The Use of Laboratory Erosion Tests for the Prediction of Wear in Pneumatic Conveyor Bends

by

Anthony John Burnett

VOL I

Thesis submitted in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy under the conditions of the award of higher degrees of The University of Greenwich

The University of Greenwich
Woolwich, London, UK

June 1996

VOLUME 1

The Use of Laboratory Erosion Tests for the Prediction of Wear in Pneumatic Conveyor Bends

Anthony J. Burnett

Abstract

This thesis describes a programme of work which has been undertaken with the objective of investigating means of using a laboratory erosion tester to predict the life of a bend in a pneumatic conveyor.

Providing a link between a laboratory erosion tester and erosion tests on a pneumatic conveyor would lead to the development of an inexpensive way of predicting the life of a pipe bend operating under any given set of conveying conditions.

An extensive literature review was carried out. From this it was concluded that very little work of an experimental corroborative nature had been carried out to substantiate whether erosion test results from a laboratory tester could be used to predict the live of a pneumatic conveyor bend.

Two test facilities were constructed to carry out tests under accurately controlled conditions. The first of these was a laboratory 'rotating disc accelerator' erosion tester, and the second an industrially scaled pneumatic conveying test facility.

Both test facilities yielded results that followed previously reported trends but also illustrated some trends that have been unreported in earlier work. It was found that the 'rotating disc accelerator' simulated erosion with minimal interference from inter-particulate collisions. For the pneumatic conveyor test bend used it was found that puncture of the bend wall occurred in the region where secondary particle impacts occurred, rather than in the region of primary impacts as reported in earlier work. Explanations for both these observations are given.

An optically based construction for a cylindrical mirror was used to predict the location of the puncture point in the bend, and the intensification of particle impacts in the region of the pipe bend due to the geometry of the bend. When this was combined with an empirical erosion model derived from results obtained from the rotating disc accelerator, an accurate estimate of the life of the bend could be made. Further development of this model is discussed.

An extensive series of recommendations for further work to address some of the findings discovered during this work are given.

Acknowledgements

Numerous people have helped and supported me throughout this project, and it would be extremely remiss of me not to thank them.

Firstly, I would like to thank both Professor Alan Reed and Dr. Mike Bradley of The Wolfson Centre for Bulk Solids Handling Technology, The University of Greenwich for initiating the project and fulfilling the roles of supervisors, mentors and, when the going got tough, motivators, so well throughout the duration of this project. Dr. Mike Bradley deserves special distinction for being so thorough during the proof reading of the final document, as well as for instigating some stimulating discussions concerning the analysis of the results obtained from the test work carried out during this project.

I gratefully acknowledge the assistance of Mr. Roger Barnes and Dr. Steve Woodhead, (both of The Wolfson Centre for Bulk Solids Handling Technology), who provided much needed assistance in my struggle to overcome difficulties with the electrical installations in both of the test rigs. Without their input I would not have got as far as I have. Dr. Mayur Patel (The University of Greenwich) and Dr. Tim Selves (now Trebor Bassett Ltd. formerly The University of Greenwich) are thanked for giving me assistance in numerical modelling and instrumentation, respectively.

Professor Sunil De Silva, Mr. G.J. Liaklev of Department of Powder Science Technology, Telemark Technological Research and Development Centre, Porsgrunn, Norway and Mr. P.T. Moore of Loughborough University of Technology, UK deserve a special word of mention for embracing the concept of collaborative erosion test rig comparison work so enthusiastically, and carrying out the work so efficiently.

The assistance of the technical staff of The Wolfson Centre for Bulk Solids Handling Technology, The University of Greenwich, in particular; Messrs Mike Holman, John O'Connor and Tony Kelly is gratefully acknowledged. Both of the test rigs used in this project would not have existed without the application of their skills to the rig construction. The assistance of the innovative outlook of Mr. Andrew Pittman in the design of critical parts of the test equipment also deserves mention, and my thanks.

Financial support from the Science and Engineering Research Council (now EPSRC) and the donation of test materials from PoliHi Solidur Ltd and Morgan Matroc Ltd. is gratefully acknowledged.

I would like to thank my family and friends. They all deserve my thanks for putting up with my mildly obsessive and anti-social behaviour at times, I sincerely hope that I can make amends. I know they have wondered why I undertook this project, but despite this they have never failed to provide me with encouragement and unconditional support.

Finally, I would like to dedicate this work to both of my grandfathers. Firstly, Dr. Jack Burnett, a man for whom the pursuit of knowledge was a passion and a hobby and, secondly, Charles Ward, a craftsman and engineer. I know they would have derived much pleasure as well as satisfaction from the completion of this work.

Author's Note

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

Table of Contents

Chapter 1
Introduction

1.1 Introduction

The focus of this thesis is directed to conveyors that rely upon a flowing pressurised gas to transport solid particles through a pipe. These systems are more commonly called pneumatic conveyors. Systems of this type are used to transport a very wide range of solid materials such as milled minerals, food products and industrial chemicals.

Many materials conveyed in pneumatic conveying systems are hard or contain hard constituents. Transport velocities of the solid material in a conveyor of this type are often in the range of 15 m/s to 45 m/s. This combination of the hard abrasive solid and its high velocity causes significant damage to the pipe work of a conveyor. This thesis concentrates on describing an attempt to predict damage caused to a pneumatic conveyor bend, by trying to link results from a laboratory scale erosion tester to those found from tests carried out on an industrial scale pneumatic conveyor.

Failure of the components of a pneumatic conveyor, because of this wear, can halt the production processes at either end of the conveyor in a plant. Maintenance of the pneumatic conveyors in a plant handling abrasive materials is consequently very important since unplanned stoppages can lead to large financial losses by operators. Through the work described in this thesis, further knowledge useful in improving the design and maintenance techniques for use on pneumatic conveyors will be obtained.

Components of a pneumatic conveyor that tend to fail most are often those where a change in direction of solid flow is effected, particularly in pipe bends. Change in direction involves the solid material impinging on the bend wall at an oblique angle and subsequently moving away from the surface of the wall. It is in this impinging action that the damage to the conveyor bend walls is caused. This behaviour and the wear damage that follow are commonly known as erosive wear.

To reduce the frequency of failure of conveyors by erosive damage, new materials have been developed and incorporated into the design of conveyor components. At the same time, a better understanding of the mechanisms affecting the successful transportation of solid materials in such systems has led to the design of systems employing reduced solid velocities, and therefore suffering reduced erosion damage. However, wear still is a significant problem in plant of this type when handling some materials.

Materials technology has been applied to help in combating the form of wear that is prevalent in the bends of a pneumatic conveyor, as described above. The materials used range from the comparatively cheap plastics, rubbers and metals to the higher cost ceramic material types or composites. All these materials behave differently when subjected to erosive wear. Materials could be applied to conveyor components depending on the erosive wear conditions that are expected in them. This will lead to a pneumatic conveyor containing a large number of components made from different materials, each component being designed to have maximum resistance to erosion damage. In this way the serviceability of a conveyor could be maximised.

However, this cannot be done at present because the current methods for finding out the wear resistance of a material at a given set of solid flow conditions have not been developed to a sufficient extent. Several types of testing apparatus have been developed, but each has a different way of simulating erosion as a consequence of their varying designs. These test facilities have either been utilised to give qualitative results only, or for detailed academic study of the mechanisms of wear of the various materials considered.

The assessment of the life of a conveyor bend in an erosive wear situation has in the past been achieved by constructing and testing a pilot sized pneumatic conveyor pipeline. These have been operated in such a way as to give similar transport conditions in the test system to those expected to occur in the intended plant system. The results obtained from this form of testing only yield results that are specific to the system and material being used. As a consequence of this, scaling erosion results to give predictions for wear in industrial plant is extremely difficult, and this leads to inaccuracies occurring. These problems are due, in part, to our poor understanding of the mechanisms of flow of solids in conveyor pipeline. It must also be stated that tests of this nature are very expensive to carry out, especially where it is necessary to test bends of several different geometries and constructed from different materials.

Very few efforts have been made to link results for erosion damage obtained on a laboratory scale erosion tester to those obtained in an actual pneumatic conveyor. This has been due to the cost of installing both sets of test facilities. However, there are significant advantages to finding a link between results obtained from a laboratory erosion tester and tests carried out on a pneumatic conveyor. When this link has been established, it should become possible to predict the life of a bend in a pneumatic conveyor simply by carrying out tests on a smaller erosion testing device. This should reduce the test and design costs involved significantly and provide the engineer with a useful prediction of the wear lives of conveyor bends.

It is an attempt to determine the link between the two testing devices that forms the bulk of this thesis.

1.2 Project Objectives

The major objective for the work detailed in this thesis was to derive a link between the results for erosion damage taken from a small scale laboratory erosion tester to those obtained from an actual pneumatic conveyor bend. If this goal could be reached, it would be possible to use the small scale laboratory erosion tester to provide more accurate quantitative predictions of the wear life of pneumatic conveyor bends than has, until now, been possible.

In the pursuit of this goal several important subsidiary objectives needed to be achieved. These are detailed below:

1. A literature survey would need to be undertaken to investigate the relevance of the large volume of work previously carried out in this field.

2. The evaluation and selection of a design for a laboratory scale erosion testing machine most likely to give results on a commercially viable basis would need to be undertaken. A review of the normal operating conditions of a pneumatic conveyor would also be carried out to decide the conditions a laboratory tester would have to simulate. This would enable adequate specifications for the design of the laboratory tester to be chosen.

3. Results obtained from the selected laboratory erosion tester for a range of tests whose conditions bracketed the value of a single chosen conveying condition to be used in the pneumatic conveyor were required. Identical materials to those selected for the pneumatic conveyor needed to be used in these tests, therefore eliminating a possible source of experimental error.

4. A detailed investigation into the erosive failure of a pneumatic conveyor bend under a single chosen conveying condition that could occur in an industrial conveyor was required. This would entail the use of a pneumatic conveyor test rig.

5. Attempts to derive a link between the results obtained from the selected laboratory erosion tester, and the pneumatic conveyor test rig will then be carried out.

6. The evaluation of the link on the basis of the results obtained from tests undertaken on both test facilities would be made.

1.3 Project Preview

This section of this introductory chapter will give a brief indication of the work that was carried out to try to meet the project objectives. The following paragraphs only give a brief overview of the work undertaken. Work details are described in much greater depth in the subsequent chapters and appendices.

Technological advances made in the field of combating erosive wear in pneumatic conveying plant were investigated early on during this project. This was carried out by undertaking an extensive literature survey. The findings of this work are presented in Chapter 2. Two major conclusions were derived from this literature review. First, it was not possible to quantitatively predict the wear life of a conveyor bend for given conditions with much accuracy. Secondly, it was found that few links between erosion damage assessment tests on laboratory erosion testers and pneumatic conveyors had been discovered.

