THE INFLUENCE OF BULK PARTICULATE PROPERTIES ON PNEUMATIC CONVEYING PERFORMANCE

by

MARK G JONES

Collaborating body
Warren Spring laboratory
Department of Trade and Industry
Stevenage
Herts.

THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY UNDER THE CONDITIONS FOR THE AWARD OF HIGHER DEGREES OF THE COUNCIL FOR NATIONAL ACADEMIC AWARDS

SCHOOL OF ENGINEERING
THAMES POLYTECHNIC
LONDON SE18 6PF

March 1988

ABSTRACT

THE INFLUENCE OF BULK PARTICULATE PROPERTIES ON PNEUMATIC CONVEYING PERFORMANCE

BY M. G. JONES

Interest in the use of dense phase conveying has grown considerably in recent years. However, not all products are capable of being conveyed in dense phase and it is often difficult to predict which products have dense phase capability without carrying out pilot conveying trials.

The main objective of this work was to investigate the effect of bulk particulate properties on pneumatic conveying performance. To achieve this, an extensive programme of conveying trials was carried out and each product tested was subjected to a series of bench scale tests to evaluate the bulk properties of the material.

A phase diagram is proposed, based on the aeration properties of a material, which groups together products of similar conveying potential. The phase diagram gives a first indication on the basis of a small sample of material whether or not a product is capable of dense phase conveying. Further, it will predict the most appropriate mode of flow.

For products capable of dense phase in a moving bed type flow regime, a further correlation is proposed which predicts the likely conveying performance in the pipeline in terms of mass throughput of product for given conditions based on the air retention characteristics of a product. The correlation has been generalised to extend its applicability to a range of pipeline configurations. The combination of the phase diagram and the correlation for dense phase moving bed type flow (the most commonly used form of dense phase conveying) provides a powerful design tool which will reduce the need for full conveying trials.

In addition, the effect of material bulk properties on blow tank performance has also been investigated and a correlation between aeration properties and blow tank discharge characteristics is proposed.

AUTHOR'S NOTE

All the work in this thesis is the sole and original work of the author, except where stated otherwise by acknowledgement or reference.

ACKNOWLEDGEMENTS

The author would like to acknowledge the financial assistance of the Department of Trade and Industry.

The assistance and guidance of Dr J S Mason, Dr D Mills, Dr C R Woodcock and Dr A R Reed during the course of this reseach programme is gratefully acknowledged.

The practical assistance of the technical staff of the School of Engineering was extremely valuable. In particular the author would like to thank Mr J Milton, Mr G Gowers, Mr B Lewis and Mr A Mason for their enthusiastic support.

NOMENCLATURE

A_t	area of throat
A	pipeline cross-sectional area
C	superficial gas velocity
C	permeability factor
C_{max}	maximum superficial air velocity
C_{min}	minimum superficial air velocity
C_d	coefficient of discharge
d	pipe diameter
d	effective particle diameter
d'	mean particle size
D	bend diameter
g	gravitational acceleration
K'	de-aeration constant
K_v'	vibrated de-aeration constant
L	length in the direction of the fluid flow (bed height)
L	conveying distance
L_e	equivalent length
L_1	initial bed height
L_2	final bed height
m	mass flow rate of gas
m_a	mass flow rate of air
m_p	mass flow rate of product
m_{max}	maximum mass flow rate of gas through nozzle
M	solids mass flux

p	pressure
p_{abs}	absolute pressure
Δp	pressure drop
p_b	nozzle downstream (back) pressure
p_o	upstream stagnation gas pressure
p_b/p_o	pressure ratio across nozzle
p^*/p_o	pressure ratio at throat section
R	characteristic gas constant
T	absolute temperature
T_o	absolute temperature of gas at stagnation condition
U	superficial percolation velocity
U_{MB}	superficial gas velocity at minimum bubbling condition
U_o	superficial gas velocity at minimum fluidising velocity
V	volumetric flow rate

γ	isentropic exponent
Γ	phase density factor
Δ	prefix meaning change in
ϵ	voidage
λ	a function of bed height, f (L)
μ	absolute fluid viscosity
π	constant 3.14159
ρ	density
ρ	product bulk density
ρ_f	density of fluid
ρ_o	upstream stagnation gas density
ρ_s	density of solids
τ	time
ϕ	phase density (solids loading ratio)

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND TO PROJECT

The use of dense phase conveyors in industry has increased significantly in recent years on a world-wide basis. Most manufacturers now market dense phase systems, many of which claim low energy consumption and minimum degradation and erosion amongst other benefits. The increased use of dense phase systems has led to an increased interest, especially by user companies, in the capabilities, design, operation and control of such systems.

Interest was such that the Department of Trade and Industry set up a collaborative research project between the Warren Spring Laboratory, Thames Polytechnic and a group of twenty companies (both manufacturers and users) with interests in the design of pneumatic conveying systems. One of the areas of concern identified by the collaborative group was the effect of product properties on pneumatic conveying performance.

Preliminary work carried out by the author whilst under contract to the Department of Industry formed the basis of the research project reported in this thesis. The initial choice of products was influenced by the suggestions of member companies who inevitably proposed materials which they found difficult to convey. This was in contrast to many researchers who often chose convenient materials which had small size distributions and were easy to convey. However, this did ensure that the research was carried out using materials which are commonly conveyed in industry and which have particular problems of conveyability.

The pipeline configurations were also dictated by the needs of the Department of Industry project since the results from the test work carried out by the author had to be compatible with the rest of the Design Guide project.

A considerable number of products have been added to those initially tested for the Department of Industry and the research has been developed considerably from that which was provided by the author for the

Pneumatic Conveying Design Guide which was the culmination of the collaborative project.

1.2 OUTLINE OF OBJECTIVES

One of the aims of the work was to attempt to identify criteria upon which a material classification could be built grouping materials of similar conveyability; in short, a phase diagram. The difficulty of identifying whether or not a product will convey in dense phase and if so in what flow regime, without carrying out full scale tests, has always been a problem. Other workers have suggested various classifications, most of which have been criticised for using parameters which do not truly characterise the material with regard to pneumatic conveying.

It was also apparent that products which can be conveyed in a moving bed type dense phase flow regime displayed a variety of conveying performance levels for given conditions of velocity and pressure drop. This indicated that the variation in performance level must be dependent on the characteristics of the product being conveyed. This was investigated and a correlation is presented in chapter 7 between performance level and bulk product characteristics.

In order to investigate the performance of the various products over as wide a range of conveying conditions as possible a high pressure blow tank was used. Both top and bottom discharge configurations were employed for feeding the products into the various pipelines under investigation

Since the conveying line can operate at a number of different product throughputs for a given set of conditions it would seem that the blow tank characteristics must vary with the type of product being conveyed. Work was carried out additionally, therefore, to investigate the effect of product type on the discharge characteristics of the blow tank. A similar relationship to that of the pipeline was found to exist and a correlation for blow tank discharge characteristics and product *properties is presented in chapter 8. In addition, a short investigation into the difference in performance of the conventional top and bottom discharge blow tank systems is also presented in chapter 8.*

1.3 STRUCTURE AND SCOPE OF THE THESIS

A detailed description of the conveying test plant and methods of measurement is given in chapter 3 and a comprehensive guide to the conveying trials is presented in chapter 4. A brief description of most of the bench scale tests is given with references made to the standard tests and procedures used. However, a slightly more detailed account is given for the determination of permeability factor since the factor is not widely used and a detailed account is given for the determination of the vibrated de-aeration constant. The vibrated de-aeration constant is a test developed by the author to obtain an indication of the air retention properties of a material avoiding many of the disadvantages of conventional tests. The test allows determination of the vibrated de-aeration constant for most products within 10 minutes.

Details of all the materials which were conveyed during the conveying trials are presented in chapter 6. One page is devoted to each product containing a size distribution, a micrograph, the relevant material properties and some comments.

A considerable proportion of the review of previous work (chapter 2) is devoted to discussing other workers' definitions of dense phase flow. This highlights the lack of agreement and confusion that exists. A popular and sensible definition which appears to have a broad spread of support and which is the definition adopted by the author is that based on non-suspension flow. That is, all flow regimes which are predominantly non-suspension in nature are considered to be dense phase. However, it follows that dense phase conveying covers a very wide spread of flow conditions under this definition. In general, the author has (in line with other workers' thinking) divided dense phase conveying into two broad flow regimes of moving (or sliding) bed type flow and plug flow.

These flow regimes are basically dependent on the product type and the pipeline conditions.

In general, the chapters in this thesis have been written so that, to some extent, they can be read and understood on their own without excessive cross referencing so that the reader can assimilate the required information without reading the whole thesis. At the beginning of each chapter there is a short introduction to set the scene and at the end of most chapters a short section of concluding remarks to summarise the most significant points.

CHAPTER 2

REVIEW OF PREVIOUS WORK AND CURRENT INDUSTRIAL PRACTICE

2.1 INTRODUCTION

The earliest published work on dense phase pneumatic conveying is that of Albright et al.(Ref. 2.1) in 1949 which was carried out in the USA. This early work was prompted by the need to convey coal to feed a coal gasification reactor using a minimum of conveying gas. Since 1949 a great deal of research work has been carried out in the field of dense phase pneumatic conveying and the last 25 years has seen a slow but steady growth in the use of dense phase systems in industry. Some confusion has occurred, however, relating to dense phase conveying due to a misunderstanding of terms and definitions which have been published both by academic institutions and manufacturers.

The manufacturers of dense phase systems have been quick to point out the advantages of their systems in terms of reduced power consumption, material degradation and pipe erosion. However, the term dense phase has been used to describe a wide range of flow conditions and therefore the term dense phase conveying does not always identify a particular flow regime. This means that two systems both described as dense phase systems can have different operating conditions in terms of velocity, solids loading ratio and pressure. This in turn will mean that material degradation, pipeline erosion and power requirements will vary considerably.

There is, as yet, no universally accepted definition of dense phase conveying and it has been used to describe virtually every flow regime other than suspension flow. At the time of writing a Glossary of Terms used in pneumatic conveying is being prepared by the British Standards Institution for this very reason. It would be useful at this stage to consider the various definitions of the term dense phase and how it is applied to the flow regimes identified by the various authors.

2.2 DEFINITIONS OF DENSE PHASE PNEUMATIC CONVEYING

Many different criteria are used in assessing whether a flow is dense phase or not. In some cases the term dense phase is used as a descriptive term to cover a range of flow regimes such as that employed by Ramachandran et al. (Ref. 2.2). In other cases the term is used specifically to describe a particular flow regime as shown by Schuchart (Ref. 2.3) who used the term to mean plug flow.

Some workers categorise the phase of conveying on the basis of phase density. Phase Density (or solids loading ratio) is simply a dimensionless ratio of the mass flow rate of product to the mass flow rate of air. Many people still relate to the Engineering Equipment Users' Association definition which is, in effect, a concentration. If the phase density (or solids loading ratio) is greater than a certain value then the flow is considered to be dense phase. Ramachandran et al. (Ref. 2.2) suggested phase densities of 25-100 for dense phase while Schuchart (Ref. 2.3) stated that values in excess of 100 indicate dense phase. Other publications (Ref. 2.4) quote values of phase density greater than about 40 as indicating dense phase flow and phase densities of between 10-40 are considered to be medium phase flow. It can be seen that even on the basis of a single criteria for defining dense phase flow considerable confusion exists.

Dixon (Ref. 2.5) pointed out that the maximum phase density that can be obtained is a function of the material properties, the pipeline system (equivalent length) and the operating conditions (mass flow rate of solids). Therefore, although for a given product in a given system the phase density may give an indication as to the flow regime, phase density is not a general guide to flow regime from one condition to another. Dixon showed how phase density for a given set of conditions could be used to estimate how far into the dense phase region a conveyor was operating when compared with the theoretical maximum calculated using his model. Dixon's model is actually derived using analysis for incipiently fluidised beds. Strictly, it is only valid for vertical conveying but, as horizontal pipes are likely to exhibit the same qualitative behaviour it is useful in demonstrating the general effect of material properties on phase density. However, although phase density may not be the ideal way of categorising the flow it is nevertheless a valuable parameter when designing a conveying system since it does not vary with air density and pressure.

Dixon and Simms (Ref. 2.6) defined dense phase on the basis of gas velocity. They suggested that for horizontal pipes, the gas flow must be insufficient to support all particles in suspension if the flow is to be considered dense phase. This view is supported by Arnold and Armitage (Ref. 2.7) who suggested that current usage of the term dense phase describes all conveying regimes where the superficial gas velocity is less than saltation velocity for horizontal sections of pipe.

Chen et al. (Ref. 2.8) define dense phase on the basis of volume concentration. They suggested that a value greater than 50% indicates dense phase. However, the problem of gas compressibility renders volume concentration a variable along the length of the pipe and therefore makes it a difficult parameter to obtain. The volume concentration definition has not been widely accepted and is not reported with the same frequency as those of velocity and phase density.

A number of workers define dense phase broadly by applying limits of both phase density and velocity. Both criteria have to be met for the flow to be considered dense phase. Shepherd (Ref. 2.9) defined dense phase conveying systems as those that operate with particle velocities less than 12m/s with high material concentrations i.e. greater than 20. Fenton (Ref. 2.10) described dense phase conveying as the condition when the conveying velocity is reduced to the point where gravitational settling of the material occurs on the bottom of the pipe. Fenton also stated that material mass loading ratios greater than 25:1 characterise dense phase conveying. Fenton singled out 'slug' flow as a third regime and does not consider it to be dense phase. This is in marked contrast to Schuchart (Ref. 2.3) who only considered plug flow to be dense phase.

It is probably not possible to define dense phase conveying in terms of specific values of phase density alone, for apart from the different response of different products, it is possible in a high pressure system to start with a low velocity in dense phase and end with a high velocity in dilute phase in the same system and all at the same phase density.

Two other ways of defining dense phase are reported by Konrad et al. (Ref. 2.11). The first is defined by the conveying of solids by air along a pipe that is filled with solids at one or more cross-sections. This is very similar to assuming that dense phase means plug or slug flow. However, it would cover many of the degenerate variations of plug flow conveying. The second definition is quite different. It is reported that some authors in the USA apply the term to any pneumatic conveying system utilising high pressure air. Using this definition, it is quite possible for a suspension flow regime to be considered dense phase particularly when conveying over long distances.

In general, the term dense phase is used to describe all flow regimes that are not suspension flow. In this work the author uses the term dense phase in a general sense to cover all non-suspension flow regimes.

2.3 THE FLOW REGIMES OF NON-SUSPENSION FLOW

Most workers broadly agree on the existence of the various modes of flow. The diversity of opinion is generally over terminology. Wen and Simons (Ref. 2.12) were amongst the first workers to identify various modes of flow. They described four modes of flow based on velocity. At high velocities the flow is a homogenous suspension of gas and solid. As the velocity is decreased particles fall out of suspension and segregate into a dune formation. As the velocity is further reduced the flow becomes intermittent with alternate slugs of solid and gas. The fourth regime occurs as the velocity becomes very low and a stationary layer is formed with ripples travelling along the top.

Some confusion in the literature is apparent over the order in which the last two flows described by Wen and Simons occur. Wirth and Molerus (Ref. 2.13) described the stationary bed occupying the lower part of the pipe cross-section as occurring before plug flow. This is also supported by the work of Doig (Ref. 2.14) and Welschof (Ref. 2.15). Wirth and Molerus also sub-divided the dune flow into continuous stratified flow and discontinuous dunes.

However, most workers effectively split the modes of flow into three major categories. In order of decreasing velocity they are dilute phase suspension flow, sliding or moving bed type flow and plug or slug flow.

In this work the author uses these three broad categories to describe the modes of flow since these three general modes of conveying have particular relevance when correlated with material properties.

It is interesting to note that Doig (Ref. 2.14) implied that mature plug flow is not possible without some innovative system such as the air knife or a bypass system to create the plugs. This is strongly refuted by Hitt (Ref. 2.16) who argued that the plugs are naturally forming without the use of special techniques especially for granular products.

2.4 REVIEW OF PREVIOUS WORK IN DENSE PHASE (NON-SUSPENSION) CONVEYING

There has been an abundance of published work in this field over the last thirty years. However most of it can be classified into three major categories for horizontal conveying:

1) *Analysis of the mechanics of flow - This normally takes the form of a force balance and often becomes a pressure drop prediction model. In general different models are formulated for the different modes of flow. Often these models are compared with experimental data from only one or two products and the models rarely have significant dependence on material properties.*

2) The use of phase diagrams - These are often qualitative. Those that are not usually relate to a particular product. This is an interesting point since it tends to show that the conveying performance varies widely depending on the product type.

3) Product suitability for dense phase conveying - It is only in the last 10-15 years that the effect of product type on conveying performance has been fully realised. Even so, much of the available literature discusses the importance of product type on conveying performance only in descriptive terms.

A detailed review of the most relevant contributions to the literature in the above categories is given below:-

2.4.1 Analysis of the Mechanics of flow

In the mid 1960's attempts were made to extend the models derived for dilute phase conveying to cover dense phase transport. The two most notable attempts were made by Rausch (Ref. 2.17) and Weber (Ref. 2.18) who both used a quasi-fluid flow model to predict pressure gradient at any point in the conveying pipeline. They both made allowances for the fact that particles were present in the flow by inclusion of an additional friction factor. However, they chose different methods to extend the model from the point where pressure gradient at a point could be calculated to being able to calculate the pressure drop across the entire pipeline.

Rausch performed an integration over the pipeline length on the equation derived for pressure gradient. This assumed that the coefficients in the pressure gradient equation remained constant. The effects of acceleration were then added to the integration. By contrast, Weber used a stepwise computer solution. This had the advantage of being able to accommodate variation in the coefficients and the acceleration effects.

Both Rausch and Weber suggested that the quasi-fluid flow approach could be used for phase densities up to 100 providing the flow was still homogenous. No attempt was made at suggesting what phase density is a reasonable maximum for homogenous flow. However, very few products, if any, are likely to yield homogenous flow conditions at such a high phase density. It is the fact that non-suspension flow by its very nature cannot be truly homogenous that prompted other workers to subsequently reject the use of quasi-fluid flow models in modelling dense phase flow.

In 1969 Muschelknautz and Krambrock (Ref. 2.19) published work that questioned the use of quasi-fluid flow methods. They showed that below a critical Froude number, i.e. a critical velocity, the additional friction factor due to the presence of the particles was sensitive to velocity. The range of Froude numbers over which the friction factor is sensitive to velocity coincides with that of sliding bed type flow. Hence, they concluded that the use of quasi-fluid flow models for these flow regimes was principally unsound.

Muschelknautz and Krambrock produced a model for what they called 'stratified' flow. They defined stratified flow conveyance as having a phase density between 10-100 and velocity of about 6 - 20m/s. The flow of fine powders with very small size distributions was described as layered and having a rolling and flowing motion very much like a fluidised bed. Coarser and less regularly shaped particles were described as forming deposits resembling low shifting dunes with a slow forward movement, often separated by rolling and fluidised layers.

The model is based on a force balance on a layer of material occupying the lower cross-section of the pipe. The forces acting are assumed to be the interior pressure across the layer; the layer weight giving rise to friction opposing movement; and a surface thrust due to the bombardment of the layer upper surface by the suspension cloud travelling along the upper cross-section of the pipe. It is assumed that the bombarding particles completely transfer their momentum to the solids layer and thereby freshly ejected particles are moving at speeds very little greater than the speed of the surface layer. Other than the transfer of momentum, the suspension cloud is considered insignificant to the problem.

This type of analysis does not lend itself to allowing for product property variations. In this model, for example, there are only two product related parameters. The first is particle diameter or mean diameter which is used in conjunction with pipe bore as a scaling factor; the second is the frictional coefficient which is said to have a very narrow range and so an average value is used. Therefore, the model does not show up the variation in conveying performance that can occur due to product type. The author shows later that, for given pipeline conditions, a variation of 20:1 in throughput can be achieved in the sliding bed type flow regime due to variation in product type.

Accuracy is claimed to be ±25% with the products tested. However, it is doubtful whether this accuracy could be achieved with a wider range of products and greater variation in size and distribution.

The other significant work on sliding bed flow is that published by Wirth and Molerus (Ref. 2.13) in 1982. Their model is valid for sliding bed flows which are continuous and steady. They divide sliding bed type flow into two groups; at higher velocity the continuous sliding bed type flow and at lower velocity the intermittent dune flow. The work represents a step forward in that the theory is derived for a clearly identified mode of flow. However, it suffers for having a narrow range of applicability and the problems of particle friction factors which are difficult to determine. As with all the other models in this category, no account is taken of product type. In general, none of the models which have been put forward for the sliding bed regime have gained universal acceptance.

A great deal has been written specifically analysing plug flow although it is often described merely as dense phase. Since the work of the author is primarily concerned with sliding bed type flow (and in particular the effect of product type on conveying performance in this flow regime) a detailed review of work analysing the mechanics of plug flow is not given.

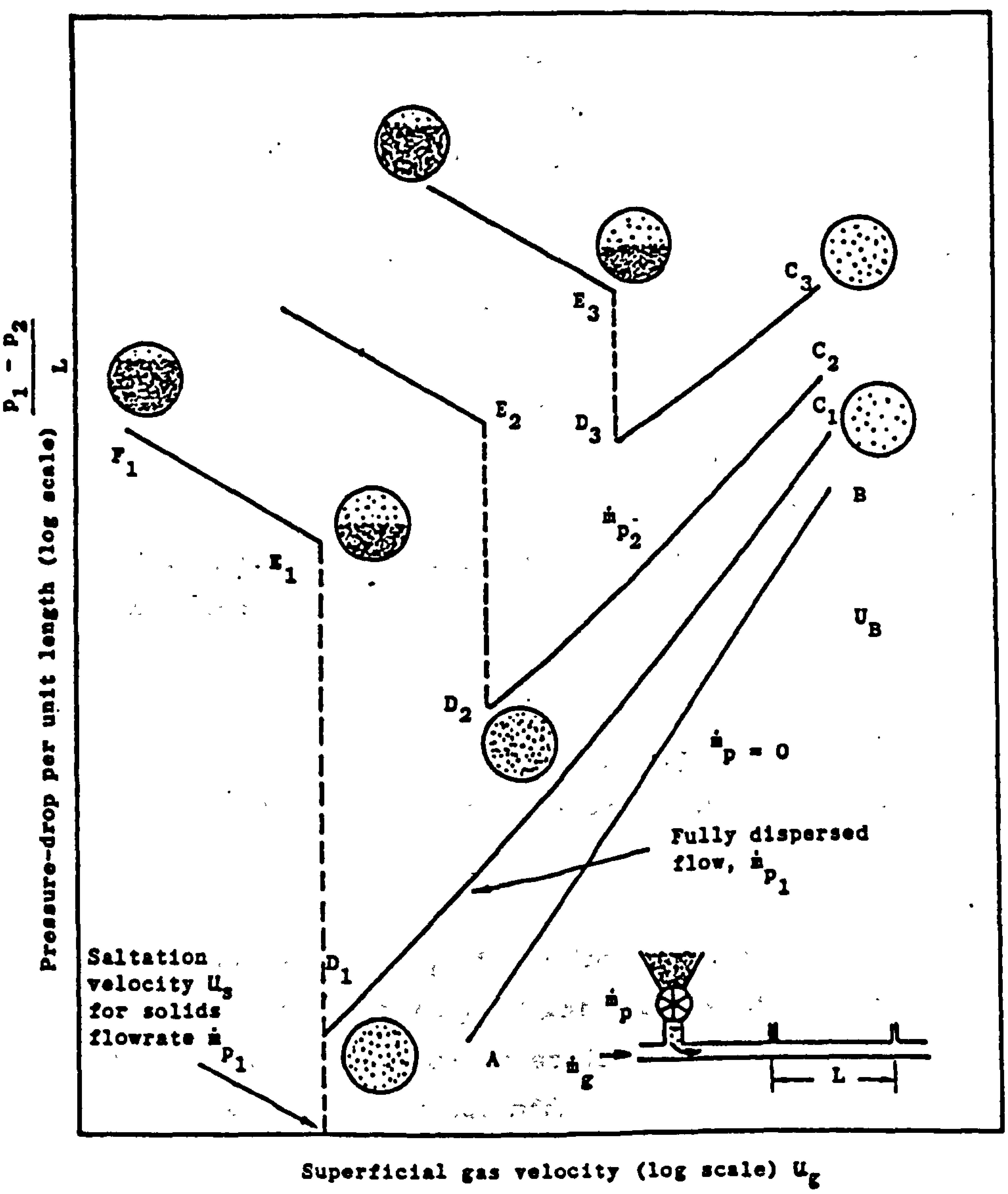
2.4.2 The Use of Phase diagrams

Konrad et al (Ref. 2.11) report that the concept of a phase diagram for two phase flow was originally proposed in 1949 by Zenz. A phase diagram is usually a plot of pressure drop per unit length against expanded superficial air velocity (i.e. at atmospheric conditions), on which lines of constant mass flow rate of solids or phase density are plotted. A log - log scale is usually used to cover as wide a range of values as possible.

A qualitative phase diagram for horizontal and vertical flows is given in the book by Zenz and Othmer (Ref. 2.20). The phase diagram for horizontal conveying is reproduced in Fig. 2.1. Line AB represents the flow of gas alone while m_{p1} and m_{p2} etc. represent increasing mass flow rate of solids. It can be seen how increasing solids loading increases the saltation velocity. Similarly, decreasing superficial gas velocity at constant mass flow rate of product increases the phase density and eventually leads to saltation. Further decrease in velocity changes the mode of flow from predominantly suspension flow to predominantly non-suspension flow.

There are slight variations in the way phase diagrams are presented, for instance Lippert (Ref. 2.21) used one length of pipe and plotted pressure drop against the mean superficial air velocity in the pipeline. Mills (Ref. 2.22) plotted pressure drop per unit length against air mass flow rate. These small differences make direct comparisons difficult.

The problem with phase diagrams is that they are different for every product. In addition, they should not be used for systems that are too far removed from the one used to produce the phase diagram and separate diagrams have to be produced for vertical and horizontal conveying. However, they are very useful in characterising the conveying performance of a product and a very powerful tool for system design.



PHASE DIAGRAM FOR HORIZONTAL GAS/SOLIDS FLOW

FIG. 2.1

2.4.3 The Suitability of Powders for Dense Phase Conveying

It is only in comparatively recent years that the effect of product characteristics on dense phase conveying has been realised. Early recognition by Zenz (Ref. 2.23) is illustrated by his paper outlining the effect of mixed particle size on conveyability. However, although many workers have appreciated and written qualitatively on the importance of product characteristics in relation to dense phase conveying, very little quantitative work had been carried out until Geldart (Ref. 2.24) published his classification of fluidisation in 1973.

Geldart suggested that the behaviour of solids fluidised by gases can be classified into four easily identified groups characterised by density difference ($\rho_s - \rho_f$) and mean particle size. The four groups are labelled as A, B, C and D and can be clearly seen in the Geldart Diagram shown in Fig. 2.2. The most easily recognised features of the groups are as follows:

- *Group A* — *Beds of powders in this group expand considerably before bubbling commences. When the gas supply is suddenly cut off the bed collapses slowly.*

- *Group B* — *In contrast with group A powders, naturally occurring bubbles start to form at or only slightly above the minimum fluidising velocity. Bed expansion is small and the bed collapses rapidly when the air supply is cut off.*

- *Group C* — *Powders in this category are extremely difficult to fluidise, often rising as complete plugs or forming stable channels (rat-holing).*

- *Group D* — *This category contains particles of large size and/or high particle density. The gas velocity is high and stable spouting beds can be formed.*

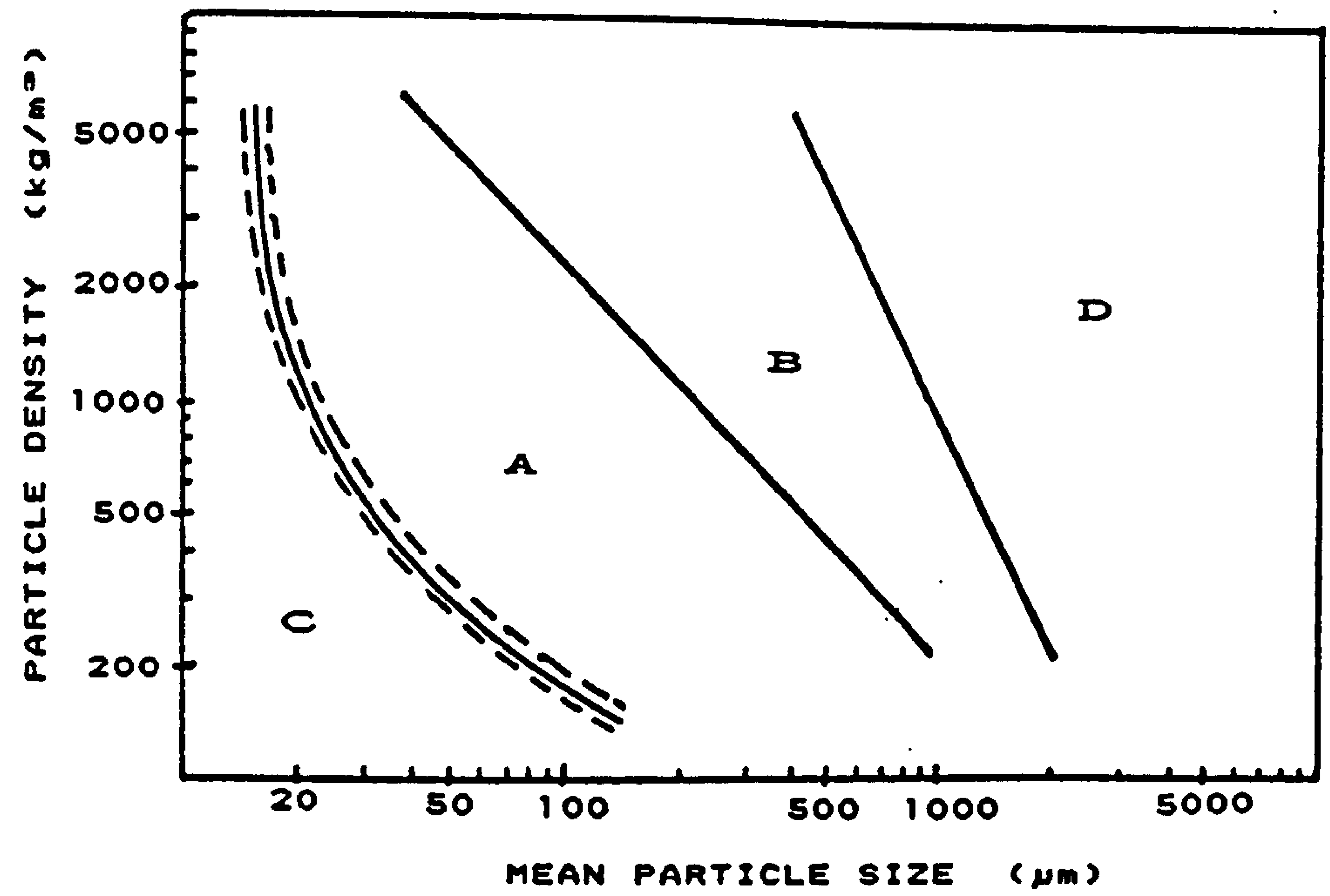
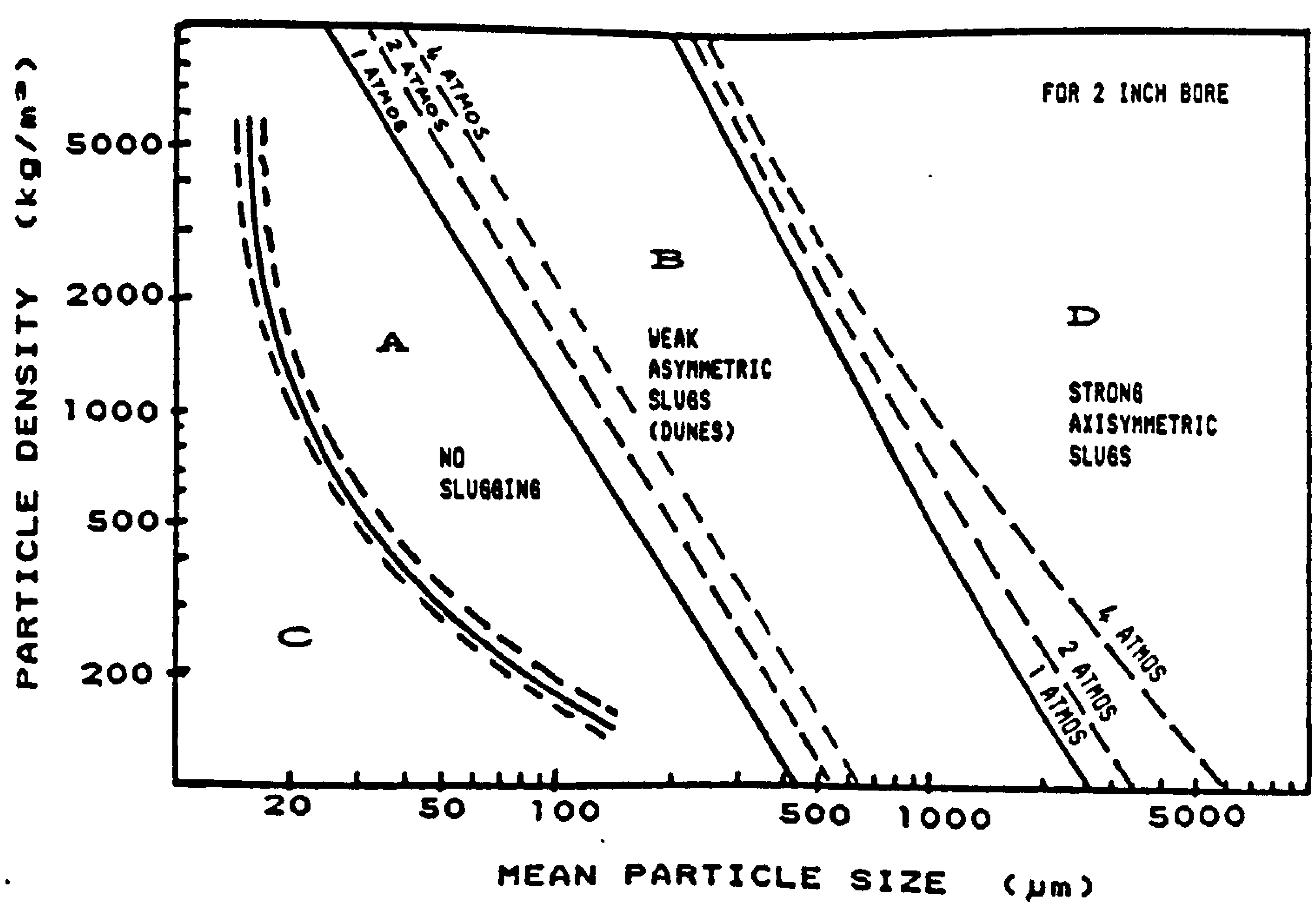


FIG. 2.2 THE GELDART CLASSIFICATION



THE DIXON SLUGGING DIAGRAM

FIG. 2.3

The boundary between groups A and C is empirical and is indistinct. Many factors affect the cohesiveness of these fine powders such as electrostatic charging, moisture content and particle shape.

The boundary between groups A and B is a theoretical one although the criterion comes about from visualisation. The criterion used involves a comparison between the superficial air velocities at minimum bubbling and minimum fluidising conditions and is described by the expression below:

$$U_{MB}/U_{o} \leqslant 1$$

where U_{MB} is the superficial gas velocity at minimum bubbling velocity and U_{o} is the superficial gas velocity at minimum fluidising velocity.

The distinction between groups B and D is not as clear-cut as for A and B. It is made on two grounds; one empirical and one theoretical. The theoretical boundary is based on calculating the density/particle size combinations of powders in which bubbles less than a given size would rise more slowly than the interstitial gas velocity. By making a number of assumptions the following equation is obtained:

$$(\rho_{s} - \rho_{f}) \ (d')^{2} \geqslant 10^{6}$$

where ρ_{s}, ρ^{f} are the densities of solid and fluid respectively.
and d' is the mean particle size.

The second criterion is empirical and is based on the observation that group D powders are capable of maintaining a stable spout in a bed more than 30 cm deep.

The Geldart classification was not originally proposed for pneumatic conveying applications but has been used by many workers as the basis of a classification for dense phase conveying. It is used particularly, for differentiating between products capable of being conveyed in various flow regimes.

Dixon (Ref. 2.5) realised that the fluidisation properties of a product have significant implications with regard to the ability of a product to be conveyed in dense phase. He produced a diagram called the 'Slugging Diagram' which uses the same axes as the Geldart Diagram and which at first sight is very similar. However, the boundaries produced by Dixon are based on quite different criteria.

Dixon uses two phase fluidisation theory and a comparison of the slug velocity to the terminal velocity of a single particle to determine the boundaries for the slugging diagram. These boundaries are plotted on the same axes as the Geldart diagram and Fig 2.3 shows the slugging diagram for a 2 inch diameter pipeline. The boundaries identify three broad groups of product type which exhibit a tendency toward particular types of flow when conveyed at low velocity. The three types of flow are 'strong axisymmetric slugging', 'weak asymmetric slugging' or duning and 'no slugging' or sliding bed type flow. The boundaries of these groups compare favourably with Geldart's boundaries for groups D, B and A.

In addition to the slugging diagram Dixon suggested a method of predicting maximum phase density for a given product. Leung and Wiles (Ref. 2.25) have defined the upper limit of dense phase flow (as opposed to packed bed flow which requires a restricted discharge) as the condition where the relative velocity between the gas and solids just equals the minimum fluidising velocity. Dixon extended this to derive an equation to predict the maximum phase density for a given product in a given pipeline. However, this equation predicts a theoretical maximum phase density which is unobtainable in practice and is not based on actual conveying data. This equation can be represented graphically and examples are given in Figs 2.4 & 2.5 for polyethylene granules and PVC powder both in a 4 inch diameter pipeline. Comparing these two diagrams illustrates that phase density with no qualification is not necessarily a reliable guide as to how far into the dense phase region a particular system is operating.

Dixon conceded that the theory, both for predicting the boundaries on the slugging diagram and for the prediction of maximum phase density, were

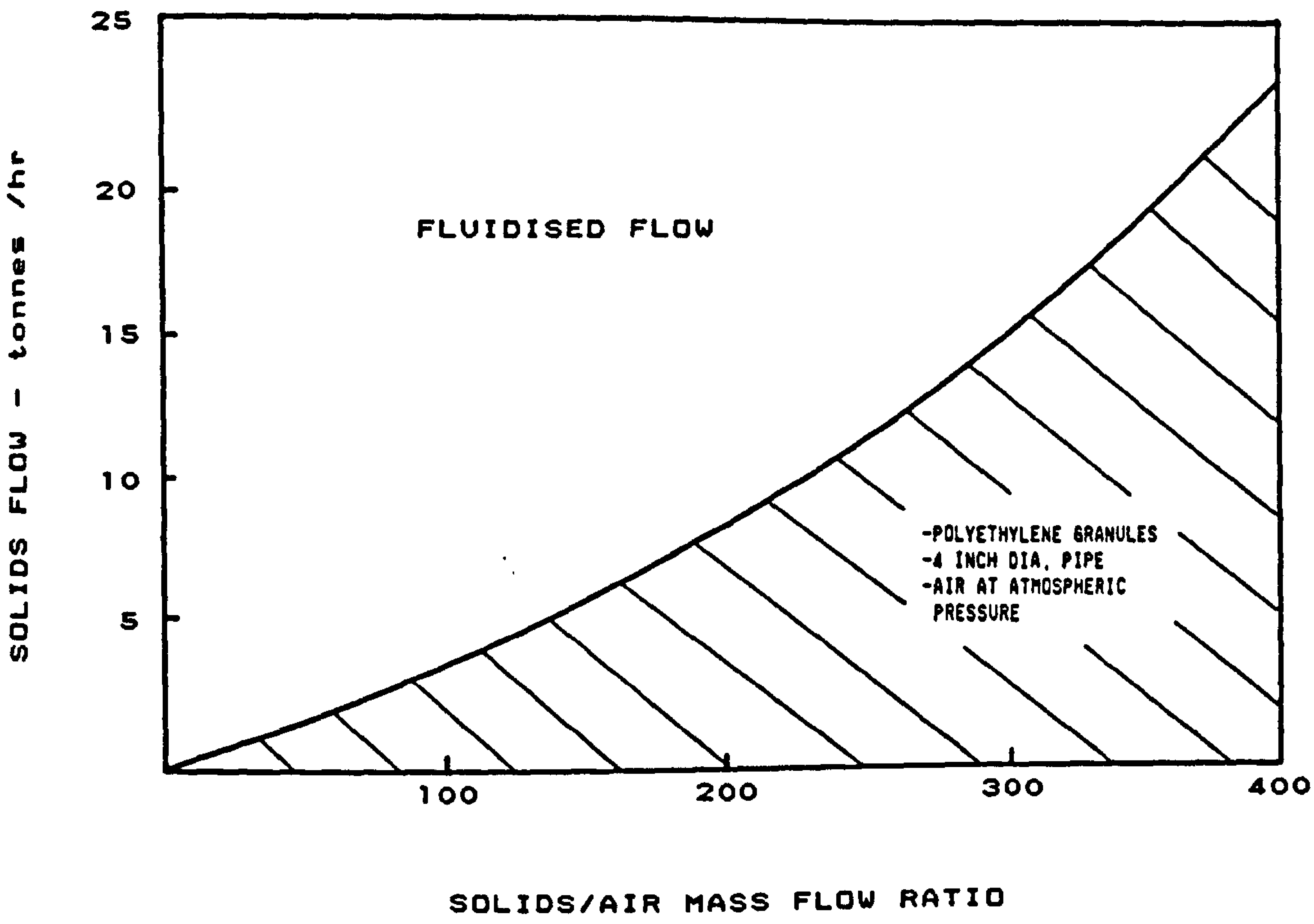


FIGURE 2.4

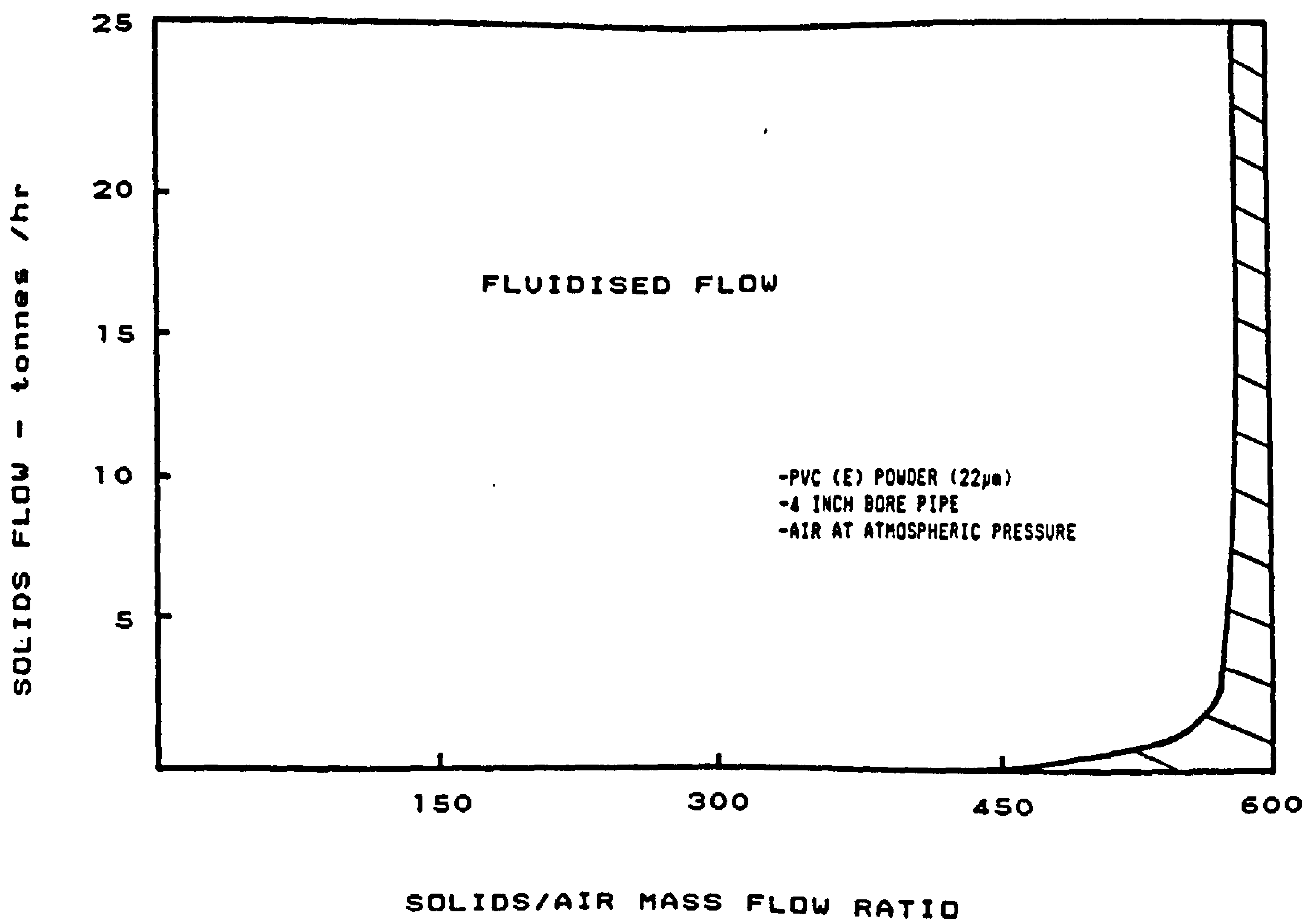


FIGURE 2.5

derived for vertical pipelines. However, since the slugging diagram is based on bubble theory in solid-gas systems he drew an analogy between air bubbles in liquids. It is reported that Zukoski (Ref. 2.26) showed that, for liquids, bubble velocities in horizontal pipes were between 0 and 30% greater than in vertical pipes. On this basis, Dixon concluded that within the wide tolerances typical of pneumatic conveying (due to the complexity of two phase flow) the diagram could be used, with caution, for horizontal as well as vertical conveying.

For the prediction of maximum phase density, Dixon argued that with a relative velocity equal to the minimum fluidising velocity the pressure differential across the plug is greater than that required to cause movement. i.e. the relative velocity is capable of supporting the weight of the plug in vertical conveying whereas it only has to overcome the frictional component of the weight at the pipe wall in the case of horizontal conveying. Consequently at maximum phase density there is excess gas in the horizontal (well fluidised) pipe and the maximum predicted phase density is likely to be an upper limit for conveying in both vertical and horizontal pipes.

Dixon concluded that it is important to take account of the powder properties when selecting dense phase conveying systems. The classification of groups on the slugging diagram (which are almost the same as the Geldart groups) are given below:

Group A These powders are the best candidates for dense phase conveying. They can be conveyed at high phase densities but are not natural 'sluggers'. However, they can be made to slug using some of the innovatory systems available.

Group B These products can be troublesome at high phase densities. Again these can be handled in dense phase using innovatory techniques.

Group C These are the cohesive powders and can be the worst candidates for dense phase conveying. Some have been conveyed but many have not. This can be attributed to their poor fluidisation characteristics, although not all group C powders have poor fluidisation characteristics.

Group D These products tend to be granular and convey well as naturally occurring slugs. However, the maximum values of phase density are rather low.

What is not clear is why one should want to convey group A powders as slugs using one of the innovatory techniques when these powders will convey perfectly well in a sliding bed type flow regime in a conventional system. Also, anomalies in the fluidisation behaviour of group C materials put a question mark over this grouping.

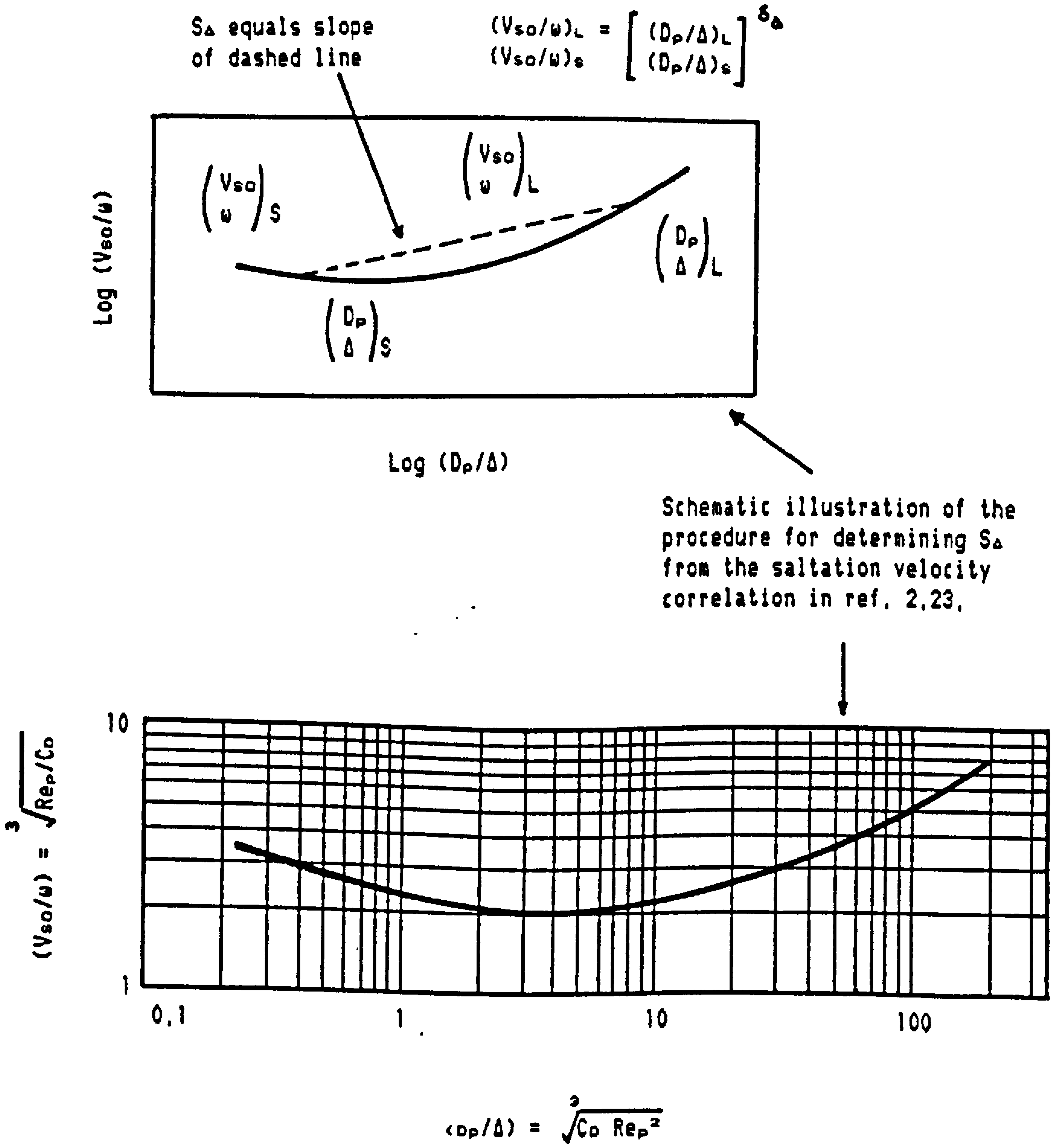
Doig (Ref. 2.14) also used the Geldart diagram to classify products for various modes of conveying. He described Group A powders as being able to be conveyed as a long continuous, homogeneous dense phase plug due to the high interstitial porosity which increases with the expansion of the motive air. In other words, the mode of flow is a continuous well fluidised sliding bed which is possible due to the air retentive properties of the powder. Doig suggested that pulsed and bypass dense phase conveying should usually be used for powders of group A and C.

Wypych and Arnold (Ref. 2.27) evaluated the Geldart and Dixon diagrams using a range of seven products tested in a pneumatic conveying system. The system used was completely conventional with no bypass, added air or pulsing system. They concluded that the diagrams provided a useful technique for predicting the suitability of a material for dense phase conveying. However, some products which were expected to convey in dense phase based on their grouping on the Geldart and Dixon diagrams in fact were not capable of dense phase conveying. This tends to indicate that additional factors such as particle size distribution (as opposed to a representative diameter) and particle shape may also need to be considered for the materials classification.

A similar point is made by Jodlowski (Ref. 2.28). He stated that a classification of particles by particle size alone is insufficient and suggested that other parameters such as particle size range, particle shape, hardness, compressibility, cohesion and product behaviour after subjection to fluidisation should be taken into account. Lohrmann and Marcus (Ref. 2.29) similarly suggested that other material properties should be taken into account particularly those of flowability such as angle of repose, compressibility, packed bulk density, aerated bulk density, cohesion, uniformity, floodability and flow functions.

The importance of particle size distribution seems to have been realised by Werner (Ref. 2.30). He carried out some pneumatic conveying experiments using glass balls in which he was able to vary the size distribution. However, the extent of the size range variation was small and was restricted to varying the percentage of the coarse and fine fractions. Consequently the conclusions were that the effect of varying the size distribution were comparatively small for horizontal conveying. It is quite probable that with variation in particle size distribution on the scale commonly experienced with products conveyed in industry a much larger effect on conveying performance would be observed.

One of the biggest problems of particle size distribution is that of representing it by a single parameter which can then be correlated with other variables. Zenz (Ref. 2.23) as long ago as 1964 recognised the problem and put forward a possible solution. The main theme centres around a constant, $S\Delta$, which characterises a product in terms of its size taking into account the spread of sizes and correlating them with saltation velocities in 1.25 and 2.5 inch pipes. The $S\Delta$ parameter is obtained by plotting a log function of saltation velocity for a single particle size against a log function of particle diameter for that size. This is repeated for each size fraction of the material. The resulting graph is a curve and is shown diagramatically in Fig. 2.6. $S\Delta$ is the slope of a straight line adjoining a point on the curve representing the smallest particle fraction to a point on the curve representing the largest particle fraction.



DETERMINATION OF THE S_Δ PARAMETER

FIG. 2.6

However, this method is not as straightforward as may first appear. The value of $S\Delta$ can become negative for powders of small particle size and relatively small range. Many simplifying decisions have to be made such as the step length for groups of sizes (although this could be done on the basis of a $\sqrt{2}$ progression as is the case for sieves) and the extent of the range for determining maximum and minimum sizes. In addition, the theory was developed using drag coefficients for particles in an air stream and therefore spheres or angular particles are the only choice of shape.

Recently, Zenz (Ref. 2.31) critically reviewed the conveyability and powder classifications. He was critical of the Geldart classification on the basis that the observations made in order to draw the broad boundaries are only valid on small scale test equipment. Zenz made reference to the work of Dixon and cited instances where the predicted behaviour has not been the case in practice. Zenz proposed a diagram based on rheological properties of surface tension and incipient fluidisation. This diagram is on the same axes as the Geldart and Dixon diagrams and it is interesting to note that the Geldart boundary dividing groups B and D coincides perfectly with the line representing a surface tension of 10 dynes/cm (Fig. 2.7). Zenz claimed that while the same rheological properties should relate to fluidisation and conveying behaviour, only surface tension and incipient fluidisation were fundamental to the Geldart classification, whereas vessel size, bubbling characteristics, deaeration time, particle size distribution and void fraction were at least of equal if not greater significance.

Zenz went on to use his $S\Delta$ parameter as a basis of deciding which type of conveying was most appropriate based on equipment and power requirement costs. The classification is shown in Fig. 2.8. However, this assumes that the most economical way to convey granular products is in dilute phase. This was rejected by Hitt (Ref. 2.16) who showed that many granular products will convey as naturally occurring slugs at low velocity without any special equipment and with similar power requirements to dilute phase conveying.

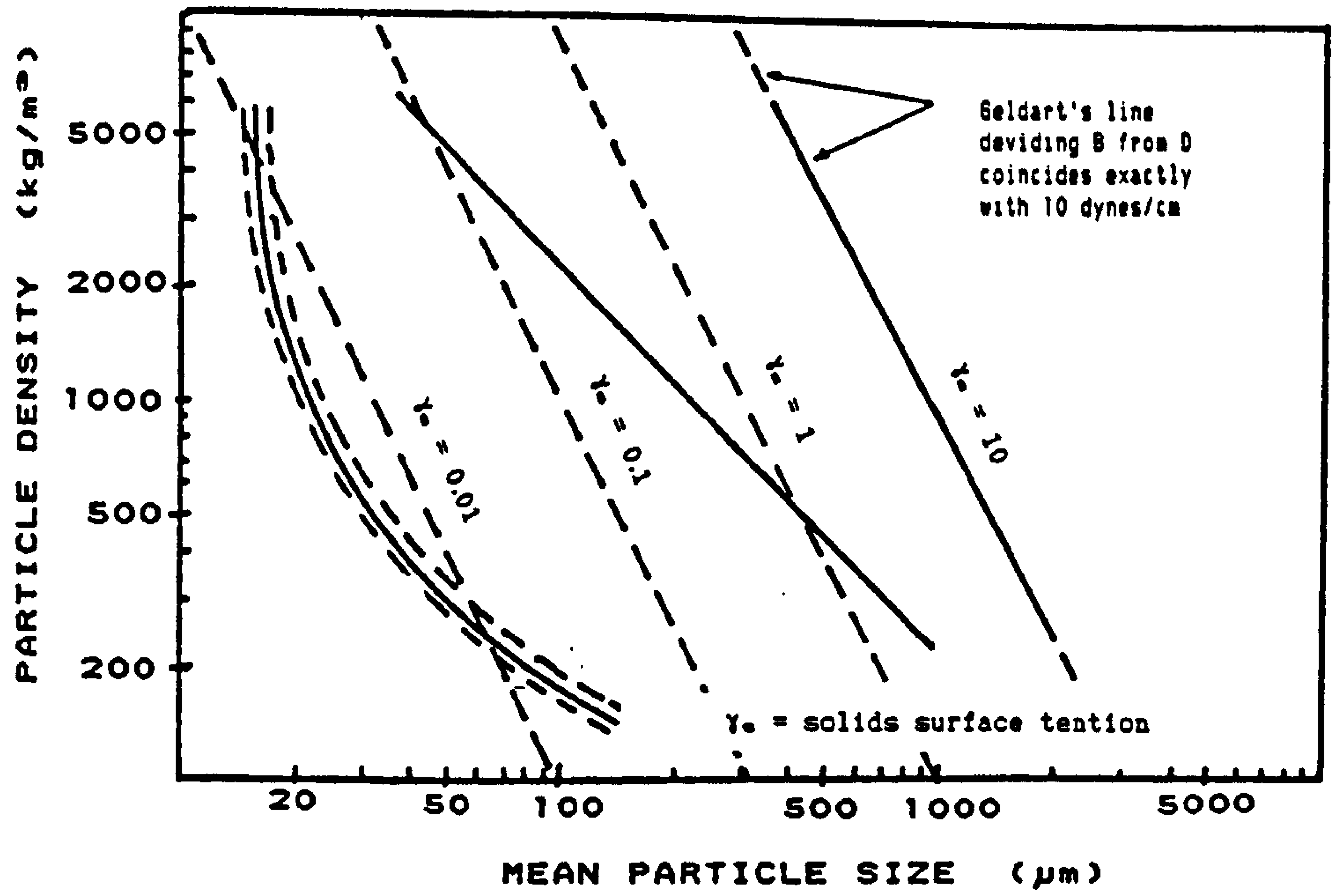


FIG. 2.7 POWDER SURFACE TENSIONS RELATIVE TO GELDART'S CLASSIFICATION

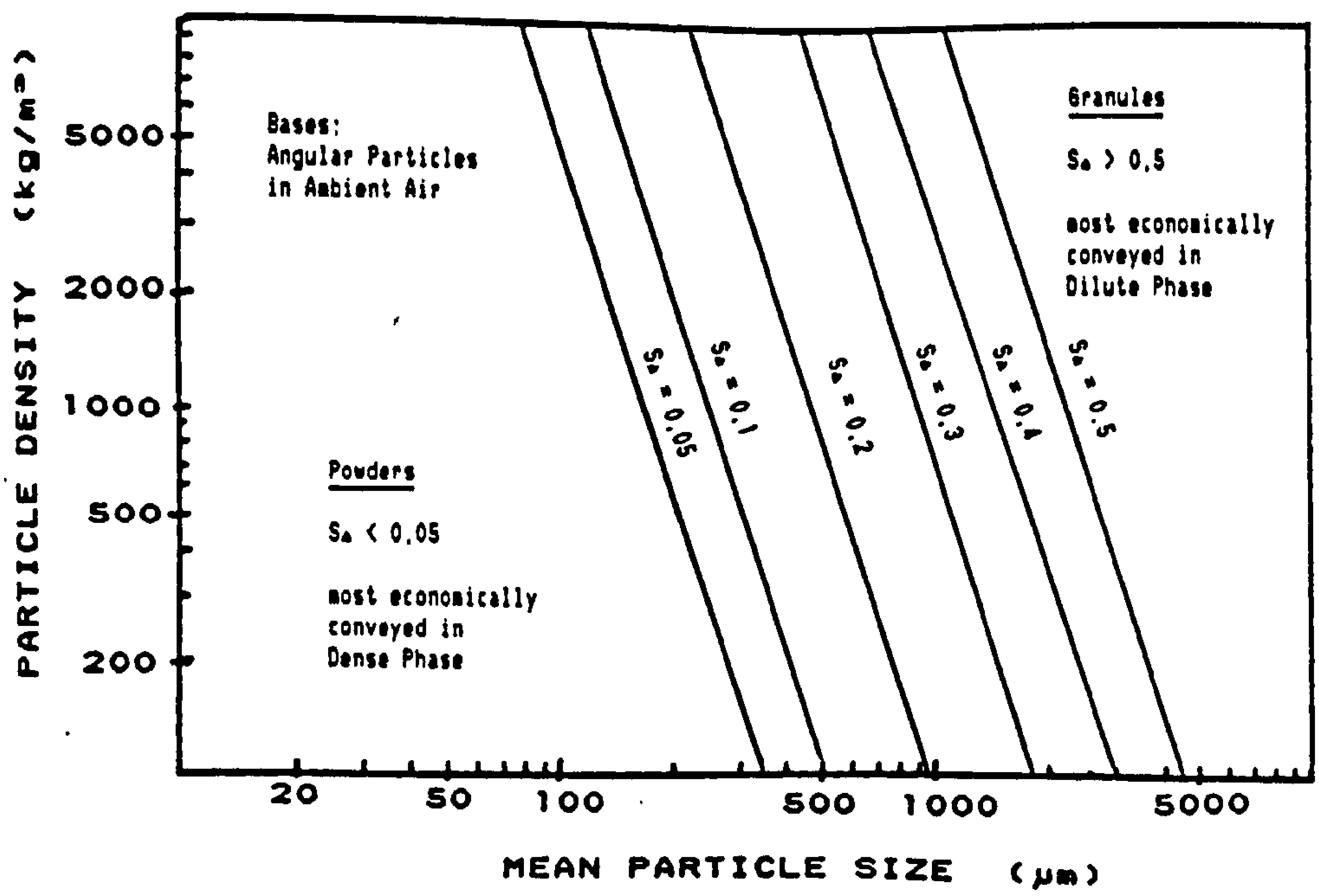


FIG. 2.8 CONVEYABILITY CLASSIFICATION IN TERMS OF S_a AS A MEASURE OF SIZE AND SIZE DISTRIBUTION

Zenz and Labourt-Ibarre (Ref. 2.33) reported on pneumatic conveying trials using two products to investigate the effect of product rheological properties on the conveying mode of dense phase conveying. They used the concept of solid viscosity which is measured in terms of the torque weight required to rotate a paddle of fixed size in a bed of fully fluidised material. They concluded that low solid surface tension and low solid viscosity indicate that the product could be conveyed in extrusion flow. High values of solid surface tension and solid viscosity indicate that the product could be conveyed in the slug flow regime. In general, however, phase density increases as the solid surface tension and solid viscosity decrease.

Workers such as Dixon (Ref. 2.5) and Doig (Ref. 2.14) have made reference to the fact that the powders falling into group C of the Geldart classification can be unpredictable. That is, some convey well and can be conveyed as a continuous plug often termed 'mass' or 'extrusion' flow while others will block the conveying line at such extreme conditions. Zenz and Rowe (Ref. 2.32) have described the materials capable of extrusion flow as usually being of small particle size (tens of microns) and of low density. However, these two conditions alone are not sufficient. For a powder to take part in extrusion flow it must possess a property that Zenz and Rowe termed 'bulk deformability'. They suggested a method for measuring bulk deformability which involved filling a 250 ml measuring cylinder with the powder to be tested and releasing a 1 cm steel ball from just above the powder surface. If the ball fell to the bottom, as if through a liquid, the powder should be capable of extrusion flow. The property must be permanent and not dependent on aeration immediately prior to the test.

It is now quite apparent that the initial attempts at predicting conveyability were largely successful. Many workers have commented that the Geldart and Dixon diagrams give a good general guide to conveyability. However, they do not always predict correctly and many workers have pointed to ways in which improvements could be made. One of the most often voiced criticisms is that the correlations do not take *into account particle size distribution and particle shape. However, these are extremely difficult parameters to incorporate.*

Caldwell (Ref. 2.34) stated that the most important material characteristics are those which involve product-air interaction. First is the ability of a product to become fluidised, that is to assume the flow properties of a fluid when air has been mixed among the particles. Second is the air retention time, or the time it takes for the product to give up the air and to return to the unfluidised condition. Caldwell also stated that the fluidisation and air retention properties depend directly upon the particle size and shape. However, no attempt was made to quantify or identify the relationship between conveying performance and these fluidisation characteristics

2.5 COMMERCIALLY AVAILABLE SYSTEMS

2.5.1 Introduction

There are many types of system available commercially which are sold under the general heading of dense phase conveying systems. In general, the majority of systems are blow tank systems and can be of either the top or bottom discharge arrangement. The choice of discharge arrangement being dependent on the application and the physical constraints of space. The major differences between the various systems are based on how and where the air is applied to the system. These differences lead to variations in the control of the systems and many manufacturers claim they lead to variations in the range of products that can be handled in dense phase.

However, there is a tendency among manufacturers to increase the complexity of the systems and claim considerable increases in performance, not all of which appear to be entirely justifiable.

The major types of system are identified and discussed in this section together with typical examples of commercial systems available by way of illustration. It is not intended that this should constitute a comprehensive catalogue of commercial systems, however.

2.5.2 Conventional Systems

Conventional systems are generally accepted to be those systems where the air supply is split between the blow tank and the supplementary air line at the start of the conveying pipeline. That is, no additional air is applied at any other point along the conveying pipeline and no pulsing or conditioning of the airflow is carried out at the beginning of the pipeline.

Typically, the supplementary air is applied to conventional systems via a swept 'T' at the beginning of the pipeline as near to the discharge from the blow tank as possible. The air directed to the blow tank normally enters the system via a plenum chamber and fluidisation membrane or a simple fluidising annulus. Alternatively, other equally simple arrangements are sometimes used.

Conventional systems are sometimes referred to as 'simple systems'. Many of the leading maufacturers market a conventional system in addition to their innovatory systems. Examples are the Neu Engineering system the Neu Dense Phase Conveyor (Ref. 2.35) and Buhler-Miag Fluidlift system (Ref. 2.36)

2.5.3 By-pass Systems

The By-pass systems might more correctly be defined as systems where control is applied along the entire length of the pipeline. The earliest work on this type of system, known to the author, is that of Lippert (Ref. 2.21) which dates back to 1966. This system is now being marketed by Buhler-Miag as the Fluidstat system. The Fluidstat system utilises a conveying pipeline with a built in by-pass pipe which is about 1/5 th the diameter of the conveying line. The by-pass line has slots at distances of approximately every 0.5 m along the complete length. Flatt and Blumer (Ref. 2.37) reported that the system relied on the fact that the resistance to the flow of air along the by-pass pipe at the point of separation was greater than the pressure required to convey a slug. This prevents any large plugs from forming which may otherwise block the pipeline. This type of system is aimed at products which have good fluidisation capability but do not naturally convey in a plug flow regime and where there is a risk that if the product did become deaerated or compacted, a blockage may occur.

Other types of control are used such as air injection along the pipeline. The main differences between these systems is the method of control of the injector. Pressure difference along a section of pipe adjacent to the injector, gauge pressure of the conveying line at the injector and constant air injection are all techniques that have been used.

The by-pass systems may be necessary in a few cases. However, it is quite possible that many of the products which are conveyed in these systems will convey perfectly well in a stable steady state sliding bed type flow regime with no tendency to block in a conventional system. Furthermore, it is a common occurrence that many systems using constant air injection are in fact considerably diluting the phase even to the point of lean phase conveying in some cases. The case for these systems is far from proved although many companies claim that the by-pass system extends the range of products that can be conveyed in dense phase.

Examples of these type of systems commercially available are the Waeschle Pneumosplit (Ref. 2.38), the Dynamic Air dense phase system with Dyna-chek boosters (Ref. 2.39) and the Buhler Miag Fluidstat (Ref. 2.40).

2.5.4 Pulse Phase Systems

Pulse phase systems might be more generally described as systems where the mode of flow is controlled at the start of the conveying pipeline. Most of these systems create a plug flow regime at the beginning of the pipeline and assume that it will be maintained along the entire pipe length.

The most well known of these systems is probably the 'Air Knife' system developed at the Warren Spring Laboratory. It was developed in the early 1970's and has since been maufactured and marketed by a number of organisations under license agreements (Refs. 2.41 and 2.42).

The system was first developed for cohesive products and consisted of a steep sided blow tank (typically 40° internal angle) which is pressurised and forces the material out of the bottom of the tank, through a 90° bend and into the pipeline. Immediately after the bend is the air knife which is basically a ring of holes in the pipeline through which air is injected intermittently. As the material passes the air knife, intermittent injection of air splits the column of material into discrete plugs. The length of the plugs and the air gaps is controlled by a timer linked to the air knife.

The reason given for splitting the column of material into discrete plugs is that the pressure required to move a plug is proportional to the square of its length (Ref. 2.43). Hence, it is preferable to convey many small plugs than one long one.

The reason for limiting the system to cohesive powders initially was the fear that permeable materials may degenerate from the originally imposed plug flow to form other stable flow regimes which may block the pipeline (Ref. 2.43). However, Hitt (Ref. 2.16) showed that granular products with good air permeability characteristics will form a stable naturally occurring plug flow regime, with no tendency to block, without artificial plug forming devices.

Another system which uses similar techniques is the Buhler Miag Takt-Schub system (Ref. 2.37). In this system the material is fed into the pipeline in sequenced pulses by directing the air supply to the blow tank and to the conveying line alternately. This system is aimed at granular products with good permeability characteristics.

2.5.5 Single Plug Systems

Another approach to low velocity conveying is the single plug systems. No supplementary air is used and fluidising air is not normally employed. The blow tank is generally pressurised from the top and, in theory, the product is pushed into the pipeline as a single plug, rather like a piston. In practice, naturally occurring discrete plugs may form with some products. These systems generally have small blow tanks with a volume of about 0.5 m^3. The size of the blow tank limits the size of the plug. High pressure air at about 6 bar gauge is normally employed to overcome the frictional resistance of the plug in the pipeline.

The most famous system is probably the Denseveyor system produced by Simon Macawber (Ref. 2.44). These systems are mainly installed for coal handling applications although it is claimed that they can handle a wide range of products (Ref. 2.45) both free flowing and cohesive. The advantages of this system over other dense phase conveyors does not seem to be particularly apparent but Macawber claim advantages in terms of low air requirements and low velocity transfer of product.

2.6 CRITICAL OVERVIEW OF THE CURRENT POSITION

Many mathematical models have been proposed to describe the flow of bulk solid materials in dense phase pneumatic conveying systems. However, none have been universally accepted as reliable for design purposes. The manufacturers of dense phase systems prefer to rely on previous experience and on testing products in their own test facilities. One of the major reasons for this is the mass of confusing information which has been published. The cause of much of the confusion is the fact that many of the models that have been produced for predicting pressure drops in pipelines for dense phase conveying have been restricted to particular types of flow regime. Furthermore, agreement on the definitions of flow regime is far from unanimous and this is to some extent because not all products behave in the same way.

Many of the mathematical approaches to the physical mechanics of flow have necessarily restricted the analysis to an 'ideal' product. Often the hypotheses are tested using very small scale equipment and using a product which is as near ideal as possible, such as mono-sized glass balls or plastic pellets. This has the effect of isolating and rejecting the effect of the bulk and particle properties on conveying performance. Since the majority of powders which are conveyed pneumatically will not be ideal, it is not difficult to see why the proposed models have not been adopted.

It has already been outlined elsewhere in this review that other workers, recognising the importance of product characteristics on conveying performance, have adopted a completely different approach. They have studied the behaviour of materials on a bench scale, particularly fluidisation, and attempted to correlate observed behaviour with actual conveying behaviour. Also, many of these workers have carried out extensive conveying trials using a range of non-ideal products to arrive at their conclusions.

The state of the art at present is basically the Geldart and Dixon diagrams (Refs. 2.24 & 2.5). The Geldart diagram was not originally proposed for pneumatic conveying but is a classification of fluidisation behaviour. Obviously, fluidisation is going to have a significant effect on conveying performance. Dixon used the basis of the Geldart diagram to provide a classification of materials for likely conveying modes based on density difference and particle size. The major criticism of both diagrams is that whilst they give a good guide to conveyability, they do not take into account particle size distribution and range or particle shape.

Many workers have pointed to these problems and cited instances where the predictions of these diagrams are inaccurate. These are often with products having wide size distributions, non-Gaussian distributions or widely differing particle shapes. The suggested solution to this problem by many workers is to find a way of including these parameters in a new or modified classification.

A common problem for both manufacturers and users of pneumatic conveying systems is predicting whether or not a product is capable of being conveyed in dense phase in a conventional system. Guidelines are often quoted in the literature such as products that will fluidise well can be conveyed in dense phase, but no quantitative analysis seems to have been undertaken.

The Dixon and other similar phase diagrams classify products essentially by size and particle density. The resulting groups are identified as likely candidates for particular flow regimes. However, no attempt is made to correlate material properties with conveying performance in terms of throughput or pressure drop.

The conclusions that can be drawn from this review are that a significant contribution to the science of pneumatic conveying could be made by investigating possible ways of predicting whether or not a product is capable of being conveyed in dense phase in a conventional system taking into account the possible variation in product characteristics; particularly those of particle size range, particle size distribution and particle shape. This may possibly take the form of a diagram relating product characteristics to some form of conveying parameter such as velocity. In addition, it would be desirable to be able to go further and predict the likely conveying performance, especially for the sliding bed type flow regime, based on bench scale tests. Ideally, this should provide detail from which preliminary design parameters could be obtained.

2.7 EXPERIMENTAL PLAN

To achieve this goal of being able to obtain preliminary design parameters from appropriate product characteristics determined from small samples of material the following programme has been devised:-

1) *To investigate the effect of material properties, especially those which involve product-air interaction, on the ability or otherwise of a product to be conveyed in a dense phase, low velocity flow regime and if possible differentiate between plug flow and moving bed type flow capability.*

2) *If the product will convey in dense phase, to determine which product properties affect conveying performance in the pipeline and establish, empirically, the nature of any correlation that may exist.*

3) *Having established which of the material properties are important to 1) and 2) above, produce diagrams which show the relationship between the product characteristics and conveying capability/performance. Ideally these diagrams should be able to predict likely conveying capability/performance of a product based on bench scale tests of a small sample of the material to be conveyed. This may involve the development of simple bench scale tests.*

4) *Extend this work to investigate the effect of the product characteristics on the discharge and control of blow tank systems.*

5) *Compare the effect of product characteristics on the performance of the blow tank in both top and bottom discharge modes as conventionally arranged.*

CHAPTER 3

CONVEYING TEST PLANT

3.1 INTRODUCTION

One of the criticisms levelled at many workers in the field of pneumatic conveying is the scale of their test plant. Although this criticism is justified in many cases, it also has to be recognised that the cost of setting up plant approaching an industrial scale is demanding on resources. However, at Thames Polytechnic, this need has been recognised and industrial scale research laboratories have been set up in order that representative conveying trials can be reliably carried out.

The selection of conveying plant was of great importance. The most significant requirement of the plant was that it should be capable of conveying over a wide range of conveying conditions. This requirement was of particular relevance in the choice of feeding device and for this reason a high pressure blow tank system was selected.

3.2 THE CONVEYING TEST RIG

The general arrangement of the test plant used for this work is shown diagramatically in Fig. 3.1. It was basically a batch type system which conveyed product from the blow tank, through the conveying line and returned it to a receiving hopper mounted above the blow tank. The receiving hopper also acted as a feed hopper with the product being dropped through a double set of valves into the blow tank for recirculation. A photograph of the rig is shown in fig. 3.2.

3.2.1 The Blow Tank

The blow tank is widely used in industry as a feeder for pneumatic conveying systems, especially for dense phase conveying. This is due not only to its ability to convey over a wide range of conditions, but also the ease of control and the fact that, as there are no moving parts, erosion and degradation are minimised. Both top and bottom discharge

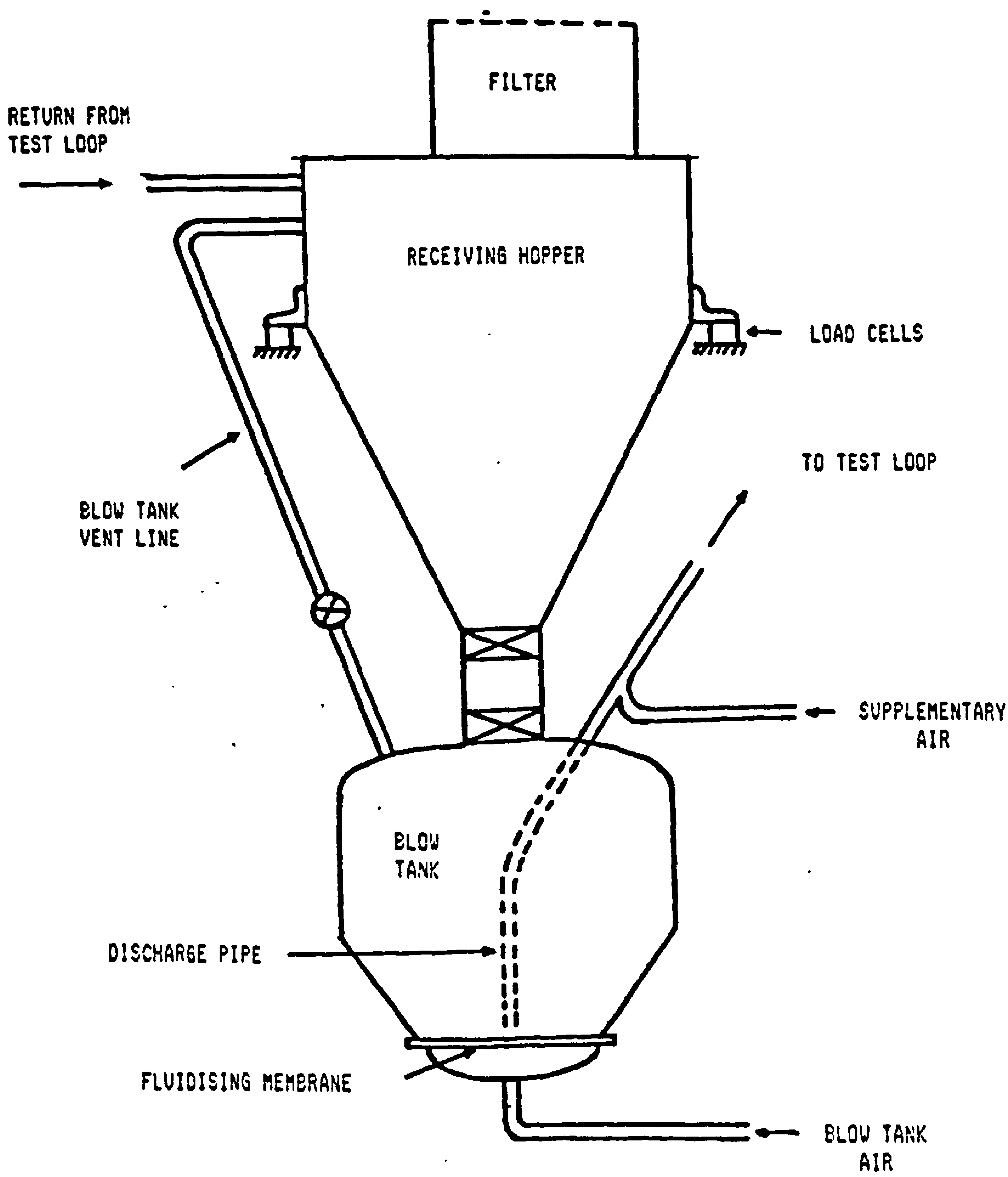


Fig. 3.1 CONVEYING PLANT LAYOUT

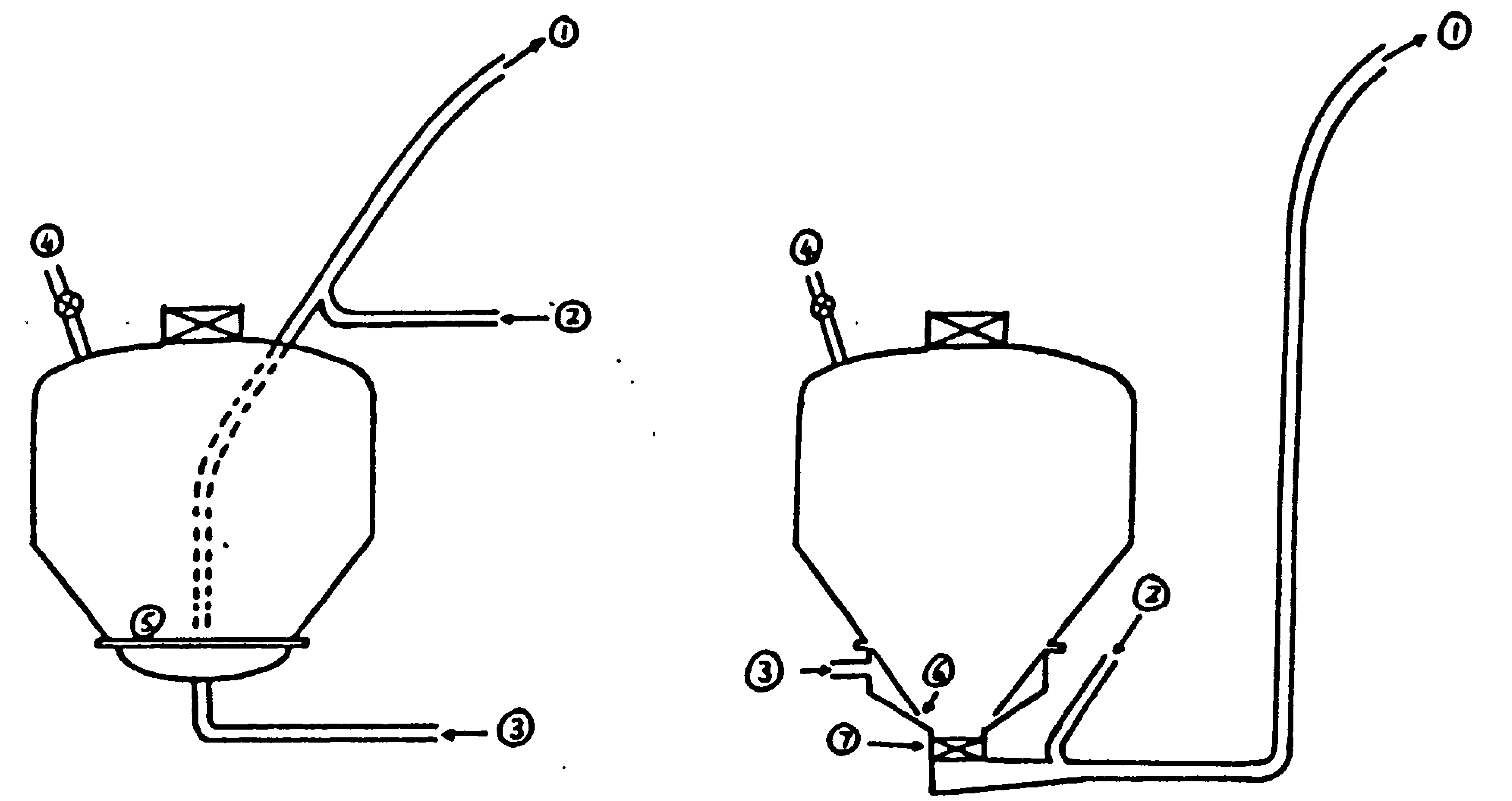
Fig 3.2

types are used and the choice is often one of convenience rather than the merits of configuration performance. However, in this work both arrangements were used.

The arrangement of the blow tank in both top and bottom discharge modes is shown in fig. 3.3. The terminology refers to the direction in which the contents of the vessel are discharged. The blow tank was originally manufactured in top discharge configuration. It is usual, as in this case, for the top discharge arrangement to have some form of fluidising membrane. Therefore, the top discharge arrangement is often considered most suitable for fine powders. The bottom discharge arrangement is normally simpler than the top discharge configuration consisting of a cone feeding directly into the pipeline and often having a discharge valve.

The top discharge arrangement used is shown in fig. 3.3A and is typical of top discharge blow tanks. A photograph showing the bottom of the tank for the top discharge mode is shown in fig. 3.4. It can be seen that the air supply entered the plenum chamber from underneath the blow tank. Inside the plenum chamber there was a deflector plate to prevent the air being directed to one part of the fluidising membrane and therefore avoiding preferential fluidisation. Between the flanges, which can just be seen in the photograph (fig. 3.4), there was a fluidising membrane which was made up of a filter cloth sandwiched between two perforated steel plates. Problems of 'blinding' the fluidising membrane can occur if sticky or hygroscopic products are conveyed. If products have hygroscopic tendencies then conditioning of the air is required to eliminate moisture as far as possible. All the air which was directed to the blow tank entered via the plenum chamber. The remainder of the air to the conveying system was termed supplementary air and entered the system as near as possible to the start of the conveying line via a swept 'T' pipe junction.

The discharge pipe from the blow tank was positioned vertically above the fluidising membrane on the centreline of the tank. The optimum position for the discharge pipe in the top discharge mode was found by Waghorn



(A)   (B)

1 TO CONVEYING LINE
2 SUPPLEMENTARY AIR
3 AIR SUPPLY TO BLOW TANK
4 BLOW TANK VENT TO RECEIVER
5 FLUIDISING MEMBRANE
6 FLUIDISING ANNULUS
7 DISCHARGE VALVE

TOP AND BOTTOM DISCHARGE BLOW TANK SYSTEMS

Fig. 3.3

Fig 3.4

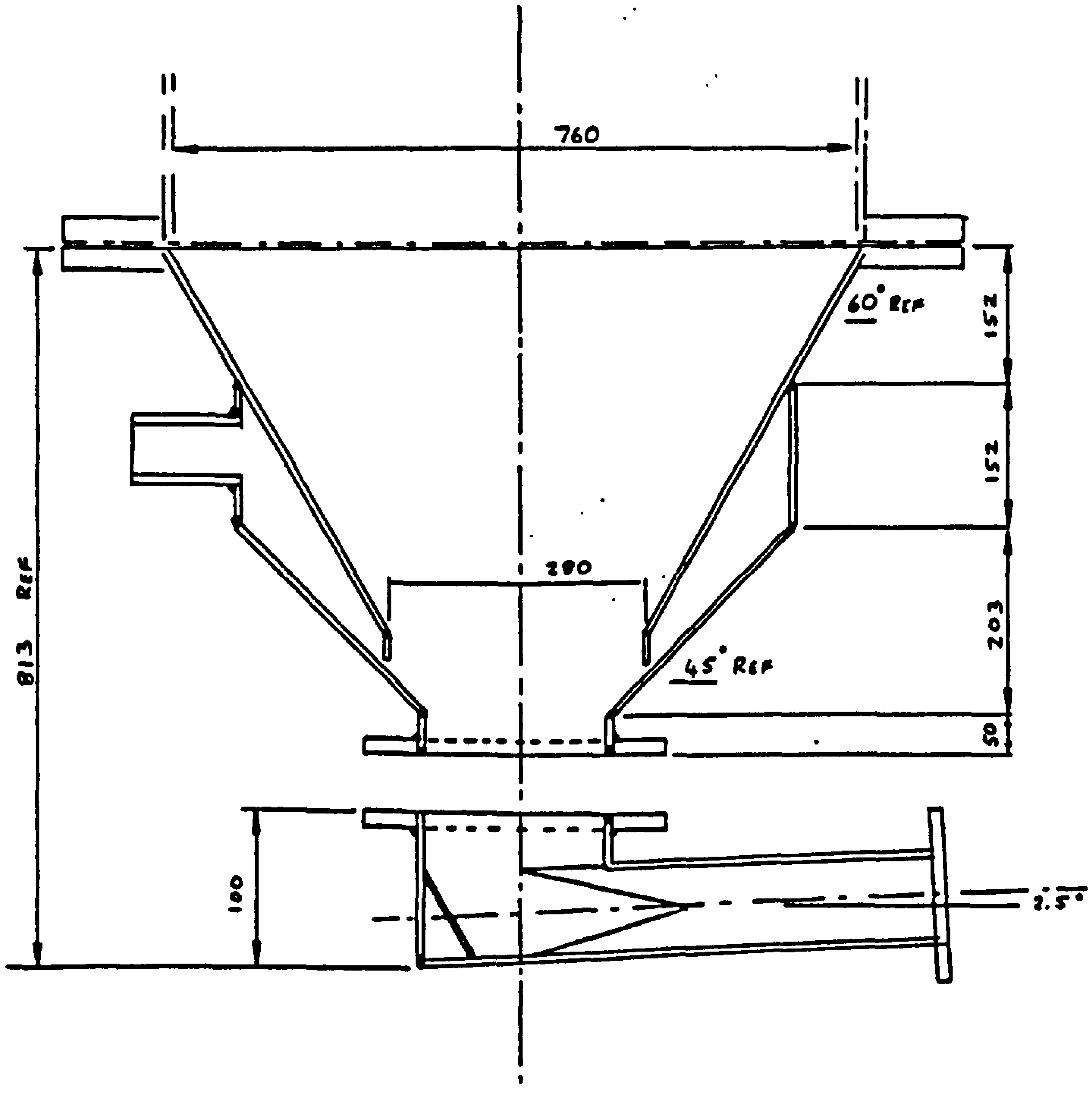
and Mason (Ref. 3.1) to be about 40mm above the fluidising membrane. If the distance between the membrane and the discharge pipe is increased, the discharge rate is almost unaffected. The only significant effect is to reduce the effective capacity of the blow tank since more product will be left in the blow tank after conveying. However, if the discharge pipe is positioned too close to the fluidising membrane then the discharge rate will be adversely affected.

Top discharge blow tanks have the advantage of requiring less head room than the bottom discharge configurations and in conventional form have the ability to effectively fluidise the product to be conveyed. For this reason top discharge arrangements are often selected for products which have good fluidisation characteristics. However, many granular products can be conveyed with equal reliability from top discharge blow tank systems. The disadvantage of top discharge blow tanks is that they do not completely discharge. This is a particular disadvantage for products such as foodstuffs where hygiene is essential.

The bottom discharge blow tank is probably the most commonly used blow tank arrangement. The discharge arrangement is very simple consisting of a cone feeding through a discharge valve into the conveying pipeline. A diagram showing the arrangement of the bottom discharge system used can be seen in fig. 3.3B. The bottom discharge arrangement was designed so that it could be bolted directly on to the existing blow tank by simply removing the plenum chamber and fluidising membrane from the blow tank in top discharge configuration and bolting the bottom discharge unit directly to the blow tank flange.

A diagram indicating the essential features of the bottom discharge design can be seen in fig. 3.5 and photographs showing both an internal and external view of the fabrication are shown in figs. 3.6 & 3.7. The cone angle was 60° which matched that of the existing blow tank. The cone discharged through an 8" pneumatically operated butterfly valve into a flat pan arrangement immediately under the valve. The outlet from the pan was inclined by 2½° to allow room for the outlet flange due to limited space under the vessel. At the outlet flange, the nominal bore of

ALL DIMENSIONS ARE APPROXIMATE AND IN MM



SCHEMATIC DIAGRAM OF THE BOTTOM
DISCHARGE BLOW TANK ARRANGEMENT

FIG. 3.5

Fig 3.6

Fig 3.7

the pipe was 106mm (4"). Tapered reducer sections were then used to reduce the bore to either 53mm (2") or 81mm (3") diameter to match the conveying pipelines used.

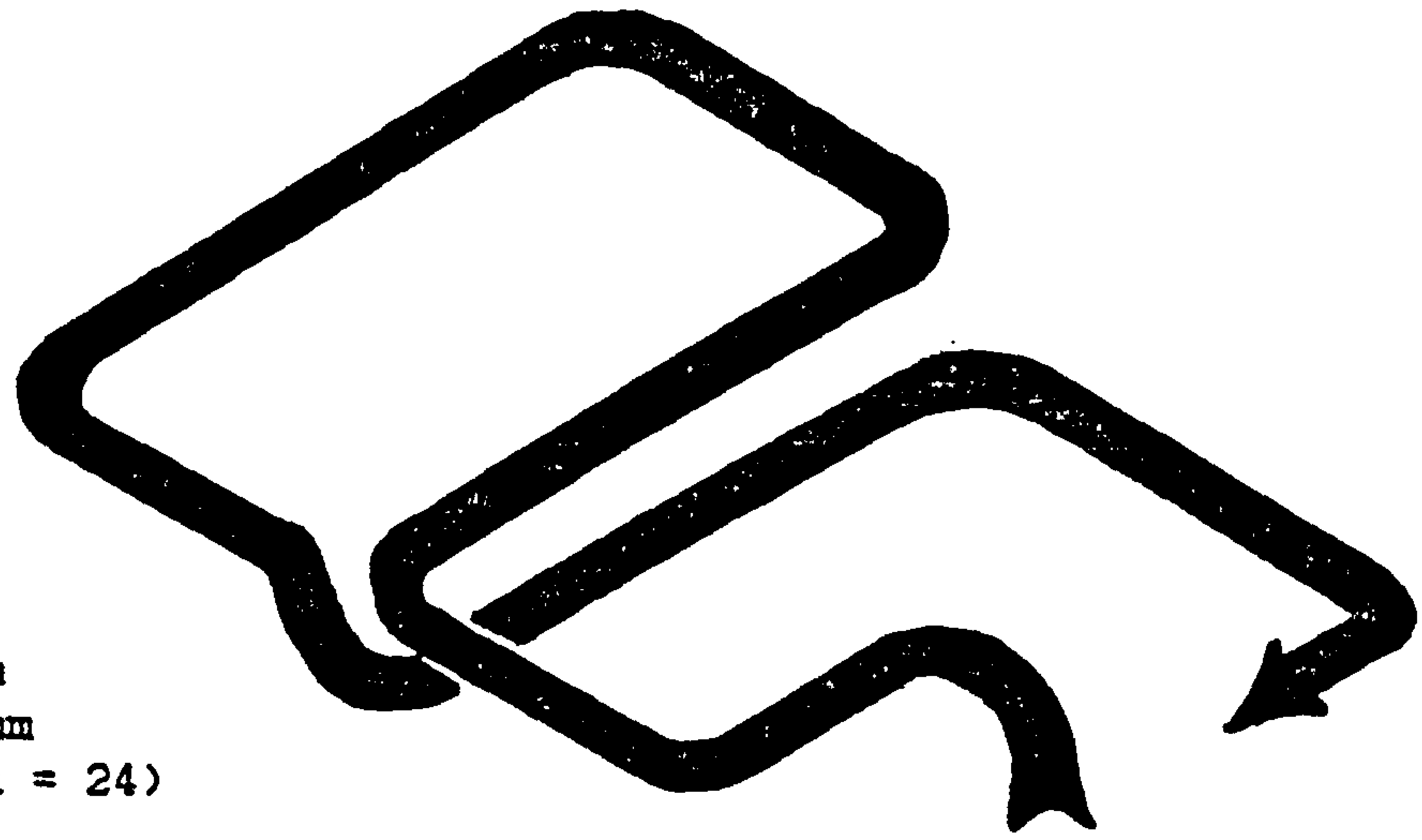
The air supply to the blow tank in the bottom discharge configuration entered a chamber formed between the internal and external walls of the cone section of the unit. The air entered the blow tank via a fluidising annulus of about 1mm in width located near the discharge point of the tank. This was the only point at which air entered the blow tank. The supplementary or conveying air entered the conveying pipeline via a swept 'T' at the reducing section as near to the blow tank as possible.

The need to design a bottom discharge configuration for the blow tank arose out of the need to convey minus 1" coal which included particle sizes in the range of 150μm to about 20mm. It was considered that a bottom discharge arrangement would be more suitable for a product with such a wide size distribution and virtually no fluidisation capability. The choice of design was governed by the need to adopt a conventional arrangement typical of those used in industrial systems.

The blow tank capacity in top discharge configuration was approximately 1.5 m^3. In bottom discharge the capacity was slightly larger. This volume was sufficient to accept about a tonne of most products and so ensure that a reasonably long period of steady state conveying could be achieved at the highest product flow rates anticipated.

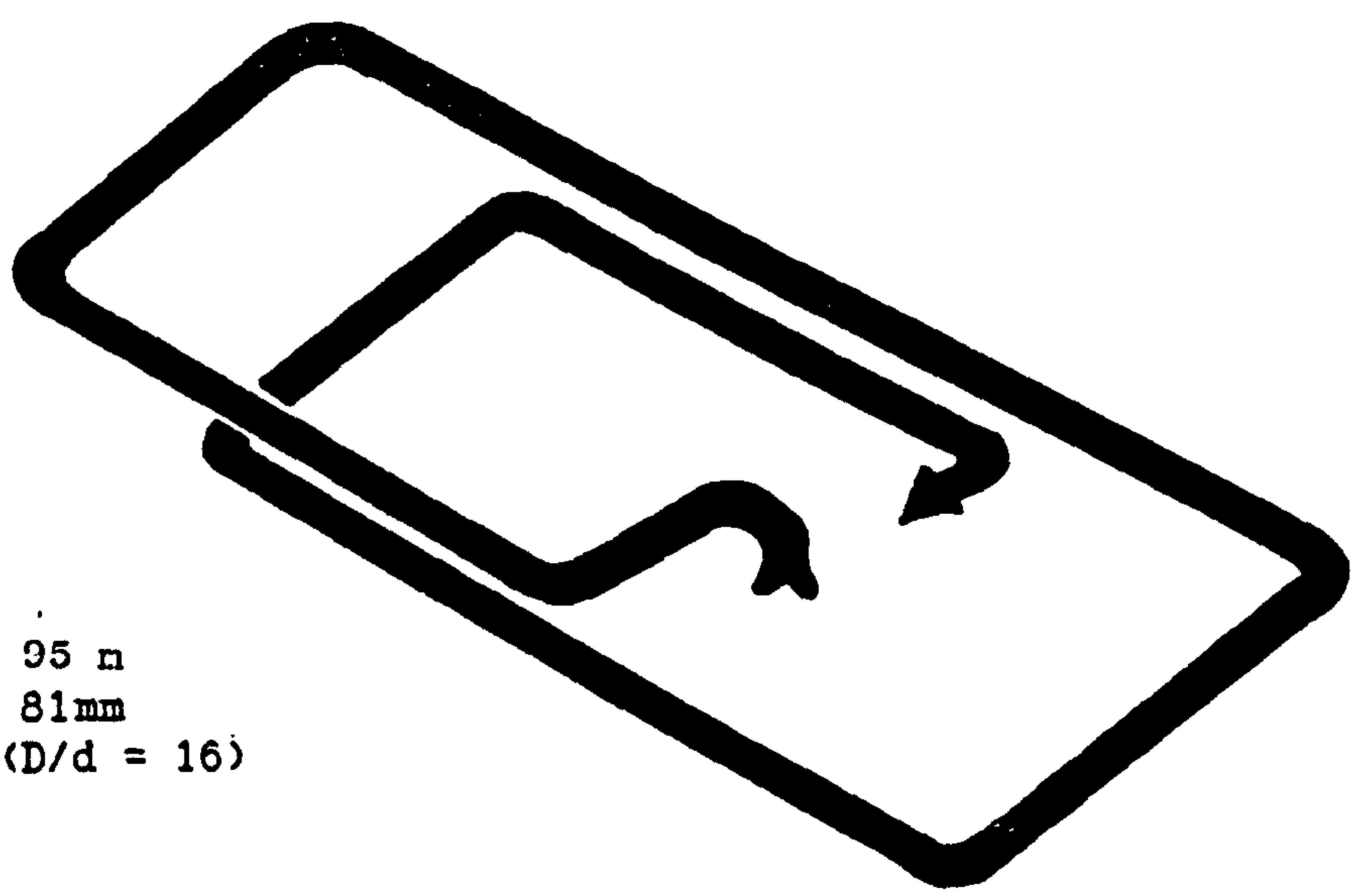
3.2.2 The Conveying Pipeline

The conveying pipelines used throughout the conveying trials test programme were made of mild steel and were of 53mm and 81mm (2" and 3" nominal) bore. The pipeline layout in the laboratory allowed maximum flexibility so that various combinations of pipeline length and number of bends could be accommodated. The pipeline geometries used during the conveying trials are shown in figs. 3.8 & 3.9. All the products were tested in the standard 53mm bore pipeline which was 50m long with nine



LENGTH = 50m
BORE = 53mm
9 BENDS (D/d = 24)

FIG. 3.8



LENGTH = 95 m
BORE = 81mm
9 BENDS (D/d = 16)

FIG. 3.9

CONVEYING PIPELINE LAYOUTS

90° bends all having a diameter of curvature to diameter of pipeline ratio (D/d) of 24. The entire pipeline was essentially in the horizontal plane with only a short vertical lift out of the blow tank at the start and into the receiving hopper at the end of the conveying line. This pipeline was adopted as the standard pipeline. As a means of checking the scaling models and assessing the effect of scale on the subsequent correlations a selection of products were also conveyed in the 81mm bore pipeline which was 95m long with 9 bends each with a D/d ratio of 16. The choice of pipeline lengths and the number of bends was partly determined by the requirements of the Department of Industry to be consistent with the Design Guide.

It was desirable that the head loss across bends be reduced to a minimum and, therefore, the choice of bend diameter ratios needed to be considered. Fig. 3.10 shows the variation in head loss round a 90° bend with diameter ratio for air only. It can be seen that for a long radius bend with a D/d greater than about 10 the variation in head loss is minimal and the diameter ratio is not critical. Recent research has indicated that a similar relationship exists with respect to gas-solid flows (Ref 3.2). Therefore, a choice of convenience of D/d of 24 for the 53mm pipe and 16 for the 81mm pipe was considered acceptable.

A problem that occurs with using steel pipelines is the inability to observe the flow. Flow visualisation is extremely important in this type of work and provision was made to view the flow through sight glasses. The sight glasses were positioned in the 53mm bore pipeline along the section in the middle of the figure of eight where two sections of the pipeline run in parallel. The two sight glasses were 1.0m long and situated at approximately a quarter and three quarters of the way along the pipeline.

The conveying line discharged into the receiving hopper which was situated immediately above the blow tank. The hopper was fitted with a bag filtration unit with a mechanical shaker.

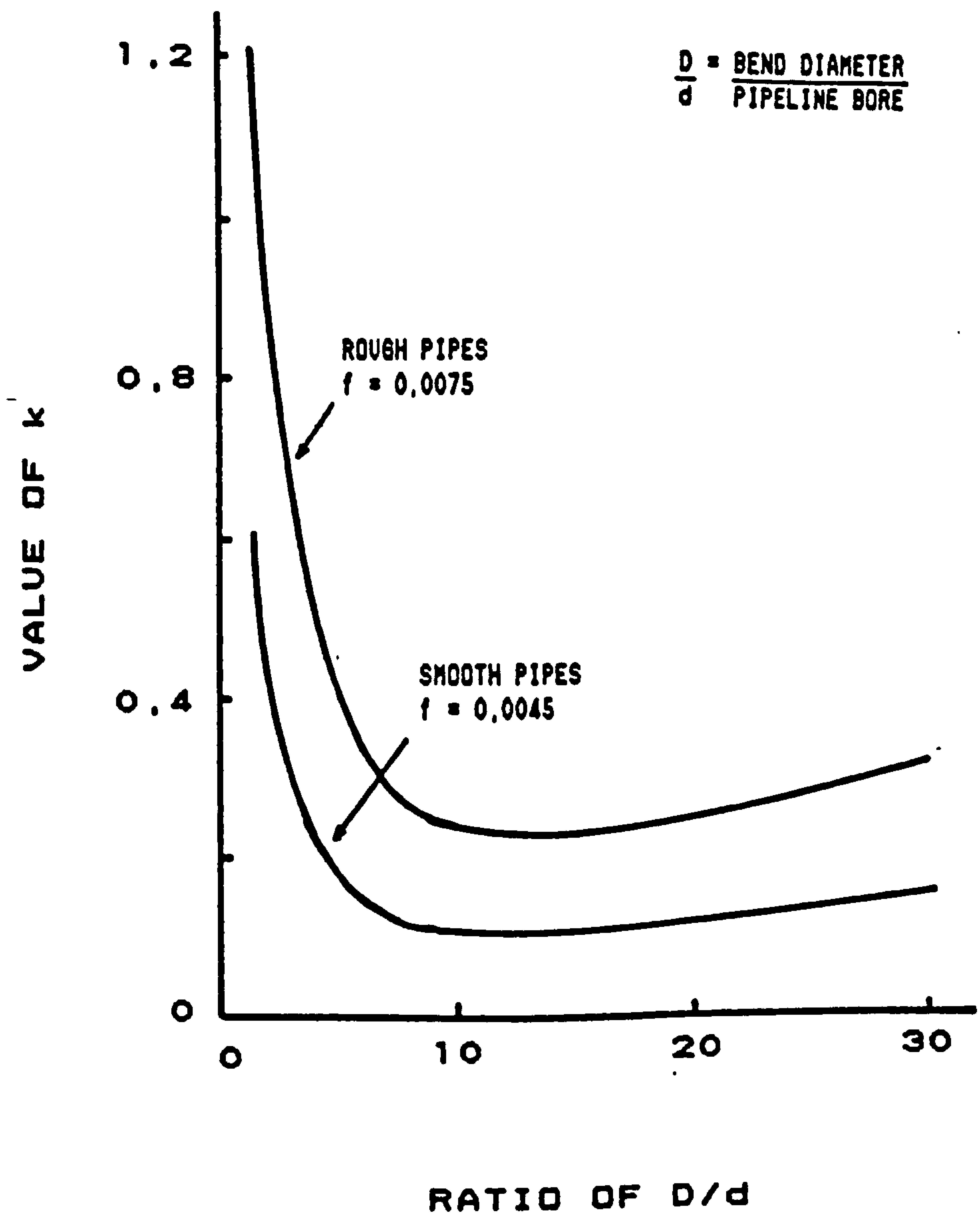


FIG. 3.10 HEAD LOSS FOR 90° BENDS FOR SINGLE PHASE FLOW

3.2.3 The Air Supply

For dense phase conveying, large conveying line pressure drops in excess of 3 bar can be encountered. For this reason, the most suitable air mover for these conveying trials was a reciprocating compressor. Three compressors were available each capable of delivering 0.095 m^3/s (202 ft^3/min) of 'free air' at a pressure of 6.9 bar (100 lbf/in^2) gauge. A diagrammatic layout of the air supply from the compressors to the conveying plant is shown in fig. 3.11. The air was passed through an air cooler and into the air receivers. The air then passed through a water trap and pressure reducing valve before splitting into two separate lines; one to the blow tank, the other to the conveying pipeline. The pressure reducing valve was the major source of system control together with the selection of critical flow nozzles for the blow tank and supplementary air lines. The pressure reducing valve enabled the upstream pressure of the critical flow nozzles to be accurately set. Overall control of the blow tank, and hence the conveying pipeline, was achieved by controlling the total mass flow rate of air to the system and the proportion of the total that was directed to the blow tank. The proportion of the total air directed to the blow tank is known as the Blow Tank Air Ratio (BTAR) and is often quoted as a percentage. Some products are particularly sensitive to moisture and in these cases it was possible to plumb in a deliquescent drier to ensure the quality of the air.

3.3 INSTRUMENTATION

3.3.1 Air Mass Flow Rate Measurement

It has already been mentioned that critical flow nozzles were used to control the air mass flow rate to both the blow tank and the supplementary air line. The critical flow nozzle has two fundamental advantages as a means of measurement and control of air flow rate over such devices as the orifice plate or rotary meters. Firstly, the mass flow rate of air will be constant for a given upstream pressure regardless of the downstream pressure provided a critical pressure ratio

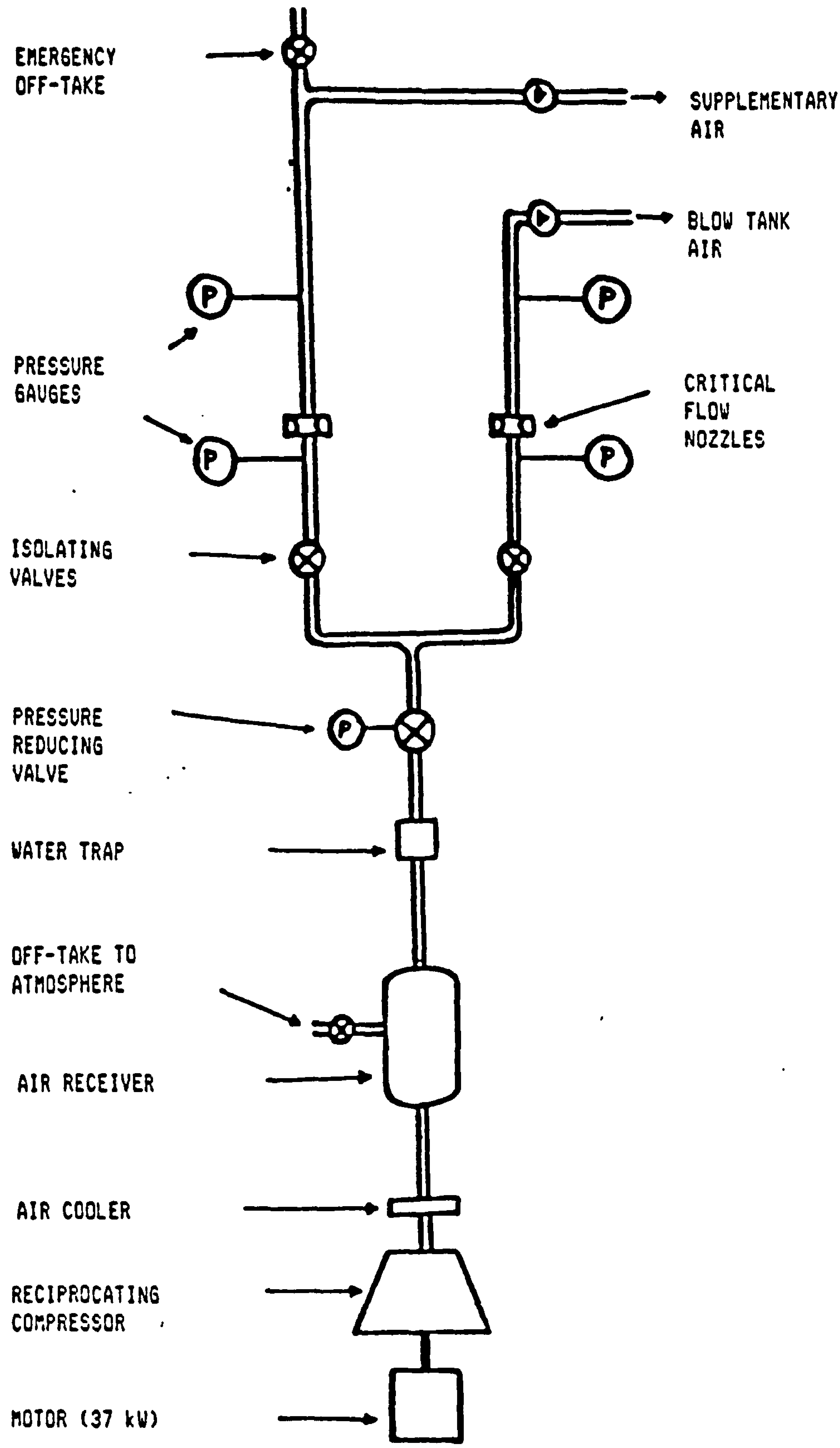


FIG. 3.11 CONVEYING PLANT AIR SUPPLY

is not exceeded and secondly, it follows that while sonic velocity is maintained at the nozzle throat, reverse flow pulsations downstream of the nozzle will not affect the flow measurement. These characteristics are extremely beneficial since it has to be recognised that downstream fluctuation in pressure due to the conveying line is inevitable.

The critical flow or convergent-divergent nozzle consists of a bell mouth converging to a throat followed by a shallow angled divergent section. The exact design can vary slightly but the general theory is illustrated in fig. 3.12. Diagram (a) shows the conceptually important sections of the arrangement. Diagram (b) shows the variation of pressure along the length of the nozzle, expressed in terms of a ratio of static pressure to the upstream stagnation pressure. The air velocity at the throat becomes sonic as the pressure ratio, p^*/p_o, at the throat section becomes critical. For air, this critical pressure ratio at the throat is 0.528. If the pressure ratio at the throat increases then sonic conditions at the throat will not be maintained and the maximum mass flow rate of air will not be achieved. Diagram (c) in fig. 3.12 shows the relationship between mass flow rate of air, expressed as a ratio of the maximum air mass flow rate, and the pressure ratio across the nozzle. The conditions at the throat and elsewhere within the nozzle depend on the pressure ratio between the downstream pressure and the upstream stagnation pressure, p_b/p_o. i.e. the pressure drop across the nozzle. If one considers the line A in diagram (b), pressure ratio p_b/p_o is high and therefore the pressure drop across the nozzle is not sufficient to induce sonic flow in the throat. If the pressure ratio across the nozzle is decreased, then the pressure ratio at the throat will reduce until the critical pressure ratio, p^*/p_o, is reached. This condition is indicated by the line B. Any further reduction in the pressure ratio across the nozzle will not affect the pressure ratio at the throat which will remain constant at the critical value. The pressure ratio across the nozzle corresponding to the condition indicated by line B is called the choking pressure ratio and represents the maximum pressure ratio for which the velocity in the nozzle throat remains sonic. Diagram (c) in fig. 3.12 shows that the pressure ratio at point A indicates that the maximum mass flow rate of air is not achieved since the pressure ratio is too high for

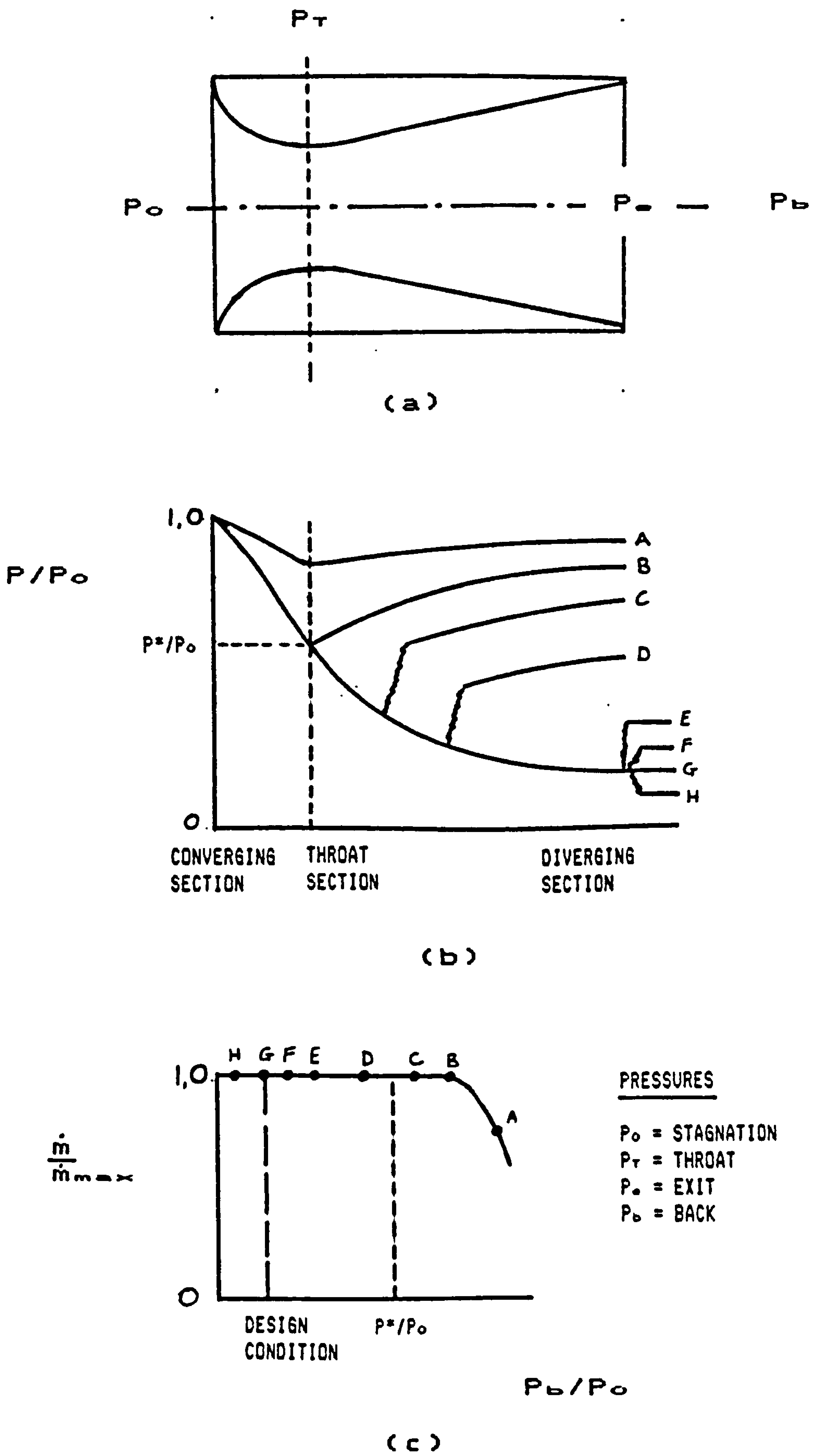


FIG. 3.12 CRITICAL FLOW NOZZLE THEORY

point A to be on the straight line part of the curve. However, point B is on the limit of the constant mass flow rate section of the curve and indicates the maximum pressure ratio that can be used whilst maintaining sonic velocity at the throat.

The maximum mass flow rate of gas through the nozzle is given by the expression,

$$m_{max} = A_t \left[p_o \, \rho_o \, \gamma \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{0.5}$$

where A_t = area of throat (m^2)
p_o = upstream stagnation gas pressure (kN/m^2)
ρ_o = upstream stagnation gas density (kg/m^3)
γ = isentropic exponent (γ = 1.4 for air)

Hence for air this expression can be simplified to:

$$m_{max} = 0.685 \, A_t \, (p_o \, \rho_o)^{0.5}$$

However, the density, ρ_o, is difficult to measure practically and so one can re-arrange the expression substituting:

$$\rho_o = \frac{p_o}{RT_o} \quad \text{using } pV=mRT \text{ and } \rho=m/V$$

to give

$$m_{max} = 0.367 \, C_d \, A_t \, p_o \left(\frac{1}{T_o} \right)^{0.5}$$

where: C_d = coefficient of discharge
T_o = Absolute Temperature (K)

Hence, the maximum mass flow rate of air is directly proportional to the upstream stagnation pressure provided the maximum pressure ratio is not exceeded. However, the maximum pressure ratio depends on the design of the nozzle. In particular, it depends on the area ratio of the throat and the exit and on the internal angle of the divergent section.

Brain and Reid (Ref. 3.3 & 3.4) suggest an internal divergence half angle of 7.5° and an area ratio of exit to throat of 4.5. With good surface finish, nozzles of this design will give a coefficient of discharge of between 0.983 - 0.996 and a maximum or choking pressure ratio of between 0.925 - 0.950.

The general arrangement of the type of nozzle used is shown in fig. 3.13. There were sixteen nozzles in total, two of eight different sizes covering the range of air mass flow rates from 0.0075 to 0.097 kg/s. The nozzles were calibrated against orifice plates according to BS 1042 (Ref. 3.5) over a range of upstream pressures from 2.0 to 4.0 bar gauge and pressure ratios from 0.200 to 0.981. Typical results are given in tables 3.1 to 3.4 and graphical representation is shown in figs. 3.14 & 3.15 for nozzles 8A and 8B. It can be seen from these graphs that downstream pressures of up to 85% of the upstream pressure were acceptable for constant mass flow rate of air and often up to 90% was acceptable. A graph showing the air mass flow rate against upstream gauge pressure for nozzles 8A and 8B can be seen in fig. 3.16. The combination of eight pairs of nozzles and the calibration of air mass flow rate with upstream pressure allowed a very large range of air flow rates and blow tank air ratios to be achieved. A table of values of air mass flow rate for all the nozzles over a range of upstream gauge pressures is presented in table 3.5.

3.3.2 Product Mass Flow Rate Measurement

The receiving hopper, into which the conveying line discharged the product, was mounted on load cells. It was for this reason that the interface between the receiving hopper and the blow tank took the form of a flexible reinforced rubber coupling and that a double set of valves was provided. All other connections to the hopper were also isolated using flexible couplings; these included the conveying pipeline junction and the vent line between the blow tank and the hopper. Three strain gauge type load cells were used with the combined electrical output signal being fed to a calibrated recording instrument and differentiated with respect to

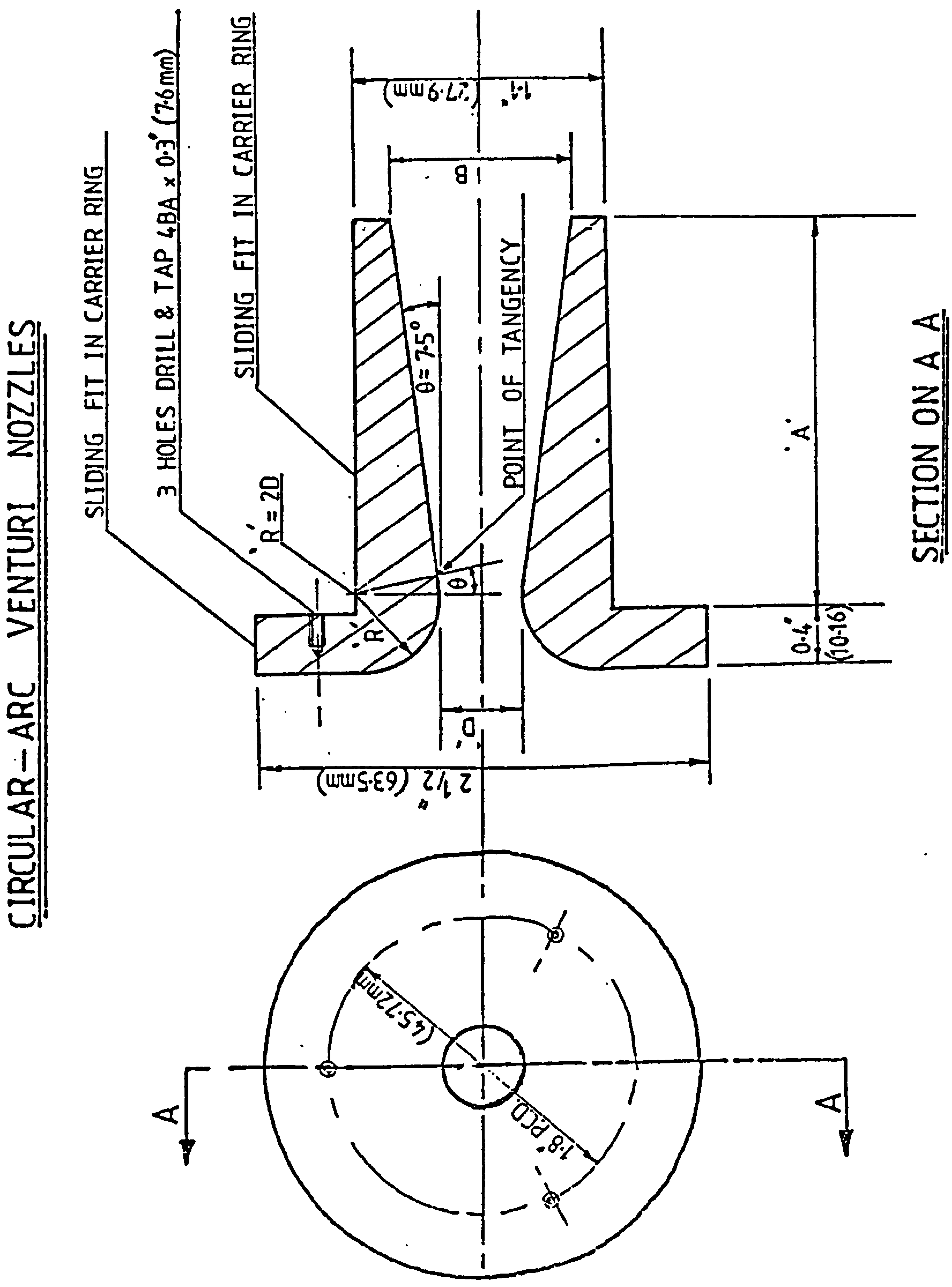

CIRCULAR—ARC VENTURI NOZZLES
SLIDING FIT IN CARRIER RING
3 HOLES DRILL & TAP 4BA x 0·3" (7·6mm)
SLIDING FIT IN CARRIER RING
1·1" (27·9mm)
B
θ = 7·5°
POINT OF TANGENCY
'A'
SECTION ON A A
R = 2D
'R'
θ
0·4" (10·16)
'D'
2 1/2" (63·5mm)
(45·72mm)
1·8" P.C.D
A
A

FIG. 3.13

CRITICAL FLOW NOZZLE CALIBRATION

BAROMETRIC PRESSURE= 1.011 BAR.A DATE: 24/4/85

	NOZZLE DATA			ORIFICE PLATE DATA		
NOZZLE NO.	UPSTREAM PRESSURE BAR.G	PRESSURE RATIO P/Pa	AIR MASS FLOWRATE KG/S	UPSTREAM PRESSURE MM.WATER	PRESSURE DIFF. MM.WATER	UPSTREAM TEMP. DEG.C.
A8	2.500	0.288	0.068	252.000	422.000	18.000
A8	2.500	0.402	0.068	249.000	426.000	18.000
A8	2.500	0.516	0.068	248.000	427.000	18.000
A8	2.500	0.630	0.068	250.000	427.000	18.000
A8	2.500	0.744	0.068	250.000	424.000	18.000
A8	2.500	0.858	0.068	250.000	422.000	18.000
A8	2.500	0.915	0.068	248.000	415.000	18.000
A8	2.500	0.972	0.054	159.000	265.000	18.000
B8	2.500	0.288	0.067	248.000	405.000	18.000
B8	2.500	0.402	0.067	246.000	409.000	18.000
B8	2.500	0.516	0.067	245.000	409.000	18.000
B8	2.500	0.630	0.067	244.000	409.000	18.000
B8	2.500	0.744	0.067	247.000	408.000	18.000
B8	2.500	0.858	0.067	244.000	409.000	18.000
B8	2.500	0.915	0.065	229.000	387.000	18.000
B8	2.500	0.972	0.054	163.000	266.000	18.000

TABLE 3.1

CRITICAL FLOW NOZZLE CALIBRATION

BAROMETRIC PRESSURE= 1.011 BAR.A DATE: 24/4/85

	NOZZLE DATA			ORIFICE PLATE DATA		
NOZZLE NO.	UPSTREAM PRESSURE BAR.G	PRESSURE RATIO P/Pa	AIR MASS FLOWRATE KG/S	UPSTREAM PRESSURE MM.WATER	PRESSURE DIFF. MM.WATER	UPSTREAM TEMP. DEG.C.
A8	3.000	0.252	0.078	331.000	548.000	18.000
A8	3.000	0.352	0.078	328.000	548.000	18.000
A8	3.000	0.452	0.078	328.000	548.000	18.000
A8	3.000	0.551	0.078	327.000	546.000	18.000
A8	3.000	0.651	0.078	327.000	547.000	18.000
A8	3.000	0.751	0.078	326.000	548.000	18.000
A8	3.000	0.850	0.077	327.000	543.000	18.000
A8	3.000	0.925	0.075	315.000	512.000	18.000
A8	3.000	0.975	0.051	144.000	240.000	18.000
B8	3.000	0.252	0.077	320.000	537.000	20.000
B8	3.000	0.352	0.077	319.000	538.000	20.000
B8	3.000	0.452	0.077	317.000	538.000	20.000
B8	3.000	0.551	0.077	317.000	536.000	20.000
B8	3.000	0.651	0.076	319.000	530.000	20.000
B8	3.000	0.751	0.076	319.000	524.000	20.000
B8	3.000	0.850	0.076	319.000	523.000	20.000
B8	3.000	0.900	0.074	304.000	500.000	20.000
B8	3.000	0.950	0.070	274.000	448.000	20.000
B8	3.000	0.975	0.061	206.000	342.000	20.000

TABLE 3.2

CRITICAL FLOW NOZZLE CALIBRATION

BAROMETRIC PRESSURE= 1.011 BAR.A DATE: 24/4/85

NOZZLE DATA				ORIFICE PLATE DATA		
NOZZLE NO.	UPSTREAM PRESSURE BAR.G	PRESSURE RATIO P/Pa	AIR MASS FLOWRATE KG/S	UPSTREAM PRESSURE MM.WATER	PRESSURE DIFF. MM.WATER	UPSTREAM TEMP. DEG.C.
A8	3.500	0.224	0.088	420.000	699.000	18.000
A8	3.500	0.313	0.089	420.000	704.000	18.000
A8	3.500	0.401	0.089	419.000	707.000	18.000
A8	3.500	0.490	0.089	420.000	705.000	18.000
A8	3.500	0.579	0.089	420.000	704.000	18.000
A8	3.500	0.667	0.088	420.000	702.000	18.000
A8	3.500	0.756	0.088	420.000	698.000	18.000
A8	3.500	0.845	0.088	416.000	693.000	18.000
A8	3.500	0.933	0.079	330.000	570.000	18.000
A8	3.500	0.978	0.058	184.000	304.000	18.000
B8	3.500	0.224	0.087	412.000	680.000	20.500
B8	3.500	0.313	0.087	412.000	685.000	20.500
B8	3.500	0.401	0.087	412.000	690.000	20.500
B8	3.500	0.490	0.087	404.000	679.000	20.500
B8	3.500	0.579	0.086	405.000	673.000	20.000
B8	3.500	0.667	0.086	404.000	676.000	20.000
B8	3.500	0.756	0.086	406.000	665.000	20.000
B8	3.500	0.845	0.086	401.000	664.000	20.000
B8	3.500	0.933	0.079	348.000	569.000	20.000
B8	3.500	0.978	0.065	239.000	384.000	20.000

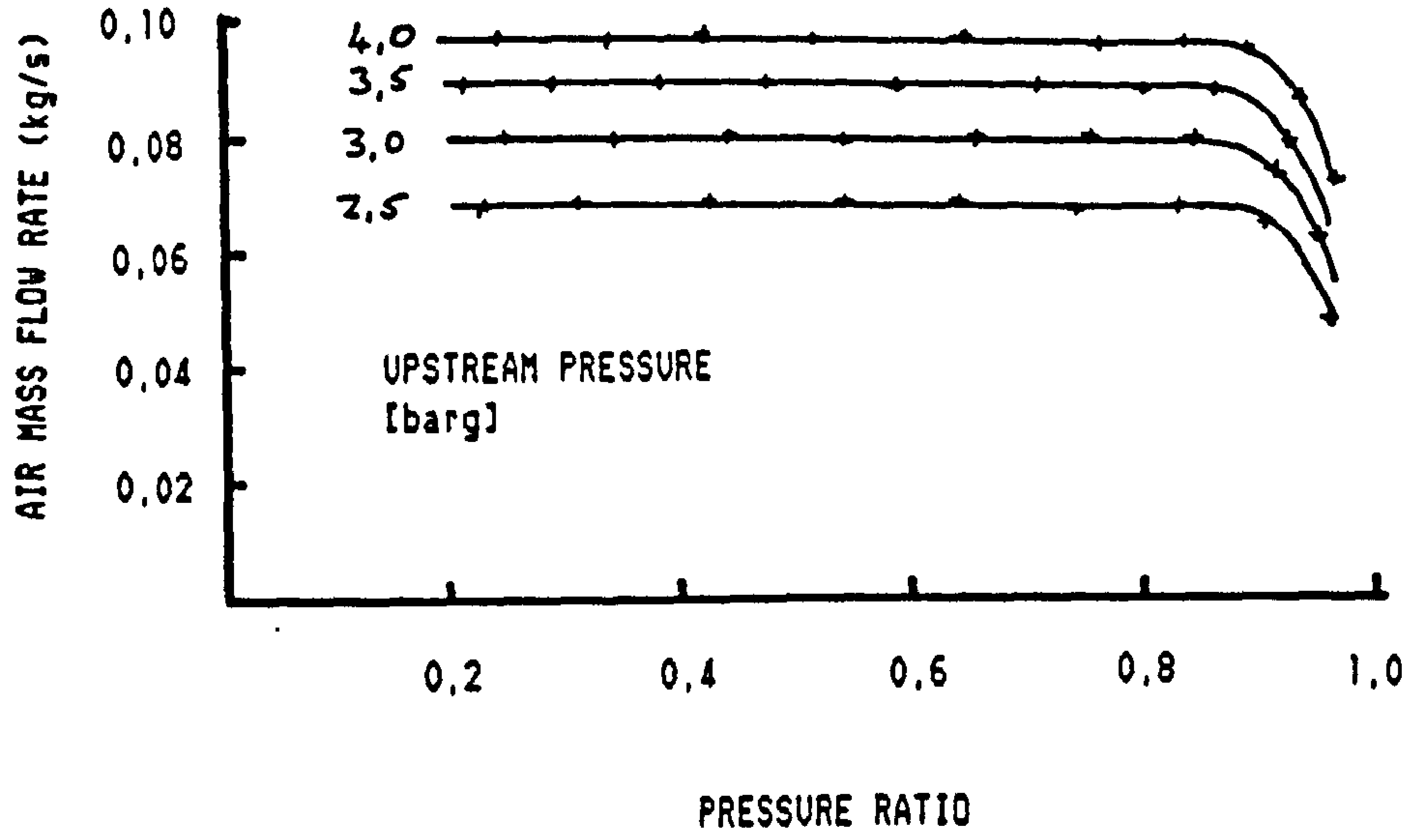
TABLE 3.3

CRITICAL FLOW NOZZLE CALIBRATION

BAROMETRIC PRESSURE= 0.998 BAR.A DATE: 12/4/85

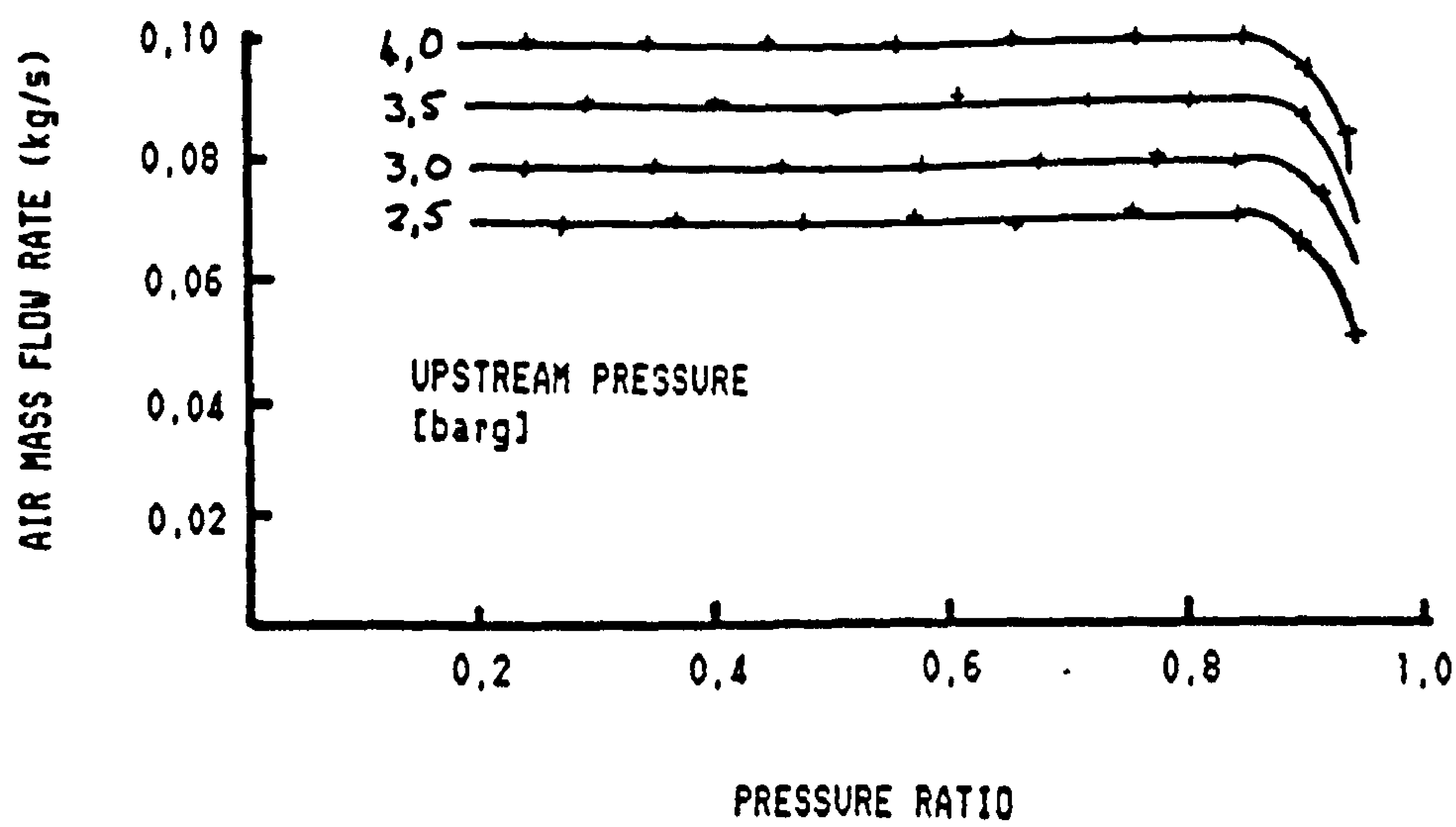
NOZZLE DATA				ORIFICE PLATE DATA		
NOZZLE NO.	UPSTREAM PRESSURE BAR.G	PRESSURE RATIO P/Pa	AIR MASS FLOWRATE KG/S	UPSTREAM PRESSURE MM.WATER	PRESSURE DIFF. MM.WATER	UPSTREAM TEMP. DEG.C.
A8	4.000	0.200	0.096	509.000	844.000	20.000
A8	4.000	0.280	0.097	508.000	847.000	20.000
A8	4.000	0.360	0.097	508.000	852.000	20.000
A8	4.000	0.440	0.097	508.000	852.000	20.000
A8	4.000	0.520	0.096	506.000	844.000	20.000
A8	4.000	0.600	0.096	507.000	844.000	20.000
A8	4.000	0.680	0.096	508.000	842.000	20.000
A8	4.000	0.760	0.096	506.000	841.000	20.000
A8	4.000	0.840	0.096	507.000	834.000	20.000
A8	4.000	0.880	0.095	501.000	823.000	20.000
A8	4.000	0.920	0.092	470.000	771.000	20.000
A8	4.100	0.961	0.081	373.000	608.000	20.000
A8	4.200	0.981	0.062	220.000	360.000	20.000
B8	4.000	0.200	0.097	518.000	860.000	20.500
B8	4.000	0.280	0.097	517.000	864.000	20.500
B8	4.000	0.360	0.097	516.000	864.000	20.500
B8	4.000	0.440	0.097	516.000	863.000	20.500
B8	4.000	0.520	0.097	516.000	863.000	20.500
B8	4.000	0.600	0.097	517.000	862.000	20.500
B8	4.050	0.673	0.097	516.000	857.000	20.500
B8	4.050	0.752	0.097	517.000	854.000	20.500
B8	4.050	0.832	0.097	512.000	848.000	20.500
B8	4.050	0.871	0.095	504.000	829.000	20.500
B8	4.100	0.941	0.088	434.000	718.000	20.500
B8	4.200	0.981	0.065	241.000	395.000	20.500

TABLE 3.4



MASS FLOW RATE v PRESSURE
RATIO FOR NOZZLE 8A

FIG. 3.14



MASS FLOW RATE v PRESSURE
RATIO FOR NOZZLE 8B

FIG. 3.15

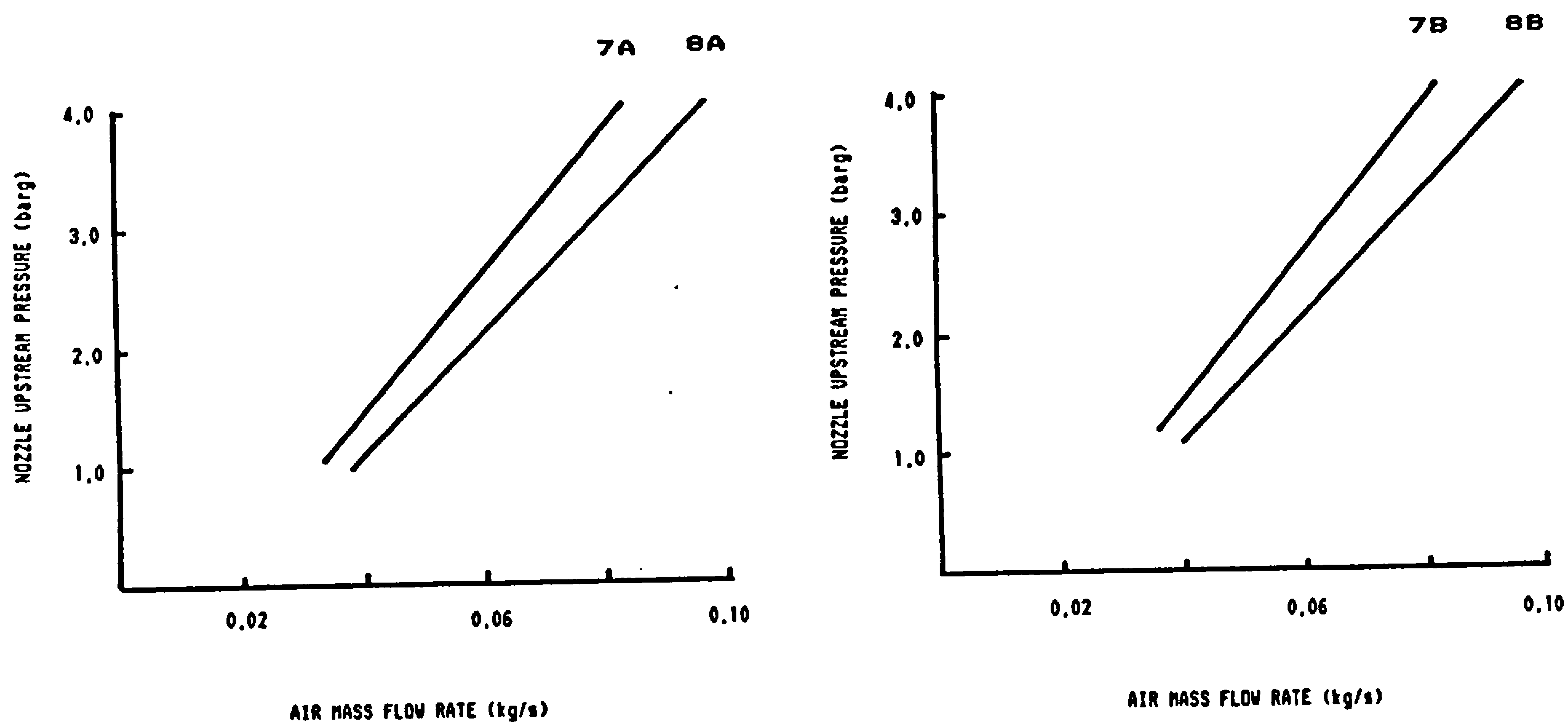


FIG. 3.16 CRITICAL FLOW NOZZLE CALIBRATION

AIR MASS FLOW RATES - kg/s					
Nozzle Number	Air Supply Pressure - bar g				
	2.0	2.5	3.0	3.5	4.0
1A	0.0075	0.0088	0.0100	0.0113	0.0126
1B	0.0073	0.0086	0.0099	0.0112	0.0125
2A	0.0148	0.0172	0.0197	0.0221	0.0245
2B	0.0148	0.0173	0.0198	0.0223	0.0247
3A	0.0211	0.0247	0.0282	0.0317	0.0353
3B	0.0211	0.0246	0.0282	0.0317	0.0353
4A	0.0297	0.0347	0.0396	0.0446	0.0495
4B	0.0299	0.0348	0.0397	0.0445	0.0494
5A	0.0365	0.0425	0.0484	0.0544	0.0603
5B	0.0366	0.0427	0.0487	0.0548	0.0609
6A	0.0436	0.0509	0.0582	0.0655	0.0728
6B	0.0439	0.0512	0.0584	0.0657	0.0729
7A	0.0498	0.0581	0.0664	0.0747	0.0830
7B	0.0492	0.0574	0.0656	0.0738	0.0820
8A	0.0579	0.0675	0.0772	0.0868	0.0965
8B	0.0582	0.0679	0.0776	0.0873	0.0970

TABLE 3.5 MAXIMUM AIR MASS FLOW RATES FOR THE CRITICAL FLOW NOZZLES AT VARIOUS UPSTREAM PRESSURES

time to give the product flow rate. The overall accuracy of the load cells was good to around 5 kg. The calibration of the load cells was checked whenever product was loaded into the rig. The consistency of calibration was good throughout the test programme.

3.3.3 Pressure Measurement

Calibrated Bourdon type pressure gauges with a range of 0 to 6 bar were used for all pressure measurement during the conveying trials. The smallest division on the gauge was 0.2 bar but with a reading capability to 0.05 bar. The gauge calibrations indicated good linear relationships with negligible zero shift over the working limits of the gauges. Four gauges were used with the pressure being measured upstream and down stream of the critical flow nozzles. The downstream gauges were positioned so as to avoid any disturbances caused by the nozzles in accordance with BS 1042 (Ref. 3.5) recommendations.

The downstream gauge in the supplementary air line was assumed to indicate the conveying line pressure drop. The justification for this assumption was that the air only pressure drop in the remainder of the supplementary air line was negligible compared with the conveying line pressure drop. This was proved to be the case by both calculation and measurement. In addition, the end of the conveying line was assumed to be at atmospheric pressure since the pressure drop across the filter unit was negligible compared to the pressure drop across the conveying pipeline. The blow tank pressure was measured directly using a calibrated bourdon gauge.

CHAPTER 4

CONVEYING TRIALS

4.1 INTRODUCTION

The main objective of this research project was to determine a correlation between pneumatic conveying performance and the physical properties of the product being conveyed. Properties of products can be determined quite easily by carrying out bench scale tests using small samples of product. The ultimate goal was to establish relationships which would enable conveying performance to be predicted from the results of such bench scale tests.

Product performance in a pneumatic conveying pipeline can vary considerably. Some products can be conveyed over a wide range of flow conditions, from high velocity dilute phase, to low velocity, dense phase. Many products, however, are restricted to dilute phase only, in conventional pneumatic conveying systems. In addition, products which are capable of being conveyed in dense phase can exhibit quite different levels of performance in terms of product throughput for a given set of conditions, particularly at low velocity. It is believed that both of these aspects of performance are dependent on the properties of the product being conveyed.

The aim of the conveying trials was to determine quantitatively the performance of a wide variety of products in a pneumatic conveying system pipeline for correlation with the results of the bench scale tests. The performance of a product was determined by producing conveying characteristics in graphical form for each of the products. The conveying characteristics are essentially a 'performance map', providing relationships between product flow rate, air flow rate and conveying line pressure drop, and indicating the limitations of a product in terms of minimum conveying conditions. The minimum conveying conditions were determined in practice by progressively reducing the conveying air velocity, over a range of conveying line pressure drop values, until the pipeline blocked. The conveying characteristics are unique for each product and provide a visual indication of whether or not a product is capable of dense phase conveying. A total of 22 products were tested in this programme of work (including the three degraded products). The relative performance of products was determined by comparing the mass throughput of product for a given set of conveying conditions. For the products which were capable of dense phase conveying, a wide range of conveying performance was recorded. Variation in relative performance also existed for dilute phase products, although the spread of results was not as great.

For dense phase conveying, flow visualisation, via sight glasses in the pipeline, played a major part in determining the flow regime in which the product was conveyed. It was also used to give visual clues to the probable mechanism of pipeline blockage. Products conveyed in dense phase adopted a variety of flow regimes although in most cases these could be grouped into either moving bed type flow or plug type flow. Most of the products tested during these trials were conveyed in the moving bed type flow regime.

