07       12.28       152.44       .00554 .00523327211 .05218146489

2                7.76        1.05       11.92       148.99       .00538 .00519921207 .05305255938

3                7.51        1.02       11.63       144.19       .00525 .00524308204 .05527476902

4                7.40        1.00       11.39       142.08       .00514 .00520945946 .05573746165

5                6.41        0.87       10.98       123.07       .00496 .00580352645 .07168249688

6                5.56        0.75       10.68       106.75       .00482 .00650192037 .09258592335

7                5.40        0.73       10.21       103.69       .00461 .00640277778 .09387736969

8                5.10        0.69        9.86        97.92       .00445 .00654411765 .10159379095

9                4.50        0.61        9.44        86.40       .00426 .00710000000 .13492002963

10 *             4.12        0.56        8.85        79.10       .00400 .00728192162 .13993071920
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5" PIPE CONCENTRATION:65% TEMPERATURE:25 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	6.75	0.91	27.87	129.60	.01258	.01397777778	.16395346612
2	6.41	0.87	27.75	123.07	.01252	.01464922402	.18094049615
3	6.22	0.84	26.92	119.42	.01215	.01465081226	.18648461813
4	6.08	0.82	26.10	116.73	.01178	.01453199692	.18922810444
5	5.85	0.79	25.62	112.32	.01157	.01483333333	.20075627730
6	5.26	0.71	24.09	100.99	.01087	.01549935637	.23329507077
7	5.01	0.68	23.26	96.19	.01050	.01571888970	.24840558404
8	4.47	0.60	21.85	85.82	.00986	.01654439525	.29302817190
9	4.11	0.55	20.19	78.91	.00911	.01662450893	.32024491330
10 *	3.89	0.52	19.13	74.68	.00863	.01664059989	.33965625392

5" PIPE CONCENTRATION:65% TEMPERATURE:35 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	7.05	0.95	28.93	135.36	.01306	.01389361702	.15603155978
2	6.52	0.88	28.34	125.18	.01279	.01471289343	.17865816130
3	6.26	0.85	27.87	120.19	.01258	.01507213579	.19062483541
4	6.09	0.88	27.40	116.92	.01236	.01522271639	.19789343752
5	5.88	0.79	26.57	112.89	.01199	.01529418018	.20592640509
6	5.33	0.72	25.62	102.33	.01157	.01628144239	.24183906100
7	4.92	0.66	24.56	94.46	.01108	.01689095914	.27180476238
8	4.41	0.59	23.03	84.67	.01039	.01767048541	.31723849116
9	4.03	0.54	21.25	77.37	.00959	.01784877860	.35063561133
10	3.48	0.47	19.48	66.81	.00879	.01894566682	.43100061930
11 *	2.96	0.40	17.48	56.83	.00789	.01999225761	.53473805013

5" PIPE CONCENTRATION:65% TEMPERATURE:45 C

SAMPLE:TAIL 80% SLAG 20% SPECIFIC GRAV:1.79 DATE:NOVEM 83

NO.	VELOCITY (FT/SEC)	DISCHARGE (CFS)	HEAD LOSS FT/100 FT	RATE OF SH 1/SEC	SHEAR STR. (PSI)	APP.VISC. LB.SEC/FT2	FRIC.FACTOR
1	7.42	1.00	30.11	142.46	.01359	.01373690861	.14657474699
2	7.31	0.99	29.88	140.35	.01348	.01383056644	.14979683772
3	7.09	0.96	29.52	136.12	.01332	.01409109609	.15734728784
4	6.43	0.87	28.70	123.45	.01295	.01510571081	.18599245614
5	5.94	0.80	27.40	114.04	.01236	.01560715538	.20801425025
6	5.37	0.73	26.69	103.10	.01205	.01683026188	.24813383200
7	4.93	0.67	25.15	94.65	.01135	.01726782894	.27729978317
8	4.52	0.61	23.85	86.78	.01077	.01787139894	.31303027351
9	4.02	0.54	22.32	77.18	.01007	.01878828712	.37001972105
10 *	3.64	0.49	21.25	69.88	.00959	.01976187750	.42979696746

APPENDIX - B

PLOTTING OF DATA

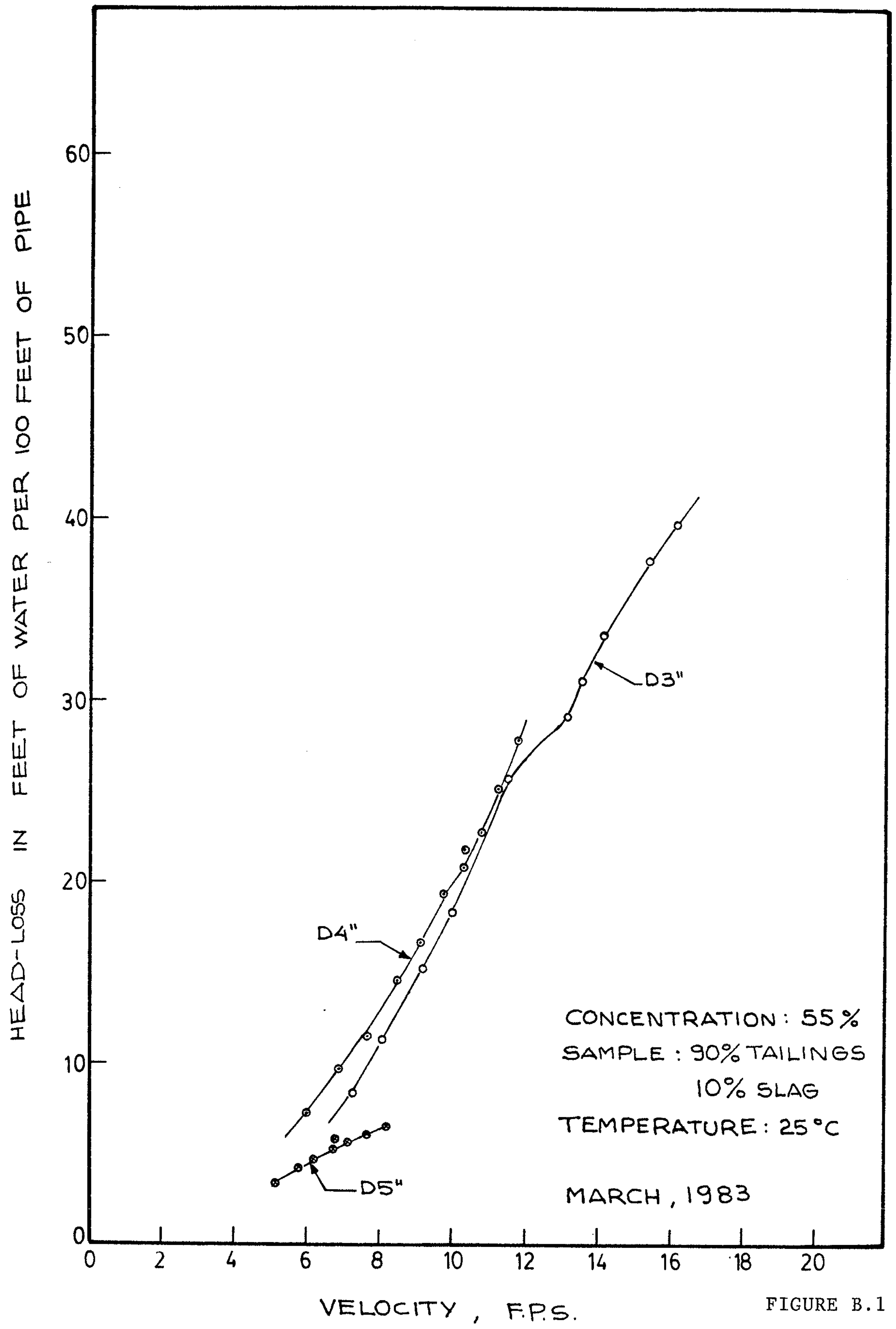

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
VELOCITY , F.P.S.
0
2
4
6
8
10
12
14
16
18
20
D3"
D4"
D5"
CONCENTRATION : 55 %
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE : 25 °C
MARCH , 1983

FIGURE B.1

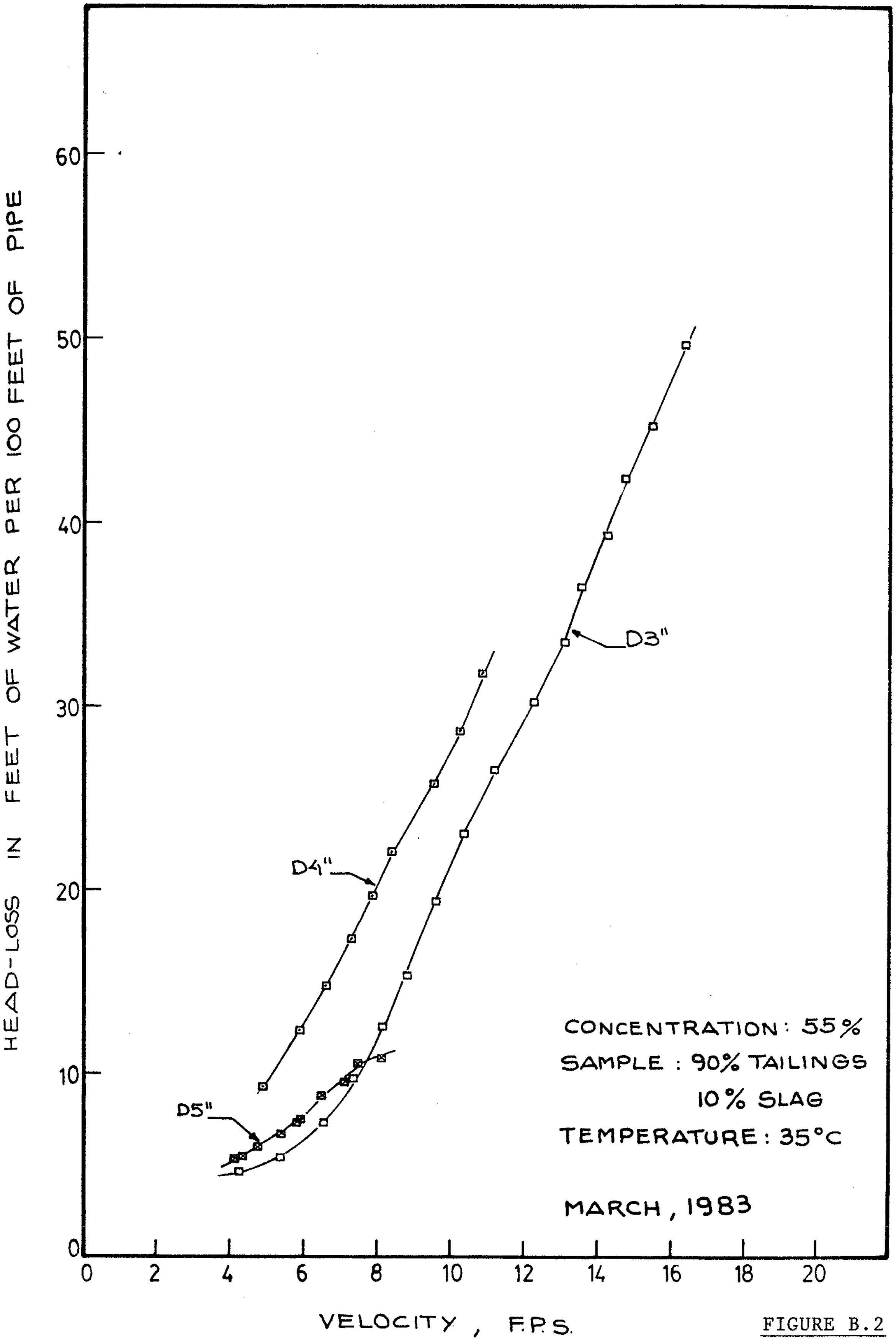

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D3"
D4"
D5"
CONCENTRATION : 55%
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE : 35°C
MARCH , 1983

FIGURE B.2

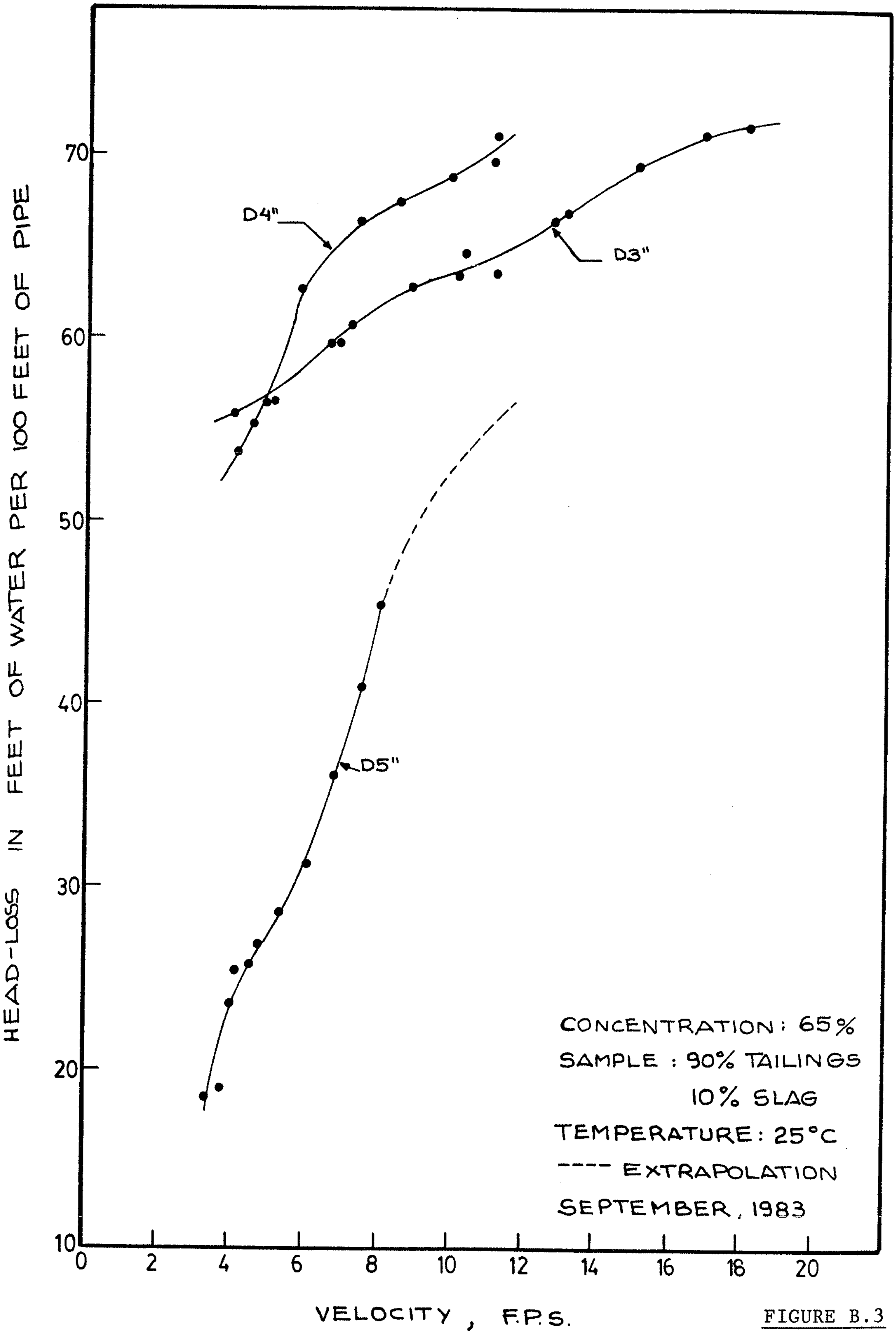

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D4"
D3"
D5"
CONCENTRATION : 65%
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE : 25°C
---- EXTRAPOLATION
SEPTEMBER, 1983

FIGURE B.3

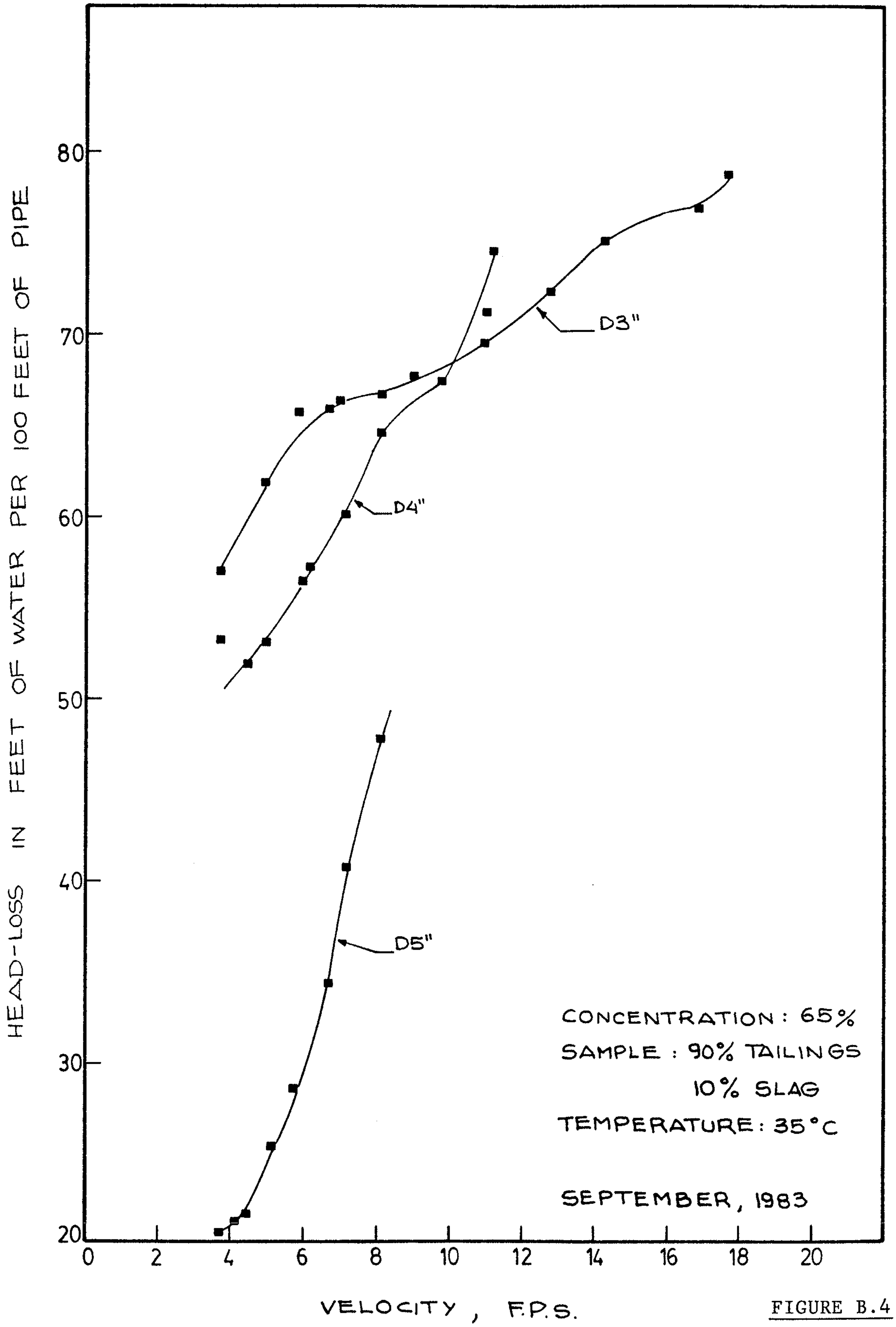

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
80
70
60
50
40
30
20
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D3"
D4"
D5"
CONCENTRATION : 65%
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE : 35°C
SEPTEMBER, 1983

FIGURE B.4

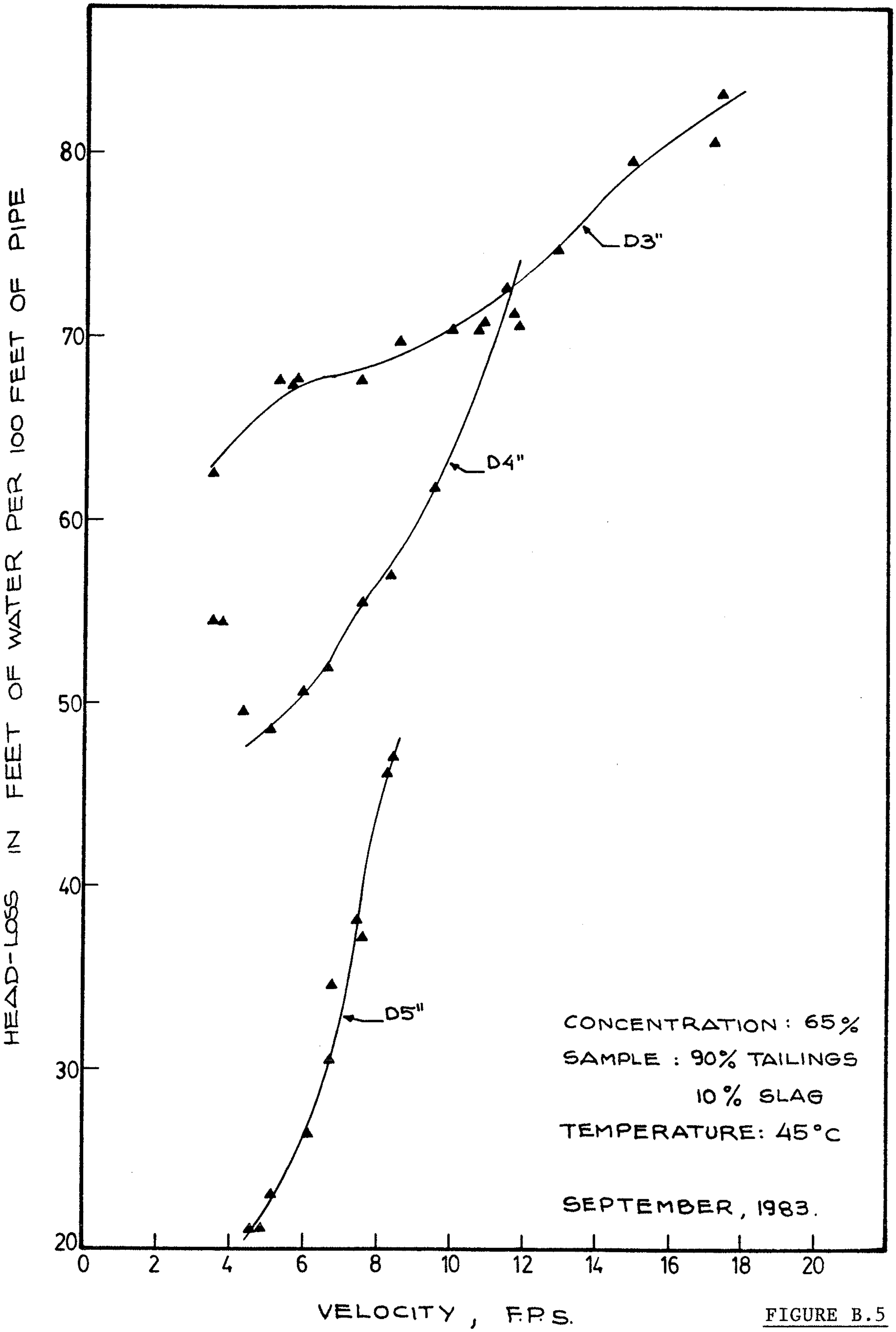

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
80
70
60
50
40
30
20
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D3"
D4"
D5"
CONCENTRATION : 65%
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE: 45°C
SEPTEMBER, 1983.

FIGURE B.5

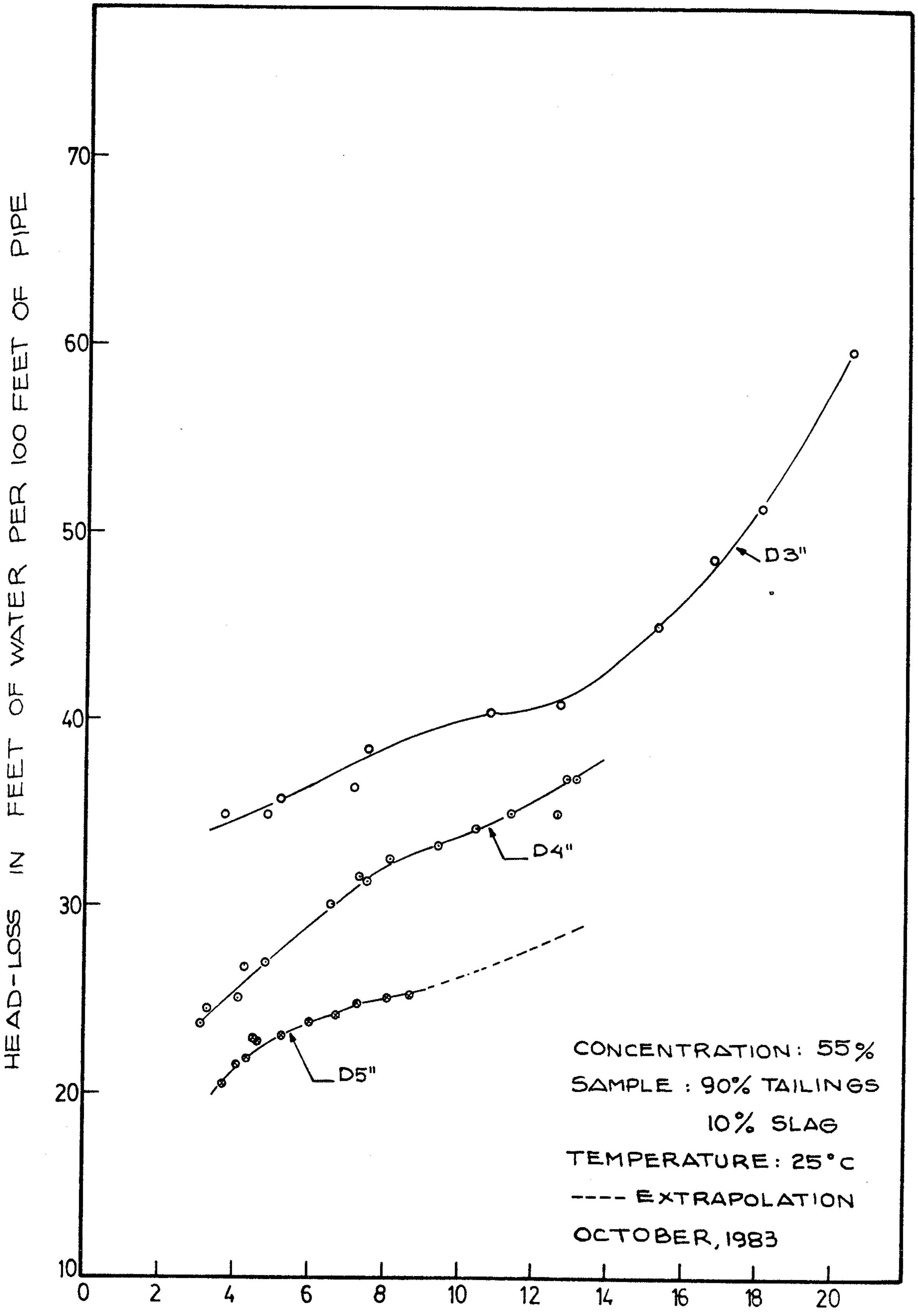
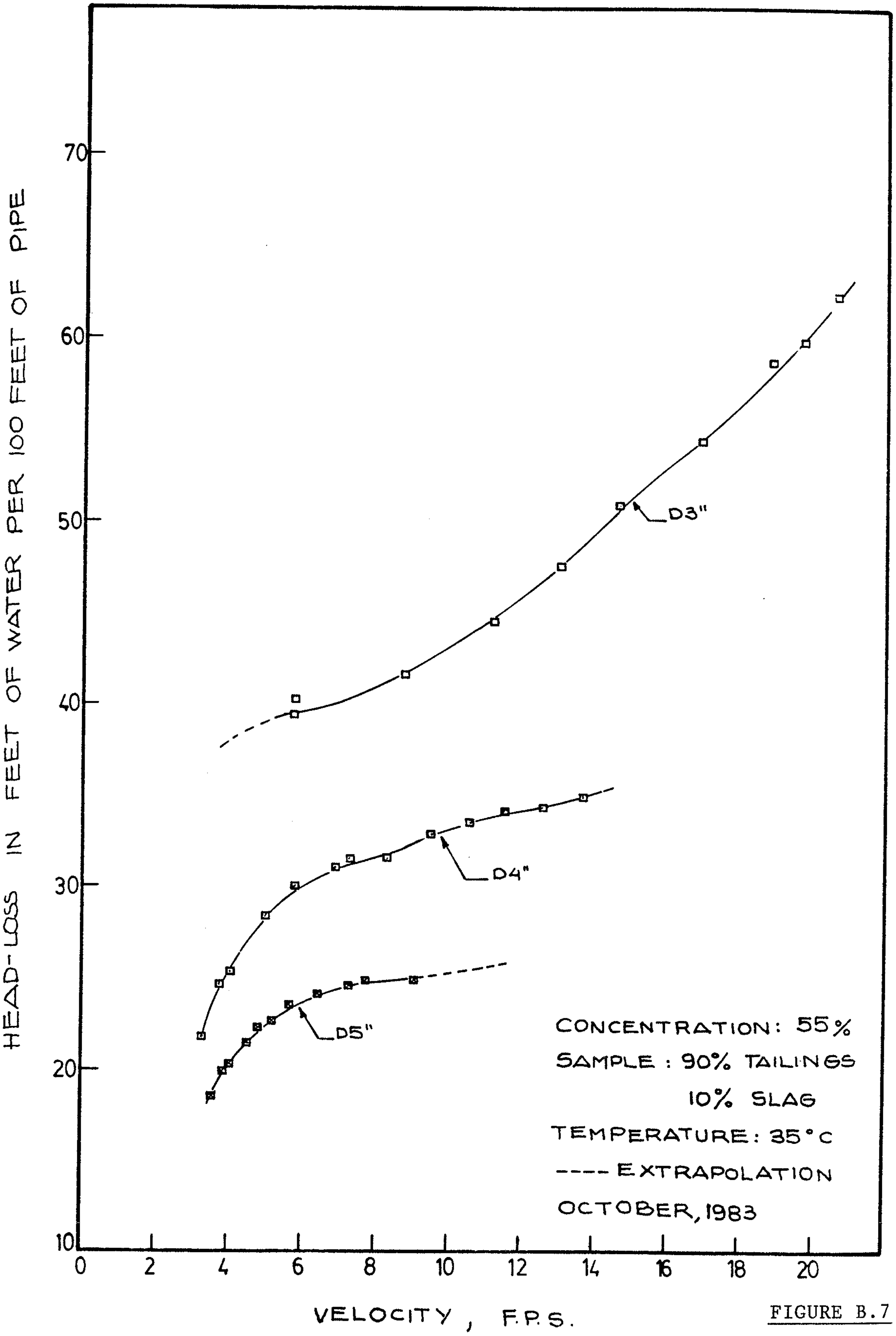

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
D3"
D4"
D5"
CONCENTRATION: 55%
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE: 25°C
---- EXTRAPOLATION
OCTOBER, 1983
VELOCITY, F.P.S.

FIGURE B.6



HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D3"
D4"
D5"
CONCENTRATION: 55%
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE: 35°C
---- EXTRAPOLATION
OCTOBER, 1983

FIGURE B.7

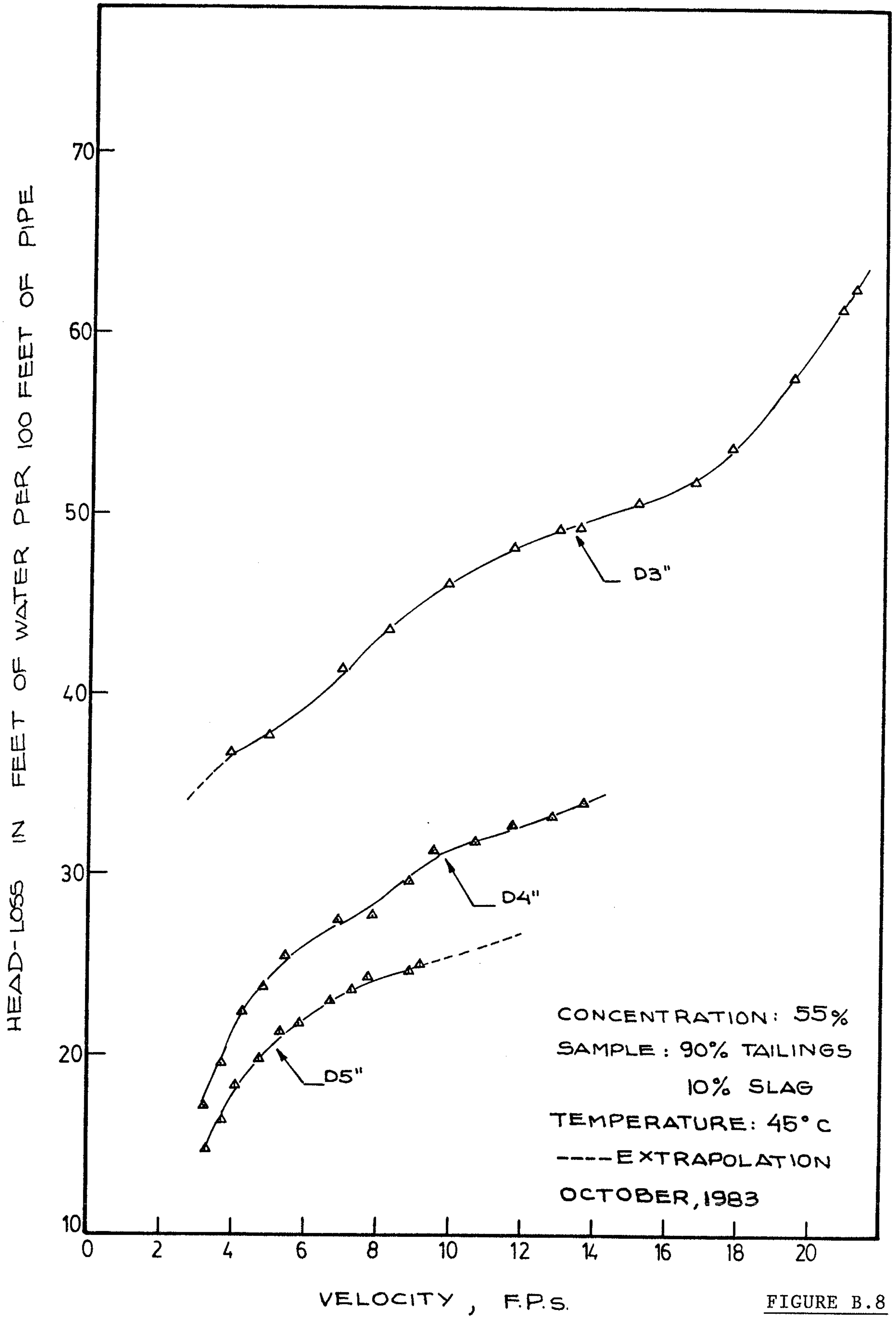

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D3"
D4"
D5"
CONCENTRATION: 55%
SAMPLE: 90% TAILINGS
10% SLAG
TEMPERATURE: 45° C
----EXTRAPOLATION
OCTOBER, 1983

FIGURE B.8

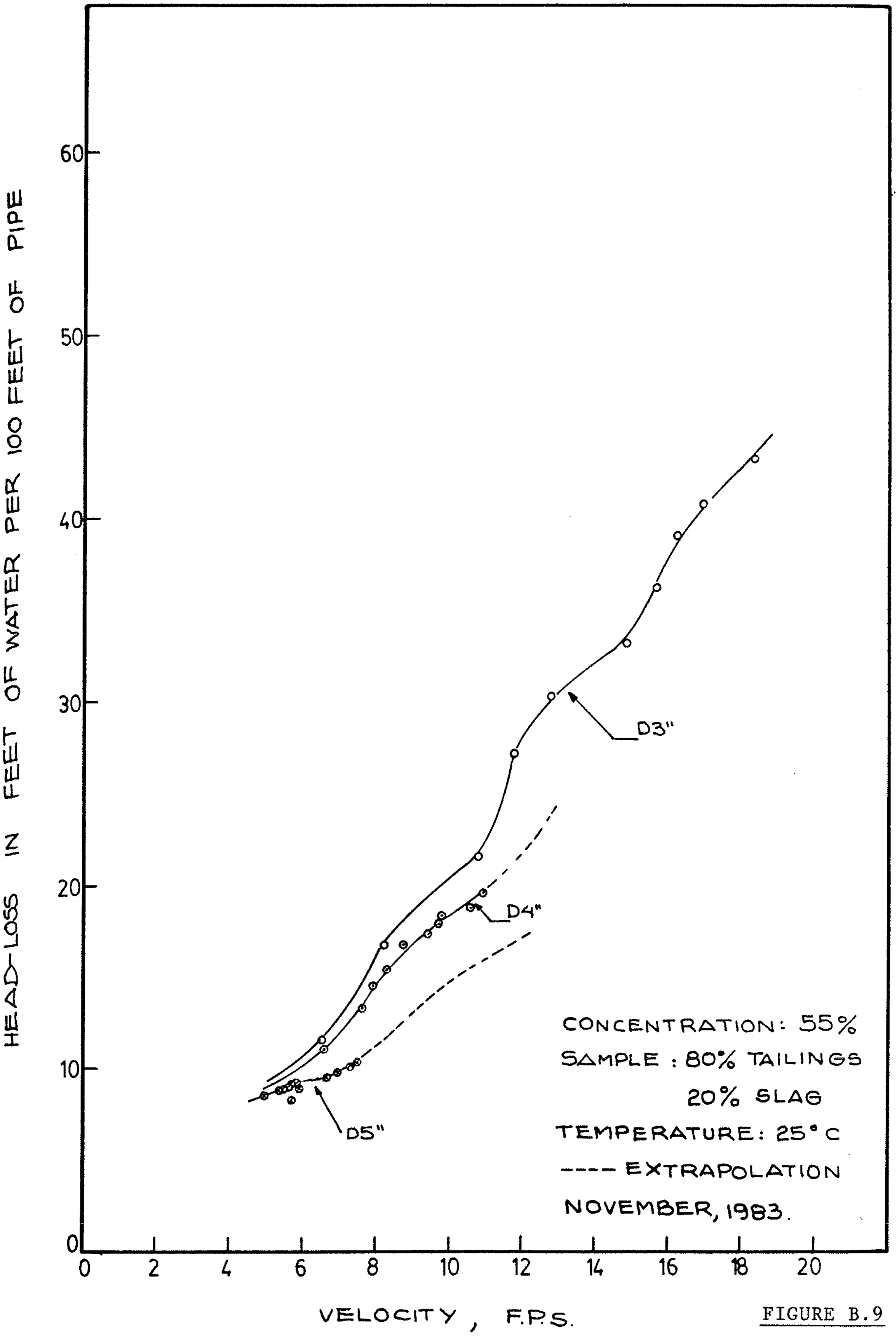

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
VELOCITY , F.P.S.
0
2
4
6
8
10
12
14
16
18
20
D3"
D4"
D5"
CONCENTRATION: 55%
SAMPLE : 80% TAILINGS
20% SLAG
TEMPERATURE: 25° C
---- EXTRAPOLATION
NOVEMBER, 1983.