These findings led to the decision to design and construct two distinctly different test facilities. The decisions are discussed in more detail in Chapter 3. These test facilities consisted of (i) a laboratory erosion tester of a form described as a 'centripetal accelerator' in previous research, and (ii) an industrial scale pneumatic conveyor. In this work the laboratory erosion tester will be called a 'rotating disc accelerator' erosion tester.

Details of the construction and use of the 'rotating disc accelerator' test equipment are provided in Chapter 4. To help in the assessment of the results obtained from this tester a numerical model was developed to aid in the understanding and evaluation of the system dynamics. This model is discussed in Chapter 4 along with a series of results for the test work carried out on this tester. An extensive series of tests using the 'rotating disc accelerator' tester were carried out on samples of mild steel taken from the steel pipe used to construct the pneumatic conveyor test bend. Detailed modelling of the results for the erosion damage performance of this material is also discussed.

The design and construction of the pneumatic conveyor test facility along with the results obtained from tests carried out on this equipment are given in Chapter 5. As in Chapter 4, models are discussed which relate to the particle dynamics occurring within the conveyor bend being studied. The method of carrying out and processing tests and the data arising from them are also included in the same chapter.

Chapter 6 discusses the links that can be made between the results obtained from the two test facilities, together with the previously derived models of the erosive wear of pneumatic conveyor bends.

Details of a new method of predicting the life of a pneumatic conveyor bend are given in Chapter 7. This method is derived from the observations made on the results obtained from both the pneumatic conveyor and 'rotating disc accelerator' erosion tester test rigs. The application of this model in the engineering design of a pneumatic conveyor is also discussed in this chapter.

The conclusions of this project are discussed in Chapter 8 along with suggestions for further work that could be undertaken.

Chapter 2

A Review of the Technology Applied to the Prediction of Erosion in Pneumatic Conveyors to Date

2.1 Introduction to the Review

A literature review was undertaken as the initial part of the programme of work that is described in this thesis. The purpose of this review was to find out the state of the technology applied to the field of predicting erosive wear in pneumatic conveyors.

The aim of this project is to propose a method by which the results for erosion damage obtained from a laboratory erosion tester can be related to those obtained from an industrial scale pneumatic conveyor. The review therefore contains a discussion of the technology that has been applied to this problem. Research carried out in other areas of work which are of interest to the overall understanding of the problems associated with these phenomena are also discussed.

2.2 A Discussion Concerning the Inter-relation of System Properties which Affect Erosion in Pneumatic Conveyors

Erosion by impinging gas/solid flows has proved to be very difficult to predict. There are several reasons for this. First, the behaviour of the flowing mixture of gas and solid phases has remained difficult to predict since the flow conditions, (velocity, concentration and material properties involved etc) vary over a large range, and the interdependence of the numerous variables involved is complex. Secondly, pneumatic conveyors are by no means standardised in shape or size, so consequently the geometries of the systems vary considerably. Thirdly, the behaviour of the materials involved in the impact event are difficult to model due to the small scale and short time duration of the impact, and the effect that these two factors have on the properties of the materials concerned. Each of these points are discussed below.

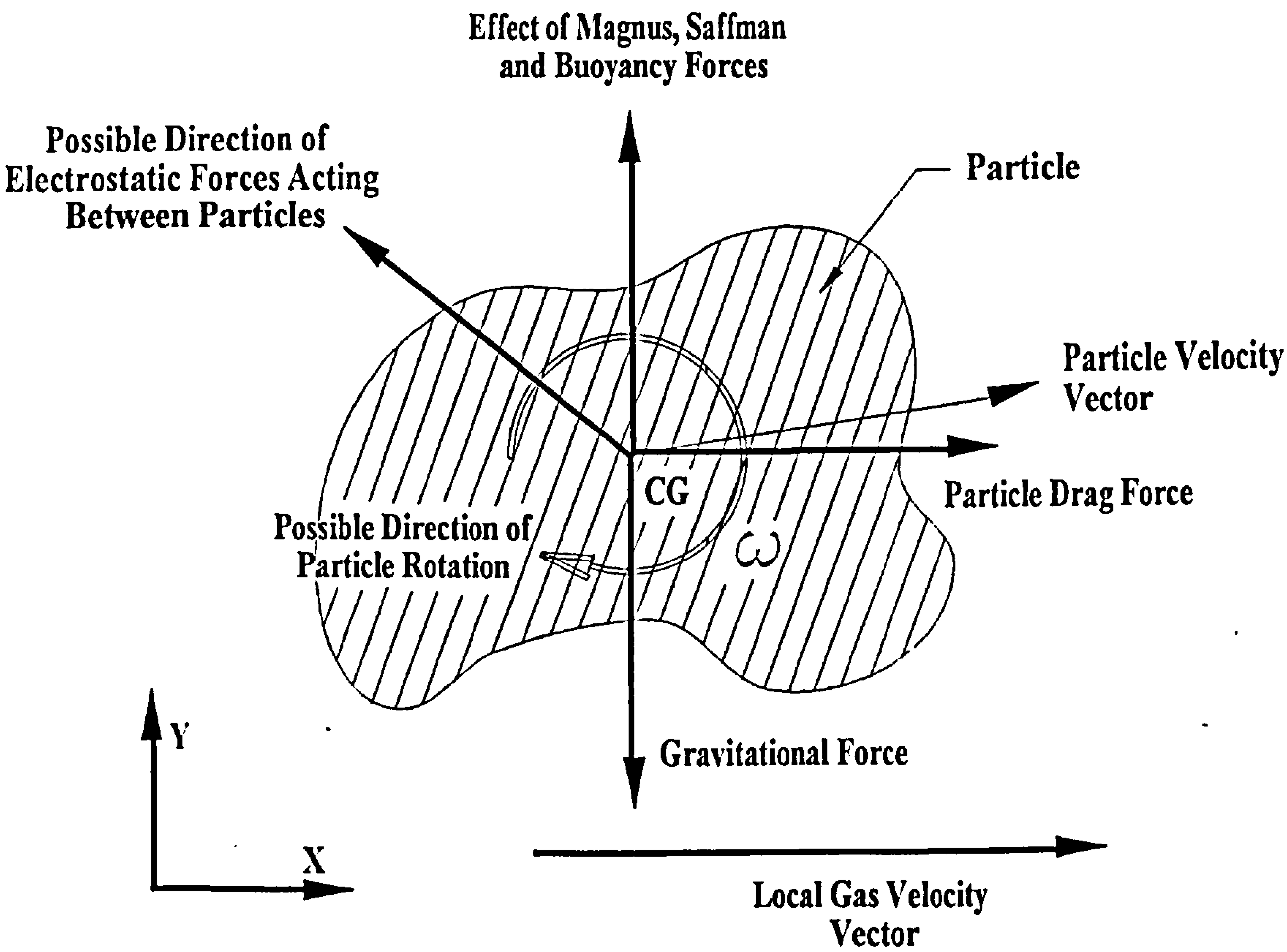
2.2.1 A Description of Two Phase Flows and Their Effect on Erosion.

The velocity of the flowing gaseous phase will normally indicate the overall behaviour of the flowing mixture, however, the motion of individual particles within this flow can vary greatly. The lower the flow velocity, the more likely it is that the solid phase will tend to fall out of suspension and travel along the bottom of the pipe bore as a sliding bed where particles bounce or slide over the pipe wall surfaces. As the flow velocity increases the suspension becomes more and more homogenous and flow, free from pulsations in pressure (and, by inference, gas velocity), predominates [N1]. Erosive wear in pneumatic conveying systems is significantly greater when a reasonably homogenous flow regime of low particle concentration and high velocity is present [M1]. It is well accepted that as the particle velocity increases, the amount of the erosion damage increases more than proportionately in magnitude. The particle velocity is the most influential variable in the study of the erosion performance of any given material. Consideration of the distribution and concentration of the particles within the flow must also be made. In certain pipe layout arrangements, the particles can tend to accumulate in the bore to form what is known as a rope [F1]. Because of the close proximity of the particles to each other in such a rope, collisions between particles when the rope strikes the pipe wall in a bend may well begin to have a significant effect on the erosion damage that occurs.

It must be stated that in most pneumatic conveying processes, the amount of moisture present, and the temperatures at which the conveying is being carried out, are low enough to ensure that corrosion does not seriously augment the erosion process.

The motion of an individual particle in a flowing fluid is caused by the action of the fluid upon the particle by means of several forces. The most important and influential of the forces acting on an individual particle is the drag force that acts between the gas and the particle, however the forces due to gravitational effect, particle rotation, lift forces, buoyancy forces and electrostatic forces can also have a significant part to play (Figure 2.1) [H1]. These are the only forces acting on the particle, other than those caused if the particles bounce off the pipe walls, provided that the density of particles in the flow (termed as the suspension density or particle concentration) is small. The magnitude of these forces depends on the size, shape and density of the particles themselves [C1,L1]. The momentum of the particle will govern how much influence the gas phase has on the particle motion. If the particle momentum is large the particle will make its own trajectory through the gas irrespective of the direction of gas flow. Conversely, if the particle momentum is small it will tend to follow the directions of motion taken by the fluid surrounding it. This is because the drag forces

Figure 2.1 Schematic view of the aerodynamic forces that could possibly act on a particle moving in a gas stream.

