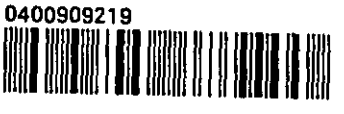
The forced gas deliquoring of filtercakes formed by pressure filtration



THE FORCED GAS DELIQUORING OF FILTERCAKES FORMED BY PRESSURE FILTRATION

by

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Dedication

to

My Wife, Maureen

who is my constant support.

INTRODUCTION

In May 1976 a proposal was solicited by Separation Process Services for research to be carried out into the forced gas deliquoring of filter cakes. This particular area had been identified by a filter manufacturer as one in which significant economies and improvements in operation might be achieved. The filter cakes considered are those formed in pressure filters using horizontal leaves with facilities for forced gas dewatering and automatic cake discharge. Satisfactory design procedures for estimating the required amounts of gas are not available and this situation frequently results in over expenditure on blowing equipment or embarrassingly high demands on works gas supplies.

Normal operating practice is that after the filtration cycle the cake is initially blown with gas at the final filtration pressure. On gas breakthrough the permeability of the filter cake to gas increases rapidly and, therefore, large volumes of gas would be required to maintain the pressure drop. Since the use of large volumes of gas is uneconomical the practice has been to switch over to the use of high volume blowers which can maintain a moderate pressure drop (approximately 70kN/m^2) across the filter cake.

The mechanisms proposed for filter cake deliquoring suggests that the commencement of the deliquoring involves piston flow in which the gas drives the wetting phase before it. As already indicated, once gas breakthrough has occured the gas permeability increases and two phase flow is established. The mechanisms proposed for this period of deliquoring are, firstly, the flow of

a film of the wetting phase brought about by the cocurrent flow of the gas and, secondly, the entrainment of wetting fluid in the gas stream. Although mass transfer may prove to be an important mechanism in some deliquoring operations such as where steam is used, it is not intended to look at this mechanism in any detail during this thesis.

The literature available is not specific to the equipment being considered. While the areas of general interest cover a considerable range of operations the most directly applicable area of research work is the investigation of deliquoring in rotary vacuum filters. This operation varies in several important aspects from deliquoring in pressure filters. The most important of these is the change in the overall pressure profile from the near constant vacuum developed in rotary vacuum filters to the rapidly decreasing pressure drop which operation of the pressure filter entails.

A comprehensive range of experiments has been carried out. These are intended to simulate industrial operations. The variables considered are saturation, pressure drop, gas consumption, time and viscosity and a range of three test materials have been used. Saturation - time profiles developed from experimental data are used to develop design procedures. Comparisons with previous work have been atempted but form no part of the design procedures. Although the main aim of the work has been to find practical solutions to the problems of deliquoring a tentative theory for the deliquoring mechanisms has been suggested.

During the development of experimental procedures a technique was found by which more rapid deliquoring could be obtained. This technique, which will be refered to as intermittent deliquoring, was

investigated further. It will be shown that it is possible to include the intermittent deliquoring technique in design procedures and that, consequently, large savings during the deliquoring in terms of both time and gas consumption may be obtainable.

At present the techniques employed in obtaining data mean that limitations are placed on the data to be obtained from each experiment. An assessment of experimental techniques and possible improvements has been made. A small number of pilot scale tests will play an important part in the design procedures.

The conclusions drawn from this work can bring about considerable improvements in the design procedures for the deliquoring operation in pressure filters. Further work will be proposed which will help in clarifying certain points of the design procedure. It will be seen that the proposed deliquoring method varies in several important aspects from present practice.

CHAPTER 1

Review of Literature

1.1 Introduction

The dewatering of filter cakes is an operation in which the simultaneous flow of two immiscible phases through a porous media is considered. The area which will be of interest in this review are, therefore, literature in which porous media are described and characterised and investigations of the characteristics of single and two phase flow in porous media. Apart from specific information obtained from past studies of filter cake deliquoring operations, subjects which have proved relevant to the project include soil mechanics, oil reservoir engineering and coal dewatering.

Having indicated methods of characterising porous media, which include capillary pressure and relative permeability curves, the application of these characteristics to correlations will be discussed. The correlations which have been developed were intended to predict the saturation and gas consumption during a range of deliquoring operations. The operations varied from determining saturation levels in countercurrent two-phase flow in packed towers to the prediction of filter cake deliquoring characteristics. An assessment of the importance of variables has been made from the past studies of two-phase flow. In conclusion the applicability of the available literature to the specific deliquoring operation being considered will be discussed.

1.2 Quasistatic Displacement.

1.2.1 Capillary Pressure

In the period 1925 to 1930 Haines (20) developed a theory which estimated the energy requirements for desaturation and imbibition in porous media using a model consisting of regularly packed equisized spheres. He accounted for residual moisture present in the system by assuming that the liquid existed as pendular rings at the point of contact between the spheres. The residual moisture in this case was defined as the irreducible level attained by slow desaturation using a fine pore block to obtain the high pressure drop required. Haines said that the pressure required to displace liquor from a pore in a pack of spheres could be calculated using the relationship:-

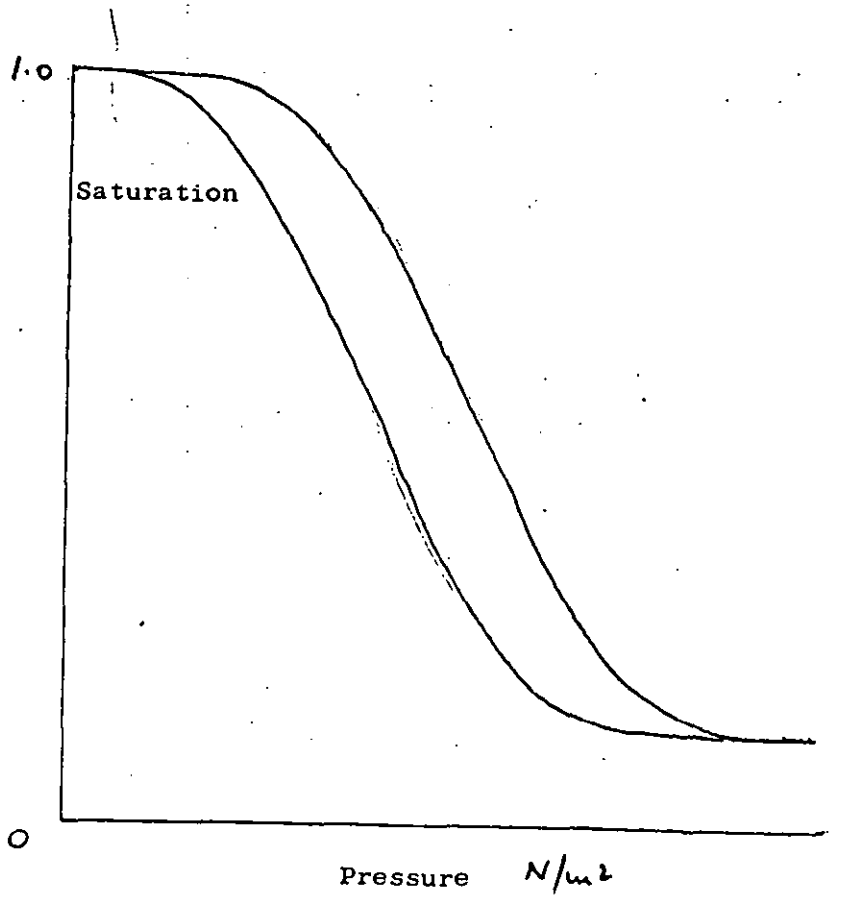
$$P_c = \gamma \left\{ \frac{1}{r_1} + \frac{1}{r_2} \right\} \qquad \text{Eqn. 1.2.1.1.}$$

Above this pressure the pore beyond the constriction would be emptied. In a similar way it was shown that if the pressure was reduced once the pore had been emptied there was a second pressure limit below which the pore would fill again.

By desaturating a porous media slowly using a fine pore block the relationship between saturation and pressure for the media can be determined. The relationship obtained is known as the capillary pressure curve. The general form taken by these curves is indicated in Figure 1.2.1.1.. The hysteresis obtained is due to the differing curvature of meniscii during deliquoring and imbibition.

More recent work by Morrow (28, 29) and by Mason (24) has gone into the concept in much greater detail. More complex models have been developed. Morrow saw the need to look further into the way in which wetting phase is retained in a porous media. He investigated the effect of changes in various parameters on the level of the

FIGURE 1.2.1.1



Capillary Pressure Curve

irreducible saturation. The conclusion reached by Morrow in this investigation was that the residual saturation level was independent of particle size and shape, porosity of the packing and particle size distribution. Overall, the parameter effecting the irreducible saturation most is the manner in which pores of different sizes are distributed and interconnected within the porous matrix. The properties of the wetting and displacing fluids were seen to have little effect on the residual saturation. For example, it was shown that viscosity variation effects only the time taken to reach the irreducible saturation and not its actual value.

Mason (24) proposed a model for the drainage of packed beds based on a statistical and probabilistic approach to the advancement of meniscii through the porous bed. In this way he was able to relate the residual moisture to the inter-connectivity of the pores in the bed and the probability of fluid filled pores being isolated from the lines of flow of fluid. Using this model estimates of residual moisture level were found to be considerably more accurate than those obtained by Haines. However, in some cases the residual moisture level was overestimated. The author suggested that this was due to continued flow through the pendular rings.

Harris and Morrow (21) and Mason (24) found that the volumes of cells trapped full totalled approximately 2 - 2.8% of the void space. Pendular moisture, which in the work of Haines was thought to account completely for the residual moisture, accounts for approximately 5% of the void space. This gives a final residual moisture content of the region of 7% - 8% which is a frequently obtained value for packings of discrete particles.

Examination of the work on capillary pressure curves and quasistatic

displacement of wetting fluid indicates the pressures required to displace liquor from pores and has also shown that there is a minimum level to which the saturation of a porous media can be reduced using air displacement. This level of residual saturation is generally approximately 8% of the void space.

1.2.2. Pore Size Distributions

The relationship between pore size and capillary pressure has already been stated (Eqn. 1.2.1.1.). From this relationship and that of saturation to capillary pressure several observations can be made about the pore size distribution of a porous medium. Scheidegger (44) indicated some of the drawbacks in trying to obtain accurate pore size distributions from capillary pressure curves. Capillarity models on which calculations are based are simple in comparison with the complexity of the porous media. Therefore, the calculated pore size distribution can not be expected to accurately reflect the true pore size distribution. Attempts have been made to improve the accuracy of predictions by making corrections for large pores connected to the surface of the porous medium by small pores thus filling at relatively high pressures. However, even with these corrections the best that can be expected is a good qualitative indication of the nature of the pore space.

A brief look has been taken at the deliquoring of porous media under ideal conditions. Under these conditions the saturation level reached is the minimum possible for that particular porous medium. Therefore, limits of deliquoring have been laid down and the first steps in characterisation of the porous medium have been taken.

1.3. Relative Permeability

1.3.1. Darcys Law

Through the experimentation of Darcy in 1856 it became possible to relate the pressure drop and flow of fluid in a porous medium. The factor used to relate these two quantities was known as the permeability and the relationship took the form:-

$$q = -\frac{1}{\mu} K \cdot \frac{\Delta P}{L} \qquad \text{Eqn. 1.3.1.1.}$$

This relationship is valid for laminar flow conditions. The permeability of porous media has been investigated in detail for single phase flow and several solutions of Darcy's Law have been proposed for specific conditions (44). The importance of Darcy's Law and permeability to two phase flow must now be considered.

When considering the permeability of a porous medium under conditions of two-phase flow a permeability for each fluid must be derived by modifying the equation to allow for the effects of one fluid on the other. Therefore a new quantity, the relative permeability of a porous media to each fluid, must be defined.

The flowrates of each of the two phases in flow can be defined by extending Darcy's Law.

$$q_w = -\frac{K.K_{RW}}{\mu_W} \cdot \frac{\Delta P_W}{L} \qquad \text{Eqn. 1.3.1.2.}$$

$$q_{nw} = -\frac{K.K_{RNW}}{\mu_{NW}} \cdot \frac{\Delta P_{NW}}{L} \qquad \text{Eqn. 1.3.1.3.}$$

Equations 1.3.1.2. and 1.3.1.3. define relative permeability. The flowrate of each phase through the porous media is modified by the presence of the second phase. The relative permeability is the

fractional flow of the phase compared to its flow as a single saturating flow under the same driving force. It can be seen from this definition that the relative permeability is dependent upon the saturation of the porous media.

In 1942 Buckley and Leverett gave one solution to Darcy's Law for immiscible fluids. They assumed that gravity, capillarity and variations in density could be neglected. They defined the fractional flow of one phase as:-

$$u(s) = \frac{|q_1|}{|q|} \qquad \text{Eqn. 1.3.1.4.}$$

u(s) being a function of saturation and viscosity only. Taking into consideration the assumption already stated the fractional flow, u(s), becomes:-

$$u(s) = \frac{|q_1|}{|q_1| + |q_2|} = \frac{K_{RW/\mu W}}{K_{RW/\mu_W} + K_{RNW/\mu_{NW}}}$$

Eqn. 1.3.1.5.

Considering flow in one dimension:-

$$\epsilon \frac{\partial s}{\partial t} + u^1(S) \cdot q_x \frac{\partial s}{\partial x} = 0$$

Eqn. 1.3.1.6.

$$\frac{\partial q}{\partial x} = 0 \qquad \text{Eqn. 1.3.1.7.}$$

Note that q_x is a function of time and it, therefore, follows that:-

$$\epsilon \frac{\partial s}{\partial t} + u^1(S)\, q_x(t) \frac{\partial s}{\partial x} = 0$$

Eqn. 1.3.1.8.

Equation 1.3.1.8. can be treated by considering the characteristics of first order differential equations and this 'treatment' gave the equations proposed by Buckley and Leverett.

$$\frac{dx}{dt} = u^1(s)\ q_x(t)/\epsilon \qquad \text{Eqn. 1.3.1.9.}$$

$$\frac{ds}{dt} = 0 \qquad \text{Eqn. 1.3.1.10.}$$

Figure 1.3.1.1. gives plots of the fractional flow and its first order differential against saturation.

1.3.2. Breakthrough Saturation

Brinkman (4) in 1948 showed that the Buckley-Leverett case had a solution in the form of a shock wave. i.e. a finite discontinuity in saturation proceeds through the porous media at a speed, c. This solution supports the idea of a piston flow regime. By looking more closely at the work of Brinkman and subsequent work by Welge (59) 1952 the level to which saturation is reduced during piston flow can be estimated. For displacement left to right the conditions are such that to the right of the shock wave saturation is 100% and to the left of the shock wave the level of saturation can be determined.

The shock condition is given by the Hugoniot equation:-

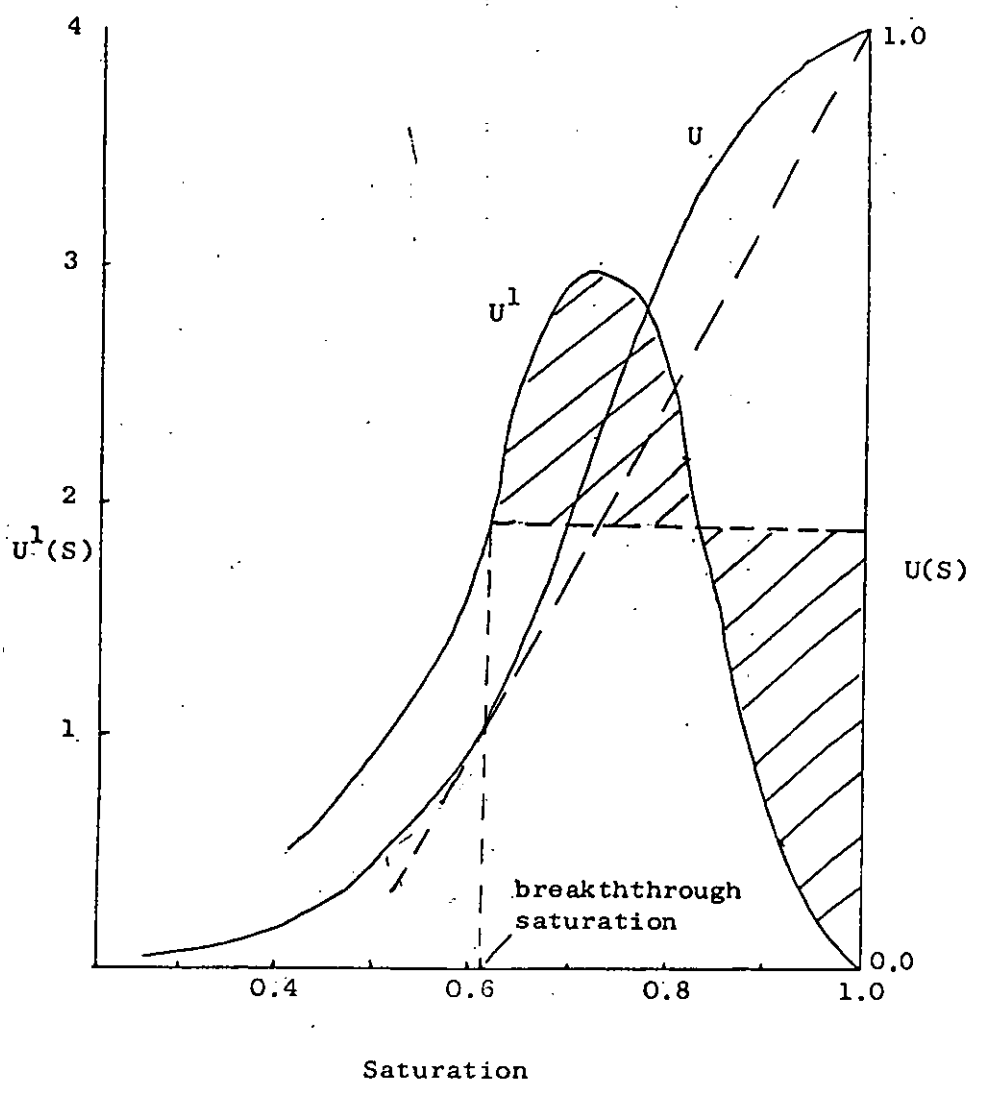
$$\epsilon c\,(1 - s) = q_x\,(1 - u) \qquad \text{Eqn. 1.3.2.1.}$$

from this the speed of shock can be obtained:-

$$c = \frac{q_x}{\epsilon}\,\frac{(1 - u)}{(1 - s)} \qquad \text{Eqn. 1.3.2.2.}$$

where u & s refer to the displaced fluid. In 1952 Welge (59) showed that a tangent could be drawn to the curve of u (S) against saturation as shown in Fig. 1.3.1.1.. This solution is valid as the saturation immediately behind the shock travels more slowly than the shock. This reduces the size of shock until an equilibrium between saturation and shock is obtained. This "equilibrium" saturation travelling at the

FIGURE 1.3.1.1.



The Welge Construction

same speed as the shock is therefore the saturation of the porous medium at breakthrough. Brinkman in 1948 also showed that a second construction in Fig. 1.3.1.1. could give the breakthrough saturation. This is based on equal areas above and below the u' (S) function. The solution, through elementary integral properties, can be shown to be directly equivalent to the tangent construction.

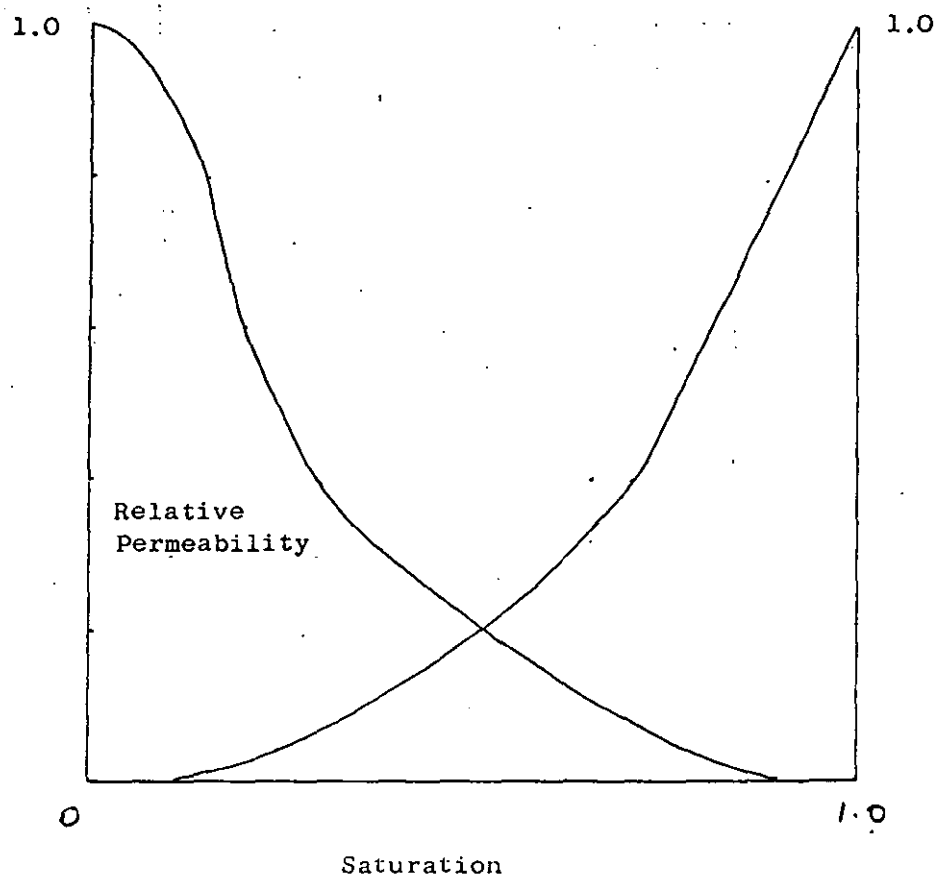
1.3.3. Relative Permeability Curves

In 1936 Wyckoff and Botset (62) carried out experiments to determine the shape of relative permeability against saturation curves. Figure 1.3.3.1. shows the typical form of relative permeability curves. However, the shape of these curves can be altered by variation of external parameters. In 1956 Wilson (60) showed that changes in applied pressure altered the relative permeability curves.

Several observations can be made from a study of the Wyckoff and Botset curves. Considering the wetting phase it can be seen that the permeability drops sharply as the saturation is reduced from 100%. At 60% saturation the relative permeability is of the order of 0.5 and at 50% saturation is approximately 0.1. The curve reaches zero permeability at a saturation of about 10% which corresponds to the residual saturation. The non-wetting phase relative permeability is similar in form. At high wetting phase saturation there is no non-wetting phase continuity and hence permeability is zero. This situation exists down to a wetting phase saturation of about 90% and again below this level there is a rapid change in the permeability of the porous media to the non-wetting phase. When the wetting phase saturation has reached the level of residual saturation no significant increase in non wetting phase permeability is obtained.

If the curves are added to obtain the total permeability it will be seen that between the two extremes of saturation where the relative permeability is 1.0 there is a pronounced minimum. This occurs in the

FIGURE 1.3.3.1



Wykoff and Botset Relative
Permeability Curves

region of saturation where the permeability of the two phases are roughly equivalent. At this point the total permeability is about 1/3rd the value of that for the media saturated with either phase.

In an attempt to reproduce these characteristics of relative permeability models have been developed. In 1961 Millington and Quirk (27) proposed a model of the capillary tube type for flow in porous media. They derived an expression for permeability of the form:-

$$K_{SAT} = \frac{(\epsilon S_{NW})^{4/3}}{8 N^2} \left\{ r_1^2 + 3r_2^2 + 5r_3^2 + \ldots (2N-1) r_N^2 \right\}$$

Eqn. 1.3.3.1.

Lloyd and Dodds (23) developed this idea further and adapted the equation to yield relative permeability for the wetting and non-wetting phases.

For the non-wetting phase:-

$$K^1_{NW} = \frac{(\epsilon S_{NW})^{4/3}}{8N^2} \left\{ \sum_{i=1}^{N_W - 1} (2i-1) r_i^2 \Big/ K_{SAT} \right\} \quad \text{Eqn. 1.3.3.2.}$$

for the wetting phase:-

$$K^1_{W} = \frac{(\epsilon S_W)^{4/3}}{8N^2} \left\{ \sum_{N_W}^{N} (2i-1) r_i^2 \Big/ K_{SAT} \right\} \quad \text{Eqn. 1.3.3.3.}$$

where there are N equal pore size classes each with a mean or average radius r_i.

The curves obtained were similar to those obtained by Wyckoff and Botset (62) and the main properties are incorporated.

1.3.4. Pore Size Distribution Index

In 1975 Wakeman published a book on filtration post-treatment processes (51). This book reviewed previous work carried out in the field of two-phase flow as related to filter cake deliquoring. At the same time the basis for the future development of Wakemans ideas on deliquoring was laid down. Referring to the work of Brooks and Corey (5)

the concepts of pore size distribution index and threshold pressure were introduced. These two factors were to be used to try to generalise relationships for a wide variety of particle size distribution and packing characteristics.

The threshold pressure is that pressure which is required to force the first drops of wetting fluid from the cake. Referring to Fig. 1.3.4.1. this corresponds to the point B at which air begins to penetrate the largest surface pores. However, Wakeman (54) proposed a modified threshhold pressure corresponding to point T, the intersection of the extrapolated lines AB and DC . The modified threshold pressure was said to be a more predictable quantity as it was less dependent upon the variations between randomly deposited cakes. Correlation of data showed that the modified threshold pressure could be represented by the equation:-

$$P_b^* = \frac{4.6\ (1 - \epsilon)\gamma}{d\epsilon} \qquad \text{Eqn. 1.3.4.1.}$$

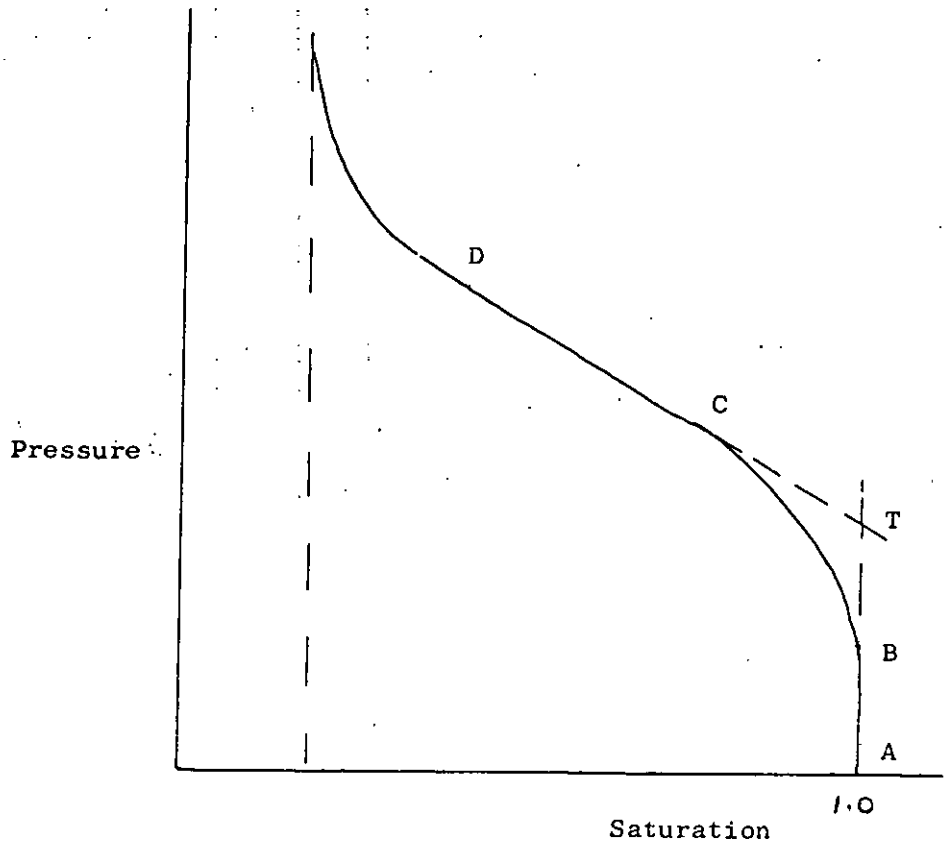
This is compared to a value of the constant equal to 6.0 as developed by Carmen in 1941.

Wakeman in the same paper (54) reintroduced the concept of pore size distribution index. Plotting reduced saturation, defined as $\frac{S - Sr}{1 - Sr}$, against pressure drop across the cake on logarithmic coordinates data was found to form a straight line except as the reduced saturation approached unity. The straight line could be represented by the equation:-

$$S_f = \left(\frac{P_b^*}{\Delta P}\right)^{\lambda} \qquad \text{Eqn. 1.3.4.2.}$$

P_b^* was found by extrapolation to ~~find~~ equal the value of ΔP at the point where S_f equalled unity. λ, the pore size distribution index represented the slope of the line.

FIGURE 1.3.4.1



Capillary Pressure Curve

The advantage of the pore size distribution index was that it depended on relative arrangement of particles in the porous bed as well as on the particle size and size distribution. In a later paper (56) it was stated that values of λ varied between 2 and 8 and that most of the data gave values lying between 3 and 6.5.

1.3.5. Relative Permeability Models

Having developed the concepts of pore size distribution index and threshold pressure Wakeman (56) attempted to apply these to the consideration of relative permeability. As Wakeman stated earlier models had failed in some respect or other to reproduce the characteristics of the relative permeability curves. The simplest and most effective models developed up to that time were those of the type developed by Lloyd and Dodds (23). The general form of the relative permeability equations was:-

$$K_{RW} = S_f^2 \frac{\int_0^{S_f} \frac{dS_f}{\left(P_c(S_f)\right)^2}}{\int_0^1 \frac{dS_f}{\left(P_c(S_f)\right)^2}} \qquad \text{Eqn. 1.3.5.1.}$$

$$K_{RNW} = (1-S_f)^2 \frac{\int_{S_f}^1 \frac{dS_f}{\left(P_c(S_f)\right)^2}}{\int_0^1 \frac{dS_f}{\left(P_c(S_f)\right)^2}} \qquad \text{Eqn. 1.3.5.2.}$$

Using the relationship Eqn. 1.3.4.2 already developed for the reduced saturation Wakeman showed that a relationship of a much simplified form could be obtained. The relative permeability equations became:-

$$K_{RW} = S_f^{(2+3\lambda)/\lambda} \qquad \text{Eqn. 1.3.5.3.}$$

$$K_{RNW} = (1-S_f)^2 \quad (1-S_f^{(2+\lambda)/\lambda}) \qquad \text{Eqn. 1.3.5.4.}$$

A plot of the relative permeability curves using these equations is shown in Fig. 1.3.5.1. Wakeman claims that this is only the first step in showing the usefullness of the pore size distribution index as a parameter for the interpretation of cake characteristics.

1.4 Pipe Flow

1.4.1. Hagen-Poiseiulle

"Capillaric" models have been the source of the most important theories developed for porous beds especially in the field of filtration. The foundation for this work was laid down by Hagen and Poisieulle in the development of the well known relationship for laminar flow down a straight circular pipe:-

$$Q = \frac{\pi d^4}{128\mu} \cdot \frac{dp}{dx} \qquad \text{Eqn. 1.4.1.1.}$$

From this beginning Kozeny, and later Carmen, went on to consider the flow properties of a bundle of capillaries. They stated that for a bundle of N capillaries each of diameter, d :-

$$\text{flow/unit area of pores} = q_1 = \frac{Q}{A} = \frac{d^2}{32\mu} \cdot \frac{dp}{dx} \qquad \text{Eqn. 1.4.1.2.}$$

Furthermore, Kozeny suggested that a hydraulic diameter should be defined such that:-

$$d = \frac{\text{volume of voids}}{\text{total internal surface area of bed}}$$

This can be developed to give:-

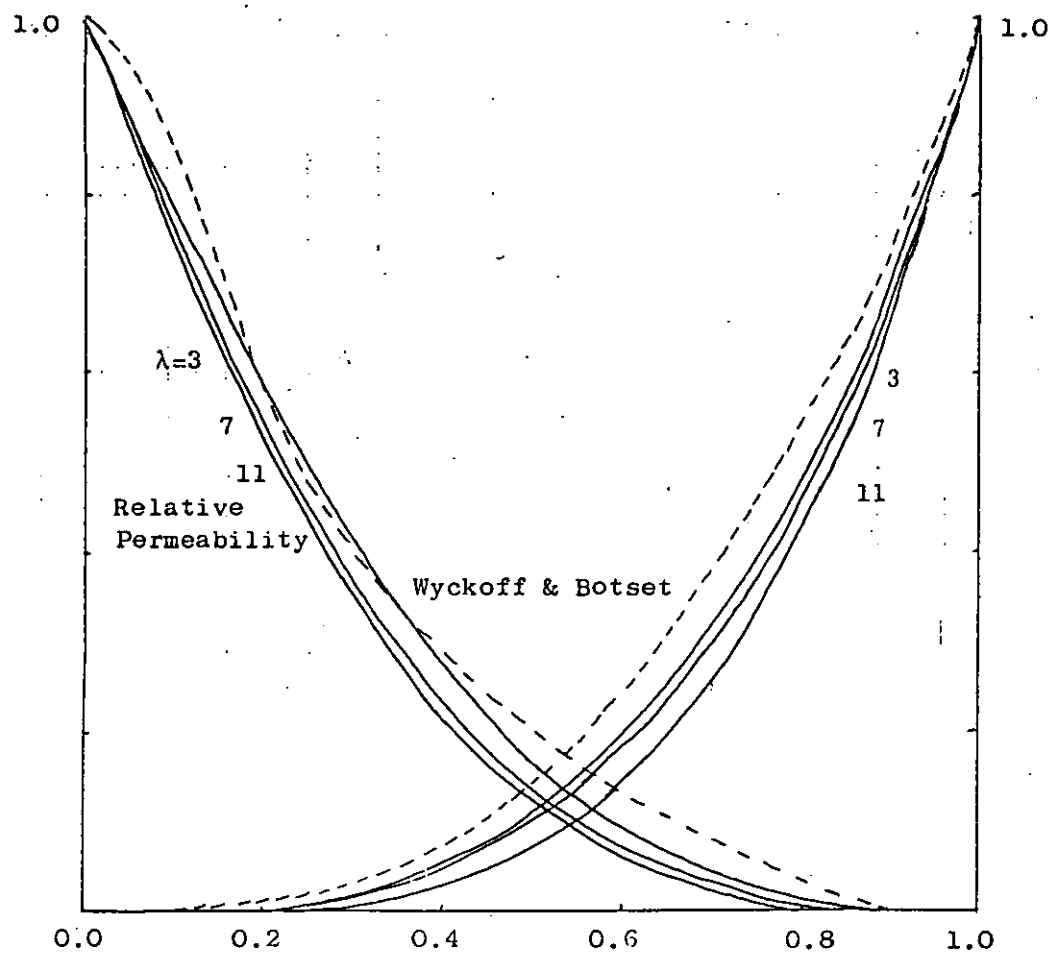
$$d = \frac{\epsilon}{A_B} \qquad \text{Eqn. 1.4.1.3.}$$

Therefore, $$q_1 = \frac{\epsilon^2}{32\mu A_B^2} \cdot \frac{dp}{dx} \qquad \text{Eqn. 1.4.1.4.}$$

Further, if the bed specific surface is related to that of the individual particles it is found that for particles in point contact:-

$$A_B = A_p(1 - \epsilon) \qquad \text{Eqn. 1.4.1.5.}$$

FIGURE 1.3.5.1



The Wakeman Relative Permeability Curves

Therefore, $$q_1 = \frac{\epsilon^2}{B \mu A^2 (1-\epsilon)^2} \frac{dp}{dx}$$ Eqn. 1.4.1.6.

Finally, converting flow per unit area of pore to flow per unit area of bed, q can be defined as :-

$$q = q_1 \epsilon = \frac{\epsilon^3}{B \mu A^2 (1-\epsilon)^2} \cdot \frac{dp}{dx}$$ Eqn. 1.4.1.7.

Experimentally B is found to range between 3.5 and 5.5 and is not 32 as the derivation suggests.

If Equation 1.4.1.7. is compared with Darcys Law as indicated in Equation 1.3.1.1. it can be seen that:-

$$K = \frac{\epsilon^3}{BA^2 (1-\epsilon)^2}$$ Eqn. 1.4.1.8.

This relationship is valid for low Reynolds numbers. The major equations take this form. The constant, B, is often considered to equal $e_o Z$ where e_o is a shape factor for the capillary and Z represents the tortuosity.

1.4.2. Brownell and Coworkers

In 1947 Brownell and Katz produced three papers (10-12) on the flow of fluids through porous media. In the first of these papers the flow of a single homogeneous fluid was discussed and the relationship between pipe flow and flow through porous media was proposed. In the second paper the simultaneous flow of two phases was considered and a correlation was developed for the calculation of the flowrates of each phase. Finally, the correlations were applied to the problem of the deliquoring of filter cakes formed on rotary vacuum filters. These papers were the basis of further work on deliquoring theory by Brownell and his coworkers and have since been used as the basic references for work on this subject.

The first paper (10) commenced with a statement of the proposed

Reynold's number and friction factors for single phase flow in the porous media and also for each of the two phases under the two-phase flow conditions. As for pipe flow the Reynolds numbers are in a dimensionless form.

In accounting for the difference between pipe flow and flow through porous media the authors stated that four factors were of importance. These were the sphericity, diameter and roughness of particles and the bed porosity. The roughness factor is only significant when considering the turbulent flow regime. Therefore, for laminar, single phase flow, the system could be defined in terms of a modified Reynolds number and friction factor.

$$Re = \frac{d\ V_L\ \rho_L}{\mu\ \epsilon^m} \qquad \text{Eqn. 1.4.2.1.}$$

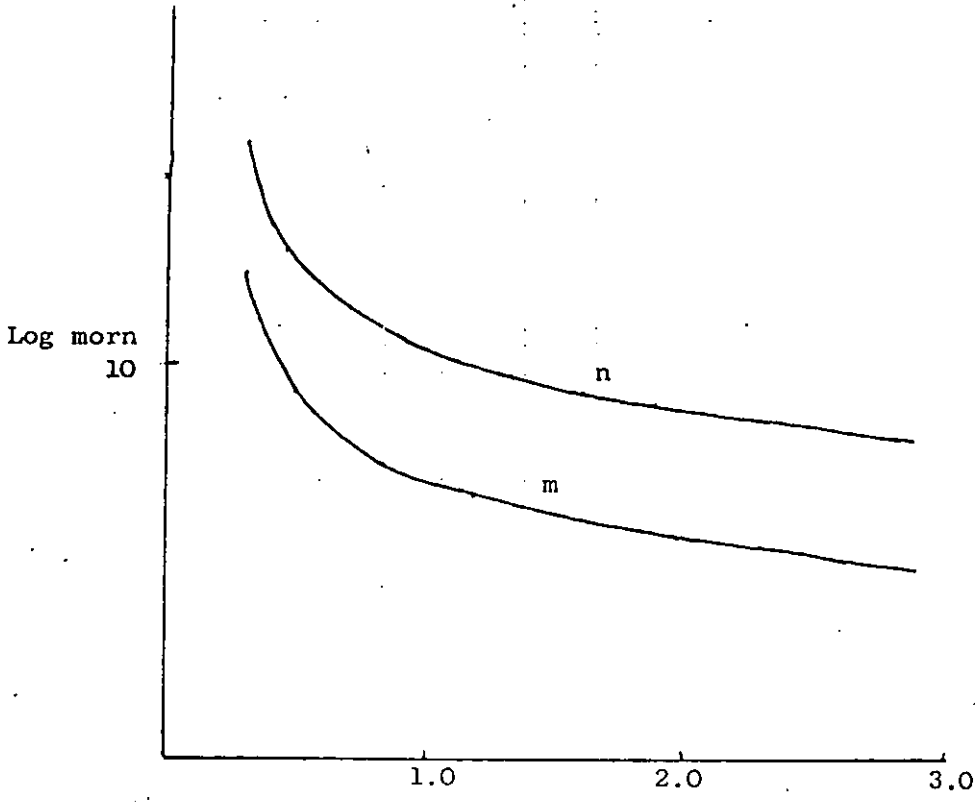
$$f = \frac{2gd\,\Delta P\,\epsilon^n}{L\,V_L^2\,\rho_L} \qquad \text{Eqn. 1.4.2.2.}$$

The exponents m and n are a function of both particle sphericity and cake porosity. Using experimental data on pressure and flow in porous media values of m and n were determined. It was claimed that a unique set of values of m and n exists which defines a porous medium. The basis of the relationship by which m and n were calculated was the ratio of sphericity to porosity. Fig. 1.4.2.1. indicates the nature of this relationship.