The products were chosen to represent a wide range of bulk properties, several of them being acknowledged as 'difficult' materials to convey pneumatically. Many of the products were chosen for their troublesome nature by industrial companies who were participating in the Pneumatic Conveying Design Guide Project.

The conveying test plant was described in some detail in chapter 3 and was notable for the fact that it was a completely conventional system with no 'innovative' techniques employed, such as additional air injection along the pipeline or air pulsation at the beginning of the conveying line. This enabled a base performance level to be found enabling direct comparison between products.

4.2 EXPERIMENTAL METHOD

Initially, the blow tank was charged with product. The volume of the blow tank in either top or bottom discharge configuration was sufficient, in most cases, to allow a tonne of product to be conveyed. The poured bulk density of most products ranged from 500 to 1500 kg/m^3; notable exceptions to this were pearlite with a poured bulk density of 100 kg/m^3 and at the other extreme Zircon sand with a poured bulk density of 2600 kg/m^3.

The choice of total air mass flow rate and the split between conveying line and blow tank (i.e. the choice of blow tank air ratio, BTAR) was not obvious for the first test run. The discharge characteristics of the blow tank were not known since they depended on the type of product being conveyed. Past experience with similar products may help in this respect, although the performance of apparently similar products can often be misleading. Therefore, a safe approach was adopted for the first run by selecting a high mass flow rate of air corresponding to a high 'free' air velocity in the pipeline and a low blow tank air ratio.

Air was then supplied to the system and the vent line between the blow tank and the hopper was closed to initiate conveying. Pressurisation began as soon as the vent line was closed and product conveying followed shortly after. The start up transient and, to a lesser extent, the depressurisation transient were dependent on the air mass flow rate and the blow tank air ratio for a given product. A diagram illustrating a typical blowing cycle is shown in fig. 4.1. At high air mass flow rates and high blow tank air ratios the transient periods and steady state conveying periods were relatively short. Conversely, at low air mass flow rates and low blow tank air ratios the transient and steady state conveying periods were relatively long. However, in general, the ratio of transient periods to steady state periods is approximately constant (Ref. 4.1) and the ratio of the steady state product flow rate to the average product flow rate over the complete cycle is approximately 2.

Throughout the cycle, measurement of conveying line pressure drop, blow tank pressure, product mass flow rate and air mass flow rate were continuously monitored. For the purpose of producing the conveying characteristics or phase diagram for the product, it was the steady state values of the pressures and flow rates that were of interest. In the 53mm bore pipeline, conveying rates varied between less than 1 tonne/hr.

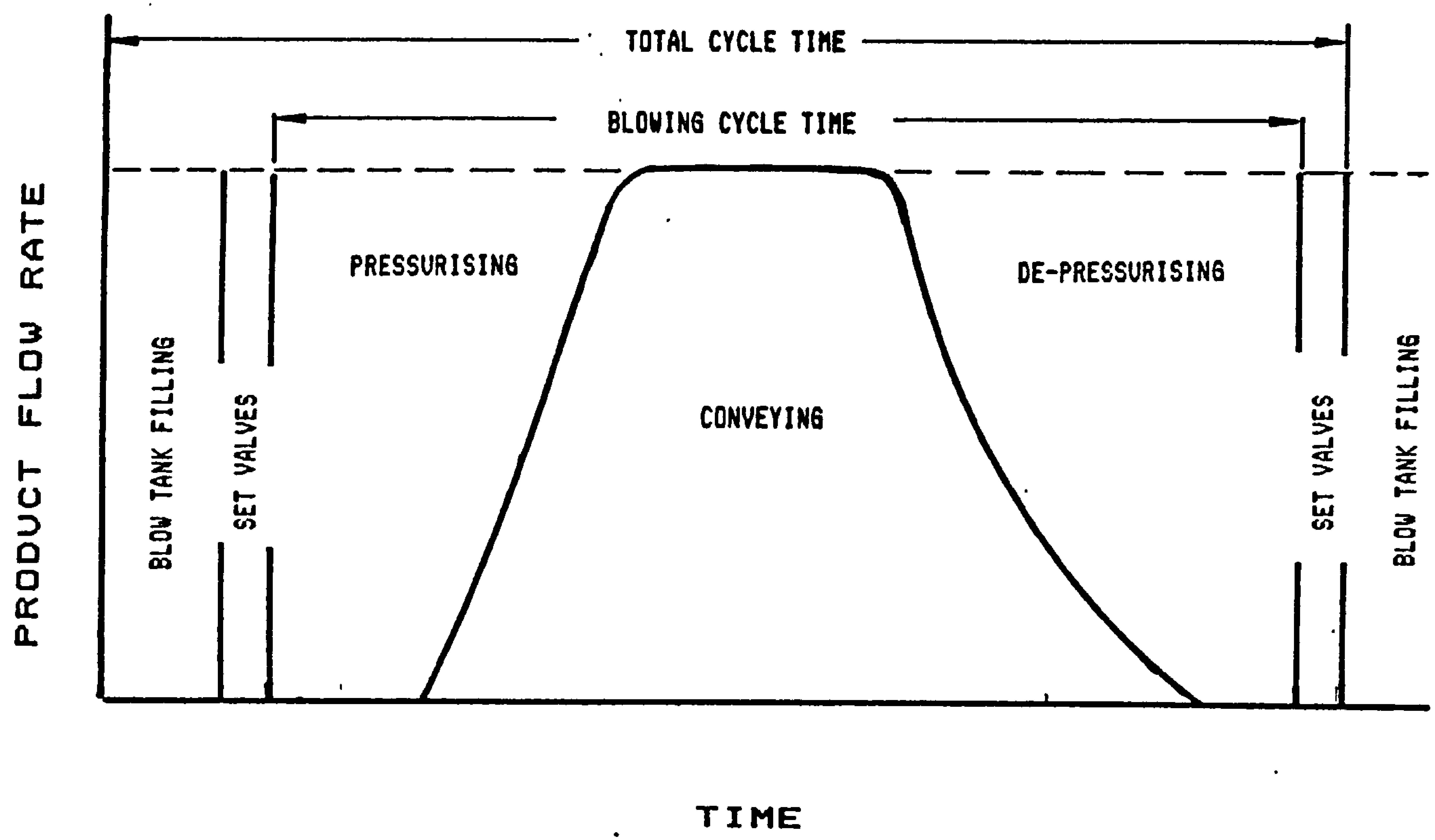


FIG. 4.1 — SCHEMATIC OF TYPICAL BLOW TANK CYCLE

to about 30 tonnes/hr. which gave steady state conveying periods of between 1 hr. and 2 minutes. In most cases, the conveying data from one run gave rise to a single point on the conveying characteristics. However, in cases where the steady state period was particularly long (longer than about 15 to 20 minutes) it was possible to obtain more than one point by varying the total air mass flow rate. This was achieved by reducing the upstream pressure of the critical flow nozzles via the pressure reducing valve and allowing the system to settle into another stable steady state condition. However, this practice was limited; firstly, by the degree to which the upstream pressure of the critical flow nozzles could be reduced, bearing in mind that the conveying line pressure (downstream pressure) must not exceed 90% of the upstream pressure; and secondly, that sufficient time was available for the transient effects to die away and that an acceptable further steady state period was available before the end of the cycle.

At the end of the cycle, after the depressurisation transient, high velocity air was passed through the pipeline to ensure that the pipeline had been completely emptied of all product.

Initial test runs were carried out using high air mass flow rates with low blow tank air ratios to ensure that the conveying regime was dilute phase. On subsequent test runs, the total air mass flow rate was progressively reduced and the blow tank air ratio increased. This had the effect of reducing the velocity in the pipeline and increasing the phase density. It was possible to observe the changes in flow regime as the conveying mode progressively developed from dilute to dense phase. This process was continued until a line blockage occurred indicating the limit of conveying. In some cases, ample warning of impending blockage was given by extreme instability of flow to the point of partial blockage and subsequent recovery. In other cases the blockage was sudden, with no warning. The only indication of the blockage having occurred being due to a sudden rise in blow tank and conveying line pressures and the absence of noise due to the lack of air flow. In most cases two or three blockages or near blockages would be observed in order to establish the limits of conveying.

Conveying test runs were carried out over as wide a range of operating conditions as possible for each product. For products which were capable of being conveyed in dense phase this would typically involve 30 to 40 test runs. For products that could only be conveyed in dilute phase, 15 to 20 test runs would be undertaken.

4.3 THE USE OF AIR MASS FLOW RATE

Phase diagrams produced for pneumatic conveying are often based on conveying velocity. A typical example is the original phase diagram produced by Zenz (Ref. 4.2). This velocity is normally taken to be the superficial air velocity at atmospheric pressure (that is, the velocity based on the empty cross-section of the pipe). The problem with using velocity is that it is not an independent variable. Gases are compressible and their densities vary both with temperature and pressure. However, air mass flow rate is an independent variable and is therefore an ideal substitute for velocity. The air mass flow rate remains essentially constant over the entire pipeline length unlike the velocity which will increase with decreasing pressure. The superficial gas velocity, C, at any point can be determined from the Ideal Gas Law:-

$$p\ V = m\ R\ T$$

where	p = *absolute pressure*	kN/m^2
	T = *absolute temperature*	K
	R = *characteristic gas constant*	$kJ/kg\ K$
and	V = *volumetric flow rate*	m^3/s

since $V = C \times c.s.a. = \dfrac{\pi\ C\ d^2}{4}$ *for circular pipes*

Substituting this in the Ideal Gas Law and making the velocity the subject gives:

$$C = \frac{4\ m\ R\ T}{\pi\ p\ d^2}$$

The dependence of velocity on both gas temperature and pressure for a given mass flow rate is clearly shown by this expression. For a given set of conditions, the superficial gas velocity can be easily determined for any point along the pipeline.

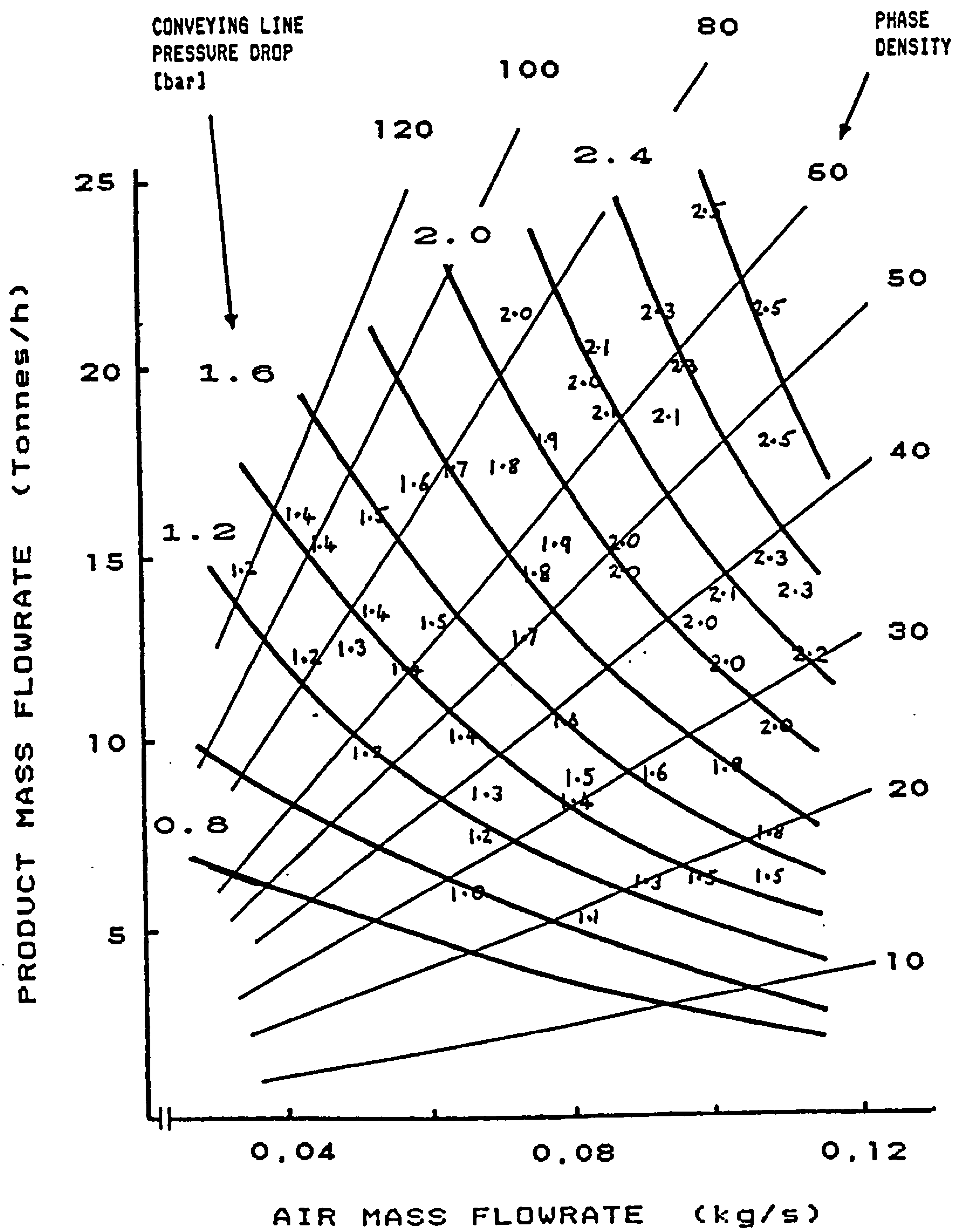
4.4 CONVEYING CHARACTERISTICS

The data obtained from the conveying trials was plotted on axes of product mass flow rate against air mass flow rate. This method of presentation was suggested by Mills (Ref. 4.3). Each run was represented by a single data point which was marked with the conveying line pressure drop associated with that run. The data recorded for pulverised fuel ash (p.f.a.) is plotted on these axes and is shown in fig. 4.2. It can be seen that the decimal point of the conveying line pressure drop represents the actual location of the test point on the graph. Having plotted the points it was possible to draw a family of curves representing lines of constant conveying line pressure drop.

4.4.1 Conveying Limitations

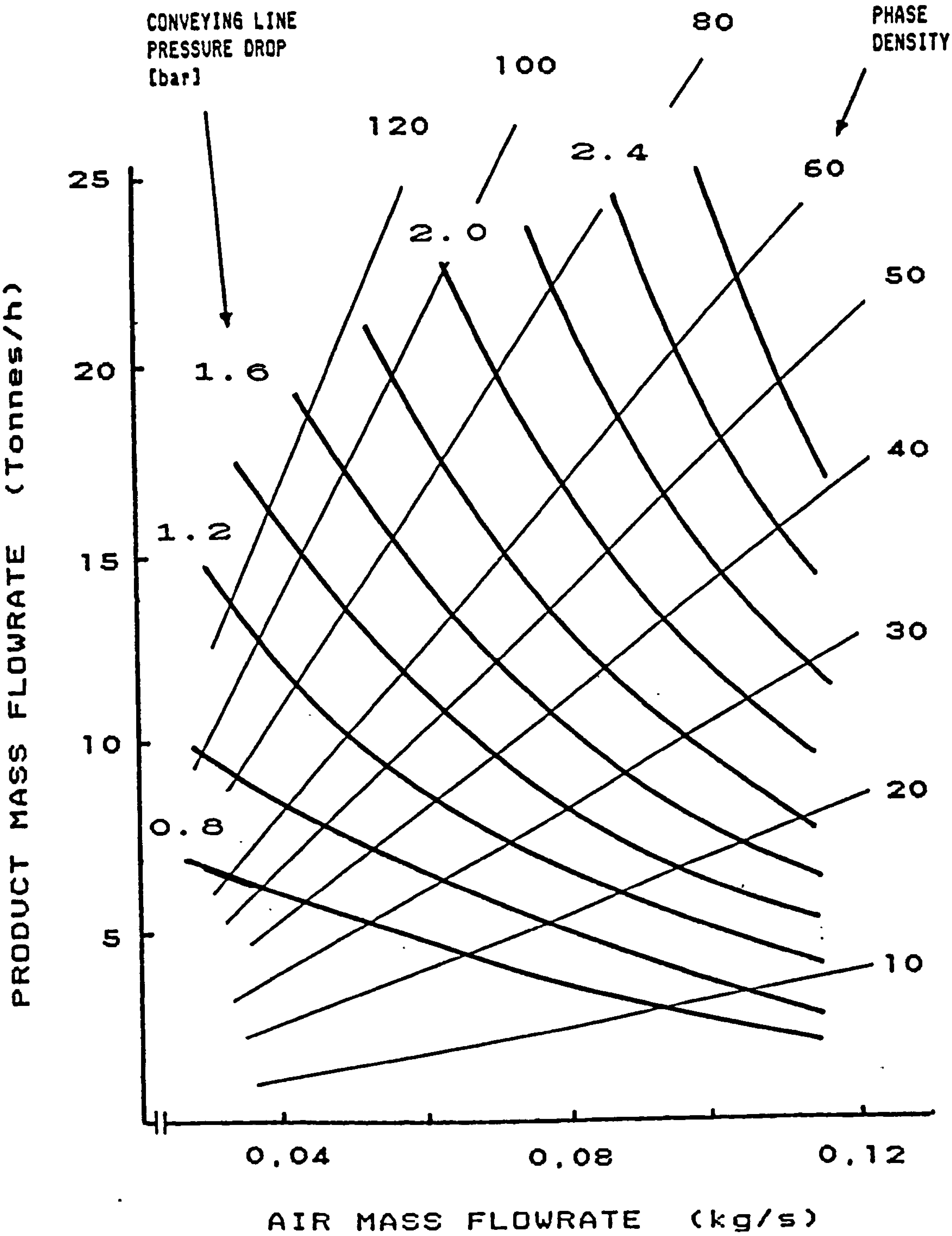
The conveying characteristics for pulverised fuel ash (p.f.a.) together with lines of constant phase density are shown in fig. 4.3. The lines of constant phase density are purely a consequence of the axes of the graph and not due to experimental data.

The bounds of the graph are due to various conveying limitations. The first is the limit on the right hand side of the graph which is set by the volumetric capacity of the fan, blower or compressor used. However,



CONVEYING CHARACTERISTICS FOR
PULVERISED FUEL ASH (No. 17)

FIG. 4.2



CONVEYING CHARACTERISTICS FOR
PULVERISED FUEL ASH (No. 17)

FIG. 4.3

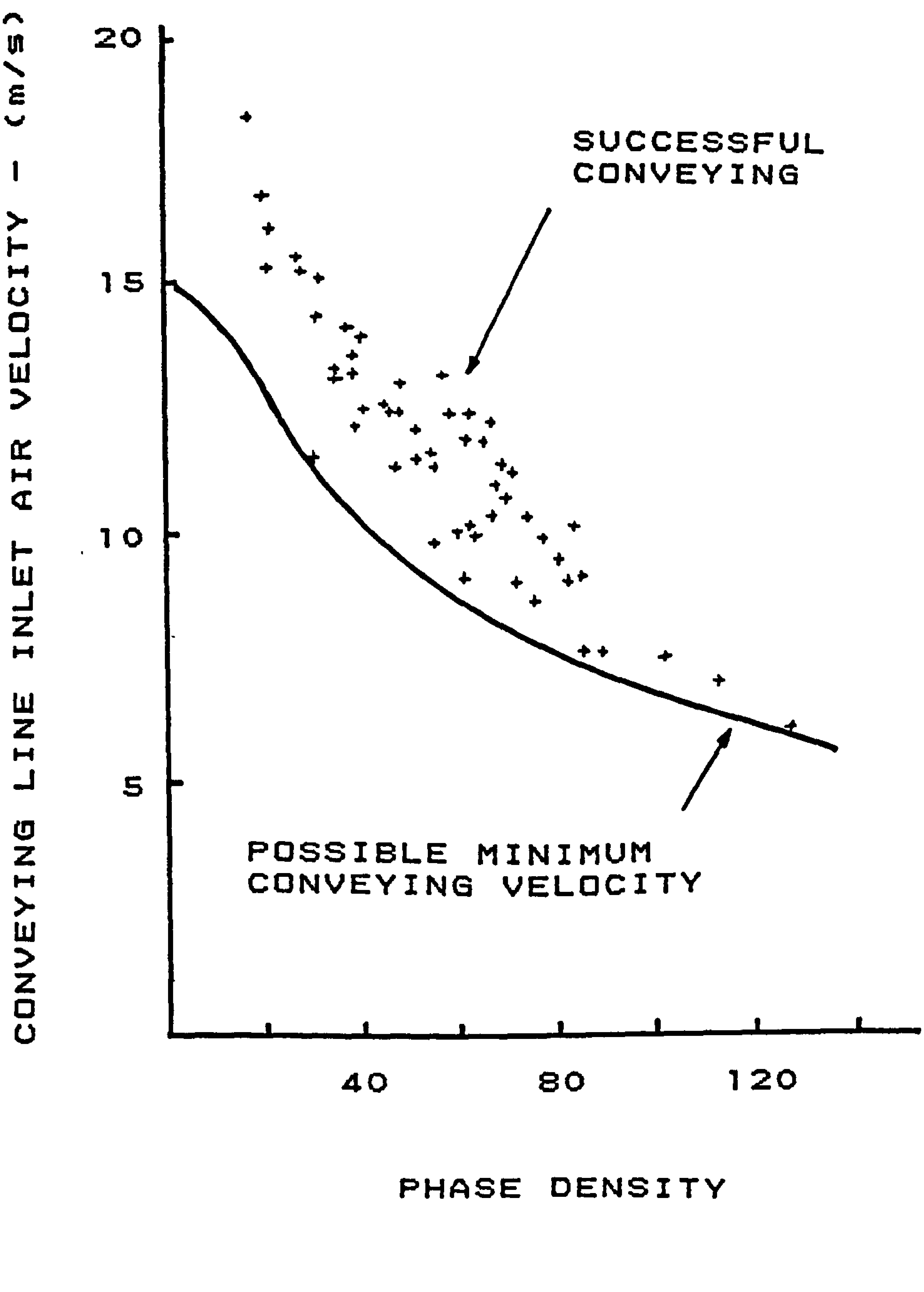
from the conveying characteristics of p.f.a. it can be seen that the limit of the right hand side of the graph corresponds to a free air velocity of around 40 m/s. This is considered to be be the upper limit for most pneumatic conveying systems. This upper limit is partly influenced by the adverse effects of velocity on product degradation and bend erosion in the pipeline. However, the most significant influence is the adverse effect of high velocity on conveying line pressure drop and hence product throughput.

The second limit is that at the top of the graph which is mainly set by the pressure rating of the air mover. However, this does depend on the nature of the conveying characteristics and hence on the product. If the lines of constant conveying line pressure drop become very steep, then the limitation may be imposed by a combination of phase density and velocity limits.

The third limit is on the left hand side of the graph and represents the approximate minimum safe conditions for successful conveying of the product. The lines actually terminate at this limit and conveying is not possible in the area to the left at lower air mass flow rates. The limit is determined predominantly by the minimum conveying velocity but also by a complex combination of phase density, product properties and conveying distance.

4.4.2 Minimum Conveying Conditions

In order to determine the minimum conditions for conveying a product, a graph of conveying line inlet velocity against phase density can be drawn and is shown in fig. 4.4. for p.f.a. A distinct pattern emerges for products that can be conveyed over a wide range of conveying conditions at low velocity. A line can be drawn representing the possible minimum conveying condition. The exact position of the curve is difficult to establish. If the pipeline is blocked no experimental point can be obtained for the test, although in some cases it is possible to estimate the approximate location of the point from preceding tests. However, it



MINIMUM CONVEYING VELOCITY v PHASE DENSITY FOR PULVERISED FUEL ASH

FIG. 4.4

is often possible to deduce that conveying conditions, in a particular test, are close to the minimum condition from pressure fluctuations which occur in the conveying line.

For products that can only be conveyed in dilute phase, it is often not possible to convey at phase densities greater than about 20. This tends to suggest that the minimum conveying velocity would be in the range of 13 to 18 m/s. This is borne out in practice with many products having a minimim conveying velocity of approximately 15 m/s. Therefore, the minimum conveying condition for products capable of only dilute phase conveying can be quantified in terms of minimum conveying velocity alone. This is not the case for products which can be conveyed over a wide range of conveying conditions. The minimum conditions for a product such as p.f.a. must be quantified in terms of both phase density and velocity. However, the minimum conveying velocity at maximum phase density is a good guide to conveyability.

4.4.3 The Influence of Conveying Air Velocity

Conveying with an unnecessarily high air mass flow rate has an adverse effect on product throughput. This is due to the square law relationship of pressure with respect to velocity which approximately applies to suspension flow. The effect of high air mass flow rates on the conveying line pressure drop, for a given product throughput, can be most clearly seen in fig. 4.5. This is an alternative way of presenting the conveying data which plots conveying line pressure drop against air mass flow rate and identifies lines of constant product mass flow rate. This graph is plotted for p.f.a. and illustrates clearly why conveying at low velocity is desirable. For example, in the case of p.f.a., one could convey at 10 tonnes/hr with a conveying line pressure drop of 1.0 bar and an air mass flow rate of 0.035 kg/s or convey at the same rate with a conveying line pressure drop of 2.0 bar and an air mass flow rate of 0.110 kg/s. For the condition when the conveying line pressure drop is 1.0 bar, the power required is 4 kW. However, when the conveying line pressure drop is 2.0 bar the power required is 20 kW. Therefore, the p.f.a. can be conveyed at

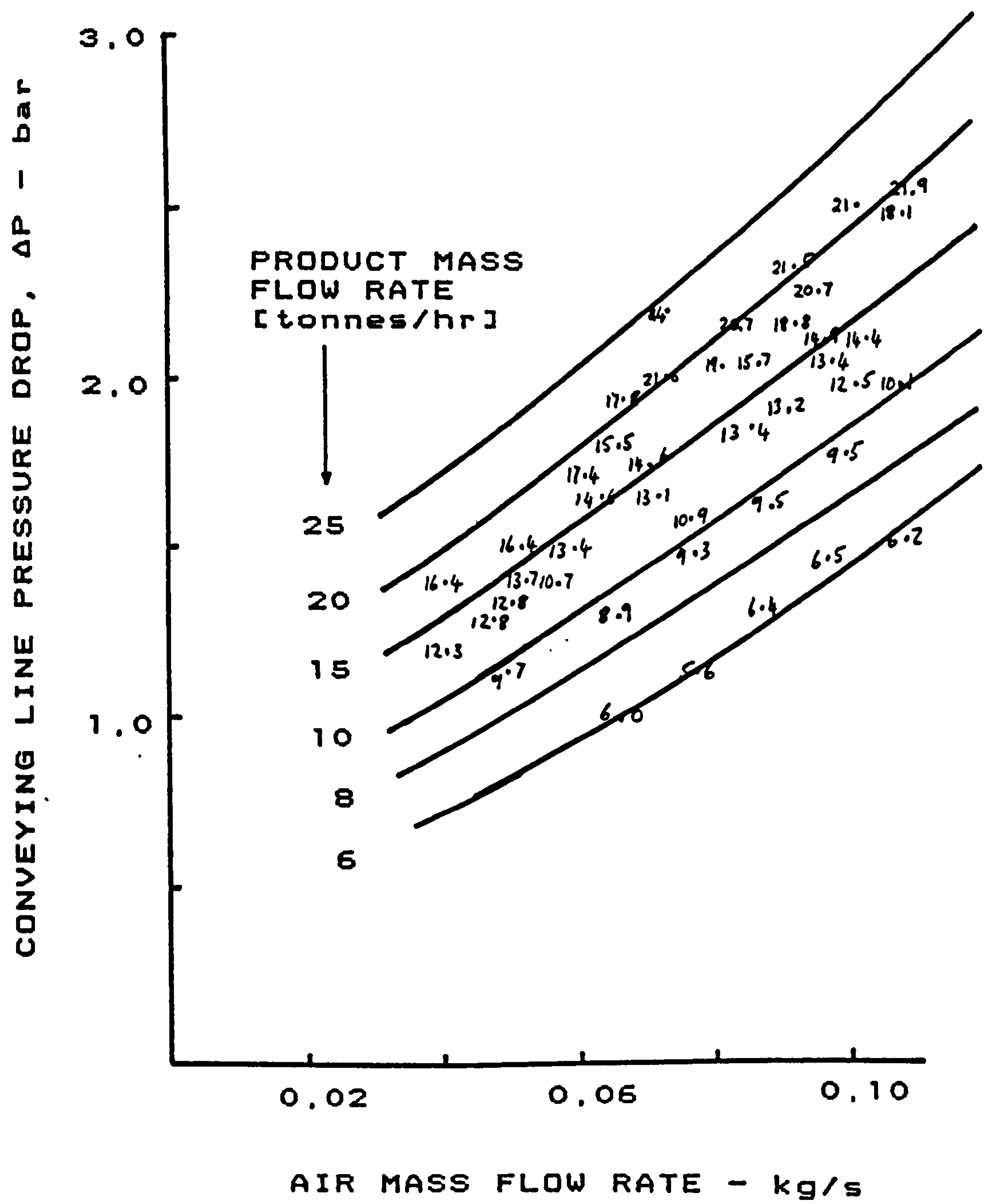


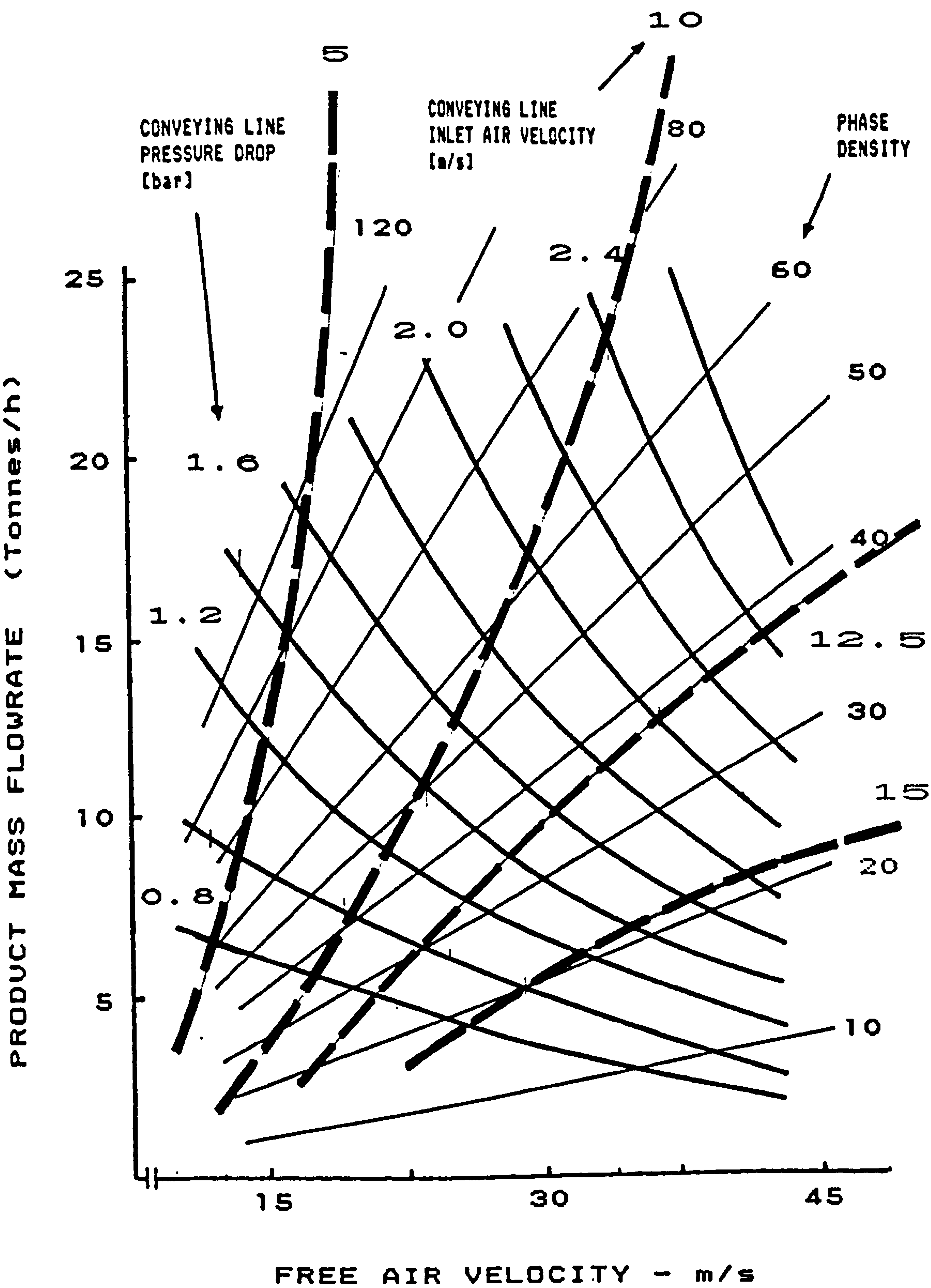
FIG. 4.5 ANALYSIS OF PRODUCT FLOW RATE DATA FOR PULVERISED FUEL ASH
(for 50m pipeline, 53mm bore, 9 bends)

10 tonnes/hr using either 4 kw or 20 kW of power depending on the conveying conditions. With some products 10 tonnes/hr can only be achieved with 2.0 bar at 0.11 kg/s of air but with other products only 1.0 bar and 0.035 kg/s of air is needed. It is important to be able to identify these products and avoid over design. Obviously, not all products are capable of being conveyed over such a large range of conditions and hence this tends to illustrate the desirability of being able to predict the likely performance of a product from a small sample of the product.

The adverse effect of high velocity is further illustrated in fig. 4.6. which shows a graph of product mass flow rate against conveying line exit air velocity for p.f.a. with lines of constant conveying line inlet air velocity superimposed. The conveying line exit air velocity is directly proportional to the air mass flow rate when the conveying line exit is at atmospheric pressure. The conveying line inlet air velocity is a function of both pressure and air mass flow rate and is, therefore, plotted graphically. It can be seen that, for a given conveying line pressure drop, as the velocity increases the product throughput decreases and consequently the phase density decreases also.

4.5 CONVEYING OF PRODUCTS

Nineteen products were conveyed in total. However, some products were particularly susceptible to degradation to the point where they could be considered two different products before and after conveying. In some cases, two sets of conveying characteristics were obtained providing two sets of conditions for correlation with product properties. A detailed discussion of these products is given in section 4.8. In addition to the products tested, two further products have been used for correlation which have been tested by colleagues at Thames Polytechnic. The products tested can be broadly grouped according to their conveying capability.



CONVEYING CHARACTERISTICS FOR PULVERISED FUEL ASH (No. 17)

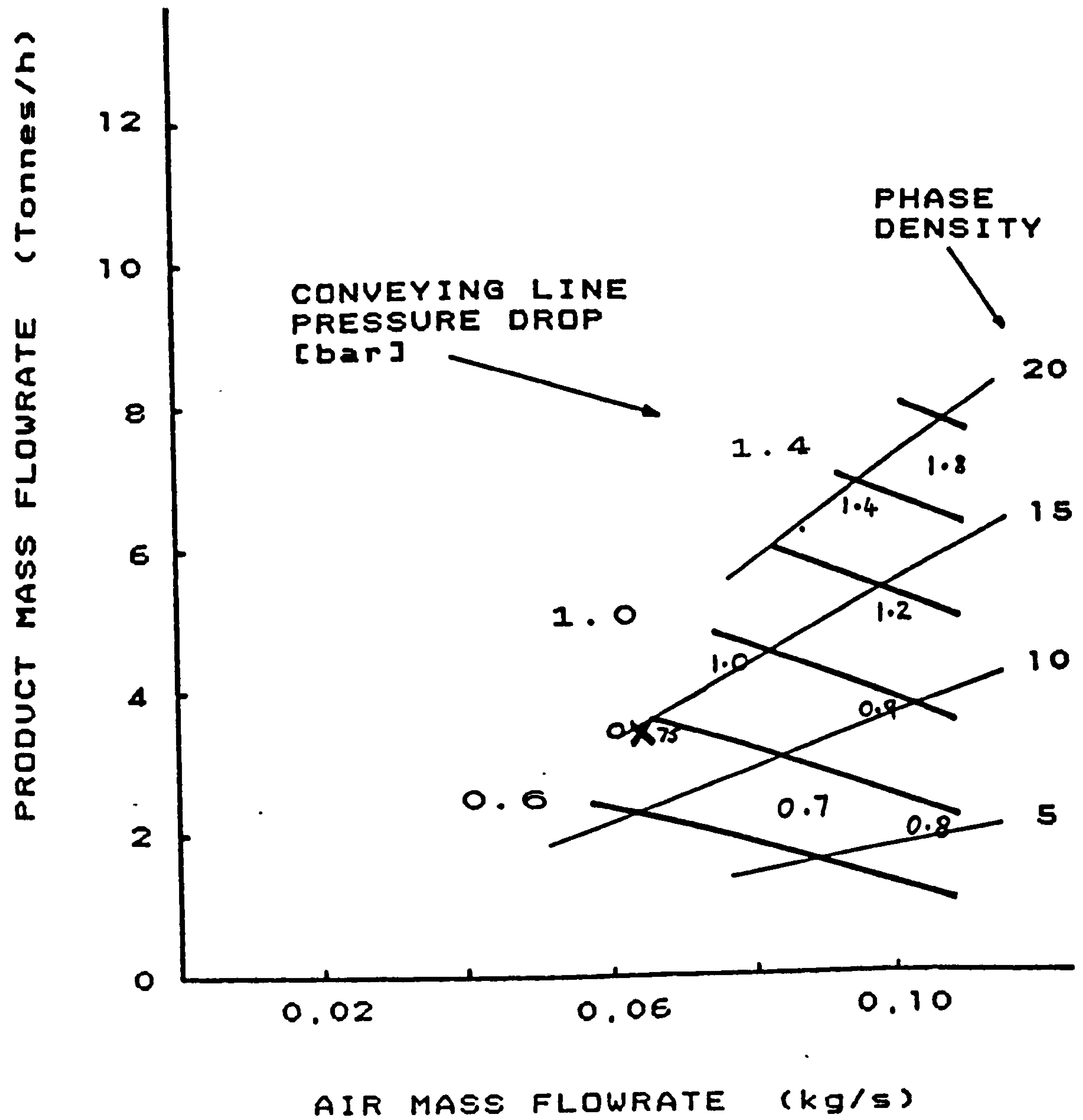
FIG. 4.6

4.6 PRODUCTS CAPABLE OF BEING CONVEYED IN DILUTE PHASE ONLY

Many of the products tested could only be conveyed in a dilute phase flow regime using a conventional system. Since the critical flow nozzles were designed to provide a range of air mass flow rates over the entire conveying range, it was difficult, in some cases, to obtain as many test points as would be ideal when conveying in lean phase only. However, as discussed in section 4.4.2, for dilute phase conveying, it is possible to determine the minimum conveying condition in terms of minimum conveying velocity alone. Therefore, it was quite a simple matter to determine the limit of conveyability. Once the limit of conveyability was established early on in the trial, the remainder of the conveying characteristics were determined over as wide a range as was possible. However, the variation in conveying charateristics between products only capable of being conveyed in dilute phase is much smaller than is the case for dense phase conveying.

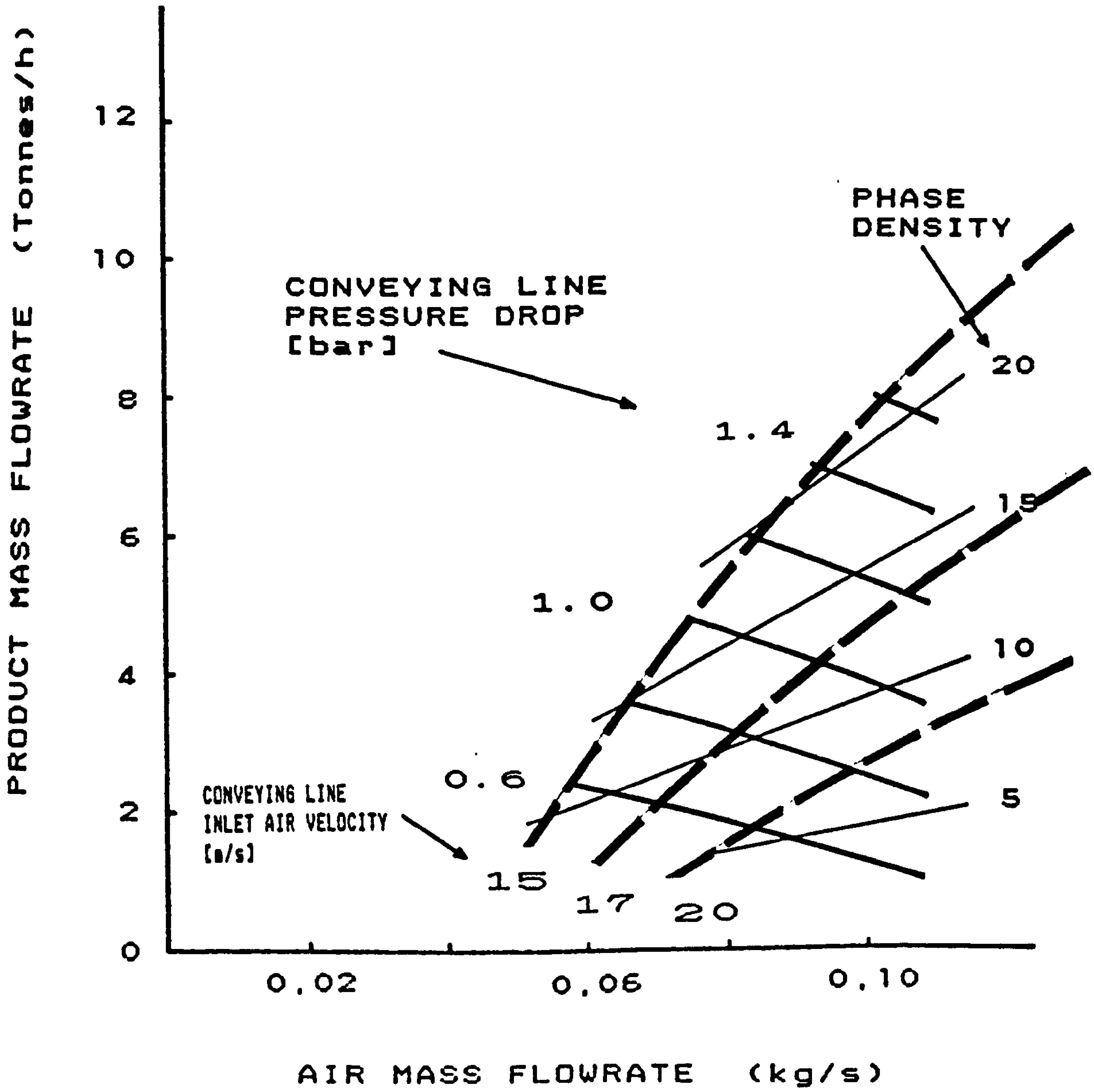
An example of a product which could only be conveyed in dilute phase in its 'as supplied' form was the agricultural catalyst. The conveying data is presented in graphical form in fig. 4.7 with the interpreted lines of constant conveying line pressure drop superimposed. A graph showing the same conveying characteristics without the data but indicating lines of constant phase density and conveying line inlet air velocity is presented in fig. 4.8. The point indicated by a cross shows the estimated product flow rate immediately prior to the line blockage. At the point when the line blocked, the air mass flow rate was 0.0675 kg/s and the conveying line pressure drop was 0.75 bar. The conveying line inlet air velocity on the basis of the measured pressure drop and air mass flow rate is approximately 15 m/s. This was taken to be the limit of conveyability.

Blockage of the pipeline occurred subsequent to two quite distinct sequences of events depending on the product being conveyed. In many cases, the only indication of pipe blockage was a sudden increase in conveying line pressure drop and a similar increase in blow tank pressure. Some products would give an indication of instability by the



CONVEYING CHARACTERISTICS FOR
AGRICULTURAL CATALYST (No. 1)

FIG. 4.7



CONVEYING CHARACTERISTICS FOR AGRICULTURAL CATALYST (No. 1)

FIG. 4.8

pressure fluctuation in the conveying line. However, this can be misleading since it may be possible to continue reducing the air flow and increasing the phase density and pass through the instability into a lower velocity flow regime. For other products, this may be the onset of a blockage and the limit of conveyability. Other products show no sign of instability and block suddenly with no warning. The other extreme is when the product can be heard hammering around the pipeline, shaking the whole test rig, resulting finally in a blocked pipeline.

4.6.1 The Mechanism of Pipeline Blockage

The mechanism of blockage was not investigated and is a whole area of research in its own right. However, from flow visualisation and the experience of unblocking the pipeline on many occasions, a number of observations were made. During conveying, it was very rare for a product to be fully suspended in the air stream below a superficial conveying air velocity of 20 m/s. This depended to some extent on phase density. Under 20 m/s, particularly as the velocity approached 15 m/s, an intermittent passive layer of material formed on the bottom of the pipe. There can be little doubt that the effect of product dropping out of suspension was likely to be exacerbated at the bends. As the velocity of the conveying air was further reduced the layer of material on the bottom of the pipe was increased. In some cases, as the material layer on the bottom of the pipe increased in depth, it became more active and began to move in a duning type flow, albeit intermittently. In other cases, the layer on the bottom of the pipe remained passive and static as the layer depth grew. In general, the products whose layer of material on the pipe bottom remained passive were the products which blocked the pipeline at around 15 m/s and could only be conveyed in dilute phase flow. Products which exhibited this type of behaviour tended to be those with poor air retention properties.

This may help explain why, in many cases, little or no warning of impending pipe blockage was given. Some products did give warning of impending blockage in the form of severe instability which led to partial blockage followed by recovery several times before final blockage of the pipeline occurred. In most cases, it was granular products such as granulated sugar or products with large lumps such as coal which exhibited this type of behaviour. It may be that blockage in these cases may in some part be due to mechanical interlocking especially at bends. As may be expected, most blockages occurred at a bend section of the pipeline.

It is interesting to note the apparent importance of 15 m/s as a minimum conveying velocity. The range of values of minimum conveying velocity for dilute phase products is very narrow with typical values being in the range of 14.5 to 16 m/s. In many cases, the minimum conveying air velocity was 15 m/s and it would be reasonable to consider 15 m/s as an approximate average value of minimum conveying air velocity for dilute phase products. For this reason, the author has assumed a minimum superficial air velocity of 15 m/s and a phase density of approximately 20 as the criteria for differentiating between dilute and dense phase conveying.

4.6.2 Comparison of the Performance of Dilute Phase Products

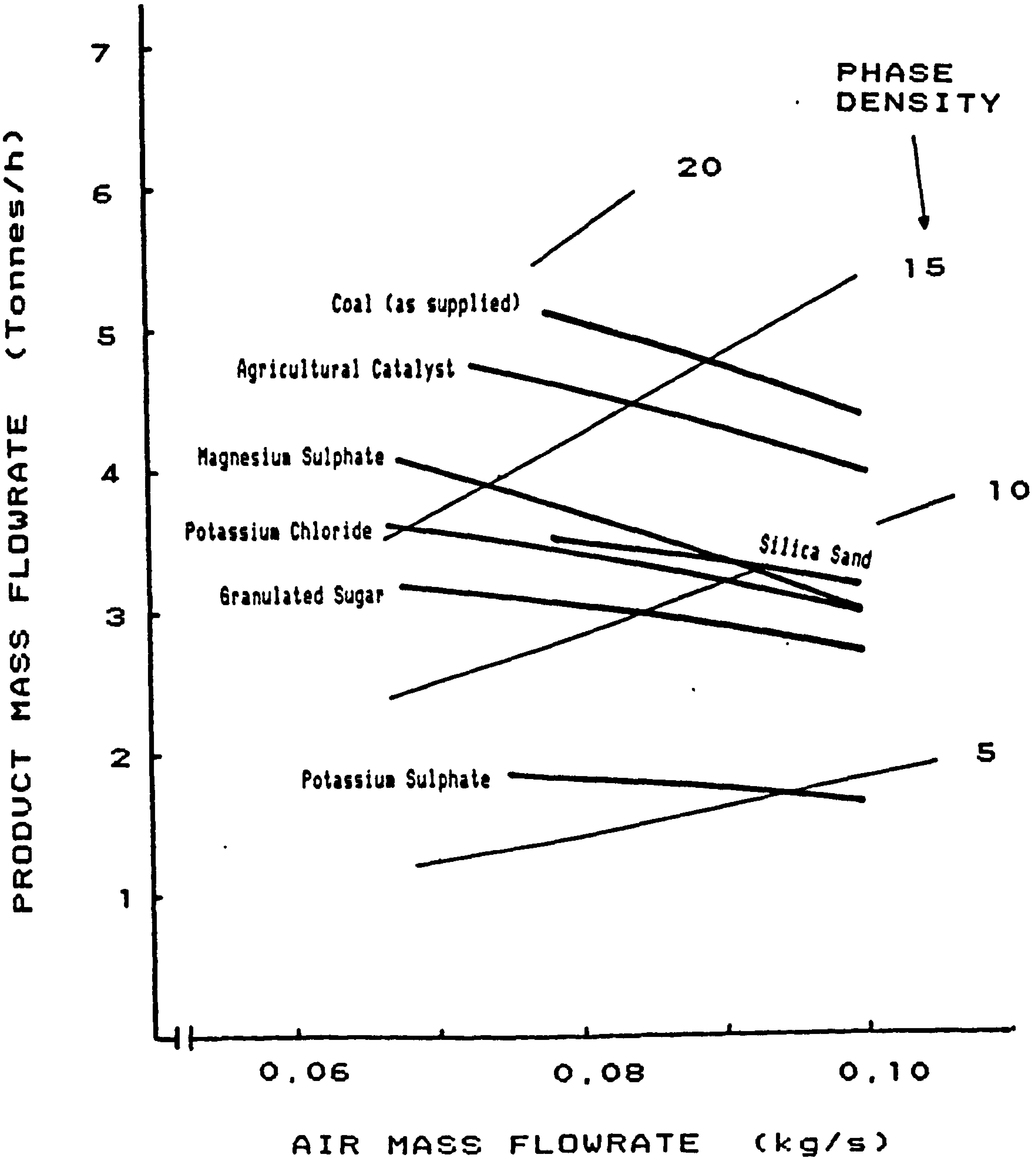
The range in product throughput performance for a given conveying line pressure drop and air mass flow rate is relatively small for dilute phase products. The relative performance of seven dilute phase products is presented in fig. 4.9. The plot is for a conveying line pressure drop of 1.0 bar in the standard 53mm bore pipeline and a false origin has been used to emphasise the variation in performance. It can be seen that the relative performance of maximum throughput to minimum throughput was about 2.5:1 for a given set of conditions. By comparison, the variation in throughput performance for dense phase products, for a given set of conditions, can be in excess of 10:1. Further discussion regarding throughput performance of dense phase products can be found in section 4.7.3

CONVEYING LINE
PRESSURE DROP = 1.0 bar

PIPELINE LENGTH = 50 m

PIPELINE BORE = 53 mm

9 BENDS (D/d=24)



A COMPARISON OF DILUTE PHASE PRODUCTS

FIG. 4.9

4.7 PRODUCTS CAPABLE OF BEING CONVEYED IN A DENSE PHASE FLOW REGIME

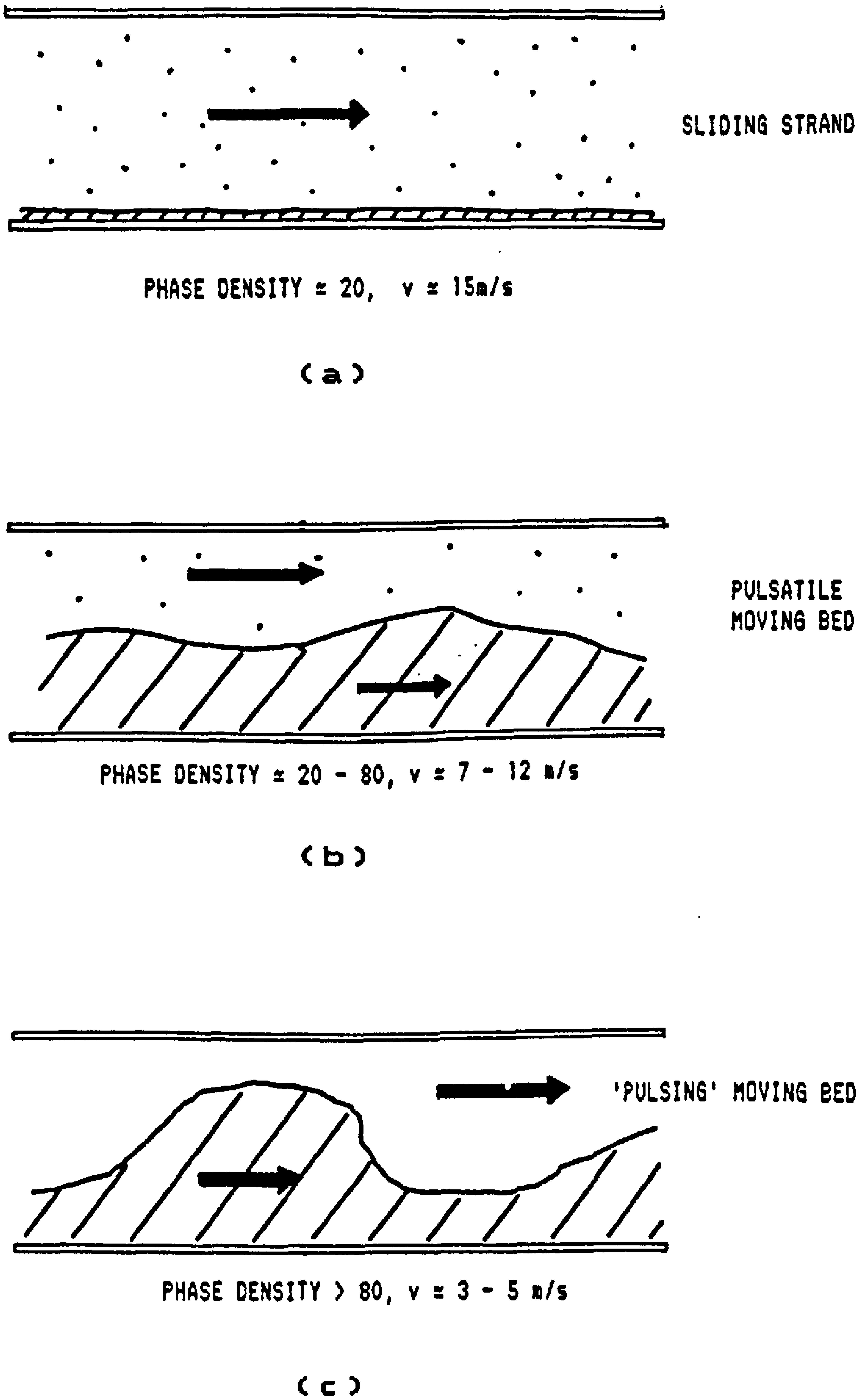
A number of the products tested were capable of being conveyed at conveying air velocities below 15 m/s and at phase densities in excess of 20. The products which were capable of dense phase conveying tended to be those products which formed stable dune type flow regimes as the conveying air velocity was reduced below 15 m/s. The layer of material on the bottom of the pipe tended to increase in depth with reducing velocity and remained 'live'. The extent to which the product remained 'live' varied from product to product and consequently there was considerable variation in flow stability.

4.7.1 Observed Modes of Flow

As the conveying air velocity was reduced from about 15 m/s the mode of flow of the product changed from a predominantly suspension flow regime to a 'moving bed' type flow. The way in which the flow changed with reducing velocity was dependent on the product type. However, from flow visualisation, a general pattern of flow modification became apparent and a diagrammatic representation of observed flow patterns is presented in fig. 4.10. As the conveying air velocity drops below about 15 m/s, material which has fallen out of suspension is conveyed as a continuously sliding strand. Typically, the phase density would be in the order of 20.

Further reduction in conveying air velocity results in a deeper moving bed which becomes intermittent and pulsatile in nature (fig. 4.10(b)). Some product is conveyed in suspension above the moving bed. Typical velocities at this stage would range between 7 and 12 m/s and typical phase densities between 20 and 80.

Conveying air velocities in the range of 3 to 7 m/s yield a flow pattern as shown in fig. 4.10(c). The pulsatile moving bed now contains the majority of the product with small whisps of product being conveyed in intermittent suspension flow. The phase densities are high being



DIAGRAMMATIC REPRESENTATION OF OBSERVED FLOW IN PIPES

FIG. 4.10

typically above 80. Under these conditions it was quite common for full bore dunes/plugs to be formed momentarily. Any further reduction in velocity could result in pipeline blockage.

It has already been established in section 4.5.1 that products which conveyed with a degree of stability in moving bed type flow were those products that displayed good air retention properties. Those that did not display good air retention properties tended to block the pipeline at saltation. The products which tend to exhibit good air retention properties tend to be the fine powders. This tends to suggest that coarser products and granular products cannot be conveyed in dense phase in a conventional system.

This is, obviously, not the case since Hitt et al. (Ref. 4.4) conveyed a number of granular products in full bore shearing plug type flow. Mainwaring and Reed (Ref. 4.5 & 4.6) suggest that the permeability of the product to air is the critical factor regarding the ability of a product to be conveyed in full bore plug flow rather than the air retention properties of the product as for moving bed type flow. Mainwaring and Reed describe how granular products can form high velocity plugs as the conveying velocity is reduced below saltation. This often results in excessive pressures being required to move the plugs and therefore blockage of the pipeline occurs. However, if the tests are started with a low conveying air velocity, then stable low velocity flow regimes can be achieved. Mainwaring and Reed suggest that this may be the reason some researchers only consider products with good air retention capabilities as candidates for dense phase.

The majority of the products tested during the conveying trials which were capable of dense phase conveying exhibited good air retention characteristics and were conveyed in a moving bed type flow. However, some of the results obtained by Mainwaring and Reed (Ref. 4.7) for granular products have been used for correlation purposes.

4.7.2 Range of 'Conveyability'

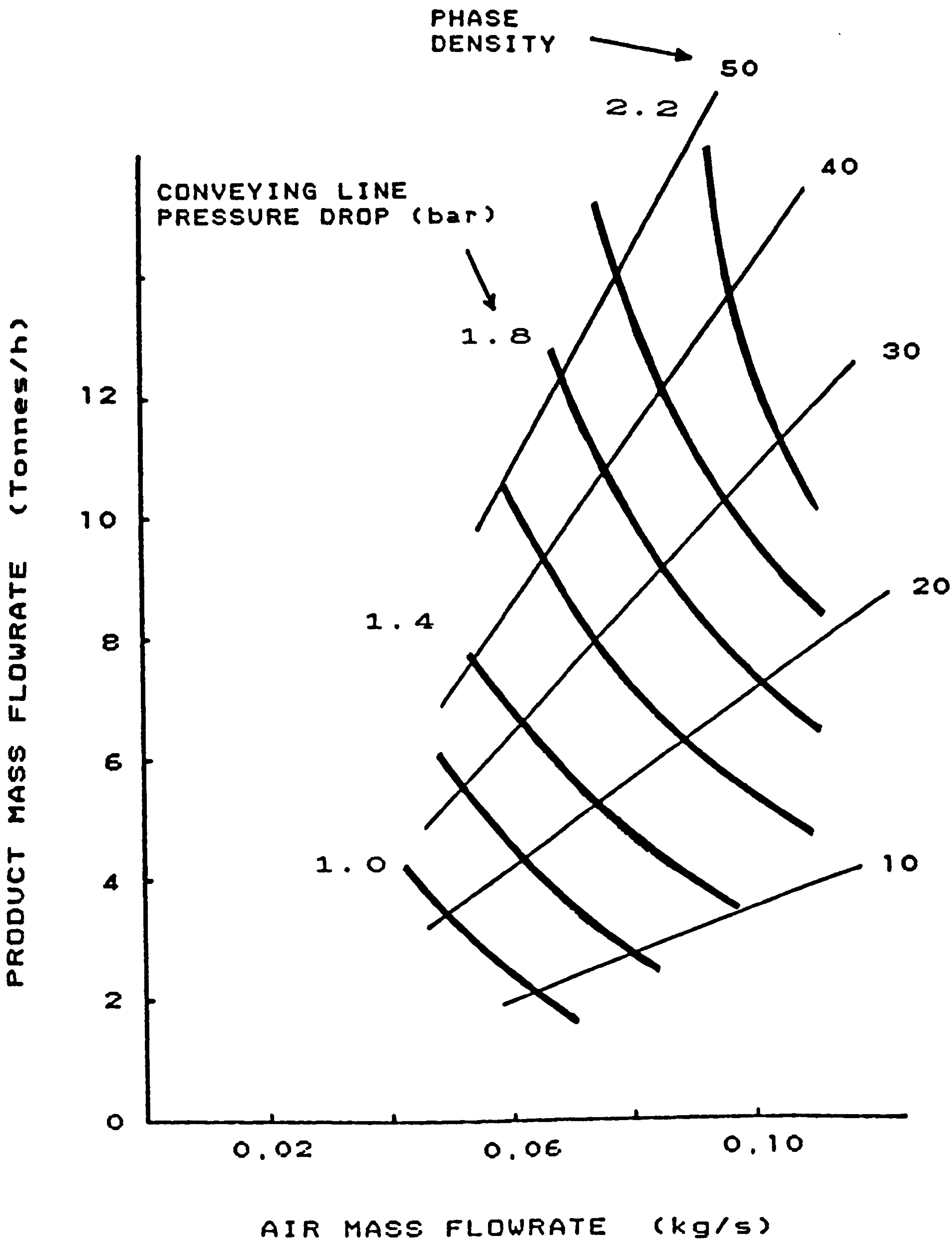
Pulverised fuel ash (p.f.a.) is an example of a particularly good dense phase product. The conveying characteristics for p.f.a. were presented earlier in fig. 4.3. Conveying was possible up to phase densities in excess of 120 and conveying air velocities down to about 3 m/s.

The minimum conveying conditions for products such as p.f.a. were determined by pipeline blockage at low velocity and high phase density. Often, the minimum conditions could not be determined due to limitations imposed by the blow tank. In such cases, products would still convey at minimum air velocities and at 100% blow tank air ratios (BTARs). Although, in these cases, the minimum condition is not found; it is sufficient, for the purposes of this work, to know that successful conveying was possible at velocities in the region of 3 m/s and at known high phase densities.

Not all products which could be conveyed at air velocities below 15 m/s could be conveyed over such a wide range of phase densities and air velocities. One such product was copper ore for which the conveying characteristics are presented in fig. 4.11. Copper ore was capable of being conveyed at phase densities up to about 50 and at conveying air velocities down to about 8½ m/s. Other products which exhibited similar conveying capabilities were the degraded sugar and degraded coal.

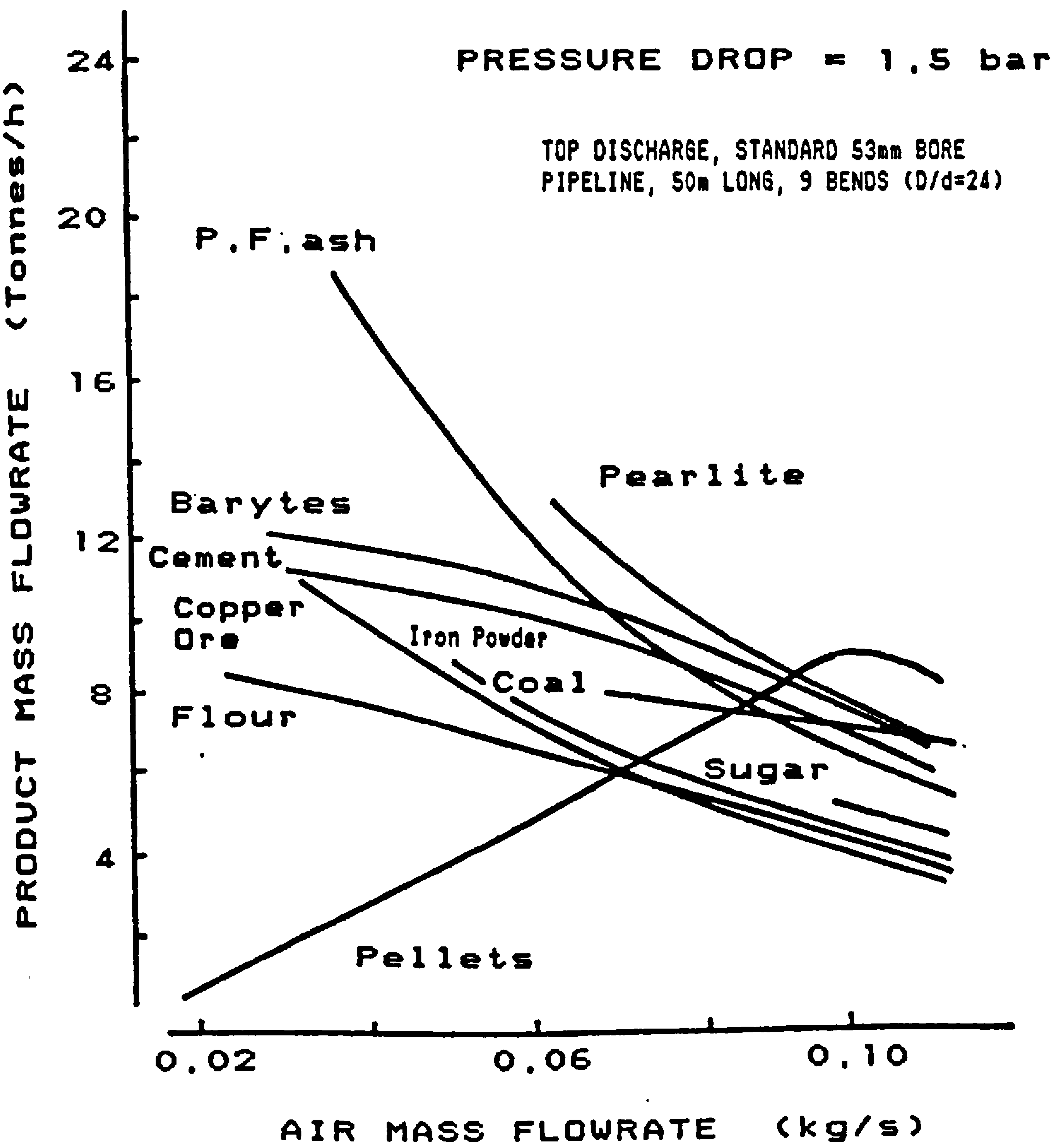
4.7.3 Comparison of Dense Phase Products

The variation in product throughput for a given conveying line pressure drop and air mass flow rate can be quite considerable for dense phase conveying. A diagram illustrating this variation for products tested during the conveying trials is presented in fig. 4.12. It can be seen that for an air mass flow rate of 0.03 kg/s and conveying line pressure drop of 1.5 bar there was a possible 10:1 variation in product throughput depending on the product being conveyed.



CONVEYING CHARACTERISTICS FOR
COPPER ORE (No. 9)

FIG. 4.11



A COMPARISON OF PRODUCTS

FIG. 4.12

4.8 THE EFFECT OF PRODUCT DEGRADATION ON CONVEYING PERFORMANCE

Friable materials can suffer serious degradation during conveying in a dilute phase system. This is due to the relatively high velocity necessary for suspension flow. The effect is made significantly worse if the pipeline has a number of bends.

The problem of degradation was significant when conveying products such as granulated suger and lump coal. Initially, both these products were only capable of being conveyed in dilute phase. The problem was of particular concern when the product was to be recirculated a number of times to obtain conveying characteristics. Each time the product was conveyed, it would be changed in terms of mean size, size range and size distribution. In addition, the largest changes would occur in the first few runs.

Granulated sugar was the first of the fragile products to be conveyed. It was suspected that the sugar would only convey in dilute phase in its 'as supplied' condition. Therefore, the blow tank air ratio and the total air mass flow rate were set at what was considered 'marginal' conditions close to the anticipated blockage condition. The first run was initiated and, as expected, ended in blockage of the pipeline. Therefore, the minimum condition, in terms of velocity, was established. A full set of conveying trials was conducted using the same recirculated product with samples of product being taken at regular intervals.

It was found that the product degraded significantly in the first ten runs with the greatest damage ocurring within the first five. However, further damage to the product after ten runs was minimal. The effect of the degradation on the conveying characteristics was limited to reducing the minimum conveying velocity. The shape of the characteristics and their absolute values remained essentially unchanged. This was verified by repeating initial conveying runs and plotting the results on the conveying characteristics.

The conveying characteristics for granulated sugar are presented in fig. 4.13. It can be seen that in the initial 'as supplied' condition the characteristics are restricted to a minimum conveying velocity of 15 m/s. In the 'after conveying' condition the minimum conveying velocity has dropped to around 7 m/s. However, the nature of the characteristic has not changed.

The same general approach was used with other friable products with particular emphasis being placed on the verification of results. In some cases this involved re-testing with fresh batches of product. However, in every case the effect of product degradation led to wider conveyability due to a decrease in the minimum conveying velocity. In each case, the shape of the characteristic and the absolute values of the conveying line pressure drops were unchanged.

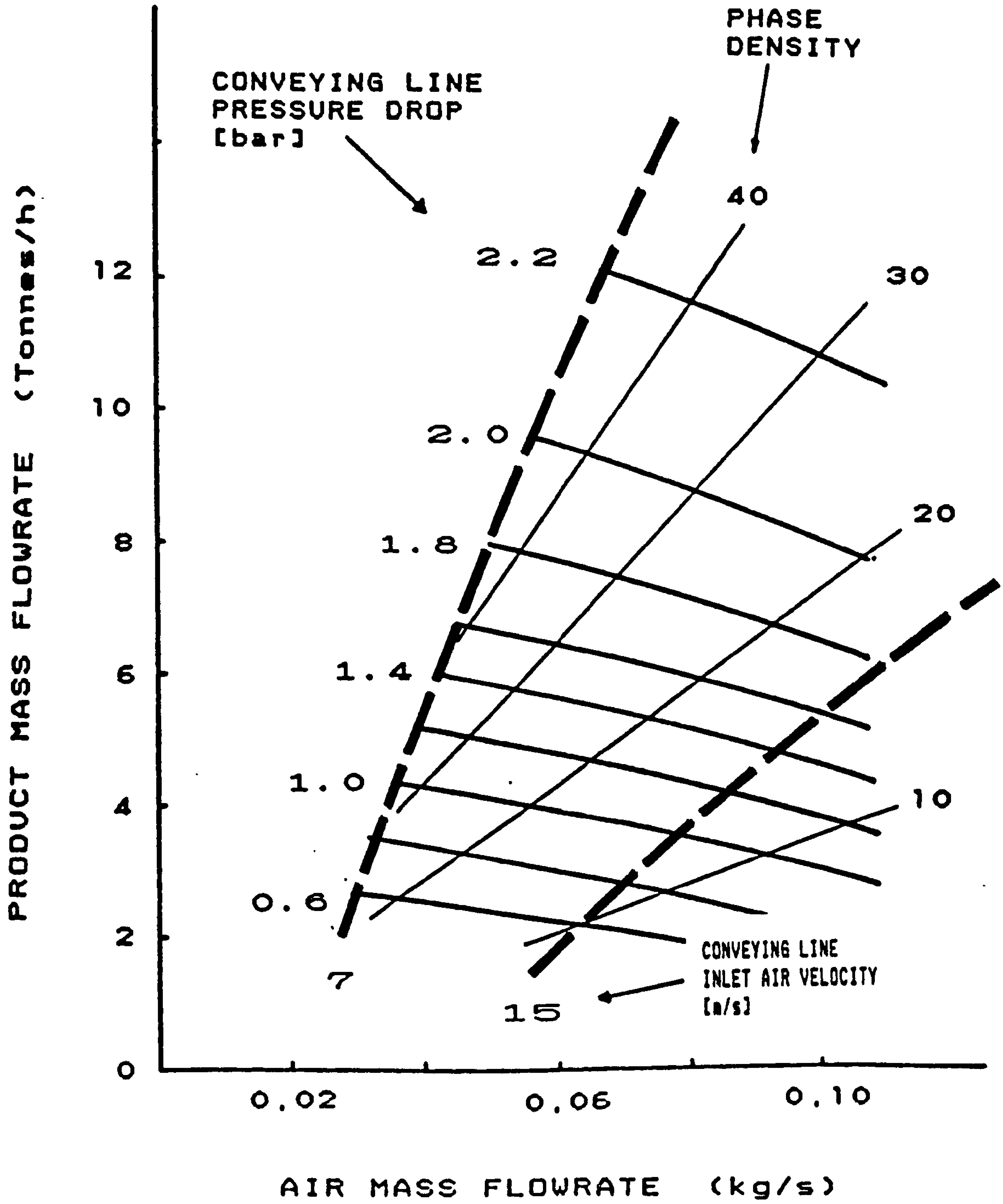
4.9 CONCLUDING REMARKS

The conveyability of a product appears to fall into one of three categories:-

1) Dilute phase only
2) Dense phase - moving bed type flow
3) Dense phase - plug/slug type flow

This categorisation is a broad approximation with variation occurring within each category. Nevertheless, these groups are clearly identifiable and provide a useful means of correlating actual conveying performance with product characterisation.

Virtually all products can be conveyed in dilute phase. Dilute phase is relatively easy to identify having clear limits of conveying range. Typical products which can only be conveyed in dilute phase are those with wide and irregular size distributions. Those products which are capable of dense phase conveying tend to fall into one of the two categories. Fine powders with narrow size distributions are often



CONVEYING CHARACTERISTICS FOR DEGRADED SUGAR (No. 21)

FIG. 4.13

candidates for the moving bed type flow regime, whereas, granular products with narrow size ranges are often candidates for plug/slug type flow. However, size alone is not a reliable guide to conveyability since many other morphological properties affect the air–product interaction.

It is interesting to note that the moving bed type flow and the plug/slug type flow occur over different ranges of velocity and phase density. There are some products which are capable of plug flow and dilute phase flow but not moving bed type flow. For these products, there is likely to be a range of conveying velocity between about 6 and 15 m/s where conveying is not possible.

CHAPTER 5

BENCH SCALE TESTS

5.1 INTRODUCTION

The ultimate goal in pneumatic conveying is that it should be possible to design a pneumatic conveying system without the need to carry out full scale conveying tests with a product. System design for single phase flow can be carried out on the basis of knowing some descriptive parameters for the fluid such as density, viscosity etc. However, the problem is very much more complicated with two phase flow. One approach is to try to correlate product properties with pneumatic conveying performance.

In the case of bulk solids many descriptive properties exist and the difficulty is trying to establish which properties affect which aspects of conveying. In this work, attention has been particularly paid to the moving bed type flow regime. In this context, the properties which involve and attempt to describe product/air interactions have been identified as properties of particular significance. A new test has been developed to assess and quantify the air retention characteristics of a product in terms of the vibrated de-aeration constant. The test has been developed by comparing the settlement of powders under the influence of gravity and vibration and overcomes many of the disadvantages of existing methods.

In addition to the properties involving product/air interactions, a number of other familiar material properties have been used to characterise the products tested.

5.2 SIZE ANALYSIS

5.2.1 Sampling

As the quantity of material required to carry out a size analysis was far less than the sample available from the batch of material delivered or from the conveying tests, it was necessary to obtain a smaller *representative sample. This was achieved by using a chute splitter consisting of a V-shaped trough along the bottom of which was a series of chutes alternately feeding two trays placed on either side of the trough. The sample was poured into the chute and repeatedly halved until a sample of the required size was obtained. If a very small sample was required for the photo-sedimentation technique of sizing then the sample produced from the chute sampler was put through the spinning riffler. A detailed account of these sampling techniques is given by Allen (Ref. 5.1).*

5.2.2 Sieve Analysis

The majority of products tested were analysed using wire mesh sieves which were mounted on a dedicated vibratory sieve platform. The samples were generally vibrated for between 10 and 15 minutes with samples of around 50g of material. In the case of particularly friable products the time of vibration was reduced. A detailed account of the sieving procedure is given by Allen (Ref. 5.1) and in the British Standard (Ref. 5.2).

5.2.3 Equivalent Spherical Size by Mass

In the case of mono-sized or nearly mono-sized particles, the nearest approximation of particle size obtained by sieving is the range between the sieve sizes which encompass the actual particle size. For large particles like polyethylene pellets, however, a number of particles can be counted and weighed. If the mass of a known number of particles (at least 50) and the particle density is known, then the size of an equivalent sphere having the same average mass can be found.

5.2.4 Photosedimentation

Sedimentation is based on the rate of settling of particles dispersed in a liquid. Photosedimentation combines the gravitational settling with photoelectric measurement. This is a technique used for measuring the size distribution for products in the size range 2 to 75 micron. All the products used for the conveying trials which fall into this size range were tested using photosedimentation. This test method allows determination of the Stokes diameter which is the diameter of a sphere which has the same density and free-falling velocity as the irregular particles under test. A detailed account of standard methods is given by Allen (Ref. 5.1) and in the British standard (Ref. 5.3).

5.3 DENSITY ANALYSIS

5.3.1 Particle Density

Particle density was measured using an air comparison pycnometer. A diagram indicating the principle of the device is presented in figure 5.1. It consists of two identical cylinders connected through a valve and differential pressure indicator, each containing a piston and output scale reading volume in cc. With the connecting valve closed any movement of the reference piston must be accompanied by an identical movement of the measuring piston in order to maintain a null reading on the differential pressure indicator. After setting the zero on the instrument the volume of any material placed in the measuring cylinder will be shown by the position of the measuring piston for a null reading on the differential pressure indicator. Hence by knowing the mass of product under test the particle density can be determined. It should be noted that the method yields the average particle density of the bulk solid. The densities of different constituent particles in a blended product can only be determined with any certainty by measuring them before mixing.

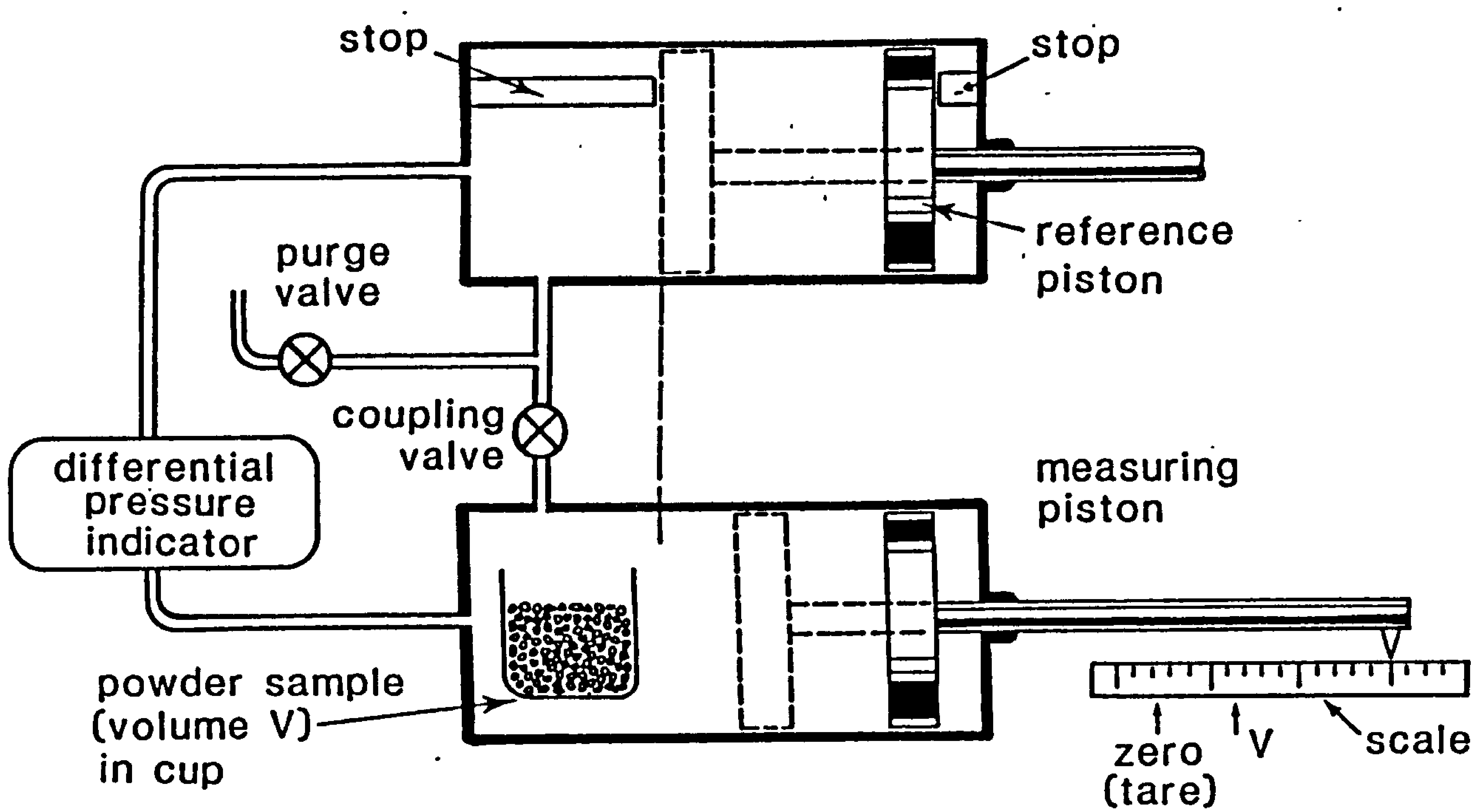


FIG 5.1 THE PRINCIPLE OF THE AIR-COMPARISON PYCNOMETER

The 'true' particle density is obtained by dividing the mass of particles by the volume they occupy excluding internal and external pores. The air comparison pycnometer yields the apparent particle density which is the mass of product divided by the volume occupied including closed pores but excluding open pores.

5.3.2 Bulk Density

To obtain the poured bulk density approximately 240ml of material was carefully poured into a 250ml measuring cylinder of known mass. The measuring cylinder was held at an angle of about 45° to the horizontal during pouring to avoid compaction. The cylinder was brought upright and the volume occupied by the material noted. The cylinder and the material were then weighed. From this the mass of material could be deduced and, hence, the poured bulk density determined.

To obtain the tapped bulk density, the cylinder was repeatedly tapped for a given number of cycles and the volume occupied by the material noted. The process was then repeated until there was no measurable change in volume. Using the final volume, the tapped bulk density could be determined. These tests were carried out a minimum of three times until good agreement of results was obtained.

5.3.3 Compaction

Compaction is simply the percentage change in bulk density from the 'poured' condition to the 'tapped' condition. The amount of compaction can give a very rough guide to air retention capability of a product.

5.4 PERMEABILITY ANALYSIS

Hitt (Ref. 5.4) identifies the permeability of a product to the conveying gas to be of major importance to the successful conveying of a product in a plug type flow regime. Many workers identify permeability as an important characteristic for dense phase conveying in general. As a test involving and describing the interaction between product and air, permeability is seen as a significant product property for correlation with pipeline conveying mode.

The flow of fluids through a packed bed has been studied extensively. The most well known work is probably that of Ergun (Ref. 5.5) who proposed the following equation:-

$$\frac{\Delta P\, g}{L} = 150\,\frac{(1-\epsilon)^2}{\epsilon^3}\,\frac{\mu\, U}{d^2} + 1.75\,\frac{(1-\epsilon)}{\epsilon^3}\,\frac{\rho\, U^2}{d}$$

where the units are Imperial and the symbols have the following meanings:-

	d	*is the effective particle diameter*
	g	*is the gravitational constant*
	L	*is the length in the direction of the fluid flow*
	U	*is the superficial percolation velocity*
	ΔP	*is the pressure drop across the bed of material*
	ϵ	*is the voidage of the bed*
	μ	*is the absolute fluid viscosity*
and	ρ	*is the density of the fluid*

The practical difficulties of using this equation lie in the determination of the effective particle diameter which is not the median particle size. The effective diameter is based upon the surface area per unit volume of solids. The easiest way to obtain an approximate value of specific surface is by carrying out an air permeability test.

The Ergun equation consists of two terms; the first term accounts primarily for the viscous energy losses, whereas the remaining term is primarily related to kinetic losses. The first term is the predominant component in the laminar flow region with the second term becoming dominant for turbulent flow. This is confirmed by the test work carried out on the materials used for the conveying trials which appear to show a linear relationship between $\Delta P/L$ and U over the low velocity range. For laminar flow, the relationship between $\Delta P/L$ and U can be expressed as follows:-

$$U = \frac{C\,\Delta P}{L}$$

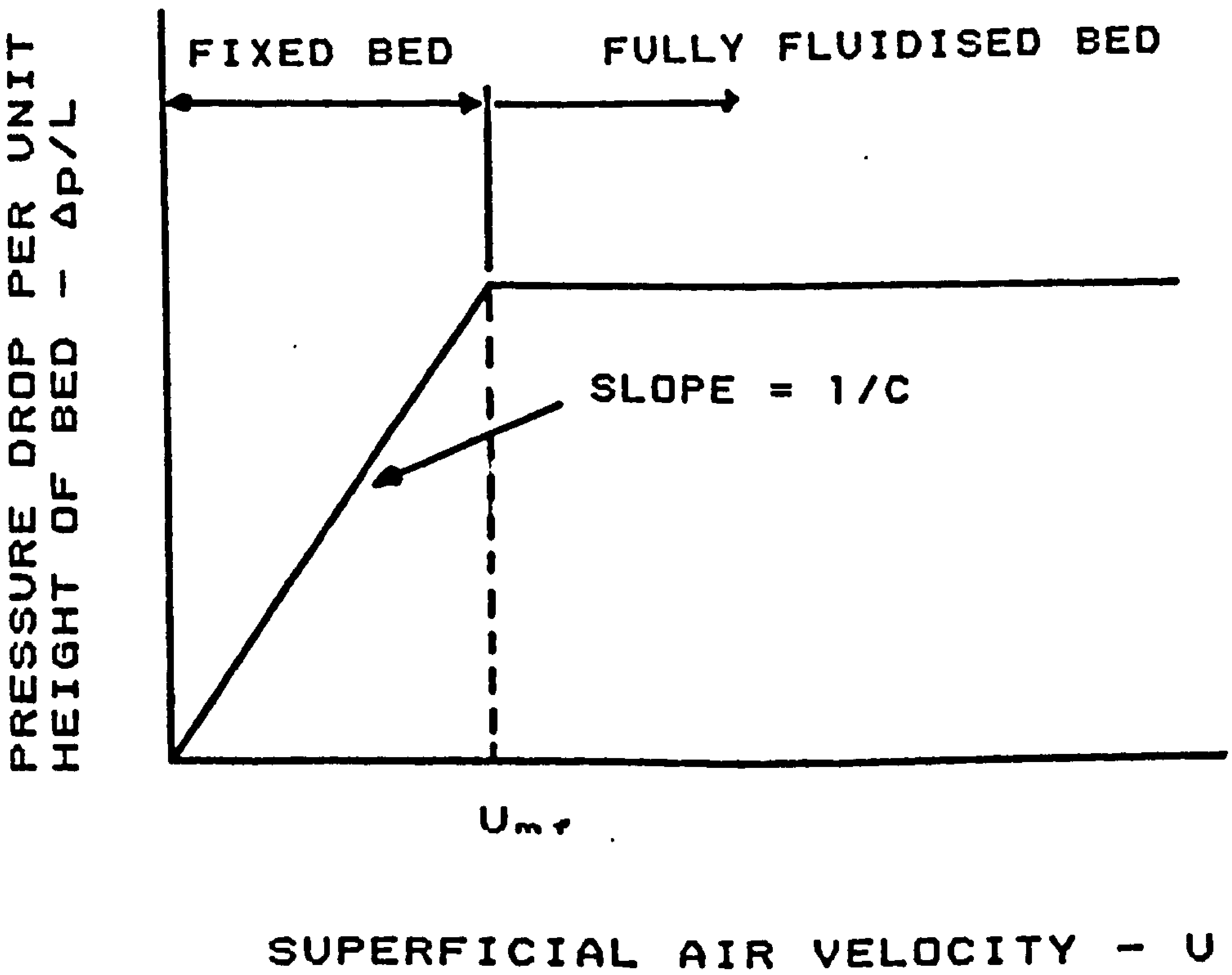
where C is a constant and dependent on the powder and fluid properties.

A diagram is presented in figure 5.2 which shows the idealised relationship between pressure drop per unit height of bed and the superficial air velocity for laminar flow. A graph of this nature can be obtained by testing a sample of material in a permeameter similar to that shown in figure 5.3. It can be seen that the fixed bed portion of the graph presented in figure 5.2 is a straight line. The British Materials Handling Board (Ref. 5.6) suggest that the inverse of the slope of this line, known as the 'permeability factor' C, is a useful parameter which characterises a product's permeability to the fluid.

The permeability factor has been adopted as an easily measurable indicator of the permeability of a product to air and has been used to correlate with pneumatic conveying performance. The results obtained for permeability factor are very reliable with regard to repeatability and produce good straight line relationships. For very coarse materials, with relatively large minimum fluidising velocities, evidence of the effect of the second term in the Ergun equation can be detected by very slight curvature of the graph at the high velocity end.

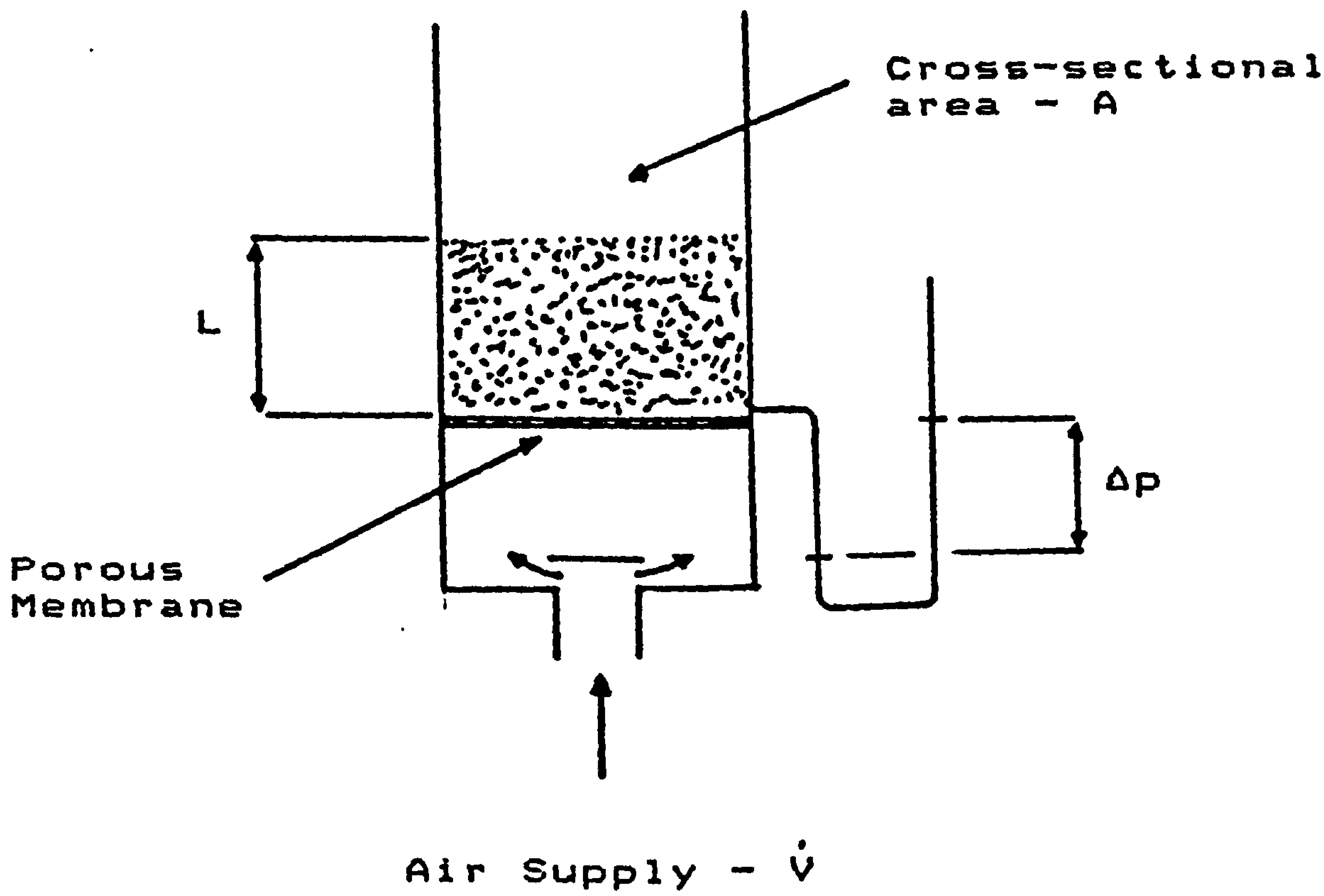
C = PERMEABILITY FACTOR

U_{mf} = MINIMUM FLUIDISING VELOCITY



IDEALISED RELATIONSHIP BETWEEN PRESSURE GRADIENT AND AIR VELOCITY FOR FLOW THROUGH A PRODUCT BED

FIG. 5.2



SKETCH OF A TYPICAL PERMEAMETER

FIG. 5.3

Results obtained for two different products at different ends of the permeability range are presented in figures 5.4 and 5.5. The results for all the products used in the conveying trials are presented in appendix 3.

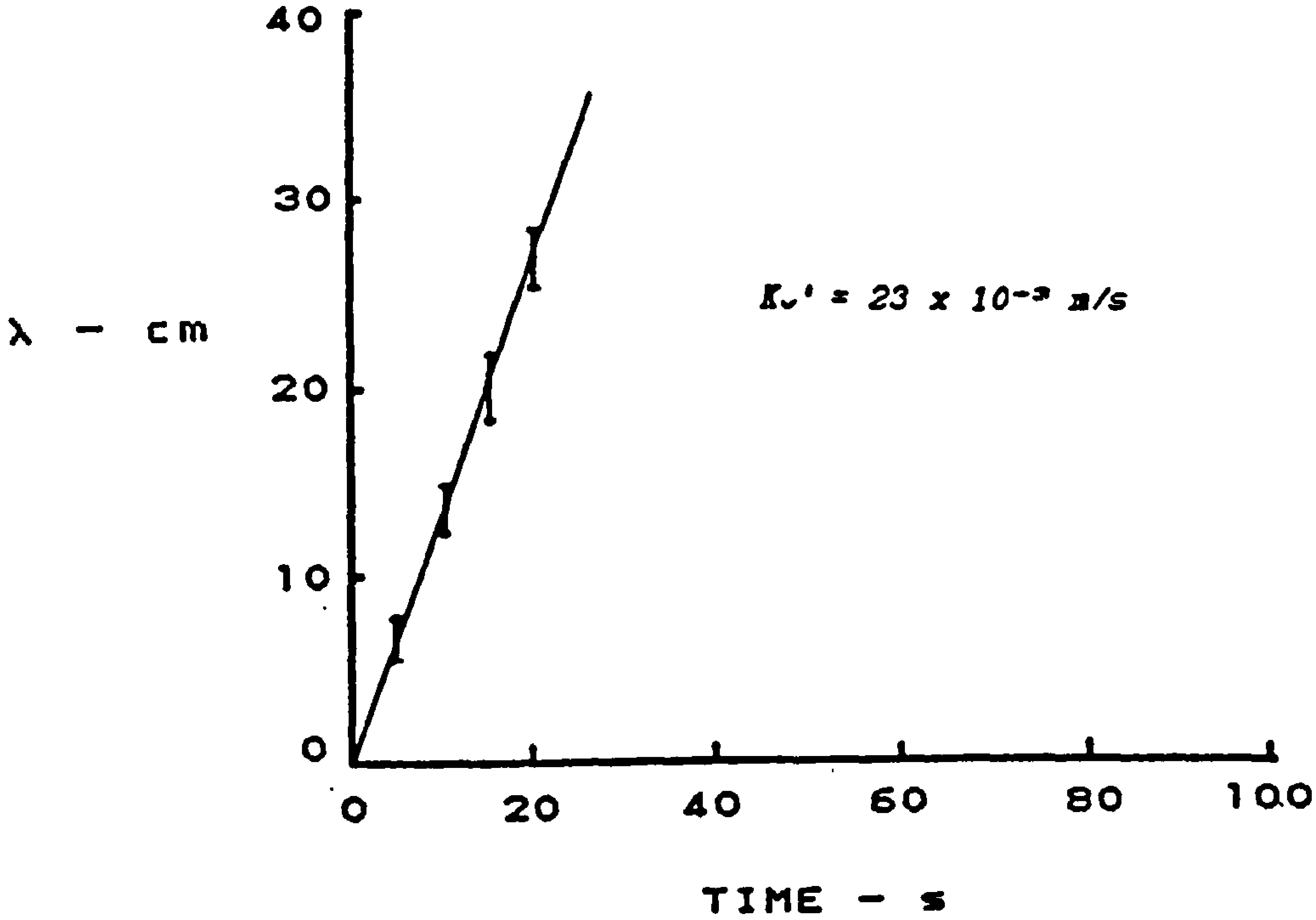
5.5 AIR RETENTION ANALYSIS

5.5.1 Introduction

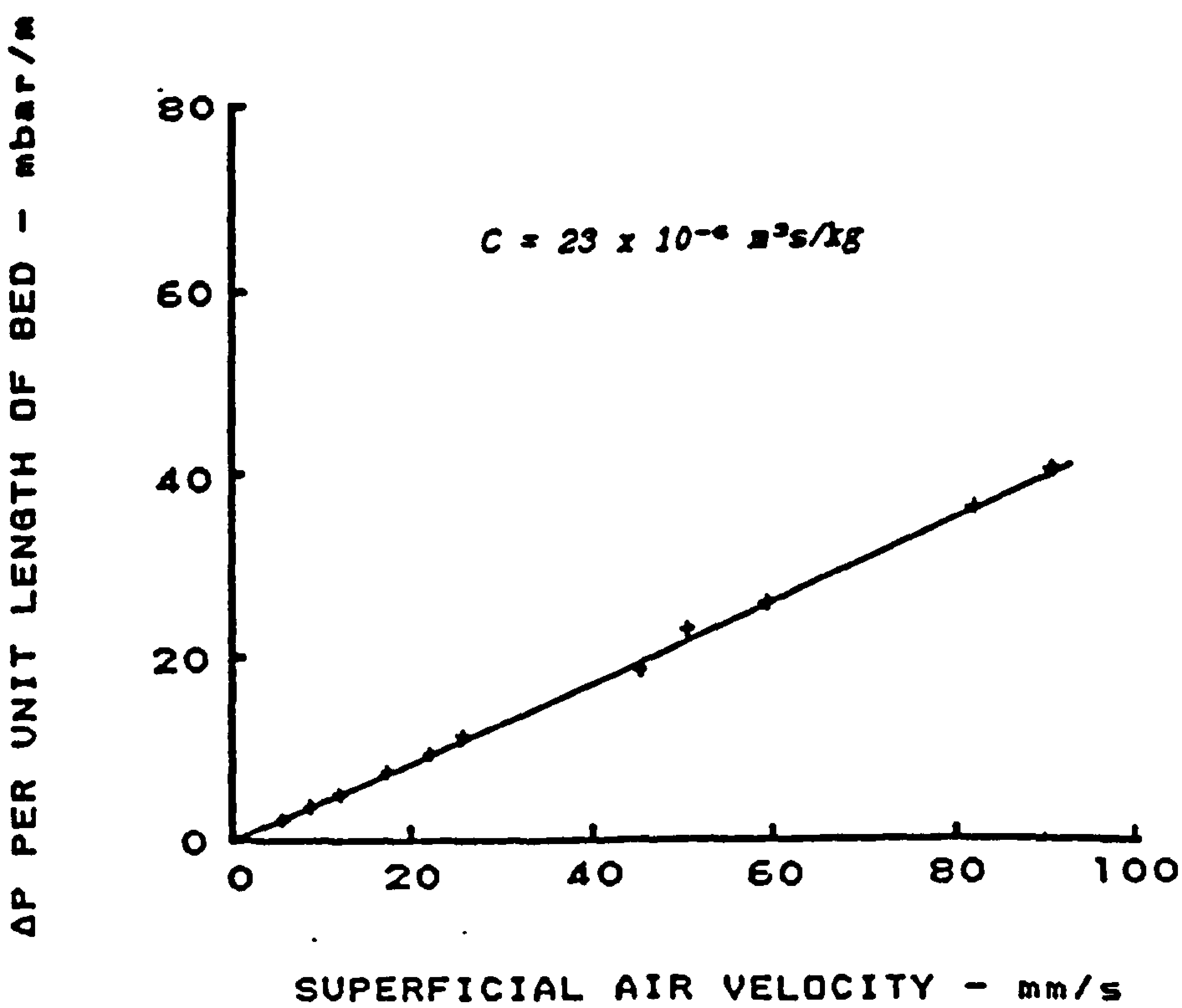
The importance of aeration properties to the flow of bulk solids, especially in hoppers and channels has long been appreciated. Caldwell (Ref. 5.7) makes particular reference to the fact that the air retention or de-aeration capability of a product was significant to conveying performance. From flow visualisation during the conveying trials it was apparent that the retained fluid-like behaviour of the product was important to the continued successful conveying in a moving bed type flow regime.

Few workers appear to have considered the de-aeration process. Sutton and Richmond (Ref. 5.8) present a method of recording the drop in bed height with time and produce a de-aeration constant particular to a material which is system-dependent. Sutton and Richmond apply Fick's law of diffusion assuming that the height of the powder level is exponentially dependent on the time of settlement. Geldart and Wong (Ref. 5.9) suggest that the relationship between the height of the powder level and the time of settlement varies according to the position of the product on the Geldart classification.

Various other workers have attempted to analyse the de-aeration process mathematically. Johanson and Jenike (Ref. 5.10) use a finite element technique to produce a mathematical model for settlement with time. Interestingly, they predict a curve approximating an exponential decay.



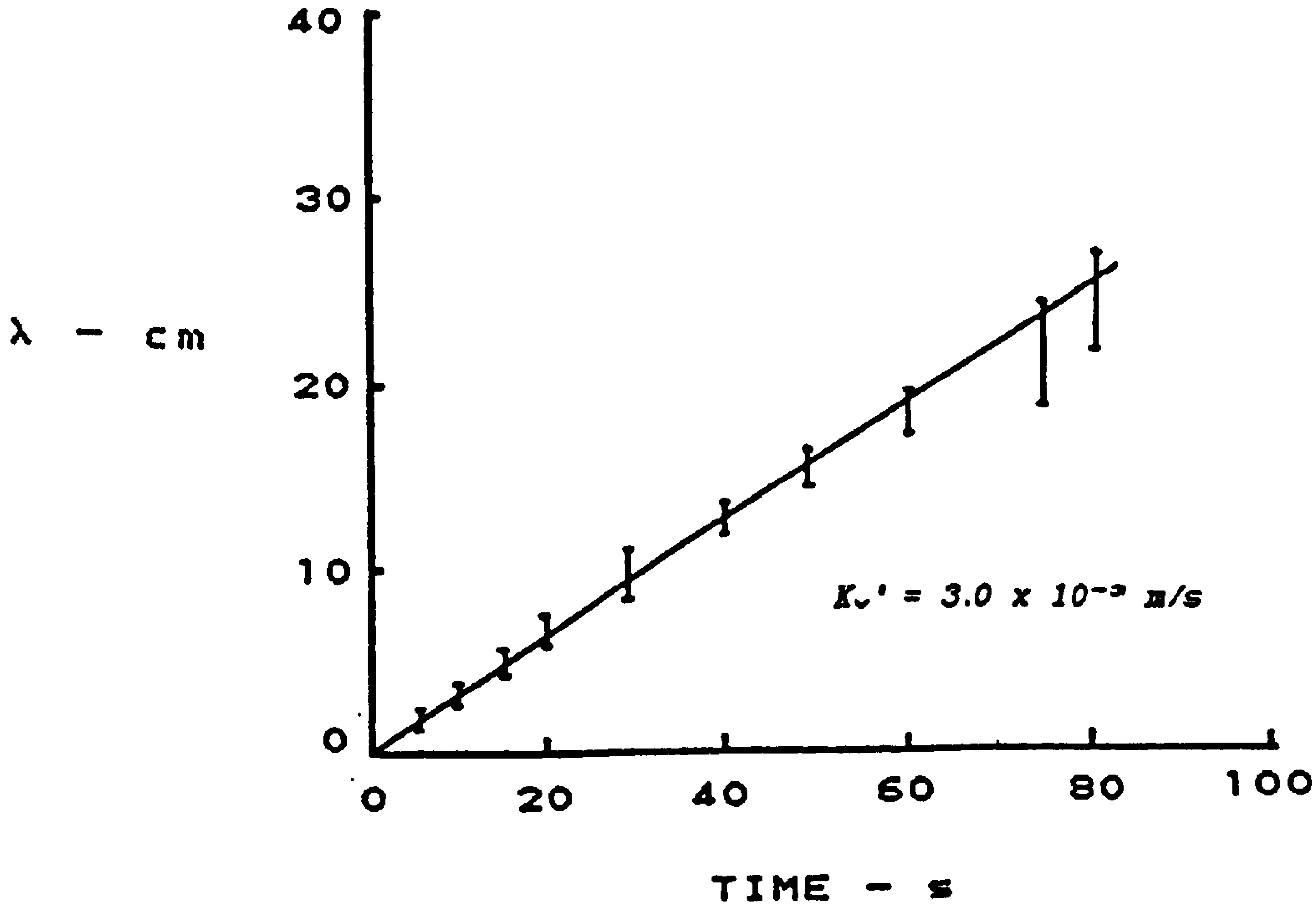
VIBRATED DE-AERATION DATA



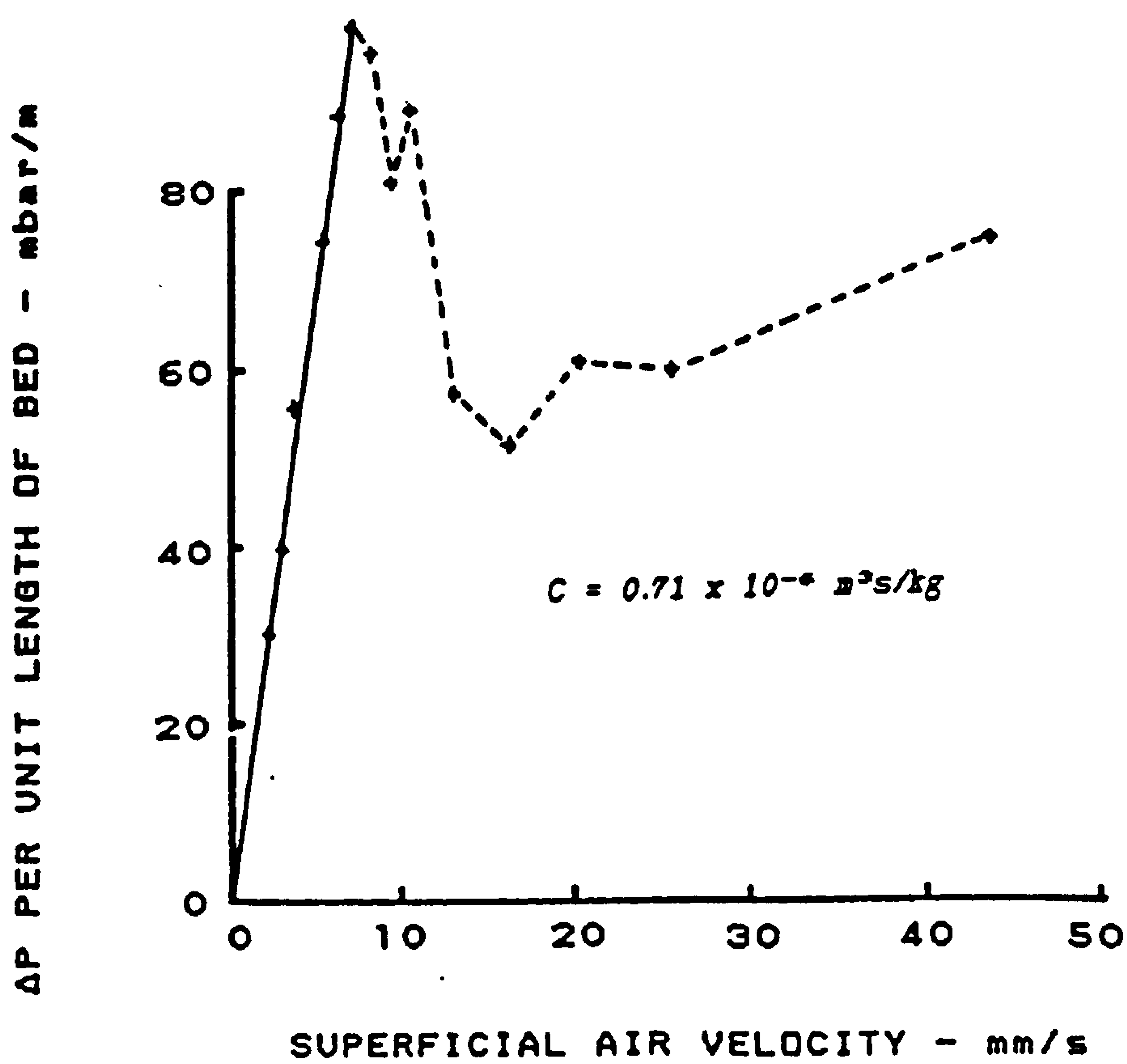
PERMEABILITY DATA

FIG. 5.4

MATERIAL No. 5 - CEMENT



VIBRATED DE-AERATION DATA



PERMEABILITY DATA

FIG. 5.5

5.5.2 De-aeration Constant

The air retention capability can be assessed in terms of the time it takes a fluidised bed of product to return to a specified bulk density after quickly shutting off the air supply. Fluidising should provide a maximum volume increase of the product without severe bubbling at the material surface. With some products the level of material falls rapidly, particularly in the early stages. In these circumstances analysis is best carried out from a video recording of the fall. In other cases products such at cement with very high air retention capability can remain in a fluidised state for a number of days. Sutton and Richmond (Ref. 5.7) analysed this transient fall by extending Fick's Law of Diffusion to the situation. The general form of Fick's law is:-

$$\frac{\delta P}{\delta \tau} = \frac{\delta}{\delta L}\left(D \cdot \frac{\delta P}{\delta L} \right)$$

where P is the air pressure and D is the diffusion coefficient

differentiating; $$\frac{\delta P}{\delta \tau} = \frac{\delta D}{\delta L} \cdot \frac{\delta P}{\delta L} + D \cdot \frac{\delta^2 P}{\delta L^2}$$

If a linear pressure gradient is assumed then $\frac{\delta^2 P}{\delta L^2} = 0$

$$\therefore \quad \frac{\delta P}{\delta \tau} = \frac{\delta D}{\delta L} \cdot \frac{\Delta P}{L}$$

where ΔP *is the pressure drop across the bed* ($P-P_\infty$) *and* P_∞ = *atmospheric pressure.*

The pressure drop across the bed is linearly proportional to the mean voidage in the bed and the mean voidage is linearly proportional to the bulk density. Therefore, if the bulk density at a point is ρ, *then:-*

$$\frac{d\rho}{d\tau} = \frac{\delta D}{\delta L} \cdot \frac{\Delta\rho}{L}$$

Experimental work carried out by Sutton and Richmond on the settlement of powders under the influence of gravity confirmed this relationship and justified the assumptions made. $\delta D/\delta L$ is a constant which, when applied to the analysis of de-aeration, Sutton and Richmond called the de-aeration constant, K'. Hence:-

$$\frac{d\rho}{d\tau} = K' \frac{\Delta\rho}{L}$$

where	ρ	*is the product bulk density, kg/m^3*
	τ	*is the time, s*
	K'	*is the de-aeration constant, m/s*
	L	*is the bed height, m*

Integration of this differential equation between suitable experimentally derived limits will yield the de-aeration constant.

The de-aeration constant will give an indication of the capability of a product to retain air. A high de-aeration constant will indicate rapid de-aeration and therefore poor air retention.

There are a number of practical problems with using this method of determining the air retention capability of a product. Firstly, for products which have poor air retention characteristics (ie de-aerate fast) there is a problem with obtaining data unless video techniques are used. Secondly, and probably more importantly, the settling time of powders exhibiting good air retention capability (ie de-aerate slowly) can run into hours and even days for some very air retentive powders. The second problem could be overcome if the settlement of powders could be accelerated. A method commonly used in industry for settlement of powders is vibration.

5.5.3 Vibrated De-aeration Constant

Initial tests using vibration to determine tapped bulk density indicated that the relationship between bed height with time was very similar to that obtained for de-aeration. Sutton and Richmond state that after a powder bed finally attains a constant value, tapping or other vibration will cause the level of the bed height to drop further. A schematic diagram showing the two stages of change in bed height with time is presented in figure 5.6. In other words the settlement under the influence of vibration from the 'as poured' state to the 'tapped' or 'compacted' state is simply an extention of the settlement from the 'fluidised' state to the 'as poured' condition. Under these conditions it is not unreasonable to apply the analysis of Sutton and Richmond to the settlement due to vibration.

The analysis of Sutton and Richmond to this case gives:-

$$\frac{d\rho}{d\tau} = k_v' \frac{\Delta\rho}{L}$$

where K_v' = vibrated de-aeration constant, m/s

$\Delta\rho = \rho_\infty - \rho$, kg/m3

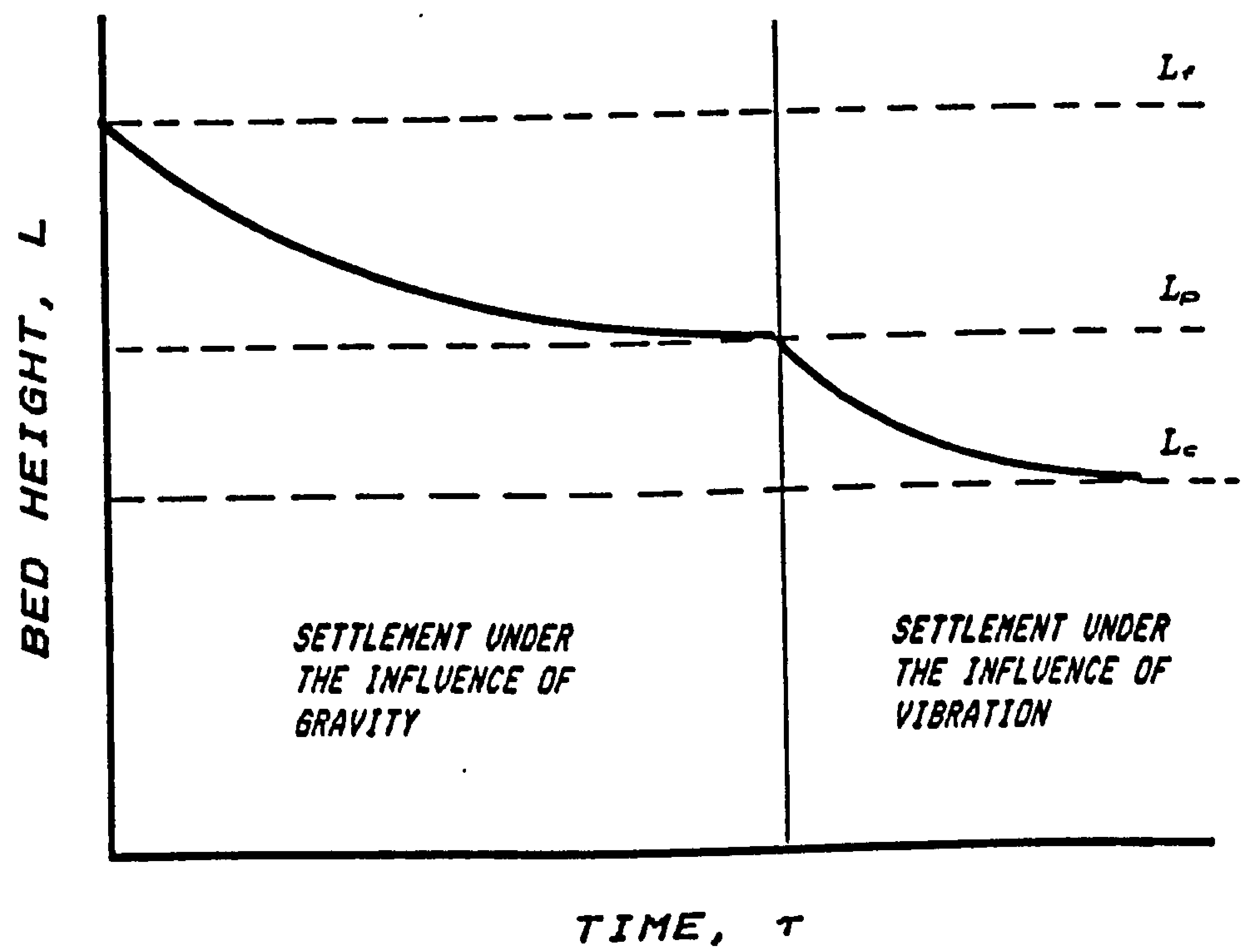
This expression can be integrated definitely between limits arising from the following boundary conditions:

$$\text{at} \quad \tau = 0, \qquad L = L_1$$
$$\tau = \infty, \qquad L = L_\infty$$

L_f = BED HEIGHT FOR THE 'FLUIDISED' CONDITION

L_p = BED HEIGHT FOR THE 'AS POURED' CONDITION

L_c = BED HEIGHT FOR THE 'COMPACTED' CONDITION



IDEALISED RELATIONSHIP BETWEEN BED HEIGHT AND DE-AERATION TIME UNDER THE INFLUENCES OF GRAVITY AND VIBRATION

FIG. 5.6

The result is:

$$K_v' \tau = L_\infty \ln \left[\frac{1}{L} \left(\frac{1}{L} - \frac{1}{L_1} \right) \bigg/ \frac{1}{L_1} \left(\frac{1}{L_\infty} - \frac{1}{L} \right) \right]$$

where L_1 = initial bed height, m

L_∞ = final bed height, m

This equation can be written in the form of a straight line graph the slope of which is the vibrated de-aeration constant:

Thus $\lambda = K_v' \tau$

where λ is a function of bed height, L, and is given below:-

$$\lambda = L_\infty \ln \left[\frac{1}{L} \left(\frac{1}{L} - \frac{1}{L_1} \right) \bigg/ \frac{1}{L_1} \left(\frac{1}{L_\infty} - \frac{1}{L} \right) \right]$$

High values of vibrated de-aeration constant indicate a high settling rate and, therefore, poor air retention capability. To carry out tests to determine vibrated de-aeration constant apparatus had to be designed.

5.5.4 Apparatus for Measuring Vibrated De-aeration Constant

The apparatus consists of a clear perspex tube or cylinder of 53mm bore and 250mm long with a graduated scale in millimetres. The bottom of the cylinder had a means of attaching it to a vibrator which oscillated in the vertical plane (longitudinally). A stop watch was used for timing the application of vibration.

5.5.5 The Test Procedure

Initial tests were carried out to assess the influence of the mode of vibration. Tests were carried out for a number of products using a *horizontal vibrator operating at a fixed frequency and amplitude. The results in terms of a graph of height against time were compared with the results obtained from the longitudinal vibrator for the same frequency and amplitude. No appreciable difference in results was obtained. This allowed the use of the longitudinal vibrator for the tests which had the advantage of variable frequency and amplitude settings. A series of tests were carried out to establish the effect of frequency and amplitude on the results for a number of products.*

It was found that at the lower frequency settings very little effect on the material was observed. For the frequency range between approximately 35 - 70 Hz a definite settling effect on the powders was observed. However, the results did not appear to be sensitive to frequency. For consistency, a frequency of 50 Hz was adopted as a standard.

Tests were carried out to establish the effect of amplitude/power of the vibration on the results obtained for settlement against time. Again, the results did not appear to be particularly sensitive to amplitude either in terms of final bed height or the time taken to achieve it. Therefore, for consistency a power setting of 7.5 watts was used throughout the test programme.

The method of obtaining a series of values of bed height against time of vibration involved carefully pouring a sample of material into the cylinder of known mass, avoiding compaction of the material. The initial bed height was then measured. The cylinder and contents were weighed and then attached to the vibrator. The cylinder was then vibrated for 5 seconds initially and the bed height recorded. The cylinder was then vibrated for a further time interval and the bed height measured again. This process was then repeated until the final bed height was reached. As the change in bed height decreased the time interval for vibration was increased. When three consecutive readings normally with time intervals of about 60 seconds indicated no change in bed height, then this was considered to be the final bed height. These values were then put into the expression derived for vibrated de-aeration constant and a straight *line graph drawn of H against time τ. The slope of the straight line graph gives the value of vibrated de-aeration constant.*

5.5.6 The Effect of Errors in the Initial and Final Bed Heights

In general the bed height can be read to an accuracy of about ±1 mm for most products. Tests were carried out to determine the effect of error occurring in the reading of initial and final bed heights. The effect of a 1mm reading error on inital bed height did not affect the value obtained for K_v'. *The slope of the graph obtained remains constant but a small zero error is detected. The effect of a 1mm reading error for final bed height does produce a change in the slope of the graph and results in a 4% error in the value of* K_v'. *In the context of pneumatic conveying, a 4% error is not considered serious.*

5.5.7 Practical Considerations

Sutton and Richmond (Ref. 5.8) emphasise the fact that the value they obtain for the de-aeration constant is not only dependent on the material under test, but it is also system-dependent. They report that on scale up from pilot scale rigs (it should be remembered that their interest was in flow promotion) large changes in absolute values of de-aeration constant were obtained although the general relative position of one material to another remained constant. This is also bound to be the case for the vibrated de-aeration constant although no tests for scale have been carried out.

The quantity being measured during the settlement of powders under the influence of vibration is obviously different to that measured for the natural settlement of powders under the influence of gravity. However, both methods appear to give an indication of the air retention capabilities of a product.

It can be argued that the settlement of a powder under the influence of vibration is made up of two components. The first is the release of interstitial air and the second is the rearrangement of particles to allow closer packing. It is probable that the release of air is the predominant action initially with the rearrangement of particle position becoming dominant as the bed approaches the final bed height. For this reason, it is the first portion of the graph obtained from the test which is treated as having greater significance.

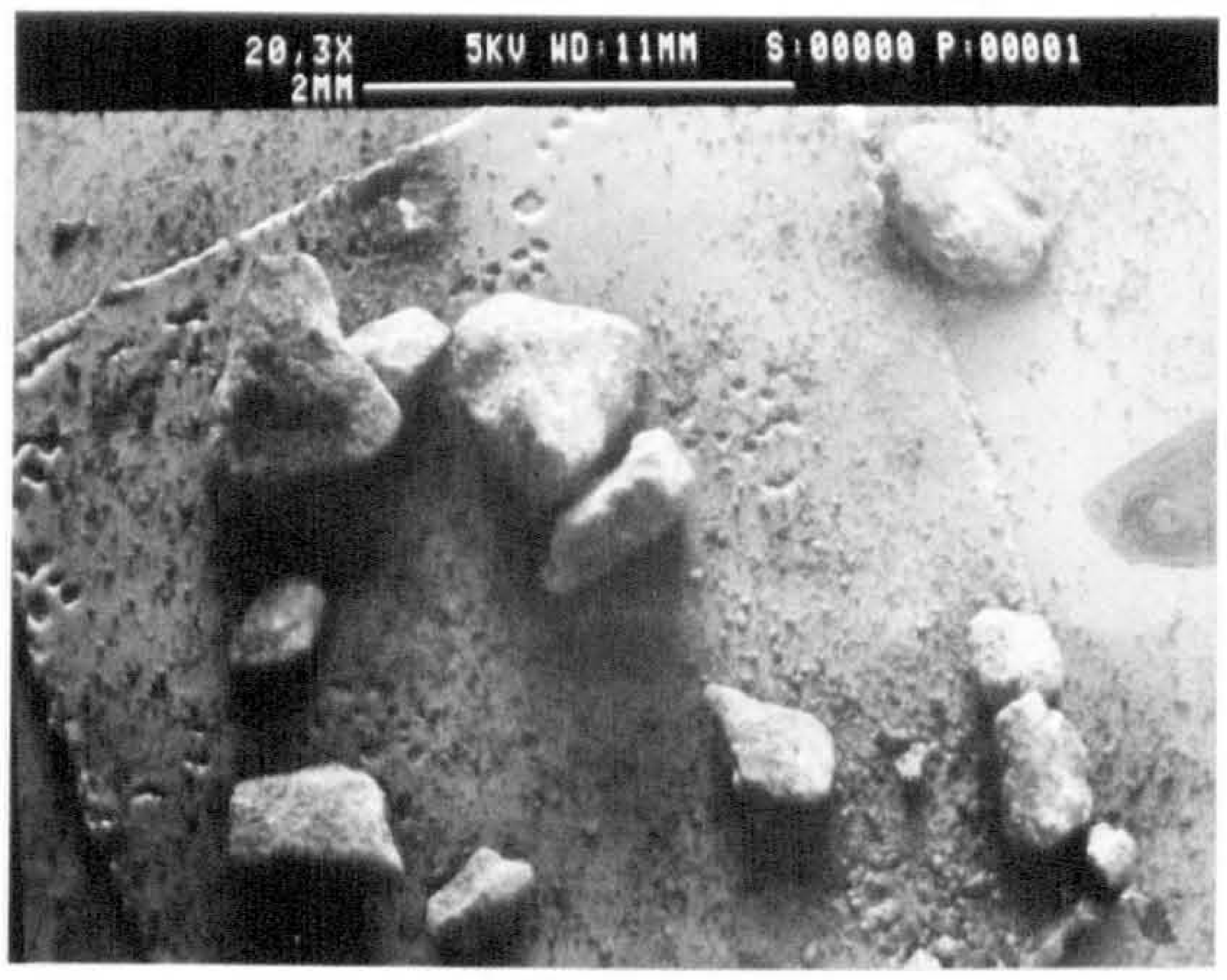
Sample results of the vibrated de-aeration test for two products at opposite ends of the air retention capability range are presented figures 5.4 & 5.5. The results obtained for all the products used in the conveying trials are presented in Appendix 3. It can be seen that, in general, good straight lines are produced making the determination of vibrated de-aeration constant a relatively easy task. This to some extent justifies the choice of adopting the Sutton and Richmond analysis and applying it to the vibrated de-aeration test.

The products which produce less clear results are the products which do not have good air retention properties. The problem centres around the difficulty in obtaining test points. However, this immediately indicates that the product is not suitable for moving bed type flow and does not present a problem to the conveying performance correlation. The products which produce very clear results are the products which have good air retention capability and these are the results with which correlation with pneumatic conveying performance is made.

CHAPTER 6

TEST MATERIALS

MATERIAL No. 1 - AGRICULTURAL CATALYST (ICI)



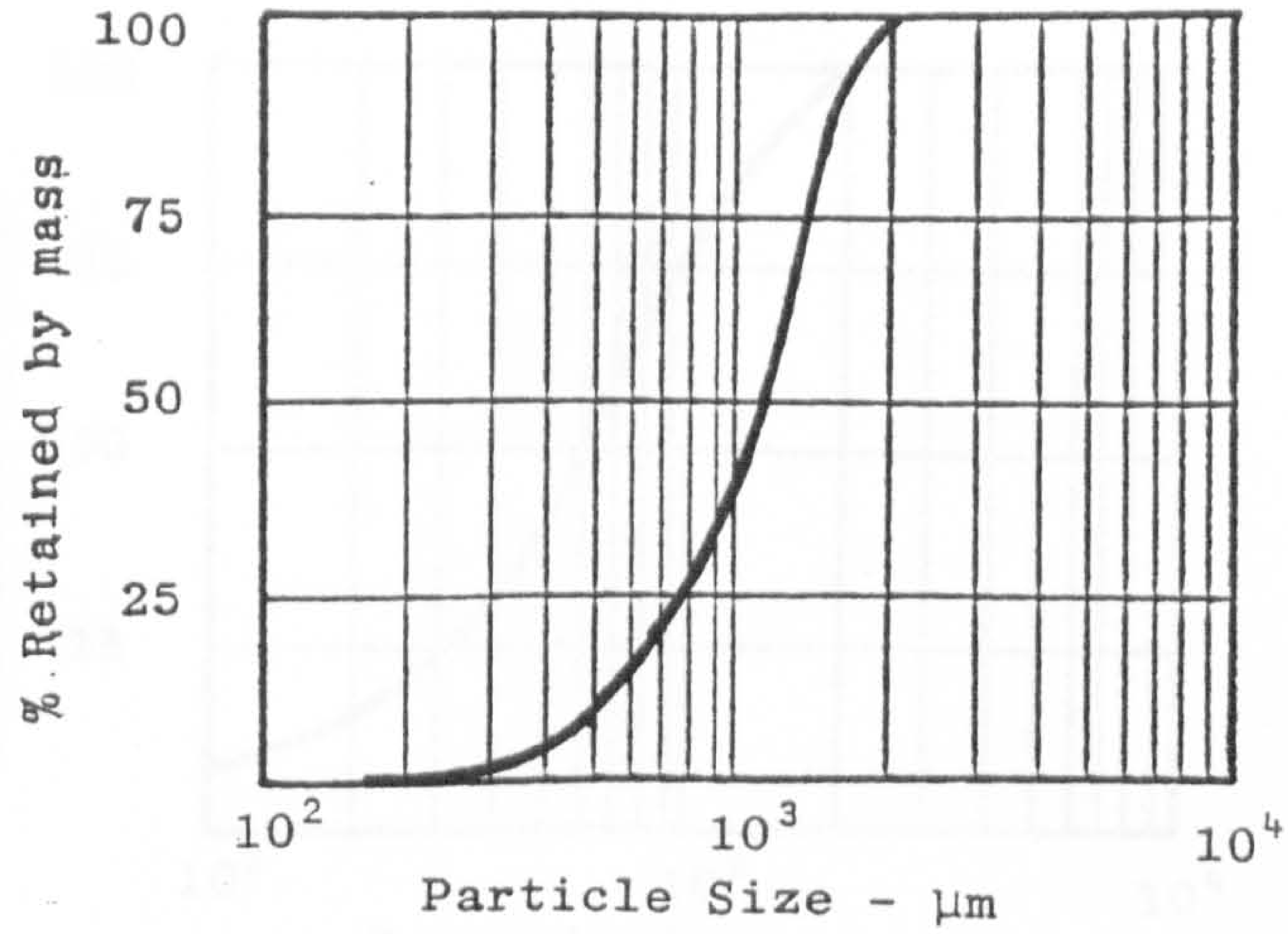
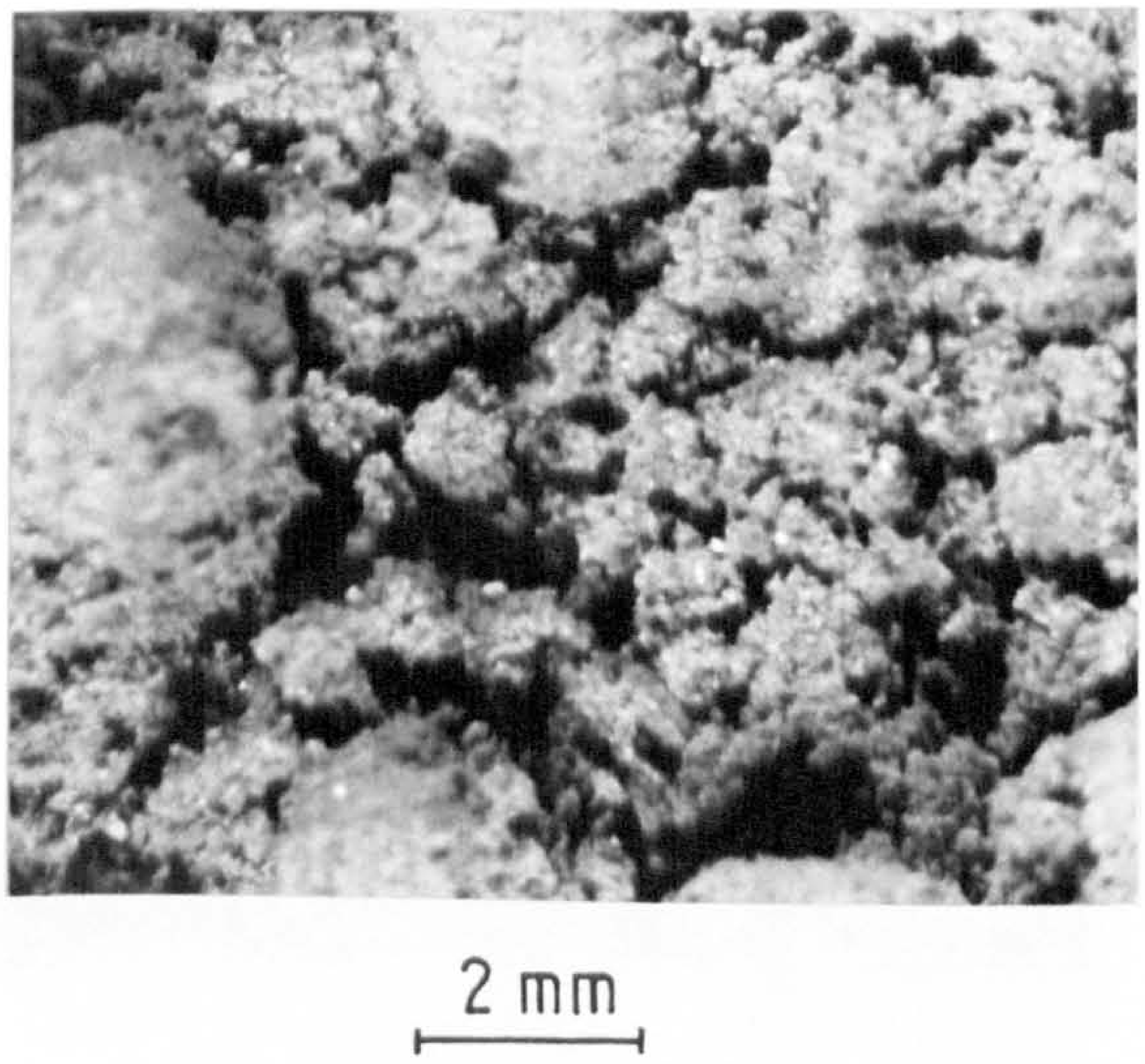


Fig. 6.1 *MICROGRAPH OF AGRICULTURAL CATALYST*

Fig. 6.2 *SIZE ANALYSIS OF AGRICULTURAL CATALYST*

Mean particle size	*782*	*µm*
Mass median particle size:	*1150*	*µm*
Particle size range (2.5%/97.5%):	*375/1900*	*µm*
Particle density:	*4655*	*kg/m³*
Poured bulk density:	*767*	*kg/m³*
Tapped bulk density:	*864*	*kg/m³*
Compaction:	*13*	*%*
Permeability factor, C:	23×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v':	23×10^{-3}	*m/s*

MATERIAL No. 2 - AGRICULTURAL CATALYST (degraded)



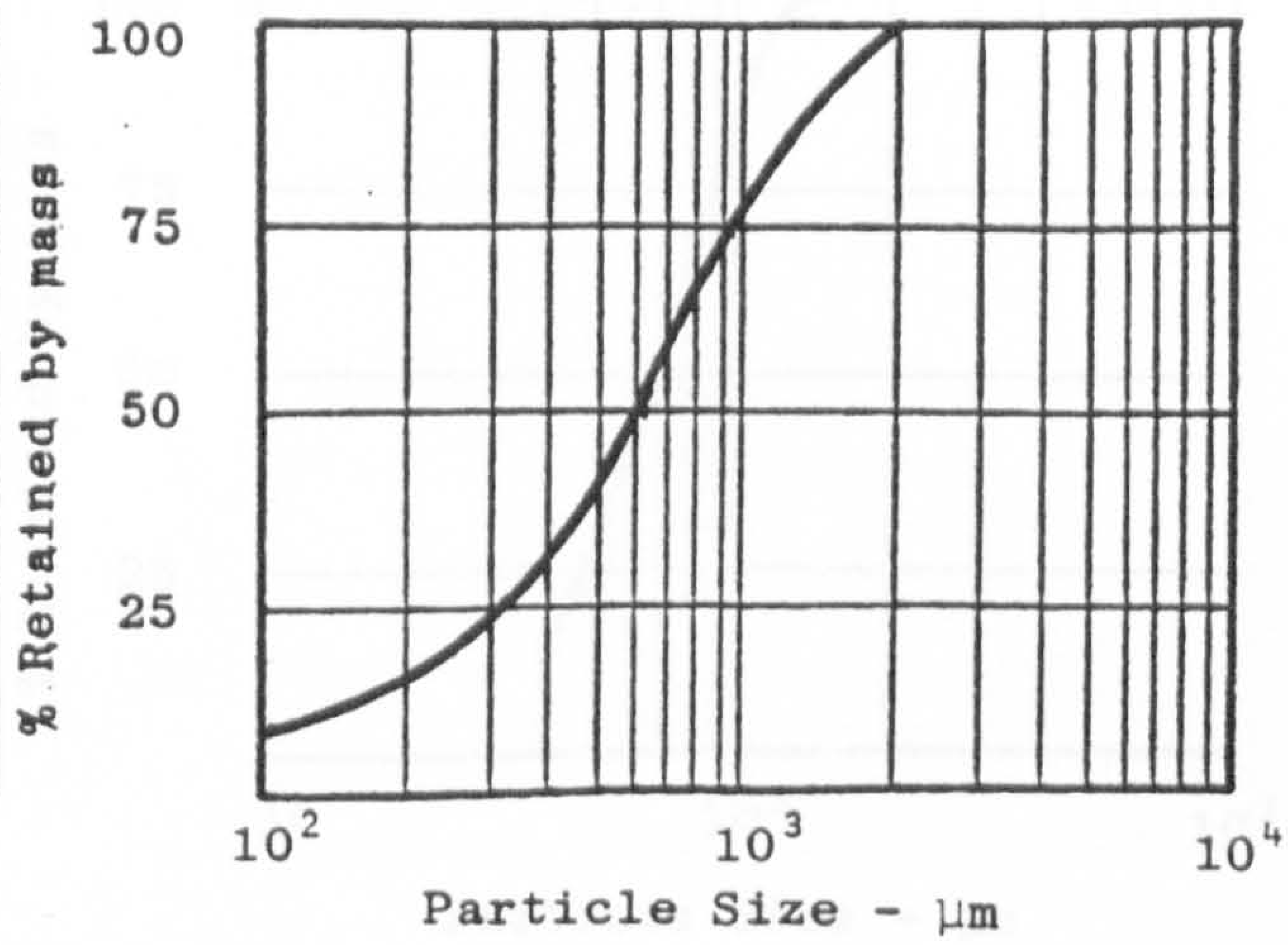
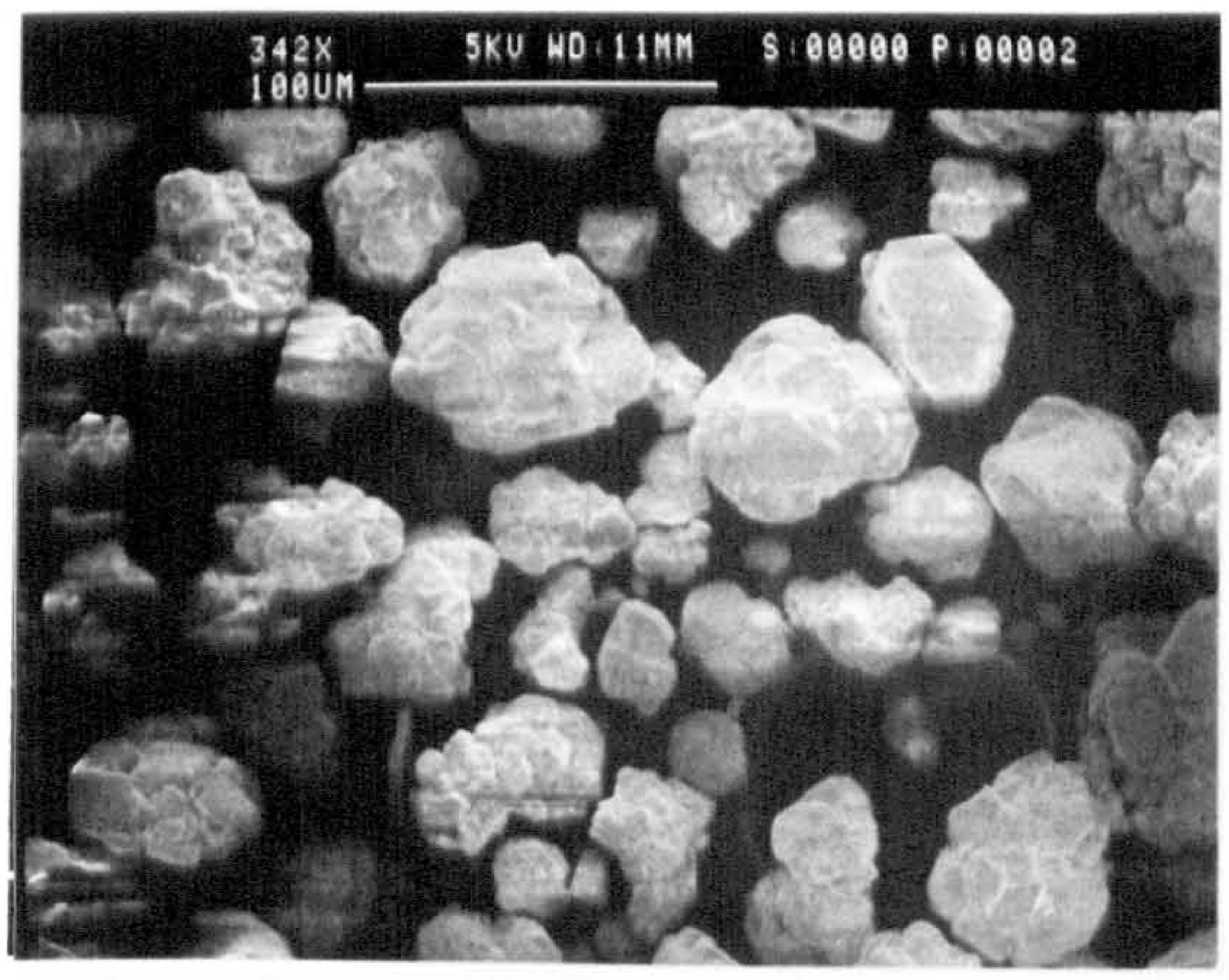


Fig. 6.3 *MICROGRAPH OF DEGRADED AGRICULTURAL CATALYST*

Fig. 6.4 *SIZE ANALYSIS OF AGRICULTURAL CATALYST -degraded*

Mean particle size	*270*	μm
Mass median particle size:	*610*	μm
Particle size range (2.5%/97.5%):	*45/1850*	μm
Particle density:	*4660*	kg/m^3
Poured bulk density:	*760*	kg/m^3
Tapped bulk density:	*1010*	kg/m^3
Compaction:	*33*	*%*
Permeability factor, C:	$1.7x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$6.7x10^{-3}$	m/s

MATERIAL No. 3 - ALUMINA



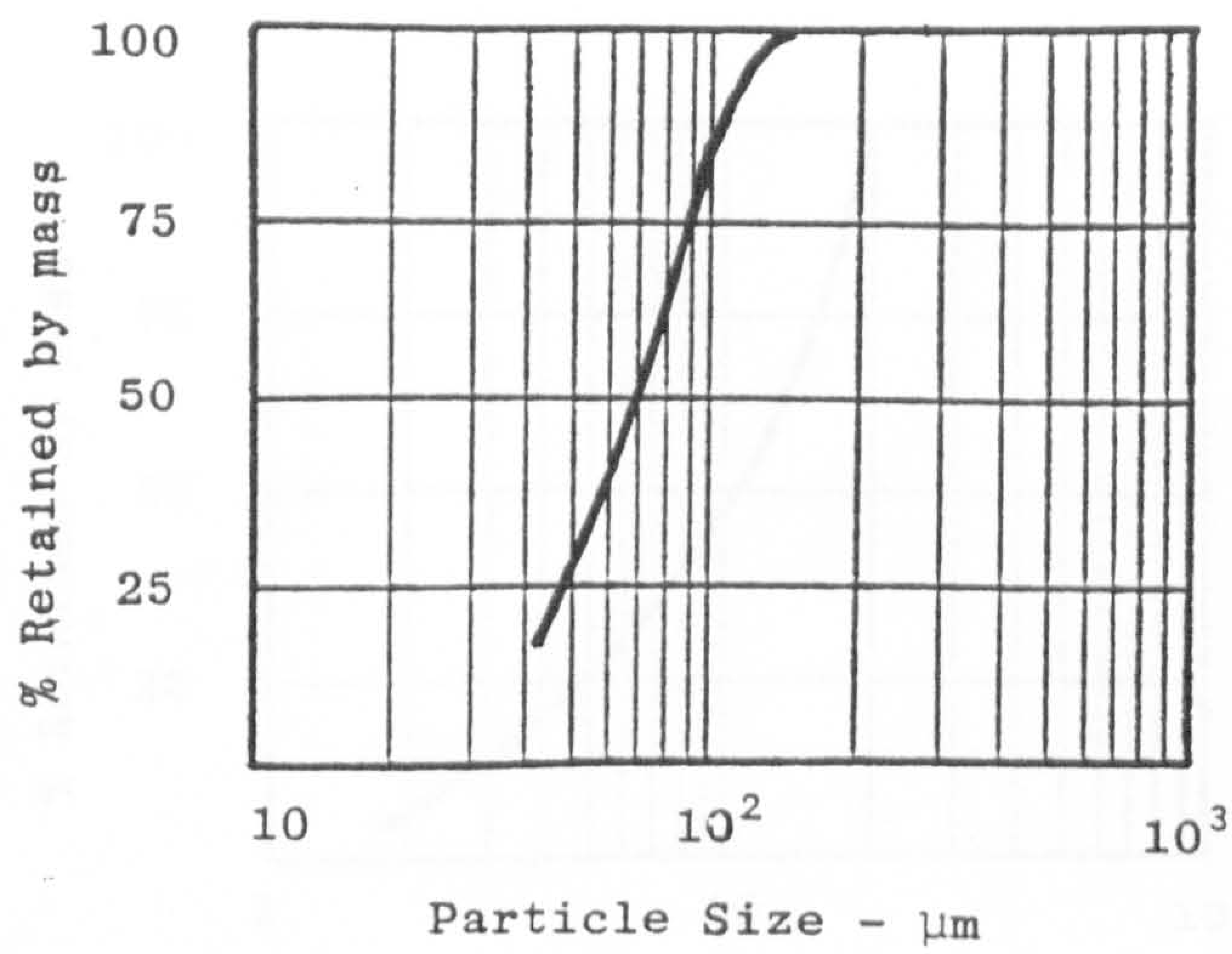


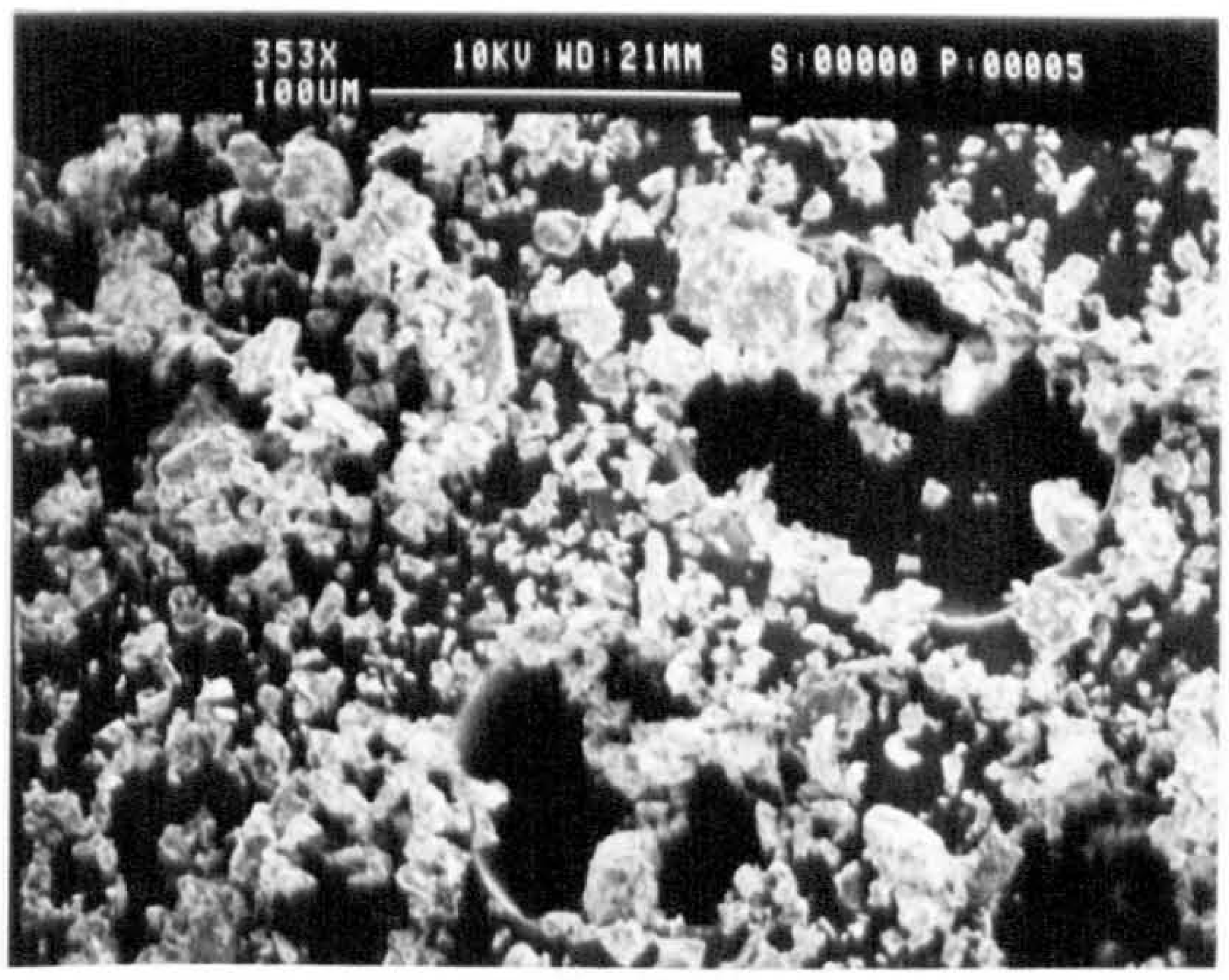
Fig. 6.5 *MICROGRAPH OF ALUMINA*

Fig. 6.6 *SIZE ANALYSIS OF ALUMINA*

Mean particle size:	*79*	*µm*
Mass median particle size:	*70*	*µm*
Particle size range (2.5%/97.5%):	*30/70*	*µm*
Particle density:	*3600*	*kg/m^3*
Poured bulk density:	*1040*	*kg/m^3*
Tapped bulk density:	*1220*	*kg/m^3*
Compaction:	*17*	*%*
Permeability factor, C:	*$0.42x10^{-6}$*	*m^3s/kg*
Vibrated de-aeration constant, K_v':	*$19x10^{-3}$*	*m/s*

Comments: Prone to electrostatic charging. Agglomerates tended to form causing a change in the conveying characteristics to occur. The product returned to its original state as the charge was dissipated.