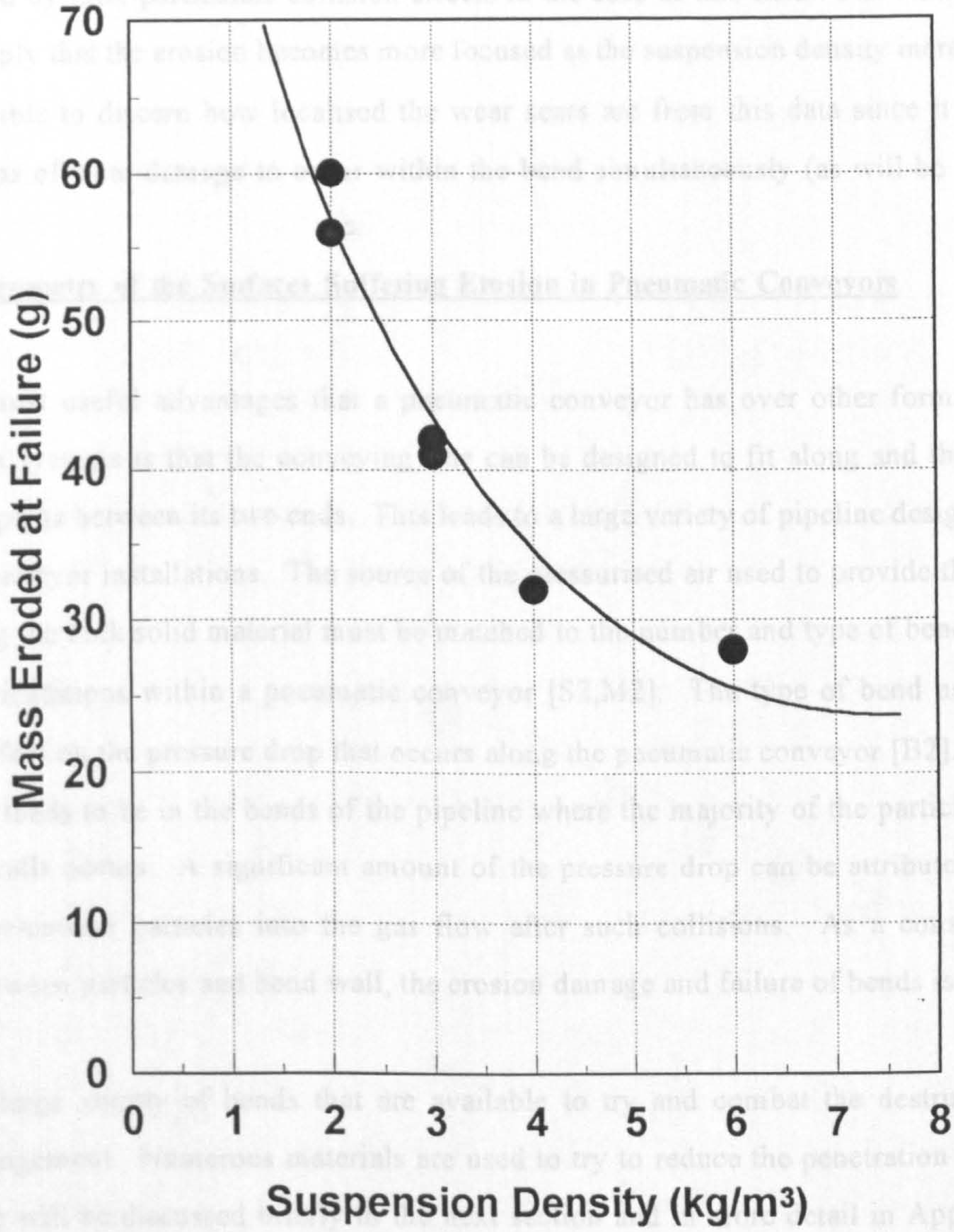


acting on the particle due to the gas motion will become as significant to the particle motion as its inertia. If the particles are very small, then there is a greater possibility that the motion of the particles will be affected by the turbulence in the gas, as well as by its mean velocity [D1,A1].

The range of particle sizes, shapes and densities that constitute many bulk solid materials is quite varied [S1]. It is therefore foreseeable that the range of possible particle trajectories through any one gas flow is quite diverse. Interaction between particles is inevitable in such a two phase system. Inter-particulate interactions can occur by fluid effects, such as the effect of the wake of one particle upon another where the particles significantly affect the motion of the gaseous phase [H1]. Alternatively direct physical contact between particles can occur [A2]. Such interactions will alter the observed flow of fluid and solid phases [L2]. Interactions between particles will occur more frequently when the flowing suspension undergoes a change in direction such as when it flows around a bend within the pipe system. This is due to the effects on the motion of the gas / particle mixture caused by distributions of particle size and shape. The larger, high momentum particles will tend to be less affected by the change in direction of motion taken by the fluid. Therefore, an accumulation of the particles against the extrados of the pipe bend occurs [K1,H2,J3]. Consequently, the probability of interaction between the particles is increased in the region where the majority of collisions of particles against the pipe wall occur [A2]. Interactions between particles have a significant effect on the amount of erosion damage that will occur to the pipe wall. It has been proposed that collisions between rebounding particles and those that are approaching the pipe wall will lead to a greater number of lower velocity collisions over a greater pipe wall surface area [A2]. This in turn will lead to a reduction in the amount of erosion damage that occurs to any particular area. The trajectories of the particles following collisions between each other and the pipe wall are very dependent upon the impact conditions as well as the particle shape and material properties [A2].

One of the major variables used to describe the actual throughput that can be achieved in any given pneumatic conveyor is the suspension density of the flowing gas/solid mixture. The higher the value of the suspension density the greater the mass of solid material conveyed per volume flow rate of gas. This variable has a significant part to play in the erosion process (see Figure 2.2). As the suspension density is increased, the likelihood that inter-particulate collisions will occur will increase. This will lead to a reduction in the average kinetic energy of particles striking the pipe wall as well as cause particle impacts to occur over a greater pipe wall area. To counteract this reduction in the amount of wear, the intensity of particle impacts per unit area of the bend wall will have a significant effect on the life of a bend. With an increase in the suspension density there will be an increase in the number of particle impacts per unit area, and, therefore, damage will increase in regions where this

Figure 2.2 The effect of suspension density on the mass removed from a mild steel bend at puncture after being eroded by quartz sand particles [M1].



takes place. In this manner the amount of material conveyed before the bend fails through puncture will decrease as shown by Mills [M1]. However, the work carried out by Mills (as shown in Figure 2.2) shows results for the total mass loss from the entire bend. Consequently, it is not possible to differentiate between the effects of an increase in intensity of particle impacts and a reduction in erosion caused by inter-particulate collision effects in the case of this data. The results presented in Figure 2.2 imply that the erosion becomes more focused as the suspension density increases, however, it is not possible to discern how localised the wear scars are from this data since it is possible for several regions of wear damage to occur within the bend simultaneously (as will be shown later).

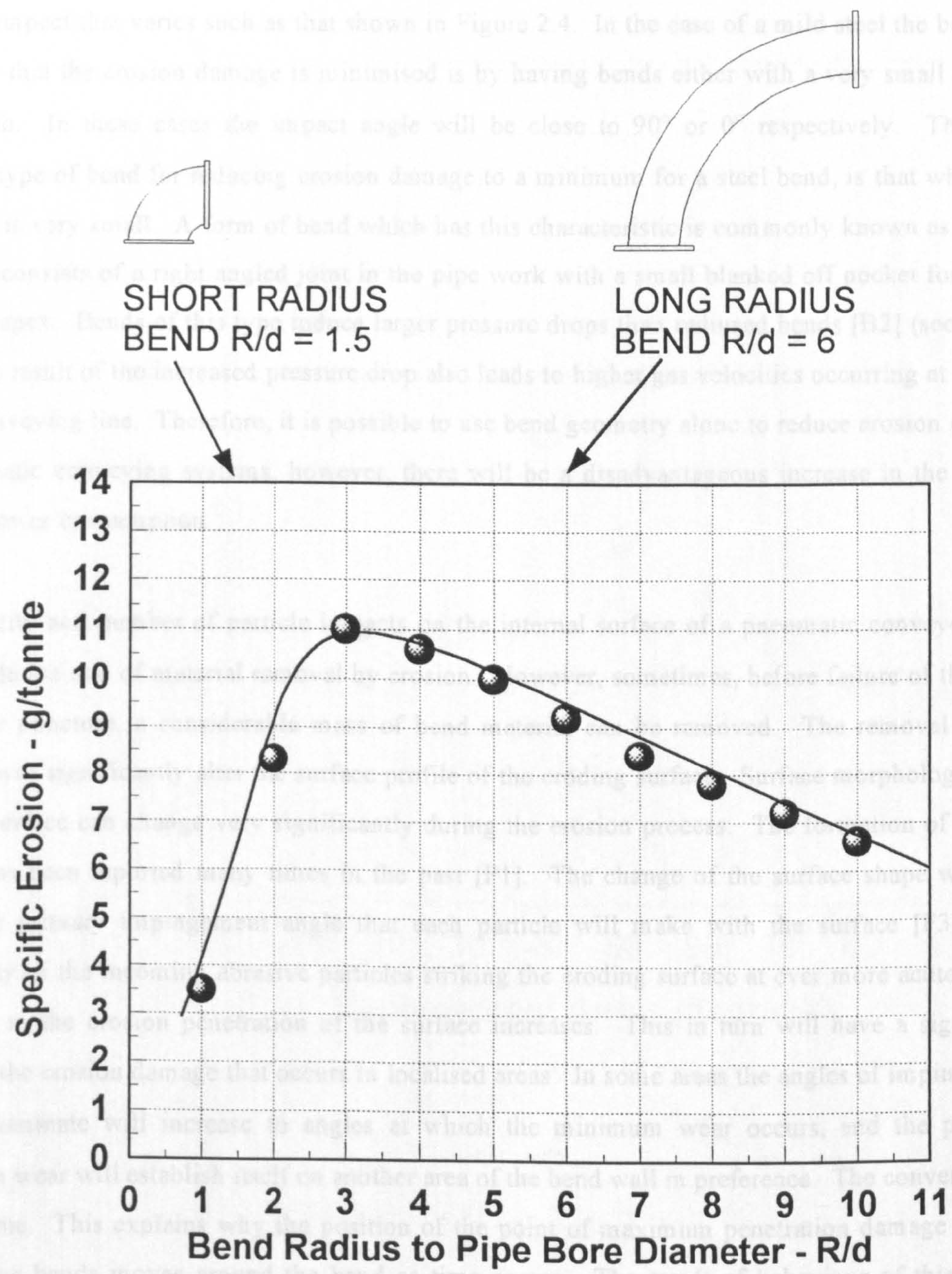
2.2.2 The Geometry of the Surfaces Suffering Erosion in Pneumatic Conveyors

One of the most useful advantages that a pneumatic conveyor has over other forms of bulk solid transportation systems is that the conveying line can be designed to fit along and through confined and tortuous paths between its two ends. This leads to a large variety of pipeline designs in industrial pneumatic conveyor installations. The source of the pressurised air used to provide the motive force for conveying the bulk solid material must be matched to the number and type of bends and straights of various orientations within a pneumatic conveyor [S2,M2]. The type of bend used will have a significant effect on the pressure drop that occurs along the pneumatic conveyor [B2]. As mentioned previously it tends to be in the bends of the pipeline where the majority of the particle impingement against the walls occurs. A significant amount of the pressure drop can be attributed to the energy required to re-entrain particles into the gas flow after such collisions. As a consequence of the collisions between particles and bend wall, the erosion damage and failure of bends is quite common.

There are a large variety of bends that are available to try and combat the destructive effects of particle impingement. Numerous materials are used to try to reduce the penetration effects on bend walls. These will be discussed briefly in the next section and in more detail in Appendix 2A.