1.4.3. Residual and Effective Saturation

The concepts of residual and effective saturation are important in the development of the Brownell and Katz correlation. The level of saturation so far defined was the irreducible saturation, the best attainable under ideal deliquoring conditions. In defining residual saturation Brownell and Katz (11) were attempting to parallel the irreducible saturation with a value of saturation which was the minimum level attainable under the prevailing deliquoring conditions. In an attempt to predict the residual saturation over a range of porous media

FIGURE 1.4.2.1



$$\frac{\text{sphericity}}{\text{porosity}} = \frac{\Psi}{\epsilon} \text{ or } \frac{\Psi'}{\epsilon'}$$

Brownell and Katz Exponents

and operating conditions dimensional analysis was employed. As a result of this the capillary number, the ratio of forces driving fluids from the bed to the forces retaining fluid, was developed. It was found that a reasonable correlation could be obtained between the capillary number and the residual saturation. The correlation took the form:-

$$S_R = 0.0116 \left\{ \frac{K \Delta P}{gL \gamma \cos \sigma} \right\}^{-0.264} \qquad \text{Eqn. 1.4.3.1.}$$

The value of the initial constant may change with bed thickness since for rotary vacuum filters with cake depth below 2" the value is thought to be about 0.025 (6).

Having defined the lowest attainable level of saturation under prevailing conditions the concept of effective saturation was introduced. The effective saturation represents the wetting fraction of the total fluids in flow and is defined by equation 1.4.3.2..

$$S_E = \frac{S - S_R}{1 - 2 S_R + S S_R} \qquad \text{Eqn. 1.4.3.2.}$$

This term is used for saturation in the Brownell and Katz flow relationships.

1.4.4. Two Phase Flow.

The Reynolds numbers and friction factors, proposed by Brownell and Katz (10), for two phases in flow have already been indicated in Section 1.4.2.. In defining these factors the independence of the two phases has been assumed. The wetting phase is best described with reference to laminar flow in pipes. The fluid will have zero velocity at the pore wall and the same velocity as the non-wetting fluid at their interface. Over the annular flow channel the wetting phase will have the same velocity profile as it would were it filling the whole of the pore cross-section. Similarily, the non-wetting fluid flows as if in a pipe of wetting fluid its velocity being zero relative to the wetting fluid at their interface.

Thus the phase moves with a minimum velocity relative to the porous bed which is equal to the interface velocity.

Using this concept Brownell and Katz (11) attempted to find a velocity distribution for each phase. For the wetting phase the velocity was integrated between zero and the interface velocity. The average linear velocity could then be found in terms of saturation for a pore. This gave:-

$$V = \frac{g\, d^2\, \Delta P\, S^2}{32 \mu L} \qquad \text{Eqn. 1.4.4.1.}$$

For a porous bed the velocity was believed to be proportional to $S_E^{\,2}$, as indicated in the previous section. From experimental data, however, the exponent of effective saturation, y, has been found to be a variable dependent upon particle size. Using this relationship Eqn. 1.4.4.1. was developed a stage further such that a new Reynolds number and friction factor could be defined.

$$Re = \frac{d\, v\, \rho}{\mu \epsilon^m S_E^{\,y}} \qquad \text{Eqn. 1.4.4.2.}$$

$$f = \frac{2gd\, \Delta P \epsilon^n\, S_E^{\,2y}}{L\, v^2 \rho} \qquad \text{Eqn. 1.4.4.3.}$$

The exponent, y, was determined from experimental data on the basis of these equations.

The physical model of the flow of the non-wetting phase was treated in a similar way to that of the wetting phase. The properties of the porous media were said to be modified by the presence of the wetting fluid. In the work of Brownell and Katz (11) these modifications took the form of adjustments to the porosity and sphericity of the medium. New quantities were defined on the basis of the wetting phase saturation These were the wetted porosity and the wetted sphericity.

1.4.5. Wetted Porosity and Sphericity

The wetted porosity, ϵ', is a measure of the proportion of pore space which is occupied by the wetting and non-wetting fluids.

$$\epsilon' = \frac{\text{(Voids occupied by non-wetting fluid + voids occupied by wetting fluid eliminated from flow)}}{\text{Volume of bed}}$$

$$= \frac{(1 - S)\,\epsilon}{(1 - S_R)} \qquad \text{Eqn. 1.4.5.1.}$$

Therefore, at 100% wetting phase saturation the wetted porosity is zero while when saturation is equal to the residual saturation the wetted porosity becomes equal to the dry bed porosity, ϵ. The wetted porosity is used in place of the dry bed porosity whenever the non-wetting phase is being considered.

The wetted sphericity has no such exact method of derivation. It is, as its name suggests, a measure of the sphericity of the wetted particles. Dry sphericity is defined as follows:-

$$\psi = \frac{\text{surface area of sphere of same volume as particle}}{\text{surface area of particle}}$$

and so lies in the range 0 - 1.0. In a similar way the wetted sphericity may be defined:-

$$\psi' = \frac{\text{Surface area of sphere of same volume as wetted particle}}{\text{Surface area of wetted particle.}}$$

Brownell and Katz have plotted several sets of data (11) setting out wetted sphericity as a function of effective saturation. The curves plotted show no consistent form and the authors suggest that this may be because the wetted diameter of the particles has not been removed from the relationship between wetted sphericity and effective saturation.

1.4.6. Porosity exponents

The relationship of the exponent m and n to sphericity and porosity as shown by Brownell and Katz has already been indicated. This relationship

was extended to permit consideration of the porous bed during flow of the non-wetting phase. The wetted equivalents of porosity and sphericity were used in the determination of the wetted values of the two exponents These new exponents were m' and n'. Using these values which were representative of a porous media modified by the presence of wetting fluid the relationship for flow of the non-wetting phase could be developed in terms of the Reynolds number and friction factor:-

$$Re = \frac{d v \rho}{\mu (\epsilon')^{m'}} \qquad \text{Eqn. 1.4.6.1.}$$

$$f = \frac{2 g d \Delta P (\epsilon')^{n'}}{v^2 \rho L} \qquad \text{Eqn. 1.4.6.2.}$$

The correlation on which the values of the exponents are based has been questioned during discussion (11). It was pointed out that Rose (41-43) had done considerable work on the porosity exponent. The relationship as found by Rose was considerably different from the value of n - m calculated by Brownell and Katz. This was particularly evident at high porosity. A comparison of the work of Rose with the Brownell and Katz value of the exponents is given in Figure 1.4.6.1.. This comparison also includes the equation for the relationship developed by Carmen:-

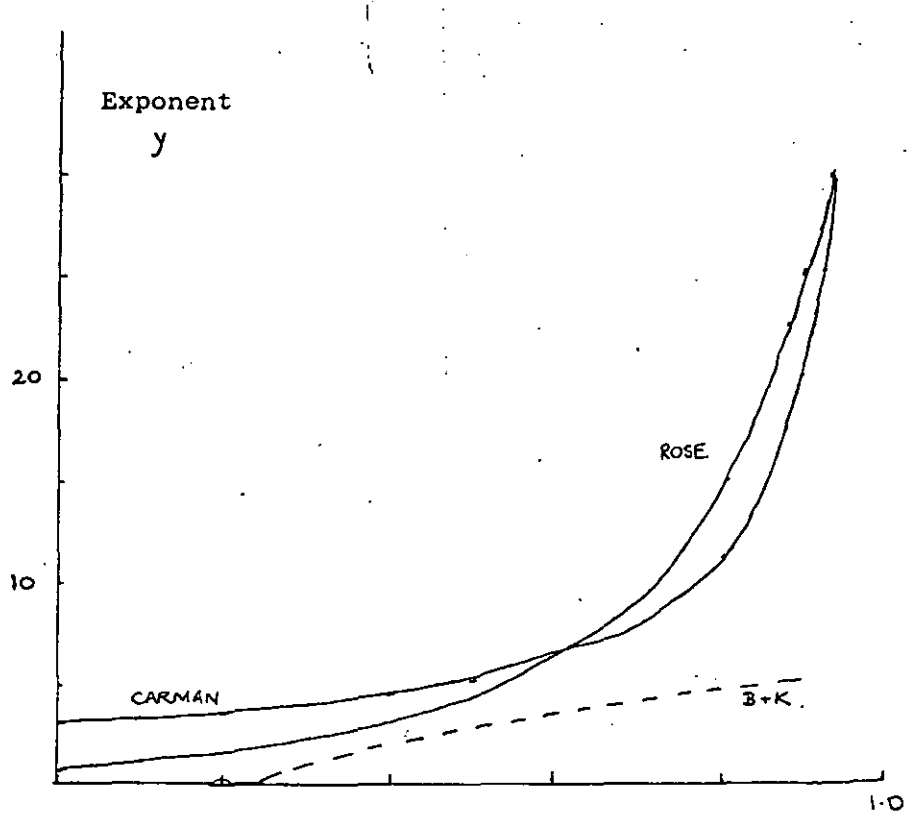
$$n - m = (3 - \epsilon) / (1 - \epsilon) \qquad \text{Eqn. 1.4.6.3.}$$

This equation overpredicts the exponent obtained in from experimental data by a considerable amount at low cake porosity.

1.4.7. Gas Deliquoring

In their first two papers (10, 11) Brownell and Katz have developed equations which are said to predict the flow characteristics of two phases flowing in a porous media. Equations 1.4.4.2. and 1.4.4.3. apply to the wetting phase while the Reynolds number and friction factors for the non-wetting phase are represented by equations 1.4.6.1. and 1.4.6.2. respectively. The third of this series of papers (12) attempts to apply the correlations to the deliquoring of rotary vacuum filter cakes. The initial part of this paper discusses the application of the single phase

FIGURE 1.4.6.1



Porosity

Porosity Exponents

Rose & B & K

flow correlation to the filtration cycle. It is the second part of the paper which sets out to predict deliquoring rates and gas consumption that is of interest to this study.

In the majority of cases deliquoring occurs in the laminar flow regime. Therefore, the Brownell and Katz approach could be further simplified using the relationship of Reynolds number to friction factor for laminar flow. The velocity of wetting fluid was given as:-

$$V = \frac{K_W \Delta P S_E^{\,y}}{\mu L} = \frac{gd^2 \epsilon^{n-m} \Delta P S_E^{\,y}}{32 \mu L} \qquad \text{Eqn. 1.4.7.1.}$$

Developing this by considering a material balance and manipulating the equation using the definitions of individual quantities Brownell and Katz arrived at the following relationship for the rate of deliquoring

$$dt = -\int_1^{S_\epsilon} \frac{\epsilon L^2 \mu}{K \Delta P S_E^{\,y}} \cdot \left\{ \frac{1 - S_R}{1 - S_R S_E} \right\}^2 dS_E \qquad \text{Eqn. 1.4.7.2.}$$

The volumes of air flowing through the filter cake were calculated in a similar way using the Reynolds number and friction factor for the non-wetting phase. The non-wetting phase was assumed to completely fill the voids of a modified porous media. The modifications, as already indicated were to take the presence of the wetting phase into consideration.

Although originally laid down in the third paper of Brownell and Katz (12) the method of calculating gas flow from this correlation is put forward more clearly in a later paper by Brownell and Gudz (9). Further approximation and simplification of the correlating procedures led to the description of a graphical correlating technique for which the two basic parameters calculated were the volume and time constants which were defined as follows:-

$$C_t = \frac{\mu_W \in L^2}{K \Delta P} \qquad \text{Eqn. 1.4.7.3.}$$

$$C_v = \in \frac{\mu_W L}{\mu_{NW}} \qquad \text{Eqn. 1.4.7.4.}$$

It was claimed that graphical correlations on the basis of Figure 1.4.7.1. would permit rapid determination of the accummulative air flow under laminar flow conditions. However, values of exponents used in developing the curves plotted were average values for granular and crystalline materials forming cake having a porosity in the region of 0.4.

A fourth paper (8) in the series on two phase flow attempted to make some slight modifications to the correlations developed in previous papers. These alterations were concerned with three of the parameters; particle diameter, interstitial velocity and the length of fluid flow paths. They were intended to improve and simplify calculations. The modified form of the correlation is laid down in a book by Brown et al (6).

1.5 Empirical Correlations

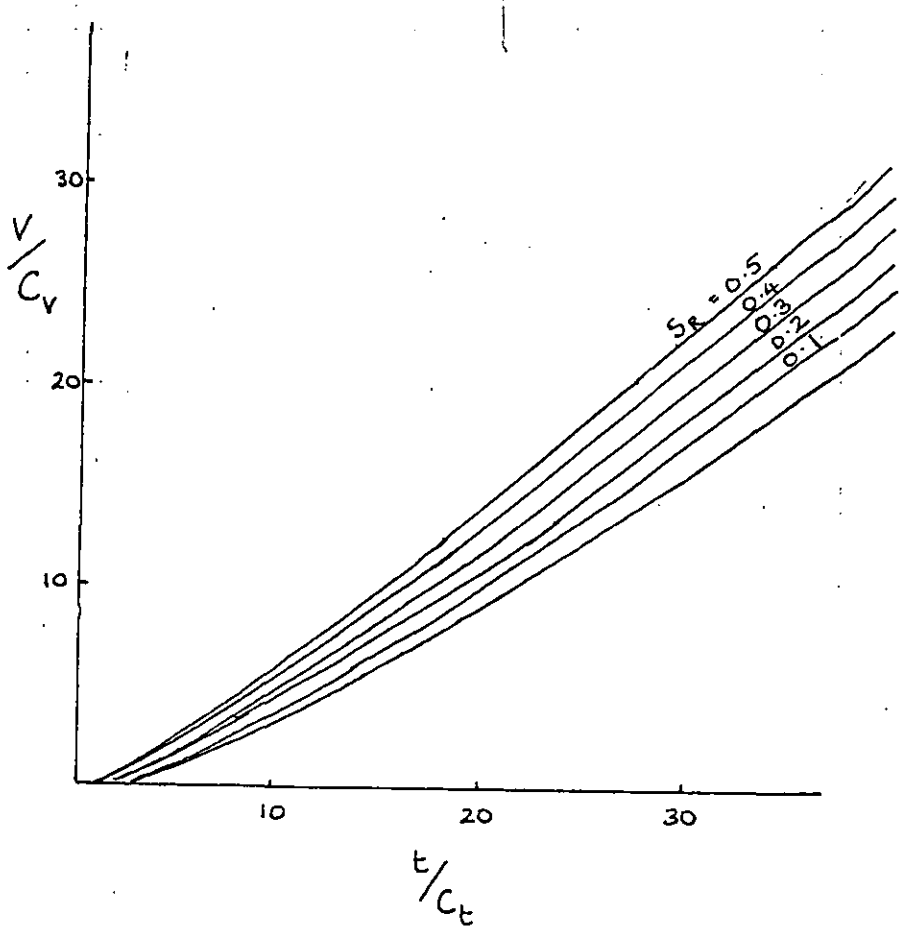
1.5.1. Dombrowski and Brownell

The aim of empirical correlations is to describe the important variables in a system and to predict their influence on the overall cake conditions. In attempting to describe two phase flow in porous media Dombrowski and Brownell (16) took into account static and dynamic effects as well as possible end effects. They did this by splitting porous media into five categories.

These were:-

1. Thick beds with no end effects
2. Thick beds with static end effects
3. Centrifugal beds with static end effects
4. Thick beds with static and dynamic end effects

FIGURE 1.4.7.1.



Graphical Correlation

5. Thin beds with static and dynamic end effects

Thick beds were those thicker than the capillary drainage height of the porous bed being considered. The cakes formed in pressure filters fall almost exclusively into the category of thin cakes. In these cakes the end effects control the saturation. To permit calculation of the drain height of a filter cake the combined effects of permeability, density and surface tension were correlated in the form of a drainage number:-

$$\left(\frac{K}{g}\right)^{\frac{1}{2}} \left\{\frac{\rho + \rho a}{\gamma \cos\sigma}\right\} = \text{Drainage No.} \qquad \text{Eqn. 1.5.1.1.}$$

It was found that a relationship existed between drainage number and drainage height:-

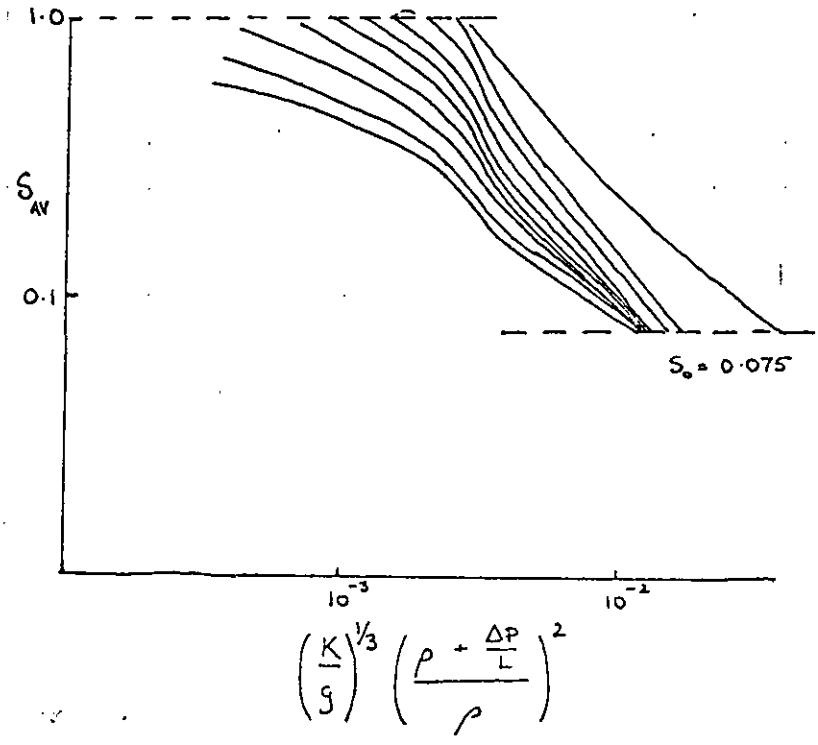
$$L_d = \frac{0.275}{\text{Drainage No.}} \qquad \text{Eqn. 1.5.1.2.}$$

The paper set out to modify the correlations previously developed and in particular the method of obtaining the residual saturation. This was to allow for the increasing importance of end effects as the bed depth decreased. For a bed of constant L/L_d ratio the average residual saturation was found to be proportional to the square of the dynamic to static driving force ratio. In a similar way the average saturation was found to vary as the permeability to the 1/3 power. These two terms were combined to give the product:-

$$\left(\frac{K}{g}\right)^{1/3} \left\{\frac{\rho + \Delta P/L}{\rho}\right\}^2$$

Figure 1.5.1.1. shows the graph obtained by plotting this product against average saturation at various L/L_d ratios. It was suggested that from this plot the residual saturation of thin cakes could be obtained with much greater accuracy. End effects were taken into account in contrast to the previous correlations developed by Brownell and coworkers .

FIGURE 1.5.1.1.



Dombrowski & Brownell

1.5.2. Dahlstrom and Coworkers

From 1952 to 1972 Dahlstrom and his coworkers published a number of papers on filtration and deliquoring using rotary vacuum filters. Several of the papers have discussed specific systems (17, 34) while others (18, 32, 46) discussed the general characteristics of moisture level reduction in rotary vacuum filter cakes. Using the work of Brownell and Katz as a basis further methods of correlating moisture content with operating conditions were proposed and the individual effects of some variables were also investigated.

In the first of their papers (37) Dahlstrom and his coworkers reasoned that the final moisture content should be a function of four variables. These variables were air consumption, deliquoring time, pressure drop and filter cake depth. The authors claimed good results for specific materials in scale-up tests, however, for fine materials the final moisture was considerably higher than for coarser fractions. Thus at least one further variable describing the materials being used would need to be introduced. Apart from this several other variables were found to warrant investigation.

1.5.2.1. Viscosity and Surface Tension

Silverblatt and Dahlstrom (45) studied the effects of viscosity and surface tension on the final moisture content of filter cakes and the rate at which this value was approached. Referring to the work of Brownell and Katz (10 - 12) two main suggestions as to the effects of the two variables were made. Firstly, surface tension appeared to determine the lower limit of saturation attainable whereas viscosity was considered to have no effect on this level. Secondly, changes in viscosity affected the rate at which the residual saturation was approached. Experimental work was carried out to test these theories and the relative importance to the deliquoring rate of the two variables was estimated. The conclusion reached was that surface tension effects were "relatively unimportant" as a

source of variation in moisture content. The wetting phase viscosity was said to be inversely proportional to the deliquoring rate. On the other hand Ng et al (33) showed that the non-wetting phase viscosity was directly related to the deliquoring rate when considering the mobilisation of blobs isolated in packs of spheres. This suggests that viscosity ratio would be a better correlating factor.

Nevertheless, as a result of their study of wetting phase viscosity the correlating factor previously suggested (37) was modified to include the term $1/\mu_W$.

The new correlating factor was:-

$$V \; t \; \frac{\sqrt{\Delta P}}{L} \; \frac{1}{\mu_W} = F_c \qquad \text{Eqn. 1.5.2.1.}$$

Although the $\sqrt{\Delta P}$ is thought only to apply to air flow in the turbulent flow regime no firm statement as to the power for laminar flow was given. However, in the following paper (32) the pressure drop term reverted to ΔP.

1.5.2.2. Filter Cake Solids

As mentioned earlier in this section the correlating factor developed by Silverblatt and Dahlstrom could not be applied to a wide range of particle sizes. In their paper Nelson and Dahlstrom (32) referred to several solids properties believed to be of importance in determining final moisture content. These included size distribution, particle shape and surface characteristics. It appears that the correlation was intended to apply to individual system each of which would have a unique correlating factor. No attempt was made to unify varying systems by correlation of the three variables mentioned.

It is recognised that, in general, the finer the solids the more difficult the reduction in moisture content becomes (19). The most consistently used method of relating particle size distribution to

deliquoring rates has been via the capillary pressure curve. The most recent of this work has been that of Wakeman (54) in his development of the pore size distribution index (section 1.3.4.). This index was an attempt to describe all the characteristics of a particle system using a single parameter.

The work of Brownell and Katz (10-12) showed that particle diameter and sphericity together with bed porosity were interrelated in a more complex way that envisaged in the early stages of their correlation development. In the correlation porosity and particle diameter had not been obtained as independent variables.

The concept of pore size distribution would seem to be more directly applicable to the deliquoring properties of a filter cake as it is the properties of the flow channels which are of prime importance in determining the flow characteristics of the two phases.

Little reference has been made by Dahlstrom and coworkers to the effects of solid properties on the level of residual saturation obtained. This would seem to be the main deficiency in the correlating technique. However, the next development they were to suggest was the introduction of an approach factor which was intended to indicate the rate at which the level of residual saturation was approached during the deliquoring cycle.

1.5.2.3. Approach Factor

The development of the approach factor (32) was based on the equation derived by Brownell and Gudz (9) for the rate of change of effective saturation with time, Equation 1.4.7.2.. From this it can be seen that the cake saturation could be represented as a function of three factors. These factors were the exponent y, the residual saturation and the approach factor. Thus the approach factor was defined as:-

$$\frac{t\,K\,\Delta P}{\epsilon\,L^2\,\mu_W} = F_a \qquad \text{Eqn. 1.5.2.2.}$$

The factor was further developed by use of basic filtration and flow equations to permit application to leaf test or pilot plant data. For cakes having a similar residual saturation i.e. those of identical solids being formed under closely matching conditions a value of the approach factor was said to be discernable at which the equilibrium saturation was reached. For the two sets of data quoted the value of approach factor obtained was approximately 30. Further analysis of data using a separate system of corn gluten as compared with the taconite concentrates used in the initial tests showed that a graph of moisture content versus the log of approach factor gave a straight line plot. Although unclear the moisture content is believed to be that moisture over and above the residual moisture content. Thus the residual moisture level is never attained under constant deliquoring conditions.

1.5.2.4. Steam dewatering.

It was indicated in an earlier section (45) that reduction in wetting phase viscosity led to a significant increase in deliquoring rate and also a reduction in the residual moisture level. As a result of this observation Dahlstrom and coworkers, in two papers (18, 46) investigated the properties of steam dewatering using steam as a means of reducing the wetting phase viscosity.

By increasing the cake moisture temperature from 60°F to 180°F the viscosity was reduced by a factor of three. This increase in temperature could not be quickly obtained using hot gases due to the limitations of cake permeability and sensible heat available in the gas. Results in the later paper (18) indicate that the improvement in deliquoring by use of steam was considerable. It also showed that viscosity was an important factor in determining the residual saturation.

A very good thermal efficiency was claimed for steam deliquoring In addition very little mass transfer was believed to occur in comparison with the increase in flow of the wetting phase. Thus the technique, on

the basis of this investigation of Dahlstrom and coworkers, would appear to be worthy of consideration in a considerable number of deliquoring operations.

1.5.2.5. The Correlating Factors.

Two main factors have been developed in the work of Dahlstrom and coworkers. These were the correlating factor indicated in section 1.5.2.1. and the approach factor as described in section 1.5.2.3. While the first of these was intended to describe the lower limit of saturation obtainable under given deliquoring conditions the second was said to reflect the rate at which this level would be approached. Thus, by use of these two factors the deliquoring operation was thought to be fully described. However, it must be made clear that the situation being considered is one in which the pressure drop existing at the end of the filtration is usually maintained during deliquoring.. Any variation between the pressure drops over the two parts of the operation is generally small. As with the majority of literature being considered the filtration operation being considered is that involving rotary vacuum filters.

1.5.3. Wakeman

Some of the work of Wakeman has already been described earlier in this chapter. In an attempt to define porous media in a more usable way he developed the pore size distribution index (54). This variable was used in conjunction with the residual saturation to predict the relative permeability curves for porous media. The curves obtained were similar to the experimental curves obtained by Wyckoff (62).

While earlier publications (51, 52) were concerened with the general aspects of filtration post-treatment processes having introduced the concepts of threshold pressure and pore size distribution index a full correlation based on the use of dimensionless groups was developed.

1.5.3.1. Dimensionless Groups

The dimensionless groups used in the correlation are those for

pressure, flowrate and time. They were defined as follows:-

$$P_W^* = P_W / P_b \qquad \text{Eqn. 1.5.3.1.}$$

$$P_{NW}^* = P_{NW} / P_b \qquad \text{Eqn. 1.5.3.2.}$$

$$V_W^* = V_W \mu_W L / KP_b \qquad \text{Eqn. 1.5.3.3.}$$

$$V_{NW}^* = V_{NW} \mu_{NW} L / KP_b \qquad \text{Eqn. 1.5.3.4.}$$

$$t^* = KP_b t / \mu_W L^2 \epsilon (1-S_R)$$

Where * indicates the dimensionless form of the variable.

Wakeman (56) developed Darcys Law to give the flowrate for each phase using the relative permeability relationship already discussed.

$$V_W = \frac{-KK_{RW}}{\mu_W} \frac{\partial P_W}{\partial x} \qquad \text{Eqn. 1.5.3.5.}$$

$$V_{NW} = \frac{-KK_{RNW}}{\mu_{NW}} \frac{\partial P_{NW}}{\partial x} \qquad \text{Eqn. 1.5.3.6.}$$

These equations were manipulated to give the dimensionless form:-

$$V_W^* = -S_R^{(2+3\lambda)/\lambda} \frac{\partial P_W^*}{\partial (X/L)} \qquad \text{Eqn. 1.5.3.7.}$$

$$V_{NW}^* = -(1-S_R)^2 \left(1 - S_R^{(2+3\lambda)/\lambda}\right) \frac{\partial P_{NW}^*}{\partial (x/L)} \qquad \text{Eqn. 1.5.3.8.}$$

The pressures in the two phases can be calculated using the relationship:-

$$P_{NW} - P_W = S_R^{-1/\lambda} \qquad \text{Eqn. 1.5.3.9.}$$

In his most recent paper Wakeman (58) has applied these theoretical

developments to practice and used them in the construction of a series of design charts. A worked example of each stage has been given. The main aim of the design procedure was to calculate the size of filter, the moisture level attainable and the quantities of air used.

1.5.3.2. Applicability of Wakemans Correlations

The examples used again considered the use of the rotary vacuum filtration operation. This somewhat limits the range of conditions over which the correlation has been tested. On observing the examples quoted in Wakemans papers (56-58) it was noted that the porosity of cakes tested were normally about 0.4 - 0.5 and the range of mean particle diameters was 50 - 230 μm. The pressure drop developed was, of course, limited by the vacuum pump in use and was normally about 13.6 kN/m^{-2}.

It might be expected that with such limitations on the systems being considered that greater accuracy would be obtained. However, the graphs comparing theoretical and experimental results show that the agreement is not as good as that obtained using the Brownell and Katz correlations and that the theory can overpredict the saturation by 100% or underpredict the average air flow rate by 25%.

Theoretically no gas flow should occur at dimensionless gas pressures less than 1.0 as this is how the gas breakthrough is defined. However, the modified threshold pressure is so defined that flow is possible through large pores at that pressure. Therefore in figure 1 of the most recent paper (58) values below 1.0 have been used in the design procedure.

It can be seen that the results of the theoretical development do not give a significant improvement on the predictions using the Brownell and Katz correlation. However, the theoretical approach attempted may prove to be an important step in understanding the deliquoring operation.

1.6. Conclusions.

The literature which has been used in this study has covered a wide range of subjects. The link between all these has been the

consideration of porous media. Thus the ways in which porous media are characterised have been investigated. Once the media has been characterised the nature of single and two-phase flow can be more clearly seen. The picture of two phase flow which has developed is one of a series of deliquoring stages.

The first stage in deliquoring is the piston flow regime during which the non-wetting phase forces the wetting phase through the porous media. This continues until breakthrough of non-wetting phase at the exit face of the porous media occurs. The extent of desaturation at this point depends upon the nature of the porous media and the forces applied. Once breakthrough of the non-wetting phase occurs true two-phase flow commences. This will continue in the form of film flow until the film breaks down and further minimal flow will occur through a small number of channels still in motion. Deliquoring will cease when insufficient force is being applied to retain the movement of the wetting phase.

The correlations developed have been for a specific range of conditions. In general these have fallen outside the range of conditions with which this investigation of pressure filters will be concerned. The size distribution, in particular, involved in pressure filters is far lower than the sizes investigated by Brownell and Katz (10-12) and by Wakeman (56-58). The most important factor which is of concern in the operation of the deliquoring cycle in pressure filters is the range of pressure drops being used. The volumes of gas required to maintain the pressure drop at or close to the level during the latter stages of the filtration cycle are excessive and the general practice is to continue deliquoring at a considerably lower flow and pressure drop. Thus the range of pressures being considered varies by a much greater amount than in the situations examined in the literature. This indicates that problems may well be encountered in attempts to apply the correlations developed in the literature to the specific operation being considered.

CHAPTER 2

EXPERIMENTAL APPARATUS

2.1 Introduction

During the course of the project the experimental apparatus has been changed by addition and modification to suit the experiments to be carried out. The experimental apparatus described in figures 2.1.1.1 (a) - (d) was used in the majority of the experimental work. A brief outline is also given of the design and development of the apparatus and reasons for major modifications are explained.

2.2 Design Tests

Initial tests were carried out using two separate pieces of apparatus. The aim of the tests was to obtain the information required to be able to design the main pieces of experimental equipment and to size the measuring instruments. The order of magnitude of pressure and air volumes had already been obtained by consideration of full scale equipment on several visits to industrial locations. The information obtained about present practice will be described later.

The first of the two pieces of test apparatus was a bench scale fluidised bed which was modified to form a filter cell. The filter cakes formed were 4 cms in diameter and ranged between 0.5 and 3 cms in depth. The equipment was not suitable for high pressure operation but pressure and air flow measurements were made up to the level of pressure permissible.

The second piece of test equipment was constructed on a larger scale. The mild steel cylinder used had a volume of approximately 10 litres and the filter area was 175 cm^2. Cakes of diatomaceous earth 1 cm in depth were formed. Basic measurements were taken. The pressure was measured using a manometer and the flow was controlled

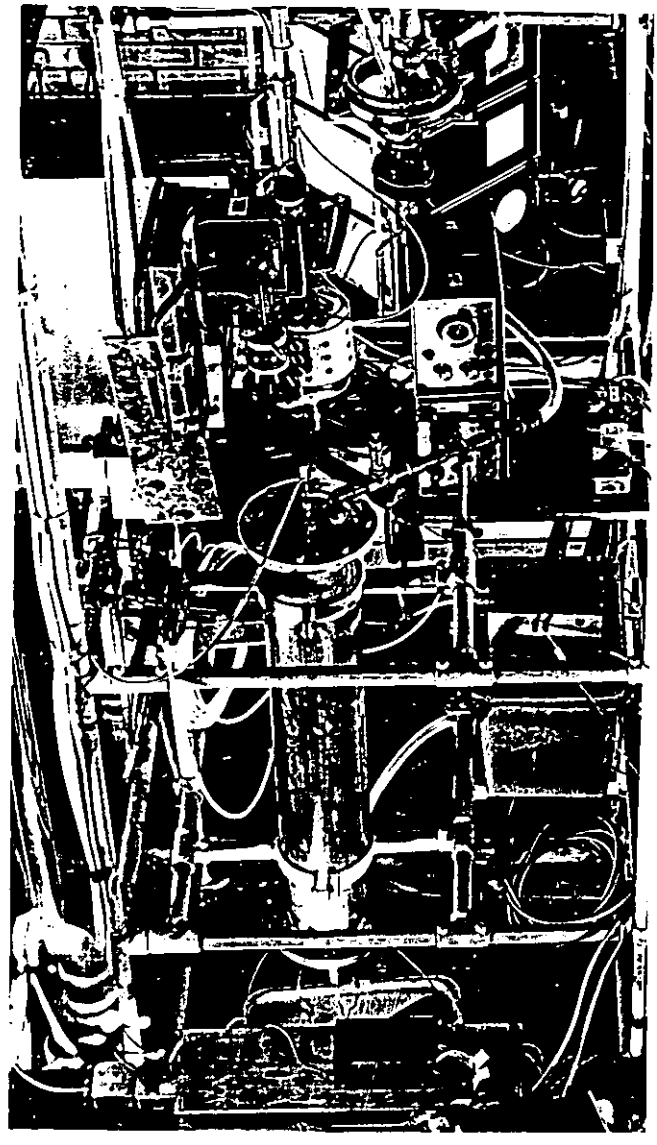


Fig. 2.1.1.1. (a). TIME LAPSE EQUIPMENT.

Fig. 2.1.1.1.(b). DATA LOGGING SYSTEM.

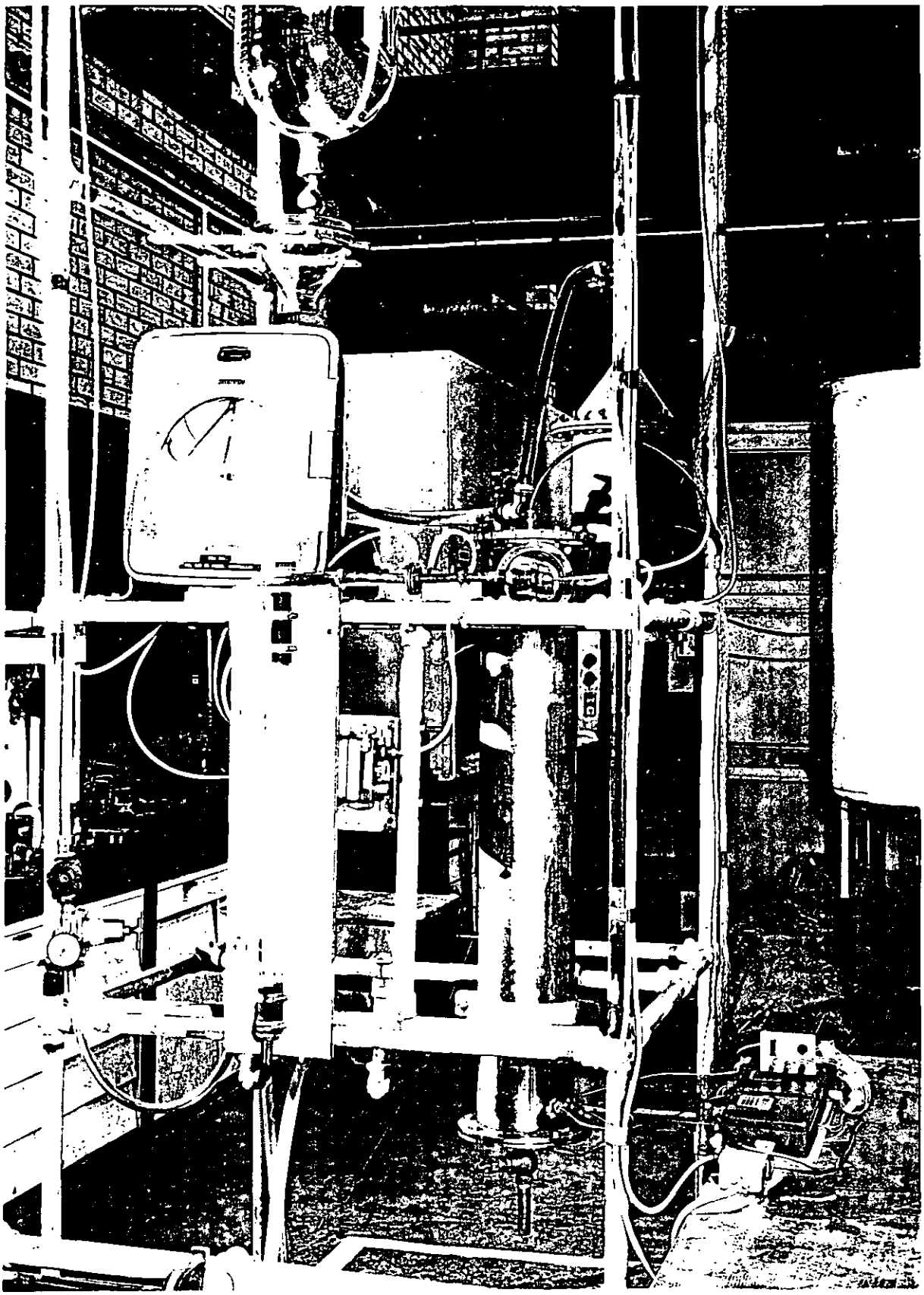
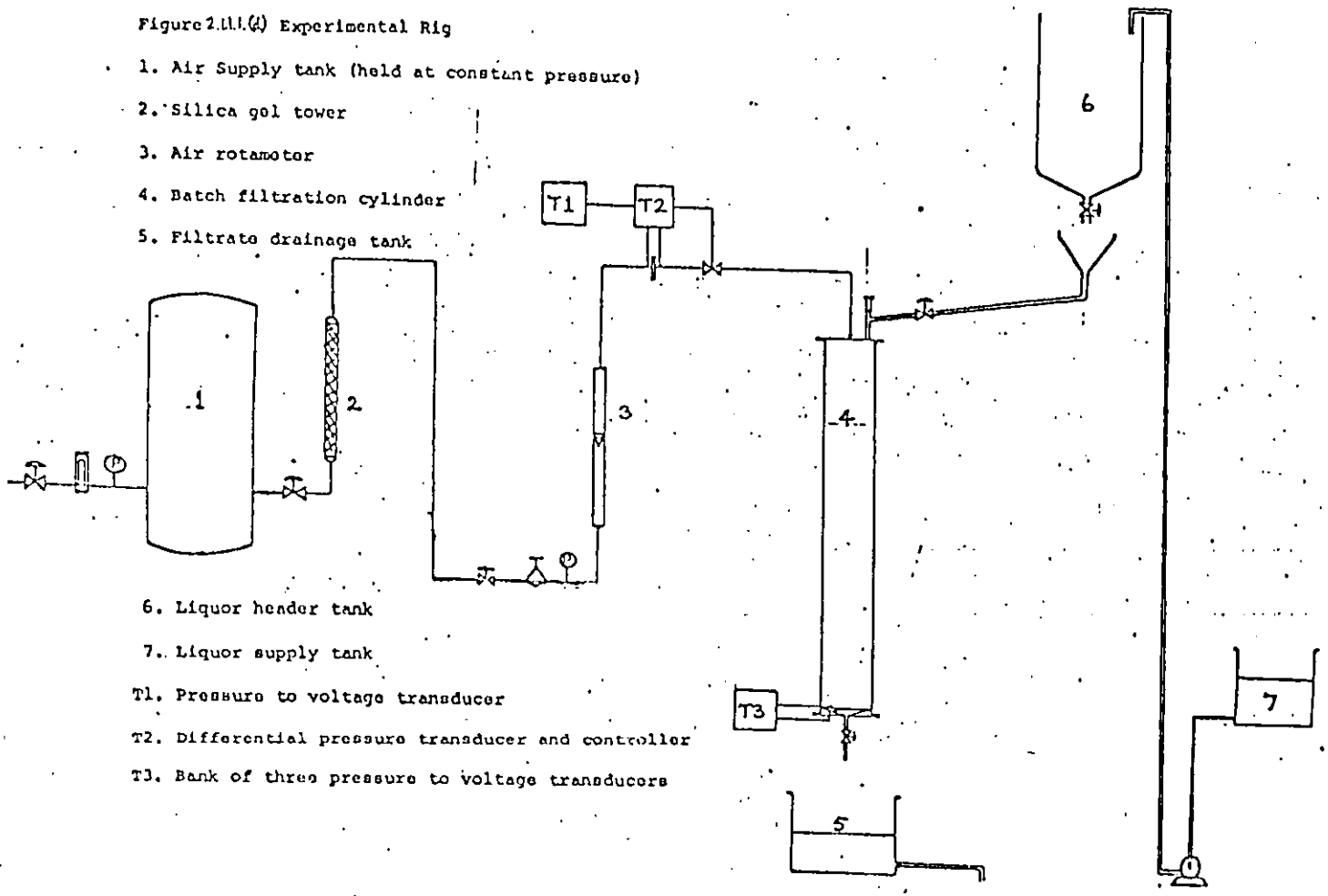


Fig 2.11.1(c). TEST EQUIPMENT

Figure 2.11.(4) Experimental Rig

1. Air Supply tank (held at constant pressure)
2. Silica gel tower
3. Air rotameter
4. Batch filtration cylinder
5. Filtrate drainage tank
6. Liquor header tank
7. Liquor supply tank
T1. Pressure to voltage transducer
T2. Differential pressure transducer and controller
T3. Bank of three pressure to voltage transducers



using a pressure regulator and measured using a rotameter. These were, of course, rough measurements. An attempt was made to estimate the rate of deliquoring by using a strain gauge to measure the rate of reduction of weight of the whole system . A method of taking samples of cake in situ at predetermined times during the deliquoring cycle was also employed.