MATERIAL No. 4 - BARYTES



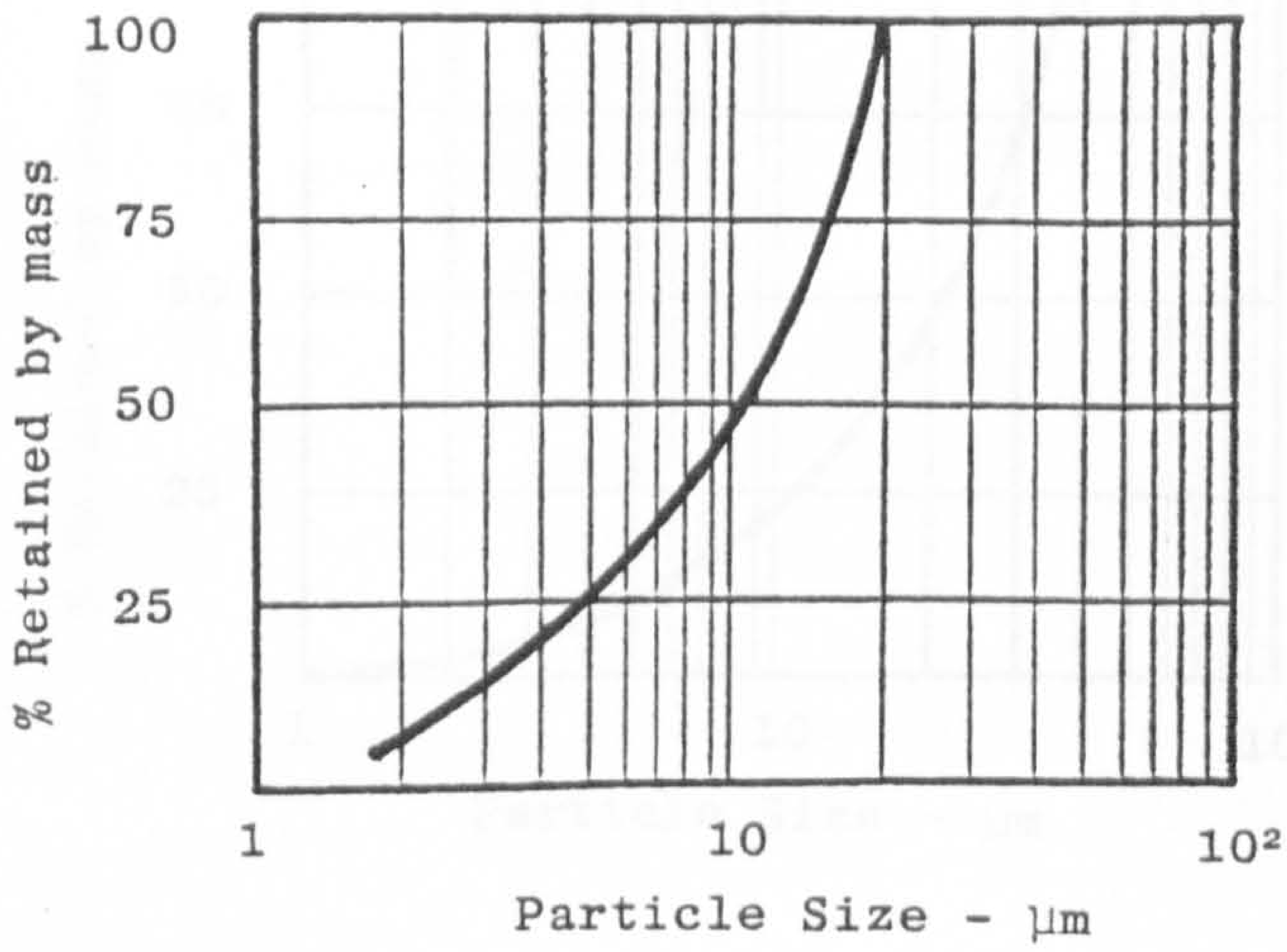


Fig. 6.7 MICROGRAPH OF BARYTES

Fig. 6.8 SIZE ANALYSIS OF BARYTES

Mean particle size:	11	μm
Mass median particle size:	12	μm
Particle size range (2.5%/97.5%):	2/28	μm
Particle density:	4250	kg/m^3
Poured bulk density:	1590	kg/m^3
Tapped bulk density:	2270	kg/m^3
Compaction:	43	%
Permeability factor, C:	0.48×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v':	3.9×10^{-3}	m/s

MATERIAL No. 5 - CEMENT (Ordinary Portland)

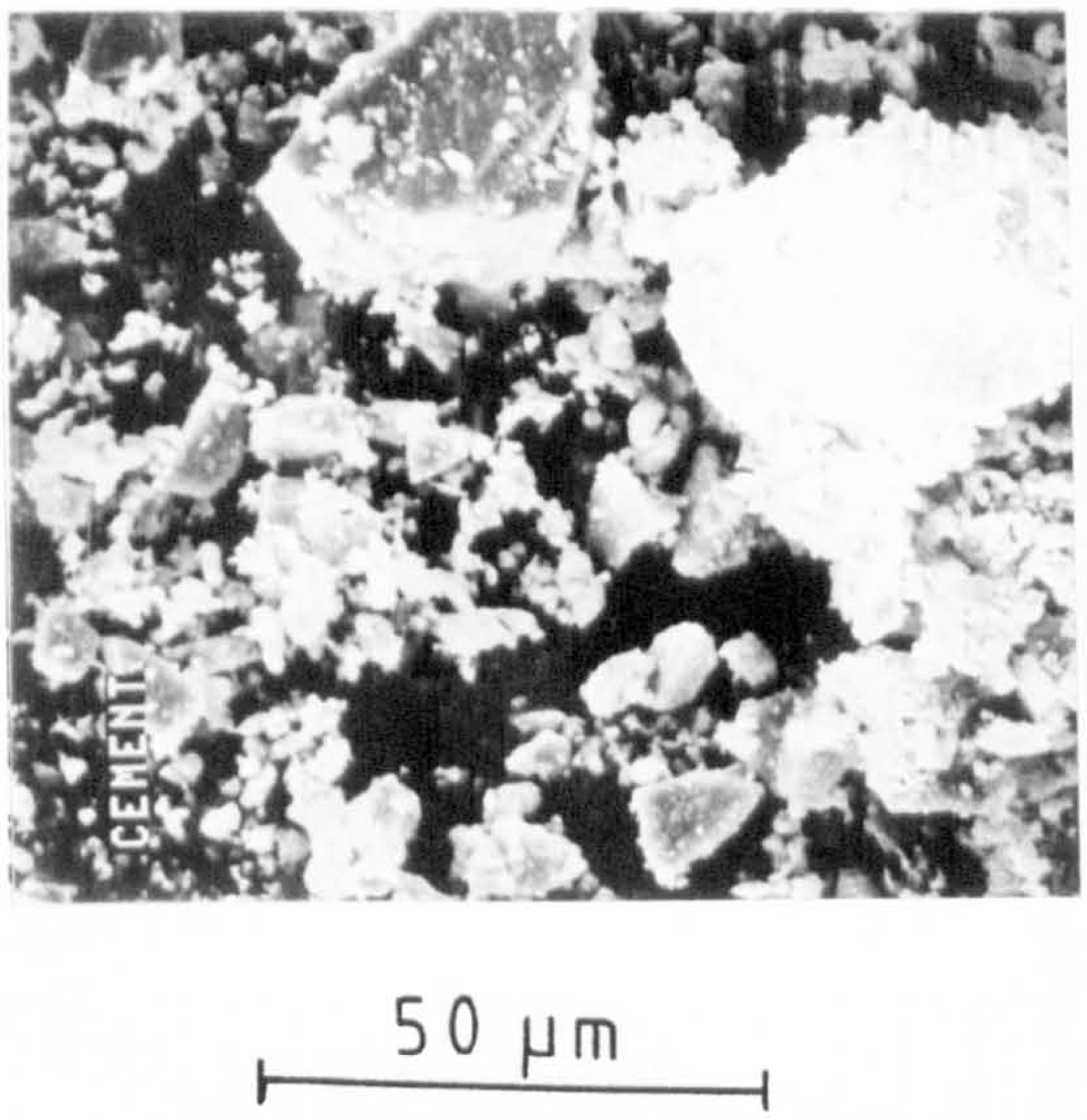


Fig. 6.9 MICROGRAPH OF CEMENT

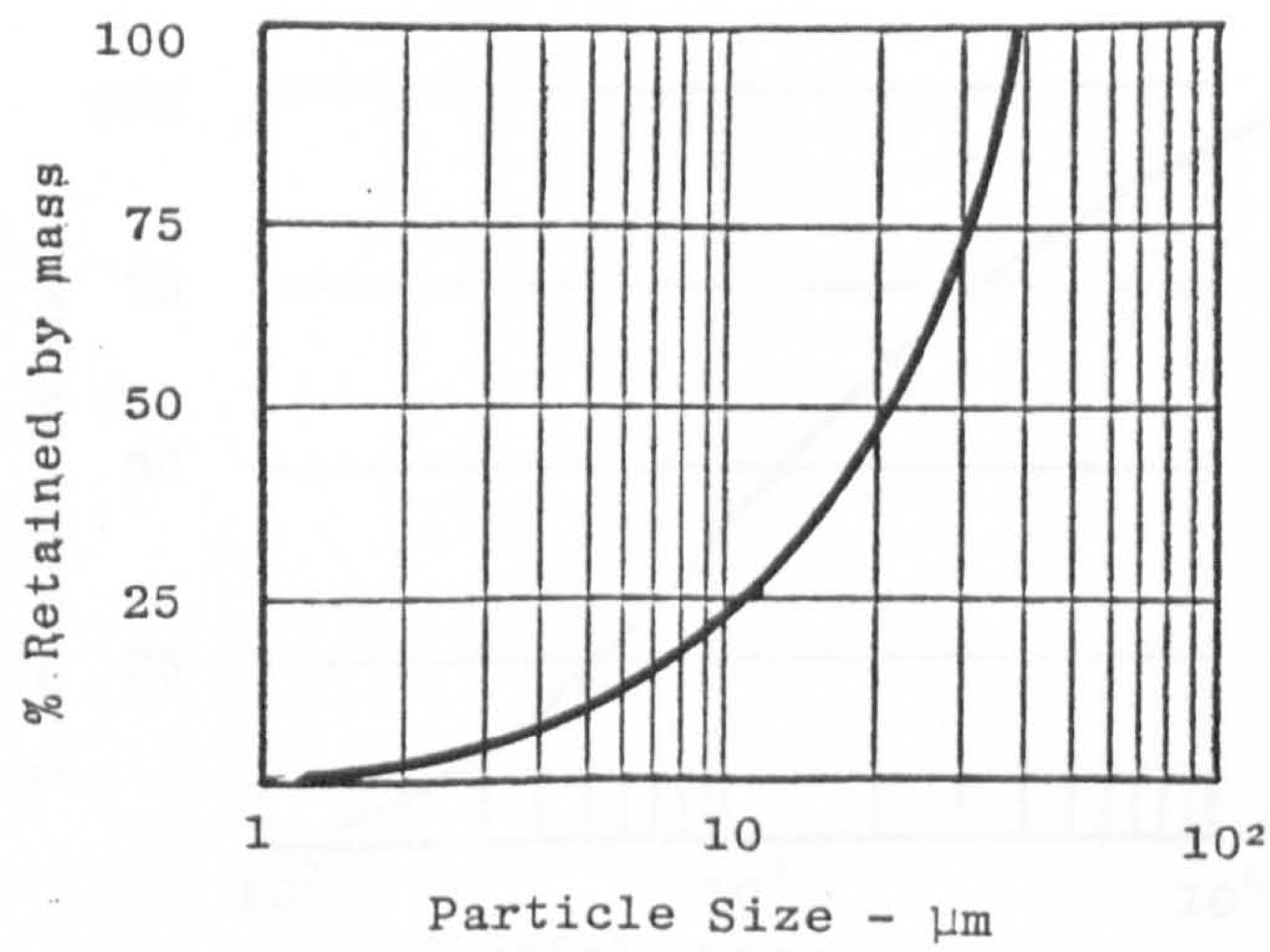


Fig. 6.10 SIZE ANALYSIS OF CEMENT

Mean particle size:	14	µm
Mass median particle size:	21	µm
Particle size range (2.5%/97.5%):	4/37	µm
Particle density:	3060	kg/m^3
Poured bulk density:	1070	kg/m^3
Tapped bulk density:	1500	kg/m^3
Compaction:	40	%
Permeability factor, C:	0.71×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v':	3.0×10^{-3}	m/s

MATERIAL No. 6 - COAL (As Supplied)

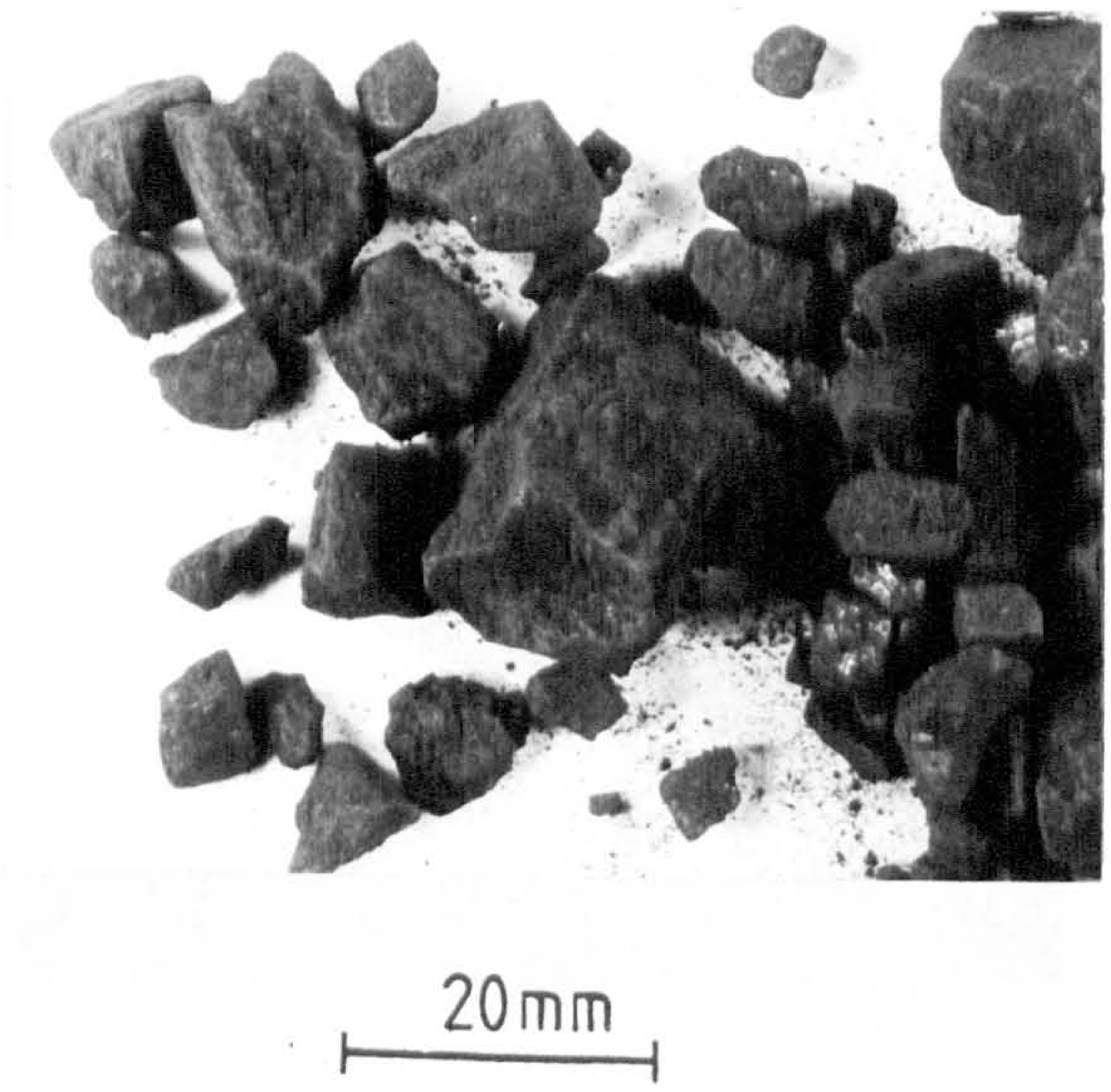


Fig. 6.11 MICROGRAPH OF COAL

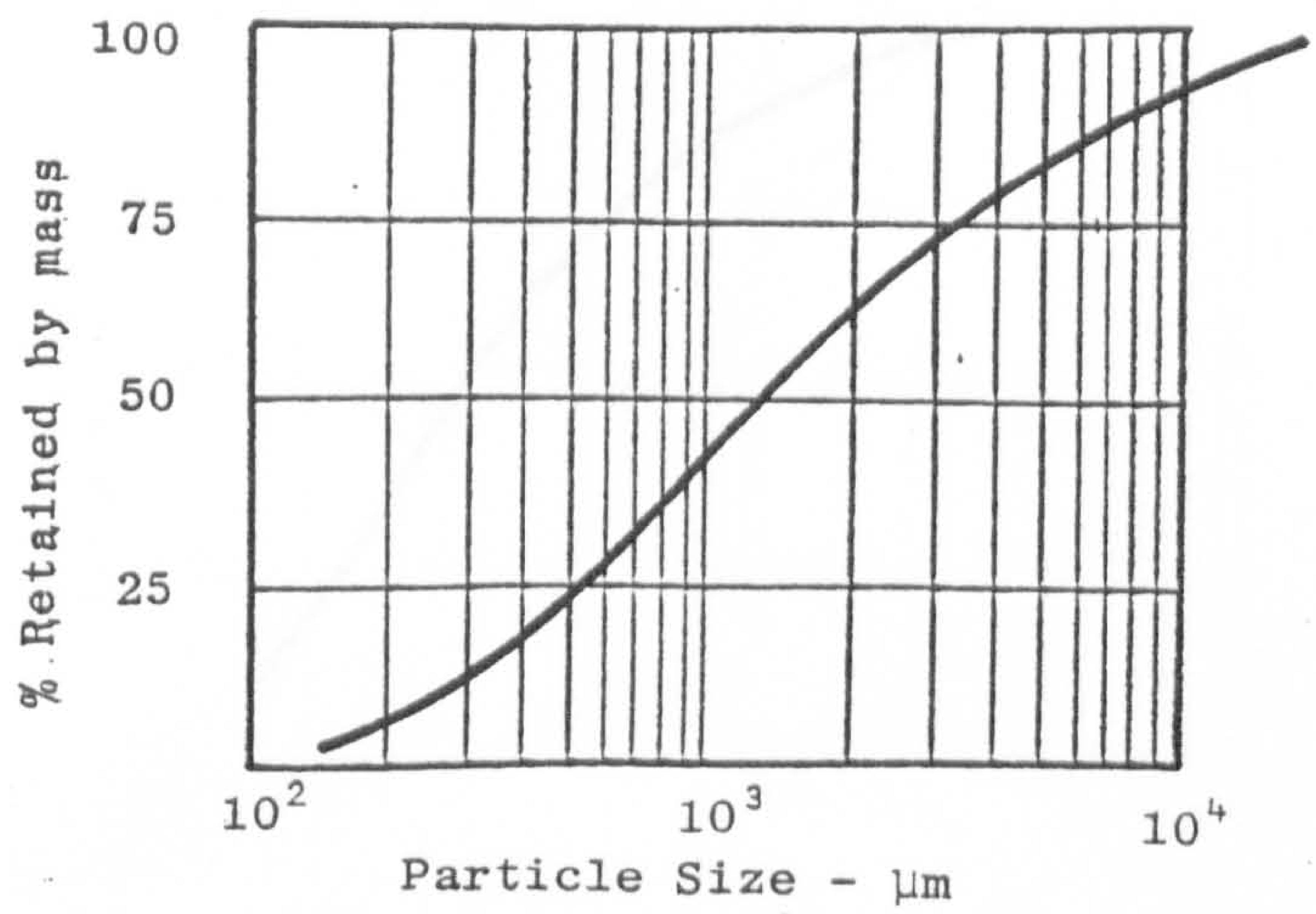


Fig. 6.12 SIZE ANALYSIS OF COAL

Mean particle size:	778	μm
Mass median particle size:	1170	μm
Particle size range (2.5%/97.5%):	150/20000	μm
Particle density:	1550	kg/m^3
Poured bulk density:	870	kg/m^3
Tapped bulk density:	1000	kg/m^3
Compaction:	14	%
Permeability factor, C:	42×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v':	24×10^{-3}	m/s

MATERIAL No. 7 - COAL (degraded)

Fig. 6.13 MICROGRAPH OF DEGRADED COAL

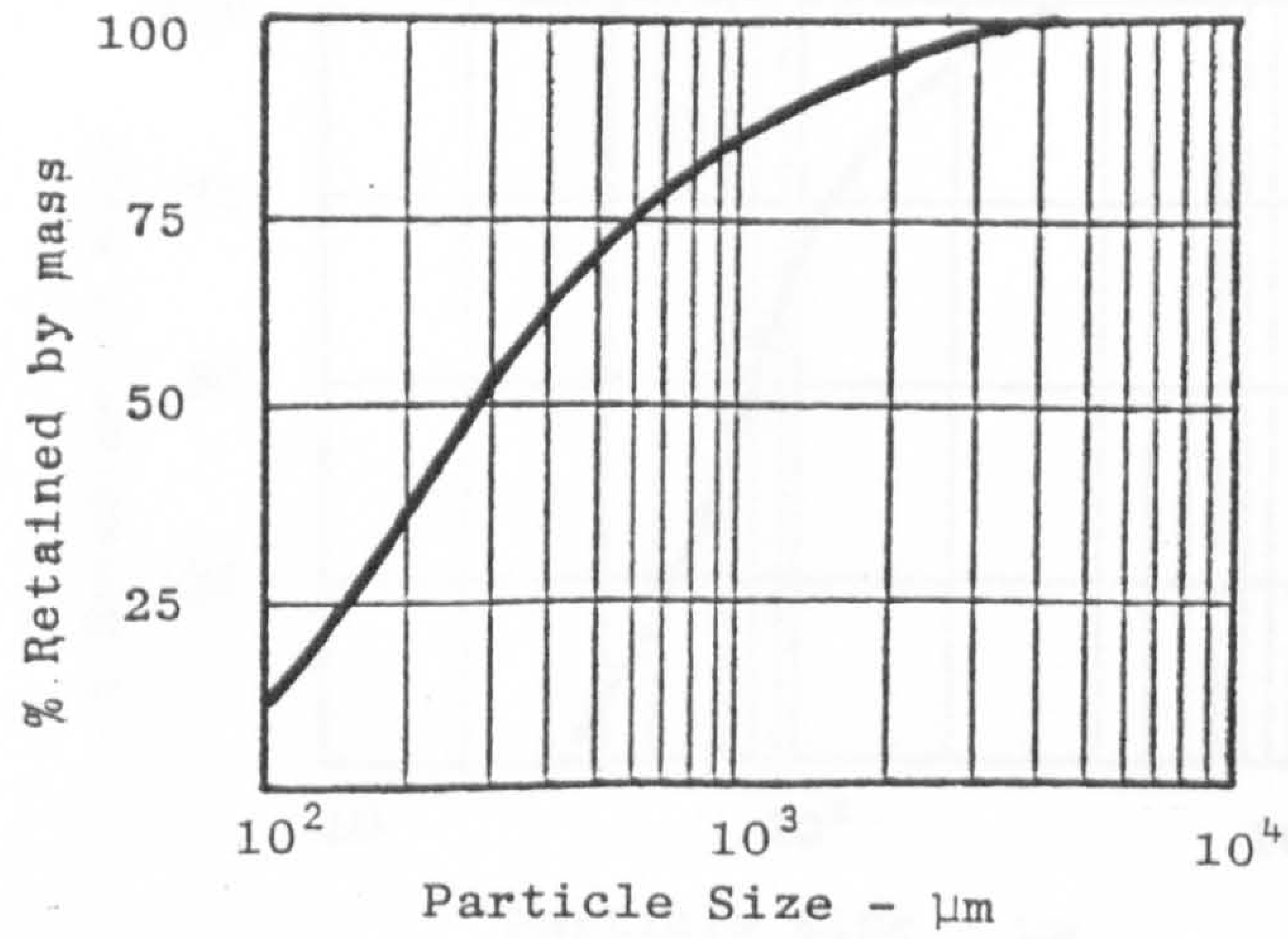


Fig. 6.14 SIZE ANALYSIS OF DEGRADED COAL

Mean particle size:	*146*	*μm*
Mass median particle size:	*260*	*μm*
Particle size range (2.5%/97.5%):	*70/2400*	*μm*
Particle density:	*1550*	*kg/m³*
Poured bulk density:	*701*	*kg/m³*
Tapped bulk density:	*953*	*kg/m³*
Compaction:	*36*	*%*
Permeability factor, C:	1.0×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v':	2.9×10^{-3}	*m/s*

Comments: Significant breakage occurred during conveying. It can be seen that the size range has been significantly reduced from the 'as supplied' condition.

MATERIAL No. 8 - COAL (Pulverised Fuel)

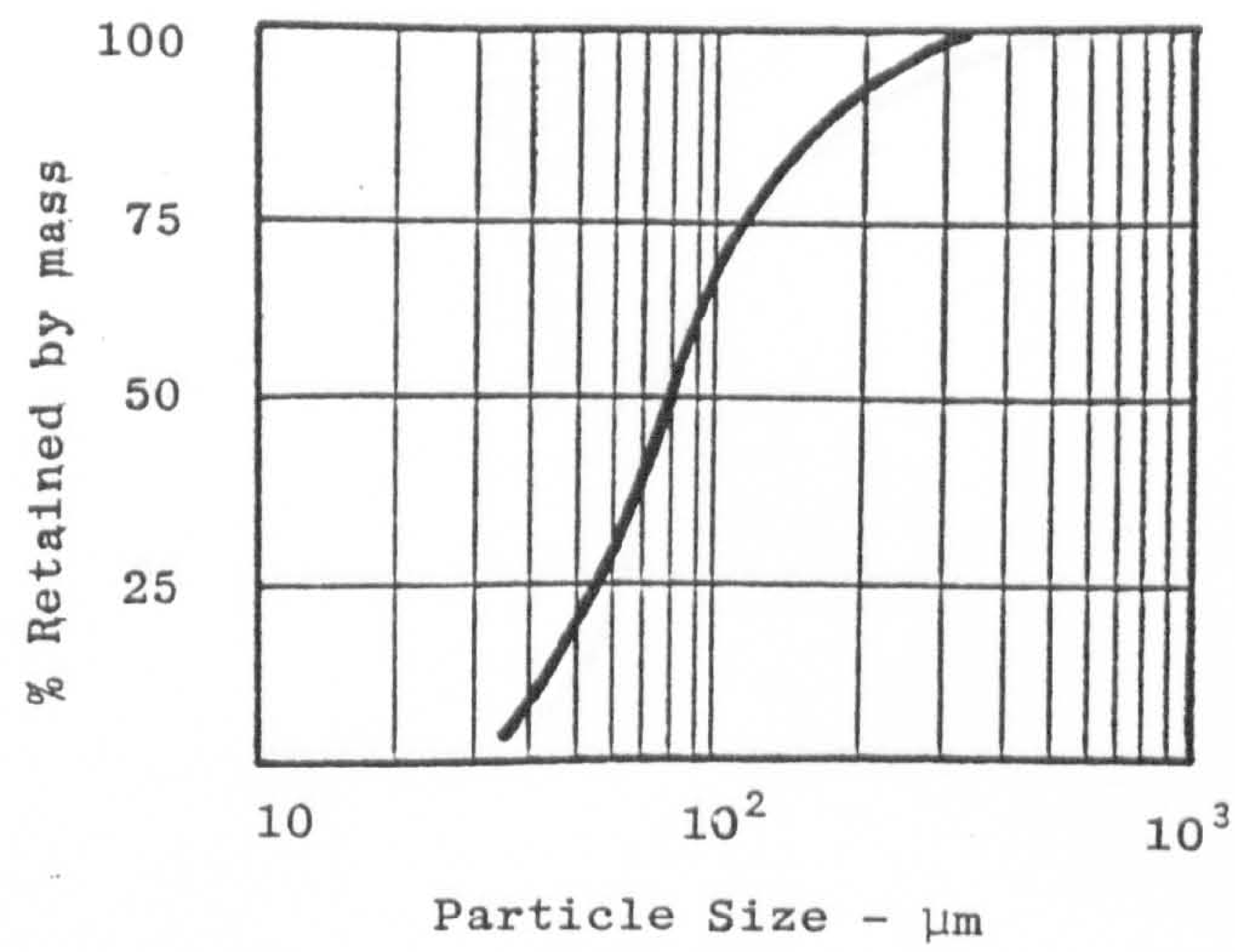


Fig. 6.15 MICROGRAPH OF PULVERISED FUEL

Fig. 6.16 SIZE ANALYSIS OF PULVERISED FUEL

Mean particle size:	*84*	*μm*
Mass median particle size:	*80*	*μm*
Particle size range (2.5%/97.5%):	*35/230*	*μm*
Particle density:	*1550*	*kg/m^3*
Poured bulk density:	*393*	*kg/m^3*
Tapped bulk density:	*514*	*kg/m^3*
Compaction:	*31*	*%*
Permeability factor, C:	*$0.53x10^{-6}$*	*m^3s/kg*
Vibrated de-aeration constant, K_v':	*$4.3x10^{-3}$*	*m/s*

MATERIAL No. 9 - COPPER ORE

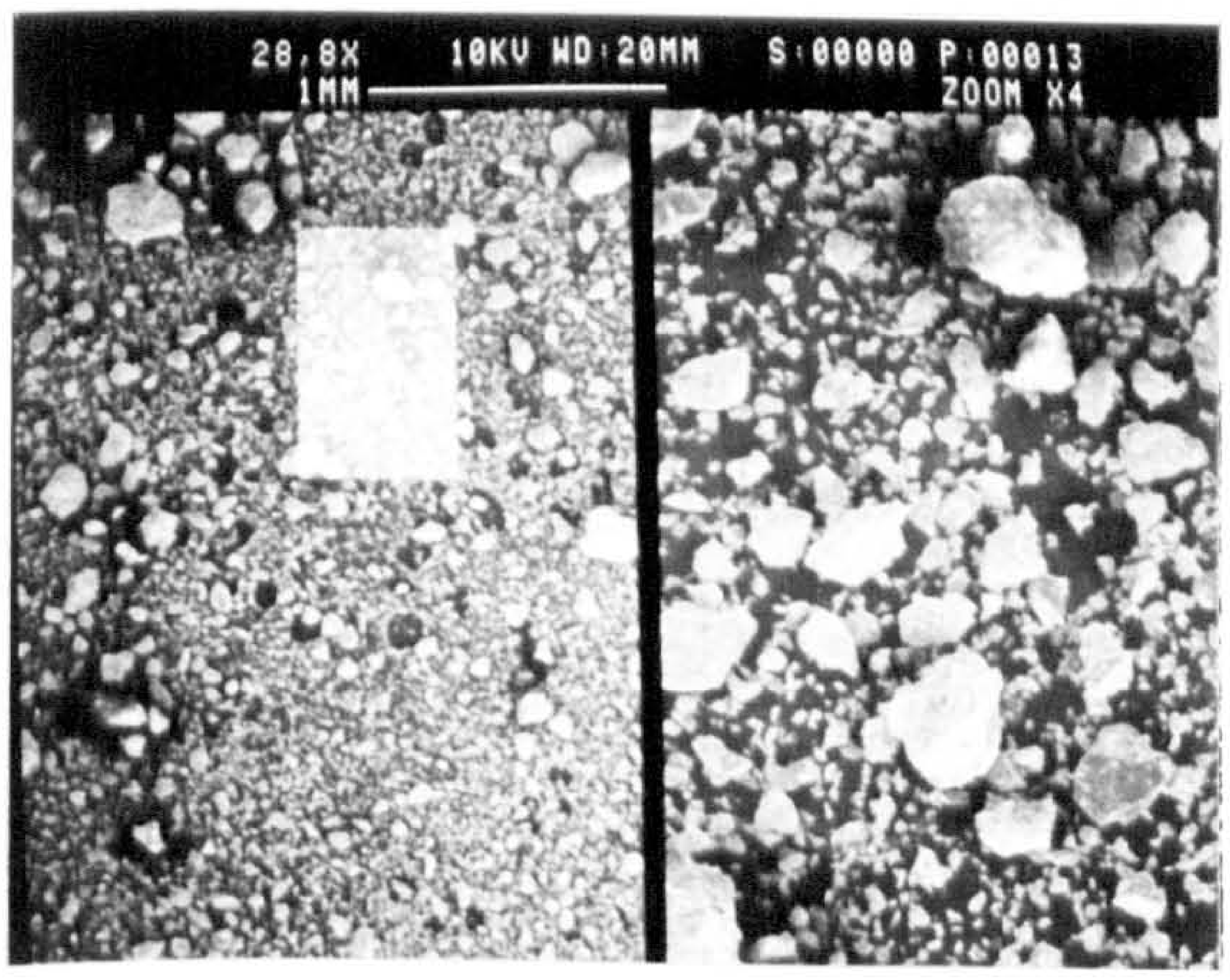


Fig. 6.17 MICROGRAPH OF COPPER ORE

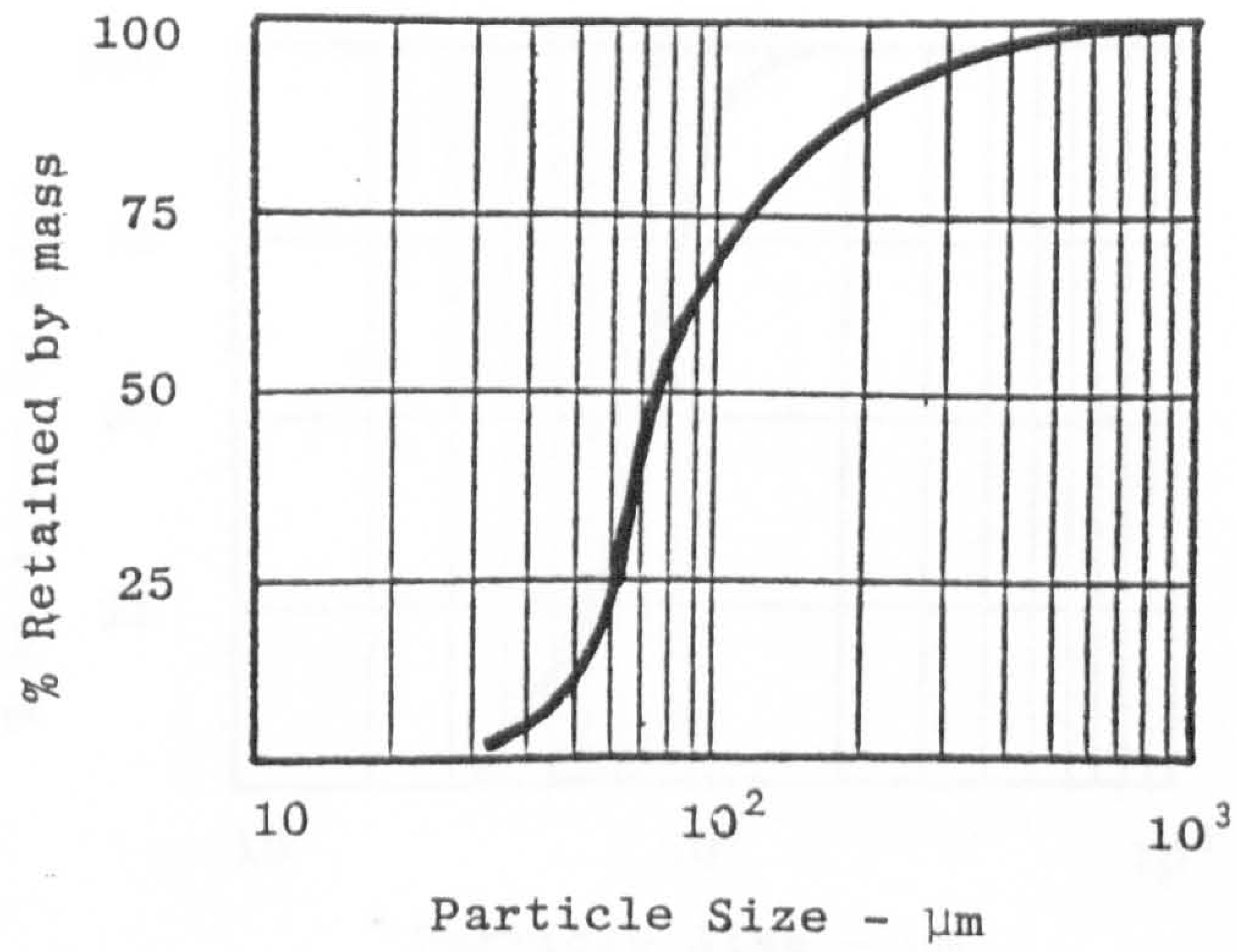


Fig. 6.18 SIZE ANALYSIS OF COPPER ORE

Mean particle size:	55	µm
Mass median particle size:	75	µm
Particle size range (2.5%/97.5%):	11/600	µm
Particle density:	3950	kg/m^3
Poured bulk density:	1660	kg/m^3
Tapped bulk density:	2150	kg/m^3
Compaction:	30	%
Permeability factor, C:	$0.33x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$9.8x10^{-3}$	m/s

Comments: In appearance, this product seems quite cohesive and deceptively fine. However, the largest particles are in excess of 600µm.

MATERIAL No. 10 - FLOUR (RHM Democrat)

Fig. 6.19 MICROGRAPH OF FLOUR

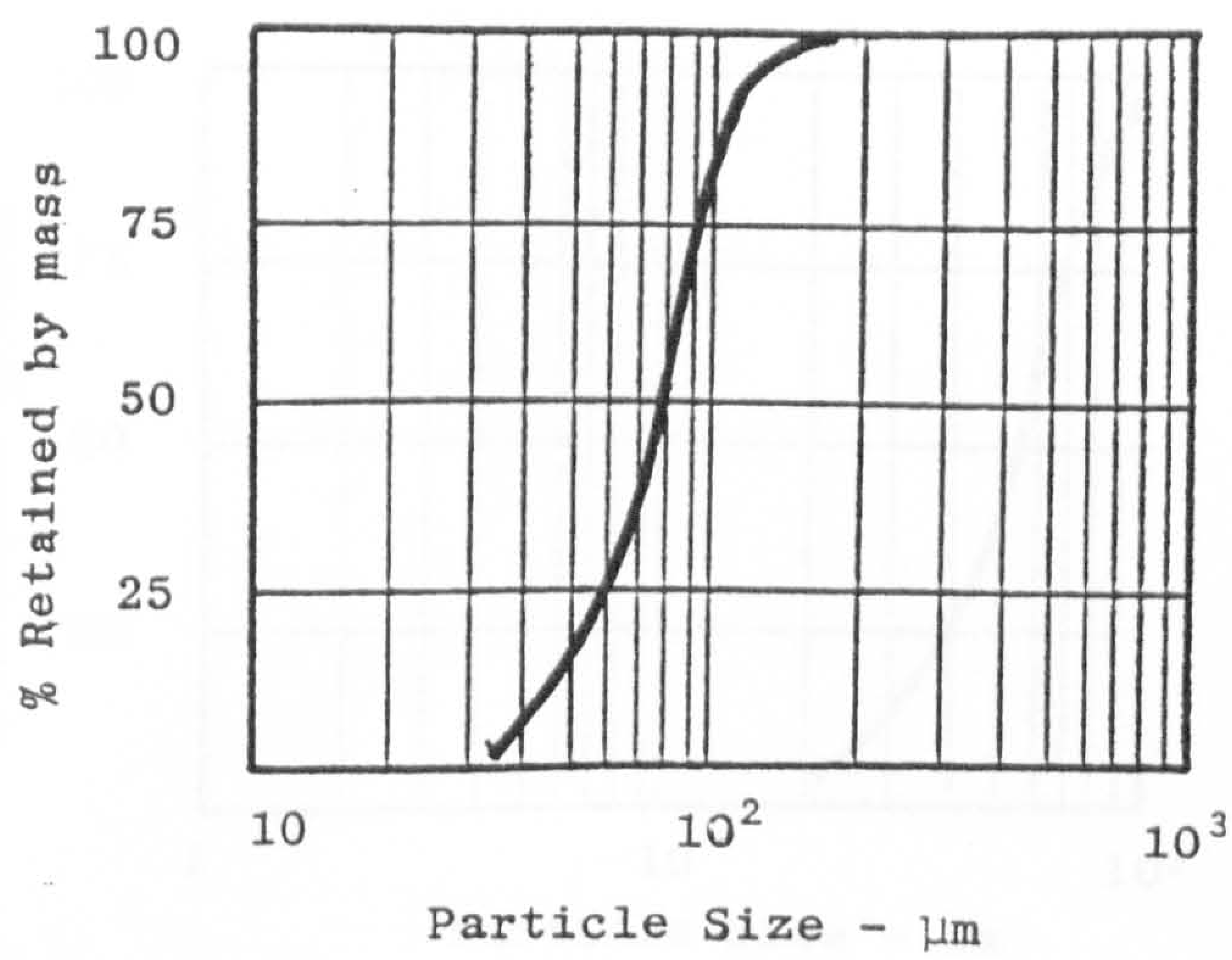
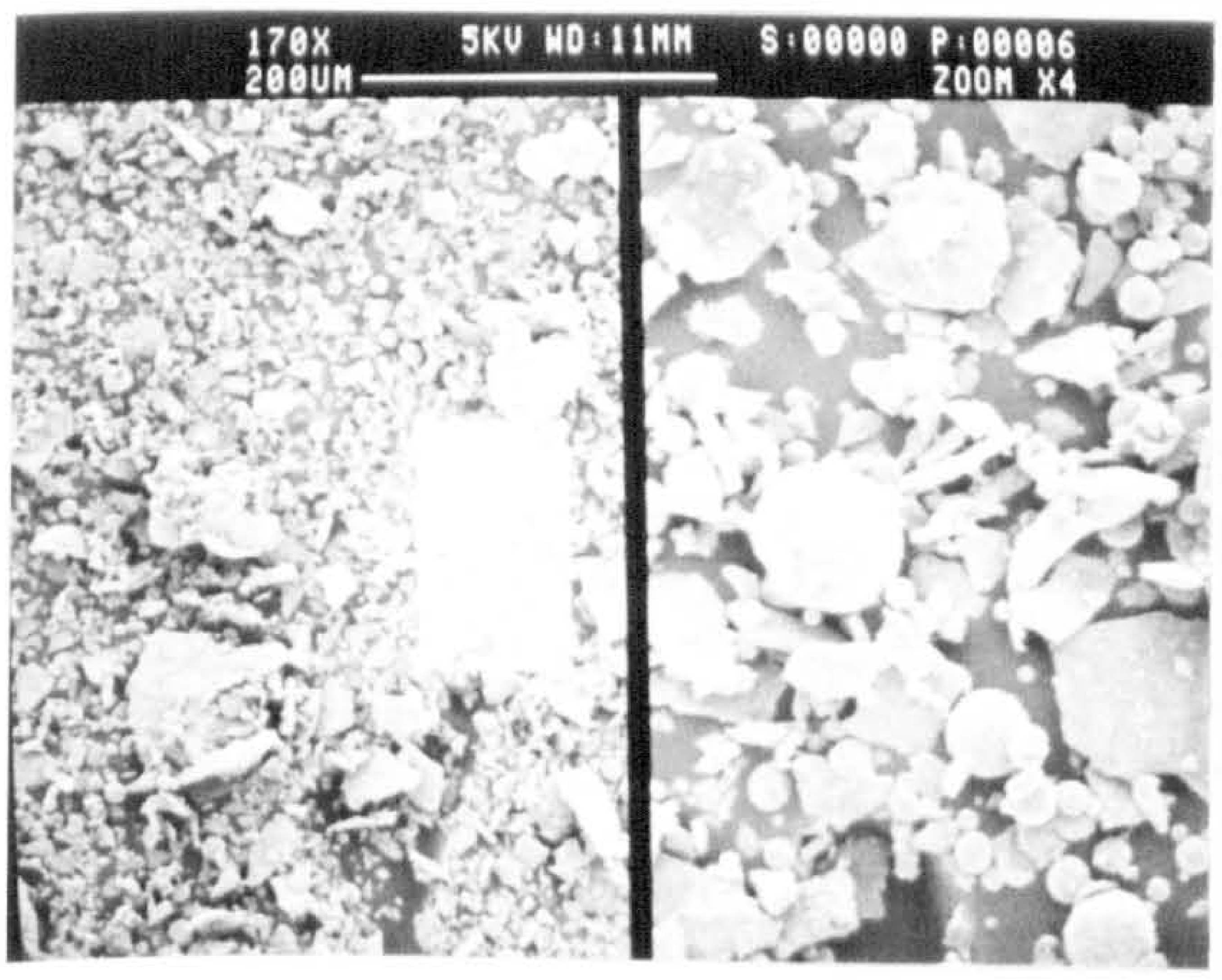


Fig. 6.20 SIZE ANALYSIS OF FLOUR

Mean particle size:	90	μm
Mass median particle size:	78	μm
Particle size range (2.5%/97.5%):	40/120	μm
Particle density:	1470	kg/m^3
Poured bulk density:	510	kg/m^3
Tapped bulk density:	700	kg/m^3
Compaction:	37	%
Permeability factor, C:	$1.3x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$6.2x10^{-3}$	m/s

Comments: A particularly cohesive product which is sometimes difficult to fluidise (rat-holes easily). This product has a high inherent moisture content of around 14%.

MATERIAL No. 11 - IRON POWDER



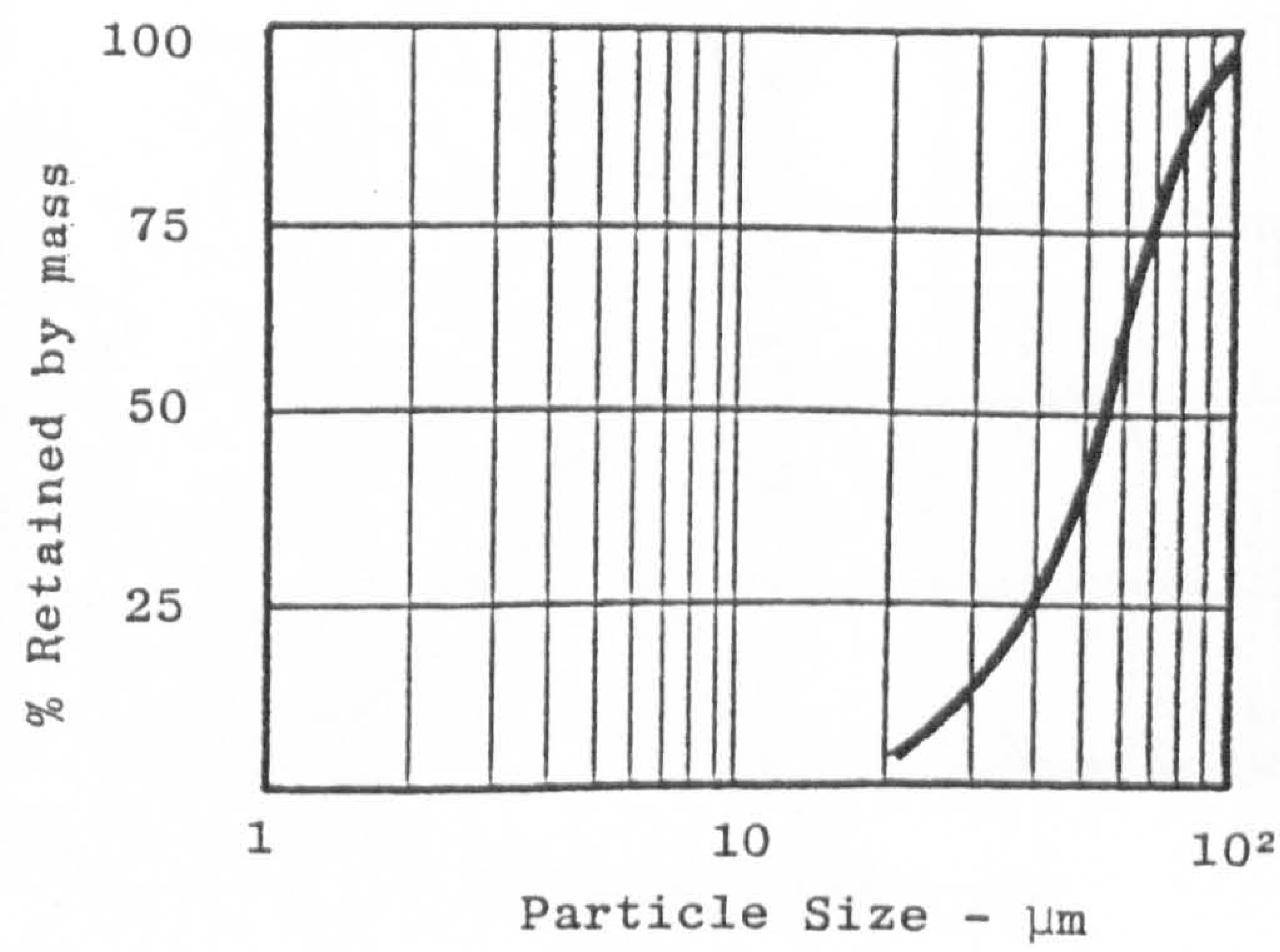
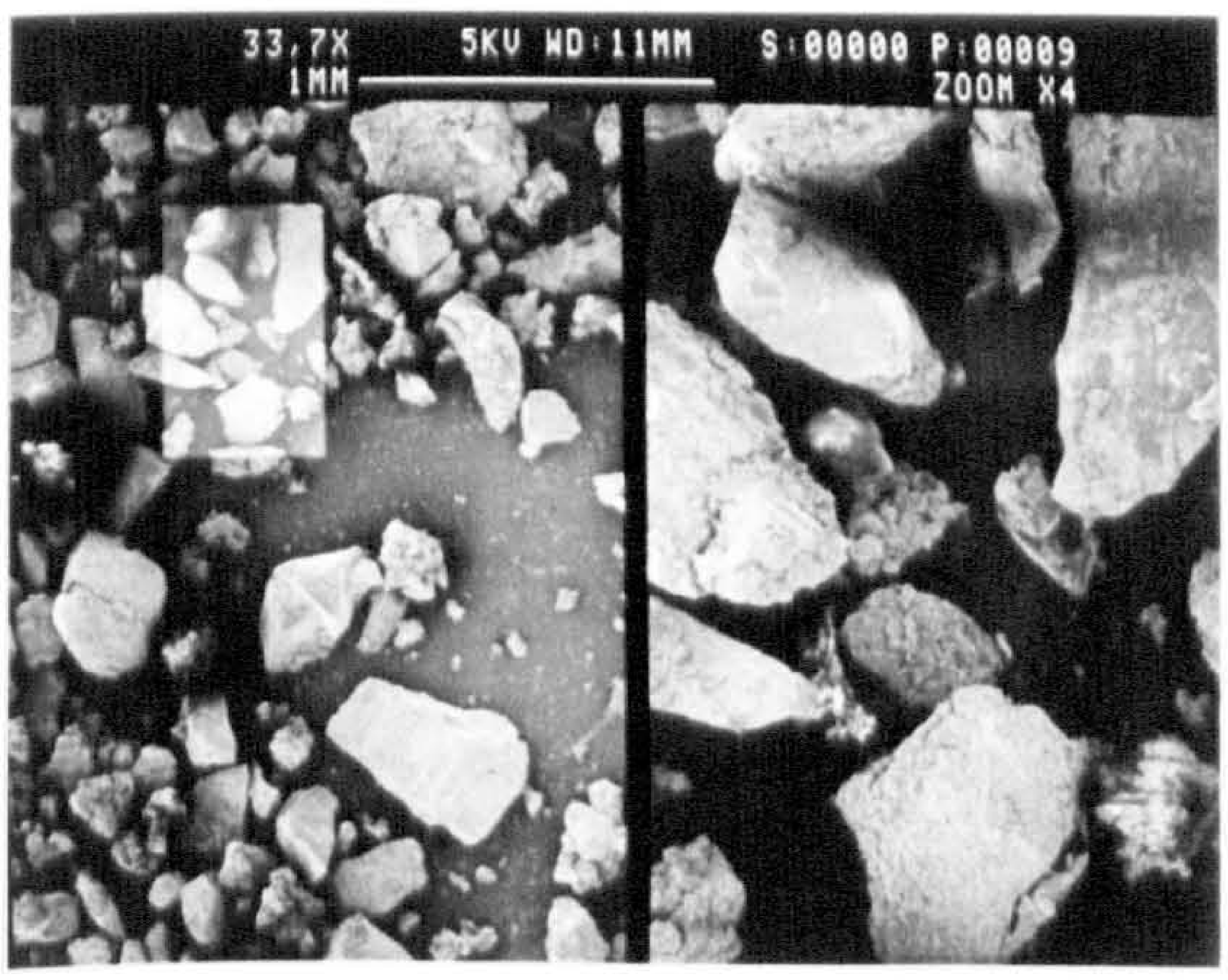


Fig. 6.21 MICROGRAPH OF IRON POWDER

Fig. 6.22 SIZE ANALYSIS OF IRON POWDER

Mean particle size:	64	μm
Mass median particle size:	66	μm
Particle size range (2.5%/97.5%):	20/100	μm
Particle density:	5710	kg/m^3
Poured bulk density:	2380	kg/m^3
Tapped bulk density:	3190	kg/m^3
Compaction:	34	%
Permeability factor, C:	0.34×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v':	7.0×10^{-3}	m/s

MATERIAL No. 12 - MAGNESIUM SULPHATE



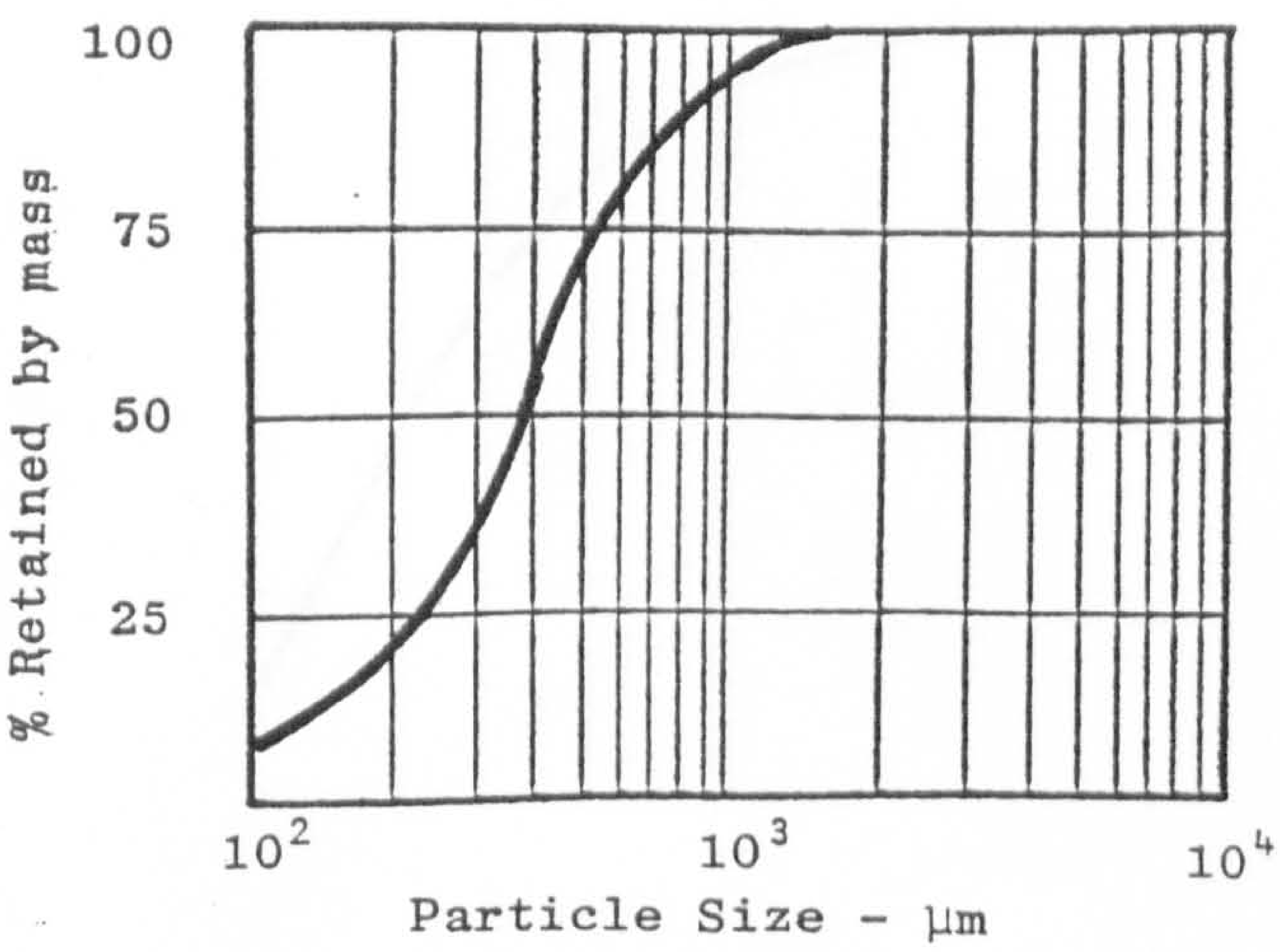


Fig. 6.23 *MICROGRAPH OF MAGNESIUM SULPHATE*

Fig. 6.24 *SIZE ANALYSIS OF MAGNESIUM SULPHATE*

Mean particle size:	224	μm
Mass median particle size:	390	μm
Particle size range (2.5%/97.5%):	100/1100	μm
Particle density:	2353	kg/m^3
Poured bulk density:	1010	kg/m^3
Tapped bulk density:	1305	kg/m^3
Compaction:	29	%
Permeability factor, C:	$6.3x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$17x10^{-3}$	m/s

MATERIAL No. 13 - PEARLITE

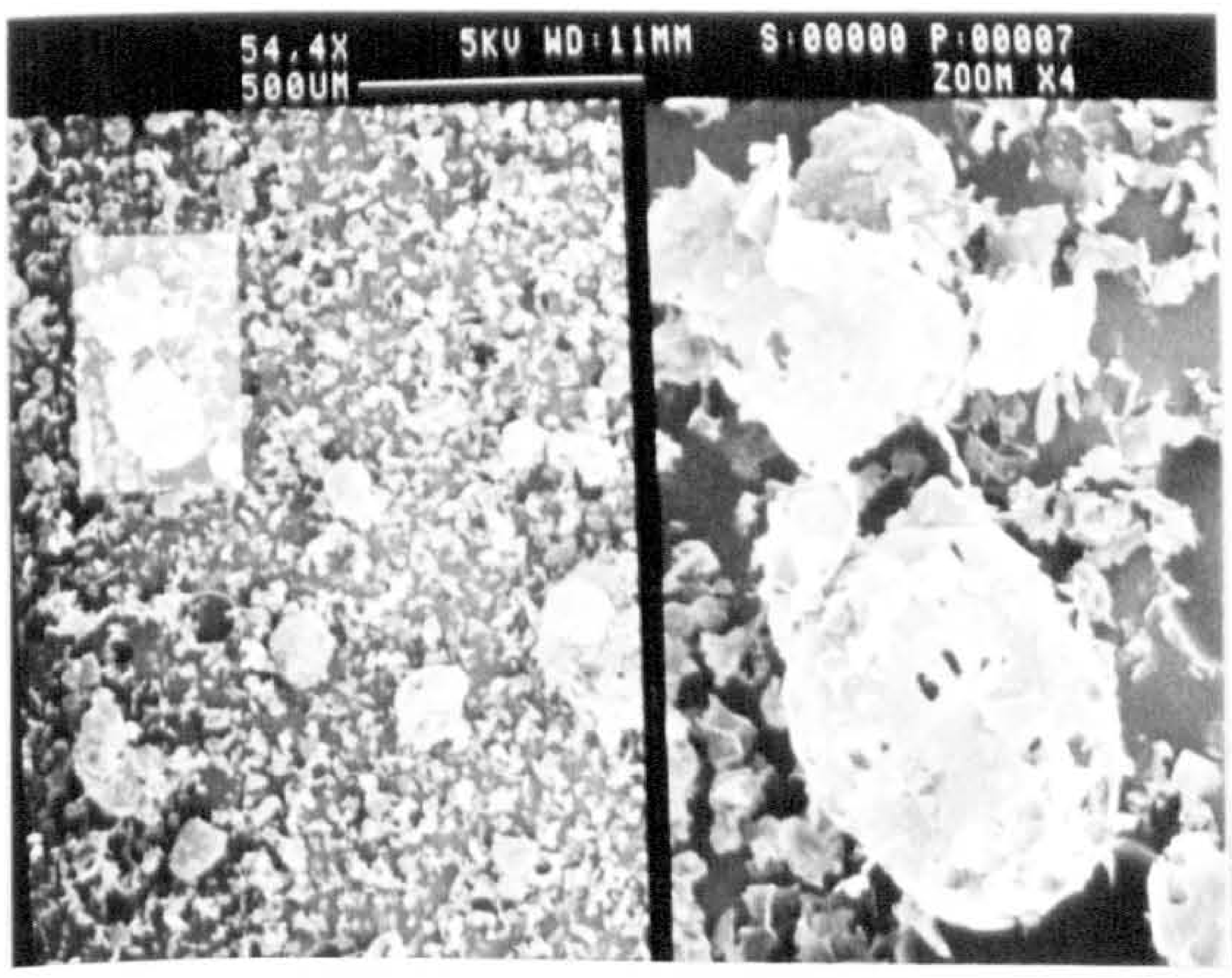


Fig. 6.25 MICROGRAPH OF PEARLITE

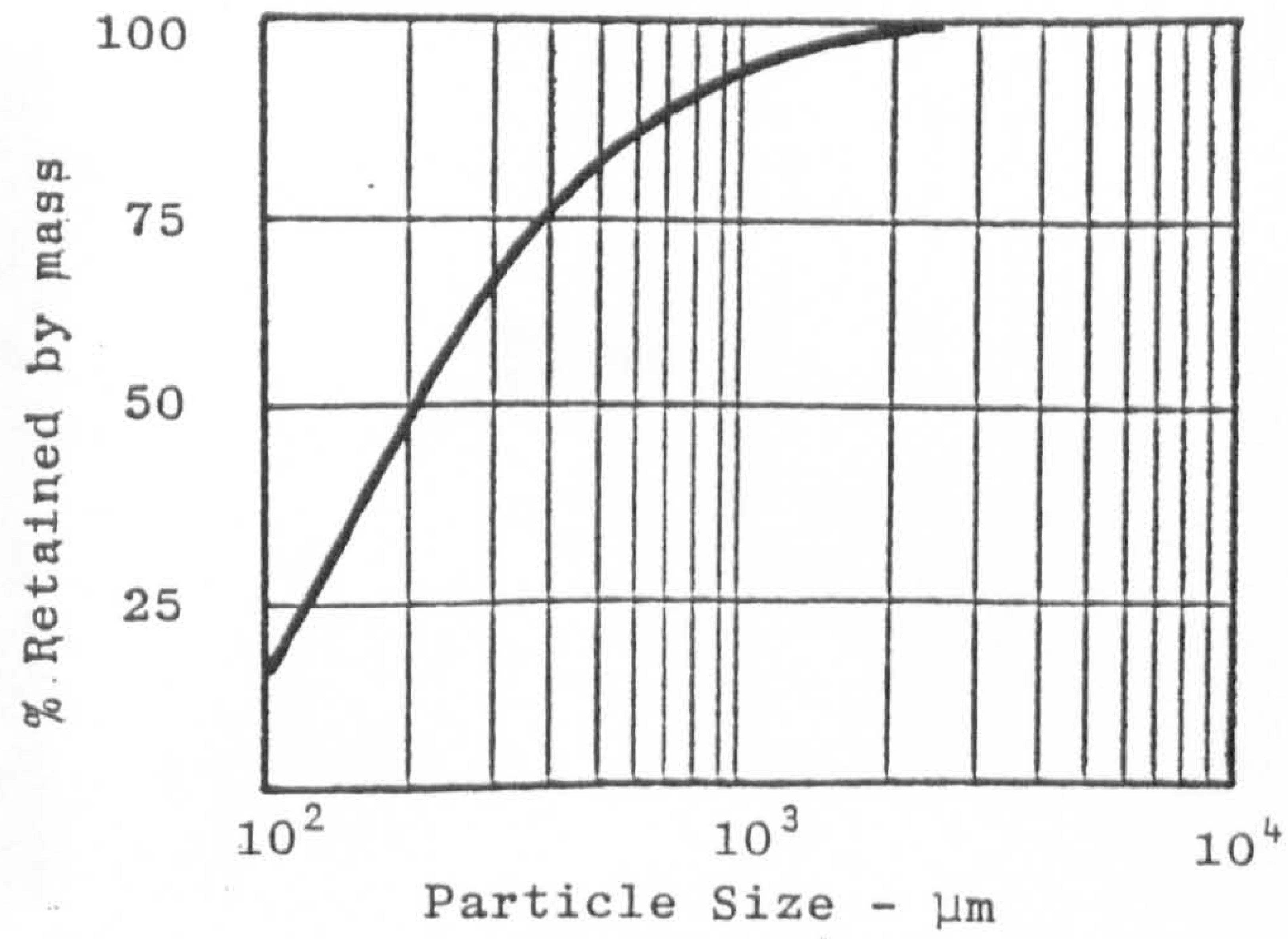


Fig. 6.26 SIZE ANALYSIS OF PEARLITE

Mean particle size:	158	μm
Mass median particle size:	200	μm
Particle size range (2.5%/97.5%):	50/900	μm
Particle density:	800	kg/m^3
Poured bulk density:	100	kg/m^3
Tapped bulk density:	130	kg/m^3
Compaction:	30	%
Permeability factor, C:	5.7×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v':	8.8×10^{-3}	m/s

Comments: Pearlite is particularly significant for its extremely low bulk density.

MATERIAL No. 14 - POLYETHYLENE PELLETS (BP Rigidex)

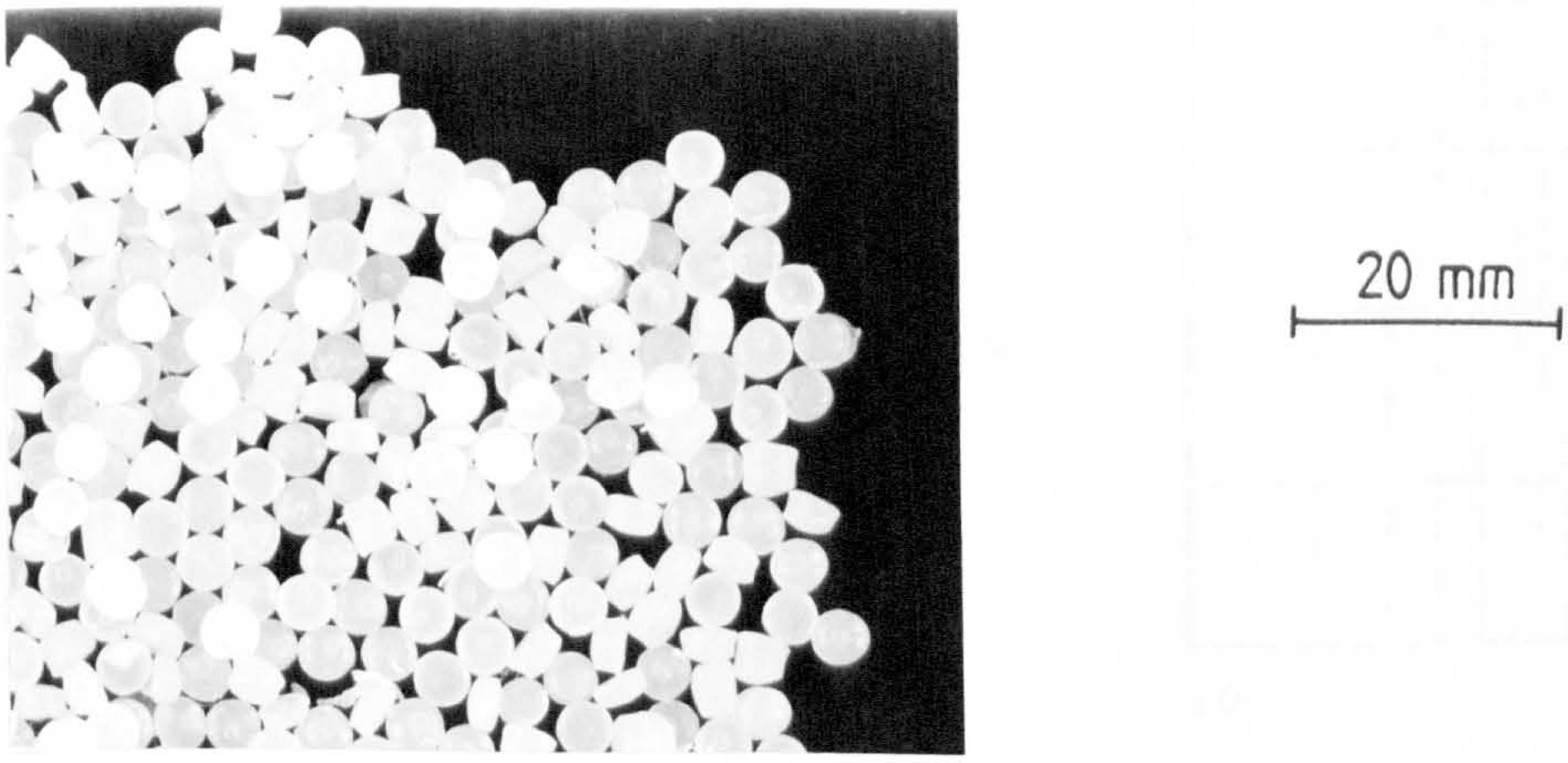


Fig. 6.27 PHOTOGRAPH OF POLYETHYLENE PELLETS

Mean particle size:	4000	μm
Mass median particle size:	4000	μm
Particle size range (2.5%/97.5%):	NIL	μm
Particle density:	912	kg/m^3
Poured bulk density:	540	kg/m^3
Tapped bulk density:	567	kg/m^3
Compaction:	5	%
Permeability factor, C:	420×10^{-6}	$m^3 s/kg$
Vibrated de-aeration constant, K_v':	60×10^{-3}	m/s

Comments: This product is composed of nearly monosized particles which are cylindrical in shape. 'Angel Hairs' can be formed when conveying this product by small slithers of plastic separating from the pellets during high velocity collision with the pipe walls.

MATERIAL No. 15 - POTASSIUM CHLORIDE

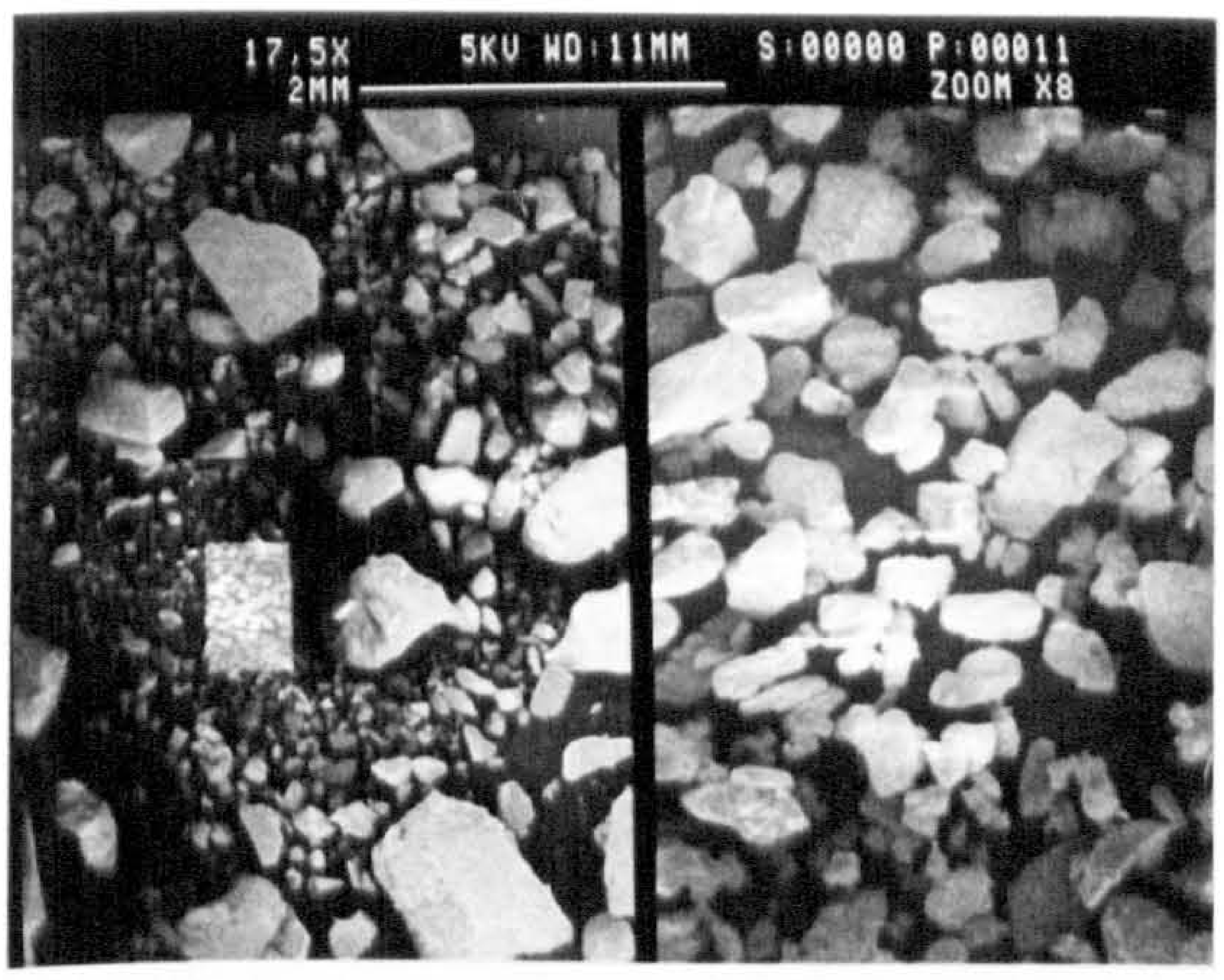


Fig. 6.28 MICROGRAPH OF POTASSIUM CHLORIDE

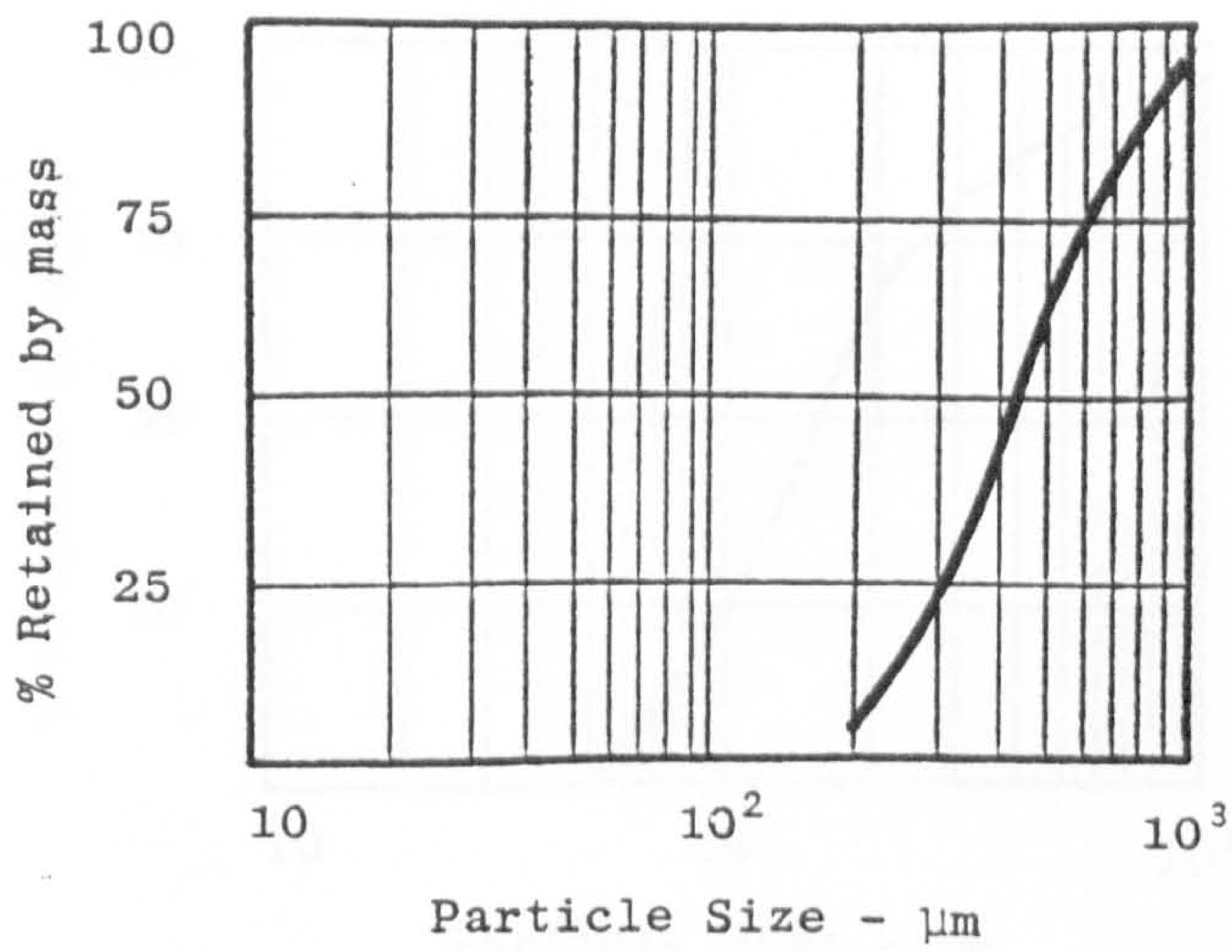


Fig. 6.29 SIZE ANALYSIS OF POTASSIUM CHLORIDE

Mean particle size:	*384*	*μm*
Mass median particle size:	*420*	*μm*
Particle size range (2.5%/97.5%):	*100/1100*	*μm*
Particle density:	*1987*	*kg/m^3*
Poured bulk density:	*1010*	*kg/m^3*
Tapped bulk density:	*1170*	*kg/m^3*
Compaction:	*16*	*%*
Permeability factor, C:	*$11x10^{-6}$*	*m^3s/kg*
Vibrated de-aeration constant, K_v':	*$26x10^{-3}$*	*m/s*

MATERIAL No. 16 - POTASSIUM SULPHATE

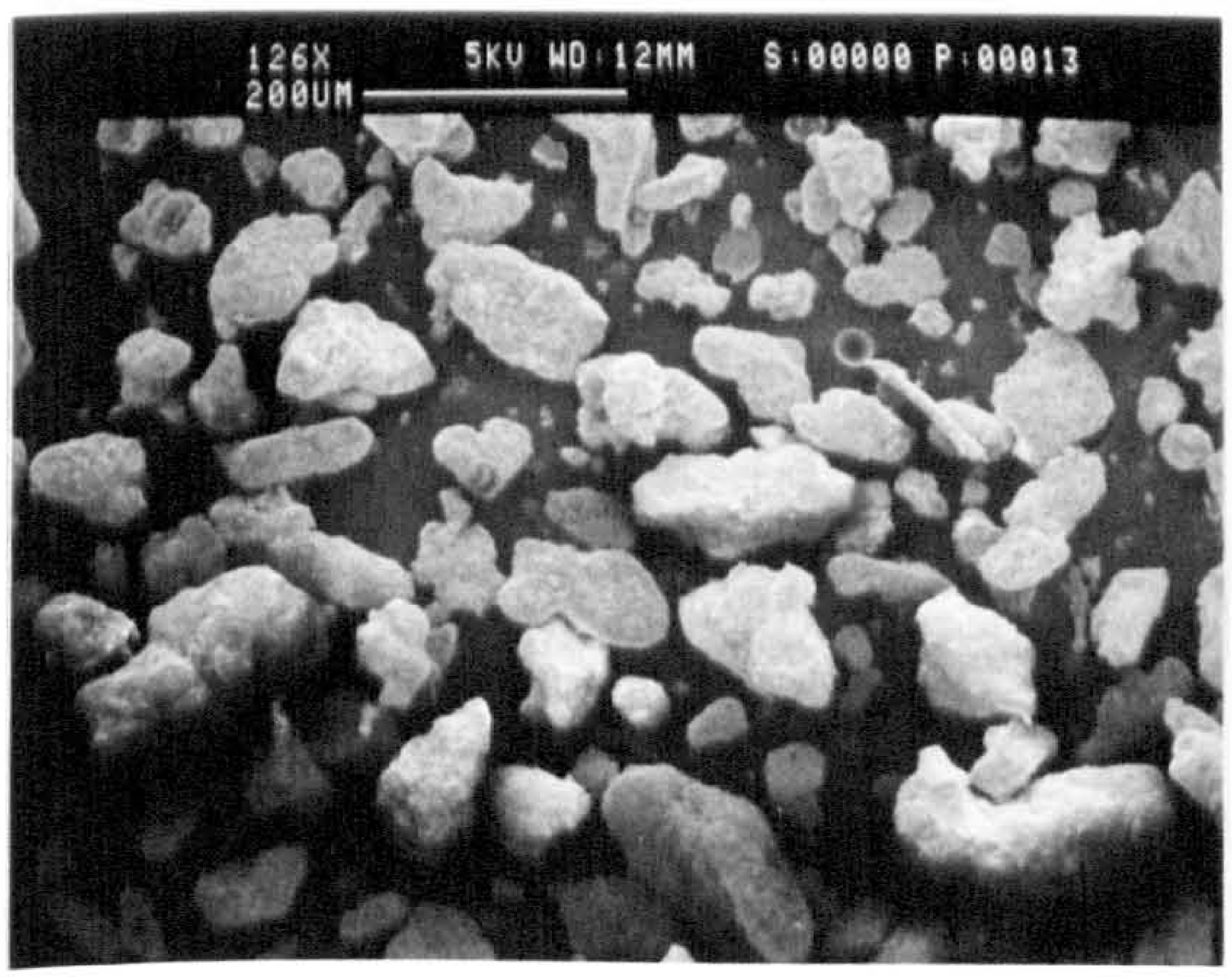


Fig. 6.30 MICROGRAPH OF POTASSIUM SULPHATE

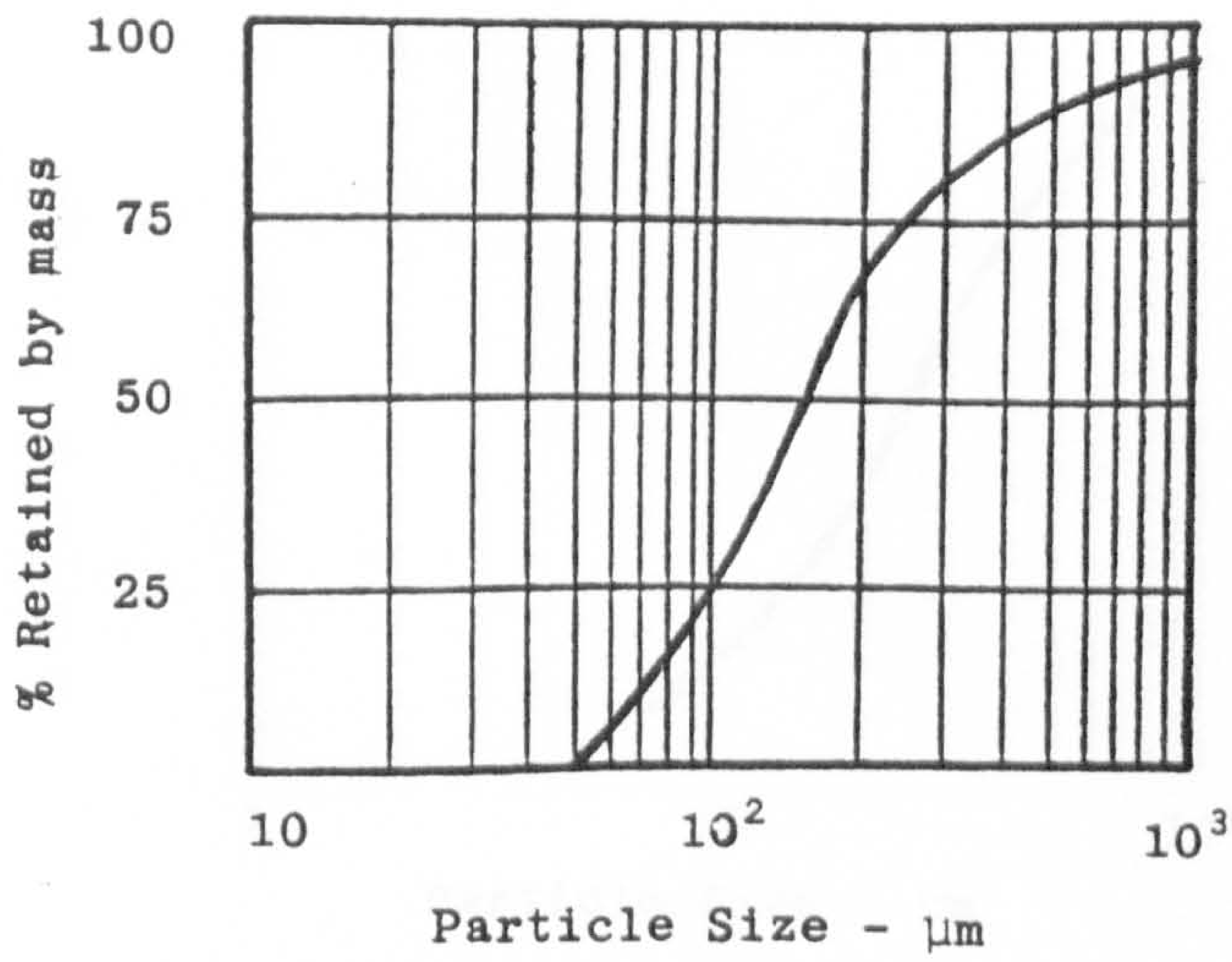


Fig. 6.31 SIZE ANALYSIS OF POTASSIUM SULPHATE

Mean particle size:	131	µm
Mass median particle size:	150	µm
Particle size range (2.5%/97.5%):	45/2400	µm
Particle density:	2625	kg/m^3
Poured bulk density:	1260	kg/m^3
Tapped bulk density:	1480	kg/m^3
Compaction:	17	%
Permeability factor, C:	0.99×10^{-6}	$m^3 s/kg$
Vibrated de-aeration constant, K_v':	18×10^{-3}	m/s

MATERIAL No. 17 - PULVERISED FUEL ASH (p.f.a.)

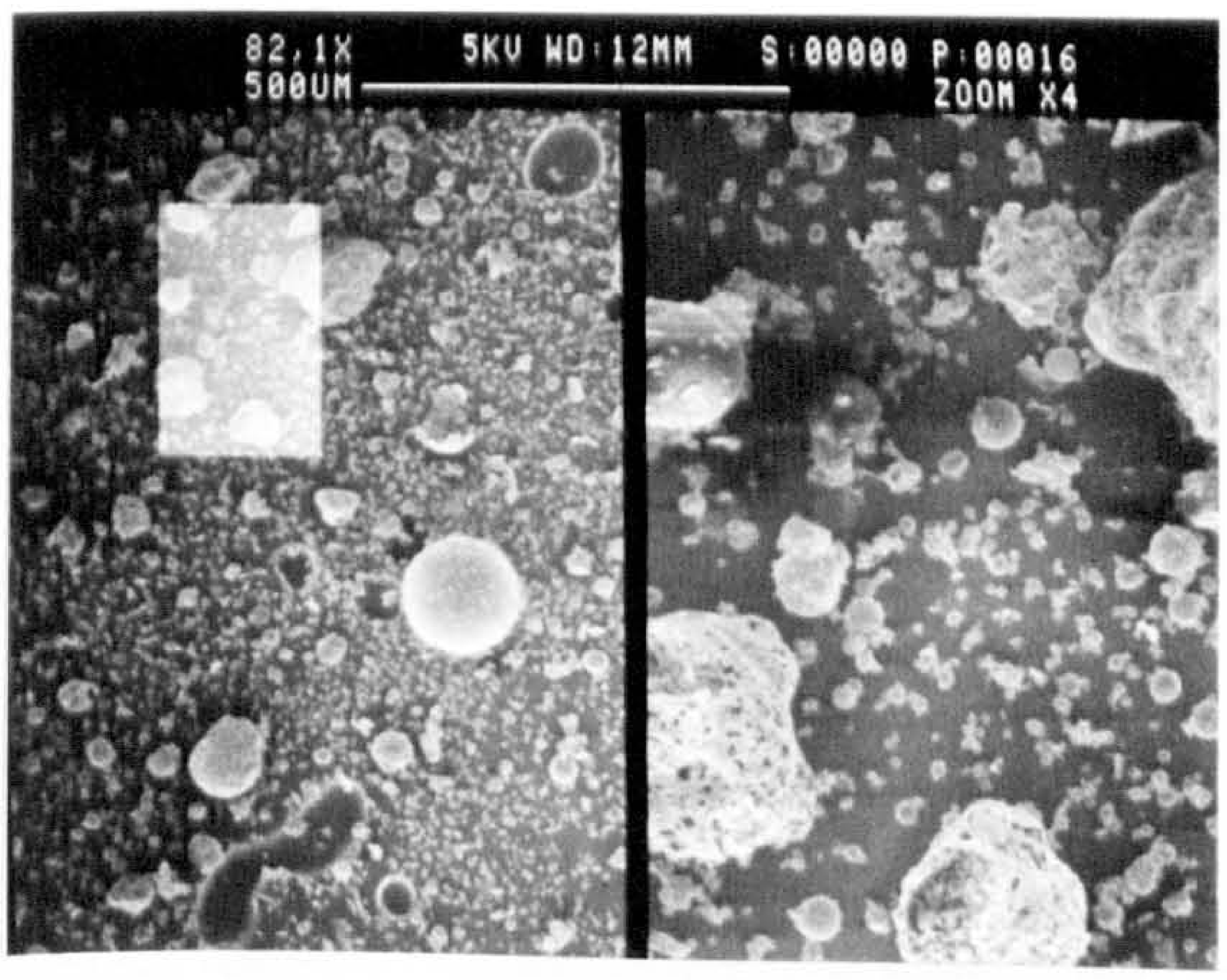


Fig. 6.32 MICROGRAPH OF PULVERISED FUEL ASH

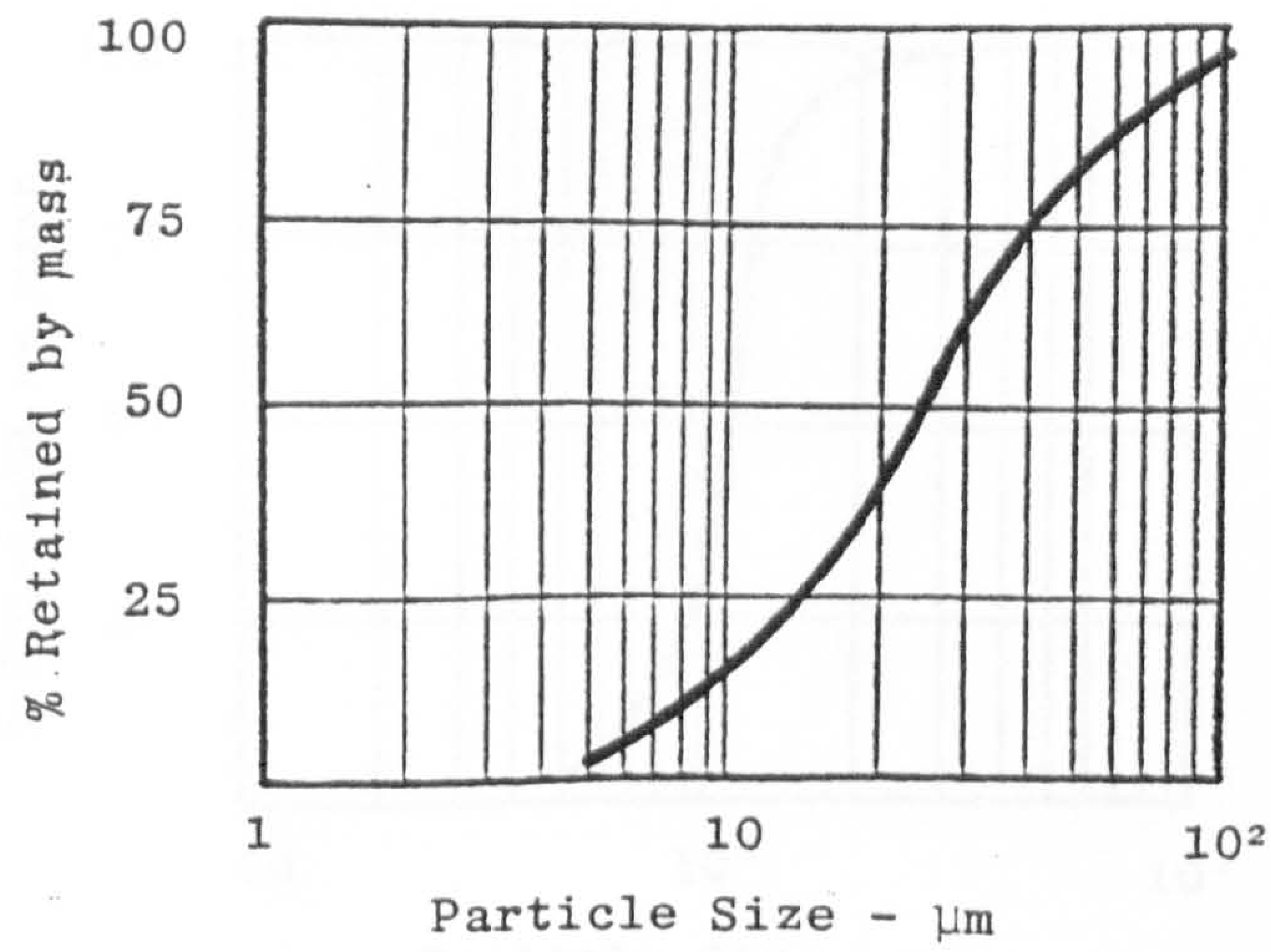


Fig. 6.33 SIZE ANALYSIS OF PULVERISED FUEL ASH

Mean particle size:	25	μm
Mass median particle size:	23	μm
Particle size range (2.5%/97.5%):	5/120	μm
Particle density:	2446	kg/m^3
Poured bulk density:	979	kg/m^3
Tapped bulk density:	1456	kg/m^3
Compaction:	49	%
Permeability factor, C:	$0.6x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$2.0x10^{-3}$	m/s

MATERIAL No. 18 - PVC POWDER

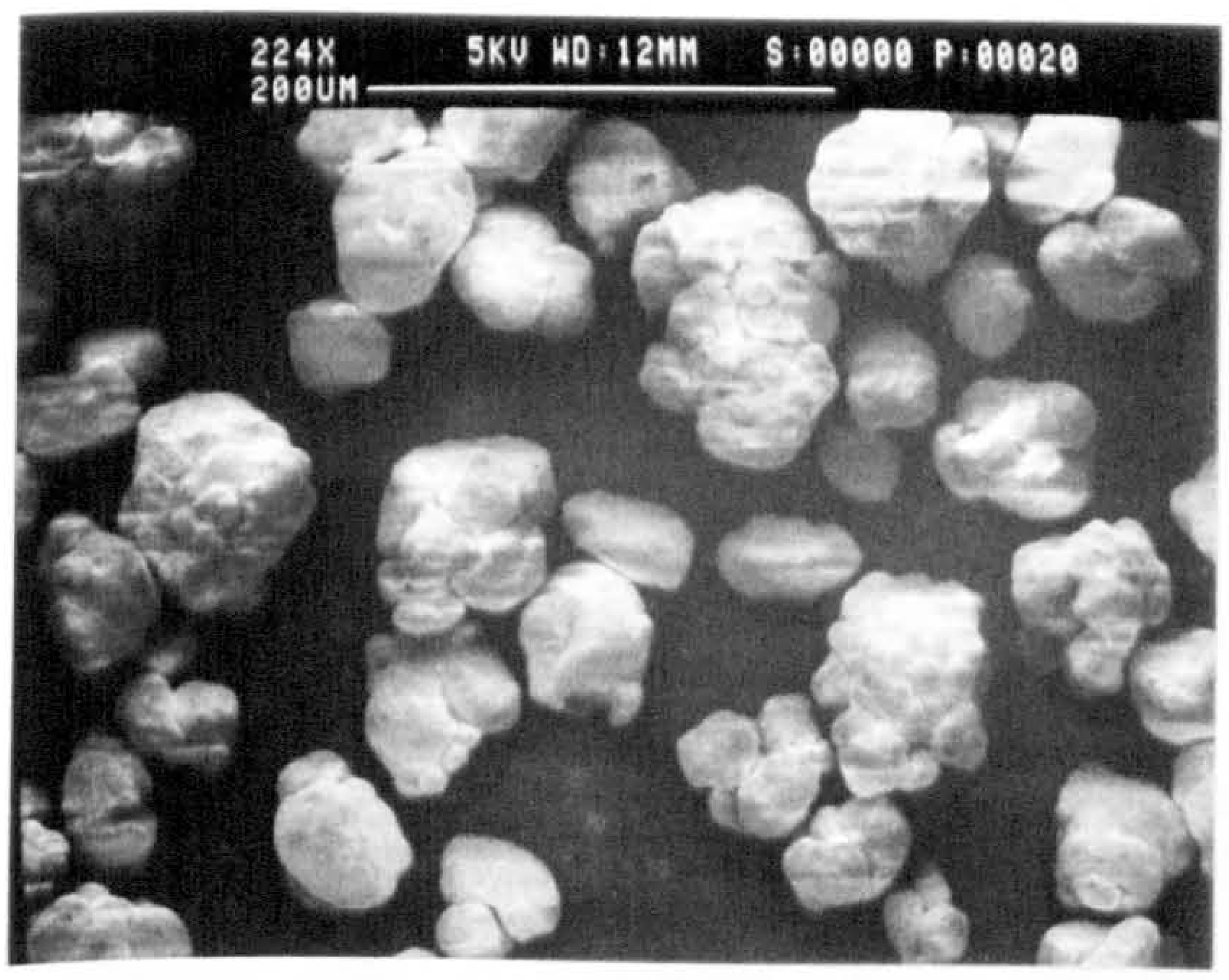


Fig. 6.34 MICROGRAPH OF PVC POWDER

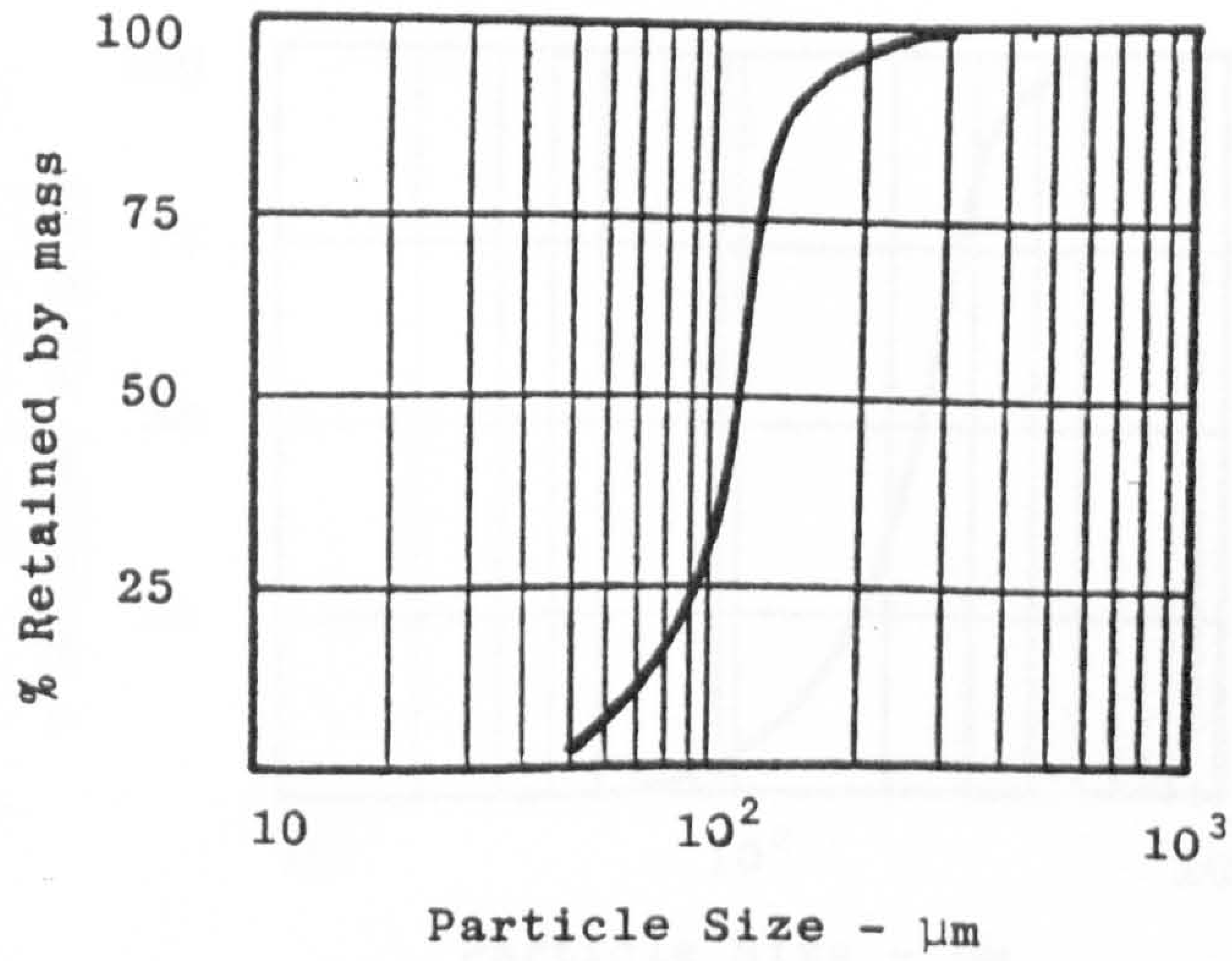


Fig. 6.35 SIZE ANALYSIS OF PVC POWDER

Mean particle size:	90	μm
Mass median particle size:	108	μm
Particle size range (2.5%/97.5%):	52/180	μm
Particle density:	990	kg/m^3
Poured bulk density:	615	kg/m^3
Tapped bulk density:	751	kg/m^3
Compaction:	22	%
Permeability factor, C:	$1.2x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$8x10^{-3}$	m/s

MATERIAL No. 19 - SILICA SAND

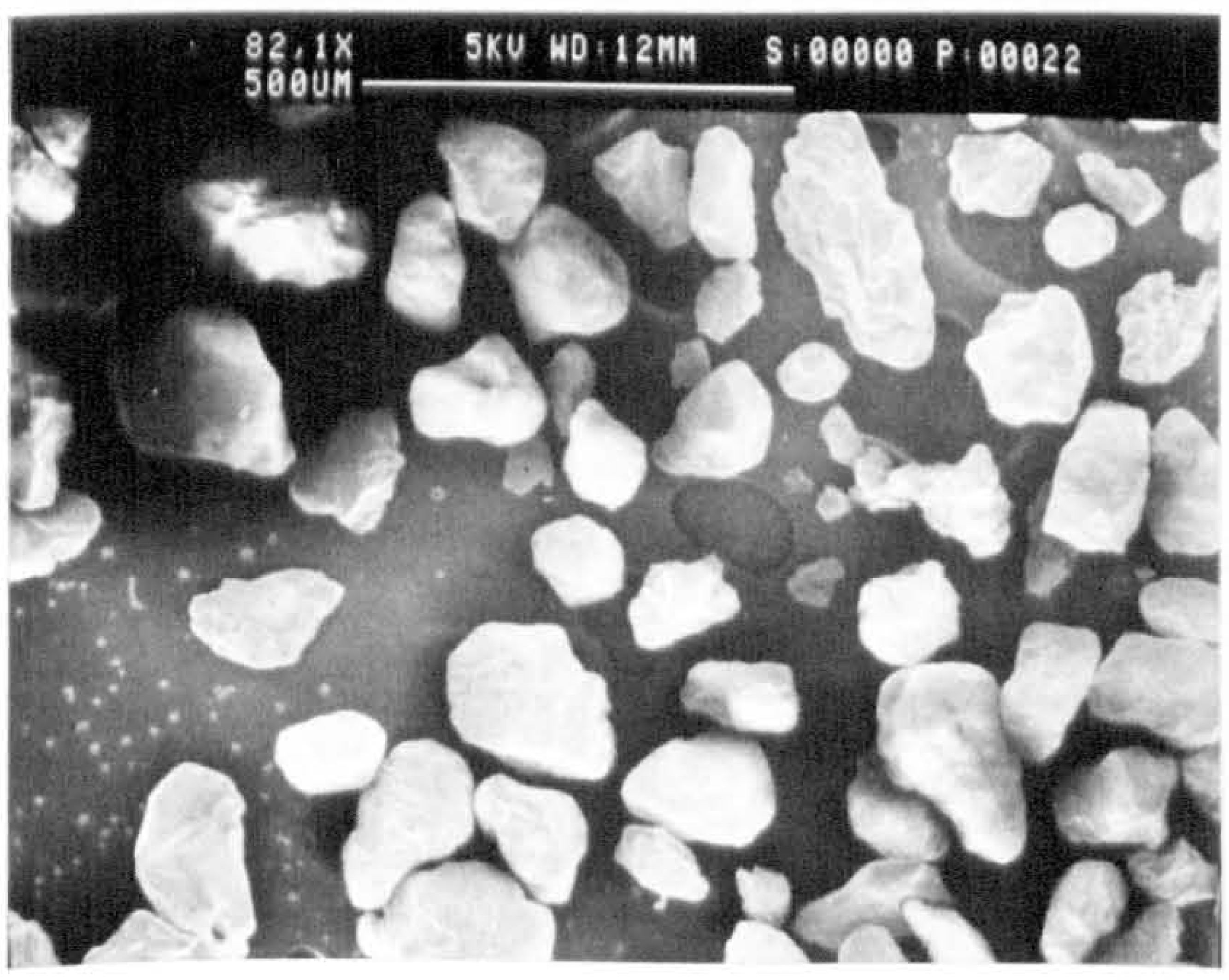


Fig. 6.36 MICROGRAPH OF SILICA SAND

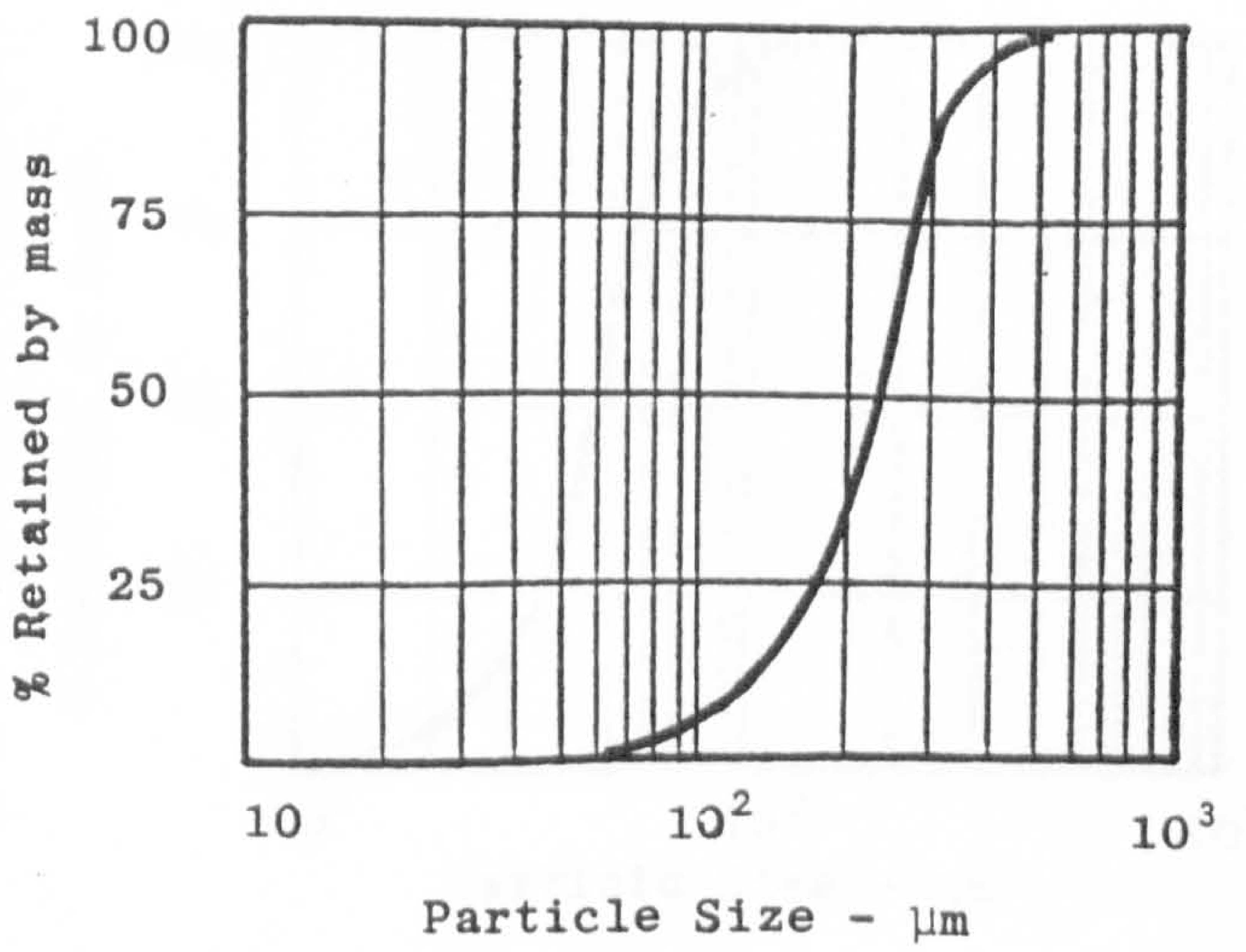


Fig. 6.37 SIZE ANALYSIS OF SILICA SAND

Mean particle size:	*174*	*µm*
Mass median particle size:	*220*	*µm*
Particle size range (2.5%/97.5%):	*105/420*	*µm*
Particle density:	*2630*	*kg/m^3*
Poured bulk density:	*1450*	*kg/m^3*
Tapped bulk density:	*1619*	*kg/m^3*
Compaction:	*12*	*%*
Permeability factor, C:	*$3.9x10^{-6}$*	*m^{3}s/kg*
Vibrated de-aeration constant, K_v':	*$34x10^{-3}$*	*m/s*

MATERIAL No. 20 - GRANULATED SUGAR (As Supplied)

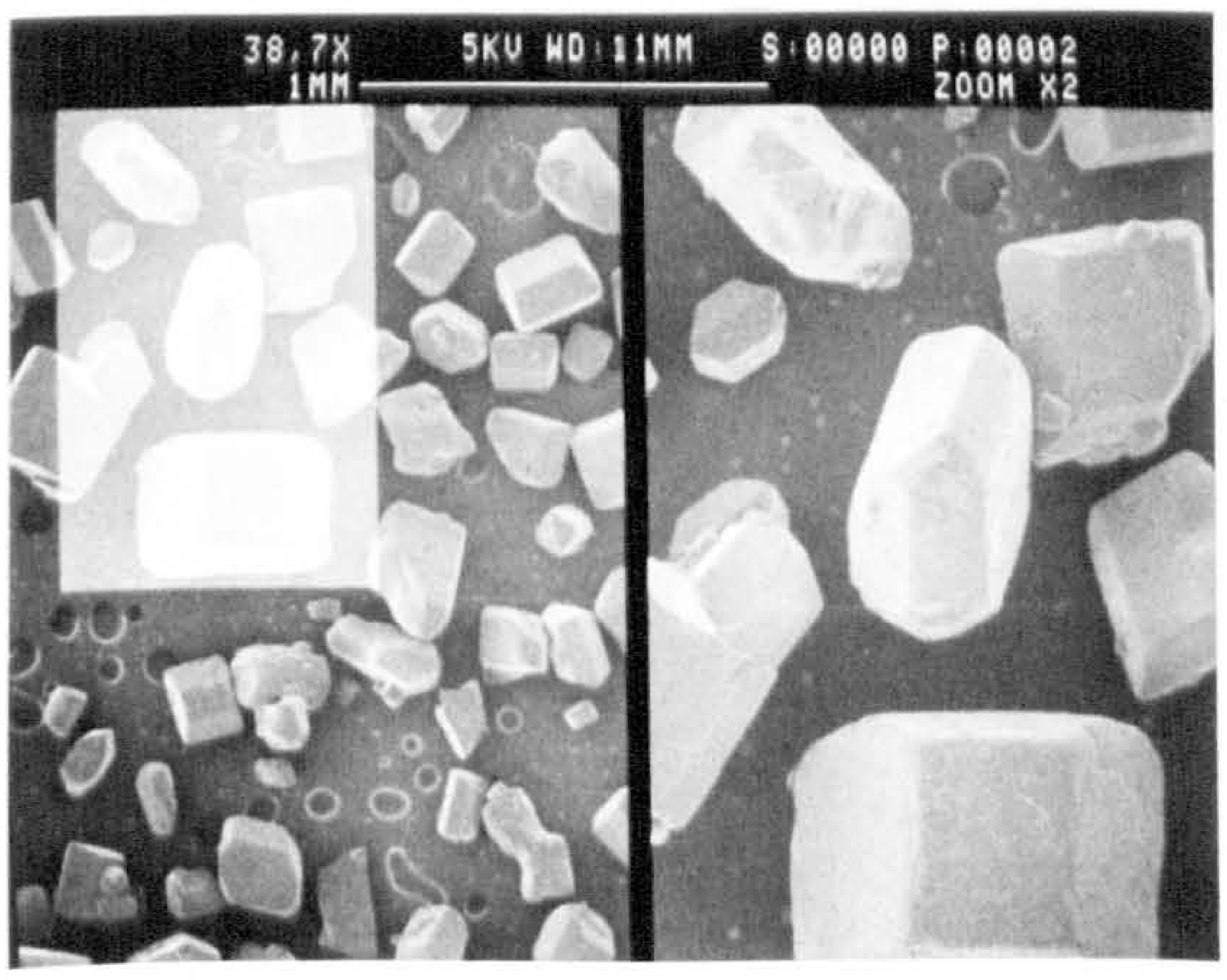


Fig. 6.38 *MICROGRAPH OF GRANULATED SUGAR*

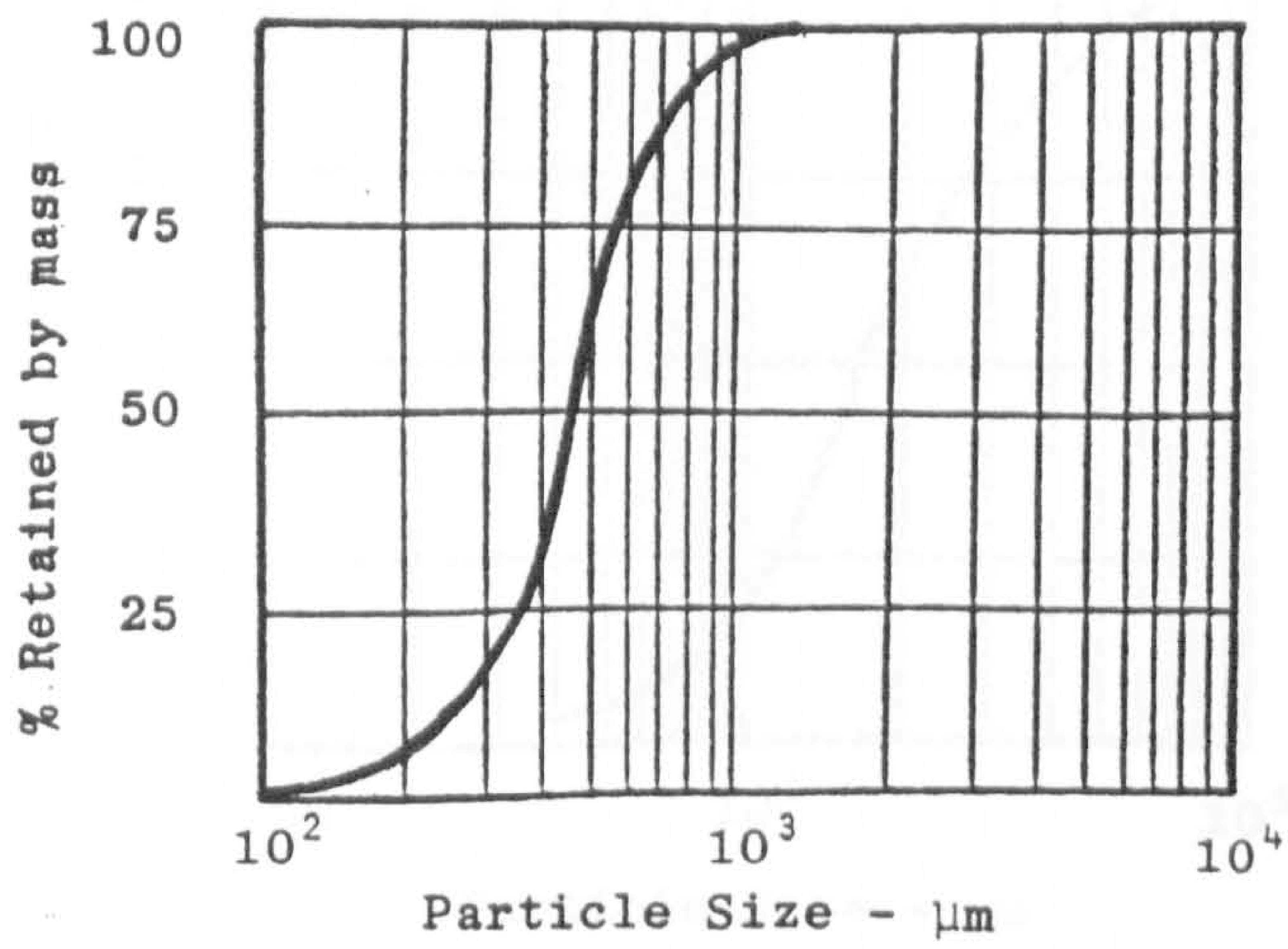


Fig. 6.39 *SIZE ANALYSIS OF GRANULATED SUGAR*

Mean particle size:	*458*	*µm*
Mass median particle size:	*460*	*µm*
Particle size range (2.5%/97.5%):	*210/750*	*µm*
Particle density:	*1580*	kg/m^3
Poured bulk density:	*890*	kg/m^3
Tapped bulk density:	*980*	kg/m^3
Compaction:	*10*	*%*
Permeability factor, C:	$20x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$13x10^{-3}$	*m/s*

MATERIAL No. 21 - GRANULATED SUGAR (Degraded)

Fig. 6.40 MICROGRAPH OF DEGRADED SUGAR

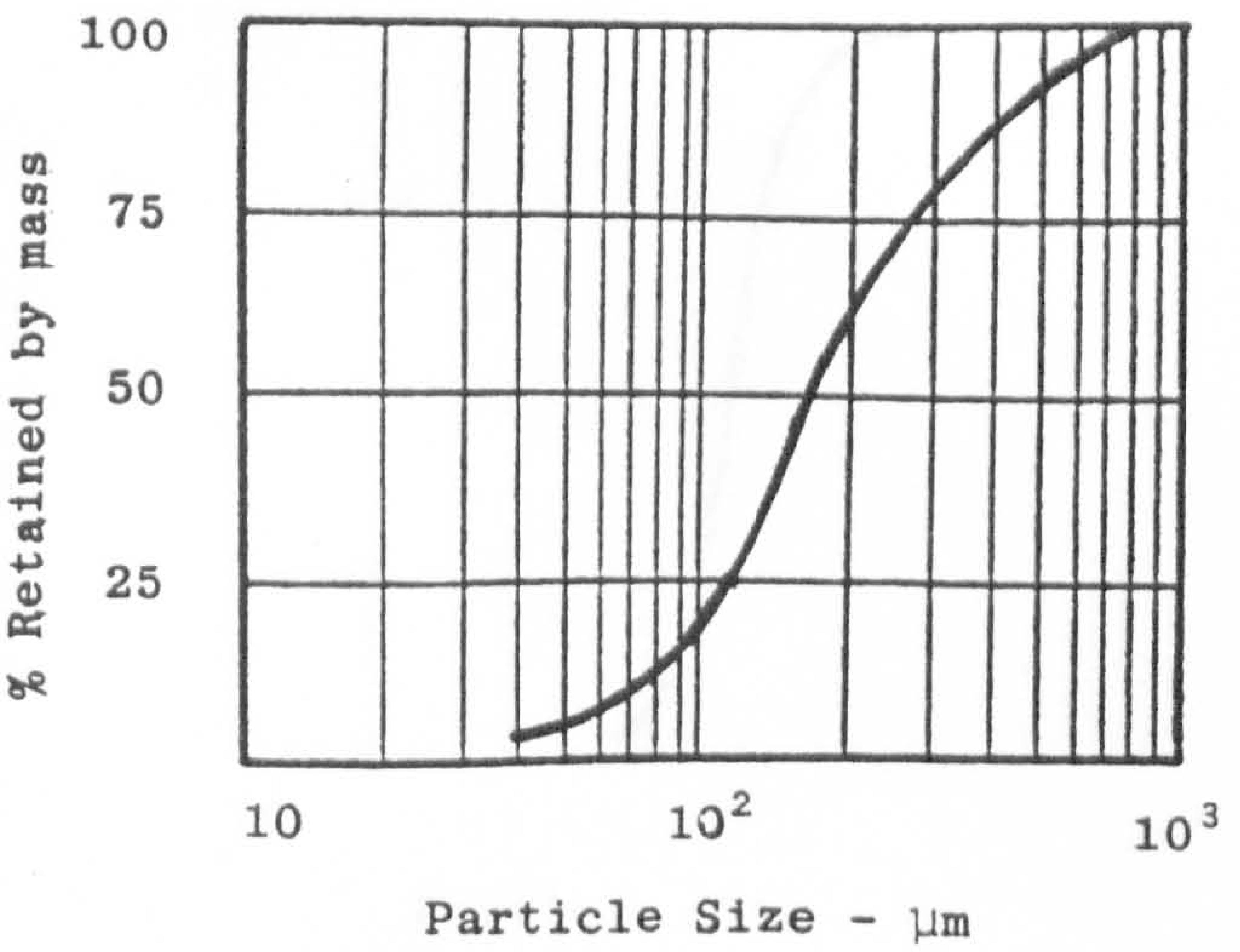
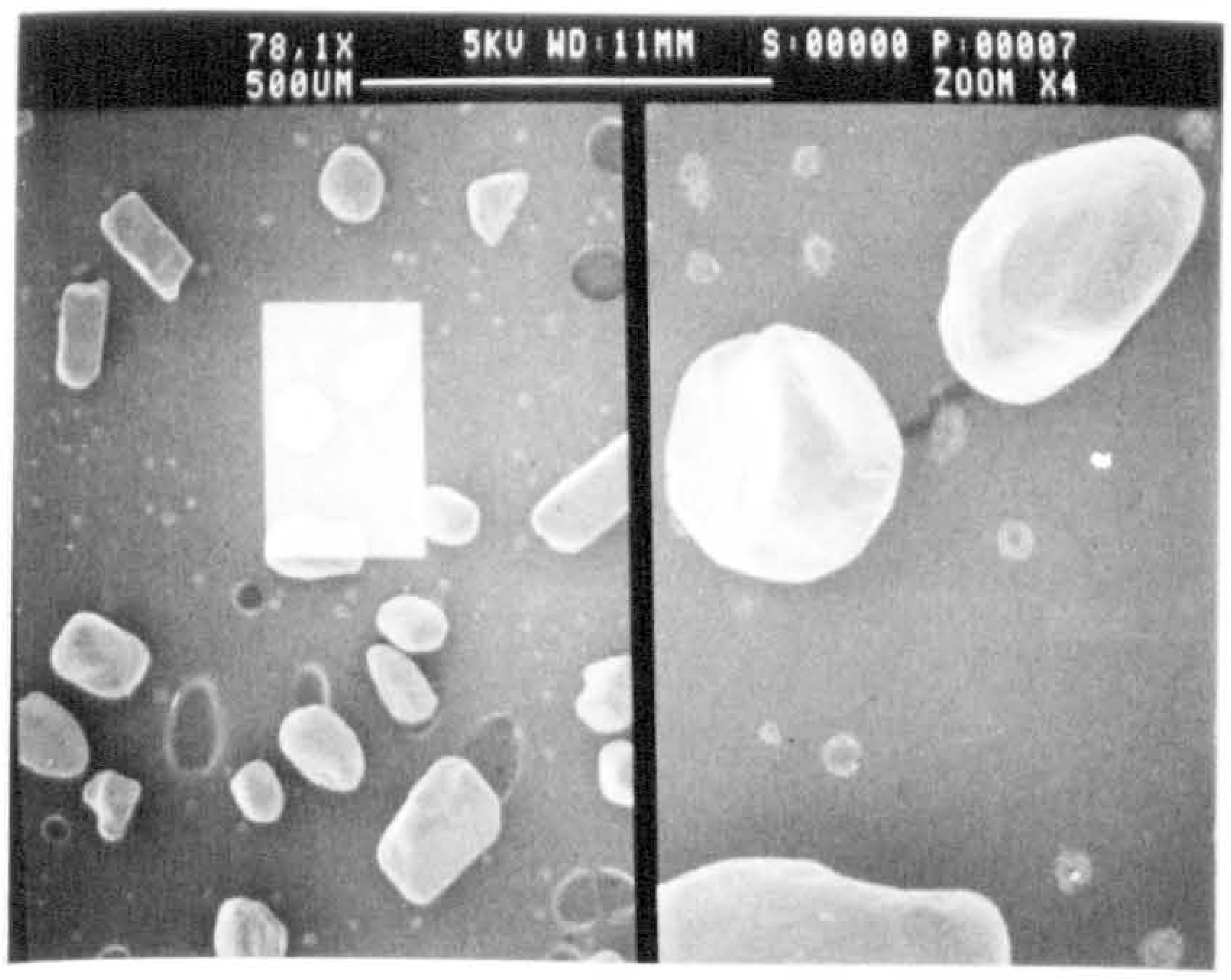


Fig. 6.41 SIZE ANALYSIS OF DEGRADED SUGAR

Mean particle size:	157	μm
Mass median particle size:	170	μm
Particle size range (2.5%/97.5%):	55/540	μm
Particle density:	1580	kg/m^3
Poured bulk density:	656	kg/m^3
Tapped bulk density:	935	kg/m^3
Compaction:	43	%
Permeability factor, C:	$1.4x10^{-6}$	m^3s/kg
Vibrated de-aeration constant, K_v':	$8.3x10^{-3}$	m/s

MATERIAL No. 22 - ZIRCON SAND



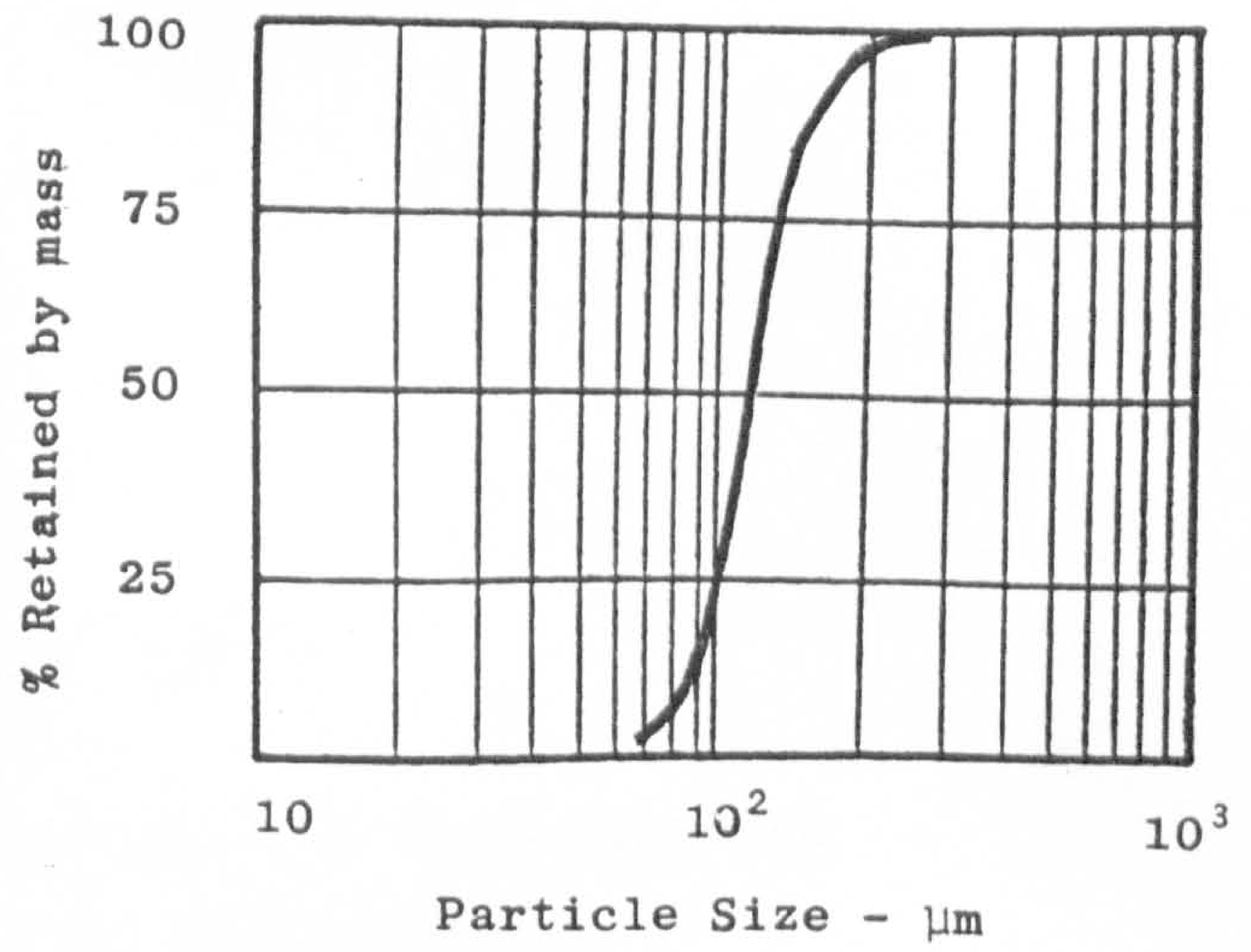


Fig. 6.42 MICROGRAPH OF ZIRCON SAND

Fig. 6.43 SIZE ANALYSIS OF ZIRCON SAND

Mean particle size:	*120*	*µm*
Mass median particle size:	*115*	*µm*
Particle size range (2.5%/97.5%):	*75/185*	*µm*
Particle density:	*4600*	kg/m^3
Poured bulk density:	*2600*	kg/m^3
Tapped bulk density:	*3000*	kg/m^3
Compaction:	*15*	*%*
Permeability factor, C:	1.3×10^{-6}	m^3s/kg
Vibrated de-aeration constant, K_v'*:*	10×10^{-3}	m/s

CHAPTER 7

THE CORRELATION BETWEEN PRODUCT CHARACTERISTICS AND CONVEYING PERFORMANCE

The following number codes have been used throughout this Chapter.

KEY TO PRODUCTS

1. *Agricultural Catalyst*
2. *Agricultural Catalyst (degraded)*
3. *Alumina*
4. *Barytes*
5. *Cement*
6. *Coal (as supplied)*
7. *Coal (degraded)*
8. *Coal (pulverised fuel)*
9. *Copper Ore*
10. *Flour*
11. *Iron Powder*
12. *Magnesiun Sulphate*
13. *Pearlite*
14. *Polyethylene Pellets*
15. *Potassium Chloride*
16. *Potassium Sulphate*
17. *Pulverised Fuel Ash*
18. *PVC Powder*
19. *Silica Sand*
20. *Granulated Sugar*
21. *Sugar (degraded)*
22. *Zircon Sand*
23. *Coarse Sand*
24. *Mustard Seed*

KEY TO SYMBOLS

◊ *Conveying limit established*

○ *Conveying limit NOT established*

□ *Data taken from other workers*

Chapter 7 The Correlation Between Product Characteristics and Conveying Performance

7.1 INTRODUCTION

A brief look at the conveying characteristics for the materials tested in appendix 2 shows the wide range of conveying performance which can be obtained for different types of product. In a conventional system not all products can be conveyed in dense phase. In addition, it is often not clear why a product will not convey in dense phase. A problem for users and manufacturers of pneumatic conveyors alike is identifying which products have dense phase capability and if they do, what mode of conveying is most suitable. An undeniable feature of pneumatic conveying is that the process relies on the interaction between the product and the conveying gas (normally air).

The importance of product properties on pneumatic conveying performance, in particular those properties which involve product/air interaction, has been appreciated by many workers in a qualitative manner. Dixon (Ref. 7.1), amongst others, realised the importance of product type on the mode of conveying and used the Geldart Classification for fluidisation behaviour (Ref. 7.2) as a basis for determining the most likely conveying mode for a given product. This classification is known as the slugging diagram and can be seen in fig. 7.1. The position of a product on the chart is dependent on the density difference between the product and the conveying fluid (usually air), and the mean particle size.

Other workers have used the Geldart Classification (fig. 7.2) as a basis for predicting conveyability and likely conveying mode. However, most of the published work is restricted to comments indicating that the Geldart Classification gives some indication of likely conveyability.

The conveying trials (Chapter 4) produced a considerable amount of valuable data which was used to check the reliability and validity of previous suggestions. In addition, the bulk product characteristics have been thoroughly researched, particularly those relating to product/air interactions (Chapter 5). This bank of data has allowed an alternative phase diagram to be proposed based on product properties which involve

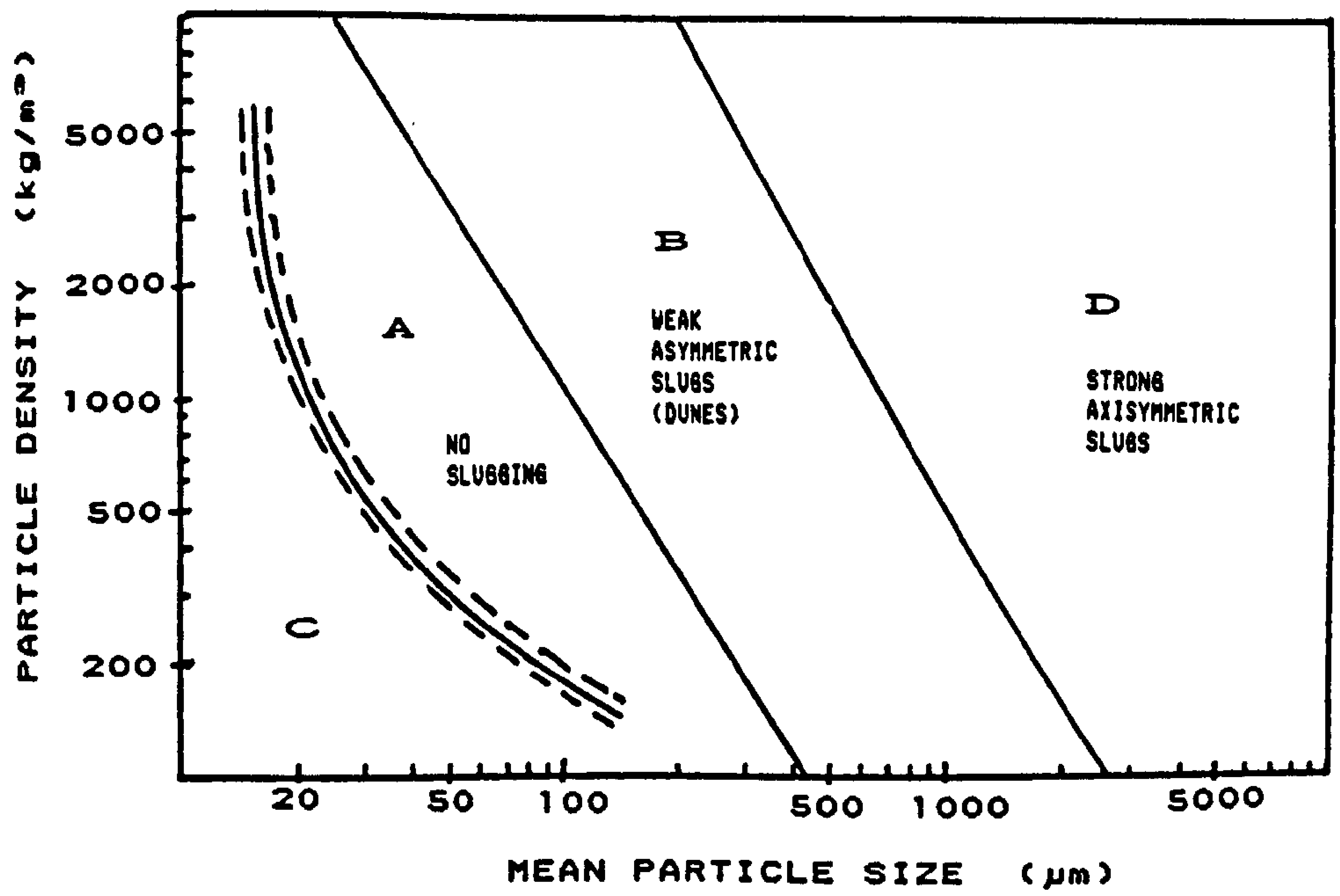


FIG. 7.1 THE DIXON SLUGGING DIAGRAM

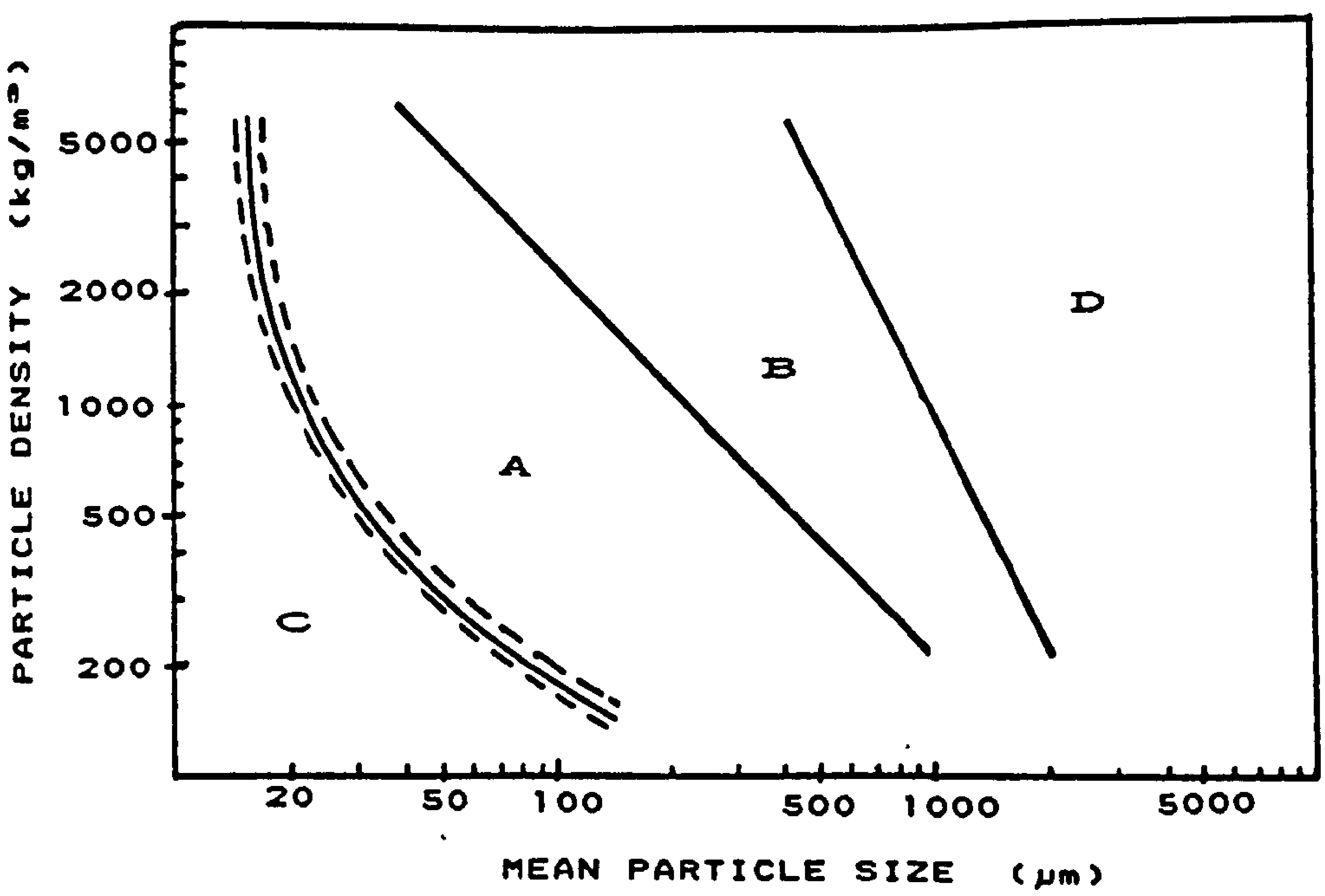


FIG. 7.2 THE GELDART CLASSIFICATION

product/air interaction. These properties are believed by the author to be more representative of the product and of greater importance to conveyability.

Having established an alternative phase diagram to classify the products according to their likely conveying mode, the author has proposed a further correlation between product throughput and the air retention characteristics of the product. This allows prediction of the likely performance level of a product in a pneumatic conveying pipeline and is therefore a powerful tool for system design.

The phase diagram together with the mass throughput correlation provide a method of predicting, not only the conveyability of a product as is the case with other proposed phase diagrams, but also a first indication of actual product throughput for a range of pipeline configurations.

7.2 THE GELDART AND DIXON CLASSIFICATIONS OF THE TEST MATERIALS

Both the Dixon Slugging Diagram and the Geldart Classification are divided up into four areas A,B,C & D. It is suggested that these four areas group together products with similar flow capability. Therefore the position a product occupies on the diagram will give some indication of the potential conveyability and mode of flow.