FIGURE B.9

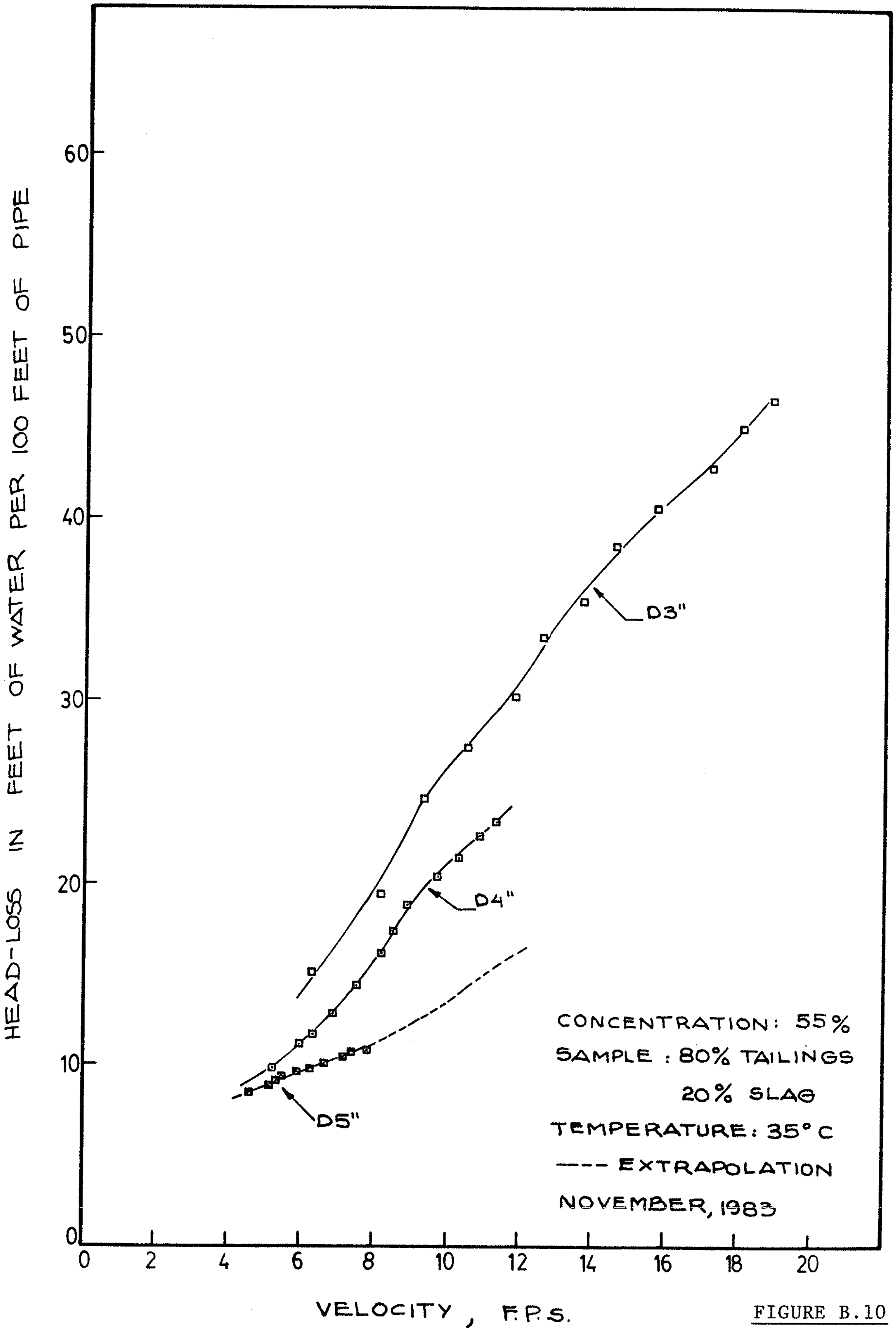

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D3"
D4"
D5"
CONCENTRATION: 55%
SAMPLE : 80% TAILINGS
20% SLAG
TEMPERATURE: 35° C
---- EXTRAPOLATION
NOVEMBER, 1983

FIGURE B.10

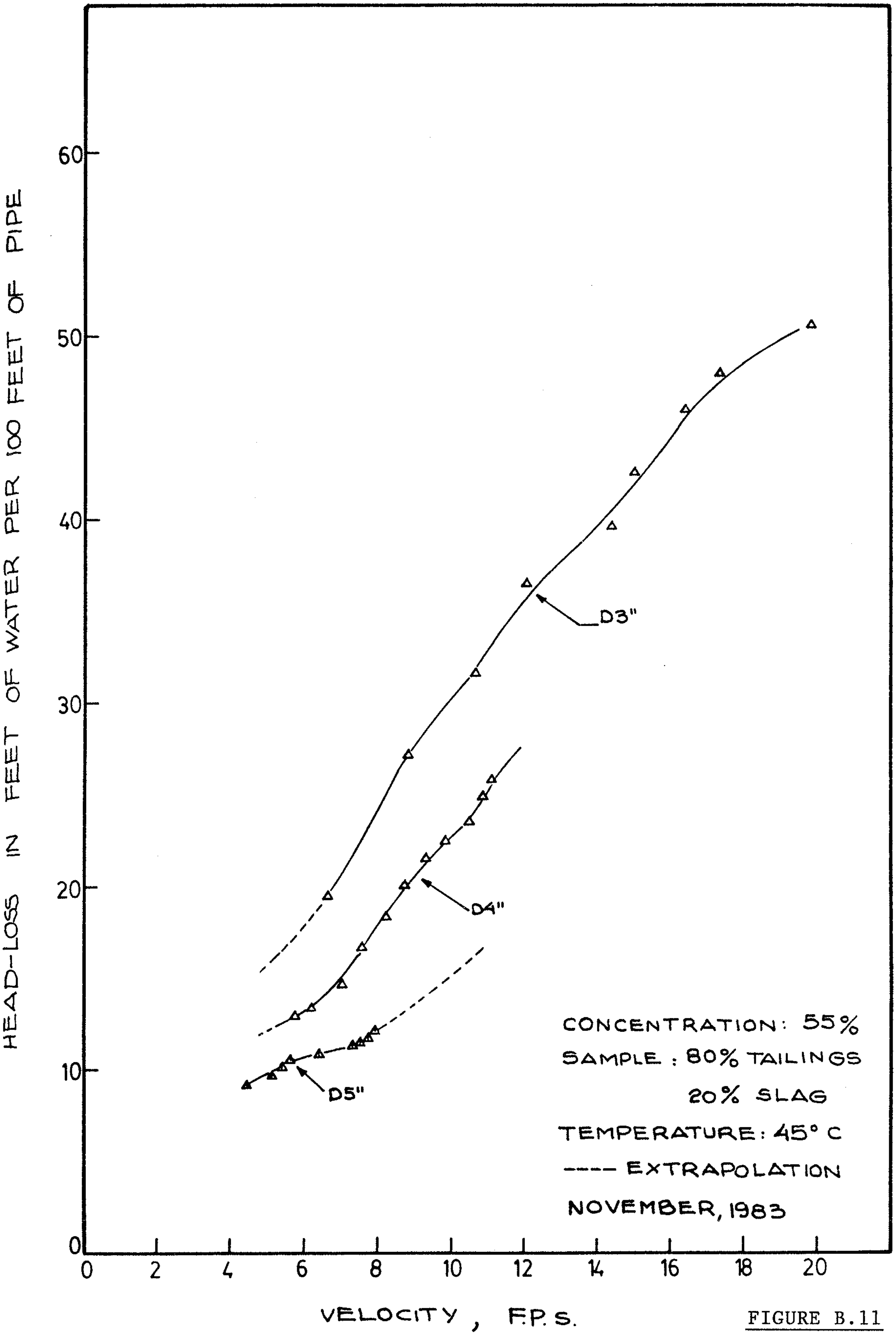

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
VELOCITY, F.P.S.
0
2
4
6
8
10
12
14
16
18
20
D3"
D4"
D5"
CONCENTRATION: 55%
SAMPLE : 80% TAILINGS
20% SLAG
TEMPERATURE: 45° C
---- EXTRAPOLATION
NOVEMBER, 1983

FIGURE B.11

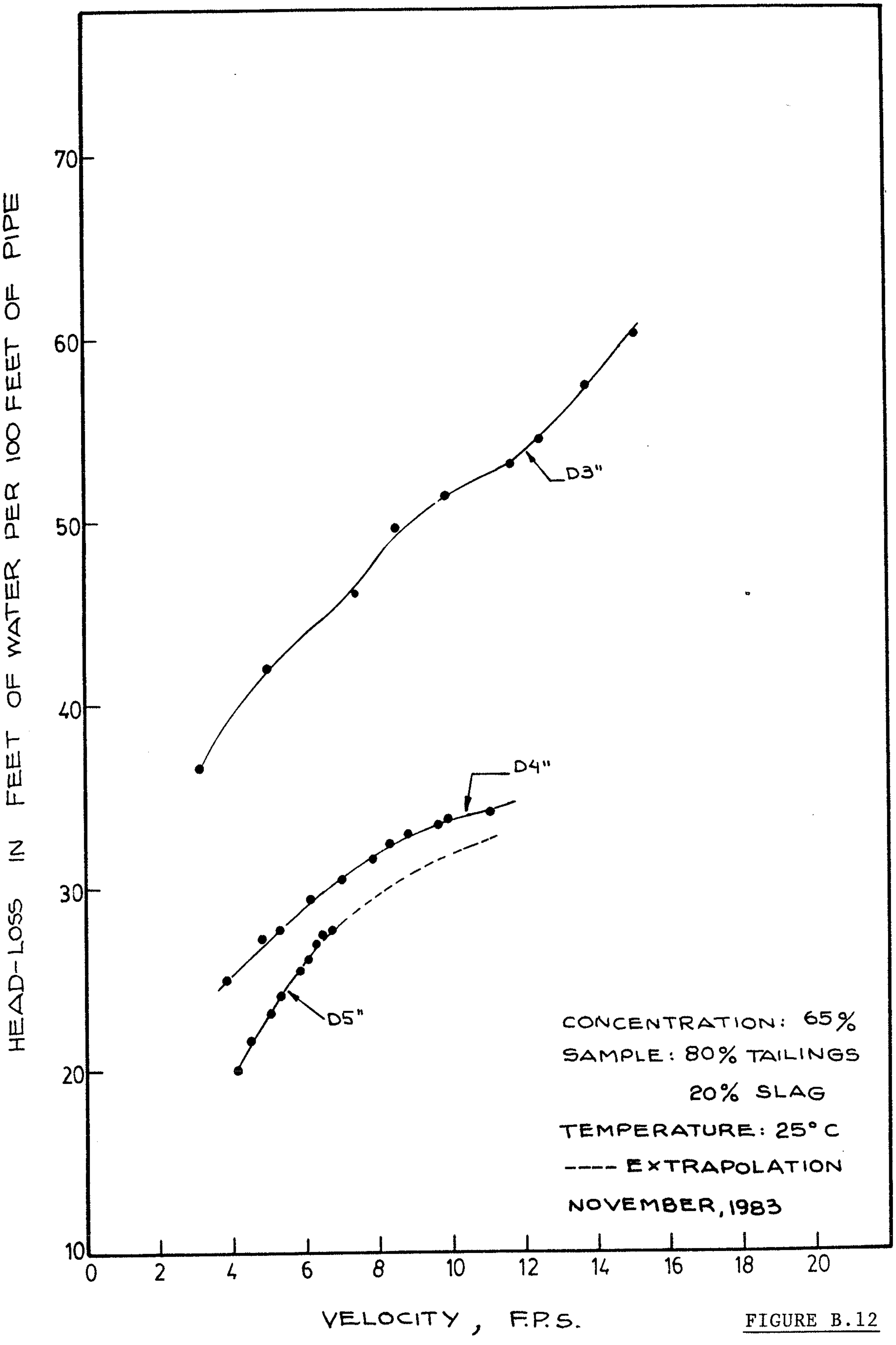

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
VELOCITY , F.P.S.
D3"
D4"
D5"
CONCENTRATION: 65%
SAMPLE: 80% TAILINGS
20% SLAG
TEMPERATURE: 25° C
---- EXTRAPOLATION
NOVEMBER, 1983

FIGURE B.12

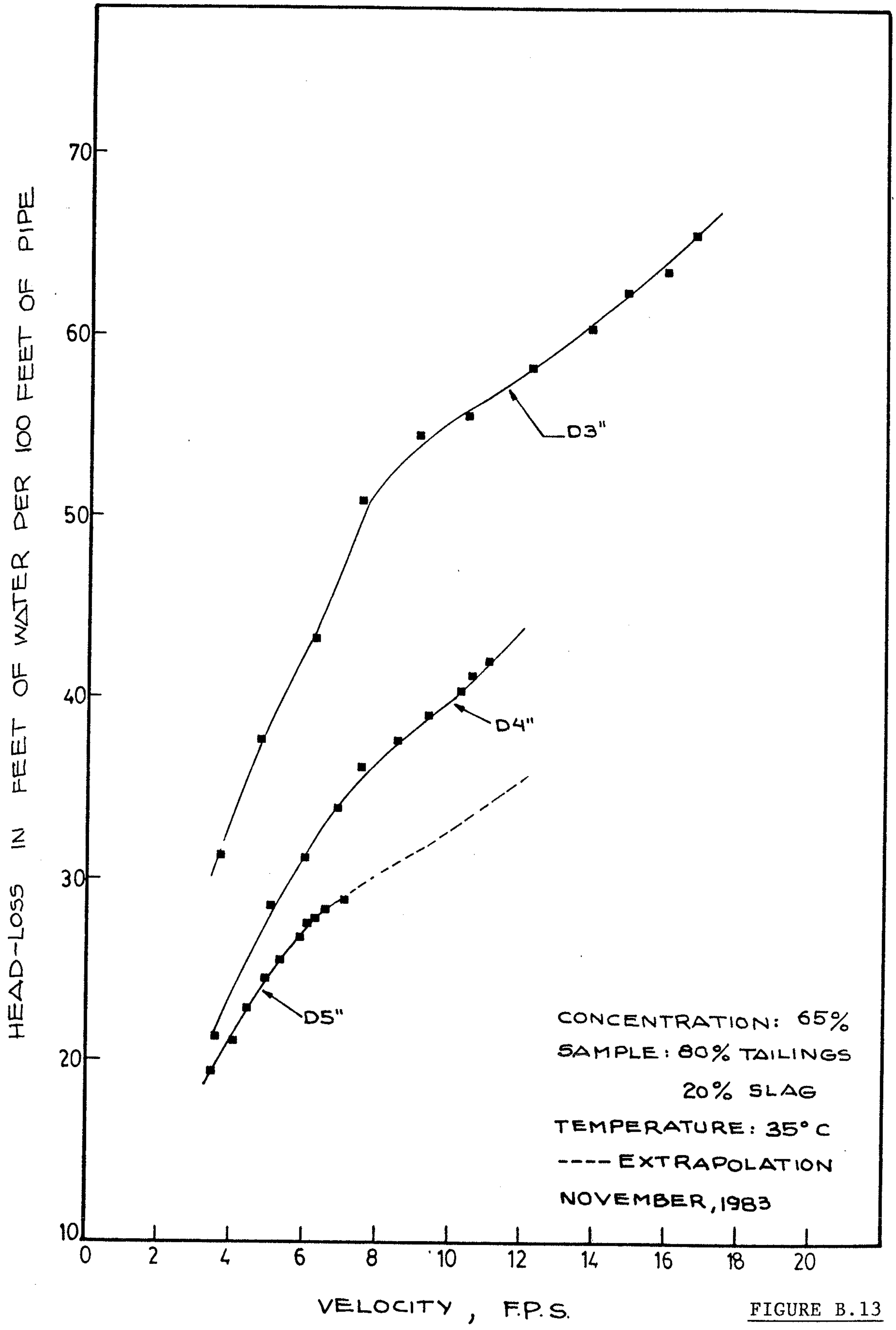

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
VELOCITY , F.P.S.
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20
D3"
D4"
D5"
CONCENTRATION: 65%
SAMPLE: 80% TAILINGS
20% SLAG
TEMPERATURE: 35° C
---- EXTRAPOLATION
NOVEMBER, 1983

FIGURE B.13

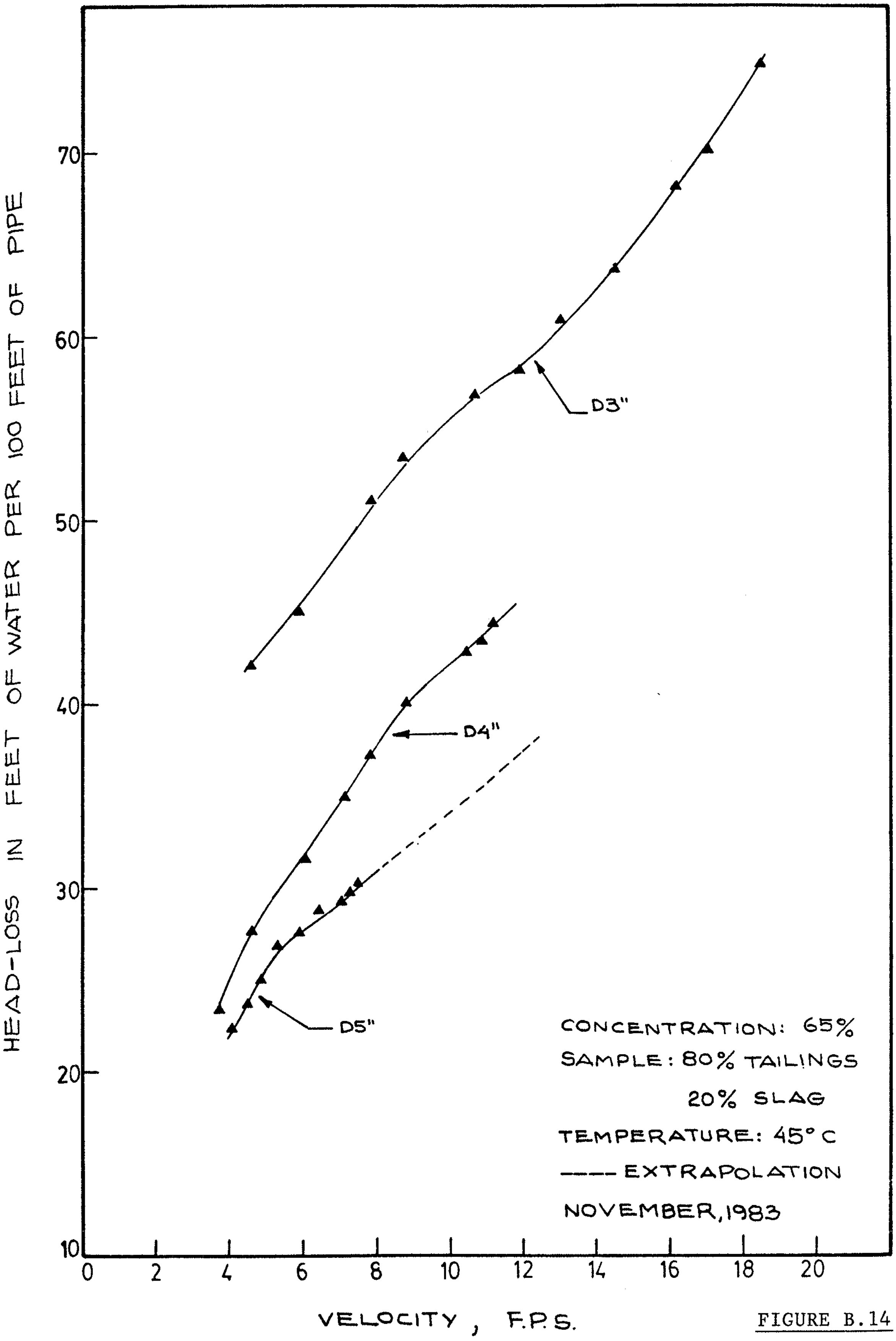

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20
VELOCITY, F.P.S.
D3"
D4"
D5"
CONCENTRATION: 65%
SAMPLE: 80% TAILINGS
20% SLAG
TEMPERATURE: 45° C
---- EXTRAPOLATION
NOVEMBER, 1983

FIGURE B.14

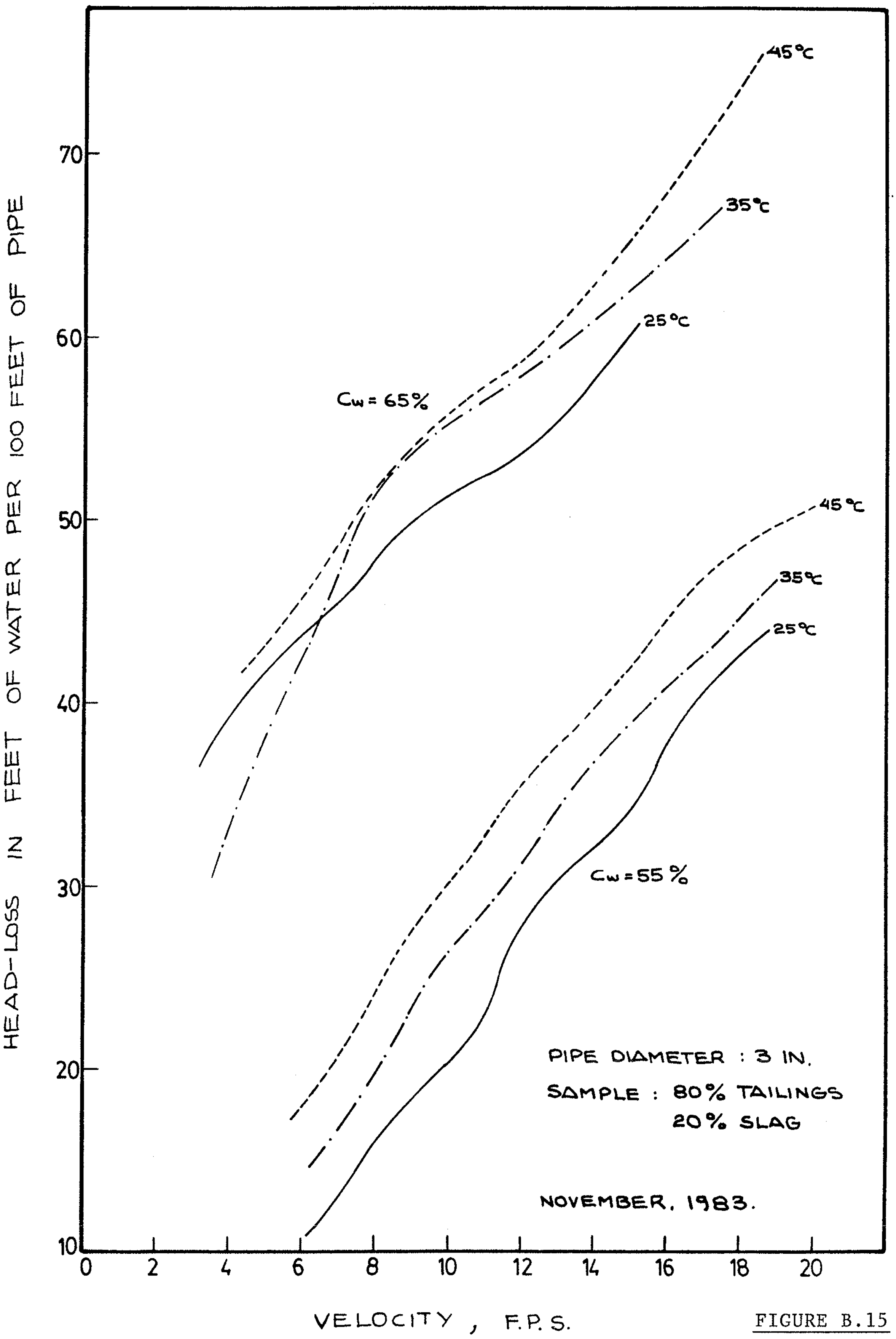

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
VELOCITY , F.P.S.
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20
Cw = 65%
45°C
35°C
25°C
Cw = 55%
45°C
35°C
25°C
PIPE DIAMETER : 3 IN.
SAMPLE : 80% TAILINGS
20% SLAG
NOVEMBER, 1983.

FIGURE B.15

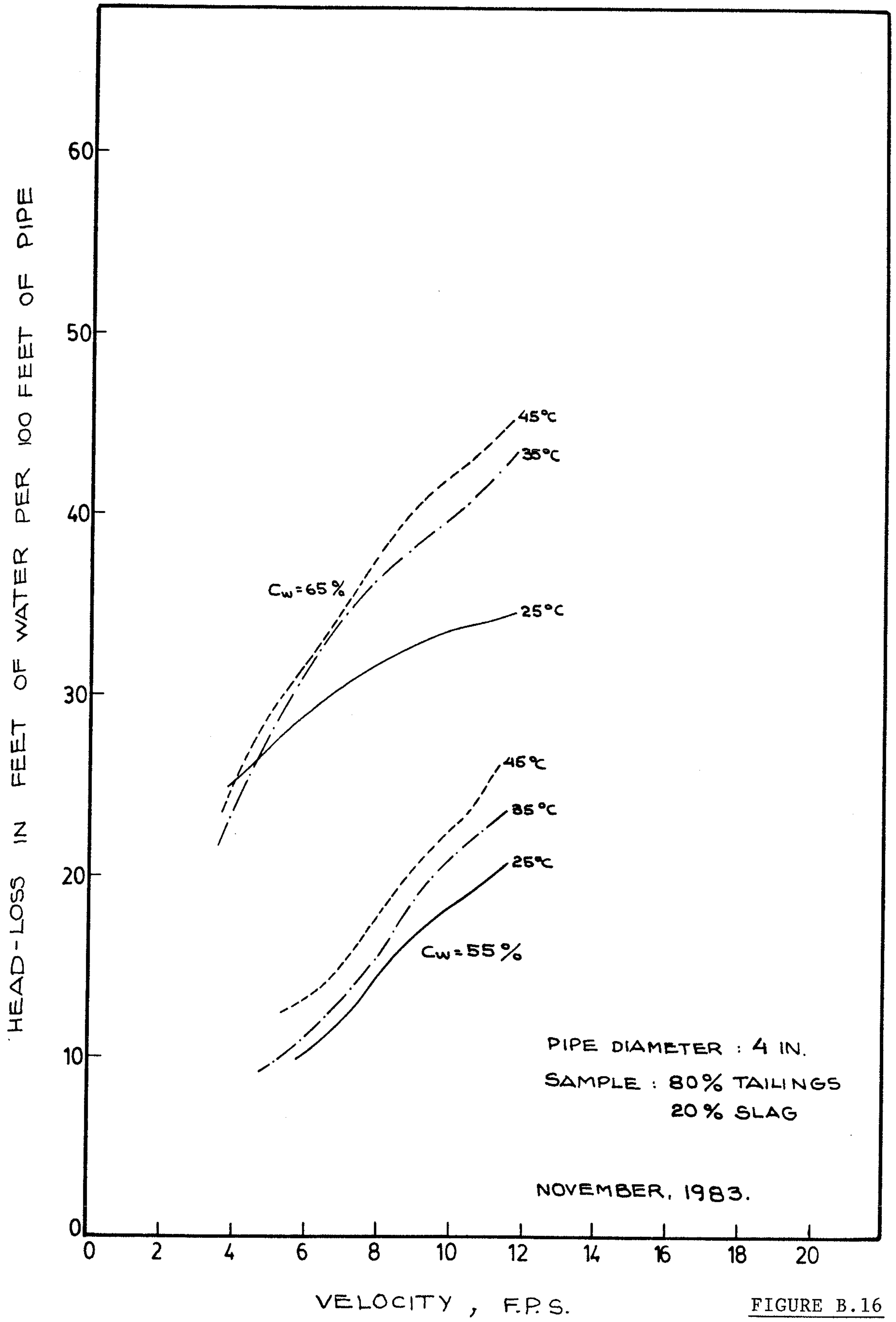

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
0
10
20
30
40
50
60
VELOCITY , F.P.S.
0
2
4
6
8
10
12
14
16
18
20
45°C
35°C
25°C
Cw=65%
45°C
35°C
25°C
Cw=55%
PIPE DIAMETER : 4 IN.
SAMPLE : 80% TAILINGS
20% SLAG
NOVEMBER, 1983.

FIGURE B.16

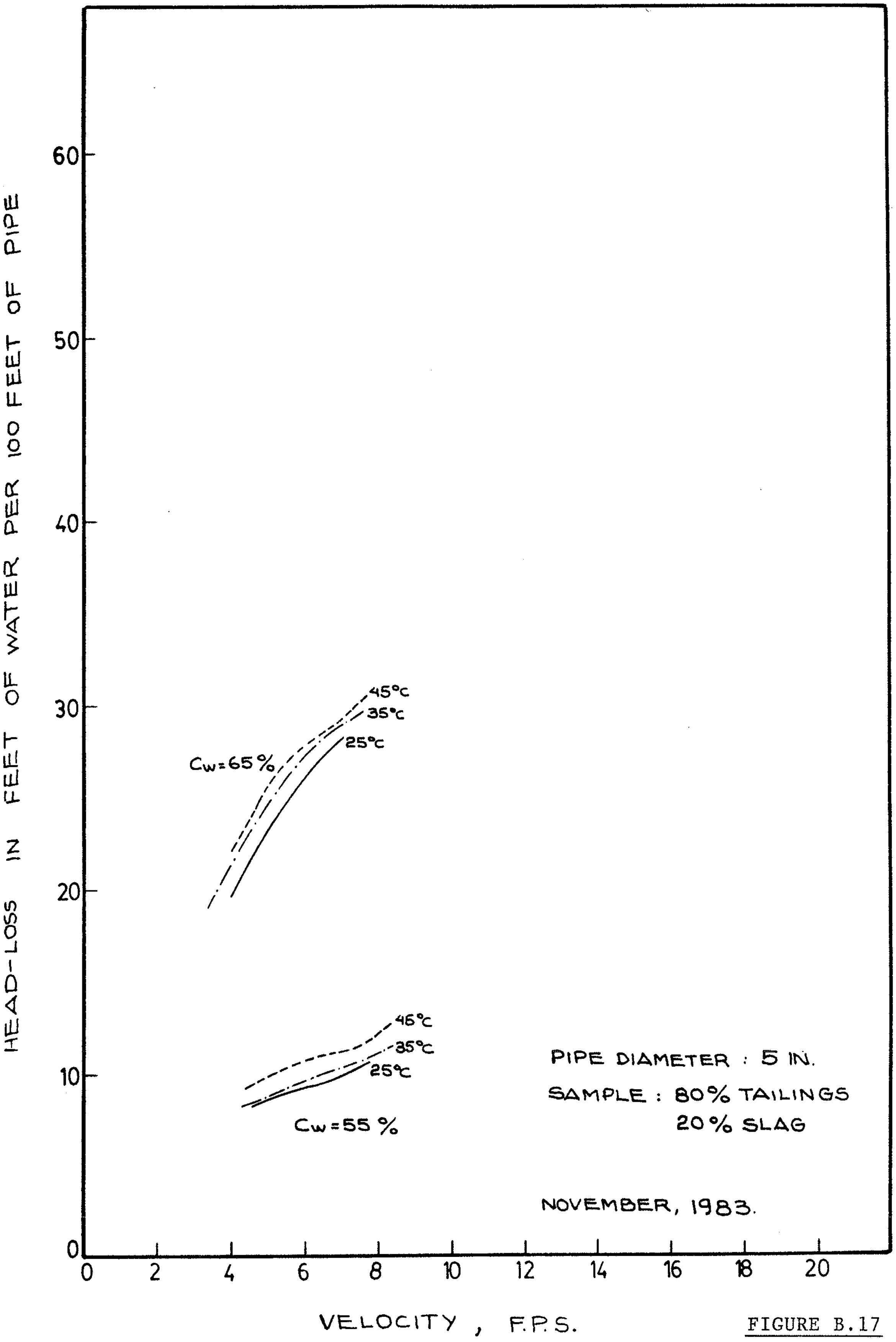
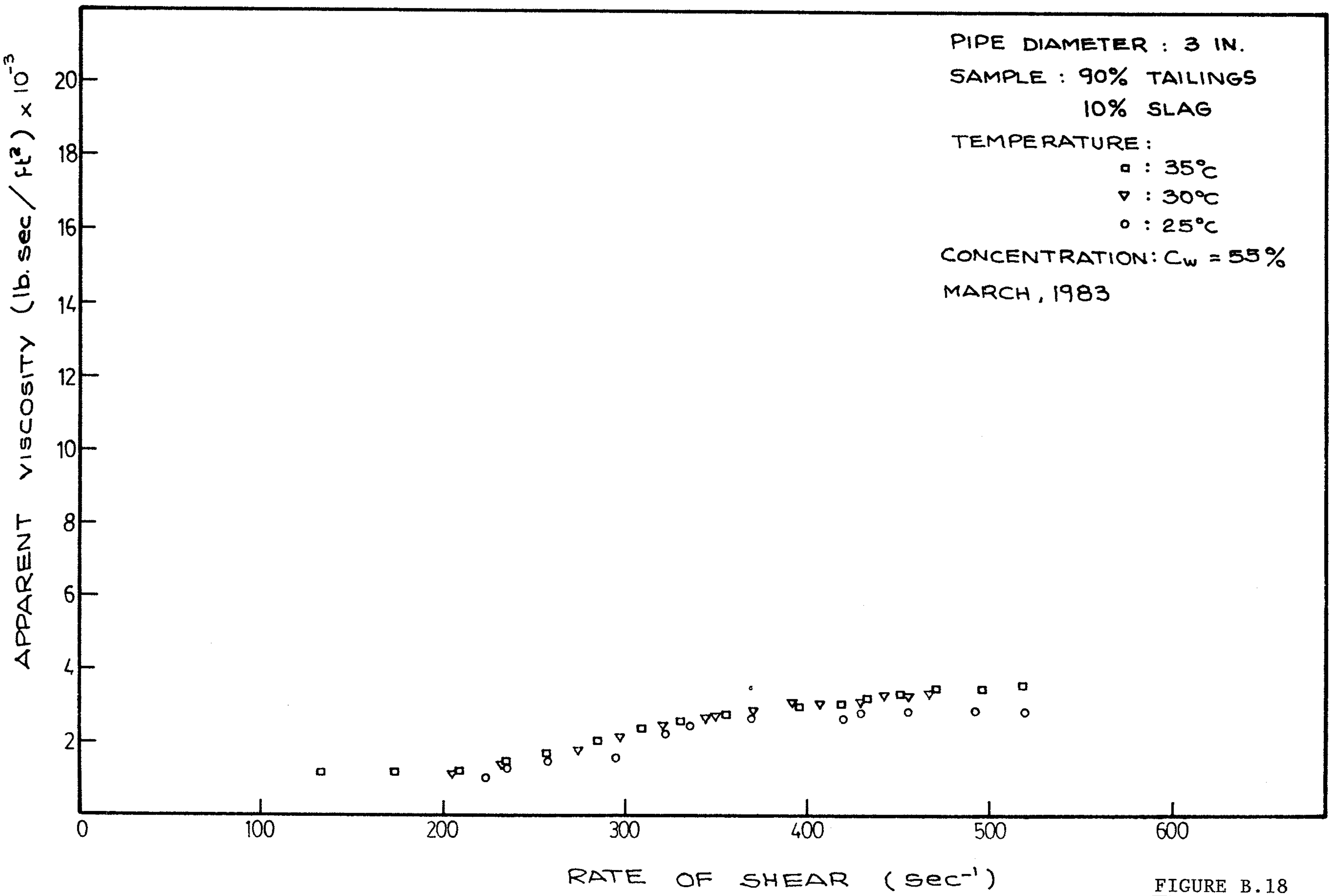

HEAD-LOSS IN FEET OF WATER PER 100 FEET OF PIPE
VELOCITY , F.P.S.
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
Cw=65%
45°C
35°C
25°C
Cw=55%
46°C
35°C
25°C
PIPE DIAMETER : 5 IN.
SAMPLE : 80% TAILINGS
20% SLAG
NOVEMBER, 1983.