There are also benefits to choosing bend geometry deliberately to minimise wear. If it is assumed that the pipeline will be constructed from a commercially available mild steel, the failure of the bends in the system can be seen to be significantly affected by the bend geometry [M1] (see Figure 2.3). For swept (radiused) bends the bend geometry is described by the ratio of bend radius, R, to pipe diameter, d. The main reason for the change in the erosion damage observed with different R/d ratios is that the mean impact angle of the particles against the bend wall varies significantly with the ratio, R/d. In bends where the R/d ratio is very low, (i.e. a very tight radiused bend), the particle-wall impingement angle approaches 90°, while as soon as the R/d ratio increases the impingement angle

Figure 2.3 The effect of bend geometry on bend wear for mild steel bends being eroded by quartz sand [M1].



decreases rapidly. In the case of mild steel the predominant mechanisms of wear suffered during particle impact are those grouped under the heading 'ductile wear' [F2]. (The details of the mechanisms involved in this form of wear are described in Appendix 2A). Past research has indicated that a material undergoing 'ductile' erosive wear follows a curve of erosion damage versus angle of impact that varies such as that shown in Figure 2.4. In the case of a mild steel the best way to ensure that the erosion damage is minimised is by having bends either with a very small or very large ratio. In these cases the impact angle will be close to 90° or 0° respectively. The most efficient type of bend for reducing erosion damage to a minimum for a steel bend, is that where the D/d ratio is very small. A form of bend which has this characteristic is commonly known as a blind tee. This consists of a right angled joint in the pipe work with a small blanked off pocket formed at the bend apex. Bends of this type induce larger pressure drops than radiused bends [B2] (see Figure 2.5). The result of the increased pressure drop also leads to higher gas velocities occurring at the end of the conveying line. Therefore, it is possible to use bend geometry alone to reduce erosion damage in pneumatic conveying systems, however, there will be a disadvantageous increase in the overall system power consumption.

The velocity and number of particle impacts on the internal surface of a pneumatic conveyor bend will decide the rate of material removal by erosion. However, sometimes, before failure of the bend occurs by puncture, a considerable mass of bend material can be removed. The removal of this material will significantly alter the surface profile of the eroding surface. Surface morphology of an eroding surface can change very significantly during the erosion process. The formation of surface ripples has been reported many times in the past [P1]. The change of the surface shape will also affect the primary impingement angle that each particle will make with the surface [F3]. The probability of the incoming abrasive particles striking the eroding surface at ever more acute angles increases as the erosion penetration of the surface increases. This in turn will have a significant effect on the erosion damage that occurs in localised areas. In some areas the angles of impingement that predominate will increase to angles at which the minimum wear occurs, and the point of maximum wear will establish itself on another area of the bend wall in preference. The converse may also be true. This explains why the position of the point of maximum penetration damage seen in long radius bends moves around the bend as time passes. The result of behaviour of this sort is severe erosion damage throughout the bend leaving a series of pockets in the bend internal surfaces (see Figure 2.6 [M3]).

Figure 2.4 Reproduction of the classic curve for 'ductile' erosive wear versus impingement angle [F5].

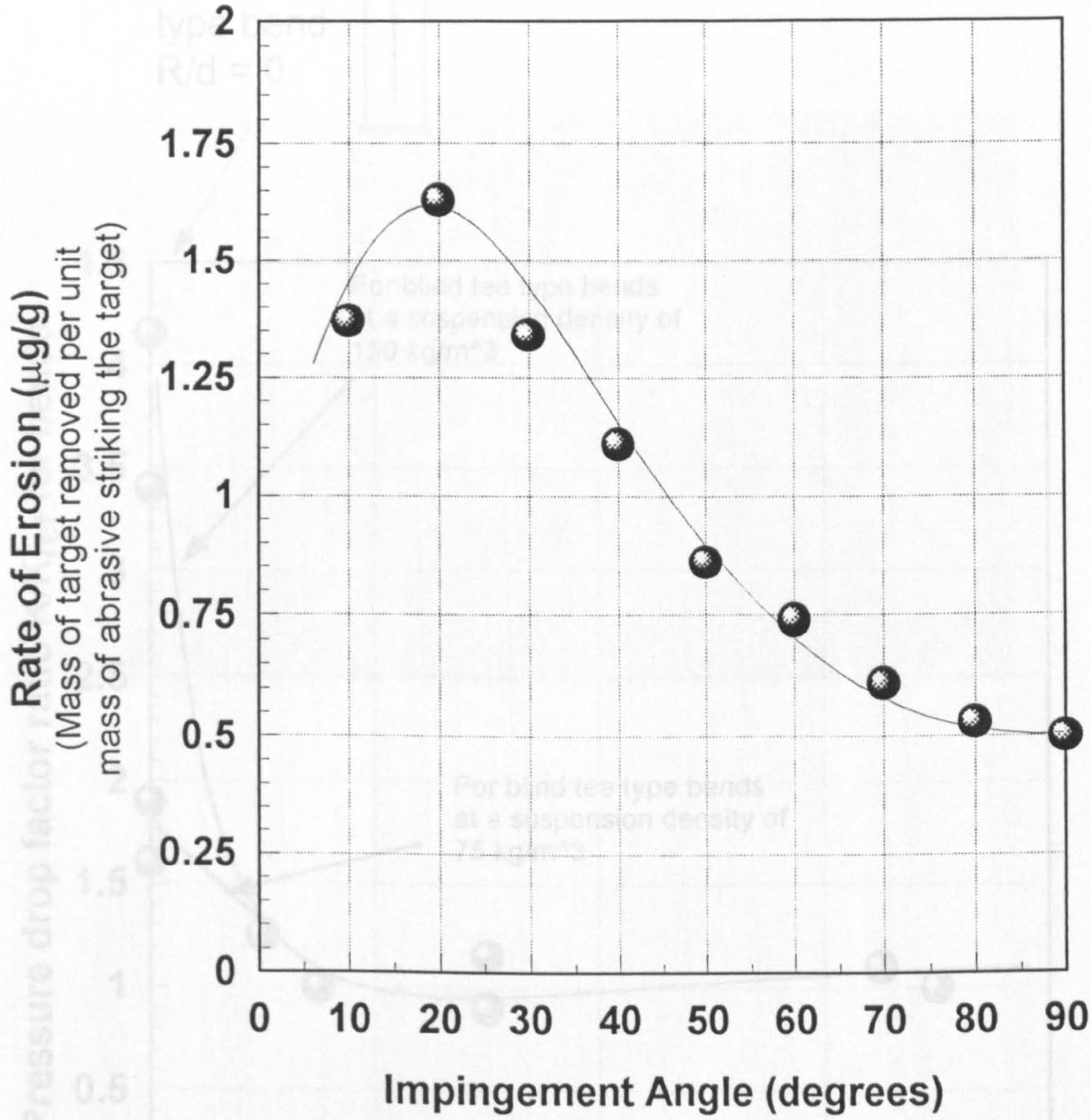


Figure 2.5 Graph of bend pressure drop versus bend R/d ratio [B2].

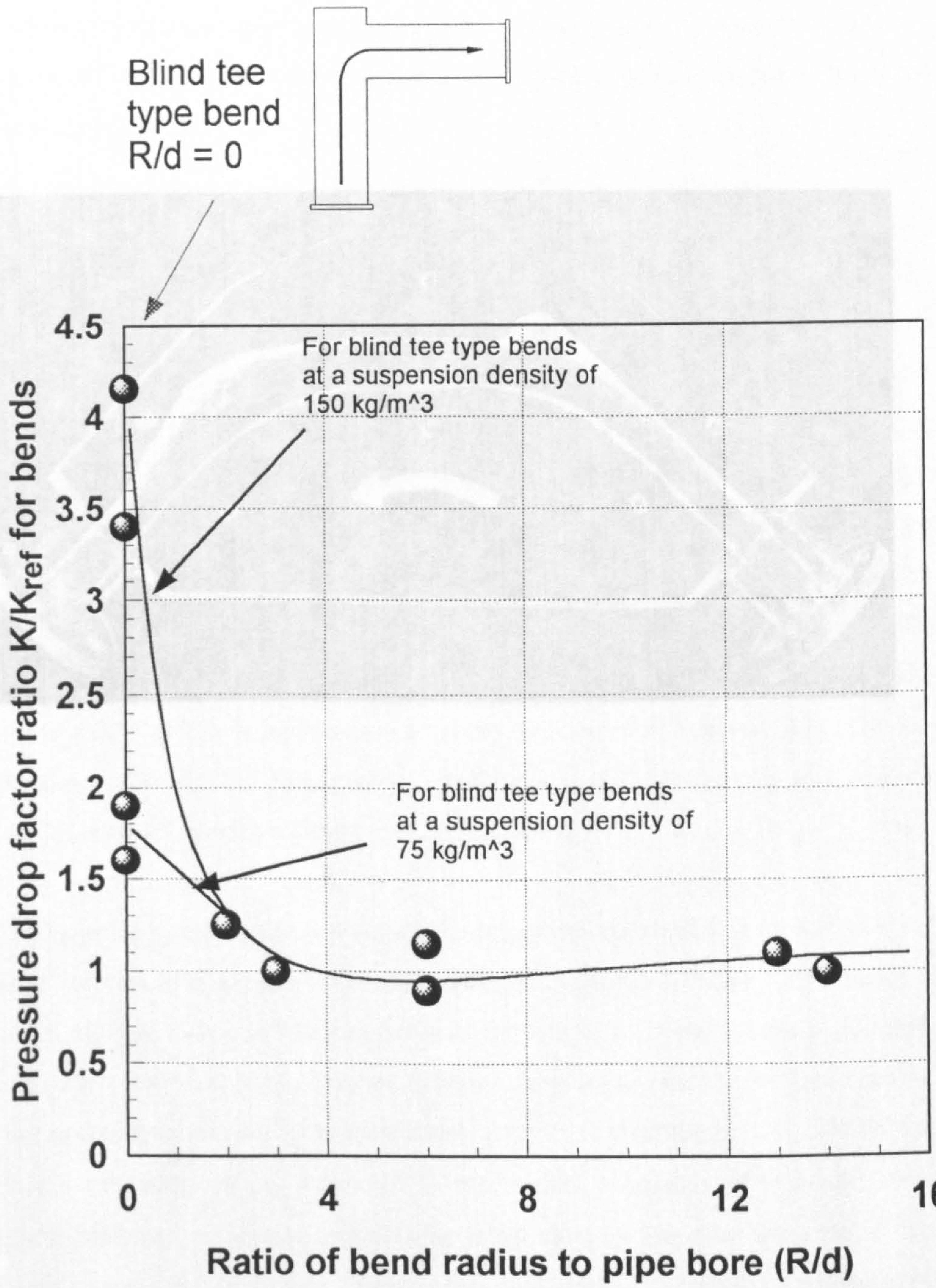
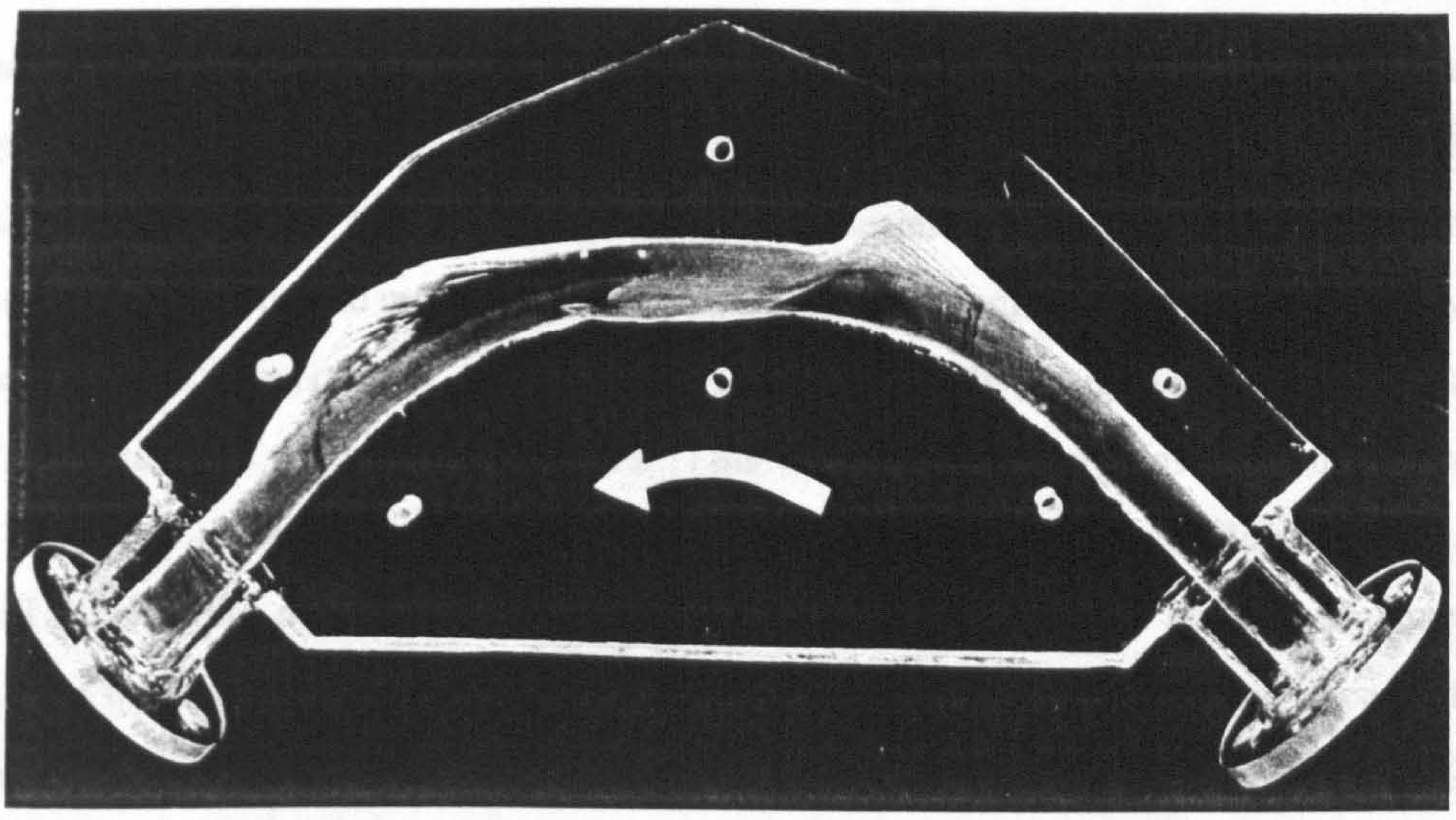