Dixon (Ref. 7.1) suggests that group A products are considered to be the best candidates for dense phase conveying. They can be conveyed at high phase densities but are not natural 'sluggers'. In otherwords, group A powders are most suited to the moving bed type flow regime. Figure 7.3 shows the position of the products tested during this programme of work on the slugging diagram. The products pulverised fuel ash and PVC powder lie in group A. This is quite consistent with the results of the conveying trials. Both products displayed good dense phase flow characteristics in a moving bed type flow regime. In addition, these products were conveyed at high phase densities. However, the products pulverised coal and flour exhibited equally good conveying performance

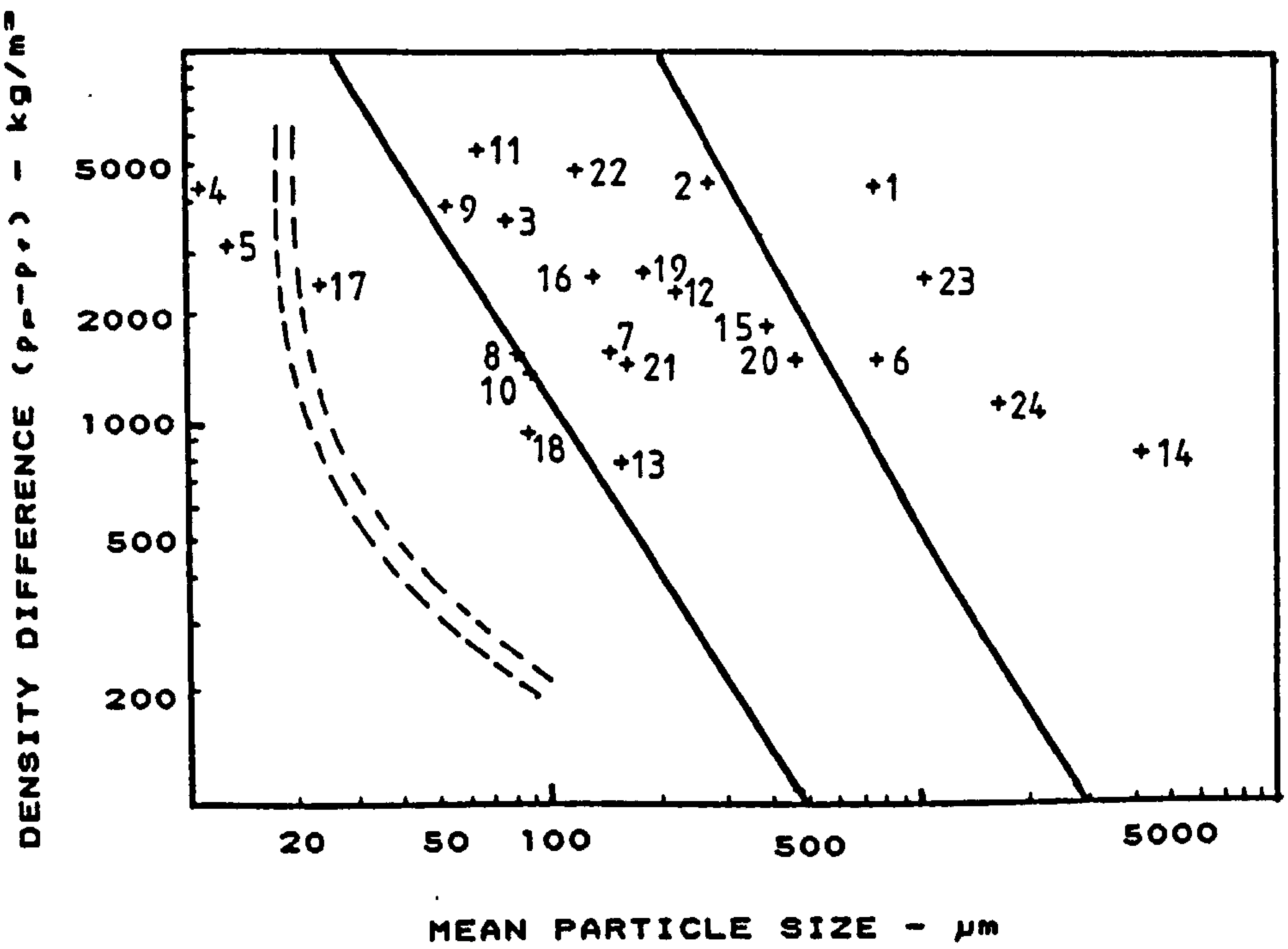


FIG. 7.3 THE DIXON SLUGGING DIAGRAM WITH PRODUCT DATA SUPERIMPOSED

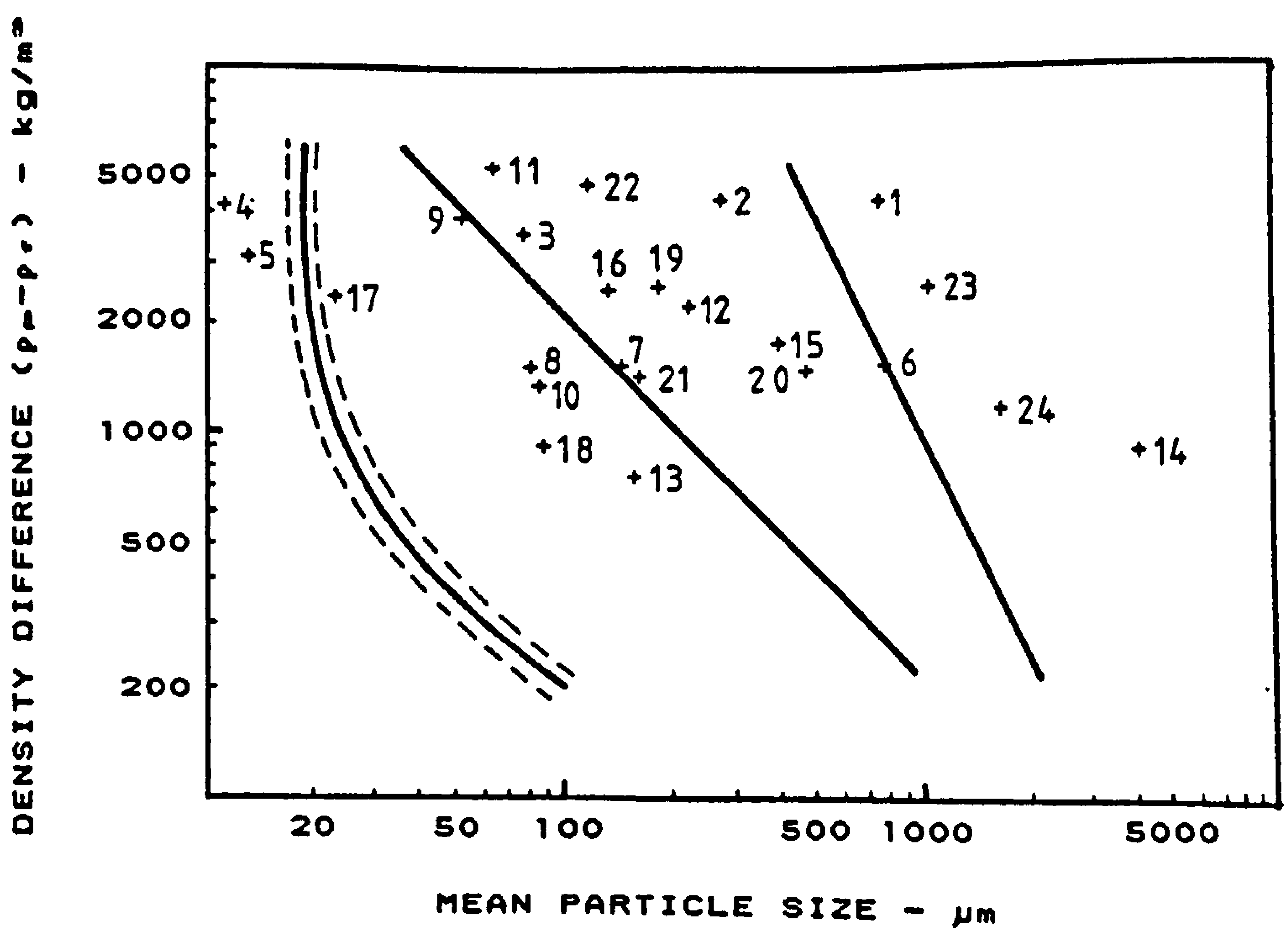


FIG. 7.4 THE GELDART CLASSIFICATION WITH PRODUCT DATA SUPERIMPOSED

and yet these products are positioned on the border between groups A and B. In the case of flour, its conveying performance was significantly better than that of the PVC powder. Other products which were tested during the conveying trials also exhibited good moving bed type flow characteristics. Copper ore, iron powder and pearlite were also conveyed in moving bed type flow at reduced velocities and high phase densities. These three products are designated group B products according to the Slugging Diagram. On the Geldart Classification, pearlite, pulverised coal, flour and copper ore all appear in group A, however, the iron powder falls into group B.

Barytes and cement are examples of products that exhibit extremely good dense phase capability in a moving bed type flow regime at high phase densities and yet are designated group C products by both classifications. To a lesser extent, the degraded forms of the agricultural catalyst and degraded sugar are also capable of lower velocity moving bed type flow but not at such high phase densities. Both of these products are designated group B products.

Group B products are considered to be troublesome for lower velocity, high phase density conveying. Dixon suggests that techniques developed by vendors (i.e. innovative systems) can overcome the natural disadvantages of these products. The implication here is that products within group B are unlikely to convey in dense phase in a conventional system. This is supported, in general, by the results of the conveying trials. The majority of products falling within group B on the slugging diagram would only convey in a dilute phase flow regime in a conventional system.

The products which fall into group B on the Slugging Diagram are alumina, degraded coal, magnesium sulphate, potassium chloride, potassium sulphate, silica sand, granulated sugar and zircon sand. None of these products were capable of dense phase conveying with pipeline blockages occurring around saltation velocity. However, in addition to the products already mentioned, copper ore, iron powder, pearlite, degraded catalyst and degraded sugar also fall within group B all of which are capable of dense phase moving bed type flow.

On the Geldart Classification, the boundary between groups A and B is positioned differently from that on the Slugging Diagram. This comes about due to a completely different method of defining the group boundaries. However, the only difference in the grouping of the test materials, due to the change of boundary, is that pearlite and copper ore appear in group A on the Geldart Classification and in group B on the Slugging Diagram.

Group D products are considered by Dixon and other workers to be natural 'sluggers'. Dixon describes the typical flow of group D products to be in the form of 'strong axisymmetric slugs'. Typically this type of flow will have a lower phase density than the moving bed type flow but can be sustained at lower velocities.

During this programme of work, only polyethylene pellets were observed to convey in a plug type flow regime. However, results from another worker, Mainwaring (ref.7.3), have been used together with polyethylene pellets to provide three group D products. The additional products were mustard seed and a coarse grade of silica sand. However, in addition to these products, the agricultural catalyst and the coal appear as group D products on the Slugging Diagram. These products have no dense phase capability in a conventional system and would, therefore, be better described by group B type behaviour. The coal had a particularly wide size distribution and tends to highlight the problem of grouping products on the basis of a single representative size. On the Geldart classification, the coal is positioned on the boundary between groups B and D.

The fourth area on both the Geldart Classification and the Slugging Diagram is group C. Group C powders are reported by Dixon to be arguably the worst candidates for dense phase conveying. This is attributed to their poor fluidising characteristics. It is suggested that group C products exhibiting group A like fluidising properties would be more likely to convey in dense phase. Barytes and cement both fell into the group C category. It would be incorrect to suggest that barytes and cement are easily fluidised, infact it is difficult to introduce air into these products. However, once fluidised, they exhibit good air retention properties. Barytes and cement were conveyed in a moving bed type flow regime at low velocities and high phase densities.

It appears that neither the Geldart Classification nor the Slugging Diagram are the ideal vehicles for predicting conveyability or mode of flow. Out of a random sample of 24 products, eight (33%) do not fall in the correct category with regard to identified group behaviour. There are a number of reasons why this may be the case.

The Geldart Classification was never developed or intended to be used as a guide to pneumatic conveying. The diagram was conceived to classify various types of observed fluidisation behaviour. However, recognising the importance of product/air interaction in the context of pneumatic conveying, many workers saw the diagram as a possible basis for identifying products with likely dense phase capability. Dixon took this a stage further by redefining the boundaries of the groups according to models developed from vertical pneumatic conveying and fluidisation. However, the four groups remained basically in the same position as on the Geldart Classification.

It is evident, from flow visualisation, that three major flow regimes exist for pneumatic conveying; suspension flow, moving bed type flow and slug or plug type flow. There can be considerable overlap between the moving bed type flow and slug flow in terms of velocity and phase density depending on the product characteristics. Within each flow regime there are many sub-divisions and variations in flow characteristics which make the problem of behavioural prediction extremely difficult. Nevertheless, the Geldart and Dixon diagrams provide a first indication of probable behaviour. Both diagrams are based on fluidisation but use only the mean particle size as a basis of categorising the product. However, it is known that a mean size alone does not take into account particle size range, distribution and shape, all of which will affect the fluidising properties of a product.

7.3 AN ALTERNATIVE METHOD OF CHARACTERISING THE PRODUCTS

Suggestions, such as those proposed by Zenz (Ref. 7.4), have been made as to how to characterise a product's size more completely by a single variable. However, since it is the fluidising capability of the product which is deemed to be of importance, it may well be just as easy to measure fluidising capability directly rather than try to relate it to particle size.

Caldwell (Ref. 7.5) made the point that it is not only the fluidising capabilities of a product which are important but also the ability of a product to retain air. The air retention properties of a product are as important as the fluidising capability of a product in many cases. It will be shown that, in some cases, the air retention properties of a product are more important than the fluidising capability.

Tests have been carried out on all the products used in the conveying trials to determine their fluidisation and air retention characteristics. A detailed account of the tests and methods used has been given in chapter 5. The fluidising capability of a product is measured using a standard technique which produces a permeability factor, C. This is a measure of the ease with which air (or the conveying gas) can permeate through the product. The test can be carried out quite quickly and produces a result with reliable repeatability.

The standard air retention tests can be time consuming. Some products such as cement can take two days or more to settle. (indicating a high degree of air retention capability). However, this is not particularly convenient when a reasonably quick result is desired. Chapter 5 describes a new method of determining a measure of air retention capability. It involves using a vibration technique and can provide an indication of product air retention capability within about ten minutes.

The test has been shown to be consistent with conventional methods of air retention measurement although the actual numbers produced and the scale are obviously different. The numbers produced are termed the 'vibrated de-aeration constant' and indicated by the symbol K_v'.

These tests are relatively easy to undertake and take no longer to carry out than the tests required to position a product on the Geldart Classification or the Slugging Diagram. A small sample of the product is all that is required and the equipment needed to carry out the tests manually is relatively simple and inexpensive.

7.4 THE CORRELATION BETWEEN MINIMUM CONVEYING CONDITIONS AND AIR PERMEABILITY

The term minimum conveying conditions has already been defined in chapter 4. A guide to minimum conveying conditions is given by the minimum conveying velocity. This alone can sometimes be misleading since it does not indicate the mode of flow or the pipeline concentration either in terms of volume or mass.

For suspension flow, the range of phase density is limited and therefore the minimum conveying velocity will give a good guide to minimum conveying conditions. For non-suspension flow, the minimum conveying velocity will vary with phase density. However, the minimum velocity obtainable will occur at maximum phase density. Therefore, the minimum conveying velocity obtainable (i.e. just prior to pipeline blockage) will give a good guide to minimum conditions but not to the mode of flow. A more complete description of minimum conditions for non-suspension flow would be a statement of minimum conveying velocity together with the observed mode of flow.

A graph of minimum conveying velocity against permeability factor is presented in fig. 7.5. Three major groups have been identified according to observed modes of flow and are marked on the diagram. On the right hand side are the group of coarse products (polyethylene pellets, coarse

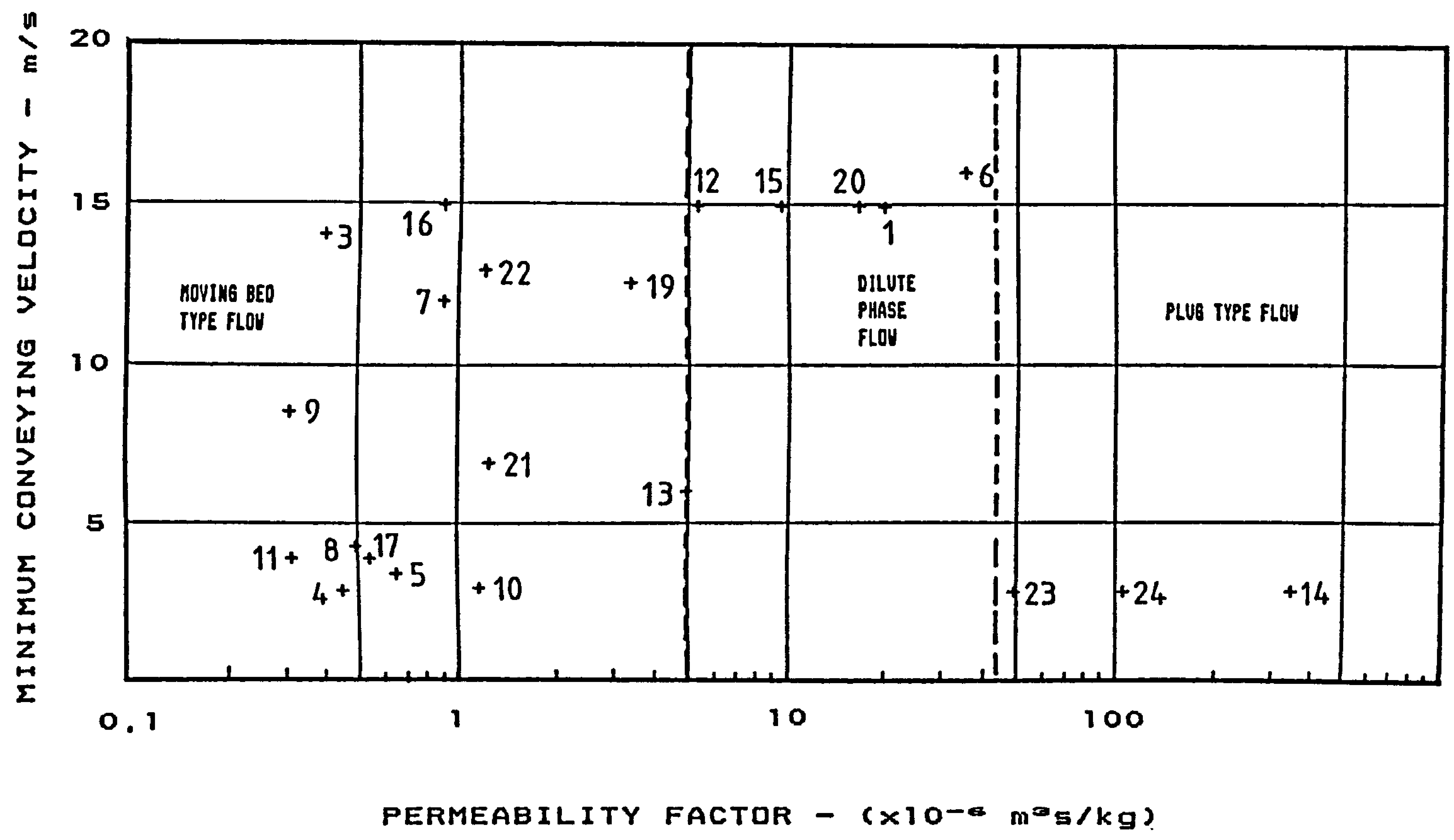


FIG. 7.5 THE RELATIONSHIP BETWEEN MINIMUM CONVEYING VELOCITY AND PERMEABILITY FACTOR

sand and mustard seed) which conveyed in slug type flow at low velocity. The middle group of products represent those with no dense phase capability in a conventional system (dilute phase only). Whilst the group on the left represent products which have good dense phase capability in a moving bed type flow regime.

It can be seen, however, that there is a group of four products which by observed conveying capability and minimum conveying velocity clearly fall into the wrong group. Alumina, degraded coal, potassium sulphate and zircon sand all fall in the moving bed type flow category although the conveying trials indicate that none of these products exhibit dense phase capability. This tends to indicate that permeability to air is not the only characteristic influencing conveyability and the mode of flow.

7.5 THE CORRELATION BETWEEN MINIMUM CONVEYING CONDITIONS AND AIR RETENTION CHARACTERISTICS

A graph of minimum conveying velocity against vibrated de-aeration constant is presented in fig. 7.6. It can be seen that an immediately identifiable correlation appears to exist between the vibrated de-aeration constant and the minimum conveying velocity. It should be noted that a reduction in the value of vibrated de-aeration constant indicates an increase in air retention capability.

The graph in fig. 7.7 shows the same plot of minimum conveying velocity against vibrated de-aeration constant but with each product identified by a number. Boundaries have been drawn between groups of products which have been observed, during conveying trials, to have similar modes of flow. The area on the left of the diagram groups products which were observed to convey in a moving bed type flow regime. The centre section of the diagram represents products which were observed to have no dense phase capability whilst the area to the right of the diagram groups together products which were observed to convey in a slug type flow regime. Only one product out of the 24 considered does not fit the correlation. This product is degraded coal.

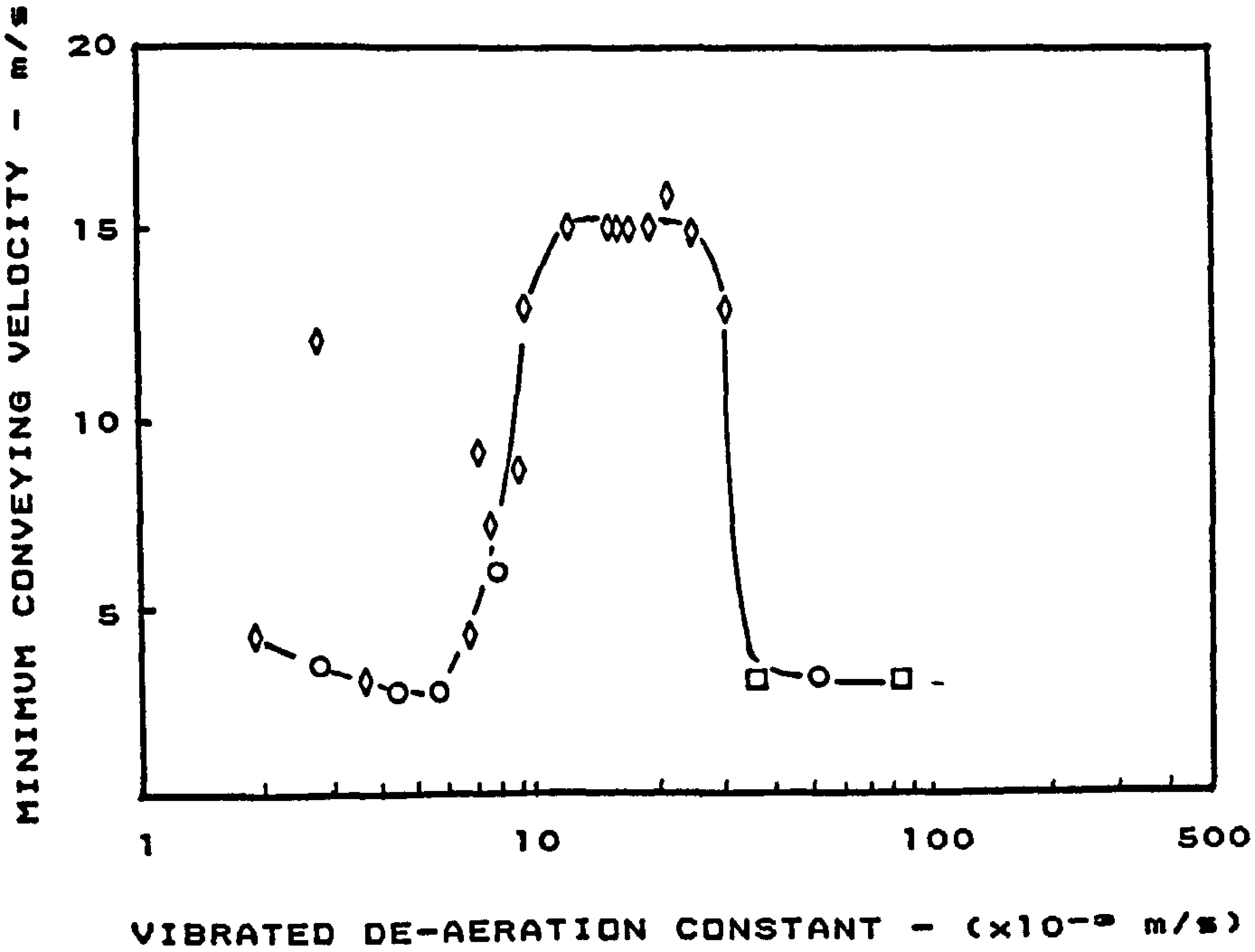


FIG. 7.6 THE RELATIONSHIP BETWEEN MINIMUM CONVEYING VELOCITY AND VIBRATED DE-AERATION CONSTANT

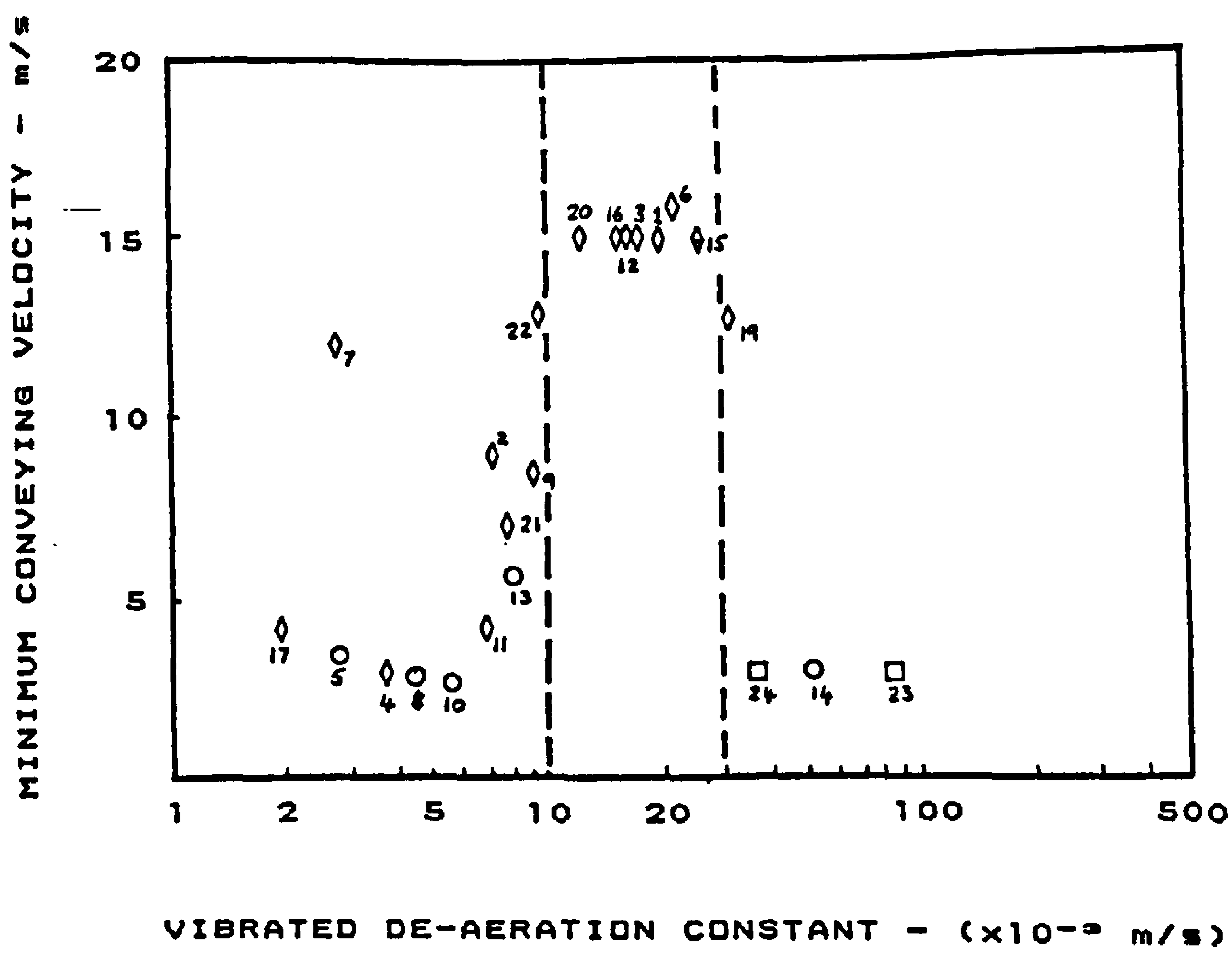


FIG. 7.7 THE RELATIONSHIP BETWEEN MINIMUM CONVEYING VELOCITY AND VIBRATED DE-AERATION CONSTANT

The degraded coal had the widest size distribution of any of the products tested other than the original coal as it was supplied. The size ranged from over 2.4 mm to under 70μm. In addition, the size distribution was far from Gaussian having two distinct peaks. This is assummed to have occurred due to the particular susceptibility of certain size fractions to particle breakage during initial conveying. It was apparent during the conveying trials that as degradation of the coal took place the minimum conveying velocity reduced. Some of the coal was being conveyed as a shallow moving bed but at relatively high velocity. As the coal degraded, a greater proportion of fines would be formed which could account for the increase in air retention properties. This increased air retentiveness would seem to explain the tendency toward a moving bed type flow regime. However, the increase in air retention appears to be out of proportion to the increase in conveyability. It may well be that products with very wide size ranges and/or size distributions that deviate widely from the Gaussian form should be viewed as possibly troublesome.

7.6 THE CORRELATION BETWEEN BENCH SCALE TESTS AND CONVEYING MODE

The diagrams presented in figures 7.5 & 7.7 relate the minimum conveying velocity to material characteristics in terms of vibrated de-aeration constant and permeability factor. In addition, from flow visualisation during the conveying trials, it has been possible to determine broad areas representing particular modes of flow. By combining the two diagrams and plotting vibrated de-aeration constant against permeability factor it has been possible to produce an empirical phase diagram for conventional pneumatic conveying.

A graph of vibrated de-aeration constant against permeability factor is presented in fig. 7.8. The points each represent a single product and have been labelled with their product identity number. A similar graph is presented in fig. 7.9 but in this case each product has been labelled with its corresponding value of minimum conveying velocity. It can be seen that the products form quite distinct groups of minimum conveying velocity range. Some of the products are represented by circular points

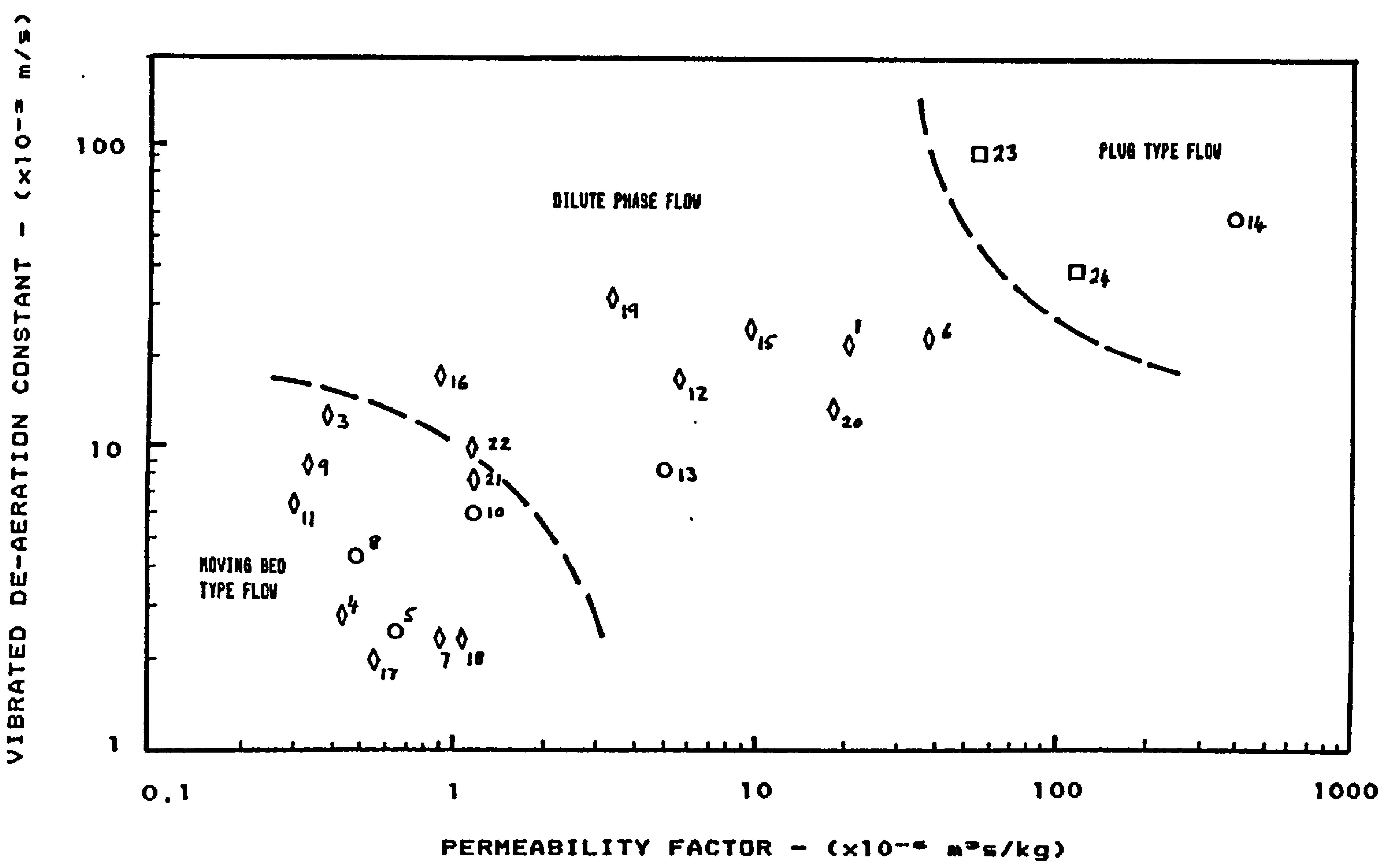


FIG. 7.8 PHASE DIAGRAM INDICATING THE POSITION OF PRODUCTS TESTED

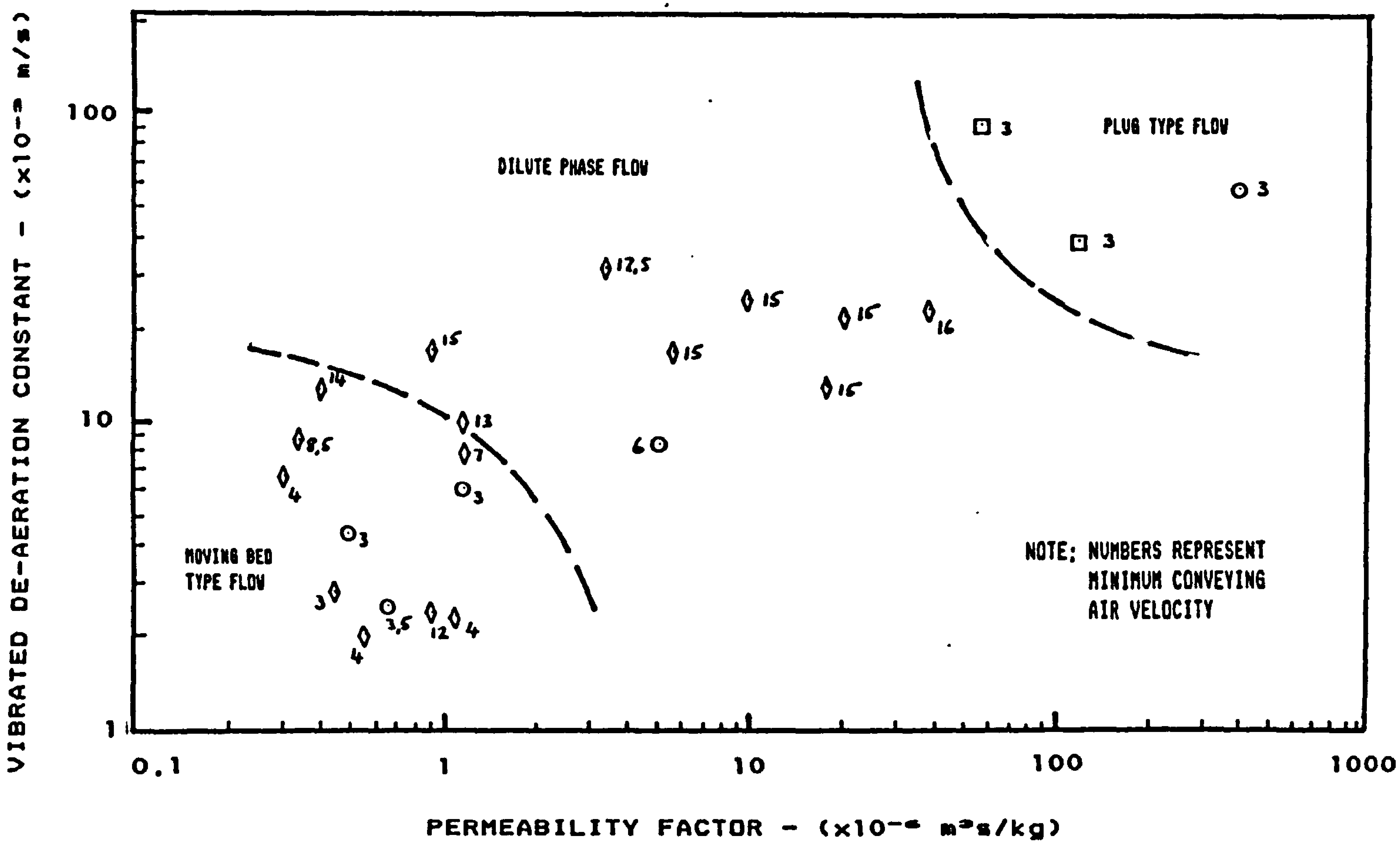


FIG. 7.9 PHASE DIAGRAM FOR PNEUMATIC CONVEYING IN A CONVENTIONAL SYSTEM

which indicate that during conveying trials a minimum conveying velocity was not found. That is, it was impossible to block the pipeline for the particular blow tank/pipeline configuration. The square points indicate products which were tested by other workers.

Using the boundaries identified for figures 7.5 and 7.7 together with the obvious broad groupings identified on the phase diagram presented in fig. 7.8 it was possible to determine approximate boundaries for the different modes of conveying. The grouping in the bottom left hand corner represents products which have dense phase capability in the moving bed type flow. The grouping in the top right hand corner represents products with dense phase capability in a plug type flow regime and the centre grouping represents products which generally are restricted to dilute phase flow in a conventional system.

It is evident that, to some extent, high values of permeability factor will imply poor air retention properties and hence high values of vibrated de-aeration constant. It can be seen from the phase diagram (fig. 7.8) that the relationship between vibrated de-aeration constant and permeability factor is only approximately linear in the broadest possible sense, indicating that the relationship is far from straightforward.

The message which seemed to emerge from a comparison of the conveying data and the bench scale tests was that different product properties were responsible for different conveying modes. From the graphs in figs. 7.5 & 7.7 it can be seen that the air retention properties of a product appear to be the predominant influence as to whether or not a product can be conveyed in a moving bed type flow regime. For slug type flow, it would appear that the permeability of the product to air is the dominating factor. These observations are supported by the work of Mainwaring and Reed (Ref. 7.6) who in particular cite permeability to air as being the significant material property with regard to plug type flow.

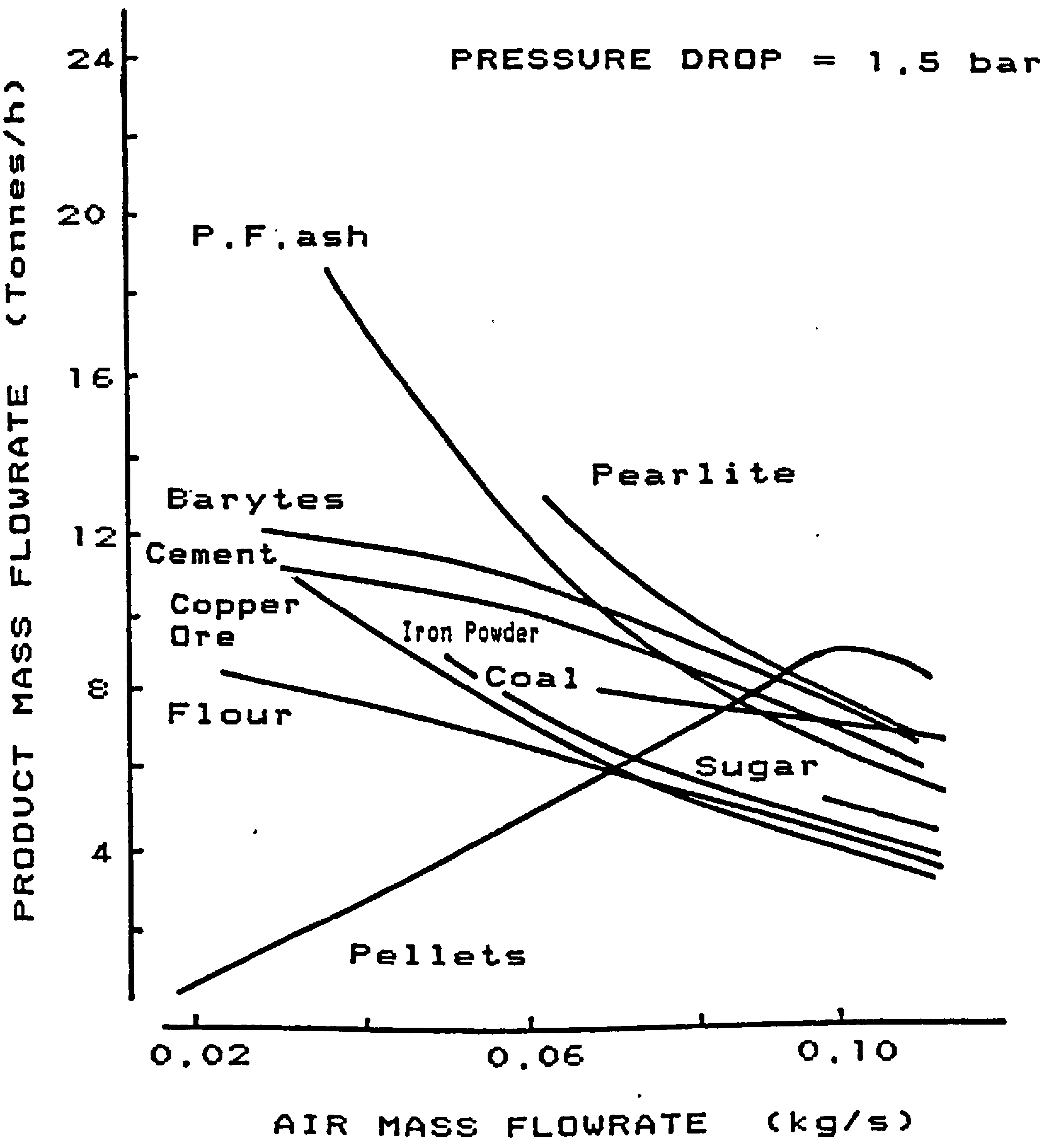
In section 7.2 the Geldart Classification and the slugging diagram were evaluated by comparing predicted modes of flow against observed modes of flow from the conveying trials. Of the products tested, over 30% were *predicted to convey in modes other than those observed during the conveying trials. For the products tested, only two products do not conform to the empirical correlation (i.e. 8%). This is not all that surprising since it is unfair to test a correlation using the data which was used to produce it. However, the correlation has been used to predict the likely behaviour of products outside the group of 24 products tested for this work and the results are very encouraging.*

Therefore, the phase diagram can be used to predict whether or not a product is likely to be a candidate for dense phase conveying in a conventional system. Furthermore, the correlation predicts the most suitable conveying mode for a product that is indicated to be capable of dense phase conveying. The position of a product on the phase diagram is obtained by carrying out two simple bench scale tests which characterise a product's interaction with air. The advantage of this phase diagram over other methods of prediction lies in the direct correlation of product/air interaction characteristics with conveying mode of flow.

7.7 THE CORRELATION BETWEEN MOVING BED TYPE FLOW PERFORMANCE AND VIBRATED DE-AERATION CONSTANT

One of the most striking points to emerge from the conveying trials was the very large range of product throughputs that could be achieved for a given set of conveying conditions with different product types. Some discussion regarding this variation has already taken place in chapter 4. The graph presented in figure 7.10 (repeated from 4.12) illustrates the wide range of product mass flow rates that can occur, particularly as the velocity is reduced and the product begins to convey in a moving bed type flow regime.

The graphs presented in figures 7.5 and 7.7 indicate that, for products being conveyed in a moving bed type flow regime, the air retention characteristics of the product appear to have a dominating influence. Most of the products tested which exhibited dense phase capability with a



A COMPARISON OF PRODUCTS

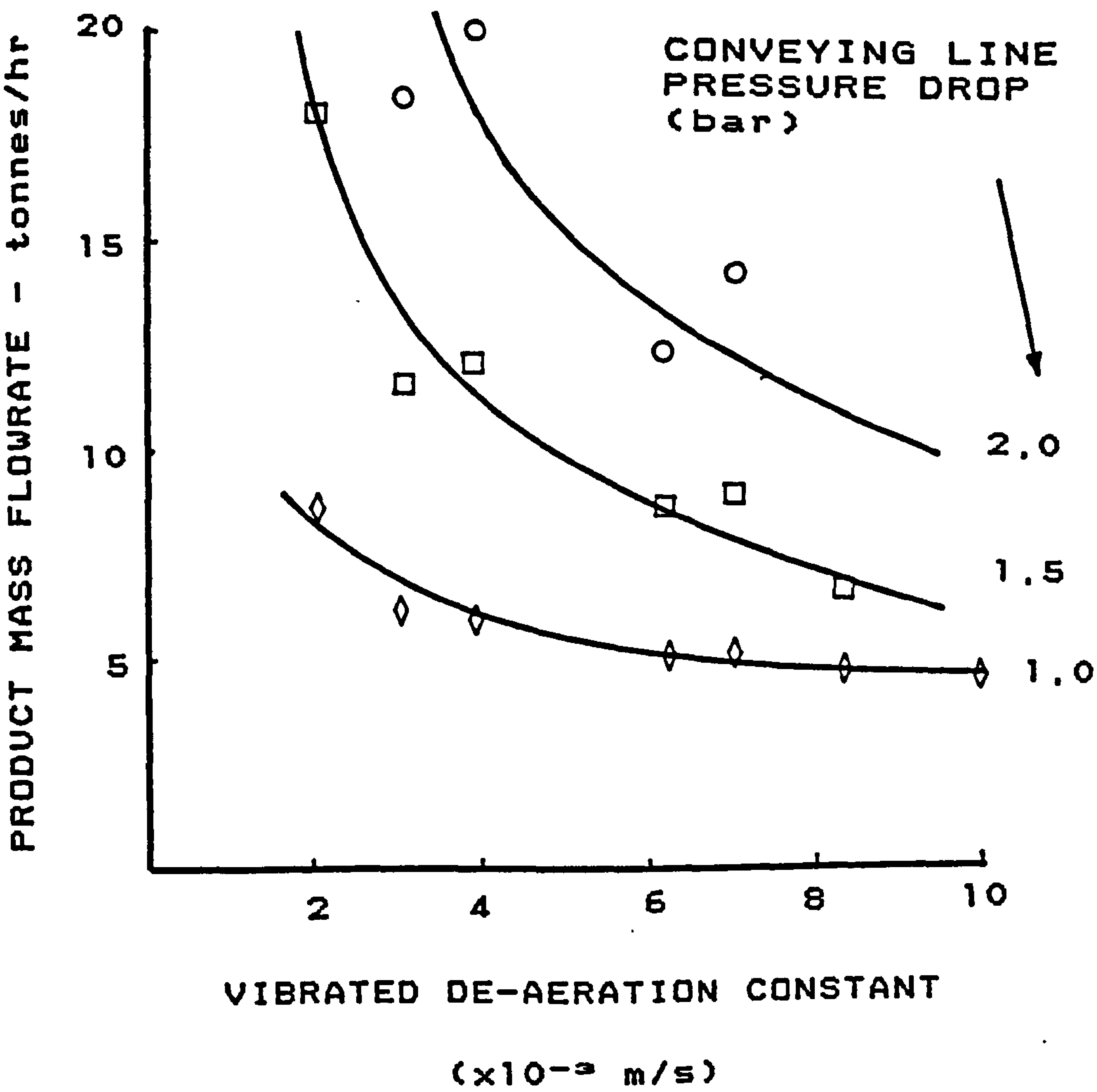
FIG. 7.10

wide variation in product throughput were fine powders which were observed to convey in a moving bed type flow regime. For this reason, a comparison was made between product conveying performance in terms of mass throughput for a given set of conditions and the vibrated de-aeration constant.

A graph of mass flow rate of product against vibrated de-aeration constant is presented in figure 7.11. The points have been plotted for the standard 53mm pipeline for a given air mass flow rate and hence a given 'free air' velocity. The curves are drawn for three different conveying line pressure drops. The graph suggests that as the value of vibrated de-aeration constant decreases (indicating an increase in air retention capability of the product) the product mass flow rate increases for a given conveying line pressure drop and air mass flow rate.

The sample size used for this analysis is rather small at eight products. However, using a regression analysis on the data points a reasonable correlation is indicated. In addition, small samples of other products have been tested and predictions, with regard to conveying performance, made using the correlation with subsequent conveying trials confirm the initial prediction.

The problem with the correlation is that it is specific to the particular pipeline for which it has been produced. However, Mills and Mason (Ref. 7.7) have been working in recent years on global scaling techniques for both conveying distance and pipe bore. In particular, efforts have been made to compensate for bend losses for two phase flow. This has enabled limited generalisation of the correlation within specific limits which has been checked against conveying data produced for pipelines of various pipeline lengths, bores and bend configurations.



NOTES

1. *The graph is drawn for the 53mm bore pipeline, 50m long with 9 x 90° bends of D/d = 24.*

2. *The mass flow rate of air, m_a = 0.04 kg/s Therefore, the 'free air' velocity, C_{max} = 15 m/s*

3. *The graph is drawn for various conveying line pressure drops.*

◊ Δp = 1.0 bar

□ Δp = 1.5 bar

○ Δp = 2.0 bar

THE CORRELATION BETWEEN PRODUCT MASS FLOW RATE AND VIBRATED DE-AERATION CONSTANT

FIG. 7.11

7.8 SCALING FOR PIPELINE LENGTH

The scale up of product mass flow rate with respect to conveying distance can be carried out, with a fair degree of accuracy, provided the extrapolation is not too great. The model used is a simple reciprocal law:

$$\dot{m}_p \propto 1/L$$

for a constant air mass flow rate and conveying line pressure drop due to product. Where $\dot{m}_p$ is the product mass flow rate and L is the conveying distance.

alternatively $\dot{m}_{p1} L_1 = m_{p2} L_2$

or $\dot{m}_p L = \text{Constant}$

This model has been shown to be quite accurate when the pipeline length is increased with little change in pipeline geometry. However, when significant changes in the number of bends are introduced there is a problem in predicting the equivalent length of straight pipe to allow for each bend. However, work carried out by Mills (Ref. 7.8) attempts to predict an equivalent length of straight pipeline which can be assumed to have a similar effect as the 90 degree bend in terms of the effect on pressure drop and mass throughput of product. Mills found that the equivalent length necessary to simulate the bend was predominantly dependent on velocity. A graph is presented in figure 7.12 which relates the bend equivalent length of straight pipe to superficial conveying line inlet air velocity. However, the graph is drawn for bends having a bend diameter to pipeline bore ratio (D/d) of 24.

The diagram presented in figure 7.13 shows the head loss for single phase flow around a 90 degree bend for various D/d ratios. The equivalent data for gas-solid flows is not available. However, recent research has indicated that a similar relationship exists with respect to gas-solid flows (Ref. 7.9). On this basis, it is reasonable to accept that the

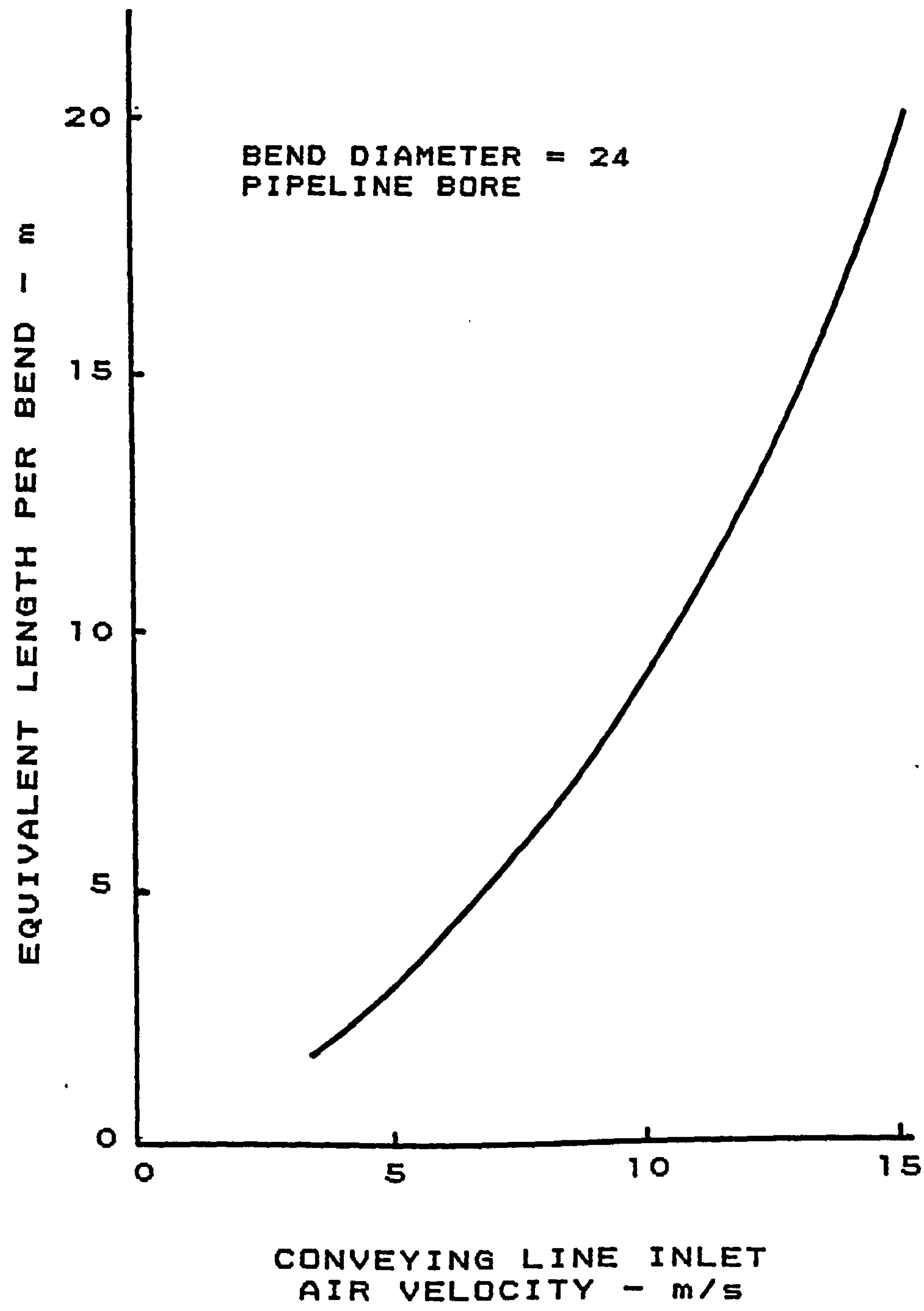


FIG. 7.12 EQUIVALENT LENGTH FOR 90° BENDS IN TWO-PHASE FLOW

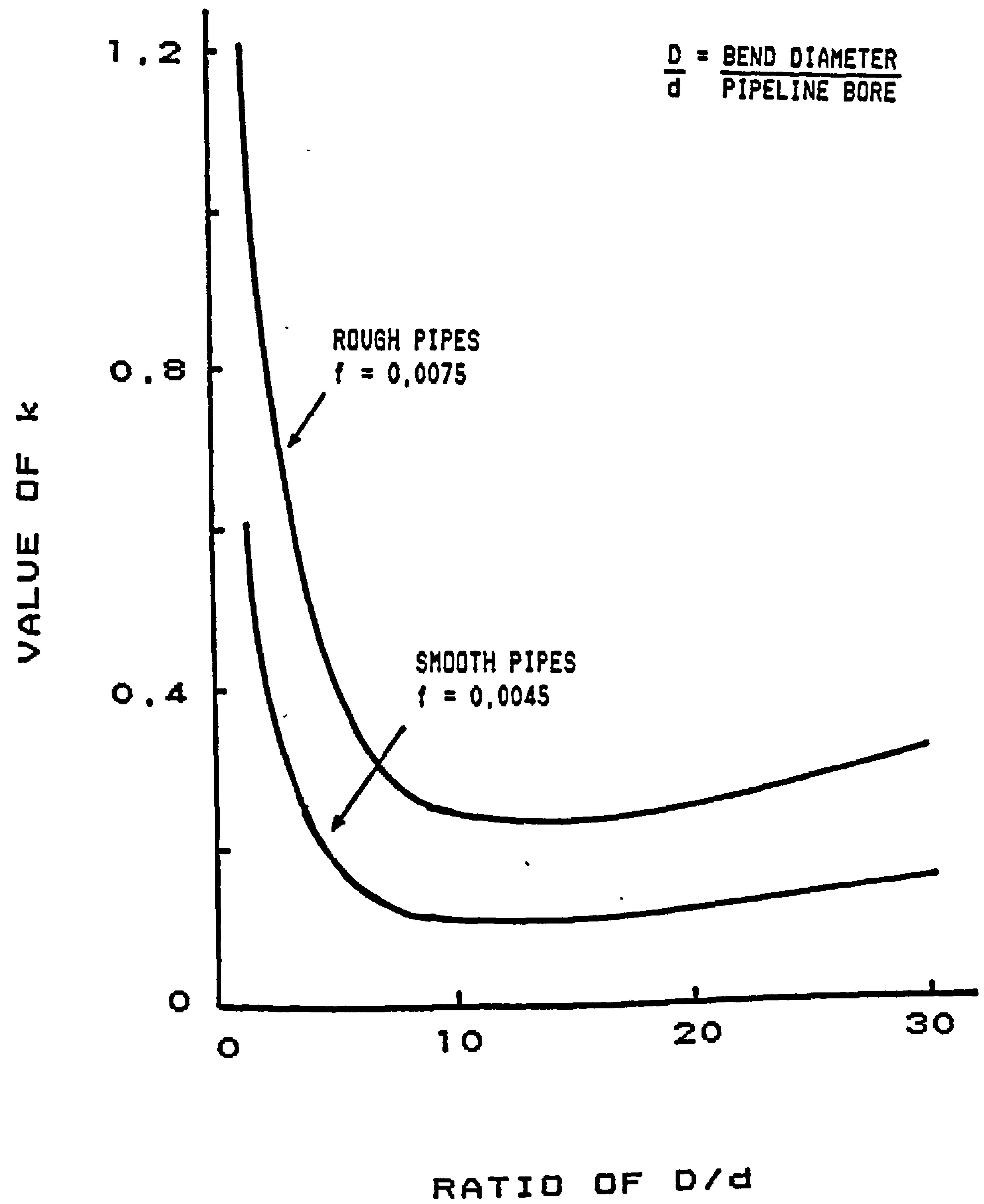


FIG. 7.13 HEAD LOSS FOR 90° BENDS FOR SINGLE PHASE FLOW

diagram in figure 7.12 could be used with caution for D/d ratios in the approximate range 5 to 30. It should be noted, however, that it would be totally unacceptable to use head loss values for single phase flow for a gas-solid flow application.

It is, therefore, apparent that the conveying distance, L, is not purely the length of the pipeline, and must be assumed to be made up of two parts:-

$$L = L_p + k.L_{e(bend)}$$

where L_p is the length of horizontal pipeline, $L_{e(bend)}$ is the bend equivalent length for an individual bend and k is the number of 90° bends in the pipeline.

The overall equivalent length for the entire pipeline is often denoted by L_e.

therefore, $$L_e = L_p + k.L_{e(bend)}$$

7.9 SCALING FOR PIPELINE BORE

Scale up of product mass flow rate with respect to pipe bore can be carried out with a reasonable degree of accuracy, provided the extrapolation is not to great, using a scaling model based on the cross-sectional area:

$$\dot{m}_p \; \alpha \; A \; \alpha \; d^2$$

This model holds provided that conveying conditions in terms of velocity and conveying line pressure drop due to the product are kept constant, where m_p is the product mass flow rate, A is the cross-sectional area of the pipe and d is the pipe bore.

alternatively
$$\frac{\dot{m}_{p1}}{d_1^2} = \frac{\dot{m}_{p2}}{d_2^2}$$

so that
$$\dot{m}_{p2} = \dot{m}_{p1}\left[\frac{d_2}{d_1}\right]^2$$

where subscripts 1 and 2 refer to the appropriate pipe bores.

However, scaling for bore will not give satisfactory results unless care is taken to ensure that the air mass flow rate is scaled to provide constant conditions with regard to velocity.

The 'free air' velocity (or the air velocity at atmospheric pressure) will be the maximum superficial air velocity in the pipeline for a positive pressure system. This is assuming that the outlet of the pipeline is at or very close to atmospheric pressure. The velocity at any point along the pipeline is given by the expression:-

$$C = \frac{\dot{m}_a\ R\ T}{A\ p_{abs}}$$

where $\dot{m}_a$ = air mass flow rate (kg/s)
R = characteristic gas constant (287 kJ/kg K for air)
T = absolute temperature (K)
A = pipeline cross-sectional area (m^2) = $\pi d^2/4$
p_{abs} = absolute pressure (N/m^2)

For the specific condition when the velocity is a maximum, $p_{abs} = 1.013 \times 10^5$ N/m^2 then:-

$$C_{max} = 3600 \frac{\dot{m}_a T}{d^2}$$

where d is the pipe bore in mm.

For scaling in terms of pipeline bore the air mass flow rate must be adjusted to ensure that the free air velocity remains constant.

7.10 THE GENERALISED CORRELATION USING SOLIDS MASS FLUX

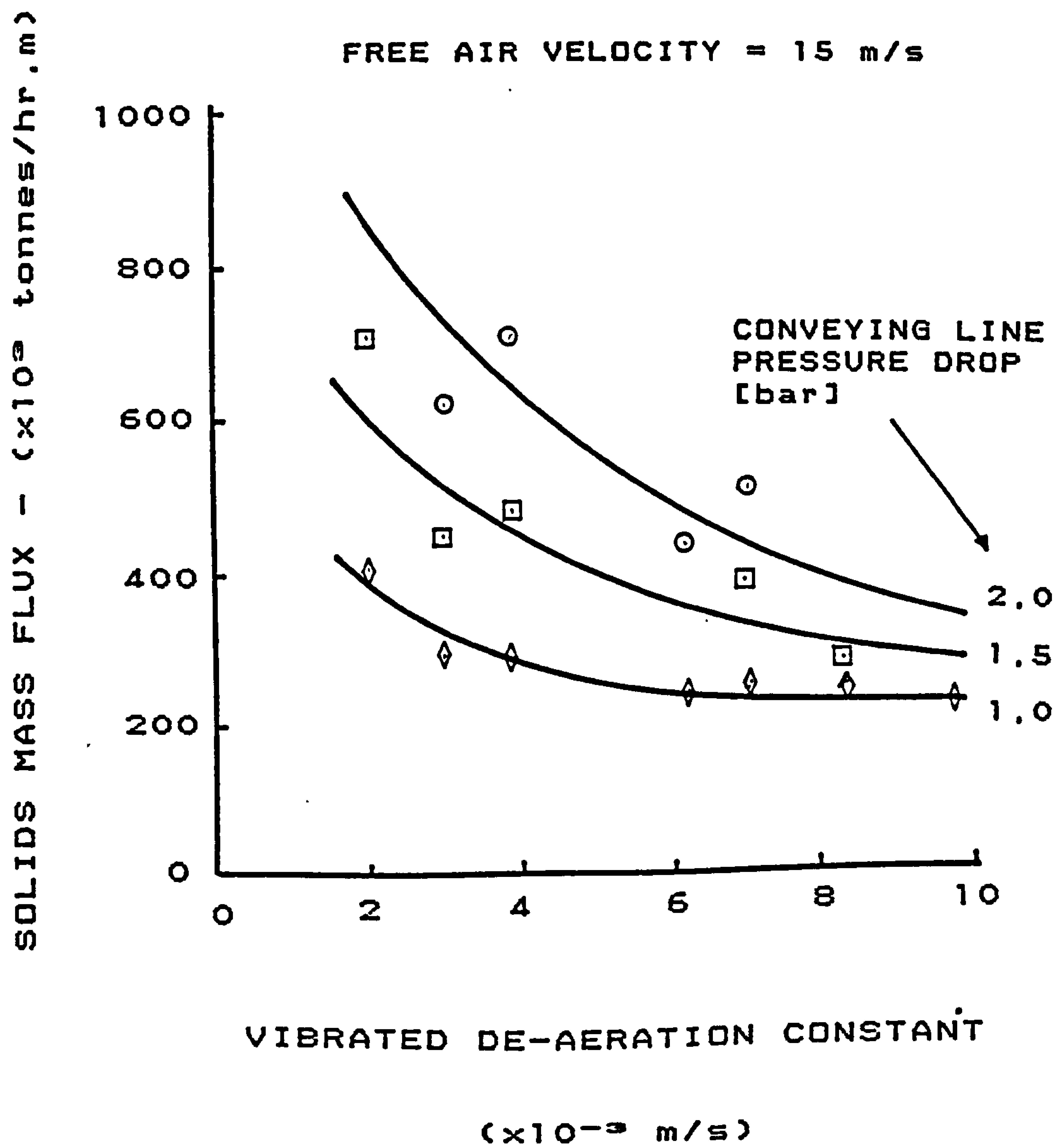
The product throughput expressed as a product mass flow rate is specific to one pipeline configuration and a single bore. If it is assumed that the scaling models are reasonably accurate provided extrapolation is limited, then the product or solids throughput can be generalised. This will allow prediction of likely conveying performance over a range of horizontal pipeline configurations.

The solids mass flux is obtained by dividing the product mass flow rate, $\dot{m}_p$, by the pipeline cross-sectional area, A, and multiplying by the equivalent length of the pipeline, L_e:-

$$\text{Solids Mass Flux, } M = \frac{\dot{m}_p L_e}{A}$$

The units become Tonnes/h.m

The graph of solids mass flux against vibrated de-aeration constant is presented in Figure 7.14. The graph is drawn for a 'free air' velocity of 15 m/s and three conveying line pressure drops of 1.0, 1.5 and 2.0 bar. The conveying line inlet air velocity for these conveying line pressure drops will be 7.5, 6 and 5 m/s respectively. This range of velocity is typical for the moving bed type flow regime.



SOLIDS MASS FLUX v AIR RETENTION CHARACTERISTISS FOR A FREE AIR VELOCITY OF 15 m/s

FIG. 7.14

The graph presented in Figure 7.14 is only valid for a single value of 'free air' velocity; that is, for a given value of air mass flow rate in a given pipe cross-section. The graphs presented in figures 7.15 & 7.16 show similar plots of solids mass flux against vibrated de-aeration constant for 'free air' velocities of 20 and 25 m/s. The associated conveying line inlet air velocities, C_{MIN} (which in most cases are the minimum velocities for that particular conveying condition) are shown in the table below, where C_{MAX} is the 'free air' velocity and Δp is the conveying line pressure drop.

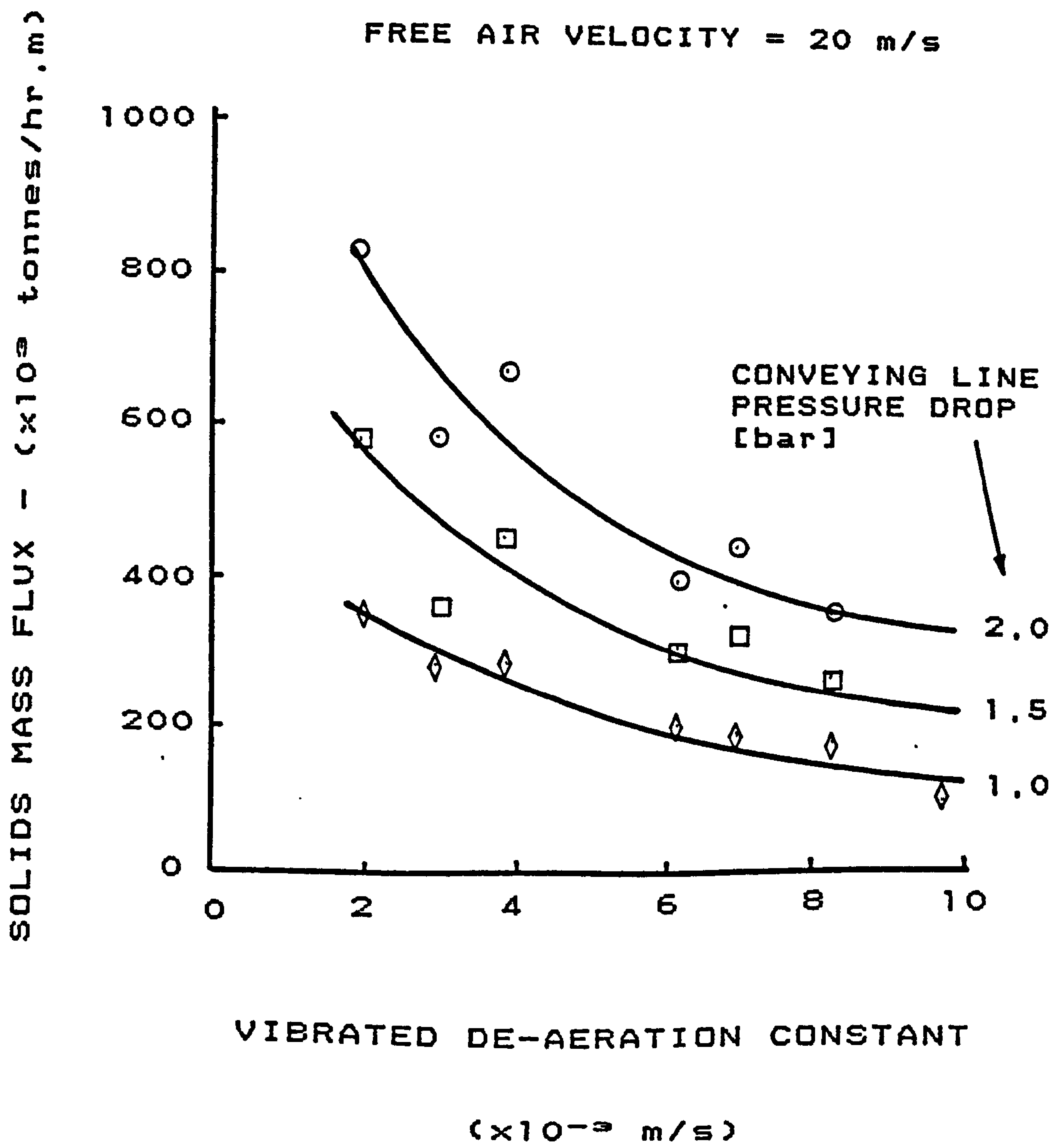
C_{MAX}	C_{MIN}		
	Δp		
	1.0	1.5	2.0
15	7.5	6	5
20	10	8	6.7
25	12.5	10	8.3

TABLE - 7.1

These graphs indicate that the identified relationship between air retention characteristics and mass throughput of product hold good throughout the range of the moving bed type flow regime of dense phase conveying.

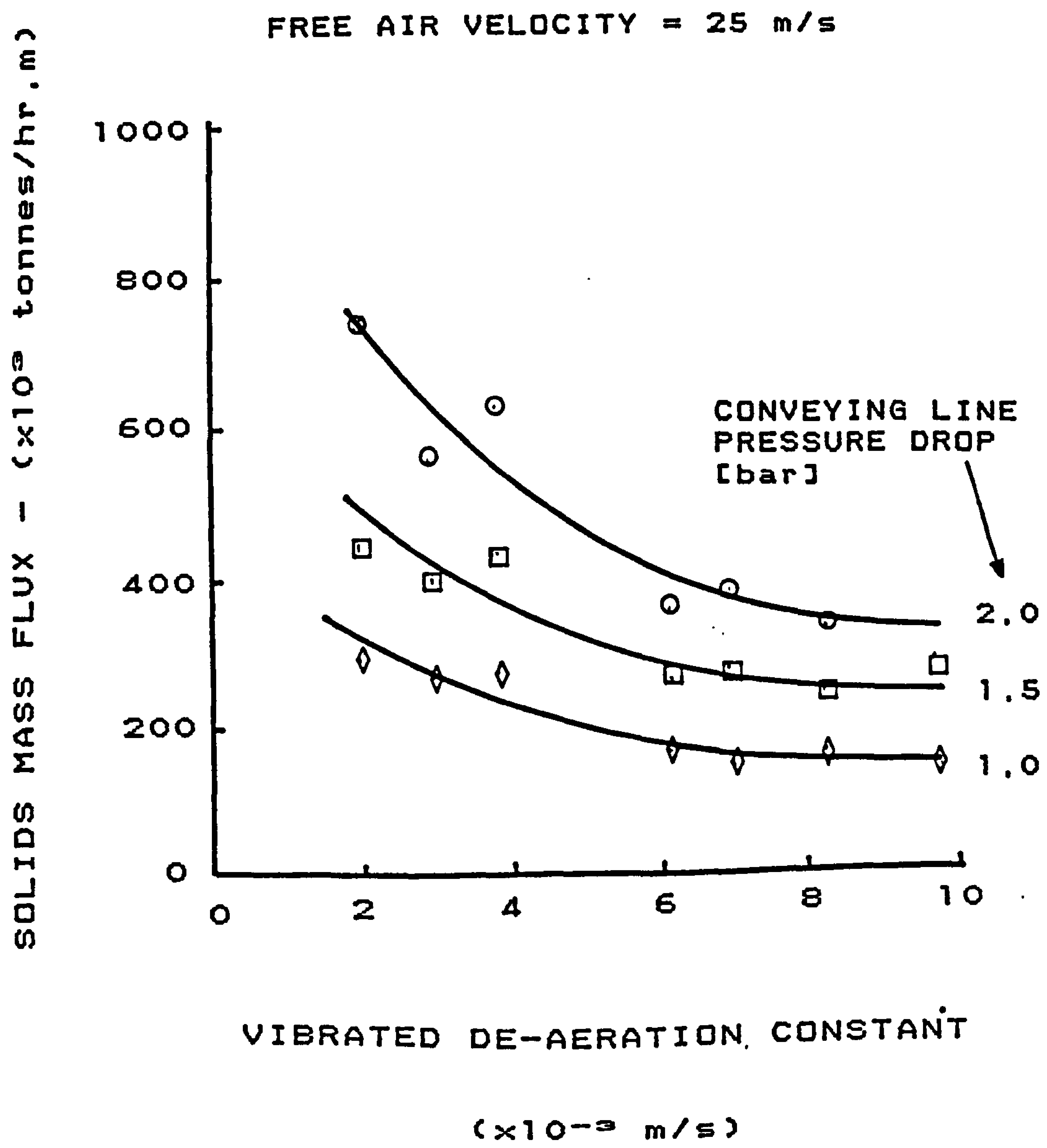
7.11 THE LIMITATIONS OF USING SOLIDS MASS FLUX

Having introduced the variable solids mass flux, it is necessary to justify its use and establish limits of applicability. Conveying characteristics for a number of products conveyed through a number of different pipeline configurations have been used to check the validity of this generalised variable. An example of typical data obtained is



SOLIDS MASS FLUX v AIR RETENTION CHARACTERISTISS FOR A FREE AIR VELOCITY OF 20 m/s

FIG. 7.15



SOLIDS MASS FLUX v AIR RETENTION CHARACTERISTISS FOR A FREE AIR VELOCITY OF 25 m/s

FIG. 7.16

presented in table 7.2 for three different pipeline configurations. Pipeline number 1 is the standard test loop that was used to obtain the conveying characteristics on which the correlation is based. Pipeline number 2 was just over twice the length of the standard pipeline at 104 m long with 9 bends. Both pipelines had a bore of 53mm. The third pipeline was of the same configuration as the standard pipeline but had a bore of 105 mm. This enabled the effect of scaling for length and for bore to be assessed independently.

Values of product mass flowrate were taken from conveying test data, for a conveying line pressure drop of 1.5 bar and a 'free air' velocity of 20m/s, for each of the three pipeline configurations. For each pipeline, under these given conditions, the conveying inlet air velocity was 8 m/s. The equivalent lengths for each of the pipelines were calculated using the techniques described in sections 7.8 and 7.9. Knowing the equivalent lengths and the cross-sectional area of the pipelines, the values for solids mass flux were determined.

If the scaling model was perfect, then the solids mass flux in all three cases would be equal. The results are shown in table 7.2 together with the percentage error. The trend indicated by these figures is typical of the data analysed to assess the suitability of the scaling models as a method of generalising the correlation. In general, the reliability of scaling for bore was more reliable than that for distance. This is not surprising as the equivalent length method for bend compensation is based on a global or 'average effect' approach.

In view of the considerable error which can occur, particularly when scaling for both distance and bore, limits need to be imposed to avoid excessive extrapolation. As a general guide, the solids mass flux correlation should not be used to predict conveying performance for distances in excess of 200m and for bores in excess of 105mm. These guidelines are approximate and care would need to be exercised when extrapolating, for example, near the limits for distance and bore simultaneously. In addition, the use of this correlation for conveying configurations with a large number of bends will accentuate the error.

	Δp = 1.5 bar C_{MAX} = 20 m/s C_{MIN} = 8 m/s		
	PIPELINE IDENTIFICATION		
	1	2	3
Pipeline length (m)	50	105	50
No. of bends	9	9	9
D/d ratio	24	24	12
L_e/bend (m)	6.3	6.3	6.3
L_e (m)	106.3	160.3	106.3
Pipeline bore (mm)	53	53	106
Pipeline c.s.a. ($x10^{-3}$ m^2)	2.2	2.2	8.8
Air mass flow rate - kg/s	0.052	0.052	0.110
Product mass flow rate - tonnes/hr	11	6	40
Solids mass flux ($x10^3$ tonnes/hr.m)	531	437	481
% Error		18	9

EVALUATION OF SOLIDS MASS FLUX AGAINST KNOWN CONVEYING DATA FOR THREE PIPELINE CONFIGURATIONS

TABLE 7.2

However, within these general limits, the correlation provides a useful tool for predicting the likely performance level of a product when conveyed in a pneumatic conveying pipeline. In addition, the prediction can be made based on straightforward material tests which can be carried out using a small sample of product.

7.12 THE CORRELATION BETWEEN PHASE DENSITY FACTOR AND VIBRATED DE-AERATION CONSTANT

Conveying performance is often measured in terms of the solids loading ratio or phase density. This is simply the ratio of product flow rate to air flow rate on a mass basis. Unlike product mass flow rate, the phase density is already a generalised variable with regard to pipe bore but does vary with pipeline length. To overcome this problem, a phase density factor has been introduced which is normalised for conveying distance in much the same way as the product mass flow rate was normalised using the solid mass flux.

$$\text{Phase density, } \phi = \frac{\dot{m}_p}{\dot{m}_a} \qquad \text{(i)}$$

and

$$\dot{m}_a = \frac{p_{abs}\ C\ A}{R\ T} \qquad \text{(ii)}$$

If p_{abs} is considered to be atmospheric pressure (i.e. 1 bar or 1×10^5 N/m^2) when C is the free air velocity then:

$$\dot{m}_a = \frac{10^5\ C_{MAX}\ A}{82656} = \frac{C_{MAX}\ A}{0.83} \qquad \text{(iii)}$$

Equation (iii) assumes R for air to be 287 J/kg.K and T to be 288 K.

∴ substituting eqn. (iii) into eqn (i):

$$\phi = \frac{0.83\ \dot{m}_P}{C_{MAX}\ A}$$

This equation holds if the $\dot{m}_P$ is in kg/s; for $\dot{m}_P$ in tonnes/hr:

$$\phi = \frac{0.23\ \dot{m}_P}{C_{MAX}\ A} \qquad \text{(iv)}$$

where C_{MAX} = free air velocity (m/s)

and A = cross-sectional area of pipe (m^2)

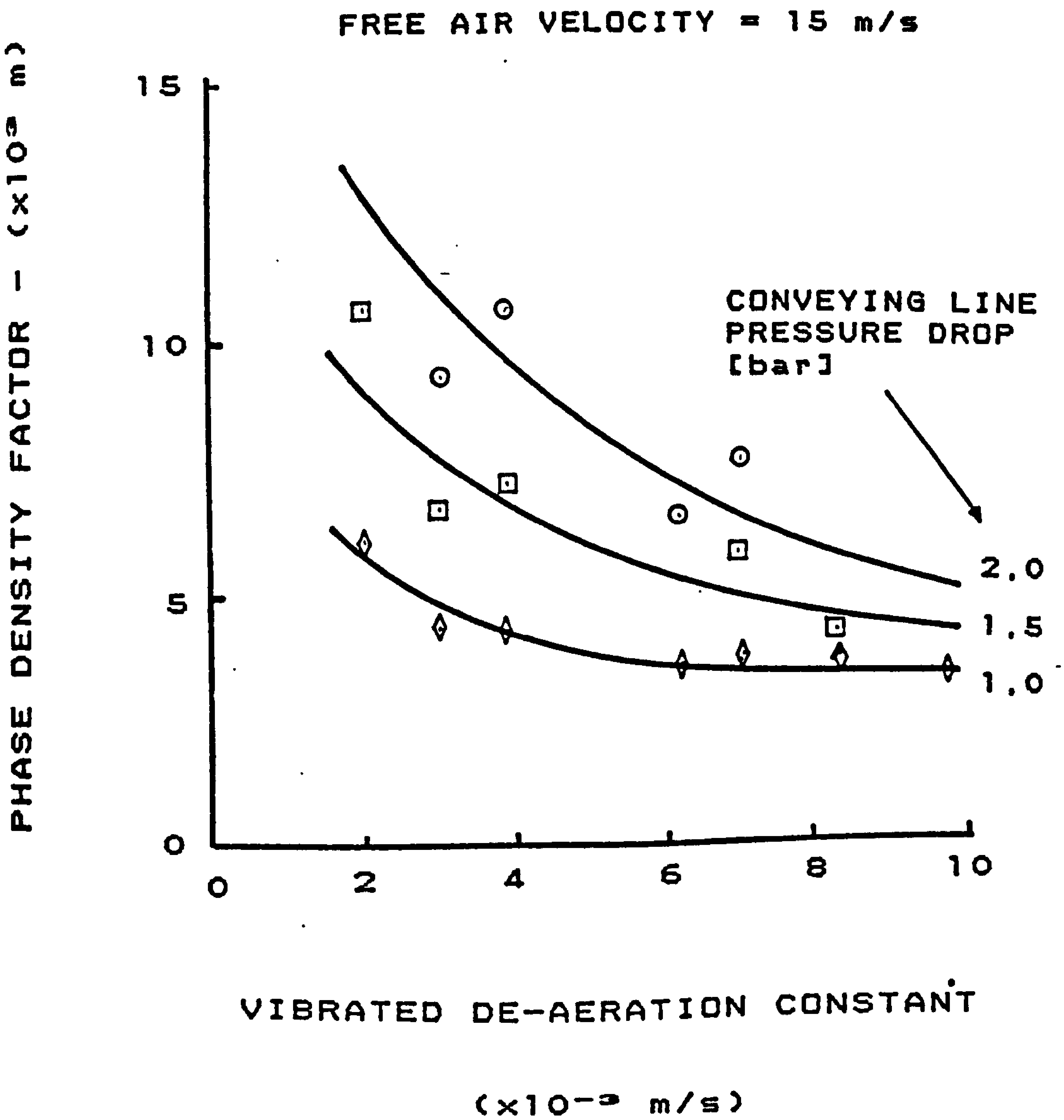
To generalise phase density with respect to conveying distance a phase density factor is introduced:-

where Phase Density Factor, $\Gamma = \phi\ L_e$

Graphs of phase density factor against vibrated de-aeration constant are presented in figures 7.17, 7.18 & 7.19 for free air velocities of 15, 20 and 25 m/s respectively. As expected, the phase density for a given set of conditions increases with a decrease in vibrated de-aeration constant in a similar way to that of solids mass flux.

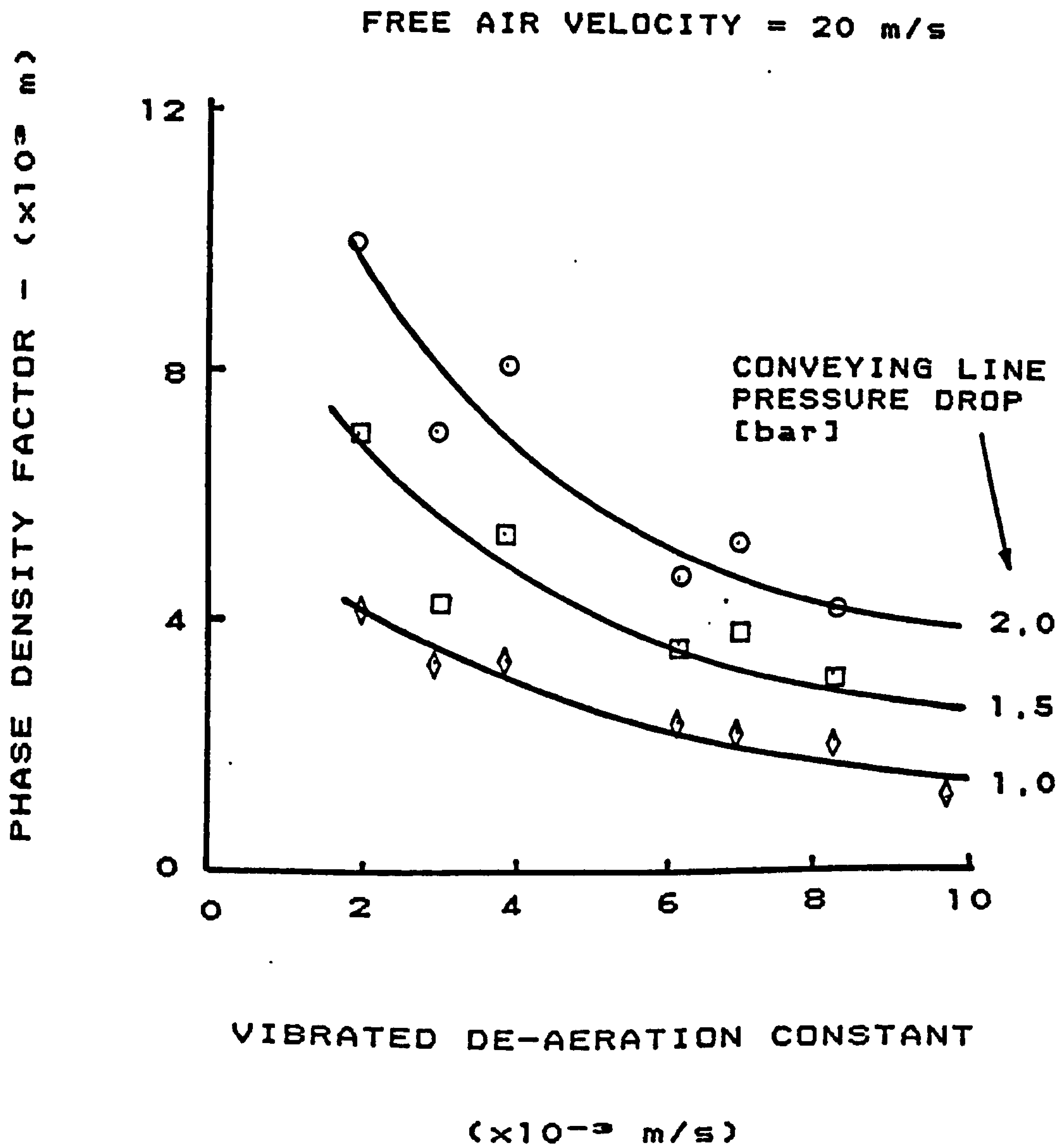
7.13 CONCLUDING REMARKS

The problems of predicting conveying behaviour are particularly difficult especially for the moving bed type flow regime. This is evident from the gap that exists between the extensive work which has been undertaken for the dilute phase flow regime and the many attempts at mathematically modelling dense phase plug flow. However, very little work has been undertaken in the moving bed type flow. All the more surprising since the majority of commercial dense phase systems operate within this flow regime.



PHASE DENSITY FACTOR v AIR RETENTION CHARACTERISTICS FOR A FREE AIR VELOCITY OF 15 m/s

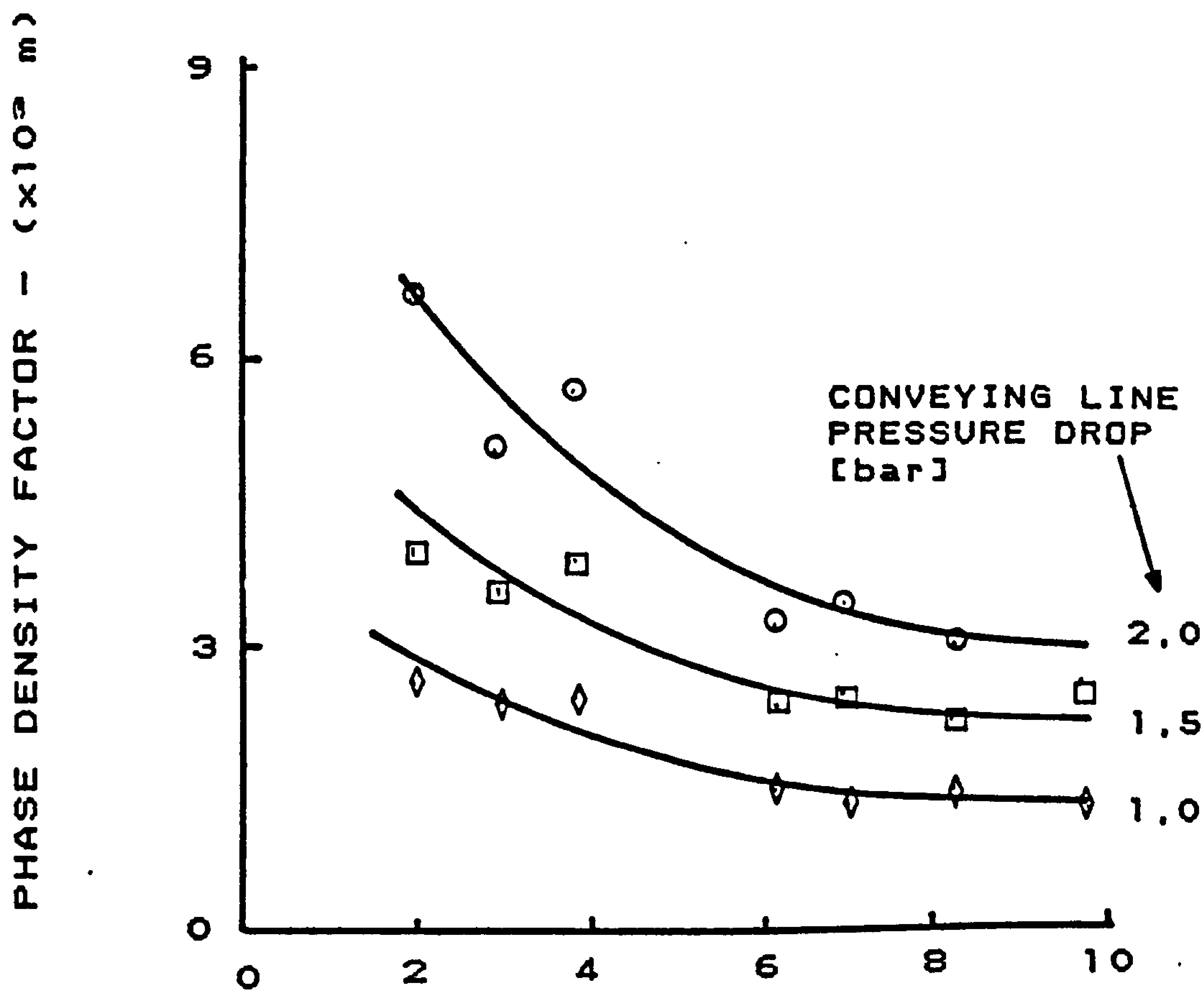
FIG. 7.17



PHASE DENSITY FACTOR v AIR RETENTION CHARACTERISTICS FOR A FREE AIR VELOCITY OF 20 m/s

FIG. 7.18

FREE AIR VELOCITY = 25 m/s



VIBRATED DE-AERATION CONSTANT

(x10⁻³ m/s)

PHASE DENSITY FACTOR v AIR RETENTION CHARACTERISTICS FOR A FREE AIR VELOCITY OF 25 m/s

FIG. 7.19

This chapter has presented a method of assessing the suitability of products for conveying in a conventional dense phase pneumatic conveying system by testing a small sample of material. Having established the most suitable flow regime for a product, a correlation has been suggested for predicting the likely level of conveying performance based on simple bench scale tests for products that are suited to the moving bed type flow regime of dense phase pneumatic conveying.

CHAPTER 8

THE CORRELATION BETWEEN PRODUCT CHARACTERISTICS AND BLOW TANK PERFORMANCE

Chapter 8 The Correlation Between Product Characteristics and Blow Tank Performance

8.1 INTRODUCTION

Blow tanks are widely used in industry for the pneumatic conveying of bulk materials through pipelines. This is because of the ease with which they can be controlled and the fact that they can be used over a very wide range of air supply pressures. They can, therefore, be used equally well for both dilute and dense phase conveying. It is for precisely this reason that a blow tank feeder was chosen for this work.

The emphasis of this research has been directed towards the pipeline. It has been found that the product type has a significant effect on pipeline performance and, hence, a phase diagram and performance correlation have been proposed to quantify these effects. Since the product/air interaction has been identified as a significant factor affecting pipeline performance, it follows that the same interactions are likely to affect blow tank performance. Suprisingly little work has been published with regard to the effect of material type on blow tank performance. That which is reported is based on only two or three products all of similar type.

A correlation is proposed which quantifies the effect of material characteristics on the performance of the blow tank. This is based on the same material characteristics that were identified as having a significant effect on pipeline performance and a similar type of correlation is identified. A comparison was made between the performance of the blow tank in conventional top and bottom discharge arrangements. This suggested that the key to optimum blow tank performance lies in the effective fluidisation of the product for materials which exhibit good air retention properties.

Details regarding the blow tank used for this work are given in chapter 3. The blow tank allowed conveying over a wide range of conditions with pressures up to 4 barg. Control of the blow tank, and hence the pipeline product mass flow rate, was achieved by controlling the total air mass flow rate and the proportion of the total directed to the blow tank. The proportion of the air directed to the blow tank is known as the 'Blow Tank Air Ratio' (BTAR).

8.2 FACTORS AFFECTING DISCHARGE RATE

The factors which affect discharge from the blow tank have been studied by many workers. Jotaki and Tomita (Ref. 8.1) analysed the discharge characteristics of a top discharge blow tank using PVC powder and polyethylene pellets. The blow tank used was a conventional top discharge arrangement with a fluidising membrane being the only inlet for blow tank air. Jotaki and Tomita show a direct relationship between the superficial air velocity in the blow tank discharge pipe (i.e. the inlet to the conveying pipeline) and the discharge rate of product regardless of the BTAR or the pipeline conditions. However, it is clear from the graphs produced for the two products tested that the discharge rate is product dependent.

Vaghorn and Mason (Ref. 8.2) suggested that the effects of pipeline bore and pipeline back pressure were important and produced models for discharge rate prediction based on pipeline diameter and blow tank pressure. However, the work reported was based on one product.

Many workers have attempted to model the characteristics of blow tanks. However, the majority have neglected the effect of product type. With a difficult problem of this nature, it is understandable that workers have limited the number of variables by assuming an 'ideal product' or adopting a single product type. However, from the experience of the conveying trials it is evident that the blow tank characterisics are heavily product dependent. Workers such as Marcus and Lohrmann (Ref. 8.3) and Kennedy et al. (Ref. 8.4) have recognised the importance of product properties on the discharge characteristics of a blow tank.

Marcus and Lohrmann undertook a series of tests, using a bottom discharge blow tank, on three products all of which fall into group A on the Geldart Classification. The three products were pulverised fuel ash (pfa), manganous oxide and calcine. It was expected that the conveying capability of all three products would be similar and that the discharge rates achieved would be roughly in proportion to their densities. However, the results obtained showed that the pfa had the largest discharge rate as expected but the manganous oxide, which was the heaviest product, achieved a greater discharge rate than the calcine. This tends to indicate that basing the discharge rate on density is not realistic. However, it does show that products which are identified as dense phase candidates on the basis of the Geldart or Dixon Classifications may well have vastly different capabilities in terms of discharge rates for a given blow tank.

8.3 BLOW TANK CHARACTERISTICS

Since the data obtained from the conveying trials contained all the information required to produce the blow tank characteristics, a selection of products covering the range of conveyability were chosen to carry out an analysis of the blow tank discharge rate for the chosen products. The products selected were flour, pfa, polyethylene pellets, pearlite and sugar.

The blow tank characteristics were produced in much the same way as the conveying characteristics for the pipeline. The co-ordinates of air mass flow rate and product mass flow rate were plotted for each conveying run but, instead of each point being marked with the associated conveying line pressure drop, each point was marked with the blow tank air ratio (BTAR). Lines of constant BTAR were drawn to provide a record of the blow tank characteristics for the particular product being conveyed. An example of the data obtained is presented in figure 8.1 for pfa.

The blow tank characteristics for the five products are shown in figures 8.2 - 8.6. In each case the characteristics are for the top discharge blow tank configuration using the 50 metre long pipeline of 53mm bore and 9 bends. The blow tank characteristics for sugar are the only ones where it was not possible to explore the whole of the blow tank feeding

TOP DISCHARGE, STANDARD 53mm BORE
PIPELINE, 50m LONG, 9 BENDS (D/d=24)

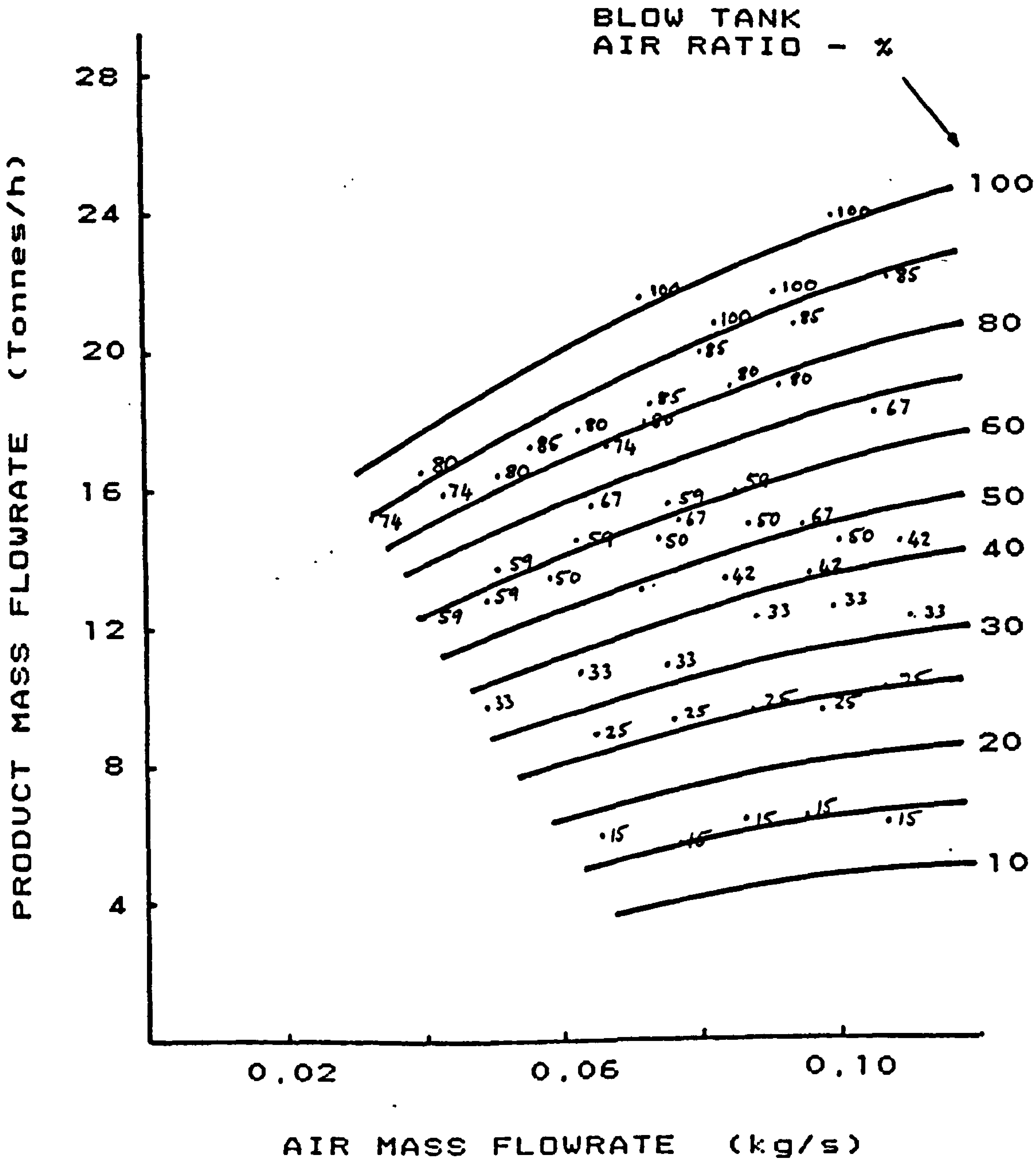


FIG. 8.1 BLOW TANK CHARACTERISTICS FOR PULVERISED FUEL ASH SHOWING DATA POINTS

TOP DISCHARGE, STANDARD 53mm BORE
PIPELINE, 50m LONG, 9 BENDS (D/d=24)

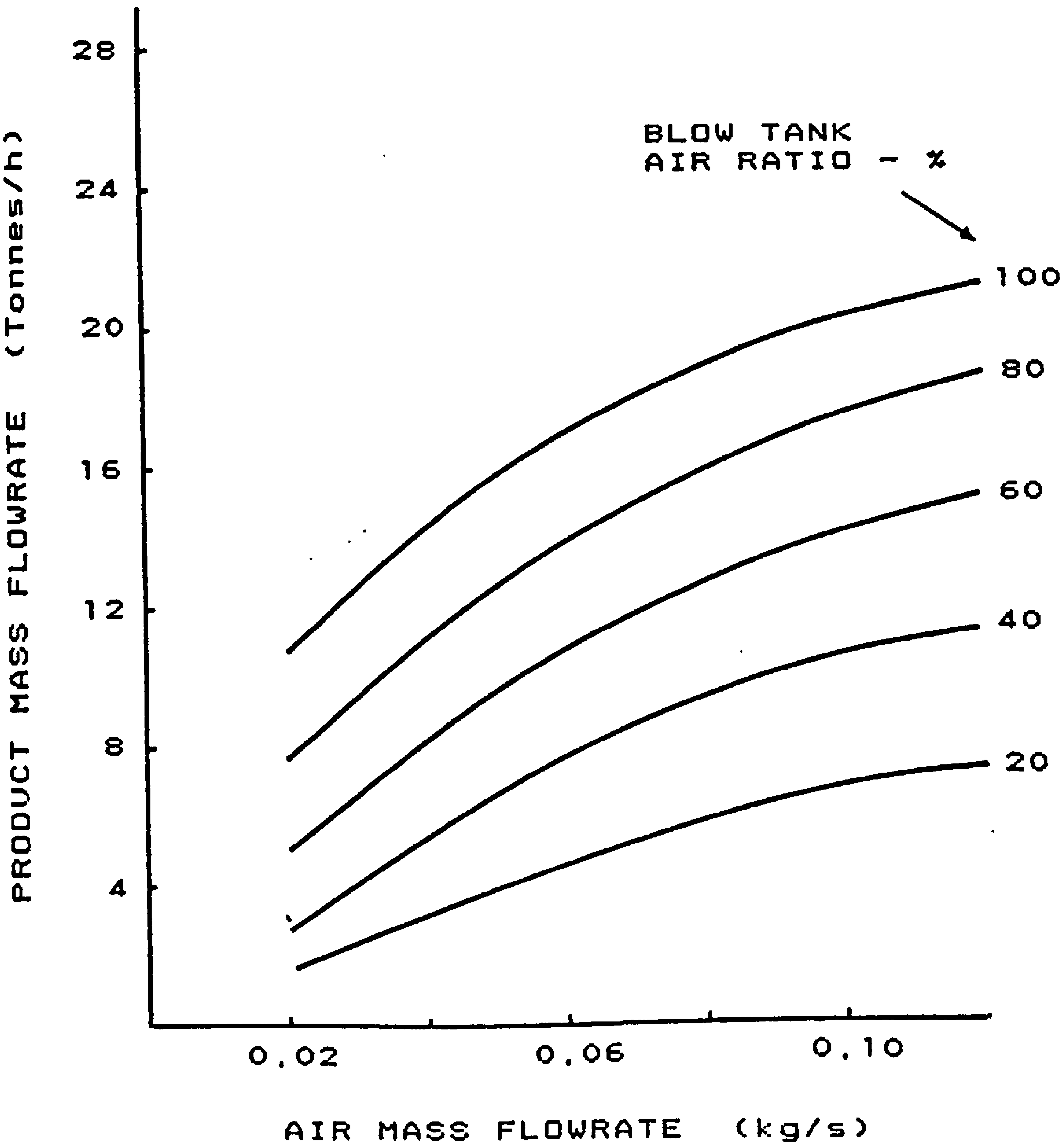


FIG. 8.2 BLOW TANK CHARACTERISTICS FOR FLOUR

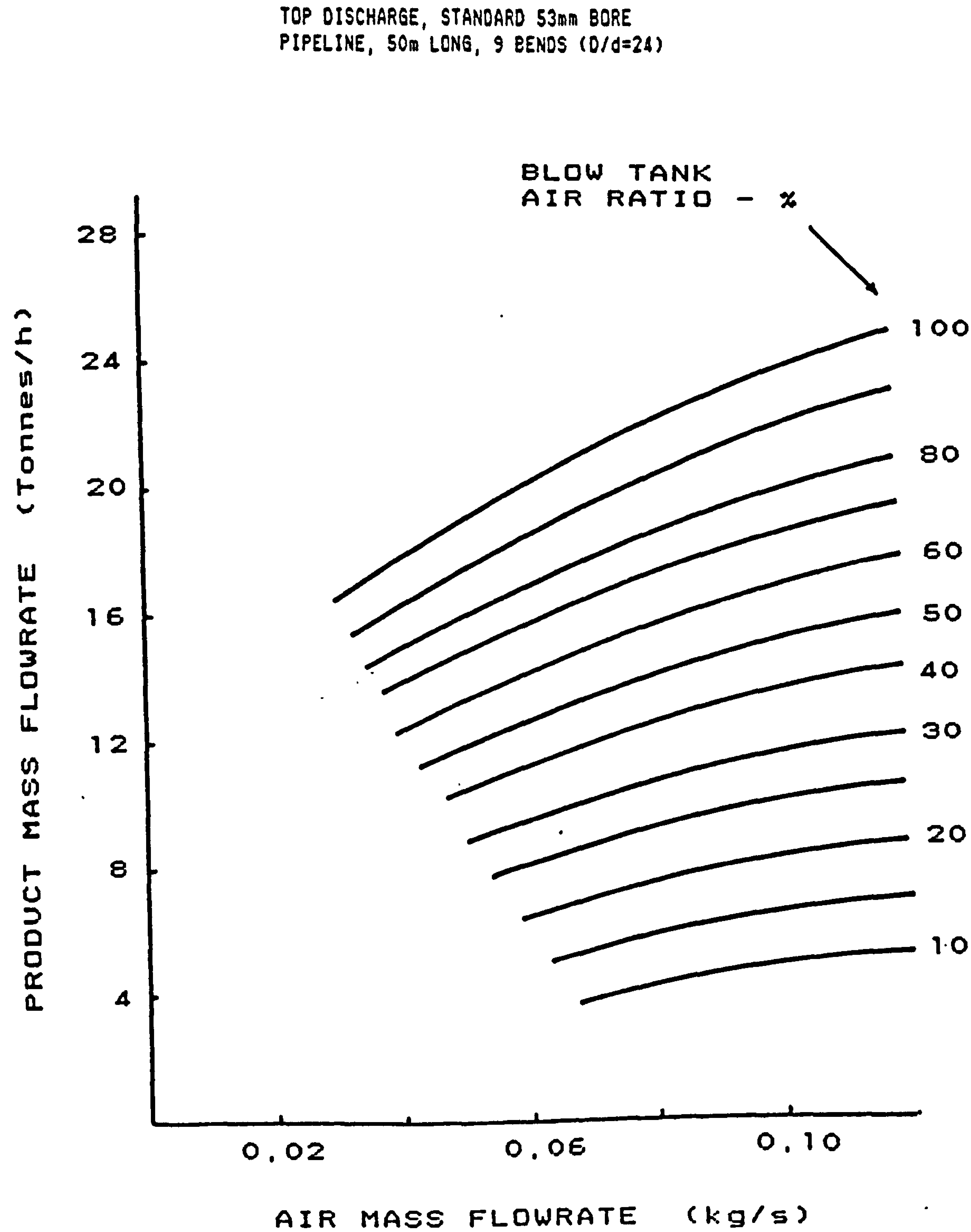


FIG. 8.3 BLOW TANK CHARACTERISTICS FOR PULVERISED FUEL ASH

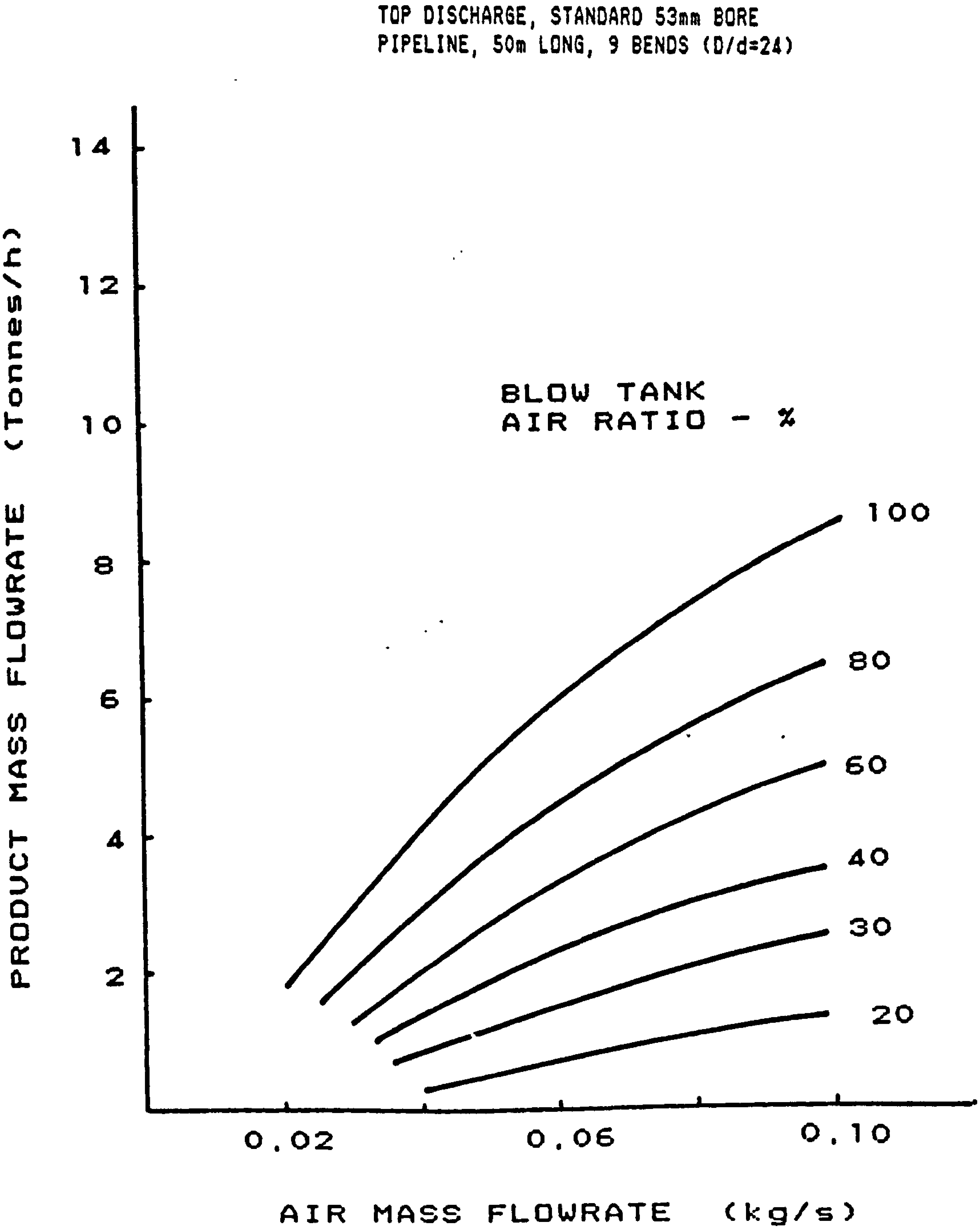


FIG. 8.4 BLOW TANK CHARACTERISTICS FOR POLYETHYLENE PELLETS

TOP DISCHARGE, STANDARD 53mm BORE
PIPELINE, 50m LONG, 9 BENDS (D/d=24)

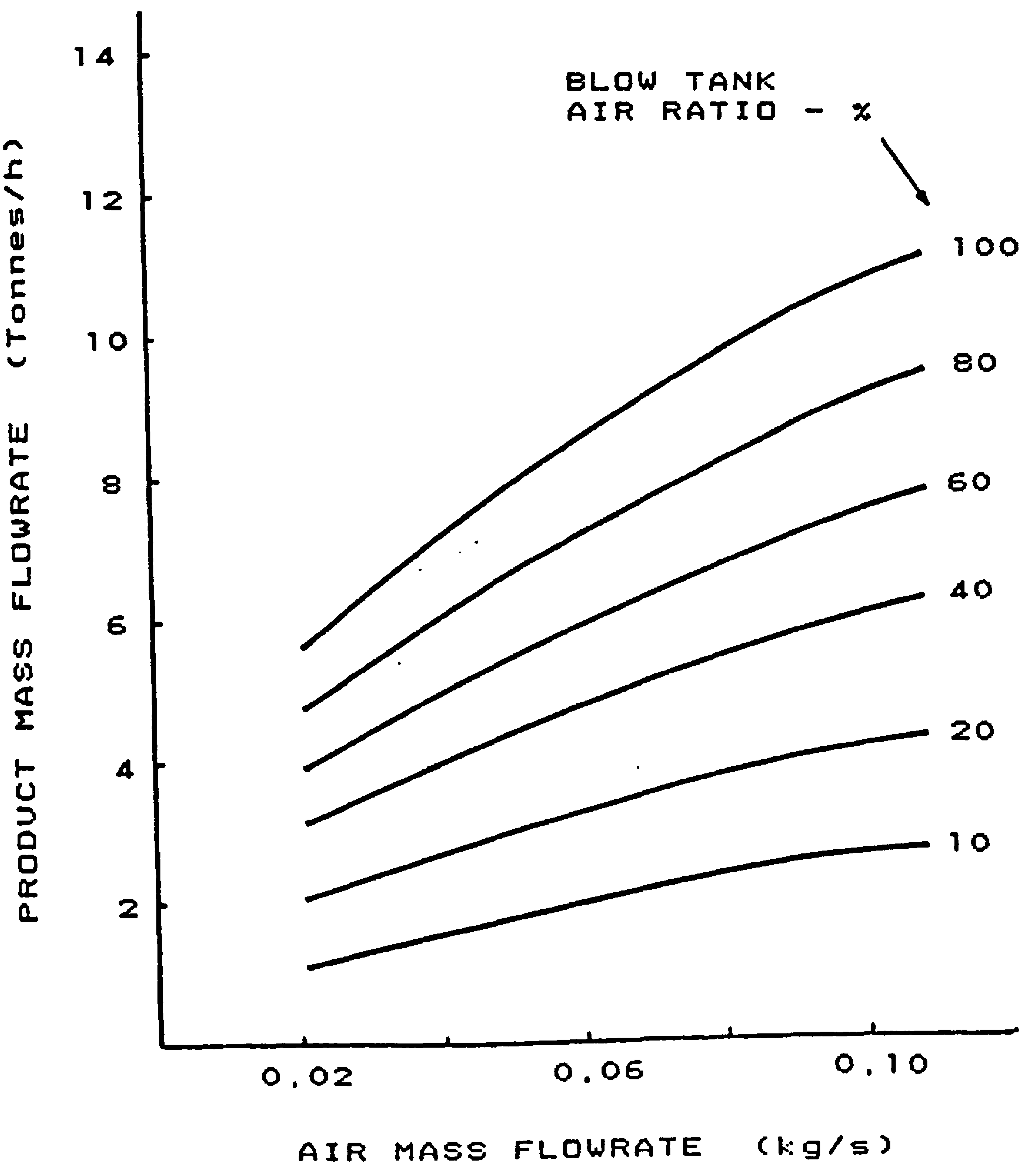


FIG. 8.5 BLOW TANK CHARACTERISTICS
FOR PEARLITE

TOP DISCHARGE, STANDARD 53mm BORE
PIPELINE, 50m LONG, 9 BENDS (D/d=24)

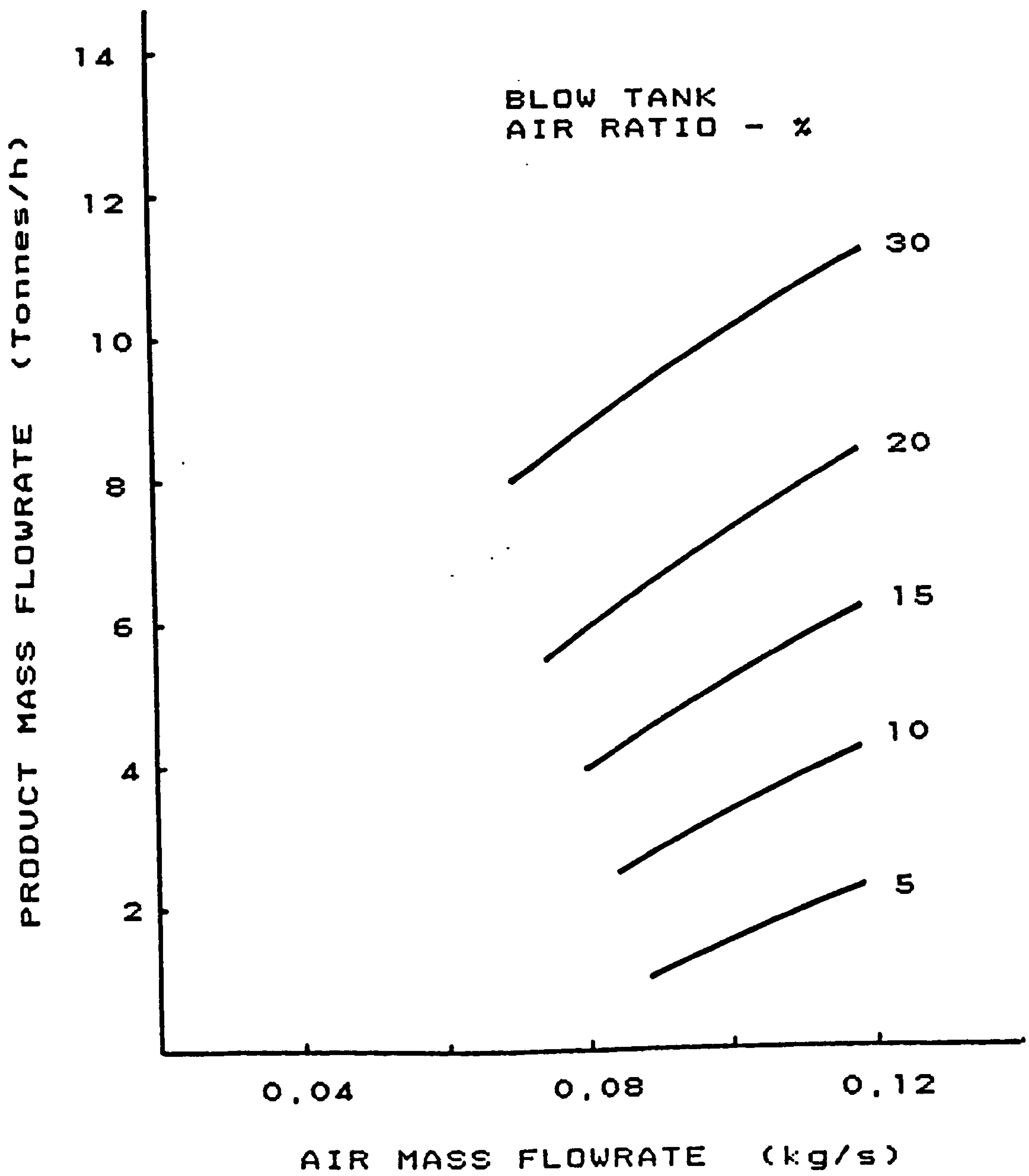


FIG. 8.6 BLOW TANK CHARACTERISTICS
FOR GRANULATED SUGAR

capability due to limitations imposed by the conveying capability of the product in the pipeline. Sugar in its granulated form had a minimum conveying velocity of around 15 m/s and was only capable of being conveyed in dilute phase. It was felt important to include a product that could only be conveyed in dilute phase so that as wide a range of product property values as possible could be tested.

The other four products exhibited similar characteristics in terms of curve shape but the discharge rates for particular BTAR values at a given air mass flow rate varied considerably. Comparative plots are presented in figures 8.7 and 8.8 for BTARs of 15% and 75% for each of the products. These plots highlight the variation in discharge rate for different products for a given set of conditions. The comparative plot for a BTAR of 75% indicates a 4:1 ratio of product discharge rates for an air mass flow rate of 0.12 kg/s. This tends to suggest that the material characteristics are responsible for the variation in discharge rates obtained.

8.4 THE CORRELATION OF BLOW TANK PERFORMANCE WITH AERATION PROPERTIES

If one considers the comparative plot for a BTAR of 75% (Fig. 8.8) it is noticeable that as the product mass flow rates decrease from pfa to flour to pearlite to polyethylene pellets, the products become coarser. This obviously has implications for the aeration properties of the products tested. It is quite reasonable to assume that the product/air interaction within the blow tank is every bit as significant as the product/air interaction in the conveying pipeline. On this basis, the results of the bench scale tests described in chapter 5, that is permeability factor and vibrated de-aeration constant, have been used to correlate product properties with blow tank discharge performance.

A graph of phase density against permeability factor is presented in figure 8.9 for two values of BTAR at a constant air mass flow rate. This relationship suggests that as the air permeability factor decreases, the discharge rate increases. This general trend appears to be supported by

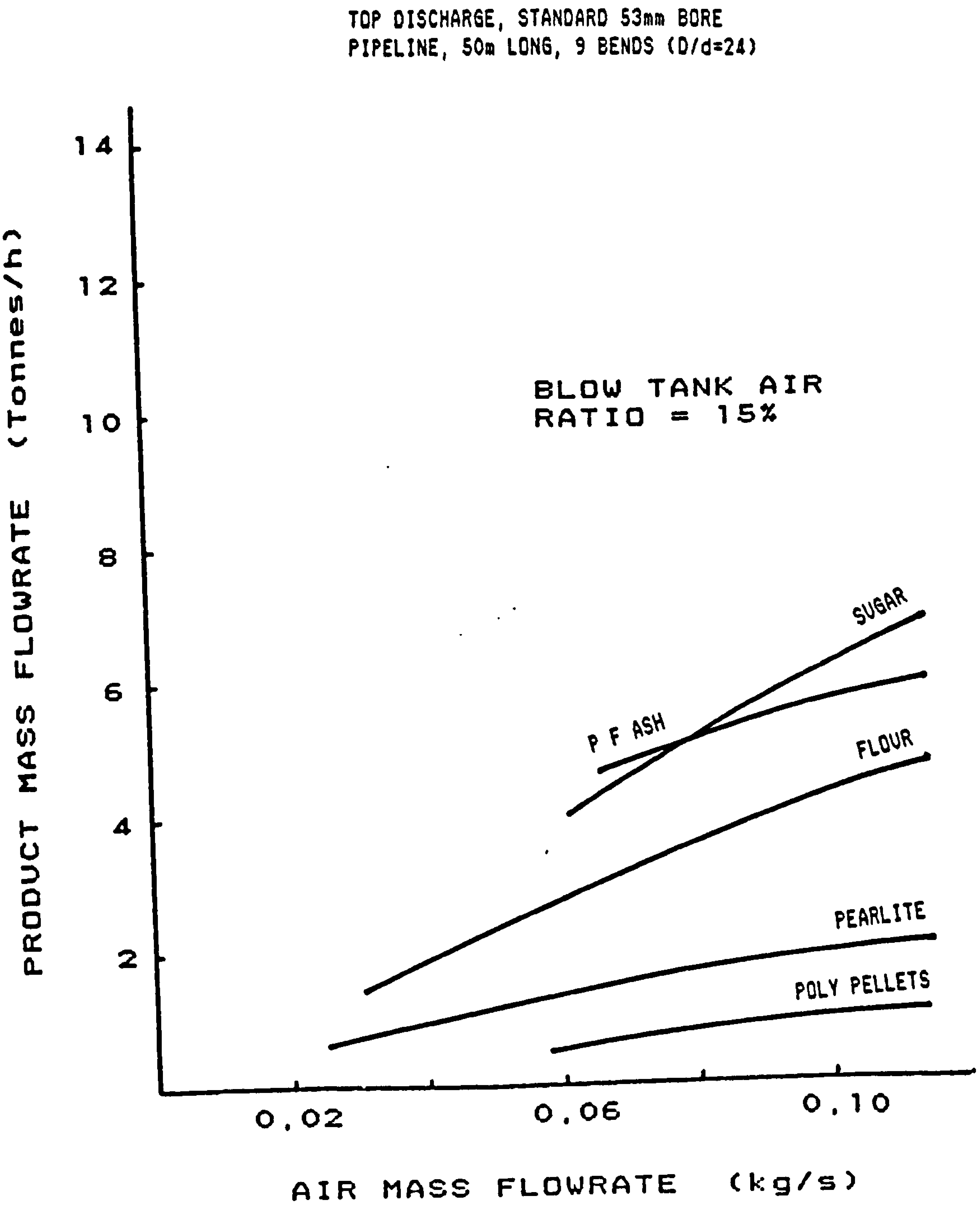


FIG. 8.7 COMPARISON OF PRODUCTS FOR A BTAR OF 15%

TOP DISCHARGE, STANDARD 53mm BORE
PIPELINE, 50m LONG, 9 BENDS (D/d=24)

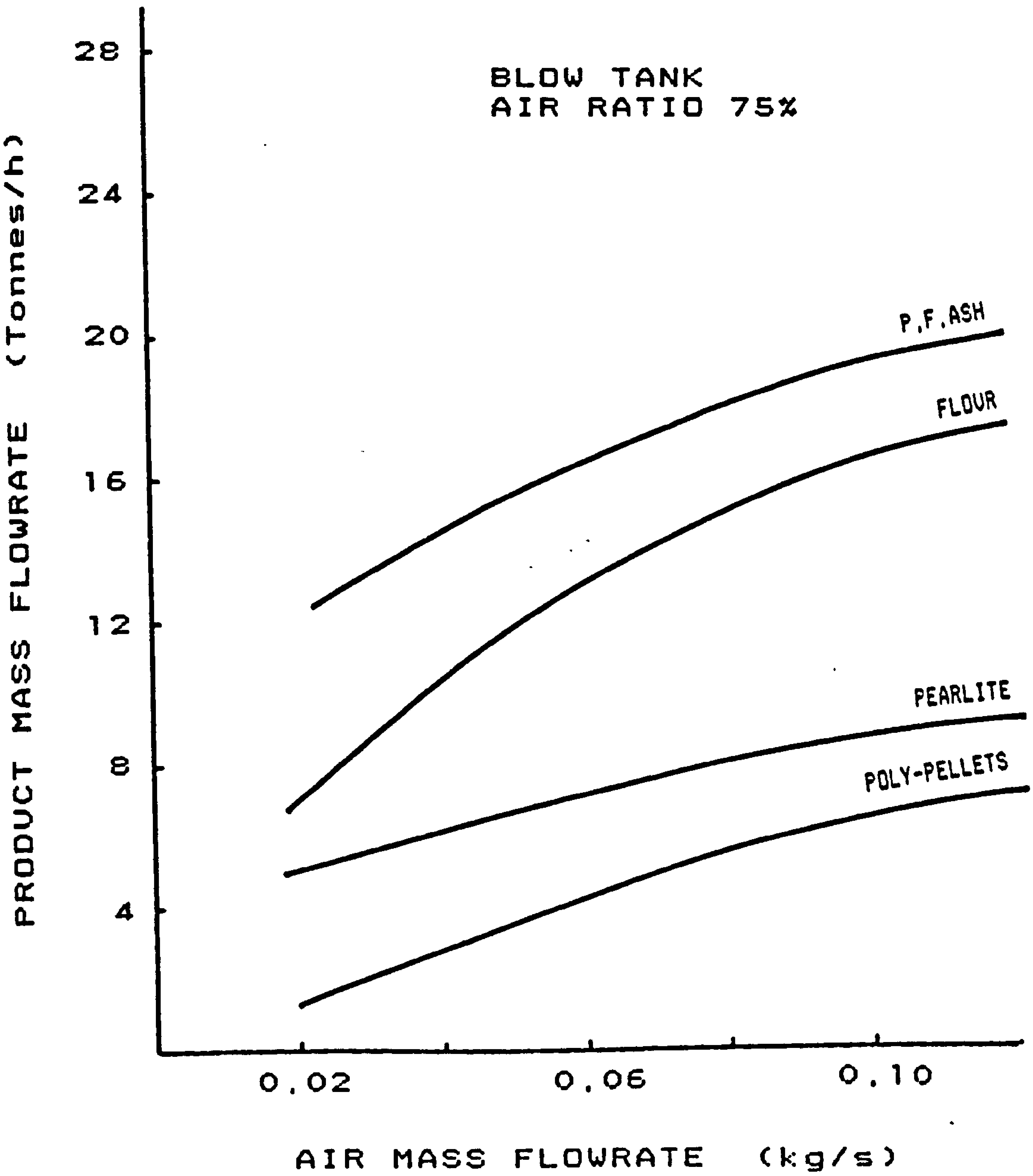


FIG. 8.8 COMPARISON OF PRODUCTS
FOR A BTAR OF 75%

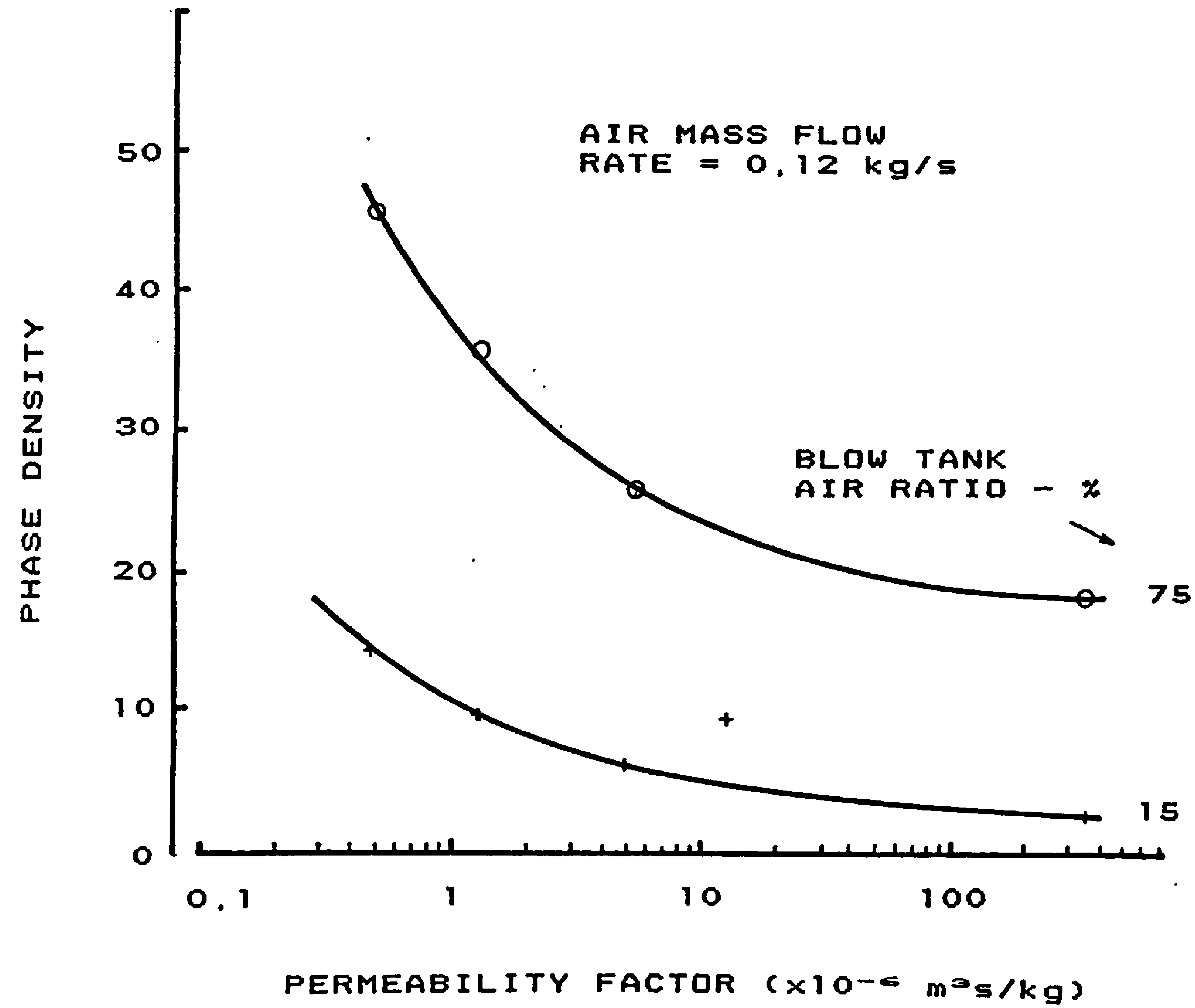


FIG. 8.9 EFFECT OF PERMEABILITY FACTOR ON BLOW TANK DISCHARGE CHARACTERISTICS

the apparent relationship between the discharge rate and the vibrated de-aeration constant which is presented in figure 8.10. This suggests that as the vibrated de-aeration constant decreases (which indicates an increase in air retention capability) the discharge rate increases.

Therefore, products which have good air retention capability and relatively poor air permeability will tend to achieve greater discharge rates than products with lesser air retentive capability and greater air permeability. This could well explain the unexpected results of Marcus and Lohrmann (Ref. 8.3). Pulverised fuel ash can have particularly good air retention capability. Athough the other two products, calcine and manganous oxide, have similar mean particle sizes, there is no information regarding the size range or the distribution, both of which will have a significant effect on air retention and air permeability capabilities.

8.5 A COMPARISON BETWEEN TOP AND BOTTOM DISCHARGE OPERATION

Being in the very fortunate position of having a blow tank capable of being used in both top and bottom discharge configurations, the opportunity was taken to undertake a comparative analysis of performance. A detailed account of the hardware used for these comparative trials is given in chapter 3. However, a schematic diagram showing the essential features of the two arrangements is presented in figure 8.11. It should be noted that, as far as possible, the pipeline configuration remained constant at 50 metres long, 53mm bore and with 9 bends.

Three products were tested in both top and bottom discharge configurations to cover a range of product types. These products were pulverised fuel ash (pfa), polyethylene pellets and silica sand. Most of the work concentrated on the pfa because it can be conveyed over a wide range of conveying conditions with ease.

The blow tank characteristics for pfa in top and bottom discharge modes are presented in figures 8.3 and 8.12. To compare the feeding capability

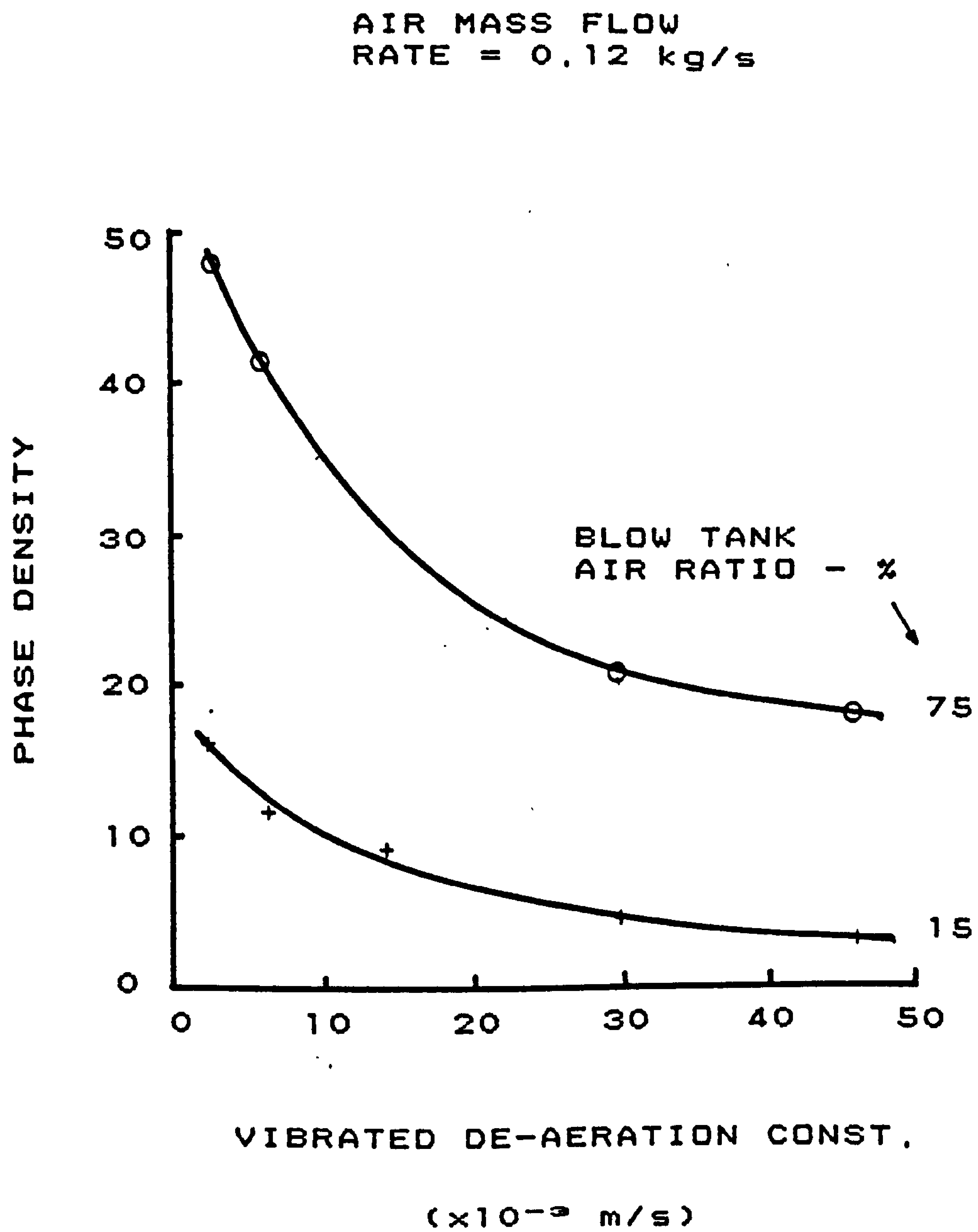
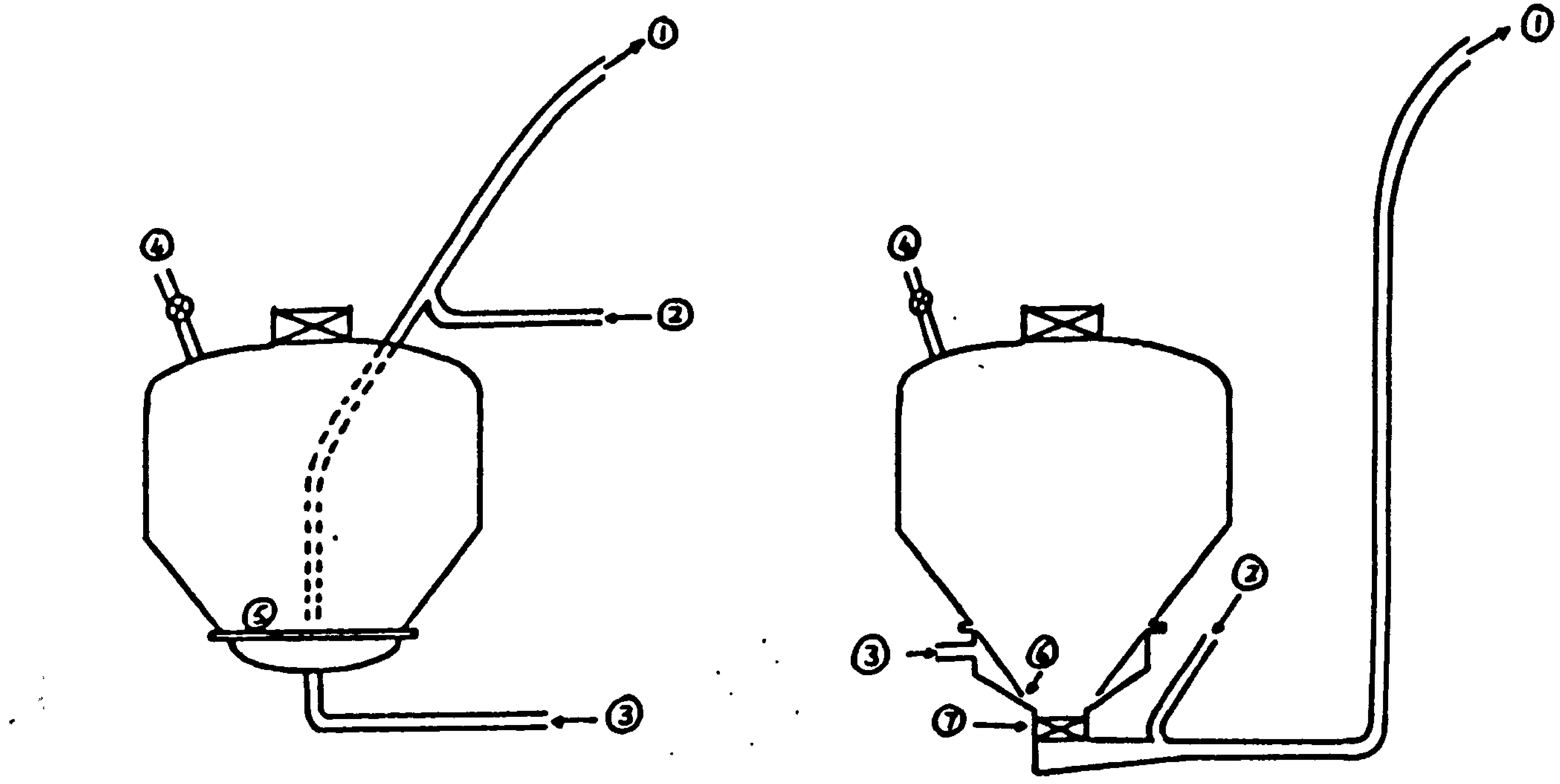


FIG. 8.10 EFFECT OF AIR RETENTION PROPERTIES ON BLOW TANK DISCHARGE CHARACTERISTICS



(A) (B)

1 TO CONVEYING LINE
2 SUPPLEMENTARY AIR
3 AIR SUPPLY TO BLOW TANK
4 BLOW TANK VENT TO RECEIVER
5 FLUIDISING MEMBRANE
6 FLUIDISING ANNULUS
7 DISCHARGE VALVE

FIG. 8.11 TOP AND BOTTOM DISCHARGE BLOW TANK SYSTEMS

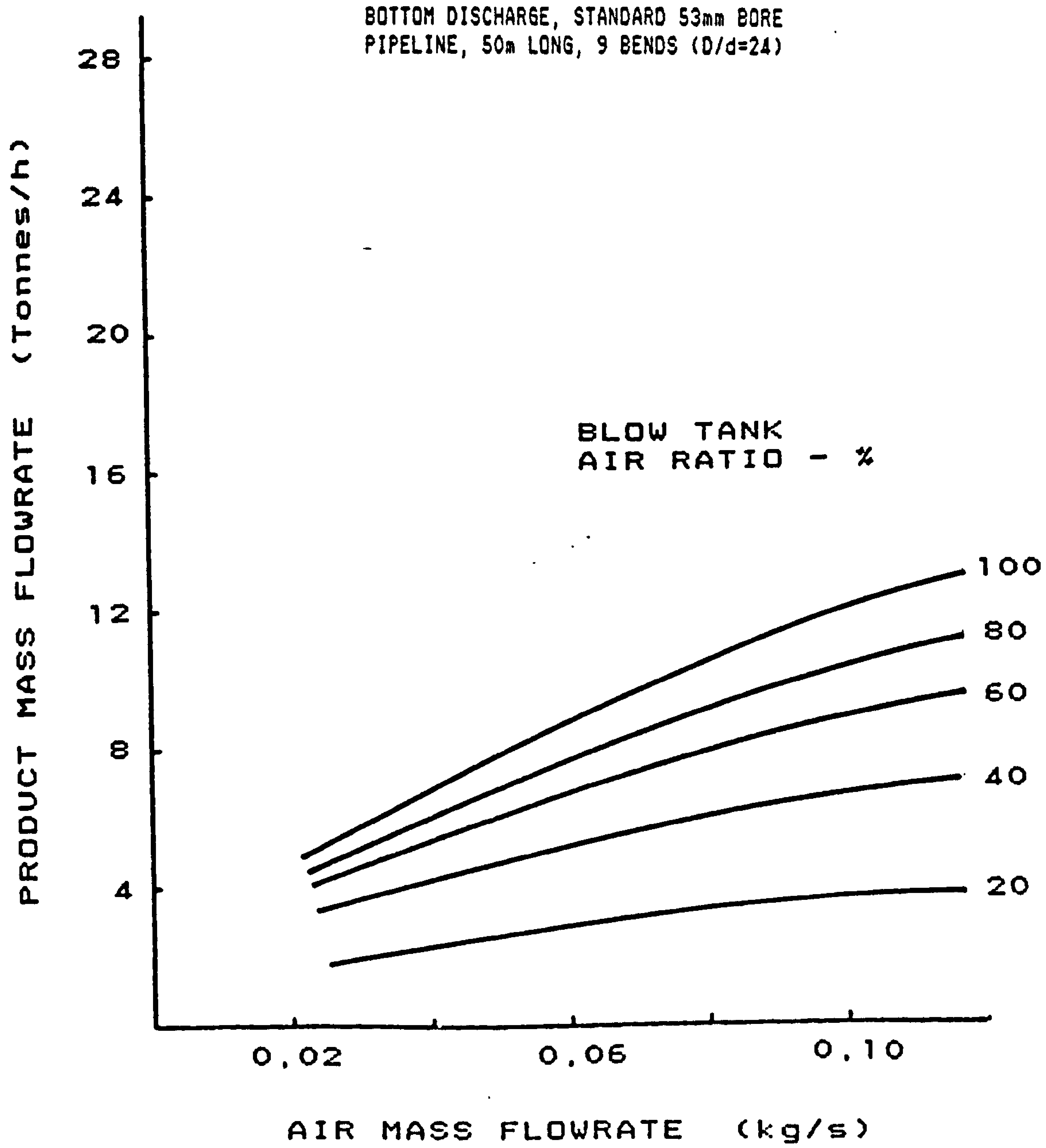


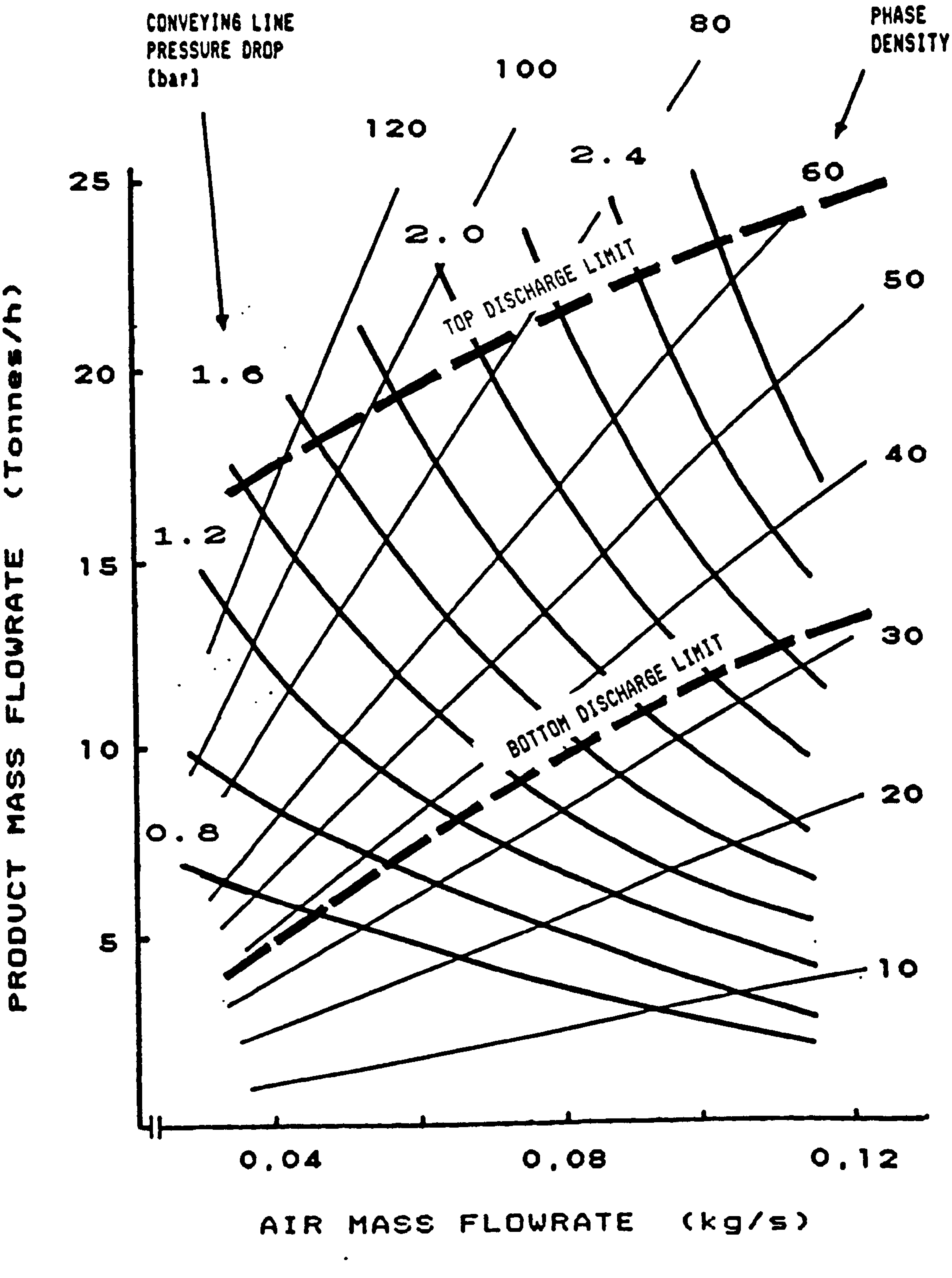
FIG. 8.12 BOTTOM DISCHARGE BLOW TANK CHARACTERISTICS FOR P.F. ASH

of the blow tank in top and bottom discharge configurations, it is necessary to compare the two sets of blow tank characteristics. These two graphs show clearly that the blow tank characteristics for top and bottom discharge configurations are quite different. A much higher discharge rate is achieved with the top discharge arrangement. A comparison of the discharge limits imposed by the two discharge arrangements is superimposed on the pipeline conveying characteristics for pfa in figure 8.13. It can be seen that the variation in discharge rates between the two configurations is approximately 2:1. It is obvious from both the conveying characteristics for the pipeline and the blow tank characteristics that, for dense phase operation, the choice of blow tank arrangement could be critical. If a conventional bottom discharge blow tank had been selected to feed the pipeline used for this test work in an operational situation, then the blow tank would not be able to achieve a discharge rate compatable with the optimum performance of the pipeline.