FIGURE B.17



PIPE DIAMETER : 3 IN.
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE :
□ : 35°C
▽ : 30°C
○ : 25°C
CONCENTRATION: Cw = 55%
MARCH, 1983
APPARENT VISCOSITY (lb. sec / ft²) x 10⁻³
20
18
16
14
12
10
8
6
4
2
0
100
200
300
400
500
600
RATE OF SHEAR (sec⁻¹)

FIGURE B.18

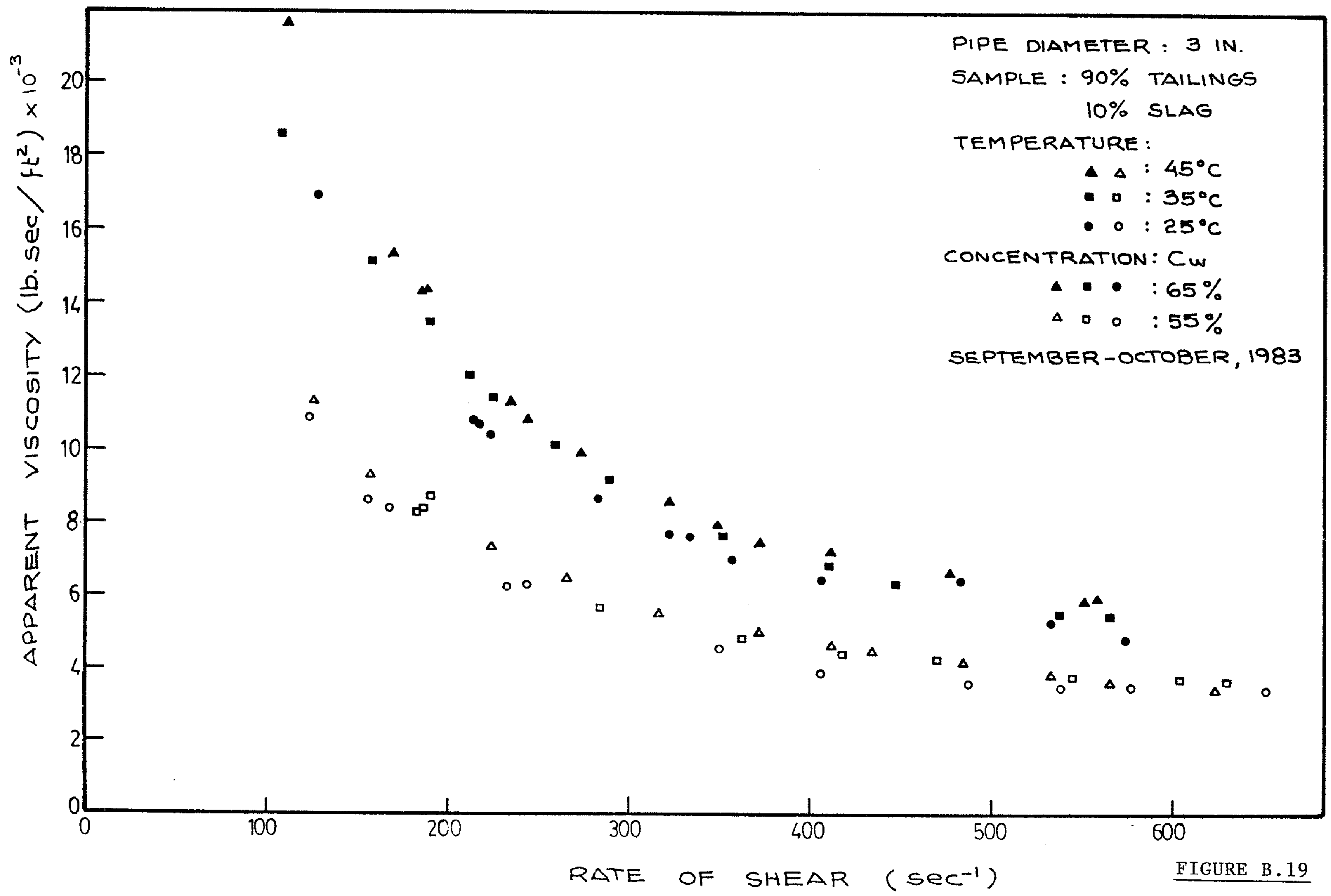

PIPE DIAMETER : 3 IN.
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE :
▲ △ : 45°C
■ □ : 35°C
● ○ : 25°C
CONCENTRATION : Cw
▲ ■ ● : 65 %
△ □ ○ : 55 %
SEPTEMBER-OCTOBER, 1983
APPARENT VISCOSITY (lb.sec/ft²) x 10⁻³
0
2
4
6
8
10
12
14
16
18
20
0
100
200
300
400
500
600
RATE OF SHEAR (sec⁻¹)

FIGURE B.19

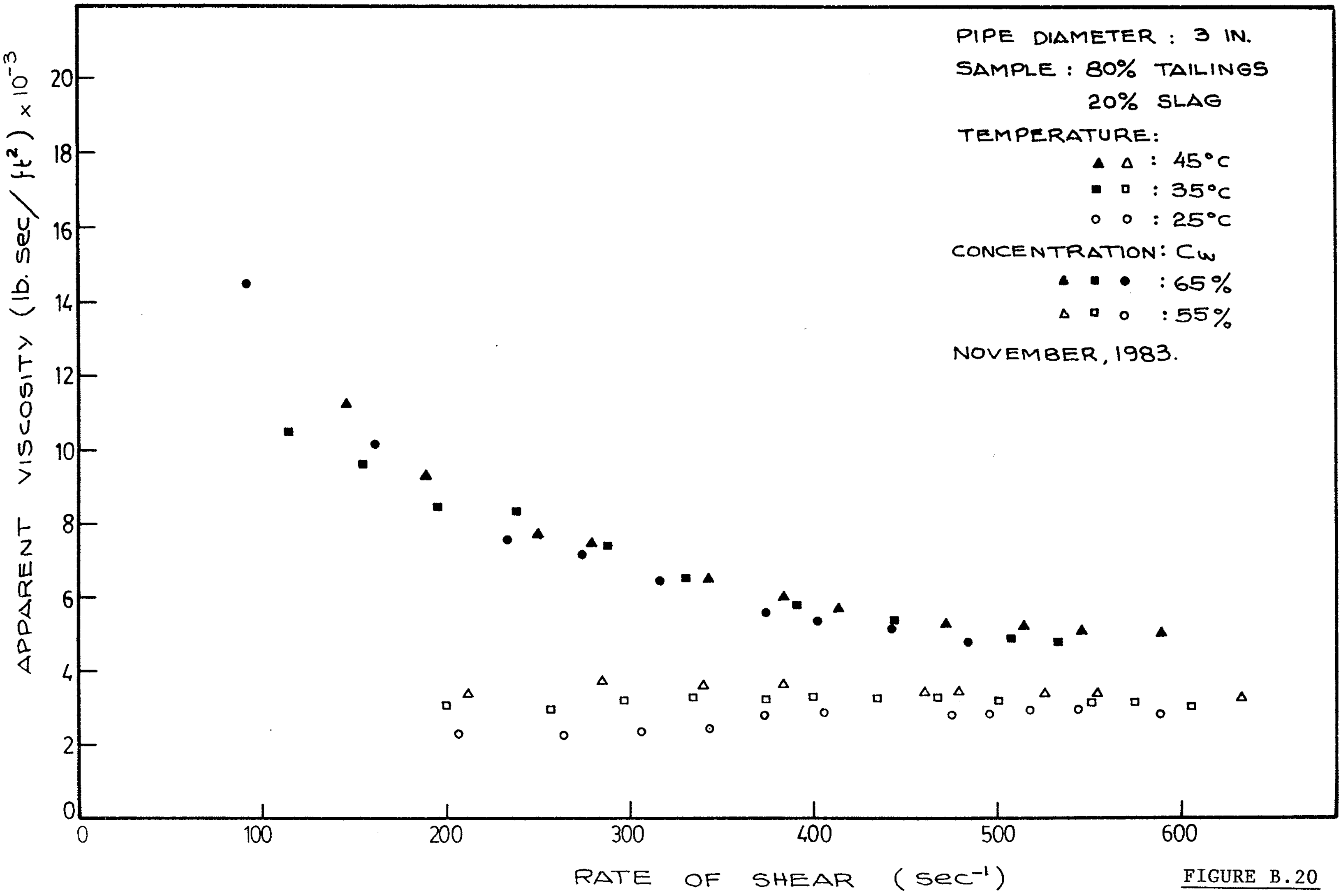
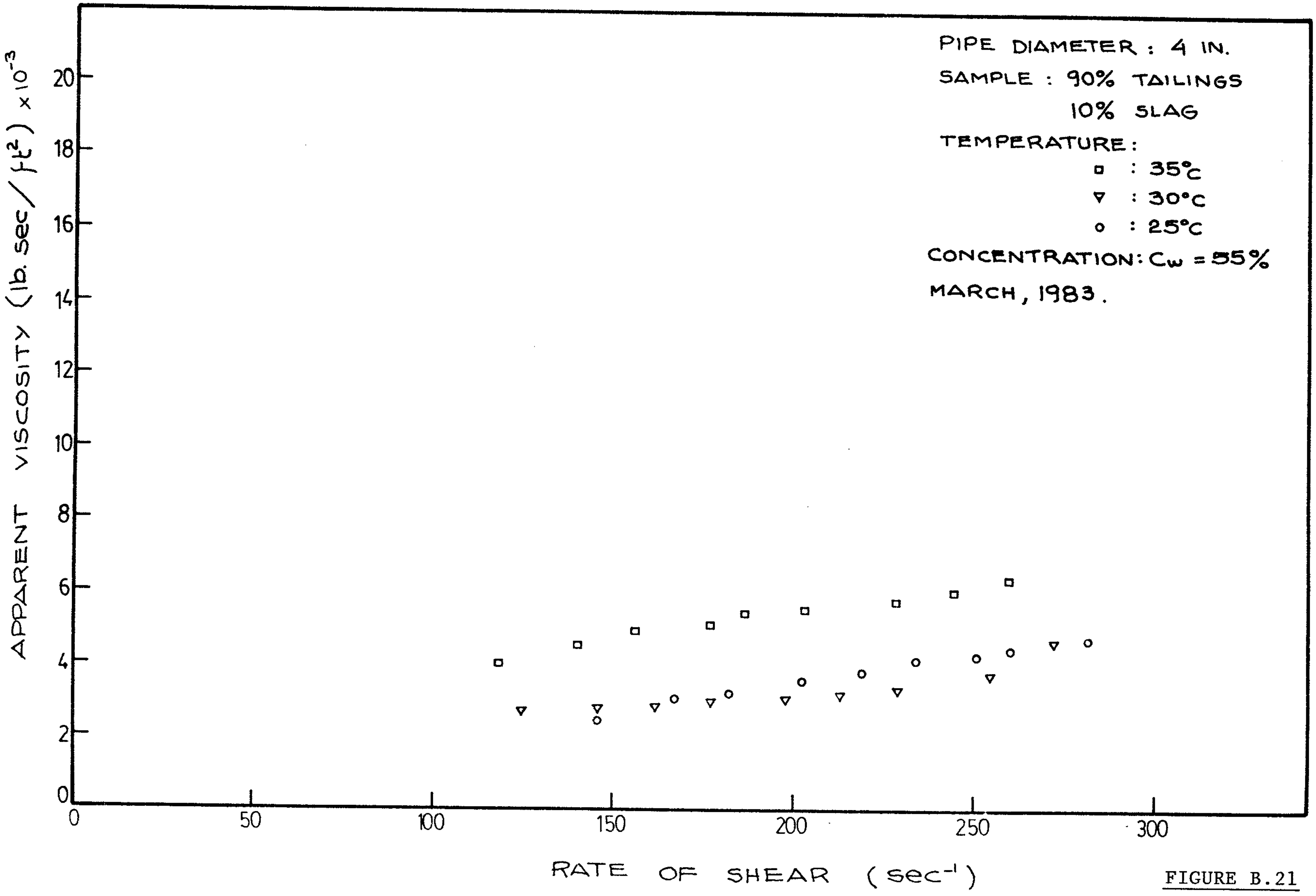
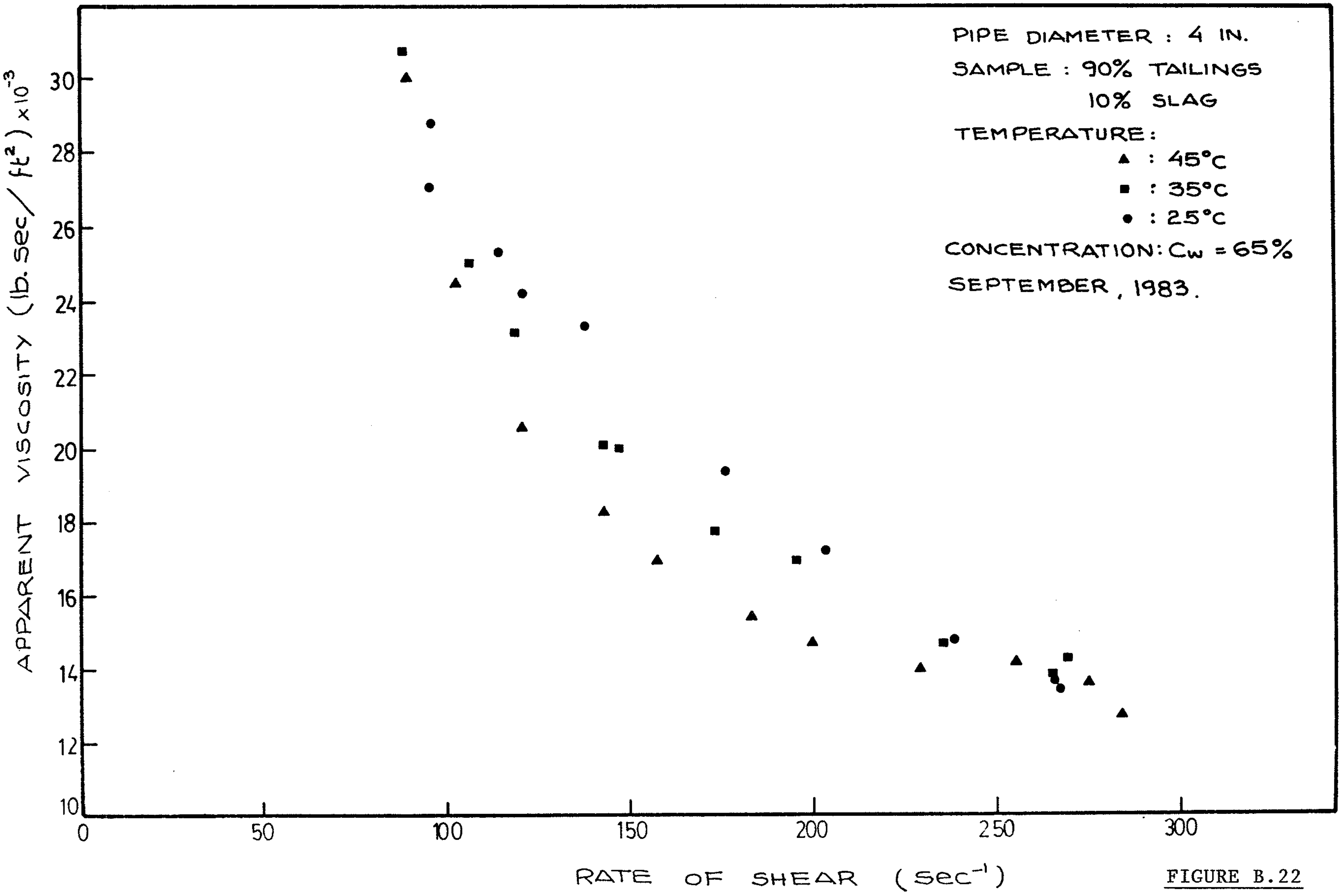

PIPE DIAMETER : 3 IN.
SAMPLE : 80% TAILINGS
20% SLAG
TEMPERATURE:
▲ △ : 45°c
■ □ : 35°c
● ○ : 25°c
CONCENTRATION: Cw
▲ ■ ● : 65%
△ □ ○ : 55%
NOVEMBER, 1983.
APPARENT VISCOSITY (lb. sec/ft²) × 10⁻³
0
2
4
6
8
10
12
14
16
18
20
0
100
200
300
400
500
600
RATE OF SHEAR (sec⁻¹)

FIGURE B.20



PIPE DIAMETER : 4 IN.
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE :
□ : 35°C
▽ : 30°C
○ : 25°C
CONCENTRATION : Cw = 55%
MARCH, 1983.
APPARENT VISCOSITY (lb. sec/ft²) x 10⁻³
0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
RATE OF SHEAR (sec⁻¹)

FIGURE B.21



PIPE DIAMETER : 4 IN.
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE:
▲ : 45°C
■ : 35°C
● : 25°C
CONCENTRATION: Cw = 65%
SEPTEMBER, 1983.
APPARENT VISCOSITY (lb. sec/ft²) x10⁻³
30
28
26
24
22
20
18
16
14
12
10
0
50
100
150
200
250
300
RATE OF SHEAR (sec⁻¹)

FIGURE B.22

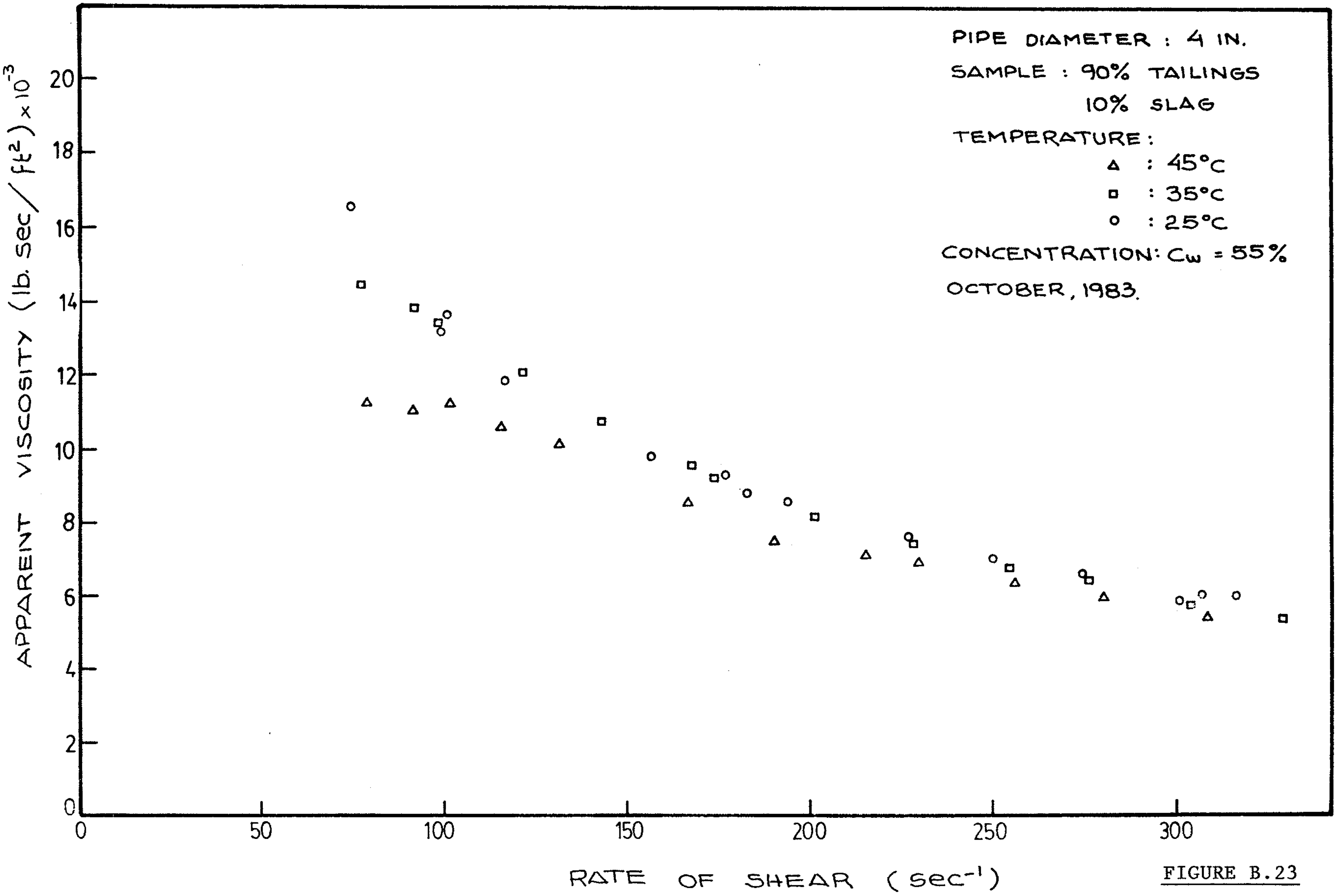

PIPE DIAMETER : 4 IN.
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE :
△ : 45°C
□ : 35°C
○ : 25°C
CONCENTRATION: Cw = 55%
OCTOBER, 1983.
APPARENT VISCOSITY (lb. sec / ft²) × 10⁻³
0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
RATE OF SHEAR (sec⁻¹)

FIGURE B.23

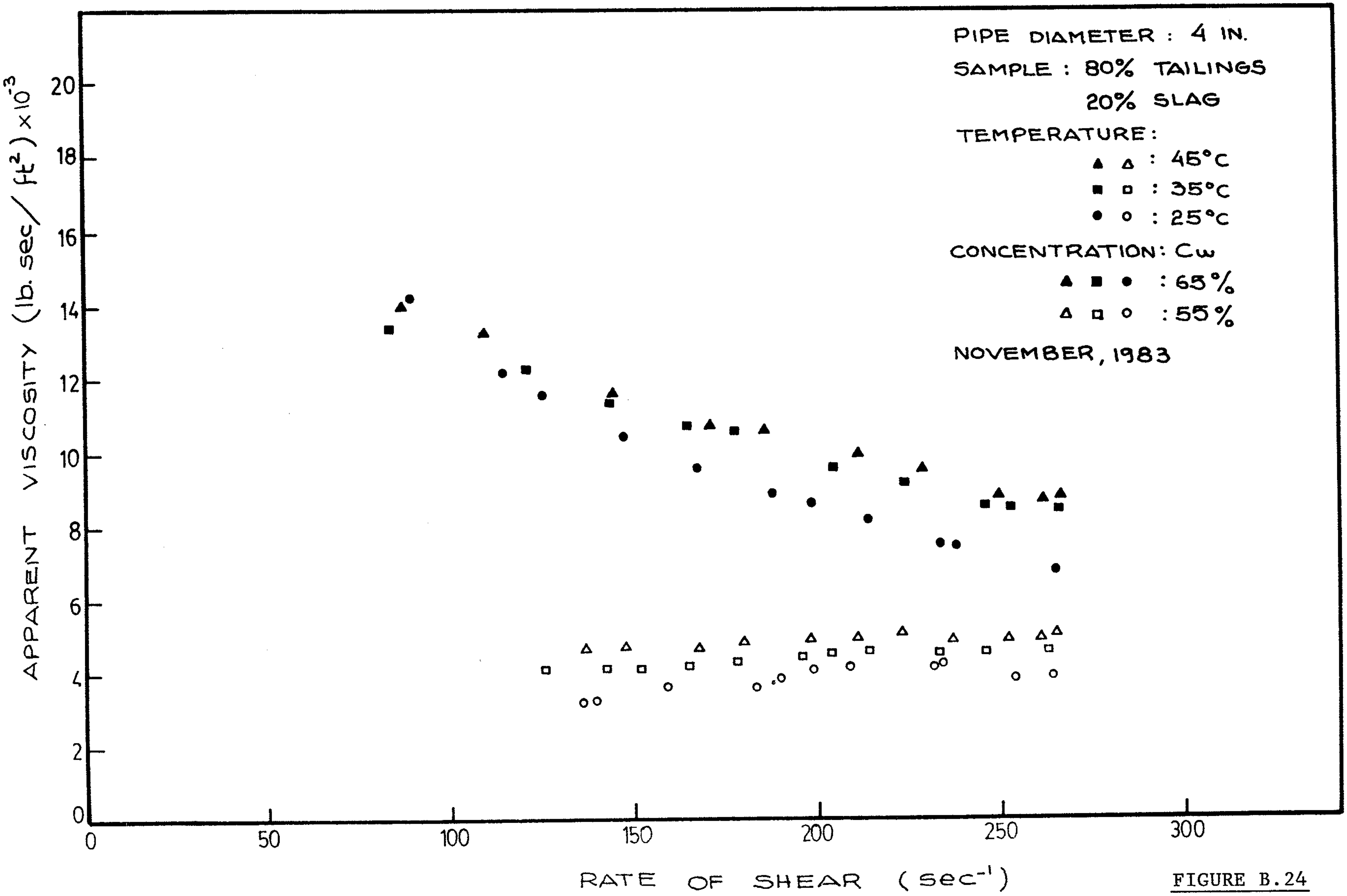

PIPE DIAMETER : 4 IN.
SAMPLE : 80% TAILINGS
20% SLAG
TEMPERATURE:
▲ △ : 45°C
■ □ : 35°C
● ○ : 25°C
CONCENTRATION: Cw
▲ ■ ● : 65%
△ □ ○ : 55%
NOVEMBER, 1983
APPARENT VISCOSITY (lb. sec/ft^2) ×10^{-3}
0
2
4
6
8
10
12
14
16
18
20
RATE OF SHEAR (sec^{-1})
0
50
100
150
200
250
300

FIGURE B.24

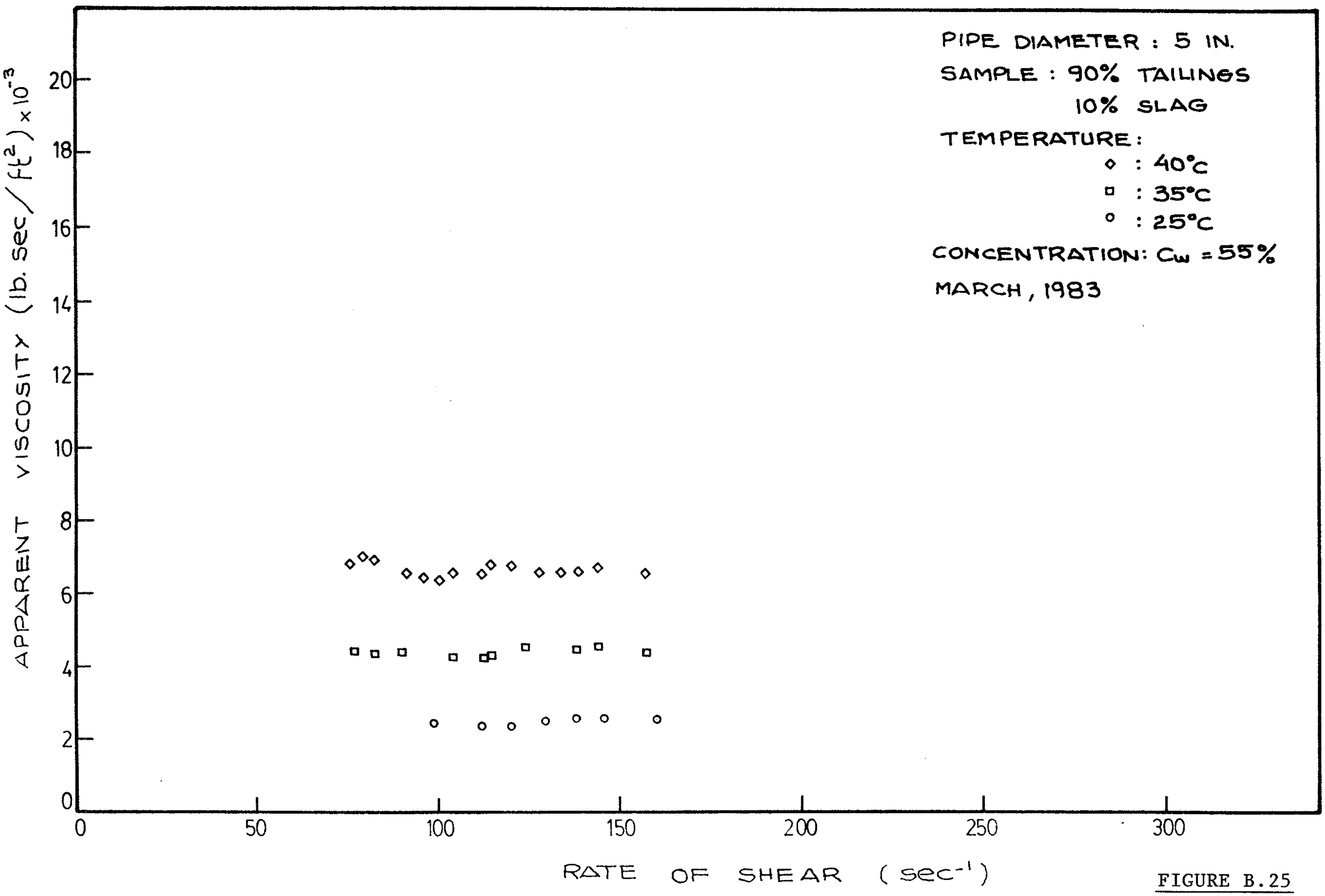
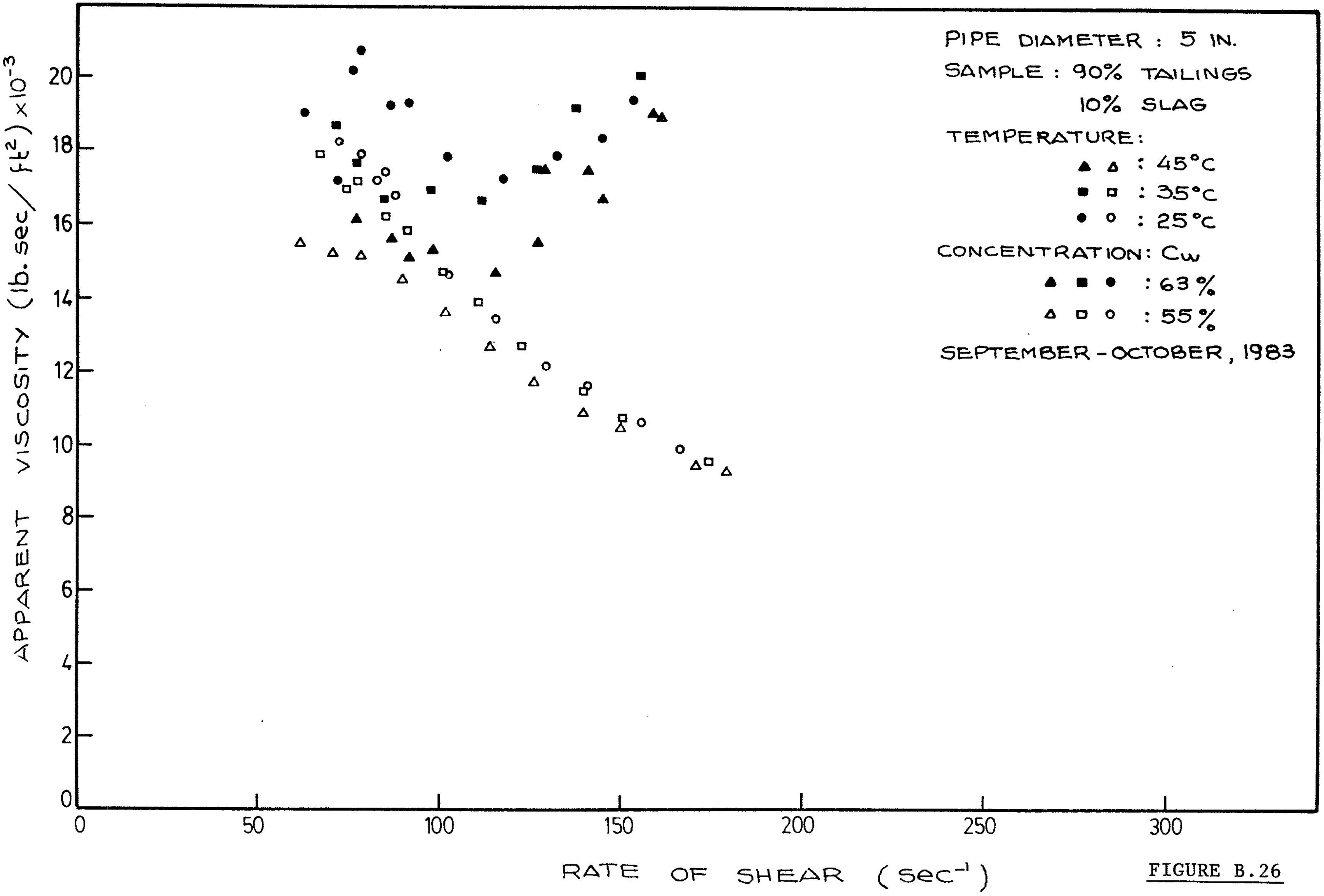

PIPE DIAMETER : 5 IN.
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE :
◇ : 40°C
□ : 35°C
○ : 25°C
CONCENTRATION: Cw = 55%
MARCH, 1983
APPARENT VISCOSITY (lb. sec/ft²) x 10⁻³
0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
RATE OF SHEAR (sec⁻¹)

FIGURE B.25



PIPE DIAMETER : 5 IN.
SAMPLE : 90% TAILINGS
10% SLAG
TEMPERATURE:
▲ △ : 45°C
■ □ : 35°C
● ○ : 25°C
CONCENTRATION: Cw
▲ ■ ● : 63%
△ □ ○ : 55%
SEPTEMBER-OCTOBER, 1983
APPARENT VISCOSITY (lb. sec/ft²) ×10⁻³
0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
RATE OF SHEAR (sec⁻¹)

FIGURE B.26

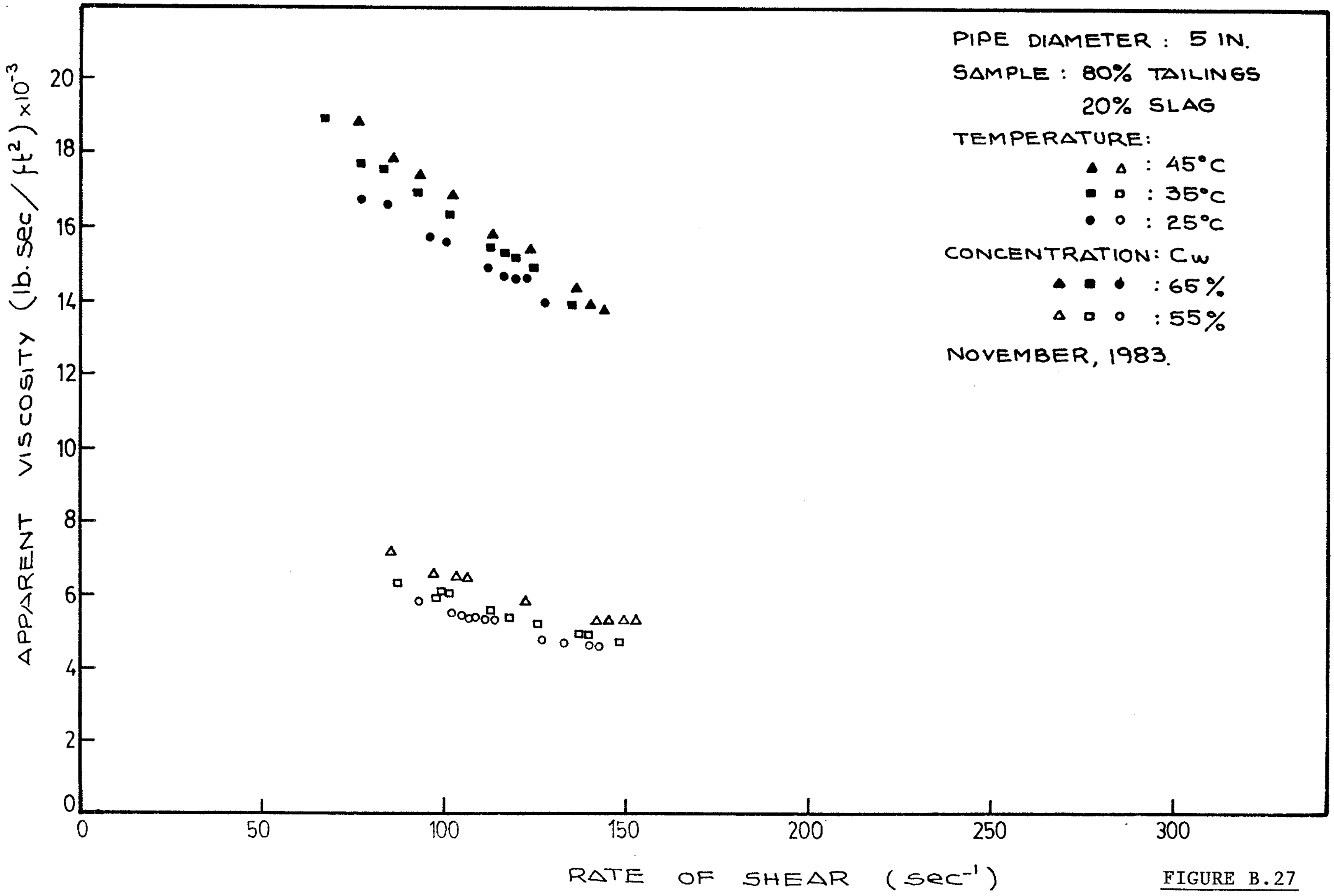
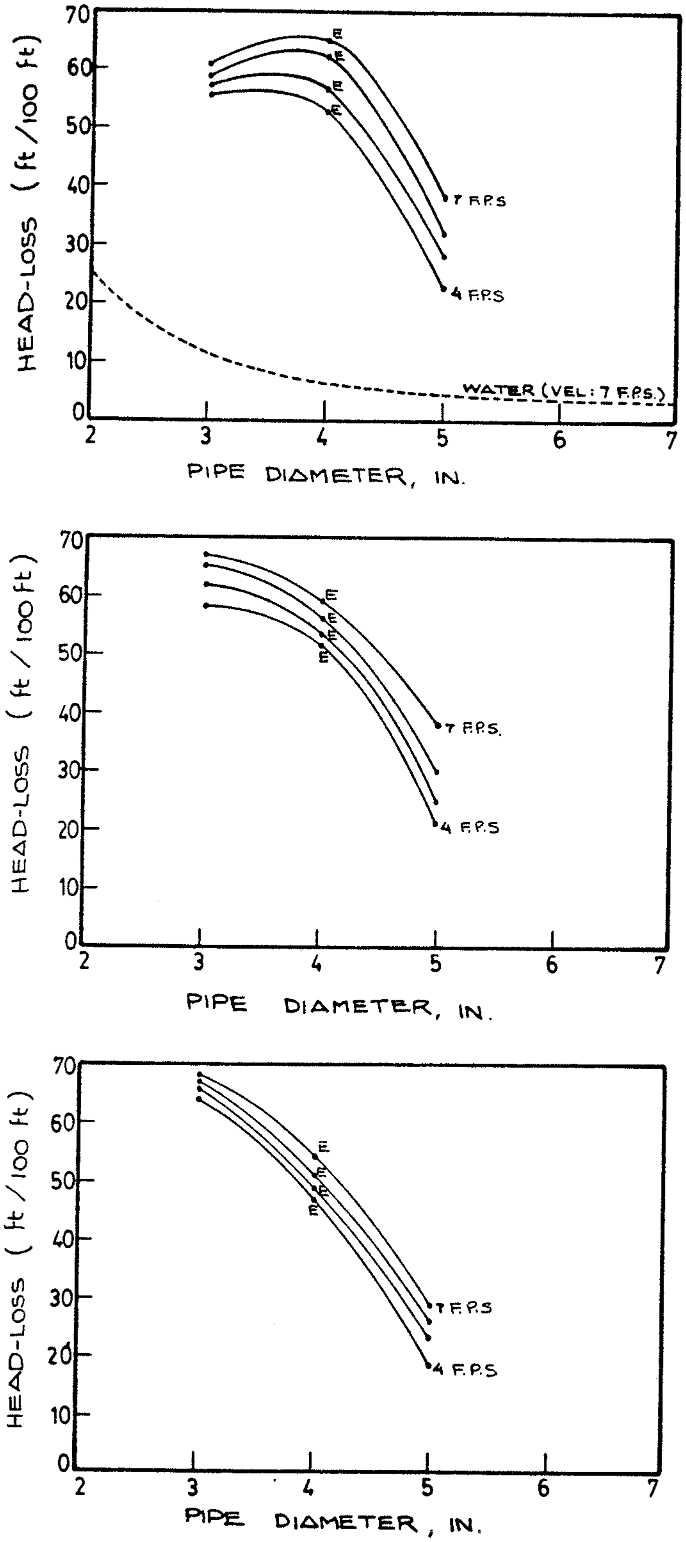

PIPE DIAMETER : 5 IN.
SAMPLE : 80% TAILINGS
20% SLAG
TEMPERATURE:
▲ △ : 45°C
■ □ : 35°C
● ○ : 25°C
CONCENTRATION: Cw
▲ ■ ● : 65%
△ □ ○ : 55%
NOVEMBER, 1983.
APPARENT VISCOSITY (lb. sec/ft^2) ×10^{-3}
0
2
4
6
8
10
12
14
16
18
20
RATE OF SHEAR (sec^{-1})
0
50
100
150
200
250
300

FIGURE B.27



a

SAMPLE : 90/10

C_w = 65% (3", 4")

C_w = 63 % (5")

TEMPERATURE: 25°C

VEL.: 4, 5, 6, 7 F.P.S.

SEPTEMBER, 1983

b

SAMPLE : 90/10

C_w = 65% (3", 4")

C_w = 63% (5")

TEMPERATURE : 35°C

VEL. : 4, 5, 6, 7 F.P.S.