No significant results were obtained from the strain gauge measurements. This was considered to be due to the relatively small fluctuations expected during deliquoring compared to the total weight of the equipment. There was also thought to be a large holdup of wetting fluid in the support media. The sampling probes used were in the form of hollow cylinders which were pushed vertically into the filter cake. It was intended that the technique, with further development, might be used to take accurate saturation samples. The sample probes were incorporated in the design of the experimental rig.

The experiments carried out indicated that the test filter would need to be 12 to 15 cms in diameter. The sealing system was found to be awkward and on several occasions concave cakes were formed indicating excessive filtration around the edges of the filter cloth. The filter cloth itself blinded very quickly. This was due both to the general unsuitability of the particular cloth used and to the effects of rust on the purity of the filter liquor.

From the information gained during these tests a design for the main experimental rig was drawn up. The following pages describe the apparatus as used in the majority of experimental tests.

2.3 Filter Cylinder

Due to the problems encountered whilst using mild steel in the design tests and the requirements of working at pressures up to 450 kN/m^2 it was decided to construct the main cylinder in stainless steel. The cylinder, 1 metre in height, was constructed of 9 m.m. wall thickness stainless steel pipe and had an internal diameter of 15.2 cms. The volume of the cylinder was 18 litres.

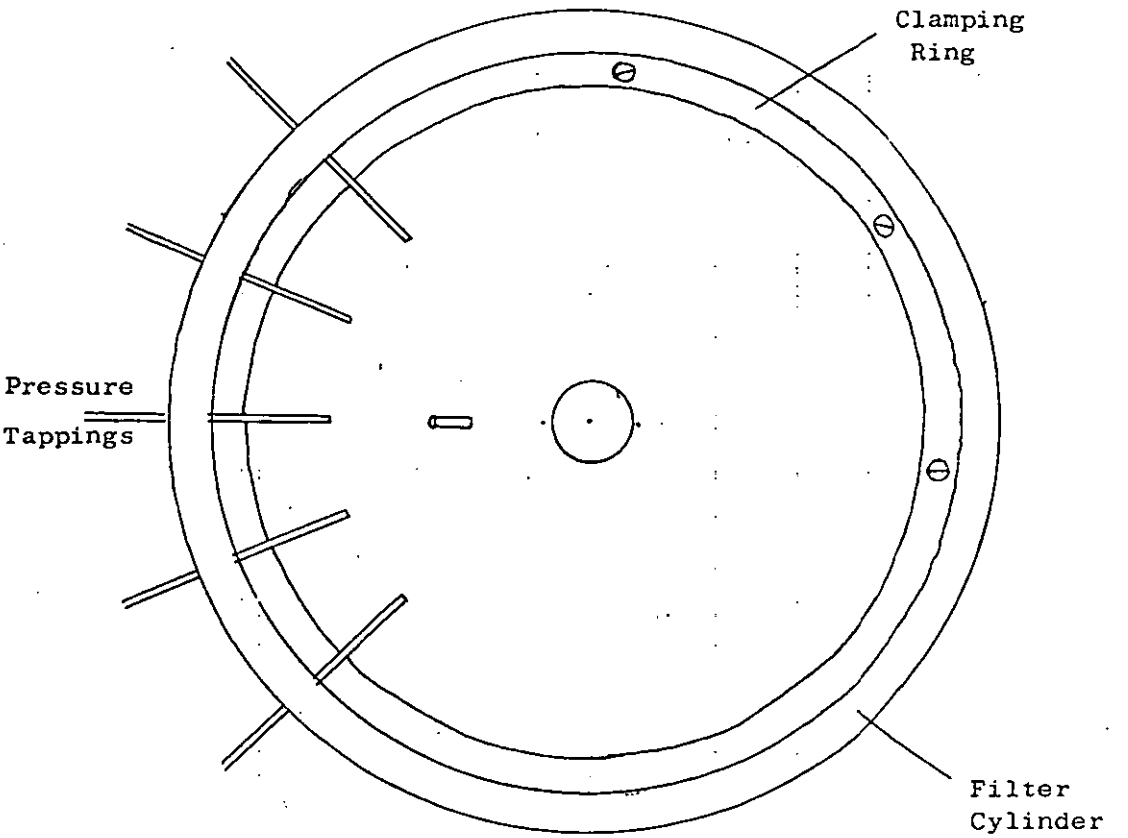
2.4 Filter Block

As can be seen, the cross sectional area of the cylinder was 180 cm^2. The filter block was constructed so that it fitted into the base of the cylinder as indicated in figure 2.4.1.1. The base plate was machined from a 25 mm thick piece of stainless steel. This had the effect of raising the filter to approximately 15 mm above the flange level.

During the first month after construction of the equipment several cloth support systems were tested together with techniques for sealing the cloth into position. The requirements of the support system were that it should withstand pressures upto 450 kN/m^2 whilst allowing proper drainage of liquor from the filter cake. Directly below the filter cloth was placed a stainless steel wire gauze of approximately 20 mesh. This facilitated good drainage while a 6 mm thick, drilled stainless steel plate supplied the support required. This thickness of plate was required because of the amount of drilling needed to give good drainage. 4 m.m. holes were drilled on a triangular matrix with 6 m.m. between centres. The holes were slightly countersunk on the filter cloth side.

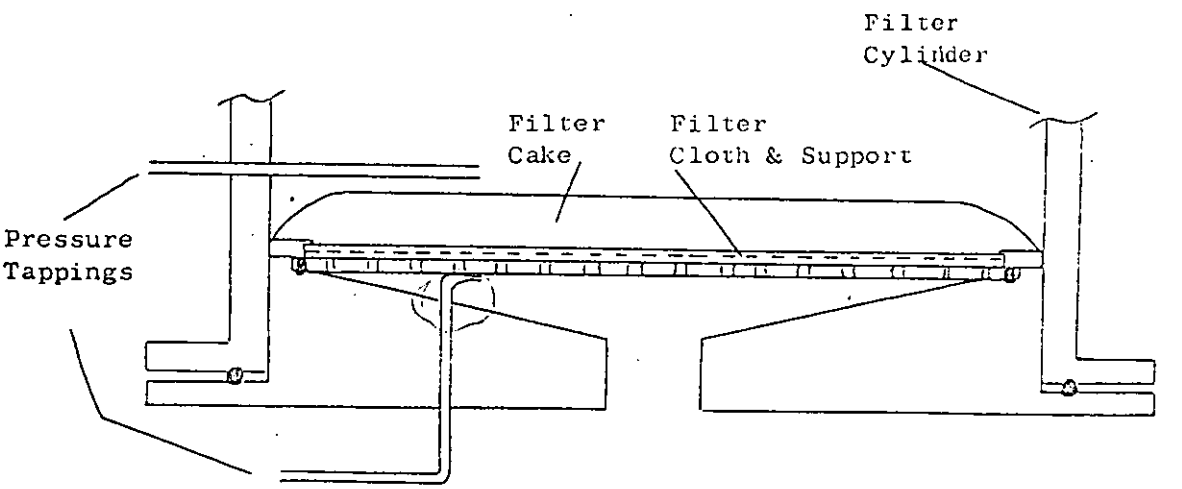
The technique developed for sealing the filter media in position consisted of trapping the cloth between the top rim and the support plate. Initially silicone rubber was used as a liquid gasket. Once the cloth was set in position it was trimmed and the "filter block" was

FIGURE 2.5.1.1



The Filter Block

FIGURE 2.4.1.1.



The Filter Block

fitted to the base plate and sealed into position using silicone rubber. This technique was employed whilst textile filter cloths were being used. Later woven wire cloths were employed. The improved life of these cloths permitted the permanent positioning of the cloth and support media which were glued into the attaching rim.

The final area of filter cloth obtained was determined principally by the requirements of sealing. The diameter of the filter cloth was 12 cm giving an actual filter area of 112 cm^2. This was found to be sufficient to give a good filter cake where the edge effects were not excessive.

Below the support plate a recess of 2 mm was left before the base sloped, at an angle of 15° to the horizontal, to a central drain hole of 2.5 cms. in diameter. A gate valve was fitted to the filtrate outlet to permit closure of the filter cell.

2.5 Pressure Tappings

The purpose of the pressure tappings was to allow for measurement of the gauge pressure at various positions above, below and also within the filter cake. For this reason holes were drilled in the cylinder as indicated in figures 2.4.1.1. and 2.5.1.1. A pressure tapping was also positioned in the base plate so that the pressure directly below the cloth and supports could be measured.

Fine stainless steel tubing was used to transmit the pressures to the pressure transducers used. The tubing had an outside diameter of 2.5 mm and an inside diameter of 1.75 mm. Fine tubing was used in order to keep the volume of fluid in the tubing to a minimum. The tubing extended approximately 4-5 cms. towards the centre of the filter cake so that the pressure readings were taken above or within the main body of the filter cake.

2.6 Top Plate

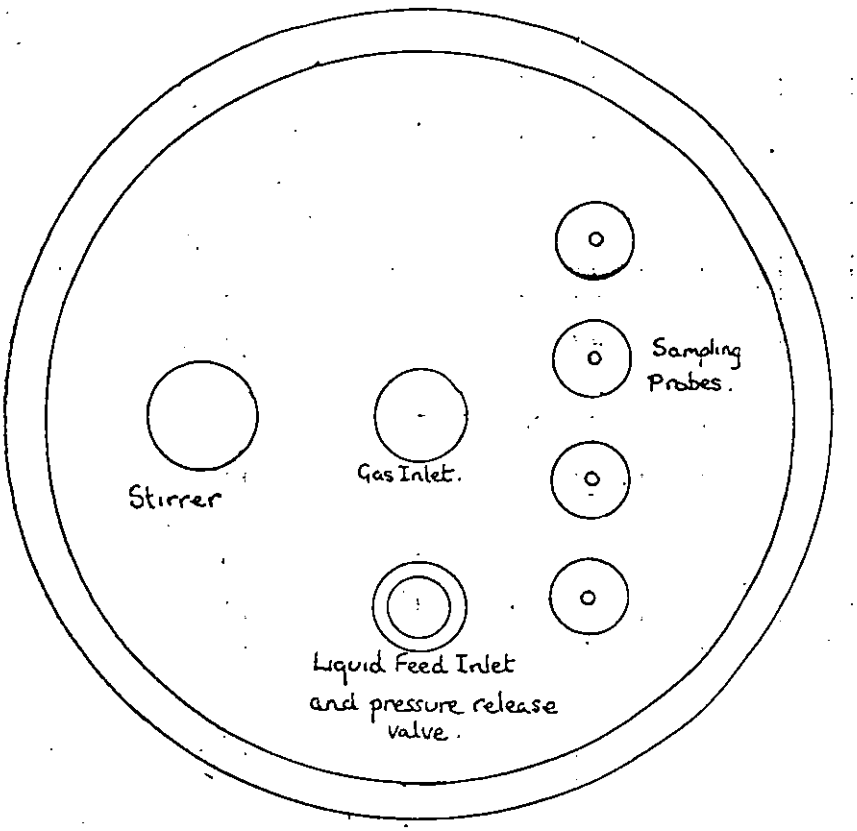
Two top plates were made for the experimental work. The second of these was made of 1.6 cm perspex. This plate was used to facilitate observation of the filter cake during deliquoring and it enabled time lapse photography of the deliquoring to be carried out. The facilities available on this top were limited by the open area required for lighting and photography. Air and liquid inlets were positioned in one quadrant of the top. The first top was made of stainless steel.

As can be seen from figure 2.6.1.1. there are several inlets on the top of the plate. These consist of four sampling positions, one opening for a stirrer, the air and water inlets and a position for a pressure relief valve. In the case of the perspex top the pressure relief valve was positioned on the water inlet pipe.

The stirrer took the form of perforated plate. The diameter of the plate was just less than the diameter of the cylinder and it was attached to a 1 metre long stirrer handle which was not attached centrally. The stirrer was used by a reciprocating movement from top to bottom of the tank. Once stirring was completed the perforated plate was positioned at the top of the tank and sealed using a compressed 'O' ring. In this position it also acted as a distributor for the air flow.

The sampling probes, as already mentioned, were previously employed on the test rig used for design tests. The samplers were small hollowed cylinders of about 3 cms in depth, open at one end, with a threaded section at the top by which they were attached to the sampler rods. These rods held the samplers at 10-18 cms above the filter cake surface until they were required. A guide for the rods was welded in at approximately 20 cms above the filter surface. As with the stirrer, while not being moved, the sampler rods were sealed into the lid using compressed 'O' rings. A plate was welded to the underside of the top

FIGURE 2.6.1.1.



Cylinder Top Plate with tappings.

plate when it was discovered that the majority of air leakage from the cylinder was along the screw threads used in the tightening of the stirrer and sampler rods into the top plate.

The description given to this point has been of the design and construction of the batch filter and of the equipment directly connected to the filter cylinder. The following sections describe, firstly, the supply and control systems for air and water and, secondly, the systems for collection and processing of data.

2.7 Feed Systems

2.7.1. Liquid Feed.

The mains water available in the university was found to contain a considerable amount of impurities. It was, therefore, decided to use distilled water in all experiments. This was transferred from a still to the base tank and was then pumped into the top storage tank which could hold enough water for two batch tests. The water was fed into the cylinder as required ensuring that the air supply line was removed to permit escape of air from the cylinder. Once filtered the water, in most cases, was allowed to go to the drains.

2.7.2. Air Feed System.

Air is supplied at pressures of 550-600 kN/m^2 from the mains air supply. Figure 2.1.1(a) shows the layout of the air supply system. The first air tank had a volume of 100 litres and was held at a pressure of 450 kN/m^2 by use of a pressure regulator. Before passing to the air feed controlling system the air was dried by passing it through a tower of silica gel. The tower was 30 cms high and 4 cms in diameter. The air supply pipe had a diameter of 0.9 cm.

A Saunders valve was used to turn the air supply on and off and directly downstream a pressure regulator controlled the pressure at the level required for the particular test. The first volume measurement was made using a rotameter which had been calibrated, at several pressures,

to give the flowrates of air at s.t.p.. The second volume measurement was made using orifice plates. The plates had orifice diameter of 1 to 2.5 mm and were calibrated for individual flow ranges. The signal from the orifice plate was also used to control the opening of the needle valve placed downstream of the orifice plate. The air flowed into the filter cylinder at the centre of the top plate.

2.8 Measurement.

2.8.1. Pressure Transducers.

As already described the pressure tappings were positioned at the base of the filter cylinder. Fine bore stainless steel tubing was used to transmit the pressure to the transducers. Three transducers were used so that three tappings could be employed for any one test. S.E. Labs (EMI) Ltd. type SE21/V transducers were used with a pressure range of 450 kN/m^2. The transducers were supplied by an unstabilised 24V dc. supply and the output was 0-1 Volt over the range 0-450 kN/m^2. The maximum linearity and hysterisis error for all transducers was 0.1%.

Calibrations were carried out between the three transducers. The transducers were connected to the cylinder and the voltages were recorded for each at several cylinder pressures. In this way it was possible to ascertain the offset in voltage values between the transducers as they were connected for experiments.

2.8.2. Flow Control

As has already been mentioned a rotameter calibrated at pressure was used for flow measurements. A second measurement was also taken by use of an orifice plate. The pressure drop across the orifice plate was calibrated against the voltage output (0-10V) of a transducer constructed in the department. The orifice plate signal was also used as the input to a second transducer.

The second transducer was a Taylor Instruments Differential Pressure Transducer. Taking the input signal from the orifice plate in the range 20-200" water gauge its output to the controller was in the range 3-15 p.s.i. The controller was a Foxboro, two term controller and the signal of 3-15 p.s.i. output from the controller determined the opening of the needle valve setting the air flow.

The three air flow readings which can be obtained are the rotameter, the controller indicator and the voltage from the transducer. Each of these had to be calibrated together. This was carried out by mounting a second rotameter downstream of the needle valve. This rotameter was open to the atmosphere. As mentioned earlier the system was calibrated at several pressures and a number of orifice plates were used each covering a specific flow range.

Over the initial tests with the experimental equipment a certain amount of air leakage was observed. This leakage was gradually reduced by improvements in sealing and jointing. By the time the bulk of the experimental work was commenced the leakage of air from the filter cylinder while at pressures up to 300 kN/m^2 had been reduced to a negligible amount.

No attempt was made to measure the outflow of air from the base of the cylinder as entrainment of moisture in the air stream would have made such measurements difficult and inaccurate.

2.9. Data Logging Systems

The method of obtaining pressure and flowrate measurements in the form of voltages has already been described. The signals from the transducers were recorded on paper tape. This was done by means of one of two data logging systems. The first of these consisted of a Solatron digital volt meter with timer and autocorrelator. The data tape was punched on a data dynamic tape punch and took the form of a channel number, voltage and scaling factor. Each channel was read

at equal time intervals predetermined by the setting of the timer.

After this data logging system had been used for the first eighteen months of the project, problems developed in the operation of both logging system and tape punch. Due to the unreliability of the equipment an effort was made to obtain another system. After a short period a new data logging system was borrowed. This system has been used for the majority of the experimental programme and has proved to be more reliable and versatile than the previous data logging system.

The second logging system consisted of a Schlumberger data transfer unit and a Facit tape punch together with a Solatron digital volt meter. The head units were capable of taking in upto 20 channels but a maximum of five were recorded at any time. Three recorded pressure measurements, a fourth recorded flowrate measurements while the fifth was a spare channel.

The voltages on the five channels were scanned together. The rate at which the scanning could be repeated was determined by the speed of the recording instrument, in this case the tape punch. It was found that the recording of the five channel scan took approximately 1-2 seconds and therefore the maximum scan rate used was one, five channel scan every two seconds. The clock, which controlled the scanning was set at zero for the start of filtration. The scan rate could be adjusted at any time during the running by switching off the scanning and adjusting the scan command before recommencing the scanning. On adjusting the scan command the next scan was carried out at the next multiple of the scan rate from zero time. eg. scanning changing from 10 second to 1 minute intervals may scan at 3 minutes 20 seconds and next at 4 minutes. The scan rates employed ranged from every 2 seconds to once every hour on the longest tests.

The digital volt meter could cope with voltages up to 100 volts and the reading range could be adjusted to suit the voltages being measured. The voltage ranges on the channels being used were 0-1 volt from the pressure transducers and 0-10 volts from the flow metering transducer. To scan on the 0-10 volt range would have considerably reduced the accuracy of measurements. Therefore, the automatic range finder was used.

The data transfer unit was interfaced to two output units. These were the tape punch already mentioned and a paper reader. The rate of recording was further reduced if both units were operating in parallel reducing the scanning rate obtainable to one every 10 seconds. For this reason the paper reader was used in calibration or checking of the system.

The output of this system took the form of six lines for every scan. The first line was the time of scan and the following five lines consisted of channel numbers, voltages and scale factors for the five channels being scanned. This had the advantage of giving a time output. For the first system used time had always been taken as a function of the number of scans completed since the start of recording.

2.10 Computing.

The information obtained from the experimental work was put onto file on the university's ICL 1900 computer. The data was processed on several different computer programmes each to obtain a separate set of results. The details of the computer programmes will be given in a later section. The data fed into the computer came from two sources. The first of these was the paper tape the format of which has already been described. Supplementary data was typed directly into one of the computer's filing systems.

Two methods were used to transfer data to the main university filing system.. The method first used was to feed the tape onto the Modular 1 terminal unit. From there the file of data could be transferred between the Modular 1 temporary filer and the main filing system as required. The Modular 1 files could be edited or added to as necessary using a series of simple editing commands.

After two years of the project a new interactive computer system called Prime was introduced. This system was much more reliable than the Modular 1 as with the Modular 1 the date tape was fed in at a terminal. The operation was somewhat faster (a factor of 2) on the Prime. The filing system on the Prime was permanent and so files were retained on the Prime until editing had been completed. At any stage a full copy of the file could be obtained for detailed checking. The files were transferred to the 1900 filing system by use of two small computer programmes. The first of these transferred the file to a magnetic tape while the second completed the transfer to the main computer filing system.

The University ICL 1900 computer worked on the George 2 system and several computer languages were available. For all the computing carried out the language used was Fortran. All computer programmes were stored on files and called up for use by card commands as required.

2.11. Time Lapse Photography.

The design of a perspex top for the filter cylinder has already been described. The perspex top was used to facilitate the photography of the filter cake during the deliquoring cycle. Some forty experimental tests were filmed using time lapse photography.

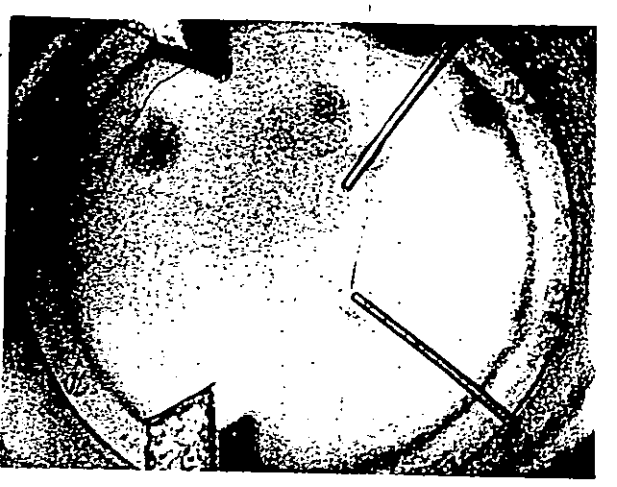
The lighting of the filter cylinder was a major problem. Both camera and lighting had to be positioned close to the top of the

cylinder and room was very limited. To obtain an even light without shadows being cast on the filter cake a hooded spotlight was used. This was positioned approximately 20 cms. above the perspex top. The light was directed at the side of the cylinder just above the filter cloth. The side reflected sufficient light to give an even brightness across the whole of the cake. The light was screened down to the level of the perspex top thus preventing reflection of light directly into the camera lens. The spot light was not designed to be used while mounted vertically and so forced convection had to be supplied to cool the bulb. This was done by directing a stream of air from the compressed air supply through the spotlight casing.

The system used for the time lapse photography consisted of a Bolex camera fitted with a synchro-stepping camera motor which was connected to a Paillard-Wild variometer. The variometer consisted of a control unit and a timer unit. A picture of the time lapse photography system is given in Fig. 2.1.1.1(a) and some individual frames of film are shown in Figs. 2.11.1.2 (a)-(h).

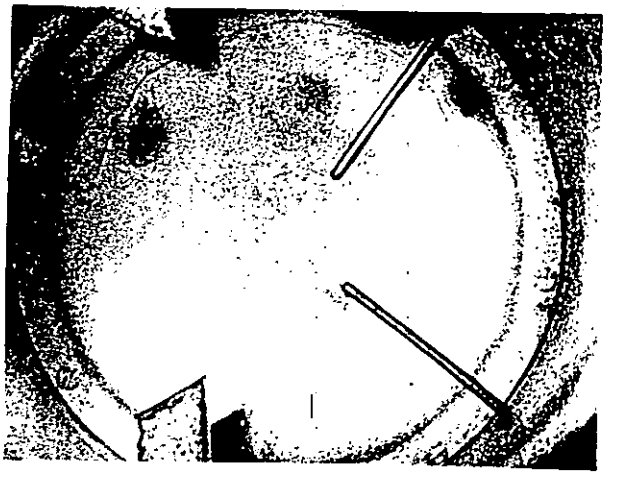
The camera motor was directly attached to the wind-on system of the Bolex camera which was loaded with Kodax Plus-X Reversal film. The control unit was capable of giving exposure times in the range 0.3 secs. while being set automatically. With manual control longer exposure times are possible. The timer was used to set the time between exposures. The time intervals attainable could be varied between 0.3 seconds and 6 hours. A counter on the control unit kept a record of the number of frames taken.

FIG. 2.11.1.2.(a) - (d).
TIME LAPSE PHOTOGRAPHS.



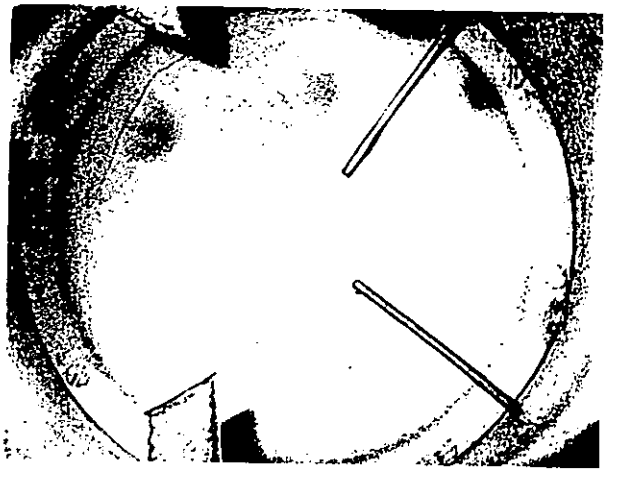
(a)

Photographs (a) - (d) taken at 1 sec. intervals just after the commencement of a deliquoring flow surge

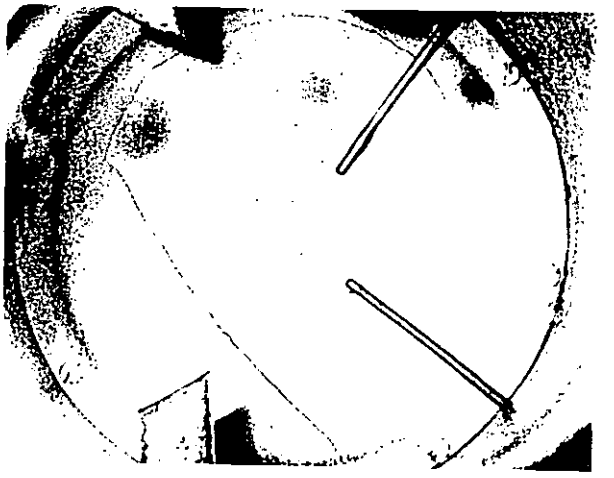


(b)

Photographs (e) - (f) at 1 sec intervals on a second test showing the effect of reapplying pressure.

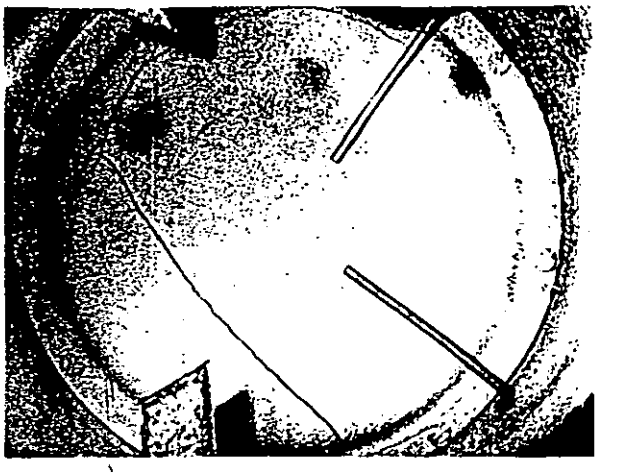


(c)

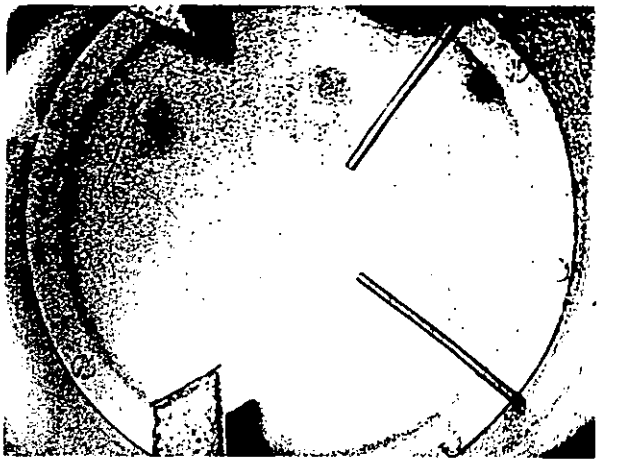


(d)

Fig. 2.11.1.2. (e)-(h).
TIME LAPSE PHOTOGRAPHS.

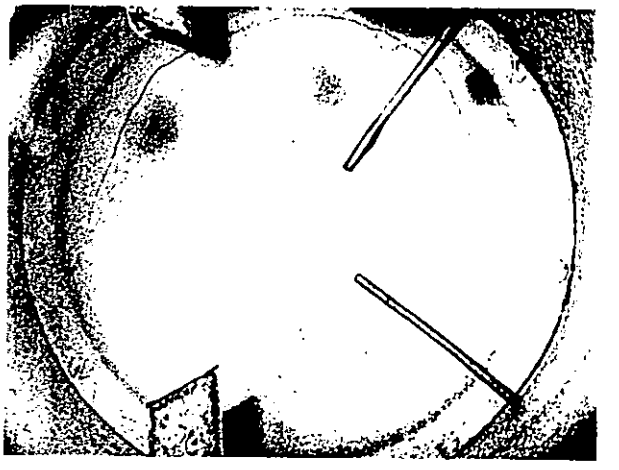


(e)

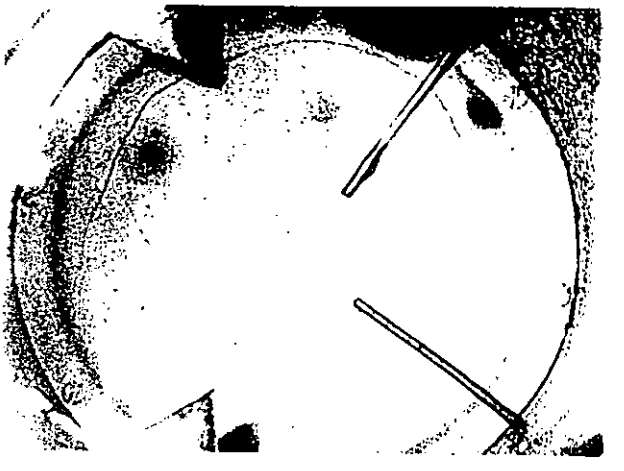


(f)

Photographs (g)-(h) taken at the onset of further deliquoring in the same experiment as (e)-(f).



(g)



(h)

CHAPTER 3

3.0 Experimental Procedure

3.1 Development of Procedures

The initial stages in developing the experimental procedures were carried out on the early design rig. Observations from this rig, apart from enabling the full experimental rig to be designed, indicated several requirements of the operational procedures. These were mainly related to the positioning and sealing of the filter cloth and the sealing of the filter cell. The method of sampling first used on the design rig was put into use on the experimental rig and procedures for taking samples were developed further. A series of twenty experiments were carried out on the experimental rig and it was during this period that the experimental procedure was fully developed.

The major decision made during the initial series of tests was to discontinue the use of the sampling probes. The construction of the sampling probes has already been indicated in the description of experimental apparatus. The procedures for use of the probes were developed considerably during the experiments. At a predetermined time during deliquoring the sealing plate on an individual probe was loosened and the probe was pushed into the filter cake. A mark on the sampler rod indicated the position of the rod when fully inserted. The sealing ring was then tightened. When the filter cylinder was opened the sample probes were removed and the samples emptied from them. Saturations were determined by drying. Large errors were incurred with this sampling system and the inaccuracies of readings were such that samples of similarily deliquored cakes varied in saturation by 10% or more. The main sources of error were thought to

be moisture held on the probes after the end of filtration and the cracking of the cake as the probe was inserted. Although the number of experiments required was greatly increased due to the decision not to employ this sampling technique the increased accuracy of results more than compensated.

3.2 Filter cake preparation

After the initial series of twenty experimental tests further tests were carried out to determine the quantities and type of solids to be used in the main series of tests. During this period the woven metal cloths were introduced with a corresponding increase in the rate at which tests could be carried out. The following description of experimental procedure is that used once the metal filter cloths had been introduced.

At the start of each day the air and electrical supplies were connected. The pressure transducers required a 25 volt unstabilised supply connected to a mains supply while the flow transducer was connected directly to the mains supply. The data transfer unit and tape punch also used a mains supply and having switched these on the interface between the two pieces of equipment was connected. Air at 150 kN/m^2. was supplied to the controller, the differential pressure transducer and the pressure to voltage transducer. This air supply was routed from the mains supply and not from the supply tank held at 450 kN/m^2.

3.2.1. Filter base

The individual runs were commenced by the assembly of the clean filter unit. As already mentioned the majority of tests were carried out with the metal cloths permanently sealed into the sealing disc. A gasket was placed between the base plate and the sealing disc. The sealing disc was clamped down firmly using counter sunk screws. Care was also taken to fasten each down evenly to obtain a complete seal. The plate and disc were set in the same place for each run by the use of aligning marks.

In a similar way the base section was positioned below the cylinder. The base could be placed only in the one orientation and was a very tight fit. To help in the location of the base two long bolts were used to hold the base 5cm. below its eventual position. The base was raised into position on these two bolts before the other six bolts were fitted and then sealed to the cylinder on the 'O' ring seal. The base outlet valve was closed and the pressure tapping below the cloth connected to the transducer.

3.2.2. Filling

To carry out the filling operation the liquid feed valve was opened and the air line disconnected. Disconnecting the air line allowed air to escape from the cylinder as the liquid was fed in. Opening the base valve of the top storage tank distilled water was fed via a funnel into the filter cylinder. The volume of the filter cylinder was 18 litres and, therefore, a maximum volume of 17 litres was used. The initial amount of liquid fed into the filter cylinder was 14 litres. the remaining liquid was used to slurry the solids and to wash the solids into the cylinder. These operations were carried out after several other operations in preparation for the filtration had been completed.

3.2.3. Preparatory Operations

The controls of the data logger were set to those positions required for the start of the run. The time clock was "set" at zero on the data transfer unit. The control in the "set" position held the clock at zero time until switched to "run". The rate control was also set at the initial recording rate required. This was generally one scan every ten seconds. A short section of tape was run through the punch and the run number was written on this section of tape.

The pressure reducer just upstream of the air flow control circuit was set at the pressure required for the filtration operation. This was

done by opening the air valve upstream of the reducer while keeping the needle valve closed. Having done this the needle valve was opened fully by setting the controller to give maximum flow. This permitted the set pressure to be obtained during the filtration cycle.

3.2.4. Slurry Feed.

As mentioned earlier the initial feed of distilled water was 14 litres and a further 3 litres was to be used to complete the liquid feed. Of the 3 litres up to 1 litre was used to slurry the solids in a beaker using a spatula to stir in the solids. Once the solid had been slurried it was poured into the funnel to feed it into the filter cylinder. The remaining distilled water was used to wash any retained solids from the beaker or the funnel into the cylinder.

Immediately the liquid from the feed line had drained into the cylinder the air supply line was connected and the liquid feed valve closed. The slurry was then stirred in the tank using the reciprocating stirrer. The stirrer was moved vertically over the top 75% of liquor depth four or five times as rapidly as possible. The sampler rod locating bar restricted further movement. The stirrer was retracted to the top of the cylinder and sealed in position by tightening down three screws. Once stirring had been completed the filtration was started as quickly as possible to minimise settling of the solids.

3.2.5. Pressurisation.

Having completely sealed the cylinder the air inlet valve was opened and the pressure increased to the level set on the reducing valve. The cylinder was assumed to be at the correct pressure when the air rotameter showed no flow. During early tests there were some problems with leakage of air while the cylinder was at pressure. The leakage was indicated by the continued flow of air into the cylinder. The air rotameter was, therefore, used as a check for excessive air leakage in subsequent tests.

Once pressurisation was thought to be complete the timing switch on the data transfer unit was set to "run" and the recording switch was switched from "off" to "on". After the initial scan period a scan of the channels was made, thus recording the pressure in the cylinder. This was the last operation to be carried out before the start of the filtration cycle.

3.2.6. Filtration

As soon as the recording of the pressure in the cylinder had been made the filtration cycle was commenced. The stop watch was started and the valve at the base of the filter cylinder was opened. After an initial drop in the filtration pressure the pressure approached a value slightly lower than that set on the reducer. This was within the first few seconds of the filtration.

While filtration continued the clarity and temperature of the filtrate were checked. In some instances excessive bleeding of solids gave a cloudy filtrate this was generally caused by bad sealing around the filter disc. The run was discarded in such cases. Bleeding of solids generally showed as in the cake formation as channels in an otherwise even cake. The temperature of filtrate was fairly constant at 15°C with seasonal changes in ambient conditions giving a 5°C range of filtrate temperatures.

The air flow into the cylinder dropped off during filtration until it fell below the air flow rate required for the deliquoring cycle. This was the case for all the deliquoring conditions considered. Therefore, at a point during the filtration the air control system was set to the level of control required for the deliquoring phase. The filtration generally took 1 to 2 minutes the time for this phase being noted as the first signs of air flow were seen at the base of the cylinder.

3.3 The deliquoring cycle.

At this stage the procedures were split into two distinct operations.

The first of these was for deliquoring by continuous air flow. This is the form of deliquoring in general use. The second form of deliquoring was the intermittent flow of air through the cake. Early tests had shown that this technique might give certain advantages.

3.3.1. Continuous Deliquoring.

With the air control system being used for the deliquoring it was found to be best to control the air flow manually during the early stages. In this way excessive overshooting of the required value was prevented and proper control was obtained more rapidly. To retain the reproducability of the control system a standard procedure was used for the manual control. This consisted of setting the manual control to 80% of the flow value required and then raising it slowly to the required level once a maximum had been reached.