Fig 2.6 Photograph of long term erosion damage in a swept radius thick walled perspex conveyor bend after erosion by alumina particles [M3].



2.2.3 Pipe Wall and Particle Material Properties Which Affect Erosion.

There are a large variety of materials that can be used to combat wear in pneumatic conveying systems in industry. These range from ultra-hard ceramics and ceramic composites to elastomers and natural rubbers [L3]. Each of these material groups behave differently when subjected to solid particle impact (see Appendix 2A).

There are several wall material, particle material and geometry properties which it has been suggested will significantly affect the amount of erosion that occurs. These depend on the type of material from which the pipe is made or lined, and the bulk solid material that is being conveyed. A more detailed appraisal of the work on the mechanisms of erosive wear are included in Appendix 2A. Measurement of the mechanical properties of the wall materials is relatively straightforward, but it is much more difficult to determine those of the particles. This is because the particles are usually very small and consist of a large variety of constituents (e.g. coal [R1]). It is quite probable in many cases that not only will the eroding pipe wall material be suffering damage, but the particles themselves may be breaking up on impact. It has been suggested in previous work that the presence of fragments of particles will increase the amount of erosion damage since the particle fragments will strike and detach lips and ridges of highly deformed and weakly attached wall material [T1]. Obviously, if the particles fragment at impact the particle shapes will alter as well. Ultimately this will also have an effect on the quantity of erosion damage that occurs [M1].

The impact of a solid particle against a surface under conditions similar to those that would be seen in pneumatic conveying equipment are short duration, high load events. The strain rate of the deformation of the materials involved can be very high [H3,B3], 10^6 per second is possible. Material properties at strain rates this high are quite different from those that can be measured at the strain rates that are normally associated with traditional engineering operations [C2]. Doubt can therefore be cast on the relevance of any reference to mechanical properties of materials obtained from experiments carried out at normal engineering strain rates, when they are used in a discussion regarding solid particle impact erosion. Despite this, researchers have been continuing to try to model erosion phenomena in terms of standard engineering material properties. The most prevalent amongst these is hardness which is measured using Vickers, Rockwell or Brinell equipment. Several useful trends have been discovered by relating erosion results to hardness of the particles and the eroding surface [H4], however, as yet no definitive model of erosion has been developed [B22,E1,H21,K3,S18,S3,R5,R8].

Another set of variables that has a significant effect on the erosion process is that of particle shape, and the texture of the surface of the particle that is in contact with the eroding surface. These variables will dictate the contact area between the particle and the eroding surface, as well as the main cause for the effective friction that occurs during the contact phase of the particle impingement [K2,K3,B4,C3]. Obviously the impact energy will be imparted to the eroding surface via the contact surface area between the particle and the pipe wall, and this will therefore affect the amount of erosion damage that occurs. If the contact area is reduced, for any given incident kinetic energy the intensity of energy transfer per unit area will increase. It is likely that the deformation of the materials involved will increase in this instance as the strain rate of the deformations will also increase.

A surface which is struck by a solid particle striking at an oblique angle to the eroding surface will be affected by the effective friction between the surface and particle. Whether the particle slides during the contact or rolls has a significant effect on the erosion mechanisms [H5,R2,B5]. The effective friction during the impact and the rotational velocity of the particle has an effect on the magnitude of the erosion damage as well as the subsequent trajectory of the particle after impact [K3,B5].

Most of the modelling that has taken place to date for the solid particle erosion of various surfaces has been based on empirical expressions utilising material properties determined under normal engineering test conditions [H6,S3,E1]. However, apart from the supposed effect of strain rate, several other material properties have been noted to have an effect on erosion. These include a heavy dependence of erosion damage on surface microstructure and morphology. Work on the morphology of steels has been undertaken by Levy [L4] and the microstructure of ceramics has been suggested as being important to the erosion behaviour of these materials [A3]. Further investigations into the effects of the morphology of steels are currently being undertaken at The University of Greenwich.

Due to the high strain rate deformation of the eroding surface it has been suggested that elevated temperatures are generated in the immediate surface layers of the material. The magnitude and effects of these temperatures have been investigated by Hutchings, Doyle, Gommel and Neilson [H7,D2,U1,N2]. It has been suggested that the temperatures are high enough to re-anneal a heat treated steel surface.

The erosion of composite materials is further complicated by the fact that there are normally at least two phases to such a material. The first of these is a soft binder and the second a series of much harder particles which are effectively 'glued' together by the binder. Each of these two phases are affected quite differently by the particle impact. The other difficulty that is faced is that of the relative size difference between the hard particle spacing in the composite, and the size of the abrasive particle. If the abrasive particles are small enough, they will be able to wear away the soft binder material without hindrance from the harder particles in the composite. As a consequence of this the binder can be removed, allowing the harder particles to fall out of the surface [V2].

2.3 Erosion Studies Previously Carried Out on Pneumatic Conveyor Bends, and the Models that have been Derived for the Prediction of their Lives

This section of the thesis is laid out in chronological order.

2.3.1 Brauer H. and Kriegel E. 1964-1970.

There are four papers in this group [B6,B7,K4,K5]. The majority of this work was dedicated to the study of the motion and damage caused by individual particles striking various surfaces. Some pneumatic conveying tests were carried out by Kriegel, however, the range of variables investigated were limited [K4,K5]. These studies were also associated with hydraulic conveying [B6,B7].

2.3.2 Mason J.S., Smith B.V., *et al.* 1972-1973 and Yeung W.S., 1979.

This group of papers was the first to describe work whose purpose was to investigate erosion within pneumatic conveyor bends [M4,M5,M6]. The major emphasis of this work was directed at identifying the progress of erosion within perspex bends with artificially thick walls from the primary impact site to secondary and tertiary wear points within the pipe bore. This work formed a small part of a study directed at an investigation of gas-solids flows around bends in pneumatic conveyors. Two interesting methods were adopted in this work. The first was that these authors expressed the erosion damage in terms of the depth of wear. Secondly, they elected to use the air velocity in the bend to express the particle velocity, rather than going to the trouble of trying to measure the particle velocity directly.

The first model which aimed at the prediction of the erosive penetration of the wall of a pneumatic conveyor bend was based upon the findings of these authors [M4]. It was devised by Yeung [Y1], who used an erosion model proposed by Finnie (see Appendix 4F) to try to predict the findings of

Mason and Smith *et al.* The model consisted of a Lagrangian finite differencing routine which only permitted a single mode of gas-particle coupling effect, i.e. that of particle drag, all other particle forces were disregarded as being non-influential. The model also did not account for the effects of the turbulence in the flowing gas. No attempt has been made to rectify these restrictions since. Neither was any attempt made to account for the localised particle concentration. For a more detailed account of the use of this model see Appendix 5F in this thesis.