SEPTEMBER, 1983

c

SAMPLE : 90/10

C_w = 65% (3", 4")

C_w = 63% (5")

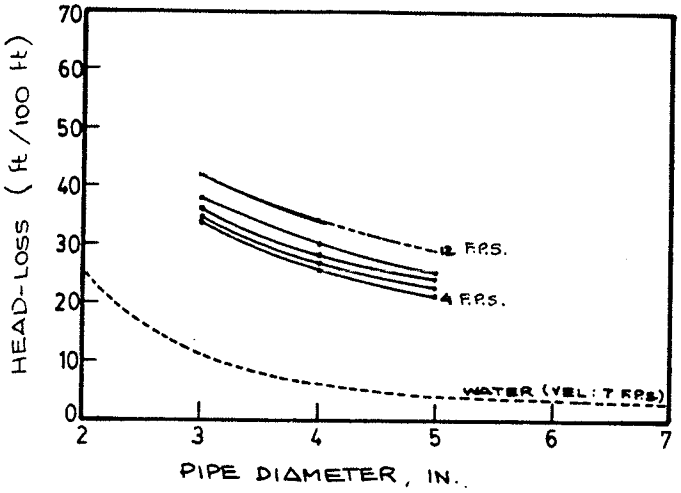
TEMPERATURE : 45°C

VEL.: 4, 5, 6, 7 F.P.S.

SEPTEMBER, 1983

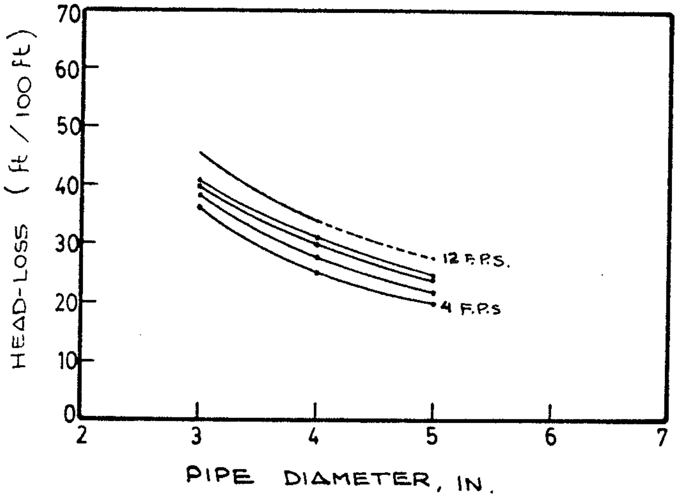
FIGURE B.28

NOTE: ERROR DUE TO LEAKING MANOMETER (E)



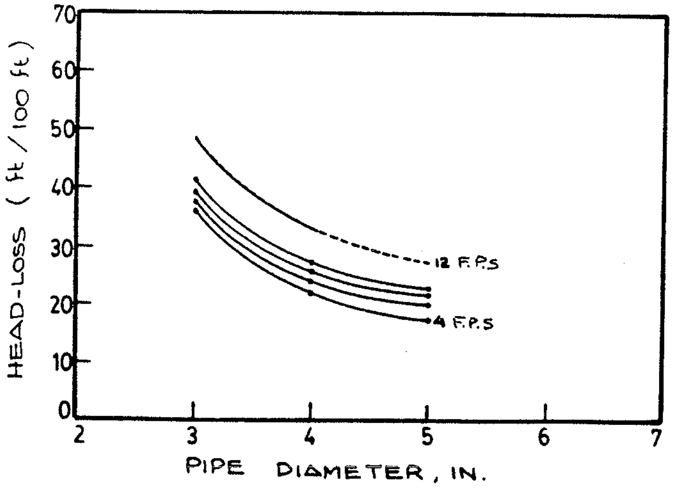
a

SAMPLE : 90/10
C_w = 55 %
TEMPERATURE : 25°C
VEL. : 4, 5, 6, 7, 12 F.P.S.
OCTOBER, 1983



b

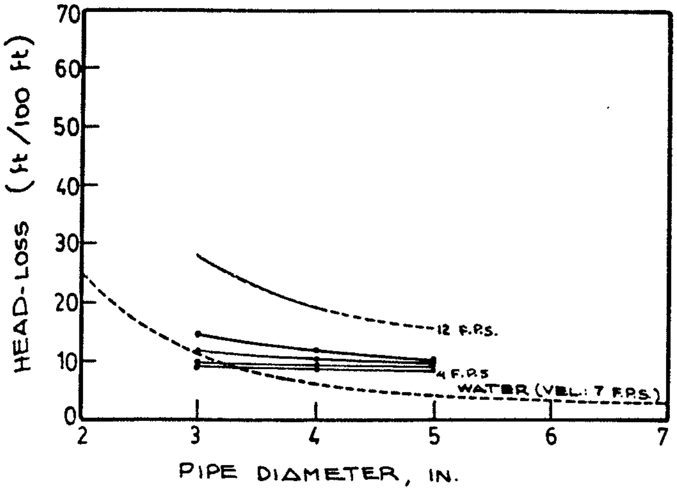
SAMPLE : 90/10
C_w = 55 %
TEMPERATURE : 35°C
VEL. : 4, 5, 6, 7, 12 F.P.S.
OCTOBER, 1983



c

SAMPLE : 90/10
C_w = 55 %
TEMPERATURE : 45°C
VEL. : 4, 5, 6, 7, 12 F.P.S.
OCTOBER, 1983

FIGURE B.29



a

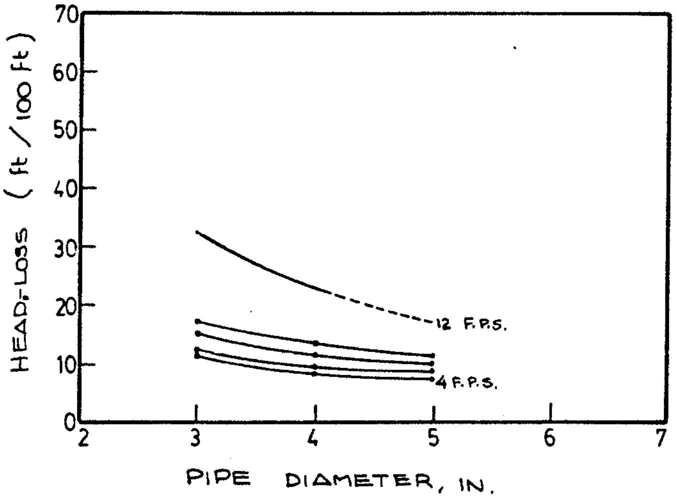
SAMPLE : 80/20

C_w = 55 %

TEMPERATURE : 25°c

VEL. : 4,5,6,7,12 F.P.S.

NOVEMBER, 1983.



b

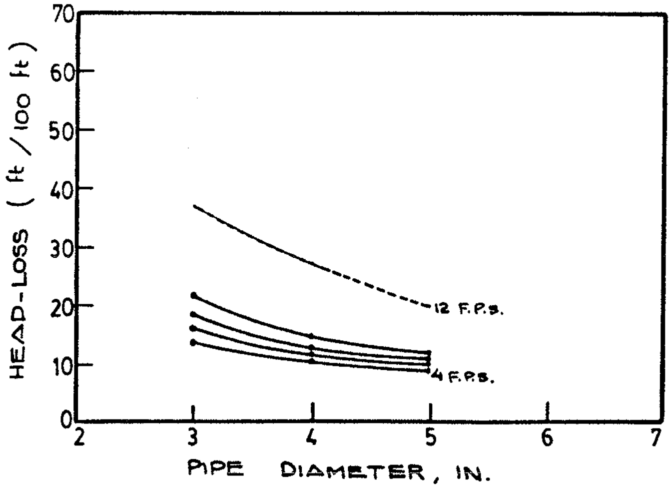
SAMPLE : 80/20

C_w = 55%

TEMPERATURE : 35°C

VEL. : 4,5,6,7,12 F.P.S.

NOVEMBER, 1983.



c

SAMPLE : 80/20

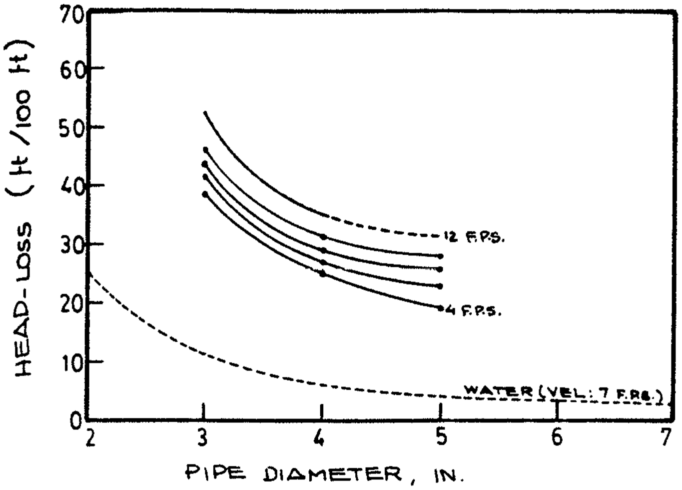
C_w = 55%

TEMPERATURE : 45°C

VEL. : 4,5,6,7,12 F.P.S.

NOVEMBER, 1983.

FIGURE B.30



a

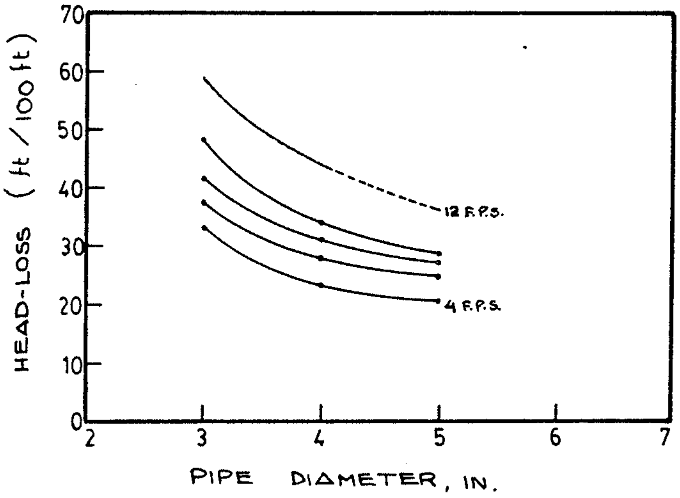
SAMPLE : 80/20

C_w = 65 %

TEMPERATURE : 25°C

VEL. : 4, 5, 6, 7, 12 F.P.S.

NOVEMBER, 1983.



b

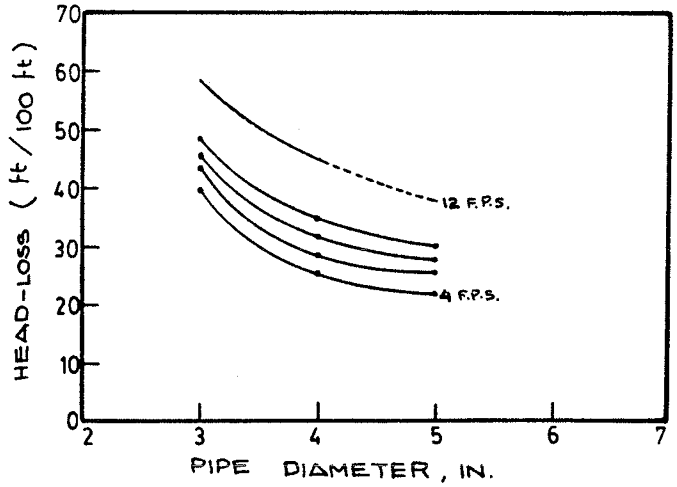
SAMPLE : 80/20

C_w = 65 %

TEMPERATURE : 35°C

VEL. : 4, 5, 6, 7, 12 F.P.S

NOVEMBER, 1983.



c

SAMPLE : 80/20

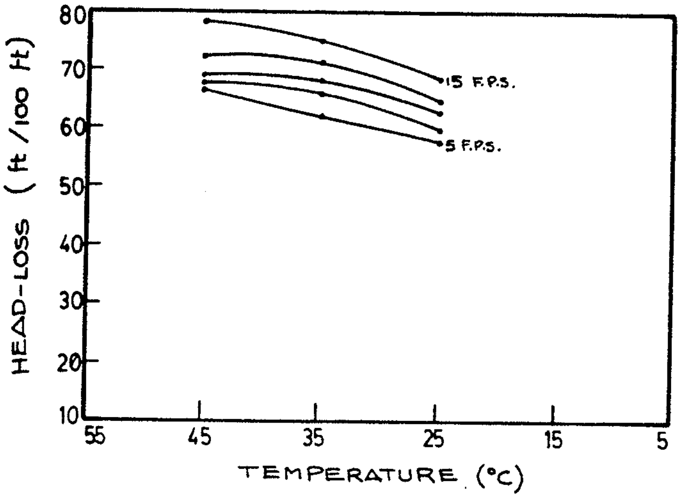
C_w = 65%

TEMPERATURE : 45°C

VEL. : 4, 5, 6, 7, 12 F.P.S.

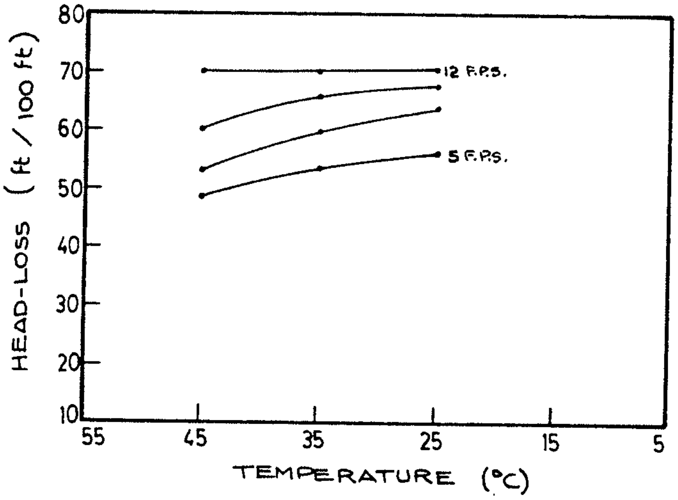
NOVEMBER, 1983.

FIGURE B.31



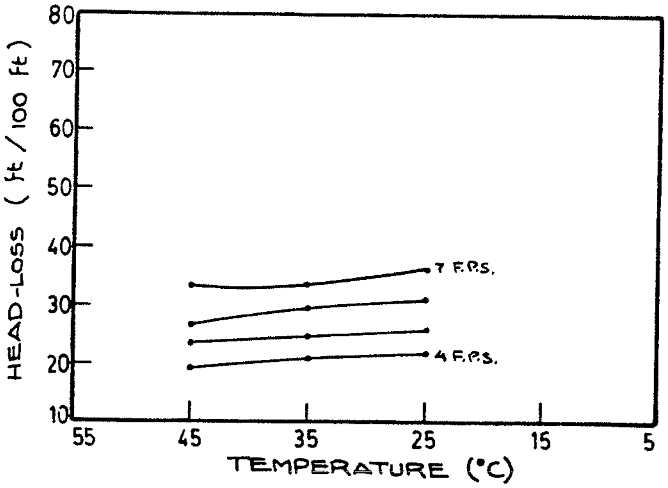
a

SAMPLE : 90/10
C_w = 65 %
DIAMETER = 3 IN.
VEL.: 5, 7, 9, 12, 15 F.P.S.
SEPTEMBER, 1983



b

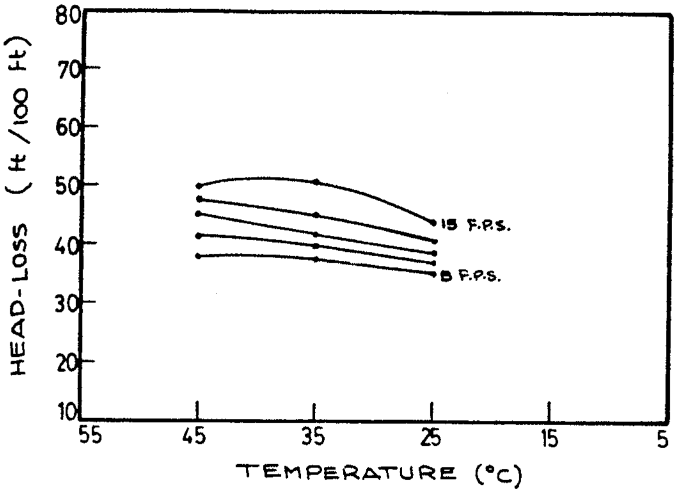
SAMPLE : 90/10
C_w = 65%
DIAMETER = 4 IN.
VEL.: 5, 7, 9, 12 F.P.S.
SEPTEMBER, 1983



c

SAMPLE : 90/10
C_w = 63%
DIAMETER = 5 IN.
VEL.: 4, 5, 6, 7 F.P.S.
SEPTEMBER, 1983.

FIGURE B.32



a

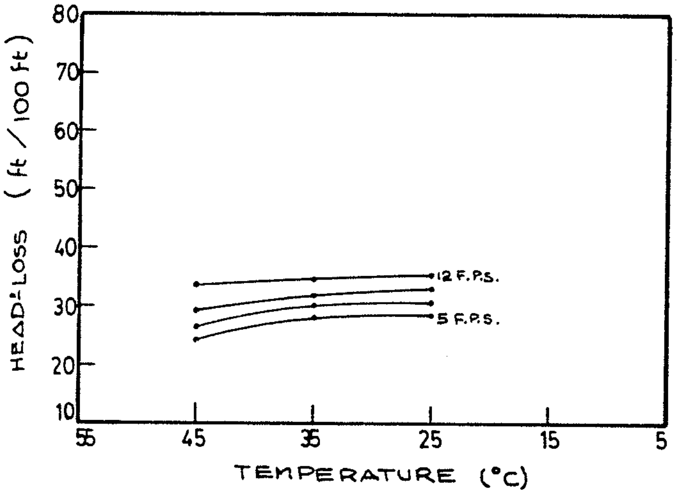
SAMPLE : 90/10

C_w = 55 %

DIAMETER = 3 IN.

VEL. : 5, 7, 9, 12, 15 F.P.S.

OCTOBER, 1983



b

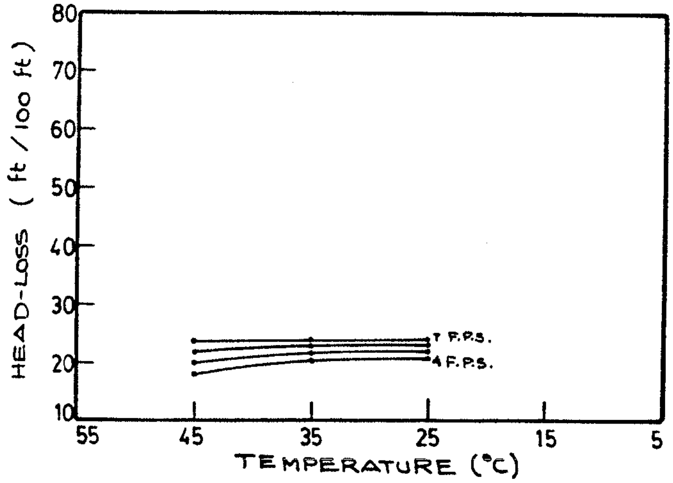
SAMPLE : 90/10

C_w = 55%

DIAMETER = 4 IN.

VEL.: 5, 7, 9, 12 F.P.S.

OCTOBER, 1983.



c

SAMPLE : 90/10

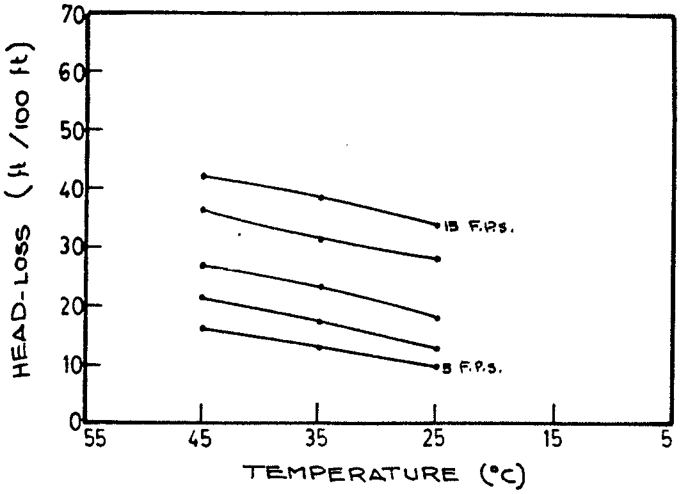
C_w = 55%

DIAMETER = 5 IN.

VEL.: 4, 5, 6, 7 F.P.S

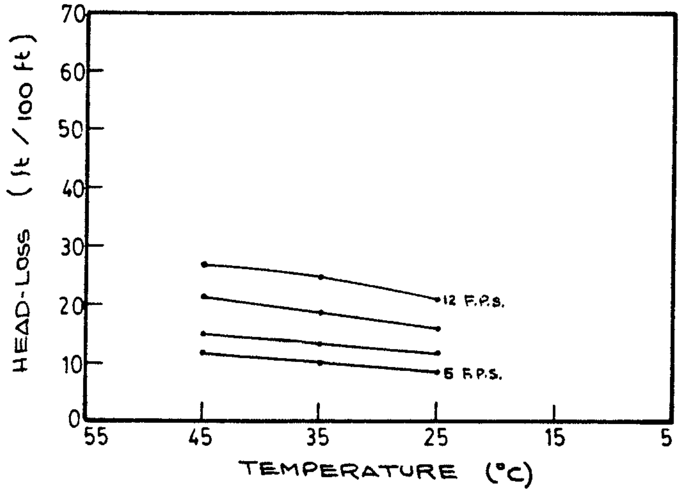
OCTOBER, 1983.

FIGURE B.33



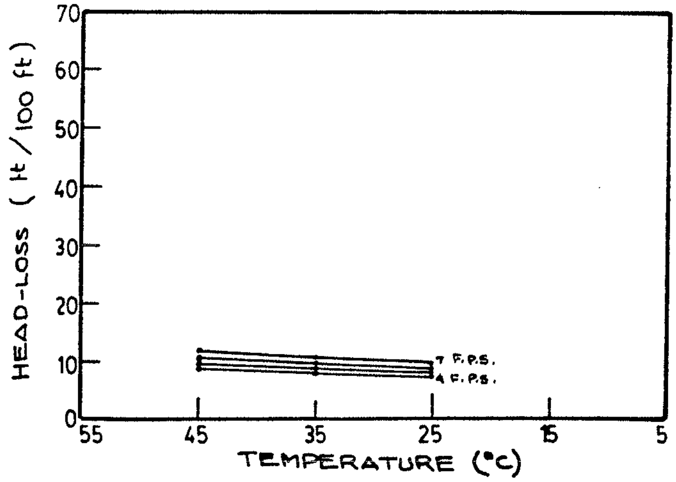
a

SAMPLE : 80/20
C_w = 55 %
DIAMETER = 3 IN.
VEL.: 5, 7, 9, 12, 15 F.P.S.
NOVEMBER, 1983.



b

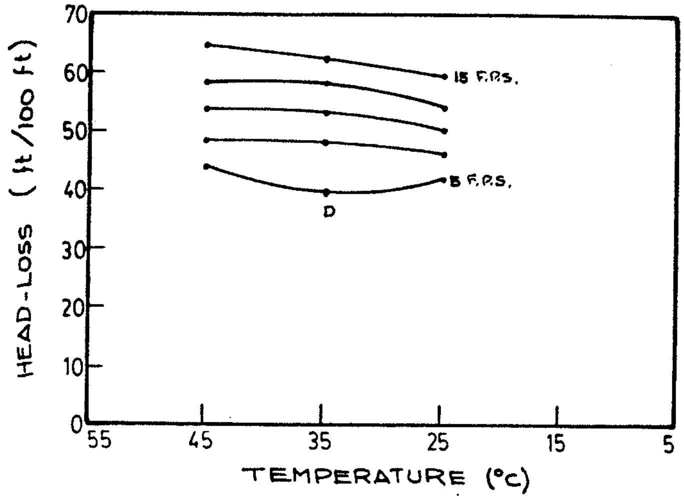
SAMPLE : 80/20
C_w = 55 %
DIAMETER = 4 IN.
VEL.: 5, 7, 9, 12 F.P.S.
NOVEMBER, 1983.



c

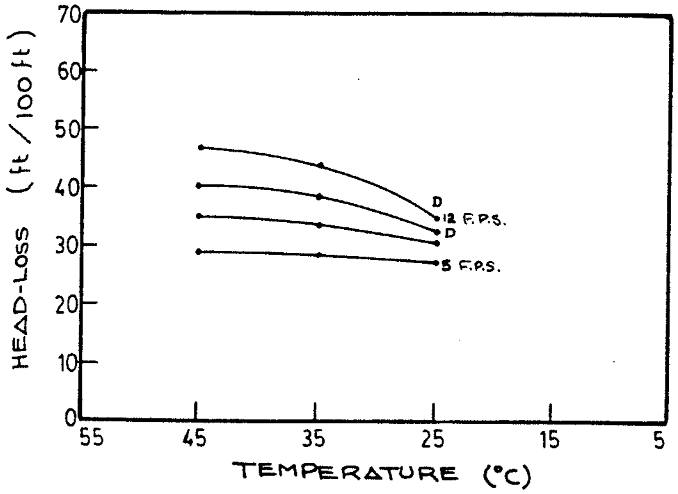
SAMPLE : 80/10
C_w = 55 %
DIAMETER = 5 IN.
VEL.: 4, 5, 6, 7 F.P.S.
NOVEMBER, 1983.

FIGURE B.34



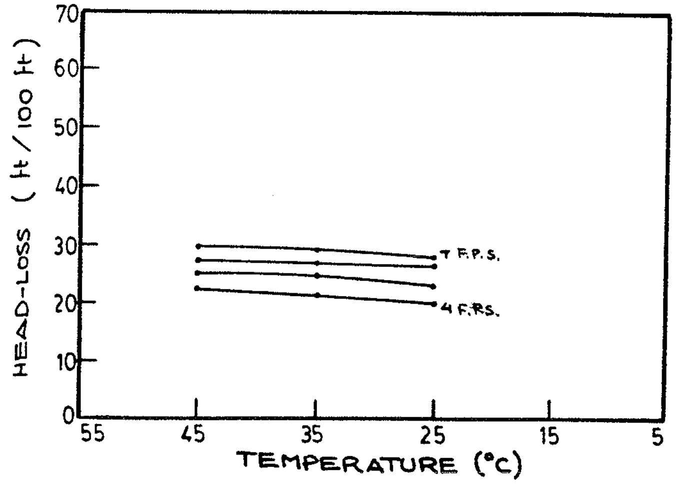
a

SAMPLE : 80/20
C_w = 65 %
DIAMETER = 3 IN.
VEL.: 5, 7, 9, 12, 15 F.P.S
NOVEMBER, 1983.



b

SAMPLE: 80/20
C_w = 65%
DIAMETER = 4 IN.
VEL.: 5, 7, 9, 12 F.P.S.
NOVEMBER, 1983.

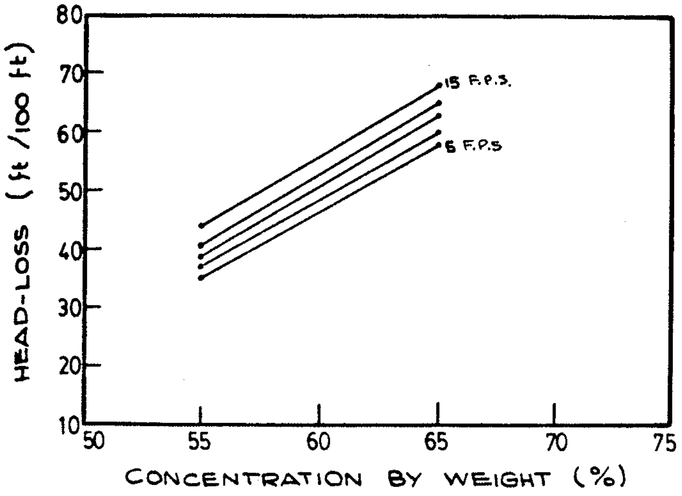


c

SAMPLE: 80/10
C_w = 65 %
DIAMETER = 5 IN.
VEL.: 4, 5, 6, 7 F.P.S.
NOVEMBER, 1983.

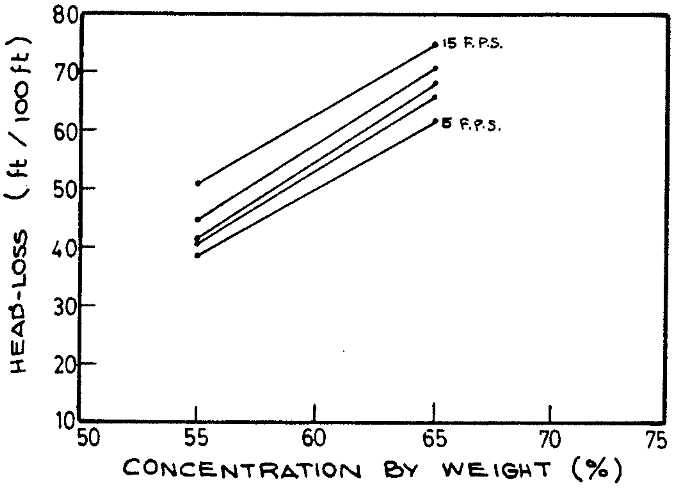
FIGURE B.35

NOTE: DISCREPANCY (D)



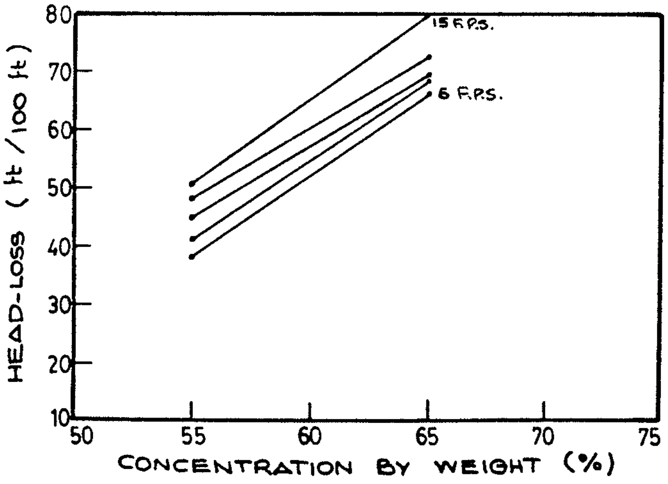
a

SAMPLE : 90/10
DIAMETER = 3 IN.
TEMPERATURE = 25 °C
VEL.: 5, 7, 9, 12, 15 F.P.S.
OCTOBER, 1983.



b

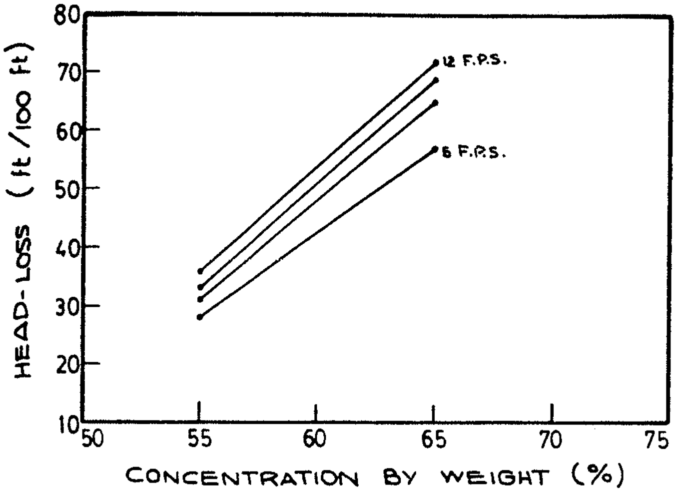
SAMPLE: 90/10
DIAMETER = 3 IN.
TEMPERATURE = 35 °C
VEL.: 5, 7, 9, 12, 15 F.P.S.
OCTOBER, 1983.



c

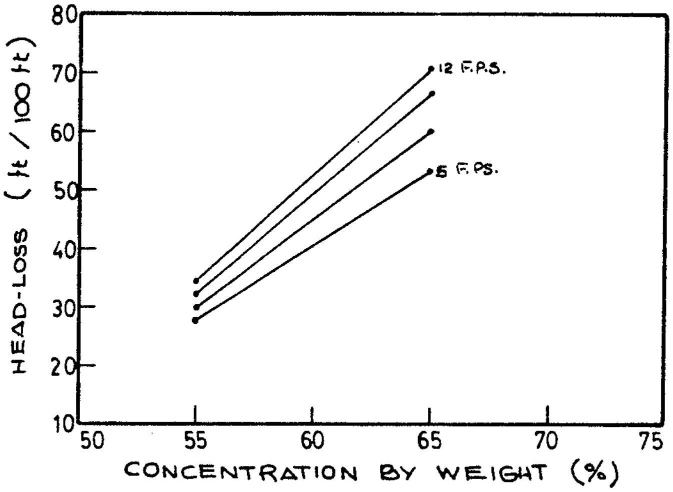
SAMPLE : 90/10
DIAMETER = 3 IN.
TEMPERATURE = 45 °C
VEL.: 5, 7, 9, 12, 15 F.P.S.
OCTOBER, 1983.

FIGURE B.36



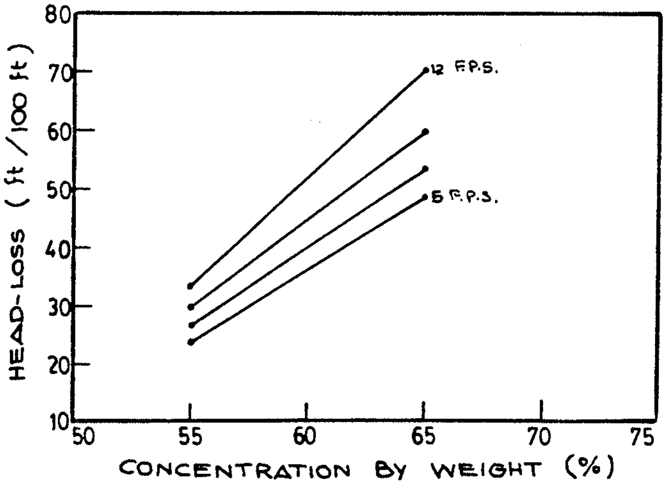
a

SAMPLE : 90/10
DIAMETER = 4 IN.
TEMPERATURE = 25 °C
VEL.: 5, 7, 9, 12 F.P.S.
OCTOBER, 1983



b

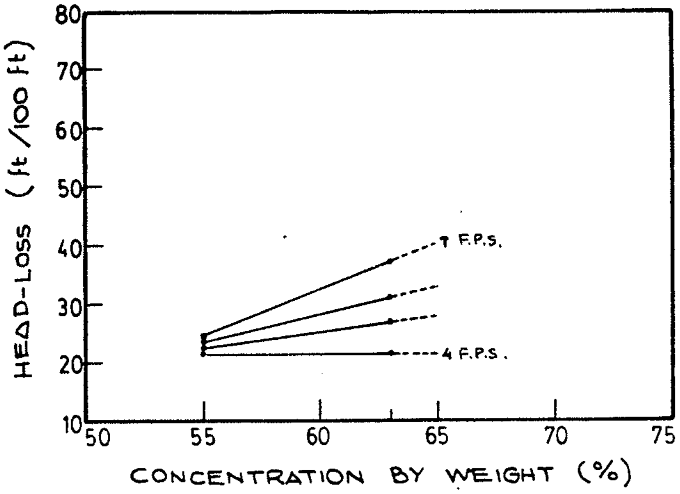
SAMPLE: 90/10
DIAMETER = 4 IN.
TEMPERATURE = 35 °C
VEL.: 5, 7, 9, 12 F.P.S.
OCTOBER, 1983.



c

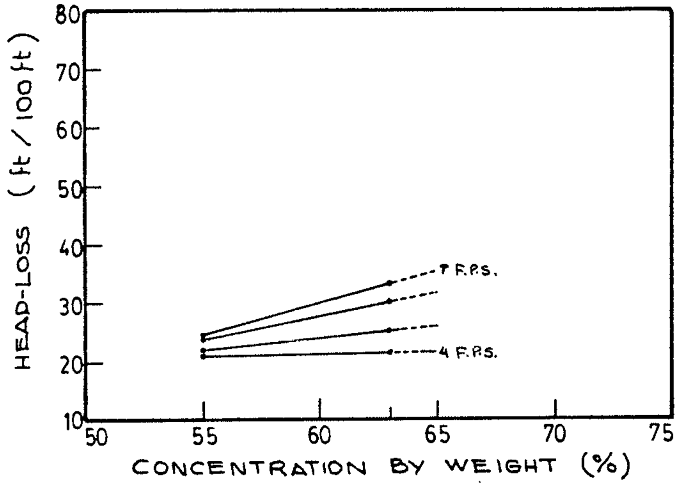
SAMPLE: 90/10
DIAMETER = 4 IN.
TEMPERATURE = 45°C
VEL.: 5, 7, 9, 12 F.P.S.
OCTOBER, 1983.