The blow tank characteristics for sand in both top and bottom discharge configurations are presented in figures 8.14 and 8.15. The limitation on discharge rate in the case of the sand was that imposed by the conveying line. However, it can be seen that the blow tank air ratio required to achieve the same discharge rate in bottom discharge as that in top discharge is considerably higher. This indicates the same tendency towards an enhanced discharge rate from the top discharge configuration. However, the improvement in discharge rate is not as great as that for pfa.

The blow tank characteristics for top and bottom discharge configurations are presented for polyethylene pellets in figures 8.4 and 8.16. It is interesting that the characteristics for the two configurations are very similar with the 100% BTAR lines being almost identical. This tends to indicate that there is little or no difference in discharge rate between top and bottom discharge for polyethylene pellets.

The question arises as to why there is such variation in the blow tank discharge rates for the two configurations for the pfa and apparently no



A COMPARISON OF CONVEYING
LIMITATIONS FOR TOP AND BOTTOM
DISCHARGE BLOW TANK ARRANGEMENTS
FOR PULVERISED FUEL ASH

FIG. 8.13

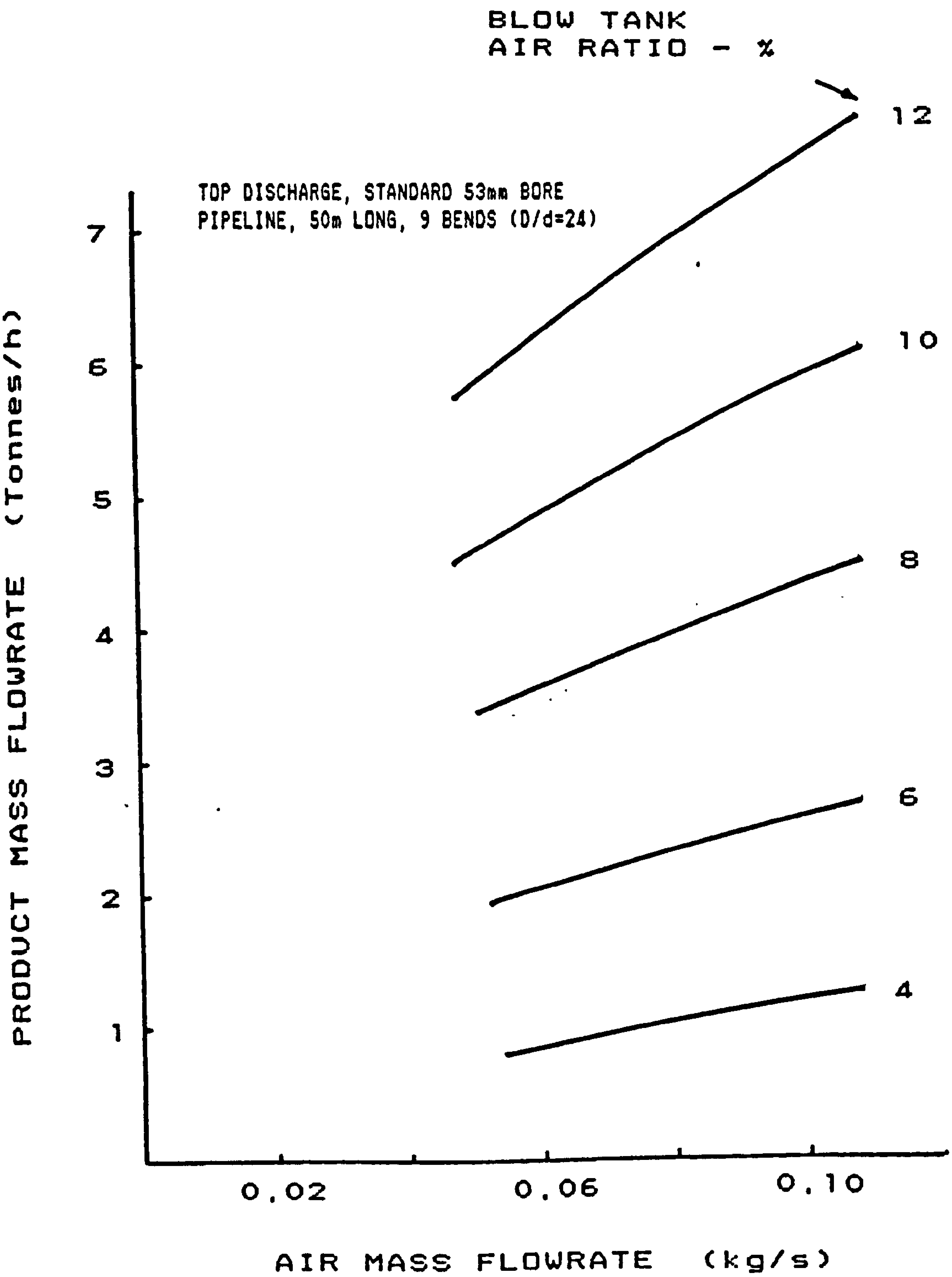


FIG. 8.14 TOP DISCHARGE BLOW TANK CHARACTERISTICS FOR SAND

BOTTOM DISCHARGE, STANDARD 53mm BORE
PIPELINE, 50m LONG, 9 BENDS (D/d=24)

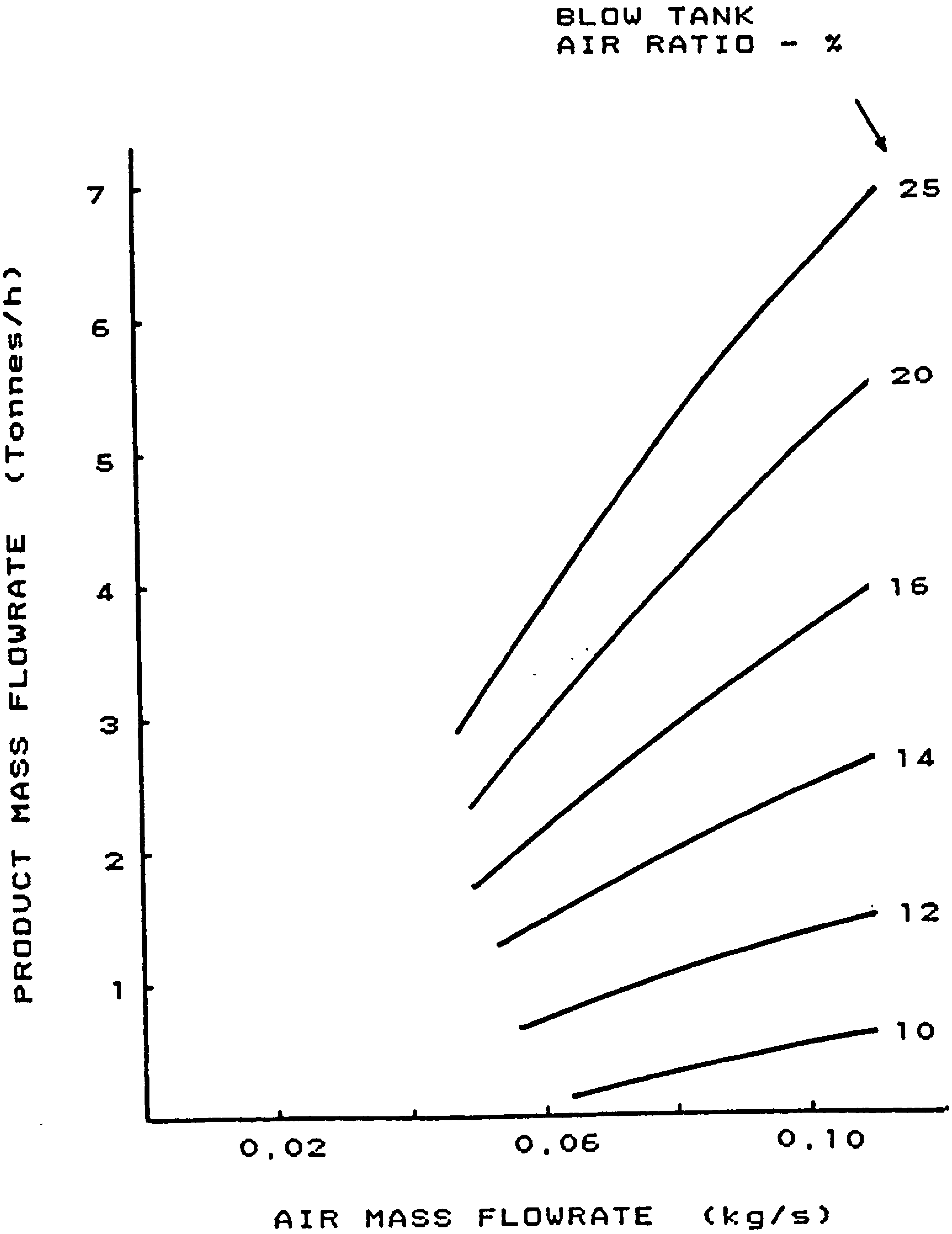


FIG. 8.15 BOTTOM DISCHARGE BLOW TANK CHARACTERISTICS FOR SAND

BOTTOM DISCHARGE, STANDARD 53mm BORE
PIPELINE, 50m LONG, 9 BENDS (D/d=24)

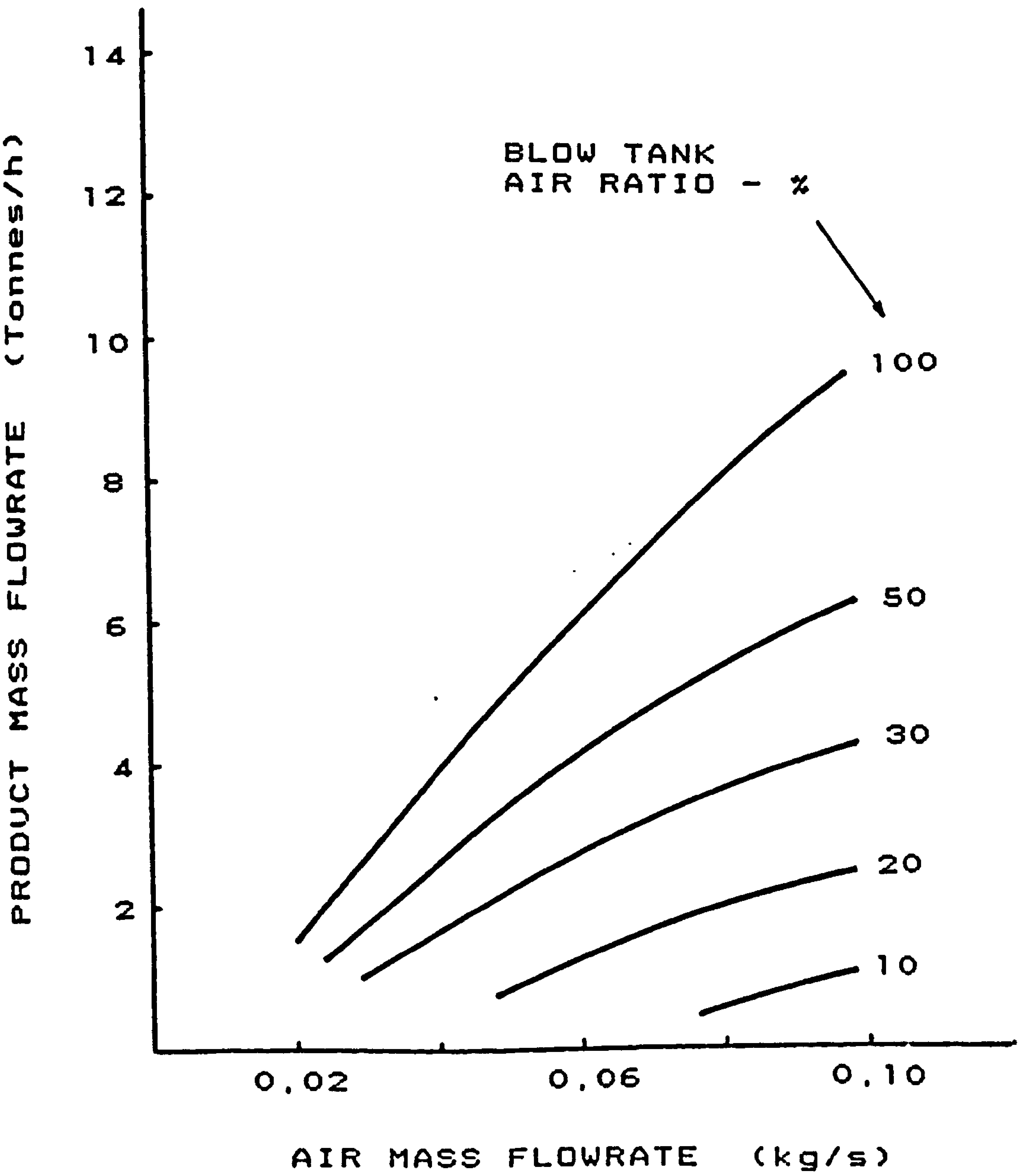


FIG. 8.16 BOTTOM DISCHARGE BLOW TANK CHARACTERISTICS FOR POLYETHYLENE PELLETS

difference in the case of polyethylene pellets. It has already been established that the product type will influence the discharge rate. Products with good air retention capability are likely to achieve higher discharge rates than products with poor air retention characteristics. Since the fundamental concepts of pneumatic conveying lie with the product/air interaction, and the fluidisation of the products is shown to affect blow tank discharge rates, perhaps one should consider the introduction of air to the blow tank in both configurations.

8.6 THE IMPORTANCE OF EFFECTIVE FLUIDISATION

The top discharge blow tank arrangement is shown in figure 8.11(a). The arrangement is quite conventional with the air entering the tank via a fluidising membrane. The large fluidising surface provides effective fluidisation of the product. However, for very cohesive products, preferential pathways may be established (rat-holing) in which case a different fluidising membrane would need to be selected.

In the case of the bottom discharge arrangement, there is scope for variation. The design used for this work is fairly common with the air being introduced via a fluidising annulus. Mainwaring (Ref. 8.6) carried out tests on varying the position of introduction of the air to a bottom discharge blow tank. He introduced the air in three different positions; directly into the top of the blow tank using a diffuser plate, through a fluidising ring similar in position to the fluidising annulus and a blow-through arrangement at the bottom of the blow tank. The results of these tests showed no significant difference in discharge rates with change in the position of the air introduction.

Kennedy, Wypych and Arnold (Ref. 8.4) report on the effect of using a fluidising cone on a bottom discharge blow tank. They report significant increases in product mass flow rate when using the fluidising cone. This tends to suggest that the fluidising annulus does not, infact, fluidise effectively.

It would appear that the key to increasing the discharge rate lies with effective fluidisation of the product whilst in the blow tank. Obviously, this can only be the case with products which exhibit good fluidising and air retention characteristics. Products like polyethylene pellets will not respond in terms of enhanced discharge rate with fluidisation. However, for products such as pfa, which are the products which are likely to be conveyed in a moving bed type dense phase, effective fluidisation within the blow tank can mean the difference between achieving the optimum conveying condition in the pipeline and not.

8.7 CONCLUDING REMARKS

The discharge rate for a blow tank is dependent on a number of factors. Attempts have been made to determine the discharge rate for a blow tank purely in terms of air supply to the blow tank or on the basis of the inlet conveying line velocity. These models may be of use when the product to be conveyed has no fluidising capability. However, tests have shown that widely differing blow tank discharge rates can be obtained which appear to be dependent on the material being conveyed.

As with the correlation between product aeration properties and pipeline performance, the same product properties influence the operation of the blow tank. It appears that the discharge rate can be significantly enhanced for products with good fluidising capability if effective fluidising within the blow tank is provided. The conventional top discharge blow tank arrangement is inherently good from the fluidising point of view. This is, probably, why it is generally recognised in the industry that the top discharge blow tank is good for fine powders. However, little quantitative work exists which correlates product properties with discharge performance.

The bottom discharge blow tank is inherently poor from the effective fluidisation point of view. The significance of the variation in discharge rates between top and bottom discharge configurations becomes apparent when designing a system. Products that are likely to be conveyed in dense phase are the very products that show a significant difference in discharge rate in conventional top and bottom discharge blow tank configurations. This means that it is possible to design a system using a bottom discharge blow tank that is not capable of conveying at the intended rate due to the limitations imposed by the blow tank.

Although the conventional bottom discharge blow tank severely restricts the feeding capability of the pipeline, little difference was observed in the product conveying characteristics. Thus, apart from the conveying limit imposed, there is no significant difference in the pressure, and hence energy, required to convey the product through a pipeline at a given product flow rate and phase density, whether the pipeline is fed by a bottom or top discharge blow tank.

It has been shown by other workers that effective fluidisation can be achieved in a bottom discharge blow tank by the use of a fluidising cone. There may well be little difference between the discharge rates of the top and bottom discharge configurations under these conditions.

CHAPTER 9

CONCLUSIONS

9.1 PREDICTION OF DENSE PHASE CAPABILITY

Although, in recent years, dense phase pneumatic conveying has gained in popularity, the majority of industrial systems are still based on suspension flow. Many of the products conveyed in dilute phase may well be capable of dense phase operation but are conveyed in a suspension flow regime simply because the dense phase potential of the product is not appreciated. The potential of a product to be conveyed in dense phase is often difficult to assess.

Qualitative assessment of the potential of a product for dense phase conveying is often made on past experience of having conveyed a similar product before. However, this method is notoriously unreliable and is illustrated by the fact that two products which by visual inspection appear to be very similar, may have very different conveying potential. One might convey in dense phase, the other might not.

Recognition of these problems has led to a number of workers attempting to predict the likely conveyability of a product based on product properties. The Geldart Classification of fluidisation behaviour (Ref. 9.1) has been evaluated by many workers in the field of pneumatic conveying and, in general, the Classification is recognised as being a useful first indicator. The Slugging diagram (Ref. 9.2) was an attempt to produce a phase diagram based on the Geldart Classification specifically for pneumatic conveying.

However, many workers such as Wypych and Arnold (Ref. 9.3), Lohrmann and Marcus (Ref. 9.4) and Jodlowski (Ref. 9.5) cite the use of a single representative diameter for particle size as inadequate since the size range and distribution as well as other factors such as particle shape are likely to have a significant effect on conveying performance. These workers present results which indicate that products classified by a single representative size can fall into the wrong category based on actual conveying performance. However, Marcus suggests that the attractiveness of the Geldart Classification in terms of its simplicity should not be overlooked.

The work presented in this thesis is an attempt to produce a phase diagram based on product characteristics which have been identified as important to conveying performance. A method has been devised to quantify the air retention capability of a product using a simple test which can be carried out in a short time.

Air retention and air permeability have been identified as product properties of particular significance to the product/air interaction which takes place in the pipeline. Other workers (Ref. 9.6 & 9.7) identify the permeability of a product to air as being significant to the plug type flow regime. This work identifies the air retention capability of a product as being of particular significance to the moving bed type flow regime of dense phase conveying.

A phase diagram has been developed which is presented in figure 9.1. It is a plot of vibrated de-aeration constant against permeability factor. Broad empirical boundaries have been drawn which divide the diagram into three groups each of which have been identified with a particular mode of conveying:-

Group 1 *Products in this group have good air retention capability. In general they fluidise well. However, products with particularly low values of vibrated de-aeration constant and permeability factor may be quite cohesive making initial fluidisation difficult. Products in this group are probably the best candidates for dense phase conveying in a conventional system and have been particularly identified with the moving bed type flow regime. They tend to convey at low velocities and high phase densities.*

Group 2 *Products in this group have mid range values of vibrated de-aeration constant and permeability factor. This indicates no special capability for fluidisation or air retention. In general, these products will not convey in dense phase in a conventional system. These products can be conveyed in suspension at high velocities and low phase densities and will*

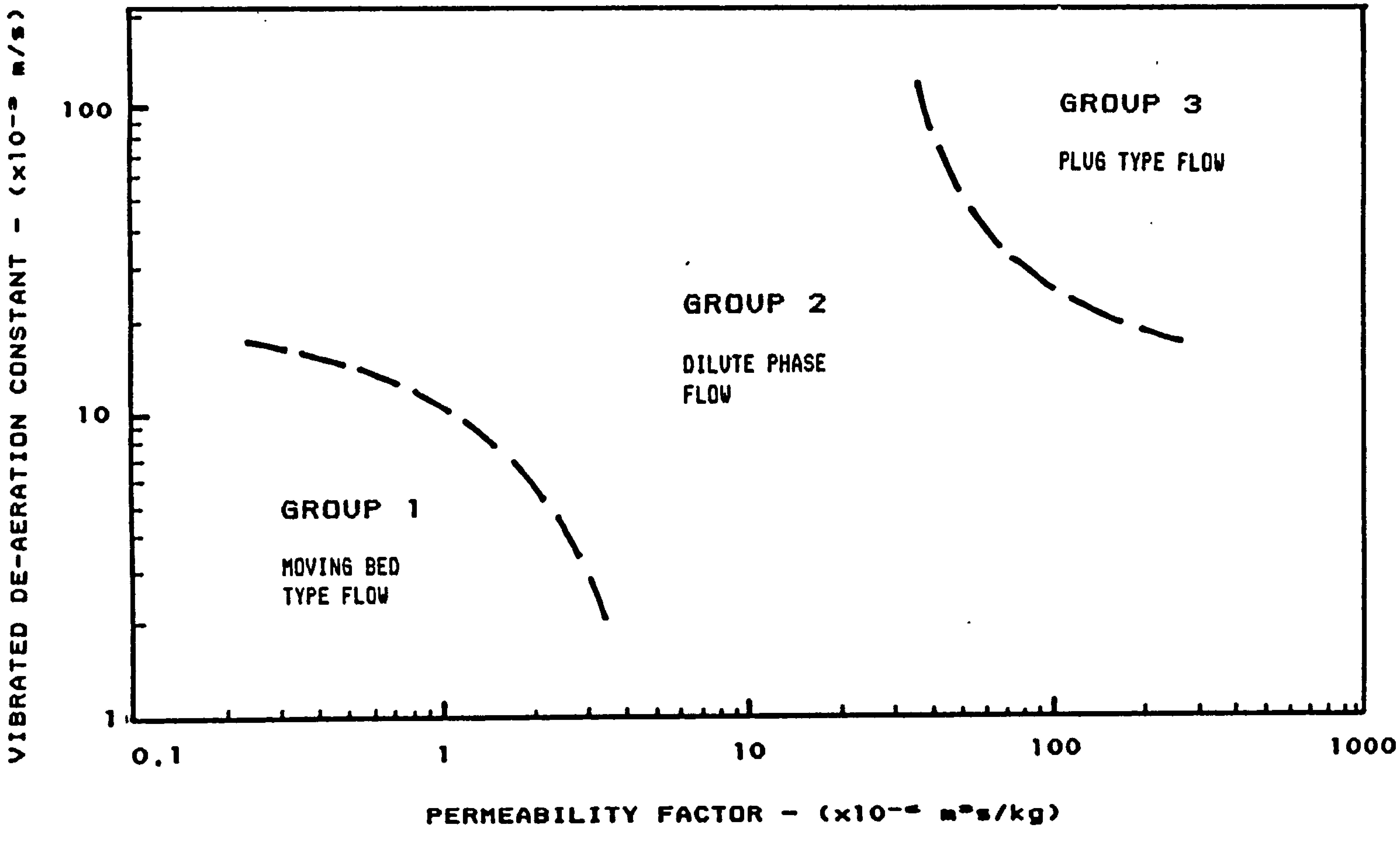


FIG. 9.1 PHASE DIAGRAM FOR PNEUMATIC CONVEYING IN A CONVENTIONAL SYSTEM

tend to block the conveying line at or near the saltation velocity (generally around 14 - 16 m/s). Some products within this group may be conveyed in dense phase in some of the innovative systems available.

Group 3 Products in this group have good air permeability and poor air retention. These products are capable of being conveyed in dense phase and are particularly associated with the plug type flow regime.

The advantage of this classification of products over existing methods is that the tests carried out to position a material on the diagram and hence determine its likely conveyability are based on product/air interactions which take into account particle size range and distribution. In addition, the bench scale tests are simple to carry out and the results take no longer to obtain than those necessary to position a product on the Geldart Classification.

9.2 PREDICTION OF PNEUMATIC CONVEYING PERFORMANCE IN THE MOVING BED TYPE FLOW REGIME

The performance of a product in terms of product mass flow rate for a given set of conditions can vary greatly in the moving bed type flow regime of dense phase pneumatic conveying. A 20:1 variation has been obtained during the conveying trials for this work. This variation could be vitally important when designing a system for dense phase conveying.

In most cases, the performance level of a product is determined by carrying out a set of pilot conveying trials using a system which is as similar to the actual application as possible. Very little work has been reported with regard to attempts at predicting the performance level of a product in dense phase. Those which are reported, are based on models derived by an analysis of the mechanics of flow which does not, generally, take into account variation in product properties other than a particle friction factor. Frequently, these models are based on plug flow. Dixon (Ref. 9.2) attempts to predict a theoretical maximum phase density, which is unlikely to be achieved in practice, based on minimum fluidising velocity, voidage and particle density.

During the conveying trials, it became apparent that products which exhibited good air retention capability appeared to achieve higher product throughputs for given conditions. Products tested which conveyed in dense phase as a moving bed were used to investigate possible links between air retention capability and conveying performance. The graph presented in figure 9.2 is an example of the relationship which exists between the product throughput and the air retention capability of the product. The product throughput is expressed in terms of the generalised variable solids mass flux which is defined by the following expression:

$$\text{Solids Mass Flux, } M = \frac{\dot{m}_p \, L_e}{A}$$

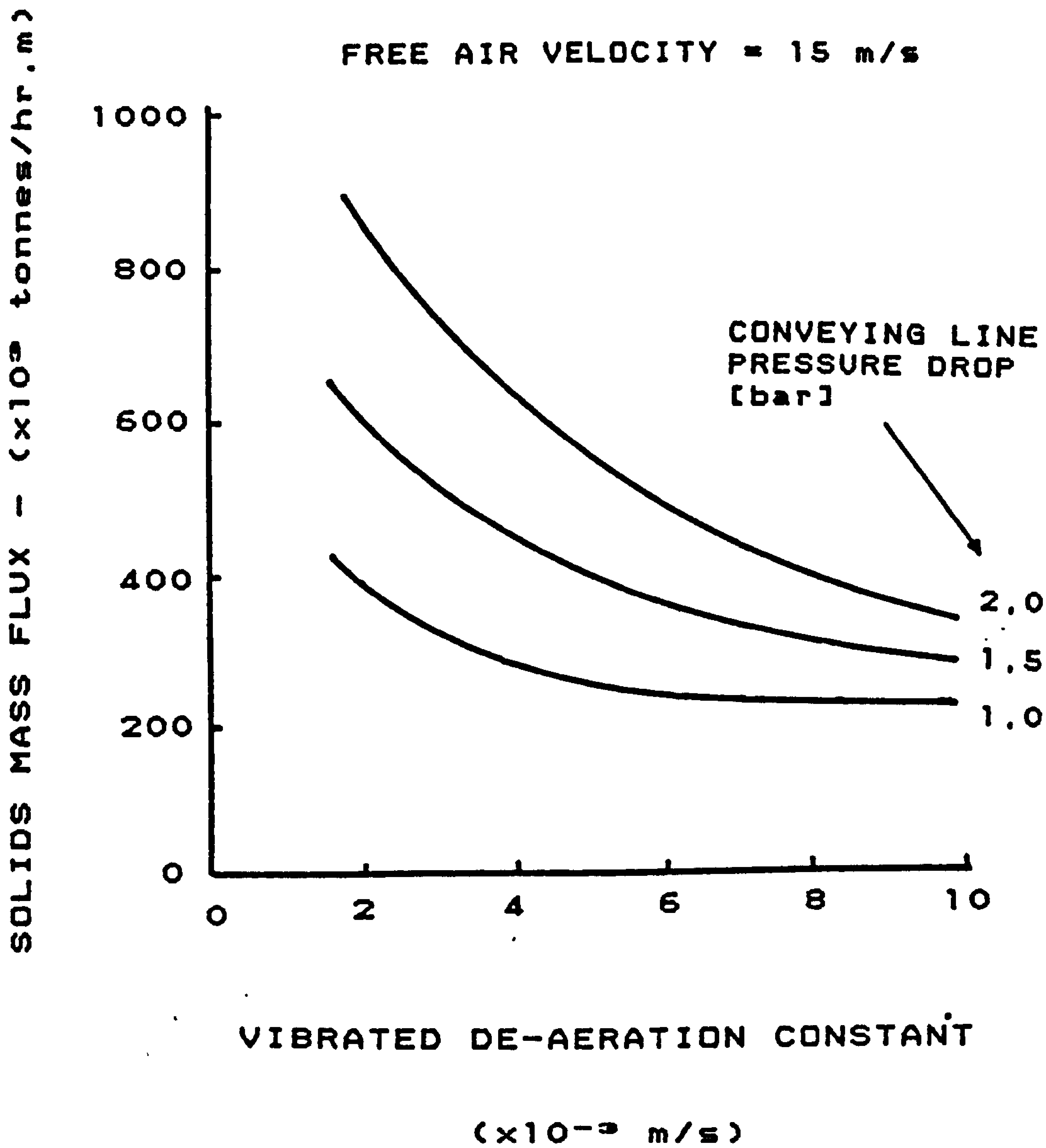
where $\dot{m}_p$ = product mass flow rate (tonne/h)

L_e = equivalent length of conveying pipeline (m)

A = cross-sectional area of conveying pipeline (m^2)

The air retention capability of the product is determined using a new test developed during this research programme by the author which is described in chapter 5. The test measures the air retention capability of the product in terms of the vibrated de-aeration constant. It can be seen from figure 9.2 that as the air retention capability increases (vibrated de-aeration constant decreases), the product throughput for a given conveying line pressure drop and free air velocity increases. Graphs relating product throughput and air retention are produced for three free air velocities covering the range of conditions for the moving bed type flow regime. Graphs representing free air velocities of 20 and 25 m/s are presented in figures 7.15 and 7.16 in chapter 7.

Hence, once a product has been identified as capable of being conveyed in a dense phase moving bed type flow regime using the phase diagram, the relationships derived between product throughput and air retention



THE CORRELATION BETWEEN BULK PROPERTIES AND PNEUMATIC CONVEYING PERFORMANCE

FIG. 9.2

capability can be used to estimate the likely conveying performance. The use of the generalised variable solids mass flux allows prediction of product mass flow rate for a limited range of pipeline lengths and bores.

It has also been identified that the minimum conveying velocity of a product can be correlated with the air retention capability of the product. Figure 9.3 presents the relationship between minimum conveying velocity and vibrated de-aeration constant. This relationship provides a guide to the likely minimum conveying velocity of a product based on the vibrated de-aeration test.

Together, the graphs presented in figures 9.2 and 9.3 provide the necessary information based on bench scale tests of the product to predict the likely conveying performance for pipeline bores in the range 50 to 105mm and pipeline lengths up to 200m.

9.3 THE EFFECT OF PRODUCT CHARACTERISTICS ON BLOW TANK PERFORMANCE

The main thrust of the test programme was concerned with the pipeline. However, to obtain a wide range of conveying conditions, a blow tank was used as a feeder. The results of the correlation of product properties with pipeline performance led to closer attention being paid to the operation of the blow tank. The blow tank is probably the most widely used feeder for dense phase conveying and as such is an important system component with regard to successful operation.

It has been established by other workers (Ref. 9.8) that fluidisation of the product can enhance the discharge rate. However, in the light of the correlation between the aeration properties of the product and the product performance in the pipeline, the data obtained during the conveying trials which relates to the blow tank characteristics was analysed and correlated with the same product properties. Since fluidisation is known to be important to blow tank performance it was felt that similar product properties may well have a significant effect on blow tank discharge rates.

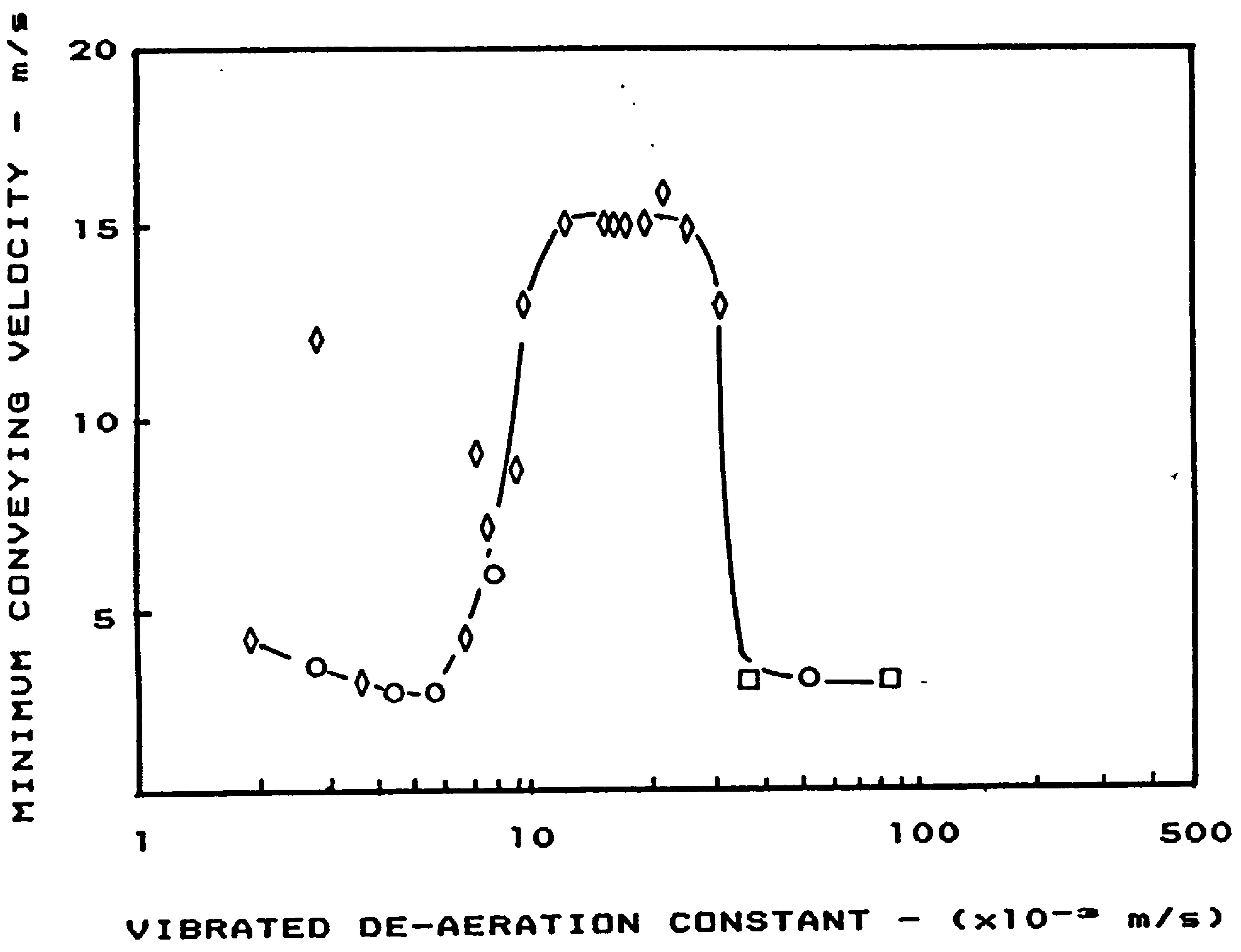


FIG. 9.3 THE RELATIONSHIP BETWEEN MINIMUM CONVEYING VELOCITY AND VIBRATED DE-AERATION CONSTANT

The graphs presented in figures 9.4 and 9.5 show the effect of air retention capability and air permeability on the blow tank discharge rate in terms of phase density. It can clearly be seen that as the air retention properties increase and the air permeability decreases, the blow tank discharge rate increases.

These results led to a comparison of conventional top and bottom discharge blow tank systems. The blow tank used for this work was designed to operate in either top or bottom discharge configuration with a few minor changes. Full details of the two arrangements are given in chapter 3. The comparison involved testing three different products with varying degrees of air retention capability and air permeability in both top and bottom discharge arrangements using the same pipeline configuration. The outcome of the tests was to suggest that, for products which have good air retention capability, the effective fluidisation of the product in the blow tank was critical if optimum conveying rates were to be achieved in the pipeline.

For pulverised fuel ash, the discharge rates achieved in the bottom discharge arrangement were about half those achieved in top discharge. For products such as polyethylene pellets, which have virtually no air retention capability, the difference in discharge rates obtained in top and bottom discharge configurations was negligible. This tended to indicate that the effective fluidisation of air retentive products was crucial if maximum discharge rates were to be achieved. It also indicated that the conventional bottom discharge arrangement is not particularly effective with regard to fluidisation of the product.

9.4 CONCLUDING REMARKS

The importance of product properties with regard to pneumatic conveying has been recognised by many workers qualitatively. Some attempts have been made to produce phase diagrams which have been based on a mean particle size. This work attempts to classify products by means of a phase diagram which is based on product properties which involve

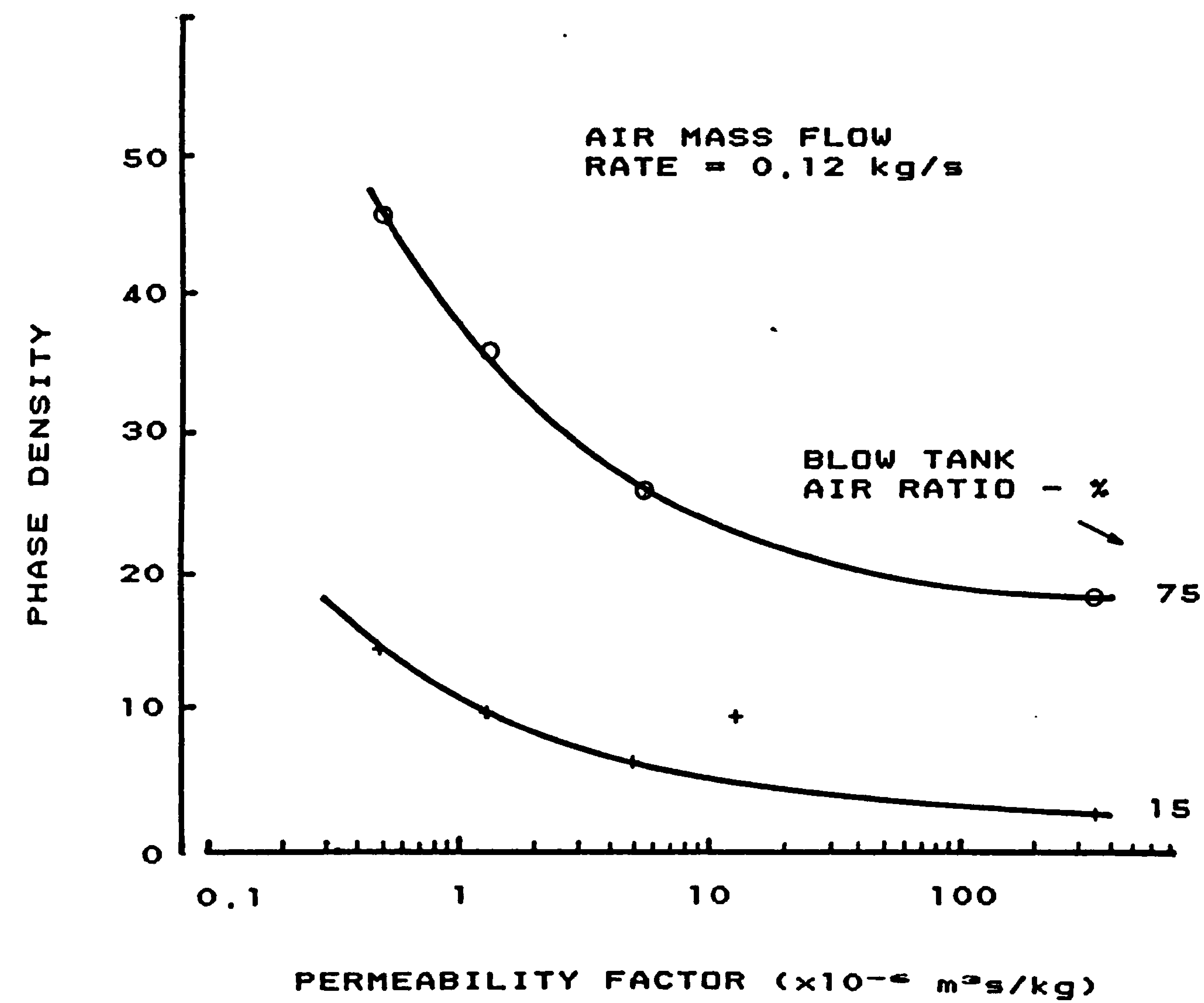


FIG. 9.4 EFFECT OF PERMEABILITY FACTOR ON BLOW TANK DISCHARGE CHARACTERISTICS

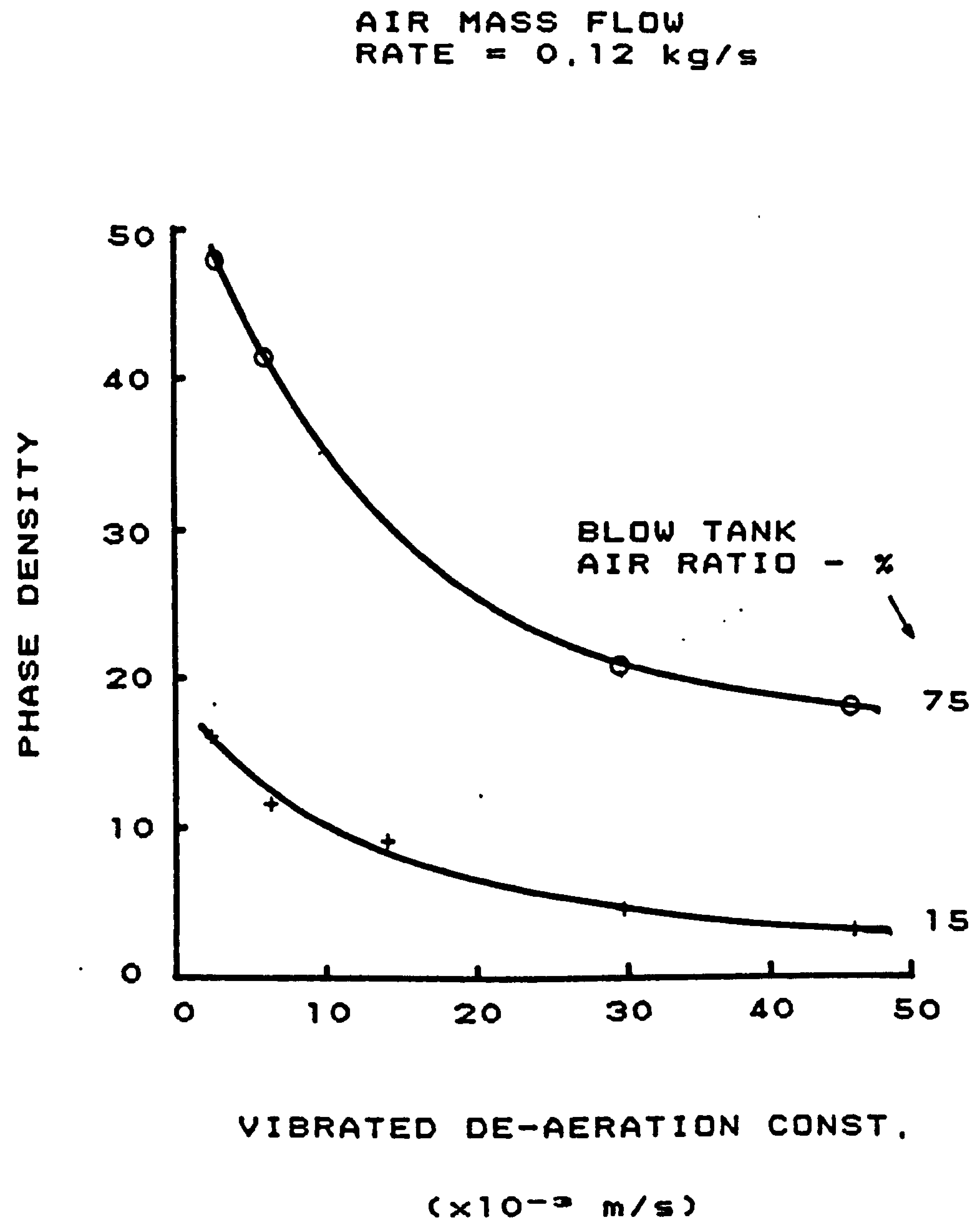


FIG 9.5 EFFECT OF AIR RETENTION PROPERTIES ON BLOW TANK DISCHARGE CHARACTERISTICS

product/air interaction. It is believed by the author that these product properties are more representative of the interactions that take place between the product and air in the pipeline than basing fluidisation behaviour on a single representative size. In addition, the product properties used for the correlations are all embracing taking into account size range and distribution as well as factors such as particle shape. The tests required to position a product on the phase diagram are simple and should take no longer than the time required to carry out a size analysis and particle density test.

For products which are indicated as likely to be conveyed in a moving bed type flow (which is the most commonly used mode of dense phase conveying) a correlation is proposed which will give a first indication as to the likely conveying performance in terms of mass throughput for given conditions. A correlation indicating probable minimum conveying velocity is also proposed.

The importance of effective fluidisation on blow tank performance for air retentive products is discussed. The performance of the blow tank can be critical to the overall performance of the system. A correlation is proposed which indicates the effect of product type on the discharge of the blow tank. The correlation is based on work for a single pipeline and for the top discharge blow tank arrangement. However, it is believed by the author that the trends indicated in this correlation could be extended in principle to other systems qualitatively.

CHAPTER 10

SUGGESTIONS FOR FURTHER WORK

10.1 THE GLOBAL APPROACH

The global approach involves the production of empirical correlations based on a macroscopic analysis of the system under consideration. This approach provides a method of identifying those parameters which have a significant affect on the overall system performance. This is important when the correlation is to be used as a design tool. These aims are achieved by observing the complete system and attempting to eliminate as many variables as possible. For example, in this work the pipeline configuration, number and type of bends and blow tank arrangement remained constant which allowed the results of the conveying trials for a range of products to be compared on the basis that the system variables were constant. Therefore, any substantial variation in system performance must be product dependent. The scope of the correlations presented in this work would be difficult to achieve by conventional mathematical modelling.

The phase diagram presented in this thesis is based on 24 products. This is a relatively large number when one considers the work involved in assessing each of the products' capabilities i.e. full scale conveying trials and the bench scale tests. However, in terms of the number of data points these products provide to produce a phase diagram, the number is quite small. There is obviously a need to expand the database to allow further development of the correlations.

The global approach can be a powerful design tool. However, by its very nature tends to be a macroscopic view of the subject in question and is relatively insensitive. For practical applications, the global approach is advantageous due to its wide applicability. For this reason, the development of the global approach, in terms of extending the database and refining and modifying the correlations on the basis of new data has to be an area for further work.

10.2 THE MATHEMATICAL MODELLING APPROACH

One of the advantages of the global approach is that there is no need to make a large number of simplifying decisions in order to contain the problem within constraints that make mathematical modelling possible. The correlations are made on an empirical basis and therefore represent an observed pattern of behaviour rather than a modelled approximation. The correlation is then used to predict the behaviour of an unknown product on the basis of past observation. Because the correlation does not involve many assumptions and often has a wider applicability than the mathematical models, the empirical correlations are often viewed by industry as being of more use. This is probably true in the short term.

However, one should not overlook the usefulness of mathematical modelling especially in the long term. Progress with mathematical models is a much longer process. Many of the problems associated with mathematical modelling stem from the validity of assumptions i.e. identifying which parameters are particularly significant for particular modes of flow. In many ways the results of empirical correlations such as those presented in this work give an indication as to which parameters should be considered when trying to model a particular flow regime.

Much work has been published with regard to the mathematical modelling of the plug flow regime. However, trying to model sliding bed type flow is much more difficult. Those that have tried to model sliding bed type flow have done so by considering higher velocity low phase density forms of the regime which allow a steady state, continuous flow type model to be produced. In most cases, these models do not take into account product properties.

It is easy to understand why steady state, continuous flow conditions have been adopted. It is because of the problems invoved in modelling non-steady flows and the difficulty in incorporating the product properties mathematically. However, with the increasing sophistication of computer software packages using finite element methods for fluid flow, it is now possible to model these difficult flow regimes over small time intervals using non-linear differential equations. These allow continual updating with each consecutive time interval.

Therefore, in the long term, the use of computing power together with mathematical modelling has the potential for a powerful analytical approach. However, this is not likely to yield a quick solution and the wide applicability of the empirical correlation is likely to remain the most powerful design tool for some time to come.

10.3 THE BLOW TANK

Unlike the correlations for the pipeline, the correlations proposed for the blow tank are based on a single blow tank in two different configurations. However, the work reported by other researchers suggests that the trends identified can be assumed to hold for different blow tank sizes. A generalised correlation can be produced using the phase density as a measure of blow tank discharge performance. However, it would be useful to know how the geometry of the blow tank affects the discharge performance and whether any change in performance is due to a change in fluidisation capability of the revised geometry or due to some other cause. This would be difficult to achieve since several blow tanks may have to be used.

APPENDIX I

REFERENCES TO THE LITERATURE

REFERENCES TO THE LITERATURE

Chapter 2: Review of Previous Work and Current Industrial Practice

2.1 ALBRIGHT C W, HOLDEN J H, SIMONS H P & SCHMIDT L D (1949)
Pneumatic Feeder for Finely Divided Solids. Chem Eng.
June, pp 108-111.

2.2 RAMACHANDRAN P S, BURKARD D G & LAUER B E (1970)
Studies of Dense Phase Horizontal Flow of Gas Solids Mixtures.
Indian J Technol 8, June, pp 199-204.

2.3 SCHUCHART P (1970)
Pneumatic Conveying. Chem and Process Eng. May, pp 76-80.

2.4 MASON J S, MILLS D, REED A R & WOODCOCK C R (1984)
Pneumatic Handling of Bulk Materials. Part A, Short course notes.
Thames Polytechnic, London. p 19.

2.5 DIXON G (1979)
The Impact of Powder Properties on Dense Phase Flow. Proc. Int.
Conf. on Pneumatic Conveying. Jan. London. UK

2.6 DIXON G & SIMMS C H (1978)
ICI Dense Phase Conveying Project. Confidential Preliminary Report.
Imperial Chemical Industries Ltd - Plastics Division, Welwyn Garden
City. May.

2.7 ARNOLD P C & ARMITAGE W R (1982)
Dense Phase Pneumatic Conveying of Bulk Solids. Process & Control
Eng. vol. 35, No. 12, December, pp 10-15.

2.8 CHEN T Y, WHLAWENDER W P & FAN L T (1979)
J. for Bulk Solids Technol. vol.3, no. 3.

2.9 SHEPHERD N G (1979)
Dense Phase Pneumatic Conveying of Coarse Granular Materials in
the Extrusion Flow Regime. Proc. of the Tech. Prog. of the 4th Int.
Powder and Bulk Solids Handling and Processing Conf. organised by
Ind. and Scientific Conf. Management Inc., 222 West Adams St.
Chicago, Illinois 60606, USA.

2.10 FENTON D L (1979)
Pneumatic Conveying Overview., Proc. Int. Powder and Bulk Solids
Handling and Processing Conf., Philadelphia. May 15-17.

2.11 *KONRAD K, HARRISON D, NEDDERMAN R M & DAVIDSON J F (1980)*
Proc. Pneumotransport 5, Organised by BHRA Fluid Engineering, Cranfield, Bedford, UK. p 225.

2.12 *VEN C Y & SIMONS H P (1959)*
Flow Characteristics in Horizontal Fluidised Solids Transport. A.I.Ch.E. Journal, Vol. 5, no. 2., June, pp 263-267.

2.13 *VIRTH K E & MOLERUS O (1982)*
Prediction of Pressure Drop with Pneumatic Conveying of Solids in Horizontal Pipes. Proc. of Pneumatech 1 organised by the Powder Advisory Centre, PO Box 78, London. UK.

2.14 *DOIG I D (1975)*
Design and Performance Aspects of Dense Phase Pneumatic Conveying Systems. The South African Mechanical Engineer, Vol.25, December. pp 394-403.

2.15 *VELSCHOF G (1962)*
Pneumatische Forderung bei grossen Fordergutkonzentrationen (Pneumatic Conveying at High Particle Concentrations) VDI-Forschungsheft 492.

2.16 *HITT R J (1984)*
An Investigation into the Low Velocity Pneumatic Conveying of Bulk Solids. PhD Thesis, Thames Polytechnic, London. UK.

2.17 *RAUSCH W (1966)*
Untersuchungen uber die Pneumatische Dichtstromforderung. (Dense Phase Pneumatic Conveying). Fordern und Heben, Vol.16, No. 12, pp 968-976.

2.18 *VEBER M (1966)*
Kompressible rohstromung von gas-feststoff-gemischen bei honen Material Beladugen (Compressible Flow of Gas-Solid Mixtures in Pipelines at High Material Transport Rates). Aufbereitungs - Technik, Vol.10, pp 603-613.

2.19 *MUSCHELKNAUTZ E & KRAMBROCK W (1969)*
Vereinfachte Berechnung Horizontaler Pneumatischer Forderleitungen bei Hoher Gutbeladungen mit Feinkornigen Produkten (Simplified Calculations on Horizontal Pneumatic Feed Pipes at High Loading with Finely Divided Granular Products). Chemie-Ing-Techn, Vol.41, Jahrg, No. 21, pp 1164-1172.

2.20 *ZENZ F A & OTHMER D F (1960)*
Fluidisation and Fluid-Particle Systems. Reinhold Chem. Eng. Series, Reinhold Publishing Corp., New York. p 314.

2.21 *LIPPERT A (1966)*
Pneumatic Conveyance of Large Concentrations of Solids. Chemie-Ing-Techn, Vol. 38, No.3, pp 350-355.

2.22 *MILLS D (1980)*
The Operational Velocity Range in Pneumatic Conveying and its Influence on Product Flow Rate. Pneumotransport 5, Paper C1. Organised by BHRA Fluid Engineering, Cranfield, Bedford, UK.

2.23 *ZENZ F A (1964)*
Conveyability of Materials of Mixed Particle Size. I & E C Fundamentals, Vol. 3, No.1, February.

2.24 *GELDART D (1973)*
Types of Gas Fluidisation. Powder Technology, Vol.7(1973), pp 285-292.

2.25 *LEUNG L S & WILES R J (1976)*
Pneumotransport 3, Proc. Paper C4, BHRA Fluid Engineering, Cranfield, Bedford. UK.

2.26 *ZUKOSKI E E (1966)*
J. Fluid Mech. Vol. 25, part 4, pp 821-837

2.27 *WYPYCH P W & ARNOLD P C (1984)*
The Use of Powder and Pipe Properties in the Prediction of Dense Phase Pneumatic Transport Behaviour. Proc., 2nd Int. Conf. on Pneumatic Conveying Technology (Pneumatech 2), Sept., Canterbury. UK.

2.28 *JODLOWSKI C (1984)*
Considerations on Two Phase Gas/Solid Flow at Low Velocities. Proc. 2nd Int. Conf. on Pneumatic Conveying Technology (Pneumatech 2), Sept., Canterbury. UK.

2.29 *LOHRMANN P C & MARCUS R D (1983)*
The Performance of a Bottom Discharge Blow Vessel Pneumatically Conveying Three Group A Materials. Int. Conf. on Bulk Materials Storage, Handling and Transportation., August, Newcastle, Australia.

2.30 *WERNER D (1983)*
Influence of Particle Size Distribution During Pneumatic Dense-Phase Conveying in Vertical and Horizontal Pipes. Bulk Solids Handling. Vol.3, No. 2, June.

2.31 *ZENZ F A (1984)*
Conveyability and Powder Classification. Proc. 9th Annual Powder and Bulk Solids Conf. and Exhib., O'Hare Expo. Centre, Rosemont, Chicago. May.

2.32 *ZENZ F A & ROWE P N (1976)*
Particle Conveying in Extrusion Flow. Fluidisation Technology. Vol.2, Ed. by D L Keairns, Hemisphere Pub. Co. Washington. USA.

2.33 ZENZ F A & LABOURT-IBARRE P (1986)
Understanding Dense Phase Conveyance of Solid Particulates via their Rheological Properties and the Fluid-Solid Phase Diagram. Proc. 11th Annual Powder and Bulk Solids Conf., O'Hare Expo. Centre, Rosemont, Chicago. May.

2.34 CALDWELL L G (1979)
Clarifying the Definition of Modes of Flow by Which Particulate Solids are Pneumatically Conveyed. Proc. Technical Prog., Int. Powder and Bulk Solids Handling and Processing Conf., May.

2.35 ANON - (Trade Literature)
Dense Phase Conveying Systems. Neu Engineering Ltd, Planet House, Guildford Road, Woking, Surrey. GU22 7RL.

2.36 ANON - (Trade Literature)
Fluidlift Pneumatic Conveying System, Buhler Miag GmbH, Postfach 3369, D-3300 Braunschweig/BRD.

2.37 FLATT W & BLUMER P (1982)
Low Velocity Pneumatic Conveying of Loose Bulk Materials., Proc. of Int. Powder and Bulk Solids Handling and Processing Conf. Tech. Prog., Rosemont, Illinois, USA.

2.38 ANON - (Trade Literature)
PNEUMOSPLIT®DBF - Dense Phase Conveying System. Waeschle Maschinenfabrik GmbH, Postfach 2440. D-7980 Ravensburg.

2.39 ANON - (Trade Literature)
Dense Phase/Low Velocity Pneumatic Conveying Idea Book. Dynamic Air Inc., 1125 Wolters Blvd, PO Box 43074, St. Paul, Minnesota 55164 USA.

2.40 ANON - (Trade Literature)
Pneumatic Conveying Systems, Buhler Miag GmbH, Postfach 3369, D-3300 Braunschweig/BRD.

2.41 ANON - (Trade Literature)
Sturtevant Engineering company Ltd., Westergate Road, Moulsecomb Way, Brighton, BN2 4QB.

2.42 STB Engineering Ltd, Fromehill Works, Stroud, Glos.

2.43 LANCHESTER F G (1971)
Pneumatic Conveying - a new concept. Sturtevant Engineering Co., 20th Oct. Available from Sturtevant Welbeck Ltd, Westergate Road, Moulsecombe Way, Brighton. BN2 4QB.

2.44 ANON - (Trade Literature)
Macawber Ash Handling - Denseveyor systems for all ash handling applications. Simon Macawber Ltd., Shaw Lane Industrial Estate, Doncaster, South Yorkshire, England DN2 4SE.

2.45 *CRAWLEY M F (1976)*
Pneumatic Conveying for Foundries. Presented to the South African Institute of Foundrymen. FWP Journal, January.

Chapter 3 Conveying Test Plant

3.1 *VAGHORN D J & MASON J S (1976)*
The Effect of Aeration and Position of Inlet to the Conveying Line on the Discharge Characteristics of a Blow Tank. Bulk Solids Storage, Handling and Flow Conf., Nov., Stratford Upon Avon, Powder Advisory Centre.

3.2 *MILLS D & MASON J S (1985)*
The Influence of Bend Geometry on Pressure Drop in Pneumatic Conveying System Pipelines., Proc. 10th Powder and Bulk Solids Conf., Rosemont, Illinois, May 7-9.

3.3 *BRAIN T S & REID J (1973)*
Performance of Small Diameter Cylindrical Critical-Flow Nozzles. NEL Report No 546, National Engineering Laboratory, East Kilbride, Glasgow, Scotland.

3.4 *BRAIN T S & REID J (1974)*
Operating Characteristics of Circular-Arc Critical Flow Venturis. NEL Report No 564, National Engineering Laboratory, East Kilbride, Glasgow, Scotland.

3.5 *BRITISH STANDARDS INSTITUTION*
BS 1042 : Section 1.1 : 1981., Methods of Measurement of Fluid Flow in Closed Conduits. Part 1 : Pressure Differential Devices.

Chapter 4 Conveying Trials

4.1 *MASON J S, MILLS D, REED A R & WOODCOCK C R (1984)*
Pneumatic Handling of Bulk Materials. Part B, Short course notes. Thames Polytechnic, London.

4.2 *ZENZ F A & OTHMER D F (1960)*
Fluidisation and Fluid-Particle Systems. Reinhold Chem. Eng. Series, Reinhold Publishing Corp., New York. p 314.

4.3 *MILLS D (1979)*
The Determination of Product Conveying Characteristics for Pneumatic Conveying Systems. Proc. Int. Conf. on Pneumatic Conveying, Cafe Royal, London.

4.4 HITT R J (1984)
An Investigation into the Low Velocity Pneumatic Conveying of Bulk Solids. PhD Thesis, Thames Polytechnic, London. UK.

4.5 MAINWARING N J & REED A R (1987)
An Appraisal of Dixon's Slugging Diagram for Assessing the Dense Phase Potential of Bulk Solid Materials. Pneumatech 3, 3rd Int. Conf. on Pneumatic Conveying Technology, 24-26 March, Jersey.

4.6 MAINWARING N J & REED A R (1987)
Permeability and Air Retention Characteristics of Bulk Solid Materials in Relation to Modes of Dense Phase Pneumatic Conveying., Bulk Solids Handling, Vol. 7, No. 3, June 1987

4.7 MAINWARING N J & REED A R - Personal Communication

Chapter 5 Bench Scale Tests

5.1 ALLEN T (1981)
Particle Size Measurement - Powder Technology Series, 3rd Ed., Published by Chapman and Hall Ltd., 11 New Fetter Lane, LONDON.

5.2 BRITISH STANDARDS ISTITUTION
BS 1796: 1976 Methods for Test Sieving

5.3 BRITISH STANDARDS INSTITUTION
BS 3406 Methods for the Determination of Particle Size of Powders. Part 2: 1963 Liquid Sedimentation Methods.

5.4 HITT R J (1984)
An Investigation into the Low Velocity Pneumatic Conveying of Bulk Solids. PhD Thesis, Thames Polytechnic, London. UK.

5.5 ERGUN S (1952)
Fluid Flow Through Packed Columns. Chem Eng Prog, 49 , No. 2, February, pp 88 - 94.

5.6 BRITISH MATERIALS HANDLING BOARD (1983)
Bulk Solids Physical Property Test Guide. pp 54 - 59.

5.7 CALDWELL L G (1979)
Clarifying the Definition of Modes of Flow by Which Particulate Solids are Pneumatically Conveyed. Proc. Technical Prog., Int. Powder and Bulk Solids Handling and Processing Conf., May.

5.8 SUTTON H M & RICHMOND R A (1973)
How to Improve Powder Storage and Discharge in Hoppers by Aeration. Process Engineering, September.

5.9 GELDART D & WONG A C Y (1985)
Fluidisation of Powders Showing Degrees of Cohesiveness - II. Experiments on Rates of De-aeration. Chemical Engineering Science, Vol. 40, No. 4, pp 653-661.

5.10 JOHANSON J R & JENIKE A W (1972)
Settlement of Powders in Vertical Channels Caused by Gas Escape. Journal of Applied Mechanics, Transactions of the ASME, December, pp 863-868.

Chapter 7 The Correlation between Product Characteristics and Conveying Performance

7.1 DIXON G (1979)
The Impact of Powder Properties on Dense Phase Flow. Proc. Int. Conf. on Pneumatic Conveying. Jan. London. UK

7.2 GELDART D (1973)
Types of Gas Fluidisation. Powder Technology, Vol.7(1973), pp 285-292.

7.3 MAINWARING N J - Personal Communication, Thames Polytechnic.

7.4 ZENZ F A (1964)
Conveyability of Materials of Mixed Particlè Size. I & E C Fundamentals, Vol. 3, No.1, February.

7.5 CALDWELL L G (1979)
Clarifying the Definition of Modes of Flow by Which Particulate Solids are Pneumatically Conveyed. Proc. Technical Prog., Int. Powder and Bulk Solids Handling and Processing Conf., May.

7.6 MAINWARING N J & REED A R (1987)
An Appraisal of Dixon's Slugging Diagram for Assessing the Dense Phase Potential of Bulk Solid Materials. Pneumatech 3, 3rd Int. Conf. on Pneumatic Conveying Technology, 24-26 March, Jersey.

7.7 MILLS D & MASON J S (1985)
The Influence of Conveying Distance on the Performance and Air Requirements of Pneumatic Conveying System Pipelines., Int. Symposium on the Reliable Flow of Particulate Solids., Chr. Michelsen Inst. Bergen. August.

7.8 MILLS D (1985)
Pneumatic Conveying Design Guide, Chapter 10: Design of the Pipeline Layout. Confidential Report No. CR 2664 (MH), Co-operative Research Project. (Thames Polytechnic/Department of Trade and Industry.)

7.9 *MILLS D & MASON J S (1985)*
The Influence of Bend Geometry on Pressure Drop in Pneumatic Conveying System Pipelines., Proc. 10th Powder and Bulk Solids Conf., Rosemont, Illinois, May 7-9.

Chapter 8 The Correlation between Product Characteristics and Blow Tank Performance

8.1 *JOTAKI T & TOMITA Y (1978)*
Characteristics of a Blow Tank Solids Conveyor and its Operating Points working on Pipelines., Pneumotransport 4, 4th Int. Conf. of Pneumatic Transport of Solids in Pipes. Paper D4. Organised by BHRA, Cranfield, Bedfordshire. 26-28 June.

8.2 *VAGHORN D J & MASON J S (1977)*
An Approach to Modelling the Discharge Characteristics of a Blow Tank and Comparison with experimental results., Proc. 2nd Int. Powder and Bulk Solids Handling and Processing Conf., Rosemont, Illinois, USA. May.

8.3 *MARCUS R D & LOHRMANN P C (1984)*
The Performance of a Bottom Discharge Blow Vessel Pneumatically Conveying Three Group A Materials. Bulk Solids Handling, Vol. 4, No. 2, June.

8.4 *KENNEDY O C, WYPYCH P W & ARNOLD P C (1987)*
The Effect of Blow Tank Air Injection on Pneumatic Conveying Performance. Pneumatech 3, 3rd Int. Conf. on Pneumatic Conveying Technology, 24-26 March, Jersey.

8.5 *VAGHORN D J & MASON J S (1976)*
The Effect of Aeration and Position of Inlet to the Conveying Line on the Discharge Characteristics of the Blow Tank., Bulk Solids, Storage, Handling and Flow Conf., sponsored by the Powder Advisory Centre and Inst. Mat. Handling, UK, November.

8.6 *MAINWARING N J - Personal Communication, Thames Polytechnic.*

Chapter 9 Conclusions

9.1 *GELDART D (1973)*
Types of Gas Flüidisation. Powder Technology, Vol.7(1973), pp 285-292.

9.2 *DIXON G (1979)*
The Impact of Powder Properties on Dense Phase Flow. Proc. Int. Conf. on Pneumatic Conveying. Jan. London. UK

9.3 *VYPYCH P W & ARNOLD P C (1984)*
The Use of Powder and Pipe Properties in the Prediction of Dense Phase Pneumatic Transport Behaviour. Proc., 2nd Int. Conf. on Pneumatic Conveying Technology (Pneumatech 2), Sept., Canterbury. UK.

9.4 *LOHRMANN P C & MARCUS R D (1983)*
The Performance of a Bottom Discharge Blow Vessel Pneumatically Conveying Three Group A Materials. Int. Conf. on Bulk Materials Storage, Handling and Transportation., August, Newcastle, Australia.

9.5 *JODLOWSKI C (1984)*
Considerations on Two Phase Gas/Solid Flow at Low Velocities. Proc. 2nd Int. Conf. on Pneumatic Conveying Technology (Pneumatech 2), Sept., Canterbury. UK.

9.6 *HITT R J (1984)*
An Investigation into the Low Velocity Pneumatic Conveying of Bulk Solids. PhD Thesis, Thames Polytechnic, London. UK.

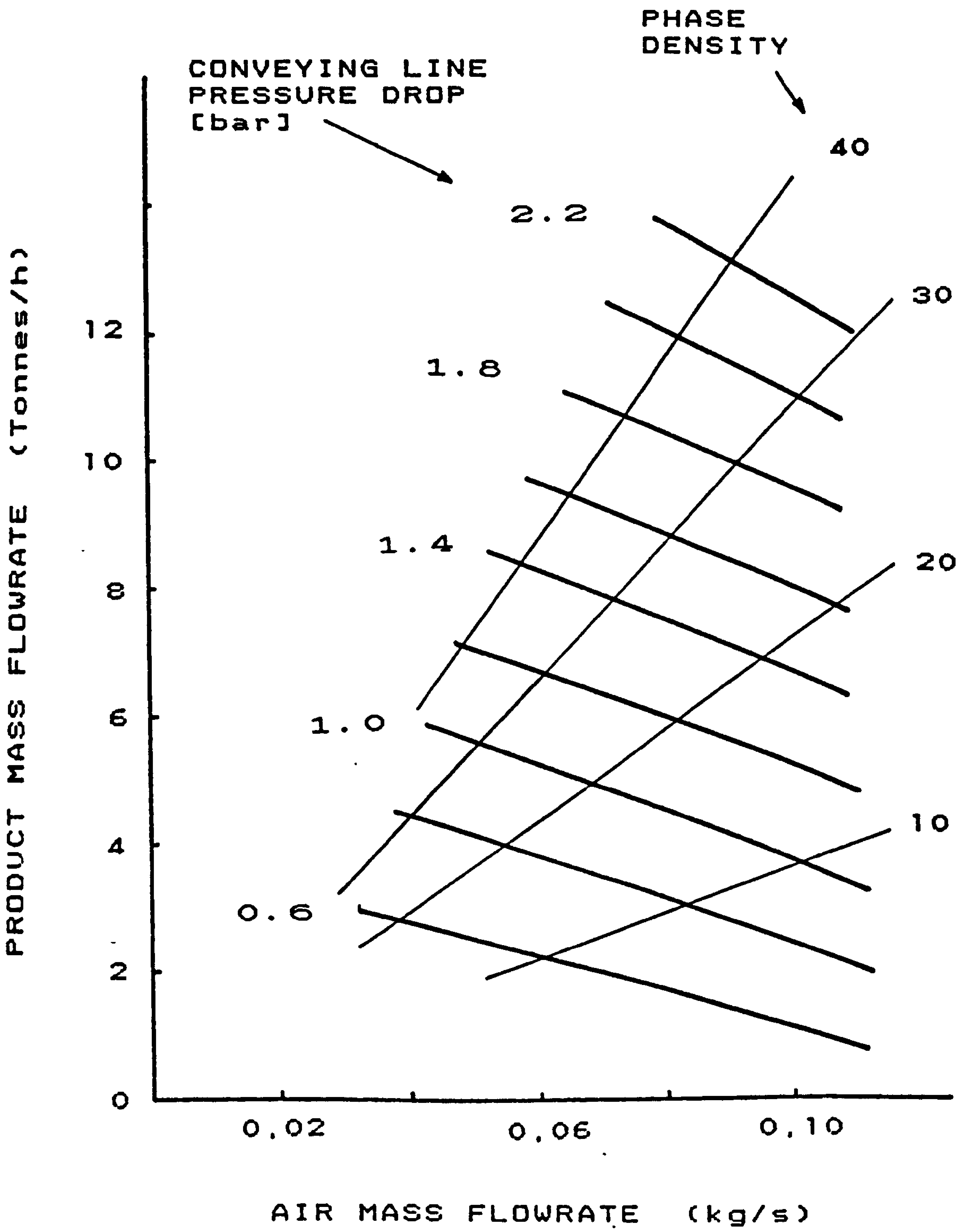
APPENDIX II

CONVEYING CHARACTERISTICS FOR ALL PRODUCTS CONVEYED

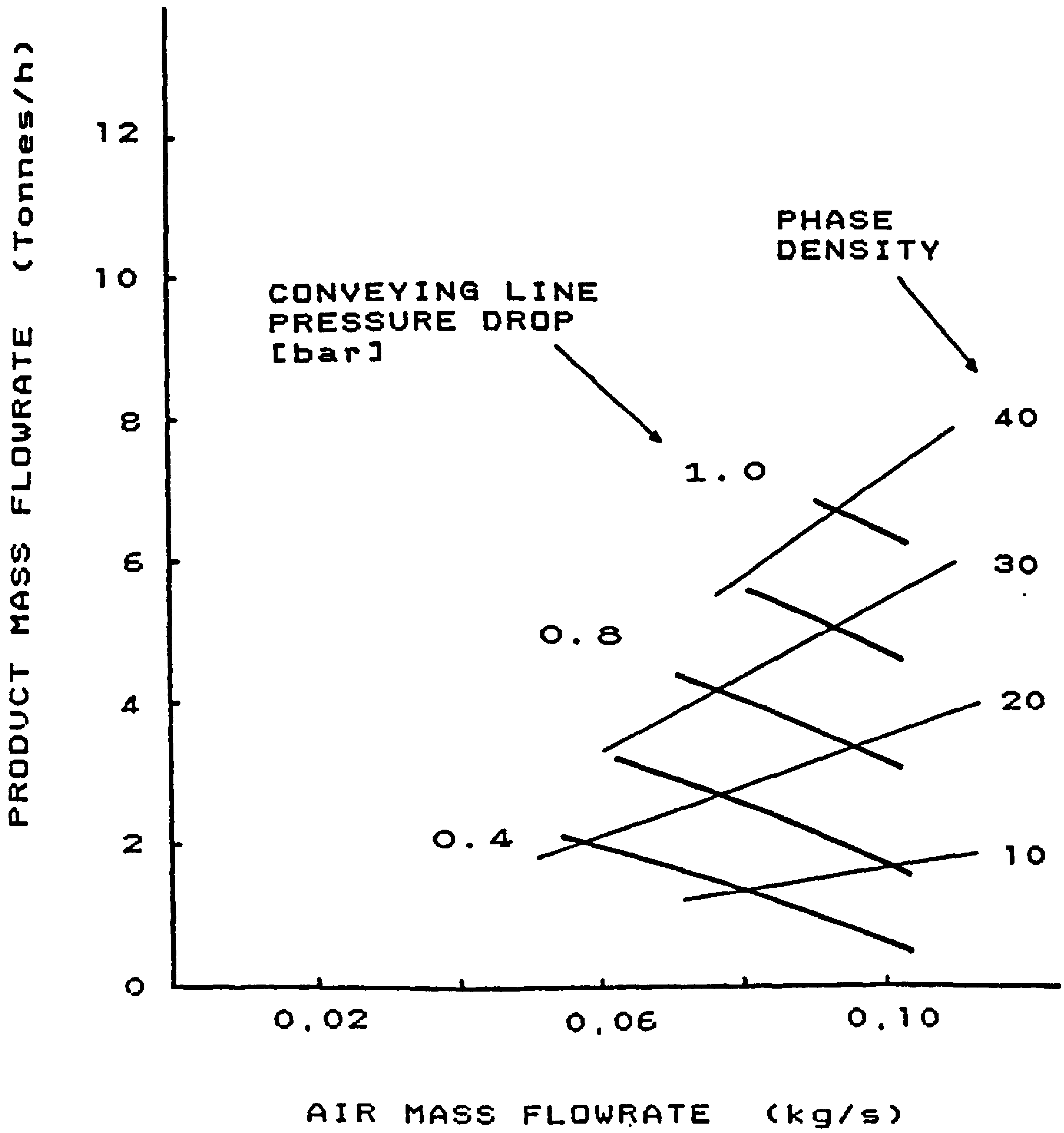
KEY TO PRODUCTS

1. Agricultural Catalyst
2. Agricultural Catalyst (degraded)
3. Alumina
4. Barytes
5. Cement
6. Coal (as supplied)
7. Coal (degraded)
8. Coal (pulverised fuel)
9. Copper Ore
10. Flour
11. Iron Powder
12. Magnesiun Sulphate
13. Pearlite
14. Polyethylene Pellets
15. Potassium Chloride
16. Potassium Sulphate
17. Pulverised Fuel Ash
18. PVC Powder
19. Silica Sand
20. Granulated Sugar
21. Sugar (degraded)
22. Zircon Sand

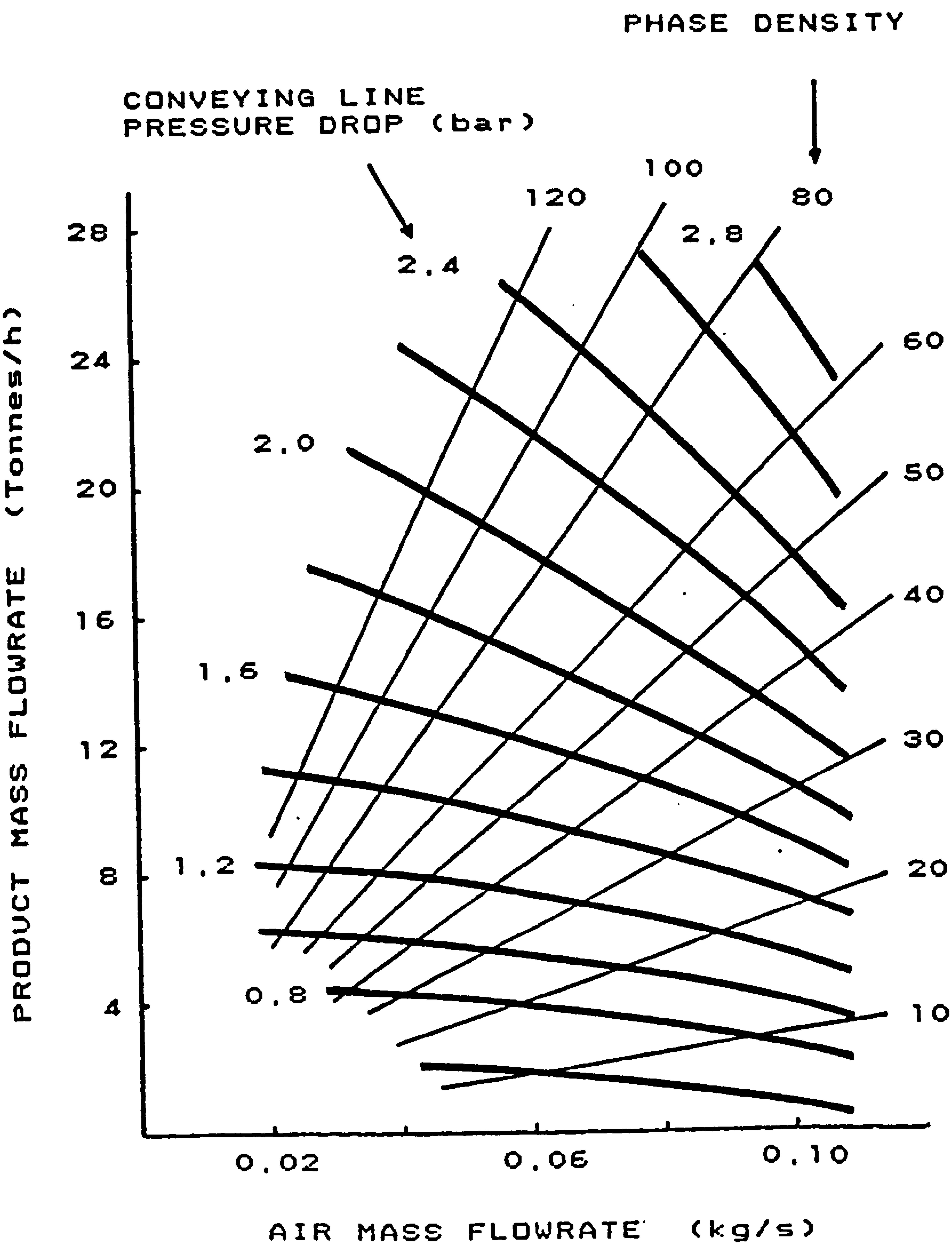
NOTE - All conveying characteristics for products are for a 50m, 53mm bore pipeline with 9 x 90° bends each with a D/d ratio of 24.



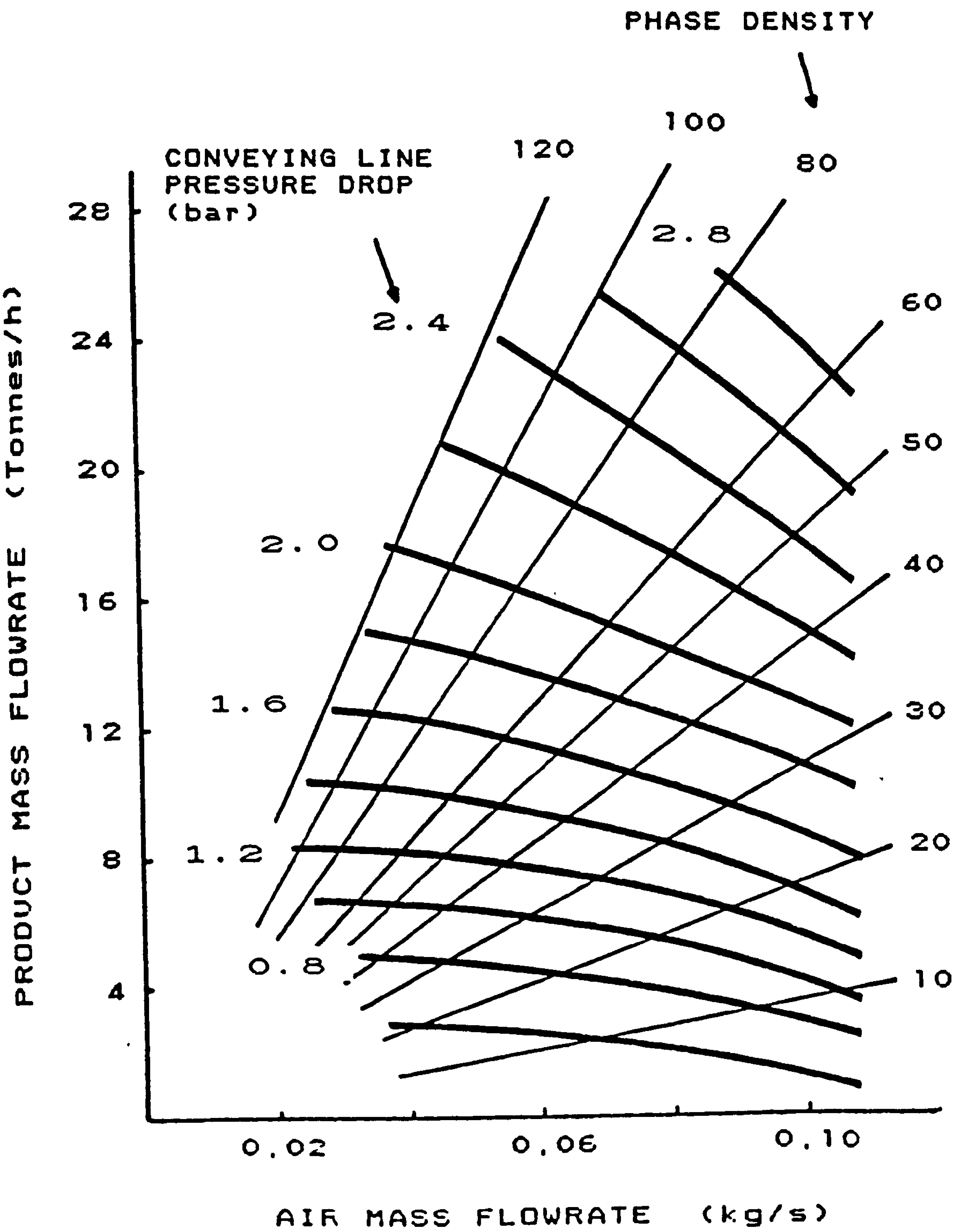
CONVEYING CHARACTERISTICS FOR DEGRADED AGRICULTURAL CATALYST (No. 2)



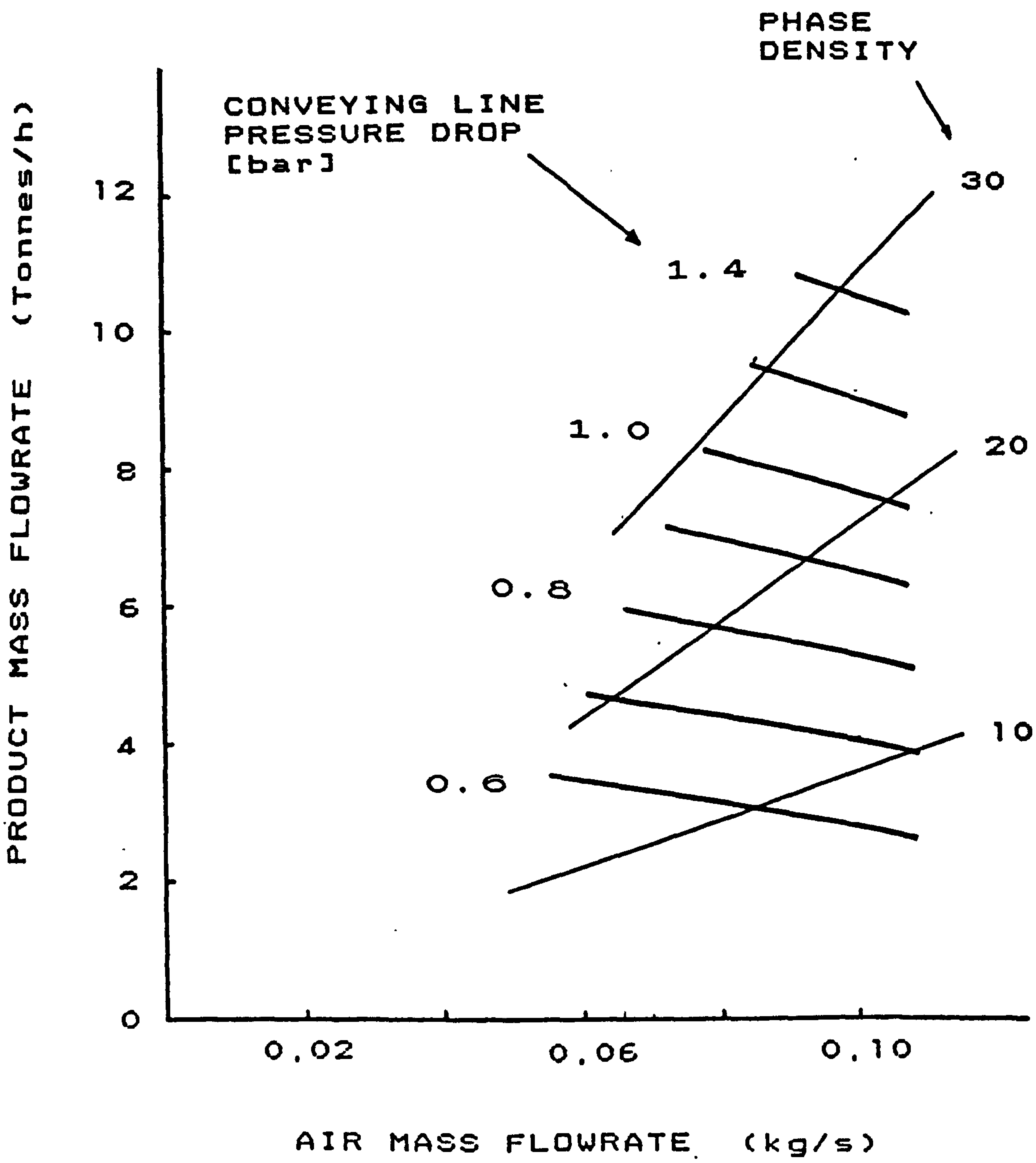
CONVEYING CHARACTERISTICS FOR ALUMINA (No. 3)



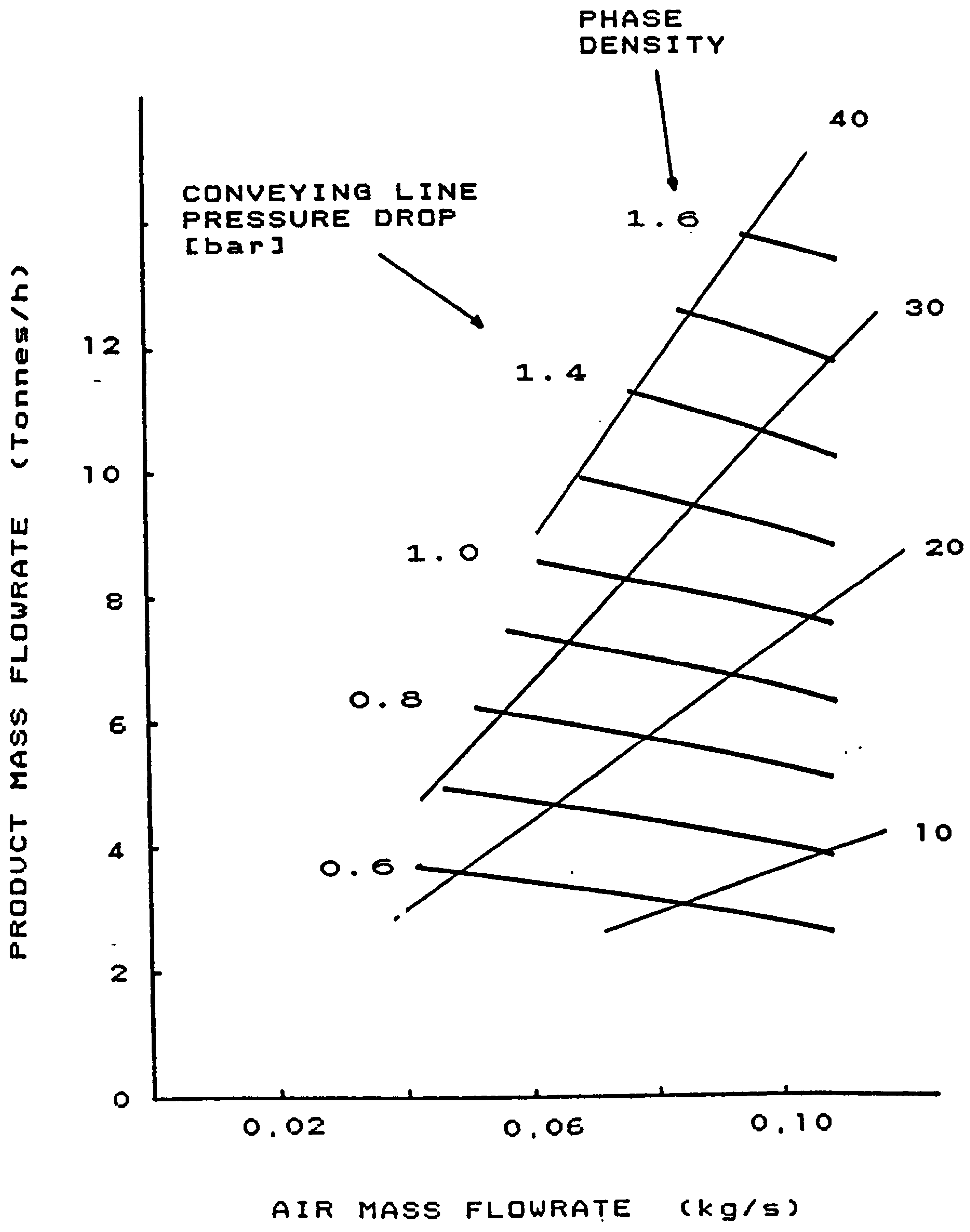
CONVEYING CHARACTERISTICS FOR BARYTES (No. 4)



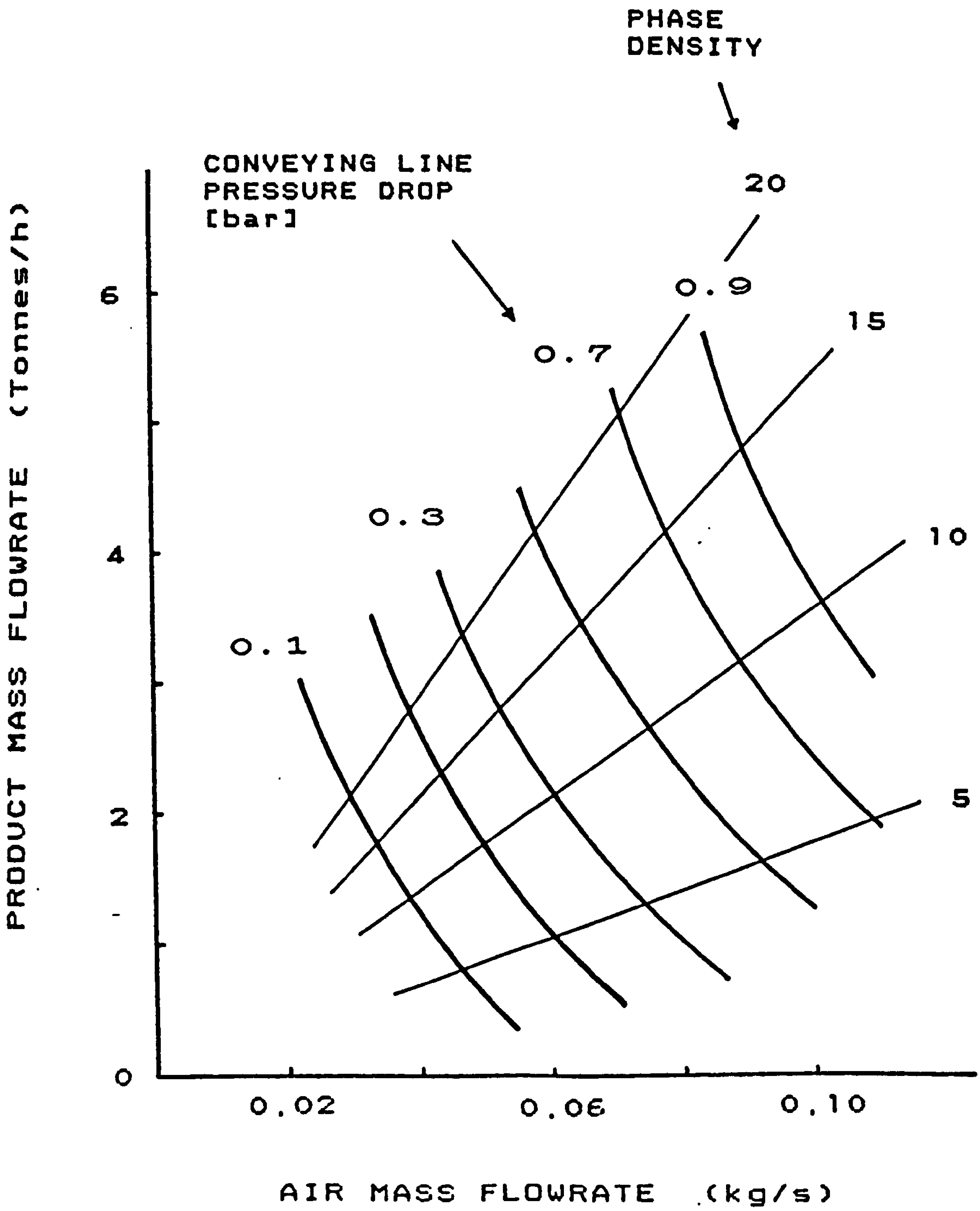
CONVEYING CHARACTERISTICS FOR
ORDINARY PORTLAND CEMENT (No. 5)



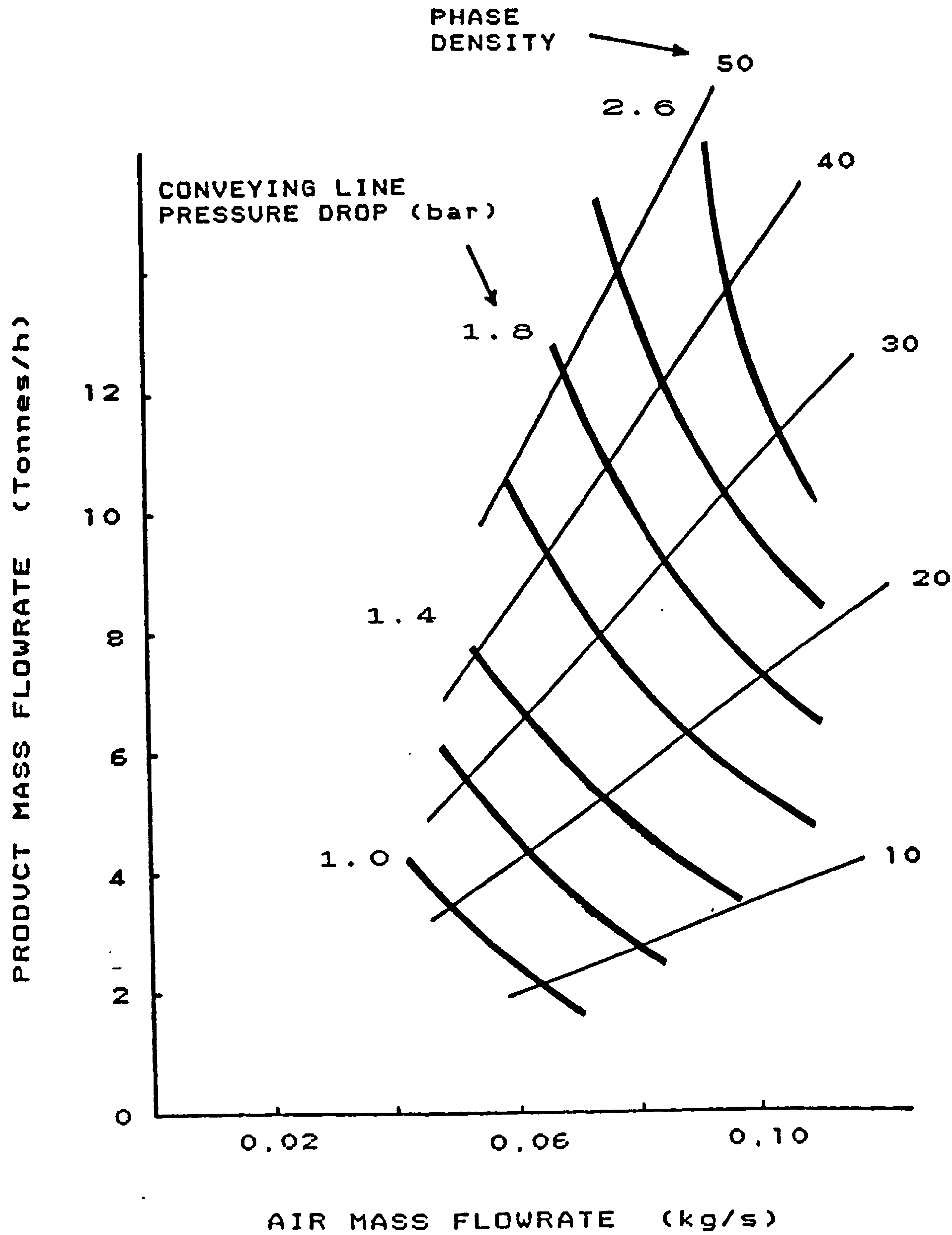
CONVEYING CHARACTERISTICS FOR COAL (No. 6)



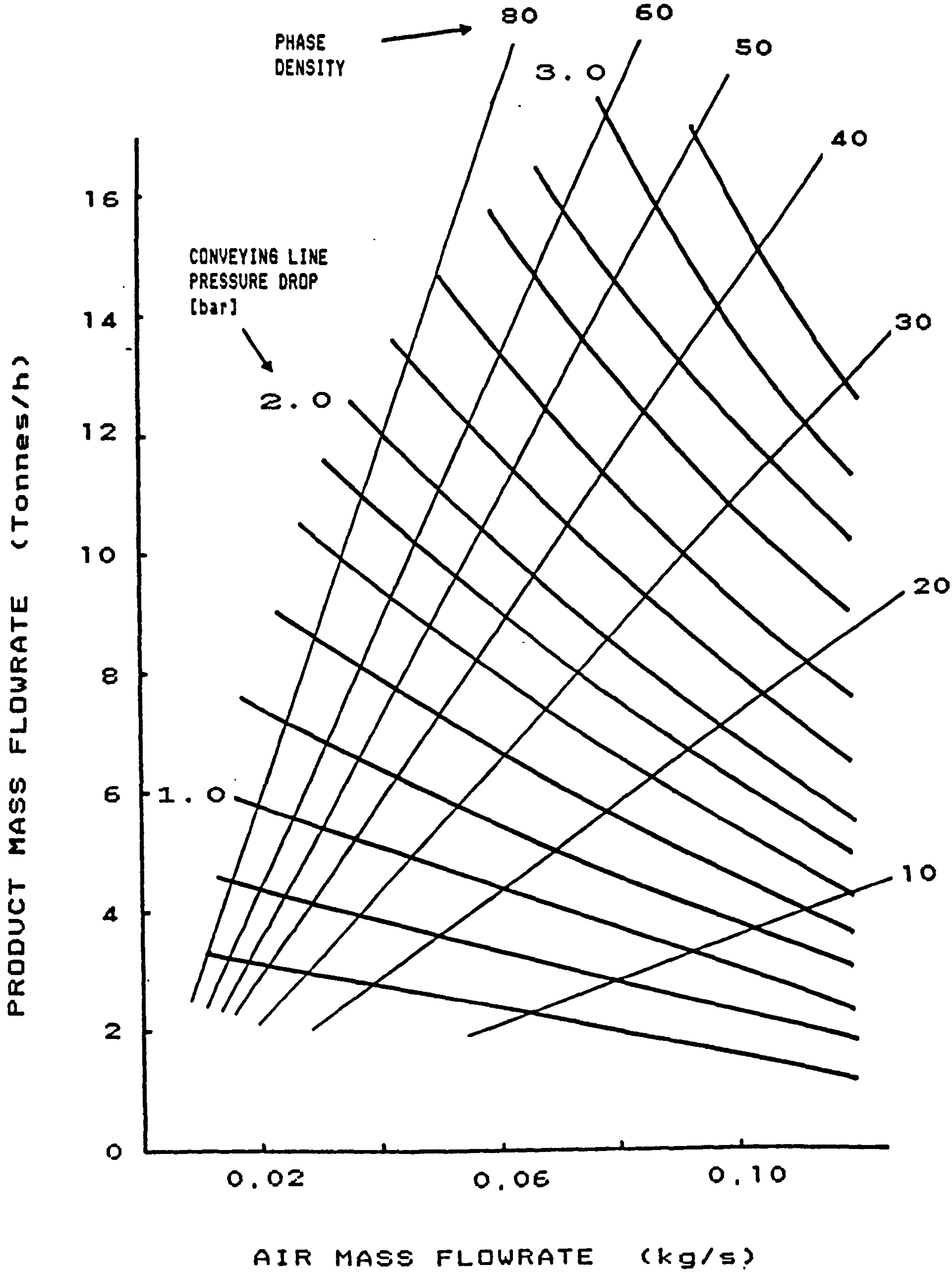
CONVEYING CHARACTERISTICS FOR
DEGRADED COAL (No. 7)



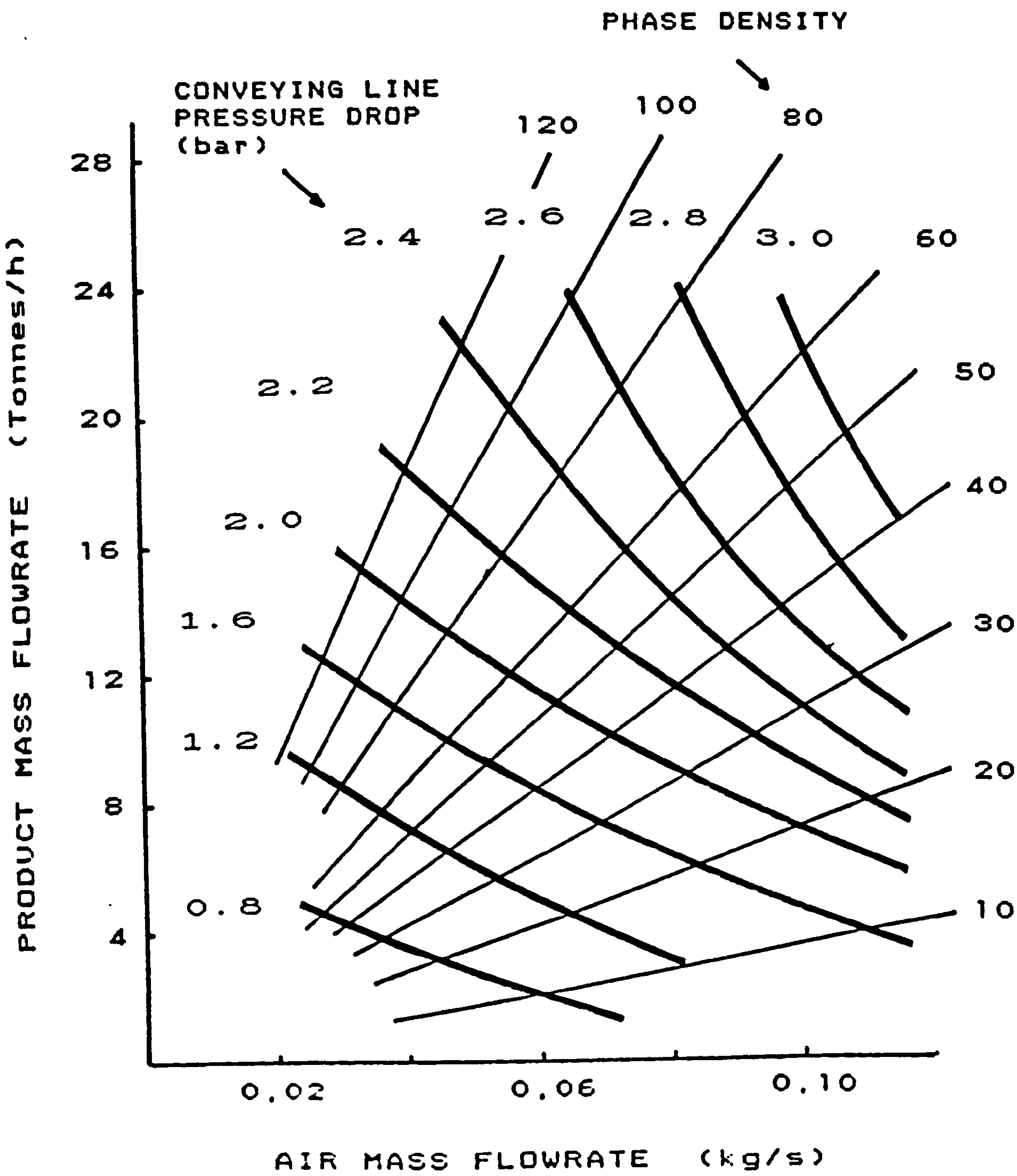
CONVEYING CHARACTERISTICS FOR PULVERISED COAL (No. 8)



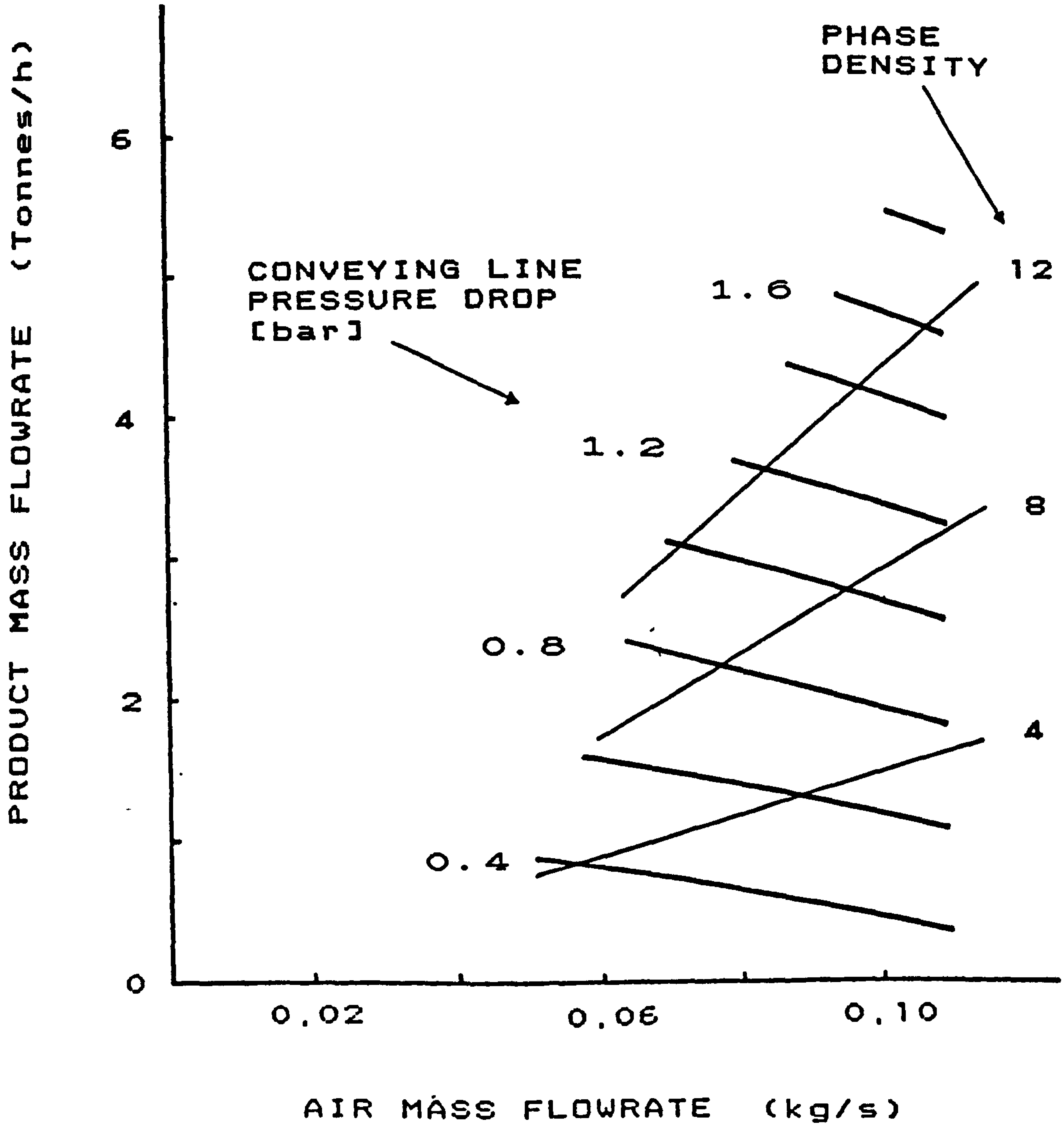
CONVEYING CHARACTERISTICS FOR
COPPER ORE (No. 9)



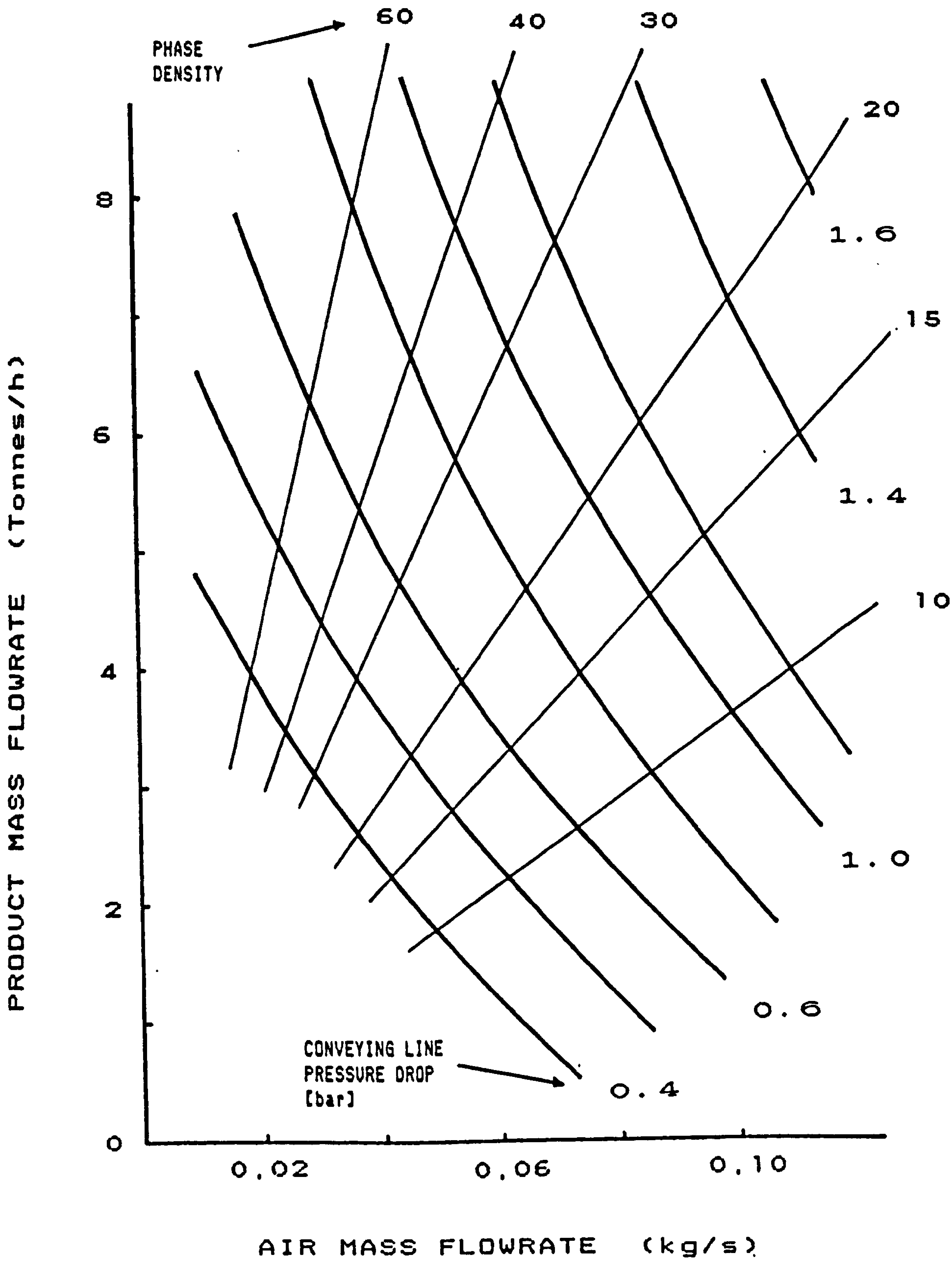
CONVEYING CHARACTERISTICS FOR FLOUR (No. 10)



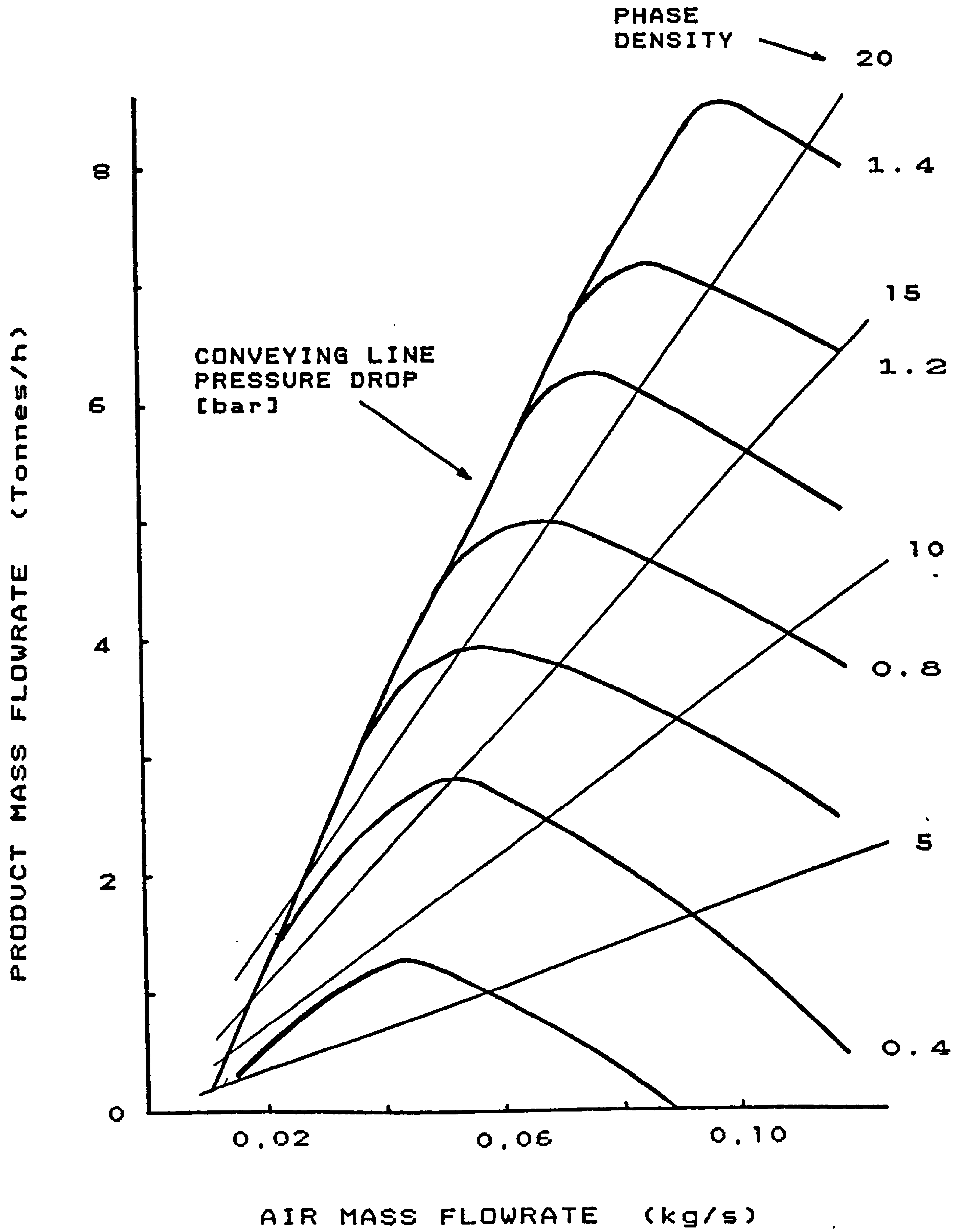
CONVEYING CHARACTERISTICS FOR
IRON POWDER (No. 11)



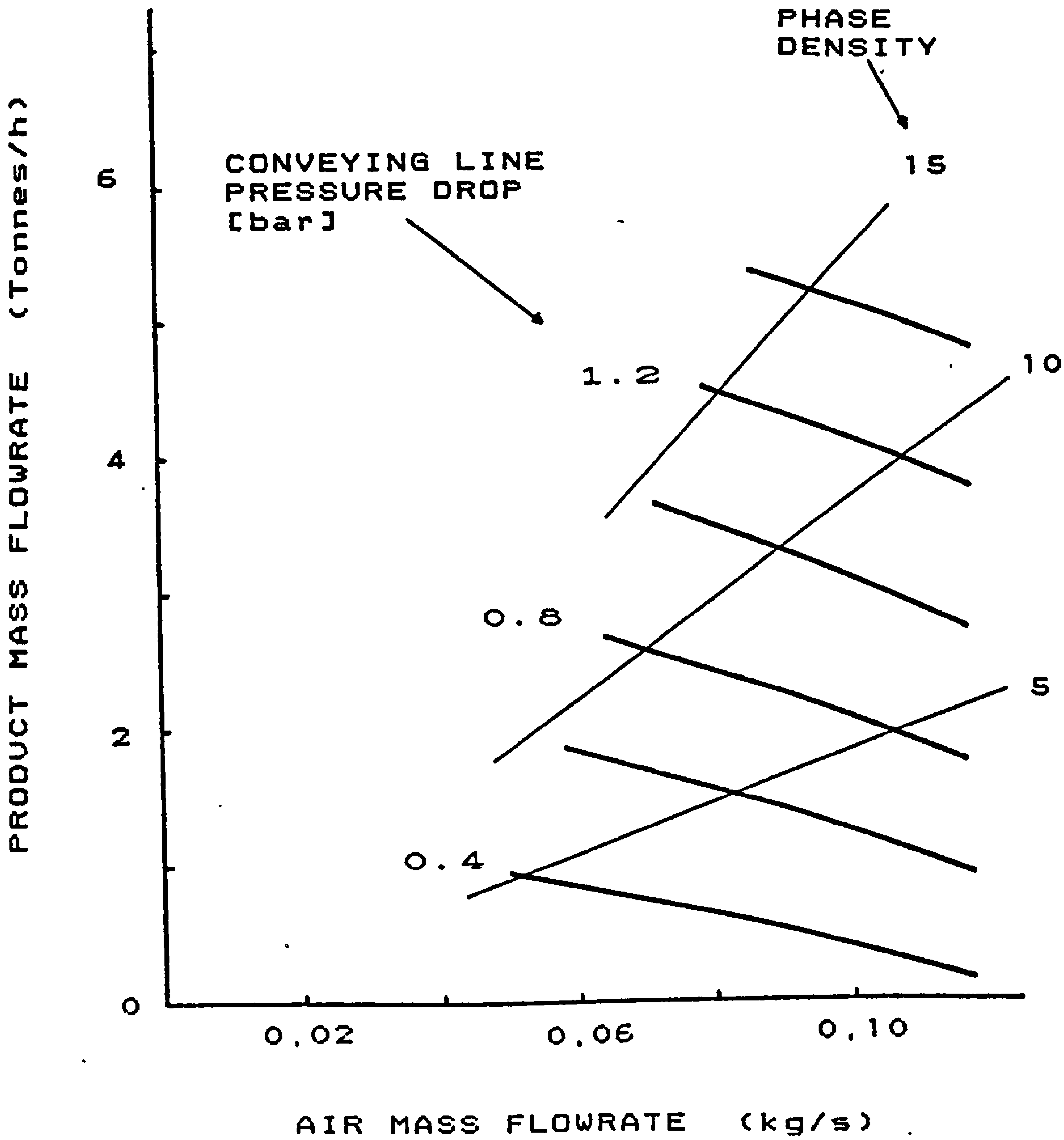
CONVEYING CHARACTERISTICS FOR MAGNESIUM SULPHATE (No. 12)



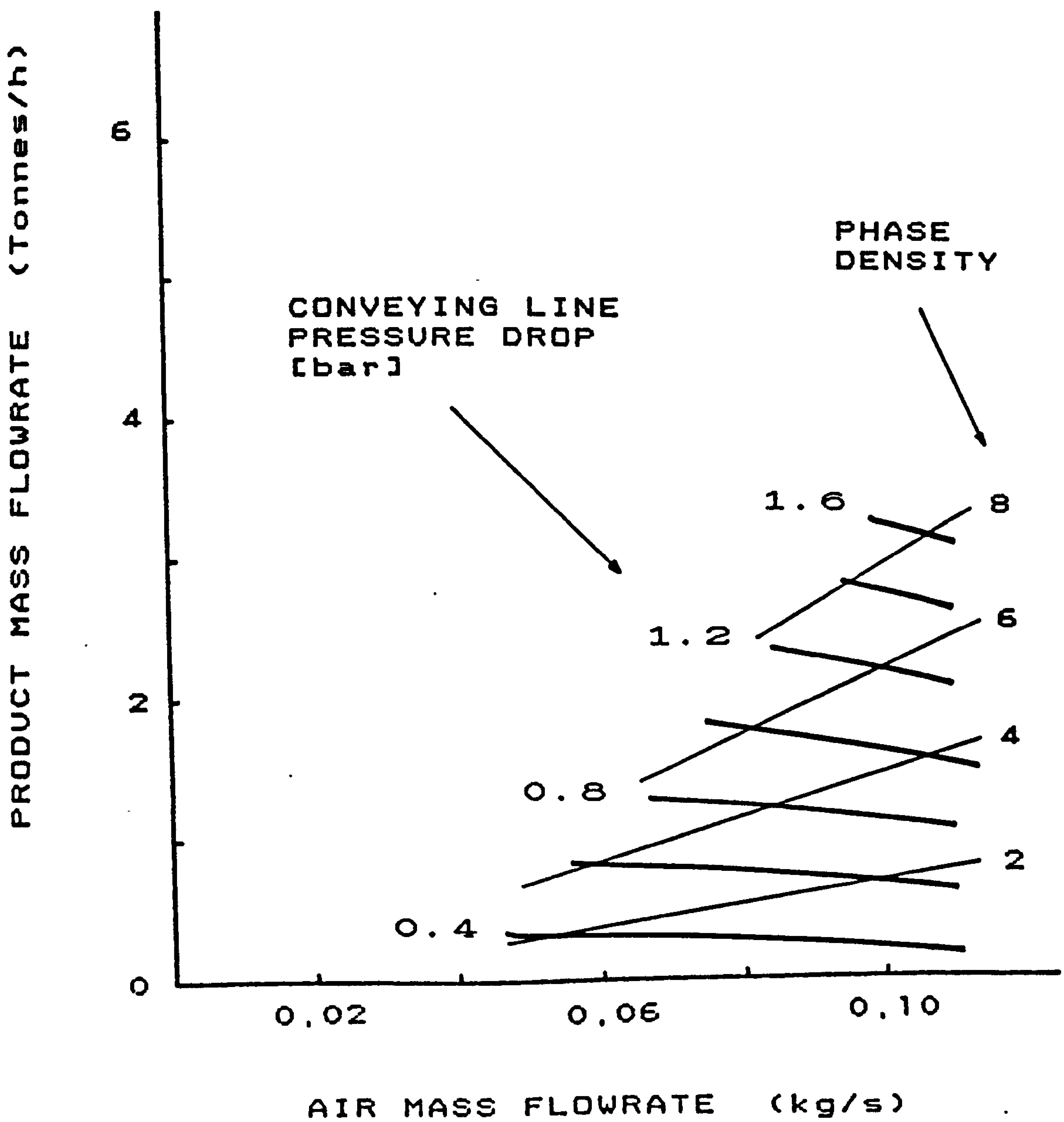
CONVEYING CHARACTERISTICS FOR PEARLITE (No. 13)



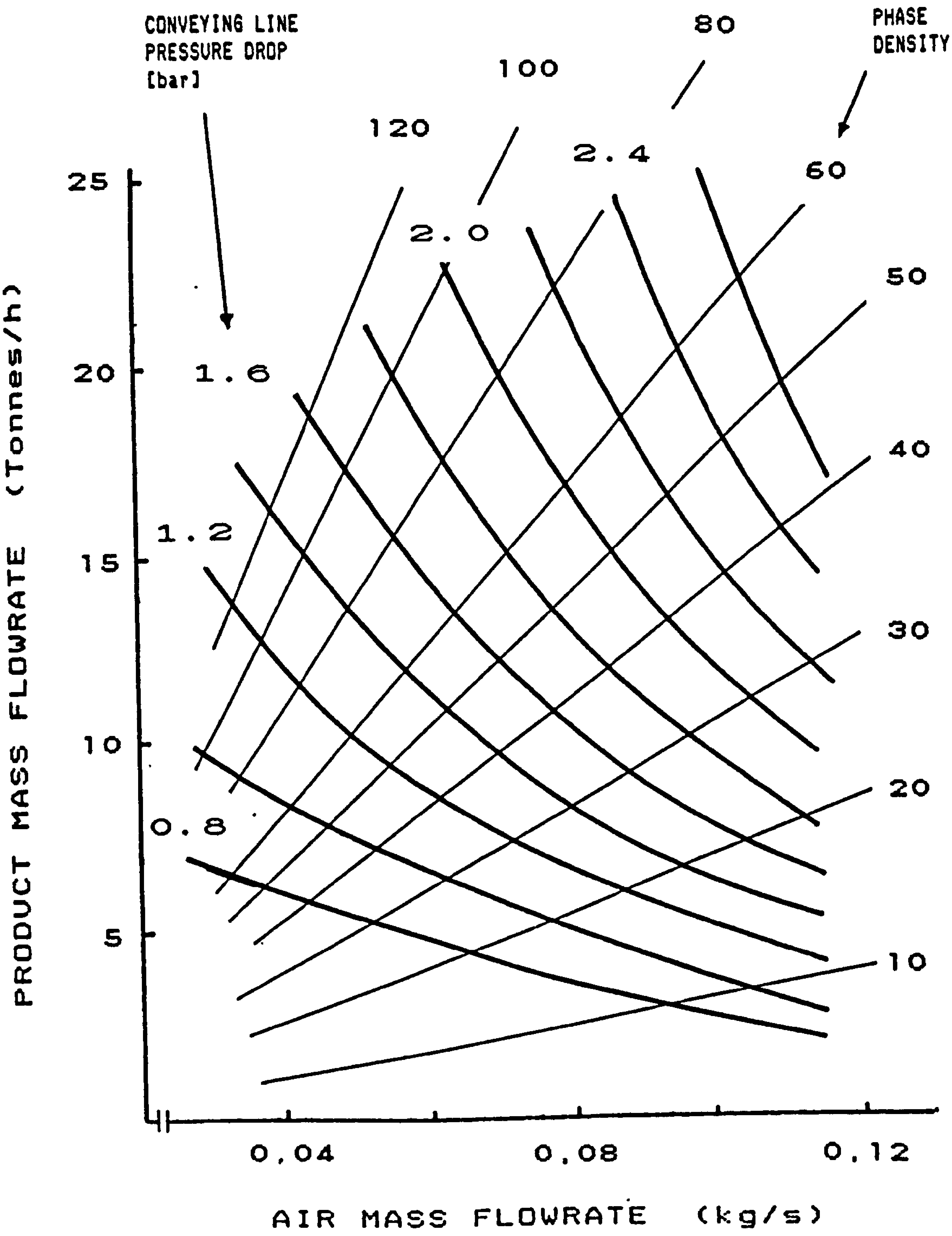
CONVEYING CHARACTERISTICS FOR POLYETHYLENE PELLETS (No. 14)



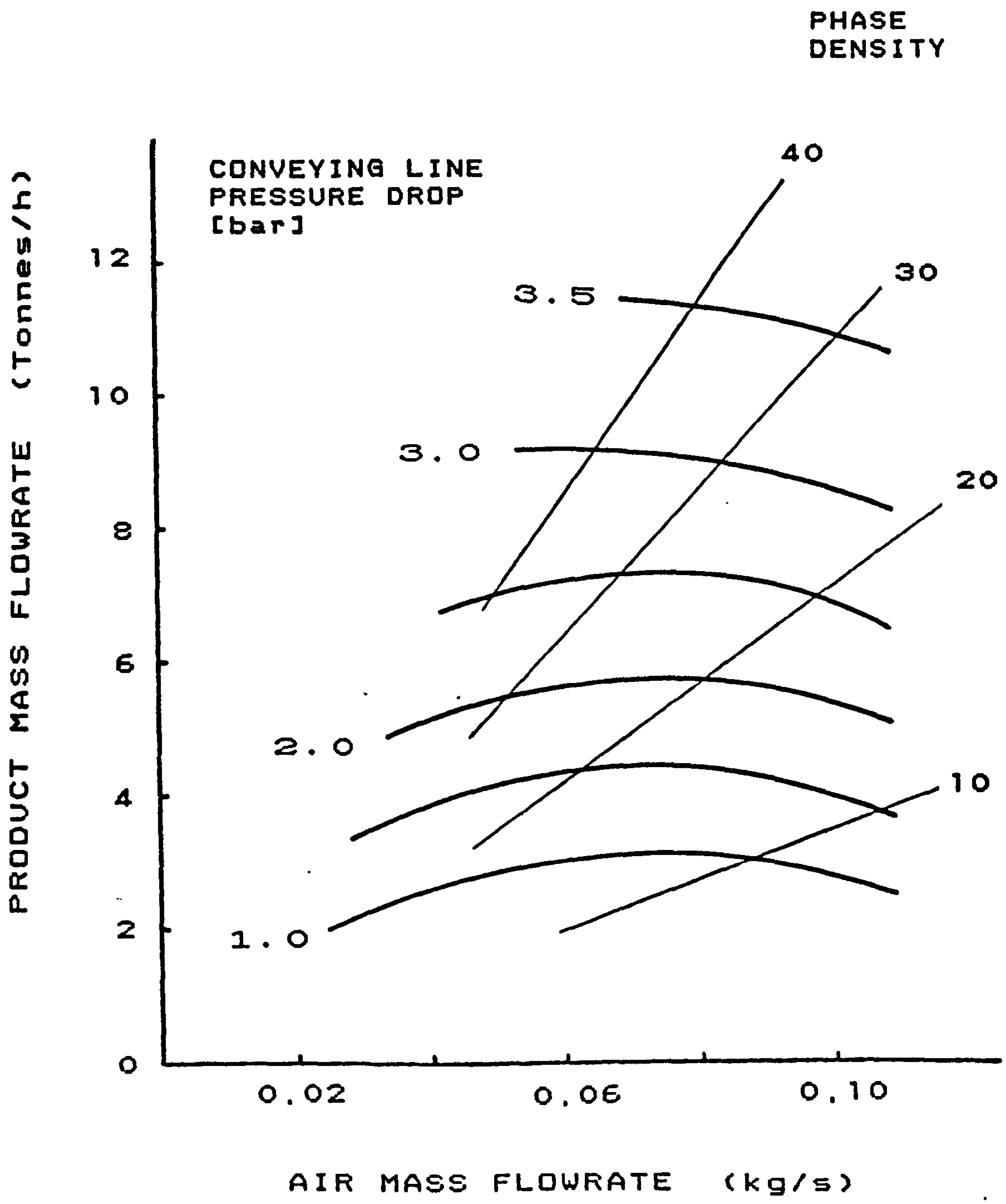
CONVEYING CHARACTERISTICS FOR
POTASSIUM CHLORIDE (No. 15)



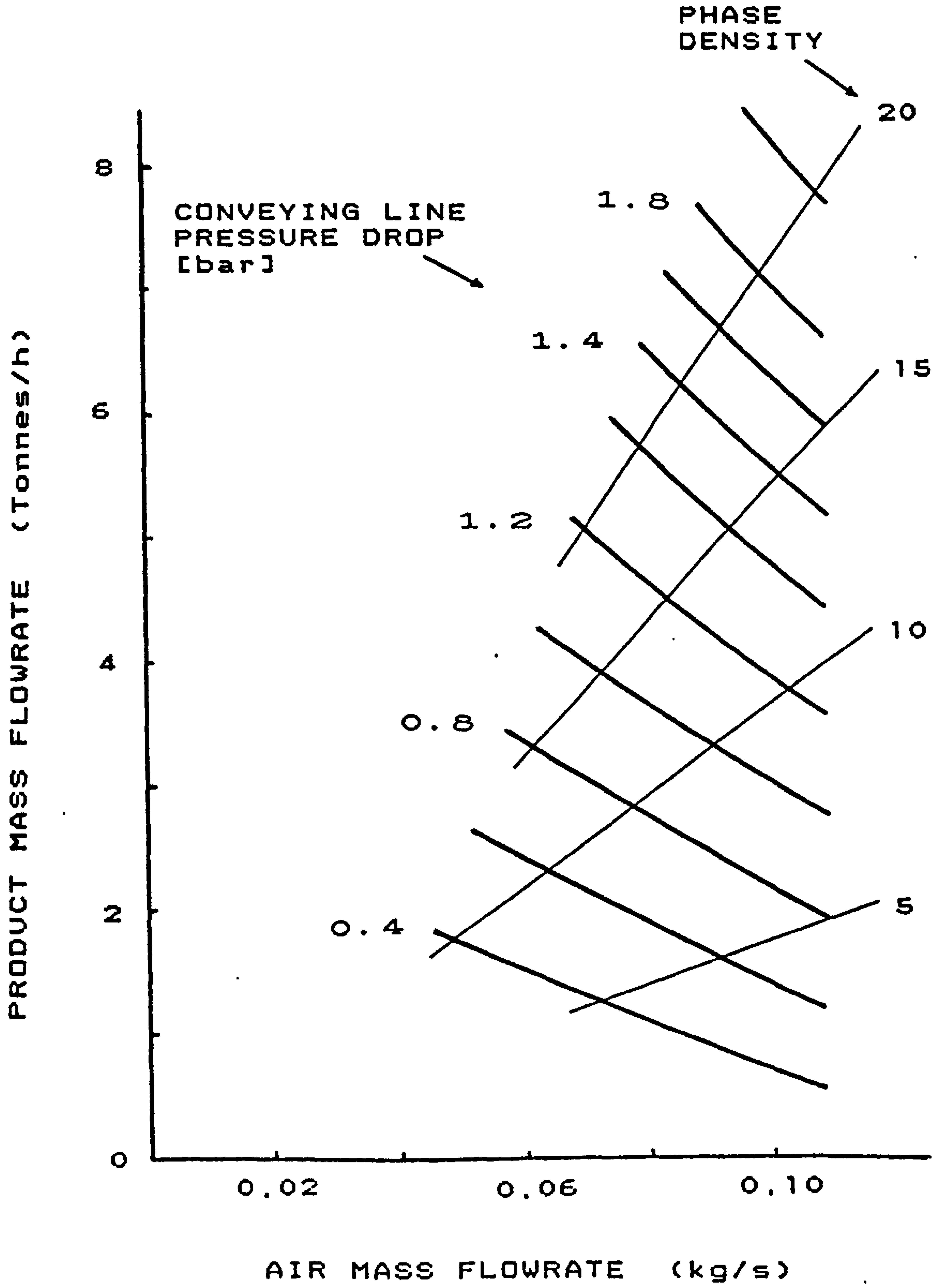
CONVEYING CHARACTERISTICS FOR POTASSIUM SULPHATE (No. 16)



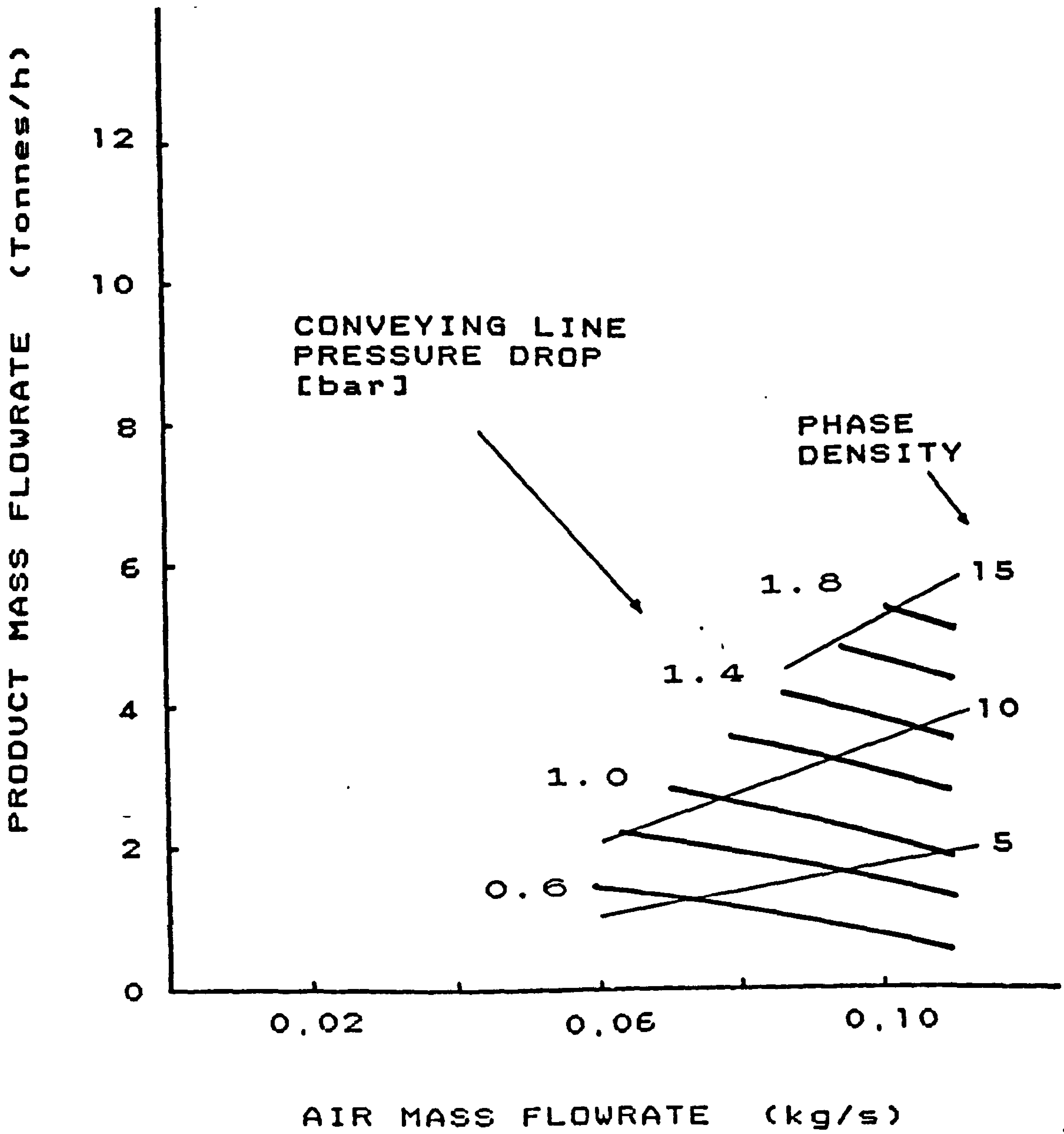
CONVEYING CHARACTERISTICS FOR PULVERISED FUEL ASH (No. 17)



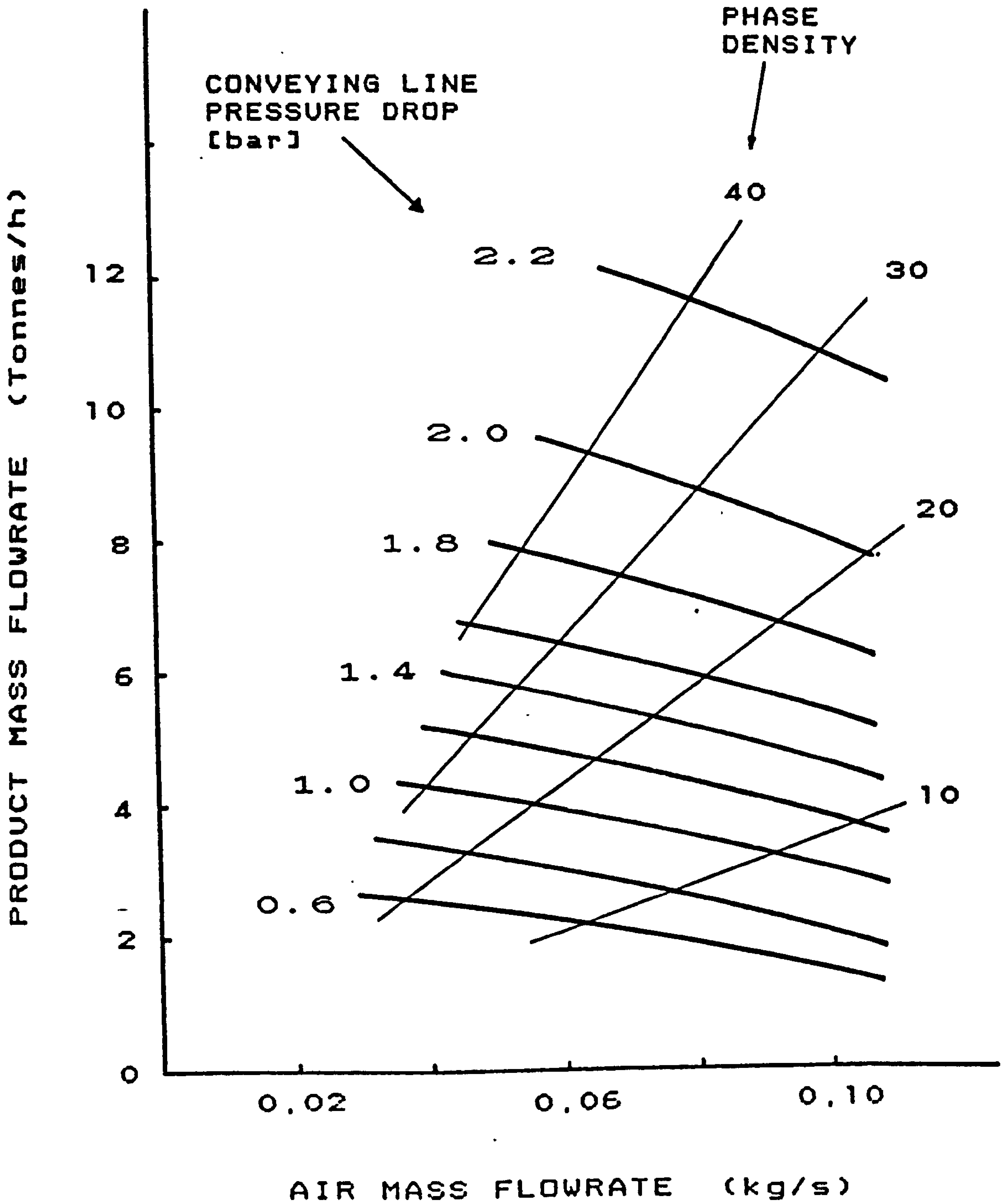
CONVEYING CHARACTERISTICS FOR
PVC POWDER (No. 18)



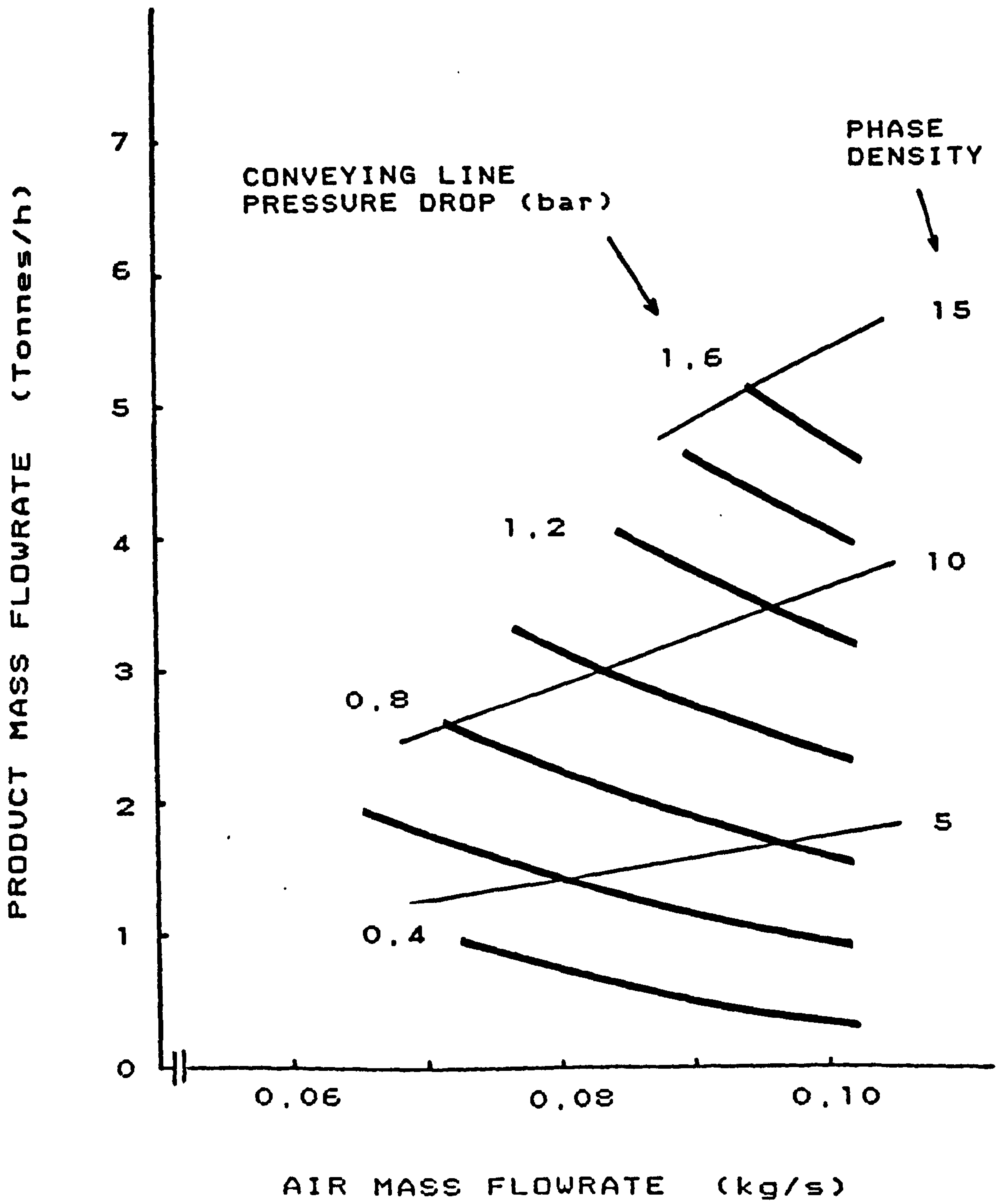
CONVEYING CHARACTERISTICS FOR SILICA SAND (No. 19)



CONVEYING CHARACTERISTICS FOR GRANULATED SUGAR (No. 20)



CONVEYING CHARACTERISTICS FOR DEGRADED SUGAR (No. 21)