Once a relatively steady flow had been obtained, generally after about 10-20 seconds the control was switched to automatic. Occasionally, over the next 1-2 minutes some drifting of air flow occured. This was checked for and corrections were made as necessary. At 3 minutes after the start of the filtration (i.e. 1-2 minutes into the deliquoring cycle) the scanning control was reset to scan once every 2 minutes.

The overall length of test was determined by the deliquoring time required and one minute before the end of the deliquoring time the scanning control was again reset to record at once every 10 seconds. At the end of the deliquoring time the supply valve was turned off. However, recording continued for 30 seconds while the pressurised air in the cylinder continued to flow through the cake. Within this thirty seconds the pressure dropped to 5% of the controlled flow gauge pressure.

3.3.2. Intermittent Deliquoring.

For the tests carried out on intermittent deliquoring the air supply valve was shut off at the first signs of air flow through the

cake. Air flow through the cake was first indicated by an increase of air flow into the filter cylinder. The pressure was allowed to drop off to a maximum of 10% of the filtration pressure before the base valve was closed. The air supply valve was then opened and the cylinder was pressurised to a predetermined level and the air supply valve shut again. Scanning and recording were continued at the same rate as the filtration cycle until repressurisation was started. At this stage the recording was stopped. Scanning was continued so that the pressure level in the cylinder could be observed. If the pressure attained exceeded the required level the pressure was allowed to fall very slowly using a valve connected to one of the upper pressure tappings. In the case of pressures exceeding those required by 10 kN/m^2 or more the experiment was redefined to use a still higher pressure.

Once the pressure required was attained scanning was recommenced and the time was noted. Immediately after the next scan the base valve was opened thus releasing the pressure by air flow through the filter cake. The pressurisation/pressure release cycle was repeated upto three times during any one experiment and each time the same pressure was used.

After the last pressure release air flow was commenced and controlled as for the continuous deliquoring. Once the flow was controlled measurements were recorded for one minute before shutdown procedures were carried out as previously described. A check was made to see that the cylinder pressure attained during this period was well below the pressure used in the intermittent deliquoring.

3.4. Dismantling the Cylinder.

Once recording was stopped the air line was removed from the top of the cylinder and any remaining air was released. The valve on the liquid feed line was not touched as on opening this valve dripping from the line frequently occured. These could badly damage the filter cake.

Next the base pressure tapping was disconnected and the base was unbolted. The nuts were retained on the two long bolts but were loosened off to the ends. The tight fitting base was then gradually prised down until it dropped onto these two remaining nuts. The nuts were then removed and the filter base was lifted onto its support which consisted of a modified gas cylinder stand.

3.5 Saturation Samples

The sampling probes having been disguarded, saturation samples had to be taken once the cylinder base had been removed. Generally the cake was cut into quadrants to give the samples. However, for special tests more specific portions of the cake were used. The samples were placed in foil dishes which had been weighed and numbered some time earlier. The dishes with wet samples were then immediately weighed and placed in an oven to dry. The drying period required was of the order of 2 - 4 hours. However, it was convenient to leave samples in the oven overnight and to weigh all the dry samples from the previous days tests first thing every morning.

While taking the samples of cake several measurements and observations were made. Firstly, the thickness of the cake was noted. The greatest accuracy obtainable for this measurement was to the nearest 0.5 mm. and as such it was used as a check on the quality of the filtration. The extent of cracking and the friability of the cake were also noted. Further to these observations a qualitative assessment was made of the cake/cloth interaction. The ease of removal of the cake from cloth was noted as was the quantities of solids sticking to the cloth.

3.6 Cleaning of the Equipment.

After the removal of the filter base the cylinder could be cleaned. The liquid feed valve was opened and the line was flushed with the distilled water. The top of the cylinder was only

occasionally removed as no great problems with solids hold-up occured here. The base of the cylinder was washed to remove any clinging solids and the pressure tappings were checked to see that they were not blocked by any solids.

The filter base was cleaned thoroughly. The earlier cloths had to be replaced after every test so that it was a question of discarding the cloth and cutting and fitting a new one. For the permanent filter units a set cleaning procedure was developed. Firstly, all the parts were rinsed after the sealing ring had been unscrewed from the base unit. This removed any solids sticking to the surface of the filter cloth. Secondly, the cloth and support unit was backwashed using a jet of mains water to dislodge solids trapped in the cloth and supports. This process of dislodging solids was continued by submerging the unit in an ultra sound bath which contained water with a small amount of teepol. Finally, the unit was thoroughly rinsed with distilled water before being fitted onto the base again.

3.7 Subsidiary Procedures.

The main procedures for the operation of the experimental rig have been described. Several other operations were carried out as required. These included the drying of the silica gel in the drying tower, the fitting of new roles of paper tape and the refilling of the distilled water tanks. The procedures for the taking of time lapse photography once the equipment had been set up were simple. Once filtration had commenced the spotlight was turned on and the time lapse system was switched on. This was set to take one exposure every second with an exposure time of 0.3 seconds. The camera was allowed to run until deliquoring had finished and was switched off about the same time as data recording was stopped.

Between runs 100 blank frames were run off to give a short gap. The air cooling the spotlight was put on well before each run and the spotlight was switched off immediately after each run to avoid overheating. While the perspex top was on the cylinder for photographed experiments the condition of the cake was checked at frequent intervals throughout the run.

No stirring facility existed on the perspex top and therefore filtration was commenced as soon after slurry input as possible. The lack of stirring did not appear to adversely effect the quality of cake formed. i.e. the evenness of the cake was unaffected and no size segregation could be detected.

CHAPTER 4

Experimental Programme

4.1 Introduction

A considerable number of experiments were used to develop the apparatus and procedures involved in the project. Once the operating procedures had been refined a full experimental programme was laid down. The aim of this programme was to provide a full set of data on the deliquoring characteristics of a range of materials. The conditions and time scale of experiments were intended to parallel the operation of industrial equipment. Tests carried out using the intermittent deliquoring technique already described had showed improved deliquoring rates over the continuous deliquoring technique. For this reason a set of experiments on intermittent deliquoring was carried out in parallel with continuous deliquoring tests.

4.2 Filter Cloth

During the development of equipment several filter cloths were tried. At first multifilament nylon and terylene cloths were used. However, these cloths tended to blind very quickly and had to be replaced after only one or two experimental runs. Cloth permeability varied widely between runs thus reducing the reproducibility of results. On observing the used filter cloths under a microscope it was found that the flow paths between individual filaments of the multifilament bundles had been blocked by small particles. It was, therefore, decided to change to monofilament cloths and a number of wire woven cloths were obtained for tests.

The cloths tested had apertures ranging from 30 μm to 130 μm. The weaves tested included HF, Hollander and Panzer types. The cloths

of 75 μm and larger did not retain solids sufficiently well. A cloudy filtrate was obtained. The cloth finally chosen for the bulk of experimental tests was a 50 μm aperture stainless steel cloth. Satisfactory filtration of all the tests slurries was obtained with negligible bleeding of solids. Being stainless steel the cloth was very hard wearing. Furthermore, by thorough washing the original permeability of the cloth could be regained prior to each test. This added both to the reproducibility of results and to the speed with which experiments could be made. Three to four tests per day could be carried out as opposed to the previous one or two.

4.3 Solid Materials

A variety of materials were considered for use in the experimental tests. It was decided that those chosen should be the same as those used for incompressible cakes as this would remove one variable from consideration thus simplifying the system being considered. The three chosen were a diatomaceous earth, a silica test dust and crushed anthracite. The choice of these materials gave a wide range of porosities as well as a variety of material types.

Hyflo-Supercel filter aid was the diatomaceous earth used. Full information on the characteristics of this and the other solids used is given in Appendix A. The average porosity of the filter cakes formed using the filter aid was 85%. The mean particle size based on the particle surface area was 3.8 μm. The particles varied widely in their shape.

The silica test dust was HPF3 silica sand, a fine grade foundry sand. To improve the filtration characteristics of the sand the finer particles (those below 10 microns) were removed using an Alpine Classifier. The modified silica sand formed filter cakes of 49% porosity. The mean particle size of the material was approximately 20 μm. The solid

particles were roughly spherical in form.

The third solid used was crushed anthracite. Pellets of "anthrasorb" a proprietary activated carbon from anthracite were crushed using a small cone crusher. The coarse fraction (above 250 microns) was removed using a sieve. In crushing the anthracite a certain amount of very fine dust was obtained. Further processing using traditional techniques would have caused more size reduction due to the nature of the solid and, therefore, to remove the residue of very fine material the crused material was tossed in a light stream of air. A single batch of the solid was prepared which was sufficient for all the planned tests. The porosity of the cakes formed was 60% while the average particle size was 43 μm. The particles had an angular shape.

The majority of experiments were to be carried out using the first two solids. It was found that these solids had almost identical wetting phase permeabilities. This simplified the comparison of the two solids by removal of the ratio of the two permeabilities as a variable to be considered.

4.4 Wetting and Non-Wetting Phases

The non-wetting phase used throughout the experimental programme was air. This was supplied from the departments compressed air system. To ensure a constant quality of air supply the air humidity was controlled using a silica gel tower. The pressure of the supply was about 500 kN/m^2. However, to ensure a stable supply a large buffer tank was held at a pressure of 450 kN/m^2.

For the majority of tests distilled water was used as the wetting phase. However, in a small number of tests a sugar solution was employed to vary the wetting fluid viscosity. The temperature of the wetting fluid was also noted for each test so that variations in viscosity could be recorded.

4.5 Time Scale of Experiments

In deciding on a time scale for the experimental programme it was intended to follow the operation of industrial equipment. The experiments on intermittent deliquoring were independent of time in the deliquoring phase and, therefore, only the continuous flow experiments needed to be considered. Initial tests were carried out with deliquoring periods ranging from 4 to 8 minutes and the results of these tests were used to decide the deliquoring times for subsequent tests. The 4 to 8 minutes deliquoring period reflected the shorter end of the time scale for industrial deliquoring operations.

The time scale decided on for the main group of test was 15 to 60 minutes for the silica test dust and 10 to 30 minutes for the diatomaceous earth. These time scales permitted saturations down to 0.25 to be obtained without the cakes being allowed to dry out completely. The average deliquoring time of 20 to 30 minutes was comparable to the length of time allotted in industrial situations.

4.6 Range of Cake Depths

The three cake depths chosen for the experimental programme were 0.45 cm, 0.9 cm and 1.35 cm. In general cakes of 0.5 cm to 2 cm are formed in pressure filters. However, it was felt that the major variations in cake characteristics would manifest themselves in cakes of 1 cm and less and, therefore, emphasis was laid on an examination of cake below 1.5 cm in depth. The weights of solid were chosen so that cakes of as near as possible equal depth would be formed.

4.7 Non-Wetting Phase Flowrate.

Silverblatt and Dahlstrom quoted a value of superficial gas velocity of approximately 4.5 cm/sec at vacuum for the maximum value in the deliquoring of a rotary vacuum filter cake. In choosing the range of operating conditions for experiments this was taken into consideration. Air rates of 20, 30 and 40 l/min of air at atmospheric pressure were

used which represented superficial gas velocities at the outlet face of the filter cake ranging from 2.5 to 5.0 cm/sec.

4.8 Filtration and Intermittent Surge Pressure

During the initial tests on the experimental rig several levels of filtration pressure were used which ranged from 100 to 200 kN/m^2. Due to the incompressibility of the filter cakes being formed there was little variation between the cakes formed under the different pressure conditions. The value of 150 kN/m^2 for the filtration pressure was chosen for two main reasons. Firstly, using higher pressures caused more bleeding of solids through the filter cloth during the early stages of the filtration cycle. Secondly, the range of filtrations times for the three cake depths varied from 1 minute to 1 minute 45 seconds when operating at 150 kN/m^2. This length of filtration ideally suited the operating requirements of the equipment.

During the intermittent deliquoring tests the air flow through the filter cake was characterised by the pressure to which the filter cell was raised prior to pressure release. The pressures used in these tests were decided on the basis of several initial tests at the lowest cake depths. At very low pressures (less than 30 kN/m^2) little reduction in saturation was obtained. Above pressures of about 110 kN/m^2 little further desaturation was obtained. The four pressures at which the majority of tests were carried out were 30, 50, 80 and 110 kN/m^2. These were the nominal values of pressure planned for the experiments; accurate measurements of pressures obtained were made for each run.

4.9 Experimental Duplication

In early experiments it was found that there was considerable variation between saturation obtained under identical conditions on separate runs. Having examined the saturation measurements obtained in these experiments it was decided that to obtain mean values of

improved accuracy for each set of conditions two runs should be carried out. In all the intermittent deliquoring tests at the main programme conditions three parallel tests were carried out. However, for the continuous flow tests only occasionally were three runs attempted. In the majority of these tests one or two runs were carried out while for the 30 l/min air flow tests the central point of the programme matrix was not used due to the limited time available for experimentation.

4.10 Further Experiments

The main groups of experiments with silica sand and diatomaceous earth having been completed a considerable number of further experiments were carried out. These experiments consisted mainly of those with crushed anthracite and those in which the wetting phase viscosity had been modified. In each of these cases a small number of runs were carried out in an attempt to obtain an indication of the characteristics of the system used. Groups of experiments were also carried out to investigate the effects of varying the filter cell volume on intermittent deliquoring characteristics. Once some indications of trends in deliquoring had been found a small number of experiments were carried out with cakes at other depths to those used in the main test programme.

4.11 The Total Programme

The development of an experimental programme has been described in considerable detail. The full extent of the experiments made is indicated in Appendix B which gives a tabulation of all experiments carried out once the experimental rig and procedures had been fully developed. Some earlier experiments have been used in analysis of results and checking the extent of errors in various procedures. These experiments will be described as they are used. No overall description of these earlier tests can be given which is applicable to the main set of experimental runs as the tests were designed to improve procedures.

Only in a limited number of experiments is it felt that a comparison with subsequent tests is viable.

CHAPTER 5

Discussion and analysis of results.

5.1. Introduction

The basic data collected during the experimental programme consisted of flowrates, pressures and saturations. Other information obtained included approximate cake depth measurements as well as qualitative assessments of the condition of the filter cake formed. The flowrates measured were those taken for the non-wetting phase. Attempts to measure the outflow of the wetting phase directly were unsuccessful. The pressure transducers, the first positioned directly above the filter cake and the second positioned below the cake support system, gave the two pressure values used in calculations. The saturation of the filter cake was measured once the equipment had been dismantled at the end of an experimental run. In situ saturation measurements could not be developed to give the required accuracy. All numerical information logged on paper tape was put onto computer files and edited before being processed on the University's ICL 1900 computer. A full description of the data and processing files employed is given in Appendix C.

This chapter describes the trends indicated by the basic data for the continuous and intermittent deliquoring flow tests. A statistical analysis of these results has been made. An investigation of the relative importance of the main variables leads to the proposal of a theory which accounts for the trends in cake behaviour during the deliquoring operation.

5.2 Continuous Flow.

5.2.1 Saturation-Time Profiles

The saturation results for continuous flow tests are given in Appendix D. These consist of nine classes of run for each of the two main solids, as indicated in the experimental programme, together with a small number of other continuous flow tests. A typical set of results for two of the classes is plotted in Figure 5.2.1.1.. Examination of the saturation-time profiles indicated that, as a first approximation, each class of experiments appeared to follow a straight line relationship. As a first step in testing this relationship a "least squares fit" for each class of data was calculated. In the majority of classes the variations of data points from the best straight line do not change with time. i.e. little bias towards curvature was detected. However, as a further test of the validity of a straight line construction a more complex curve fitting exercise was attempted.

The computer programme employed was developed by Drott (Appendix C) to fit concentration-time data to a curve of an exponential form. Written in Basic Plus and run on a PDP11 computer programme developed the best fit by use of the differential equation

$$\frac{ds}{dt} = k\,S^{n} \qquad \text{Eqn. 5.2.1.1.}$$

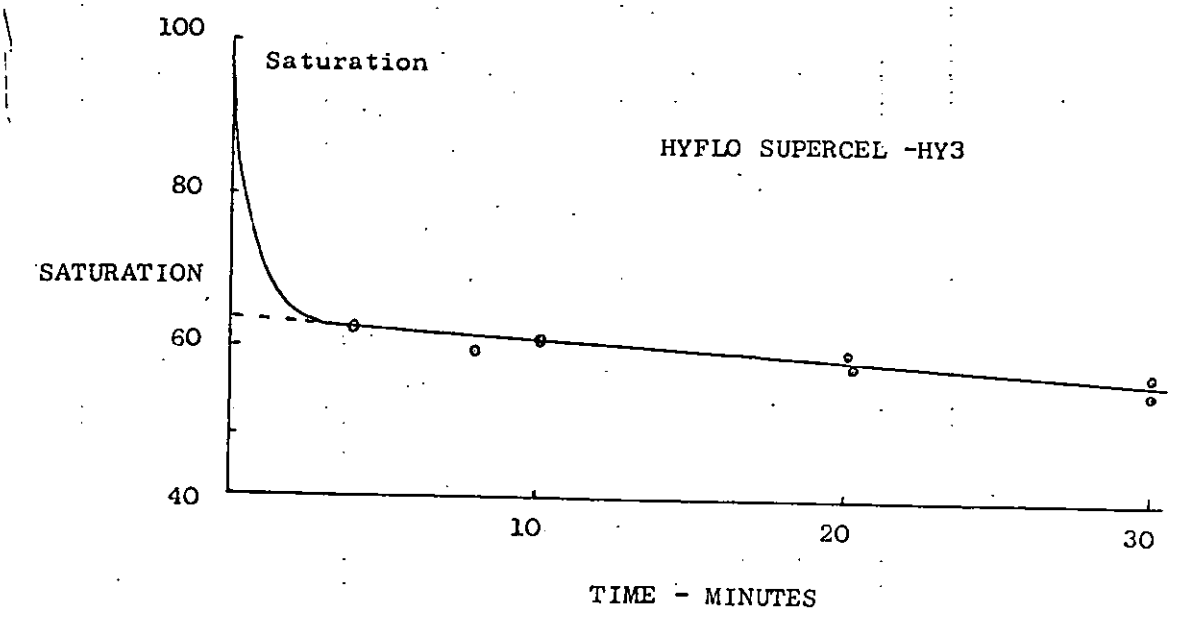
Integration and rearrangement of this equation gives

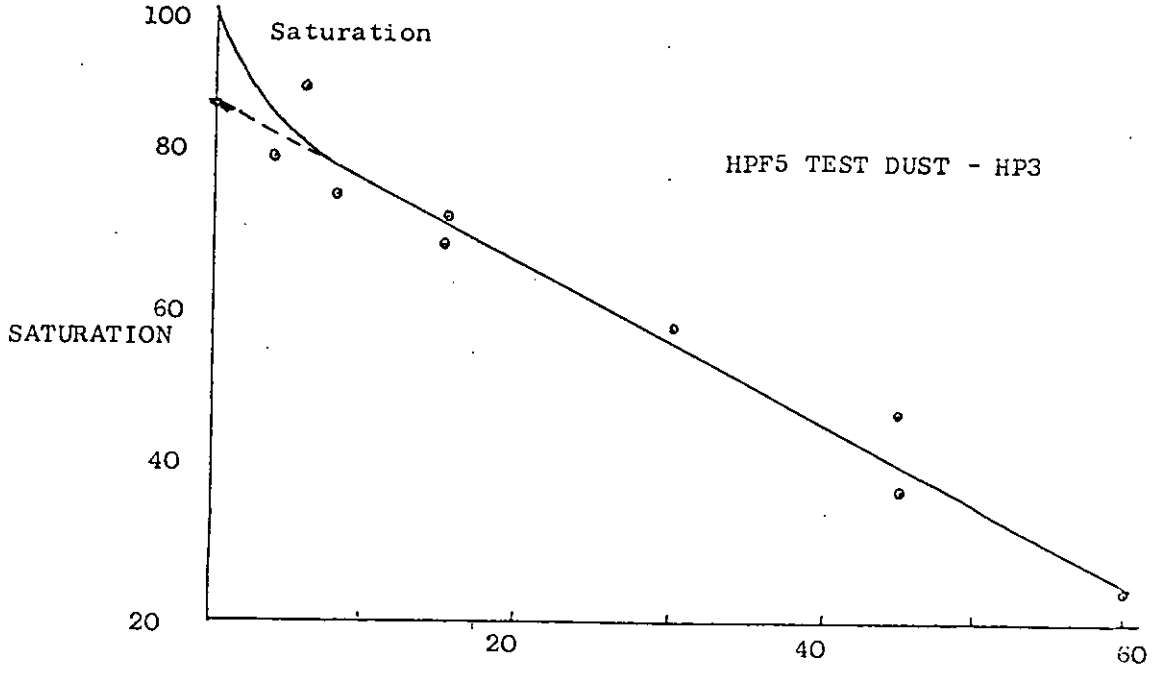
$$\frac{1}{S^{n-1}} = \frac{1}{S_o^{n-1}} + k(1-n)t \qquad \text{Eqn. 5.2.1.2.}$$

Sample input and output for the programme is given in Appendix E which also includes the results of the curve fitting computations for the two main solids. As can be seen from the sample run a full statistical assessment of the data used and the accuracy of the curve fit is obtained. There is also the facility to compare any specific

FIGURE 5.2.1.1.

~~FIGURE 5.2.1.1~~





SATURATION TIME - PROFILES

model with the best fit. For each class of data a best fit and comparison with the best straight line were computed.

Table 5.2.1.1. shows the exponents obtained from the curve fitting programme for the nine classes of each solid. It can be seen that there is a much wider variation in exponents for the Hyflo-Supercel than for the HPF5 test dust. The confidence limits for the exponents are correspondingly wider for the Hyflo-Supercel. The reason for lack of confidence in the Hyflo-Supercel tests is that the extent of deliquoring over the continuous deliquoring period is of the same order of magnitude as the experimental variations. In the case of the HPF5 test dust, although experimental variations are larger than for the Hyflo-Supercel, the rate of deliquoring is considerably higher in all classes. This gives a better ratio of percentage saturation reduction to experimental variations. Thus experimental error is of much less significance in the tests with HPF5 test dust.

On examining the exponents obtained from the curve fitting of the HPF5 test dust data it can be seen that the majority of values are close to zero. This value represents a straight line. The two classes as defined in Appendix A which vary most from this are HP4 and HP7. These are the classes in which thick cakes have been deliquored at low gas flowrate. This trend is mirrored in the equivalent Hyflo-Supercel classes. As a first step in the analysis of the saturation-time profiles a straight line relationship for the constant flow deliquoring can initially be assumed. However, it will also be useful at this stage to note any trends in the exponents computed in the curve fitting programme. The method used to detect any trends which may exist was to form a matrix of the exponents computed for the

HPF5

Cake Depth	Controlled gas flow. 20	30	40	Mean Values
0.45	-2.49	0.55	0.04	-0.63
0.9	11.7	1.0	0.58	4.43
1.35	22.0	2.8	-0.12	8.23
Mean Values	10.40	1.45	0.17	4.01

HYFLO

CAKE DEPTH	Controlled gas flow. 20	30	40	Mean Values
0.45	-5.56	7.69	-3.18	-0.35
0.9	31.5	-6.93	-3.36	7.07
1.35	36.2	-6.0	-15.0	5.07
Mean Values	20.71	-1.75	-7.18	11.79

Table 5.2.1.1. Exponents ~~Experiments~~ from curve fitting exercise

nine classes. The rows and columns of these matrices were summed. The result of this operation was that two trends became evident. Firstly, as the air flow used is increased, the value of the exponent obtained decreases from a large positive value to a value close to zero. Secondly, as the thickness of cake formed was increased, the exponent also increased. This second trend becomes less evident as the air flowrate is increased, such that at the largest flow value it appears to be no longer significant.

Having assumed a straight line relationship for the constant flow deliquoring period the two values enumerated by this first calculation can be examined. The two values obtained for each class of experiment are the intercept value of saturation and the gradient of the saturation-time straight line.

5.2.2. Deliquoring Rates

The rates of deliquoring calculated from the straight line fitting exercises for each experimental class are given in Table 5.2.2.1.. The extent of experimental variations has already been indicated in considering the curve fitting operations. However, it is possible to gain an assessment of the general relationships between cake depth, gas flowrate and deliquoring rate.

In considering the changes in deliquoring rate with cake depth it can be seen that more rapid deliquoring is gained with thinner cakes. When examining classes HP3, HP6 and HP9 it was found that the relationship approached one of equal volume of filtrate removal per unit time at constant gas flowrate. On this basis Table 5.2.2.2. was drawn up which gives the ratio of wetting phase flow to non-wetting phase volume flowrate at s.t.p.. In this table variations with depth in classes HP3, HP6 and HP9 are no longer

HPF5

Controlled gas flow.

CAKE DEPTH.	20	30	40
0.45	0.0036	0.00665	0.0103
0.9	0.00342	0.00275	0.0051
1.35	0.00055	0.00193	0.00328

HYFLO

Controlled gas flow.

CAKE DEPTH.	20	30	40
0.45	0.00057	0.00181	0.00267
0.9	0.000616	0.00082	0.00171
1.35	-0.000463	0.00062	0.000828

Rate of desaturation in %/minute

Table 5.2.2.1. Gradients of best straight line

HPF5

Controlled gas flow.

Cake Depth.	20	30	40
0.45	0.00519	0.00639	0.00742
0.9	0.00986	0.00528	0.00735
1.35	0.00238	0.00556	0.00709

HYFLO

Controlled gas flow.

Cake Depth.	20	30	40
0.45	0.00144	0.00305	0.00337
0.9	0.00311	0.00276	0.00432
1.35	(-1.00351)	0.00313	0.00314

Wetting phase removal (cm^3)/litre non-wetting phase at s.t.p.

Table 5.2.2.2. Two-phase flow ratio.

clearly outlined. To locate any further variations the deliquoring rates were averaged for each row i.e. all classes at a given depth. By considering these averages it can be seen that a further relationship exists. However, the major variations that exist are those related to changes in gas flowrate as shown in Table 5.2.2.2.. The relationship of gas flowrate to deliquoring rate will now be looked at more clearly.

The gas flowrates used in the calculations so far have been based on the volumes of gas at atmospheric pressure. A pressure differential exists across the filter cake and cloth and therefore the actual volume flowrate through any level of the cake is modified by the pressure at that level. The pressure differential is a function of both the cake depth and the gas superficial velocity and it follows that the mean pressure is also a function of these two variables. Thus, for each condition of cake depth and superficial gas velocity a filter cake will have a different mean pressure which will modify the mean gas flowrate.

To adjust the correlation for this factor the first step is to define the mean pressure. It should be noted that the pressure in the cake varies from the pressure at the filter cake surface to that at the cake/cloth interface. Without any firm evidence to support the use of a specific mean the pressure at a point halfway between these extremes will be used. This gives a mean pressure of the form:-

$$P_{MEAN} = \frac{\Delta P_{cl} + \Delta P_c}{2} \qquad \text{Eqn. 5.2.2.1.}$$

Therefore, the correction to gas flowrate will take the form:-

$$Q_{MEAN} = Q_A \left(\frac{P_A}{P_A + P_{MEAN}} \right) \qquad \text{Eqn. 5.2.2.2.}$$

Having found a mean pressure for each of the experimental classes a new gas flowrate for each class can be calculated. It was on the basis of this gas flowrate that further correlation was attempted.

Table 5.2.2.2. has already been used as a first step in introducing the gas flowrate to the correlation. This gave the ratio of wetting phase removal rate to gas flowrate at s.t.p.. On adjusting the gas flowrate to obtain a value at the mean cake pressure it was found that a satisfactory correlation could be obtained by increasing the power of gas flowrate to two. In this way the correlating factor becomes:-

$$k_1 = \frac{-\Delta S \cdot \epsilon \cdot A \cdot L}{\Delta t \cdot Q^2} \qquad \text{Eqn. 5.2.2.3.}$$

The results of this stage of the correlation are indicated in Table 5.2.2.3.. As can be seen the adjustments made to the gas flowrates included in the correlation have modified the correlating factor in terms of the cake depth so that overall agreement is obtained for both cake depth and gas flowrate except for the tests at 20l/min where experimental error was large. The mean pressure chosen appears to give excellent agreement over the range of conditions being considered. With the data available no more detailed correlation for these two variables can be supported.

5.2.3. Intercept Values.

The second parameter calculated on the assumption of constant rate deliquoring was the saturation extrapolated to zero time. At first sight this would appear to be an unusable value as it seems to represent a discontinuity in the saturation-time profile. The parameter may be explained without the consideration of such a discontinuity by reference to Fig. 5.2.3.1.. In effect it is

HPF5

Controlled gas flow.

Cake Depth.	20	30	40	
0.45	2.748	2.400	2.159	2.432
0.9	6.709	2.596	2.810	4.04
1.35	1.640	2.750	2.786	2.39
	3.94	2.79	2.77	3.17

HYFLO

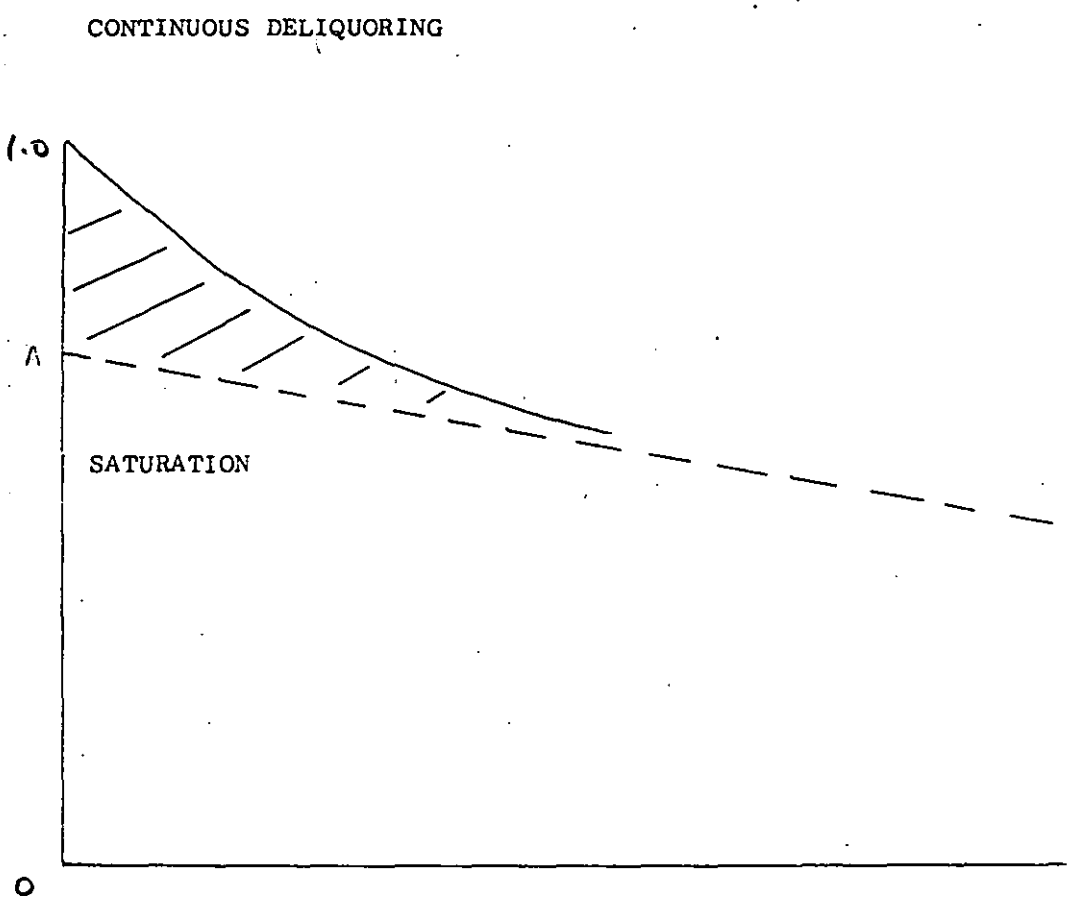
Controlled gas flow.

Cake Depth.	20	30	40	
0.45	0.926	1.336	1.157	1.140
0.9	2.107	1.276	1.555	1.616
1.35	-2.297	1.507	1.152	0.121
	0.215	1.373	1.288	0.959

Values = $k_1 \times 10^6$

Table 5.2.2.3. Best Correlation for depth and gas flow.

FIGURE 5.2.3.1.



Proposal for flow regimes

proposed that the intercept values should be thought of as representative of a capacity of the filter cake to be deliquored over the initial minutes of the deliquoring cycle. It will be shown in the intermittent deliquoring tests that the intercept values of saturation calculated in continuous flow tests were not reached immediately on gas breaking through the cake. The theory of the mechanisms which bring about the various regimes in the deliquoring cycle will be expounded later in this chapter. For now the development of a correlation relating the prevailing filter cake conditions to the subsequent saturation level attained will be indicated. The intercept values calculated from the straight line extrapolation are given in table 5.2.3.1.. These values include all experimental points for which a deliquoring of ten minutes of greater was used. A limited number of tests were carried out over shorter deliquoring periods but have been excluded at this stage to obtain a uniform time scale of tests for the various classes.

The filter cakes having been formed using a reproducible procedure the first stage of the deliquoring cycle is the flow of the wetting-phase up to the point where gas breaks through the bottom or outlet surface of the cake. As a first part of the investigation of the intercept values this portion of the cycle was examined more closely. A successful correlation was found between the initial gas flowrate and the intercept saturation for cakes of 0.9 and 1.35 cms.. The timescale of data collection was such that the important parameters could not be measured accurately for the thinnest cakes.

The initial calculation carried out was to ascertain the volume flowrate of gas passing through the base of the cake at the time of

HPF5 Test Dust

Controlled gas flow

CAKE DEPTH.	20	30	40
0.45	0.893	0.880	0.872
0.9	0.633	0.587	0.565
1.35	0.547	0.505	0.483

HYFLO - SUPERCEL

Controlled gas flow

CAKE DEPTH.	20	30	40
0.45	0.715	0.670	0.639
0.9	0.538	0.527	0.501
1.35	0.500	0.498	0.458

Table 5.2.3.1. Extrapolated Intercept Values - A

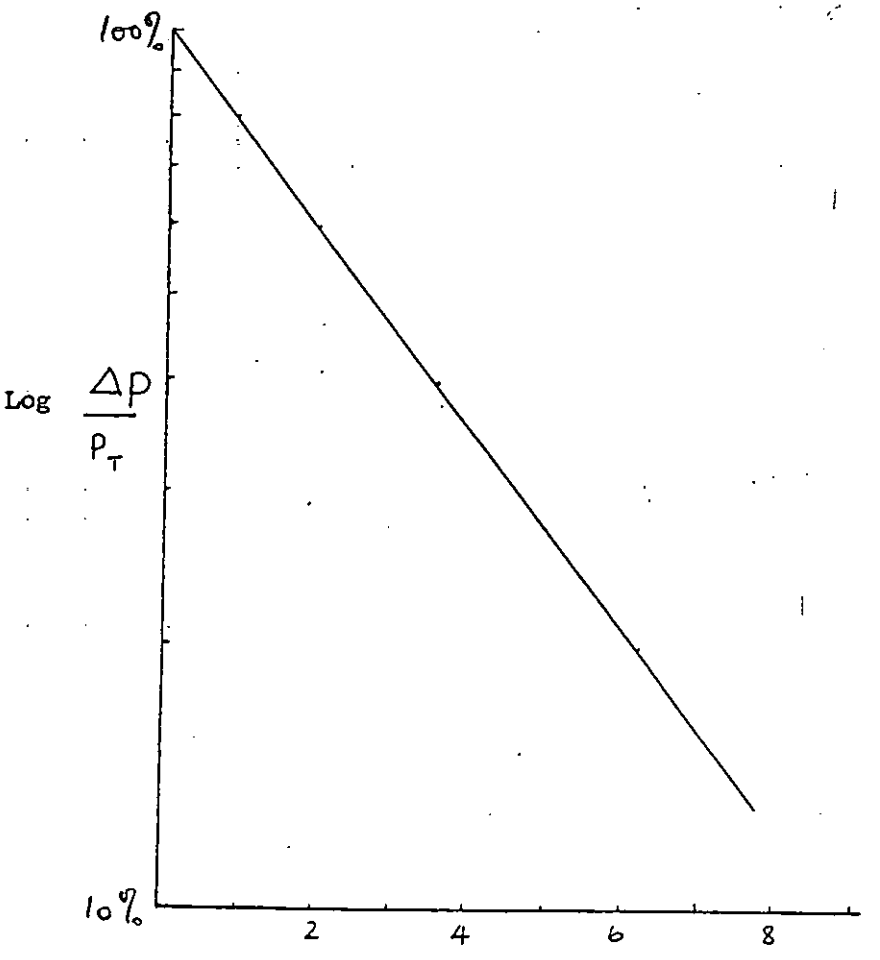
breakthrough. This was accomplished by measuring the rate of falloff in pressure in the filter cylinder and then relating the pressure drop to the gas outflow. The fall off of pressure from the filtration value to the controlled flow value generally took 30-40 seconds but was much less for very thin cakes. Because of this rapid rate of pressure loss as compared to the scanning time of every 10 seconds relatively few data points were obtained for each run. Therefore, to gain a better assessment of the value of pressure loss a composite curve was constructed for each of the experimental classes. From this curve it was found that experimental data gave a roughly log-linear fall off in pressure as indicated in Fig. 5.2.3.2.. Using this relationship the initial rate of fall of pressure was calculated and from the known dimensions of the filter cell this was converted into a gas flowrate as indicated in Eqn. 5.2.3.1..

$$\frac{dV}{dt} = -\frac{aV_T}{P_A}\left(P_F - P_D\right) e^{-at} \qquad \text{Eqn. 5.2.3.1..}$$

Having calculated the initial gas flowrate for each of the experimental classes where a composite curve could be constructed a plot of these values against the intercept saturation was made. The points plotted, as indicated on Fig. 5.2.3.3., fall roughly on a straight line. As with other attempts at obtaining correlation the results for Hyflo-Supercel are more scattered that the corresponding results for HPF5. The point plotted for the thin cakes of HFP5, however, does show a marked deviation for the straight line correlation. This may well mark the breakdown of this technique for thin cakes or at high initial gas flowrates.

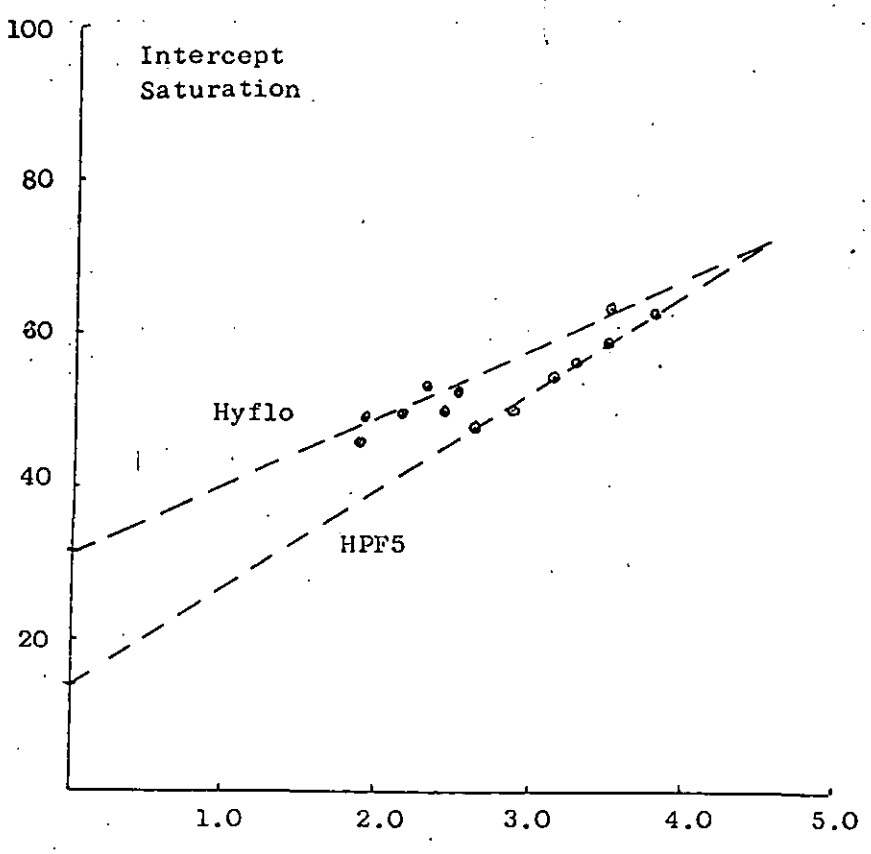
The saturation values at zero flow obtained from Fig. 5.2.3.3. show a considerably higher saturation for

FIGURE 5.2.3.2.