FIGURE B.37



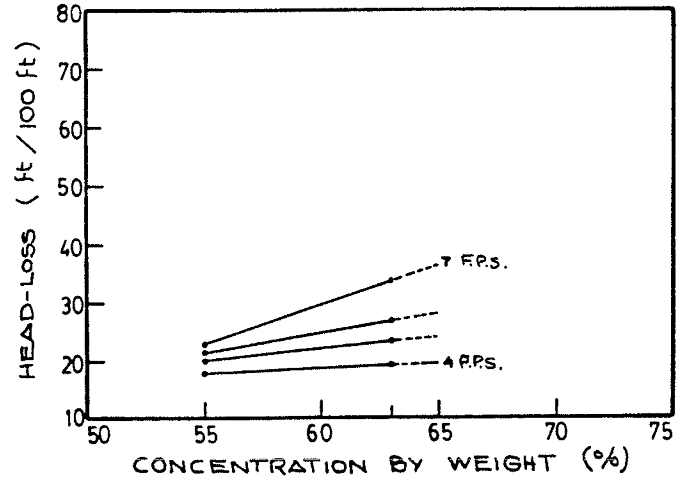
a

SAMPLE: 90/10
DIAMETER = 5 IN.
TEMPERATURE = 25 °C
VEL.: 4, 5, 6, 7 F.P.S.
OCTOBER, 1983.



b

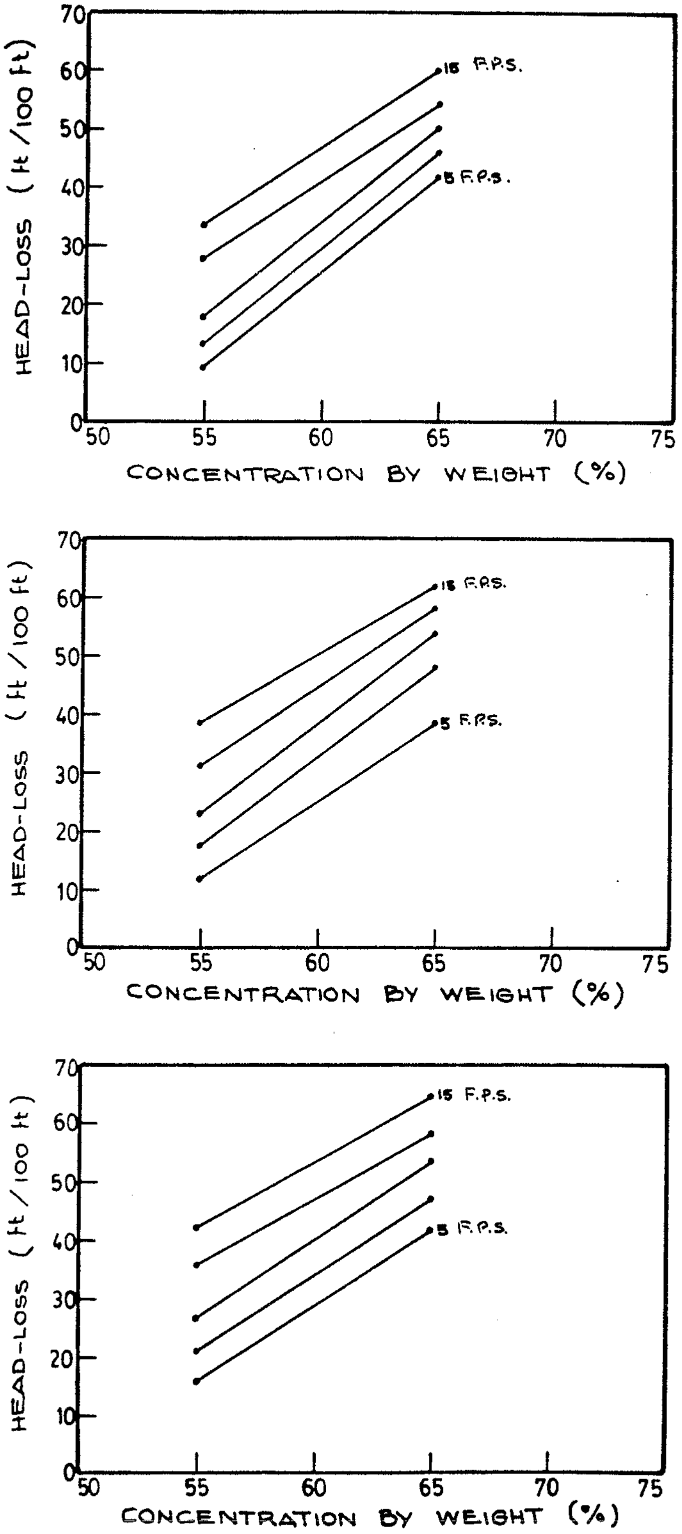
SAMPLE: 90/10
DIAMETER = 5 IN.
TEMPERATURE = 35 °C
VEL.: 4, 5, 6, 7 F.P.S.
OCTOBER, 1983.



c

SAMPLE: 90/10
DIAMETER = 5 IN.
TEMPERATURE = 45 °C
VEL.: 4, 5, 6, 7 F.P.S.
OCTOBER, 1983.

FIGURE B.38



a

SAMPLE: 80/20
DIAMETER = 3 IN.
TEMPERATURE = 25 °C
VEL.: 5, 7, 9, 12, 15 F.P.S.
NOVEMBER, 1983.

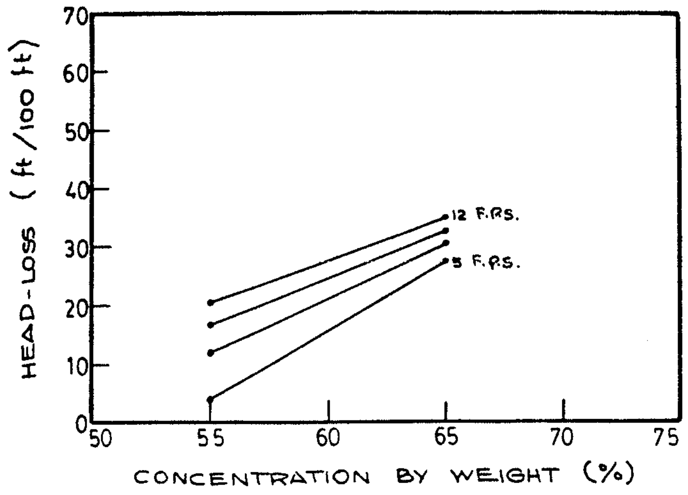
b

SAMPLE: 80/20
DIAMETER = 3 IN.
TEMPERATURE = 35 °C
VEL.: 5, 7, 9, 12, 15 F.P.S.
NOVEMBER, 1983.

c

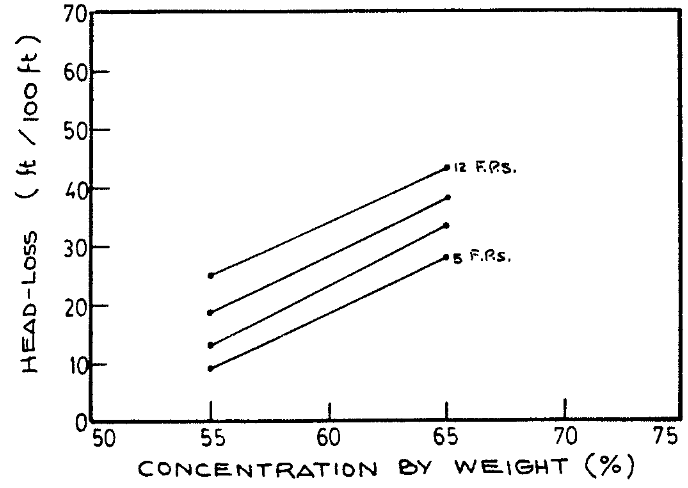
SAMPLE: 80/20
DIAMETER = 3 IN.
TEMPERATURE = 45 °C
VEL.: 5, 7, 9, 12, 15 F.P.S.
NOVEMBER, 1983.

FIGURE B.39



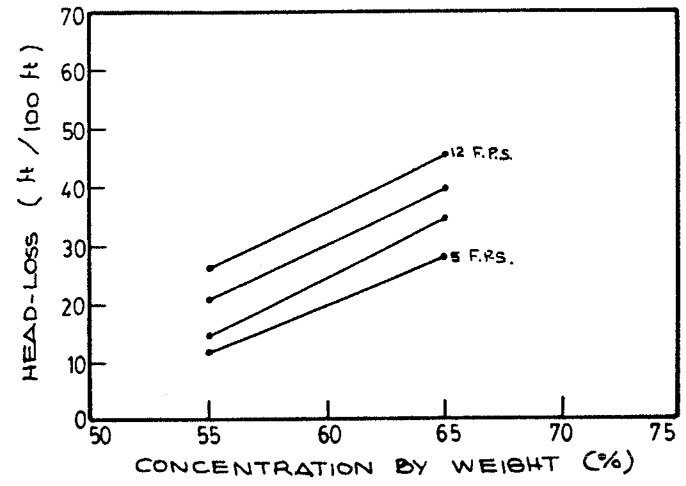
a

SAMPLE: 80/20
DIAMETER = 4 IN.
TEMPERATURE = 25°C
VEL.: 5, 7, 9, 12 F.P.S.
NOVEMBER, 1983.



b

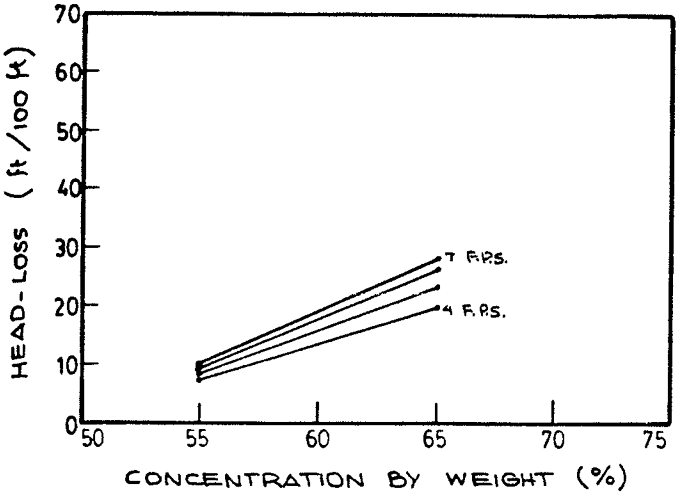
SAMPLE: 80/20
DIAMETER = 4 IN.
TEMPERATURE = 35°C
VEL.: 5, 7, 9, 12 F.P.S.
NOVEMBER, 1983.



c

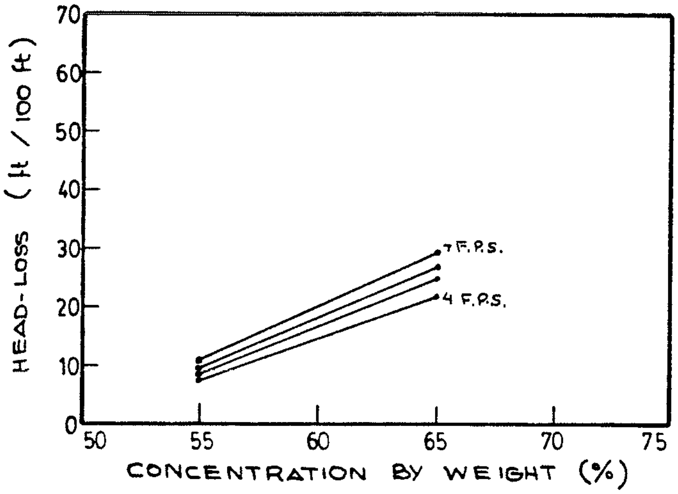
SAMPLE: 80/20
DIAMETER = 4 IN.
TEMPERATURE = 45°C
VEL.: 5, 7, 9, 12, F.P.S.
NOVEMBER, 1983.

FIGURE B.40



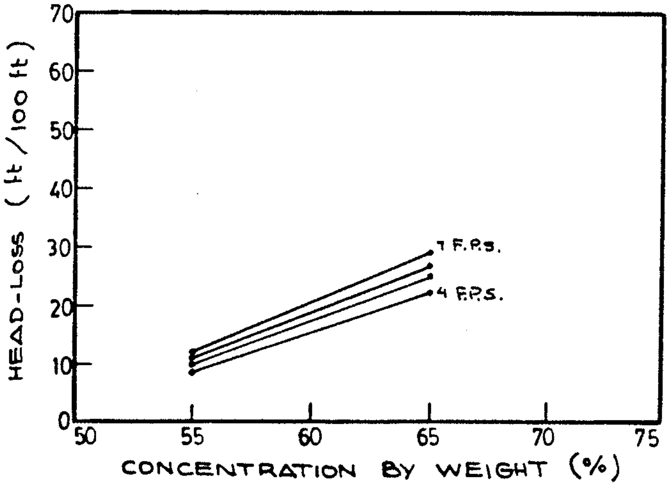
a

SAMPLE : 80/20
DIAMETER = 5 IN.
TEMPERATURE = 25 °C
VEL. : 4, 5, 6, 7 F.P.S.
NOVEMBER, 1983.



b

SAMPLE : 80/20
DIAMETER = 5 IN.
TEMPERATURE = 35 °C
VEL. : 4, 5, 6, 7 F.P.S.
NOVEMBER, 1983.



c

SAMPLE : 80/20
DIAMETER = 5 IN.
TEMPERATURE = 45 °C
VEL. : 4, 5, 6, 7 F.P.S.
NOVEMBER, 1983.

FIGURE B.41

APPENDIX - C

FORMULAS FOR τ, du/dy and f

SHEAR STRESS IN PIPE FLOW (τ)

Figure C.1 shows a horizontal pipe in which the flow is laminar. The mean velocity is V, and the pipe diameter is D

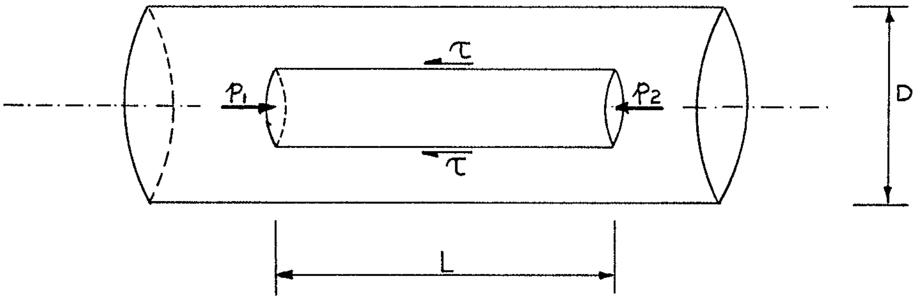


Figure C.1 Laminar flow in pipes

A number of concentric cylinders sliding one upon another may be used to describe the mass flow. One of the forces acting on the cylinder radius, y, and length, L, is the fall in pressure due to the viscous resistance defined by + $(p_1 - p_2)$ or ΔP. This pressure difference is counterbalanced by a shear force of equal magnitude at the circumference of the cylinder. The total shear force is :

$$\tau \times 2\pi y L$$

For dynamic equilibrium

$$\tau \times 2\pi y L = \Delta P \times \pi y^2$$

so that $\tau = \dfrac{y\, \Delta P}{2L}$

The shear stress exerted on the interior pipe wall is τ_w:

$$\tau_w = \frac{D\,\Delta P}{4L} \qquad (C.1)$$

RATE OF SHEAR IN CIRCULAR PIPES (du/dy)

The shear stress is related to the velocity by the expression:

$$\tau = -\mu \left(\frac{du}{dy}\right)$$

u = point velocity

y = radius measured outwards in Fig. C.1 (negative sign adopted)

μ = viscosity

Substituting the value of τ from Equ (C.1):

$$\frac{du}{dy} = \frac{-y\Delta P}{2L\mu} \qquad (C.2)$$

if

$$du = \frac{-y\Delta P}{2L\mu}\,dy$$

Integrating

$$u = \frac{-\Delta P}{4L\mu}\,y^2 + \text{constant}$$

with a viscous fluid the velocity at the boundary is zero. $u = 0$ when $y = D/2$.

Solving for the constant we obtain

$$u = \frac{\Delta P}{4L\mu}\left(\frac{D^2}{4} - y^2\right)$$

which is the equation of a parabola. The maximum u will occur when $y = 0$, a the center line of the pipe.

$$u_{max} = \frac{\Delta P\ D^2}{16\ L\mu}$$

From the geometry of the paraboloid the mean velocity is:

$$V = \frac{u_{max}}{2} = \frac{\Delta P\ D^2}{32L\mu}$$

or $$V = \frac{D\Delta P}{4L\mu}\ \frac{D}{8}$$ and;

$$\frac{8V}{D} = \frac{D\Delta P}{4L\mu} \qquad (C.3)$$

replacing (C.3) in (C.2) when y = D/2 we obtain the Equation for rate of shear (or velocity gradient) in circular pipes.

$$\frac{du}{dy} = \frac{8V}{D} \qquad (C.4)$$

FRICTION FACTOR (f)

From the Darcy-Weisbach formula for pipe friction

$$hf = \frac{f L\ V^2}{2g\ D}$$

where:

f = friction factor

thus $$hf = \frac{f\ V^2}{2}\ \frac{L}{gD}$$

rearranging this formula and introducing ρ in both sides:

$$\frac{2}{\rho V^2} = f\frac{L}{Dg\rho hf}$$

since $\Delta P = g\rho hf$

so $$\frac{8}{\rho v^2} = f\ \frac{4L}{D\Delta P} \qquad (C.5)$$

replacing Equ. (C.1) in (C.5)

we obtain the Equation for Friction Factor in terms of

$$f = \frac{8\tau}{\rho V^2} \qquad (C.6)$$

APPENDIX - D

COMPUTER PROGRAM FOR RAW DATA REDUCTION

by Foh-Kim Tai[*]

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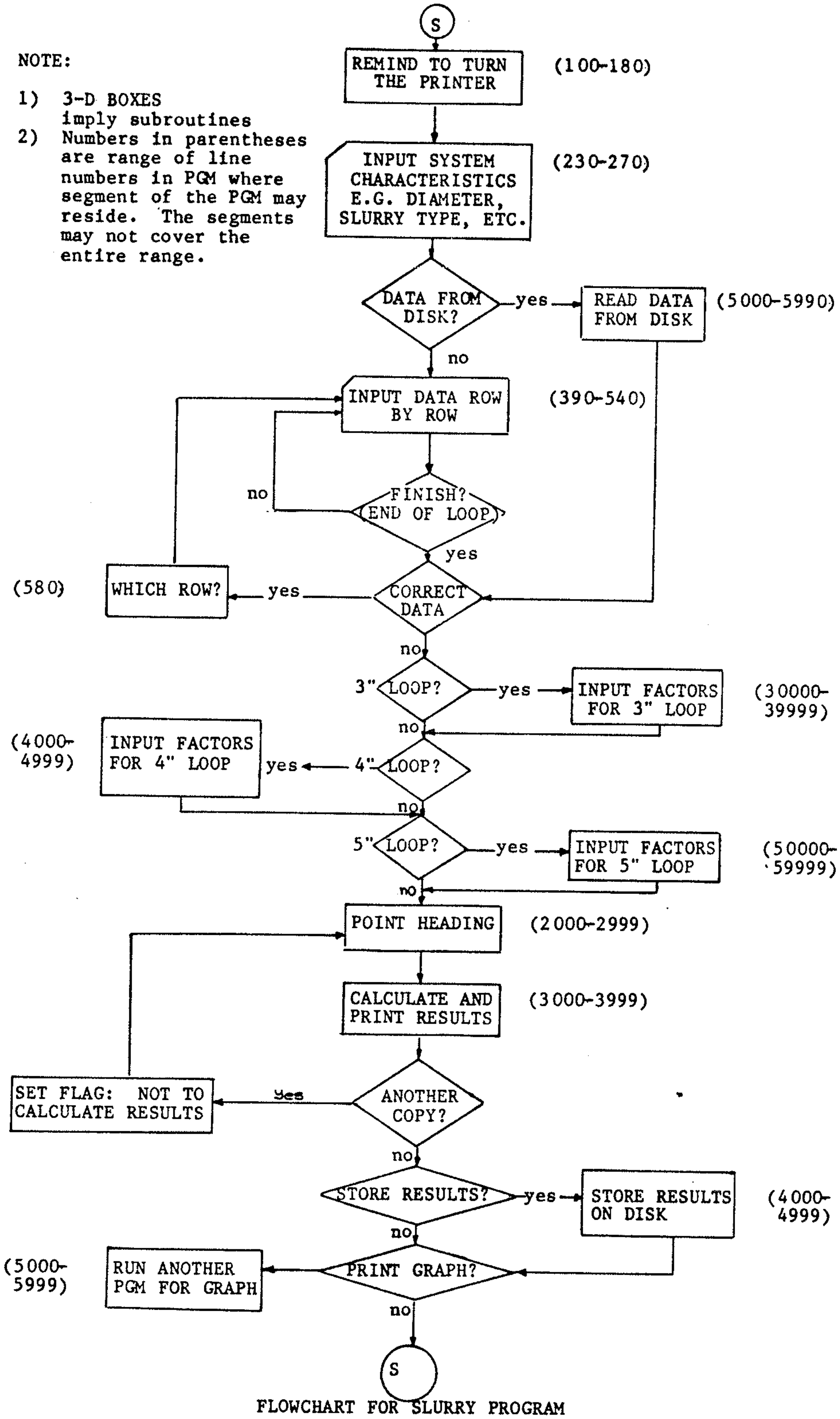
[*] Graduate student at the University of Manitoba, Civil Engineering Department.

APPENDIX D

This report briefly explains the structure and organization of the program. The following points are the main features of the program:

1. The program written is intended to be user-friendly. The computer, therefore "talks" to the user. As such, no programming experience is required on the part of the user.
2. Modular programming technique is employed. This implies that the program is divided into modules (subprograms or subroutines) so that it is easier to debug (see flow chart).
3. A range of line number is reserved for different segments (sub-routines) of the program. This facilitates the ease of searching for any particular segment of the program (see flow chart). The computer language is BASIC.
4. If one looks at the back of the form prepared by Mr. J. Pomalaza Raez, one can observe the similarities between corresponding equations in different loop systems (3", 4" and 5" loop) i.e. the equations are the same except for the multiplying factors. Therefore, one needs only to write computer codes for one loop and store the constant terms in subroutines.

The next page shows the organization of the program. For completeness, the computer codes and associated variable dictionary are listed.



NOTE:

1) 3-D BOXES imply subroutines
2) Numbers in parentheses are range of line numbers in PGM where segment of the PGM may reside. The segments may not cover the entire range.

FLOWCHART FOR SLURRY PROGRAM

VARIABLE DICTIONARY

A()	ARRAY VARIABLE FOR COLUMN A (SEE FORM PREPARED BY J. POMALAZA)
AA$	CHAR. VAR FOR GENERAL (YES/NO) ANSWER
AD$	CHAR. VAR (Y/N) FOR INPUTTING DISK DATA
AR	X-SECTION a AREA OF PIPE
B()	ARRAY VAR. FOR COLUMN b
BC	BULK CONCENTRATION
C()	ARRAY VAR. FOR COLUMN c
CH$	CHAR. VAR. (Y/N) FOR CHANGING (CORRECTING) DATA
D()	ARRAY VAR. FOR COLUMN d
DIAM	DIAMETER OF PIPE
DT$	DATA
E()	ARRAY VAR. FOR COLUMN e
F()	ARRAY VAR. FOR COLUMN f
FILE$	FILENAME ON DISK
FP	MULTIPLYING FACTOR FOR P()
FQ	MULTIPLYING FACTOR FOR Q()
FR	MULTIPLYING FACTOR FOR R()
FT	MULTIPLYING FACTOR FOR T()
FU	MULTIPLYING FACTOR FOR U()
FV	MULTIPLYING FACTOR FOR V()
FW	MULTIPLYING FACTOR FOR W()
FX	MULTIPLYING FACTOR FOR X()
G()	ARRAY VAR. FOR COLUMN g
GA$	CHAR. VAR. (Y/N) FOR GAMMA LOGGER READING
H()	ARRAY VAR. FOR COLUMN h
I()	ARRAVY VAR. FOR COLUMN i
I	INDEX FOR LOOPING
IJ	INDEX FOR LOOPING

J()	ARRAY VAR. FOR COLUMN j
K()	ARRAY VAR. FOR COLUMN k
L()	ARRAY VAR. FOR COLUMN 1
LA	CONSTANT IN REGRESSED EQN FOR L()
LB	CONSTANT IN REGRESSED EQN FOR L()
LF$	LINE FLUID
M()	ARRAY VAR. FOR COLUMN m
N()	ARRAY VAR. FOR WEIGHING TANK
NAMES$	NAMES
ND	NUMBER OF ROWS OF DATA
NT$	CHAR. VAR. (Y/N) FOR WEIGHING TANK
O()	ARRAY VAR. FOR COLUMN o
P()	ARRAY VAR. FOR COLUMN p
Q()	ARRAY VAR. FOR COLUMN q
R()	ARRAY VAR. FOR COLUMN r
RA$	CHAR. VAR. (Y/N) TO CHECK IF STORED DATA ARE TO BE UPDATED
REF$	SAME AS FILE$
S()	ARRAY VAR. FOR COLUMN s
SG	SPECIFIC GRAVITY
SP$	SPACES
ST$	SLURRY TYPE
SOUND	VAR. FOR SOUND
T()	ARRAY VAR. FOR COLUMN t
TIME$	TIME
TL	TEST LENGTH
V()	ARRAY VAR. FOR COLUMN v
W()	ARRAY VAR. FOR COLUMN w
X()	ARRAY VAR. FOR COLUMN x

```
]LIST ,330

100 D$ = "": REM  CONTROL-D
110  HOME : VTAB 10
120  PRINT "NOTE: IF THE COMPUTER
      HANGS": PRINT
130  PRINT "CHECK TO SEE IF PRINT
     ER'S ": PRINT
140  PRINT "'ON LINE' BUTTON SHOW
     S ": PRINT
150  PRINT "      GREEN LIGHT."
160  PRINT D$"PR#1"
170  PRINT  CHR$ (18);"  ": REM
      TURNS OFF CONDENSED MODE

180  PRINT D$"PR#0"
190  HOME : VTAB 10: PRINT "DO YO
     U DATA READ FROM DISK(Y/N):"
     ;: GET AD$
200  IF  LEFT$ (AD$,1) = "Y" THEN
      GOSUB 5000
210  IF  LEFT$ (AD$,1) = "Y" THEN
      GOTO 550
220  HOME
230  INPUT "DATA COLLECTED BY: ";
     NAMES$
240  INPUT "DATE (E.G. OCT 10/82)
     : ";DT$
250  INPUT "TIME (E.G. 10 AM): ";
     TIME$
260  INPUT "SLURRY TYPE: ";ST$
270  INPUT "WHICH LOOP (DIAMETER-
     INCH): ";DIAM
280  IF DIAM < 3.0 OR DIAM > 5.0 THEN
      GOTO 300
290  GOTO 320
300  PRINT "NO SUCH PIPE!!"; CHR$
     (7); CHR$ (7)
310  GOTO 270
320  HOME : VTAB 10: PRINT "IS GA
     MMA READING=S.G.(SLURRY) (Y/
     N):";: GET GA$: PRINT : PRINT

325  HOME : VTAB 10: PRINT "HAS T
     HE WEIGHING TANK BEEN USED (
     Y/N):";: GET NT$: HOME
330  INPUT "# OF ROWS OF DATA: ";
     ND
```

```
]LIST 340,590

340  HOME : PRINT "START INPUT DA
     TA"
350  PRINT "    (";ND;" ROWS)"
360  DIM A(ND),B(ND),C(ND),D(ND),
     E(ND),F(ND),G(ND),H(ND),I(ND
     ),J(ND),R(ND),V(ND)
370  DIM K(ND),L(ND),M(ND),N(ND),
     O(ND),P(ND),Q(ND),S(ND),T(ND
     ),U(ND),W(ND),X(ND)
380 AA$ = "N"
390  FOR IJ = 1 TO ND
400  PRINT : PRINT : PRINT
410  PRINT "INPUT DATA FOR ROW ";
     IJ: PRINT : PRINT
420  FOR I = 1 TO 70:SOUND =  PEEK
     ( - 16336): NEXT I
430  INPUT "PUMP POWER (%): ";A(I
     J)
440  INPUT "POLYSONIC RDG (L/S):
     ";B(IJ)
450  INPUT "GAMMA LOGGER RDG: ";C
     (IJ)
460  INPUT "U-TUBE RDG (MF-INCH):
      ";D(IJ)
470  INPUT "COLLECT+SHIFT TIME (S
     EC): ";E(IJ)
480  INPUT "VOLUME (U.S. GALLONS)
     : ";F(IJ)
490  INPUT "WEIGHT (LB): ";G(IJ)
500  INPUT "MAG. METER RDG: ";H(I
     J)
510  INPUT "TEMPERATURE (CELCIUS)
     : ";I(IJ)
520  INPUT "U-TUBE RDG (HG-CM): "
     ;J(IJ)
530  IF  LEFT$ (AA$,1) = "Y" THEN
      GOTO 560
540  NEXT IJ
550  HOME : VTAB 10
560  INPUT "ANY CHANGE ON DATA (Y
     /N): ";AA$
570  HOME : VTAB 10
580  IF  LEFT$ (AA$,1) = "Y" THEN
      INPUT "WHICH ROW: ";IJ
590  IF  LEFT$ (AA$,1) = "Y" THEN
      GOTO 400
```

```
]LIST 593,2020

593  IF AD$ = "Y" THEN 598
595  HOME : VTAB 12: INPUT "GIVE
     REFERENCE NUMBER: ";REF$
597  GOTO 640: REM  CONTINUE CALC
     ULATIONS
598  HOME : VTAB 10: PRINT "DO YO
     U WANT RESULTS(DISK) RECALCU
     LATED:";: GET RA$
599 REF$ = FILE$
600  REM
610  REM  CALL ROUTINES
620  REM
630  REM  CALL MULTIPLYING FACTOR
     S FOR 3" PIPE
640  IF DIAM = 3.0 THEN  GOSUB 30
     000
650  REM  CALL M. FACTORS FOR 4"
     PIPE
660  IF DIAM = 4.0 THEN  GOSUB 40
     000
670  REM  CALL M. FACTORS FOR 5"
     PIPE
680  IF DIAM = 5.0 THEN  GOSUB 50
     000
690  GOSUB 2000: REM   PRINT HEAD
     ING
700  GOSUB 3000: REM   CALCULATES
      RESULTS
710  GOSUB 4000: REM   STORE RESU
     LTS
720  GOSUB 6000: REM  CALL GRAPHI
     C  ROUTINE
730  HOME : VTAB 10: PRINT "GOOD
     BYE ......."
740  PRINT : PRINT : PRINT "HAVE
     A NICE DAY!"
750  PRINT : PRINT : PRINT
760  END
770  REM  **********************

780  REM
2000  PRINT D$: PRINT D$"PR#1"
2010  PRINT : PRINT  CHR$ (18)
2020  PRINT  CHR$ (27); CHR$ (67)
     ; CHR$ (32): REM     SET FOR
     M LENGTH=32
```

```
]LIST 2030,2215

2030  PRINT  CHR$ (27);"0": REM
     LINE SPACING=1/8"
2050 SP$ = "                    ":
      REM   20 SPACES
2060  PRINT  CHR$ (14);SP$; CHR$
     (14);"THE UNIVERSITY OF MANI
     TOBA"
2070  PRINT
2080  PRINT  CHR$ (14);SP$; CHR$
     (14);"DEPT. OF CIVIL ENGINEE
     RING"
2090  PRINT
2100  PRINT  CHR$ (14);SP$; CHR$
     (14);"   INCO  SLURRY PROJEC
     T"
2105 LINE$ = "-------------------
     ---------------------------
     ---------------------------
     ---------------------------
     ----------------------"
2110  PRINT LINE$
2120 SP$ = SP$ + SP$
2130  PRINT : PRINT SP$;"DATA COL
     LECTED BY: ";NAMES$
2140  PRINT : PRINT SP$;"DATE: ";
     DT$: PRINT : PRINT SP$;"TIME
     : ";TIME$
2150  PRINT : PRINT SP$;"ACTIVE L
     OOP: "; CHR$ (14);DIAM;" INC
     H"
2160  PRINT : PRINT SP$;"X-SECTIO
     NAL AREA: ";AR;" SQ. FEET"
2170  PRINT : PRINT SP$;"TEST LEN
     GTH: ";TL;" FEET"
2180  PRINT : PRINT SP$;"SLURRY T
     YPE: ";ST$: PRINT
2190  PRINT LINE$
2200  PRINT
2210  PRINT "                :
             LINE               :
      VENTURI : MIXTURE :  DISCHA
     RGE   :  VELOCITY  :   LIN
     E      :  "
2215  PRINT
```

```
]LIST 2220,3070

2220  PRINT  CHR$ (15);"
        PUMP    SONIC    GAMMA  P
     RESS.    C&S     VOL.     WT
     .    MAG.   TEMP   PRESS.
     HEAD    S.G.    CONC      WT
     .        WT.    MAG.     WT.
        MAG.    SONIC  PRESS.   P
     RESS.  HEAD       SHEAR
       VEL."
2230  PRINT  CHR$ (15);"   ROW
        POWER   RDG.    LOGGER
             TIME     U.S.
          METR
     LOSS     (S)      (WT)      TAN
     K       TANK    METR     TANK
        METR
            LOSS       STRESS
       GRAD"
2240  PRINT  CHR$ (15);"
         (%)     L/S             (
     INCH)  SEC.      GAL.      LB
     .    RDG.   (C)      (CM)
     FT-W             (%)       GPM
            CFS      CFS      F/S
        F/S       F/S    FT-S
     FT-W   /100        PSI
       /SEC"
2250  PRINT  CHR$ (18);LINE$
2280  RETURN
2295  REM  **********************

3000  REM
3005  POKE 1657,233: REM  233 COL
     UMNS
3020 AA$ = "N"
3025  IF AD$ = "Y" THEN AA$ = AD$
     : REM  CHECK IF DATA IS READ
      FROM DISK
3030  FOR IJ = 1 TO ND
3035  IF RA$ = "Y" THEN 3050
3040  IF  LEFT$ (AA$,1) = "Y" THEN
      GOTO 3520
3050 BC = BC + M(IJ)
3060 K(IJ) = J(IJ) / 18.6819: REM
         HEAD LOSS (FT. OF H2O)
3070 CX = C(IJ)
```

```
]LIST 3080,3595

3080  IF DIAM = 3.0 OR DIAM = 4.0
      THEN L(IJ) = CX / (LA + LB *
     CX)
3090  IF DIAM = 5.0 THEN L(IJ) =
     LA + LB * CX
3095  IF GA$ = "Y" THEN L(IJ) = C
     (IJ)
3100  IF NT$ = "Y" THEN N(IJ) = (
     60.0 / E(IJ)) * F(IJ): REM
      Q (GPM)
3110 O(IJ) = N(IJ) * 0.002228: REM
      Q(CFS)
3120 R(IJ) = H(IJ)
3150 P(IJ) = R(IJ) * FP: REM  MAG
     METER              (CFS)
3155  IF NA$ <  > "Y" THEN N(IJ) =
     P(IJ) / 0.002228
3160 Q(IJ) = O(IJ) / FQ: REM   WE
     IGH TANK (F/S)
3170 T(IJ) = (D(IJ) * FT) / L(IJ)
     : REM                 FEET OF
      SLURRY
3180 U(IJ) = D(IJ) * FU: REM   (F
     EET OF H2O)
3190 V(IJ) = U(IJ) * FV: REM (FT
     OF H2O/100' OF PIPEE)
3215 W(IJ) = U(IJ) * FW
3220 X(IJ) = R(IJ) * FX: REM   VE
     L.GRAD. (/SEC)
3520  PRINT  CHR$ (15)
3553  CALL 49568:IJ;I4,A(IJ);I9,B
     (IJ);F7.1,C(IJ);F7.2,D(IJ);F
     6.1,E(IJ);F7.3,F(IJ);F6.1,G(
     IJ);I7,H(IJ);F5.1,I(IJ);F6.1
     ,J(IJ);F6.1,K(IJ);F6.2,L(IJ)
     ,M(IJ),N(IJ);F9.2,O(IJ);F6.2
     ,P(IJ),Q(IJ),R(IJ),S(IJ),T(I
     J),U(IJ),V(IJ),W(IJ);F11.6,X
     (IJ);F9.2:
3560  PRINT  CHR$ (13)
3570  NEXT IJ
3580  PRINT : PRINT : PRINT  CHR$
     (18);" "
3590  PRINT LINE$
3595  PRINT "


                                ";"RE
     F: ";REF$
```

```
]LIST 3600,4027

 3600  PRINT D$;"PR#0"
 3610  HOME : VTAB 10
 3620  PRINT "RUN ANOTHER COPY (Y/
     N): ";: GET AA$
 3630  IF  LEFT$ (AA$,1) <  > "Y" THEN
      GOTO 3730
 3640  HOME : VTAB 10
 3650  PRINT "ANY CHANGES ON DATA:
      ";: GET CH$
 3660  IF  LEFT$ (CH$,1) = "Y" THEN
      GOTO 570
 3670  PRINT D$"PR#1"
 3680  GOSUB 2000: REM  PRINT HEAD
     ING
 3690  PRINT D$"PR#1"
 3700  GOTO 3030: REM  GOTO PRINT
     ROUTINE
 3710  GOTO 3620
 3720  PRINT D$"PR#0"
 3730  RETURN
 3740  REM  **********************

 3750  REM
 4000  HOME : VTAB 10
 4003  INVERSE
 4005 D$ = "": REM    CONTROL-D
 4006  PRINT "NOTE: IF YOU WANT GR
     APH PRINTED": PRINT
 4007  PRINT "AND DATA IS INPUTTED
      FOR THE FIRST ": PRINT
 4008  PRINT "TIME, YOU HAVE TO ST
     ORE YOUR DATA": NORMAL : PRINT
     : PRINT
 4010  PRINT "DO YOU WANT DATA STO
     RED ON DISK(Y/N):";: GET AA$

 4015  PRINT : PRINT
 4020  IF  LEFT$ (AA$,1) <  > "Y" THEN
      GOTO 4190
 4025  PRINT "IS FILE NAME SAME AS
      REF.#( ";REF$;" ): ";: GET
     AA$
 4027  IF AA$ = "Y" THEN FILE$ = R
     EF$
```

```
]LIST 4030,5090

 4030  HOME : VTAB 10
 4040  INPUT "GIVE A FILENAME: ";F
     ILE$
 4045  PRINT : PRINT D$
 4050  PRINT D$"MON C,I,O"
 4060  PRINT D$"OPEN ";FILE$
 4070  PRINT D$"WRITE ";FILE$
 4080  PRINT NAMES$
 4090  PRINT DT$
 4100  PRINT TIME$
 4110  PRINT ST$
 4115  PRINT GA$
 4120  PRINT ND
 4130  PRINT DIAM
 4140  FOR IJ = 1 TO ND
 4150  PRINT A(IJ): PRINT B(IJ): PRINT
     C(IJ): PRINT D(IJ): PRINT E(
     IJ): PRINT F(IJ): PRINT G(IJ
     ): PRINT H(IJ): PRINT I(IJ):
      PRINT J(IJ): PRINT K(IJ): PRINT
     L(IJ): PRINT M(IJ): PRINT N(
     IJ): PRINT O(IJ): PRINT P(IJ
     )
 4160  PRINT Q(IJ): PRINT R(IJ): PRINT
     S(IJ): PRINT T(IJ): PRINT U(
     IJ): PRINT V(IJ): PRINT W(IJ
     ): PRINT X(IJ)
 4170  NEXT IJ
 4180  PRINT D$"CLOSE ";FILE$
 4190  RETURN
 4200  REM  **********************

 4210  REM
 5000  HOME : VTAB 10
 5005 D$ = "": REM  CONTROL-D
 5010  INPUT "WHICH FILE (NAME): "
     ;FILE$
 5020  PRINT D$"MON C,I,O"
 5030  PRINT D$"OPEN ";FILE$
 5040  PRINT D$"READ ";FILE$
 5050  INPUT NAMES$
 5060  INPUT DT$
 5070  INPUT TIME$
 5080  INPUT ST$
 5085  INPUT GA$
 5090  INPUT ND
```

```
]LIST 5100,30600

5100  INPUT DIAM
5110  DIM A(ND),B(ND),C(ND),D(ND)
     ,E(ND),F(ND),G(ND),H(ND),I(N
     D),J(ND),K(ND),L(ND),M(ND),N
     (ND),O(ND),P(ND),Q(ND),R(ND)
     ,S(ND),T(ND),U(ND),V(ND),W(N
     D),X(ND)
5120  FOR IJ = 1 TO ND
5130  INPUT A(IJ): INPUT B(IJ): INPUT
     C(IJ): INPUT D(IJ): INPUT E(
     IJ): INPUT F(IJ): INPUT G(IJ
     ): INPUT H(IJ): INPUT I(IJ):
      INPUT J(IJ): INPUT K(IJ): INPUT
     L(IJ): INPUT M(IJ): INPUT N(
     IJ): INPUT O(IJ): INPUT P(IJ
     )
5140  INPUT Q(IJ): INPUT R(IJ): INPUT
     S(IJ): INPUT T(IJ): INPUT U(
     IJ): INPUT V(IJ): INPUT W(IJ
     ): INPUT X(IJ)
5150  NEXT IJ
5160  PRINT D$"CLOSE ";FILE$
5165 REF$ = FILE$
5170  RETURN
5180  REM  *********************

5190  REM
6000  HOME : VTAB 10: PRINT "DO Y
     OU WANT GRAPH PLOTTED (Y/N):
     ";: GET AA$
6010  IF  LEFT$ (AA$,1) <  > "Y" THEN
     GOTO 6030
6015 D$ = "": REM  CONTROL-D
6017  PRINT D$
6020  PRINT D$"RUN GRAPHIC PKG FI
     NAL"
6030  RETURN
6040  REM  *********************

30000  REM
30100  REM  INPUT FACTORS FOR 3"
     PIPE
30300 FR = 3.864:FP = 0.0491
30400 FQ = 0.0491:FT = 1.046
30500 FU = 1.046:FV = 4.688
30600 FW = 0.00127:FX = 32.0
```

```
]LIST 30700,51000

30700 AR = 0.491: REM  (SQ. FEET)

30800 TL = 21.33: REM   (TEST LEN
     GTH           =FEET)
30900 SG = 13.55: REM   (M-FLUID)

31000 LF$ = "MERCURY": REM  LINE
     FLUID TYPE
31100 LA =  - 8853.51:LB = 12.1: REM
      CONSTANTS (A & B) FOR THE R
     EGRESSED GAMMA LOGGER EQN
31200  RETURN
40000  REM
40100  REM  INPUT FACTORS FOR 4"
     PIPE
40200  REM
40400 FR = 2.173:FP = 0.0873
40500 FQ = 0.0873:FT = 1.046
40600 FU = 1.046:FV = 5.917
40700 FW = 0.00214:FX = 24.0
40800 AR = 0.0873:TL = 16.9
40900 SG = 2.95:LF$ = "MERIAM FLU
     ID (PINK)"
41000 LA =  - 2261.56:LB = 3.786
41100  RETURN
50000  REM
50100  REM  INPUT FACTORS FOR 5"
     PIPE
50300 FR = 1.391:FP = 0.1360
50400 FQ = 0.1360:FT = 0.1630
50500 FU = 0.1630:FV = 7.246
50600 FW = 0.00327:FX = 19.2
50700 AR = 0.136:TL = 13.8
50800 SG = 1.75:LF$ = "MERIAM FLU
     ID (BLUE)"
50900 LA = 6.37:LB =  - 0.0073
51000  RETURN
```

APPENDIX - E

PROPOSED EXPERIMENTS TO STUDY SLURRY VISCOSITY DUE TO CHANGES IN ZETA POTENTIAL

APPENDIX E

EXPERIMENT BASED ON A ROTATIONAL VISCOMETER

1. Prepare a fresh sample in a tin can (coffee can) with the required concentration of solids.
2. Use drill, with attached propeller, to generate a pseudo-homogeneous mix.
3. Place the viscometer disc into the mixture at a fixed location and depth.
4. At intervals immerse zeta probe to obtain zeta potential readings. Fix the location of the probe to avoid influence on viscometer.
5. Plot viscosity versus zeta readings.
6. Test the mix adding flocculant to avoid colloidal dispersion.
7. Add cement and retest.
8. Run different concentrations.