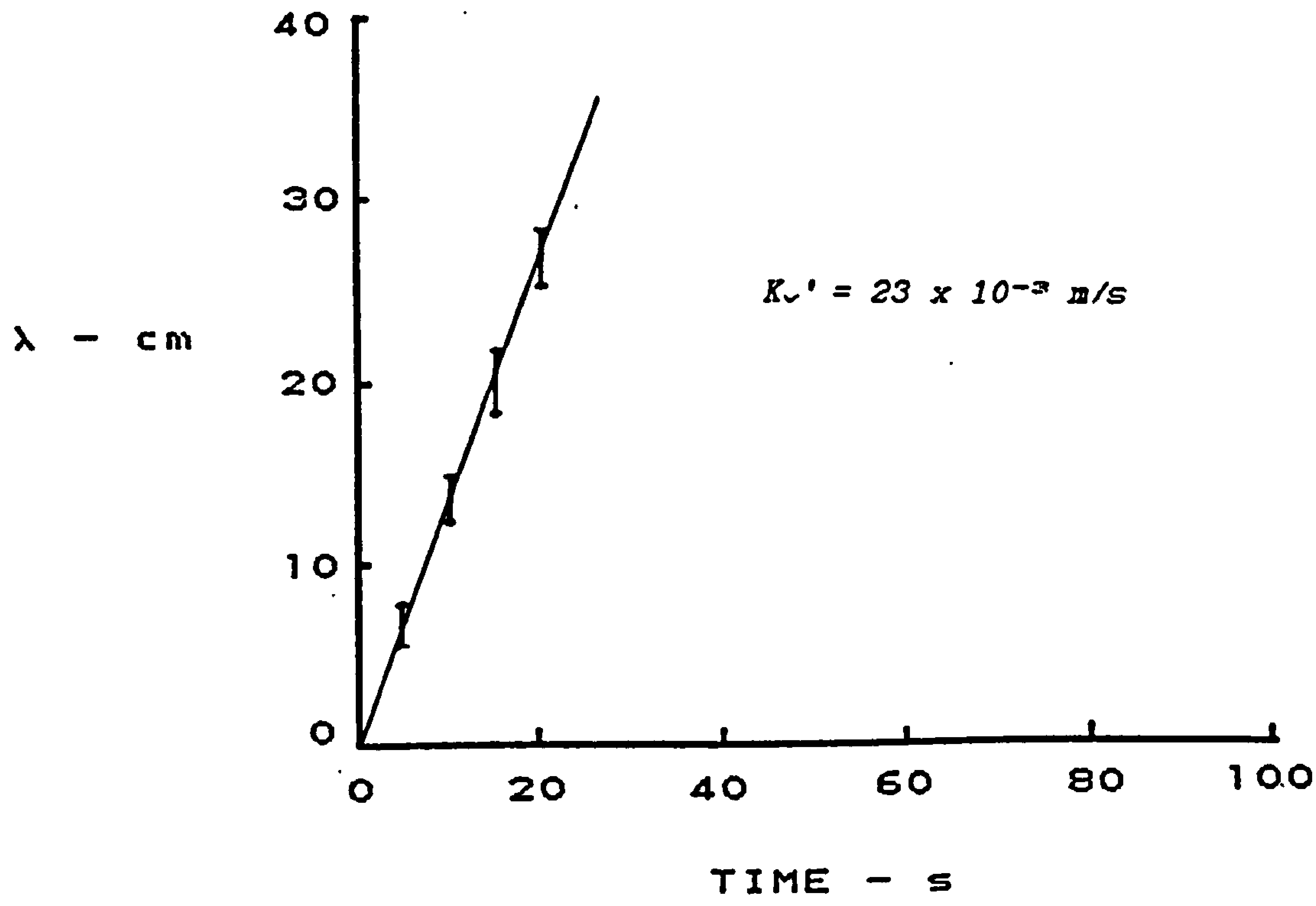


CONVEYING CHARACTERISTICS FOR ZIRCON SAND (No. 22)

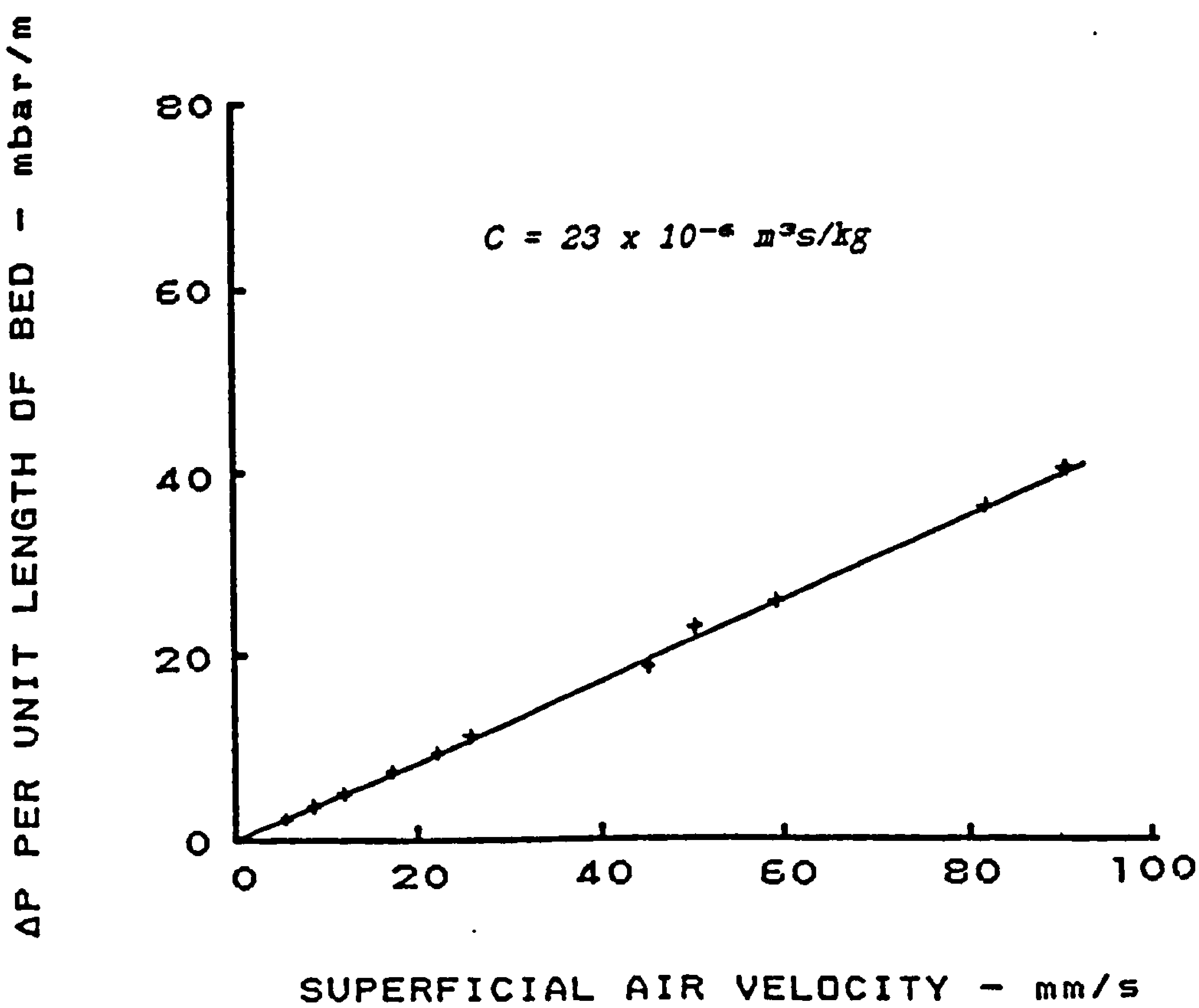
APPENDIX III

AERATION PROPERTIES OF MATERIALS TESTED

MATERIAL No. 1 - AGRICULTURAL CATALYST

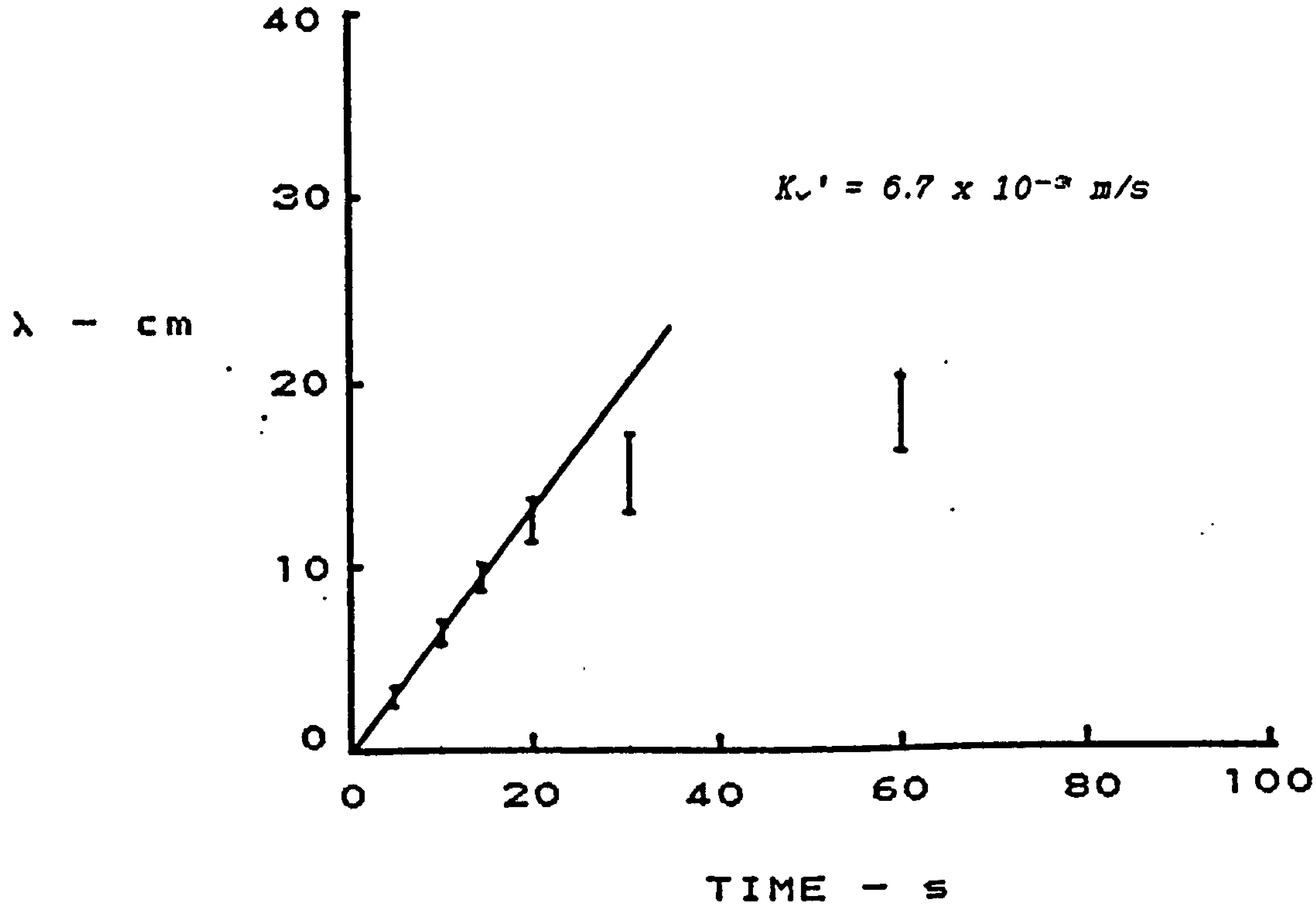


VIBRATED DE-AERATION DATA

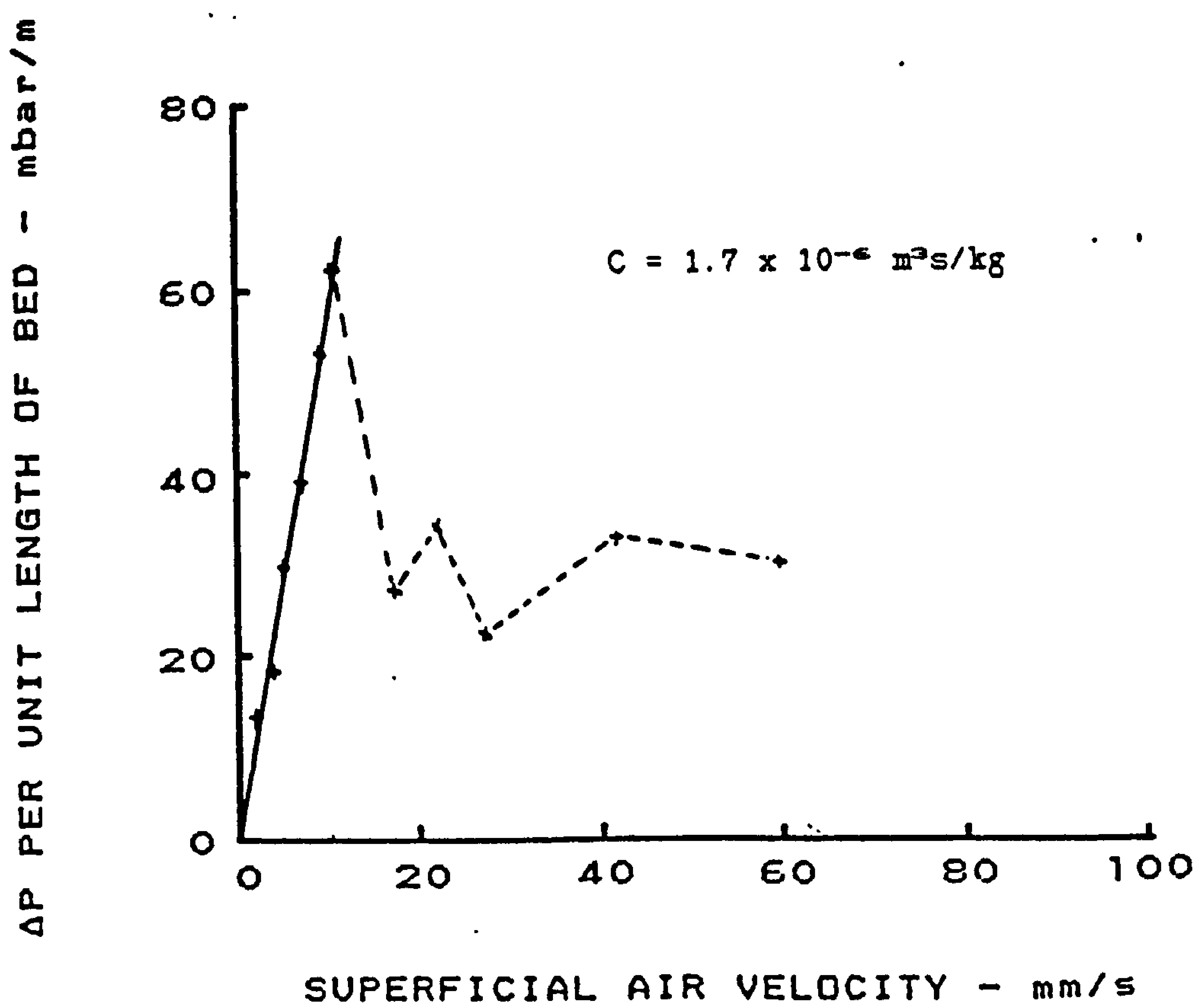


PERMEABILITY DATA

MATERIAL No. 2 - AGRICULTURAL CATALYST (Degraded)

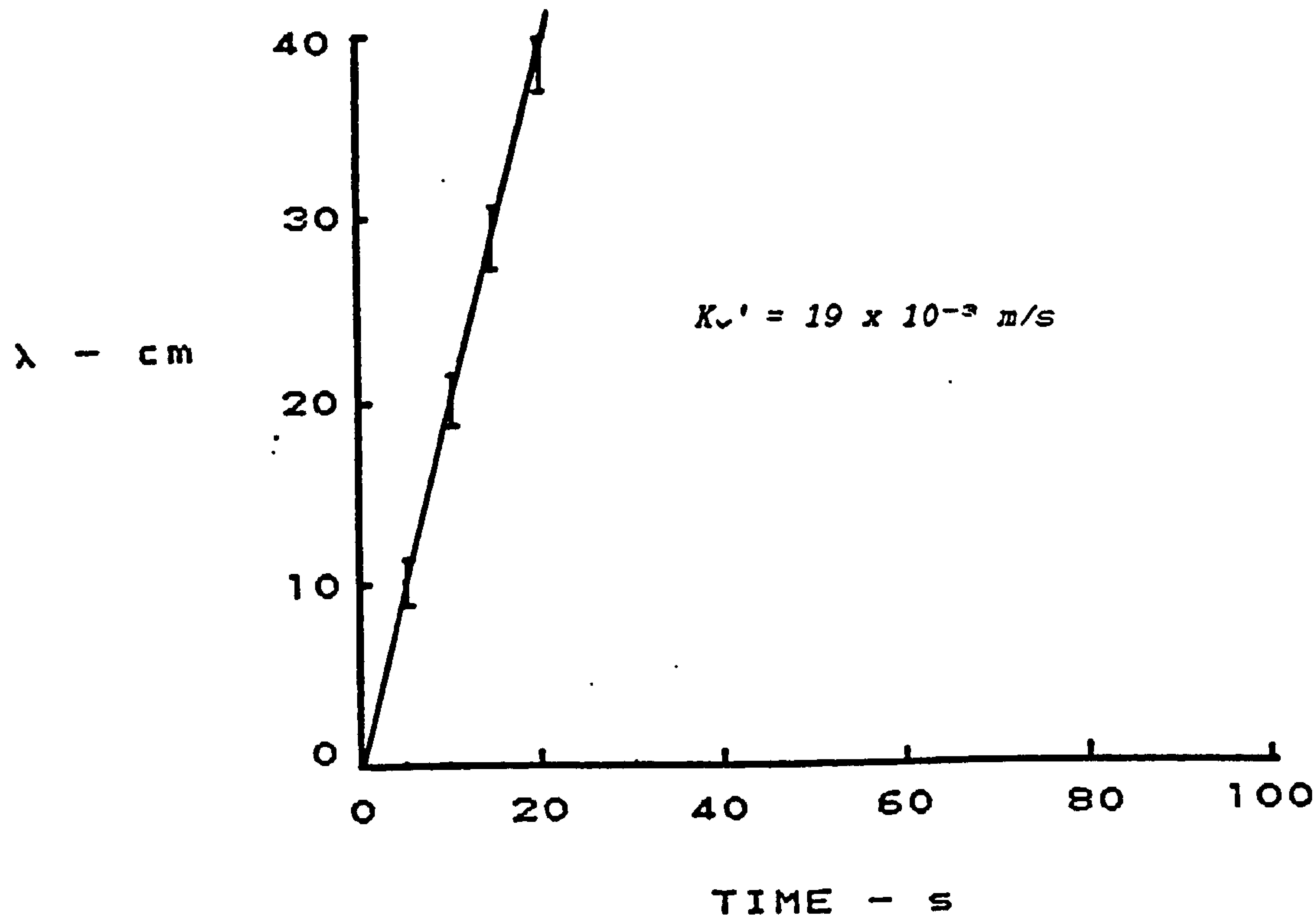


VIBRATED DE-AERATION DATA

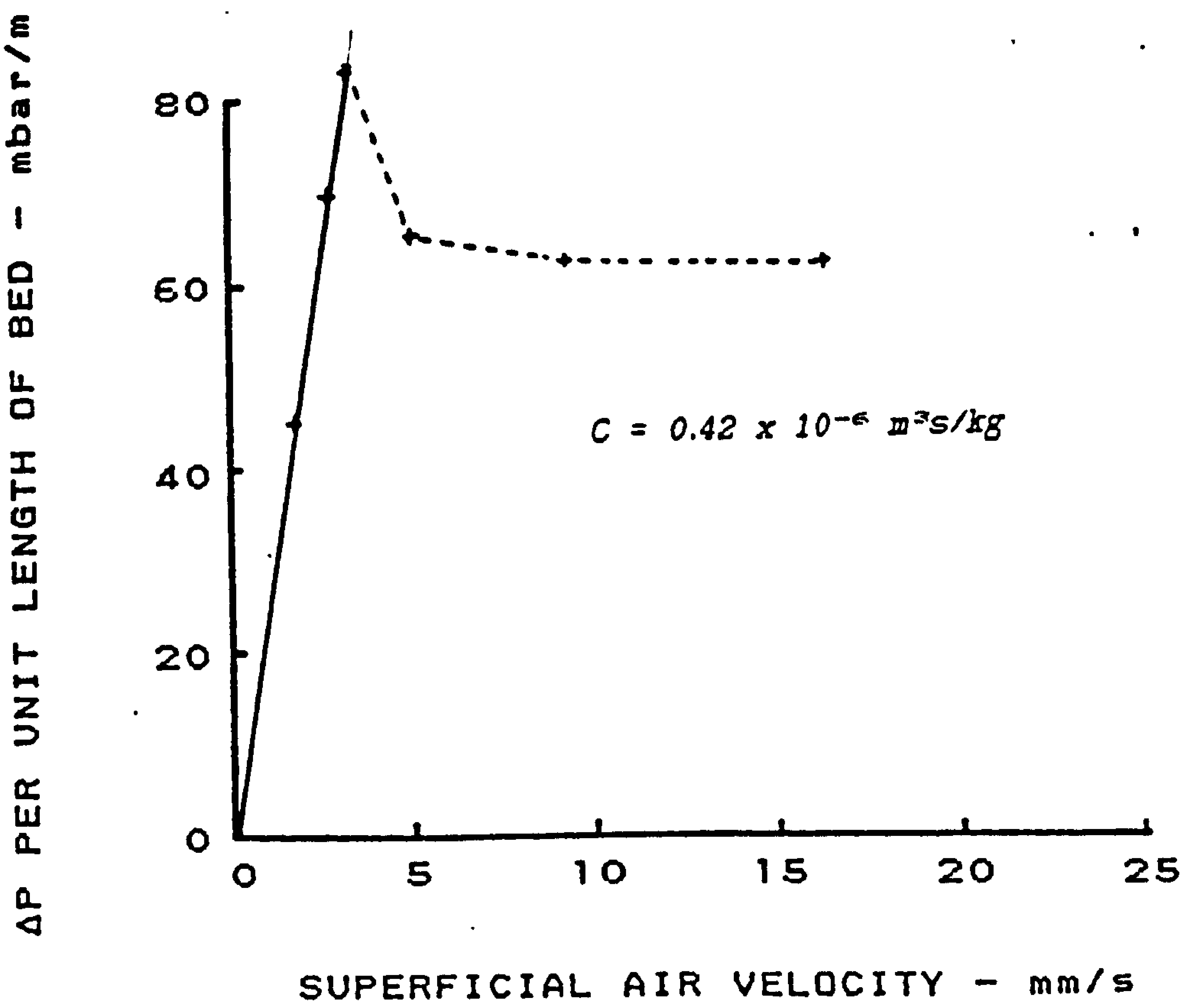


PERMEABILITY DATA

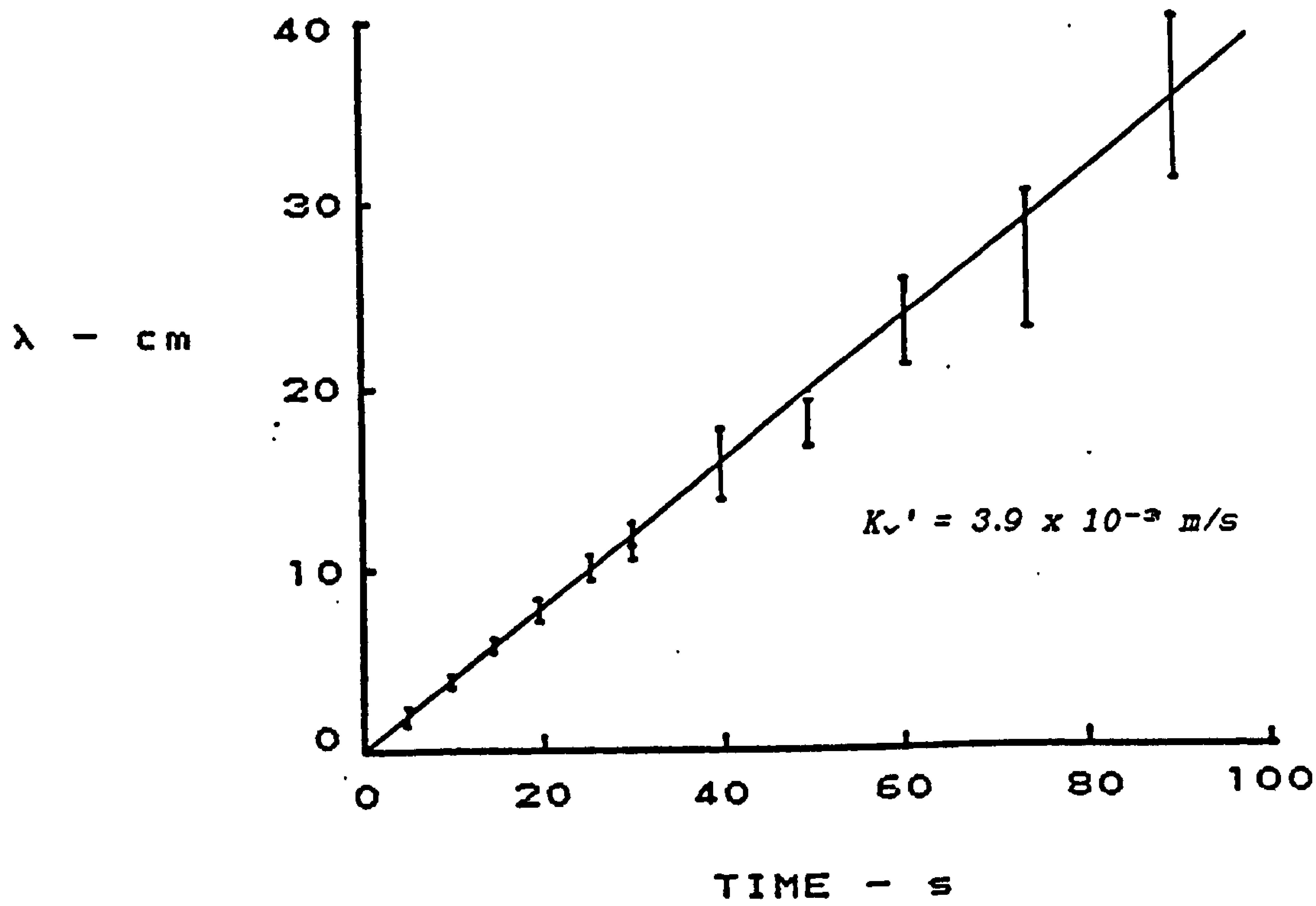
MATERIAL No. 3 - ALUMINA



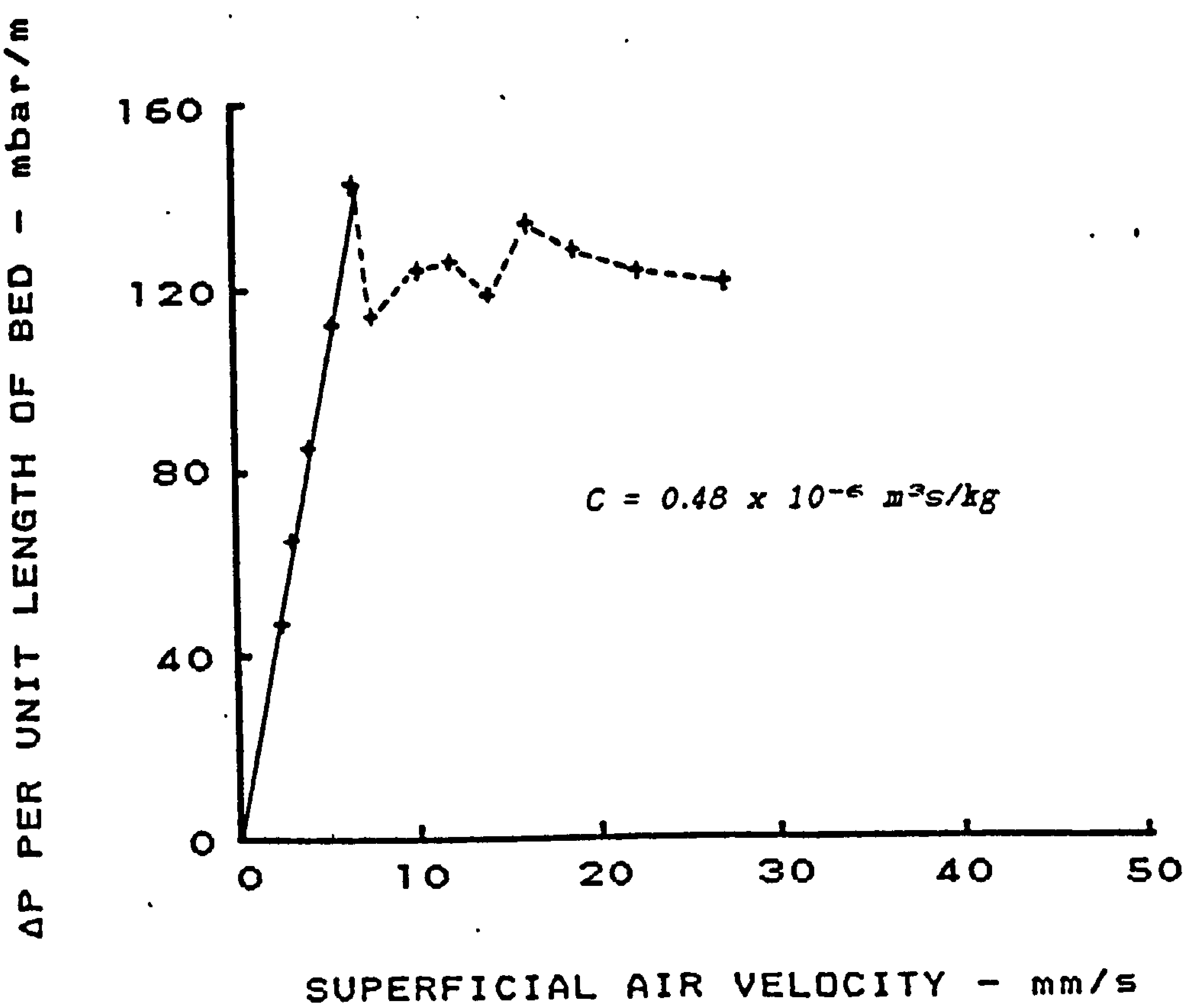
VIBRATED DE-AERATION DATA



PERMEABILITY DATA

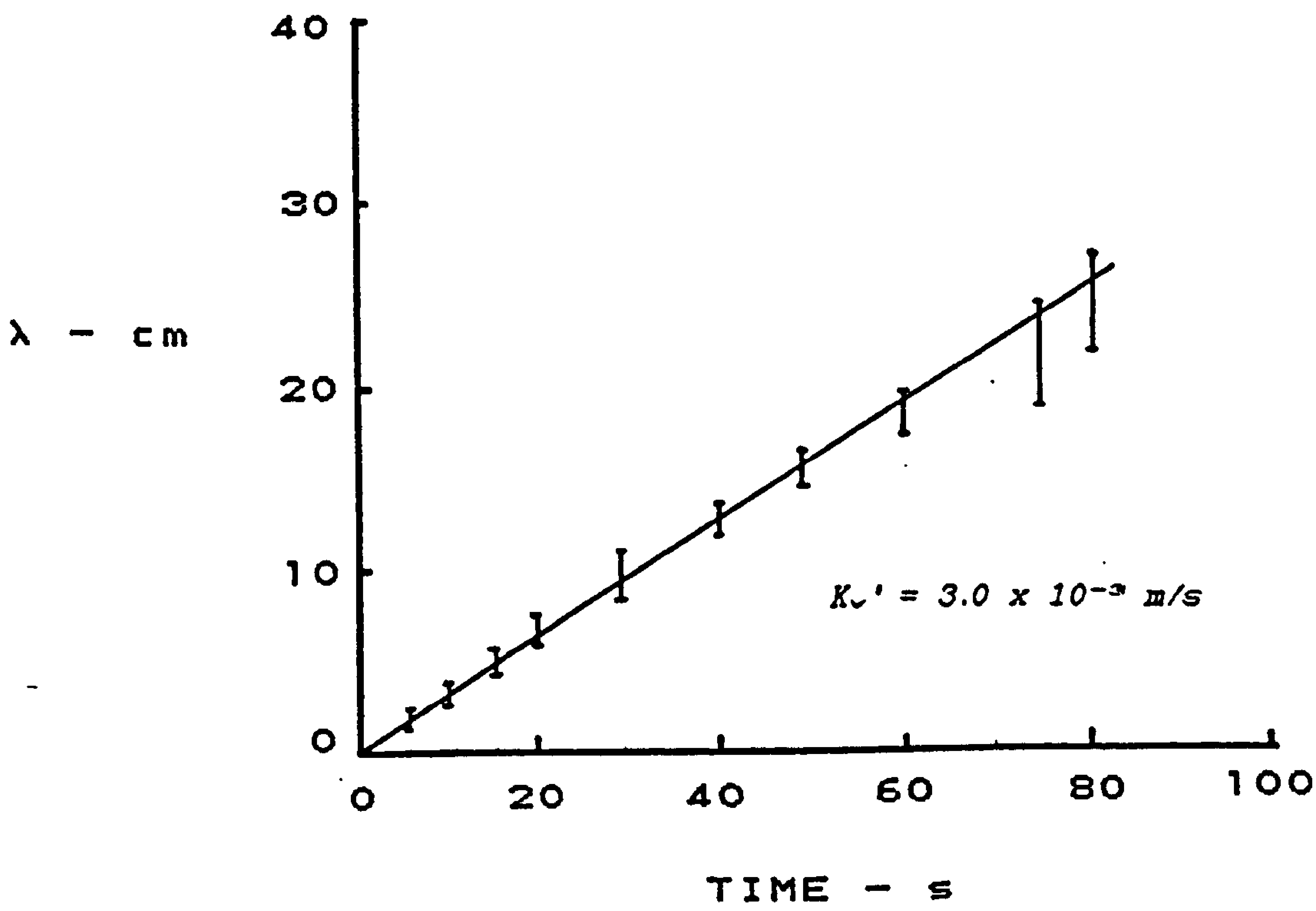


VIBRATED DE-AERATION DATA

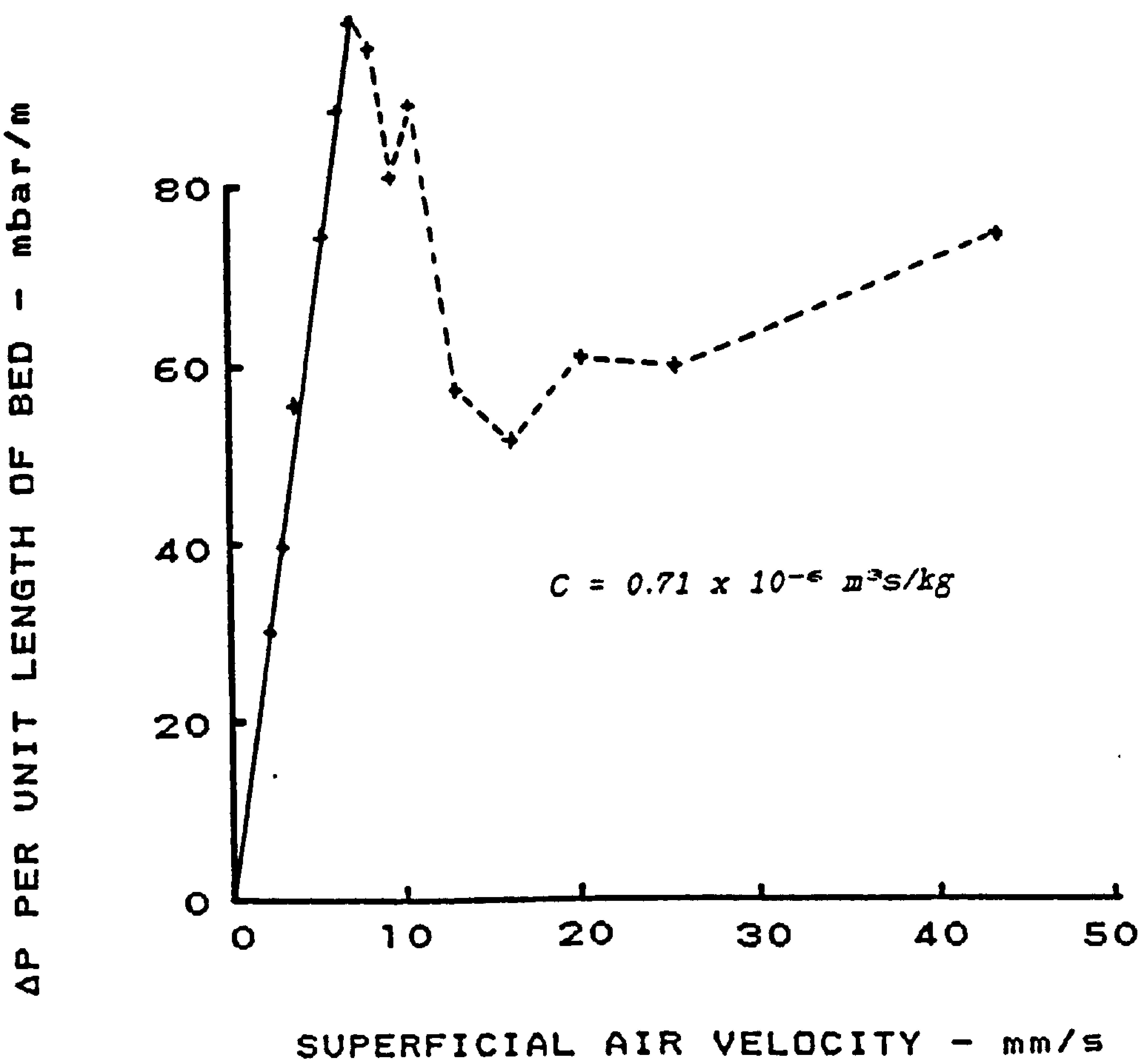


PERMEABILITY DATA

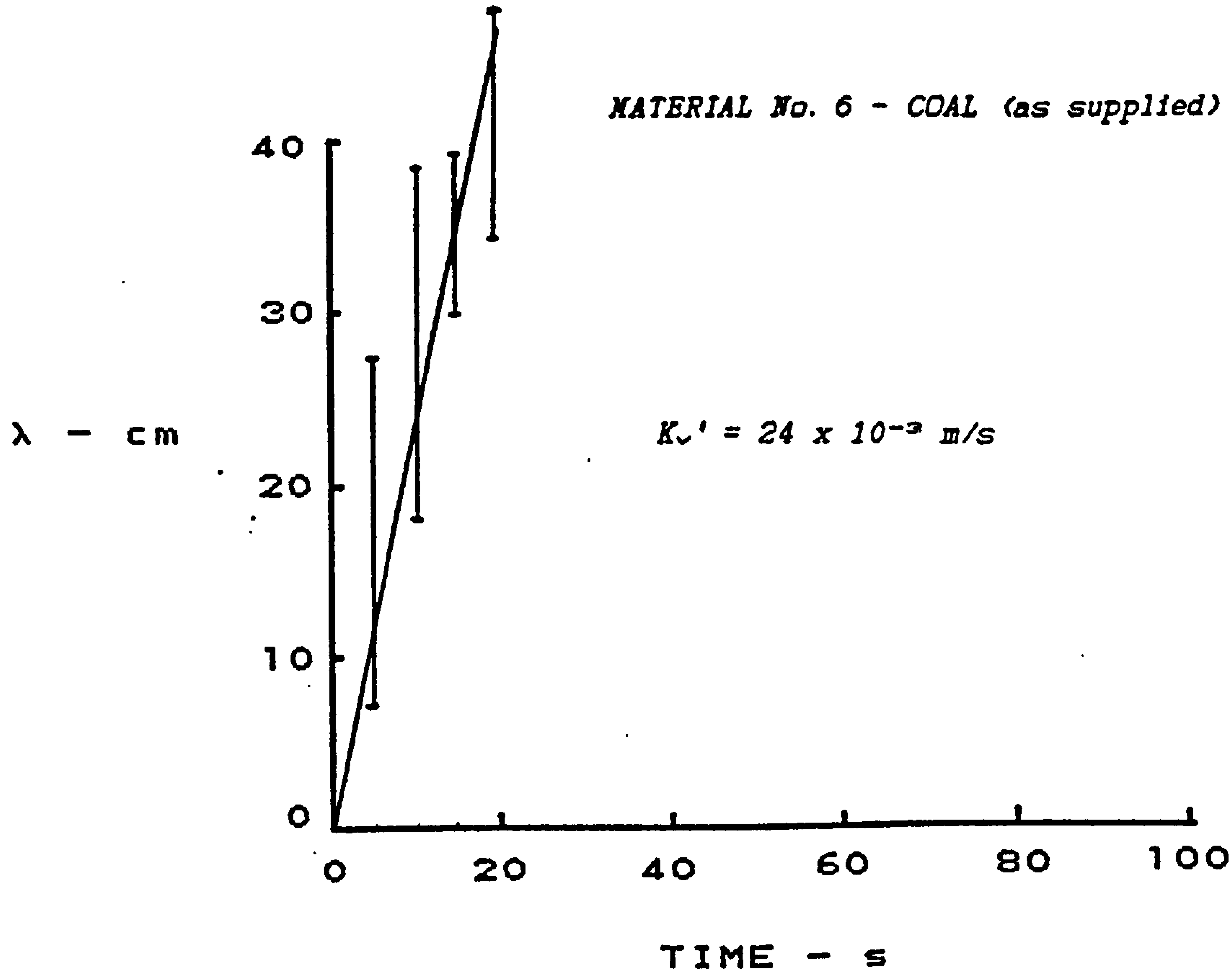
MATERIAL No. 5 - CEMENT



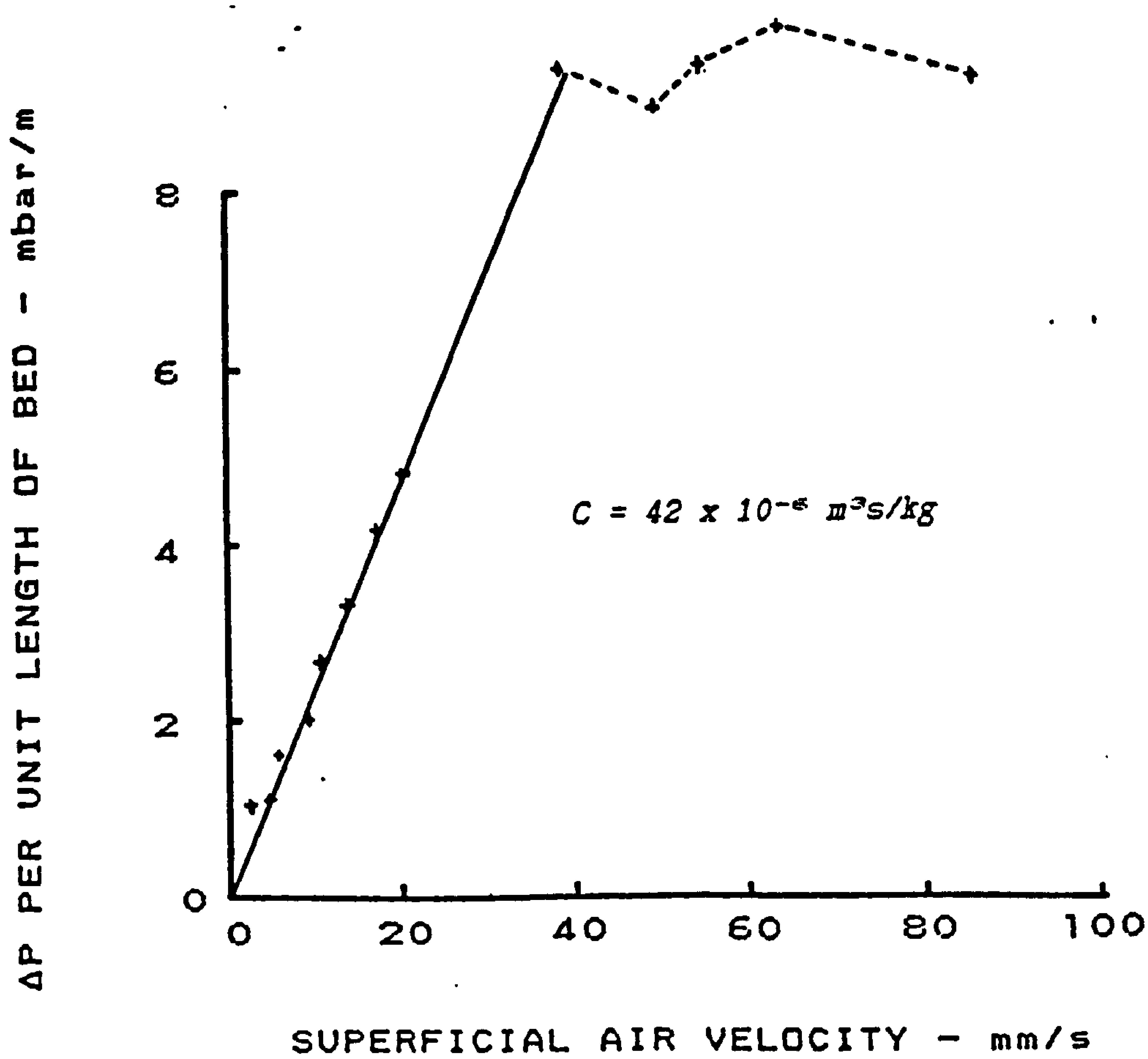
VIBRATED DE-AERATION DATA



PERMEABILITY DATA

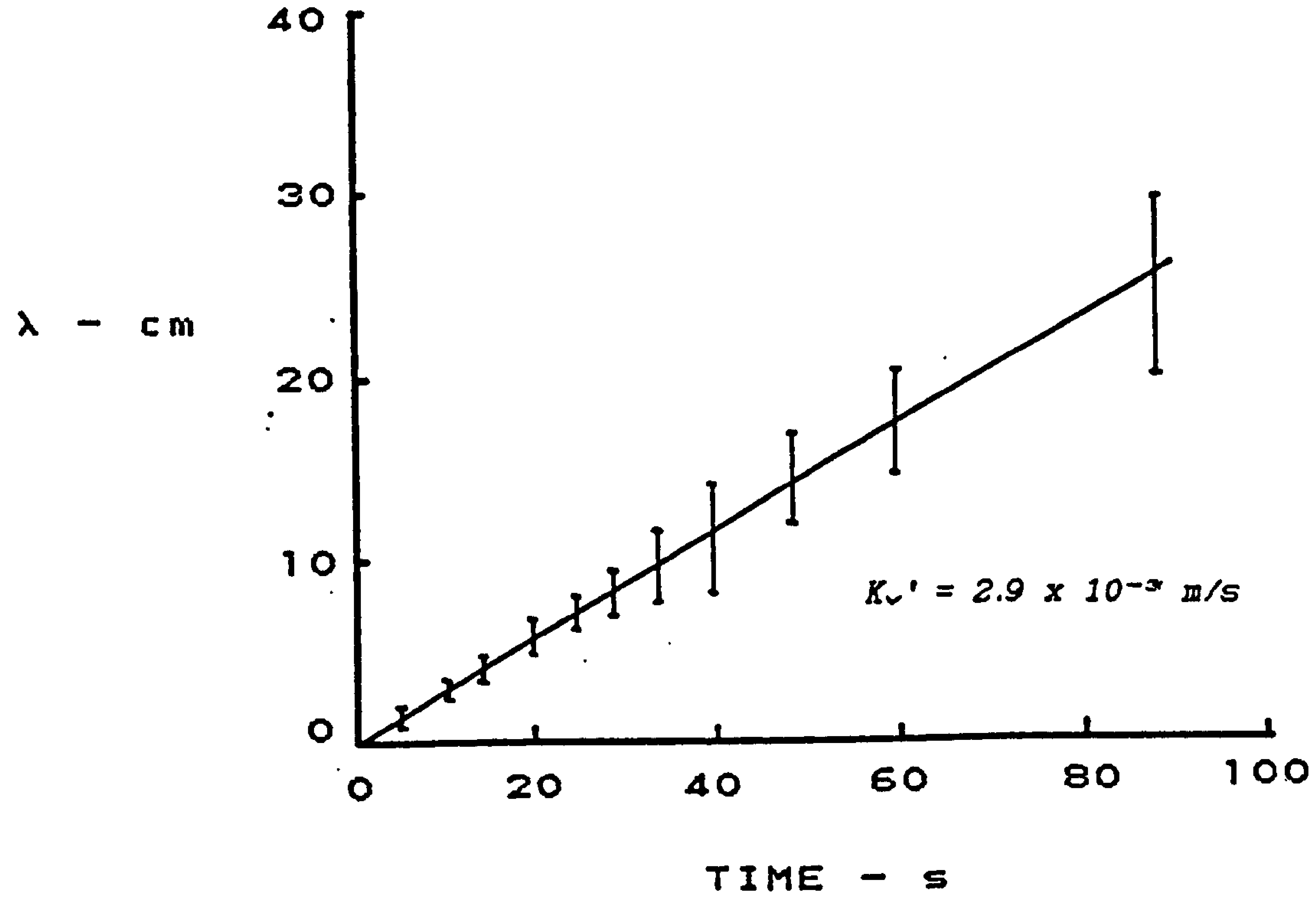


VIBRATED DE-AERATION DATA

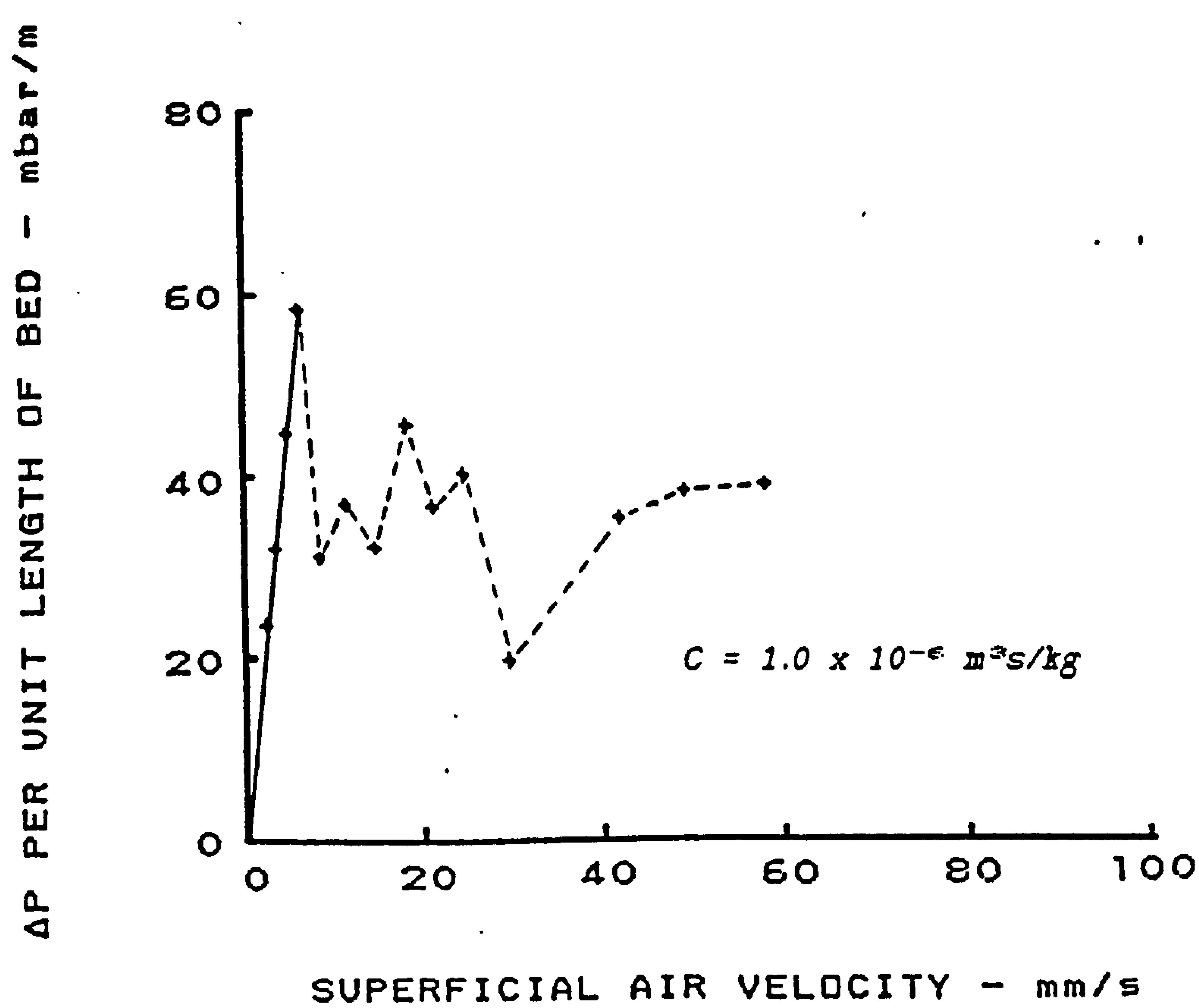


PERMEABILITY DATA

MATERIAL No. 7 - COAL (Degraded)

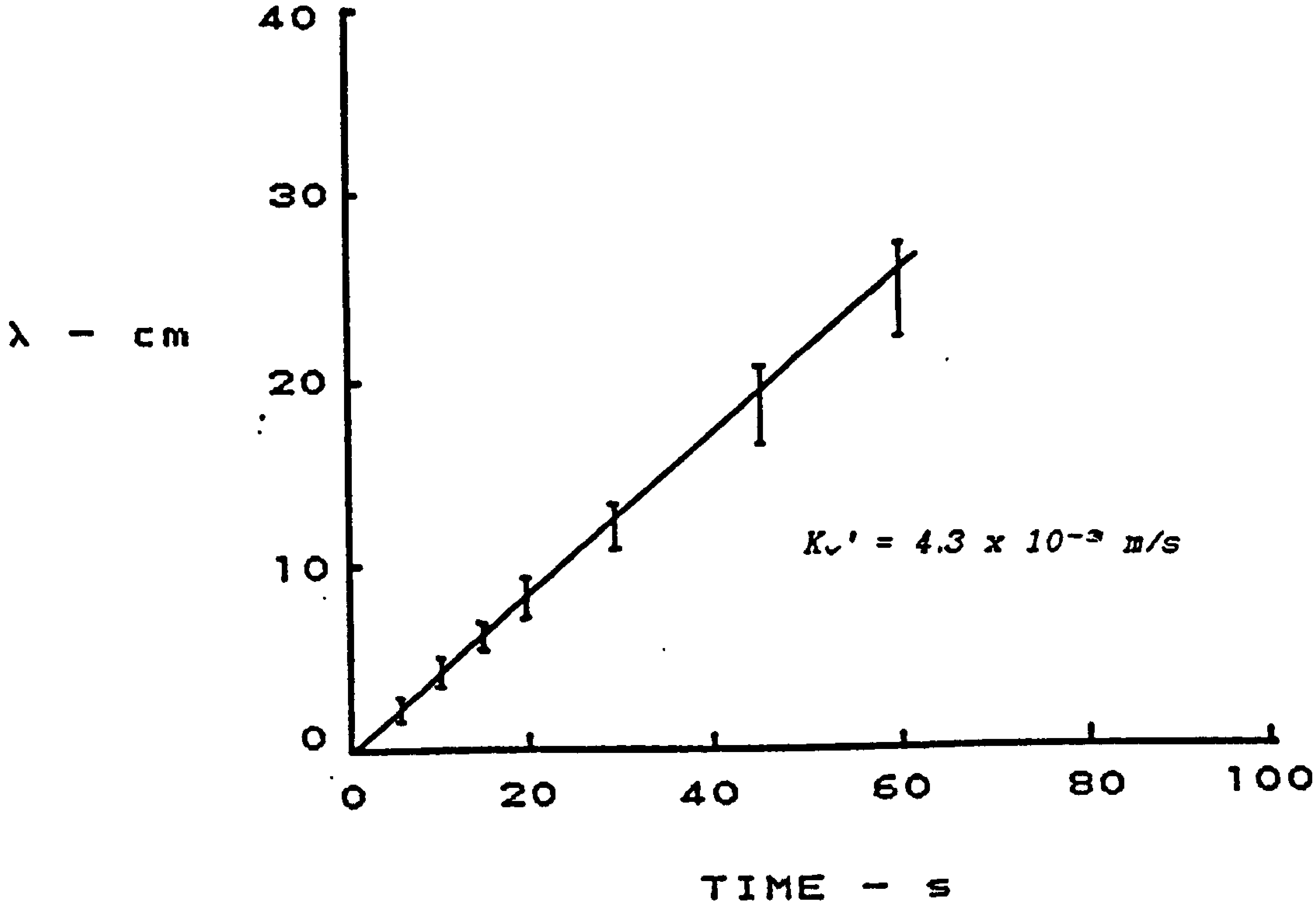


VIBRATED DE-AERATION DATA

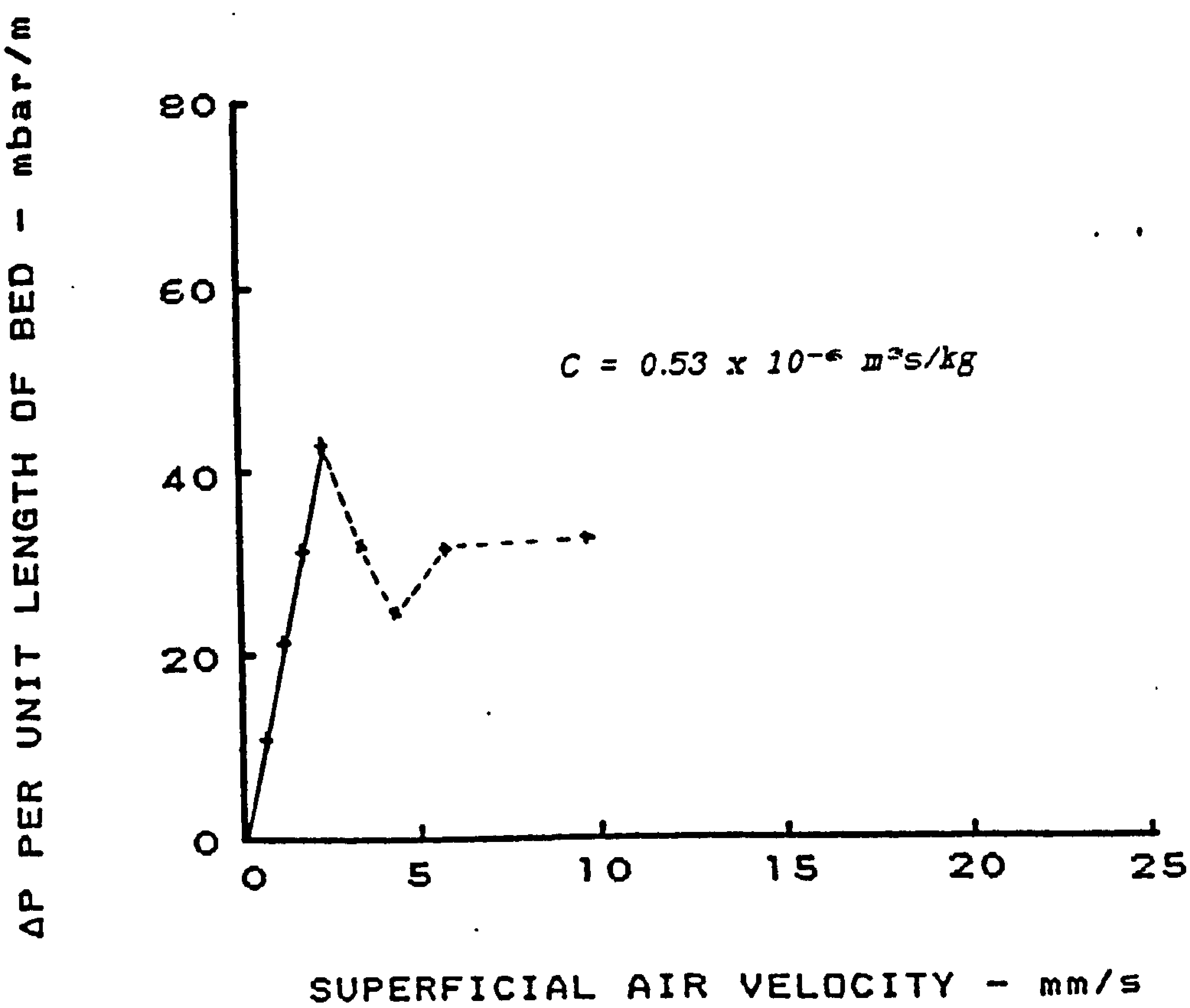


PERMEABILITY DATA

MATERIAL No. 8 - PULVERISED COAL

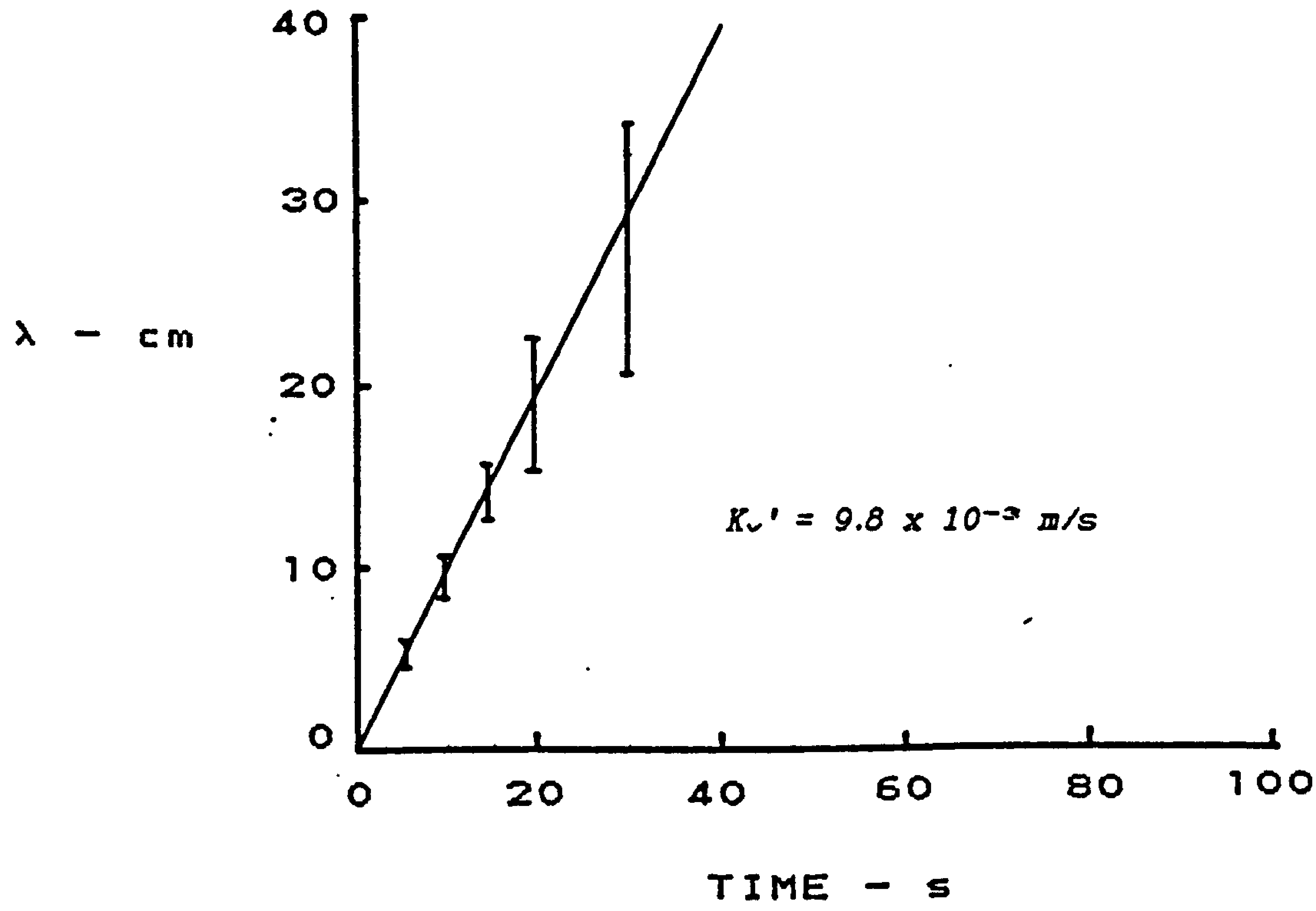


VIBRATED DE-AERATION DATA

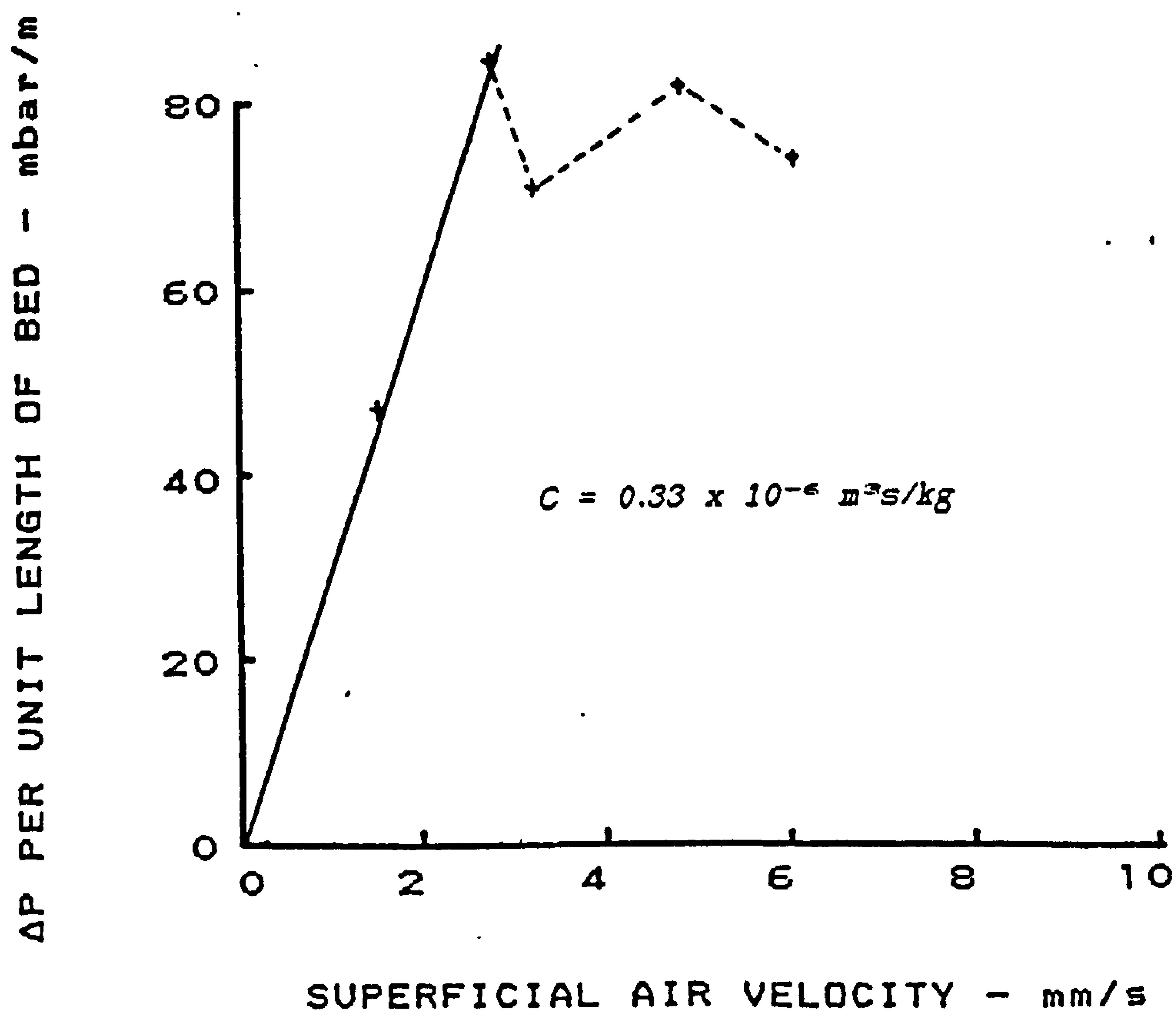


PERMEABILITY DATA

MATERIAL No. 9 - COPPER ORE

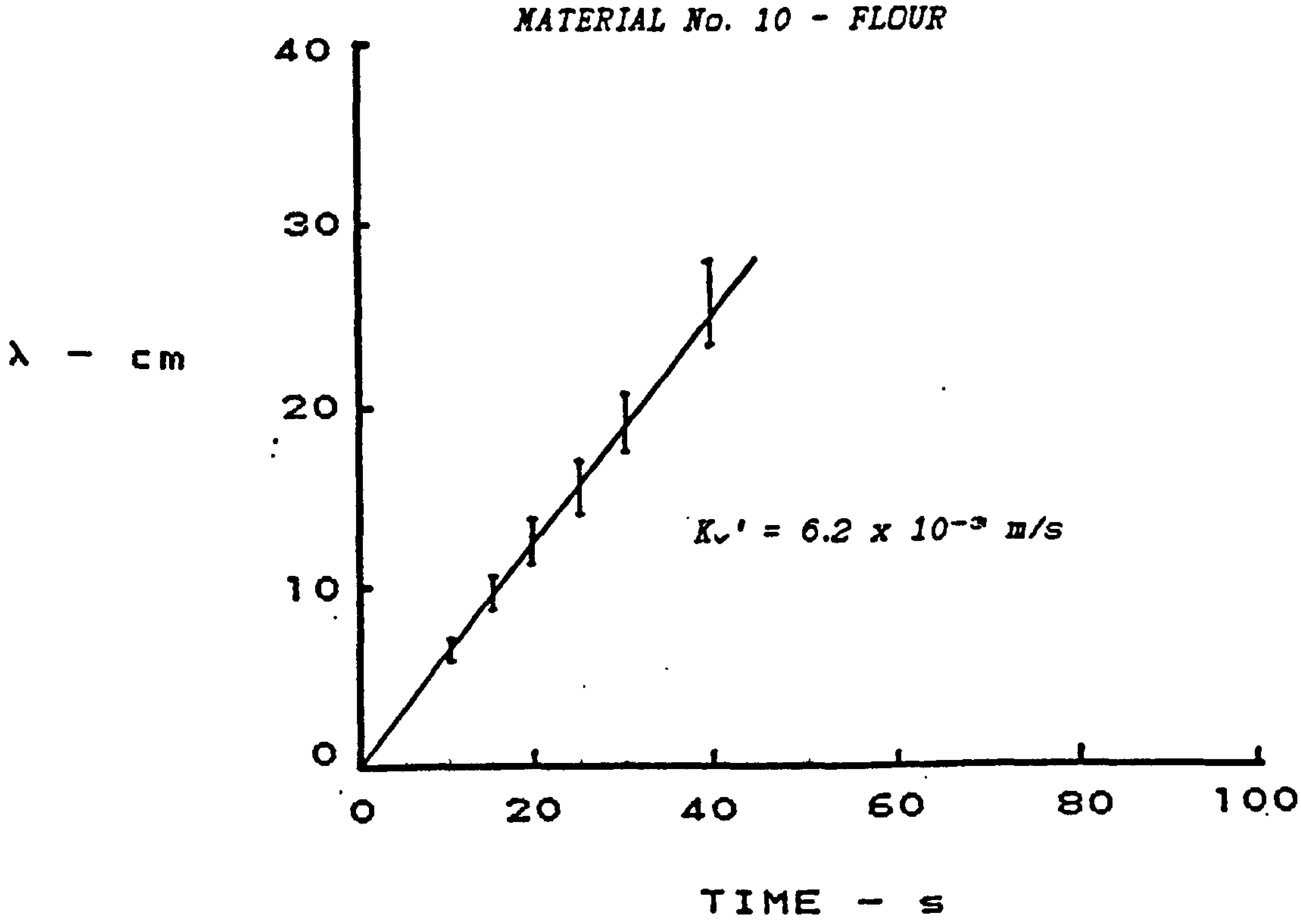


VIBRATED DE-AERATION DATA

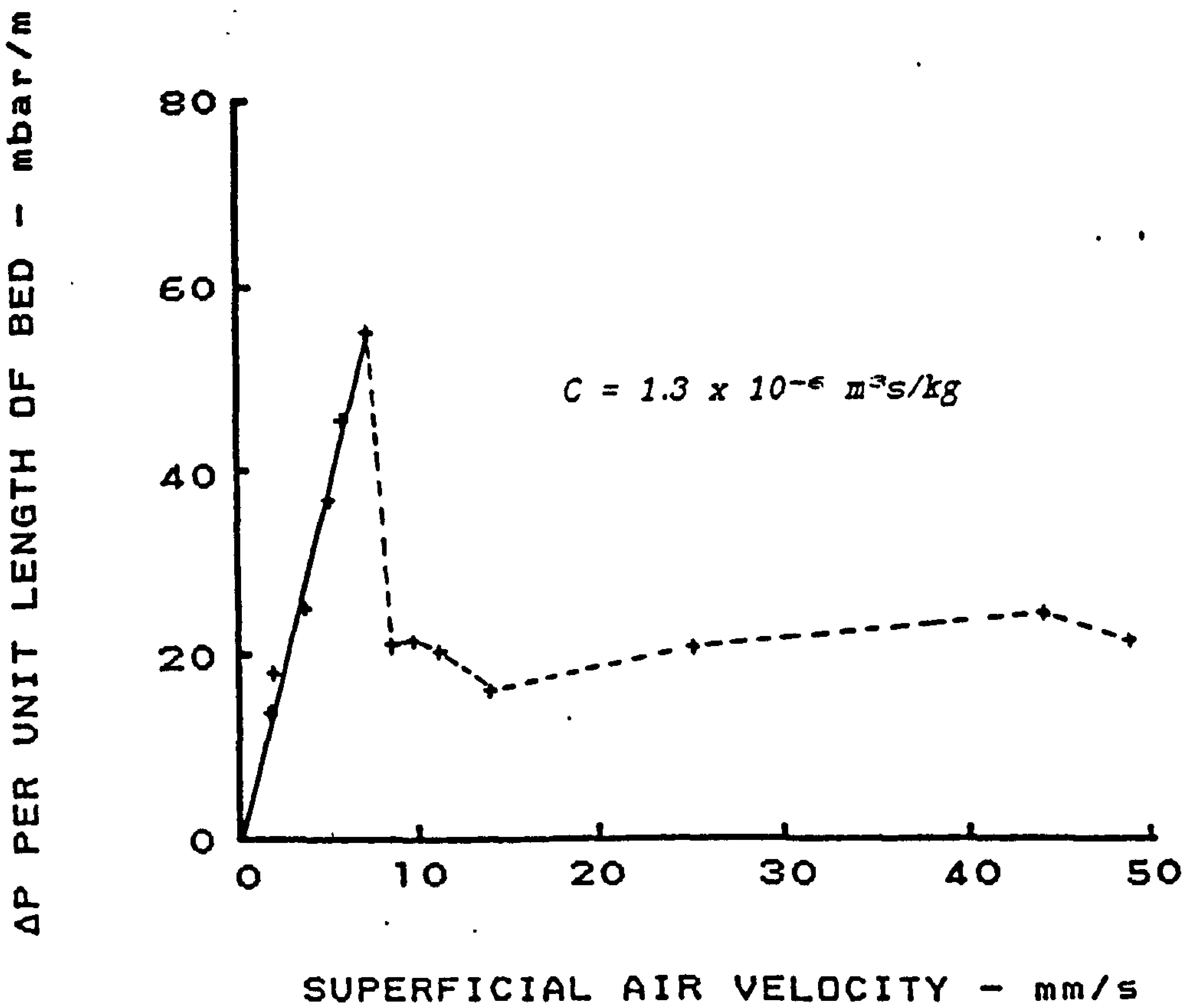


PERMEABILITY DATA

MATERIAL No. 10 - FLOUR

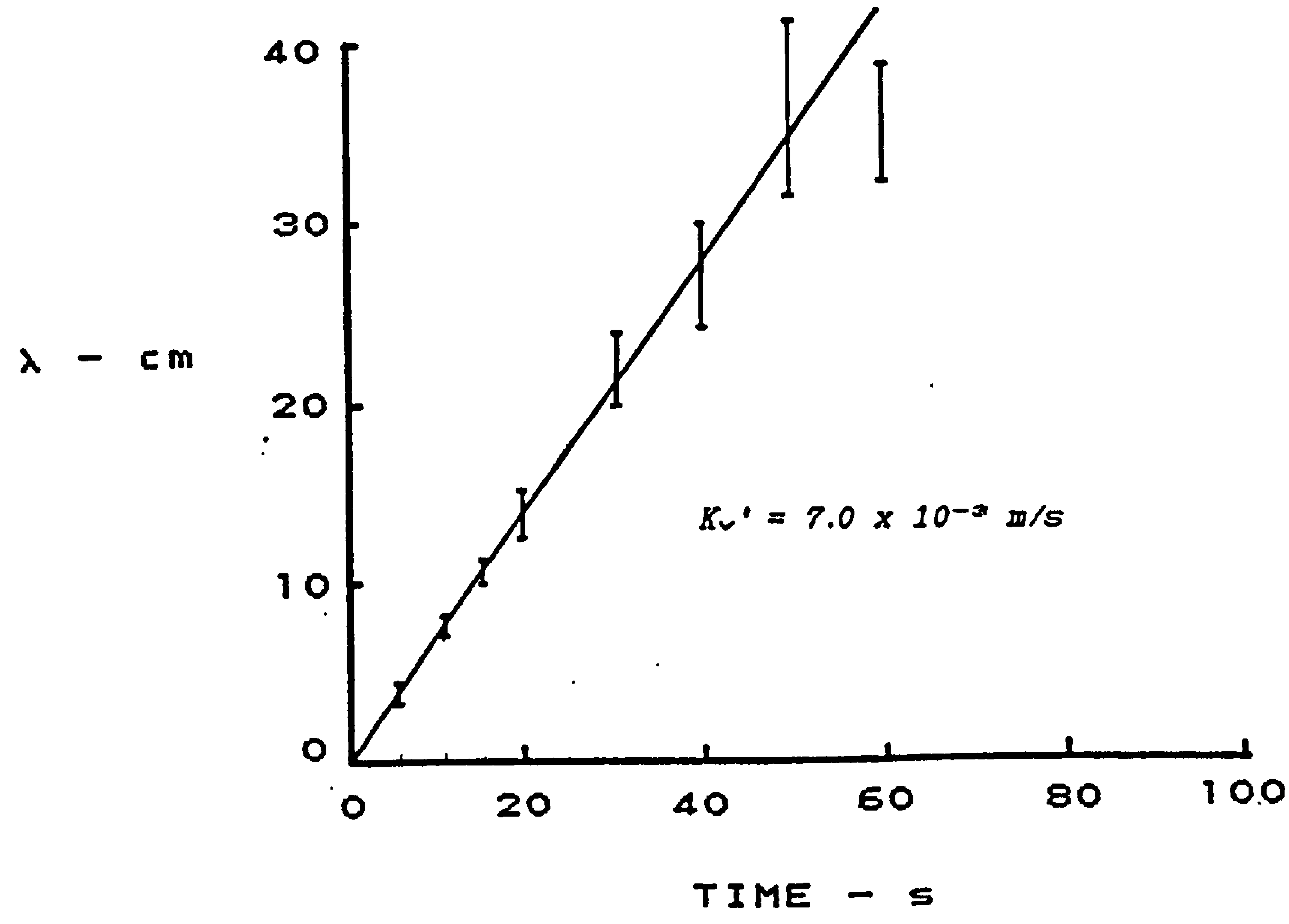


VIBRATED DE-AERATION DATA

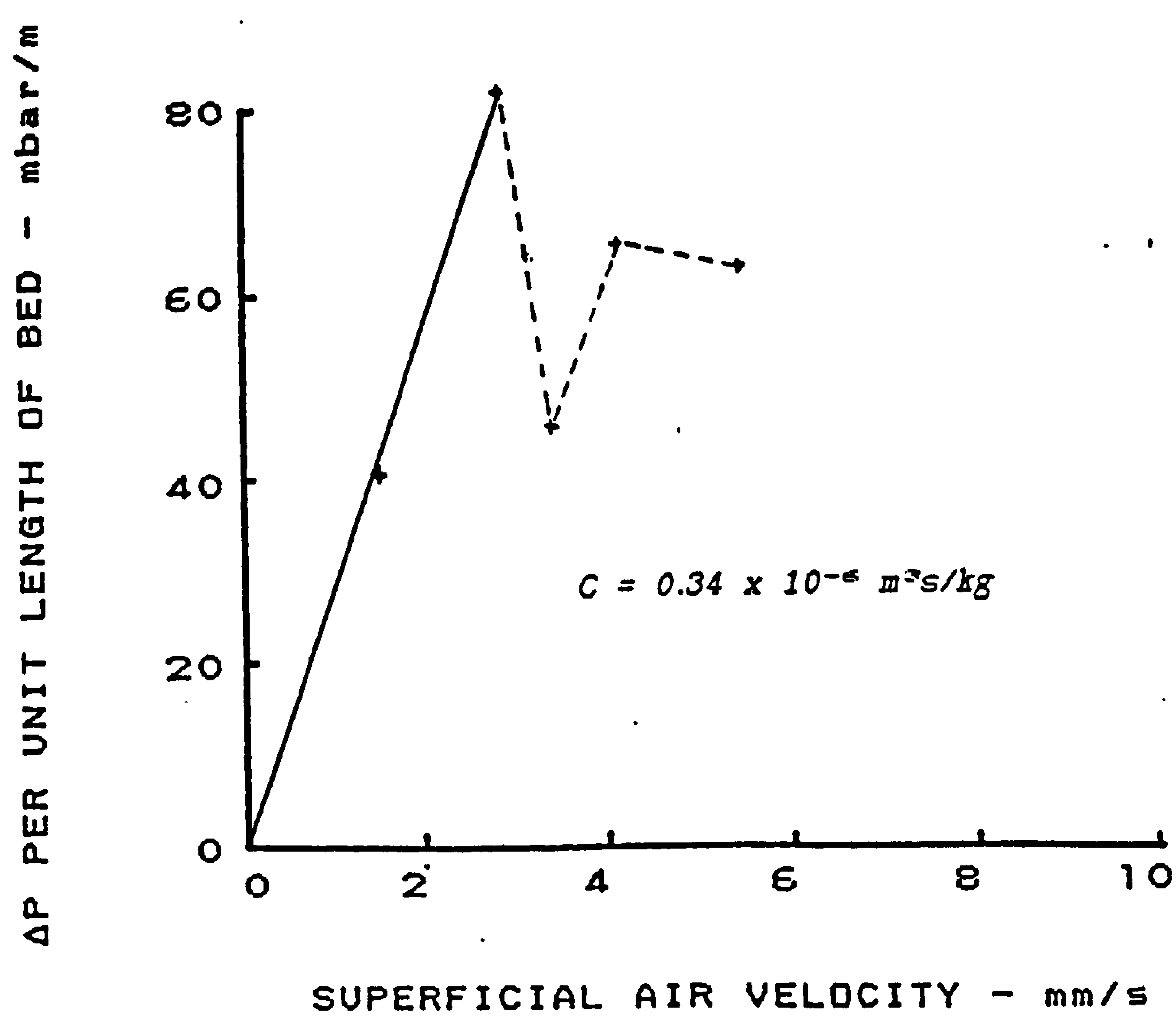


PERMEABILITY DATA

MATERIAL No. 11 - IRON POWDER

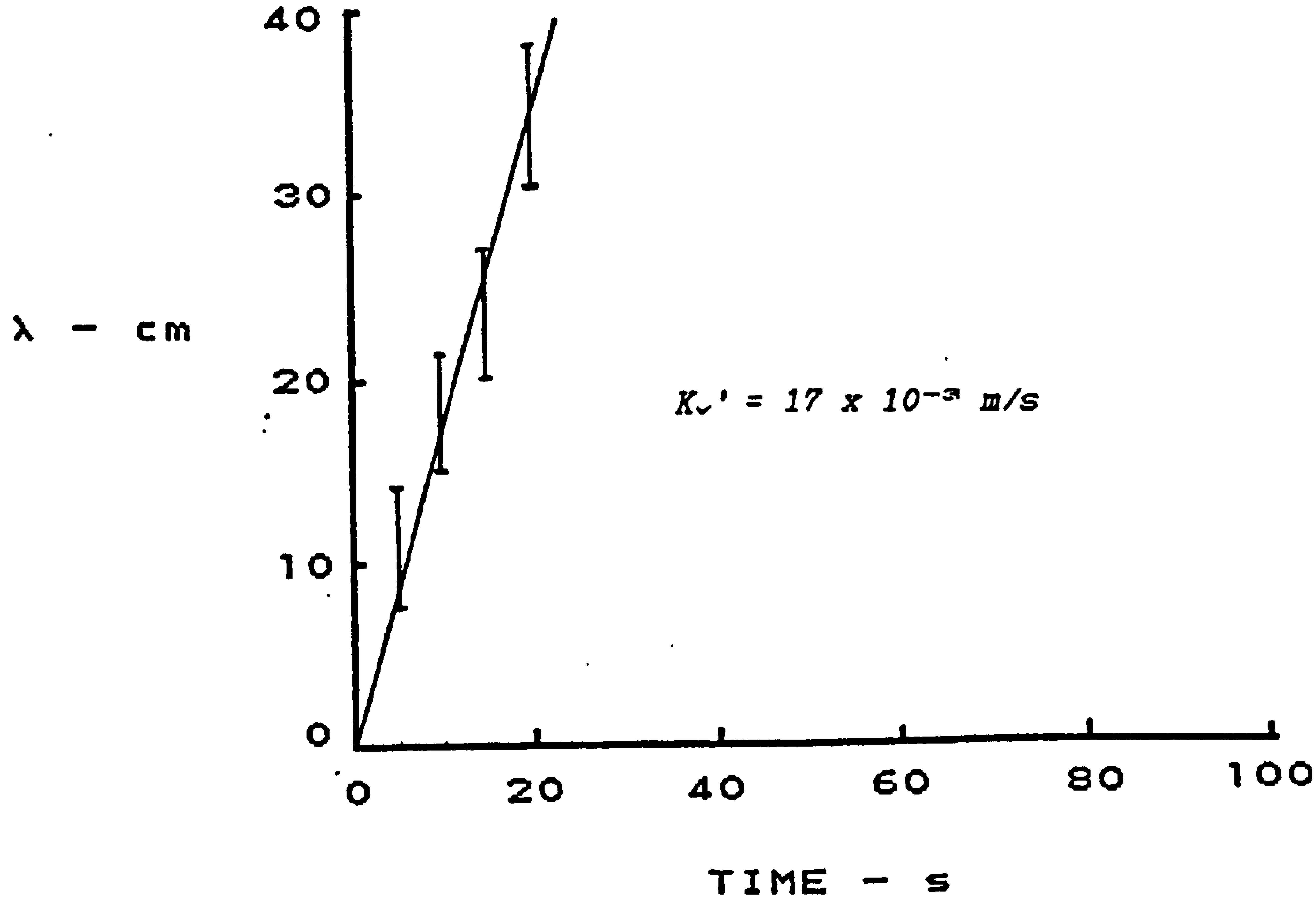


VIBRATED DE-AERATION DATA

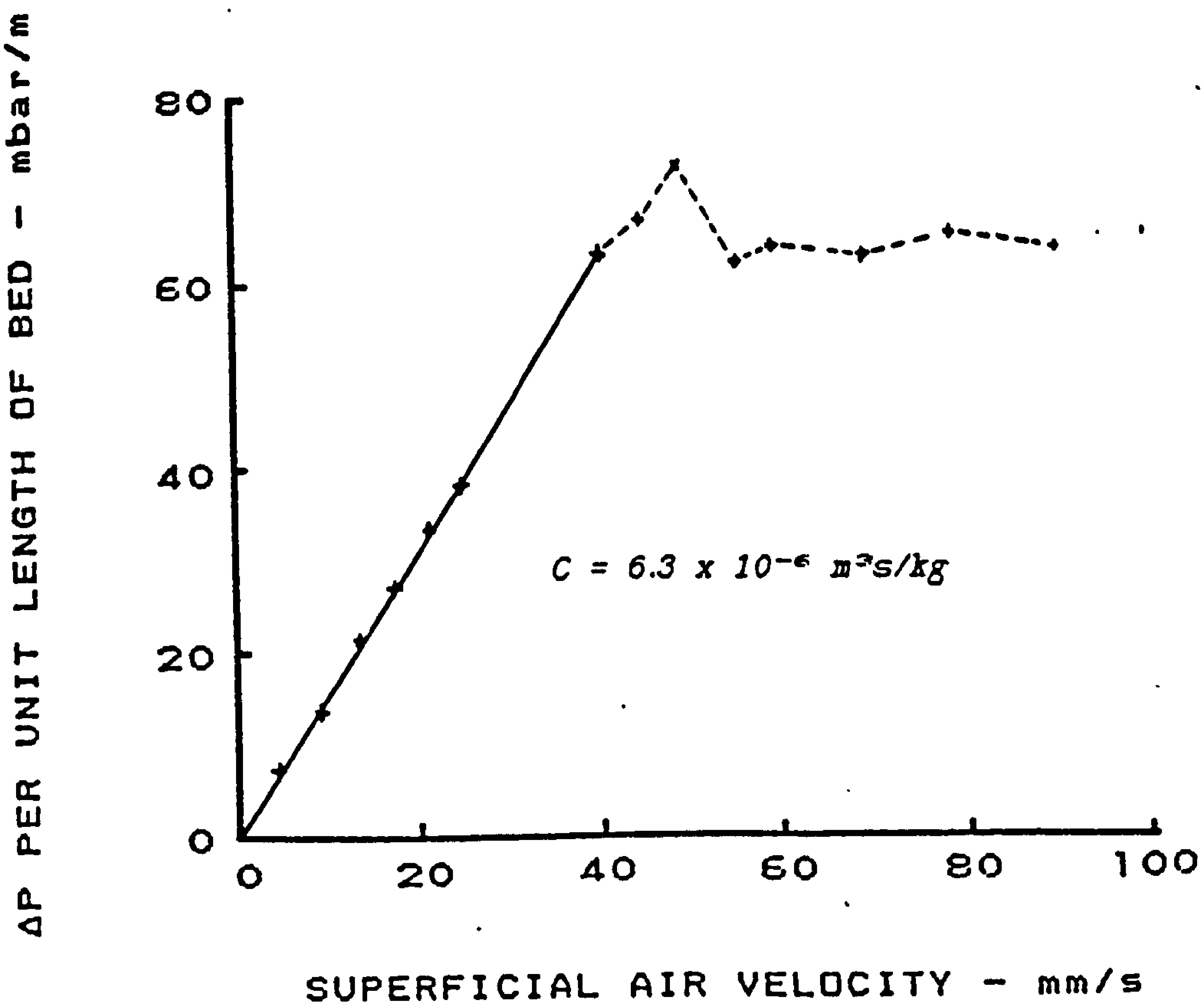


PERMEABILITY DATA

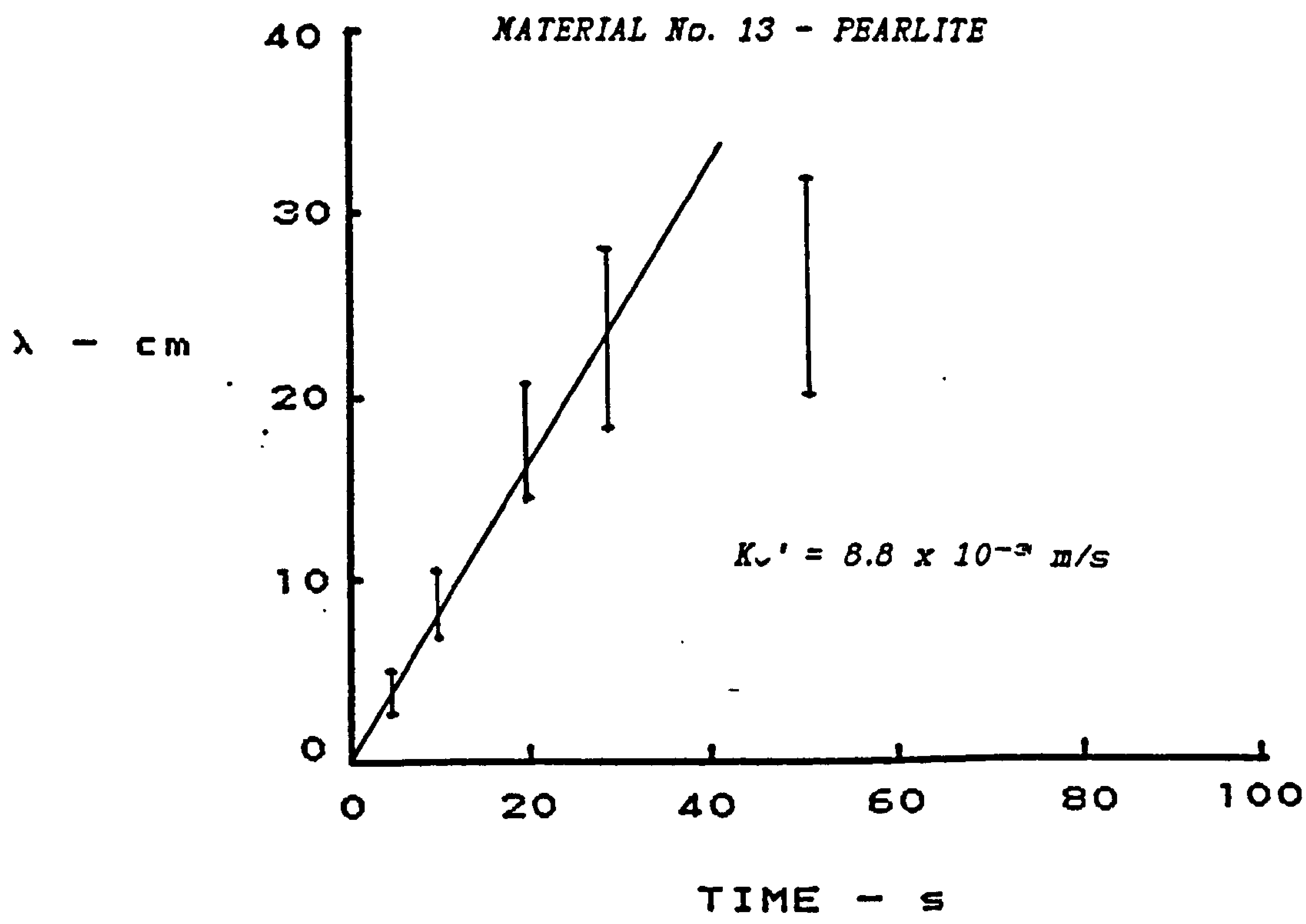
MATERIAL No. 12 - MAGNESIUM SULPHATE



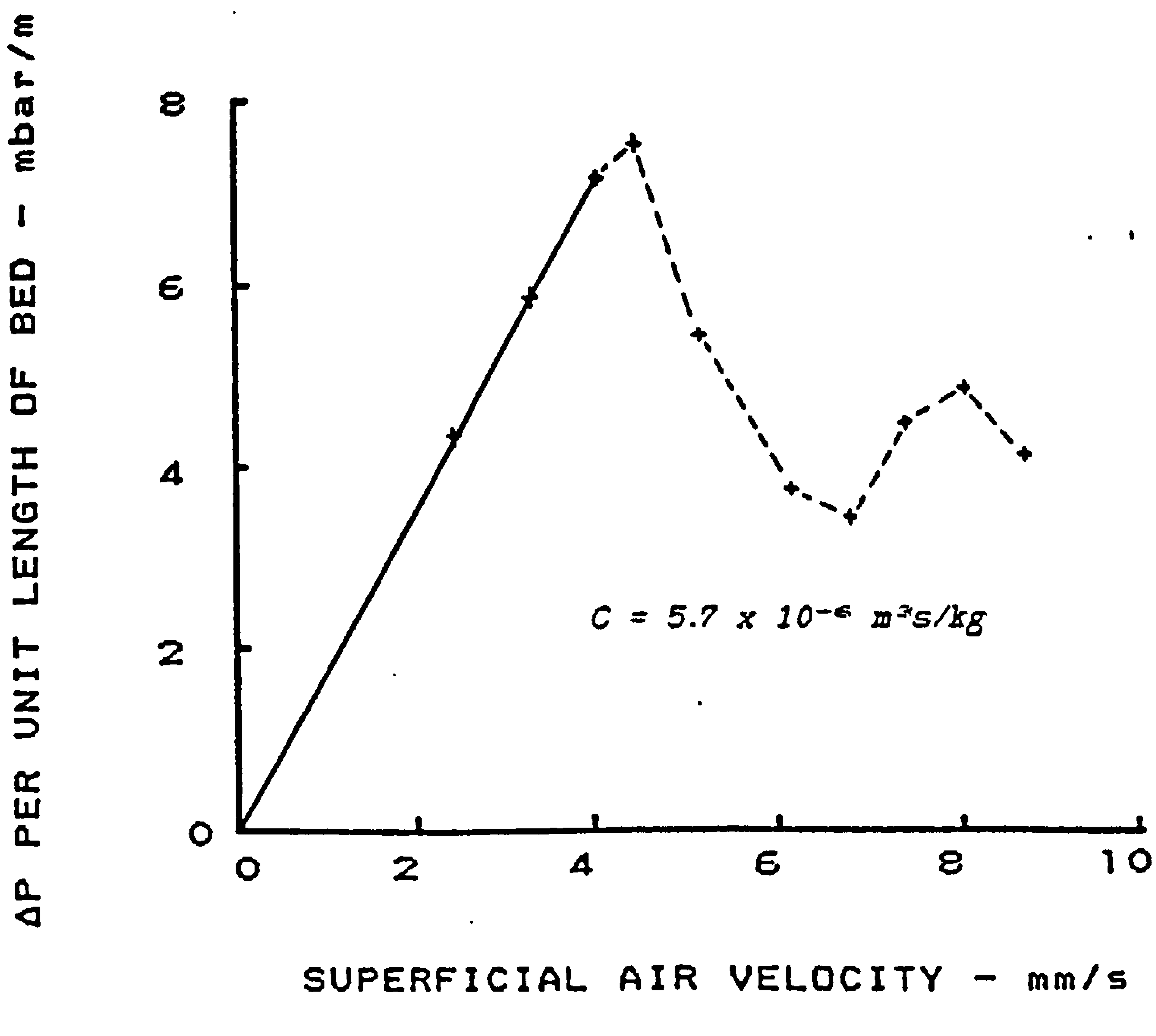
VIBRATED DE-AERATION DATA



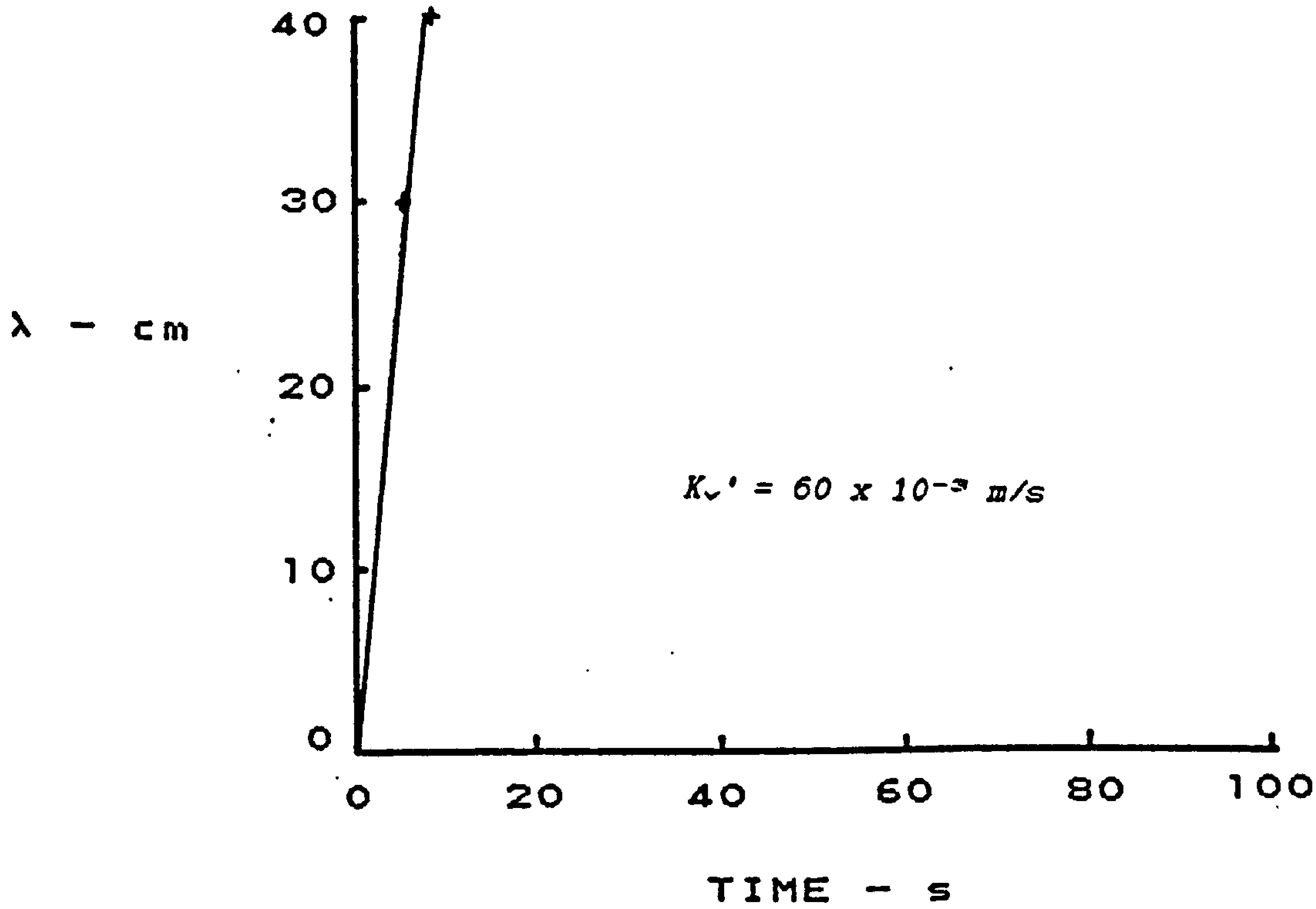
PERMEABILITY DATA



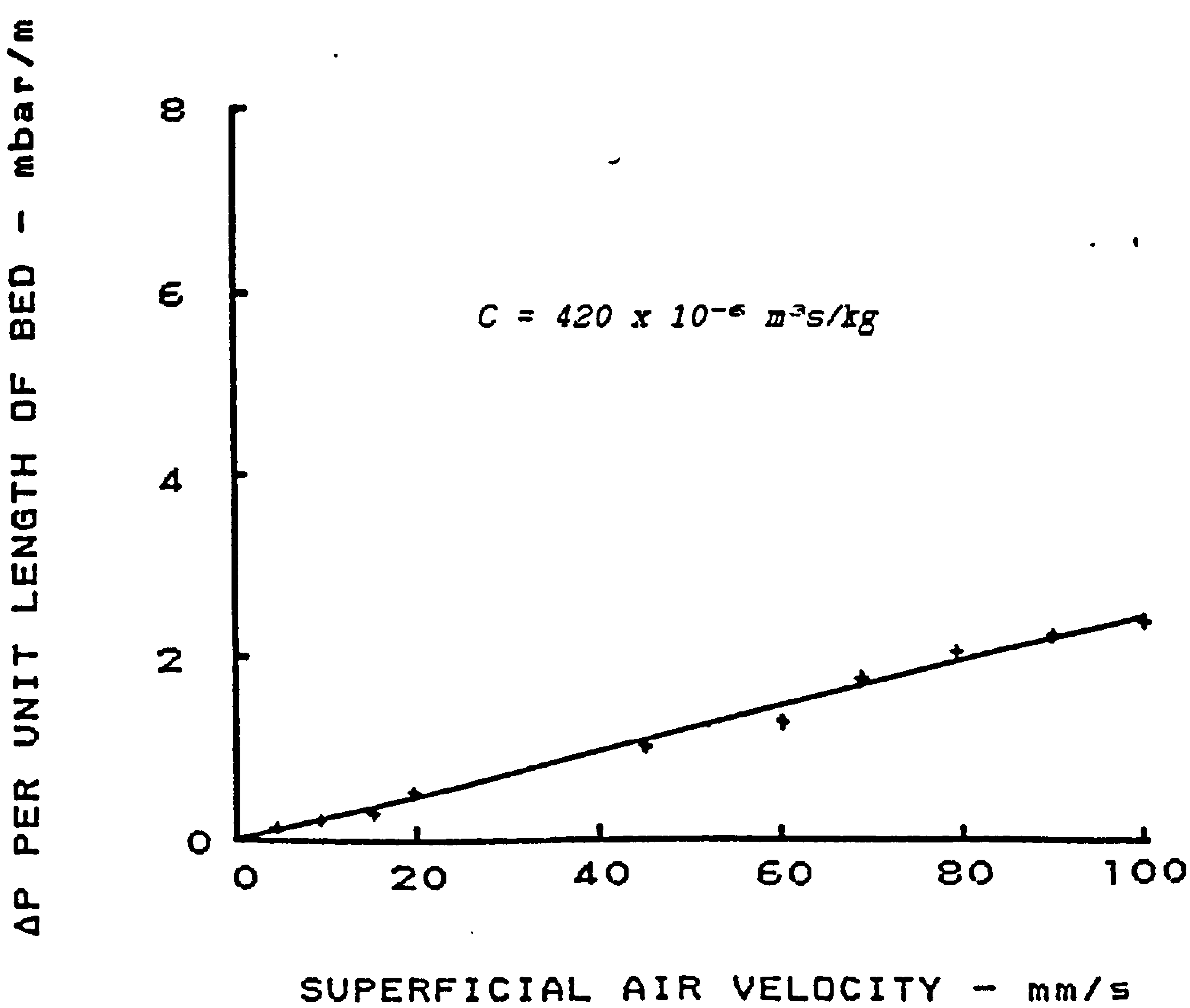
VIBRATED DE-AERATION DATA



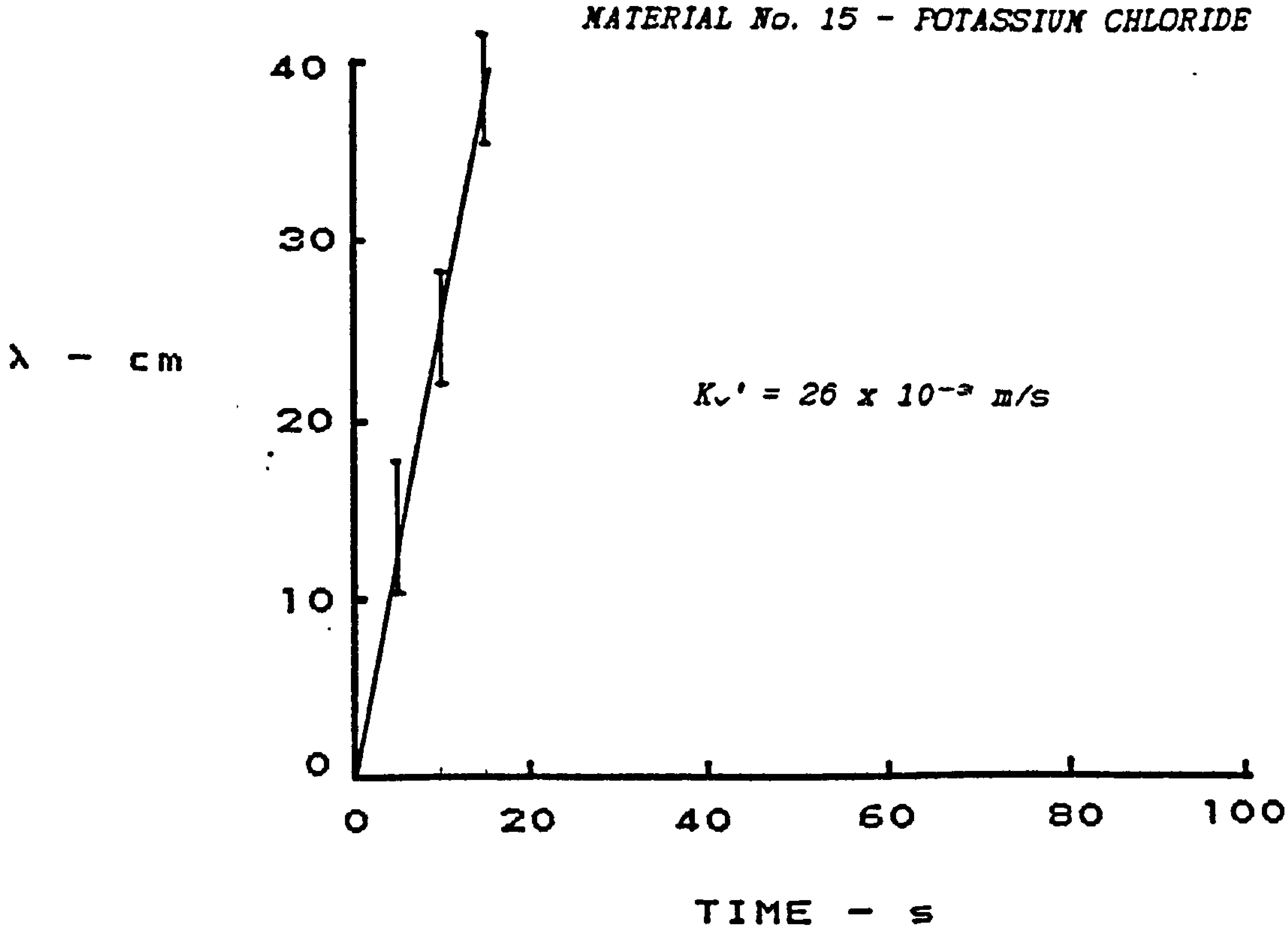
PERMEABILITY DATA



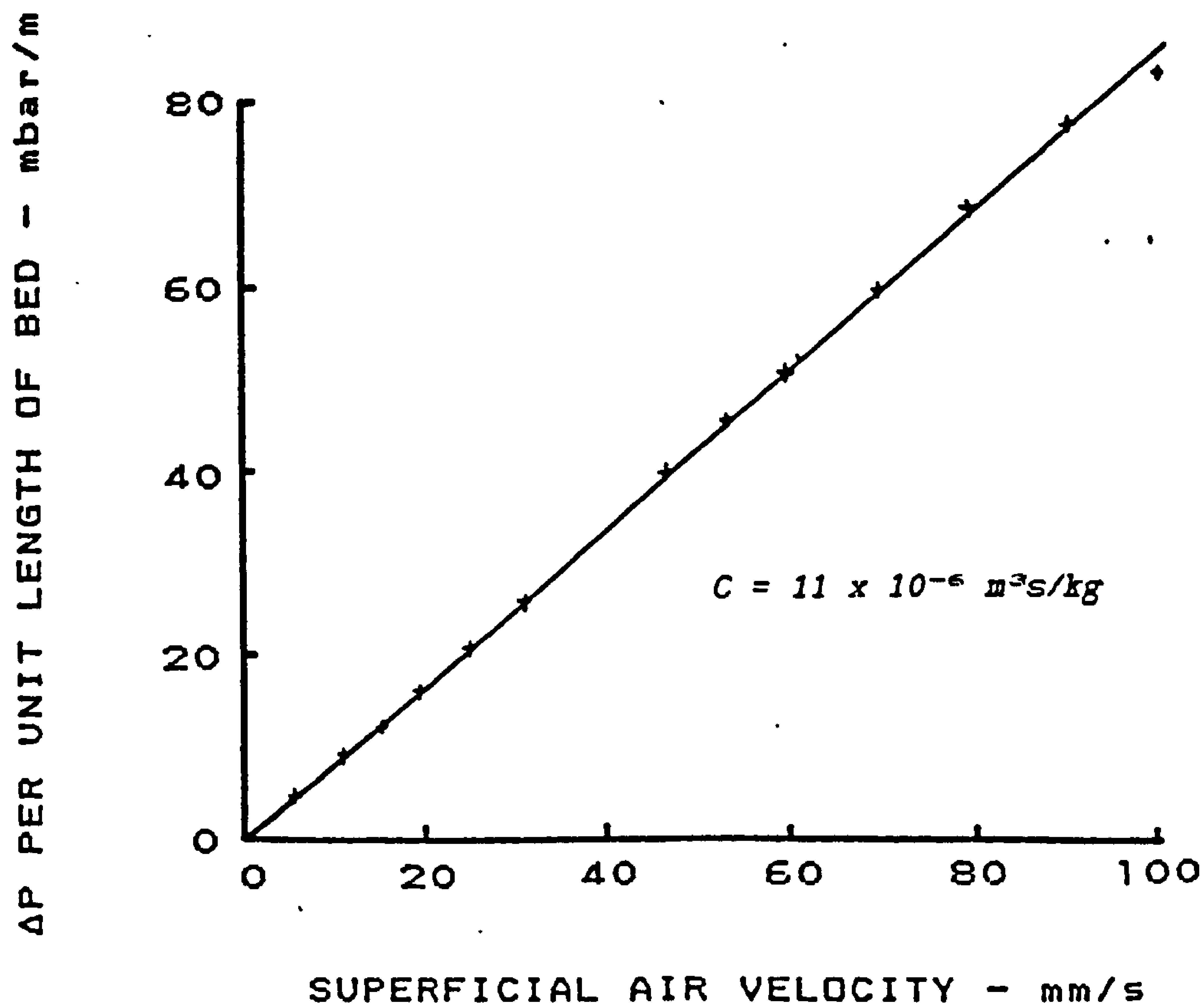
VIBRATED DE-AERATION DATA



PERMEABILITY DATA

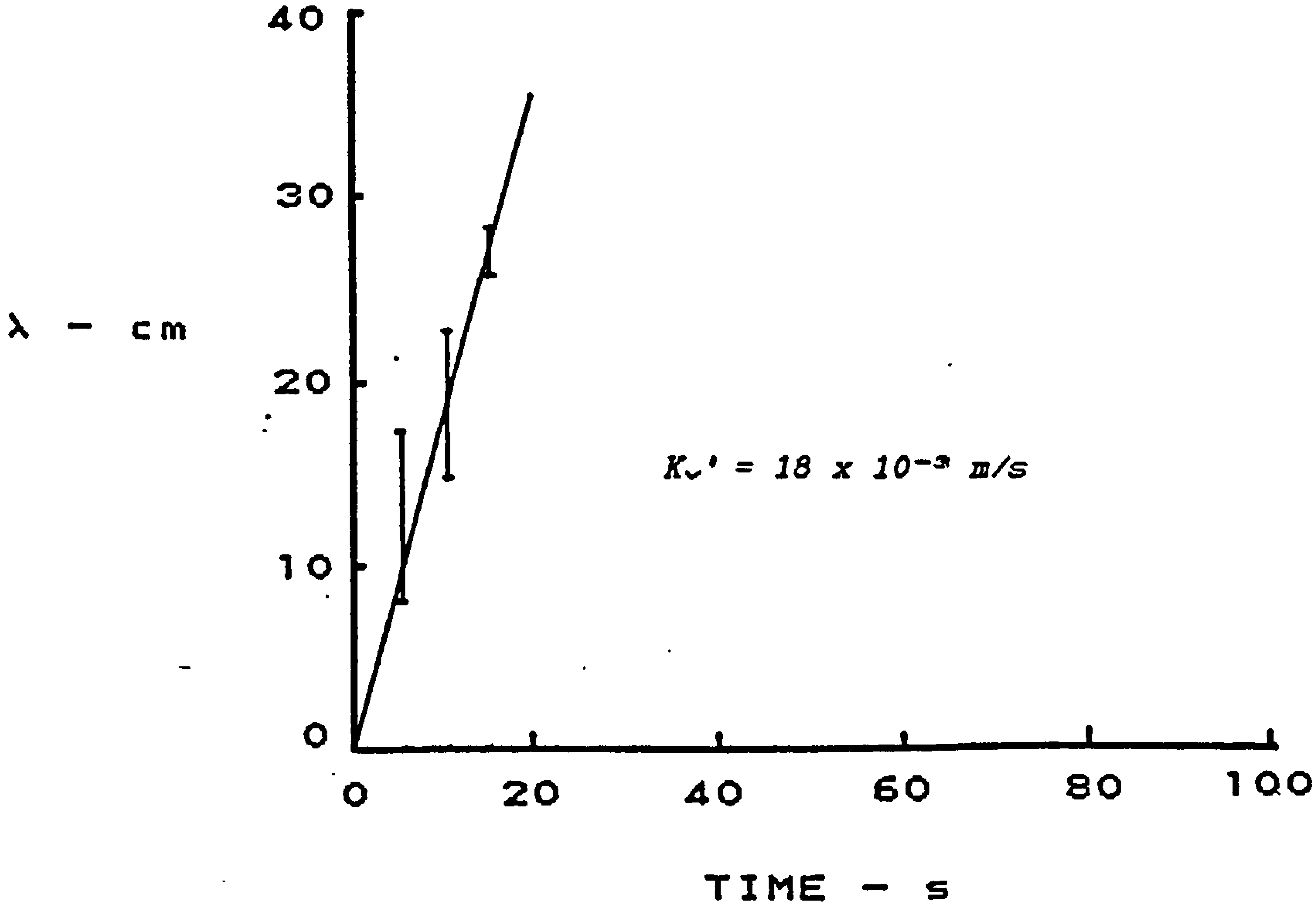


VIBRATED DE-AERATION DATA

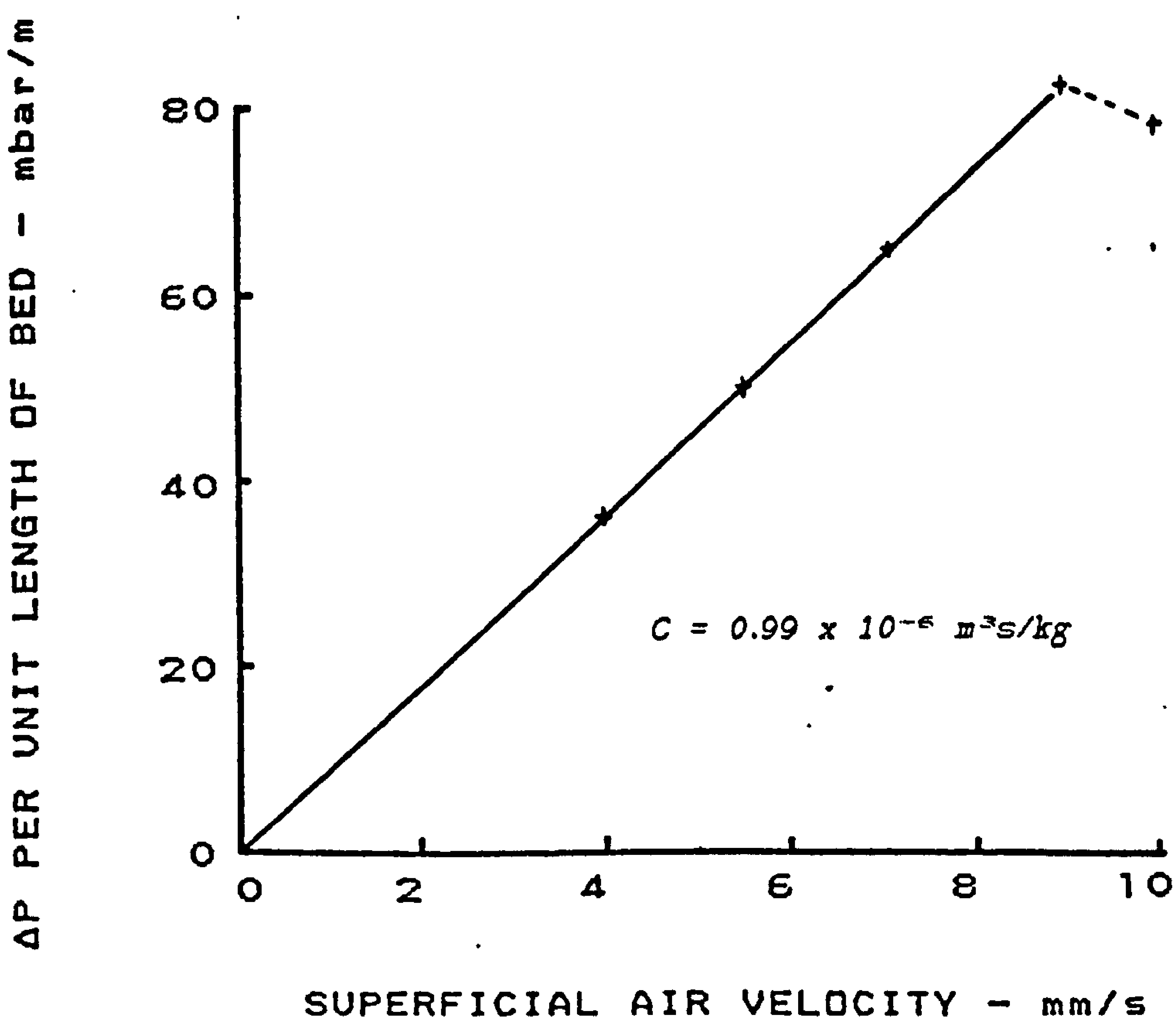


PERMEABILITY DATA

MATERIAL No. 16 - POTASSIUM SULPHATE

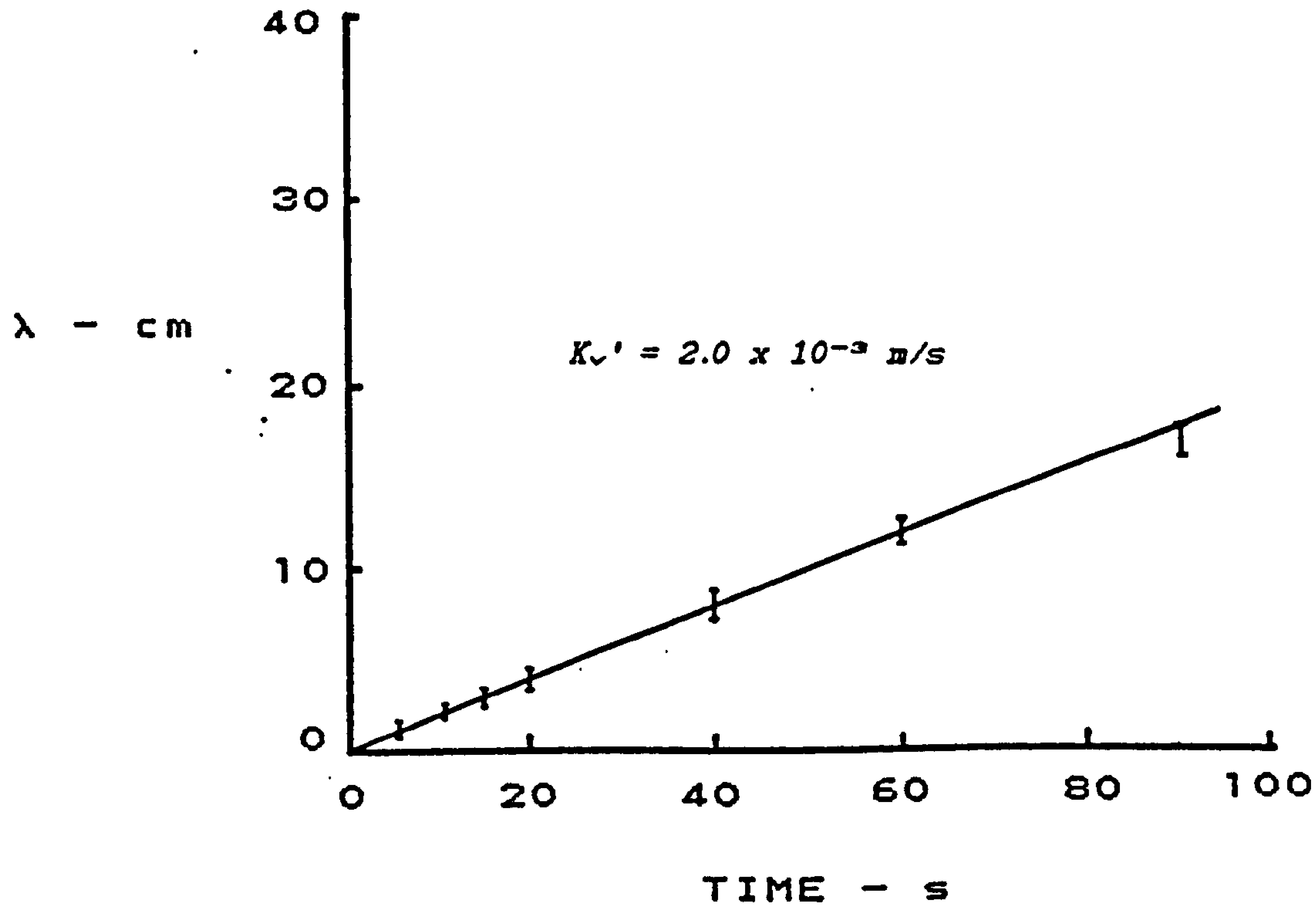


VIBRATED DE-AERATION DATA

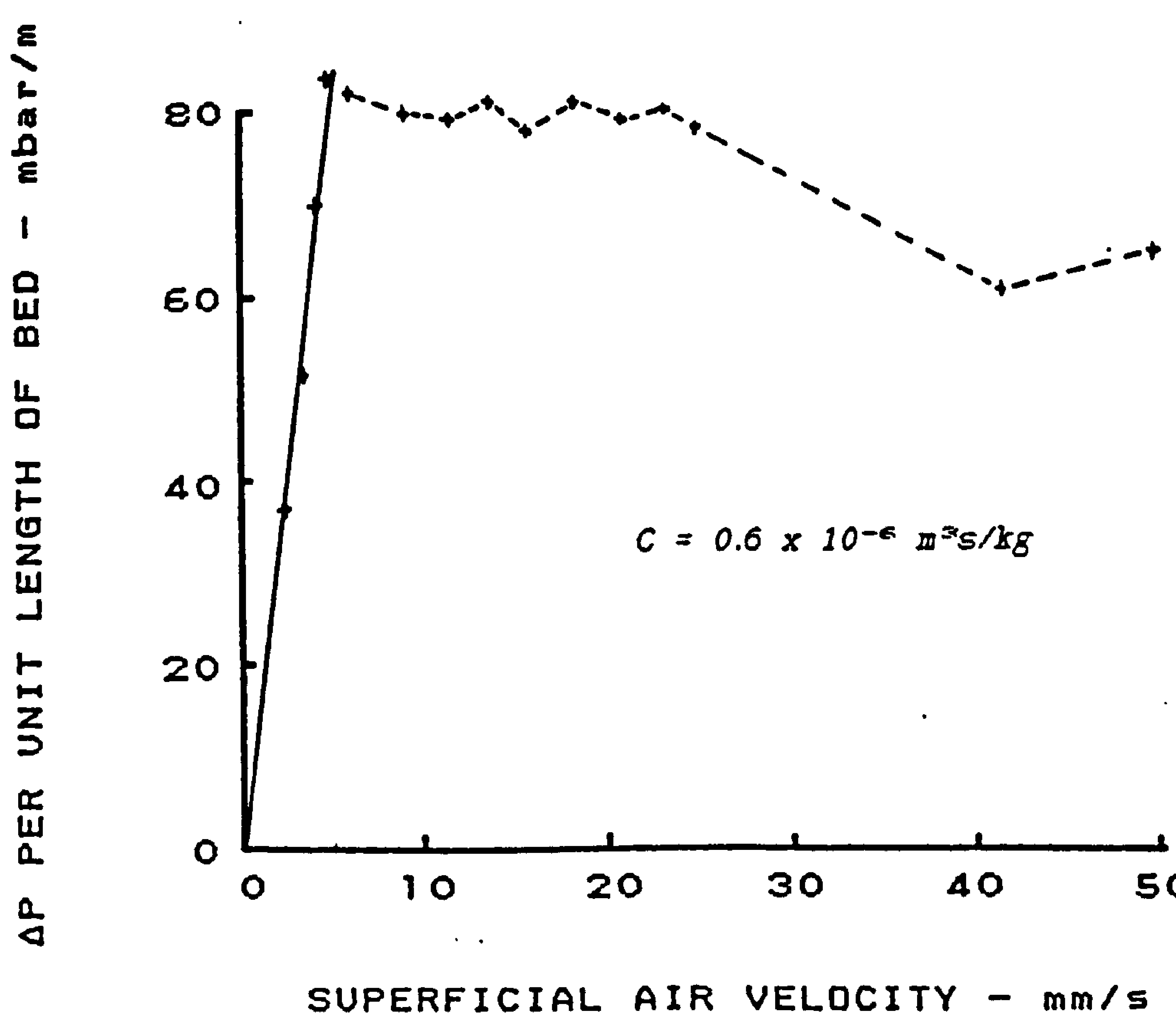


PERMEABILITY DATA

MATERIAL No. 17 - PULVERISED FUEL ASH

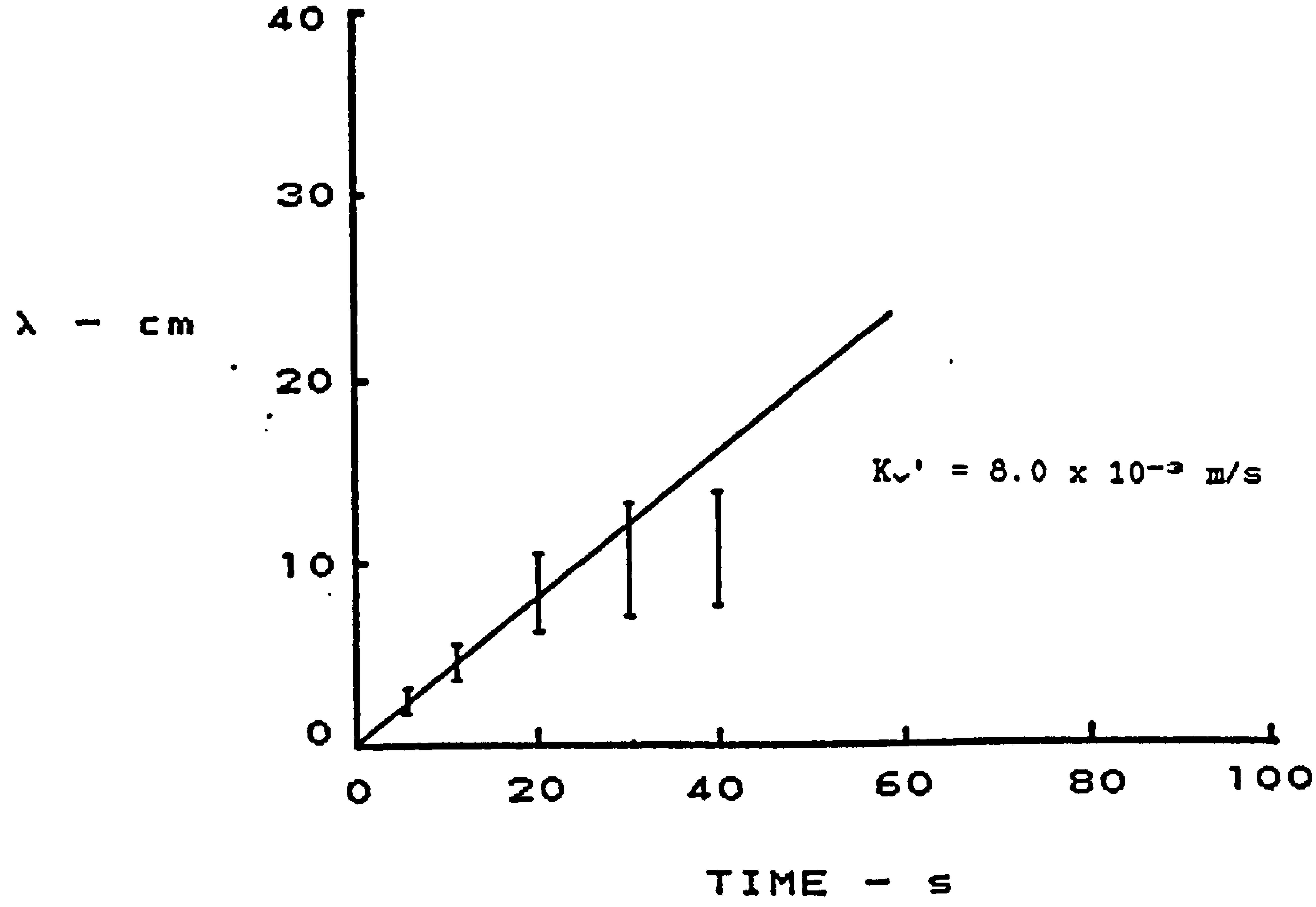


VIBRATED DE-AERATION DATA

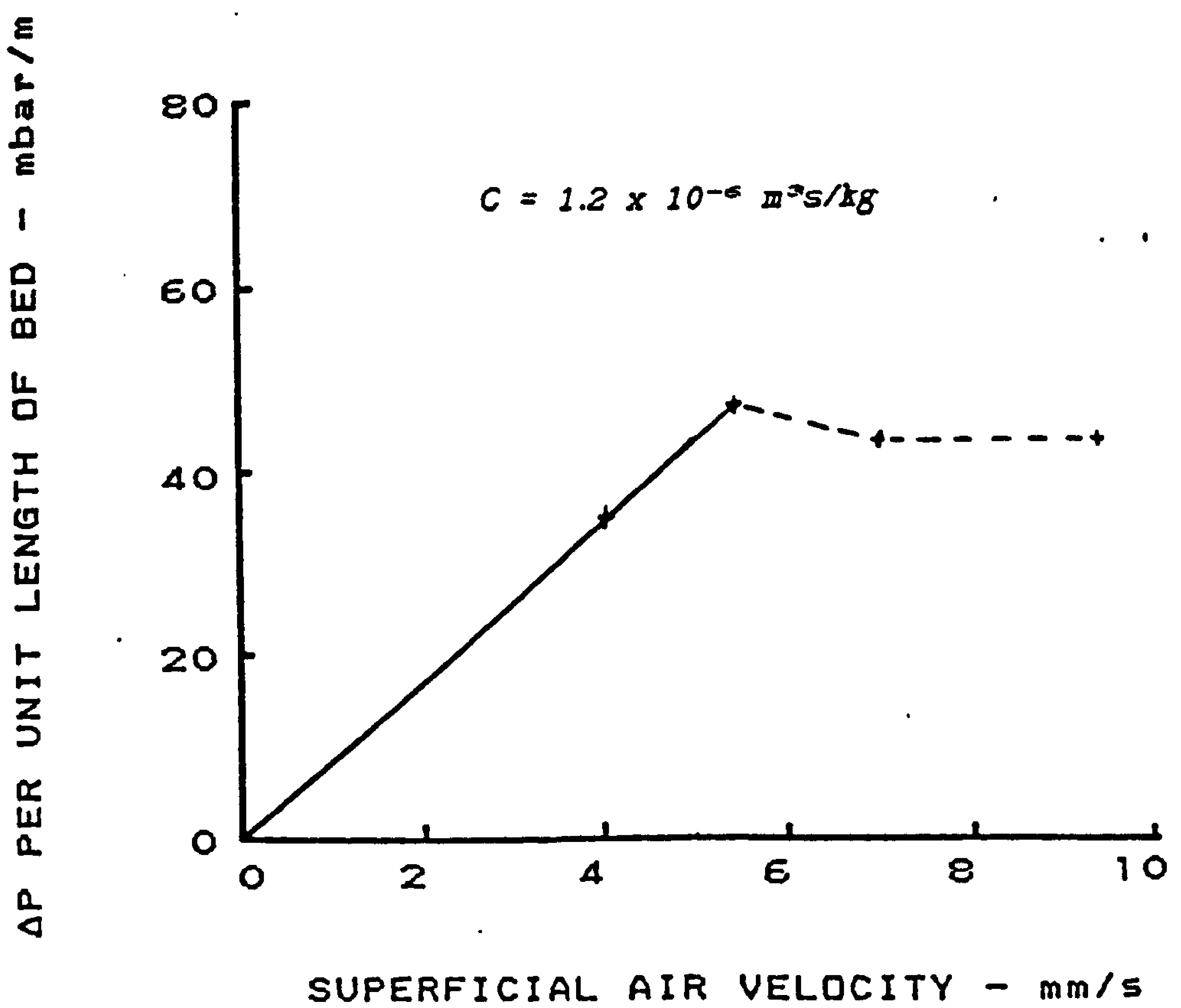


PERMEABILITY DATA

MATERIAL No. 18 - PVC POWDER

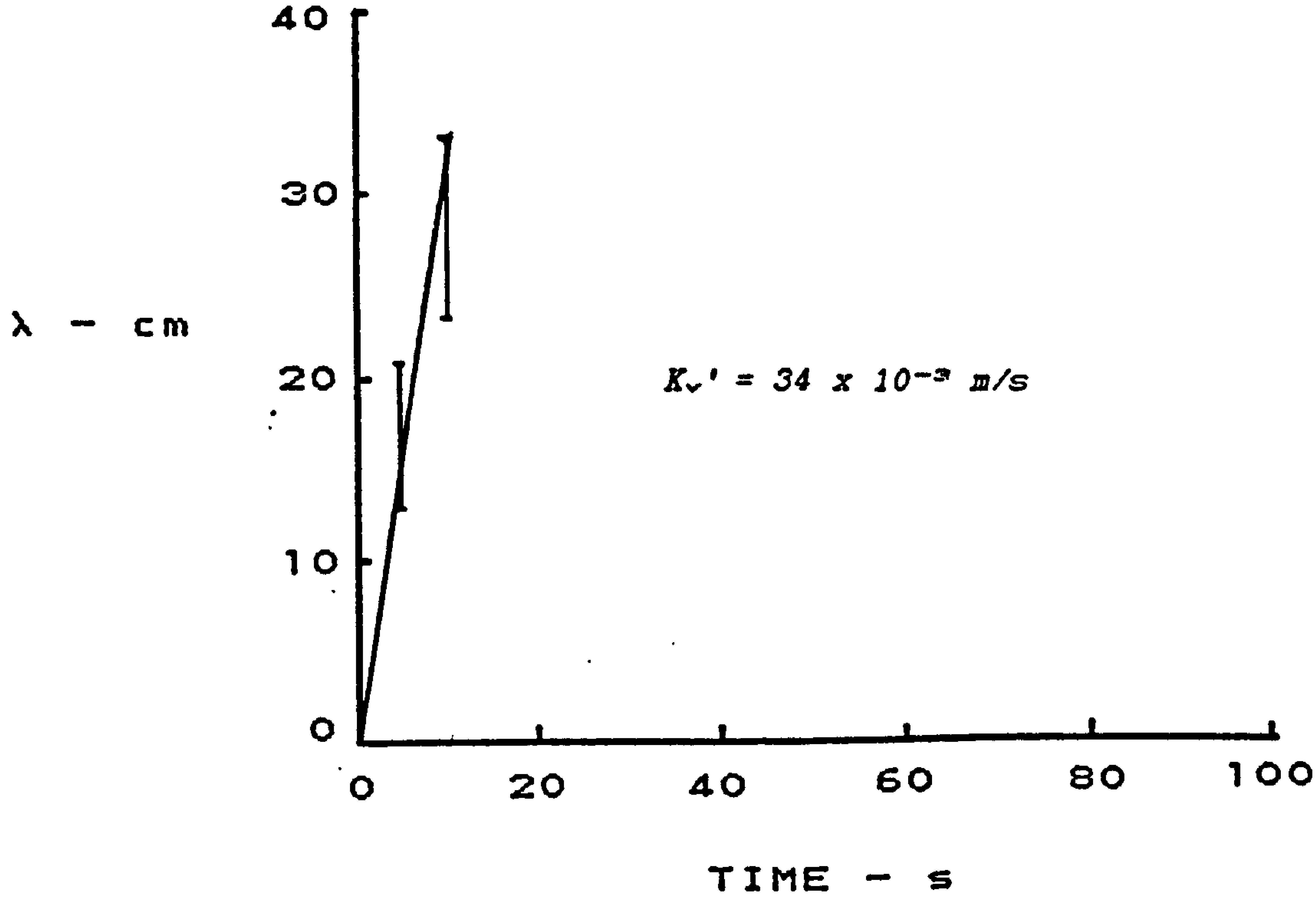


VIBRATED DE-AERATION DATA

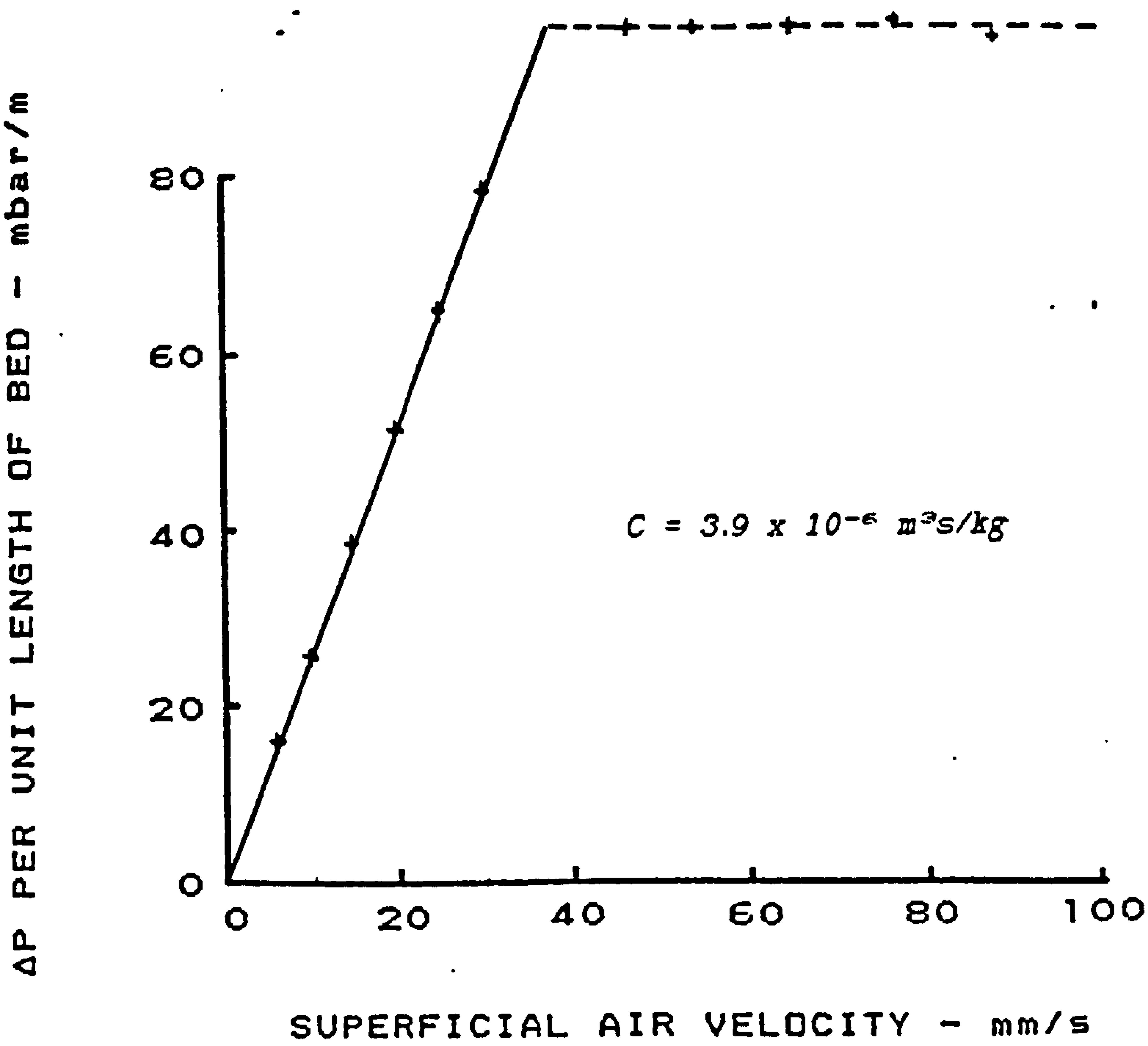


PERMEABILITY DATA

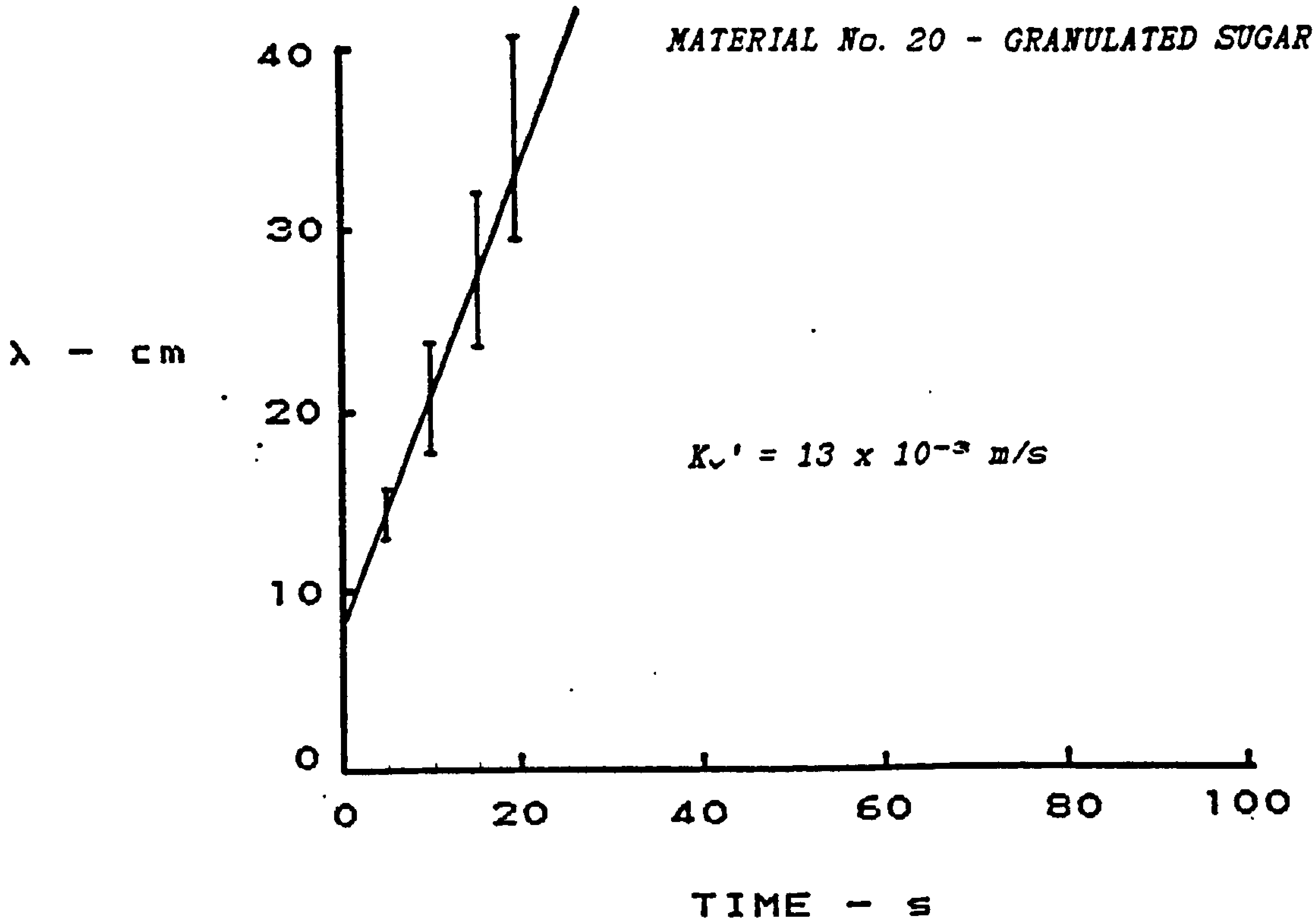
MATERIAL No. 19 - SILICA SAND



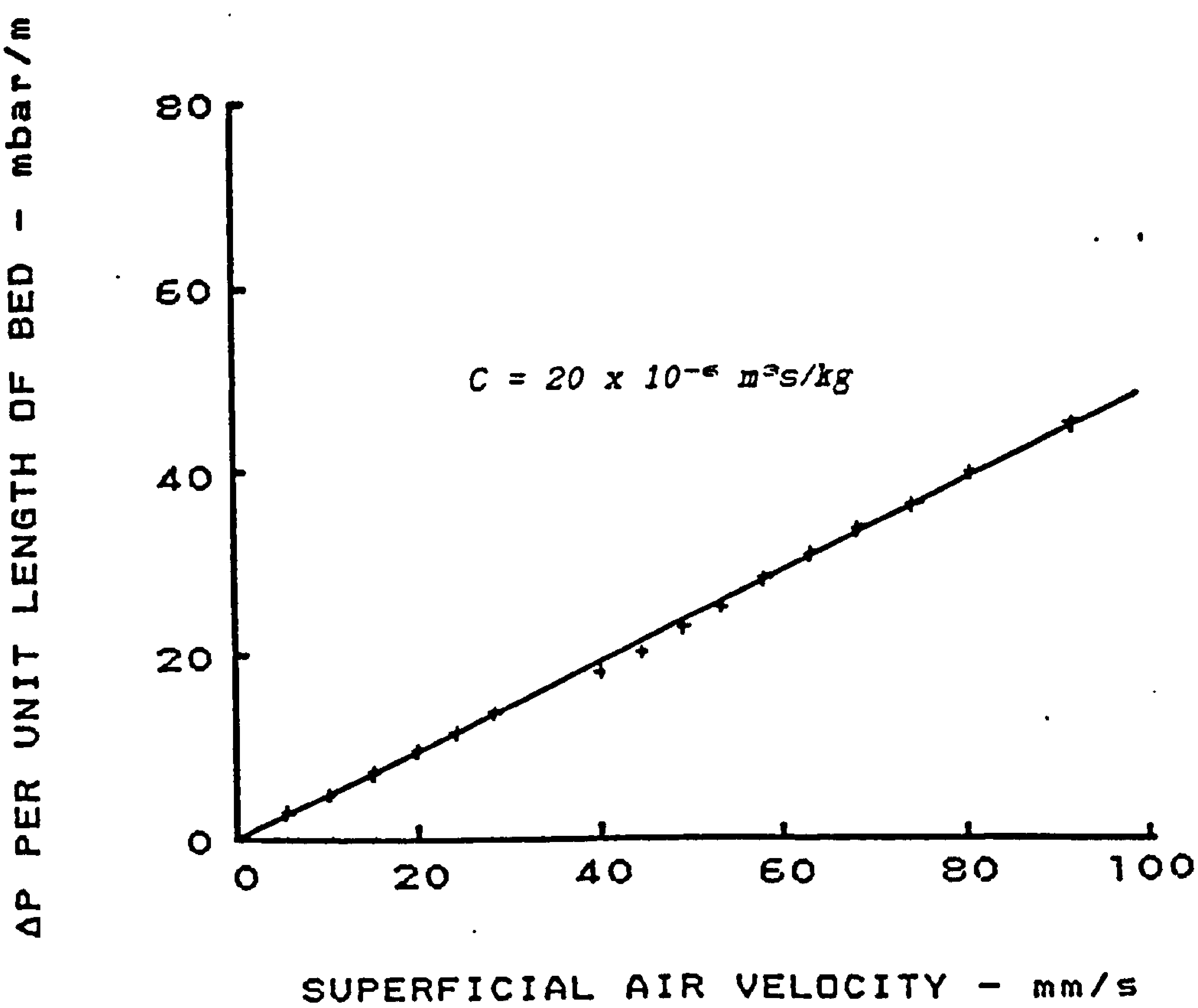
VIBRATED DE-AERATION DATA



PERMEABILITY DATA

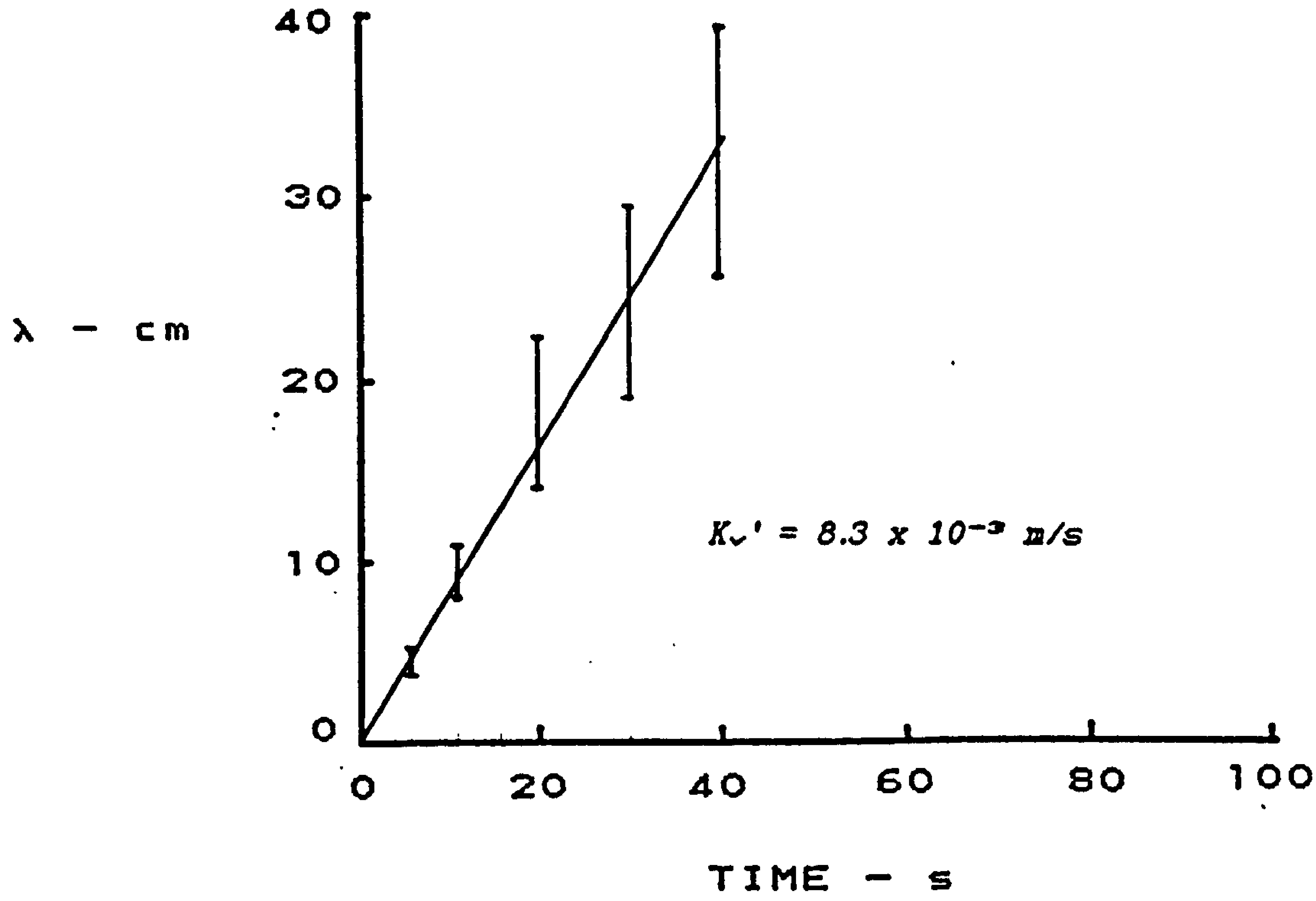


VIBRATED DE-AERATION DATA

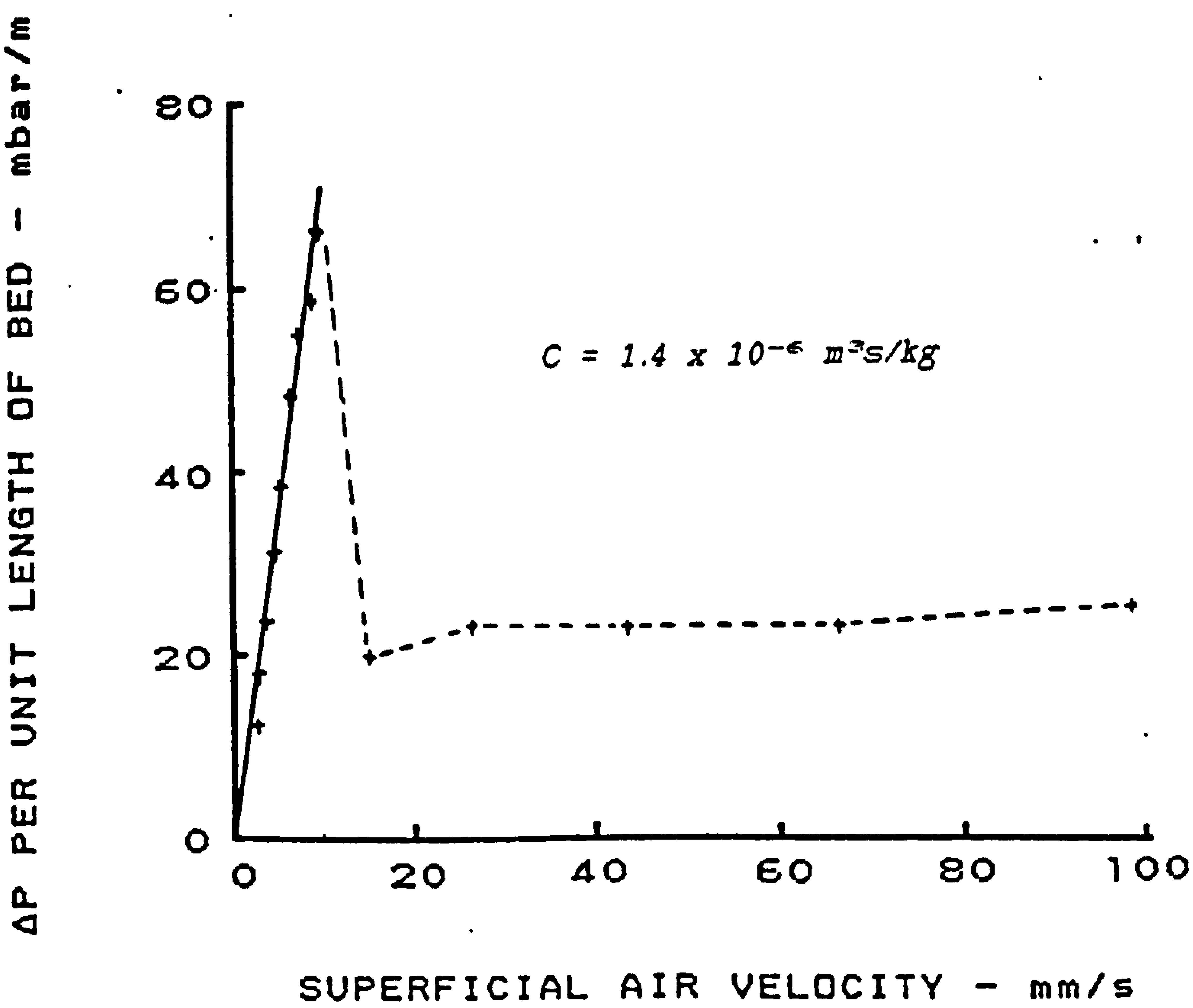


PERMEABILITY DATA

MATERIAL No. 21 - SUGAR (Degraded)

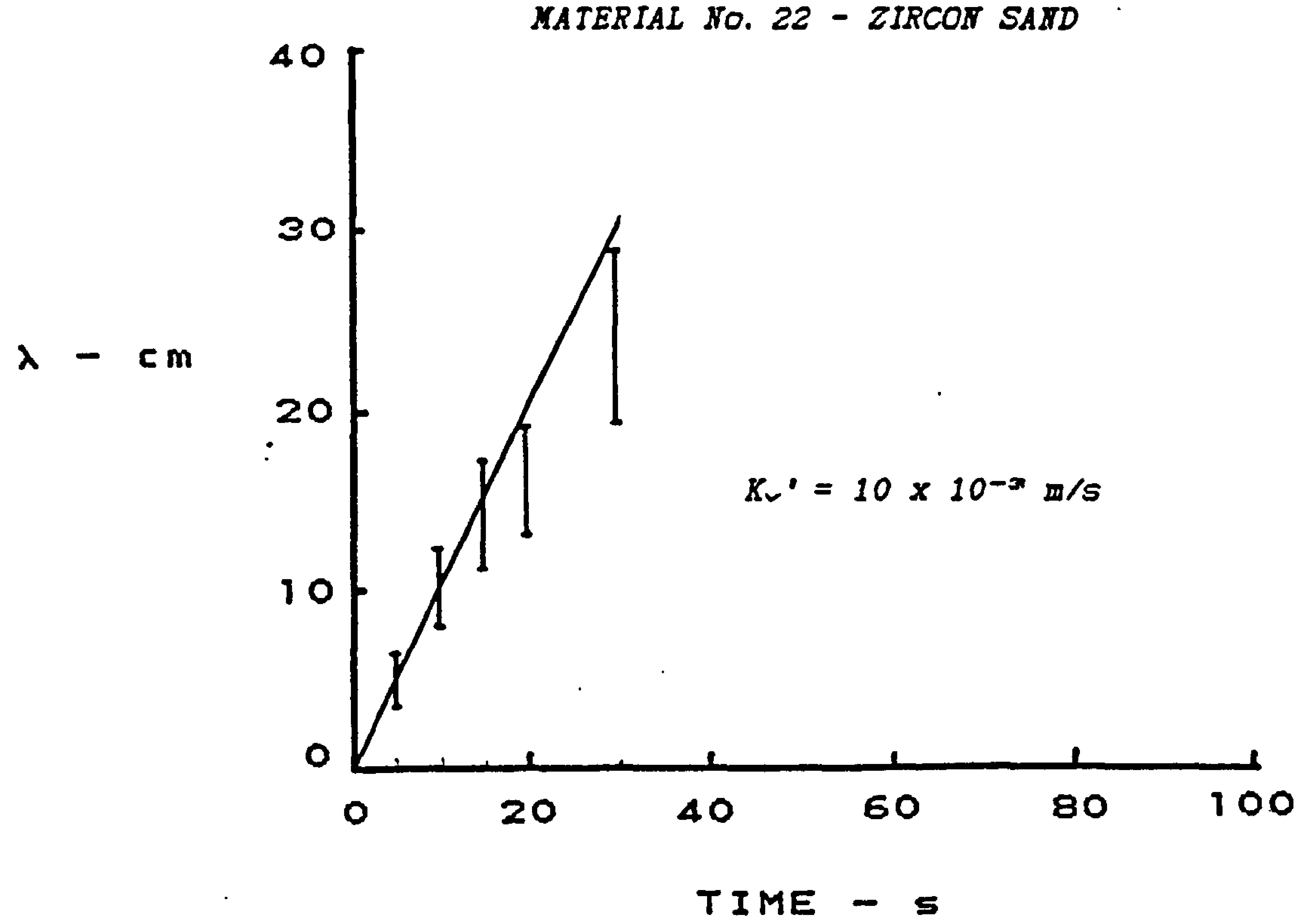


VIBRATED DE-AERATION DATA

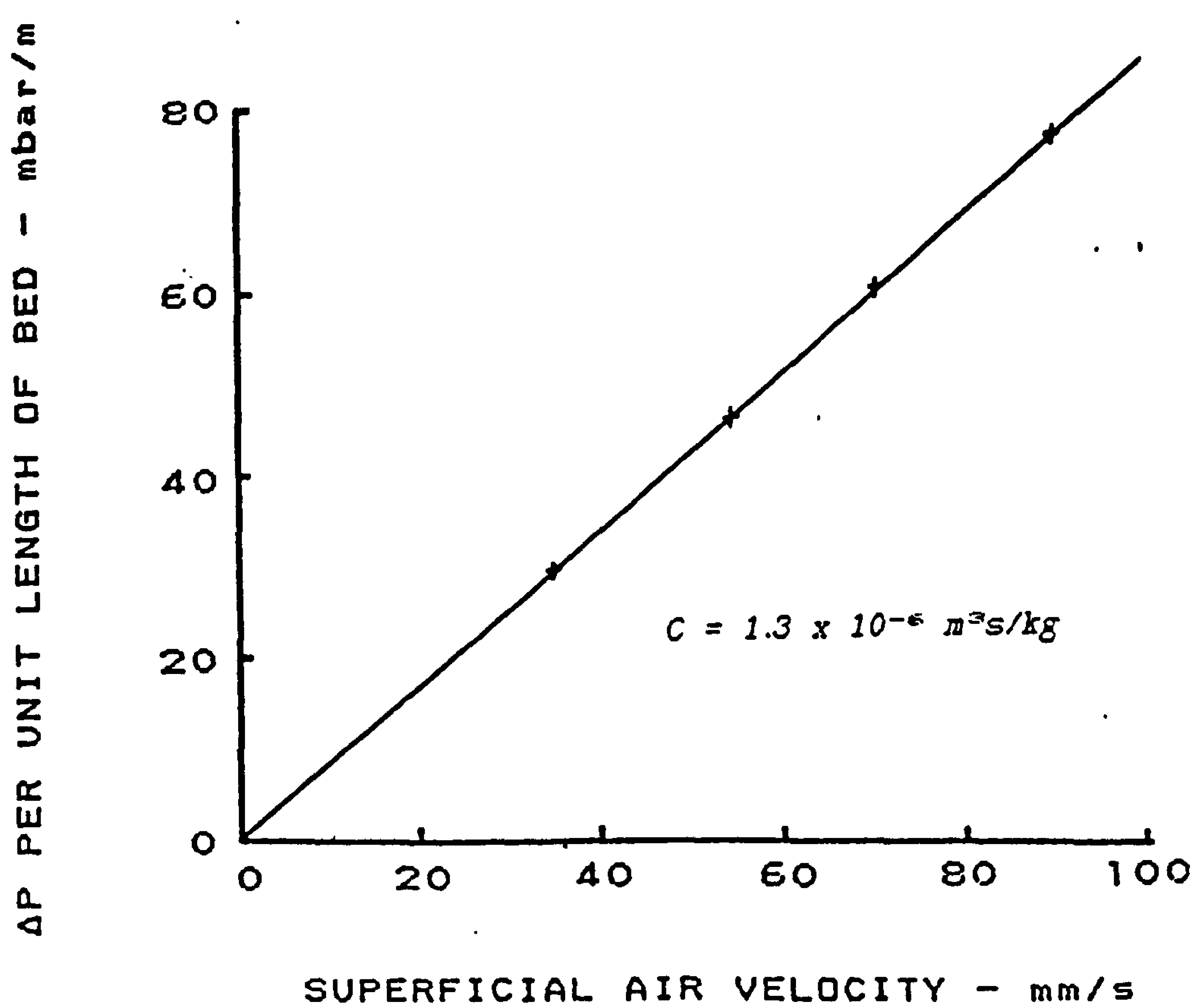


PERMEABILITY DATA

MATERIAL No. 22 - ZIRCON SAND



VIBRATED DE-AERATION DATA



PERMEABILITY DATA

APPENDIX IV

PUBLISHED PAPERS

PUBLISHED PAPERS

1. *THE INFLUENCE OF PRODUCT TYPE ON BLOW TANK PIPELINE FEEDING CHARACTERISTICS. Proc. 11th Annual Powder and Bulk Solids Conference, Rosemont, Illinois, USA. May 1986*

2. *A COMPARISON OF THE PERFORMANCE OF TOP AND BOTTOM DISCHARGE BLOW TANK SYSTEMS. Proc. Solidex '86, Solids Handling Conf., Harrogate, UK. 10-12 June 1986.*
   NOTE: This paper was also published in Bulk Solids Handling, The Int. Journal of Storing and Handling Bulk Materials, Vol. 7, Number 5, October 1987.