2.3.3 Bikbaev F.A., Maksimenko M.Z, Krasnov V.I. *et al.* 1972-1973.

The work carried out by these authors is presented in two papers [B8,B9]. These papers report a series of results obtained from carrying out detailed tests on a 50 mm bore pneumatic conveying pipeline with a single 90° test bend. Tests were undertaken with one abrasive material at a range of conveying conditions similar to those seen in industrial service. Empirical modelling was carried out based upon the results of the test work. The authors predominantly concentrated on finding out the effect of particle velocity and concentration on the erosion damage. The erosion damage was described in terms of penetration per unit time.

2.3.4. Mills D., Mason J.S., Tong K.N., and Agawal V.K. 1975-1986.

This is the most substantial group of papers dedicated to the investigation of erosion in pneumatic conveyor bends. It consists of twenty seven papers. Numerous investigations were carried out over this time period into the effects of several variables. The findings of this work were clearly summarised in a set of short course notes presented at The SOLIDEX '86 Solids Handling Conference at Harrogate in 1986 [M1].

Most notable amongst the variables investigated for their effects on erosion damage were conveying velocity, concentration of particles, particle size, particle shape and bend geometry. These authors investigated how important penetration rate was in predicting the failure of pneumatic conveyor bends. This work was carried out using the suggested methods of expressing erosive damage and velocity of flow suggested by Mason and Smith as stated above. The authors derived power law curve models for the mass of material removed from the internal surfaces of the bend, as well as for the penetration rate of the bend wall. These models were derived from macroscopic measurements of the major system variables which were highly dependent on the materials being conveyed. They can therefore be regarded as being specific to the tests carried out.

2.3.5 Shimoda K. and Yukawa T., 1983

This single paper [S4] reports the results of work carried out on the prediction of erosion damage in pneumatic conveyor bends. Tests were carried out on a pneumatic conveyor test rig to investigate the behaviour of the flowing suspension in the pipe bend, and to determine the most prevalent impact angle that occurred during the operation of the conveyor. A gas blast erosion tester was used to quantify the erosion performance of the material under conditions designed to simulate those that occurred in the pneumatic conveying test facility used by these authors. The maximum angle of impact found from the pneumatic conveyor trials was used to interpolate to a point on the gas blast erosion tester results. Subsequent to the erosion rate being found for the conveying conditions seen in the pneumatic conveyor, other investigations were carried out to evaluate the effects of particle concentration, particle size and wall surface hardness on erosion damage. In conclusion, an empirically derived equation to be used for the prediction of the erosion damage in a pneumatic conveyor bend was presented. The equation takes the form of those suggested by Mills *et al.* as mentioned above, and the values of the exponents used in the two models are similar.

2.3.6 Hoadley D. and Johnson T.D. 1985-1987

This work consists of a group of four papers [H8,J1,H9,J2] involving a model for the erosion of pneumatic conveying bends which includes a simple trajectory model. The effects of using various bend lining materials are included. The model does not include any mention of the effect of the suspension density of the flowing mixture on the erosion process. The work was carried out with UK coal and no other material; therefore the results are very specific. However, it is an interesting illustration of industrial problems. The model takes the form of a time stepping finite differencing routine which is of the Lagrangian form. The particle motion is super-imposed upon a model of the gas flow which is assumed to be of the potential flow variety. These authors carried out an extensive series of tests using a gas blast form of erosion tester on a wide range of wear resistant materials that are commonly used in pulverised fuel injection systems. Empirical power law curve fit models were applied to the data obtained from using the gas blast erosion tester. These empirical models were then used in conjunction with the trajectory model.

2.3.7 Flemmer R.L.C., Flemmer C.L. *et al.*, 1988

This work is presented in a single paper which includes a simple model for the prediction of erosion in a pneumatic conveyor bend [F4]. The effect that particle concentration/suspension density has on the erosion process is modelled to some degree in this case. Wear modelling is achieved by using a simple but effective form of empirical curve fitting based upon the impact angle and the kinetic energy of the a particle at impact.

2.3.8 Sato S., Shimizu A., Yagi Y., Yoshida H., and Yokomine T. 1993-1994

This recent work consists of two papers [S5,S6]. The work concentrates on the modelling of the erosion of a bend that was square in cross-section and of a right angle shape, in a 50 mm bore pneumatic conveyor pipeline. The model for the erosion process was based upon that proposed by Finnie and Bitter (see Appendix 4F). However, this was super-imposed upon a model of the flow of particles within the test bend. This took the form of a Lagrangian finite differencing routine and modelled the turbulent flow of the gas so that the motion of the gas effected the particles, but movement of the particles did not effect the gas flow. The erosion model required empirically derived constants. These were found using a rotating disc accelerator erosion tester of a type similar to that discussed later in this thesis. The major faults with this work were that the pneumatic conveyor was square cross-sectioned and that little account was made for the particle concentration and its effect on the erosion process.

2.4 Investigation of Erosion Using Bench Sized Erosion Testing Devices

2.4.1. Introduction to the Requirement and Use of Small Scale Erosion Testing Devices

There are numerous problems attendant with attempts to obtain accurate data regarding the penetrative erosive wear of pneumatic conveyor bends from pneumatic conveyors for the purposes of the development of predictive models. These problems include a lack of control over the major variables such as the particle impact velocity vector (magnitude and direction) and the localised particle concentration at the impact site. Also there are considerable difficulties in the measurement of these variables. Difficulties have also been found in the predictive modelling of the flow of a combined flow of solid particles and a gas [B10]. Another problem arises from the fact that the surface suffering erosive damage undergoes substantial changes in shape. This affects the flow of the suspension, since not only will the motion of the gas be affected but the rebound trajectories of particles striking the eroded surface will alter as the amount of erosion damage increases. Also, inter-particulate collisions tend to have a significant effect on the flowing suspension. There are considerable problems in accounting for these variables. The need to control them becomes most important if detailed erosion studies are to be undertaken, and the effect that each of the variables has on the erosion process needs to be ascertained in isolation. To this end several forms of erosion tester have been developed in the past to enable these more fundamental studies to be carried out.

The following sections of this chapter include brief descriptions of the various devices that have been used in the past. Appendix 2B describes the advantages and disadvantages of the various forms of erosion tester. Large quantities of work on erosive wear have been carried out using testing equipment of the sort described in the next few sections, however, it is beyond the scope of this thesis to catalogue this volume of work. This is because in the majority of cases the conditions, (i.e. particle velocity and concentration), under which the work was carried out were not relevant to the studies undertaken in this project.

2.4.2 Rotating Disc Accelerator Erosion Tester.

This form of tester relies on the forces generated on passing particles through a series of tubes mounted in a rotating disc, to accelerate them to the required velocity. At the edge of the disc the particles part contact with the disc and travel to strike a series of targets arranged around the periphery of the acceleration mechanism. This form of rig was originally proposed for use in the study of solid particle impact erosion in Estonia by Kleis [K6] in 1956. They have been used continuously to date by the former Soviet Union countries and have been the subject of standardisation; GOST 23201.078 is the designated code for this standard [G1]. See figure 2.7.

2.4.3 Gas Blast Erosion Tester.

In this form of erosion tester a pressurised gas is allowed to expand through a small nozzle hence developing high gas velocities. A constant stream of abrasive particles is fed into the high velocity gas flow. The particles are accelerated by using the drag forces that occur as a consequence of the magnitude of the relative velocity between the particles and the surrounding gas. This form of device was one of the first forms of erosion tester used in Western Europe and the USA. The first mention of a device of this type was found in a paper by Finnie in 1958 [F5] although the concept of the device has been used for commercial bead blasting equipment and undoubtedly predates this. This form of tester has been the subject of standardisation; DIN 50332 [D3] of the Federal Republic of Germany, and ASTM G76-83 [A4] a standard of the USA. See Figure 2.8.

Fig 2.7 Schematic view of the rotating disc accelerator erosion tester.