EXPERIMENT BASED ON THE RESEARCH APPARATUS

1. Load fresh 80/20 mix in system and run.
2. Keep temperature, velocity and pipe diameter constant.
3. Record run time, changes in zeta potential and head-loss.
4. Plot head-loss versus zeta readings.

APPENDIX - F

PHOTOGRAPHIC REPRESENTATION OF THE TEST FACILITY

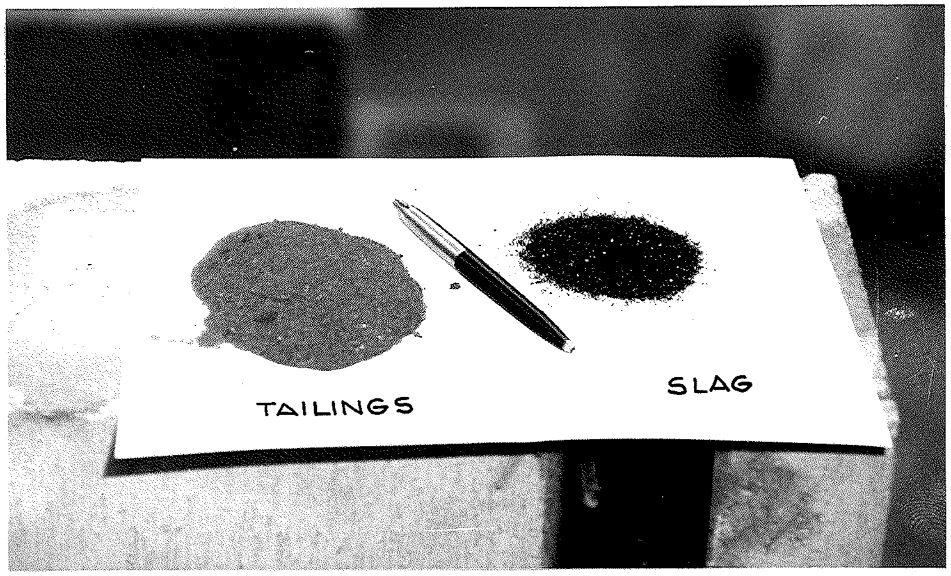


PLATE 1. Sample of Solid Materials: Tailings & Slag

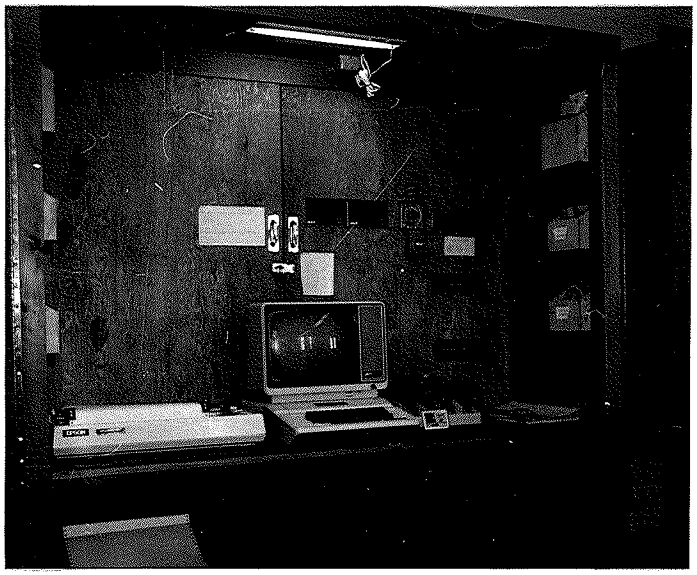


PLATE 2. Computer Data Analysis System
(a) Temperature Control

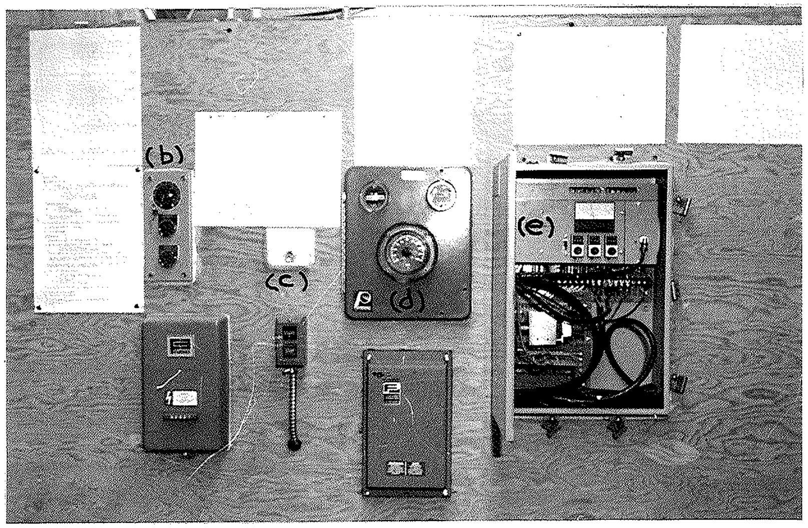


PLATE 3. Panel Meter: (b) Pump Control, (c) Mag-meter, (d) Polysonic-meter, (e) Gamma-Ray Electronics Unit

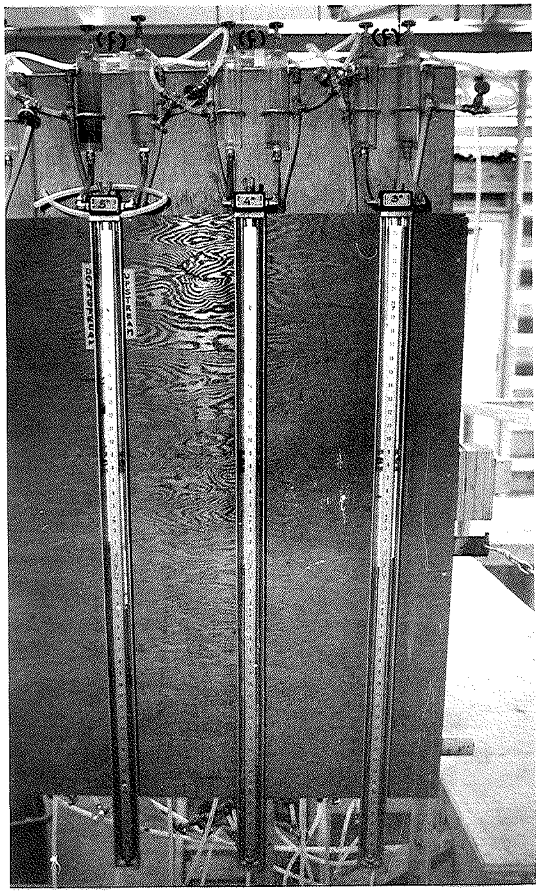


PLATE 4. U-Tube Manometers
(f) Pressure Transducers

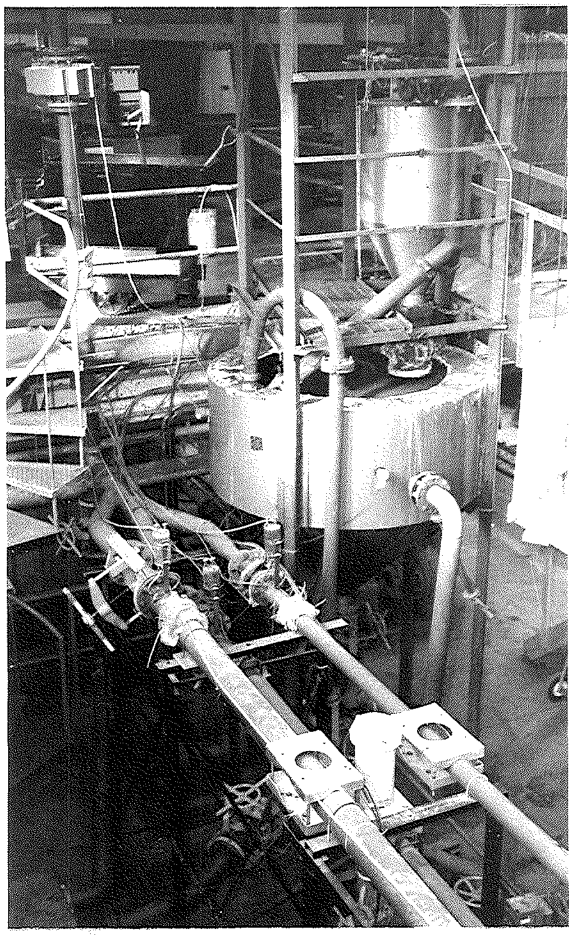


PLATE 5. General North View of Apparatus

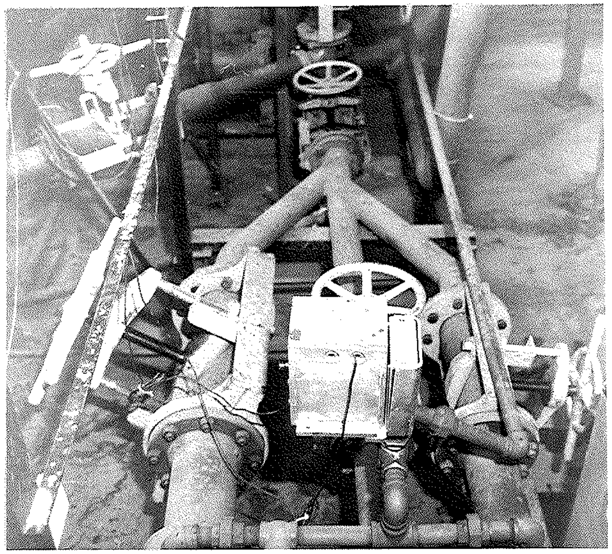


PLATE 6. First Level Manifold Showing Pinch Valves

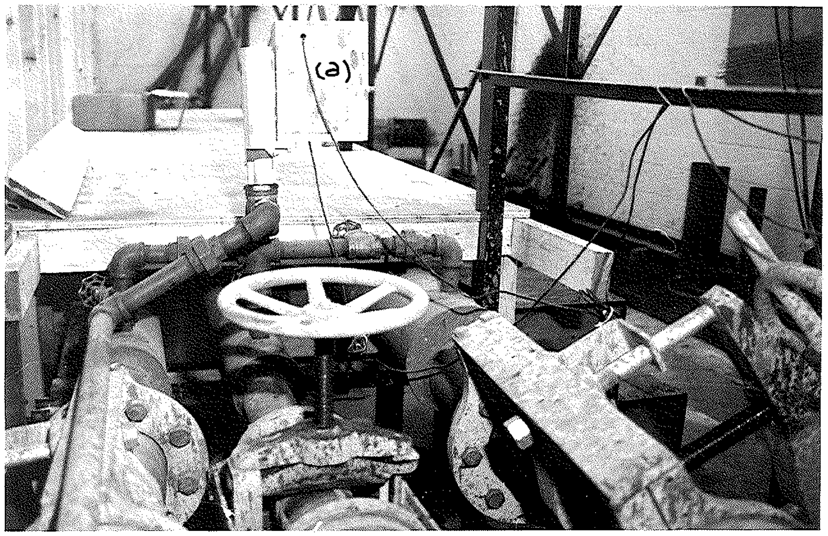


PLATE 7. Beginning of Cooling Jacket
(a) Automatic Valve Control

PLATE 8. Mixing Tank

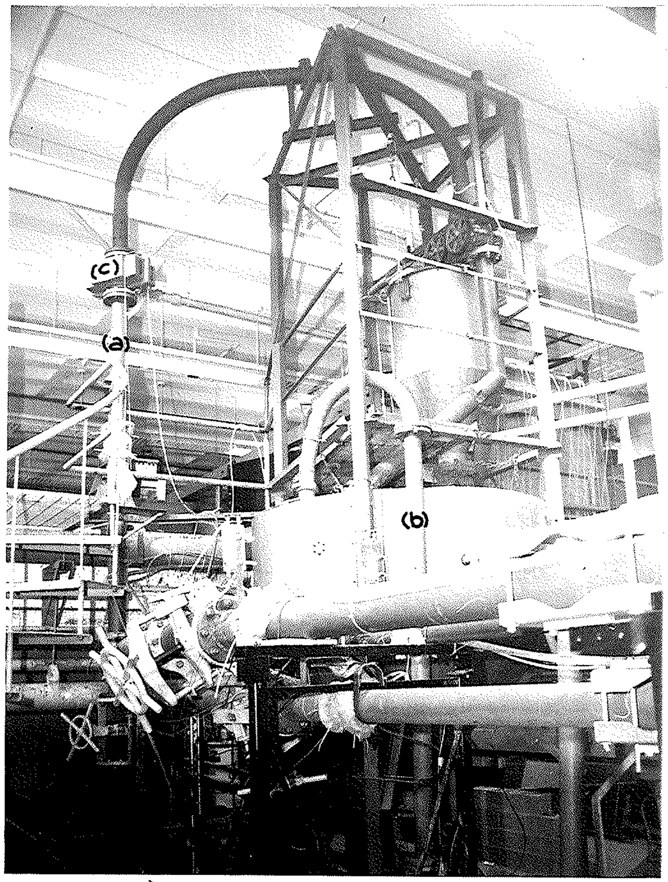


PLATE 9. Rising Pipes: (a) Main line (b) Short Loop, (c) Magnetic Flowmeter

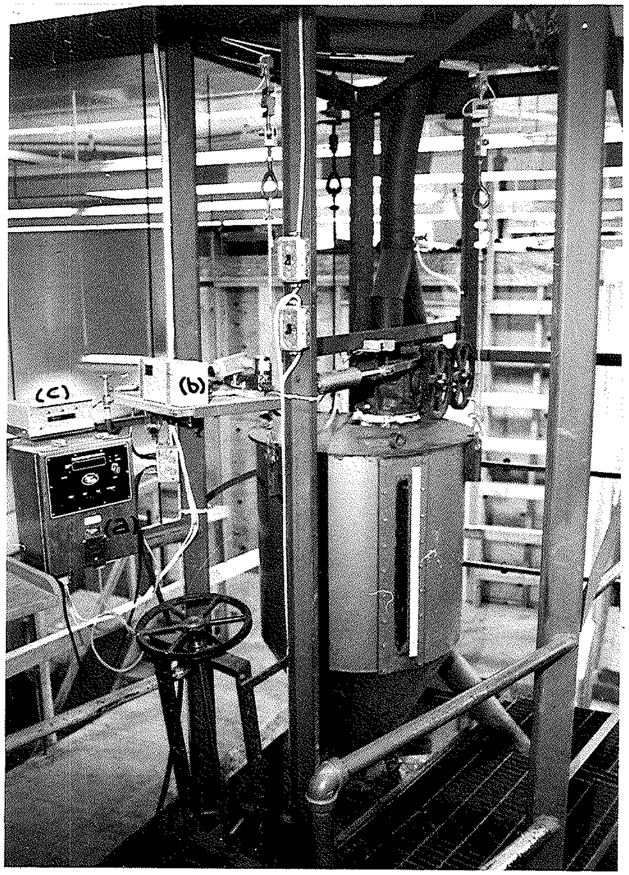


PLATE 10. Weighing Tank:
(a) Weight-meter
(b) Collection Timer
(c) Shift Timer

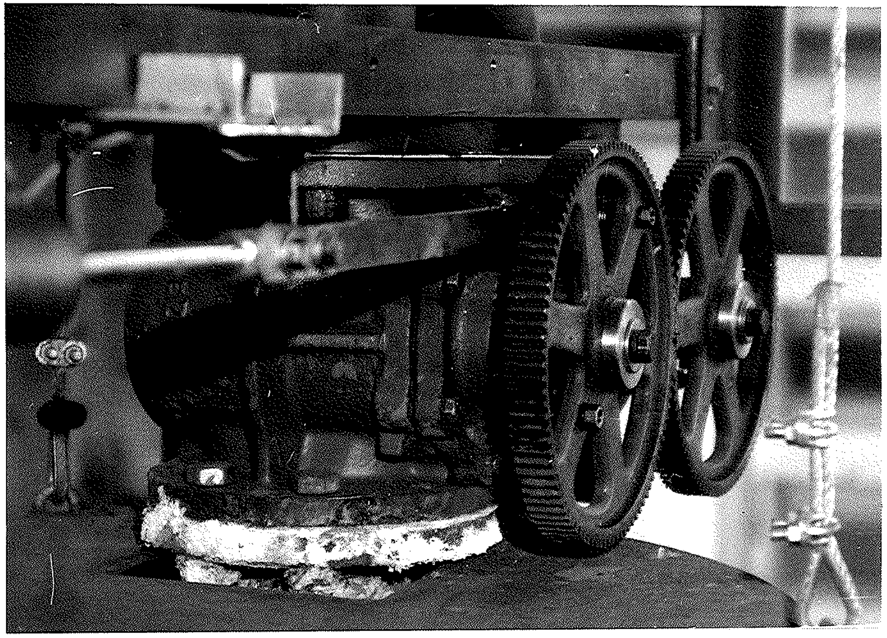


PLATE 11. Plug-valves

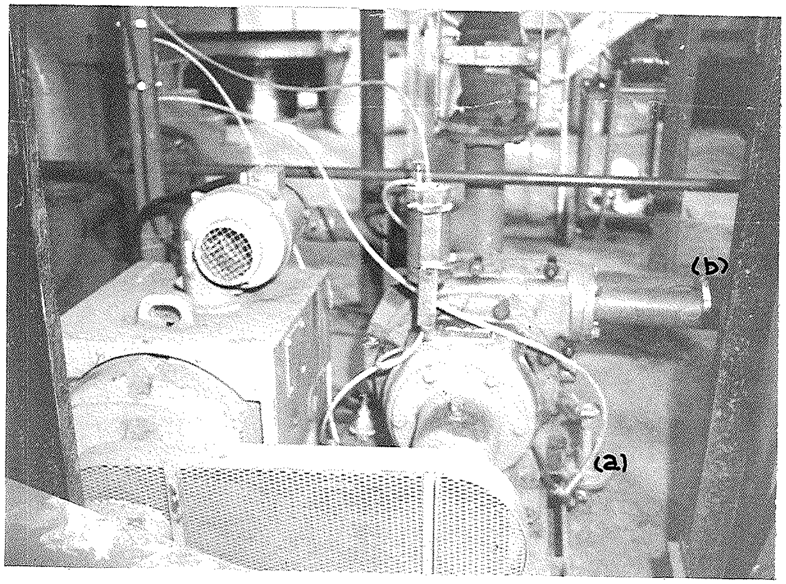


PLATE 12. Motor and Centrifugal Pump
(a) Differential Pressure Relief Valve
(b) Polysonic-meter Sensor

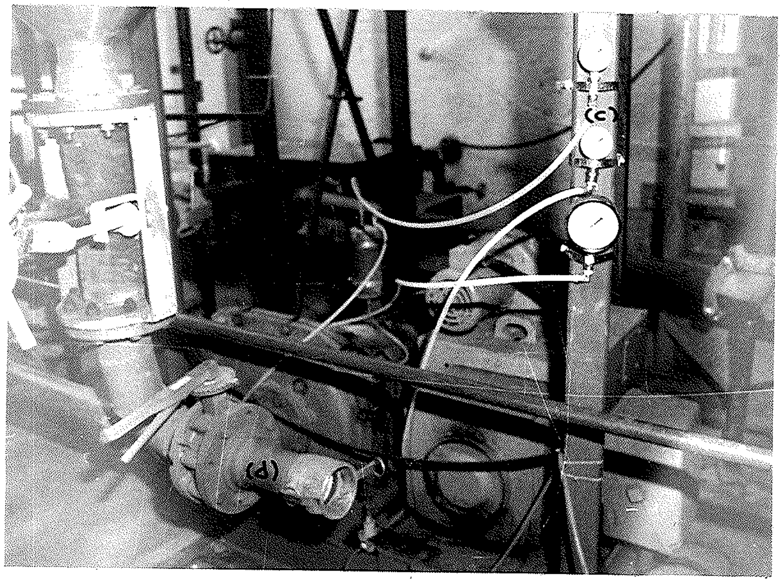


PLATE 13. (c) Pressure-meters for Pump Flushing
(d) Main Drain of Apparatus

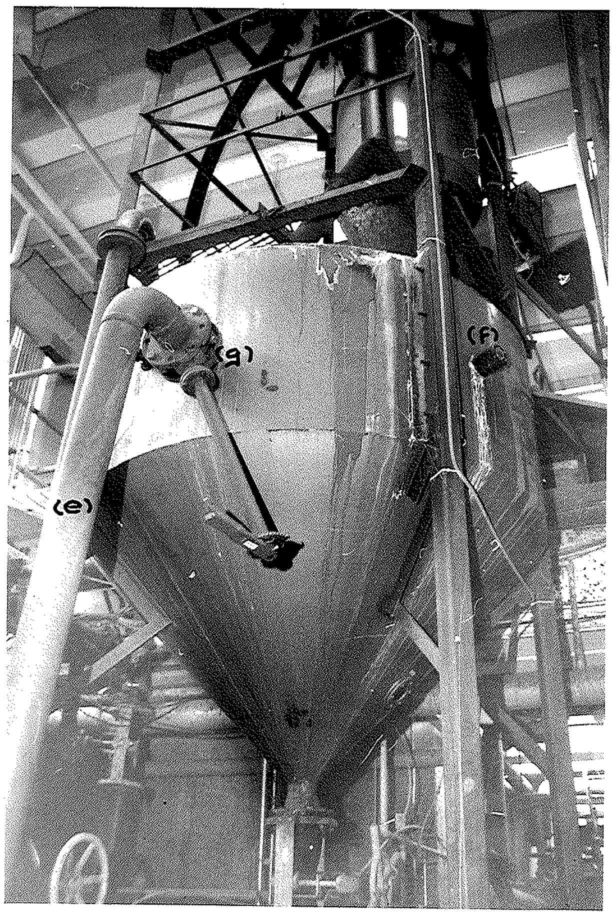


PLATE 14. Mixing Tank:
(e) By-pass Line
(f) Heating Element
(g) Butterfly-valve

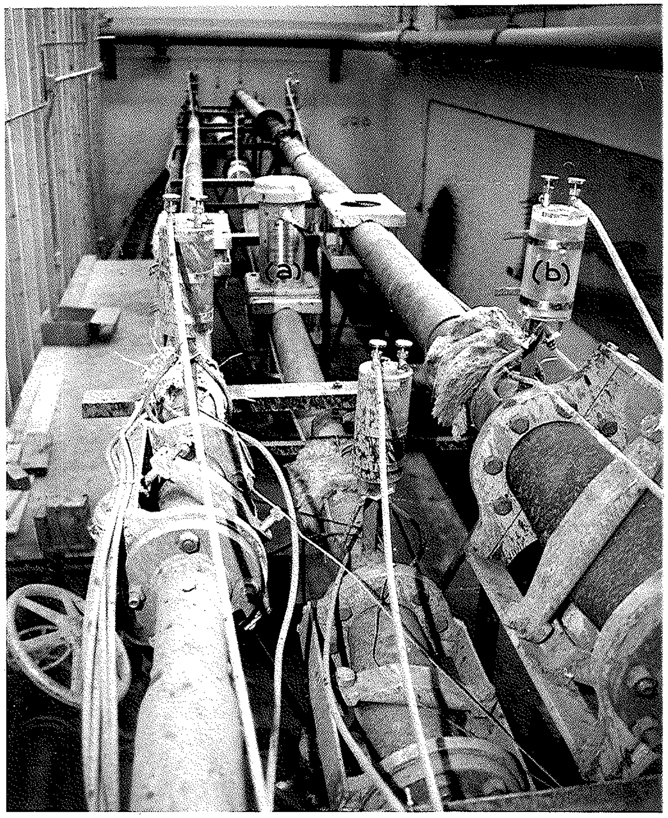


PLATE 15. Second Level Showing
(a) Gamma-logger detector
(b) Sand-traps

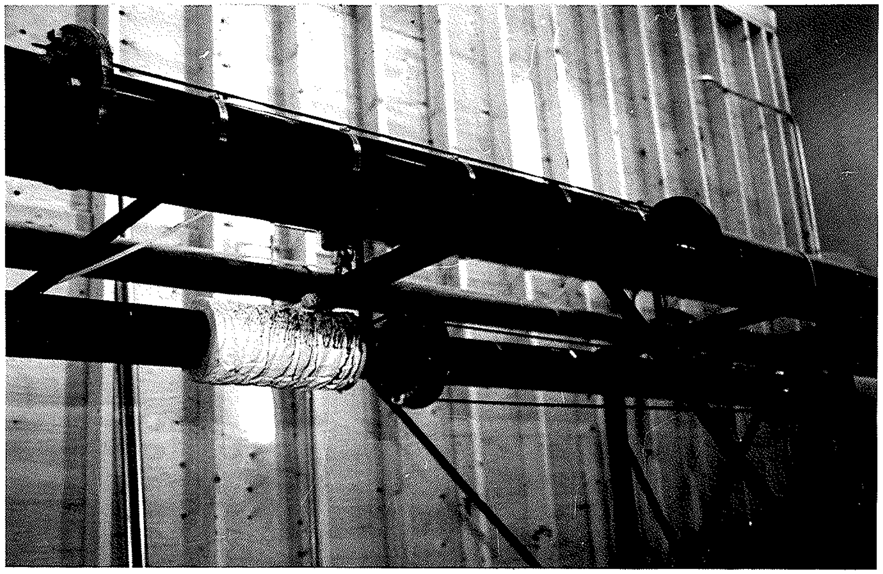
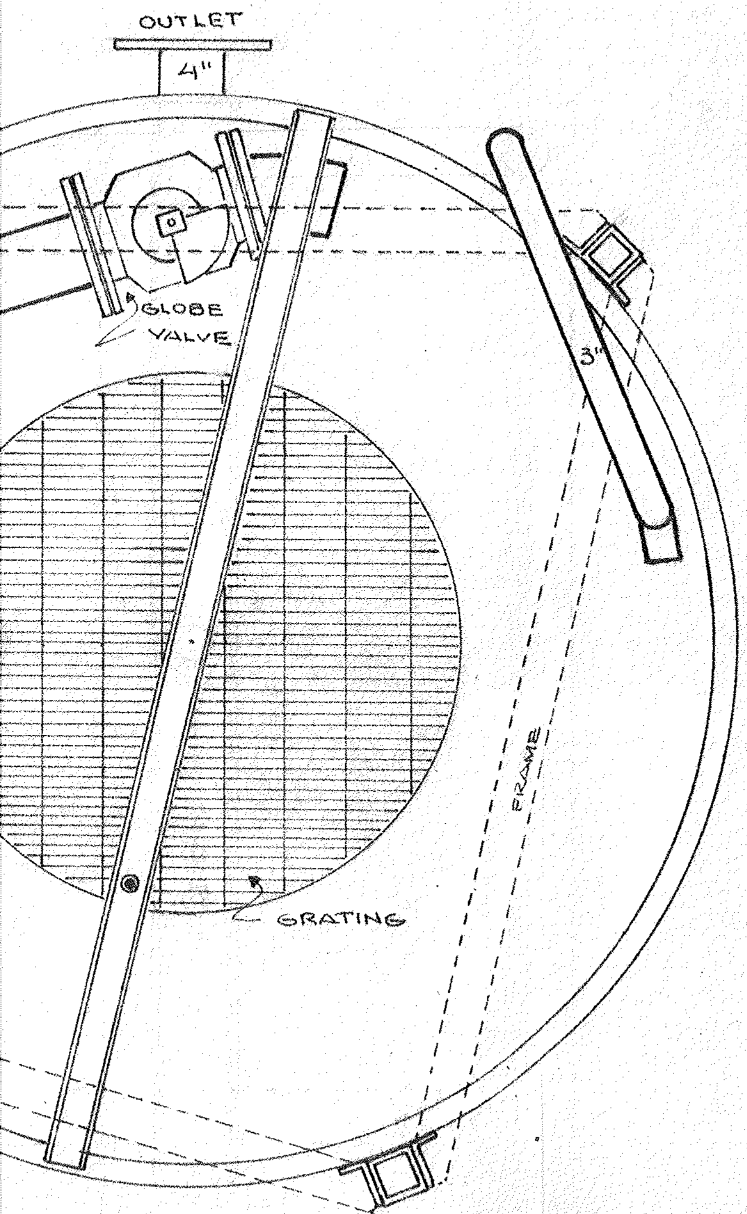
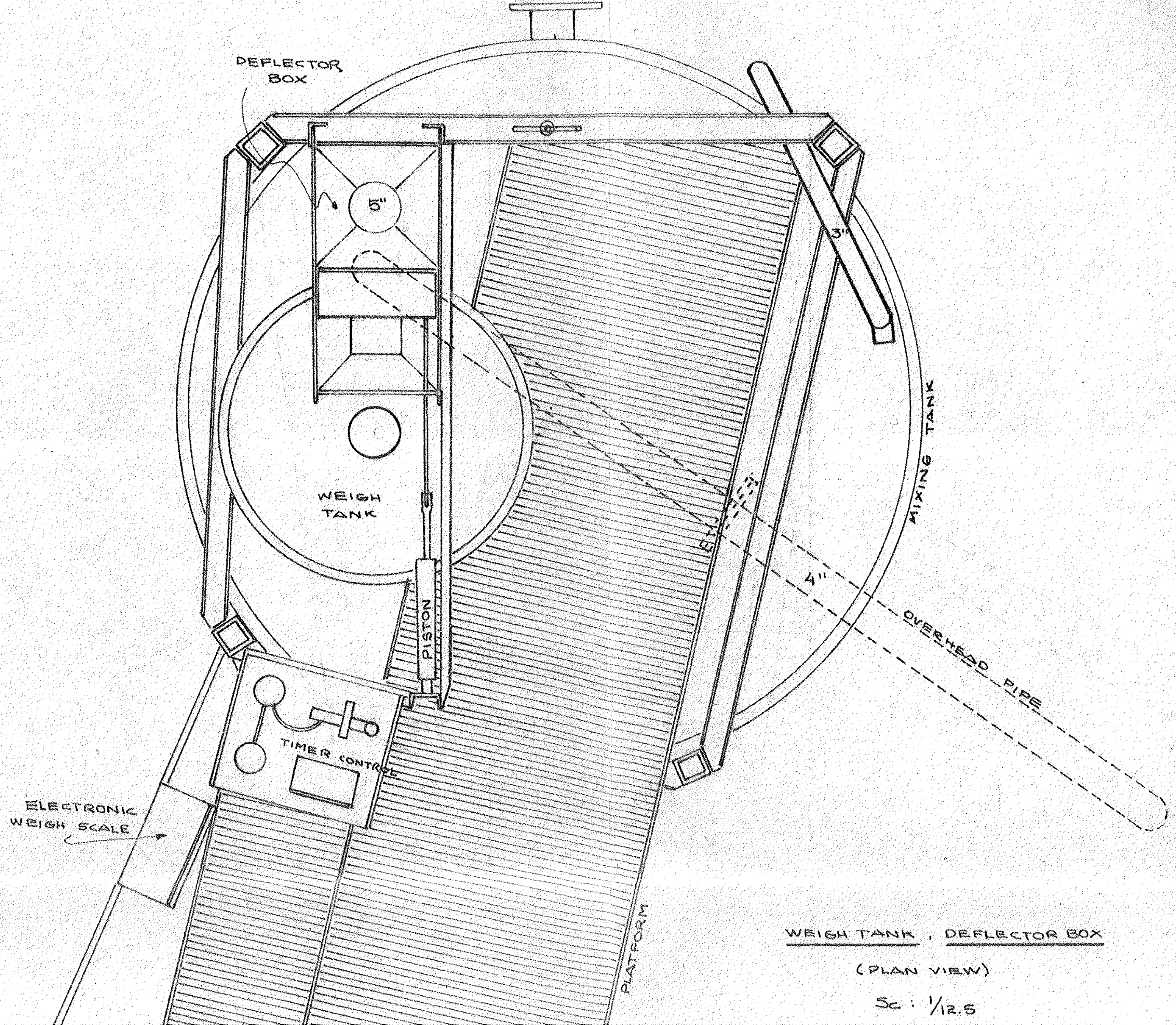


PLATE 16. Observation Section



G TANK (PLAN VIEW)

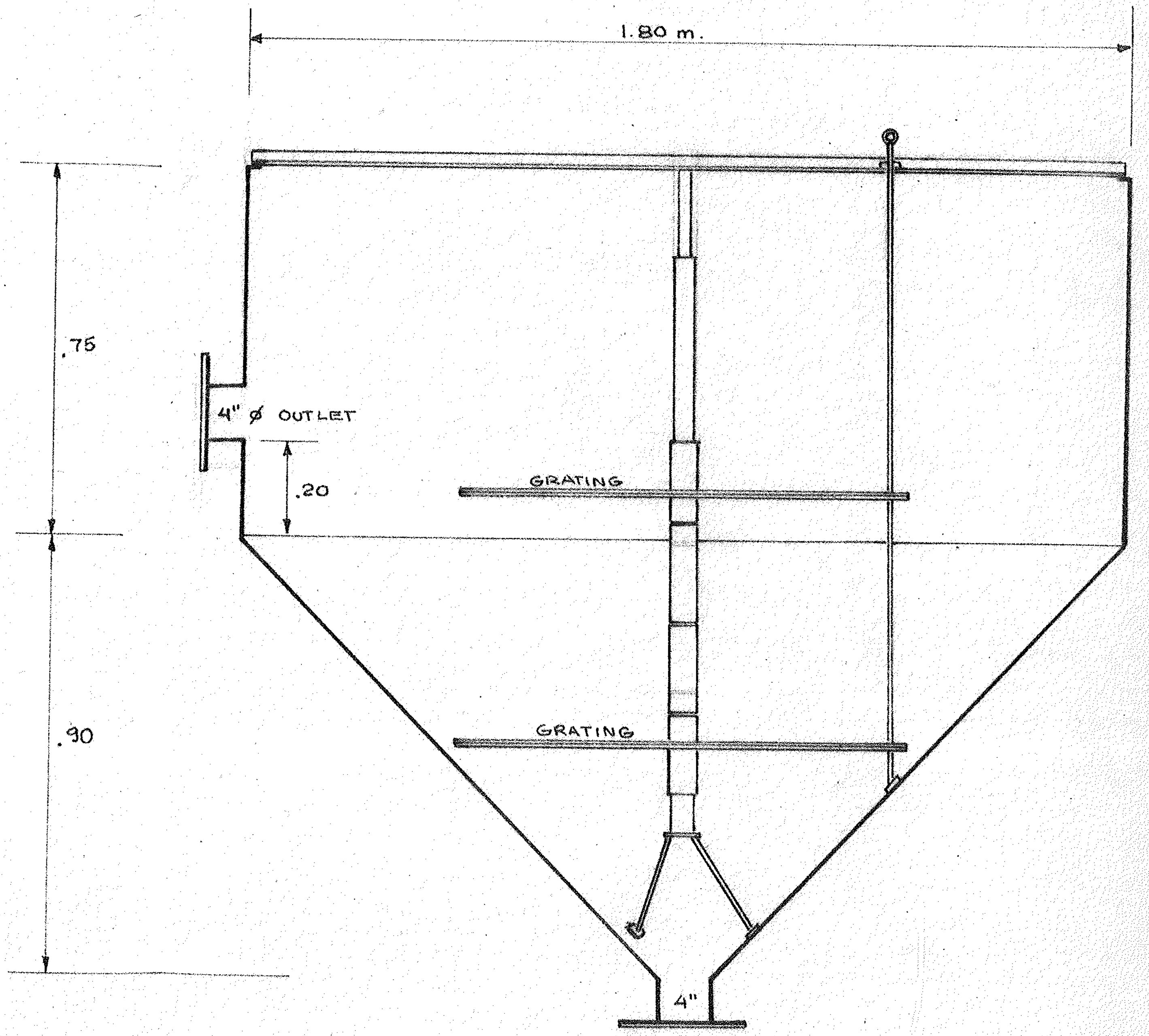
: 1/12.5



WEIGH TANK , DEFLECTOR BOX

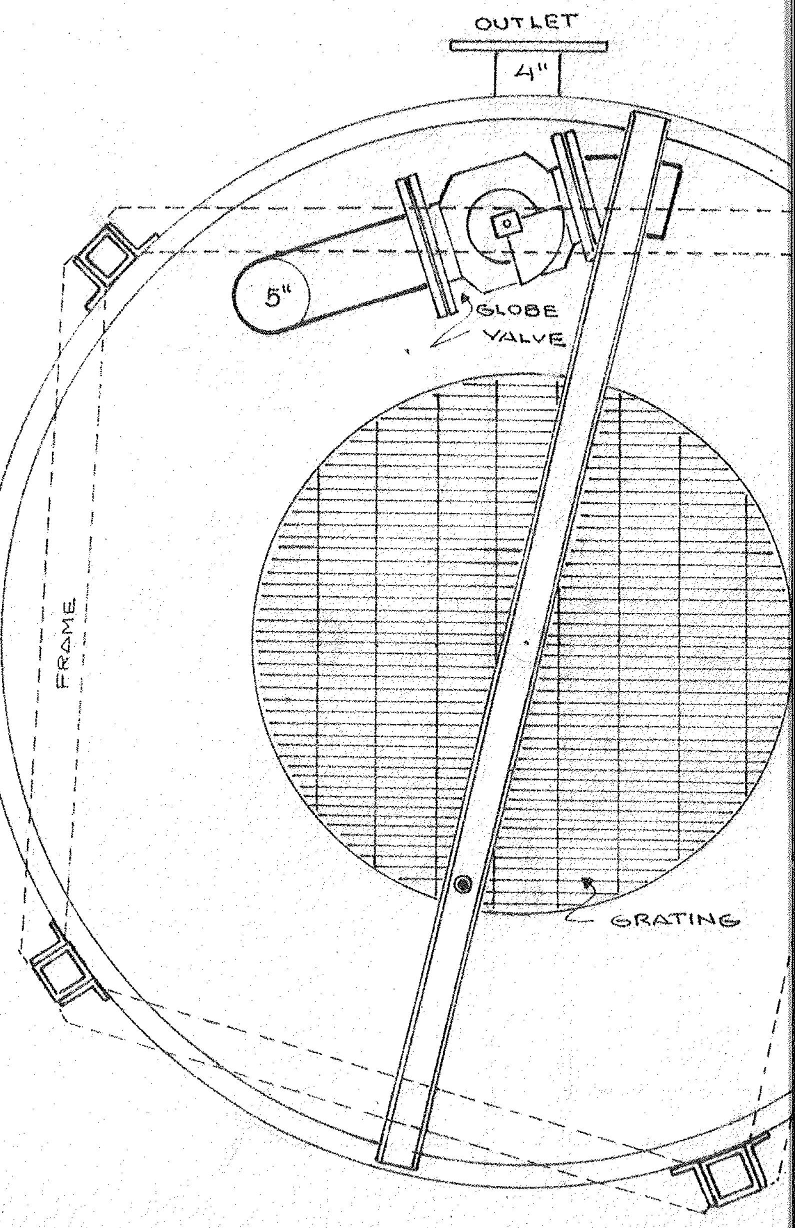
(PLAN VIEW)