3. *PNEUMATIC CONVEYING OF HIGH BULK DENSITY PRODUCTS. Proc. Pneumatech 3, Int. Conf. on Pneumatic Conveying., Grand Hotel, Jersey. March 1987.*

4. *THE SELECTION OF BLOW TANK FEEDING ARRANGEMENT FOR PNEUMATIC CONVEYING. Proc. 12th Annual Powder and Bulk Solids Conf., Rosemont, Illinois, USA. May 1987*

THE INFLUENCE OF PRODUCT TYPE ON BLOW TANK PIPELINE FEEDING CHARACTERISTICS

by

M G JONES, D MILLS AND J S MASON,
Thames Polytechnic,
London
UK

SUMMARY

Blow tanks are widely used in industry for the pneumatic conveying of bulk materials through pipelines. This is because of the ease with which they can be controlled and the fact that, as there are no moving parts, erosion and degradation are minimised. Blow tanks can be used over a remarkable range of operational duties from dilute to dense phase conveying. The characteristics of a blow tank in terms of the proportion of the total air mass flowrate required to pass through the blow tank to achieve a particular product throughput at a given total air mass flowrate is dependent on the physical properties of the product being conveyed. The work reported in this paper shows the variation in blow tank characteristics for a range of materials which cover both dilute and dense phase conveying. The work has been carried out on a pilot-scale experimental facility and the results are presented to show the effect of product type on the blow tank characteristics.

1. THE CONVEYING PLANT

The conveying plant was basically a batch type system with the product being conveyed from the blow tank around the pipeline and into the receiving hopper. The product was then dropped through the double valves back into the blow tank for recirculation. The supply air to the blow tank entered through a plenum chamber under the fluidising membrane. This both fluidised the product and pressurised the blow tank. The supplementary air entered the system via a swept 'T' in the discharge pipe as close as possible to the top of the blow-tank in order to minimise the pressure drop across the discharge pipe. A small blow tank was used for loading the product initially into the receiving hopper. After use the product was discharged from the main blow tank into an elevated storage or off-loading hopper.

2. THE AIR SUPPLY

Three compressors were available each capable of 0.095 m^3/s (202 ft^3/min) of 'free air' at a pressure of 6.9 bar (100 lbs/sq. in) gauge. A diagrammatic layout of the air supply from the compressors to the conveying plant is shown in Fig. 2. For this work, only one compressor was required since a 53 mm bore pipeline was used and this represents a free air velocity of 42 m/s. Part of the air was directed to the blow tank and the rest was directed to the supplementary air line. The control of the air supply was by use of a pressure reducing valve to control the upstream pressure and critical flow nozzles placed in the two air supply lines.

3. INSTRUMENTATION

Five variables were measured. These were both air mass flowrates, product mass flowrate, pipeline pressure drop and blow tank pressure. The air mass flowrates were measured by using critical flow nozzles. The advantage of using this device is that since it relies on the air flow being choked (i.e. the velocity at the throat is sonic), then for a fixed upstream pressure the air mass flowrate is constant over a wide range of downstream pressures and the effects of pulsations are avoided. The control of the air mass flowrate through a particular nozzle was achieved by altering the upstream pressure. Operation with pressure ratios of up to 0.9 is possible with good convergent-divergent nozzles. The nozzles were positioned in the air supply lines to the blow tank and the conveying line as shown in Fig. 2. The total air mass flowrate for conveying the product through the pipeline is the sum of the blowtank and supplementary air mass flowrates.

The product mass flowrates were obtained from the load cells on which the receiving hopper was mounted. Three load cells were used. The combined elecrical output signal was fed into a recording instrument and integrated with respect to time to give the product flowrate.

The air supply pressure was measured immediately before the product pick-up point in the supplementary air supply line and was recorded. With the discharge being into the receiving hopper at atmospheric pressure, the conveying line pressure drop was obtained. The blow tank pressure was measured directly.

4. EXPERIMENTAL TECHNIQUES

The only control over the blow tank, and hence the pipeline, was achieved by controlling the total air mass flowarate and the proportion of the total air mass flowrate going to the blow tank. The proportion of air to the blow tank is known, as the 'Blow Tank Air Ratio' (BTAR). The BTAR was controlled by the appropriate selection of critical flow nozzles for use in the air lines to the blow tank and conveying line. The total air mass flowrate was the sum of the air mass flowrates to the blow tank and to the conveying line. The total air mass flowrate could be adjusted by varying the upstream air supply pressure.

To start conveying, the BTAR and the total air mass flowrate were set. The blow tank vent line (Fig. 1) was closed and the blow tank began to pressurise. When steady state conditions were reached the pressures and product mass flowrate were recorded over a reasonable time period, typically 2 to 3 minutes. The data recorded on one pass provides a single point on the blow tank characteristics. The data from 30 to 40 runs, for a product that would convey in dense phase, was then plotted on a graph of product mass flowrate against total air mass flowrate as shown in Fig. 4. Lines of constant BTAR could then be drawn to provide a record of the blow tank characteristics for the particular product being conveyed. This procedure was then repeated for each of the other products.

5. PRODUCTS TESTED

The products have been chosen to give as wide a range of blow tank characteristics as possible. A table is given below to indicate the salient features of the products tested.

PRODUCT	BULK DENSITY 'As poured' kg/m^3	MEAN PARTICLE SIZE μm	PARTICLE DENSITY kg/m^3
Flour	515	78	1470
P.F.Ash	979	40	2446
Poly pellets	540	4000	912
Pearlite	100	200	800
Sugar	890	460	1580

6. ANALYSIS OF BLOW TANK CHARACTERISTICS

The blow tank characteristics for the five products tested are shown in Figs. 5-9. The blow tank characteristics for sugar are the only ones where it was not possible to explore the whole range of the blow tank feeding capability due to the limitations imposed in the conveying pipeline. Sugar in its granulated form has a minimum conveying velocity of around 15 m/s and is only capable of being conveyed in lean phase. It was felt important to include a product that can only be conveyed in lean phase so that as wide a range of product properties as possible could be tested.

The other four products tested exhibit similar characteristics in terms of curve shape but the product flowrates for particular BTAR values at a given air mass flowrate vary considerably. Comparative plots (Figs. 10 and 11) show the 15% and 75% BTAR lines for each of the products and highlights the variation in characteristics for the various products. The comparative plot using a BTAR of 75% shows a 4:1 ratio of product flowrates for an air mass flowrate of 0.12 kg/s. Since the system is unchanged from one product trial to the next, it is probable that the material characteristics are responsible for the variation in discharge rate. With the relatively small number of products that have been studied so far it is difficult to identify with any certainty possible relationships between material properties and the blow tank characteristics. However, certain basic product properties seem to align themselves to the trend in the blow tank characteristics.

If one considers the comparative plot for a BTAR of 75% (Fig. 10) it is noticeable that as the product mass flowrates decrease from P.F ash to flour to pearlite to poly. pellets, the product median particle size increases. This has implications for the specific surface area. As the particle size increases the specific surface area of the material will decrease with a consequent increase in the air permeability. Waghorn and Mason (Ref. 1) have published data on the influence of aeration on blow tank discharge showing that the discharge rate is enhanced if the product is aerated.

The products used in this study have been tested for air permeability properties using an air permeameter. The values for permeability factor obtained from the air permeameter have been used to investigate the relationship between discharge rate and aeration properties by plotting phase density against permeability factor (Fig. 12). It is unreasonable to assume this to be a definitive relationship but it does seem to indicate a trend which suggests that as the air permeability factor decreases, the discharge rate increases. Independent support for this general trend is provided by the apparent relationship between discharge rate and vibrated de-aeration constant.

The vibrated de-aeration constant is a measure of a product's air retention properties. In general, products exhibiting poor permeability properties have good air retention properties. Fig. 13 shows a plot of phase density against vibrated de-aeration constant. The trend indicates that products with good air retention properties produce high discharge rates. This supports the indications suggested by the apparent relationship between permeability factor and phase density.

7. CONCLUSIONS

The discharge rate of a blow tank can vary widely depending on the product being conveyed. For this reason it is important to have some knowledge of the product to be conveyed when designing or specifying blow tank systems.

Products which exhibit good aeration properties seem to produce blow tank characteristics with high discharge rates for a given air mass flowrate and blow tank air ratio. Similarly, products exhibiting poor air permeability properties seem to achieve high discharge rates from a blow tank system. In general it is products with small median particle sizes and narrow size distributions which exhibit the above described qualities.

The models proposed in this paper are not definitive but show a general trend. Further study in this field may yield a more definite correlation. However, the work described here provides a general awareness of the influence of product type on blow tank pipeline feeding characteristics.

8. REFERENCES

1. Waghorn D J and Mason J S.: 'The Effect of Aeration and Position of Inlet to Conveying Line on the Discharge Characteristics of a Blow Tank'. Bulk Solids, Storage, Handling and Flow Conf., Nov. 1976, Stratford Upon Avon, Powder Advisory Centre.

2. Waghorn D J.: 'The Performance Characteristics of a Blow Tank for Feeding a Pneumatic Conveying System', PhD Thesis, 1977, Thames Polytechnic, London.

3. Mason J S and Mills D.: 'An Investigation Into the Control of the Flow of Powdered and Granular Materials in a Blow Tank Pneumatic Conveying System'. Proc. Conf. on Measurement and Control in the Handling and processing of Materials. IEE, London, April 1978.

4. Mason J S and Mills D.: 'The Control of the Flow of Materials in a Blow Tank Pneumatic Conveying System'. Int. Powder and Bulk Solids Handling and Processing Conf., Chicago, May 1978.

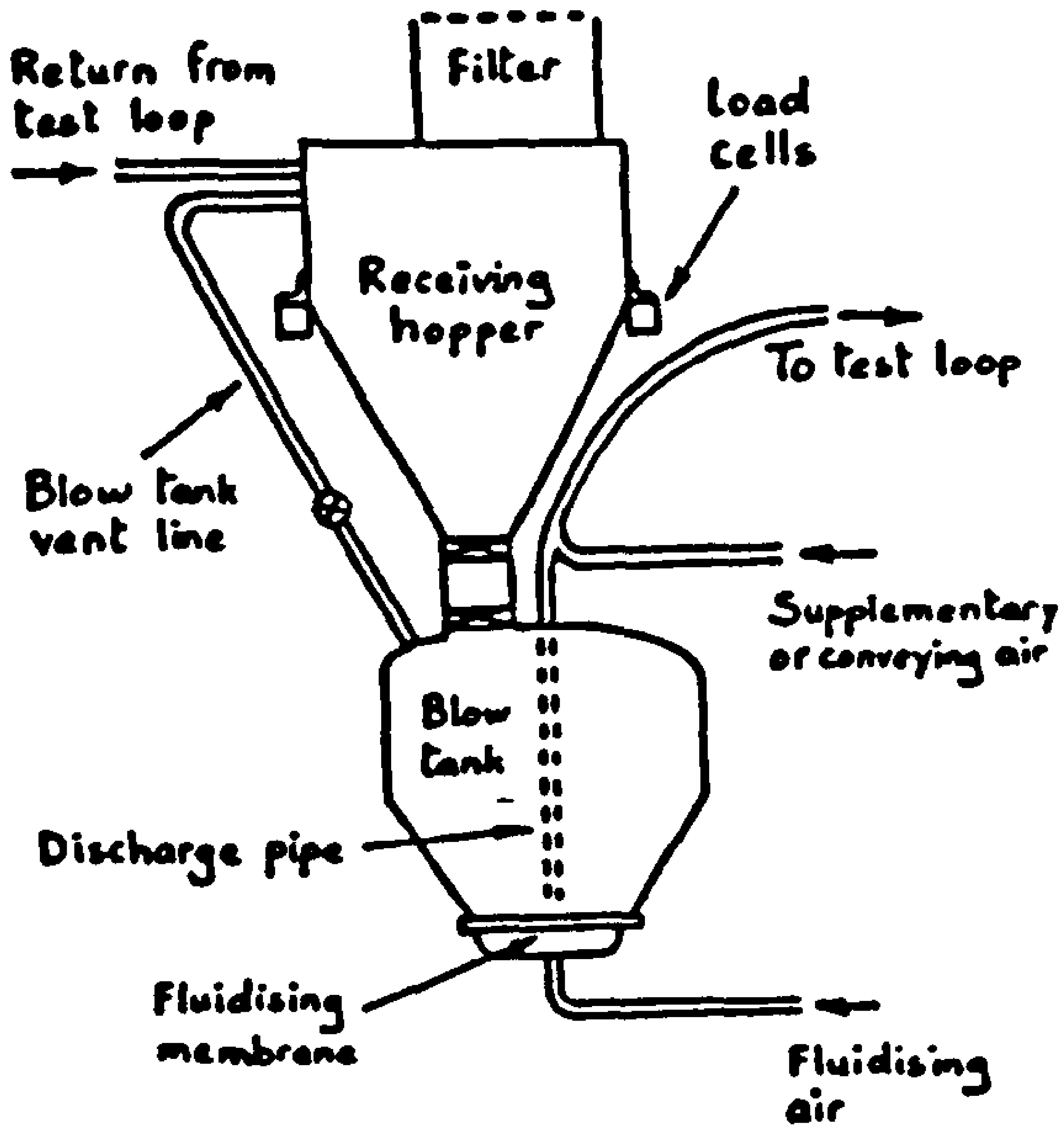


Fig.1 Conveying Plant Layout

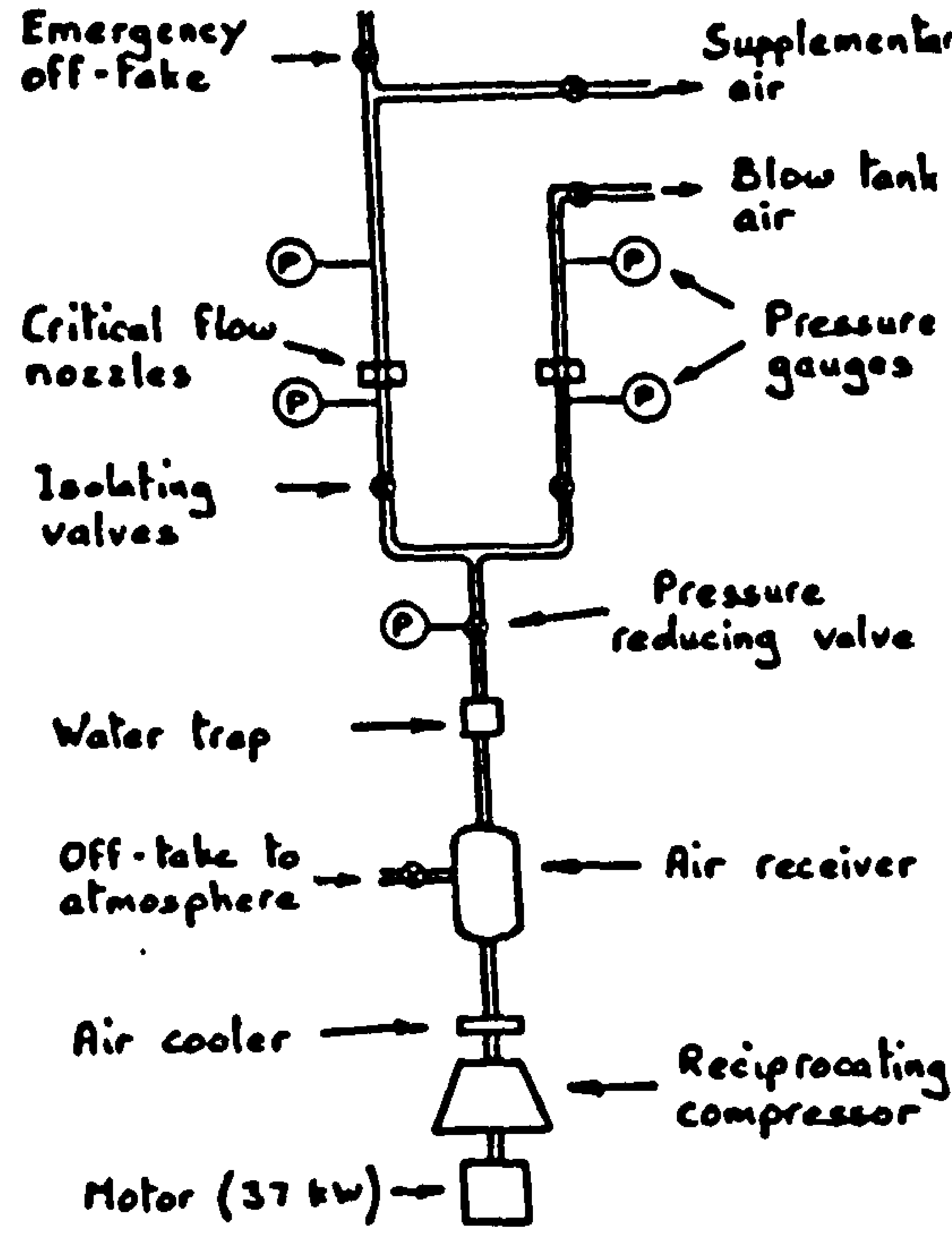
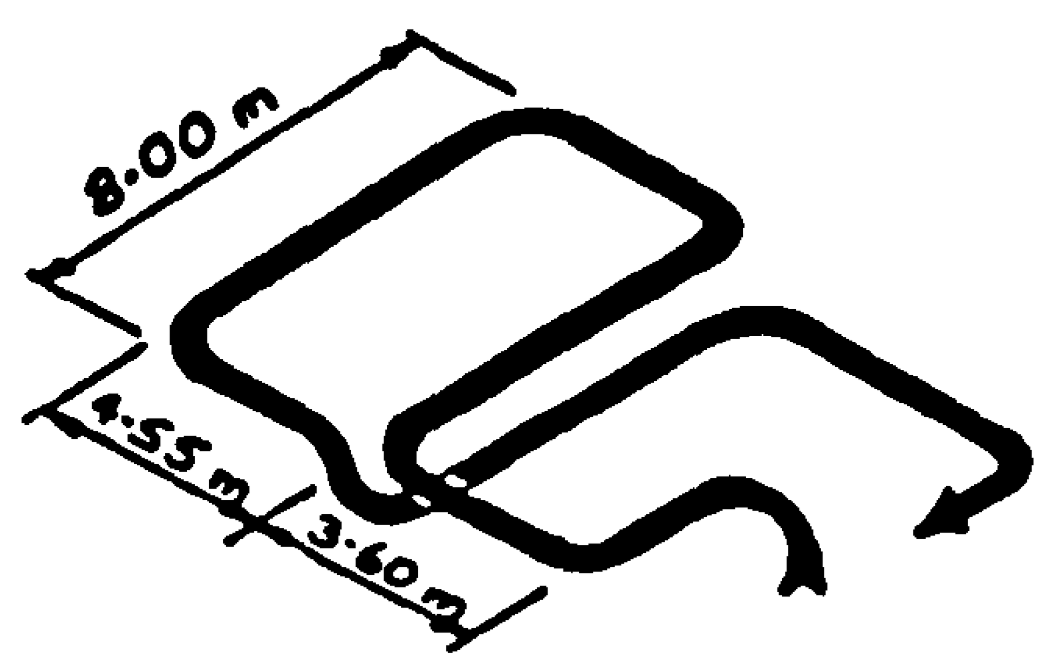


Fig. 2 Conveying Plant Air Supply



50 m (165 ft) long
53 mm (2 in) bore
9 bends (D/d = 24)

Fig. 3 Conveying Pipeline Layout

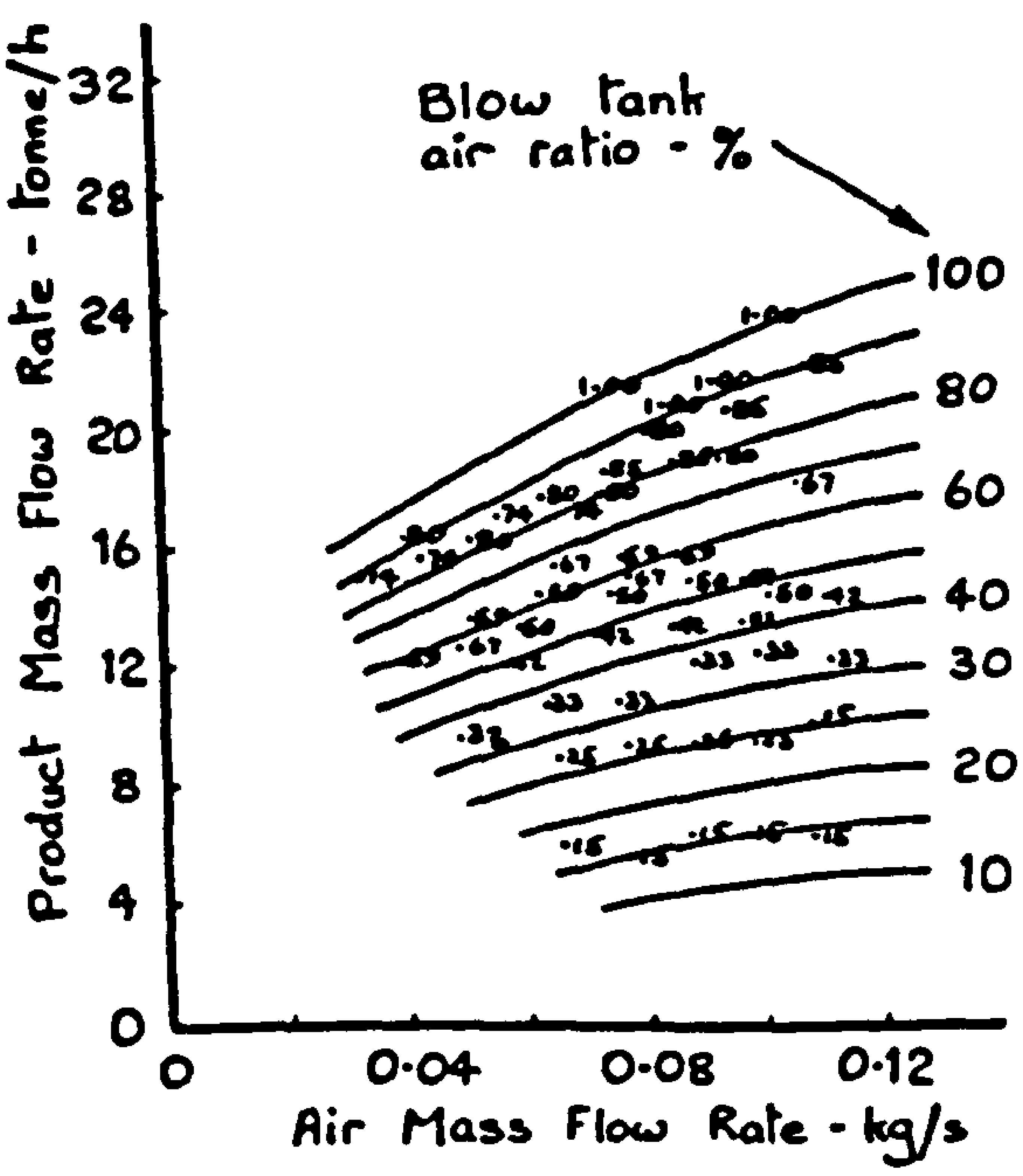


Fig. 4 Blow Tank Characteristics for p.f. ash - Data Points

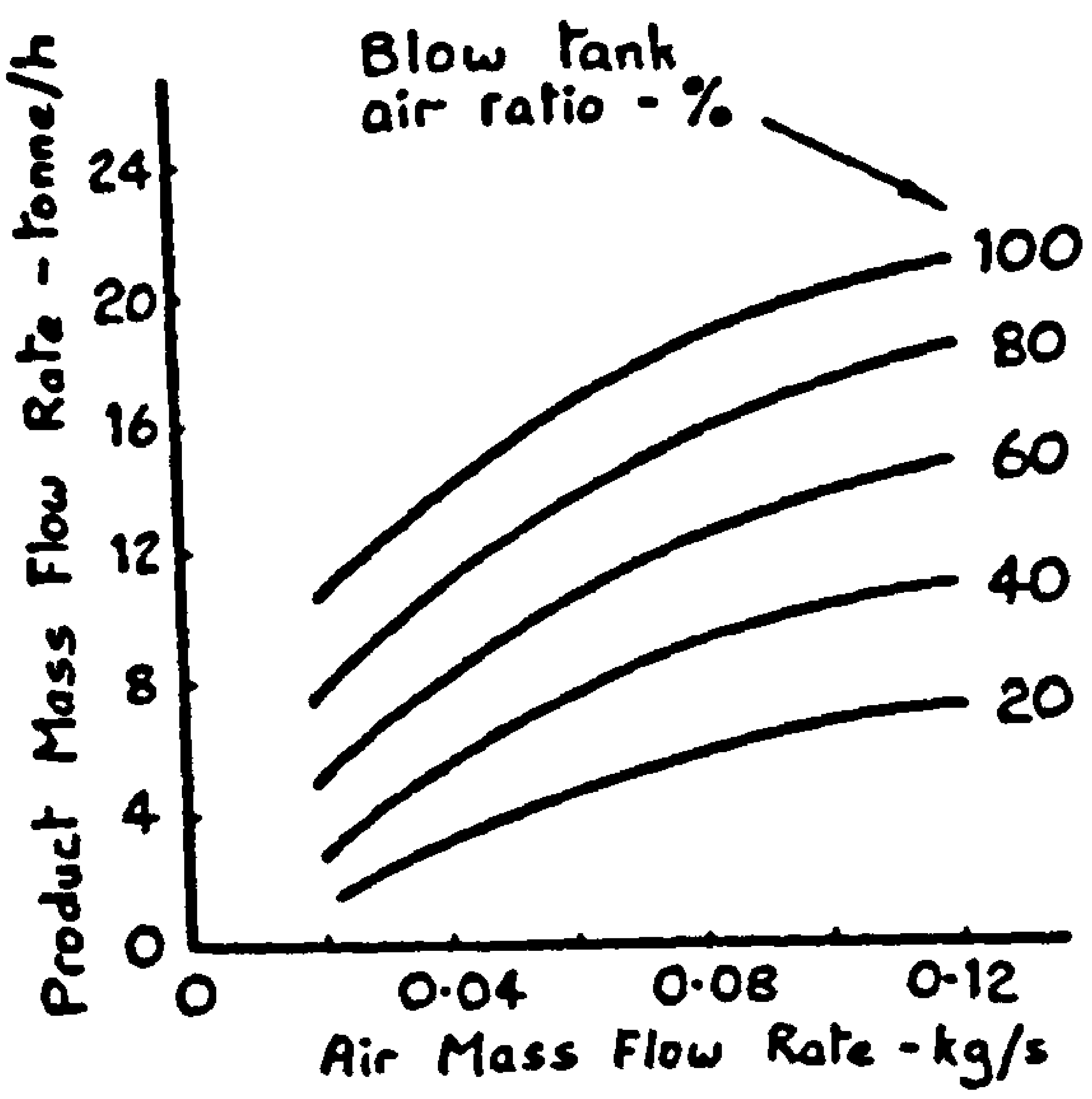


Fig. 5 Blow Tank Characteristics for Flour

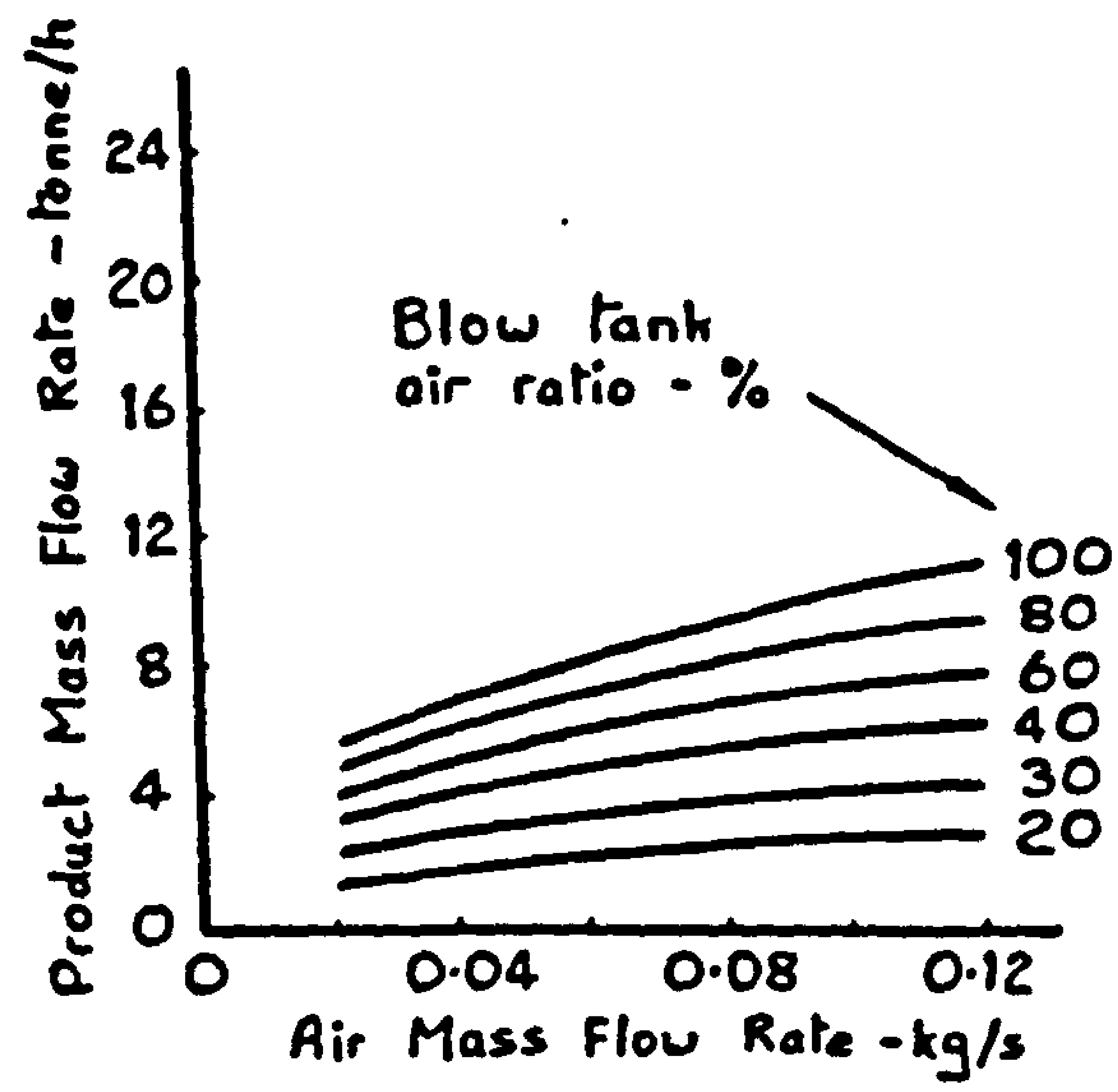


Fig. 6 Blow Tank Characteristics for Pearlite

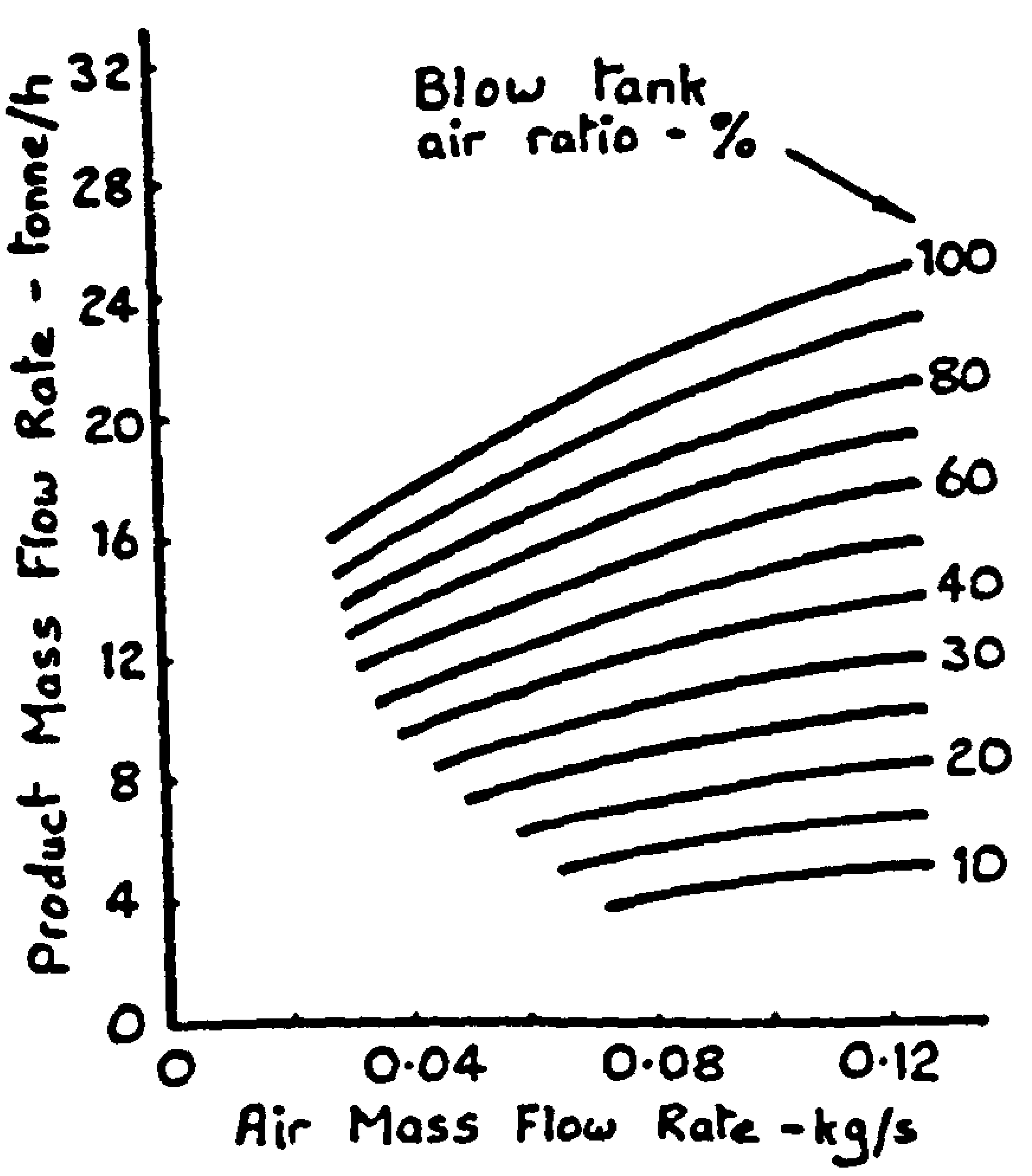


Fig. 7 Blow Tank Characteristics for p.f. ash

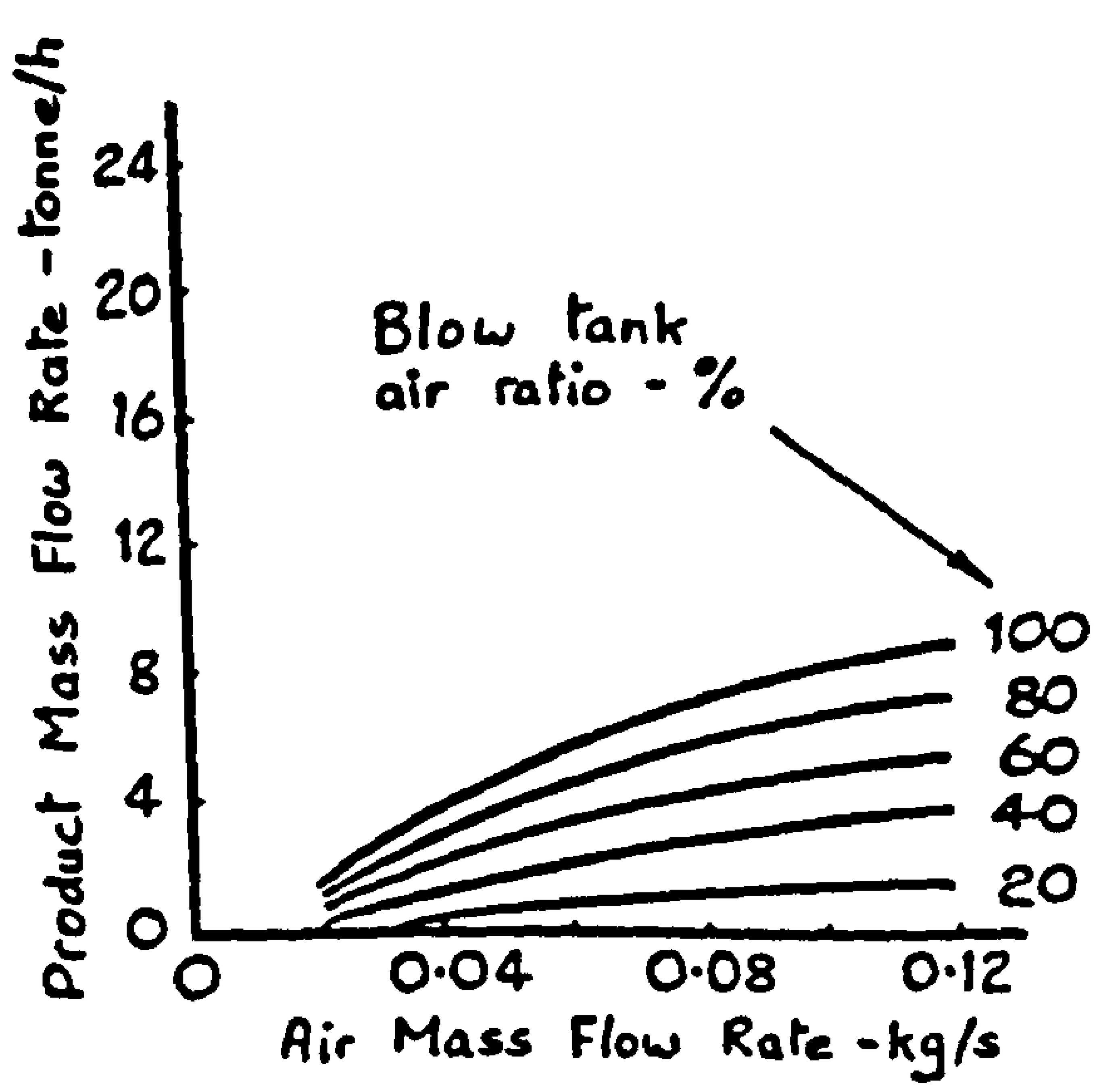


Fig. 8 Blow Tank Characteristics for Polyethylene Pellets

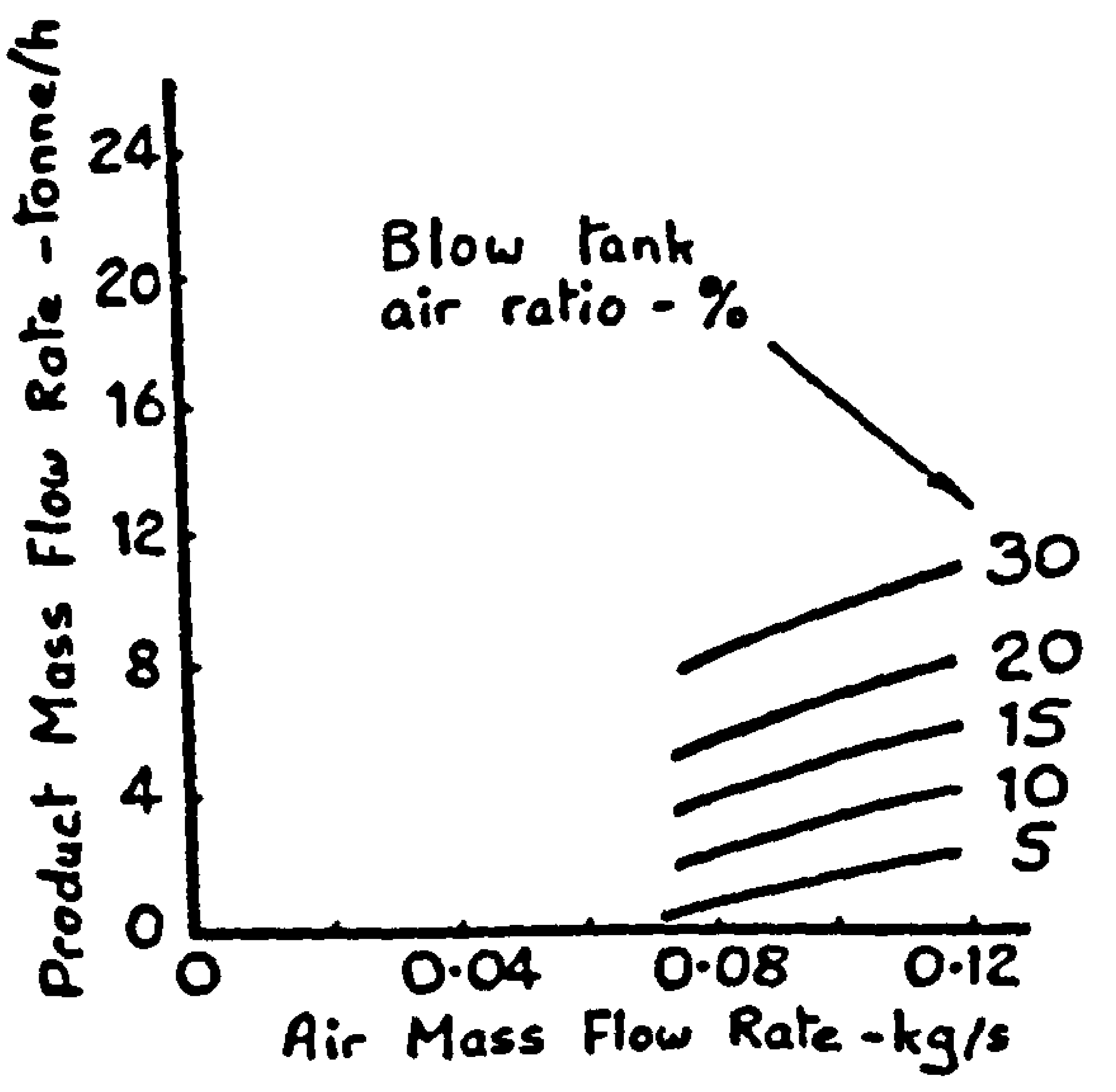


Fig. 9 Blow Tank Characteristics for Granulated Sugar

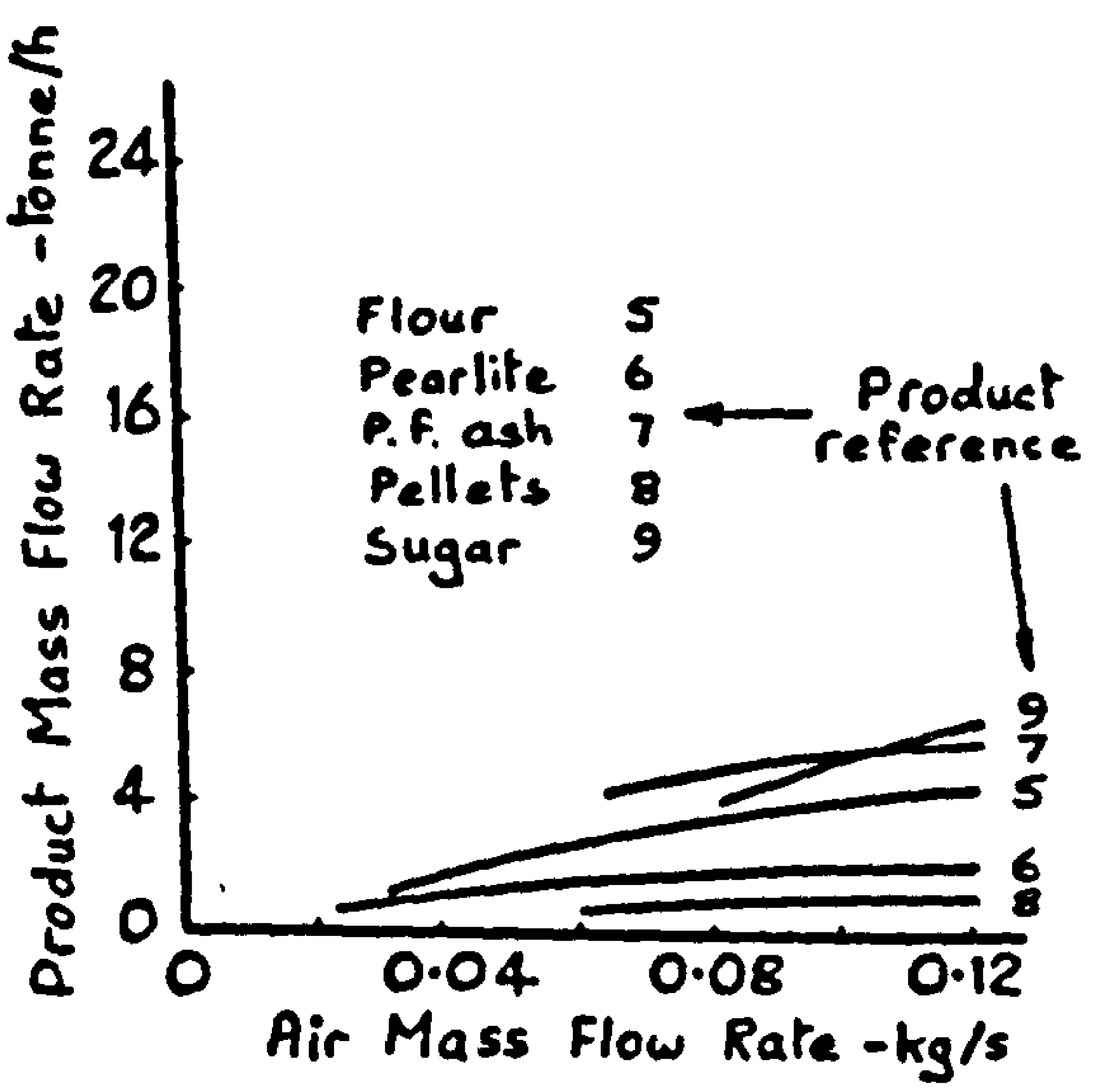


Fig. 10 Comparison of Products for a Blow Tank Air Ratio of 15%

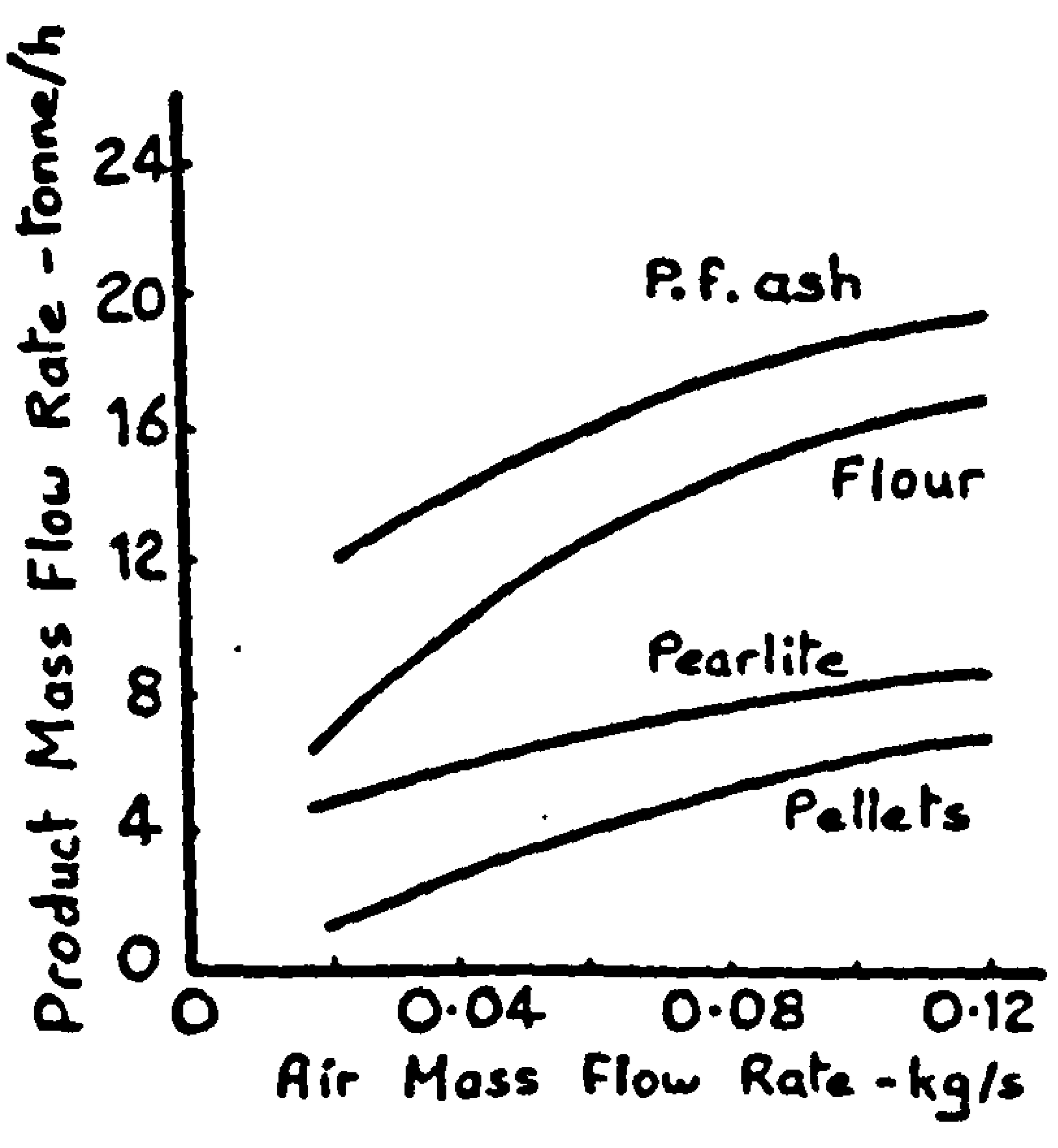


Fig. 11 Comparison of Products for a Blow Tank Air Ratio of 75%

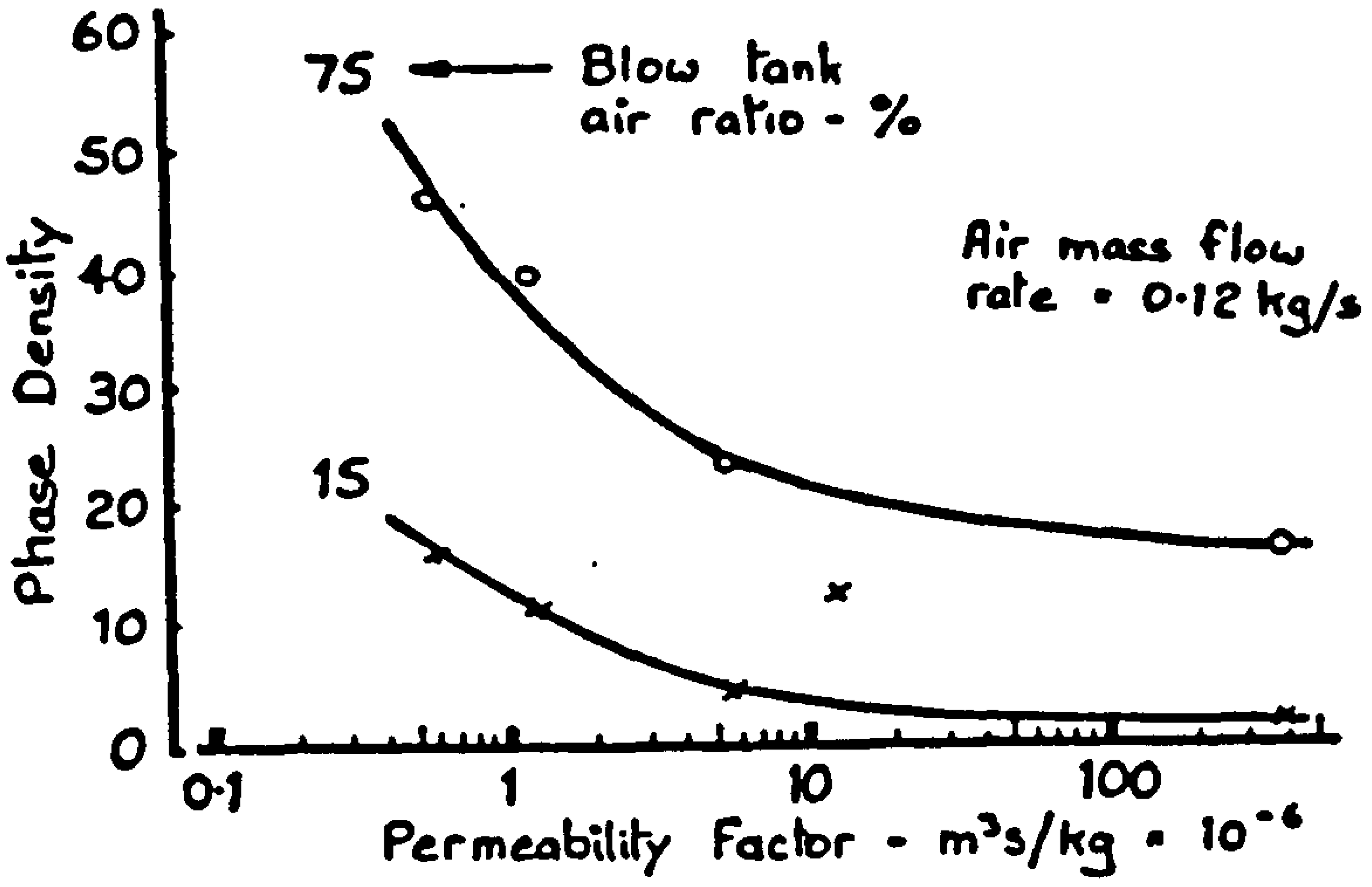


Fig. 12 Effect of Permeability Factor on Phase Density

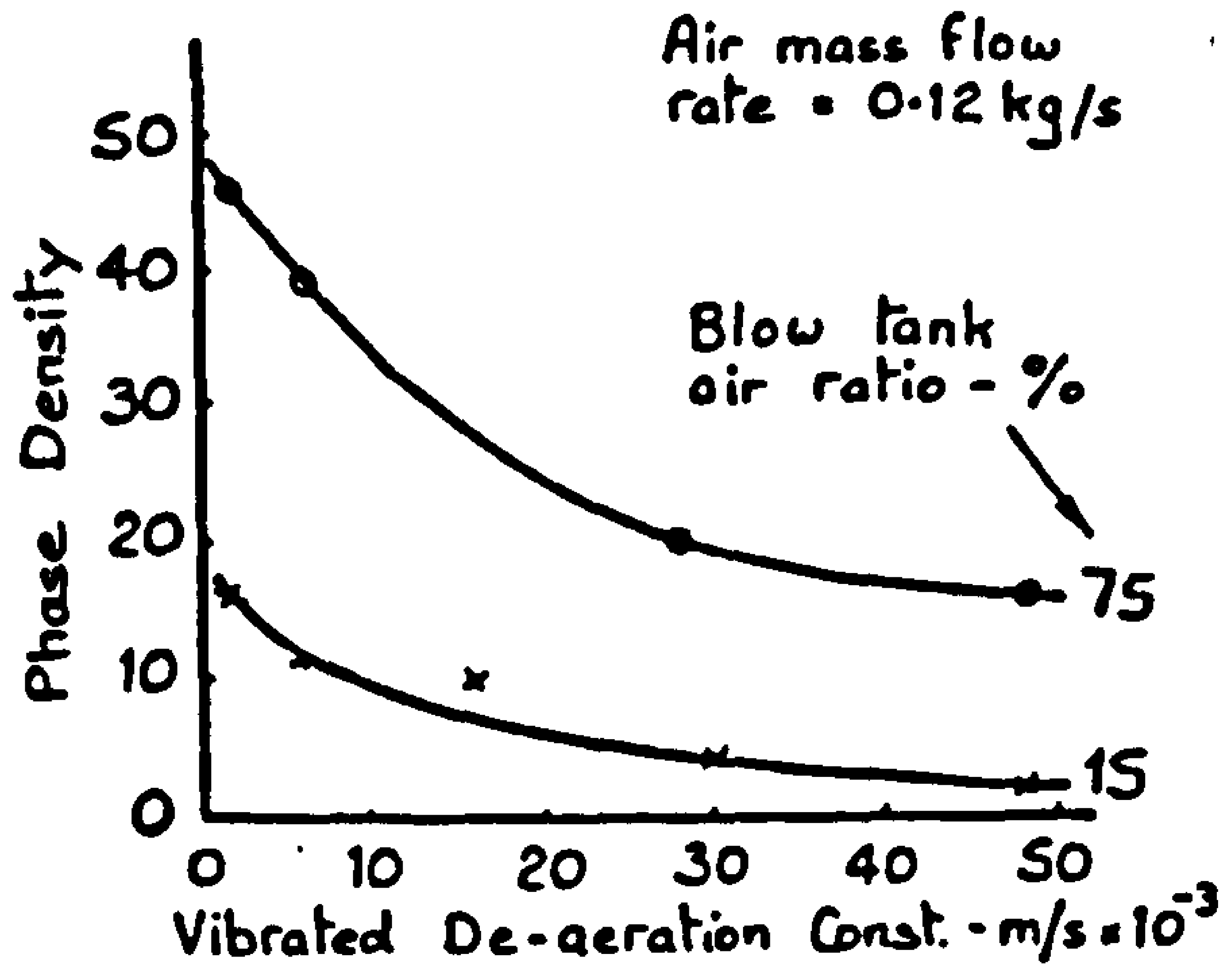


Fig. 13 Effect of Air Retention Properties on Phase Density

PAPER C2

SOLIDS HANDLING CONFERENCE

A COMPARISON OF THE PERFORMANCE OF TOP AND BOTTOM DISCHARGE BLOW TANK SYSTEMS

M G Jones, Dr D Mills and Dr J S Mason

Thames Polytechnic, London

SUMMARY

Blow tank systems are widely used in industry for the pneumatic conveying of bulk materials. This is because of the ease of control and the fact that, as there are no moving parts, erosion and degradation are minimised. Both top and bottom discharge configurations are used in industry but the choice of configuration is largely based on convenience rather than the merits of configuration performance. To date, very little information has been published regarding comparisons of blow tank performance in the top and bottom discharge modes. The work reported in this paper presents a direct comparison between top and bottom discharge performance in terms of feeding capability for given constant conditions. The work was carried out on a pilot scale facility using a blow tank that could be arranged in both top and bottom discharge configuration with minimum changes in pipeline geometry. Blow tank characteristics are presented for PFA in both top and bottom discharge modes.

THE CONVEYING PLANT

The conveying plant used was basically a batch type system with the product being discharged from the blow tank and conveyed through the pipeline into a receiving hopper. The product was then dropped through double valves back into the blow tank for recirculation. A diagrammatic layout of the conveying plant and pipeline is shown in Figs. 1 to 3. Fig. 4 shows the arrangement of the blow tank in both top and bottom discharge modes.

a) Top Discharge Blow Tank

The supply air to the blow tank entered through a plenum chamber under the fluidising membrane. This both fluidised the product and pressurised the blow tank. The supplementary air entered the system via a swept 'T' in the discharge pipe as close as possible to the top of the blow tank. There was no valve in the discharge line in this configuration.

b) Bottom Discharge Blow Tank

The top discharge blow tank was transformed into a bottom discharge blow tank by producing a fabrication that could be bolted directly onto the bottom flange of the blow tank replacing the fluidisation membrane and plenum chamber. The

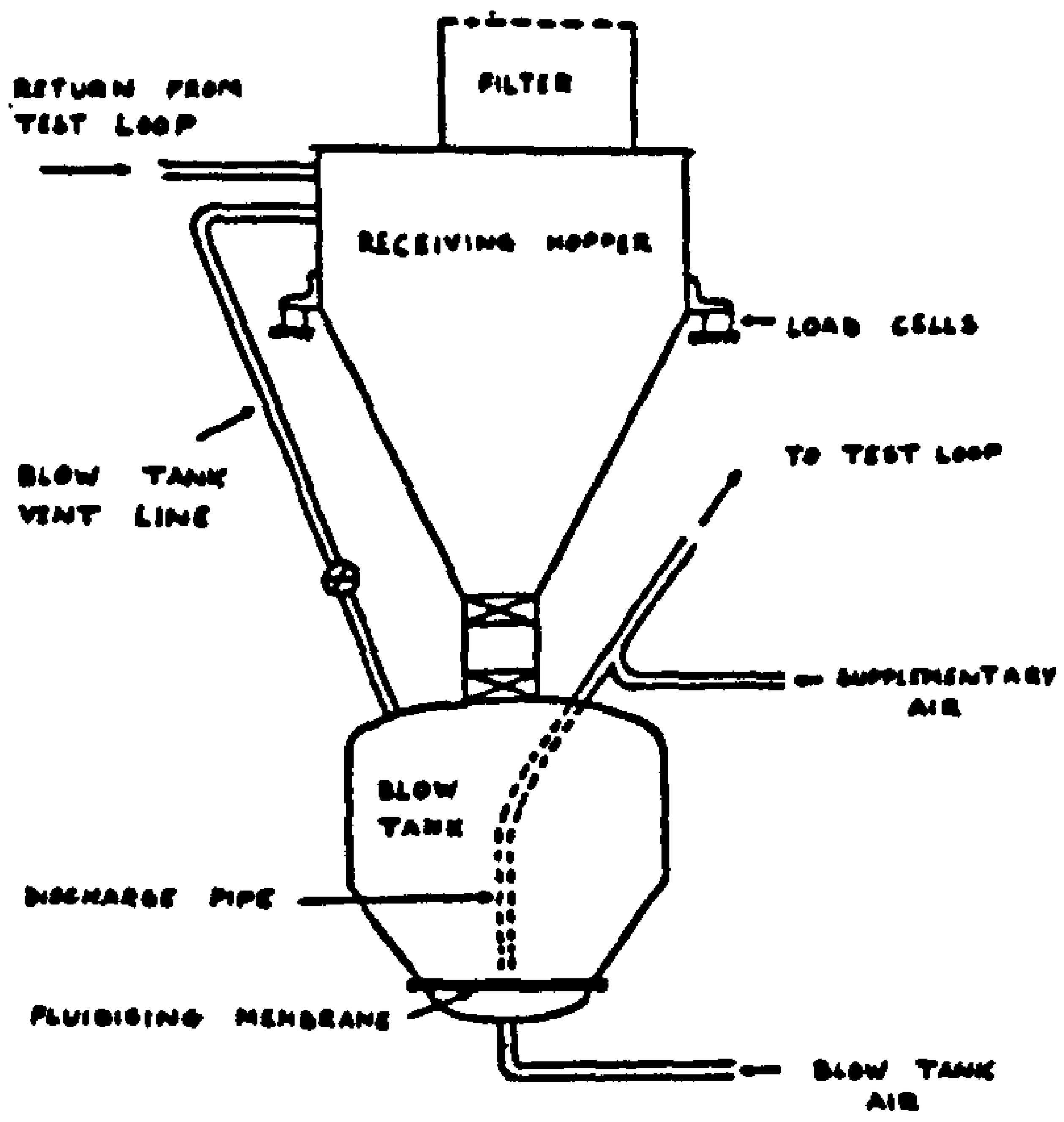


Fig 1 CONVEYING PLANT LAYOUT

TOP DISCHARGE MODE

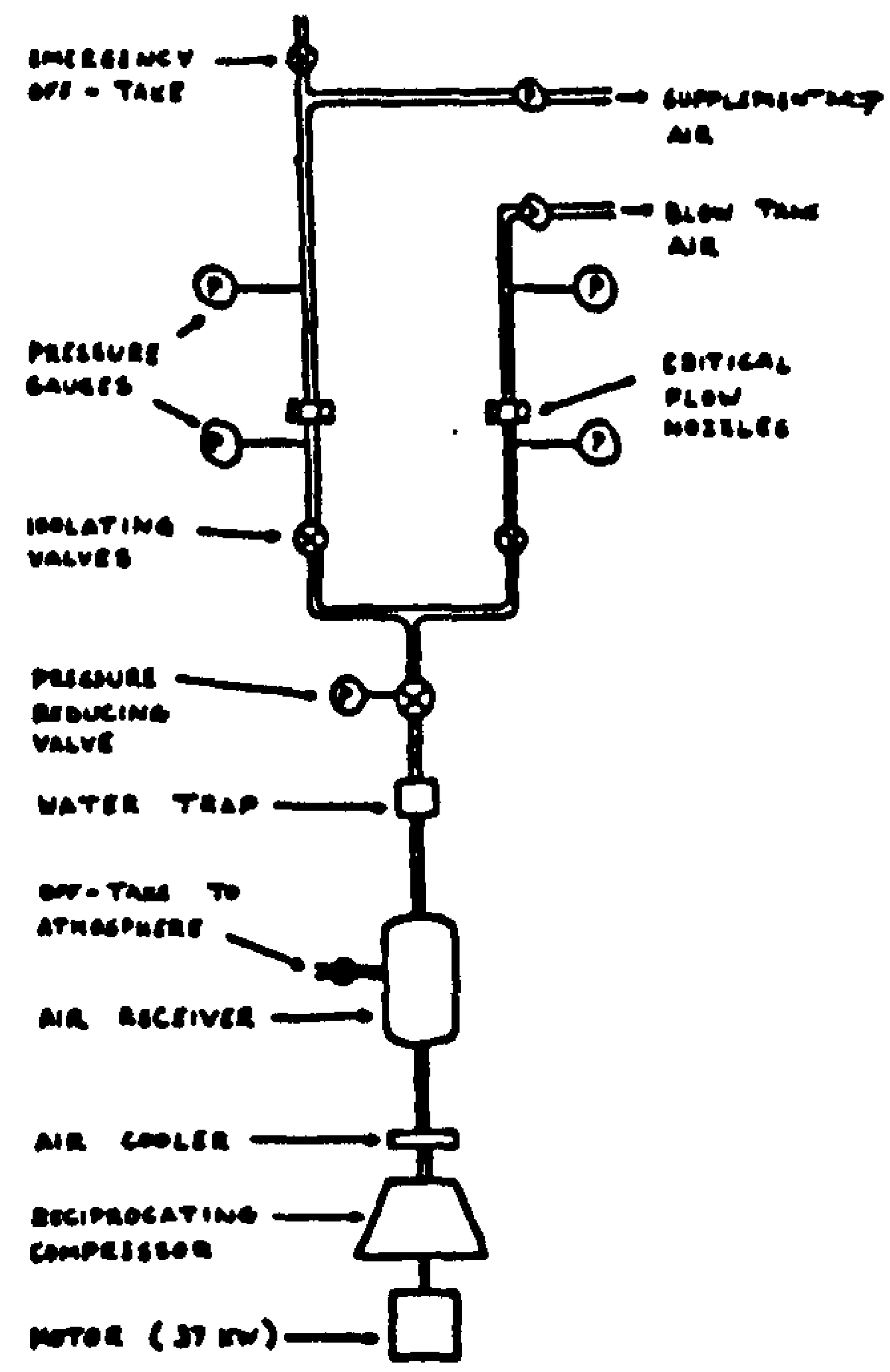


Fig 2 CONVEYING PLANT AIR SUPPLY

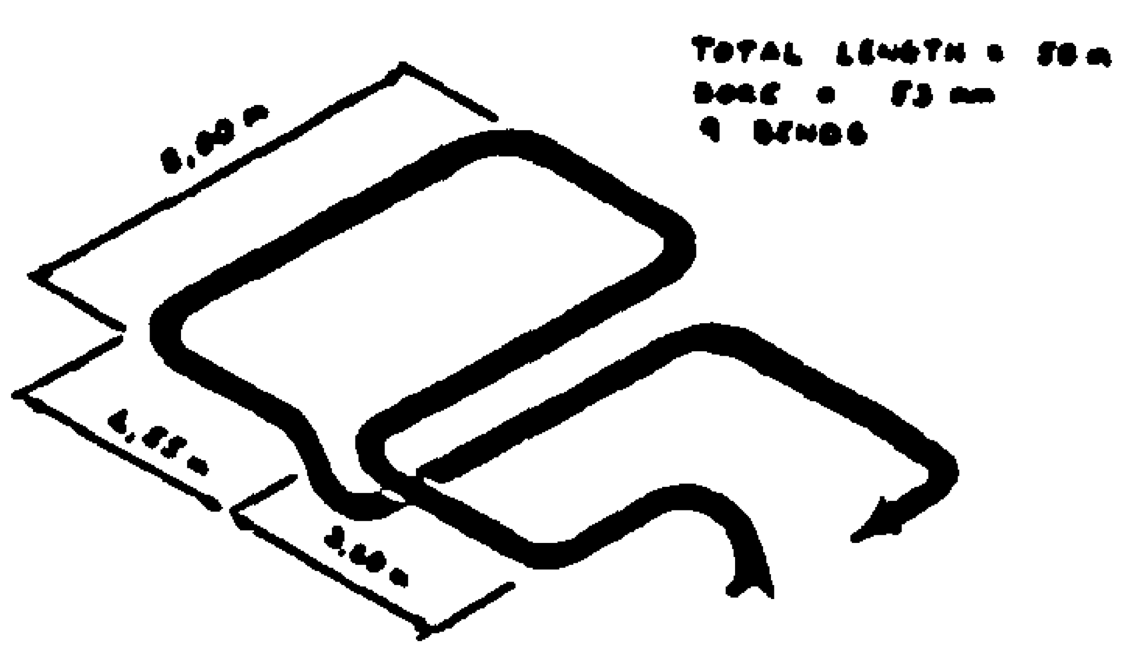


Fig 3 CONVEYING PIPELINE LAYOUT

C-11

discharge pipe used in the top discharge mode was blocked off. The supply air to the blow tank enters the tank via a fluidising annulus. A discharge valve at the base of the blow tank allows the blow tank to be pressurised or part pressurised before conveying began. Since a discharge valve was not available for the blow tank in the top discharge mode, this discharge valve was not used in bottom discharge operation. The supplementary air entered the pipeline just downstream of the discharge valve.

In general, the conveying line geometry was the same for both top and bottom discharge. Slight differences occur due to the position of the discharge pipes for top and bottom discharge modes. These differences are shown in Fig. 4

THE AIR SUPPLY

Three compressors were available each capable of 0.095 m^3/s (202 ft^3/min of "free air" at a pressure of 6.9 bar (100 lbs/sq. in) gauge. A diagrammatic layout of the air supply from the compressors to the conveying plant is shown in Fig. 2. For this work, only one compressor was required since a 53 mm bore pipeline was used and this represents a free air velocity of 42 m/s. Part of the air was directed to the blow tank and the rest was directed to the supplementary air line. The control of the air supply was by use of a pressure reducing valve to control the upstream pressure and critical flow nozzles placed in the two air supply lines.

INSTRUMENTATION

Five variables were measured. These were both air mass flowrates, product mass flowrate, pipeline pressure drop and blow tank pressure. The air mass flowrates were measured by using critical flow nozzles. The advantage of using this device is that since it relies on the air flow being choked (i.e. the velocity at the throat is sonic), then for a fixed upstream pressure the air mass flowrate is constant over a wide range of downstream pressures and the effects of pulsations are avoided. The control of the mass flowrate through a particular nozzle was achieved by altering the upstram pressure. Operation with pressure ratios of up to 0.9 is possible with good convergent-divergent nozzles. The nozzles were positioned in the air supply lines to the blow tank and the conveying line as shown in Fig. 2. The total air mass flowrate for conveying the product through the pipeline is the sum of the blowtank and supplementary air mass flowrates.

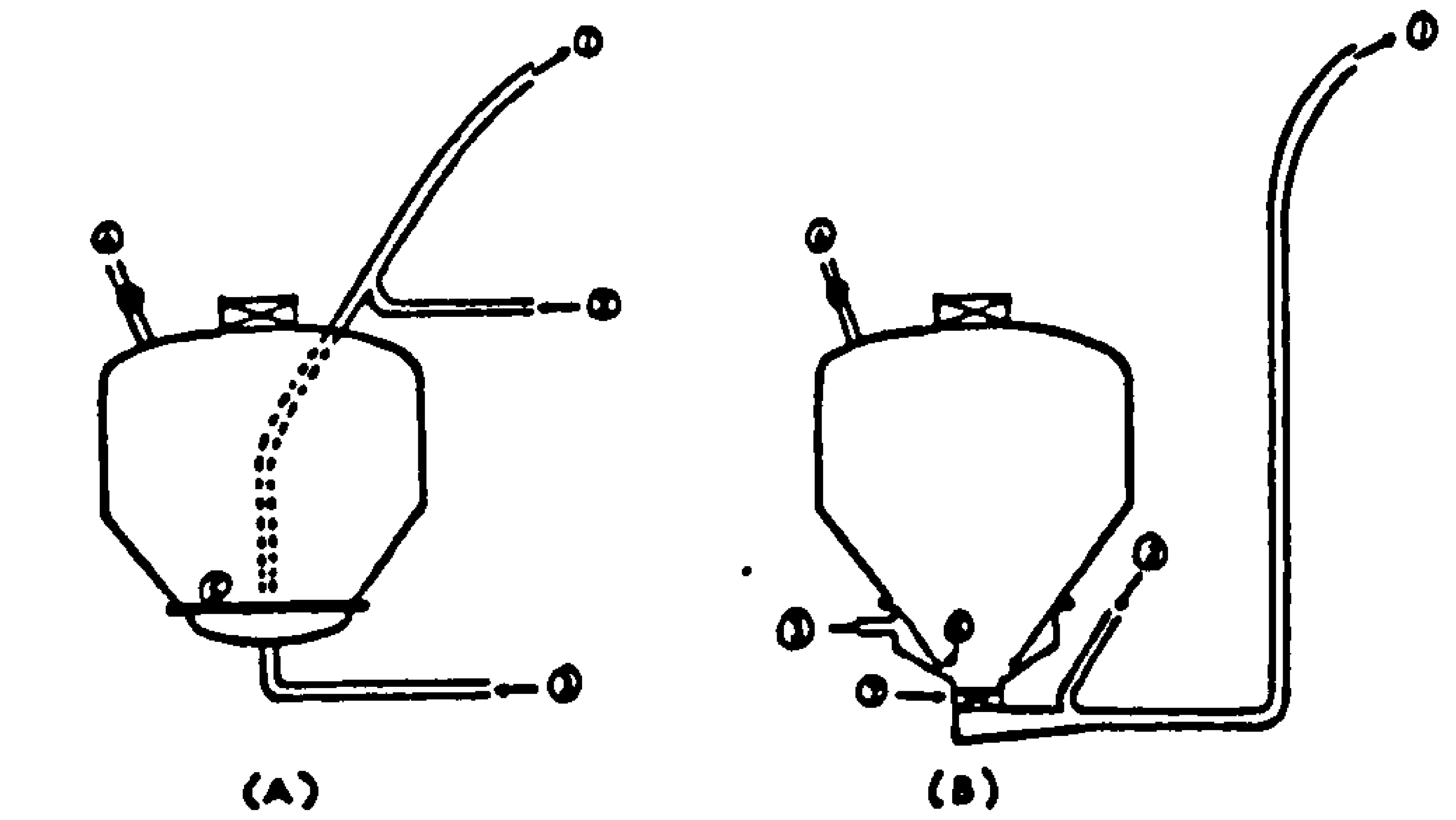
The product mass flowrates were obtained from the load-cells on which the receiving hopper was mounted. Three load-cells were used. The combined electrical output signal was fed into a recording instrument and integrated with respect to time to give the product flowrate.

The air supply pressure was measured immediately before the product pick-up point in the supplementary air supply line and was recorded. With the discharge being into the receiving hopper at atmospheric pressure, the conveying line pressure drop was obtained. The blow tank pressure was measured directly.

PRODUCT TESTED

The product "Pulverised Fuel Ash" (PFA) has been used throughout this test work. PFA was chosen because of its ability to be conveyed easily in dense phase. It can be conveyed at velocities as low as 3 to 4 m/s and at phase densities in excess of 100. The salient features of PFA are given below.

Median Particle Size	42 μm
Particle Density (mean)	2446 kg/m^3
Bulk Density (as poured)	979 kg/m^3



TO CONVEYING LINE
SUPPLEMENTARY AIR LINE
AIR SUPPLY TO BLOW TANK
BLOW TANK VENT TO RECEIVING HOPPER.
FLUIDISING MEMBRANE
FLUIDISING ANNULUS
DISCHARGE VALVE

FIG 4 TOP AND BOTTOM DISCHARGE BLOW TANK ARRANGEMENTS

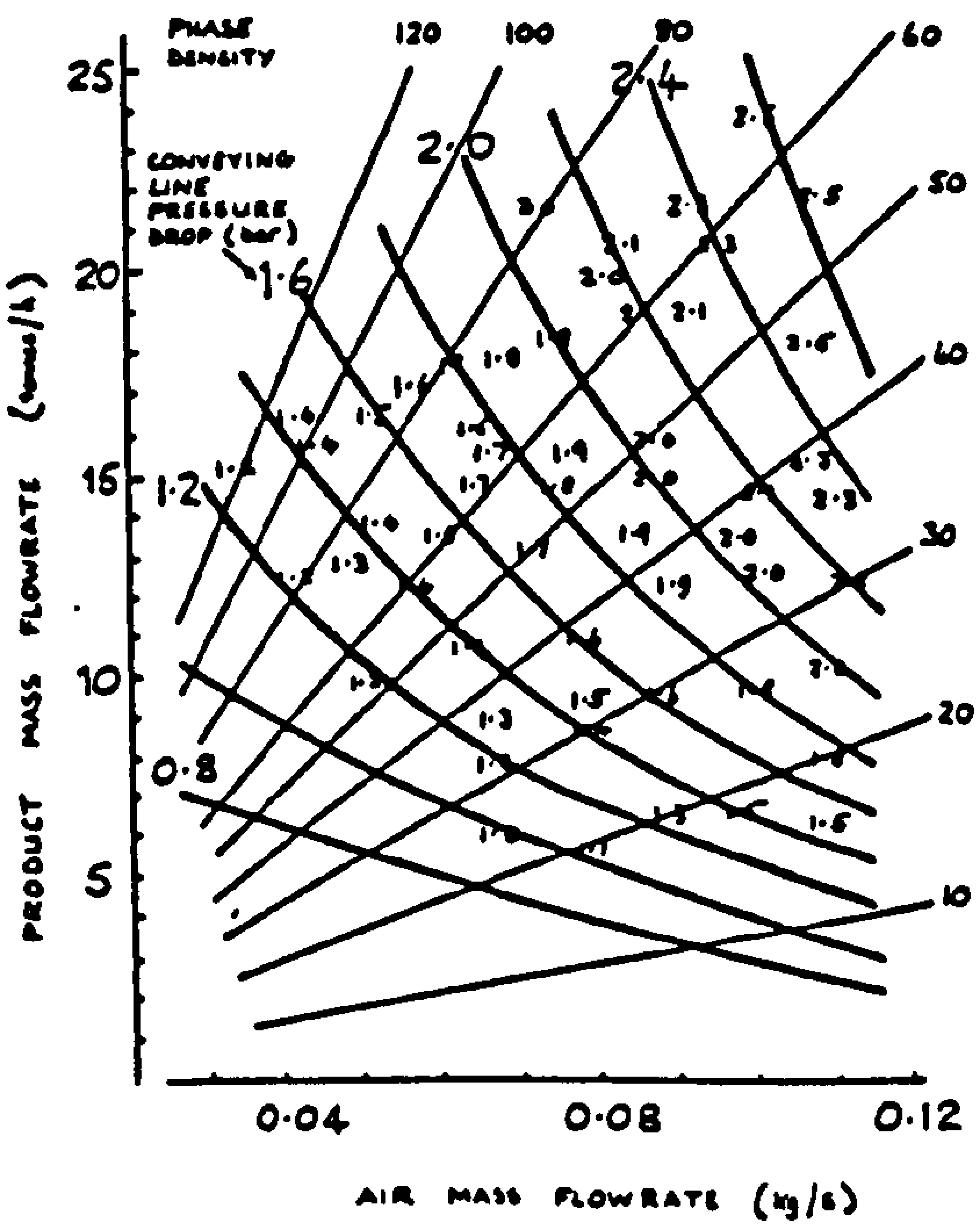


Fig 5 CONVEYING CHARACTERISTICS FOR PFA (TOP DISCHARGE)

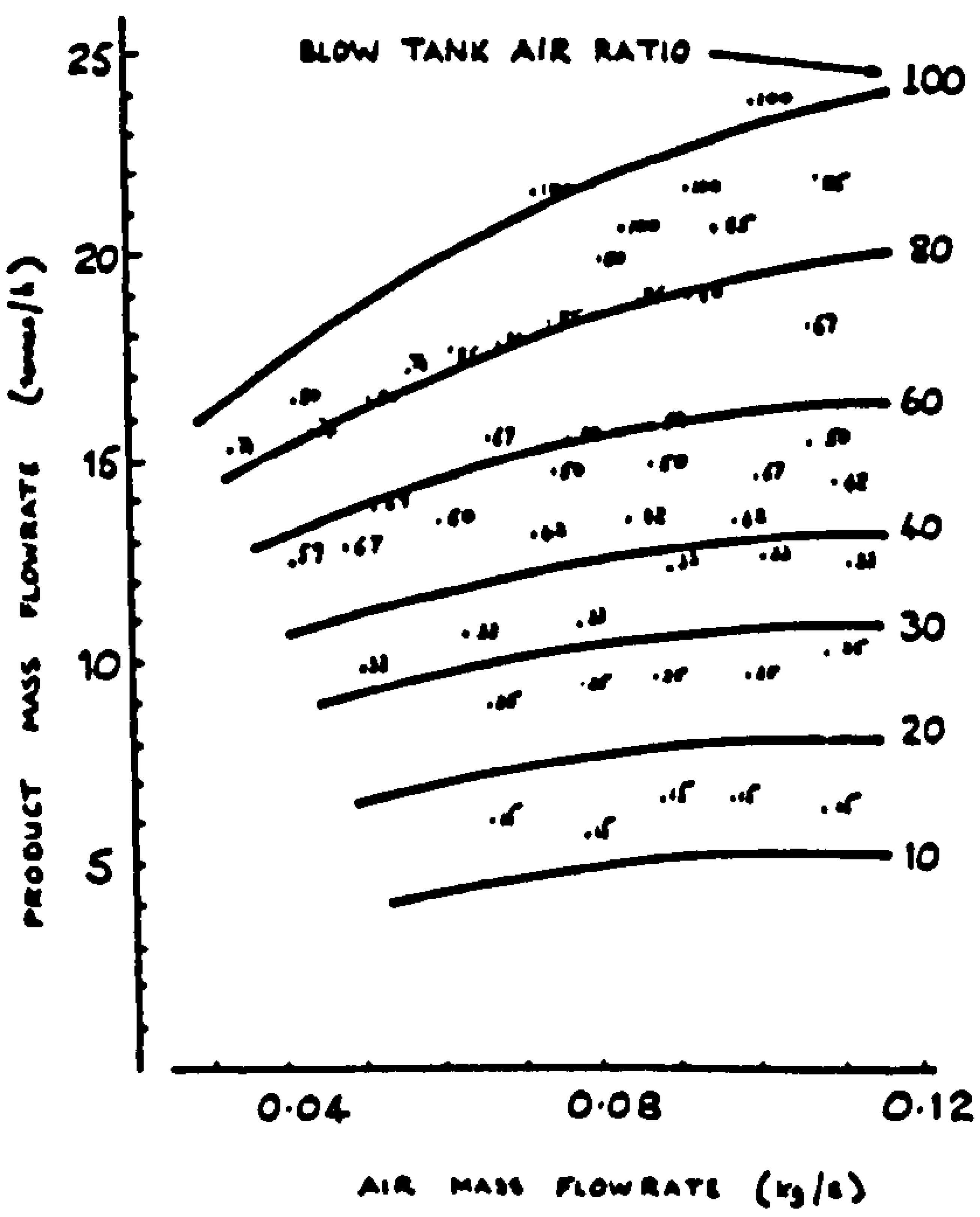


Fig 6 TOP DISCHARGE BLOW TANK CHARACTERISTICS FOR PFA

C-16

EXPERIMENTAL TECHNIQUES

The only control over the blow tank, and hence the conveying line, was achieved by controlling the total air mass flowrate and the proportion of the total air mass flowrate going to the blow tank. The proportion of air to the blow tank is known as the "Blow Tank Air Ratio" (BTAR). The BTAR was controlled by the appropriate selection of critical flow nozzles for use in the air lines to the blow tank and conveying line.

To start conveying, the BTAR and the total air mass flowrate were set. The blowtank vent line (Fig. 1) was then closed and the blow tank began to pressurise. Since the discharge valve was not used when conveying in the bottom discharge configuration, the procedures used for the top and bottom discharge conveying trials were identical. When steady state conditions were reached the pressures and product mass flowrate were recorded over a reasonable time period; typically 2 to 3 minutes. The data recorded on one pass provides a single point on the conveying characteristics and on the blow tank characteristics. The data from 30 to 40 runs for each configuration was plotted on graphs of product mass flowrate against total air mass flowrate as shown in Figs. 5 and 6. Lines of constant BTAR and constant conveying line pressure drop could then be drawn on the respective graphs, as shown.

CONVEYING LIMITATIONS

Tests were carried out over as wide a range of conveying conditions as could be achieved with the product and the plant. Maximum air flowrates were dictated by the capability of the air mover, but with conveying velocities of up to 42 m/s, the normal range of operation is adequately covered. Maximum product flowrates are set when 100 per cent of the air is directed to the blow tank, as shown in Fig. 6. The minimum value of air flowrate, or conveying velocity, is dependent upon the capability of the product. In the case of PFA it is clearly capable of being conveyed in dense phase, with values of phase density up to about 120. In Fig. 7 the data from the top discharge tests is presented on a plot of conveying line inlet air velocity against phase density. A line drawn below the data represents the probable minimum conveying air velocity relationship for the product. Conveying line pressure drop depends upon the pipeline length, phase density and the product flowrate and so is limited by other parameters than feeding capability.

ANALYSIS OF EXPERIMENTAL RESULTS

The experimental data obtained can best be illustrated on four graphs. These graphs are presented in Figs. 8 to 11 and show the conveying pipeline characteristics and the blow tank characteristics for the PFA in both top and bottom discharge modes. Initially it is useful to look at the general conveying characteristics in both top and bottom discharge configurations.

The conveying characteristics for both top and bottom discharge modes are shown in Figs. 8 and 9. It is noticeable immediately that in top discharge the conveying characteristics cover a greater range of conveying conditions than in bottom discharge configuration. This is particularly the case in the low air mass flowrate - high product flowrate area of the characteristics. However, if the two sets of characteristics are superimposed, it can be seen that the characteristics for the bottom discharge mode are the same as those for the top discharge configuration but with the boundaries restricted. This is not surprising since the shape of the constant pressure lines on the pipeline conveying characteristics should be independent of the type of feeding device. However, the boundaries to the characteristics may well be determined by the feeding device if the device cannot feed at the maximum rate that the pipeline can accommodate.

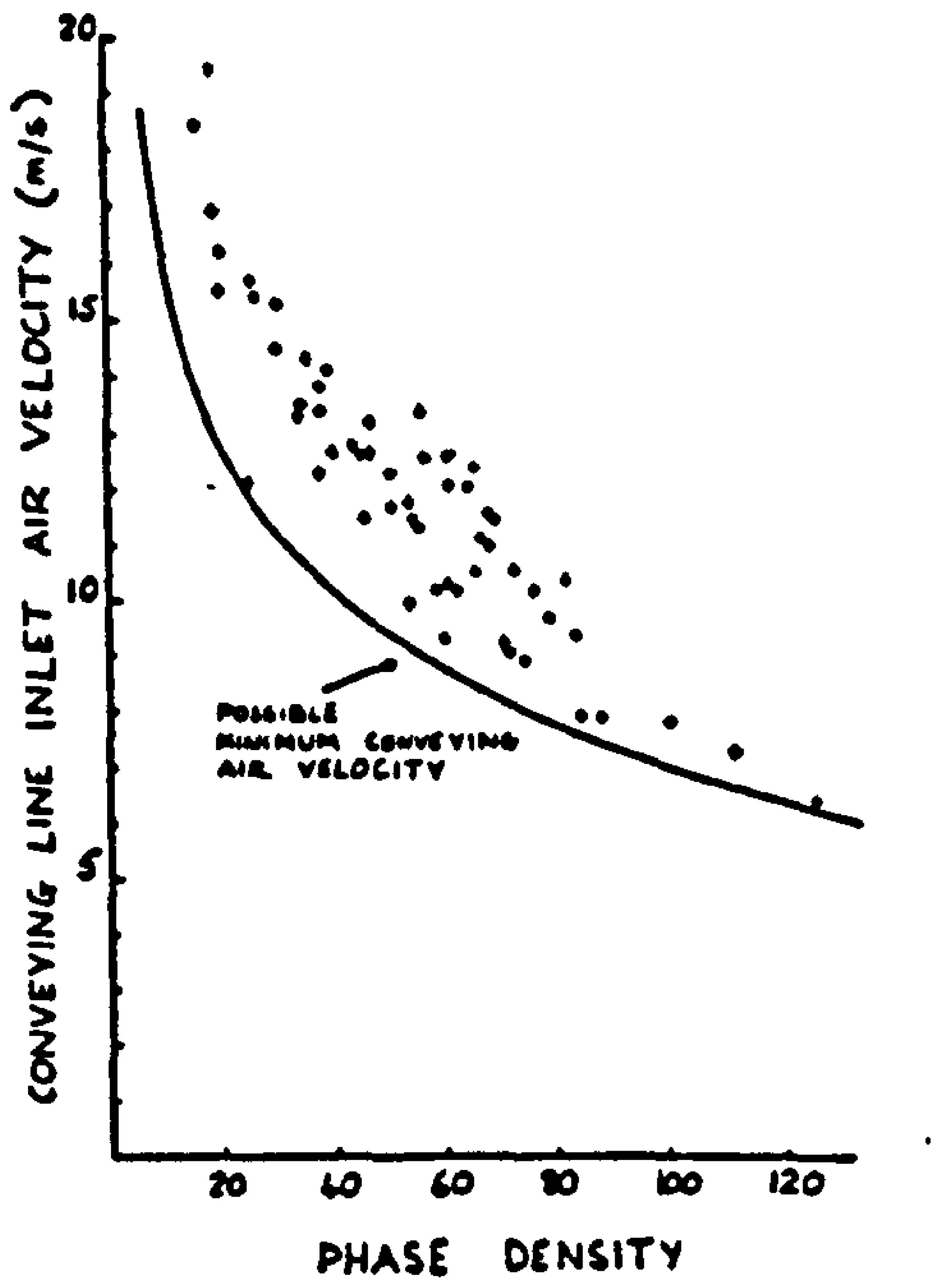


Fig 7 MINIMUM CONVEYING VELOCITY v PHASE DENSITY TOP DISCHARGE MODE

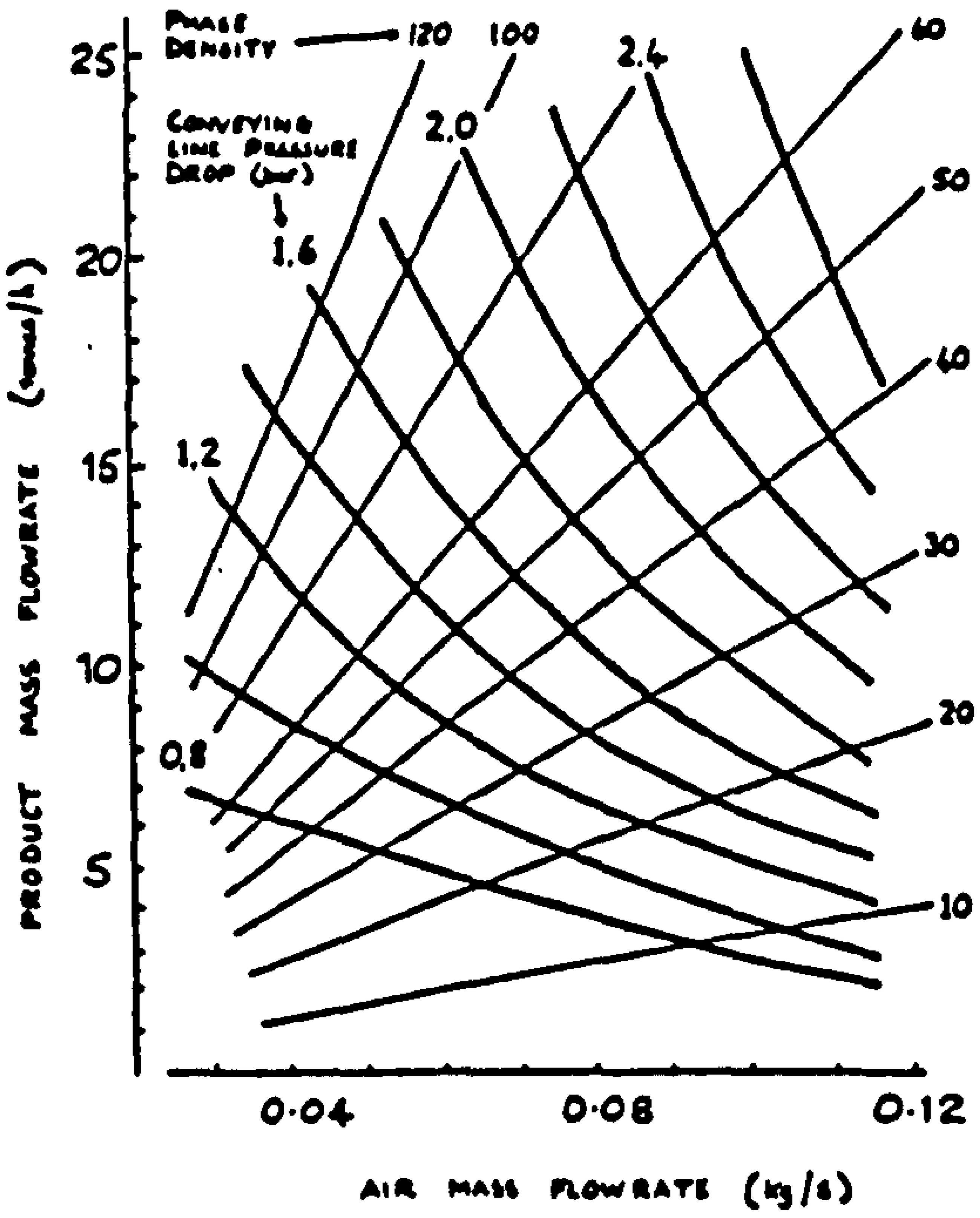


Fig 8 CONVEYING CHARACTERISTICS FOR PFA (TOP DISCHARGE)

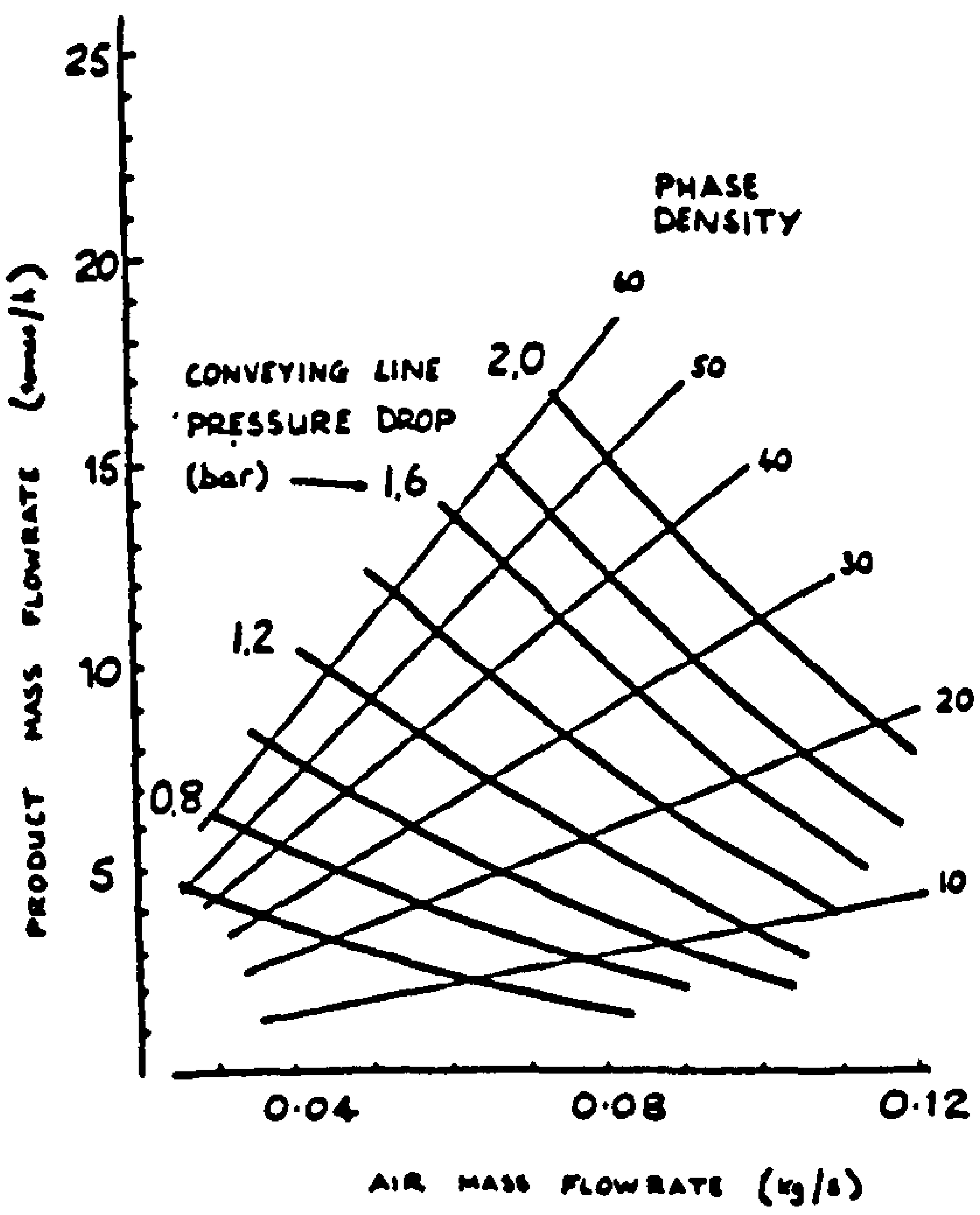


Fig 9 CONVEYING CHARACTERISTICS FOR PFA (BOTTOM DISCHARGE)

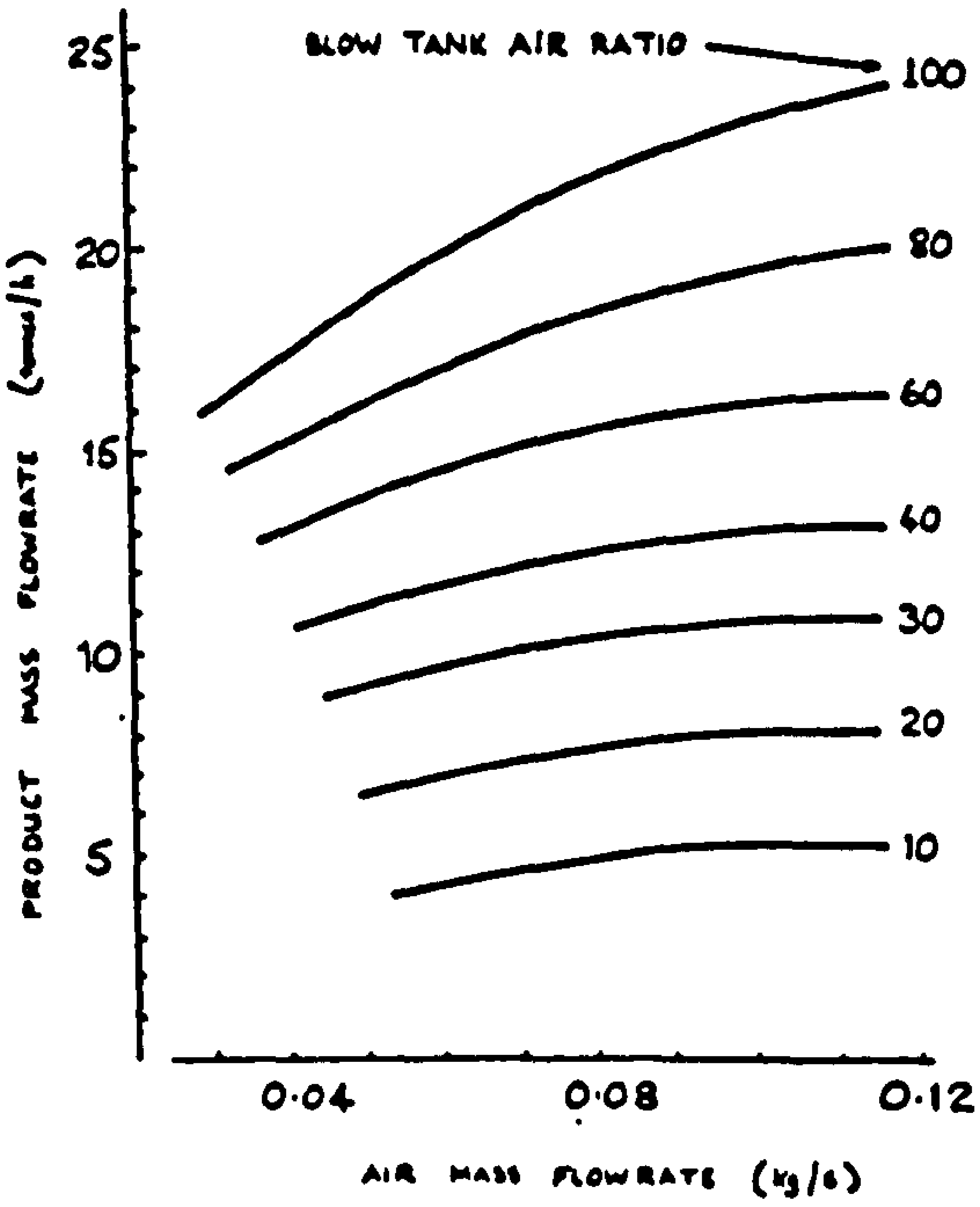


Fig 10 TOP DISCHARGE BLOW TANK CHARACTERISTICS FOR PFA

C-18

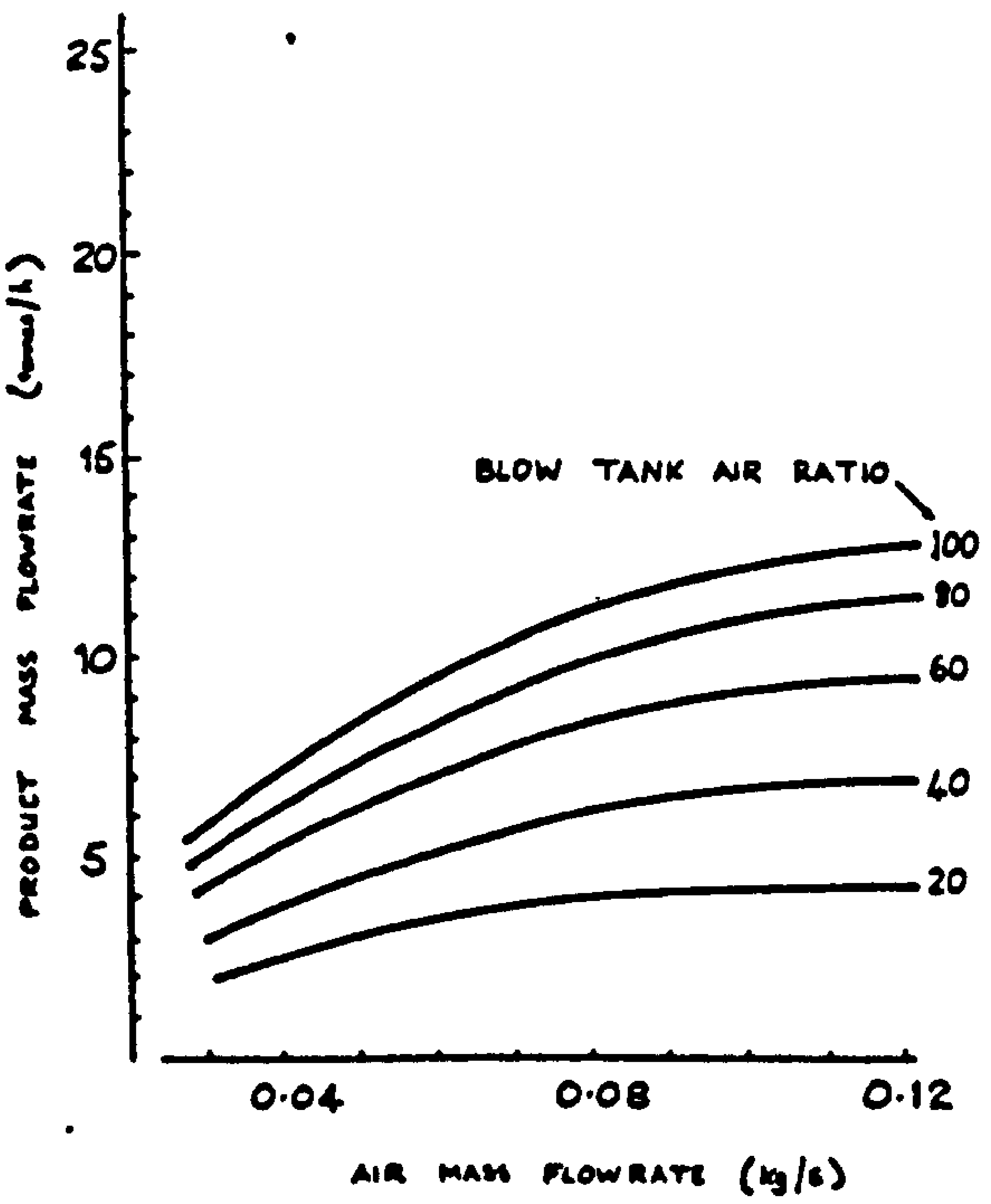


Fig 11 BOTTOM DISCHARGE BLOW TANK CHARACTERISTICS FOR PFA

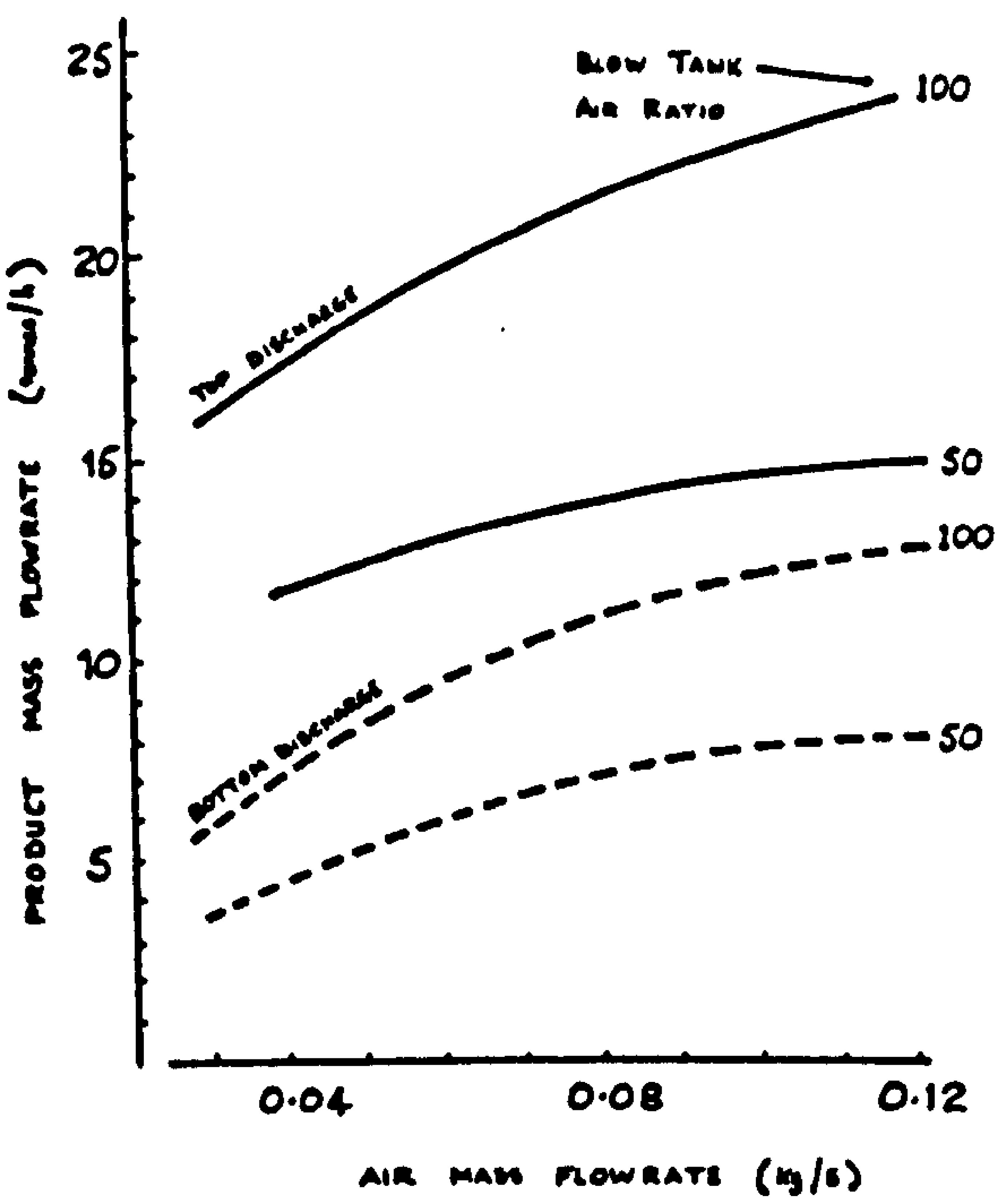


Fig 12 COMPARISON OF DISCHARGE RATES FOR TOP AND BOTTOM DISCHARGE CONFIGURATIONS

To compare the feeding capability of the blow tank in top and bottom discharge configurations it is necessary to compare the two sets of blow tank characteristics. Figs. 10 and 11 show the blow tank characteristics for the two configurations. The curves represent lines of constant BTAR. These two graphs show clearly that the blow tank characteristics for top and bottom discharge configurations are quite different. A much higher discharge rate is clearly achieved with the top discharge arrangement than with the bottom discharge configuration. A graph showing a comparison of the performance of top and bottom discharge modes is shown in Fig. 12. This shows the 50 per cent and 100 per cent BTAR lines for top and bottom discharge configurations. If one considers an air mass flowrate of 0.10 kg/s and compares the discharge rate in top and bottom discharge modes for a BTAR of 100 per cent then the rate for bottom discharge is 11 tonnes/h and for top discharge is 24 tonnes/h. This represents a ratio of 2.2:1 in discharge rates. If a BTAR of 50 per cent is considered for the same conditions the ratio is 2:1. It is obvious from both the conveying and blow tank characteristics that for dense phase operation, the choice of blow tank configuration could be critical. If the bottom discharge blow tank had been selected to feed the pipeline used for this test work in an operational situation the blow tank would not be able to achieve a discharge rate that would be compatible with the optimum performance of the pipeline.

DISCUSSION

The question now arises as to why there is such a variation in blow tank discharge rates for the two differnt configurations. The problem is that there are too many unknowns in the problem at present. An extensive programme of experimental work would need to be undertaken and is outside the scope of this paper. However, there are a few points that can be discussed.

The physical properties of the product being conveyed will influence the discharge rate. Jones et al (Ref. 1) have reported that for products that will convey in dense phase the discharge rate increases as the air retention properties increase and the air permeability decreases. Waghorn and Mason (Ref. 2) report that for a given product, the discharge rate can be increased by fluidising the product. Both of these papers refer to top discharge blow tank configurations. Since the fundamental concepts of pneumatic conveying lie with the air/product interaction, and the fluidisation of products is shown to affect discharge rates, perhaps one should consider the introduction of air to the blow tank in both configurations.

If one considers the top discharge blow tank (Fig. 4) the design of the blow tank is conventional. It is extremely common for the air to enter the blow tank through a fluidising membrane. The vertical position of the discharge pipe relative to the fluidising membrane is critical. Waghorn and Mason (Ref. 2) found the optimum position to be about 40 mm above the membrane. Introduction of the air to a top discharge blow tank at any other position is most uncommon.

If one considers the introduction of air to the bottom discharge blow tank configuration there is scope for variation. The design used for this test work is fairly common with the air being introduced via a fluidising annulus.

Mainwaring (Ref. 3) carried out some tests on varying the position of introduction of the air to a bottom discharge blow tank. He introduced the air in three differnt positions; directly into the top of the blowtank using a diffuser plate, through a fluidising ring similar in position to the fluidising annulus and a blow-through arrangement at the bottom of the blow tank. The result of these tests showed no significant difference in discharge rates with change in position of air introduction. This implies that the fluidising ring was not very effective at fluidising the product in the blow tank.

Although the fluidising annulus, used for this test work, is a different design to the fluidising ring, used by Mainwaring, it is unlikely that it would be significantly better although there is 'no hard' evidence one way or the other. The question remains as to the effectiveness of fluidising the product using an annulus compared with using a membrane. The answer is unclear but it is probable that the fluidising membrane is significantly more effective. This may be partly responsible for the higher discharge rates experienced with the top discharge configuration.

The obvious next stage would be to fit the bottom discharge blow tank with a fluidising cone in the lower region funnelling the product towards the discharge point and into the pipeline. This should have the effect of improving the fluidisation of the product in the bottom discharge configuration. If a significant increase in discharge rates is achieved then it would be reasonable to assume that effective fluidisation improves blow tank performance.

Other products have been tested in both top and bottom discharge configurations such as sand and polyethylene pellets. These products have poor air retention properties and have good air permeability. These products have very similar blow tank characteristics in both top and bottom discharge modes. This would obviously fit in with the hypothesis that fluidisation of the product affects discharge rates if the product has good aeration properties. It is probably not a coincidence that the products which have good air retention properties are also the best candidates for dense phase conveying. Hence it can be seen that the choice of blow tank type when designing for dense phase conveying could be critical to the success or otherwise of the system.

CONCLUSIONS

The blow tank characteristics for the top and bottom discharge configuration for a product exhibiting good aeration properties show a marked difference in discharge rate for the same fixed BTAR and air mass flowrate. This is significant since a product displaying good aeration properties is a likely candidate for dense phase conveying.

The most likely reason for the variation in discharge rates in top and bottom discharge configurations is probably the lack of effective fluidisation in the bottom discharge mode. However, there is little experimental evidence to support this conclusion at present, although it is known that progressive fluidisation in a top discharge blow tank configuration enhances the discharge rate. A further extensive programme of work would be necessary to prove or disprove this hypothesis.

The significance of the variation in discharge rates for the two configurations becomes apparent when designing a system. Products that are likely to be conveyed in dense phase are the very products that show a significant difference in discharge rate in conventional top and bottom discharge blow tank configurations. This means that it is possible to design a system using a bottom discharge blow tank that is not capable of conveying at the intended rate due to the limitations imposed by the blow tank.

Although the bottom discharge blow tank severely restricts the feeding capability of the pipeline, little difference was observed in the product conveying characteristics. Thus, apart from the conveying limit imposed, there is no significant difference in the pressure, and hence energy, required to convey a product through a pipeline at a given product flowrate and phase density, whether the pipeline is fed by a bottom or top discharge blow tank.

REFERENCES

1. Jones M G, Mills D and Mason J S : "The Influence of Product Type on Blow Tank Pipeline Feeding Characteristics". Int. Powder and Bulk Solids Handling and Processing Conf., Chicago, May 1986.

2. Waghorn D J and Mason J S : "The Effect of Aeration and Position of Inlet to Conveying Line on the Discharge Characteristics of a Blow Tank". Bulk Solids, Storage, Handling and Flow Conf., Nov. 1976, Stratford-Upon-Avon, Powder Advisory Centre.

3. Mainwaring N J - Personal communication.

PNEUMATIC CONVEYING OF HIGH BULK DENSITY PRODUCTS

M G Jones*, D Mills and J S Mason
Bulk Solids Handling Unit
Thames Polytechnic,
Wellington Street,
Woolwich SE18 6PF
UK

ABSTRACT

There are two major modes of flow in pneumatic conveying; suspension flow and non-suspension flow. These modes of flow are often referred to as dilute and dense phase. It is always a problem to predict whether or not a product is capable of being conveyed in a non-suspension flow. There is often an advantage in conveying products in a non-suspension flow in terms of reduced degradation of friable products or a reduction in the level of pipeline erosion. The work reported in this paper describes a method of predicting the potential of a product to be conveyed in dense phase using a correlation between certain product characteristics and the mode of conveying. The correlation is also used to predict the probable conveying performance in terms of product throughput for a given set of conveying conditions. The products tested cover a range of product characteristics with an emphasis on high bulk density. The conveying characteristics and product properties are presented together with graphical representations of the empirical correlations.

INTRODUCTION

The first part of this paper describes the test rig and equipment which was used to carry out the conveying trials in order to determine the conveying characteristics for the five products. The conveying characteristics provide detailed information on the conveyability of the product. The experimental method and oprating procedures are discussed.

A brief description of the relevant material characteristics is given. It has been found that the bench tests that involve product-air interaction such as air permeability and the air retention properties of the material provide the most reliable correlations with conveying mode and performance.

DETAILS OF TEST RIG USED

Conveying Plant.

The conveying plant used for tests consisted of a high pressure blow tank having a volume of about 1.5 m , and a similar sized hopper mounted on load cells vertically above. A diagrammatic layout of the conveying plant is shown in Fig. 1. The blow tank was fitted with a fluidising membrane consisting of a terylene cloth sandwiched between perforated metal plates. The discharge pipe within the blow tank was 53 mm bore and was positioned about 40 mm above the centre of the fluidising membrane.

It is basically a batch type system with the product conveyed from the top of the blow tank, through the conveying line and back into the receiving hopper. For the purpose of this work the products were recirculated. The

Air for fluidising the product in the blow tank was introduced at the bottom, beneath the fluidising membrane. The supplementary air was introduced into the discharge pipe as close as possible to the top of the blow tank in order to minimise the pressure drop in the discharge pipe. A small blow tank was used for charging the product into the hopper, and after use the product was discharged from the main blow tank into an elevated storage or off-loading hopper.

The pipeline used was 50 m long, had an internal diameter of 53 mm (2 inch nominal bore), and incorporated nine ninety degree bends. A sketch of the test loop is given in Fig. 3. The bends in the pipeline had a bend diameter (D) to pipe bore (d) ratio of 24:1.

Air Supply

The arrangement of the air supply to the conveying plant is shown in Fig. 2. A reciprocating compressor was used for this work, driven by a 37 kW motor. The compressor was capable of delivering about 0.11 kg/s (200 ft /min) of free air at a pressure of about seven bar gauge. The compressed air was cooled by means of an air blast after cooler. The air supply pressure could be controlled by means of a pressure reducing valve situated immediately before the air supply split to blow tank and conveying line.

Instrumentation

Air mass flow rates were recorded by means of calibrated choked flow nozzles. These were positioned in the air supply lines to the blow tank and conveying line as shown in Fig. 2 (Ref. 1). The total air flow rate used for conveying the product in the pipeline was the sum of the fluidising and supplementary air flow rates. The product mass flow rates were obtained from the load cells on which the receiving hopper was mounted. Three load cells were used. The combined electrical output signal was fed to a recording instrument and integrated with respect to time to give product flow rate.

The air supply pressure immediately before the product pick-up point in the supplementary air supply line was recorded, and with the discharge being into the receiving hopper at atmospheric pressure, the conveying line pressure drop was obtained.

Operation and Control

The only control available on the blow tank was that over the air supply. There were, however, eight different sizes of choked flow nozzle which could be used on both the blow tank fluidising line and the supplementary air supply line. This allowed a maximum of sixty four different combinations of the ratio of the air supply to the blow tank to the total air supply to be used. Many of the nozzle combinations would require air flow rates which are too high for the compressor, or give air flow rates which are too low for the product. Others result in excessively high product flow rates, and hence high conveying line pressure drops. With such a large potential number of combinations, however, it is always possible to fine a sufficient number which can be used in order to identify the conveying limits for most of the products, and to test the product extensively over its range of conveyability.

The actual value of the total air supply could be varied over a wide range for any choked flow nozzle combination by varying the air supply pressure. This was achieved by adjustment of the pressure reducing valve. By varying the air supply pressure and changing the choked flow nozzles, a very wide range of conveying conditions could be obtained. There was, however, no way in which these could be pre-set to give the desired product flow rates for a test run (in advance of the conveying characteristics being obtained). There was also no valve at the outlet from the blow tank prior to the conveying line. At the start of each run, therefore, the nozzles were chosen and the air supply pressure was set, and conveying commenced when the blow tank vent line to the receiving hopper was closed.

The blow tank pressure soon built up to a steady operating pressure and, steady conveying conditions prevailed over a reasonable part of the conveying cycle, even in tests at very high product flow rates. For each conveying run the load cell reading (and hence product flow rate), and the supplementary air supply pressure (and hence conveying line pressure drop) were recorded continuously with respect to time.

EXPERIMENTAL PLAN

Since it was not possible to convey at a given product flow rate, or at a set conveying line pressure drop, two of the nozzles and an air supply pressure were selected and the product was conveyed. The recordings which were taken during each test run enabled the product mass flow rate to be evaluated. Experience obtained in handling the products in the conveying system led to a number of such tests being carried out. In order to establish the conveying limits with the products, tests were carried out with as many nozzle combinations and over as wide a range of conveying conditions as possible.

ANANLYSIS OF DATA

Presentation of Results

The results for the five products tested are shown in graphical form in terms of conveying characteristics for each product (Figs. 4-9). If two variables are chosen for the x- and y- axes of the graph, the test results for a third variable can be plotted. The values are appropriately rounded for convenience with the decimal point indicating the actual location of the test results. Lines of constant value can then be drawn through the data to provide a family of curves.

In Fig. 4 conveying line pressure drop results have been plotted on a graph of product mass flow rate against air mass flow rate. The pressure drop, of course, is a primary variable in the problem, for this is a limitation imposed by the compressor used. Air mass flow rate is also one of the major variables, and conveying air velocity can be evaluated from it. Lines of constant conveying line pressure drop have been drawn through the data points to provide a family of curves. This allows prediction of the product throughput knowing the conveying line pressure drop and the total air consumption on a mass basis. (It should be noted that this is for a given pipeline but scaling techniques can be used over a limited range to give reliable predictions for alternative pipelines). The results in this form are known as the conveying characteristics and provide a powerful and concise analysis of the conveying potential of the product.

Conveying limitations

Apart from the lower limit of zero for the product mass flow rate, there are three other limitations on the plot in Fig. 4. The first is the limit on the right hand side of the plot which is imposed by the volumetric capacity of the compressor used. The air mass flow rate of 0.11 kg/s gives a free air velocity of about 42 m/s which for most pneumatic conveying systems is near the upper limit. This upper limit is partly influenced by the problems of product degradation and bend erosion in the conveying line, but is mainly due to the adverse effect on conveying line pressure drop and the consequent reduction in product mass flow rate.

The second limit is that at the top of the graph. For a long pipeline this limit will be set by the pressure capability of the compressor used. With this relatively short pipeline, however, the limit was set by the discharge capability of the blow tank in the case of the Cement and Barytes and by the conveying pipeline limitation due to velocity and pressure in the case of the other three products. (The pipeline limitation will be discussed later in this paper).

The third limit is that on the left hand side of the graph and this represents the minimum conditions for successful pneumatic conveying with the product. The lines actually terminate and conveying is not possible in the area to the left at lower air mass flow rates. Any attempt to convey with a lower air mass flow rate would result in a blockage of the pipeline.

Minimum Conveying Conditions

Due to the compressibility of air, the conveying air velocity will vary with pressure along the pipeline. It is for this reason that air mass flow rate is chosen as the variable for the X-axis for the conveying characteristics. However, whilst it is useful to be able to eliminate the effect of variation in velocity for the purpose of producing such characteristics, ignoring the fact can be disastrous. In many respects it is the conveying velocity that determines the minimum conveying conditions. However, due to the fact that it is very difficult to obtain the actual velocity of the air or the solids especially in sliding-bed type flows at any given point along the pipeline, correlation work usually uses superficial air velocity based on the cross-sectional area of the pipeline. This is common practice and therefore future reference to velocity in this paper will mean superficial air velocity.

Determination of minimum conveying conditions is achieved by producing a graph of conveying line inlet air velocity against phase density. An example is shown in Fig. 10. The spread of results was obtained because a wide range of conveying conditions was required for the characteristics to be drawn. A curve representing possible minimum conditions can be drawn. The exact position of the curve which represents the minimum conveying conditions is rather difficult to locate. If the pipeline is blocked no experimental data can be obtained although it is often possible to estimate the approximate position from tests which precede it. In general, however, it is often possible to deduce that conveying conditions in a particular test are near to the minimum condition from the unstable nature of the flow indicated by erratic pressure fluctuations in the pipeline.

PRODUCT CHARACTERISATION

It has long been established that material properties of a product to be conveyed must influence the conveyability of the product. However, there has been very little work done in the past to specifically quantify the effect of various material characteristics, be they bulk or particle characteristics, on the conveyability of the product. Many papers refer qualitatively to the effect that various product properties give an indication as to the suitability or otherwise of a product to be pneumatically conveyed.

Since pneumatic conveying involves the transport of particulate solids in air, it is probable that the most likely correlation between conveying characteristics and material properties is to be found from bench tests that involve significant product-air interaction. Fluidisation in its various forms provide the necessary techniques.

The two properties which have been identified as most useful for the purposes of determining conveyability are the permeability of a product to air (or the conveying fluid) and the ability of a product to retain air. The permeability characteristic of a product is measured in terms of a 'permeability factor'; the absolute value of which is of little significance but the relative value compared with other products is of great use. The air retention properties of the material are measured in terms of a 'Vibrated De-aeration Constant' which involves a method of measuring air retention in a much quicker way that the established methods. The absolute values are, again, of no real value, it is the comparison with other products which provides useful information.

A summary of product characteristics is given in Table 1. The salient features of each product are given in terms of their size and densities as well as the other properties already mentioned.

DISCUSSION OF RESULTS

Product Characteristics and Conveying Mode

It is widely accepted that most products can be pneumatically conveyed in suspension flow. There may be many reasons why it is not practicable such as degradation, bend erosion or problems with feeding or collecting, but if only the pipeline is considered most products can be conveyed. However, in many cases it is desirable that products be conveyed at lower velocity in a non-suspension mode of flow. It would, therefore, be useful if some assessment could be made as to the potential of a product to be conveyed in a non-suspension mode of flow.

In general terms, a product will remain in suspension flow whilst the velocity remains sufficient. A value of around 15 m/s is normally considered the minimum velocity which is consistent with suspension flow. For many products, pipeline blockage is the result if the conveying line air velocity is allowed to drop below this nominal figure. The probable reason for blockage is an inability on the part of the product to be conveyed in a non-suspension flow regime. Therefore, if one wishes to evaluate the potential of a product to be conveyed in such a mode, one must identify which material characteristics are responsible for the ability or otherwise of a product to be conveyed in a non-suspension mode of flow. There are many modes of non-suspension flow but they can be grouped into two major flow regimes: sliding-bed type flow and plug or slug type flow (Ref. 2). In this work tests were carried out at velocities down to about 3 m/s and is therefore restricted to sliding-bed type flow regimes. For the rest of the paper, non-suspension flow will be referred to as 'dense phase'.

Minimum Conveying Velocity

The graph in Fig. 11 shows the velocity limitations for the various products tested. The axes are the same as those used for the conveying characteristics. It is noticeable that the zircon sand has a very high minimum velocity indicating that it will not convey in dense phase. The cement and barytes will convey with ease at low velocities and the minimum velocities indicated were imposed by the limitations of the test facility and not by line blockage. It is possible therefore that they will convey at even lower velocities. The iron powder did block the pipeline at a minimum velocity of about 4 m/s.

Effect of Air Retention Properties on Minimum Conveying Velocity

The graph in Fig. 12 shows the relationship between minimum conveying velocity and the vibrated de-aeration constant. An increase in the vibrated de-aeration constant indicates a reduction in the air retention capability. Therefore, the better the product retains air the lower the minimum conveying velocity. Products that exhibit good air retention properties are the most likely candidates for dense phase conveying.

Effect of Permeability on Minimum Conveying Velocity

The graph in Fig. 13 shows the relationship between minimum conveying velocity and air permeability factor. An increase in the permeability of the product indicates an increase in the minimum conveying velocity. This result seems to be complementary to that of air retention since it seems reasonable to suggest that an increase in permeability would result in a reduction in air retention qualities. However, when the permeability becomes very low the trend is reversed and the minimum conveying velocity increases once more. The reason for the reversal is probably due to the particularly high bulk density of the copper ore and the iron powder. The copper ore has a particularly wide size distribution which combined with its high bulk density gives a predictably low permeability. However, the high bulk density also produces a poor air retention capability. In the case of the iron powder the size range is much smaller and produces a similar but much reduced effect. It is interesting to note that the effect of the high bulk density is noticeable but does not affect the validity of the correlation.

The experimental data used to evaluate the vibrated de-aeration constant is quite independent of the data obtained from fluidisation. Therefore, the cross correlation of the trends provides support to the validity of the results.

Product Characteristics and Conveying Performance

The correlation described so far gives an indication as to whether or not a product can be conveyed in dense phase. From a small sample of material, simple tests can be undertaken to determine the permeability factor and vibrated de-aeration constant which provide this indication.

The graph in Fig. 14 shows a comparison of products. Lines of constant conveying line pressure drop of 1.6 bar for each of the products have been plotted on a standard set of axes of product mass flow rate against air mass flow rate. It can be seen that for different products, variation in product throughput occurs for constant air mass flow rate and conveying line pressure drop. To analyse the effect of the product properties on the variation in throughput, values of product throughput have been plotted against various product properties for a fixed conveying line pressure drop and various air mass flow rates. The three air mass flow rates are marked by the vertical lines on Fig. 14. The graphs plotted in Figs. 15-16 use phase density, or solids loading ratio, rather than product mass flow rate. Phase density is the mass ratio of product to air.

Effect of Air Retention Properties on Conveying Performance

A very easily obtained indication of the likely air retention capabilities of a product can be obtained from the 'poured' and 'tapped' bulk densities of a product. The 'degree of compaction' or the 'percentage increase in bulk density' gives a good indication of the level of throughput. The graph of phase density against percentage increase in bulk density (Fig. 15) shows three curves, one for each air mass flow rate. The curves indicate a general increase in phase density and hence throughput for a given pressure drop and air mass flow rate as the degree of compaction increases.