Pressure loss on gas breakthrough

FIGURE 5.2.3.3.



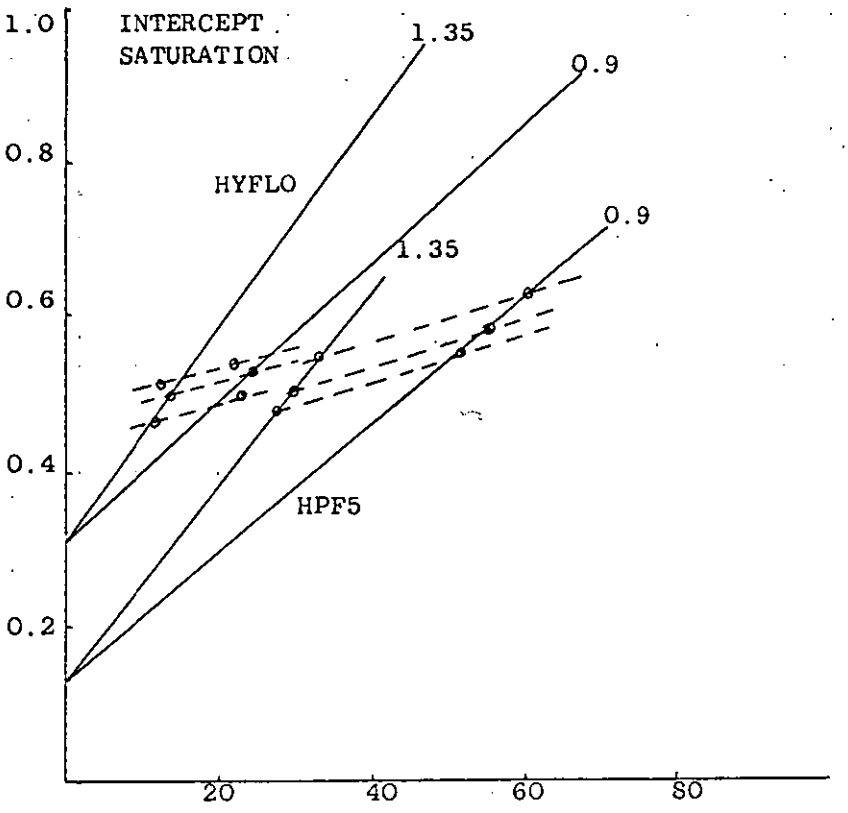
Initial Superficial velocity correlation

the Hyflo-Supercel than for the HPF5. The significance of zero gas flowrate is that it corresponds to displacement under near equilibrium conditions. Therefore, it is suggested that the value of saturation found by extrapolation to zero flow corresponds in some way to the residual saturation obtained in capillary pressure tests. The nature of such a relationship may possibly be determined by more detailed experimentation on a wide range of solids. Considering the two solids used in the majority of experimental tests a much higher saturation at zero flow is obtained for Hyflo-Supercel.

Having examined the results of the correlation closely it was decided to attempt a further development by recalculating the data points in terms of the void volume displacement rate. Fig. 5.2.3.4. shows the resultant graph. The three full lines reflect the correlation already developed with each line now representing a specific cake depth. The broken lines drawn in show an interesting characteristic of this plot. For the HPF5 test dust the experimental points corresponding to the sum controlled gas flowrates appear to follow lines which parallel each other through the points of varying cake depth. It is suggested that these parallel lines represent a characteristic of the overall system which determines the range of initial gas displacement rates which can be obtained for a given cloth and cloth support system. The cloth and cloth support system is believed to be the main factor which modifies the pressure, flow and permeability relationships of the filter cake thereby affecting its deliquoring characteristics.

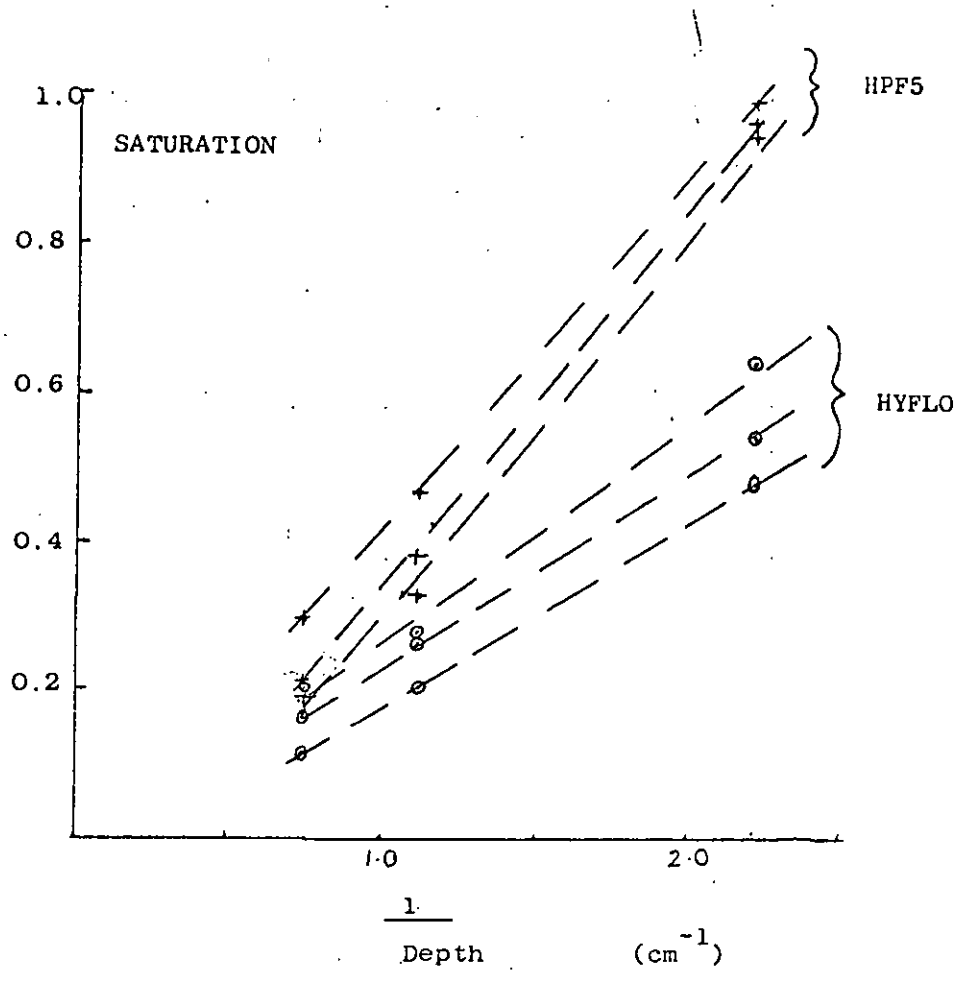
As a further test of this step in the correlating procedure a graph of intercept saturation against the reciprocal cake depth was plotted as shown in Fig. 5.2.3.5.. It can be seen that three distinct

FIGURE 5.2.3.4.



Void Volume Displacement Rate Correlation

FIGURE 5.2.3.5.



lines are present, one for each controlled gas flowrate used. This off setting over a range of gas flowrates may be due to one of two factors. Firstly, the effect of the controlled flow over the first few minutes of deliquoring may be to reduce the intercept saturation. Secondly, the initial inflow into the cylinder at the end of the filtration cycle, although assumed to be equal to the end filtration rate, may also need to be adjusted to allow for the immediate response of the air supply system to the size of signal received. The size of signal is, of course, dependent upon the eventual control level sought.

It is the first of these factors which would tend to reduce the intercept values for higher gas flowrate but it must still be noted that it is the cake depth which is by far the more important of the variables over this stage of the deliquoring cycle. Using the nine points available as indicated on Fig. 5.2.3.5. a curve fitting exercise identical to that used in establishing the basis for these correlations was carried out. The power obtained for this curve fit was 1.9 as shown in Appendix E. The value 2.0 represents the straight line plot as assumed from Fig. 5.2.3.5.. This coincides with the extension of the correlation from consideration of gas flowrate to the rate of void volume displacement.

The preceding development of a correlation for continuous flow deliquoring is a simplified form which has brought into consideration the variables of cake depth and gas flowrate. Brief reference has also been made to the filter cloth characteristics. The correlating technique is intended to be simple at this stage. Several refinements will be suggested to improve the accuracy of prediction

later in this chapter. Having defined the structure of the correlation it is now intended to look at the further tests carried out at varying viscosities, at the tests on the third solid and the tests in which humidity measurements were taken.

5.2.4. Viscosity

A total of twelve experimental tests were carried out at two different viscosities using the HPF5 test dust. The sugar solution used gave relative viscosities to the distilled water of 1.47 and 1.65. The number of tests carried out was insufficient to be able to fully determine the nature of the relationship between the extent of deliquoring and the wetting phase viscosity. However, as a general rule over the initial stages of the deliquoring it was found that an increase in viscosity was beneficial. In all cases studied for deliquoring over a period of 15 minutes the greater the viscosity the greater was the reduction in saturation obtained.

The explanation for this somewhat unexpected result is thought again to lie in the consideration of the initial deliquoring conditions. By increasing the viscosity of the wetting phase one consequence is the reduction in the initial gas flowrate which on the basis of the correlation already developed would have the effect of reducing the intercept saturation. The construction of the time-saturation profile required to obtain the deliquoring rate and intercept saturations could not be completed due to the limitations on the number of experiments carried out. However, it is possible to draw some conclusion from the data available. The fall off in pressure at the end of the filtration cycle is noticably slower with increasing viscosity. The total effect of an increase in relative viscosity to 1.65 is less than the effect of increasing cake depth from 0.45 cm to 0.9 cm but for cakes increasing from

0.9 to 1.35 cm the reduction in intercept saturation is of the same order as the reduction obtained in increasing the viscosity by the factor of 1.65.

This would suggest that a good initial estimate of the effect of changing the wetting phase viscosity was that the result of doubling the viscosity would be much the same as doubling the cake depth in terms of the change in the intercept saturation. In order to fully determine the effects of changing viscosity further tests would be required. The experiments carried out so far have indicated a tentative relationship. It is possible on the basis of these experiments to be much more specific about the requirements of a future investigation.

5.2.5. Anthracite Test Material.

The filter cake formed by the anthracite test material has a porosity which falls between that of the other test materials used. However, the permeability of this filter cake is considerably higher. Due to this higher cake permeability the rate of fall of pressure at the end of the filtration cycle is very rapid. The implication from the correlating method already developed of this rapid pressure loss is that the initial reduction in saturation as represented by the intercept saturation will be much less than for the other two materials. This deduction is supported by the results obtained as indicated in Appendix D.

Again the time scale of pressure measurements is not in the correct range to be able to construct an accurate pressure profile over the first 20-30 seconds of the deliquoring cycle. It is only by noting that fall off of pressure is rapid and by considering the actual saturations obtained that assessment of the deliquoring

characteristics of this material can be made.

The saturations have been estimated from the results obtained. These values indicate that virtually no deliquoring is attributable to the initial conditions until the cake depth increases to 1.25 cms. However, from the two values calculated for the constant rate deliquoring regime the correlation would appear to still be valid because the result of using the correlation tends to unify the values calculated. The experimental variations are, as with the other materials, large and therefore no further clarification of the correlation can be obtained on the basis of present data.

5.2.6. Humidity Tests

Three tests were carried out under varying conditions of solid,gas flowrate and cake depth to find out how much mass transfer occured in the test equipment and to test for drying from the filter cake. The inlet humidity of the gas was retained at a constant level, as for all tests, by use of a silica gel tower. This did not completely dry the air. During the humidity tests the outlet humidity was measured at intervals of five minutes by the use of a wet and dry bulb thermometer. The increase in moisture content of the air at outlet was calculated. An example of the humidity test results is given in Table 5.2.6.1..

It was found that in all cases the take up of moisture exceeded the rate deliquoring of the filter cake during the period correlated as "straight line" deliquoring. The reasons for this cannot be fully determined but the main point to be considered is the point at which the mass transfer occurs. The moisture takeup in excess of the level of deliquoring attained can be accounted for by assuming some drying of the sides of the filter cell or by evaporation

Humidity of air at inlet = 30% = 0.005 lb/lb

Time	Air Satn	Humidity lb/lb
2	85	0.013
5	85	"
10	85	"
15	80	0.012
30	80	"
45	75	0.0115
60	70	0.011
75	70	"

0.45 cm cake deliquored at 20 l/min. HPF5 solid.

Final saturation of 0.5705

Table 5.2.6.1. Humidity Tests

of the moisture once it has flowed out of the cake and is held on the support media apart from the possibility of mass transfer occuring in the cake itself. It is believed that each of these factors contributes to the final humidity of the gas. The fact that humidity falls off while the deliquoring rate remains constant would suggest that the first two regimes of drying gradually contribute less if all the cake deliquoring is attributed to mass transfer. On the other hand it may be that the flow of moisture from the cake to the support media is maintaining this source of evaporation.

With the equipment available it is not possible to detect the points of evaporation but by consideration of the filter cake in terms of the variables which would effect evaporation rate it would appear that this is the part of the system in which the evaporation is most likely to occur. This assumption is based on the consideration of surface area which is far larger within the filter cake.

A final point that was noted in the humidity tests was that over the extended deliquoring periods used the deliquoring rate appeared to increase. As with other tests the overall deliquoring rate for the straight line period was calculated and for all humidity tests this was found to be considerably higher that the values calculated for the shorter test runs. The reason for this is not known. It is possible that reducing the saturations through the levels being considered opens more of the cake to film flow or that, as the moisture film thickness in the cake is reduced, the area which is open to mass transfer is increased. The important fact is that over the time scale being considered deliquoring rates may, if anything, be slightly underestimated.

5.2.7 Further Experiments.

The remaining experiments carried out under continuous gas flow conditions consisted of the tests used in developing the experimental apparatus and procedures together with a small number of tests where thin cakes were formed. The experiments on thin cakes confirmed the form of correlation previously discussed. However, it should be noted that for very thin cakes the intercept saturations predicted exceeded the maximum i.e. a completely saturated cake. It is felt that below a certain cake thickness the full structure of the filter cake is not established thus causing a breakdown in the deliquoring regimes. Another possible explanation is that the deligniation between the two regimes has not been properly defined for this lower range of cake depths.

The tests carried out in developing the equipment and procedures consisted mainly of tests with a second filter cloth under various filtration conditions. The nylon and terylene cloths used in early tests had lower permeability and blinded more quickly than the metal cloths. They also gave quicker, more extensive deliquoring. It is believed that the permeability of the cloth is a significant factor in determining the intercept saturation. The few experiments that can be used in comparison with the main set of tests show lower saturations throughout. Furthermore, the experiments carried out with an old cloth, on its second or third run and considerably reduced in permeability, exhibited an even larger initial reduction in saturation.

Having described the outcome of the experimental programme and the subsequent correlation development it is now intended to look at the theoretical aspects of the filter cake deliquoring. The theory developed will not necessarily coincide with the

correlation proposed at this stage as the correlation is intended as a method of attaining a best possible estimate of the deliquoring characteristics of the filter cake while the theory is intended to reflect the mechanisms which are acting in the deliquoring process.

5.3 Continuous Deliquoring Theory

The correlation developed in section 5.2 has given considerable insight into the factors of importance in deliquoring filter cakes. A significant fact in this investigation has been that considerable constraints have been placed on various parameters so that operations coincide as much as possible with those prevailing in industrial situations. This, in particular, applied to the volume of gas consumed in the deliquoring operation. As when developing the experimental programme, and later the correlating technique, the theory proposed must be broadly based on the area in which industrial operations are carried out. In this case the conditions attainable are far from those which would ideally be sought for the most rapid or the most extensive saturation reduction. It is intended to propose a theory on the basis of the observed filter cake deliquoring characteristics in an attempt to visualise the route of the deliquoring operation.

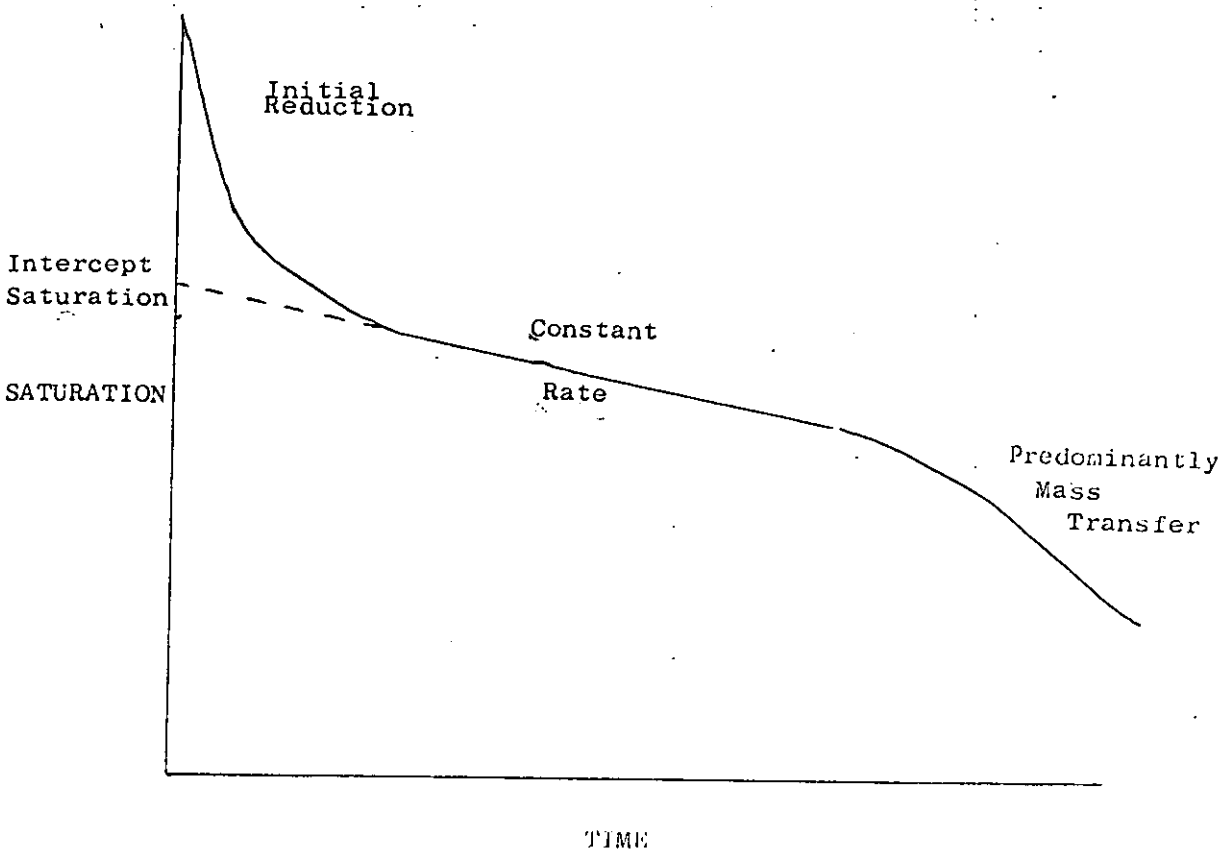
It has been indicated that a slow displacement of the wetting phase from the point of 100% saturation to the point of gas breaking through the bottom surface of the cake enhances the initial reduction is saturation obtained. Although not immediate this initial reduction would appear to be developed in the first 2 to 10 minutes of deliquoring. Over the next period of time deliquoring appears to follow a straight line relationship. However, some trends towards

an exponential rate of deliquoring have been detected. A limited number of runs over longer periods have suggested that later in the deliquoring cycle deliquoring rates would tend to increase again. These trends in deliquoring indicate a saturation-time profile of the form shown in Fig. 5.3.1.1.. Can this profile be supported and explained ?

The conditions under which gas breakthrough occurs have been shown to be of considerable importance in determining the level of saturation initially obtained. On reaching the top surface of the filter cake the wetting phase boundary with the gas phase will begin to extend into the pores. The experimental evidence shows that it is the speed of advance of the boundary which is of most importance. The faster the advance the smaller the initial reduction obtained. The theory of oil reservoir engineering (44) indicates that rapid displacement can cause instability in the boundary between the two phases causing more rapid advance in the slightly larger pores. It is on this fact that the theory of this first stage will be based. However, for a fuller explanation the structure of the cake and the mode of advance of the boundary must be examined more closely.

At 100% saturation the boundary is at the surface of the filter cake. For all the cakes being considered the capillary drainage height is much greater that the cake thickness so that without a pressure differential being applied no desaturation would occur. As a differential pressure is applied the pores with largest diameters at the cake surface will begin to empty. If this process is slow i.e. the differential pressure is of the same order as the capillary pressure this emptying will cease if a constriction is reached where the capillary pressure is significantly larger. At the same time other pores across the cake will be emptying leaving a film of

FIGURE 5.3.1.1.



Proposed deliquoring Profile

moisture on the pore walls. This film will be dependent upon the surface characteristics of the solid and the interface properties of the solid, wetting phase and gas phase.

The picture so far has been of a boundary of moisture advancing at varying rates through pores of different shapes and, therefore, resistances. The flow is slowed or checked dependent upon constrictions. By the time the boundary reaches the filter cloth level in one pore others have also been emptied to a large extent. However, once breakthrough has occured and gas flow through one pore is established this flow detracts from the forces being applied to deliquor other pores. Pores near to being opened to flow at this stage would generally have sufficient flow momentum in the gas phase to complete the breakthrough. On the other hand as more pores are opened to flow the pressure differential rapidly decreases consequently stopping the flow in partially emptied pores. In some cases imbibition of wetting phase from the holdup on cloth and supports may even occur.

The pores opened to gas flow will be those exhibiting least resistance and, therefore, in general the larger pores. While some pores will be too fine to be deliquored at all others may be partially emptied before being isolated. This isolation can be defined as a condition in which insufficient pressure drop can be developed across a pore to cause the flow of its wetting phase. The initial saturation level reached is a measure of the range of pore sizes over which the necessary differential pressure has been attained to empty or partially empty that pore.

As already stated the faster the initial advance of gas through the filter cake the smaller is the initial saturation reduction and, consequently, the narrower the range of pore sizes opened to flow.

This would appear to be due to the increased instability of the advancing boundary. This instability can be defined as a condition in which the momentum forces existing in the larger pores are considerably greater than any resistance to flow to be encountered in those pores. Thus the displacement rate in the larger pores is relatively greater than for the slightly smaller pores. The breakthrough in the larger pores occurs more rapidly with a result that there is a faster fall off in pressure differential across other pores. The fall off in differential pressure again causes a slowing of the pore opening process but this occurs before such a wide range of pore sizes have been opened to flow. In this way a smaller initial reduction in saturation is obtained.

It will be seen in the consideration of intermittent deliquoring that the intercept saturation is not immediately attained on breakthrough but that this saturation level is reached after a period of several minutes. This suggests that breakthrough creates a condition under which drainage of the filter cake can proceed to the level of intercept saturation. There are several mechanisms by which this may occur. The first of these would be a continuation of the pore opening process. The extent of this would be dependent upon the overall level of pressure drop developed across the cake after breakthrough and more specifically on the pressure drop developed across the full or partially emptied pores. The second mechanism is thought to be one of film flow where the opened pores, still having wetted walls, are further desaturated. The rate of film flow is dependent upon the force applied to the film wetting phase by the central core of gas flowing through the pore. This will, of course, depend upon the friction between the two phases and the

gas flow conditions. This mechanism is analysed in great detail by Brownell and Katz (10, 11). A third mechanism possibly contributing to the desaturation at this stage is the drainage of pores into opened channels. This could be considered as a situation between the previous two mechanisms where both pressure drop conditions and gas flow assist in the movement of wetting phase from a pore connected to an open channel. A certain amount of mass transfer will occur at this stage but this is of minor importance.

The time period over which the intercept saturation is obtained has been estimated. It was found in analysing the results that there was a tendency towards curvature in the predicted straight lines particularly at low flows and high cake depth. The time period over which the curve fitting was attempted was similar for each class of results. Based on these facts it is proposed that the time taken to obtain equlibrium conditions for this first regime is dependent upon gas flow and cake depth. Both reduction in gas flowrate and increase in cake depth will have the effect of reducing the pressure drop developed across the cake. Apart from reducing the desaturation attainable this will reduce the rate of film flow and therefore extend the period over which this mechanism operates.

Having determined the intercept saturation through the consideration of the initial deliquoring conditions it has been shown that desaturation continues at an almost constant rate over the next 20-30 minutes. The two main mechanisms which can be proposed for this part of the cycle are those of continued film flow and an mass transfer. Each of these mechanisms would be individually

capable of maintaining a constant rate of deliquoring. However, it is felt more likely that the two mechanisms both contribute to the deliquoring. The means of distinguishing between the effects of the two mechanisms were not available during the experimental investigation.

Finally, it was noted that during extended periods of deliquoring the earlier estimates of deliquoring rate were considerably less than those actually obtained. It is felt that this is due to an increased rate of mass transfer in the filter cake. It is proposed that at the point where film flow can no longer be maintained and the thickness of films is decreasing the surface area of contact between the two phases increases allowing this increase in mass transfer rate. The surface area will also increase as pores are opened by evaporation of the contained moisture. This mechanism will later cause a slowing in the desaturation rate again once a maximum has been reached.

The mechanisms proposed for all stages of the deliquoring process are beleived to be those to which the majority of desaturation can be attributed. A further possible mechanism is the movement of droplets through the filter cake once they have been detached from the solid surface. However the gas velocity is such that this mechanism is not thought to contribute any significant momentum to the deliquoring operation.

5.4 Intermittent Deliquoring.

The aim of the intermittent deliquoring technique is to reduce the quantities of gas required to achieve a filter cake saturation of a predetermined level. The greater efficiency in gas usage is gained by improving the pressure conditions under which deliquoring

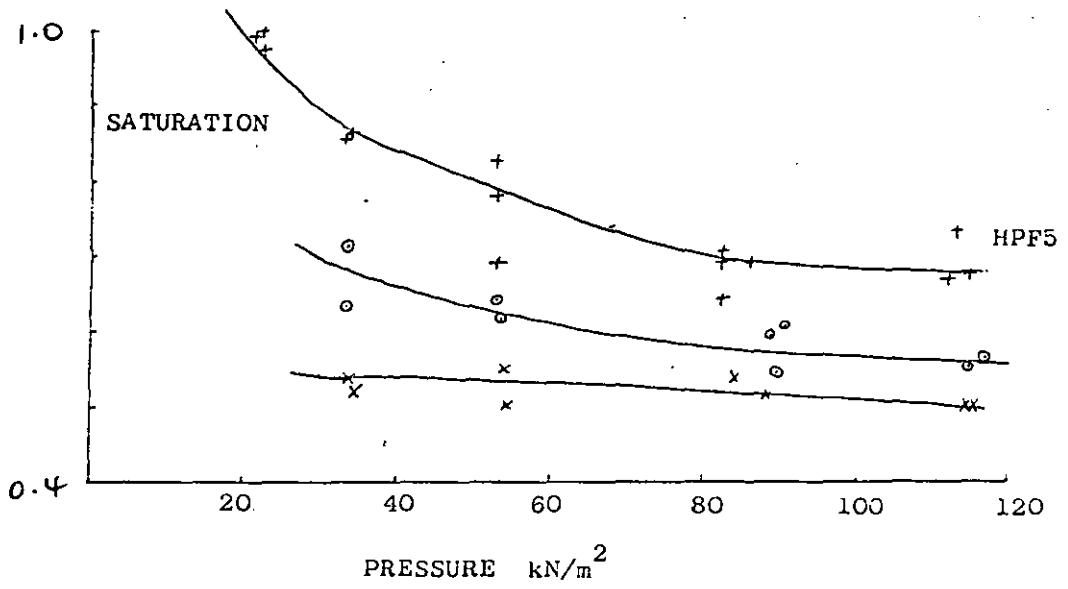
takes place while reducing the total time of gas flow by a considerable amount. The difference between this and normal deliquoring operations is that a high pressure drop is developed across the cake after the point at which two-phase flow is established in the cake.

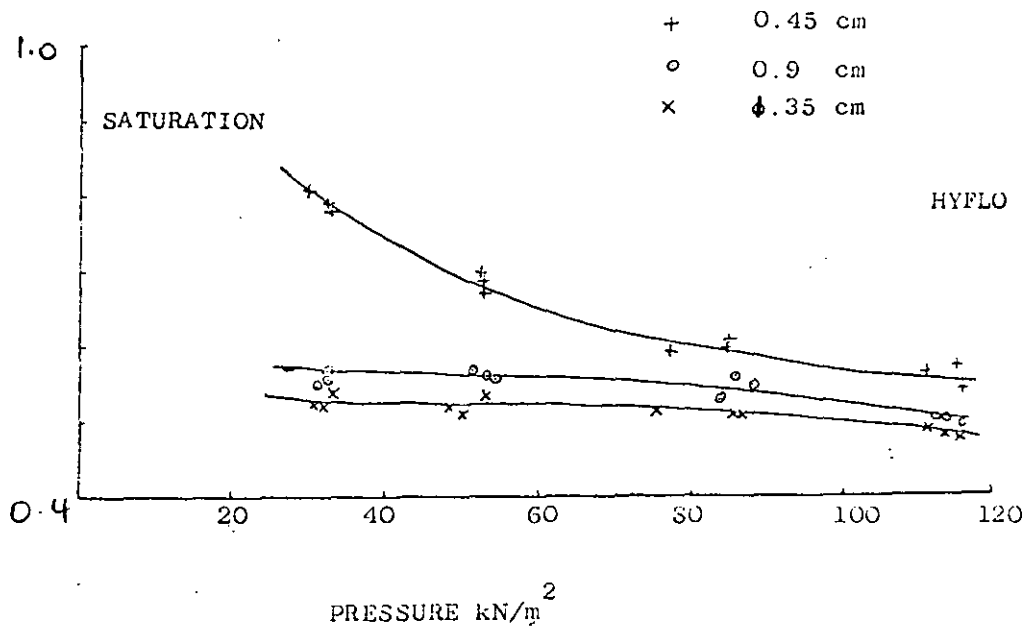
The saturation-pressure tests carried out are tabulated in Appendix B and the basic results in Appendix D. Fig. 5.4.1.1 shows these results graphically. The tests were carried out over a range of pressures upto the pressure used in the filtration cycle and the saturations obtained in this process were of the same order as the intercept saturation for filter cakes of the same depth formed under the same conditions. This level of saturation would not generally be attained until 5 minutes or more into the deliquoring cycle with the resultant greater consumption of gas. The time scale of the deliquoring operation is dependent upon the gas supply available as this will be determine the time required for repressurisation.

5.4.1. Experimental Reproducibility

The results of the intermittent flow tests, in contrast to the continuous flow tests, are more reproducible for the Hyflo-Supercel than for the HPF5 test dust. This is thought to be due to the differing nature of the two solids. The HPF5 having a more rounded particle form gives a less cohesive filter cake which is prone to damage under the changing pressure differentials. Cake damage can be defined as the alteration of the structure of the filter cake after the end of the filtration cycle and is characterised by excessively high permeabilities of the filter cakes under conditions of gas flow. On the other hand the varying particle shapes, which make up the Hyflo-Supercel, form a much stronger cake structure which is less likely to be damaged under the varying pressures. This view of the differing cake structures is supported by the time lapse

FIGURE 5.4.1.1.





Intermittent Deliquoring Results

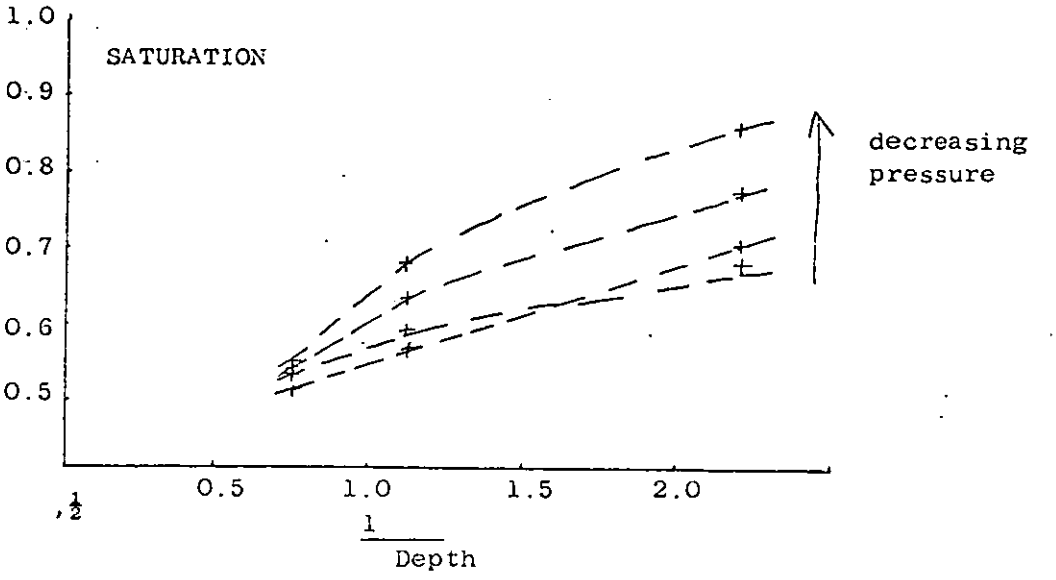
photography of the deliquoring cycle taken over a number of both continuous and intermittent tests. While during continuous tests little or no cracking was observed while gas flow was maintained an increasing amount of cake cracking was observed as the pressure of intermittent deliquoring was increased. However, it was at the point when the filter cake had no pressure differential across it that the surface cake cracks most frequently appeared. This would suggest that the cracking was a consequence of the loss of a positive pressure drop across the filter cake and therefore due to mechanical consideration related to the flexing of the filter cloth. In addition to this the reduction in saturation of the cake would bring with it a reduction in cake strength as the wetting-phase acts as a binding force.

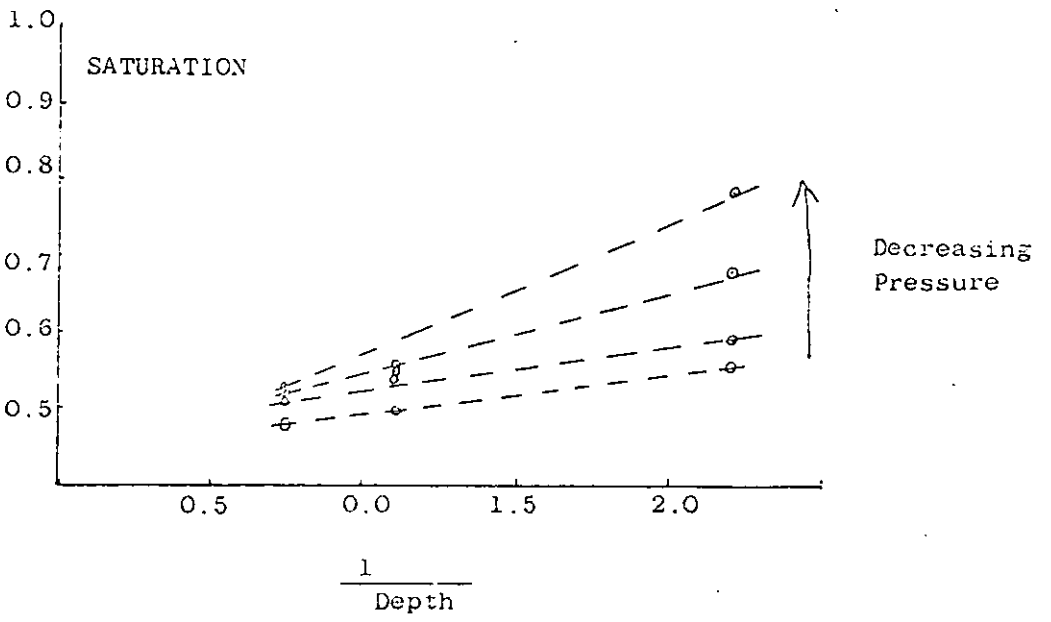
The filter cake cracks appeared to seal themselves on reapplication of the differential pressure. It can only be assumed that the original structure was virtually regained but that there would still be a channel larger than previously which would accomodate greater gas flowrate thus reducing the overall efficiency. Some individual frames from the time lapse photography were shown earlier in Fig. 2.11.1.2.

5.4.2. Saturation-Pressure Profile.

The general trends indicated by the experimental data are that the cake depth is again an important parameter. The increase in cake depth gives an increase in attainable saturation reduction. For the Hyflo-Supercel a similar treatment to that used in the continuous flow correlation was attempted. The saturation was plotted against the reciprocal depth as shown in Figure 5.4.2.1.. It can be seen that the curvature of the lines joining the data points varies from negative in two cases to slightly positive in the other cases. It would be the best

FIGURE 5.4.2.1.





Intermittent Deliquoring depth correlation

estimate to assume that this plot would give a strainght line if experimental variations could be removed.

Gas breakthrough of the filter cake occurs under the same conditions as for the filter cakes deliquored by the continuous flow technique and it is only after this stage that the operations diverge. Therefore, there are two specific parts to this operation and one aim of this analysis must be to determine the amount of desaturation attributable to each of the two sections. However, before attempting this analysis the overall trend of results must be observed.

Fig. 5.4.1.1. shows the plot of saturation versus pressure for the main group of experiments on both sets of solids. As with the continuous flow data a curve fitting exercise was attempted using the programme described in section 5.2.1.. The results of this curve fitting are indicated in Appendix E. It can be seen that the confidence interval for N'^{n} is at a minimum for the thin cakes and that the mean value of exponent for the two solids is approximately 3.6. On all other classes the exponents calculated had much greater confidence limits. There are two possible reasons for this increasing uncertainty in results. Firstly, the cake structure would appear to be more easily cracked the thicker the cake thus making the effectiveness of the pressure surges variable. This increasing damage for thicker cakes was indicated from observation of the cake and from the time-lapse photography carried out. Whether this is also a function of saturation has not been determined. Secondly, one section of the experimental procedure used may introduce errors in the experiments.

The section of procedure referred to is the short period of constant rate gas flow used in an attempt to determine the non-wetting phase permeability of the deliquored cake. Overall this measurement succeeded in showing that the structure of the cake was damaged during

the intermittent deliquoring operation. The non-wetting phase permeability was generally calculated to be greater than the permeability of a dry cake indicating a difference in cake structure from the cake deliquored slowly using the continuous flow technique. However, in addition to this the continuous flow period may contribute to the deliquoring of the cake even though a minimal amount of gas is used. This is evident particularly in the thicker cakes when low deliquoring pressure has been used.

No overall relationship for the individual saturation pressure profiles has been determined and the experimental variations are such that the curve fitting does not clarify the exact trends of the data. However, a relationship between the different cake depths has already been proposed and this relationship is of the same nature as the saturation-depth relationship for continuous flow tests. This leads to the suggestion that there may be some further comparison to be drawn between the two deliquoring operations.

The first step in this comparison was to examine the pressures at which the continuous flow intercept saturations would be obtained during the intermittent deliquoring operations of comparable cake classes. A trend has been observed in these values and is indicated in Table 5.4.2.1.. This shows that in general the pressure required in intermittent deliquoring surges to obtain the comparative saturation for continuous flow is in direct ratio to the depth of cake. It would appear that it may then be the pressure drop per unit depth which determines the extent to which the intercept saturation is approached or the extent to which the saturation level obtained falls below this value.