Sc : 1/12.5



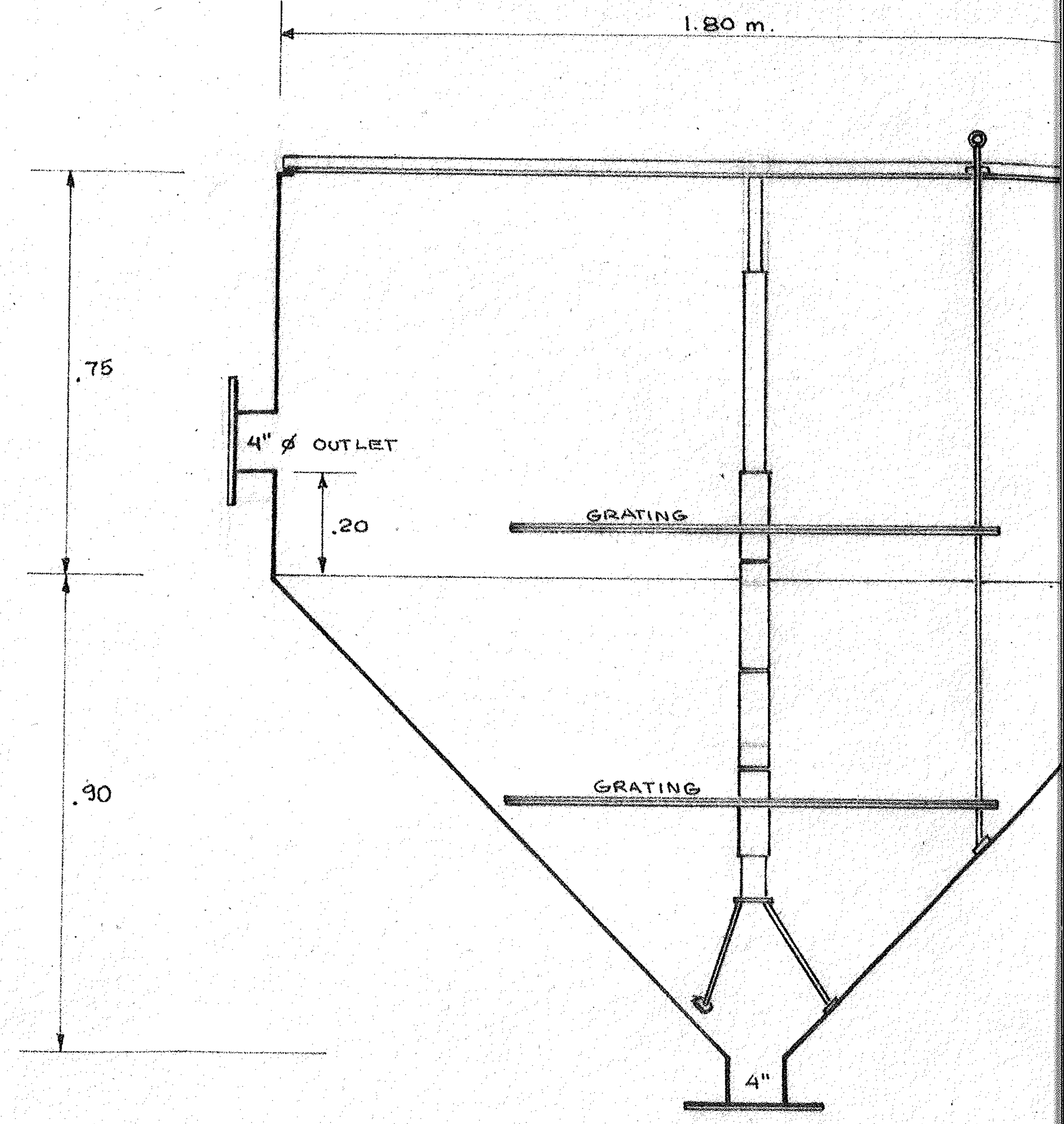
MIXING TANK (SECTION)

Sc: 1/12.5



MIXING TANK (PLAN VIEW)

Sc: 1/12.5

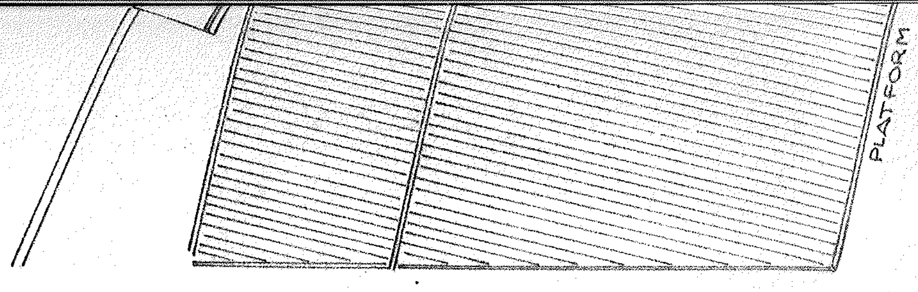


MIXING TANK (SECTION)

Sc: 1/12.5

TANK (PLAN VIEW)

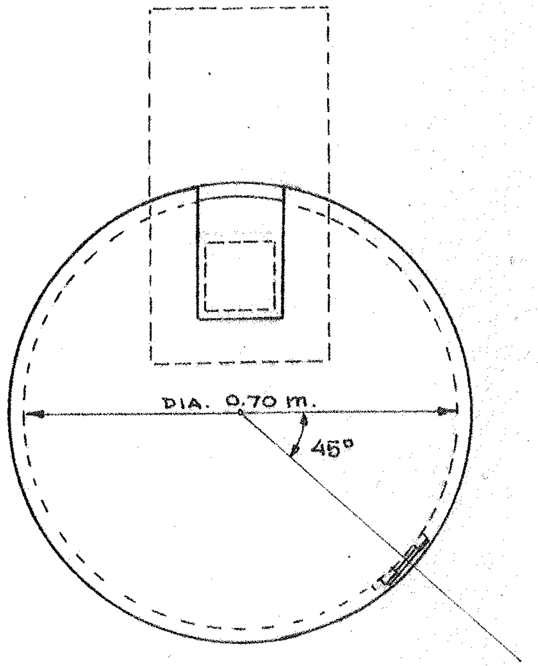
1/12.5



WEIGH TANK, DEFLECTOR BOX

(PLAN VIEW)

Sc: 1/12.5



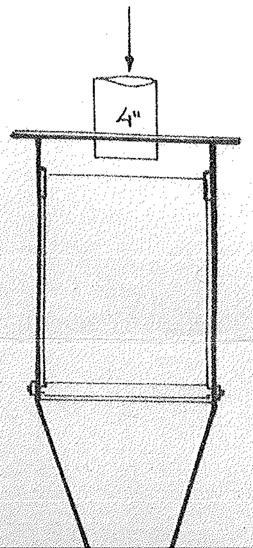
PLAN VIEW

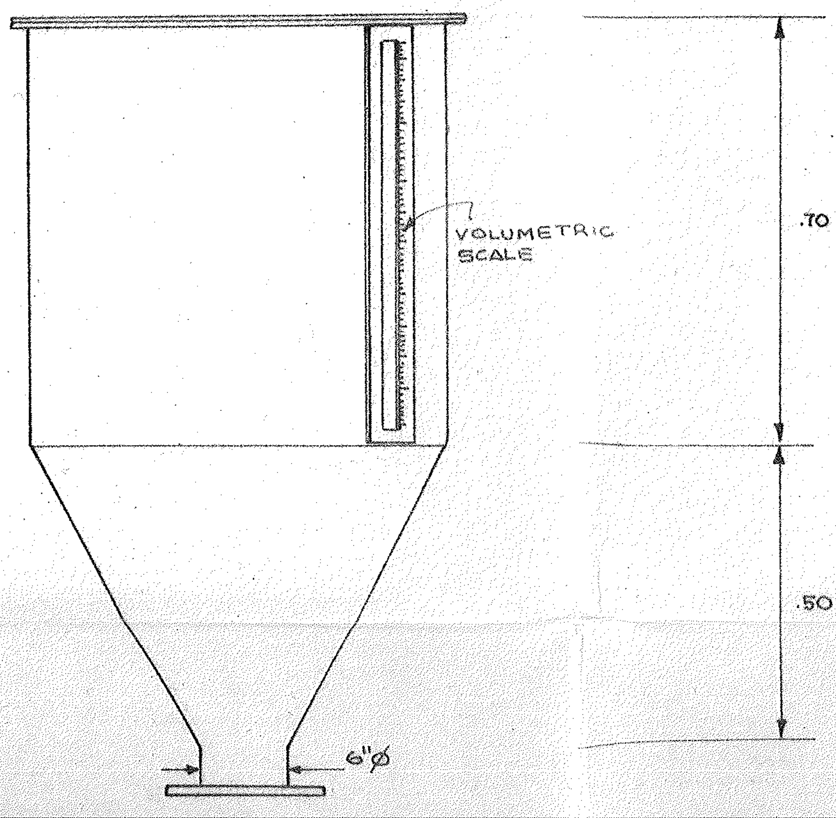
WEIGH TANK

Sc: 1/12.5

DEFLECTOR BOX

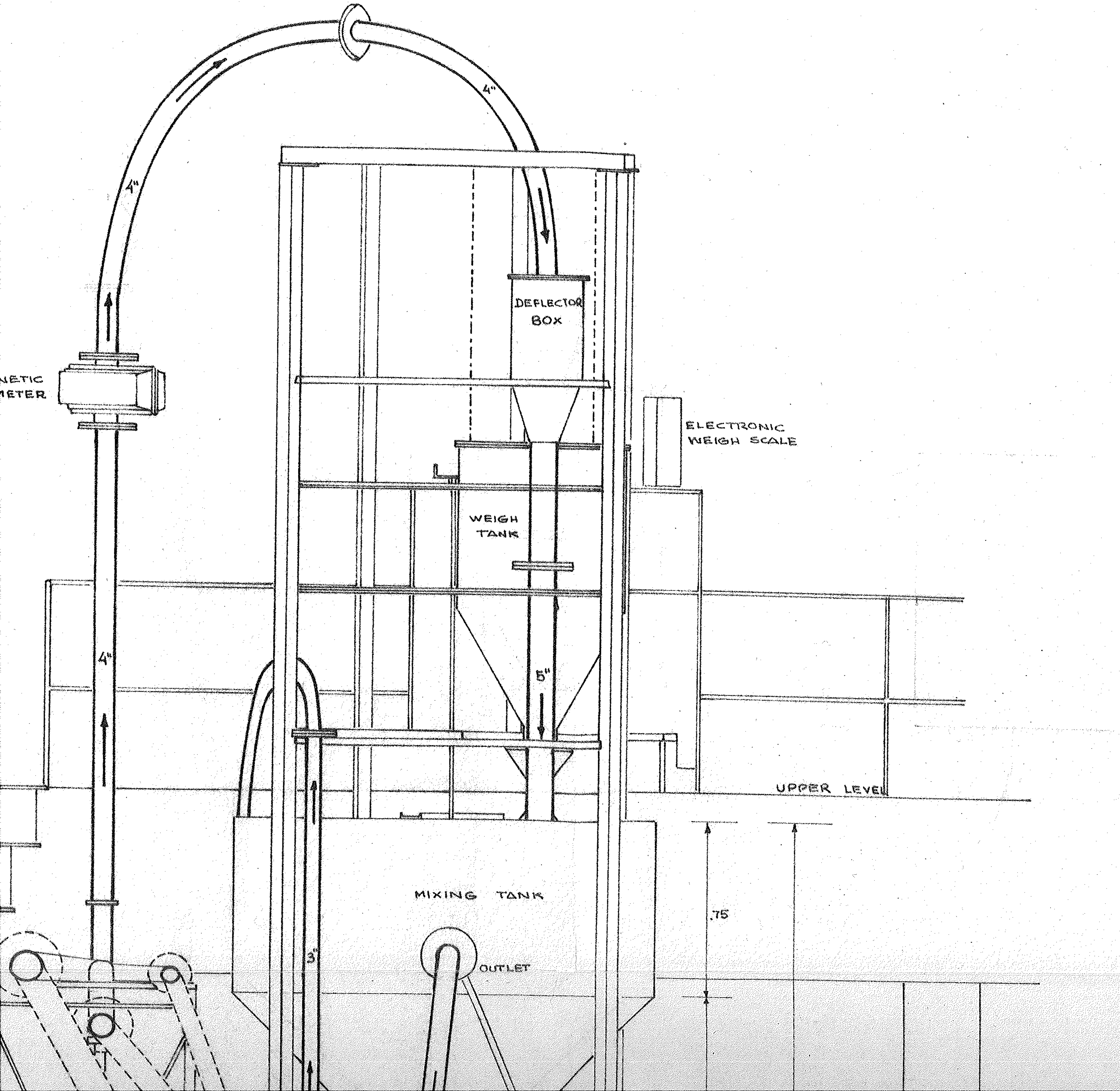
Sc: 1/12.5

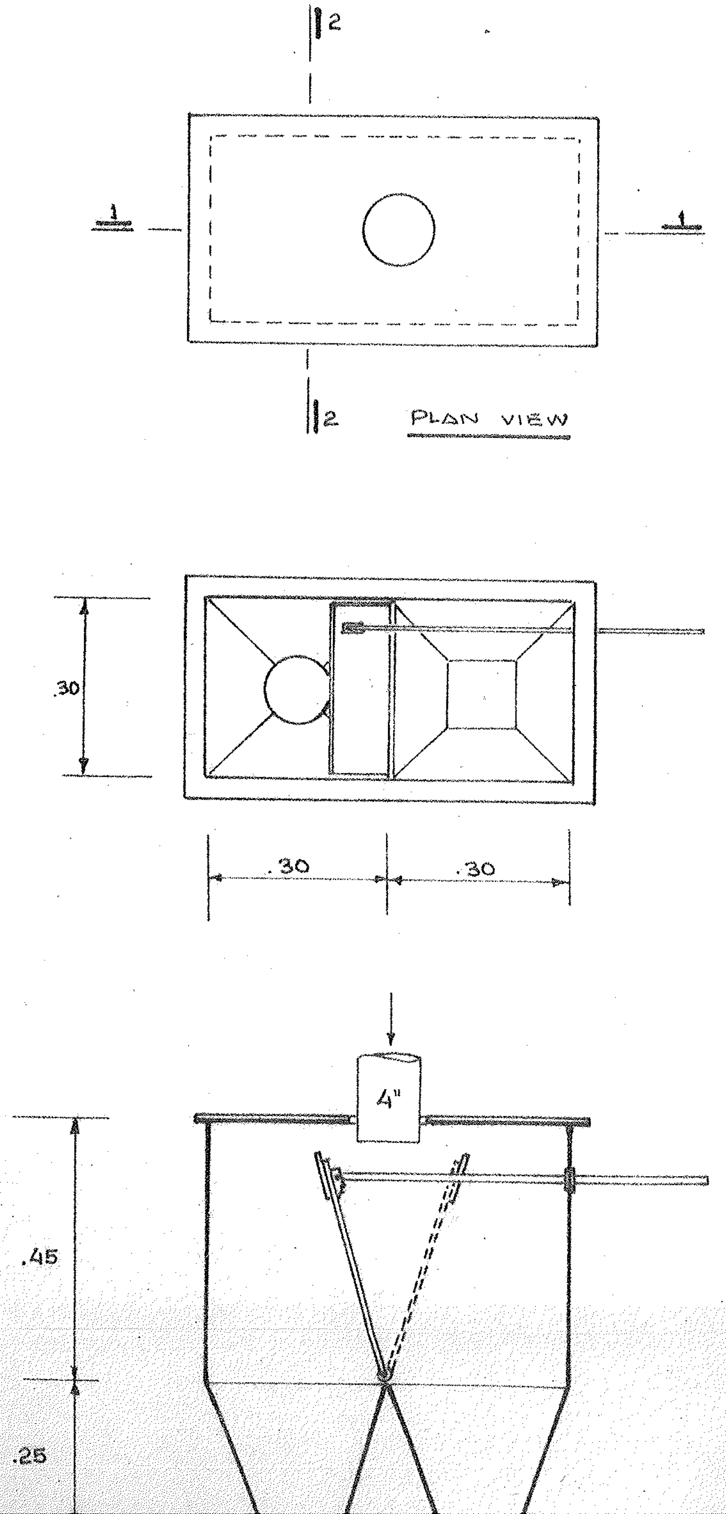


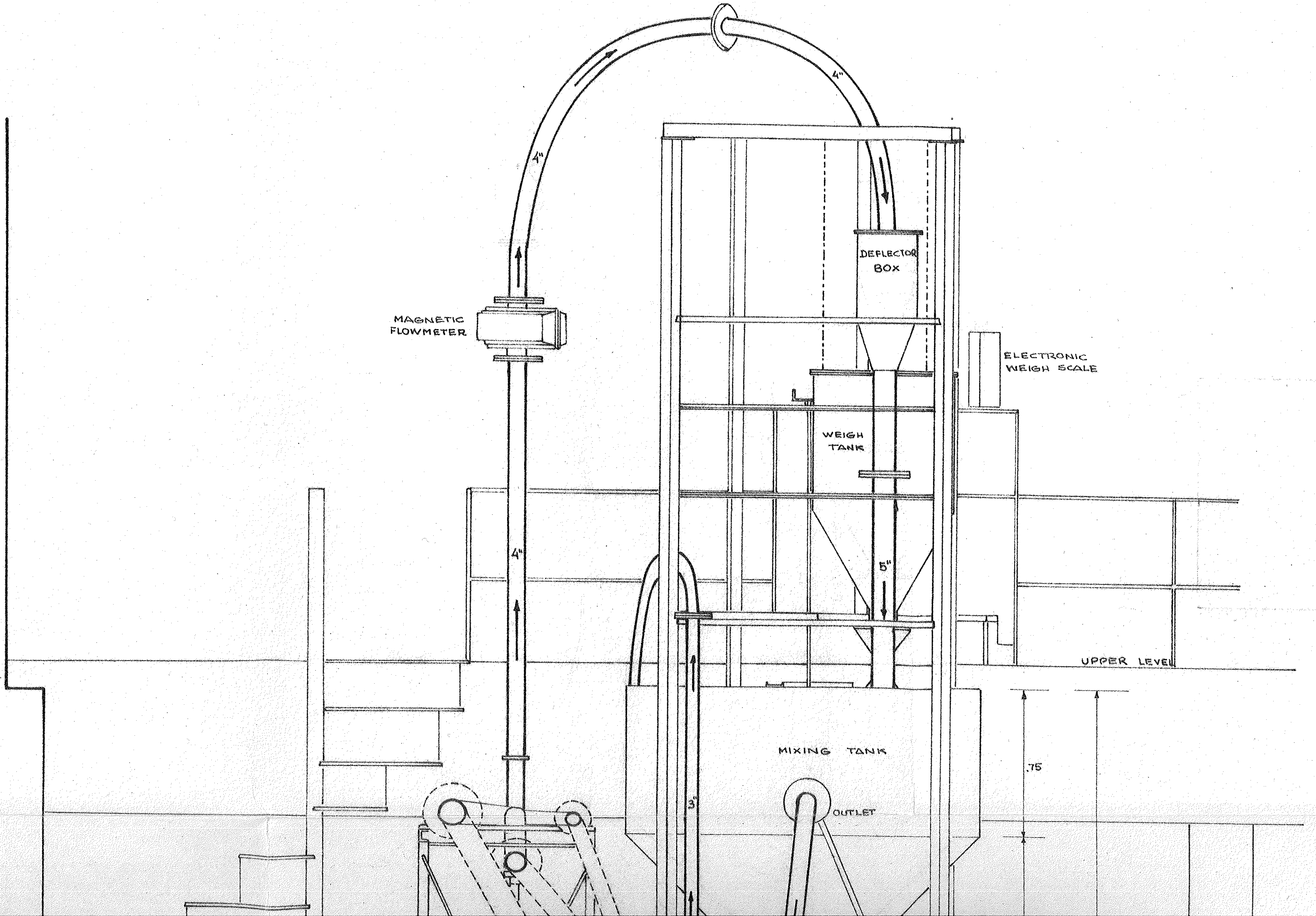


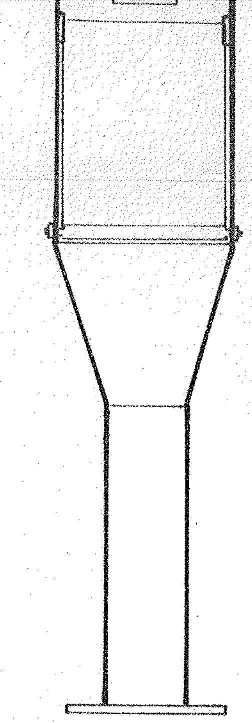
MIXING TANK

Sc: 1/12.5

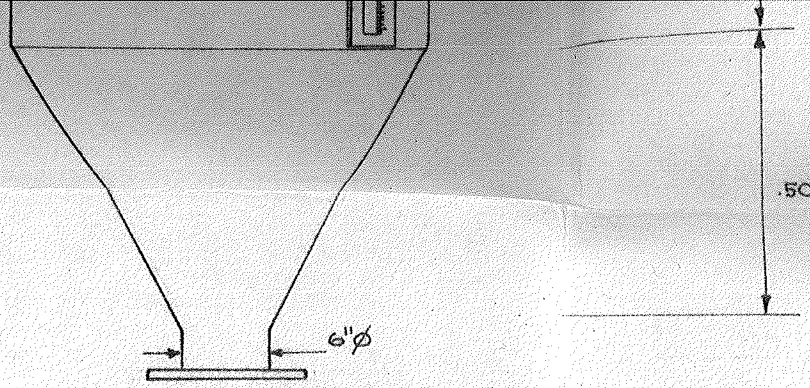





4"
4"
MAGNETIC FLOWMETER
DEFLECTOR BOX
ELECTRONIC WEIGH SCALE
WEIGH TANK
4"
5"
UPPER LEVEL
MIXING TANK
.75
3"
OUTLET



SECTION 2-2



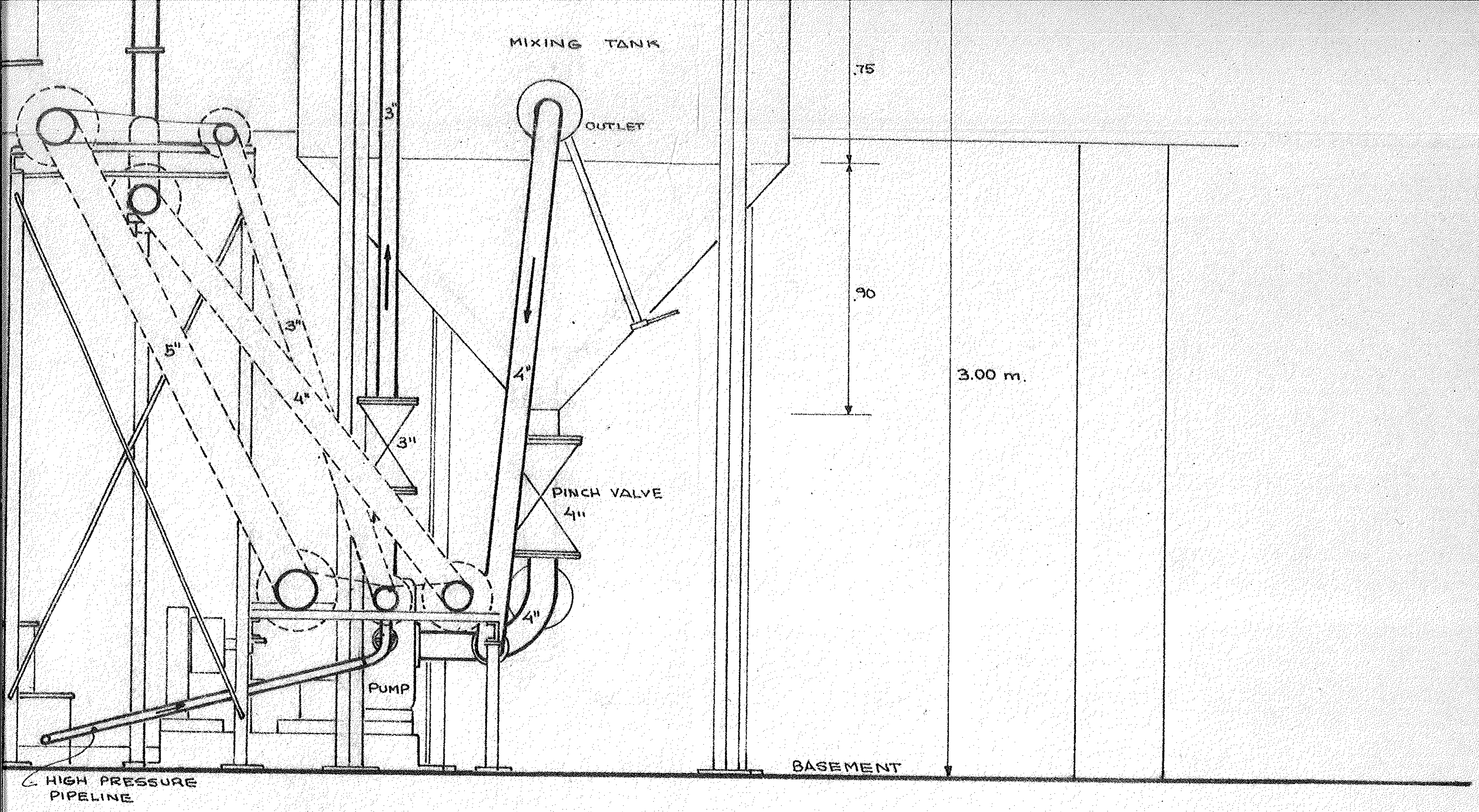
ELEVATION

WAS
PLUG--
1983

UNIVERSITY OF MANITOBA
HYDRAULICS LABORATORY

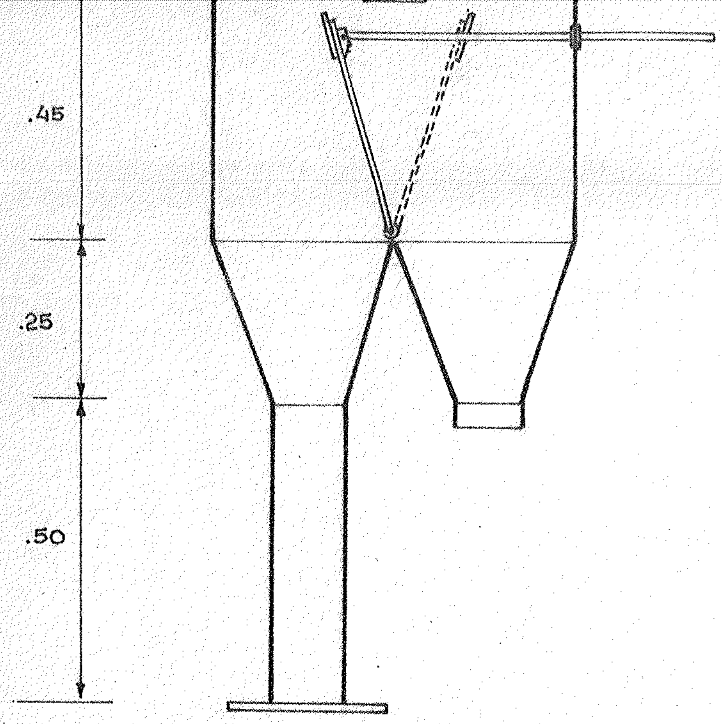
SLURRY PIPELINE TESTING RIG

DRAWN BY : Jorge L. Pomalaza	CHECKED BY : Dr. Luis MAGALHAES
APPROVED BY : Dr. AL TAMBURI	DATE : APRIL 30 - 1982
SCALE : 1/20 - 1/12.5	DRAWING Nº 2 OF 2



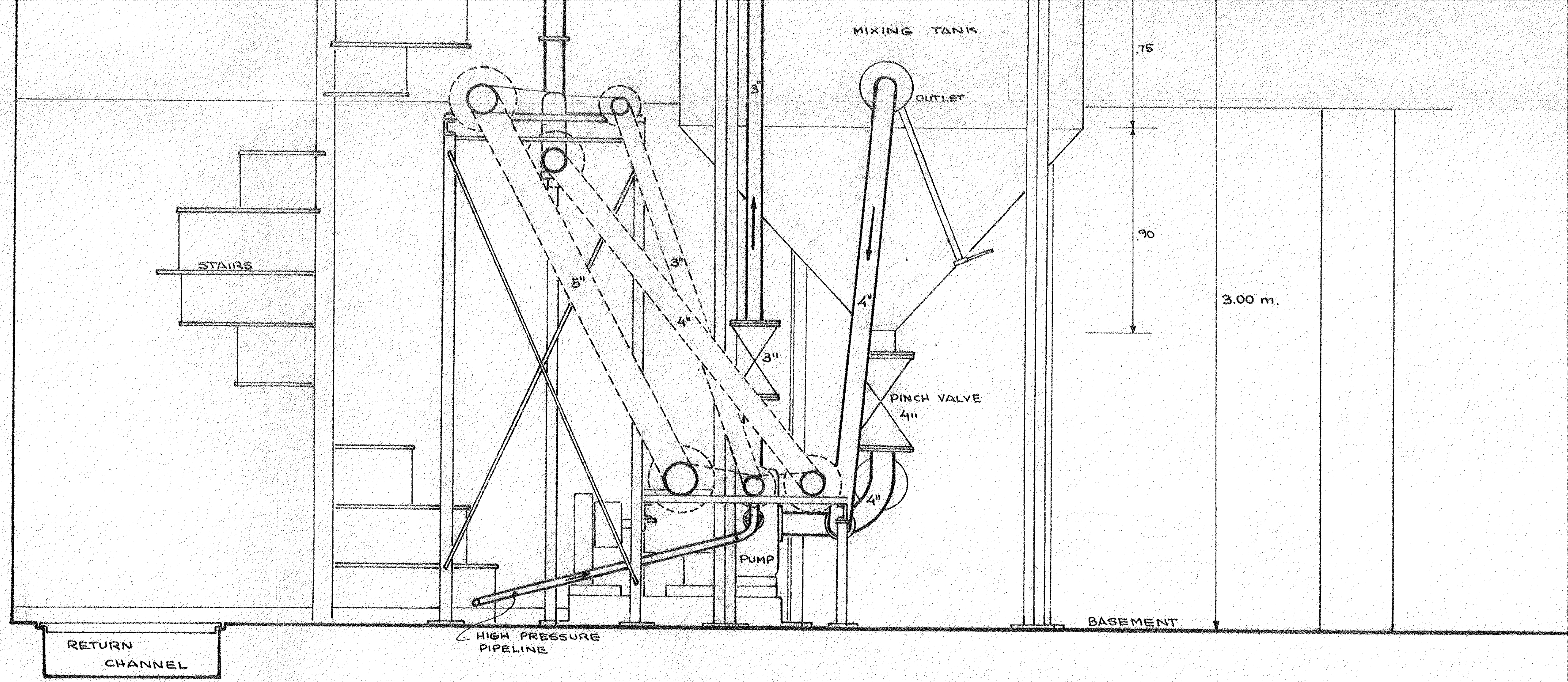
ELEVATION B

Sc. 1/20



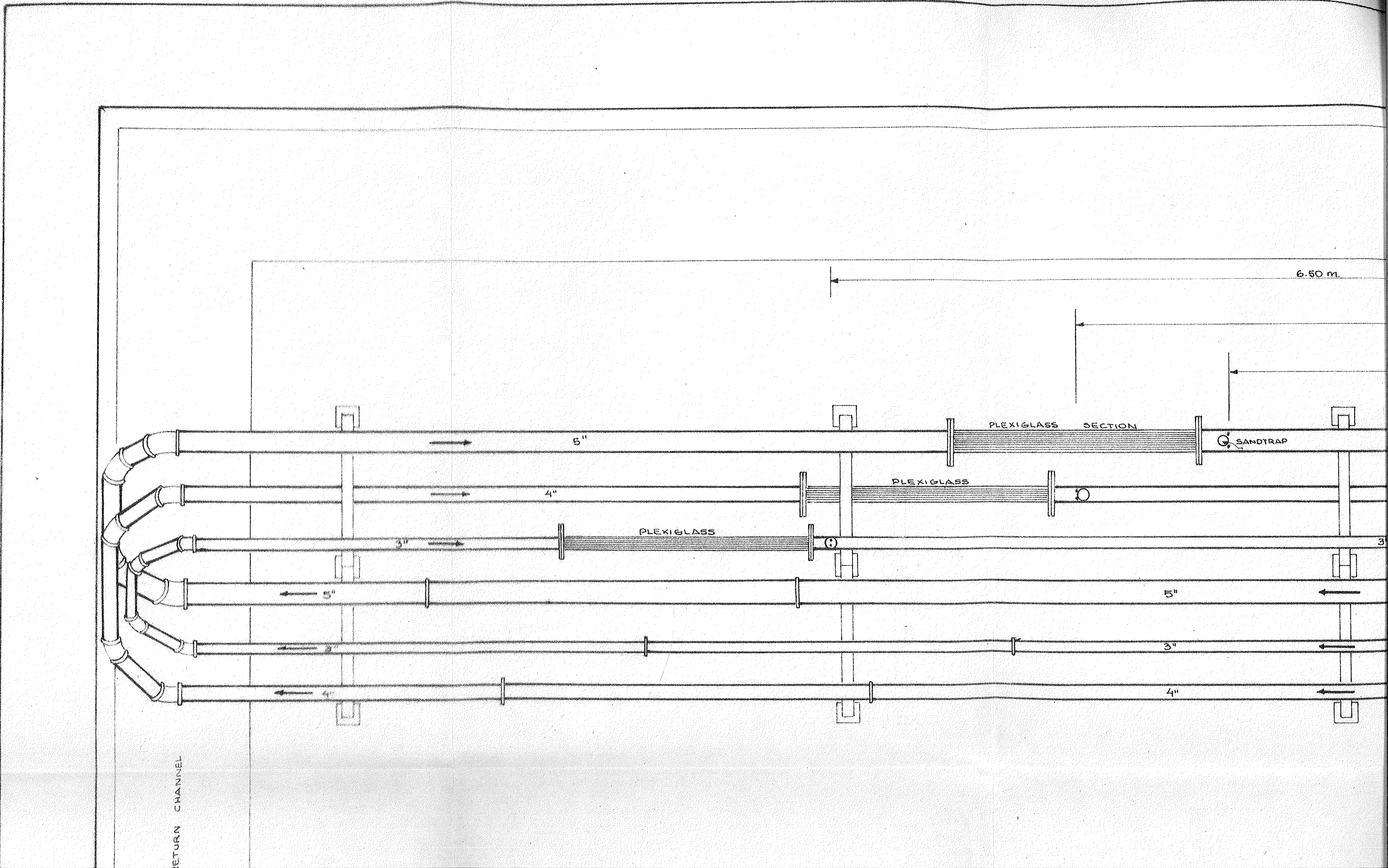
SECTION 1-1

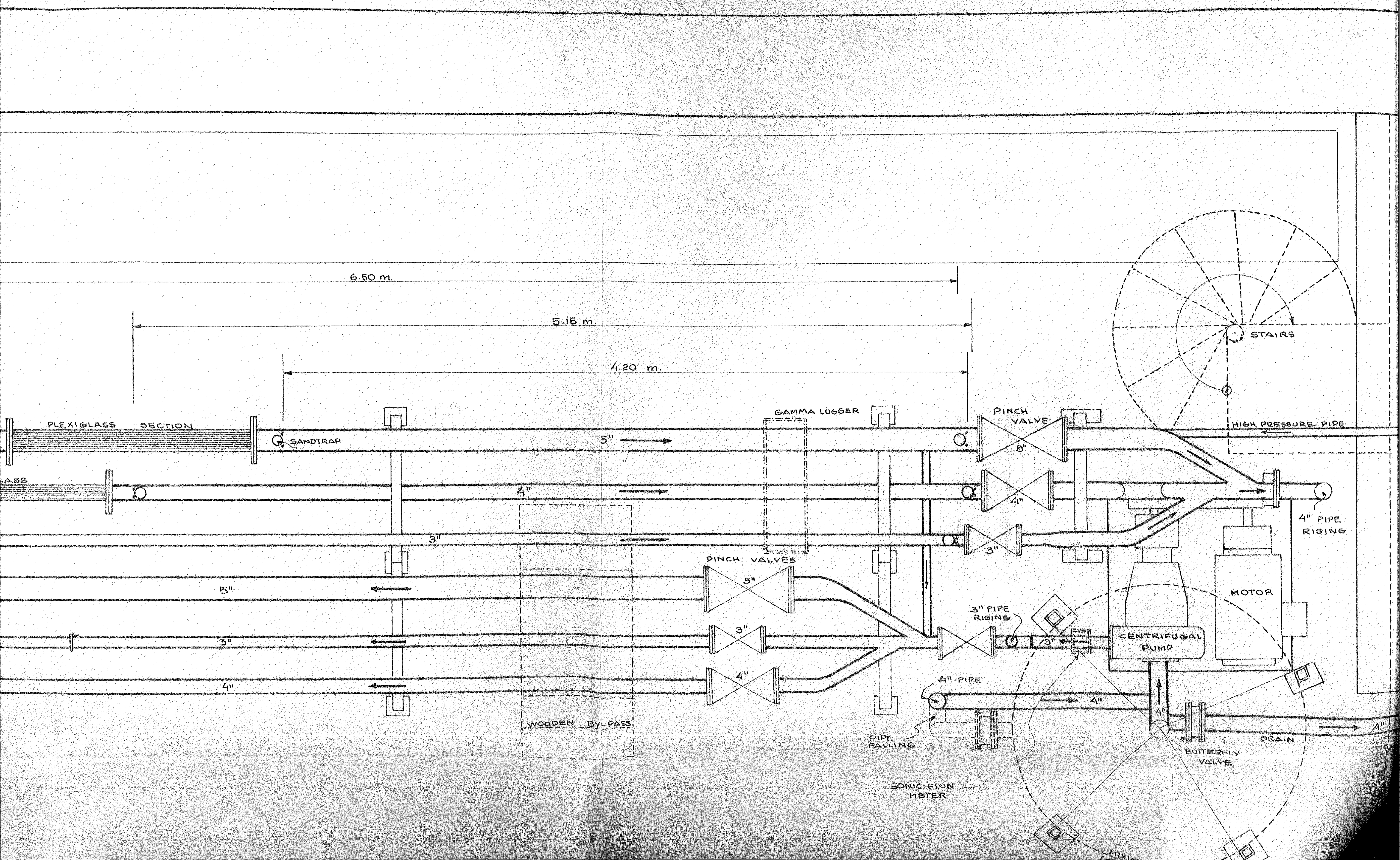
NOTE: THE DEFLECTOR BOX WAS REPLACED BY TWO PLUG-VALVES IN JANUARY 1983 (see Plate 11)