The graph in Fig. 16 shows the relationship between phase density and vibrated de-aeration constant for the same three air mass flow rates and constant conveying line pressure drop as in Fig. 14. The curves indicate a general increase in throughput for the given conditions as the vibrated de-aeration constant decreases. A decrease in vibrated de-aeration constant indicates an increase in air retention capability. Therefore, in general an increase in the air retention properties of the product produces an enhanced product throughput for a constant set of conditions.

Effect of Permeability on Conveying Performance

The permeability factor has an inverse relationship to the air retention properties. In general, good air retention is accompanied by poor air permeability. Hence, it is no surprise to find that a decrease in permeability factor will increase the phase density achieved for a given set of conditions. The graph in Fig. 17 shows three curves representing three different air mass flow rates.

However, if the permeability factor is very low, which is the case with the two particularly high density products, then the trend is reversed and the phase density reduces as the permeability factor is further reduced for given conditions. This tends to indicate that there is a range of values of permeability factor over which optimum conveying performance is achieved.

CONCLUSIONS

The conveyability of a product can be predicted by analysing a small sample of material to determine the product-air characteristics in terms of air retention and air permeability properties. Products that exhibit good air retention properties are the most likely candidates for dense phase conveying. Products that have these qualities can be conveyed at relatively low velocities. Products that exhibit relatively poor air permeability characteristics are also good candidates for dense phase conveying.

Products which have particularly high bulk (or particle) densities will have very low air permeability characteristics. However, the high bulk densities have an adverse effect on air rtention properties resulting in a possible increase in minimum conveying velocity.

Having established the ability of a product to be conveyed in dense phase the same data will predict the likely level of product throughput or phase density.

However, unlike the analysis to determine mode of flow, the absolute values of phase density are specific to the conveying line used in the test but the inforation provides a relative measure of the likely conveying performance and over limited ranges the data could be scaled.

As is the case when determining conveying mode,. the effect of high bulk density is to reduce the air retention properties of the product. Therefore, the likely level of throughput for a particular set of conditions is likely to be lower than might otherwise be the case.

REFERENCES

1. Mills, D, Mason, J S and Duffell C H. The Horizontal Pneumatic Conveying from a High Pressure Blow Tank. Proc. Pneumatech 1. Powder Advisory Centre Conf., Stratford, May 1982.

2. Woodcock, C R. (Ed.) Pneumatic Handling of Bulk Materials, Thames Polytechnic Short Course Notes, 1986.

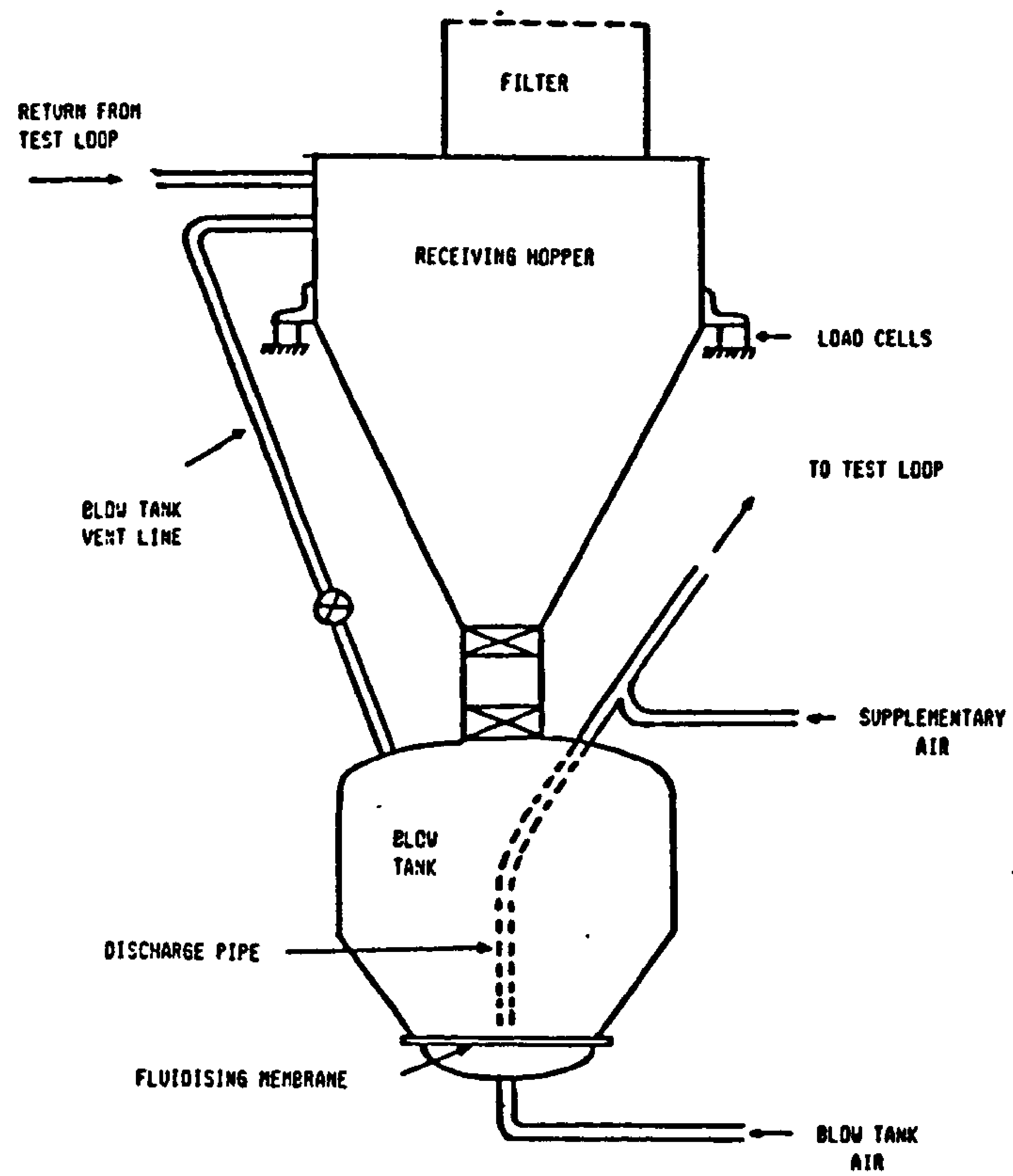


FIG. 1 – CONVEYING PLANT LAYOUT

PRODUCT	MEAN PARTICLE SIZE µm	SIZE RANGE (2%-97%) µm	PARTICLE DENSITY kg/m³	BULK DENSITY (poured) kg/m³
BARYTES	12	2 - 28	4250	1590
CEMENT	21	4 - 37	3060	1070
COPPER ORE	75	11 - 600	3950	1660
IRON POWDER	66	20 - 100	5710	2380
ZIRCON SAND	115	75 - 185	4600	2600

PRODUCT	BULK DENSITY (tapped) kg/m³	PERMEABILITY FACTOR ($x10^{-6}$) m^3s/kg	VIBRATED DE-AERATION CONSTANT mm/s	MINIMUM CONVEYING VELOCITY m/s
BARYTES	2270	0.48	3.9	3.0
CEMENT	1500	0.71	3.0	3.5
COPPER ORE	2150	0.33	9.3	8.5
IRON POWDER	3190	0.34	7.0	4.0
ZIRCON SAND	3000	1.31	10.2	13.0

TABLE 1

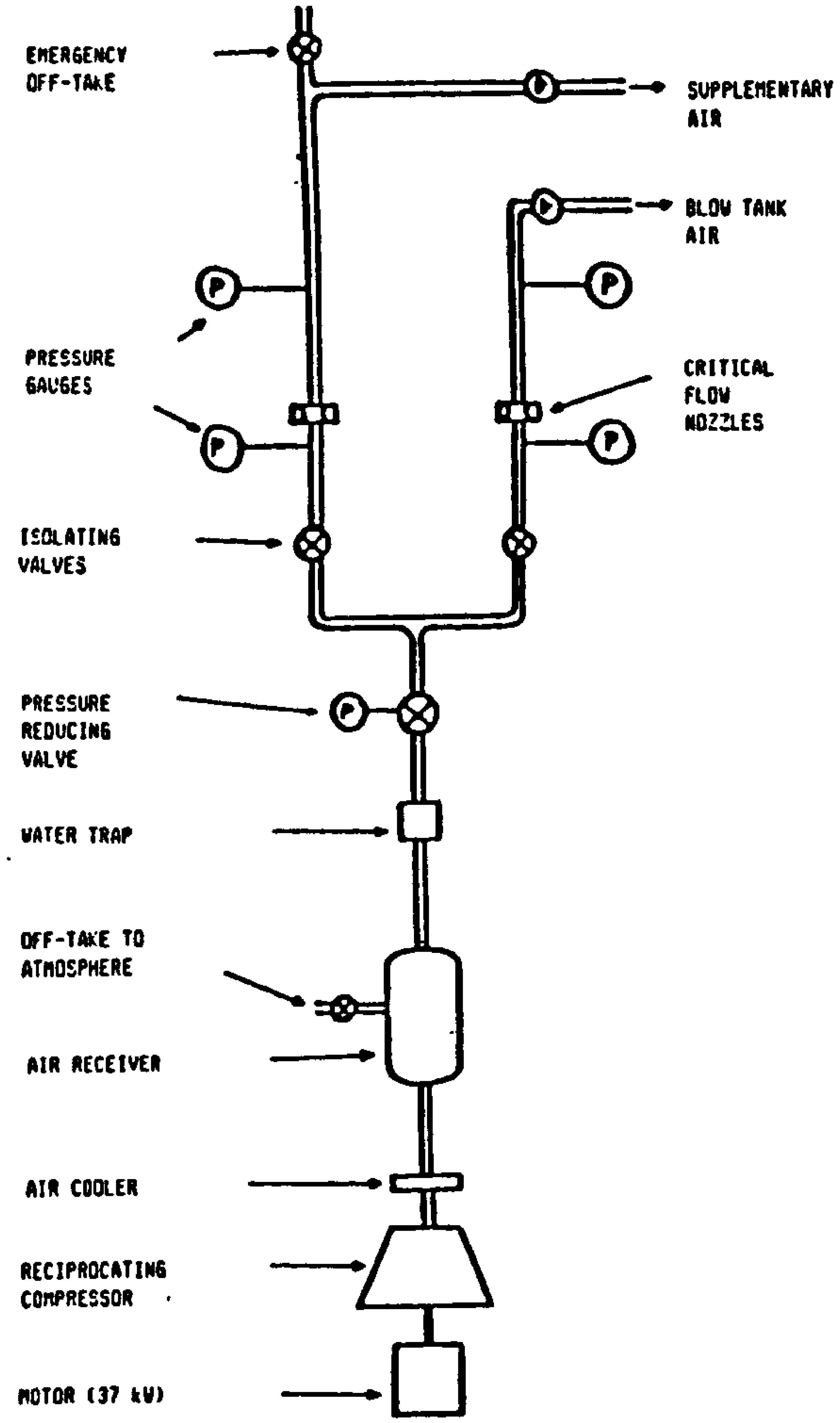


FIG. 2 - CONVEYING PLANT AIR SUPPLY

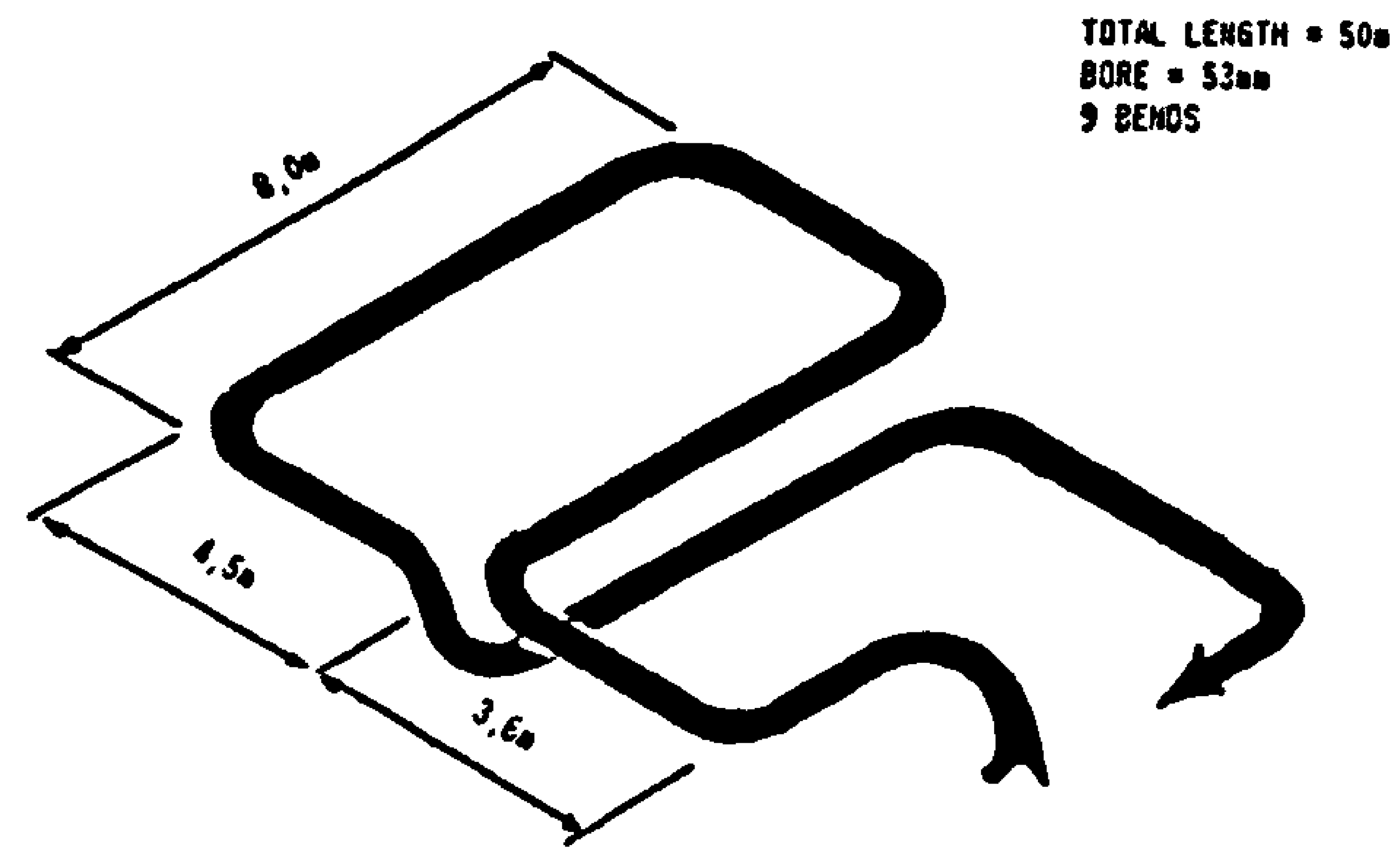


FIG. 3 - CONVEYING PIPELINE LAYOUT

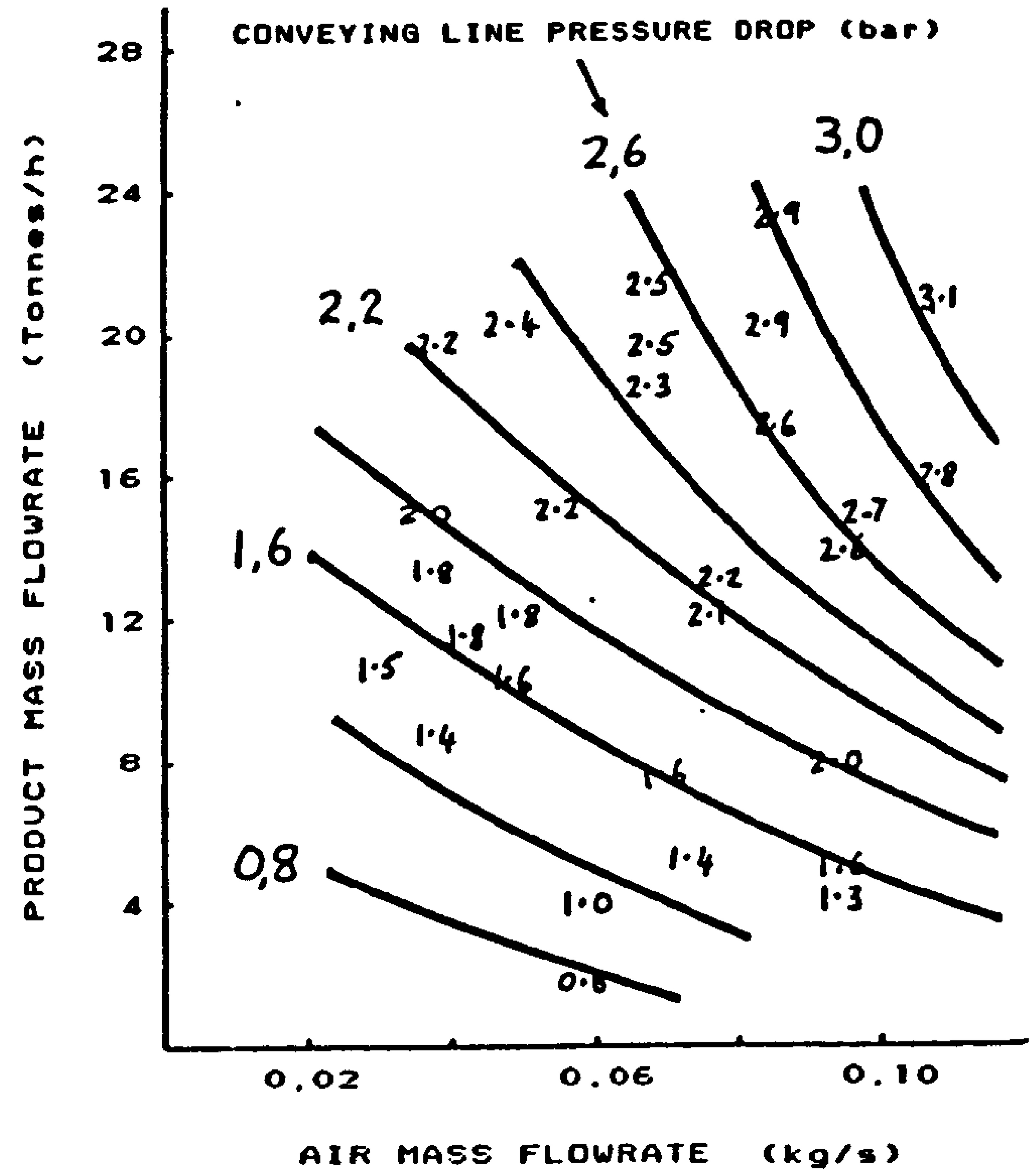


FIG. 4 – CONVEYING DATA FOR IRON POWDER

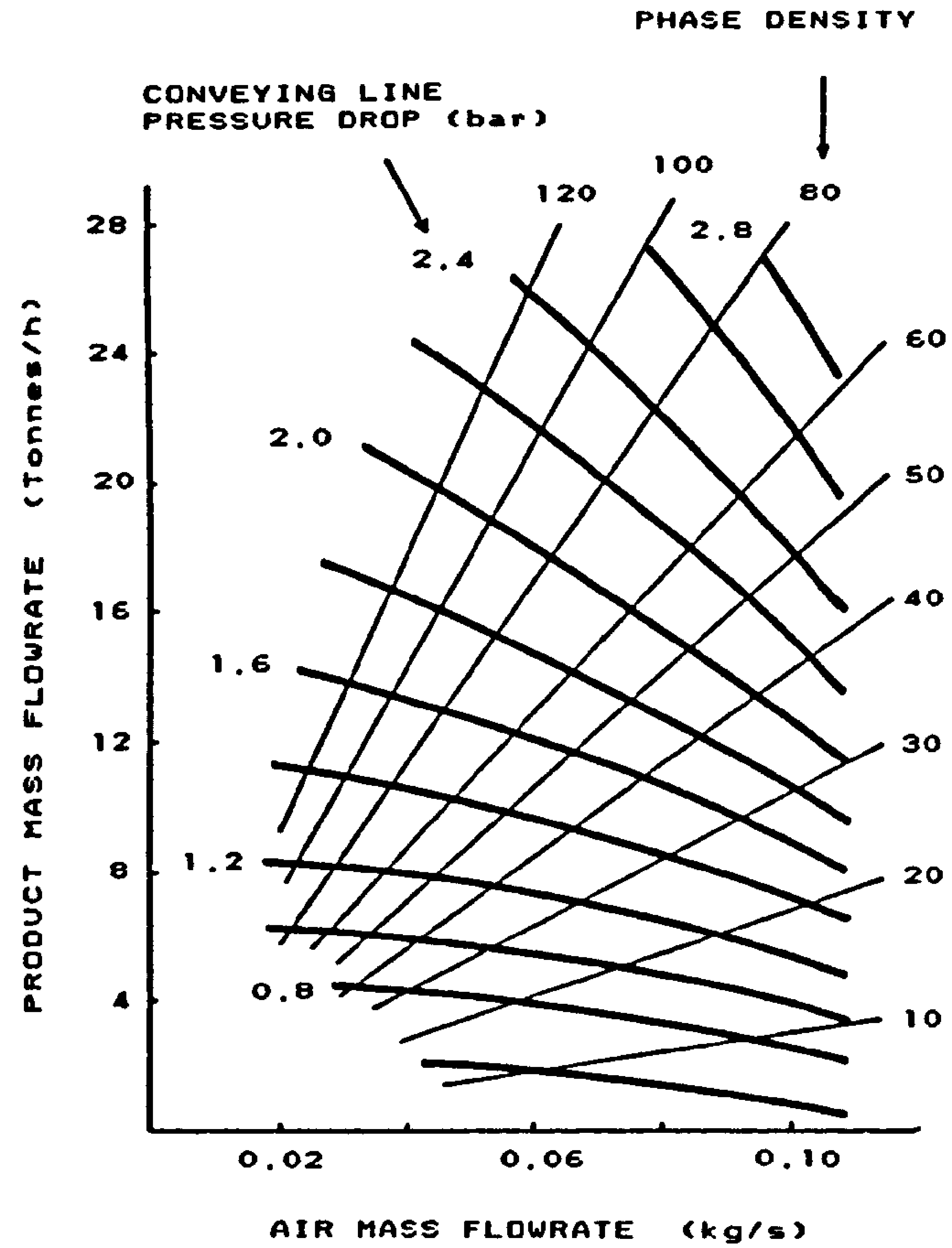


FIG. 5 – CONVEYING CHARACTERISTICS FOR BARYTES

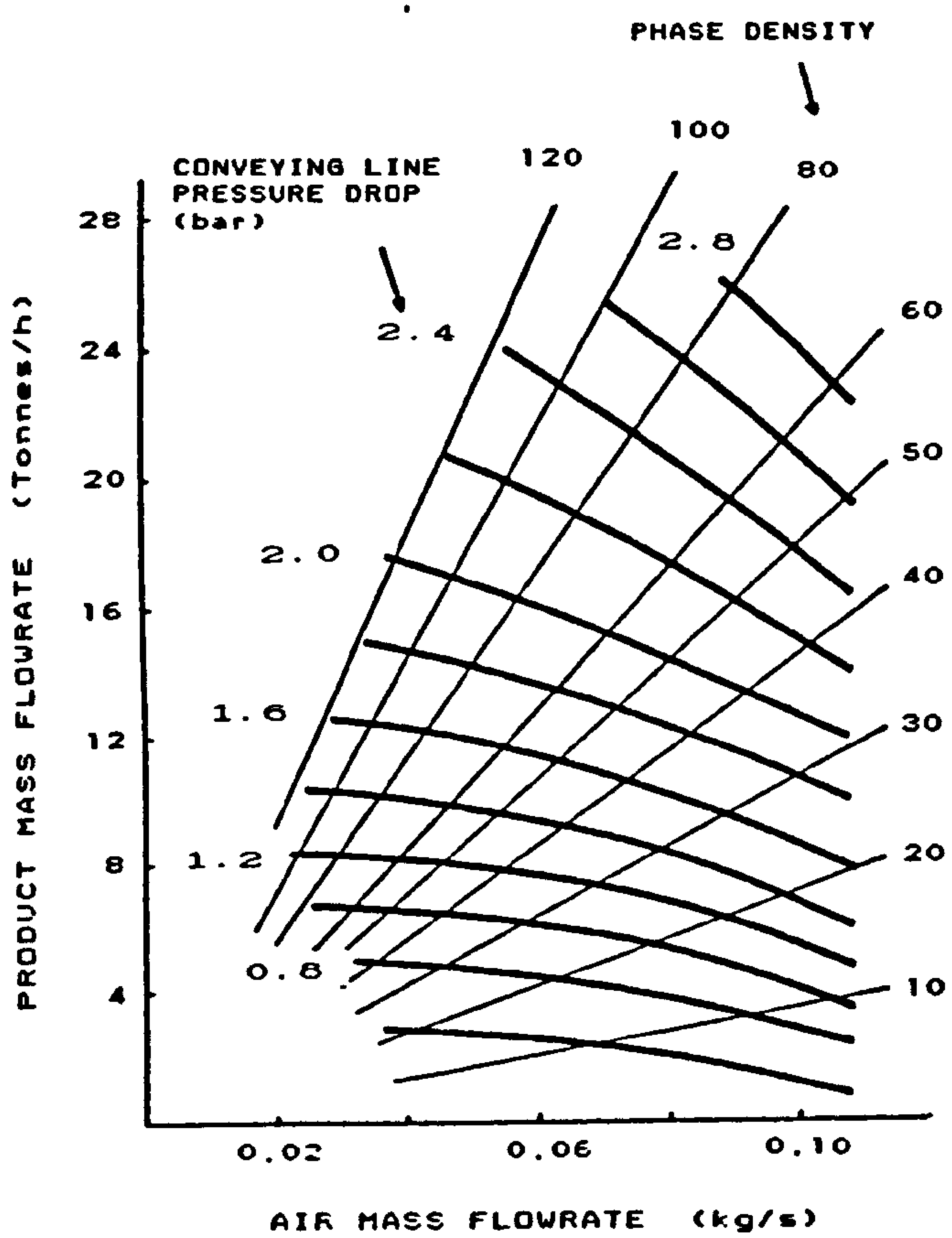


FIG. 6 – CONVEYING CHARACTERISTICS FOR CEMENT

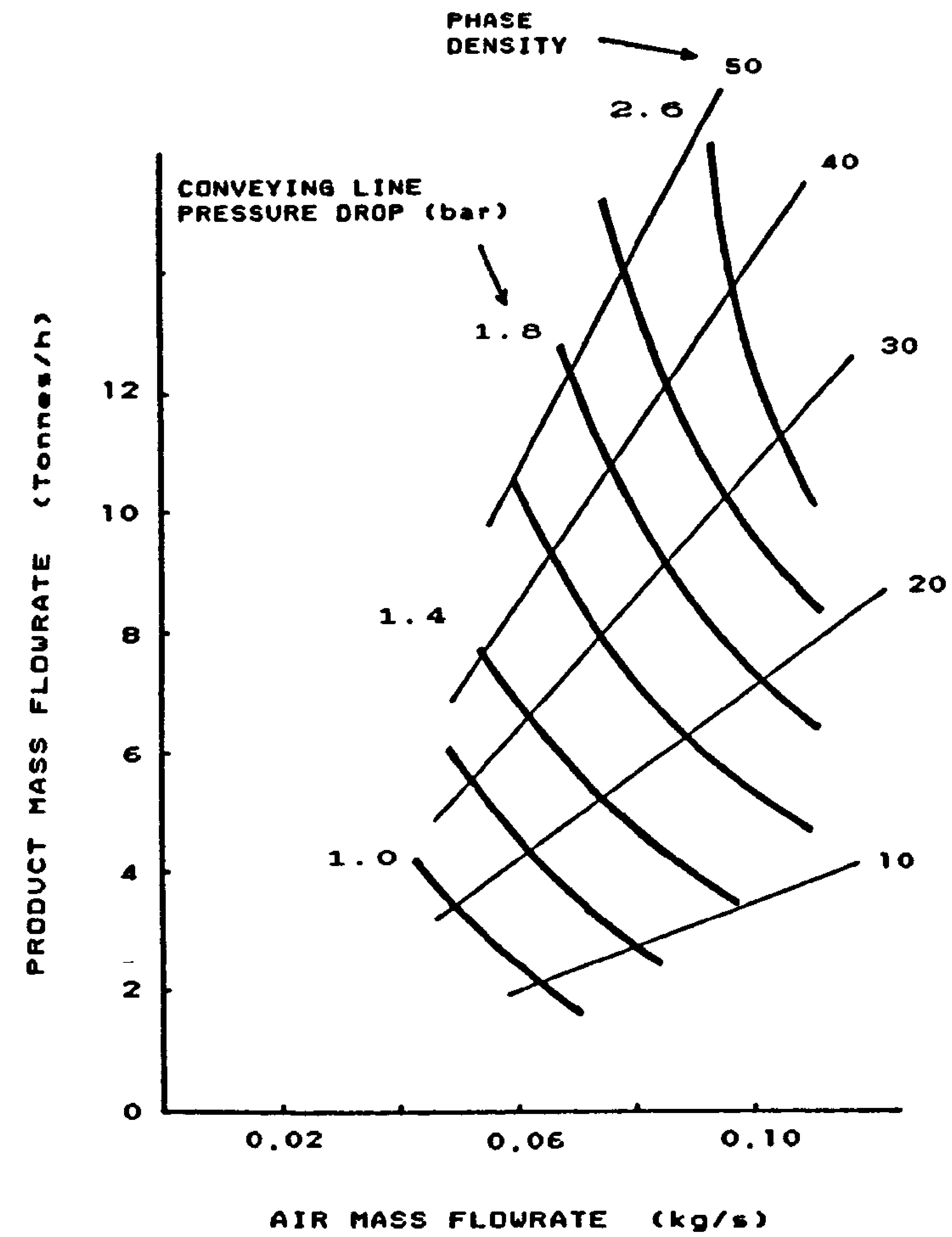


FIG. 7 – CONVEYING CHARACTERISTICS FOR COPPER ORE

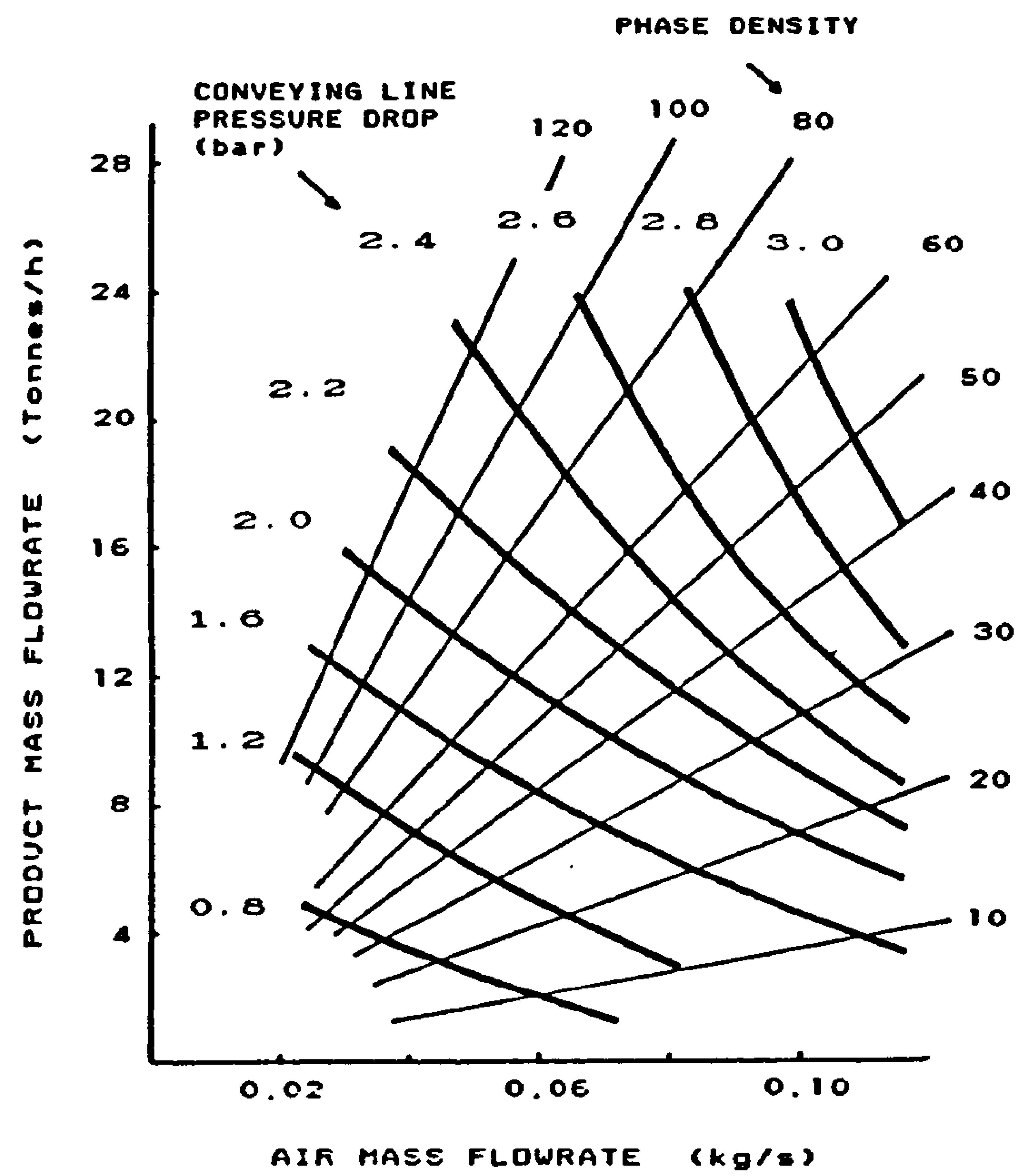


FIG. 8 - CONVEYING CHARACTERISTICS FOR IRON POWDER

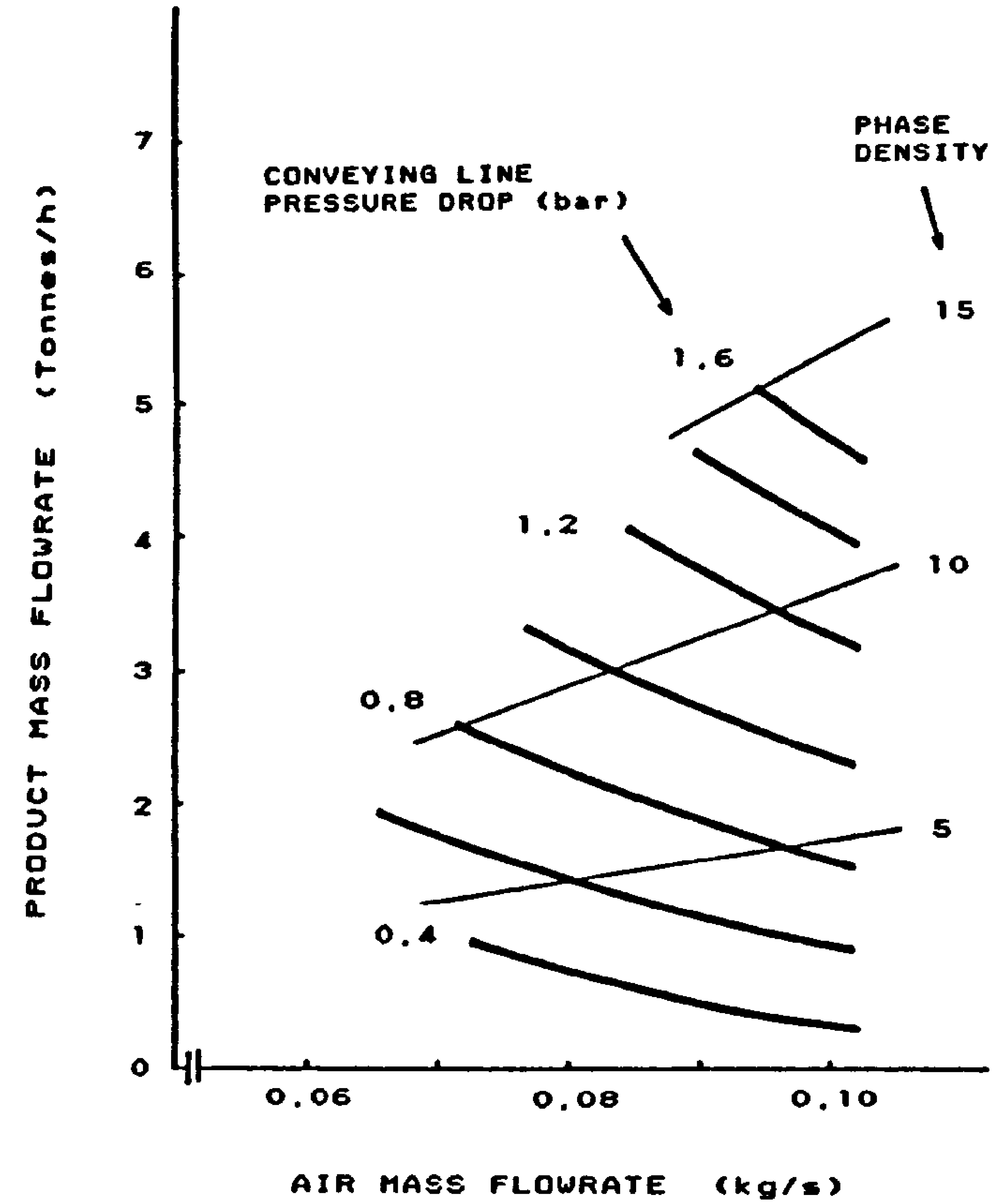


FIG. 9 - CONVEYING CHARACTERISTICS FOR ZIRCO SAND

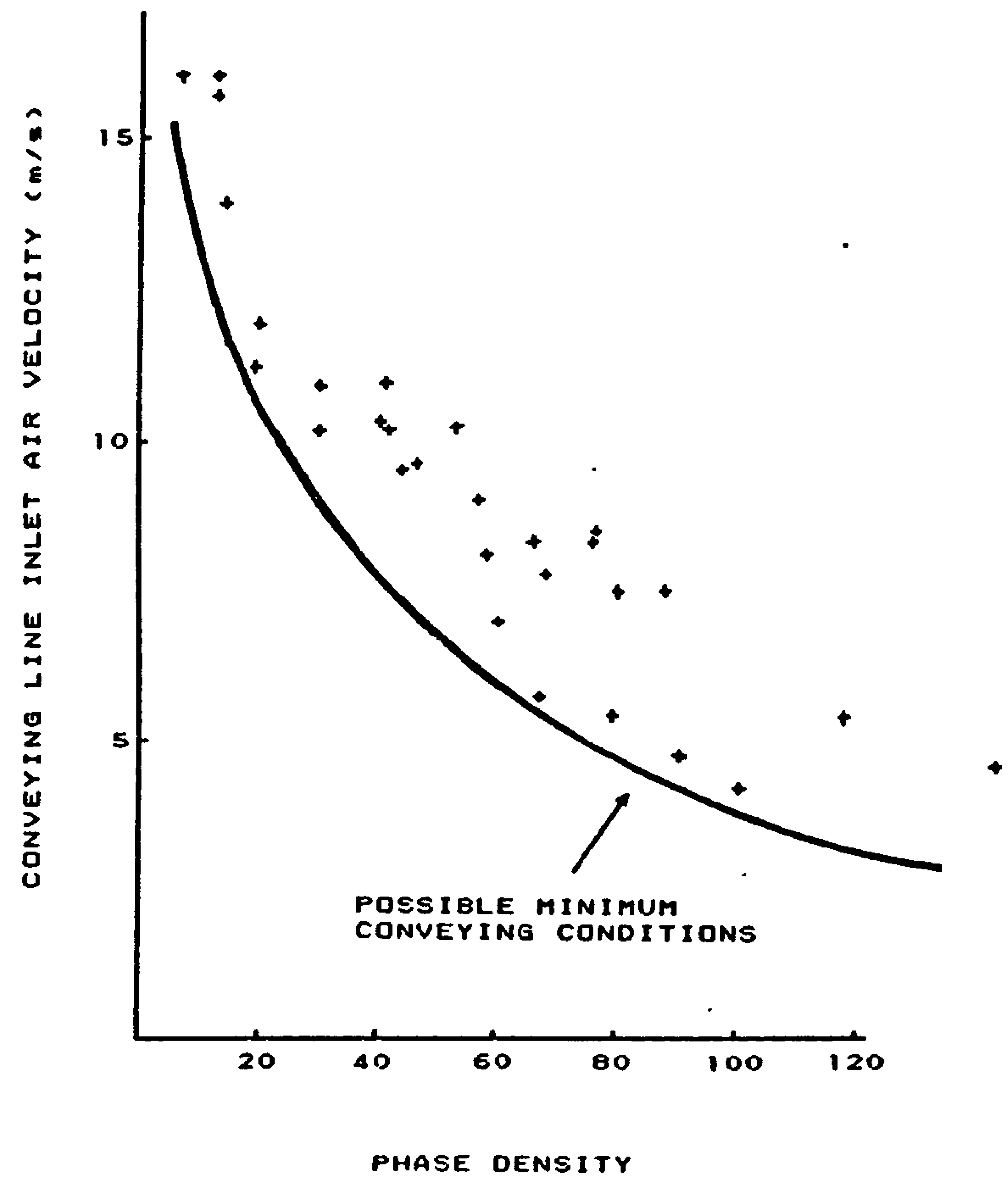


FIG. 10 – PHASE DENSITY v CONVEYING LINE INLET AIR VELOCITY FOR IRON POWDER

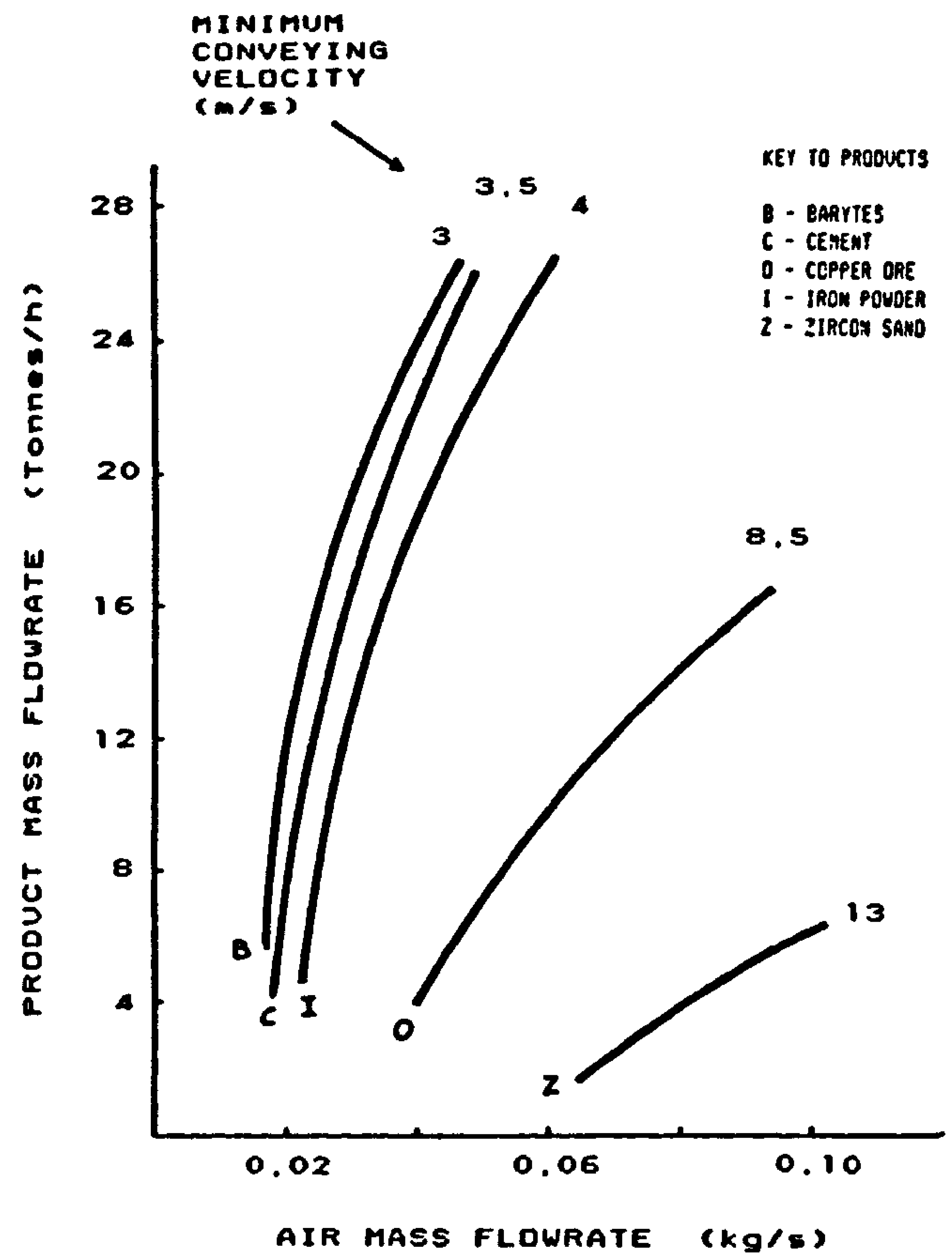


FIG. 11 – COMPARISON OF MINIMUM CONVEYING VELOCITY FOR THE FIVE PRODUCTS

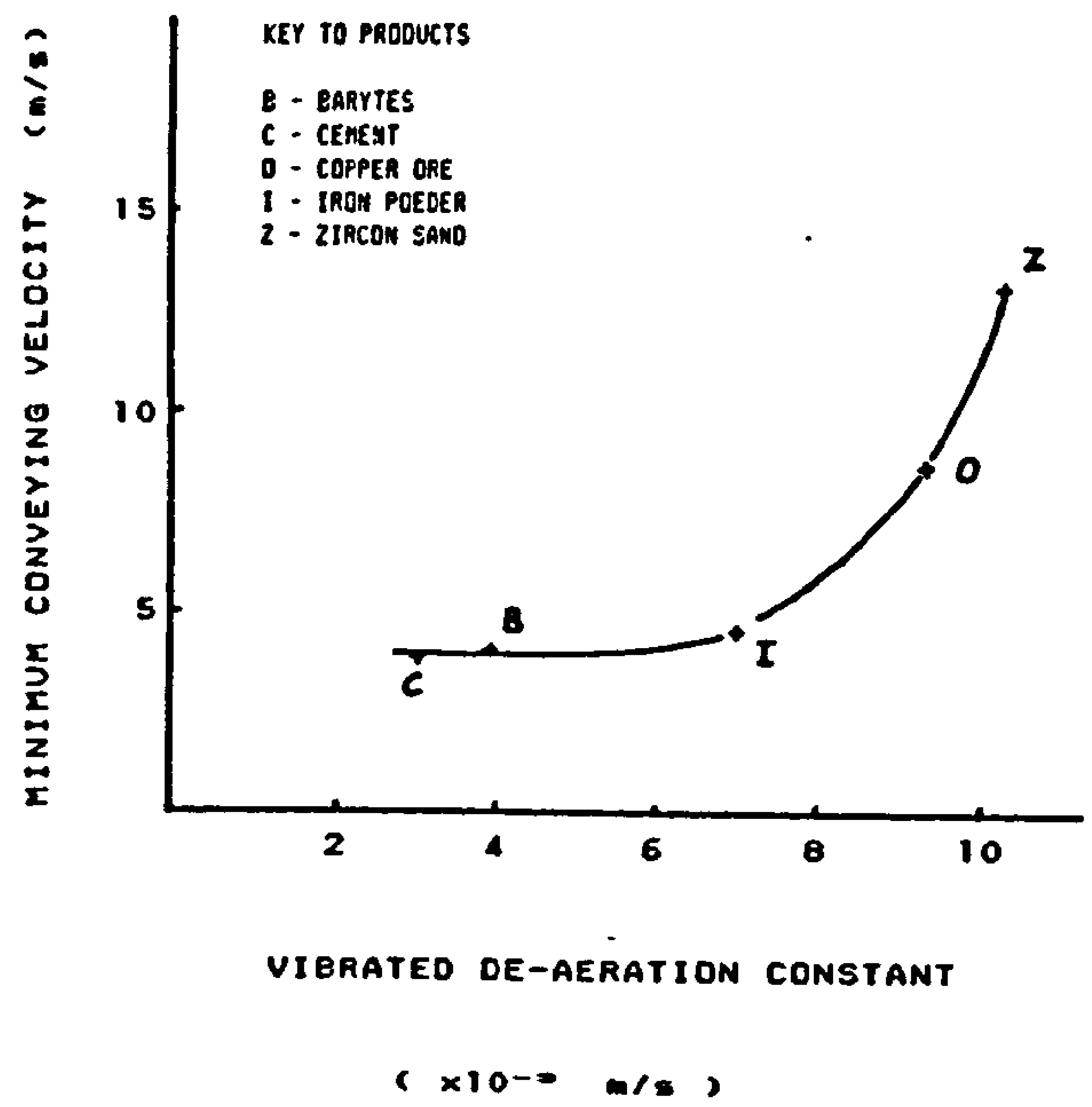


FIG. 12 – THE EFFECT OF VIBRATED DE-AERATION CONSTANT ON MINIMUM CONVEYING VELOCITY

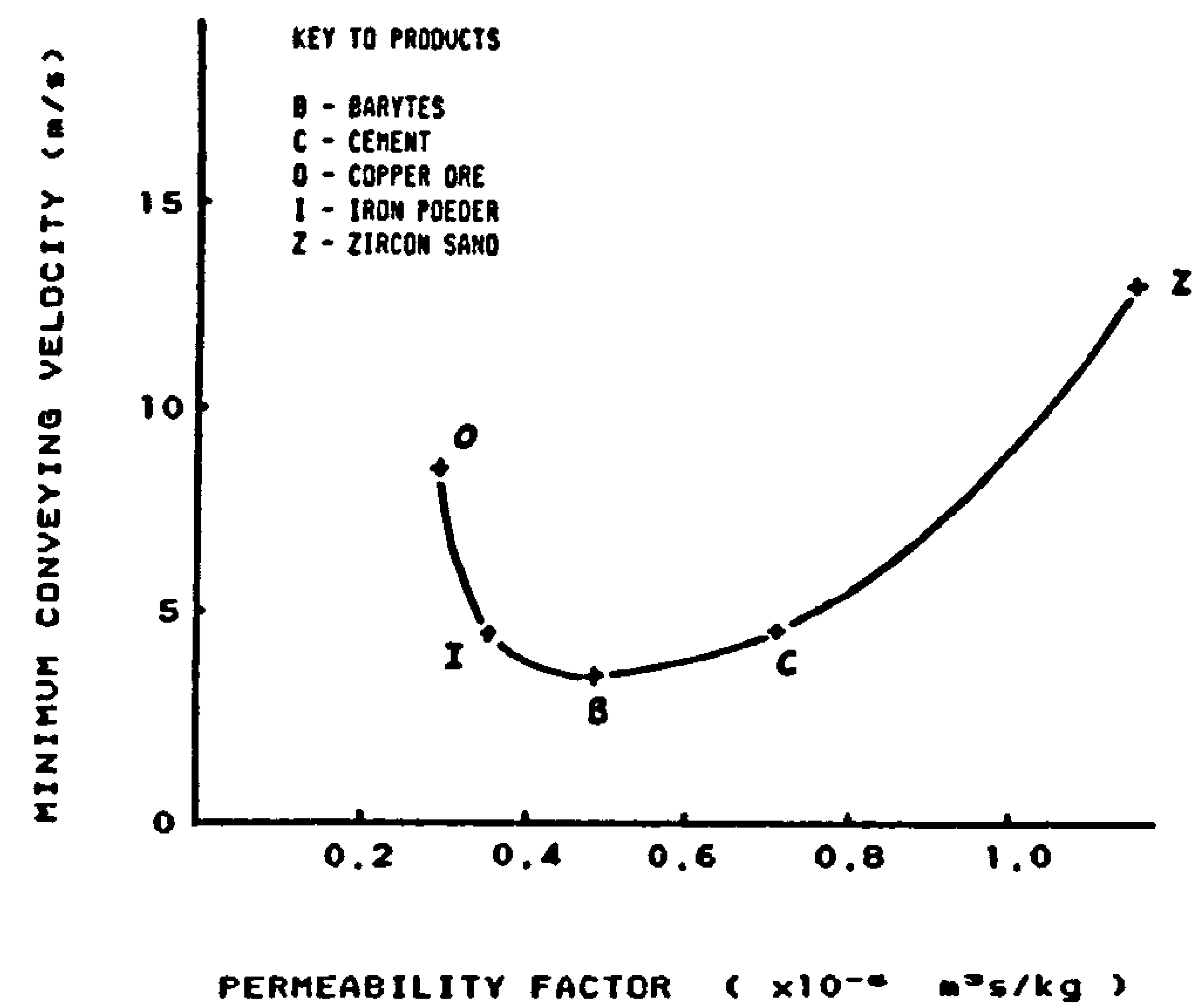


FIG. 13 – THE EFFECT OF PERMEABILITY FACTOR ON MINIMUM CONVEYING VELOCITY

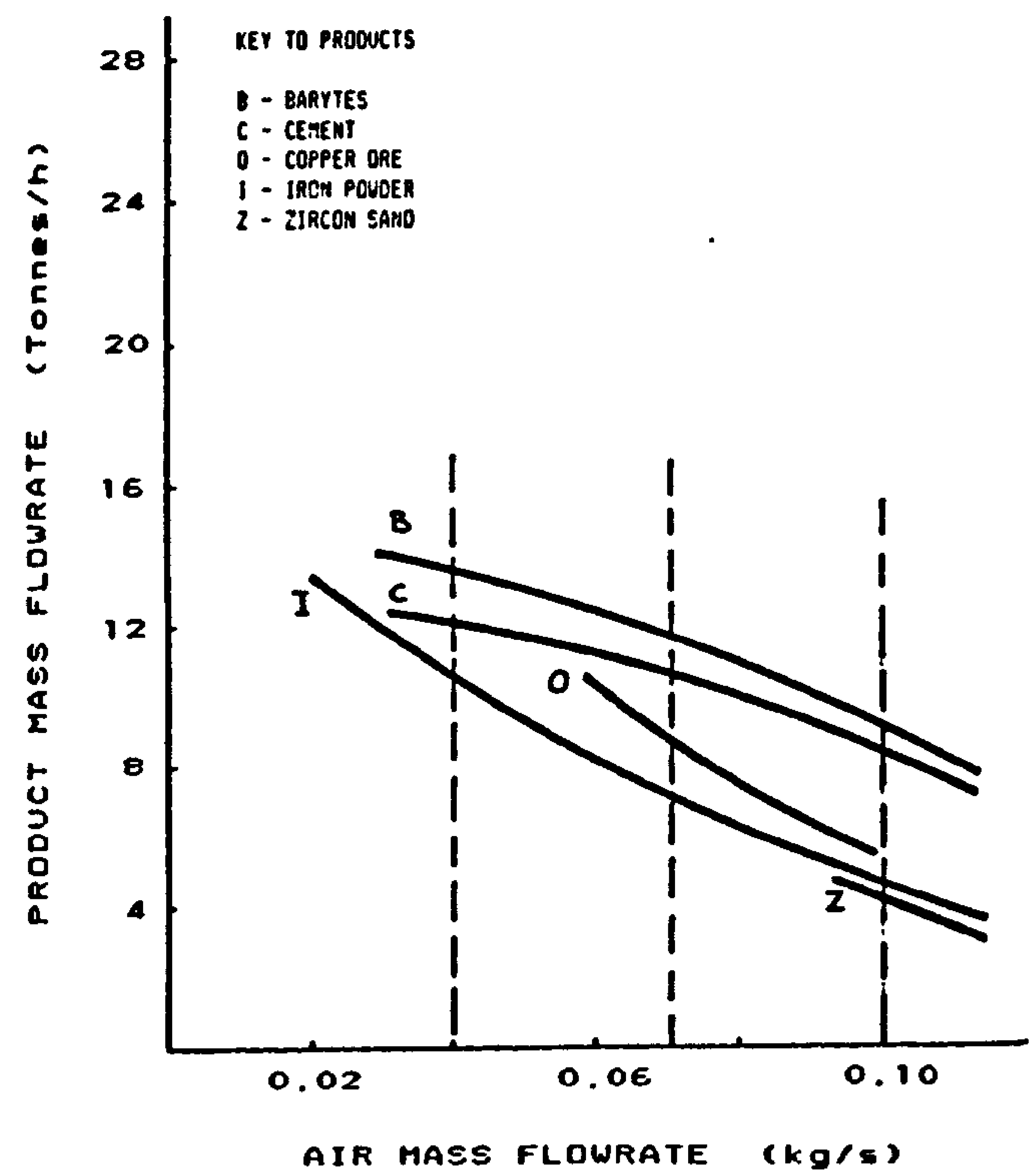


FIG. 14 - COMPARISON OF PRODUCTS

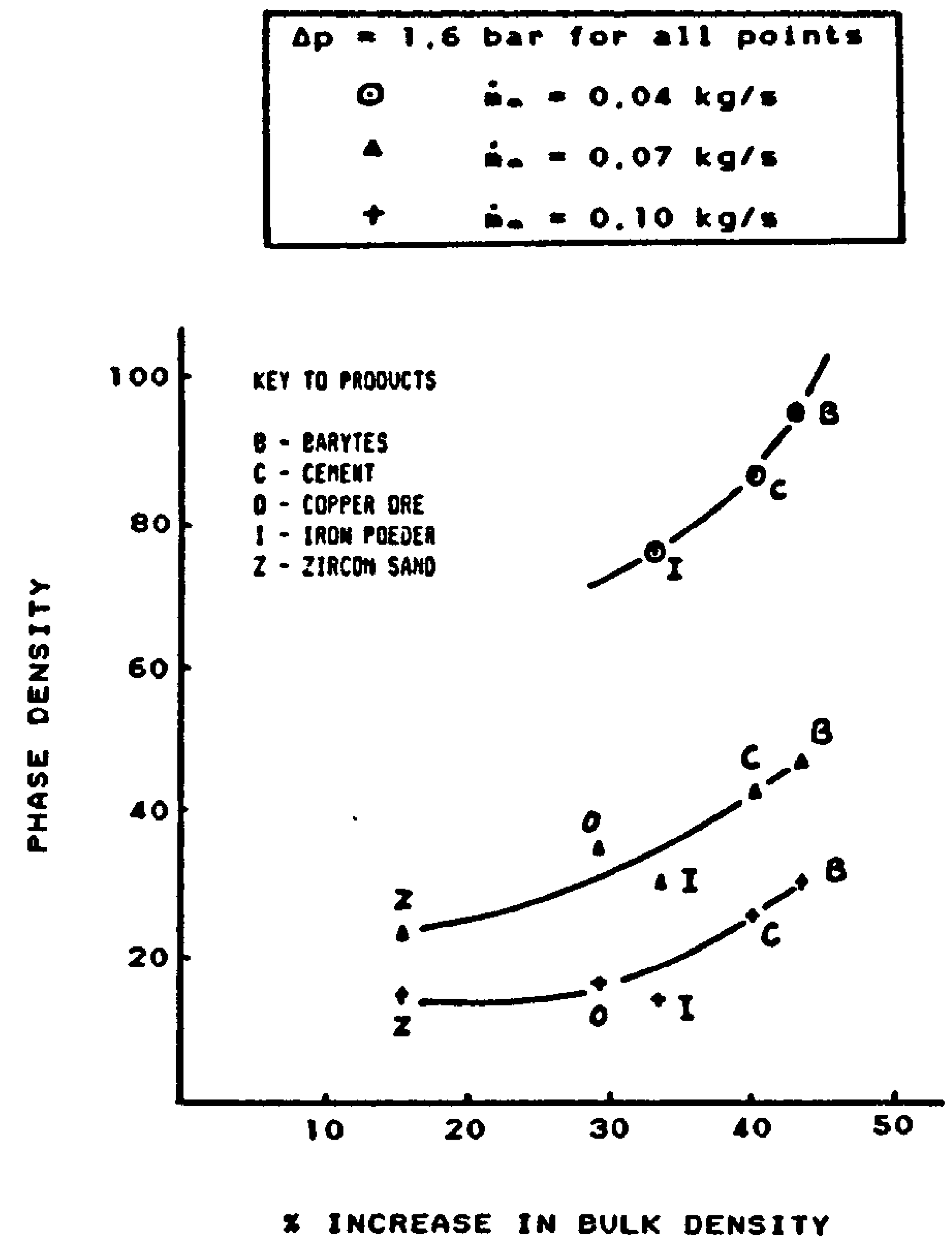


FIG. 15 - THE EFFECT OF DEGREE OF COMPACTION ON PHASE DENSITY

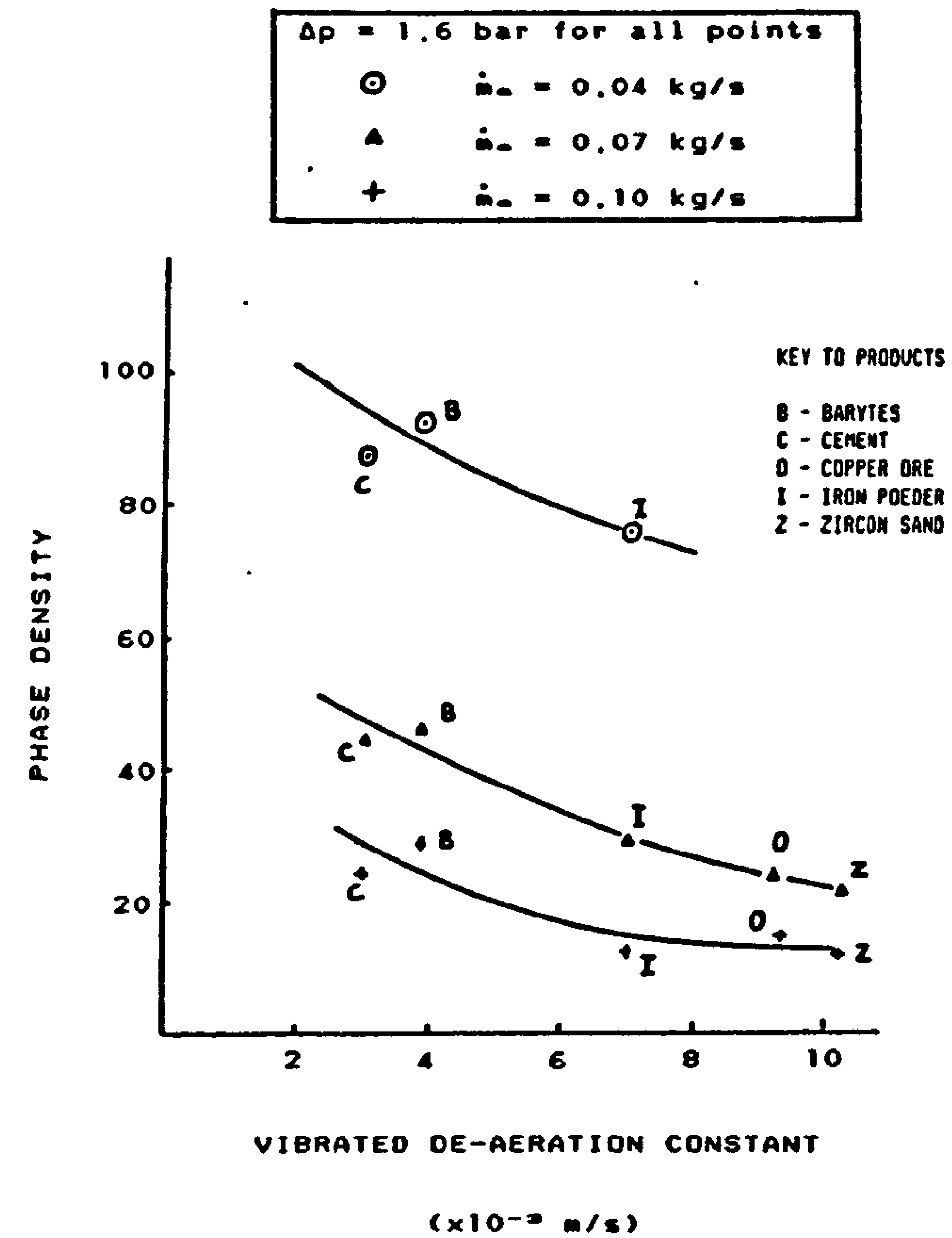


FIG. 16 - THE EFFECT OF VIBRATED DE-AERATION CONSTANT ON PHASE DENSITY

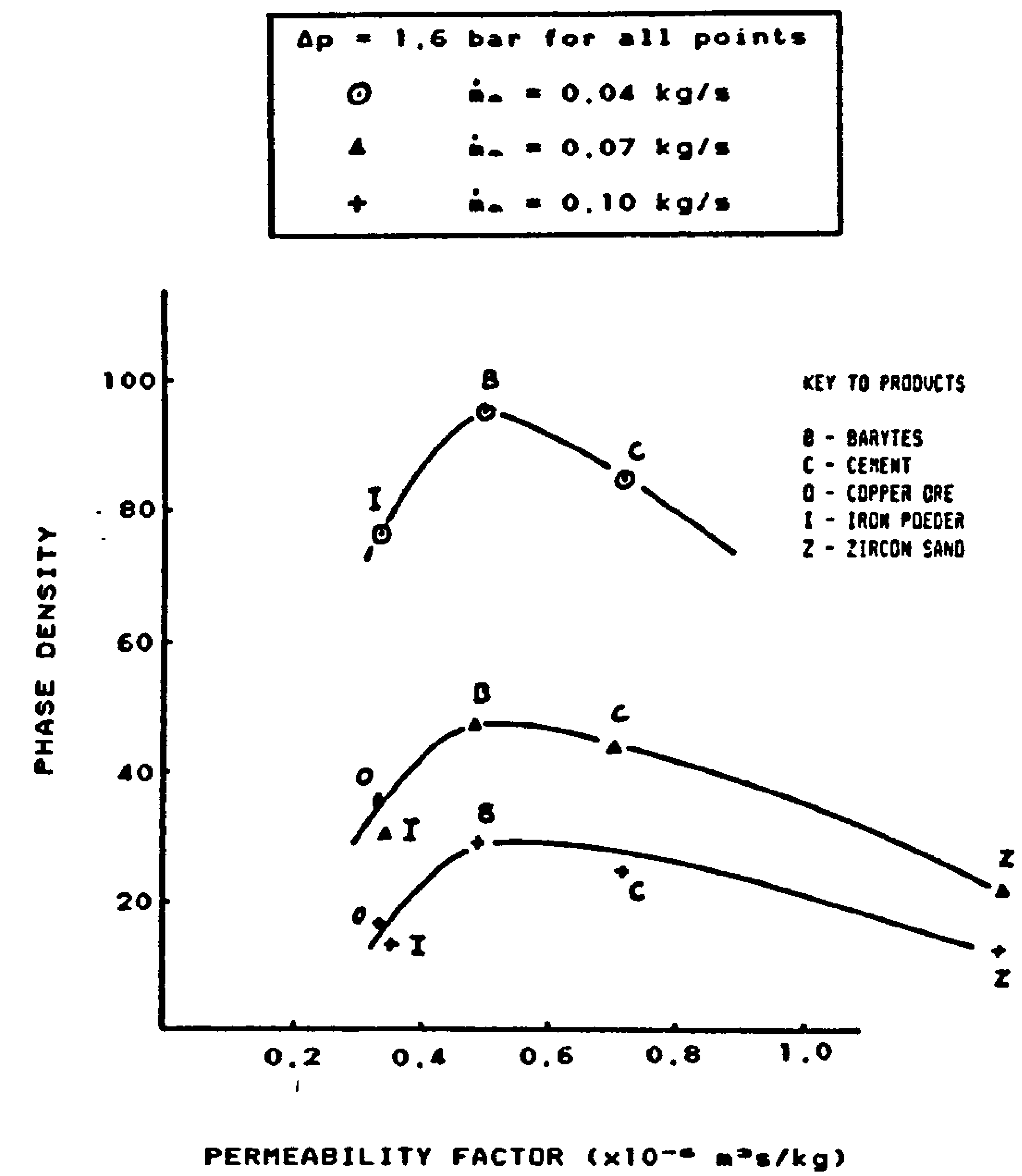


FIG. 17 - THE EFFECT OF PERMEABILITY FACTOR ON PHASE DENSITY

THE SELECTION OF BLOW TANK FEEDING ARRANGEMENT FOR PNEUMATIC CONVEYING

by

M G JONES, D MILLS AND J S MASON
Thames Polytechnic
London,
UK

SUMMARY

Blow tank systems are widely used in industry for the pneumatic conveying of bulk materials. This is because of the ease of control and the fact that, as there are no moving parts, erosion and degradation are minimised. Both top and bottom discharge configurations are used in industry but the choice of configuration is largely based on convenience rather than the merits of configuration performance. To date, very little information has been published regarding comparisons of blow tank performance in the top and bottom discharge modes. The work reported in this paper presents a direct comparison between top and bottom discharge performance in terms of feeding capability for given constant conditions. The work was carried out on a pilot scale facility using a blow tank that could be arranged in both top and bottom discharge configuration with minimum changes in pipeline geometry. Blow tank charactristics are presented for various materials in both top and bottom discharge modes.

THE CONVEYING PLANT

The conveying plant used was basically a batch type system with the product being discharged from the blow tank and conveyed through the pipeline into a receiving hopper. The product was then dropped through double valves back into the blow tank for recirculation. A diagrammatic layout of the conveying plant and pipeline is shown in Figs. 1 to 3. Fig. 4 shows the arrangement of the blow tank in both top and bottom discharge modes.

Top Discharge Blow Tank Arrangement

The supply air to the blow tank entered through a plenum chamber under the fluidising membrane. This both fluidised the poduct and pressurised the blow tank. The supplementary air entered the system via a swept 'T' in the discharge pipe as close as possible to the top of the blow tank. There was no valve in the discharge line in this configuration.

Bottom Discharge Blow Tank Arrangement

The top discharge blow tank was transformed into a bottom discharge blow tank by producing a fabrication that could be bolted directly on to the bottom flange of the blow tank replacing the fluidisation membrane and plenum chamber. The discharge pipe used in the top discharge mode was blocked off. The supply air to the blow tank enters the tank via a fluidising annulus. A discharge valve at the base of the blow tank allows the blow tank to be pressurised or part pressurised before conveying began. Since a discharge valve was not available for the blow tank in the top discharge mode, this discharge valve was not used in bottom discharge operation. The supplementary air entered the pipeline just downstream of the discharge valve.

In general, the conveying line geometry was the same for both top and bottom discharge. Slight differences occur due to the position of the discharge pipes for top and bottom discharge modes. These differences are shown in Fig. 4.

THE AIR SUPPLY

Three compressors were available each capable of 0.095 m^3/s (202 ft^3/min) of 'free air' at a pressure of 6.9 bar (100 lbs/sq. in.) gauge. A diagrammatic layout of the air supply from the compressors to the conveying plant is shown in Fig. 2. For this work, only one compressor was required since a 53 mm bore pipeline was used and this represents a free air velocity of 42 m/s. Part of the air was directed to the blow tank and the rest was directed to the supplementary air line. The control of the air supply was by use of a pressure reducing valve to control the upstream pressure and critical flow nozzles placed in the two air supply lines.

INSTRUMENTATION

Five variables were measured. These were both air mass flowrates, product mass flowrate, pipeline pressure drop and blow tank pressure. The air mass flowrates were measured by using critical flow nozzles. The advantage of using this device is that since it relies on the air flow being choked (i.e. the velocity at the throat is sonic), then for a fixed upstream pressure the air mass flowrate is constant over a wide range of downstream pressures and the effects of pulsations are avoided. The control of the air mass flowrate through a particular nozzle was achieved by altering the upstream pressure. Operation with pressure ratios of up to 0.9 is possible with good convergent-divergent nozzles. The nozzles were positioned in the air supply lines to the blow tank and the conveying line as shown in Fig. 2. The total air mass flowrate for conveying the product through the pipeline is the sum of the blow tank and supplementary air mass flowrates.

The air supply pressure was measured immediately before the product pick-up point in the supplementary air supply line and was recorded. With the discharge being into the receiving hopper at atmospheric pressure, the conveying line pressure drop was obtained. The blow tank pressure was measured directly.

PRODUCTS TESTED

Three products have been used covering a range of poduct types. Most of the work concentrates on the pulverised fuel ash (PFA) because it can be conveyed over a wide range of conveying conditions with ease. It can be conveyed at velocities as low as 3 to 4 m/s and at phase densities in excess of 100.

The other products tested were polyethylene pellets and a fine sand. These products exhibit quite different characteristics to the PFA. Polyethylene pellets are a nearly mono-sized granular product which is capable of being conveyed at lower velocities and sand is a product with no dense phase capability in a conventional system and is therefore limited to suspension flow. The salient features of the three products are given below.

PRODUCT	MEDIAN PARTICLE SIZE m	PARTICLE DENSITY (mean) kg/m	BULK DENSITY (As Poured) kg/m
PFA	42	2446	979
Pellets	4000	960	570
Sand	70	2700	1250

EXPERIMENTAL TECHNIQUES

The only control over the blow tank, and hence the conveying line was achieved by controlling the total air mass flowrate and the proportion of the total air mass flowrate going to the blow tank. the proportion of air to the blow tank is known as the 'Blow Tank Air Ratio' (BTAR). The BTAR was controlled by the appropriate selection of critical flow nozzles for use in the air lines to the blow tank and conveying line.

To start conveying, the BTAR and the total air mass flowrate were set. The blow tank vent line (Fig. 1) was then closed and the blow tank began to pressurise. Since the discharge valve was not used when conveying in the bottom discharge configuration, the procedures used for the top and bottom discharge conveying trials were identical. When steady state conditions were reached the pressures and product mass flowrate were recorded over a reasonable time period, typically 2 to 3 minutes. The data recorded on one pass provides a single point on the conveying characteristics and on the blow tank characteristics. The data from 30 to 40 runs for each configuration was plotted on graphs of product mass flowrate against total air mass flowrate as shown in Figs. 5 and 6. Lines of constant BTAR and constant conveying line pressure drop could then be drawn on the respective graphs, as shown.

CONVEYING LIMITATIONS

Tests were carried out over as wide a range of conveying conditions as could be achieved with the product and the plant. Maximum air flow rates were dictated by the capability of the air mover, but with conveying velocities of up to 42 m/s, the normal range of operation is adequately covered. Maximum product flow rates are set when 100% of the air is directed to the blow tank, as shown in Fig. 6. The minimum value of air flow rate, or conveying velocity, is dependent upon the capability of the product. In the case of PFA it is clearly capable of being conveyed in dense phase, with values of phase density up to about 120.

In Fig. 7 the data from the top discharge tests is presented on a plot of conveying line inlet air velocity against phase density. A line drawn below the data represents the probable minimum conveying air velocity relationship for the product. Conveying line pressure drop depends upon the pipeline length, phase density and the product flow rate and so is limited by other parameters than feeding capability.

ANALYSIS OF EXPERIMENTAL RESULTS

The experimental data obtained can best be illustrated on four graphs. These graphs are presented in Figs. 8 to 11 and show the conveying pipeline characteristics and the blow tank characteristics for the PFA in both top and bottom discharge modes. Initially it is useful to look at the general conveying characteristics in both top and bottom discharge configurations.

The conveying characteristics for both top and bottom discharge modes are shown in Figs. 8 and 9. It is noticeable immediately that in top discharge the conveying characteristics cover a greater range of conveying conditions than in bottom discharge configuration. This is particularly the case in the low air mass flowrate - high product flowrate area of the characteristics. However, if the two sets of characteristics are superimposed it can be seen that the characteristics for the bottom discharge mode are the same as those for the top discharge configuration but with the boundaries restricted. This is not surprising since the shape of the constant pressure lines on the pipeline conveying characteristics should be independent of the type of feeding device. However, the boundaries to the characteristics may well be determined by the feeding device if the device cannot feed at the maximum rate that the pipeline can accommodate.

To compare the feeding capability of the blow tank in top and bottom discharge configurations it is necessary to compare the two sets of blow tank characteristics. Figs. 10 and 11 show the blow tank characteristics for the two configurations. The curves represent lines of constant BTAR. These two graphs show clearly that the blow tank characteristics for top and bottom discharge configurations are quite different. A much higher discharge rate is clearly achieved with the top discharge arrangement than with the bottom discharge configuration. A graph showing a comparison of the performance of top and bottom discharge modes is shown in Fig. 12. This shows the 50% and 100% BTAR lines for top and bottom discharge configurations. If one considers an air mass flowrate of 0.10 kg/s and compares the discharge rate in top and bottom discharge modes for a BTAR of 100% then the rate for bottom discharge is 11 tonnes/h and for top discharge is 24 tonnes/h. This represents a ratio of 2.2:1 in discharge rates. If a BTAR of 50% is considered for the same conditions the ratio is 2:1. It is obvious from both the conveying and blow tank characteristics that for dense phase operation, the choice of blow tank configuration could be critical. If the bottom discharge blow tank had been selected to feed the pipeline used for this test work in an operational situation the blow tank would not be able to achieve a discharge rate that would be compatible with the optimum performance of the pipeline.

The conveying characteristics for Rigidex (polyethylene pellets) and sand are shown in Figs. 13 and 14. In both cases, the shape of the constant pressure characteristics were the same for top and bottom discharge modes. However, unlike the PFA, the conveying boundaries remained the same for both configurations. Figs. 15 to 18 show the blow tank characteristics for the two products in both top and bottom discharge modes. It can be seen that while there is some difference between the two sets of characteristics for the sand the difference between the two sets of characteristics for the Rigidex is minimal.

DISCUSSION

The question now arises as to why there is such a variation in blow tank discharge rates for the two different configurations. The problem is that there are too many unknowns in the problem at present. An extensive programme of experimental work would need to be undertaken and is outside the scope of this paper. However there are a few points that can be discussed.

The physical properties of the product being conveyed will influence the discharge rate. Jones, et al (Ref. 1) have reported that for products that will convey in dense phase the discharge rate increases as the air retention properties increase and the air permeability decreases. Waghorn and Mason (Ref. 2) report that for a given product, the discharge rate can be increased by fluidising the product. Both of these papers refer to top discharge blow tank configurations. Since the fundamental concepts of pneumatic conveying lie with the air/product interaction, and the fluidisation of products is shown to affect discharge rates, perhaps one should consider the introduction of air to the blow tank in both configurations.

If one considers the top discharge blow tank (Fig. 4) the design of the blow tank is conventional. It is extremely common for the air to enter the blow tank through a fluidising membrane. The vertical position of the discharge pipe relative to the fluidising membrane is critical. Waghorn and Mason (Ref. 2) found the optimum position to be about 40 mm above the membrane. Introduction of the air to a top discharge blow tank at any other position is most uncommon.

If one considers the top discharge blow tank (Fig. 4) the design of the blow tank is conventional. It is extremely common for the air to enter the blow tank through a fluidising membrane. The vertical position of the discharge pipe relative to the fluidising membrane is critical. Waghorn and Mason (Ref. 2) found the optimum position to be about 40 mm above the membrane. Introduction of the air to a top discharge blow tank at any other position is most uncommon.

If one considers the introduction of air to the bottom discharge blow tank configuration there is scope for variation. The design used for this test work is fairly common with the air being introduced via a fluidising annulus. Mainwaring (Ref. 3) carried out some tests on varying the position of introduction of the air to a bottom discharge blow tank. He introduced the air in three different positions; directly into the top of the blow tank using a diffuser plate, through a fluidising ring similar in position to the fluidising annulus and a blow-through arrangement at the bottom of the blow tank. The result of these tests showed no significant difference in discharge rates with change in position of air introduction. This implies that the fluidising ring was not very effective at fluidising the product in the blow tank.

Although the fluidising annulus, used for this test work, is a different design to the fluidising ring, used by Mainwaring it is unlikely that it would be significantly better although there is no hard evidence one way or the other. The question remains as to the effectiveness of fluidising the product using an annulus compared with using a membrane. The answer is unclear but it is probable that the fluidising membrane is significantly more effective. This may be partly responsible for the higher discharge rates experienced with the top discharge configuration.

The obvious next stage would be to fit the bottom discharge blow tank with a fluidising cone in the lower region funneling the product towards the discharge point and into the pipeline. This should have the effect of improving the fluidisation of the product in the bottom discharge configuration. If a significant increase in discharge rates is achieved then it would be reasonable to assume that effective fluidisation improves blow tank performance.

Other products have been tested in both top and bottom discharge configurations. In particular Rigidex (polyethylene pellets) and fine sand. The fine sand is a product which exhibits average air retention properties and average air permeability properties. From the work in Ref. 4 it was shown that products in this category are unlikely to be candidates for dense phase conveying. This is confirmed by the apparent reluctance for the sane to be conveyed below around 15 m/s. Therefore, the limitation imposed on the conveying characteristics for sand shown in Fig. 13 is a pipeline imposed limitation and not a limit imposed by the blow tank. If one compares the blow tank characteristics for sand in both top and bottom discharge modes (Figs. 15 and 16) it can be seen that a much lower BTAR is required in the top discharge configuration to achieve the same product throughput than is required in the bottom discharge mode.

The polyethylene pellets are relatively large mono-sized particles and hence have virtually no air retentive properties at all. The product is also extremely permeable to air. If the superior performance of the top discharge configuration is due to effective fluidisation, then the performance of the two configurations with polyethylene pellets would be expected to be the same. Figs. 17 and 18 confirm this. The blow tank characteristics for polyethylene pellets in both configurations are essentially the same.

CONCLUSIONS

The blow tank characteristics for the top and bottom discharge configuration for a product exhibiting good aeration properties show a marked difference in discharge rate for the same fixed BTAR and air mass flowrate. This is significant since a product displaying good aeration properties is a likely candidate for dense phase conveying.

The most likely reason for the variation in discharge rates in top and bottom discharge configurations is probably due to the lack of effective fluidisation in the bottom discharge mode. However, there is little experimental evidence to support this conclusion at present, although it is known that progressive fluidisation in a top discharge blow tank configuration enhances the discharge rate. A further extensive programme of work would be necessary to prove or disprove this hypothesis.

The significance of the variation in discharge rates for the two configurations becomes apparent when designing a system. Products that are likely to be conveyed in dense phase are the very products that show a significant difference in discharge rate in conventional top and bottom discharge blow tank configurations. This means that it is possible to design a system using a bottom discharge blow tank that is not capable of conveying at the intended rate due to the limitations imposed by the blow tank.

Although the bottom discharge blow tank severely restricts the feeding capability of the pipeline, little difference was observed in the product conveying characteristics. Thus, apart from the conveying limit imposed, there is no significant difference in the pressure, and hence energy, required to convey a product through a pipeline at a given product flow rate and phase density, whether the pipeline is fed by a bottom or top discharge blow tank.

It is probable that if the product could be fluidised as effectively in the bottom discharge configuration as it appears to be in the top discharge mode, then the throughput for given conditions may be little different. However, there are inherent differences in the designs which have not been explored in this paper but which may have a more subtle effect on performance.

REFERENCES

1. Jones M G, Mills D and Mason J S : 'The Influence of product Type on Blow Tank Pipeline Feeding Characteristics'. Int. Powder and Bulk Solids Handling and Processing Conf., Chicago, May 1986.

2. Waghorn D J and Mason J S : 'The Effect of Aeration and Position of Inlet to Conveying Line on the Discharge Characteristics of a Blow Tank'. Bulk Solids, Storage, Handling and Flow Conf., Nov. 1976, Stratford Upon Avon, Powder Advisory Centre.

3. Mainwaring N - Personal communication.

4. Jones M G, Mills D and Mason J S : 'Pneumatic Conveying of High Bulk Density Products'. Pneumatech 3, Jersey, March 1987.

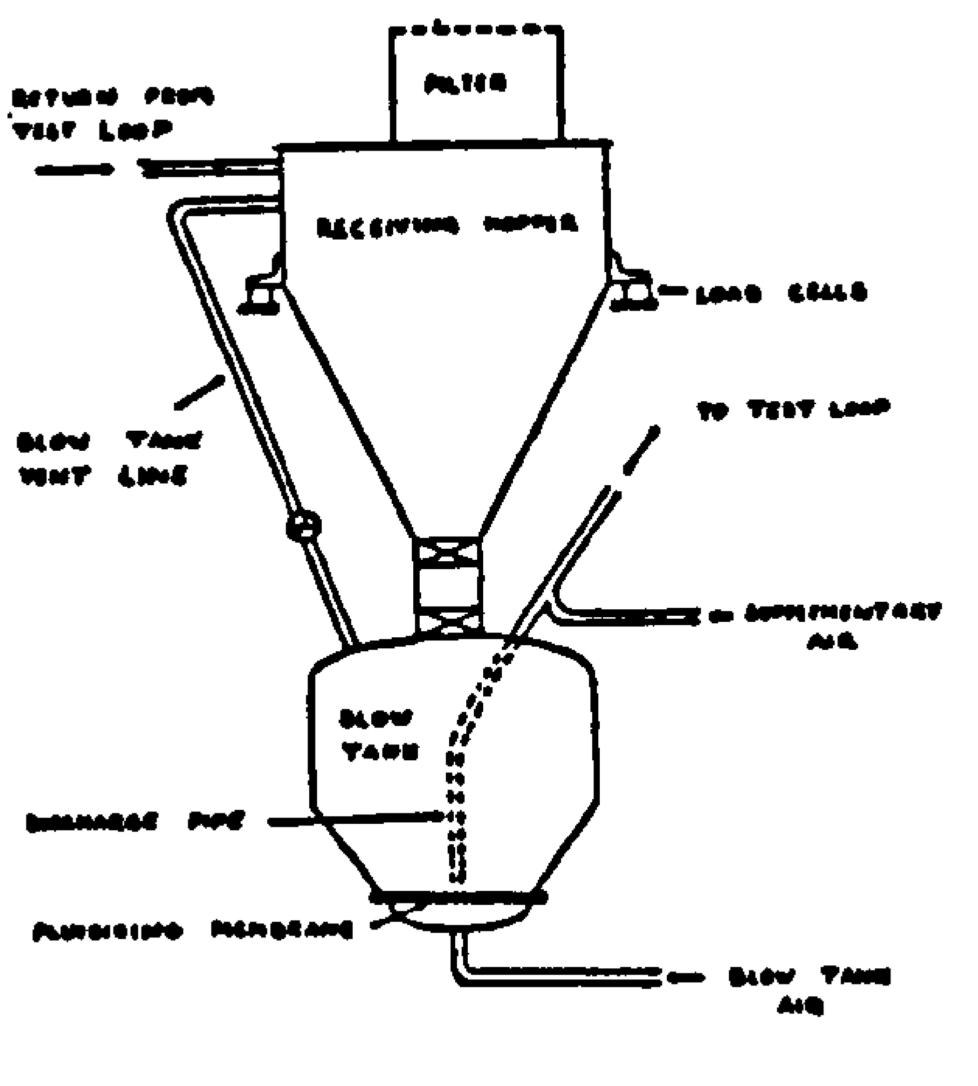


Fig 1. CONVEYING PLANT LAYOUT
TOP DISCHARGE MODE

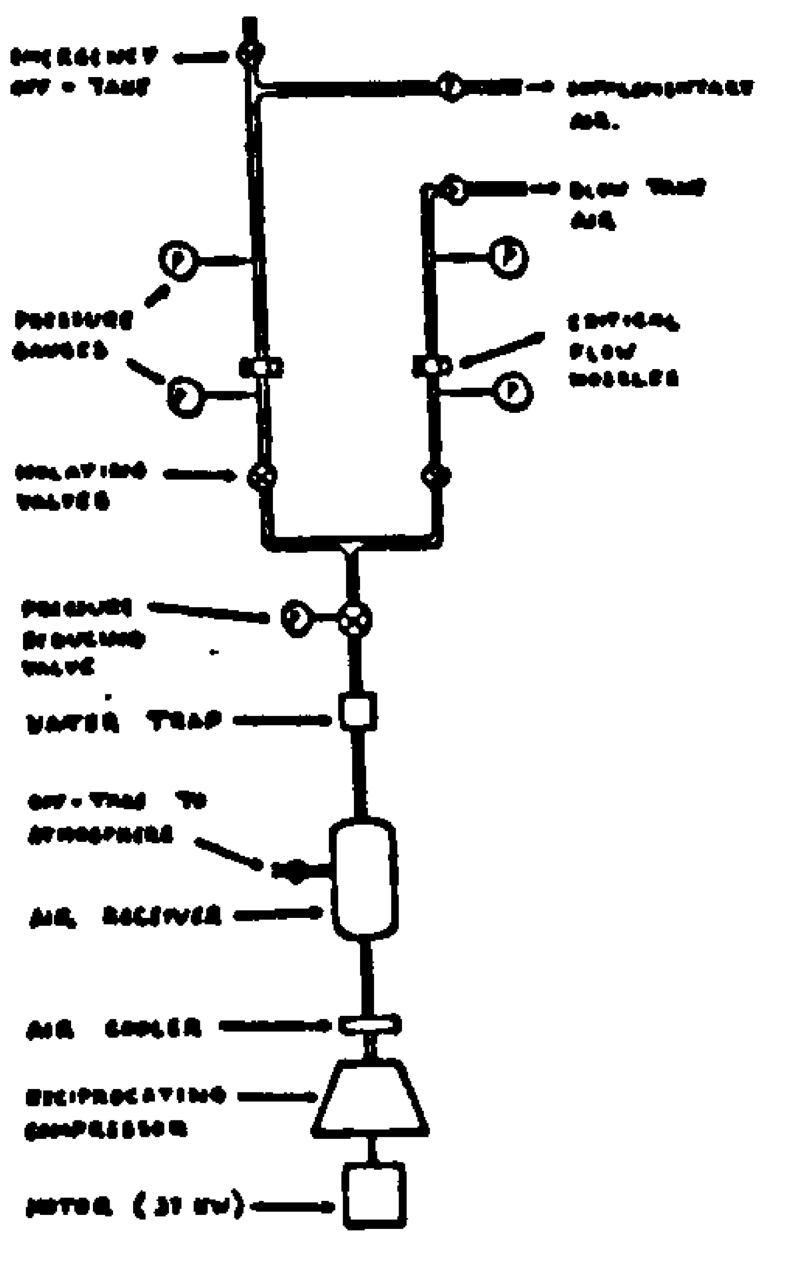


Fig 2 CONVEYING PLANT AIR SUPPLY

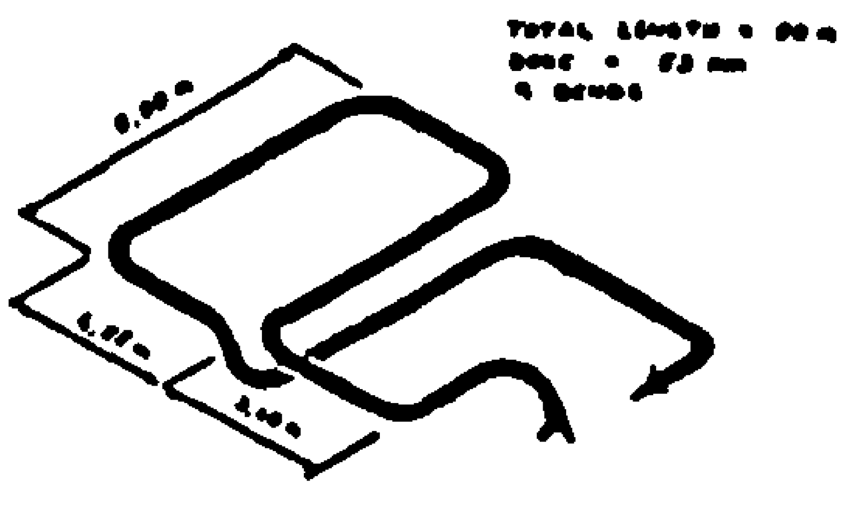


Fig 3 CONVEYING PIPELINE LAYOUT

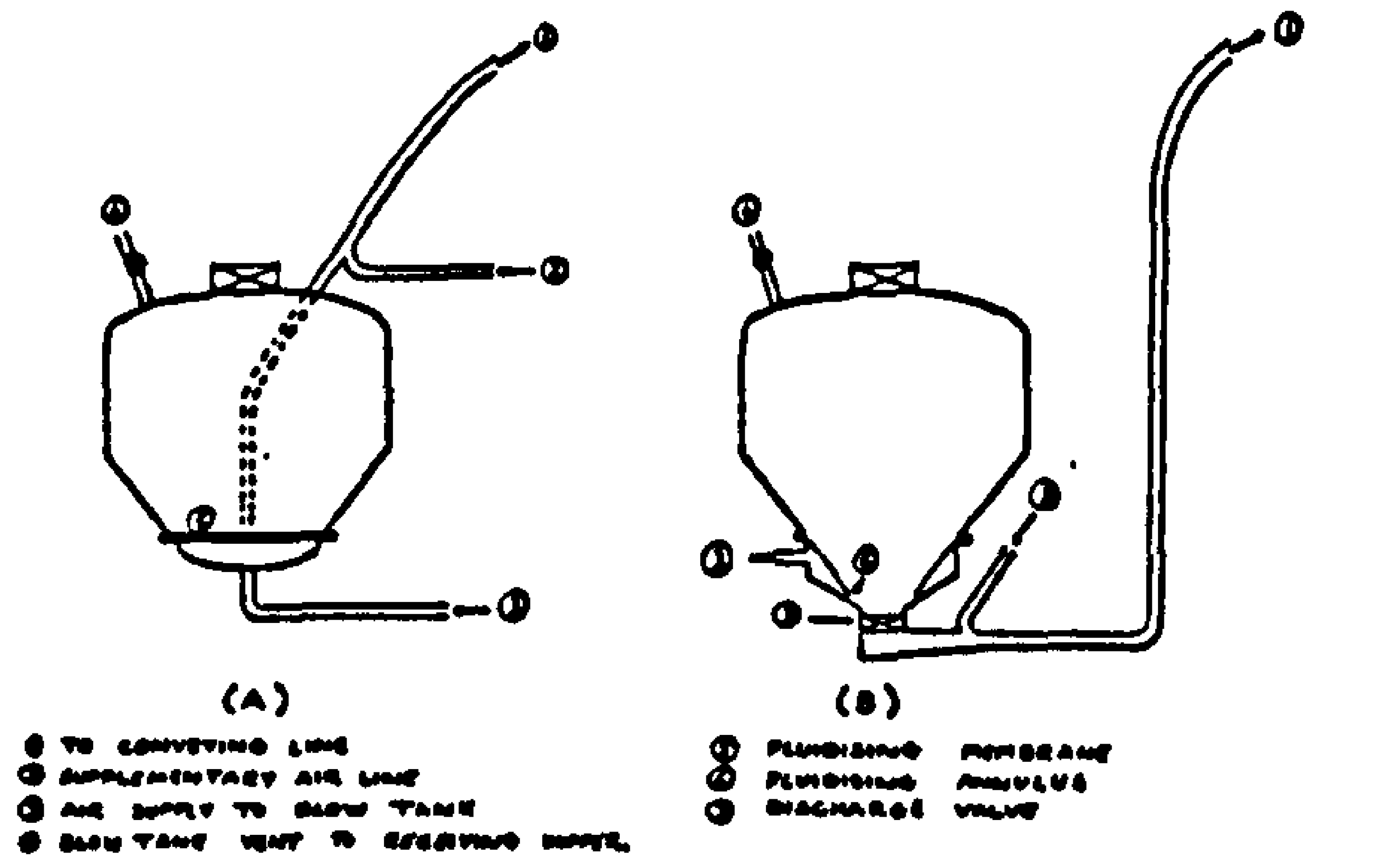


FIG 4 TOP AND BOTTOM DISCHARGE BLOW TANK ARRANGEMENTS

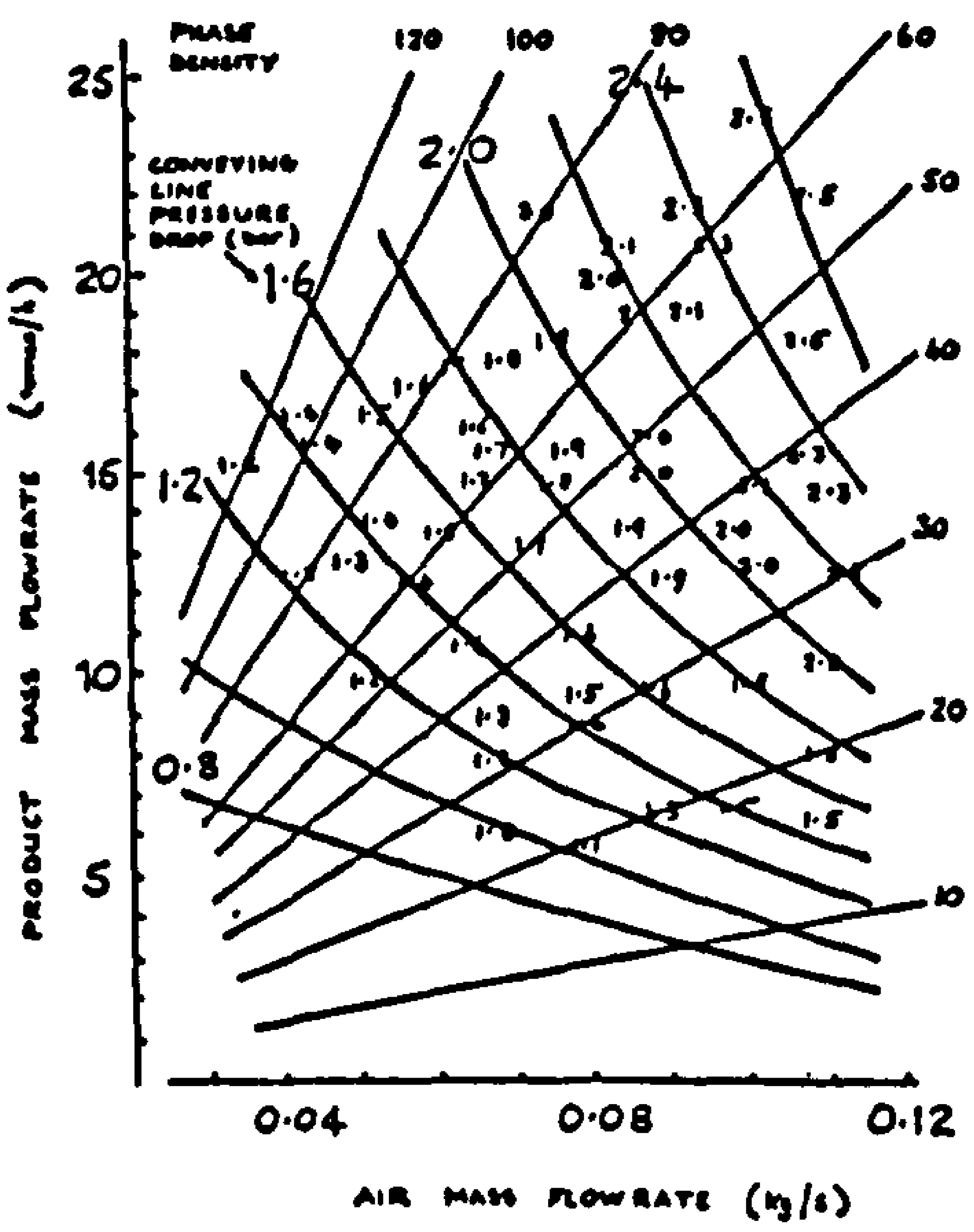


Fig 5 CONVEYING CHARACTERISTICS FOR PFA
(TOP DISCHARGE)

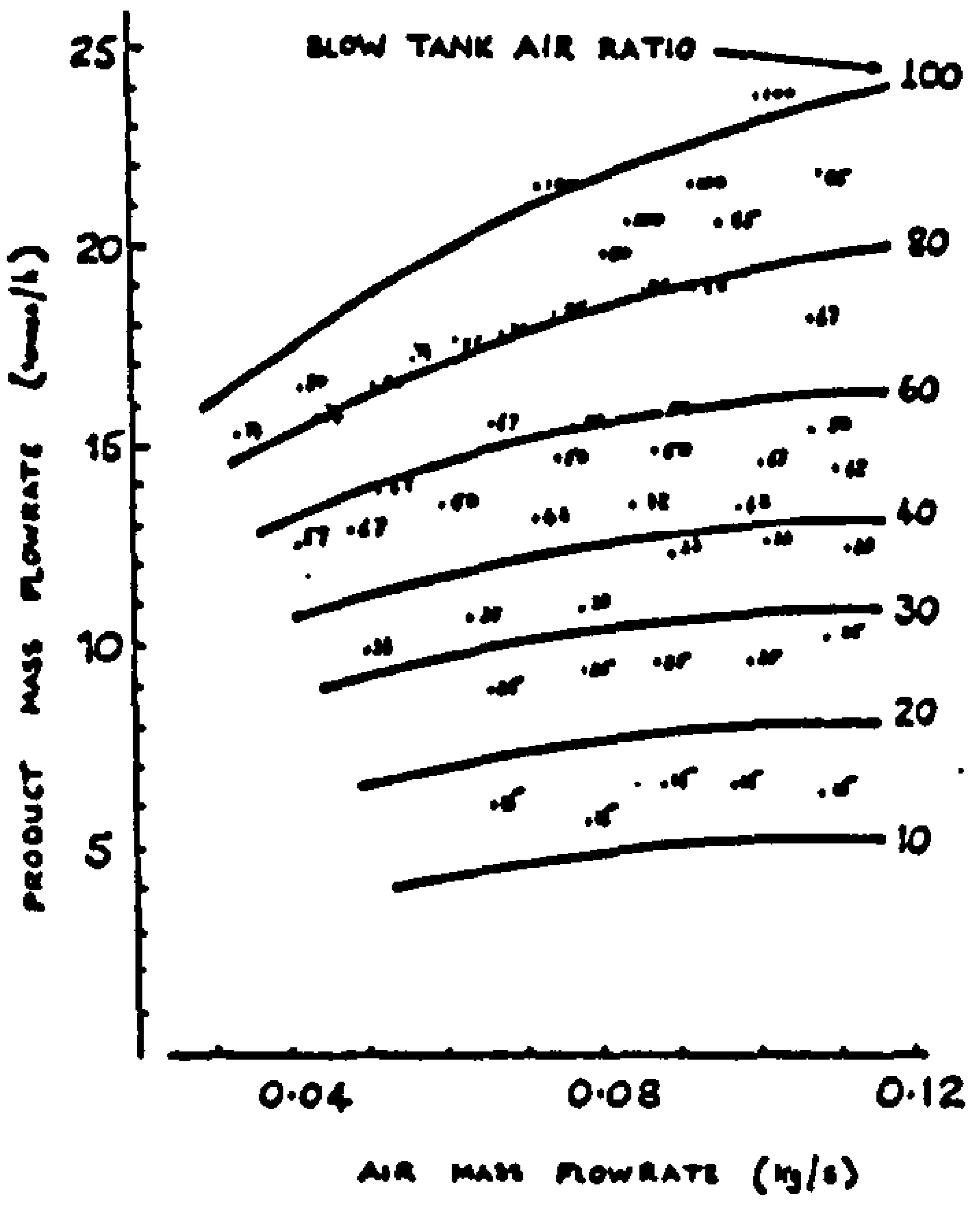


Fig. 6 TOP DISCHARGE BLOW TANK CHARACTERISTICS
FOR PFA

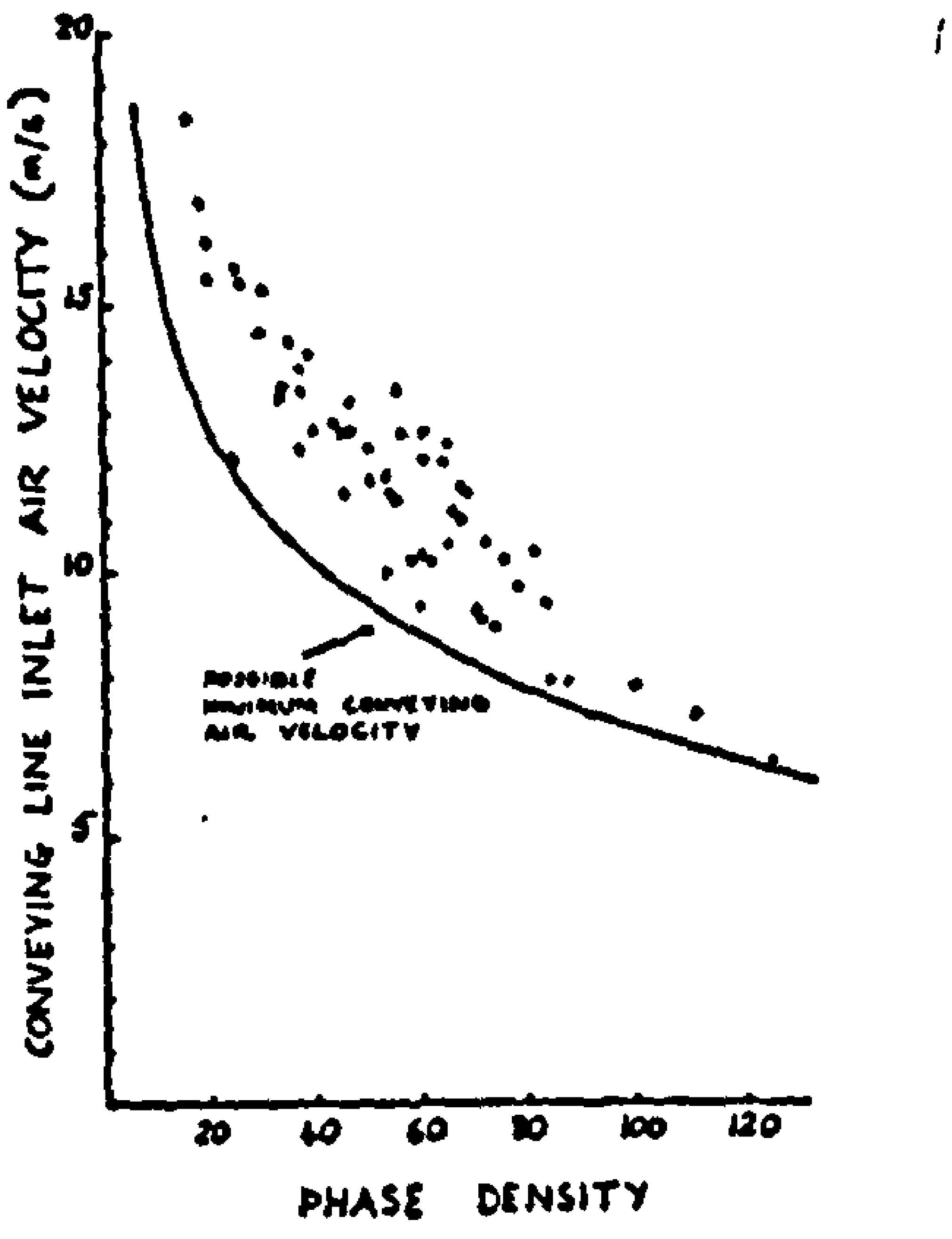


Fig 7 MINIMUM CONVEYING VELOCITY v PHASE DENSITY
TOP DISCHARGE MODE

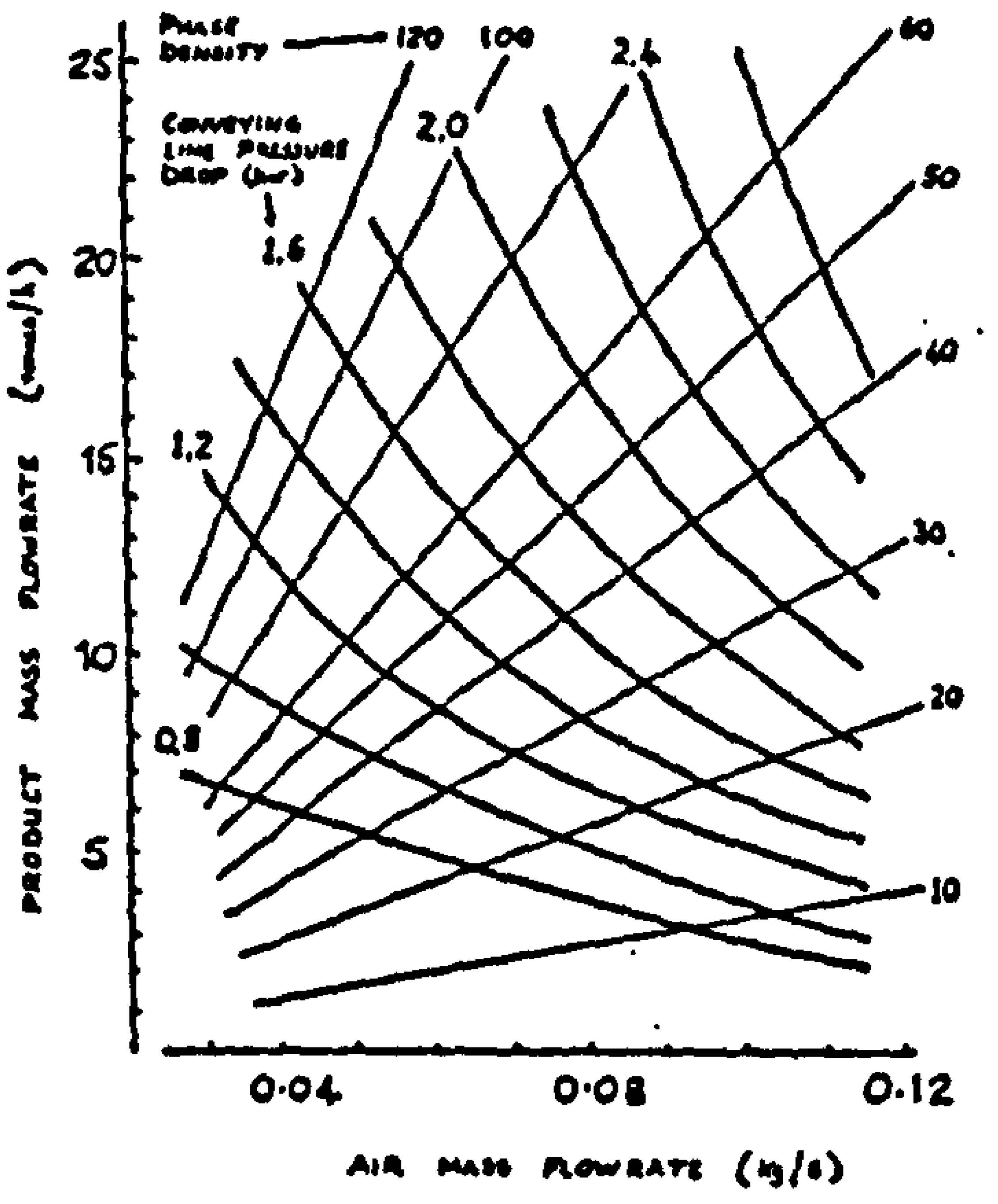


Fig 8 CONVEYING CHARACTERISTICS FOR PFA
(TOP DISCHARGE)

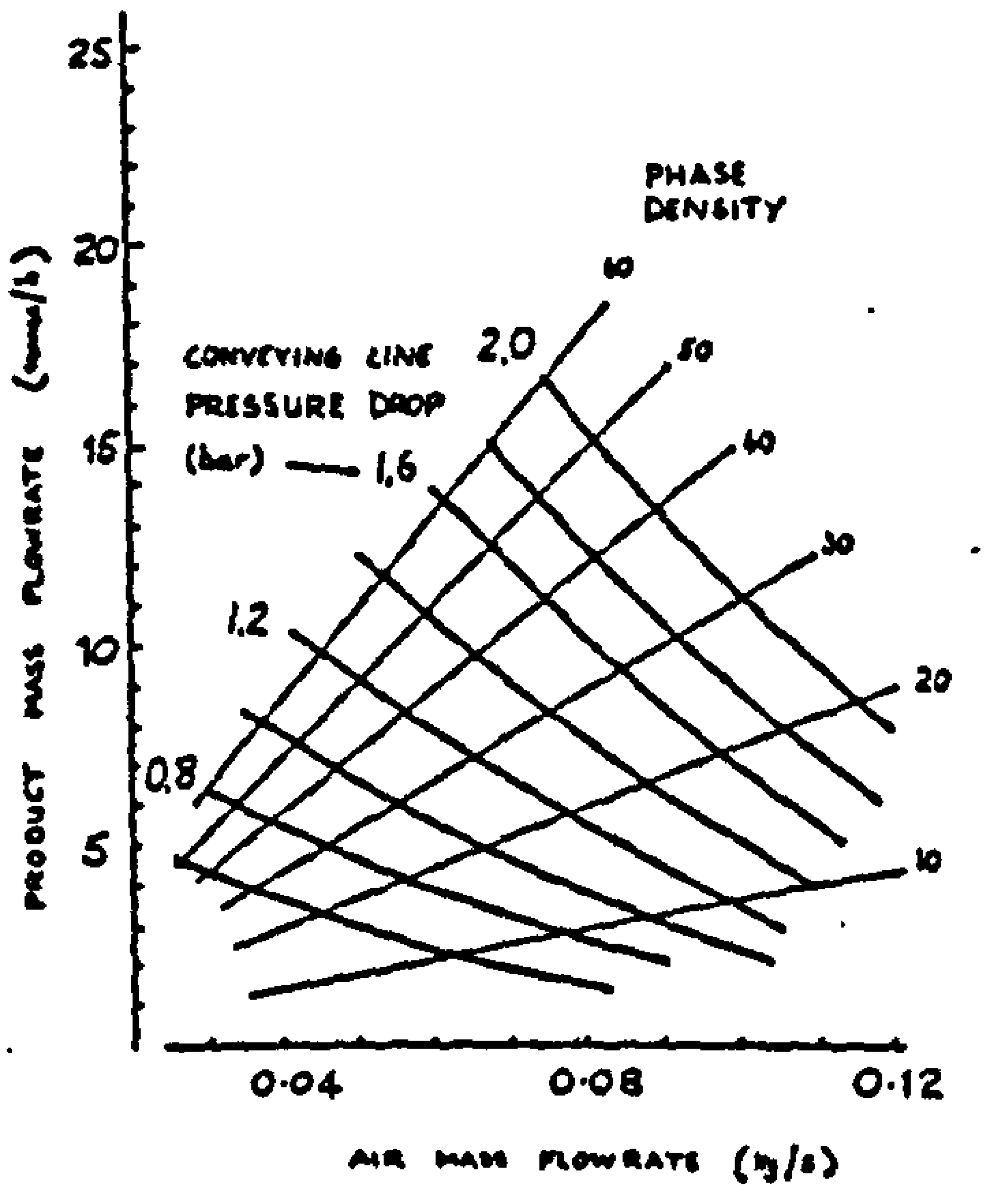


Fig. 9 CONVEYING CHARACTERISTICS FOR PFA
(BOTTOM DISCHARGE)

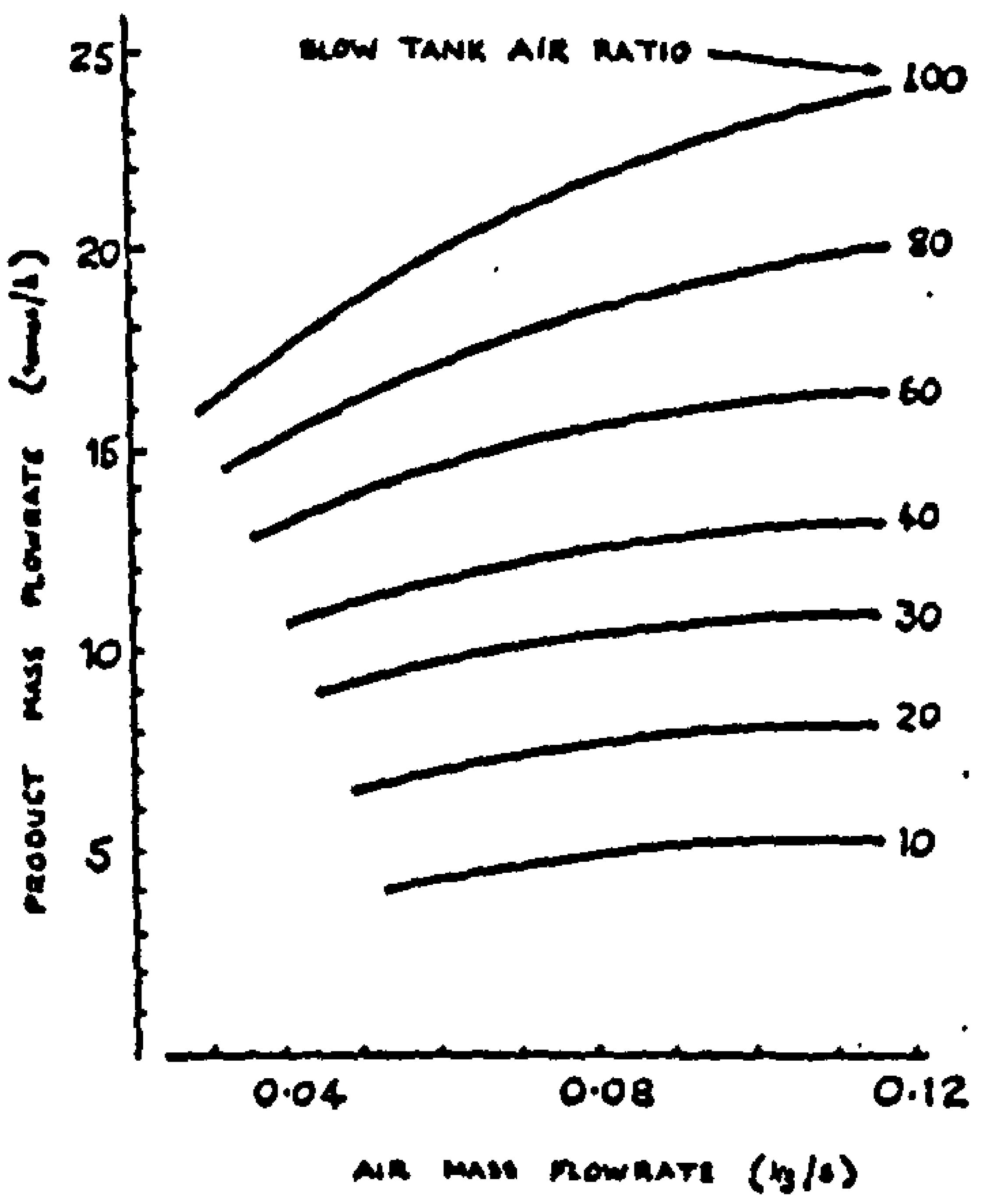


Fig. 10 TOP DISCHARGE BLOW TANK CHARACTERISTICS
FOR PFA

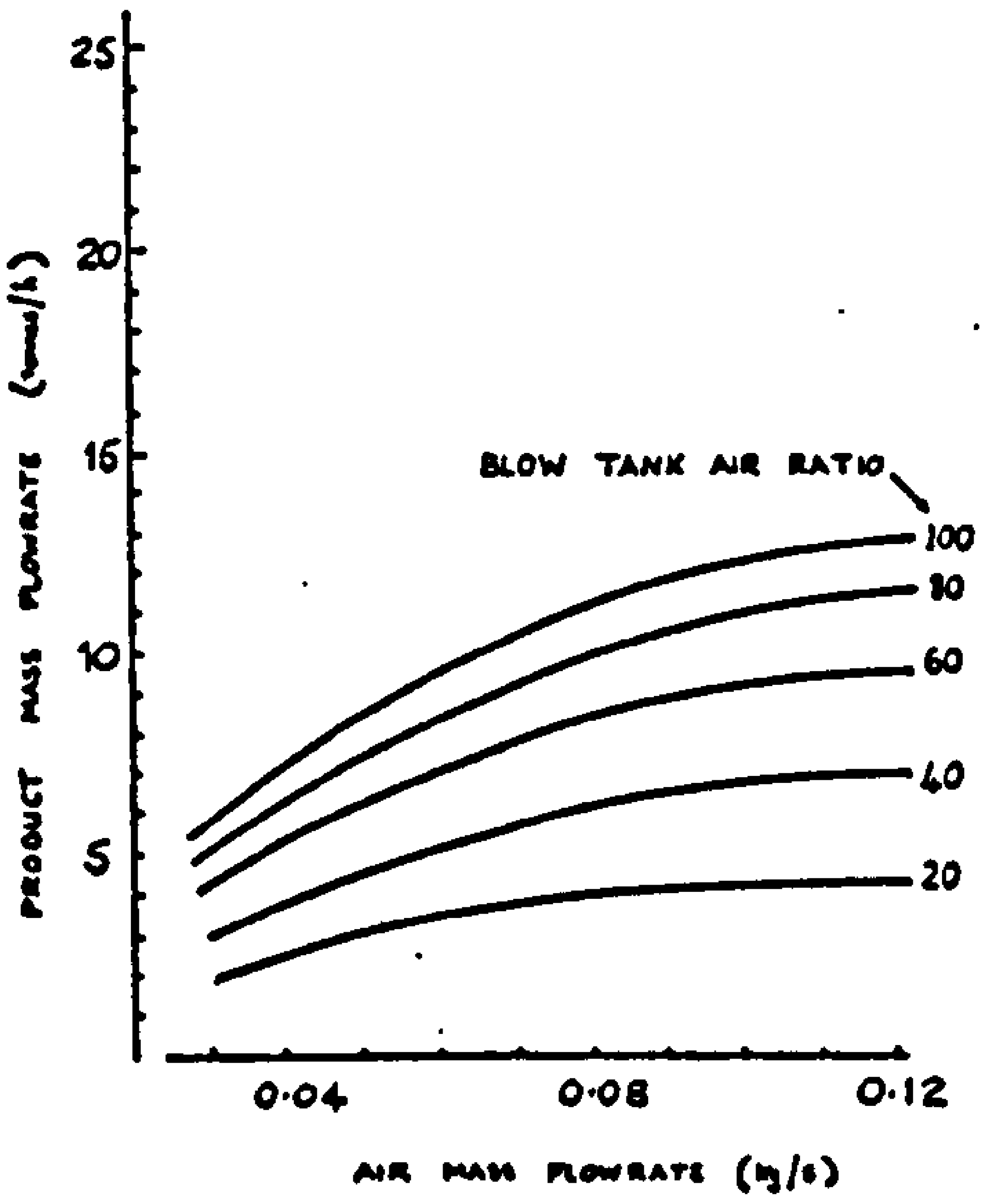


Fig.11 BOTTOM DISCHARGE BLOW TANK CHARACTERISTICS FOR PFA

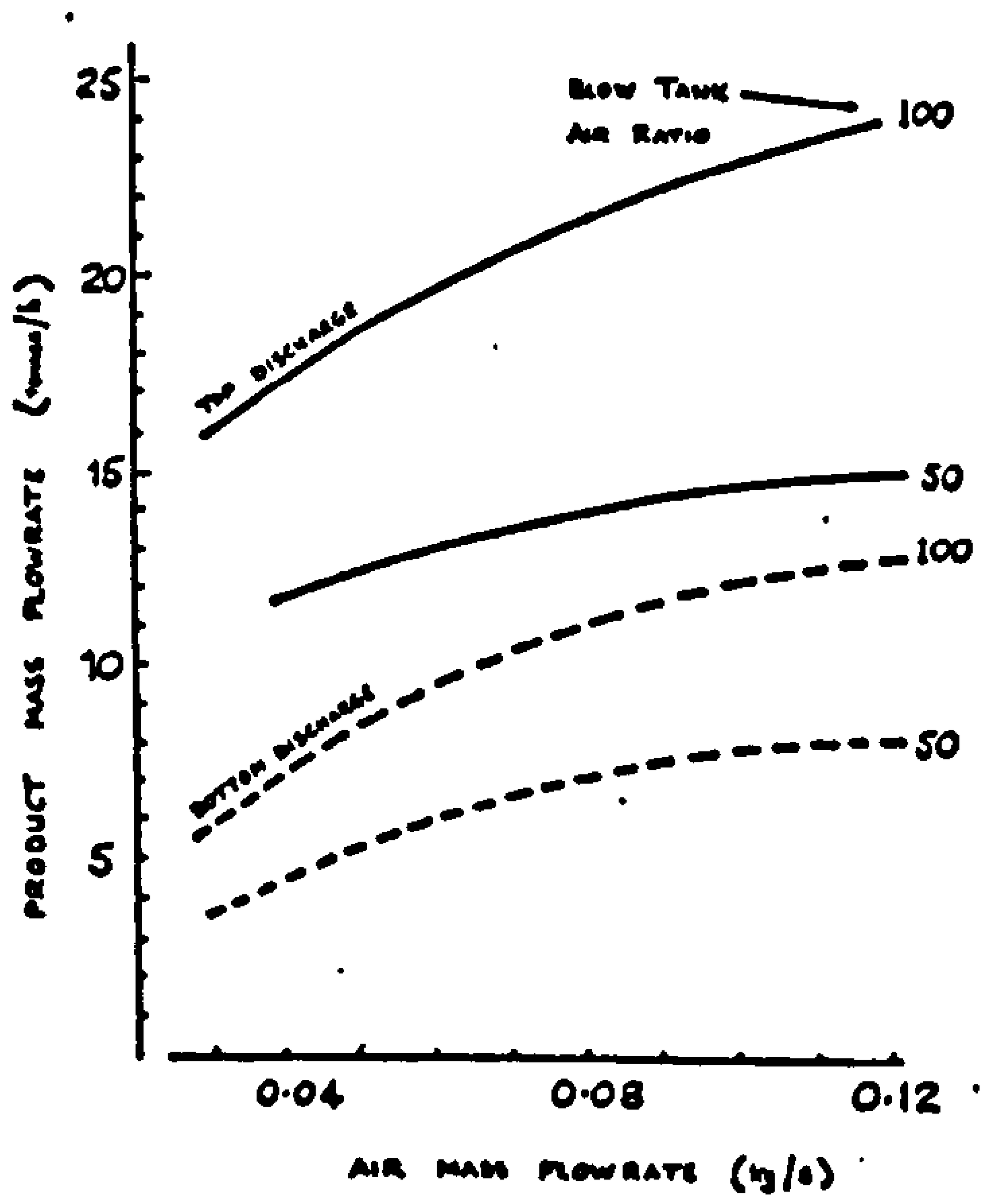


Fig 12 COMPARISON OF DISCHARGE RATES FOR TOP AND BOTTOM DISCHARGE CONFIGURATIONS

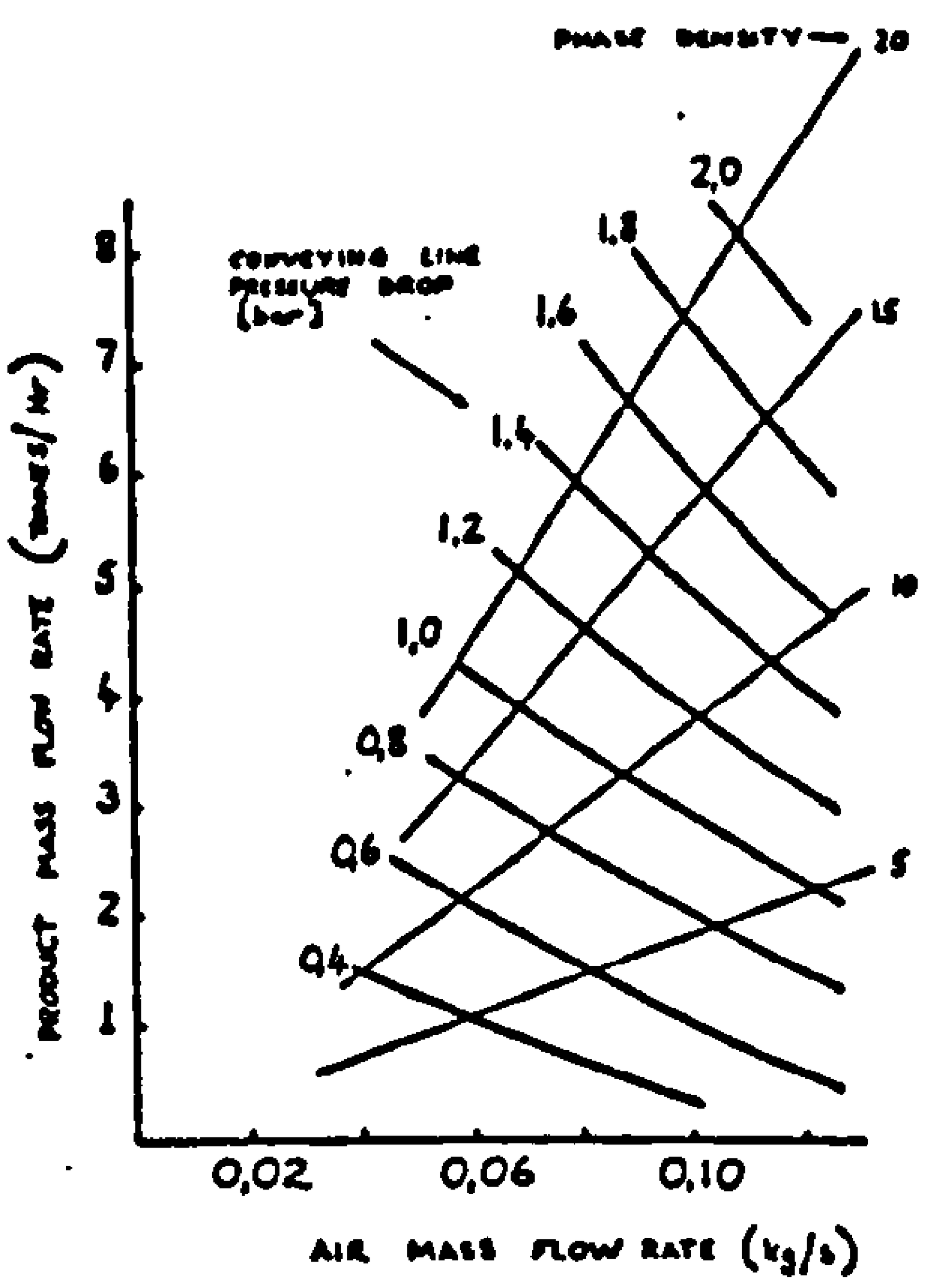


FIG 13 - CONVEYING CHARACTERISTICS FOR SAND (BOTTOM DISCHARGE)

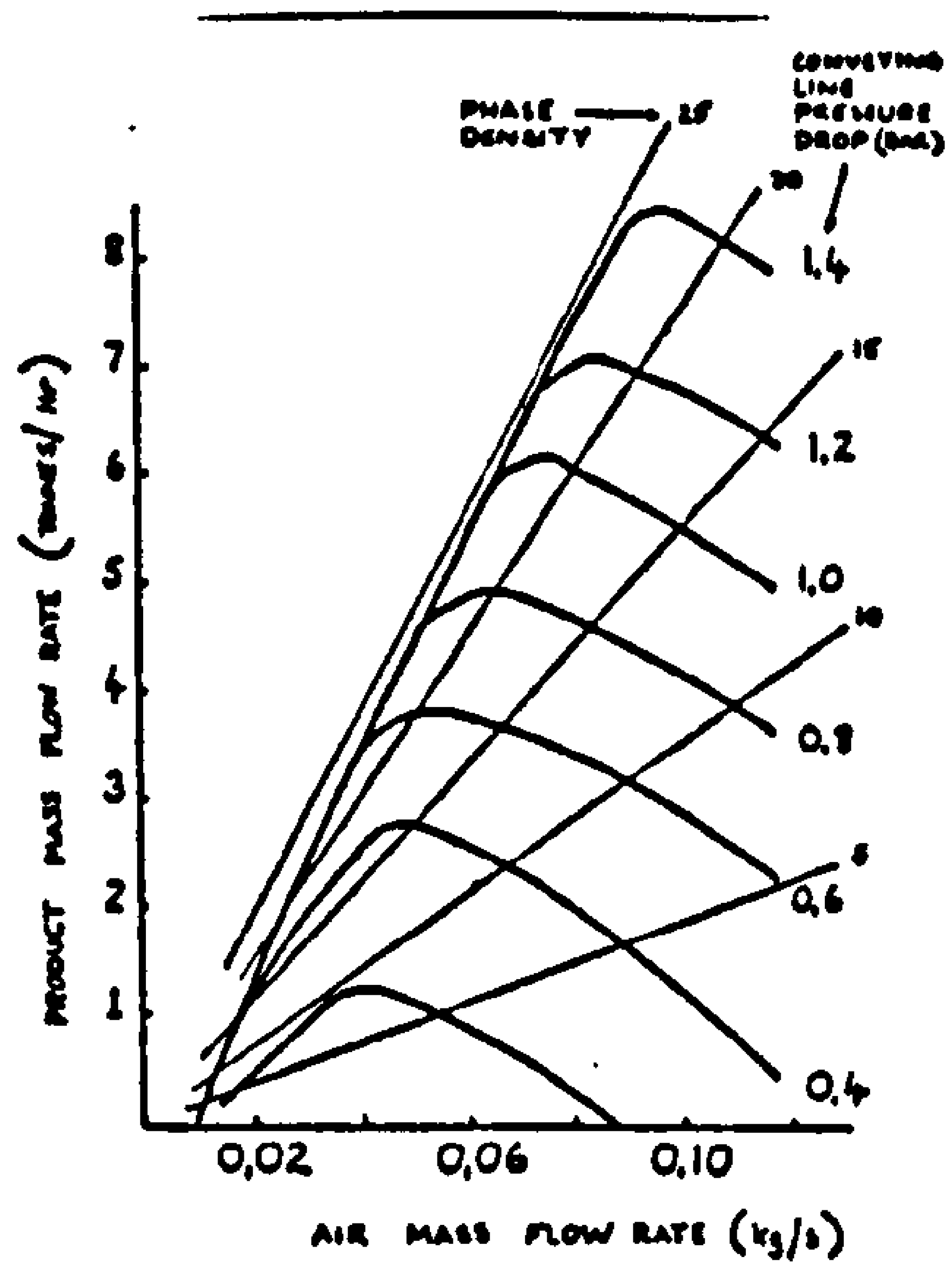


FIG 14 - CONVEYING CHARACTERISTICS FOR RIGIDEX (TOP DISCHARGE MODE)

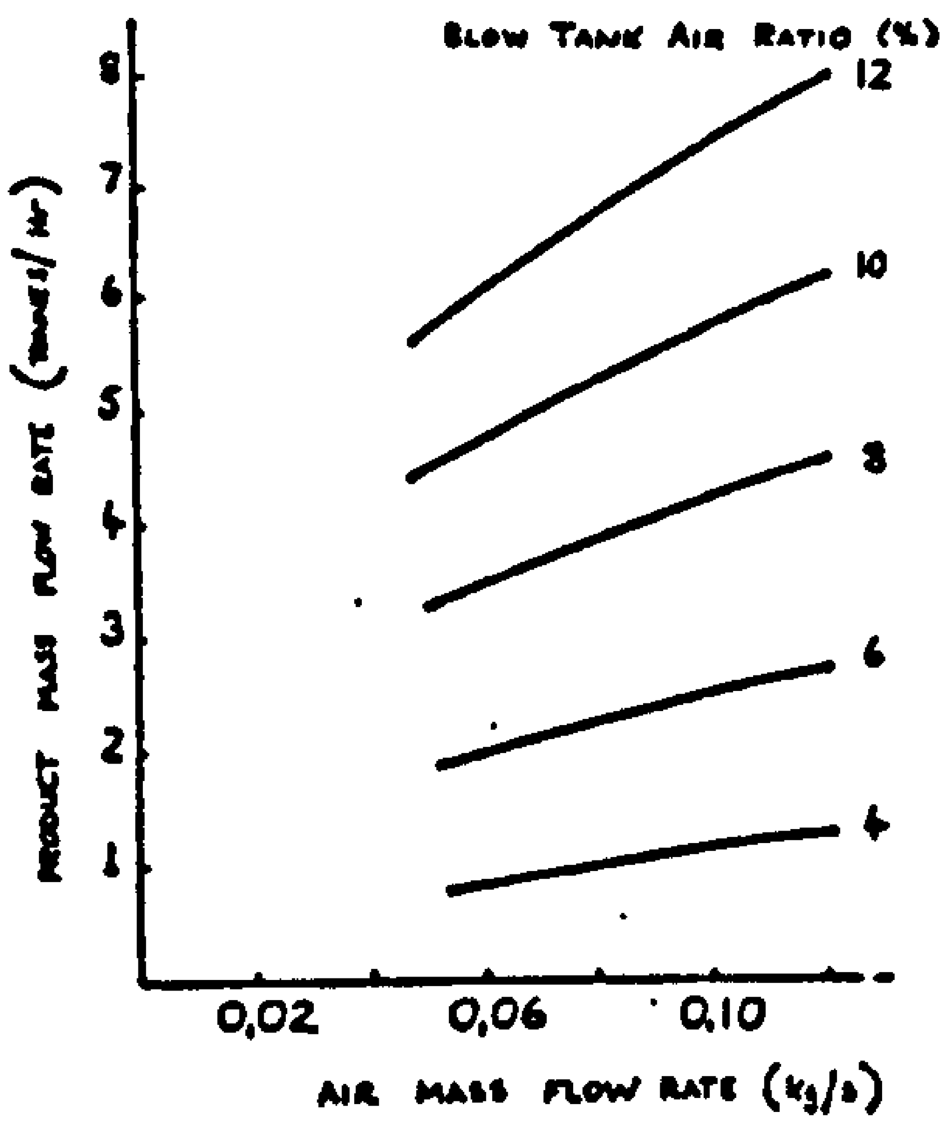


FIG 15 - BLOW TANK CHARACTERISTICS FOR SAND (TOP DISCHARGE)

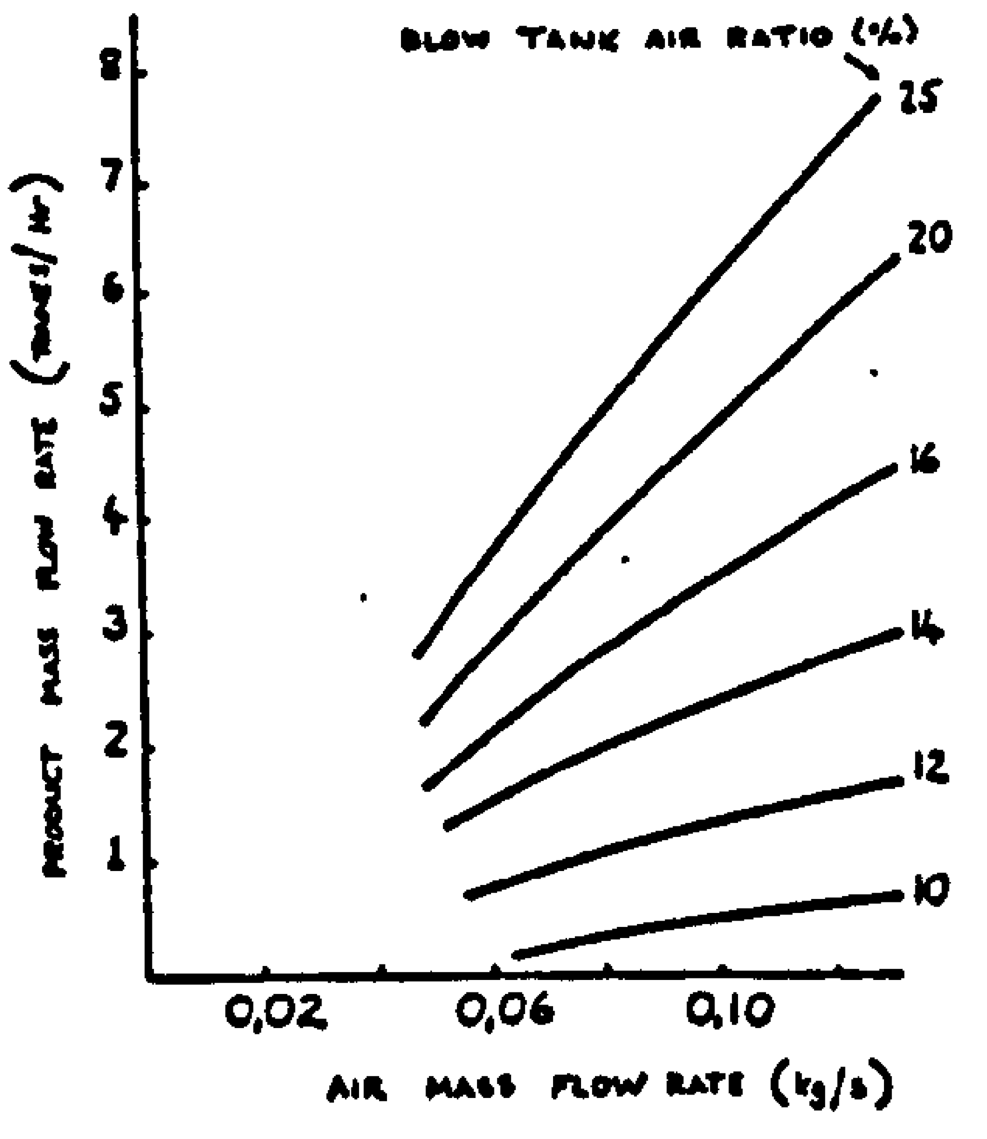


FIG 16 - BLOW TANK CHARACTERISTICS FOR SAND (BOTTOM DISCHARGE)

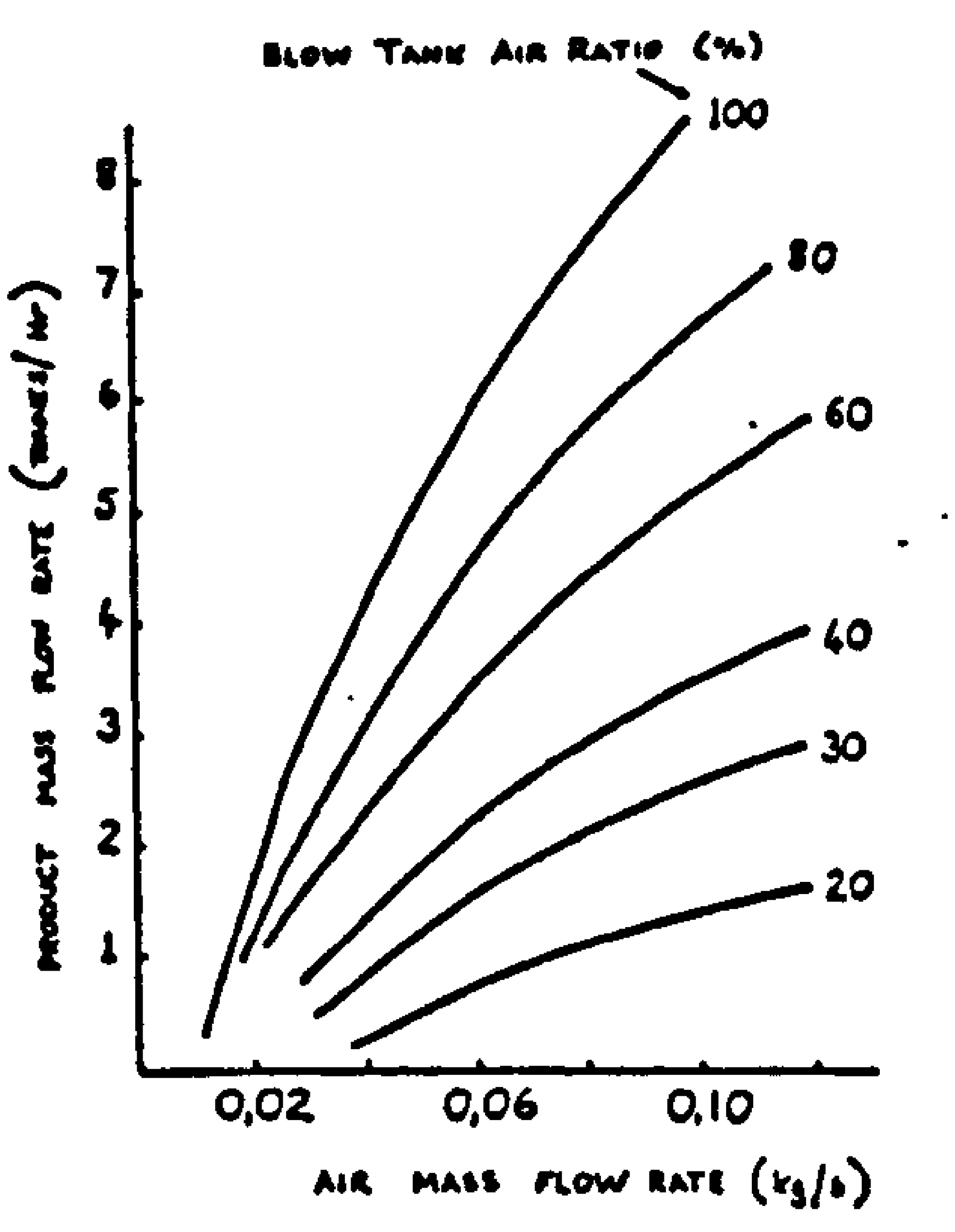


FIG 17 - BLOW TANK CHARACTERISTICS FOR RIGIDEX (TOP DISCHARGE MODE)

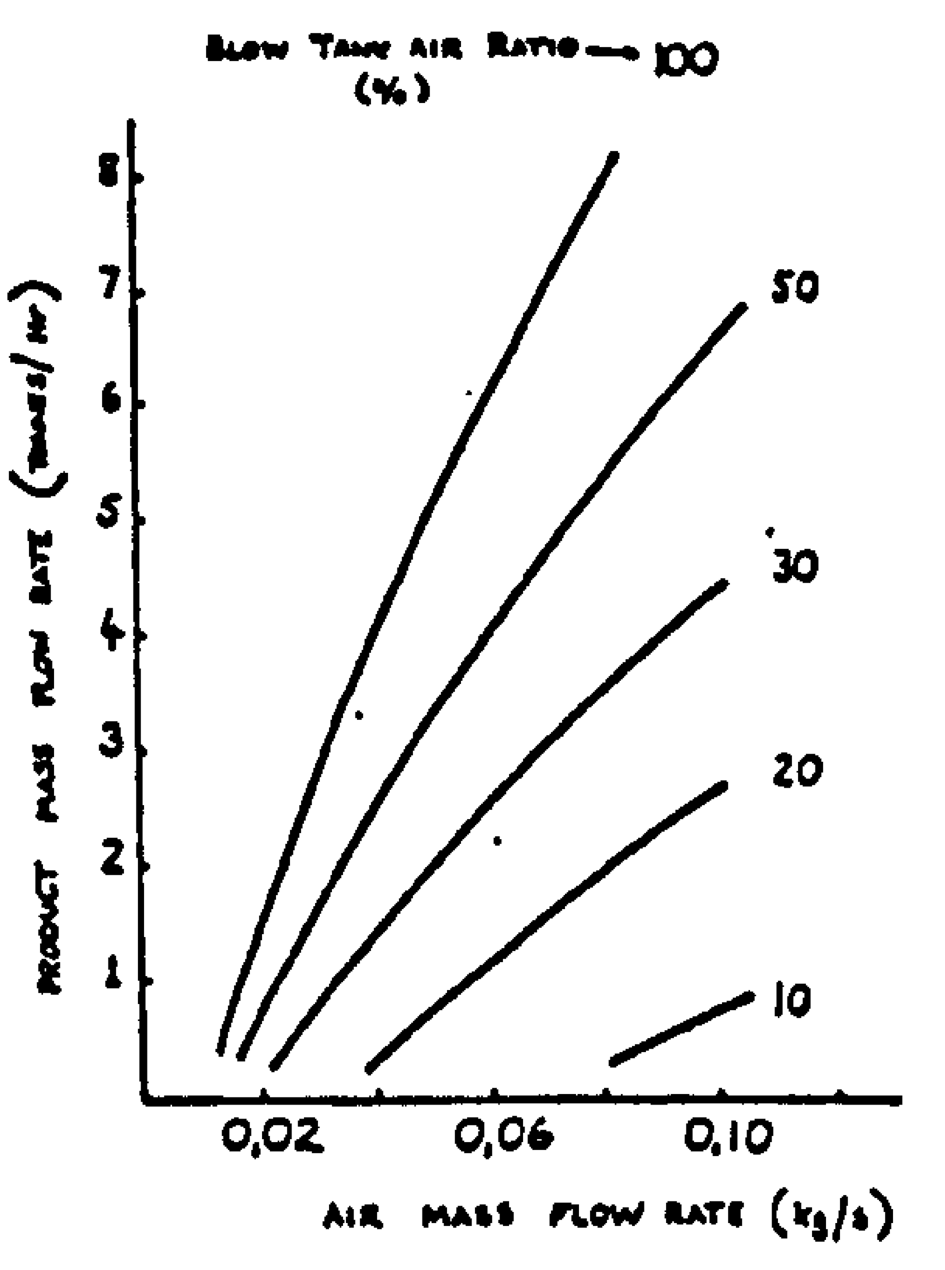


FIG.18 - BLOW TANK CHARACTERISTICS FOR RIGIDEX. (BOTTOM DISCHARGE MODE)