HPF5

Intercept Saturation	Cake Depth	Pressure Reqd. kN/m^2
0.893	0.45	27
0.880	0.45	28
0.872	0.45	31
0.633	0.9	29
0.587	0.9	90
0.565	0.9	85
0.547	1.35	54
0.505	1.35	110
0.483	1.35	145

Table 5.4.2.1. Continuous - Intermittent Comparison.

Table 5.4.2.1. (continued).

HYFLO-SUPERCEL

Intercept Saturation	Cake Depth	Pressure kN/m^2
0.715	0.45	47.5
0.670	0.45	59
0.639	0.45	69
0.538	0.9	78
0.527	0.9	88
0.501	0.9	108
0.500	1.35	75
0.498	1.35	92
0.458	1.35	163

5.4.3. Viscosity

During the viscosity tests carried out using the continuous flow technique one test was completed on the intermittent flow technique. This was carried out at a pressure developed in the filter cell of 80 kN/m^2 on a HPF5 test dust cake of 0.9 cm. in depth. The relative viscosity compared to the other intermittent tests was 1.65. The saturation obtained in this test is below the level of saturation obtained in any of the other HPF5 test dust intermittent experiments. The value also falls below the saturations obtained in continuous flow tests at this higher viscosity. On the basis of the correlation developed for continuous flow in relation to viscosities an estimate of the expected saturation has been made. This has been done by extrapolating on the basis of cake depth assuming that the effects of the two variables were comparable as for the continuous flow correlation. The saturation obtained by extrapolation was in the region 50-52% while the test gave a saturation of 47%. Even when considering the possible experimental error this difference seems exceptionally large. Therefore, it is believed that some further mechanism may be operating and that in the case of intermittent deliquoring increasing of viscosity has a benefit to deliquoring greater than that of increasing cake depth.

5.4.4. Surge Repetition

Several tests were carried out where the number of surges were varied from the normal two surges at near identical pressures. When one or three surges were attempted no significant change in saturation was noted. The final saturation level would, therefore, appear to be attained after a single surge. This observation was supported by the fact that a smaller experimental error was found in correlating the saturations to the first surge pressure as opposed to a maximum or subsequent surge pressure. It is for this reason that

the pressures tabulted in Appendix D are the initial surge pressures for each experiment.

5.5 Intermittent Deliquoring Theory

The intermittent flow technique of filter cake deliquoring is characterised by short bursts of air flow during which a high pressure drop is developed across the cake. The main variables to be considered are cake depth, surge pressure and wetting phase viscosity. A further factor of importance would appear to be the cake strength.

The condition of the filter cake on gas breakthrough will be identical to that of a cake to be deliquored by the continuous flow technique as procedures have not yet diverged. However, at this point the pressure is allowed to fall off with no air being supplied. It is believed that this may be an initial cause of cake damage as it was at this stage that cracks appeared in the filter cake surface and were recorded by time lapse photography. The saturation at this stage of the operation has been reduced only slightly but it is the distribution of the opened or partially opened pores which is believed to be of great importance in determining future deliquoring characteristics.

Once the pressure in the filter cylinder has been raised to the required level it is released by flow through the cake. On commencing flow a large pressure drop is developed across the cake. During the time no pressure differential has been applied some rearrangement of the wetting phase may have occured by film flow in partially opened pores. This will, in general, increase the resistance to flow through these pores. Thus on reapplication of a pressure differential all pores will again have a large pressure drop developed across them. In the case of most partially opened pores this will be sufficient to effect considerable further deliquoring while pores previously unaffected could now be opened to flow due to the pressure drop developed across them. The extent of

the deliquoring at this stage will be dependent upon the pressure used and upon the condition of the filter cake just prior to the surge. This condition is controlled by the initial gas breakthrough characteristics as in the continuous flow technique and, therefore, it is believed that a considerable amount of the experimental variation can be attributed to this initial condition.

The second important factor is that of cake damage. The greater the damage and, therefore, the unused pressure of a surge the less the cake will be deliquored. The filter cake is thought to be extensively damaged during gas surges such that further surges at the same pressure will prove ineffective. However, a higher pressure may be effective if allowance is made for the amount of effective damage caused by preceeding surges. Also if cake damage could be reduced or avoided further surges may be of benefit.

The single test on viscosity variations showed a lower than expected saturation level being reached. It has been assumed that, as when considering cake depth, part of the variation during intermittent deliquoring is attributable to the pre-surge condition of the filter cake. If a further relationship for viscosity does exist it is thought that this must be of the same nature as that assumed in the initial breakthrough stage.

Having looked at a proposed theory for the intermittent deliquoring technique a considerable number of comparisons have been drawn between that and continuous flow. In the two technuques there would appear to be two extremes, one of large air volumes and another of high pressure drop. It is, therefore, reasonable to assume that some optimum condition may exist.

5.6. Optimum Operation of Deliquoring.

It has been suggested in the previous section that some optimum condition for deliquoring may exist between the two techniques discussed. If this is so what factors influence the determination of the optimum and can the optimum be accurately assessed ? As stated earlier the conditions under which the deliquoring can be carried out are restricted by other parts of the process and overall process efficiency. Therefore, a generally applicable optimum cannot be stated; on the other hand for a specific operation a particular optimum may be obtained.

The damage to the filter cake during intermittent deliquoring is the main constraint on this technique but this may be reduced by maintaining a certain level of pressure drop across the filter cake. (The actual level is unknown but could be as little as $10kN/m^2$). This would be possible as the initial breakthrough is the important factor as opposed to the total flow during this part of the operation. The pressurisation to the surge level could therefore be commenced well before the pressure level in the filter cell had fallen too low. The pressure to which the filter cell is raised is the second important factor and this again could be determined by checking the damage incurred by permeability measurements on the deliquored cake. The best condition here would be one of minimum damage to the cake structure. At the same time it is important that the repressurisation does not take an excessive period as some of the advantages of intermittent deliquoring would be lost.

Multiple surges to deliquor a filter cake are not thought to be either efficient or practicable as the amounts of desaturation obtained falls rapidly with each surge. At the point where the first surge is

instituted it is proposed that the continuous flow technique should begin to be employed not allowing the pressure drop across the cake to be completely lost. The level of air flow during the continuous flow period would be calculated by reference to the analysis of those results earlier in this chapter. However, in some cases it will be found that to obtain a sufficiently low level of saturation no continuous flow regime will be required.

The requirements of equipment and operational procedures in the optimisation of the complete deliquoring operation will be discussed in Chapter 7.

5.7 Comparison of Solids

Having succeeded in finding a correlation for each of the two test materials individually some attempt should now be made to obtain a correlation which will cover a variety of materials. This may prove difficult as the correlation consisting of two regimes may not be applicable to some solids over the time scale of deliquoring envisaged. Only by experimentation will it be possible to determine the time scale of the initial regime. Considering the two materials used in the majority of tests a simple extension to the correlating factor for the "straight line" deliquoring period has proved to give suprisingly good agreement between the two solids. This extension is the inclusion of the porosity of the cake in the correlating factor given as Eqn. 5.2.2.3.. This gives a new factor which takes the form:-

$$-\frac{\Delta S}{\Delta t_s} \times \frac{A.L}{Q^2} \times \epsilon^2 = k_s \qquad \text{Eqn. 5.7.1.1.}$$

The mean values of the constant obtained for the two solids were 1.131×10^{-8} and 1.348×10^{-8} (sec. cm^{-1}). for Hyflo-Supercel and HPF5 respectively. These means again exclude the tests at flow of

20 l/min. The validity of this correlating factor can not be established without further experimental investigations.

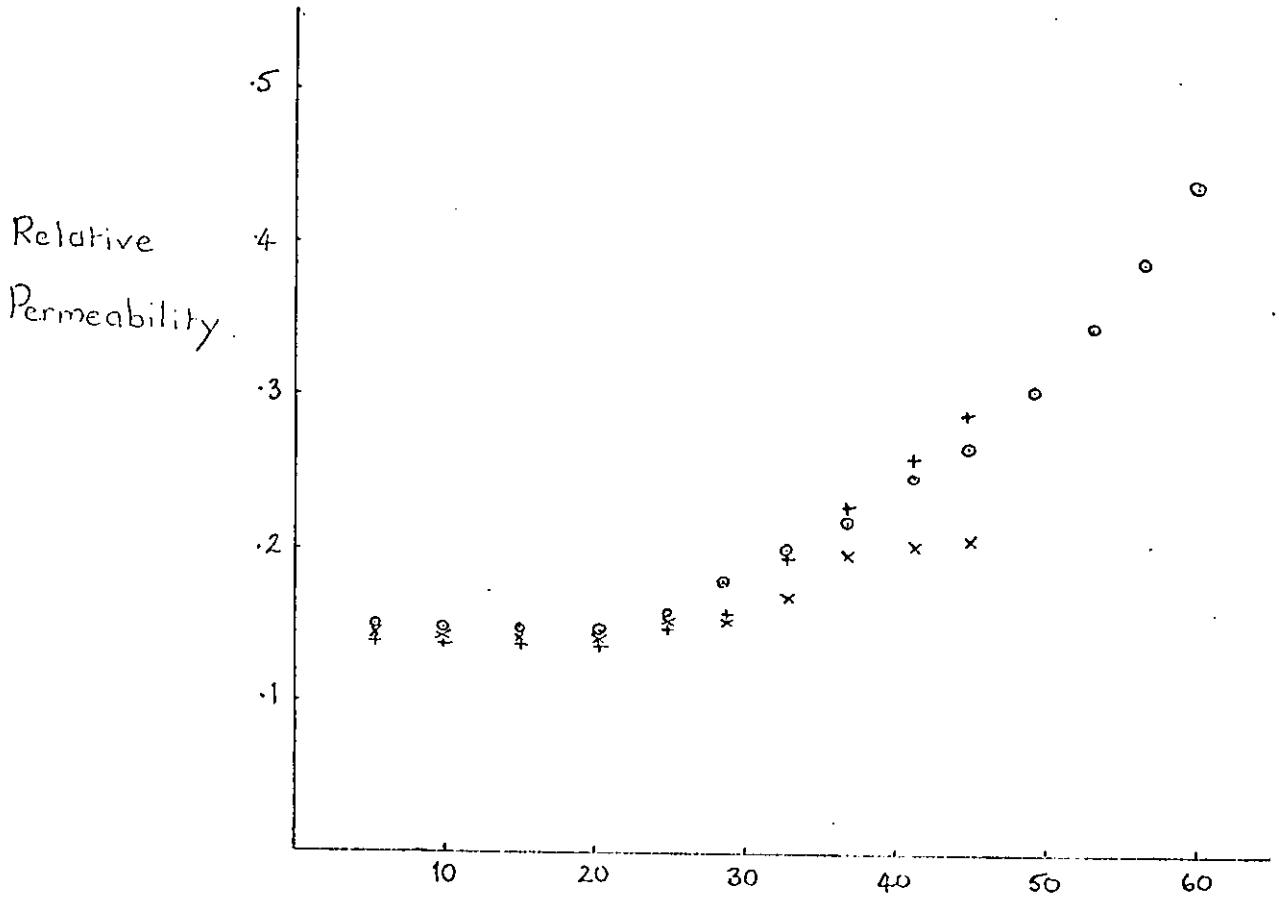
The second part of the comparison is that of the intercept saturation calculated for the two solids. The relationship between solids in this case would apprear to be far more complex. The third solid results may help to indicate the trends. The factors which are believed to be of greatest importance are the cake porosity and the initial gas flowrate obtained. The second of these will, furthermore, depend on both the filter cloth and support resistance and the permeability of the cake itself. The actual relationship can not be obtained on the basis of the available data.

5.8. Further Calculations

During attempts at correlation of data several basic quantities were calculated from the experimental tests. These calculations included the relative permeability of the filter cakes throughout the period of deliquoring. A typical relative permeability profile for a filter cake is shown in Figure 5.8.1.1.. As can be seen the relative permeability of the filter cake remains virtually constant over the first twenty to thirty minutes of the deliquoring operation before climbing steadily. The gradient of this portion of the relative permeability versus time graph is dependent on the cake depth and the gas flowrate. Over the initial period of the deliquoring operation relative permeability remains almost constant, and therefore, correlation of this parameter with saturation is not practicable.

The correlating factors developed by other workers on this subject have been calculated and the details of this investigation are described in Chapter 6.

Fig. 5.8.1.1.



Variations in Relative Permeability with Time.

CHAPTER 6

State of the Art

6.1 Introduction

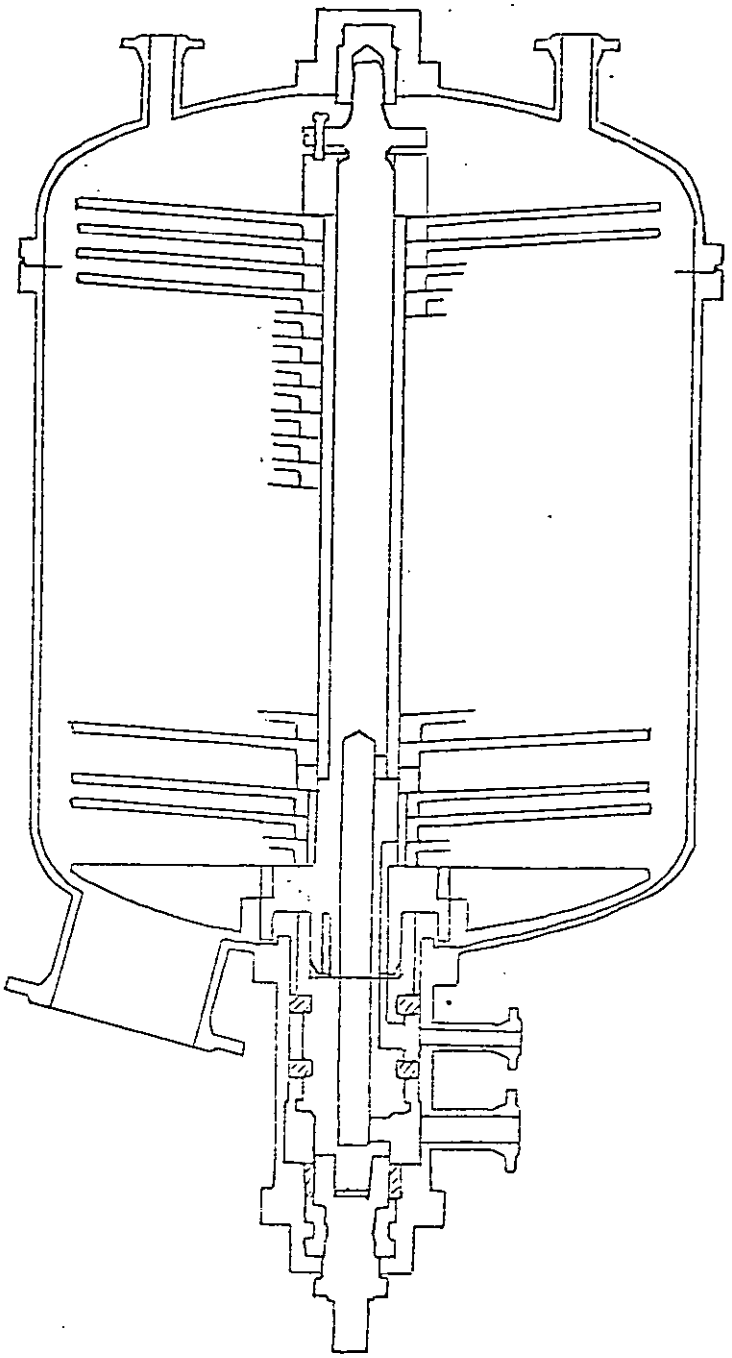
This chapter discusses the extent to which the deliquoring cycle of the filtration operation in pressure filters has been developed in industrial applications. It will be shown that on the industrial sites examined no attempt has been made to measure the volumes of gas consumed. Furthermore, measurements of the final saturations of cakes are not generally taken but a purely qualitative assessment of the cake and its performance during discharge is made.

In a later section the correlations developed in previous work are discussed with reference to the experimental work carried out during this project. The comparison of the experimental work with correlations has not given a clear agreement between the results of this project and previous work. However, this will be explained in relation to the range of operating conditions being considered.

6.2 Industrial Practice

Three types of rotary discharge pressure filters which form the core of equipment to which this investigation can be applied directly are represented by the Funda, Schenk, and Udhe filters. The Udhe filter is shown in Figure 6.2.1.1.. Each is capable of dry discharge of filter cake after a period of gas flow through the filter cake. During an examination of industrial practice the filters available for the survey were exclusively of the Funda type. While a small filter was examined thoroughly and the cake observed in situ at the start and during the deliquoring operation larger filters were observed in operation on two industrial sites. The small filter was later loaned to the Chemical Engineering

FIGURE 6.2.1.1.



THE UDHE FILTER.

Department for use in some scale-up tests.

6.2.1. Filtration of carbon from plasticiser

A visit was made to Scott-Bader at Woolaston, Northamptonshire where activated carbon was used to remove impurities from a plasticiser. A single filter was being utilised to filter batches of the plasticiser. The operating temperature was initially 150°C-200°C and this dropped to 110°C-130°C during the deliquoring. The temperature of the wetting phase was felt by the operators to be an important factor in determining the extent of deliquoring attainable. Nevertheless, the filter had not been insulated.

Precoating of the filter was carried out once every three batches of plasticiser. This operation consisted of the circulation of 5 kgs of filter aid mixed into a small quantity of plasticiser. The quality of the precoat layer at the commencement of each filtration could only be assessed by observation of the pressure and flow at that point in the operation. Deterioration occured, as expected, with each run as blinding and damage to the precoat increased. 2-3 kgs of filter aid were also used as body feed and together with the solids already in the plasticiser it is expected that in general the precoat and main filter cake would have approximately equal depths.

During the first year of operation a considerable number of problems were encountered. However, on reduction of the filter area by approximately 45% a noticeable improvement in the discharge of filter cake was observed. The adjustment would have the effect of increasing the depth of filter cake formed. As seen in the previous chapter doubling the cake depth can have a considerable effect on the level of saturation reached during the initial moments of the deliquoring cycle.

A 50μm filter cloth has been used throughout the life of the filter and filtration took place at pressures in general increasing to 350 kN/m^2 at the end of the filtration cycle. Occasionaly pressures of 480-550 kN/m^2 were obtained. The filtration could take as little as 30 minutes but normally took 60-75 minutes. Rest volume filtration took 45 minutes and at the end of this period deliquoring was commenced at a pressure of 280 Kn/m^2. Nitrogen was used as the inert gas. It was supplied from the mains line which had a pressure of 280 kN/m^2 and was $\frac{1}{2}$" in diameter. No instrumentation was available for flow measurement. Over the deliquoring period which was generally 20 minutes (longer if time was available) the pressure in the filter cylinder fell to 35-48 kN/m^2.

Considerable problems occured over the initial period of operation of this filter. These problems were found to be related to the poor deliquoring of the filtercake leading to unsatisfactory discharge. The steps taken to remedy the problem were to increase filter cake depth and the frequency of renewal of the precoat. These measures are consistent with the experimental observations made in Chapter 5. Although the viscosity was felt to be of importance no direct evidence of the effects on the deliquoring operation alone was available.

6.2.2. Filtration of Mercury from Caustic Soda.

The second industrial visit made was to I.C.I. Mond Division at Runcorn to examine the Funda filters being used in the removal of Mercury from sodium hydroxide produced by electrolysis. Other impurities in the 50% NaOH included small quantities of carbon. It was required to reduce the mercury content from 20 ppm to

0.5 ppm. Seven filters have been commissioned since 1969 to be used in this operation.

The filtration and subsequent deliquoring operation used on this process varies considerably from the normally accepted operation of the filters. A technique known as "shuffling" has been employed which greatly increases the length of the filtration operation. The general outline of the operation was as follows:-

(i) Precoating using wood carbon

(ii) Filtration until limiting pressure drop is attained

(iii) Washing of the filter cake with hot water

(iv) Resultant increase in cake permeability

(v) Repeat of the filtration and washing stages

(vi) Progression to deliquoring when washing does not effect significant permeability increase.

(vii) Deliquoring for 30 -120 minutes depending on time available.

(viii)Cake discharge and recovery of mercury

The recurring filtration operation would last for approximately one week and prior to each wash cycle the heel was removed. The quantities of air consumed during the deliquoring were not not known. The air was supplied from the compressed air mains and pressure varied with demand in other parts of the plant. The quality of cake at discharge was unpredictable and this is thought to be due to the lack of information available on the condition of the filtercake just prior to the deliquoring. This condition will depend on a wide range of variables including the concentration of the mercury at each filtration stage and the effectiveness of each of the washing stages.

Two further observations made were that, firstly, the

filters were connected to a common outlet header and, secondly, the deliquoring improved slightly when an aged cloth was in use. The first of these observations points to the fact that the backpressure on each filter varied and was dependent on the operating condition of the other filters. The improved deliquoring observed on older filter cloths has been observed in the experimental work carried out. This would appear to be an effect of the decreasing permeability of the filter cloth leading to improved deliquoring conditions in the initial stages of the deliquoring cycle.

6.2.3. Manufacturers small scale rig.

The two industrial processes discussed have involved filters with a filter area of the order of 30 m^2. On a visit to Alfa-Laval a small filter with a filter area of 0.12m^2 was seen in operation. After the filtration cycle the filter was opened up at various stages of the cycle to observe the condition of the filter cake. At the commencement of the deliquoring of the filter cake the wetting phase is still evident at the surface of the filter cake and if disturbed some flow the the "slurry" may occur. However, once the filter cylinder has been pressurised to the final filtration, the usual procedure after filtration or removal of the heel, and gas flow has commenced the filter cake quickly assumes a much drier appearance. The gas used for the deliquoring was again supplied from the compressed air available and no direct measurement of gas consumption was made.

6.2.4. Scale-up tests.

The test equipment described in section 6.2.3. was loaned to the Department of Chemical Engineering for a period of

six weeks during 1979 so that a series of tests could be carried out by a pair of final year students, under the direction of the author. The aim of these tests was to compare the Funda filter with the experimental rig and to obtain a better idea of the problems involved with deliquoring on the specific filter equipment.

Problems found by the students in operating the filter meant that the results of the tests were inconclusive. Considerable instrumentation had been added to obtain the required data. Possibly the most important variable was found to be the conditions under which the deliquoring was commenced. The rate of deliquoring over the initial period of deliquoring was high in comparison to any subsequently obtained rate if a high initial pressure drop was developed.

Some conclusions can be drawn from the experimental work carried out. These are observations of a general nature made in an examination of the project report. The first of these observations is that the trend of results is similar to those trends observed in the main experimental work. Table 6.2.4.1. shows the comparisons obtained. However, the experimental procedures had not been sufficiently well developed so that experimental variations tended to be large. Secondly, by carrying out a deliquoring operation using the intermittent deliquoring technique it was again shown that a rapid reduction in saturation level could be obtained. A single pressure surge reduced the saturation level to that generally obtained after sustained air flow over a period of 10-15 minutes. Finally, a trend in saturations from plate to plate was observed during the tests. Considerable variation was observed over the five filter plates and the same trend persisted over a number of tests. The cake depth appeared tobe even across all plates. However, the plate second from the top

Experimental Class	Experimental Rig Saturation	Scale Up Comparative Saturation
HY5	47.4	50.0
HP4	55.3	54.1
HP-I2	56.0	65.2

Table 6.2.4.1. Comparison of Scale-Up Tests

was generally 2% or more lower in saturation than the other cakes. The lowest filter cake had the highest saturation once the problem of thin cakes on this plate had been solved. This particular fact in the deliquoring of large area of cake may be important and is worthy of further investigation. Preferential flow may accentuate ~~extenuate~~ the differences in saturation observed during the tests on the small scale equipment.

6.2.5. Conclusions

Examination of industrial practise has shown that little has been done to measure gas consumption or the saturations obtained during the deliquoring operation. Some modifications have been made to operations in order to obtain better discharge of the filter cake. These modifications can be said to agree with the correlation and theory developed in this project. Due to the lack of data on the industrial operations no detailed comparison could be made.

The small scale rig used in scale-up tests has given some data on deliquoring in Funda filters. With this limited amount of data it is evident that the same trends observed in the experimental programme may exist in the operation of the Funda filter.

6.3 Correlating Techniques

During the course of the project comparison of experimental results with correlation developed by previous workers in this field was developed. In general the comparisons carried out did not give close agreement between predictions and the experimental results. The correlations considered included the work of Brownell and coworkers, Dahlstrom and coworkers and Wakeman. During early tests no information was available on the wetting phase flowrate and,

therefore, comparisons depended on the individual values of gas flow, saturation and pressure drop measured during an experimental run. Once the full deliquoring profile was determined more detailed comparison could be attempted. The extent of agreement between results obtained and the correlations examined was insufficient to warrant use of the correlations as a basis for the design procedure being developed.

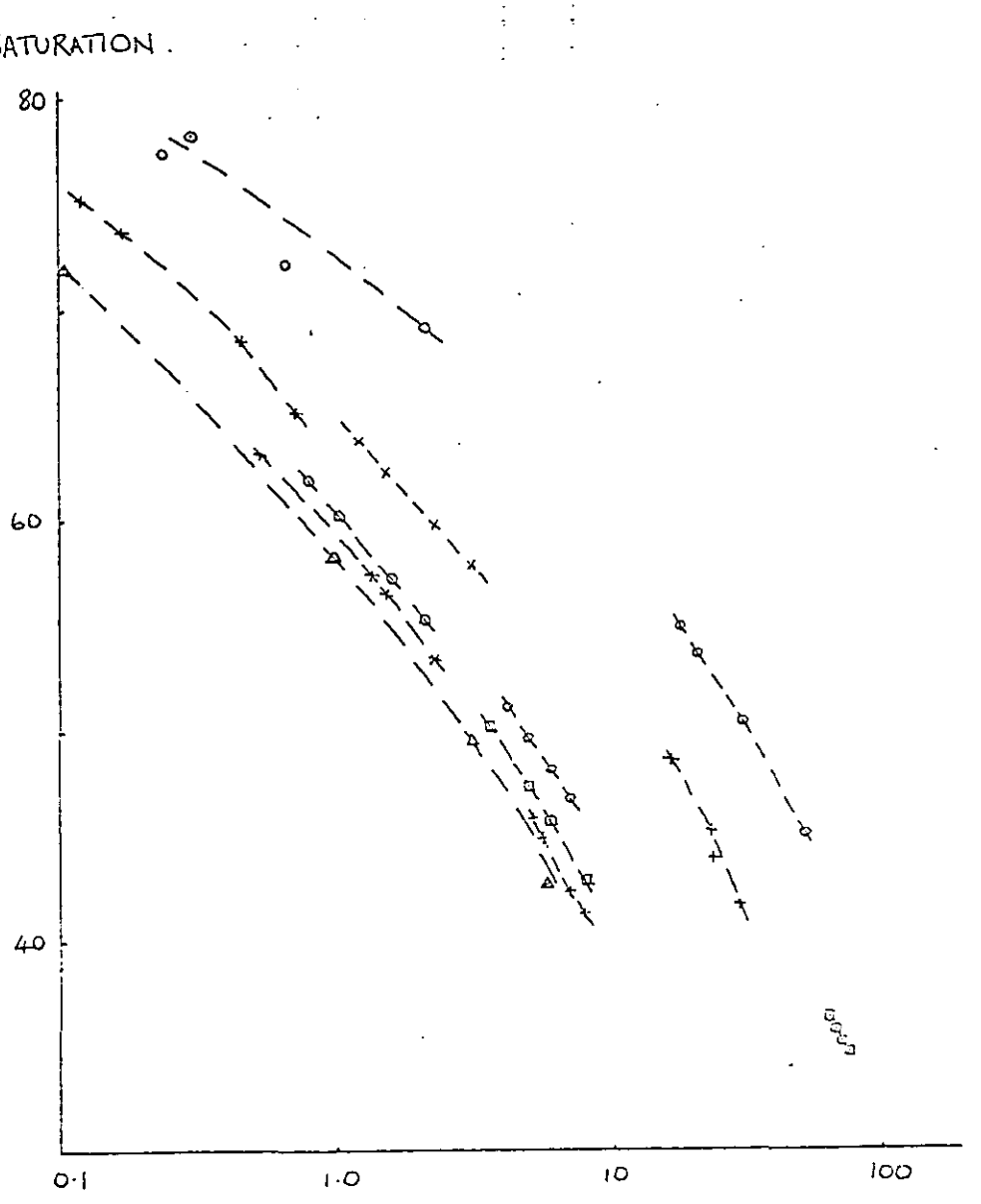
6.3.1 Brownell and Katz correlation

The results of the initial set of experiments carried out were used to calculate the gas and liquid velocities as predicted by the Brownell and Katz correlations. The correlating technique involves, as indicated in Chapter 1, the initial calculation of the residual saturation level. Values obtained for the residual saturation as calculated from the gas flows and pressure drop once constant flow had been establised varied widely from test to test. The general level of residual saturation was found to be 18% to 40%.

The main test of the correlation was the comparison of the actual and calculated gas and liquid flow rates. This comparison was carried out using an initial set of experiments not discussed in the main experimental programme. The conclusions drawn were that the gas and liquid flow rates could not be predicted with the necessary accuracy.

In predicting the gas flow it was found that use of the correlation could not give results consistent with the experimental procedures. As constant gas flow was being used at all saturation and pressure differentials the correlations should have predicted a constant gas flow. However, a distinct relationship was found between the level of saturation and the calculated gas flowrate. The nature of this relationship is indicated in Figure 6.3.1.1. An investigation

FIGURE 6.3.1.1.


% SATURATION.
80
60
40
0·1
1·0
10
100
GAS FLOW RATIO – CALCULATED / EXPERIMENTAL.

by final year students as part of equipment design tests had also indicated that the gas consumption could not be accurately predicted. On these tests the calculated gas consumption grossly underestimated the experimental flow.

Similarily, on calculating the liquid flowrate it was found that the values in no way reflected the actual rate of desaturation obtained in the experimental tests. The values throughout the desaturation period were underpredictions in the majority of tests carried out. The final year students in their examination of the correlating technique followed the route indicated by Brown et al (6) for calculation of the wetting phase velocity. However, attempts to calculate the velocity were unsuccessful as the correlation broke down before a result could be obtained.

Attempts were made to modify the correlation of Brownell and Katz so that a satisfactory agreement could be obtained between the calculated and experimental flow values. The modifications took the form of the insertion of modified exponents for effective saturation and reassessment of the values of wetted sphericity. Other random constant changes were made. While some of these steps improved the applicability of the correlation it was still felt that the Brownell and Katz correlation could not be used as a basis for the development of deliquoring relationships in this project.

6.3.2. Dahlstrom and Coworkers.

As with the correlations of Brownell and Katz a series of experiments were used to assess the applicability of the work of Dahlstrom and coworkers to the problem being considered. The two parameters considered by Dahlstrom and coworkers were the correlating factor as described in equation 6.3.2.1.

$$Vt \frac{\Delta P}{L} \frac{1}{\mu_w} = Fc \qquad \text{Eqn. 6.3.2.1.}$$

and the approach factor, equation 6.3.2.2.

$$\frac{t K \Delta P}{\epsilon L^2 \mu_w} = Fa \qquad \text{Eqn. 6.3.2.2.}$$

It was found that the runs carried out at varying depths and deliquoring times could not be correlated. The correlations take a similar form to those of Brownell and Katz in that two parameters were being considered. These were the attainable saturation level under the prevailing flow conditions and the rate at which this level was being approached. However, at different displacement conditions the nature of the displacement will vary changing the intermediate character of the filter cake. This character will vary considerably with cake depth. The condition of the filter cake at any time during deliquoring is a function of the deliquoring history of that filter cake.

Thus, considering the correlating factor, Eqn. 6.3.2.1, it can be seen that the pressure drop can be varied independently of the saturation and all the other system variables employed by varying the deliquoring history of the filter cake. This was found to be the case for the filter cakes deliquored to similar saturations by different "routes".

The correlation using the approach factor was to be applied by determining the value of that factor at which the equilibrium moisture content was reached. This equilibrium moisture as predicted by the correlation of the residual saturation was always considerably lower than the saturation levels reached and as with

the correlating factor a large scatter in results did not permit any graphical correlation to be obtained.

6.3.3. Wakeman

In the most recent paper on the subject of filter cake deliquoring by Wakeman (58), several worked examples of the correlating technique he had developed during his previous papers were given. Using these as a basis a range of the correlating factors were calculated to give values for the various intermediate steps through the correlation. In general it was found that the basic values measured lay outside the range of conditions envisaged by Wakeman in his work. This can most easily be seen in the particle sizes used. While in the majority of tests the mean particle diameter was below 30μm the experimental work of Wakeman was concernced with mean particle sizes from 50μm upto 200μm.

The values calculated from this correlation include the reduced cake saturation. Figure 1 of the Wakeman paper (58) was used to obtain predictions of reduced saturation at various dimensionless times and pressures. The reduced saturation obtained in every case underpredicted the reduced saturation obtained from direct calculation of the residual saturation. Furthermore, the dimensionless air flow rate calculated did not coincide with the graphical correlations supplied.

The pore size distribution index as described in chapter 1 was also calculated. The expected value of this index was in the range 3.0 to 6.5. However, the values obtained varied from 0.1 in the case where final saturation was as high as 90% to 1.5 when saturation in the region of 50% were obtained. The treatment as envisaged by Wakeman was intended to characterise a system by a

single pore size distribution index. ~~Obviously, with such variations over a range of saturations the attempt at a correlation has not been successful under the prevailing deliquoring conditions.~~ The difference is expected and obtained values are believed to be due to the inaccuracies in measurement of the modified breakthrough pressures of the filtercakes.

The problems encountered in applying the available correlations to the specific operating conditions are twofold. Firstly, the particle size range is well below those generally under consideration. Secondly, there is a large variation in the overall pressure drop from the end of the filtration to the controlled portion of the deliquoring cycle. This variation is much larger than any allowed for in the development of the correlations.

6.3.4. Conclusion

It can be seen that while industrial application of deliquoring in pressure filters have not been developed beyond obtaining satisfactory operating conditions the information and correlating techniques already available cannot be applied directly to this specific problem. Therefore, it is felt that considerable improvements are possible through minor modification to the present deliquoring practice.

While Chapter 5 discussed the experimental results and their implications for deliquoring operations Chapter 7 will look at how the design of the deliquoring cycle can be strengthened and the specification of plant be made with greater confidence.

CHAPTER 7

Design Procedures

7.1 Introduction

An analysis of results has been completed and a correlation developed for the experimental systems. In this chapter it is intended to show how, on the basis of the correlation, the design of the filter cake deliquoring operation can be carried out. Where new solid/liquid systems are being investigated small scale tests will play an important part in the design procedure.

This chapter will commence with a fully worked example of the design procedure. Once this procedure has been laid down the requirements of test apparatus for evaluating the deliquoring characteristics of an unknown material will be stated. After a general discussion of the optimisation of deliquoring procedures the areas in which the design procedure needs strengthening and clarifying will be indentified.

7.2. A Sample Operation

The example which is to be developed in this section will be based on materials already used in the experimental investigation. However, the way in which procedures vary dependent upon the information already available will be indicated. In defining this example the intention was to keep as close to the known industrial applications as possible.

7.2.1. Setting The Example

The sample process and equipment is as follows:-

Number of filters	=	4
Filtration area per filter	=	$2m^2$
Volume of filter tank	=	1,000 litres

Operating Cycle:-

Precoating	=	30 minutes
Filtration	=	60-90 minutes
Rest Volume	=	45 minutes
Deliquoring	=	30 minutes
Cloth Washing	=	30 minutes
Approximate Total Time	=	240 minutes

Solid for filter cake:-

Formation Rate (precoat)	=	1 cm/hr
(filtration)	=	1 cm/hr
Range of Cake Depths	=	1.5—2.0 cm.

The characteristics of the filter cake are assumed to be those of Hyflo-Supercel.

The total pressure drop at end of filtration = 350 kN/m^2

Pressure drop over cake and cloth filtration cycle = 220 kN/m^2

Approximate filtration rate = 4000-6000 l/hr.

= 6000 l/batch.

Saturation level required = 0.42

It is assumed that normal plant services are available including a supply of high pressure inert gas.

The solid residue is to be processed after discharge from the pressure filter.

7.2.2. Intermittent Deliquoring.

The aim of initial small scale tests on the intermittent deliquoring technique is to determine whether the level of saturation required can be obtained by employing this technique on its own. Therefore, for unknown materials two experimental runs would be carried out to obtain a value of saturation attainable using the technique and a first estimate of the amount of experimental variation to be expected. These experiments would be carried out using the final filtration pressure and the minimum expected filter cake depth.

In the example being considered these initial tests are not required as sufficient information is available to make an accurate prediction of the saturations attainable under conditions of intermittent deliquoring. Although the opening conditions are slightly outside those considered in the experimental programme extrapolation using the correlations developed for cake depth and surge pressure will give an accurate assessment of the deliquoring characteristics.

The values of saturation obtainable in a filter cake of Hyflo-Supercel under the conditions set in the example can be calculated as follows:-

1. Extrapolation of the pressure-saturation profiles for cakes of equal depths (Section 5.4.2.) gives saturation at the three depths tested using a pressure drop developed across the cake of 220 kN/m^2.

0.45 cm	= 0.47
0.9 cm	= 0.452
1.35 cm	= 0.445

2. Extrapolation of the graph of saturation against reciprocal cake depth (Section 5.4.2.) gives saturations at the two extremes of cake depth being considered.

1.5 cm = 0.444

2.0 cm = 0.441

The saturation levels predicted from these steps in the correlation are subject to considerable experimental variation as indicated by the results listed in Appendix E. The variations to be expected are of the order of $\pm$ 2% saturation. Thus, using the intermittent deliquoring technique saturations in the range 0.4425 $\pm$ 0.02 have been predicted. This value is higher than that required by this operation and therefore a period of continuous gas flow is necessary.

7.2.3. Continuous-Intermittent Optimum.

It has been suggested (Section 5.4.2.) that cake damage can prevent successful deliquoring. The next stage of the design tests is to determine the best deliquoring conditions in terms of the transfer from one technique to the other. The optimum condition will, in the main, consist of a maximum surge pressure above which excessive cake damage may occur. The remaining requirments will be concerned with procedural modifications.

For this example it is assumed that successful transition between the two techniques can be attained upto a surge pressure of 140 kN/m^2. Using the steps indicated in the previous section the two limits of saturations over the range of cake depths can be calculated.

1.5 cm filter cake = 0.479

2.o cm filter cake = 0.475

Again allowing for experimental variations the range of saturations to be expected is 0.455 - 0.50. This value may replace the intercept saturation and may eventually be calculated using a similar form of correlation. The determination of this optimum condition should be an aim of future work. Having determined the level of saturation attainable

using the intermittent technique the next stage is to progress to considering the continous flow regime.

7.2.4. Intercept Saturation

The existence of an optimum between the two distinct techniques investigated is still a matter of conjecture. However, during the analysis of experimental results a firm correlation was proposed for the saturation level obtained during a limited period at the commencement of constant flow deliquoring operation.. The main point to be noted in this correlation is that the initial breakthrough condition is of great importance in determining the subsequent level of saturation reached.

Using the present example the intercept saturation can be calculated. It is assumed that the flow characteristics of the equipment are identical to those of the experimental apparatus. The main variable to be considered from this point of view is the filter cloth. The relationship between cloth permeability and intercept saturation cannot be predicted as only one cloth has, so far, been used in a significant number of tests. As a general rule increasing the cloth resistance will improve the initial desaturation.

The saturations attainable will vary with both the cake depth and the controlled gas flowrate. The variation with controlled gas flow will be somewhat dependent upon the response of the gas supply system to changes in pressure in the filter cylinder. The basic saturation measurement for a given cake depth will be under a condition of no flow into the filter cylinder the gas flow through the filter cake being purely in response to the pressurised gas volume in the cylinder. The saturations predicted from the experimental results are:-

0.45 cm filter cake = 0.72

0.9 cm filter cake = 0.54

1.35 cm filter cake = 0.51

Extrapolating using the correlation developed in Section 5.2.3. Values for the new cake depth are calculated:-

1.5 cm cake = .506

2.0 cm cake = .495

These are the basic values of intercept saturation which, as already noted, may be adjusted by the initial gas input to give marginally lower saturation levels.