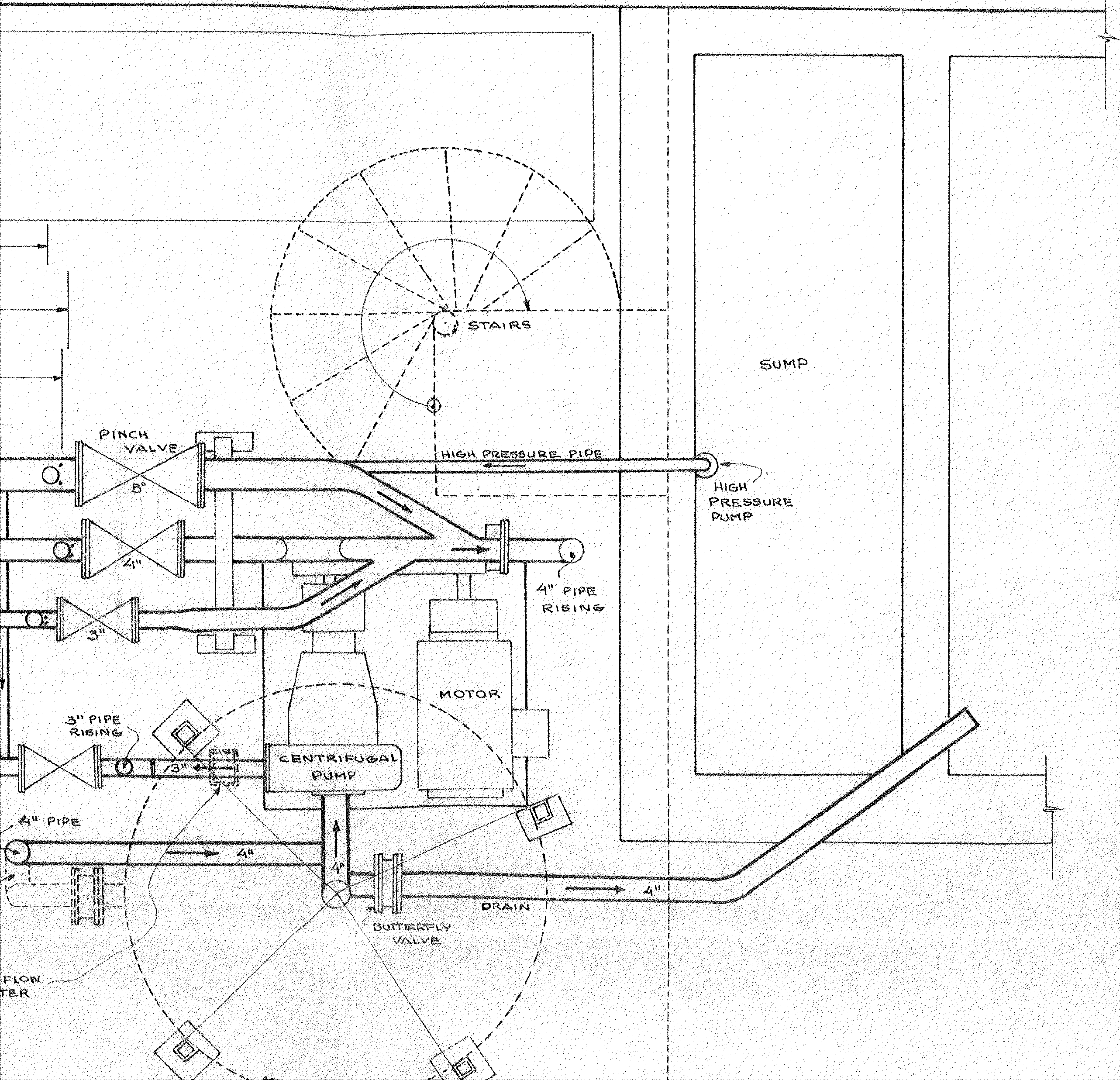


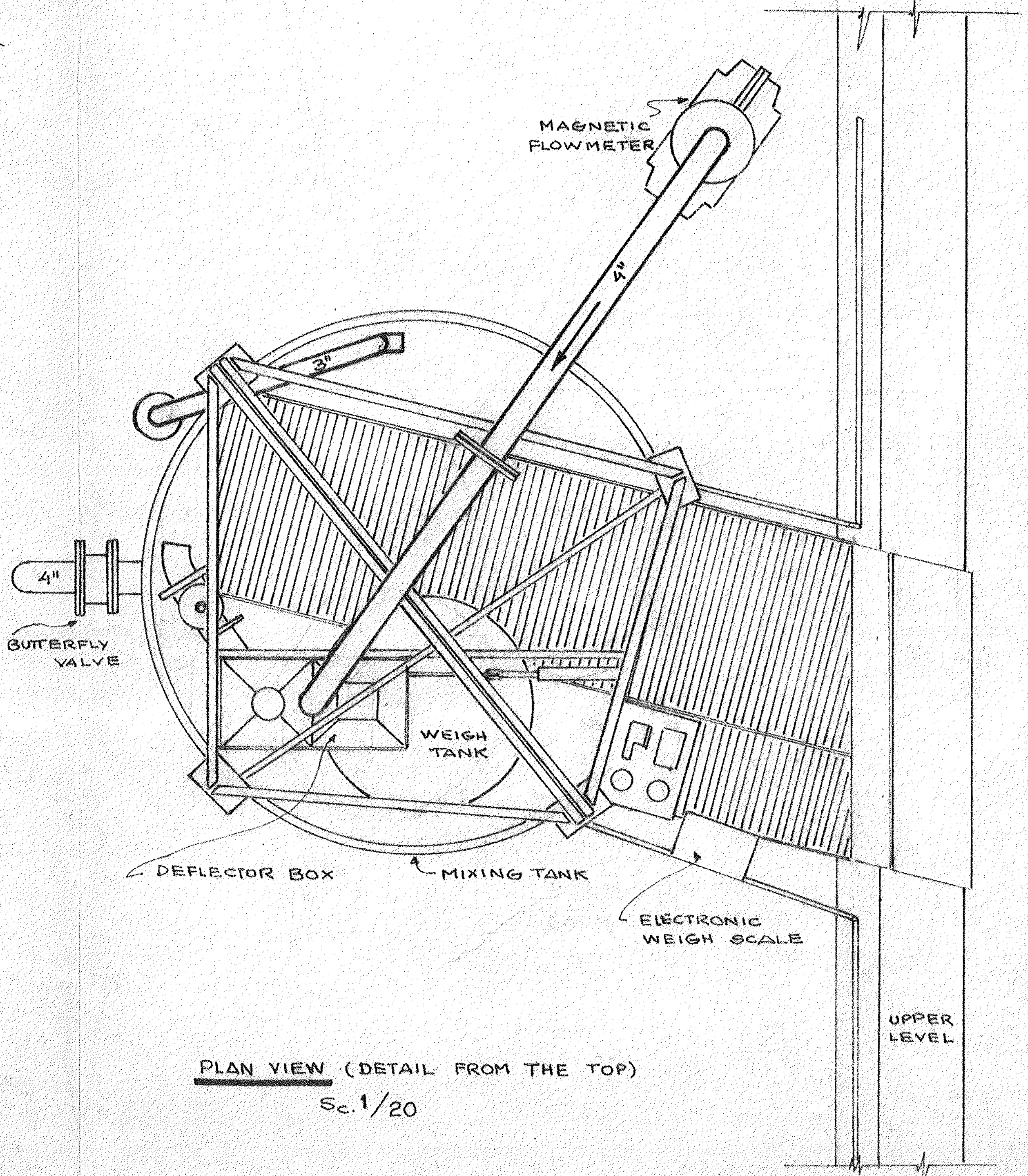
ELEVATION B

Sc. 1/20


6.50 m.
PLEXIGLASS SECTION
SANDTRAP
5"
PLEXIGLASS
4"
PLEXIGLASS
3"
3
5"
5"
3"
3"
4"
4"
ETURN CHANNEL

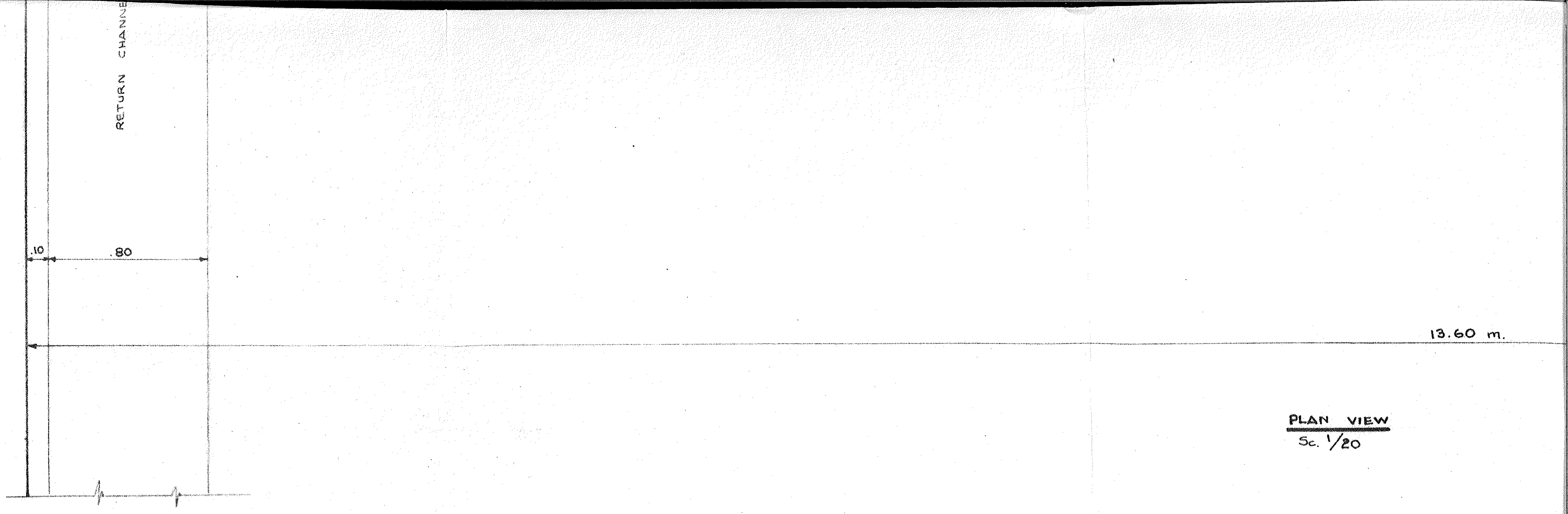

6.50 m.
5.15 m.
4.20 m.
PLEXIGLASS SECTION
LASS
SANDTRAP
5"
4"
3"
GAMMA LOGGER
PINCH VALVE
5"
4"
3"
STAIRS
HIGH PRESSURE PIPE
4" PIPE RISING
PINCH VALVES
5"
5"
3"
3"
4"
4"
WOODEN BY-PASS
MOTOR
3" PIPE RISING
3"
CENTRIFUGAL PUMP
4" PIPE
4"
4"
PIPE FALLING
BUTTERFLY VALVE
DRAIN
4"
SONIC FLOW METER
MIXI



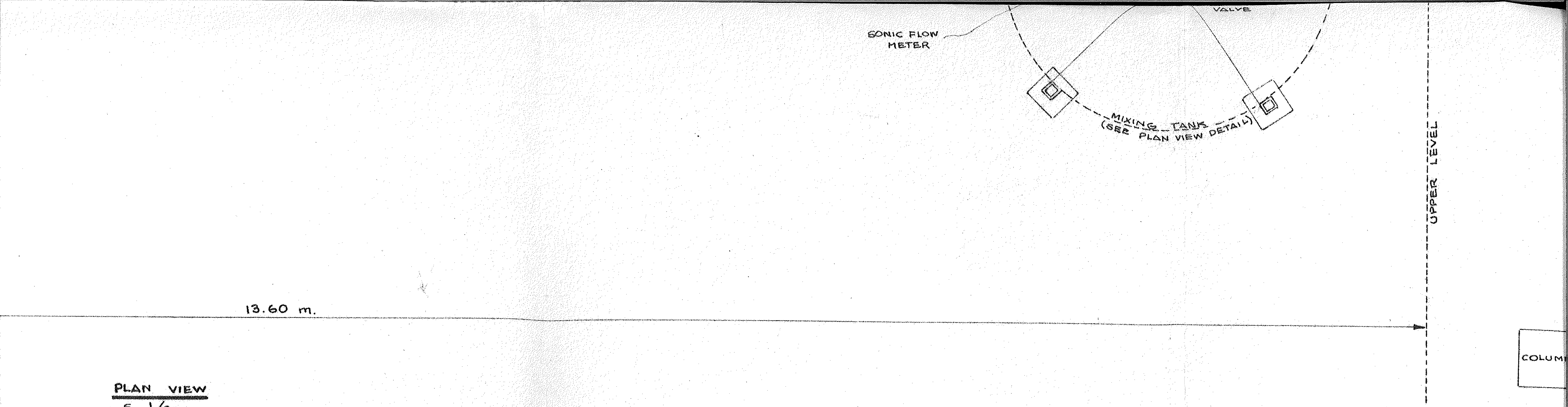


PLAN VIEW (DETAIL FROM THE TOP)

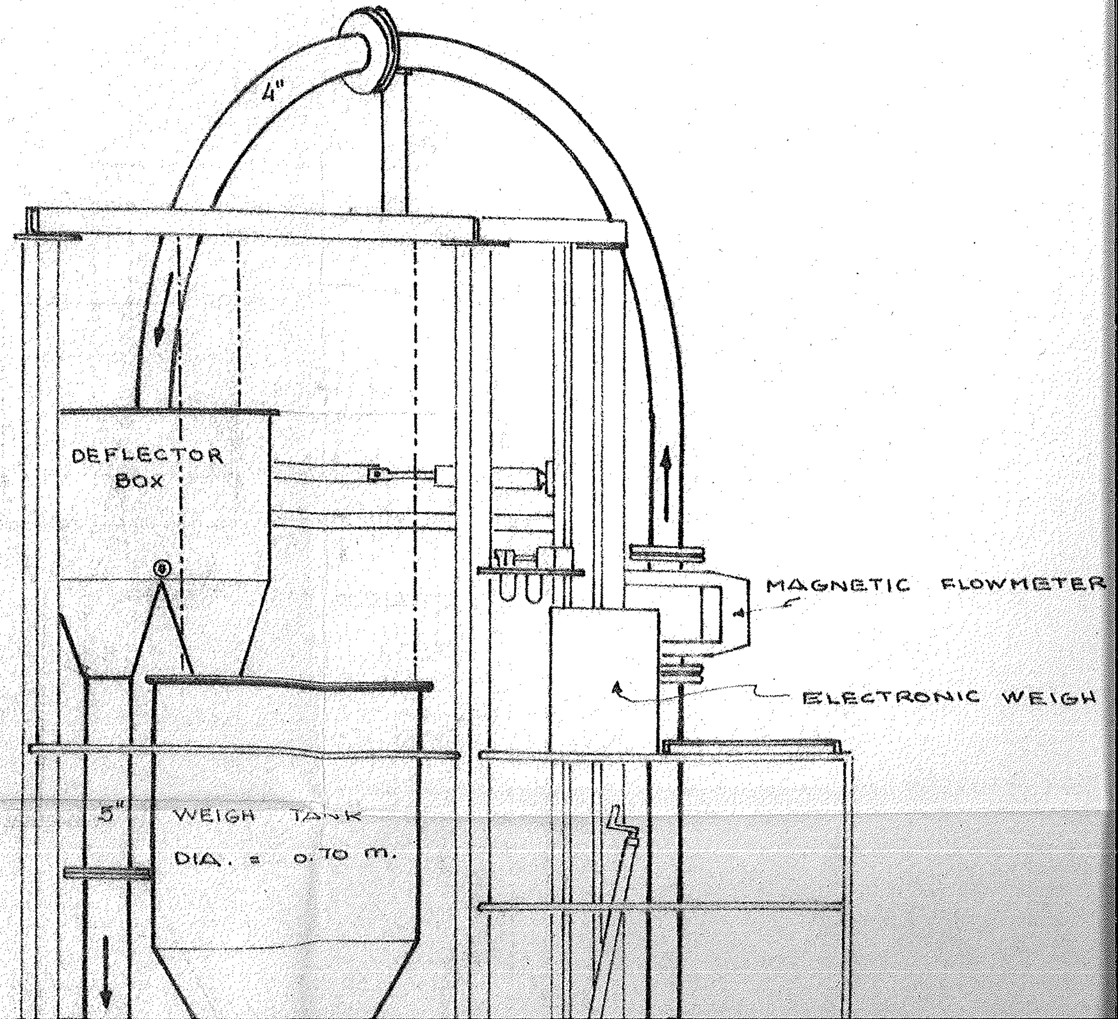
Sc. 1/20

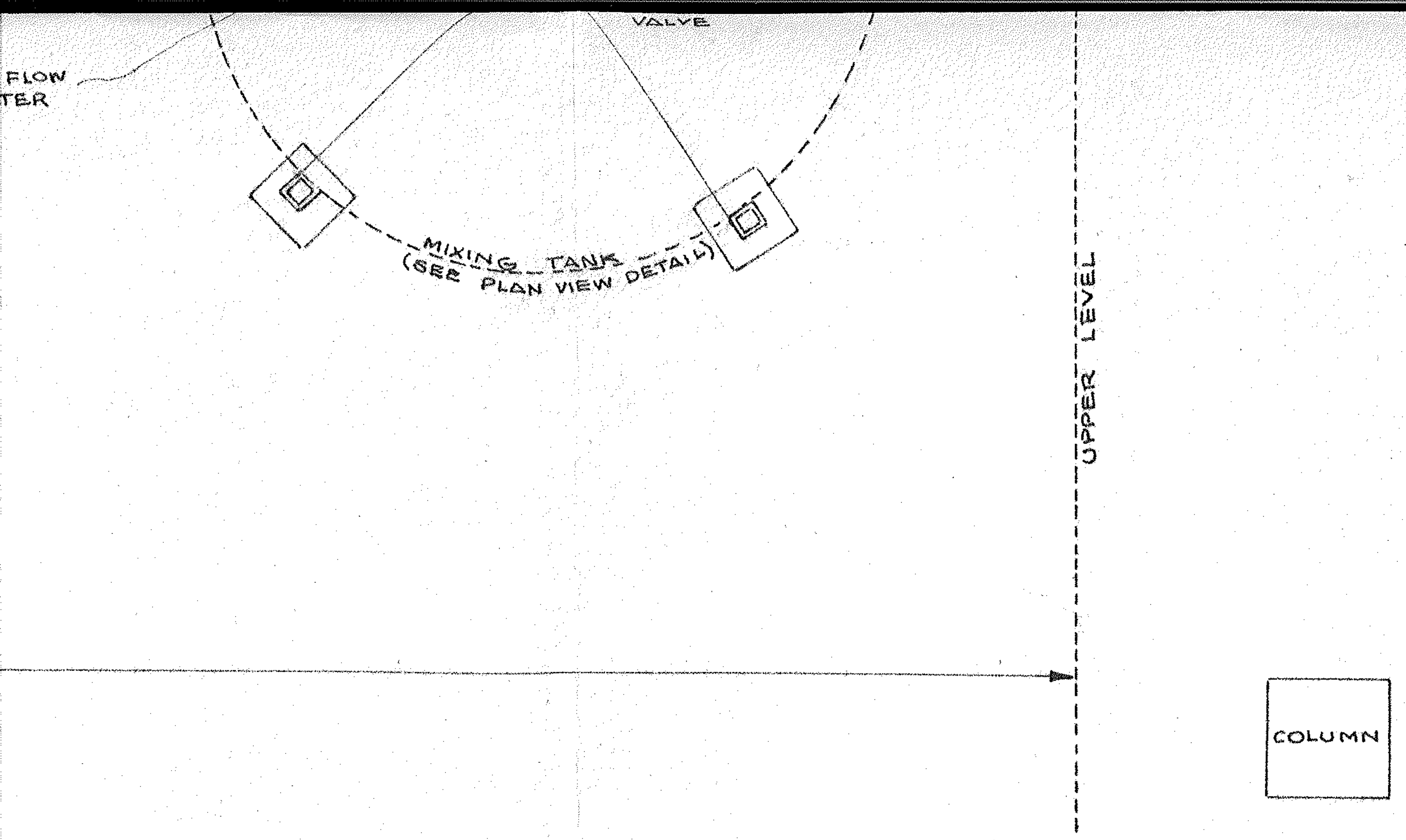


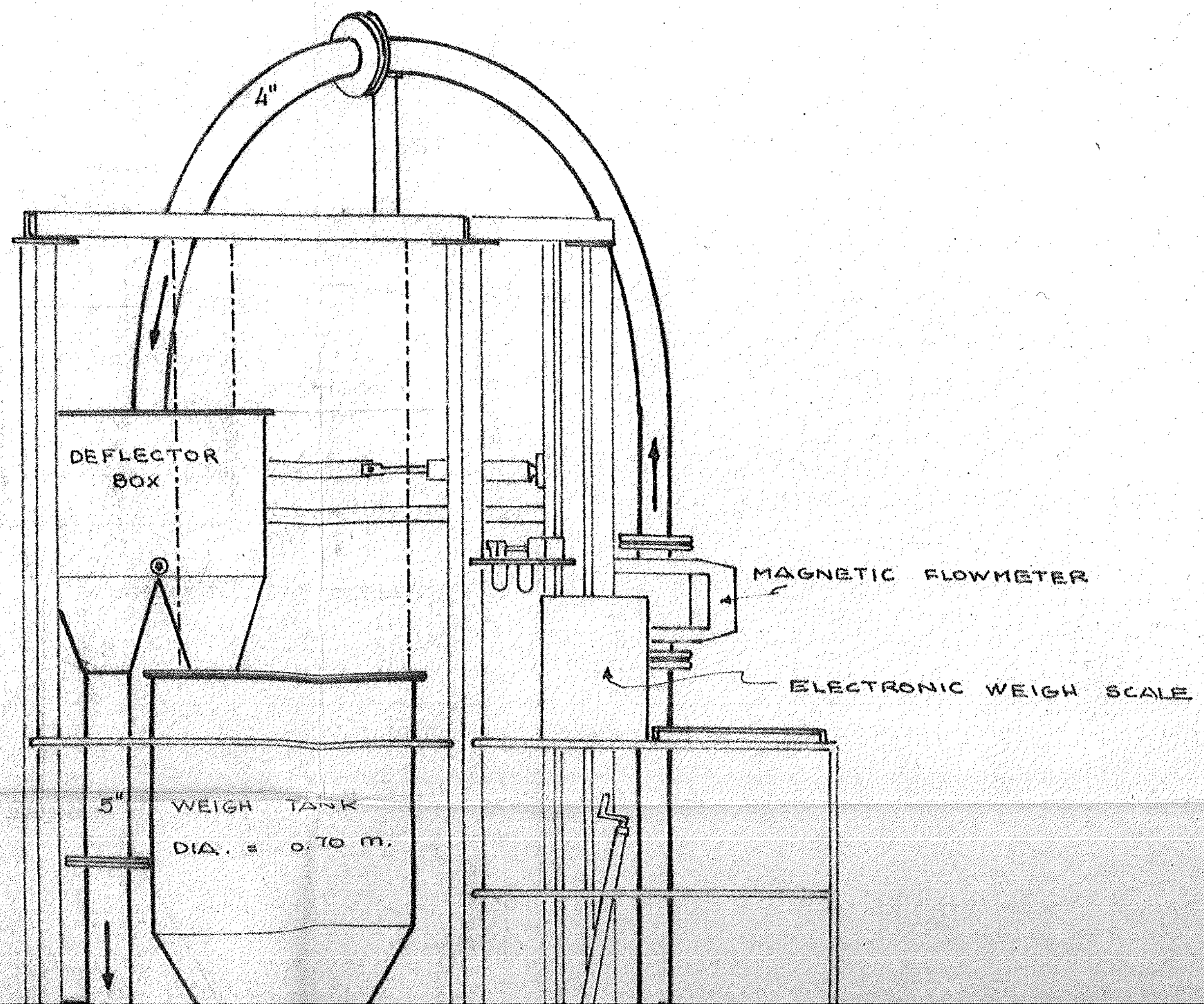
PLAN VIEW
Sc. 1/20

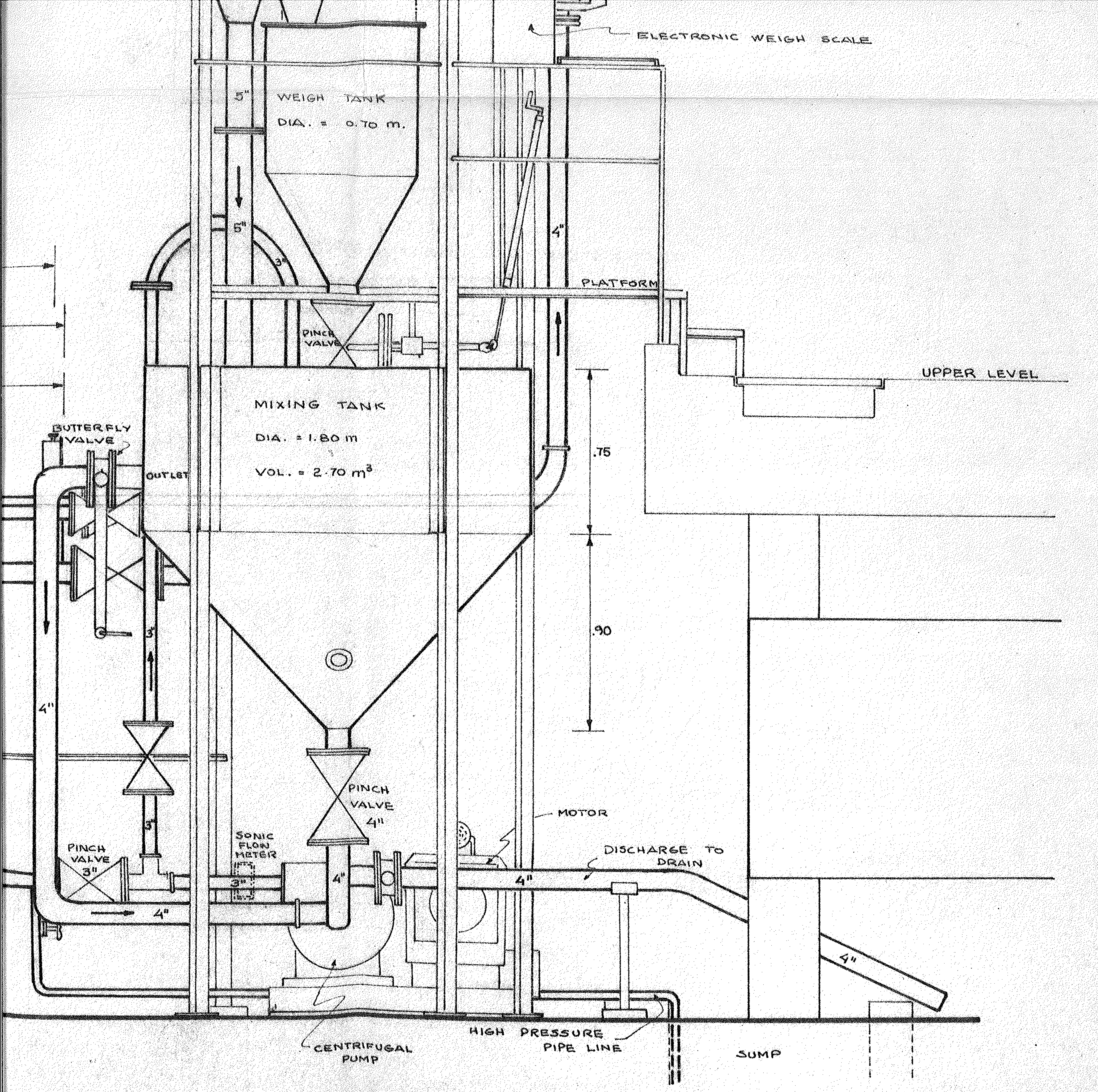


PLAN VIEW
Sc. 1/20




FLOW
TER
VALVE
MIXING TANK
(SEE PLAN VIEW DETAIL)
UPPER LEVEL
COLUMN

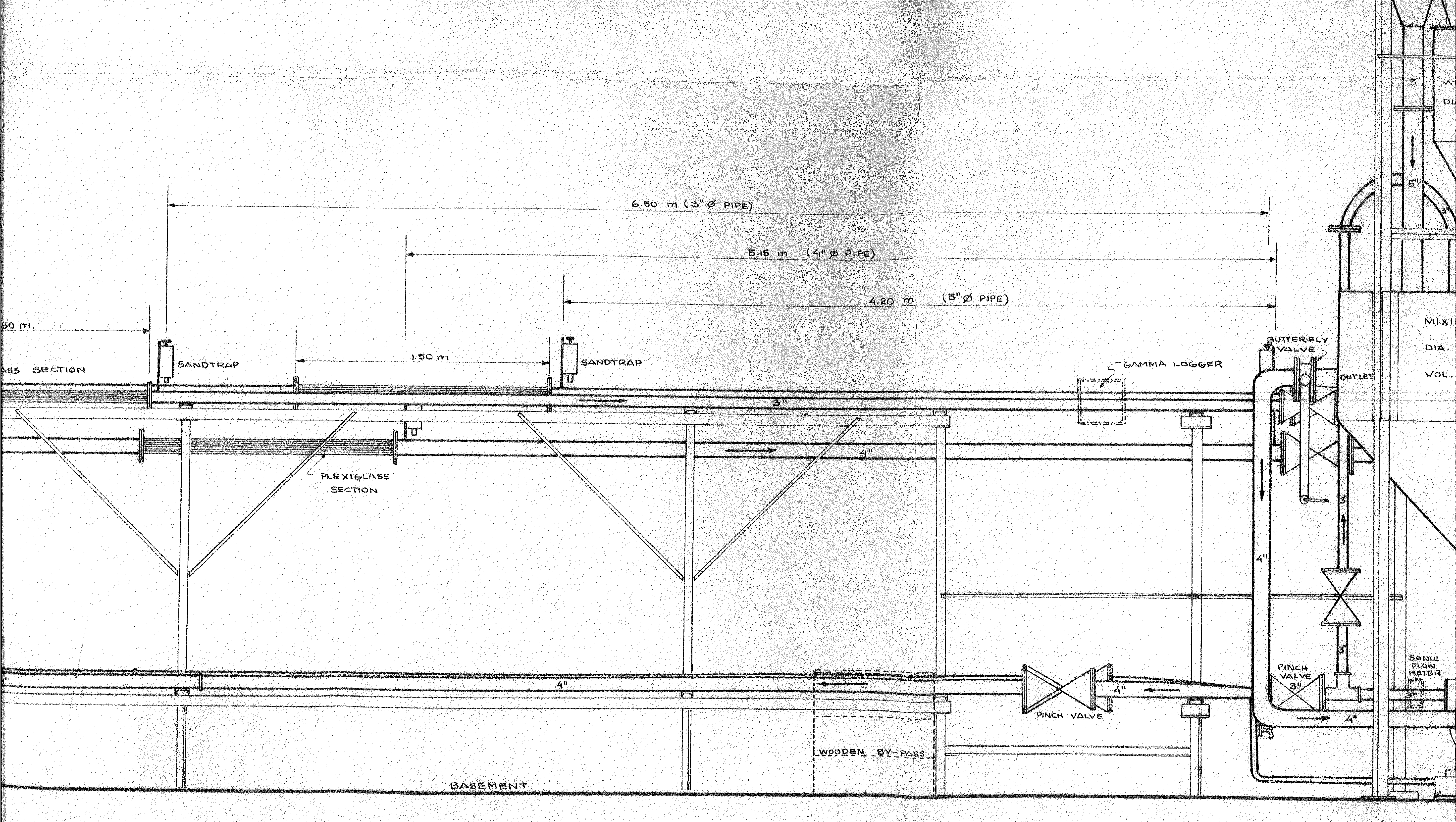

4"
DEFLECTOR BOX
MAGNETIC FLOWMETER
ELECTRONIC WEIGH SCALE
5"
WEIGH TANK
DIA. = 0.70 m.



UNIVERSITY OF MANITOBA
HYDRAULICS LABORATORY

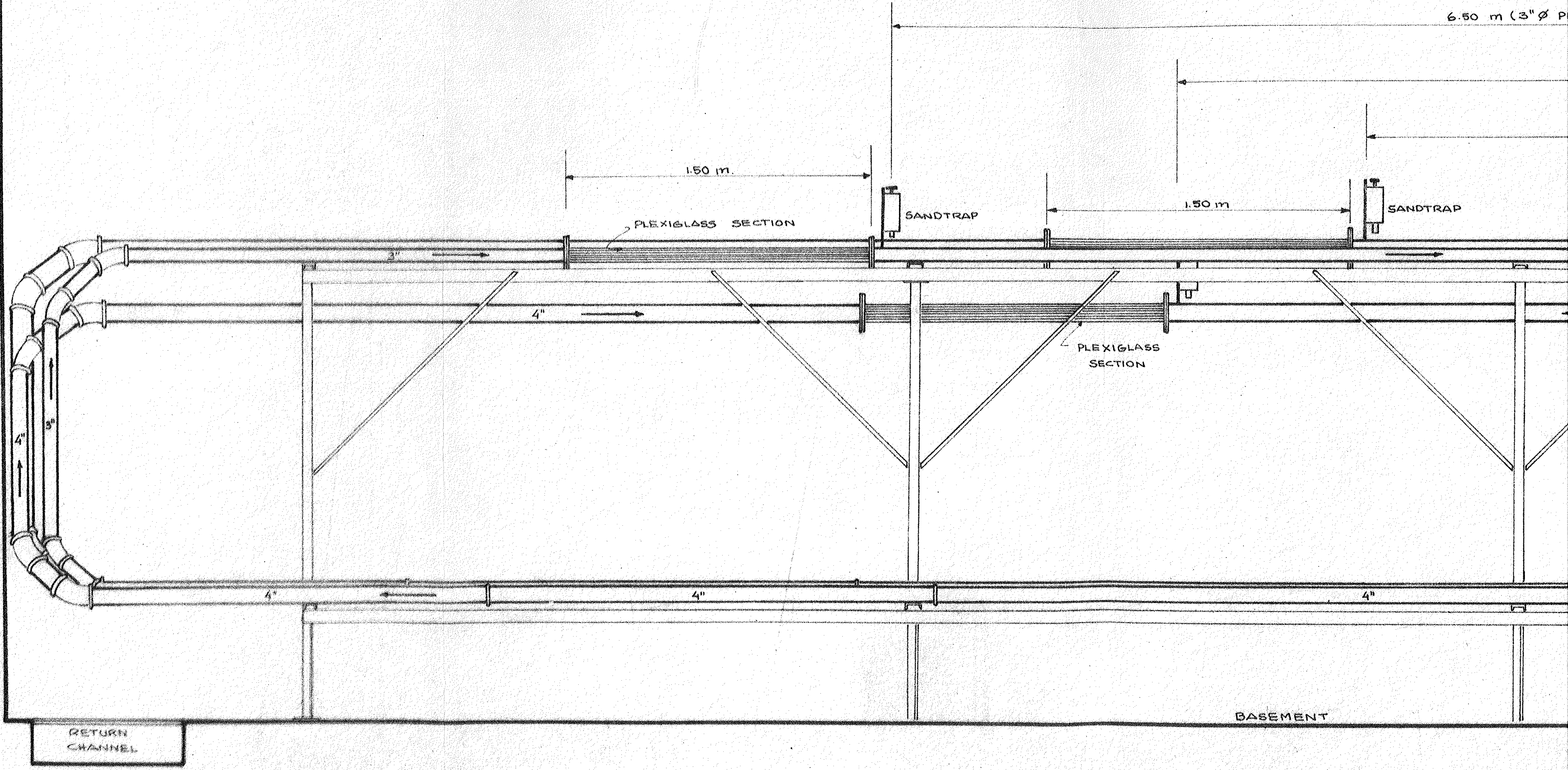
SLURRY PIPELINE TESTING RIG

DRAWN BY : Jorge L. Pomalaza	CHECKED BY : Dr. Luis Magalhaes
APPROVED BY : Dr. Al Tamburi	DATE : APRIL 30 - 1982
SCALE : 1/20	DRAWING No 1 OF 2



ELEVATION A

Sc. 1/20



ELEVATION
Sc. 1/20