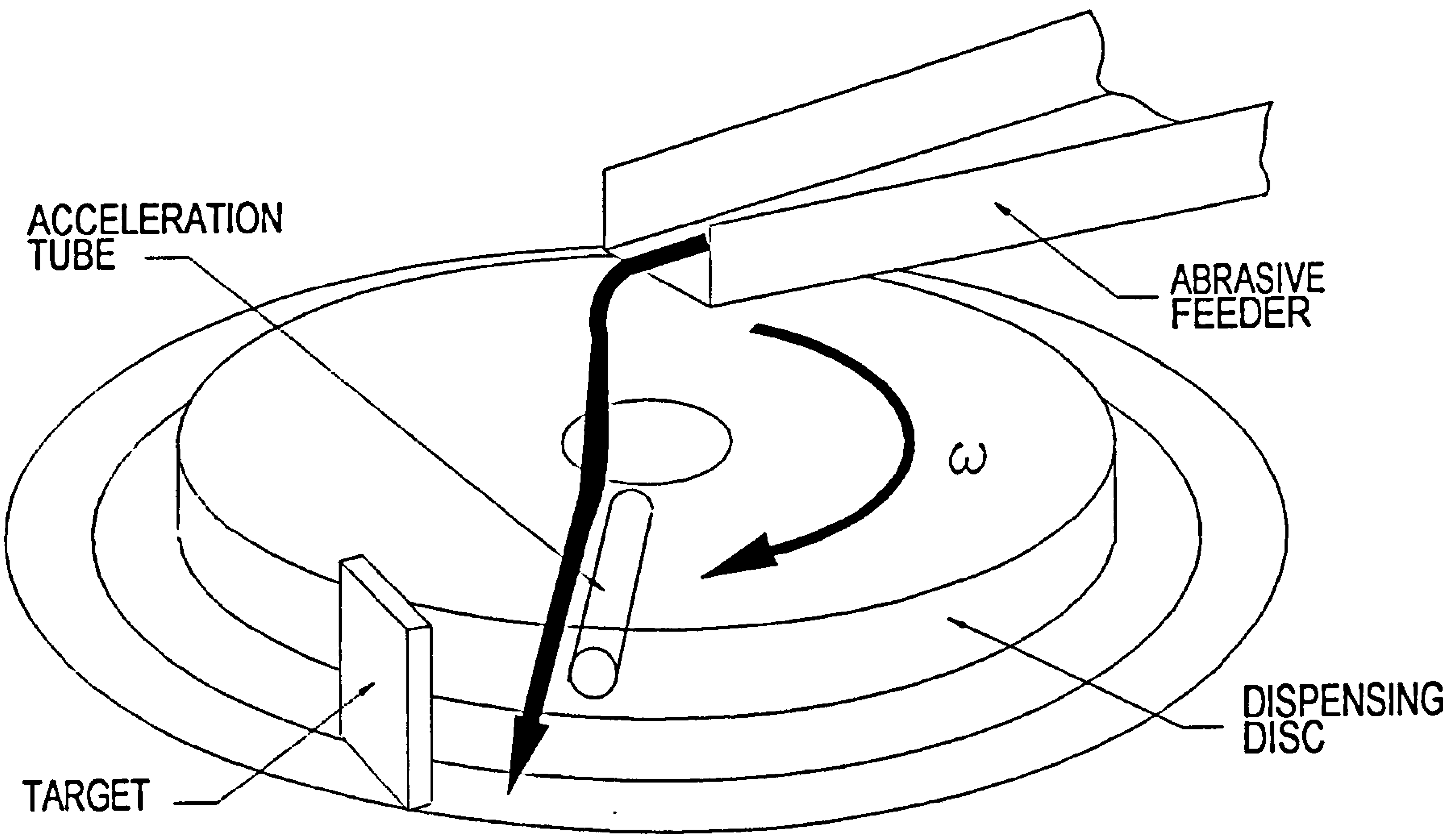
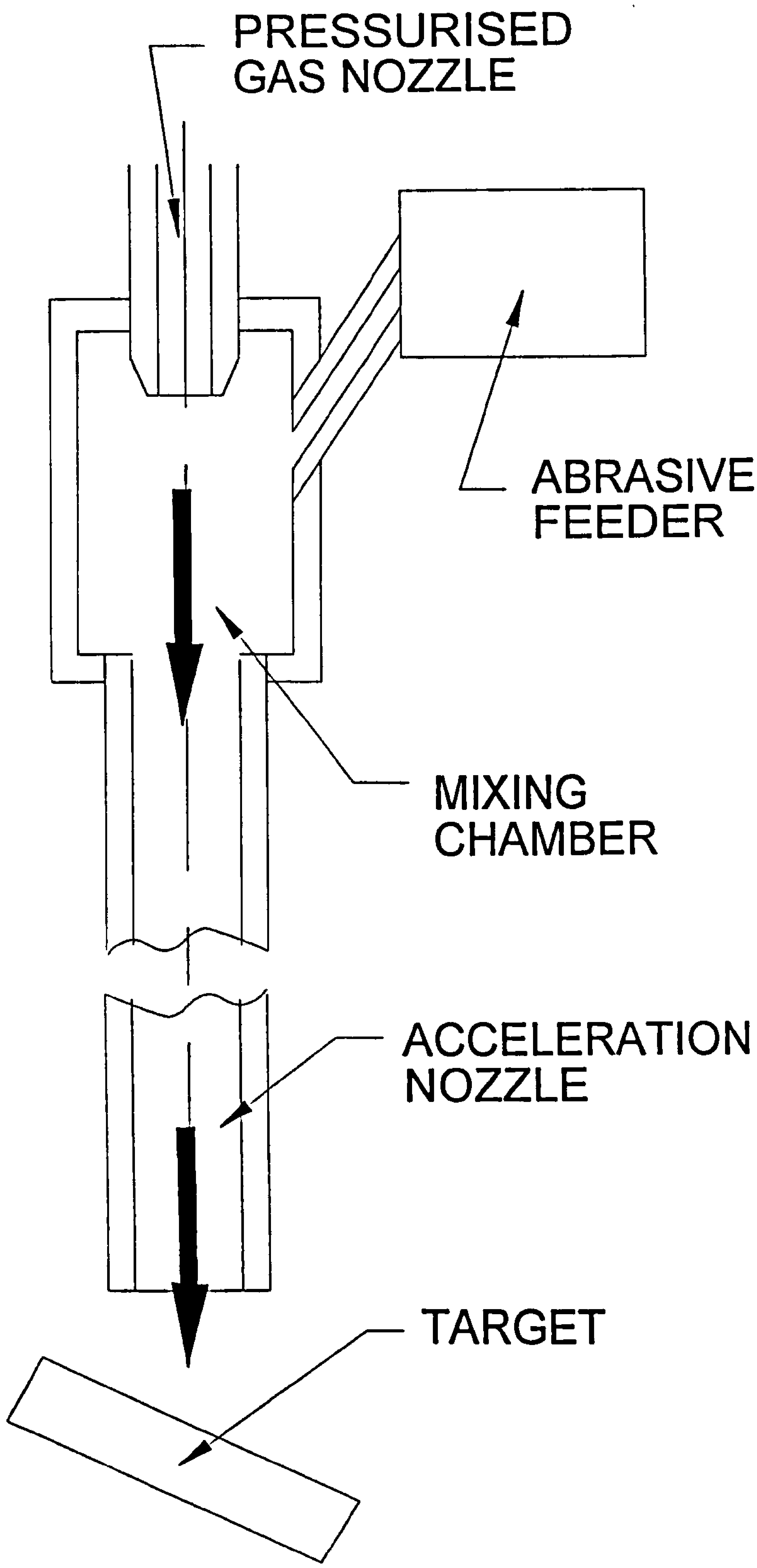


Fig 2.8 Schematic view of the gas blast type erosion tester.



2.4.4 Gas Gun Impact Testers.

In this form of erosion tester single particles are projected at a surface by using a form of gas powered projector resembling an air gun. This form of tester has been used extensively in the past to assess the behaviour of a materials response to single particle impacts. The particle velocity usually needs to be measured by some specialised means in this form of tester. This type of tester has also been extensively used in the field of assessing the degradation of fragile particles during an impact [S7]. A tester of this type has been in use at Cambridge University for many years for the measurement of damage caused by a single particle impact [W1].

2.4.5 The Whirling Arm Test Rig.

In this form of tester a continuous stream of particles is allowed to fall under the influence of gravitational forces through the path of a high speed rotating arm, on the ends of which target samples are placed. The particles strike the surface of the target each time they move through the path of the particle stream. This type of tester was originally devised by Goodwin, Tilly and Sage [G2] for the investigation of erosion by solid particle impact in turbo-machinery such as gas turbine engines.

2.4.6. Free Fall Rig.

This form of erosion tester simply consists of a device by which a controlled stream of abrasive particles are allowed to fall from a fixed height on to the surface whose erosion resistance is to be examined. This form of device has largely fallen into disuse since its last reported use for erosion experiments by Bitter [B11,B12].

2.4.7. Submerged Rotating Arm Rig

This form of rig has been used in two forms in the past. The first proposed that the samples should be attached to the ends of four arms and rotated in a container of the abrasive material [H10]. This form of tester has several drawbacks when it is considered for the low particle concentration, medium velocity erosion of bends in a pneumatic conveyor. These drawbacks include the fact that the particle concentration cannot be controlled unless the contents of the pot can be fluidised; even then the accurate simulation of particle concentrations seen in pneumatic conveyors is not possible, since control of the particle distributions in a fluidised bed are almost impossible. The other method by which devices of this form have been used is in the erosion of materials in slurry systems where the abrasive particles are suspended in a liquid [C4,C5] (in this instance they are usually known as slurry pots).

2.5 A Detailed Review of the Test Work Carried Out on Laboratory Erosion Testers and Its Comparison With Pneumatic Conveyor Tests

Only a few researchers have actively made direct comparisons between erosion tests carried out on a laboratory erosion tester and large scale pneumatic conveying erosion trials. This work has already been mentioned in section 2.2 above, however, a more detailed description of this work will be carried out here. Only four researchers or research teams have carried out work using this strategy. These were the works carried out by a) Shimoda and Yukawa, b) Mills *et al.* c) Hoadley and Johnson *et al.* and d) Sato and Shimizu *et al.* Each of these works are discussed in chronological order below.

2.5.1 Shimoda, K. and Yukawa, T., 1983 [S4]

These researchers carried out small scale erosion tests on a gas blast form of erosion tester. Tests were carried out for various angles of impingement at three different particle velocities for a series of mild steel targets being struck by quartz sand of 220μm mean particle size. Tests concerning the effects of suspension density or particle concentration were carried out on this device for an impingement angle of 30°. Also presented were the results of tests for the effects of particle size and pipe wall material hardness, but only for an impingement angle of 30°.

Pneumatic conveying trials were carried out on a 50 mm diameter bore pipeline that was 8.5 m long. The test conditions that were used were an air velocity of 28 m/s and a solids loading ratio of 8 (solids loading ratio being the mass flow rate of solids divided by mass flow rate of gas; this measure of particle concentration has been used extensively in the past). Tests were carried out with quartz sand of both 220 and 28 μm mean particle diameter. The bend geometry was a smooth 90° swept bend of 400 mm radius. Bends were constructed of clear PVC and mild steel. The PVC bends were used to observe the flow of the particles around the bend. From this work an estimate was made of the maximum impingement angle that was likely to occur. No results for the test bend erosion damage for the pneumatic conveyor test facility are given in this work. However, results of the measurement of the penetration of an industrial pneumatic conveyor bend are given. The data that are presented for this bend indicate a linear change in the penetration damage caused with mass of material conveyed. Unfortunately, a full set of the information regarding the conveying conditions is not presented for this case.

The outcome of this work led to an expression which was empirically derived and involves particle velocity, solids loading ratio (called phase density by Shimoda and Yukawa), particle diameter and the hardness of the pipe wall material. Interestingly enough, although the impingement angle is known to be important from earlier work, (most notably that of Finnie [F5] and Bitter [B11,B12]), it is not included in this expression.

The main criticism of this work is that the effect of particle impact at angles lower than 20° were not investigated. Neither were the effects of the solids loading ratio or pipe wall hardness taken into account in their work on the gas blast erosion tester. Shimoda and Yukawa seem to have taken the highest impingement angle that occurs at the primary impact location and used this exclusively, thereby ignoring the effect that impingement angle has on the wear rate. It will be shown later in this work that impingement angle has a serious effect on the wear rate that can occur [B13].

2.5.2 Mills D., *et al.*, 1987 [M7]

The aim of the work presented in this paper was to assess the value of using hardened and tempered steels, in order to increase the erosion resistance of steel pneumatic conveyor bends. As a consequence of this specific task, any investigation of the effects of particle concentration and particle velocity was neglected.

The first test facility that was used was a crude form of a gas blast erosion tester. In this instance a blow tank form of feeder was used. With a feeder of this type the particle concentration cannot be fixed and consequently the particle velocity will tend to vary. In the case of the work presented in this paper no mention is made of trying to measure the particle velocity in this rig although the solids loading ratio was stated as being approximately 1.

The second test facility used by these authors consisted of a 2" nominal bore pipeline containing seven swept 90° bends of unstated radius. Samples of the heat treated steels were placed in the bends in the form of insertable plugs. Unfortunately, the position at which the insertable plugs were placed in the pipe radius were not mentioned. It is stated that the samples were shaped so that they caused no projections into the pipe bore. Conveying conditions were such that the particle impact velocity was between 15 and 20 m/s with a mean solids loading ratio of 4.5.

The data for the results of the work carried out on the gas blast erosion tester is given in graphical form by a plot of mass lost from target versus angle of impingement for various material hardnesses. Because of this, the work is of limited use as far as studying bend penetration is concerned. A poor correlation is shown between the results obtained from the two testers, for the variation of specific erosion versus sample hardness. The poor comparison is almost certainly due to the large errors in test conditions that would occur with the feeding devices used in the test equipment utilised for the test work.