Thus, there may be an extra deliquoring capability of upto 0.06 saturation using the maximum intermittent deliquoring pressure over the desaturation attained during a short period of time after breakthrough using the continuous flow technique. Apart from this the intermittent technique appears to remove the time dependence of the step during which the intercept saturation is attained. Therefore, future developments should seek to take advantage of this enhanced rate of deliquoring. The optimum saturation calculated in section 7.2.3. will be used in the remaining parts of this example.

7.2.5. Continuous Deliquoring

The desaturation required during the continous flow deliquoring period has now been determined. This is the difference between the required saturation and that obtained under the optimum conditions in the previous section.

Further deliquoring required = 0.057

This desaturation is required if the experimental variation of $\pm$ 0.02 is acceptable in the final cake saturation. The gas flowrate required for a fixed deliquoring can now be calculated. The time period available for continuous gas flow deliquoring will be approximately 25 minutes as

5 minutes is estimated as the time necessary to carry out a pressure surge.

The correlating factor for Hyflo-Supercel as given in Section 5.7..

$$0.896 \times 10^{-6} = -\frac{\Delta S}{\Delta t_M} \frac{A^2 \epsilon^2 L}{Q^2} = K$$

$\frac{\Delta S}{\Delta t}$ = - 0.00228 desaturation/min.

A = 20,000 cm^2

ϵ = 0.85

L = 1.5 - 2.0 cm^2

$$Q = A \epsilon \sqrt{-\frac{\Delta S}{\Delta t} \cdot \frac{L}{K}} \qquad \text{Eqn. 7.2.4.1.}$$

$$= \underline{9,400 \text{ litres/min.}}$$

$$= \underline{282} \ m^3/m^2/hr.$$

This value of gas flow is measured at the mean filter cake pressure. The total pressure drop can be calculated but it is far easier to use the quantities measured in the test experiments. This requires a knowledge of the relative permeability of cake and cloth. Through calculation of the total pressure drop required to maintain the desired flow the sizing of the blower is completed. To carry out further optimisation a range of deliquoring times can be considered using the correlating equation 7.2.4.1.

7.2.6 Comparison with Industrial Practice.

Present industrial operation is believed to be based on a gas consumption of 50 - 100 $m^3/m^2/hr$. At this level, for the example quoted, deliquoring due to the constant rate regime would be of the order of 1-2% per hour.

Superficial gas velocity (industrial) = 1.4 cm/sec.

Superficial gas velocity (example) = 7.8 cm/sec.

The position at which the industrial gas flow is measured is believed to be the inlet pressure. However, even with pressure correction the ratio of the calculated flow to that at present in use is 5.. On this basis it must be assumed that industrial deliquoring can attribute very little to what has been termed constant rate deliquoring. On the contrary the flowrate is in the region where the initial regime during which the intercept saturation is attained over a considerably lengthened period of time still contributes most to the overall deliquoring. It must be concluded, therefore, that the whole of the deliquoring period is allocated in order to reduce the saturation level to a value virtually equal to the intercept saturation. In this case it must be pointed out that a single pressurisation and surge at the final filtration pressure would be required to attain an equal amount of deliquoring.

The implication is that deliquoring using large volumes of inert gas should not be considered as a mechanism by which large amounts of deliquoring can be accomplished. While the intermittent deliquoring technique is believed to be capable of bringing about the necessary desaturation in most operations as a result of the observations made here other mechanisms such as steam deliquoring may be shown in an even better light than in the past when further desaturation is required.

7.3 Test Apparatus

The prerequisites of a test cell are the measurement devices necessary for the collection of data and also the physical compatability with the full scale equipment. The operations used in the test equipment should, as closely as possible, mirror those to be used on the plant.

7.3.1. Instrumentation

The main piece of instrumentation required for data collection is a single pressure transducer. This would be a differential pressure transducer capable of making accurate measurement of the pressure drop between the filter cake top surface and a position directly below the cloth support system. The most important pressure measurements made are those about the time of gas breakthrough which indicate the initial gas flowrate. The experimental investigation showed that pressure loss is very fast and, therefore, both the response of the transducer and the speed of recording have to be able to accommodate this rapid change in pressure drop. The time scale being considered would be at least one pressure reading every two seconds and ideally once every second over the first 30 seconds to 1 minute of the deliquoring cycle. The same would be required over the initial period of an intermittent gas surge while at other times a scanning period of 20 - 30 seconds would be acceptable.

Other measurements to be taken on the test equipment would be gas flow and cake saturation readings. Gas flow has been shown to be the most important factor in determining the rate of deliquoring over extended periods of the operation. In the tests carried out the flow of gas into the filter cell has been measured. This would again be sufficient in the test equipment as long as adjustments are made for flow due to changes of pressure in the filter cell. The response of the gas control system would be of importance as this could have considerable effect on the time, pressure and flow relationships during cake breakthrough thereby modifying the initial condition of the filter cake. In all of these considerations the rule is that a maximum flexibility should be obtained so that tests can be carried out to check the sensitivity of a given system to possible control response fluctuations.

The final main piece of instrumentation which would add to the effectiveness of a test rig is an in situ method of saturation measurement During this project a survey was made of techniques available. It was found that most needed development followed by lengthy calibration work. There were several pieces of equipment being marketed which may have been capable of giving the saturation data required. However, due both to time available and financial considerations these techniques could not be persued during this project. Successful development of an in situ saturation measuring technique would have the effect of reducing drastically the number of tests required for the characterisation of a deliquoring system, and is, therefore, worth considering as a possible area for further investigation.

7.3.2. Filter Cell

It is essential that the filter area of a test cell should have a minimum value of about 100 cm^2. Below this level edge effects would become evident and as a result the reliability of measurements taken would be considerably reduced. The filter area used in experimental tests has proved adequate and, therefore, a cylinder of the same or a slightly larger diameter while having an area considerably above the minimum suggest would not be of an unmanagable size. The volume of the cell would be controlled by the solids concentration of liquor required and the thickness of cake to be formed. Flexibility in both of these could be obtained by having the facility to change the filter area. By reducing the area thicker cakes could be formed without increasing the liquor solids concentration.

Circulation of the liquor could be accomplished by use of a pump. This would modify the overall design considerably. On the other hand the main reason for doing this would be to improve the cake formation and the cake formed in the tests already carried out have been of

excellent quality. It would appear that the ideal situation would be to carry out the small scale tests on a small filter of the type being considered. This, together with the necessary instrumentation would be able to supply all the primary information required together with secondary information on the problems of discharge, scale-up and distribution of saturations over a stack of filter plates.

7.3.3. Further Requirements

There are three main further requirements of a test cell. The first two are related to the control of operations while the third is concerned with the comparability of small scale to large scale tests.

Firstly, control of the liquor and filtrate temperatures is essential. This can also be extended to the gas temperature. As temperature can drastically effect viscosity of the wetting phase in particular the temperature should be controlled whenever it is felt that large fluctuations may occur. For some systems it may also be necessary to operate the filter at high temperature.

Secondly, in some circumstances it will be necessary to control the inlet vapour pressure of the wetting phase material in the gas phase. This is done to reduce errors due to fluctuations in the amount of mass transfer which may occur within the filter. This is, of course, more important with the more volatile wetting phase fluids. Furthermore, a measurement of the outlet vapour pressure would add considerably to the data available.

Finally, it is important that the cloth and cloth support system should be as close as possible to those used on the full scale equipment. In particular the overall permeabilities should be identical. The importance of the filter cloth in determining the deliquoring characteristics has already been discussed. Further to this a similar

backpressure should be maintained across the cloth during operations.

A general outline of the requirements of test equipment has been given. The operation of the equipment should, as far as possible, mirror the operation of full scale plant and again occasional checks on the sensitivity of operations to various procedural modifications should be carried out. It would be an integral part of the design procedure to carry out a sensitivity analysis on both procedural modifications and operating variables until more information is available on a wider range of materials.

7.4 Experimental Programme

The example worked in Section 7.2 has indicated the information required to be able to design the deliquoring operations. In this section the numbers and extent of experimental tests required to obtain the information will be discussed in more detail.

7.4.1. Intermittent Deliquoring.

Using two experiments carried out under the mean operating conditions on a given system a large amount of information can be obtained about the deliquoring characteristics of the materials being used. This information will consist of the initial gas flowrate at the point of breakthrough, the saturation attainable using intermittent deliquoring and an assessment of the strength of the filter cake. The pair of experiments will also permit an initial estimate of experimental variations.

The value of saturation obtained in these initial tests will indicate whether the required level can be obtained using the intermittent deliquoring technique alone. If this saturation can be reached consideration of the continuous flow is not necessary. This being the case the remaining tests would be devoted to accurate assessment of experimental variations and prediction of desaturation over a range of cake depths and surge pressures. As indicated in Section 5.4.2

while the accurate prediction of saturation variation with cake depth can be made the accuracy of prediction of the pressure-saturation relationship is, at present, not good. Therefore, the major number of experiments would be concerned with obtaining this relationship over the range in which operations will occur.

Thus, for an unknown material the maximum number of intermittent deliquoring tests required will be six tests to determine the saturation-pressure profile at a single cake depth and a further two tests to check the variations in desaturation with cake depth. If more accurate assessment of experimental variations is required further tests may be necessary.

7.4.2. Continuous Deliquoring

Where deliquoring over and above that attained during intermittent operations is required this fact will become apparent after the first intermittent deliquoring test. Further intermittent tests will then have the aim of locating the best surge pressure prior to use of the continuous gas flow technique. The form of the tests will be similar to those already indicated but will be based around an estimate of the condition under which a minimum amount of cake damage would be incurred. Thus, using the same number of tests as for purely intermittent deliquoring the condition of the cake at the commencement of the continuous gas flow period will have been determined.

The correlation for the continuous gas flow period has been developed in Section 5.2.2.. It will be noted from this that the required gas flowrate can be calculated once a single saturation-time profile has been accurately determined. This determination would require approximately eight to ten points on a single saturation-time curve. If in situ measurements could be made this would involve a single experiment. However, at present each point requires an individual

test. The conditions set for the test would be estimated by consideration of the time available, the necessary desaturation and the nature of the material which is being used.

Were the intermittent deliquoring not employed and the basic continuous deliquoring operation was in use the number of tests required would increase. A further saturation-time profile at a second gas flowrate would be required. As indicated in Section 5.2.1. at low gas flow and for thicker cakes deliquoring down to the intercept saturation level takes a considerably longer period. The extent of this time dependence will need to be determined if intercept saturation is being used as the first step in the correlation.

Tests have shown (section 5.2.6.) that the straight line deliquoring period predicted tends to under estimate the rate of desaturation over extended deliquoring periods. The underestimation was apparent when comparing the bulk of tests with those carried out using deliquoring periods extending to 3 hours. Although this is a considerable advantage in the case where extra deliquoring time may occasionally be available it must be kept in mind that at some level of saturation the rate of deliquoring attainable will again fall off rapidly. No indication of this level has been found in the tests carried out.

7.5 Overall Design Strategy

In general rigid constraints are placed upon the deliquoring operation by the requirements of other areas of the process being considered and especially by the requirements of the filtration operation. Therefore, few variables remain to be considered in the optimisation of the deliquoring operation. The main variables are the time, gas flow, attained saturation and the non-wetting phase characteristics. While the upper limit on saturation (that permitting "dry" discharge) will,

generally, be easily attained the lower levels required will be more flexible. The minimum time and gas flow requirements will almost exclusively be met by use of the intermittent deliquoring technique. While the effects of varying the non-wetting phase in terms of viscosity and interfacial tension have not been investigated it is a reasonable assumption that deliquoring over the period of intermittent operations will be improved by increasing the viscosity of the displacing fluid.

The optimisation relies heavily on the decision as to whether intermittent deliquoring can be used exclusively. In a large number of cases this technique will prove to give sufficient desaturation such that the obvious course of action is to employ it as the sole means of cake deliquoring. In this way large savings will be made in capital outlay, time and gas consumption.

Having shown that an improved initial reduction in saturation can be obtained it has also become evident that subsequent deliquoring under a reduced pressure drop gives only a slow rate of desaturation. Furthermore, this desaturation involves the use of large volumes of gas. It is felt that where further desaturation is essential the use of other techniques such as steam dewatering should be seriously considered.

7.5 Development of Procedures

The procedures indicated in this chapter have been developed from consideration of a limited number of experimental tests on two distinct methods of cake deliquoring. The conclusions drawn from these tests have been moulded into a design procedure for the overall development of deliquoring operations. Each point in these correlations can be given an individual degree of confidence. While some steps in the procedure can be strongly supported by experimental evidence other stages fall between the areas of experimental investigation and as such are still

matters of conjecture. This section is intended to identify the areas which can be firmly stated and to suggest methods for strengthening the uncertain areas of the design procedure.

Intermittent deliquoring tests have indicated the general trend of saturations obtain using this technique when considering the variables of pressure and cake depth. While the cake depth relationship is believed to be reliable wide experimental variations appear in the saturation-pressure profile. Suggestions for improving experimental procedures may reduce these variations. The effects of viscosity have been proposed on the basis of a single test at a second viscosity and by considering the general trend of the comparable continuous flow tests. Thus, the main improvements to be made in considering the intermittent deliquoring technique consist of modifications to the experimental procedure which will result in the optimum cycle of pressure being achieved.

The continuous flow tests have resulted in a two-tier correlation being developed to predict the final saturation obtained. These parts of the procedure are felt to be well supported by experimental data. The variables considered in the experimental programme being time, gas flow conditions, viscosity and cake depth. Two solids have been investigated in detail and the general form of the correlation was found to apply for each individually. Some attempts have been made to correlate the results for the two solids but only a tentative relationship has been suggested.

The remaining part of the design procedure consists of the determination of the optimum operating condition between the two techniques. This determination and the existence of an optimum is a matter of conjecture at present. However, if the optimum can be evaluated the intercept saturation developed with the continuous low

correlation will immediately be superceded and new correlations based on the initial reduction due to intermittent deliquoring will be required. This is the area in which a major effort should be made to improve the reliability and effectiveness of the overall design procedure.

CHAPTER 8

Proposals for future work

1. Techniques for in situ measurement of saturation should be investigated further.

The satisfactory development of an in situ saturation measurement technique would be of great advantage in the further study of the deliquoring operation. It would bring about a large reduction in the extent of design tests required.

2. A range of solid materials should be tested to ascertain their deliquoring characteristics.

Only three solids have been studied so far in this project. No information has been obtained which is of sufficient clarity to indicate the characteristics of other materials used. The effects of variables such as particle size, porosity and sphericity can only be determined by the investigation of a further range of materials.

3. Tests on a variety of wetting and non-wetting phases should be carried out.

The project has investigated only the water-air system with the use of sugar solution to vary the wetting phase viscosity. A range of wetting and non-wetting phases in tests will help to determine the extent of mass transfer occurring in the deliquoring operation. For this purpose the wetting phase should be of low volatility. Also the relative viscosities of the two phases can be varied to a far greater extent.

4. Tests over a wider range of gas flow should be attempted.

Superficial gas velocities upto 5 cm/sec. have been used. Although this is the order of gas flows in general use in some cakes the pressure drop developed is low and the required flow is relatively greater. Therefore, superficial gas velocities upto 10 - 15 cm/sec. should also be investigated over shorter deliquoring periods.

5. Detailed investigation of the relationship between initial gas velocity and saturation reduction should be made.

In the experimental apparatus used during this project full scanning of the pressure transducers took 4 seconds and in the majority of tests a 10 second scan period was used. The significance of the first moments of deliquoring has already been noted. A further investigation of this portion of the deliquoring cycle is warranted. This would require the recording of pressure differential at intervals of about 1 second.

6. The optimum operating conditions which are believed to exist should be examined in more detail.

If, as suggested, excessive pressure causes cake damage the optimum conditions will be dependent upon the strength of cake formed and the stress built up in the filter cake as deliquoring progresses.

7. Tests on the interaction between cake and cloth as related to cake discharge will be valuable.

In centrifugal discharge the saturation level is of considerable importance. An initial level at which clean discharge is attainable is thought to exist at 80 - 90% saturation for a range of cake types. In the tests carried out some thin layers of cake (approx. 1 mm) were observed

to stick to the cloth particularly at higher saturations. Once a cake has been formed satisfactory discharge will be attainable only when cohesive forces exceed ~~cohesive~~ adhesive forces.

8. A major area not investigated in any depth in this project is equipment scale-up.

The extent of investigation in this project was the supervision of a 5 week project carried out by final year undergraduate students who worked on a small Funda filter. In the small number of tests that it was possible to complete several areas of interest were indicated.

(i) Variations between saturations from plate to plate.

(ii) The method of emptying the filter of filtrate heel.

(iii) Variations of cake formation from plate to plate.

In general the scale up will be purely on the basis of filter area. However, the effects of the three variables indicated require clarification.

Conclusions

During this project it has become evident that considerable modifications to the present practice of deliquoring pressure formed filter cakes may prove to be advantageous. Using the technique of intermittent deliquoring considerable savings in both time and gas consumption have been shown to be possible. The design procedures proposed have included this technique and as a result of this innovation scope for further research has been created.

The conditions under which gas breakthrough of the filter cake occurs have been shown to be of paramount importance in determining the levels of saturation obtained. A correlation between the conditions at gas breakthrough and the subsequent saturation level has been developed. This correlation relates the void volume displaced rate to the cake depth and the saturation obtained. The effects of other variables such as viscosity and the type of filter cloth need have been discussed. The saturation value calculated using this stage of the correlation was termed the intercept saturation. Rather than being an immediately obtained value of saturation the intercept saturation level is a value that could be attributed to an initial flow regime.

The theory proposed for this flow regime is that at gas breakthrough a range of pores are fully or partially opened to gas flow. During the subsequent period of gas flow partially opened pores are further desaturated. The level of saturation attained after this further desaturation has been termed the intercept saturation. This value has been successfully correlated with the conditions at gas breakthrough. The only uncertainty is the extent to which this part of the deliquoring operation is time dependent. The major

mechanism operating at this stage is believed to be film flow in pores fully opened to flow at gas breakthrough.

The second regime which has been referred to as the constant rate deliquoring period has been assumed to operate in parallel with the first regime and continue over a longer time span. The mechanisms operating during this deliquoring phase have not been clearly identified. Both film flow and mass transfer are believed to play a part in deliquoring at this stage. As the deliquoring period increases the latter will become the more important factor. Several tests over extended deliquoring periods have shown that the rate of deliquoring predicted by this straight line relationship under predicts the mean deliquoring rate measured over the longer period of gas flow.

The intermittent deliquoring tests have shown that deliquoring to a lower level than the intercept saturation can be accomplished by a single surge of high pressure gas through the filter cake. The implications of this are that considerable economies can be made by a series of simple modifications to the deliquoring operation. During this research an attempt has been made to incorporate the intermittent deliquoring technique into the design procedures. Full optimisation of the two deliquoring techniques has not been possible but this has been proposed as an important aim of future work.

Examination of the gas flows used in pressure filters as obtained from literature and manufacturers information has shown that a majority of operations are carried out at gas flows lower than those which have been calculated in this project to give reasonable deliquoring rates. The flows used would mean that the level of intercept saturation already defined would be reached after a

considerable deliquoring period this regime being time dependent. As this level can be obtained rapidly using the intermittent technique the use of low constant gas flow deliquoring may, in many cases, no longer be considered economical.

In investigating the deliquoring of pressure formed filter cakes a new technique has been brought into the design procedures. The design procedures developed form a firm basis on which future work can be carried out. The optimisation of the deliquoring operation and the collection of data on other systems should be the main aims of future work in this field.

APPENDIX A

Classification of Test Materials

I Particle Size Distribution

(i) Hyflo-Supercel

Stokes Diameter µm	Cumulative % undersize
150*	97.0
106*	92.4
75	84.6
74.62	80.63
52.48	78.08
42.36	73.67
36.49	70.12
25.5	62.93
17.79	55.49
12.65	42.78
8.69	25.42
6.14	20.18

(ii) HPF-5 Test Dust

Stokes Diamter µm	Cumulative % undersize
150*	99.0
106*	95.0
75*	79.0
54.54	64.24
38.57	45.24
27.27	26.27
19.28	11.75
14.75	4.8
10.84	0.2
1.48	0.05

(iii) Crushed Anthracite

150*	78.0
106*	41.0
75*	15.0
64.16	14.67
44.76	8.98
31.21	3.37
21.75	0.41

All measurements made using an Andreason Pipette except those marked * which are sieve points. HPF-5 Test Dust was modified by removing the fines. A cut was made at 11µm using an 'Alpine' classifier.

II Mercury Porosimeter Measurements

Internal porosity of samples were measured on a mercury intrusion porosimeter at 300 kg. cm^{-2}.

(i)	Hyflo-Supercel	-	0.468 $cm^3 g^{-1}$
(ii)	HPF-5 Test Dust	-	0.106 $cm^3 g^{-1}$
(iii)	Crushed Anthracite	-	0.024 $cm^3 g^{-1}$

Some difficulties were experienced in forcing mercury into the interparticle spaces in the Hyflo-Supercel sample. This can lead to inaccuraces in the porosity measurement as pressure is used to fill up some interparticle spaces at the same time as intraparticle spaces are being filled up.

Figure AII indicates the pore radius distribution measured from the Porosimeter tests.

III Porosity

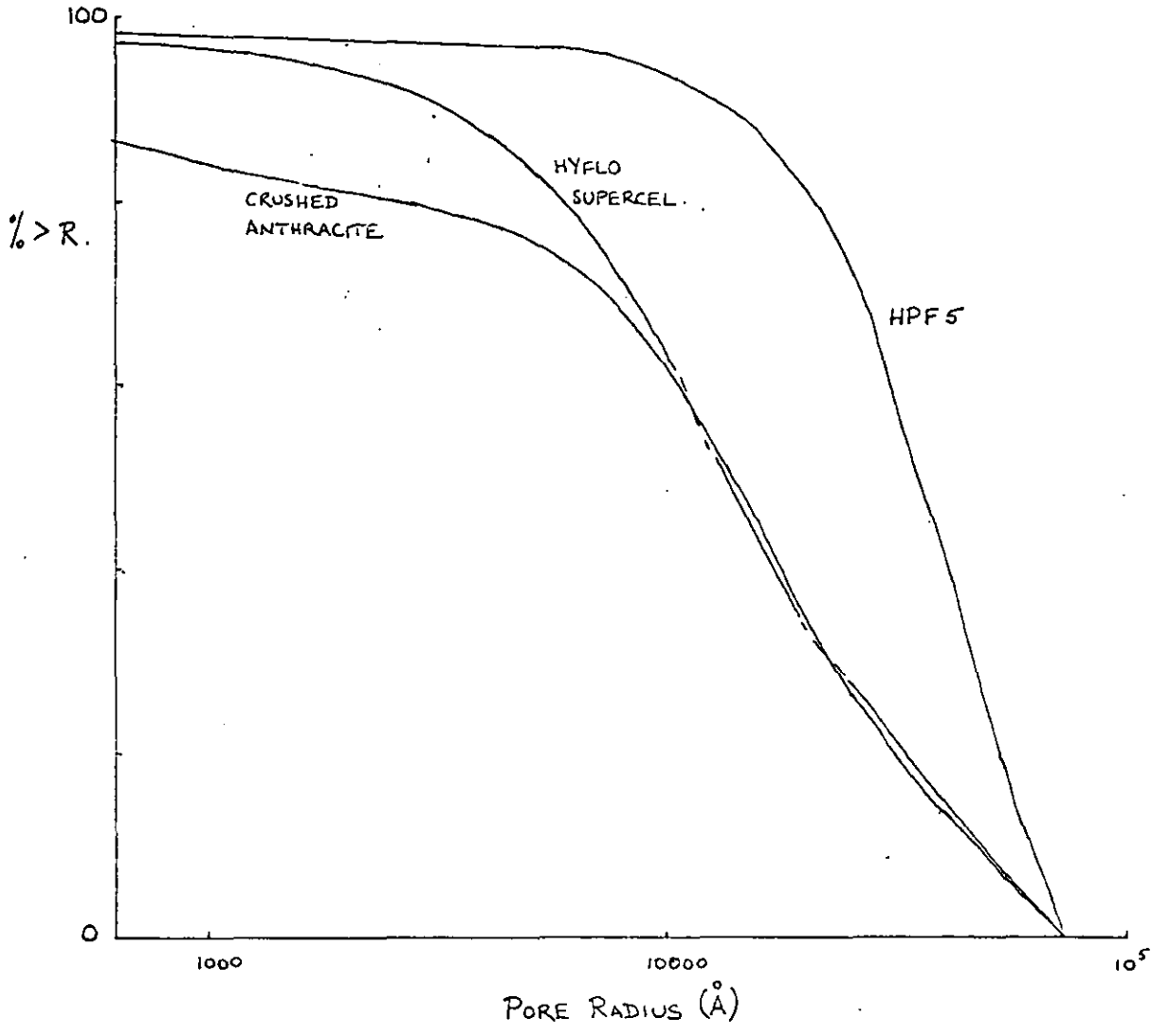
The porosity of the cakes formed using the three test materials varied by a negligible amount from test to test as the cakes were virtually incompressible. Therefore, the average porosity for each material could be found.

(i)	Hyflo-Supercel	-	0.85
(ii)	HPF5 Test Dust	-	0.485
(iii)	Crushed Anthracite	-	0.6

IV Solid Density

(i)	Hyflo-Supercel	-	2.2 gm cm^{-3}
(ii)	HPF5 Test Dust	-	2.65 gm cm^{-3}
(iii)	Crushed Anthracite	-	1.6 gm cm^{-3}

FIGURE A II



MERCURY INTRUSION POROSIMETER MEASUREMENTS

(COURTESY OF B.P. CHEMICALS LTD.)

V Further Parameters

(a) Mean Diameter

There are many methods of obtaining a mean particle diameter. The method used to obtain the values given is that employed by Brownell and Katz (10) :-

$$d = \sqrt{\frac{\sum \frac{m}{d}}{\sum \frac{m}{d^3}}}$$

The calculated diameters are as follows:-

(i)	Hyflo-Supercel	-	3.8 μm
(ii)	HPF5 Test Dust	-	20.5 μm
(iii)	Crushed Anthracite	-	43.0 μm

These represent the particle having the average area

(b) Particle Sphericity

Particle sphericity has been estimated using the correlations of Brownell and Katz as described by Brown et al (6).

(i)	Hyflo-Supercel	-	0.22
(ii)	HPF5 Test Dust	-	0.52
(iii)	Crushed Anthracite	-	0.7

(c) Modified Breakthrough Pressure

The modified pressure calculated is that employed by Wakeman (58) in an example of the use of his correlating technique.

$$P_b^* = \frac{4.6 \ (1 - \epsilon)}{d}$$

The modified breakthrough pressures are:-

(i)	Hyflo-Supercel	-	1.54×10^5 dynes/cm^2
(ii)	HPF5 Test Dust	-	1.72×10^5 dynes/cm^2
(iii)	Crushed Anthracite	-	5.14×10^4 dynes/cm^2

(d) Cake Permeability

There are several methods of obtaining a cake permeability. The methods include theoretical approaches using the parameters already developed. However, the values given are those obtained during the during the experimental programme. The measurements used gave total pressure drop and flow relationships at three cake depths. Therefore, the permeability of the cake and cloth could each be measured.

The cake permeabilities were as follows:-

(i) Hyflo-Supercel - 1.987×10^{-8} cm^2

(ii) HPF5 Test Dust - 2.25×10^{-8} cm^2

(iii) Crushed Anthracite - 8.0×10^{-8} cm^2

APPENDIX B

Classification of Experiments.

I. Continuous Flow Tests

Hyflo-Supercel

	TIME (MINUTES)	RUN Nos.
CLASS HY1	4	92
	8	90
CAKE DEPTH = 0.45 cm.	10	123, 146
AIRFLOW = 20 l/min.	20	118, 144
(at s.t.p.)	30	124, 149
CLASS HY2	10	131, 153
	30	129, 155
CAKE DEPTH = 0.45 cm.		
AIRFLOW = 30 l/min.		
(at s.t.p.)		
CLASS HY3	4	88
	8	85
CAKE DEPTH = 0.45 cm.	10	114, 136
AIRFLOW = 40 l/min.	20	115, 141
(at s.t.p.)		

Hyflo-Supercel (cont.)

	TIME (MINUTES)	RUN Nos.
CLASS HY4	4	91
	8	89
CAKE DEPTH = 0.9 cm.	10	121, 147
AIRFLOW = 20 l/min		
(at s.t.p.)	20	120, 143
	30	125, 151
CLASS HY5	10	130, 154
	30	128, 156
CAKE DEPTH = 0.9 cm.		
AIRFLOW = 30 l/min.		
(at s.t.p.)		
CLASS HY6	4	86
	8	87
CAKE DEPTH = 0.9 cm	10	113, 138
AIRFLOW = 40 l/min		
(at s.t.p.)	20	116, 139
	30	109, 134

Hyflo-Supercel (cont.)

	TIME (MINUTES)	RUN Nos.
CLASS HY7	10	122, 148
	20	119, 145
CAKE DEPTH = 1.35 cm.	30	126, 150
AIRFLOW = 20 l/min. (at s.t.p.)		
CLASS HY8	10	132, 152
	30	127, 157
CAKE DEPTH = 1.35 cm		
AIRFLOW = 30 l/min. (at s.t.p.)		
CLASS HY9	10	112, 137
	20	117, 140, 142
CAKE DEPTH = 1.35 cm	30	110, 133
AIRFLOW = 40 l/min (at s.t.p.)		

HPF5 Test Dust (cont.)

	TIME (MINUTES)	RUN Nos.
CLASS HP1	4	70
	6	68
CAKE DEPTH = 0.45 cm.	8	69
AIRFLOW = 20 l/min. (at s.t.p.)	15	206, 219
	30	204, 208
	45	203, 205, 207
CLASS HP2	4	72
	6	74
CAKE DEPTH = 0.45 cm.	8	77
AIRFLOW = 30 l/min. (at s.t.p.)	15	199, 202
	30	231
	45	200, 201
CLASS HP3	4	75
	6	78
CAKE DEPTH = 0.45 cm.	8	76
AIRFLOW = 40 l/min. (at s.t.p.)	15	105, 224
	30	106
	45	100, 225
	60	98

HPF5 Test Dust (cont.)

	TIME (MINUTES)	RUN Nos.
CLASS HP4	4	71
	8	73
CAKE DEPTH = 0.9 cm.	15	216, 221
AIRFLOW = 20 l/min (at s.t.p.)	45	214, 218
CLASS HP5	15	233
	45	230
CAKE DEPTH = 0.9 cm		
AIRFLOW = 30 l/min (at s.t.p.)		
CLASS HP6	4	80
	8	79
CAKE DEPTH = 0.9 cm	15	104, 227
AIRFLOW = 40 l/min (at s.t.p.)	30	108
	45	101, 223
	60	97

HF5 Test Dust (cont.)

	TIME (MINUTES)	RUN Nos.
CLASS HP7	15	215, 220
	30	213
CAKE DEPTH = 1.35 cm.	45	212, 217
AIRFLOW = 20 l/min (at s.t.p.)		
CLASS HP8	15	228, 234
	45	229, 232
CAKE DEPTH = 1.35		
AIR FLOW = 30 l/min (at s.t.p.)		
CLASS HP9	15	103, 226
	30	107
CAKE DEPTH = 1.35	45	102, 222
AIRFLOW = 40 l/min (at s.t.p.)	60	99

Carbon

(Class conditions as defined for Hyflo Supercel and HPF5)

CLASS	TIME (MINUTES)	RUN Nos.
C4	15	260, 262
	30	261
C6	15	265, 266
	30	267
C7	15	263
C9	15	264

HPF5 Test Dust - Viscosity Tests

CLASS	TIME (MINUTES)	RELATIVE VISCOSITY	RUN Nos.
HP1	15	1.47	252, 254
HP1	15	1.65	255, 258
HP3	15	1.47	248, 249
HP4	15	1.47	251, 253
HP4	15	1.65	256, 257
HP6	15	1.47	247, 250

HPF5 Test Dust - Thin Cakes

CAKE DEPTH (cm)	TIME (MINUTES)	RUN Nos.
0.2	10	277
	20	279
0.3	10	278
	20	280
0.6	10	281

(Airflow used in these tests was 32.6 l/min. at s.t.p.)

Humidity Tests

CLASS	CAKE DEPTH	AIRFLOW	TIME(MINUTES)	RUN Nos.
HY3	0.45	40	75	274
HY7	1.35	20	180	272
HP4	0.9	20	75	273

Drying tests

SOLID	CAKE DEPTH	RUN Nos.
HY	0.45	95
HY	0.9	96
HP	0.45	93
HP	0.9	94

II Intermittent Flow Tests

Hyflo-Supercel

	PRESSURE(kN/m^2)	RUN Nos.
CLASS HY - I1	30	159, 172, 180
	50	81, 170, 183
CAKE DEPTH = 0.45 cm	80	83, 166, 179
	110	163, 174, 187
CLASS HY - I2	30	160, 173, 182
	50	84, 168, 184
CAKE DEPTH = 0.9 cm.	80	82, 167, 178
	110	162, 175, 186
CLASS HY - I3	30	161, 171, 181
	50	158, 169, 185
CAKE DEPTH = 1.35 cm.	80	165, 177, 189
	110	164, 176, 188

HPF5 Test Dust

	PRESSURE (kN/m^2)	RUN Nos.
CLASS HP - I1	20	55, 56, 57
	30	192, 194
CAKE DEPTH = 0.45 cm.	50	59, 60, 62
	80	63, 64, 66, 190
	110	191, 196, 197
	140	193, 195
CLASS HP-I2	30	235, 244
	50	58, 61
CAKE DEPTH = 0.9 cm.	80	65, 67, 211
	110	241, 237
CLASS HP-I3	30	243, 245
	50	236, 242
CAKE DEPTH = 1.35 cm.	80	239, 246
	110	238, 240
CLASS HP-I2		
- RELATIVE VISCOSITY (1.65)	80	259

APPENDIX C

Use of Computing Systems

I Data Files

Data used in the computer programmes included the pressure and flow data supplied on punch tape and the subsidiary data including cake characteristics and operating conditions. While the punch tape was fed onto a file before being edited the subsidiary data was typed directly into a file.

(i) Modular 1 System

This system was used for data input during the early stages of the project. The tape was input at the terminal and could be edited before being transferred using a linking operation to the main computer filing system. Recall and re-editing was also possible whenever necessary.

(ii) Prime

This system was used for data input and editing once it came into operation as part of the Universitys computing facilities. Its advantages over the Modular 1 system were its reliability and speed even through transfer between the operation and the ICL 1900 was a more complex operation than the Modular 1 to 1900 transfer.

The data from each experiment existed as two small parts of separable data files and could be called for use in processing operations by reference to the line numbers in the files. A *INCLUDE command in the running instructions permitted location of the required data.

Small sections of the two types of data files are illustrated on pages 179 and 180.

EXAMPLE OF EDITED PUNCH TAPE DATA

```
DIAGNOSTIC LISTING OF SUB/PLANE05(1/1) ON 29/08/79 AT 21:32

    1.          4 #41  133
    4.          8 #41  *000010
    5.         12 #41  00 +0.13650  4
    7.         12 #41  01 +0.13635  4
    9.         12 #41  02 +0.13605  4
    9.5        12 #41  03 +0.05029  5
   11.         12 #41  04 +0.00003  6
   11.5         8 #41  *000130
   12.         12 #41  00 +0.03178  4
   10.5        12 #41  01 +0.08089  6
   11.         12 #41  02 +0.03140  4
   14.5        12 #41  03 +0.05972  5
   15.         12 #41  04 +0.00003  6
   16.          8 #41  *000140
   17.5        12 #41  00 +0.03194  4
   18.5        12 #41  01 +0.07585  6
   17.         12 #41  02 +0.03139  4
   18.         12 #41  03 +0.05445  5
   17.5        12 #41  04 +0.00003  6
   20.          8 #41  *000150
   21.         12 #41  00 +0.12833  4
   22.         12 #41  01 +0.09534  6
   23.         12 #41  02 +0.12504  4
   24.         12 #41  03 +0.05105  5
   25.         12 #41  04 +0.00003  6
   26.          8 #41  *000200
   27.         12 #41  00 +0.11284  5
   28.5        12 #41  01 +0.08145  6
   27.         12 #41  02 +0.09743  5
   30.         12 #41  03 +0.05214  5
   31.         12 #41  04 +0.00003  6
   90.5         8 #41  *000810
   91.         12 #41  00 +0.08573  6
  100.5        12 #41  01 +0.06431  6
  100.         12 #41  02 -0.00842  6
  102.         12 #41  03 +0.07912  5
  103.         12 #41  04 +0.00003  6
  104.          8 #41  *000820
  105.         12 #41  00 +0.08541  6
  103.         12 #41  01 +0.06346  6
  107.5        12 #41  02 -0.00741  5
  106.         12 #41  03 +0.07870  5
  107.         12 #41  04 +0.00003  6
  110.          8 #41  *000830
  111.5        12 #41  00 +0.08530  6
  112.         12 #41  01 +0.06525  6
  111.         12 #41  02 -0.00730  6
  114.         12 #41  03 +0.07804  5
  113.         12 #41  04 +0.00002  6
```

EXAMPLE OF SUPPLEMENTARY DATA FILES.

DIAGNOSTIC LISTING OF SOG/SIDS-3240(1/2) ON 22/06/?? AT 19:44

1.0	12	#41	0.0478		
2.0	8	#41	1.35		
3.0	12	#41	0.465		
4.0	8	#41	12.0		
5.0	8	#41	135.0		
6.0	8	#41	2.65		
7.0	8	#41	16.5		
8.0	8	#41	2.0		
9.0	8	#41	0.2		
10.0	8	#41	1.6		
11.0	8	#41	46.6		
12.0	8	#41	47.0		
13.0	16	#41	HPF-3 HF-500M		
14.0	36	#41	2.3900E-08	2.3900E-08	2.2500E-08
15.0	12	#41	0.5549		
16.0	12	#41	0.5428		
17.0	12	#41	0.5669		
18.0	12	#41	0.5703		
19.0	12	#41	0.5587		
20.0	12	#41	0.0478		
21.0	8	#41	1.35		
22.0	12	#41	0.465		
23.0	8	#41	11.72		
24.0	8	#41	135.0		
25.0	8	#41	2.65		
26.0	8	#41	16.0		
27.0	8	#41	2.0		
28.0	8	#41	0.2		
29.0	8	#41	1.65		
30.0	8	#41	31.65		
31.0	8	#41	32.0		
32.0	16	#41	HPF-3 HF-500M		
33.0	36	#41	2.3900E-08	2.3900E-08	2.2500E-08
34.0	12	#41	0.6037		
35.0	12	#41	0.5713		
36.0	12	#41	0.6059		
37.0	12	#41	0.6010		
38.0	12	#41	0.5955		
39.0	12	#41	0.0478		
40.0	8	#41	0.9		
41.0	12	#41	0.465		
42.0	8	#41	14.17		
43.0	8	#41	135.0		
44.0	8	#41	2.65		
45.0	8	#41	17.0		
46.0	8	#41	2.0		
47.0	8	#41	0.2		
48.0	8	#41	1.4		
49.0	8	#41	46.4		
50.0	8	#41	46.83		
51.0	16	#41	HPF-3 HF-500M		
52.0	36	#41	2.3900E-08	2.3900E-08	2.2500E-08
53.0	12	#41	0.5641		
54.0	12	#41	0.6093		
55.0	12	#41	0.5734		
56.0	12	#41	0.6165		
57.0	12	#41	0.5941		

II Processing Files

Over the period of this project a series of computer programmes have been written to process the experimental data. These programmes have fallen into two distinct categories.

(i) Processing of intermittent flow data

(ii) Processing of continuous flow data

While each programme included the calculation of pressures and flowrates from the voltage data supplied they varied in the correlating factors and other parameters which were computed.

During the early stages of the project the correlations of Brownell and Katz were included in the computations while during the later stages more attention was paid to the basic data and the correlating parameters indicated by Dahlstrom and coworkers and Wakeman.

The processing programmes for the intermittent and continuous flow tests are given on pages 181-187. Sections for input of data are identical for the two programmes.

The programme, written in Fortran, was processed on the University's ICL computer.

DATA PROCESSING FILE.

```
      MASTER DELIQUOR
      COMMON /ALL/ DIAM,DIFF,SPH,I3
      READ(1,94)IY
   94 FORMAT(I2)
      READ(1,93)DIAM,DIFF,SPH
   93 FORMAT(3E12.4)
      DO 10000,IZL = 1,IY
      **********

      THE CALCULATION OF PARAMETERS
     RELATED TO DELIQUORING THEORY

      ********************************

      DIMENSION ITR(60),ITM(60),ITS(60),SATN(4)
      COMMON /INPUT1/ IV1(60),IV2(60),IV3(60),IV4(60),IV5(60)
      COMMON /INPUT2/  IS1(60),IS2(60),IS3(60),IS4(60),IS5(60)
      COMMON /INPUT3/ ST,DS,PB,FR,AB,DS,CF,TS,TF,TD,TE,PDRY,PCLO,PWET,ON,
      COMMON /INTRTN/ T(60),I,PR1(60),PR2(60),PR3(60),PRA13(60)
     1,PR3(60),PRN(60)
      COMMON /FLOW/ FL(60),FLA,FLAM,FLAS,FLTOT,L,M,N,FLM(60),RATIO(60)
     1,FLS(60)
      COMMON /PERM/ EADB,FLIW,PTW,PTNW,PIW(60),PINW(60),PRW(60),PRNW
     1(60)
      COMMON /VISC/ VISW,VISA,DLIQ,PRDL,SAVE
  100 FORMAT(I3)
   99 FORMAT(1X,5I2)
   98 FORMAT(I2,I5,I2)
   97 FORMAT(F12.6)
   96 FORMAT(2A8)
   95 FORMAT(3F12.4)
   92 FORMAT(1H ,21HAVERAGE SATURATION = ,F9.6/)
   91 FORMAT(1H1)
   90 FORMAT(1H ,11HRUN NUMBER ,I3/14H**************/)
   89 FORMAT(1H ,2HA ,F4.2,33H CM. FILTER CAKE IS FORMED USING /9X,A8,15
     1HTE,T DUST ON A /9X,A8,14H  FILTER CLOTH/12X,16H**************./)
   88 FORMAT(1H ,16HAIR FLOW LASTED ,F6.2,26H MINUTES WITH AN AVERAGE  /
     110X,10H FLOW OF  ,F6.2,18H LITRES PER MINUTE/12X,12H**********./)
   87 FORMAT(1H ,17HORIFICE PLATE NO.,F4.1,9H WAS USED/10X,10H********
     ,/)
   86 FORMAT(1H ,26HTHE RED DRAINAGE HEIGHT = ,E12.4/)
   85 FORMAT(1H ,14HPERMEABILITIES/14H**************//7X,8HPART WET,6X,1
     12HPART NON-WET,5X,8HREL. WET,6X,12HREL. NON WET/7X,8H********,6X,1
     22H**********,5X,8H********,6X,12H**********/)
   84 FORMAT(1H ,10HFURTHER CORRELATION/10H**********/)
   75 FORMAT(1H ,13HEND OF OUTPUT//)
      READ(1,100)IRUN
      WRITE(2,91)
      WRITE(2,90)IRUN
      DO 1 I =  1,120
      READ(1,99)  ITR(I),ITM(I),ITS(I)
      READ(1,98) ICH,IV1(I),IS1(I),ICH,IV2(I),IS2(I),ICH,IV3(I),IS3(I),
     1ICH,IV4(I),IS4(I),ICH,IV5(I),IS5(I)
      IF(ICH.EQ.10)GO TO 2
    1 CONTINUE
    2 READ(1,97) ST,DS,PB,FR,AB,DS,CF,ON
      READ(1,97) TS,TF,TD,TE
      READ(1,96) SOLID,CLOTH
```

```
      READ(1,95) PDRY,PCL,PWET
      READ(1,97) SAT,SAVE
      WRITE(2,98)SAVE
      WRITE(2,87)DB,SOLID,CLOTH
      TDEL = TD - TF
      DLIQ = 1.002 - (2.0E-4 * CF)
      DO 3 I1 = 1,120
      TH = ITH(I1)
      TM = ITM(I1)
      TL = ITS(I1)
      T(I1) = TH * 60.0 + TM + TL/60.0
      DIF = TE-T(I1)
      IF(DIF.LT.0.05)GO TO 4
    3 CONTINUE
    4 CALL PRESSURES
      CALL FLUXS
      WRITE(2,88)TDEL,FLA
      WRITE(2,87)ON
      VISA = 1.799 * 1.0E-4
      VISW = 1.473 * 1.0E-2
      WRITE(2,85)
      CALL PERMS
      WRITE(2,84)
      CALL CONREL
      WRITE(2,75)
10000 CONTINUE
      STOP
      END


      SUBROUTINE PRESSURES
     **********************

     CALCULATION OF PRESSURE DROP
        ACROSS  THE FILTER CAKE

     ******************************

      COMMON /INPUT1/ IV1(60),IV2(60),IV3(60),IV4(60),IV5(60)
      COMMON /INPUT2/ IS1(60),IS2(60),IS3(60),IS4(60),IS5(60)
      COMMON /INPUT3/ ST,DB,PB,FR,AB,DS,CF,TS,TF,TP(3),TC,TE,PDRY,PCL,
     1,PWET,ON
      COMMON /INTRIM/ T(60),I,PR1(60),PR2(60),PR3(60),PRA13(60),
     1PRD(60),PRM(60),PM(3),PMAX,J1
   90 FORMAT(1H ,I5,5X,E12.4/)
   89 FORMAT(1H ,23HNUMBER OF AIR SURGES = ,I3/)
   88 FORMAT(1H ,I3,2X,3E16.4/)
      DO 1 I1 = 1,I
      V = IV1(I1)
      S = IS1(I1)
      PR1(I1) = (V  * 10.0 **(-S) -0.0043) *4.13688E6
      V = IV2(I1)
      S =  IS2(I1)
      PR2(I1) = (V *  10.0 **(-S) -0.0058) *4.13688E6
      V = IV3(I1)
      S = IS3(I1)
      PR3(I1) = (V * 10.0 **(-S)  +0.0052) *4.13688E6
      PRA13(I1) = (PR1(I1) + PR3(I1))/2.0
      PRD(I1) = PRA13(I1)-PR2(I1)
```

```
      WRITE(2,88)I1,PRD(I1),PRA13(I1)
    1 CONTINUE
      IF(TP(2).GT.TE)GO TO 2
      IF(TP(3).GT.TE)GO  TO 3
      ISURGES = 3
      GO  TO 4
    2 ISURGES = 1
      GO TO 4
    3 ISURGES = 2
    4 N = 1
      PMAX = 0.0
      DO 5 I2 = 1,I
      IF(ABS(T(I2)-TP(N)).GT.0.05)GO TO 5
      PM(N) = PRA13(I2)
      IF(PMAX.GT.0.0)GO TO 9
      J1 = I2
    9 DIF = PM(N) -PMAX
      WRITE(2,90)N,PM(N)
      IF(DIF.LT.0.0)GO TO 6
      PMAX = PM(N)
    6 IF(N.EQ.ISURGES)GO TO 8
      N = N + 1
    5 CONTINUE
    8 WRITE(2,90)N,PMAX,J1
      WRITE(2,89)ISURGES
      RETURN
      STOP
      END

      SUBROUTINE FLOWS
      **********

     CALCULATION OF AIR FLOWS
     DURING  DELIQUORING TESTS

    ****************************

      COMMON /INPUT1/IV1(60),IV2(60),IV3(60),IV4(60),IV5(60)
      COMMON /INPUT2/IS1(60),IS2(60),IS3(60),IS4(60),IS5(60)
      COMMON /INPUT3/ST,DB,PB,FR,AB,DS,CF,TS,TF,TP(3),TC,TE,PDRY,PCLO
     1,PWET,ON
      COMMON /INTRIM/T(60),I,PR1(60),PR2(60),PR3(60),PRA13(60),
     1PRD(60),PR4(60),PM(3),PMAX,J1
      COMMON /FLOW/ FL(60),FLA,FLTOT,L,M,N,N1,N2,FLM(60),FLS(60)
   90 FORMAT(1H ,12HEND OF FLOWS/)
   89 FORMAT(1H ,15HSURGES UNDERWAY/)
      L = 0
      M = 0
      N =  0
      FLT = 0.0
      DO 1 I1 = 1,I
      IF(T(I1).GT.TF)GO TO 2
      IF(T(I1).GT.TS)GO TO 3
      FL(I1) = 0.0
      GO TO 1
    3 FL(I1) = FR
      N1 = I1
      GO TO 1
```

```
 2 IF(TC-T(I1).GT.0.05)GO TO 14
   IF(ABS(T(I1)-TE).LT.0.05)GO TO 15
 4 V = IV4(I1)
   S = IS4(I1)
   N2 = I1
   VOLTS = V * 10.0 **(-S)
   ION = ON
   GO TO(8,9,10,11,12),ION
 8 A = 1.14
   B = 15.31
   GO TO 13
 9 A = 1.14
   B = 15.31
   GO TO 13
10 A = 1.14
   B =  22.13
   GO TO 13
11 A =  1.14
   B = 22.13
   GO TO 13
12 A = 1.8
   B = 31.25
13 IF(VOLTS.LT.1.0)GO TO 5
   IF(VOLTS.GT.8.8)GO TO6
   FL(I1)  = A * VOLTS + B
   FLT  = FLT + FL(I1)
   N = N  + 1
   GO TO 7
 5 FL(I1) = (A * VOLTS +  B)/2.0
   M = M + 1
   GO TO 7
 6 FL(I1) = (A * VOLTS + B)*1.5
   L = L + 1
 7 FLM(I1) = FL(I1) * (1.0E5/(1.0E5 + PRM(I1)))
   FLS(I1) = FL(I1) * (1.0E5/(1.0E5 + PRA13(I1)))
   GO TO 1
14 WRITE(2,89)
 1 CONTINUE
15 WRITE(2,90)
   RETURN
   STOP
   END

   SUBROUTINE PERMS
  ****************

   CALCULATION OF CAKE PERMEABILITIES
          THROUGHOUT TEST RUNS

  ************************************

   COMMON /INPUTS/ ST,DB,PB,FR,AB,DS,CF,TS,TF,TP(3),TC,TE,PDRY,PCLO
  1,PWET,ON
   COMMON /INTRIM/ T(60),I,PR1(60),PR2(60),PR3(60),PRA13(60)
  1,PRD(60),PRM(60),PH(3),PMAX,J1
   COMMON /FLOW/ FL(60),FLA,FLTOT,L,M,N,N1,N2,FLM(60),FLS(60)
   COMMON /PERM/ ERDB,FLIW,PTW,PTNW,PINW(60),PRW(60),
  1PRNW(60)
```

```
      COMMON /VISC/ VISW,VISA,DLIQ,PRDL,SAVE
      COMMON /ALL/ DIAM,DIFF,SPH,I8
   90 FORMAT(1H ,I3,2X,E12.4,4X,E12.4,4X,E12.4,4X,E12.4,4X,2E12.4/)
      EQDB = DB + 0.7
      PTNW = PDRY
      PTW  = PWET
      FLIU = 1.0E-4
      DO 1 I1 = 1,I
      IF(T(I1).LT.TS)GO TO 2
      IF(T(I1).LE.TF)GO TO 4
      IF(TC-T(I1).GT.0.05)GO TO 2
      IF(ABS(TE-T(I1)).LT.0.05)GO TO 2
      GO TO 3
    4 PIW(I1)  = (16.7 * FR * VISW * EQDB)/(PRD(I1) * AB)
      PRDL     =  PRD(I1)/EQDB
      PINW(I1) = 0.0
      PRW(I1)  = PIW(I1)/PTW
      PRNW(I1) = 0.0
      WRITE(2,90)I1,PIW(I1),PINW(I1),PRW(I1),PRNW(I1),PRD(I1)
      GO TO 1
    3 PIW(I1)  = (16.7 * FLIU * VISW * EQDB)/(PRD(I1) *  AB)
      PINW(I1) = (16.7  * FLM(I1) * VISA * EQDB)/(PRD(I1) * AB)
      PRW(I1)  = PIW(I1) /PTW
      PRNW(I1) = PINW(I1)/PTNW
      WRITE(2,90)I1,PIW(I1),PINW(I1),PRW(I1),PRNW(I1),PRD(I1)
      GO TO 1
    2 PIW(I1)  = 0.0
      PINW(I1) = 0.0
      PRW(I1)  = 0.0
      PRNW(I1) = 0.0
      WRITE(2,90)I1

      SUBROUTINE CORREL
    **********************

      CALCULATION OF OTHER CORRELATING
            FACTORS FROM THEORY

    ************************************

      COMMON /INPUTS/ ST,DB,PB,FR,AB,DS,CF,TS,TF,TP(3),TC,TE,PDRY,PCL
     1,PWET,ON
      COMMON /INTRM/ T(60),I,PR1(60),PR2(60),PR3(60),PRA1B(60)
     1,PRD(60),PRM(60),PM(3),PMAX,J1
      COMMON /FLOW/ FL(60),FLA,FLTOT,L,M,N,N1,N2,FLM(60),FLS(60)
      COMMON /PERM/ EQDB,FLIU,PTW,PTNW,PIW(60),PINW(60),PRW(60),
     1PRNW(60)
      COMMON /VISC/ VISW,VISA,DLIQ,PRDL,SAVE
      COMMON /ALL/ DIAM,DIFF,SPH,I8
      DIMENSION COR1(60),COR2(60),COR3(60),COR4(60),COR5(60),
     1COR6(60),COR7(60),PIT1(60),PIT2(60),TRED(60),PRDE(60)
      DIMENSION SR01(60),SR02(60),CAPB(60),CAPN(60),VELA(60),
     1PRAT(60),DIP0(60),DIVE(60)
   90 FORMAT(1H ,4E16.4/)
```

```
1 FORMAT(1H ,2X,26HDRAINAGE NUMBER AND HEIGHT,6X,22HDRAINAGE HEIGHT
 1RATIOS//)
2 FORMAT(1H ,2X,51HACTUAL AND THEORETICAL DIAMETERS AND PERMEABILIT
 1ES//)
3 FORMAT(1H ,2X,34HRESIDUAL AND EFFECTIVE SATURATIONS//)
4 FORMAT(1H ,2X,49HBREAKTHROUGH PRESSURE LANDA AND PARTIAL PRESSURE
 1//)
5 FORMAT(1H ,I3,2X,F12.6,4X,4E16.4/)
6 FORMAT(1H ,44HDIMENSIONLESS TIMES PRESSURES AND VELOCITIES//)
7 FORMAT(1H ,38HCORRELATING FACTORS 4 TO 7 - DAHLSTROM//)
8 FORMAT(1H ,41HCORRELATED PRESSURE FLOW AND TIME FACTORS//)
9 FORMAT(1H ,46HDOMBROWSKI-BROWNELL SATNS/CAPN/THIN BED CORREL//)
0 FORMAT(1H ,26HDRYING RUN SATURATION ZERO////)
  PTW13 = PTW ** 0.333
  PTW12 = PTW ** 0.5
  VISR  = VISA/VISW
  DRNM  = PTW12 * DLIQ * 981.0 / ST
  DRHT  = 0.275 / DRNM
  HTRL  = DB /DRHT
  HTRE  = EQDB /DRHT
  BPRM  = (4.6 * (1.0 - PB) * ST)/(PB * DIAM)
  CAPA  = (PB ** 3.0 * DIAM ** 2.0)/(ST * (1.0 - PB) ** 2.0)
  RESP  = 1.0 /(PTW * (1.0 - PB) * DS)
  DIAN  = 13.4 * SQRT((1.0 - PB)/(RESP * DS * PB ** 3.0))
  PMOD  = (DIAM ** 2.0 * PB ** DIFF)/ 32.0
  VCON1 = (PB * DB)/VISR
  VCON2 = (PB * EQDB)/VISR
  PRAF  = BPRM /(PRD1 * EQDB)
  CORN  = (PN(1) * EQDB * (VISW-(20.0-CF)* 0.0002535))/ BPRM
  DO 1 I1 = 1,I
  IF(I1.EQ.J1)GO TO 12
  IF(T(I1).LT.TC)GO TO 1
  IF(T(I1).GT.TE)GO TO 1
2 THED(I1) = T(I1) - TF
  PRDE(I1) = PRD(I1)/EQDB
  IF(PRDE(I1).LE.0.0)GO TO 17
  COR1(I1) = ((DLIQ * PRDE(I1))/ DLIQ) ** 2.0
  COR2(I1) = PTW13 * COR1(I1)
7 CAPB(I1) = 981.0 * DLIQ * PRDE(I1)
  CAPN(I1) = CAPA * CAPB(I1)
  SR01(I1) = 0.155 * (1.0 + 0.031 * CAPN(I1) ** (-0.49))
  SR02(I1) = 0.025 * CAPN(I1) ** (-0.264)
  VELA(I1) = PINM(I1) * PRDE(I1) / VISW
  PRAT(I1) = BPRM / PRD(I1)
  DIT1(I1) = (PTW * BPRM * THED(I1))/(VISW * EQDB ** 2.0 * PB *(
 11.0 - SR01(I1)))
  DIT2(I1) = (DIT1(I1) * EQDB ** 2.0)/(DB ** 2.0)
  DIPO(I1) = PRD(I1) / BPRM
  IF(I1.EQ.J1)GO TO 1
  DIVE(I1) = (16.67 * FLM(I1) * VISA * EQDB)/(PTW * PMOD * AB)
  CONTINUE
  IF(SAVE.EQ.0.0)GO TO 10
  RED1 = (SAVE - SR01(I8))/(1.0 - SR01(I8))
  RED2 = (SAVE - SR02(I8))/(1.0 - 2.0 * SR02(I8) + SAVE * SR02(I8))
  WETP = ((1.0 - SAVE) * PB)/(1.0 - SR02(I8))
  REDE = RED1 **(-0.2)
  DISP = DIPO(I8) - REDE
  ALAN = ALOG(RED1)/ALOG(PRAT(I8))
```

```
      GO TO 11
   10 WRITE(2,100)
   11 WRITE(2,91)
      WRITE(2,90)DRNM,DRHT,HTRL,HTRE
      WRITE(2,92)
      WRITE(2,90)DIAM,PTW,DIAN,PMOD
      WRITE(2,93)
      WRITE(2,90)SR01(I8),RED1,SR02(I8),RED2
      WRITE(2,94)
      WRITE(2,90)BPRM,ALAN,DISP,DIP0(I8)
      WRITE(2,96)
      DO 2 I4 = 1,I
      IF(I4.EQ.J1)GO TO 13
      IF(T(I4).LT.TC)GO TO 2
      IF(T(I4).GT.TE)GO TO 2
   13 WRITE(2,95)I4,THED(I4),DIT1(I4),DIT2(I4),DIP0(I4),DIVE(I4)
    2 CONTINUE
      WRITE(2,97)
      DO 3 I5 = 1,I
      IF(I5.EQ.J1)GO TO 14
      IF(T(I5).LT.TC)GO TO 3
      IF(T(I5).GT.TE)GO TO 3
   14 WRITE(2,95)I5,THED(I5),CORN,COR5(I5),COR6(I5),COR7(I5)
    3 CONTINUE
      WRITE(2,98)
      DO 4 I6 = 1,I
      IF(I6.EQ.J1)GO TO 15
      IF(T(I6).LT.TC)GO TO 4
      IF(T(I6).GT.TE)GO TO 4
   15 WRITE(2,95)I6,THED(I6),PRAT(I6),PRDE(I6),VELA(I6)
    4 CONTINUE
      WRITE(2,99)
      DO 5 I7 = 1,I
      IF(I7.EQ.J1)GO TO 16
      IF(T(I7).LT.TC)GO TO 5
      IF(T(I7).GT.TE)GO TO 5
   16 WRITE(2,95)I7,THED(I7),SR01(I7),SR02(I7),CAPN(I7),COR2(I7)
    5 CONTINUE
      RETURN
      STOP
      END
```

III PDP 11 Computer.

A single computer programme was employed on this system during the project. The aim of the programme was to carry out a curve fitting operation on the experimental data. The programme, developed by Dr. Drott to fit concentration-time data to a curve of an exponential form, was written in Basic-Plus. It was split into four main sections:-

(i) Filing of data

(ii) Input of data

(iii) Basic calculation

(iv) Output of results

Dr. Drott is a lecturer in the Department of Chemical Engineering at Loughborough University.

Appendix E includes a sample input and output from the curve fitting programme.

APPENDIX D

Basic Saturation Results

I Continuous Flow Tests

Class	Time	Saturations	
HY1	4	0.7100	
	8	0.7145	
	10	0.7037	0.7247
	20	0.6892	0.7169
	30	0.6940	0.7069
HY2	10	0.6741	0.6322
	30	0.6922	0.6042
HY3	4	0.6176	
	8	0.5887	
	10	0.6053	0.6084
	20	0.5859	0.5680
	30	0.5537	0.5347
HY4	4	0.5332	
	8	0.5335	
	10	0.5413	0.5240
	20	0.5245	0.5303
	30	0.5789	0.5222
HY5	10	0.5308	0.5088
	30	0.5118	0.4880
HY6	4	0.5007	
	8	0.4966	
	10	0.4778	0.4952
	20	0.4707	0.4690
	30	0.4453	0.4667

Continuous Flow Tests (cont.)

Class	Time	Saturations	
HY7	10	0.5052	0.5021
	20	0.5051	0.5118
	30	0.5260	0.4998
HY8	10	0.4875	0.4985
	30	0.4872	0.4740
HY9	10	0.4556	0.4475
	20	0.4444	0.4424
		0.4326	
	30	0.4190	0.4510

Continuous Flow Tests (cont.)

Class	Time	Saturations	
HP1	4	0.9084	
	6	0.8998	
	8	0.8946	
	15	0.8262	0.8496
	30	0.8505	0.7869
	45	0.7926	0.7311
		0.7244	
HP2	4	0.8440	
	6	0.8905	
	8	0.8828	
	15	0.8226	0.7588
	30	0.6860	
	45	0.5772	0.6429
HP3	4	0.8108	
	6	0.9002	
	8	0.7582	
	15	0.6985	0.7270
	30	0.5863	
	45	0.3785	0.4797
	60	0.2473	

Continuous Flow Tests (cont.)

Class	Time	Saturations	
HP4	4	0.7066	
	8	0.7124	
	15	0.6048	0.6069
	45	0.5483	0.5580
HP5	15	0.5454	
	45	0.4630	
HP6	4	0.6030	
	8	0.5485	
	15	0.4871	0.4854
	30	0.4605	
	45	0.3347	0.3808
	60	0.2879	
HP7	15	0.5276	0.5425
	30	0.5496	
	45	0.5156	0.5216
HP8	15	0.4661	0.4830
	45	0.4226	0.4109
HP9	15	0.4465	0.4137
	30	0.3914	
	45	0.3291	0.3467
	60	0.2796	

Continuous Flow Tests (cont.)

Class	Time	Saturations	
C4	15	0.9646	0.9573
	30	0.9309	
C6	15	0.8776	0.8726
	30	0.7767	
C7	15	0.8832	
C9	15	0.7727	

(i) Viscosity Tests

Class	Viscosity	Saturations	
HP1	1.47	0.7654	0.7396
	1.65	0.6740	0.7025
HP3	1.47	0.6181	0.6624
HP4	1.47	0.5477	0.5740
	1.65	0.5485	0.5554
HP6	1.47	0.4452	0.4716

(ii) Thin Cakes - HPF5 Test Dust

Cake Depth	Time	Saturations
0.2	10	1.0473
	20	0.9869
0.3	10	0.8821
	20	0.8723
0.6	10	0.6329

Continuous Flow Tests (cont.)

(iii) Humidity Tests

Class	Time	Saturations
HY3	75	0.3034
HY7	180	0.3579
HP4	75	0.5705

II Intermittent Flow Tests

Class	Pressure (~~kN/m^2~~) ($\times 10^5$ N/m^2)	Saturation
HY - I1	0.3024	0.8072
	0.3273	0.7805
	0.3217	0.7841
	0.5325	0.6672
	0.5244	0.6977
	0.5326	0.6847
	0.8500	0.6020
	0.7685	0.5882
	0.8499	0.6029
	1.117	0.5640
	1.149	0.5724
	1.161	0.5424
HY - I2	0.3099	0.5473
	0.3258	0.5529
	0.3276	0.5643
	0.3276	0.5643
	0.5350	0.5608
	0.5387	0.5604
	0.5138	0.5681
	0.8620	0.5587
	0.8402	0.5281
	0.8836	0.5466
	1.139	0.5044
	1.153	0.4922
	1.132	0.5047

Intermittent Flow Tests (cont.)

Class	Pressure ~~(kN/m^2)~~ ($\times 10^5$ N/m^2)	Saturations
HY - I3	0.3193	0.5188
	0.3089	0.5186
	0.3258	0.5446
	0.4854	0.5191
	0.5047	0.5055
	0.5307	0.5371
	0.7553	0.5122
	0.8640	0.5109
	0.8609	0.5106
	1.108	0.4904
	1.135	0.4869
	1.155	0.4790

Intermittent Flow Tests (cont.)

Class	Pressure ~~(kN/m^2)~~ ($\times 10^5$ N/m^2)	Saturations
HP - I1	0.2237	0.9947
	0.2203	0.9913
	0.2271	0.9687
	0.3367	0.8529
	0.3369	0.8593
	0.5287	0.6915
	0.5233	0.8257
	0.5341	0.7765
	0.8317	0.6936
	0.8268	0.7018
	0.8218	0.6376
	0.8650	0.6947
	1.136	0.7362
	1.127	0.6741
	1.155	0.6791
	1.403	0.6158
	1.400	0.6988

APPENDIX E

Stastical Analysis of Results

I Best fit to data - Continuous Tests

Test Class	N	Approximate 90% Limit	K	Approximate 90% Limit
HY1	-5.6	$\pm$ 37.4	$.8 \times 10^{-4}$	$\pm .117 \times 10^{-3}$
HY2	7.7	$\pm$ 21.5	$.59 \times 10^{-1}$	$\pm$ .112
HY3	-3.2	$\pm$ 9.5	$.46 \times 10^{-3}$	$\pm .142 \times 10^{-3}$
HY4	31.0	$\pm$ 25.0	2091	$\pm 2.54 \times 10^{5}$
HY5	-6.9	$\pm$ 33.5	$.78 \times 10^{-5}$	$\pm .26 \times 10^{-4}$
HY6	-3.4	$\pm$ 10.3	$.14 \times 10^{-3}$	$\pm .5 \times 10^{-4}$
HY7	36.2	$\pm$ 45.3	$.92 \times 10^{7}$	$\pm .34 \times 10^{8}$
HY8	-6.0	$\pm$ 45.6	$.82 \times 10^{-5}$	$\pm .16 \times 10^{-4}$
HY9	-16.0	$\pm$ 26.0	$.15 \times 10^{-8}$	$\pm .22 \times 10^{-8}$
HP1	-2.49	$\pm$ 5.5	$.22 \times 10^{-2}$	$\pm .63 \times 10^{-3}$
HP2	0.55	$\pm$ 2.5	$.79 \times 10^{-2}$	$\pm .18 \times 10^{-2}$
HP3	0.04	$\pm$ 0.6	$.11 \times 10^{-1}$	$\pm .16 \times 10^{-2}$
HP4	11.69	$\pm$ 4.1	1.42	$\pm$ .29
* HP5	1.0	--	0.55×10^{-2}	--
HP6	0.58	$\pm$ 1.2	$.84 \times 10^{-2}$	$\pm .15 \times 10^{-2}$
HP7	22.0	$\pm$ 38.0	719	$\pm$ 1070
HP8	2.8	$\pm$ 10.0	$.19 \times 10^{-1}$	$\pm .9 \times 10^{-2}$
HP9	-0.12	$\pm$ 2.0	$.29 \times 10^{-2}$	$\pm .7 \times 10^{-3}$

* Insufficient data to carry out fitting exercise

II Best fit to data - Intermittent Tests

Test Class	N	Approximate 90% Limit	K	Approximate 90% Limit
HY-I1	4.3	± 1.9	1.72	± .21
HY-I2	-7.9	± 11.4	0.46×10^{-3}	± $.20 \times 10^{-3}$
HY-I3	4.7	± 9.5	1.17	± .43
HP-I1	2.9	± 2.42	0.50	± .15
HP-I2	Curve fitting impractical due to excessive			
HP-I3	scatter of results			

III Best Straight Line - Continuous Tests

Test Class	$(K \times 10^3)$ gradient $\times 10^3$	Intercept at zero time
HY1	0.57	0.715
HY2	1.81	0.670
HY3	2.67	0.639
HY4	0.62	0.538
HY5	0.82	0.527
HY6	1.71	0.501
HY7	(-0.46)	0.500
HY8	0.62	0.498
HY9	0.83	0.458
HP1	3.6	0.893
HP2	6.65	0.880
HP3		0.872
HP4	3.42	0.633
HP5	2.75	0.587
HP6	5.10	0.565

III (continued)

Test Class	$(K \times 10^3)$ gradient $\times 10^3$	Intercept at zero time
HP7	0.56	0.547
HP8	1.93	0.505
HP9	3.28	0.483

IV Best fit for Depth/Intercept Saturation

	Power	Gradient
Hyflo Supercel		
HPF5	1.9	0.91

IV Sample input and output of curve fitting programme.

i) Input.

```
CASE NO. 1
TITLE=? HY04520
NO. OF DATA FILES=? 1
SOURCE FILE=? DATAD3
   1    4                7.100E-01
   2    8                7.145E-01
   3   10                7.037E-01
   4   10                7.247E-01
   5   20                6.892E-01
   6   20                7.169E-01
   7   30                6.940E-01
   8   30                7.069E-01
   9   10                6.741E-01
  10   10                6.322E-01
  11   30                6.299E-01
  12   30                6.042E-01
  13    4                6.176E-01
  14    8                5.887E-01
  15   10                6.053E-01
  16   10                6.084E-01
  17   20                5.859E-01
  18   20                5.680E-01
  19   30                5.537E-01
  20   30                5.347E-01
```

```
NEW OR OLD--RUNFIT

FIT: MAXIMUM LIKELIHOOD ESTIMATION USING DATA TRANSFORMATION

PRINT FILE CONTENTS? NO. OF CASES=? 0
CASE NO. 1
TITLE=? HPDPSAT
NO. OF DATA FILES=? 1
SOURCE FILE=? DATAD5
POINTS TO BE USED:[FIRST NO,LAST NO]=? 1,9

TIME SCAN FOR GRAPH:[START,FINISH,STEP SIZE]=? 0,1..04
GRAPH OF SD ERROR VS ORDER:[YES/NO]? YES
PRINT TRANSFORMED DATA ANALYSIS:[YES/NO]? YES
GRAPH OF 95% CONF. INTERVAL:[YES/NO]? YES
TRY AN ADDITIONAL MODEL:[YES/NO]? YES
ORDER=? 2
TRY AN ADDITIONAL MODEL:[YES/NO]? NO
```

(ii) Programme output.

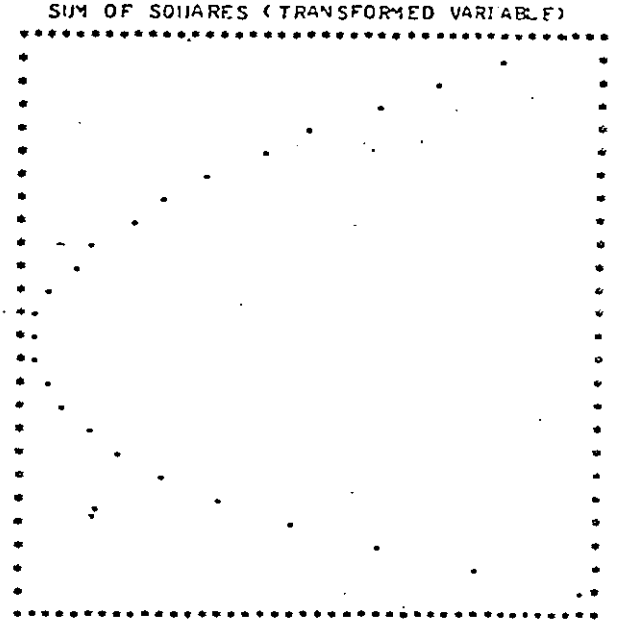
```
FIT: HP84540
------------

NO. OF DATA SETS= 1

DATA SET NO. 1
--------------
NO. OF POINTS= 9
DATA:[TIME,SATN.]
     0.00    8.1030E-01
     2.00    9.0020E-01
     4.00    7.5820E-01
    11.00    6.9850E-01
    11.00    7.2700E-01
    26.00    5.8630E-01
    41.00    3.7850E-01
    41.00    4.7970E-01
    56.00    2.4730E-01
```

N	S*2
-1.2	.101027
-1.1	.926832E-1
-1	.850683E-1
-.9	.781582E-1
-.8	.719352E-1
-.7	.663862E-1
-.6	.615042E-1
-.5	.572874E-1
-.4	.537404E-1
-.3	.508744E-1
-.2	.487072E-1
-.999999E-1	.472642E-1
.119209E-6	.046579
.1	.466944E-1
.2	.476623E-1
.3	.495473E-1
.4	.524256E-1
.5	.563356E-1
.6	.615331E-1
.7	.679907E-1
.8	.759084E-1
.9	.854275E-1
1	.967615E-1
1.1	.110122

SUM OF SQUARES (TRANSFORMED VARIABLE)



```
BEST VALUES ARE:
N= .358024E-1
K= .010522

CONFIDENCE INTERVALS FOR N:
```

CONFIDENCE LEVEL	N(MIN)	N(MAX)
90%	-.628792	.622035
95%	-.789057	.74417
99%	-1.15575	1.00392

FIT: HP04540

PROPOSED MODEL:
ORDER= .036
K= .105233E-1

CONFIDENCE INTERVALS FOR K:

CONFIDENCE LEVEL	K(MIN)	K(MAX)
90%	.89427E-2	.121038E-1
95%	.855054E-2	.012496
99%	.76043E-2	.134422E-1

UNTRANSFORMED DATA

T	C(CALC)	C(EXPER.)	RESIDUAL	% OF STD DEV
0	.541342	.8103	-.305419E-1	-64.384
2	.820435	.9002	.797643E-1	168.147
4	.799548	.7582	-.413477E-1	-87.163
11	.7266	.6985	-.280997E-1	-59.235
11	.7266	.727	.400364E-3	0.844
26	.571203	.5863	.150967E-1	31.824
41	.417332	.3785	-.038532	-81.859
41	.417332	.4797	.062368	131.474
56	.265521	.2473	-.182205E-1	-38.410

DATA STANDARD DEVIATION= .474375E-1
ANALYSIS OF VARIANCE:

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
UNTRANSFORMED DATA	3.83733	9	
UNTRANSFORMED MODEL	3.82125	2	1.91062
UNTRANSFORMED RESIDUAL	.157522E-1	7	.225032E-2

MEAN SQUARE RATIO= 849.047

TRANSFORMED DATA

T	Z(CALC)	Z(EXPER.)	RESIDUAL	% OF STD DEV
0	-.448036	-.396822	.520147E-1	63.821
2	-.412439	-.543036	-.135647	-166.354
4	-.376841	-.306274	.705673E-1	86.558
11	-.252249	-.204138	.048111	59.013
11	-.252249	-.252934	-.684947E-3	-0.840
26	.147331E-1	-.113036E-1	-.260417E-1	-31.945
41	.231715	.349612	.673963E-1	83.231
41	.231715	.173135	-.10558	-133.184
56	.545698	.581064	.323657E-1	39.700

DATA STANDARD DEVIATION= .815265E-1
ANALYSIS OF VARIANCE:

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
TRANSFORMED DATA	1.14665	9	
TRANSFORMED MODEL	1.10312	2	.550062
TRANSFORMED RESIDUAL	.046526	7	.664657E-2

MEAN SQUARE RATIO= 82.7588

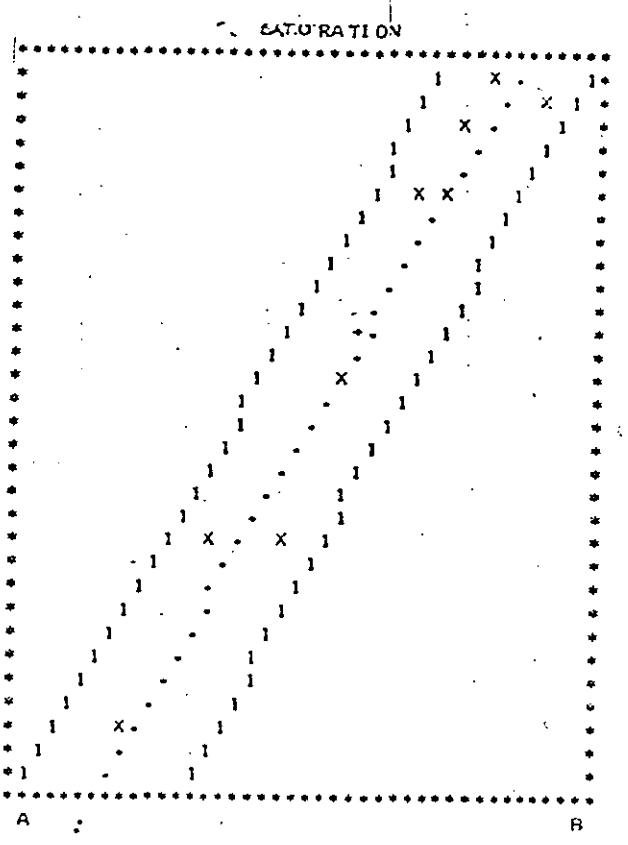
FIT: HP04540

DATA SET NO 1

ORDER= 0

C0= .840354

T-4 MIN.	SATN.
0	.840354
2	.819764
4	.799173
6	.778583
8	.757992
10	.737402
12	.716811
14	.696221
16	.67563
18	.65504
20	.634449
22	.613859
24	.593268
26	.572678
28	.552087
30	.531497
32	.510906
34	.490316
36	.469725
38	.449135
40	.428544
42	.407954
44	.387363
46	.366773
48	.346182
50	.325591
52	.305001
54	.28441
56	.26382
58	.243229
60	.222639



LEGEND

A= .821203E-1

B= .964416

X=DATA

+=BEST ESTIMATE

•=PROPOSED MODEL

1 1=95% CONFIDENCE INTERVAL FOR PROPOSED MODEL
(ASSUMING CONSTANT VARIANCE OF TRANSFORMED VARIABLE)

NOMENCLATURE

a	Centrifugal force
A	Filter area
A_P	Specific surface (particles)
A_B	Specific surface (bed)
B	Kozeny constant
c	Speed of shock
C_t	Time constant
C_v	Volume constant
d	Particle diameter
e_o	Shape factor
f	Friction factor
F_a	Approach factor
F_c	Correlating factor
g	Acceleration due to gravity
K	Permeability (W = wetting phase, NW = non wetting)
L	Bed depth
L_a	Drainage height
m	Exponent of sphericity/porosity ratio
m^1	Exponent of sphericity/porosity ratio (wetted particle)
n	Exponent of sphericity/porosity ratio
n^1	Exponent of sphericity/porosity ratio (wetted particle)
N	A general number
P_b	Breakthrough pressure
P_b^*	Modified breakthrough pressure
P_c	Capillary pressure
ΔP	Pressure drop
q	Flow rate/unit area
Q	Volume flowrate
$r_{1,2}$	Radii of meniscii
Re	Reynolds number
S	Saturation
S_E	Effective saturation
S_f	Reduced saturation
S_R	Residual saturation
t	Time
U	Fractional flow
$V_{L,G}$	Liquid or gas velocities

x	Distance
y	Porosity exponent
z	Tortuosity
γ	Surface tension
μ	Viscosity
ϵ	Porosity
ϵ'	Wetted porosity
λ	Pore size distribution index
ρ	Density
σ	Contact angle
ψ	Sphericity
ψ'	Wetted sphericity

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