2.5.3 Hoadley, D. and Johnson, T.D., *et al.*, 1987 [H8,J1,H9,J2]

The work of these authors was carried out on behalf of the CEGB (Central Electricity Generating Board, UK). Their research was directed towards trying to assess the effects of conveying coal, supplied to CEGB power stations, on the erosion of the conveying pipelines used to transport the pulverised fuel (pf) from the mills to the burners in the boilers. The work took the form of a series of detailed tests undertaken on a gas blast erosion tester for about seventy different materials with which pipe bends can be lined. The particle velocities in these tests were limited to between 20 and 60 m/s and the solids loading ratio was limited to a value of 1. The impingement angles that were adopted were from 20° to 60°. The results from this test work were used to find empirical relationships between erosive wear, and impingement angle and particle velocity only.

Accompanying this test work was a detailed attempt at modelling the trajectories of the particles within the two phase flow expected in the pf systems examined. This model, when combined with the empirical results derived from the tests carried out on the gas blast erosion tester, produced predictions for the penetration rate of the bends being considered. It was found that the model predicted that the penetration wear scar seen on the bend wall would not be affected by particle size. The major variable that was predicted to affect the erosion penetration rate was the bend geometry. Performance of this model was compared to on-site measurements taken for the penetrative damage that occurred in pipe work in UK coal fired power stations. In conclusion, this work took the form of empirically derived expressions for the penetration damage suffered by various materials on a gas blast erosion tester, included these within a model for the particle trajectory, and compared this with on-site data. This work is quite extensive and some agreement was said to have been found between the model derived as described above, and observations made on actual conveyors; However, no quantitative results are presented to support this assertion.

These researchers stated that the impingement angle that is most prevalent in the erosion of a smooth radiused bend is less than 20°. However, none of their erosion tests using the gas blast erosion tester were carried out at angles lower than this. It was stated that the behaviour of the materials being tested at angles lower than this could be extrapolated to include the lower angles, by assuming that there is no erosion at an impingement angle of 0°. It is possible to argue that erosion at 0° has no physical meaning since at this angle of impingement no particles can strike the surface of the material to cause erosion damage. This is the subject of detailed discussions later on in this thesis, where it is argued that extrapolating data to include no erosion at 0° impact angle may give false values. A second criticism that can be made is that the particle distribution within the pipeline was never homogenous. These researchers stated this fact and did attempt to assess the importance of this by modifying their erosion/trajectory model. It was not mentioned that any attempt was made to test at a variety of particle concentrations using the gas blast erosion tester. Mills [M1] indicated that particle concentration has a very significant part to play in the study of erosion by solid particle impact. Later work by Krishnamoorthy and Seetharamu [K7] have attempted to account for this variable by incorporating it into the empirical expression originally derived by Hoadley and Johnson. Further tests were also carried out by these researchers to investigate the effect of the particle mass flux at impact on the erosion resistance of materials [K8]. However, no mention of the non-homogeneity of the particle concentration within the two phase flow, which is known to occur in pneumatic conveying, was made in their work either.

2.5.4 Sato, S. and Shimizu, A., *et al.*, 1993-1994 [S5,S6]

These two papers describe the most detailed modelling carried out to date on the erosion of a pneumatic conveyor bend. The results from tests undertaken on a rotating disc accelerator erosion tester were used to form the basis of a model which was linked to a detailed trajectory model for the particles in a pneumatic conveyor duct. This model was then compared to the results obtained from carrying out detailed tests on an actual duct. The materials that were used were glass beads of 60μm mean diameter. Commercial copper plate was used for the targets.

The test work that was carried out on the rotating disc accelerator covered a range of particle velocities. These were measured using photographic techniques. However, no account was made for the effect of particle concentration on the erosion process. No indication of the values of the particle concentrations occurring in the rotating disc accelerator erosion tester was given. The particle velocities that were used were 10.0, 17.3 and 23.0 m/s. The test equipment was placed under a vacuum in order to reduce the effects of air drag on the abrasive particles once they had left the acceleration mechanism, i.e. the rotating disc. Impingement angles of the particles striking the targets were calculated using the geometrical equations described by Söderberg *et al.* [S8].

In the case of the pneumatic conveying trials a square sectioned right angled duct was used, 50 mm by 50 mm in section. Particles were trickled in through a small funnel attached to the extrados of the pipe bend. The conveying conditions used in these tests included the same particle velocities as used in the rotating disc accelerator erosion tester, and the solids loading ratio was stated to be 0.08. Erosion damage was measured by removing and weighing small copper tiles that had been incorporated into two of the walls of the pipe work. The model that was developed was used to predict the erosion damage. Good correlations were obtained in comparisons made between the predicted erosion damage seen in the pneumatic conveyor and the results obtained from the rotating disc accelerator erosion tester.

The major criticism that can be levelled against this work is that the actual conveying pipeline used was not representative of the pipe geometries used in industry. Particle concentrations were neglected in this work programme and this should be seen as a major fault in this work. It was also noted that several flaws may have been apparent in the technique of operating the rotating disc accelerator erosion tester. These centre largely around the problems of particle jet dispersion which is clearly illustrated in the works of Shimizu and Sato *et al.* [S5,S6], and the effect that this may have on the erosion of the target samples. From the geometry of the test equipment illustrated in these papers it is possible that the vertical dispersion of the particle jet was greater than the overall target height and therefore, some particles failed to strike the targets. Also it was not stated that the impingement angle on each target in such erosion testers is subject to variation across the target surfaces. This fact will also have some bearing the analysis of the results that are presented in the papers that describe the work undertaken by Sato and Shimizu.

2.6 Conclusions Made as a Consequence of this Literature Review

From the many technical works that describe erosive wear in two phase gas-solid systems it can be concluded that the damage caused by erosion and the mechanisms involved are very complicated.

Several researchers have carried out tests on pilot sized pneumatic conveying systems. However, this remains an expensive and time consuming method of carrying out tests to derive methods for predicting the life of components that comprise such systems. It is also extremely difficult to measure the important variables that affect erosion damage significantly in such systems. None of the empirical models derived from tests on large scale pneumatic conveyors have covered the full spectrum of variables required to enable reliable predictions of the life of components to be made.

Several laboratory erosion testers have been developed in the past to examine the relationships between the major variables involved in solid particle impact erosion. All of these testers have advantages and disadvantages and these have been discussed thoroughly.

It can be seen from the previous research carried out in this area, that there has been a relatively small amount of work directed towards finding links between erosion results obtained from detailed tests carried out on pneumatic conveying systems, and those obtained from any form of laboratory erosion tester. In summary there is considerable scope for improving the predictive techniques developed to date. The work described in this thesis will contribute to furthering knowledge in this area.

The next chapter describes briefly the approach that was made by this author to solving this problem.

Chapter 3

The Structure of the Experimental Investigation.

3.1 Introduction

This chapter begins with a discussion of the outcome of the literature review that was undertaken, which was presented in the previous chapter. The experimental plan that was adopted for the project is discussed in the light of the findings of the literature survey, and with reference to the declared goal of the project, which was to establish a link between results for erosion damage obtained from a laboratory erosion tester and an industrial scale pneumatic conveyor.

3.2 Choice of Variables to be Investigated

Investigating the work that had been carried out before the start of this project showed several variables to be important to penetrative wear. These variables are as follows:-

a) Erosion damage must be measured in a system of units that can be utilised to predict the life of a bend in a pneumatic conveyor. The failure of a bend in such a conveyor is taken to have occurred when the bend wall is first punctured. It is therefore necessary to be able to account for the erosive damage in terms of penetration rate [M8]. Measurement of the mass lost by a bend due to erosion does not assist in finding out the depth of penetration damage or its location within the bend. This is because wear damage can be either focused to a small area, which requires a small amount of material removal to occur before puncture takes place, or over a wider area, where the opposite is the case.

b) An accurate assessment of the velocity of the particles striking the material suffering erosive wear is essential if an accurate model is to be proposed. This is because the amount of damage inflicted on a surface is dependent to a large degree on the kinetic energy of the impinging particles [F5,B11,B12]. In addition, the angle of impingement of the particles against the surface is fundamental to the effect that the particle velocity has on erosion damage [B11,B12].

It has been widely reported in previous research literature that the erosion damage suffered by a material depends predominantly on the velocity of the particle impact. Power law curve fitting exercises have taken place where the value of the exponent has been seen to vary from 2 to 4.5 [H1,M9]. Since the value of this exponent is so variable, scaling for the effect of velocity from test results obtained from carrying out high velocity experiments, where the erosion test time can be reduced, is inaccurate. Therefore, the only way in which values for erosion damage at the comparatively low particle velocities seen in pneumatic conveyors can be assessed, is by replicating these velocities in the test equipment being used.

c) The particle concentration of the two phase flow striking the surface suffering erosive damage is important [H1,K9]. Despite this, in the past several researchers have reported that particle concentration affects the erosion process to a negligible extent. However, this can be ascribed to the fact that the range of particle concentrations that they considered was too limited to highlight the true effects that could be observed [K9].

Reports suggest that erosion damage in pneumatic conveyors must be dependent on the concentration of particles in the flowing suspension [M1]. It was reported that when the particle concentration decreased and the conveying velocity increased there was an increased occurrence of erosion damage. This is understood to be due to the dominance of the particle velocity on the magnitude of the erosion damage that is caused. In cases where erosion tests are carried out such that the same mass of abrasive strikes the surface suffering erosion damage, the magnitude of the damage does increase when the particle concentration is reduced. However, the erosion rate on a time basis decreases since it takes significantly more time for any given mass of abrasive to strike the surface being considered. As a consequence of this, the particle concentrations that were selected for this test programme were commensurate with those typically seen in low particle concentration conveying conditions. It is during conveying under such conditions that the worst wear per tonne of material conveyed occurs.

d) The properties of the materials that comprise the particles and the surface being eroded are important. The hardness, Young's modulus, Poisson's ratio, yield strength are a few among many properties that have been used to try to provide a correlation with erosion damage. There are, however, no definitive accurate models of erosive wear that account for these variables [B22,E1,H21,K3,S18,S3,R5,R8].

To avoid the problems of trying to account for the variation of these properties in the tests being carried out for this project, the same material suffering erosive damage was used in both test facilities used for this project.

c) The size and shape of the particles causing the erosive wear also greatly affects the erosion process [C3]. However, as mentioned in the previous chapter the shape of the particles remains very difficult to quantify in any way.

The way in which this problem was overcome was by utilising the same abrasive media for the tests in both the laboratory scale erosion tester and the pneumatic conveyor test facility. An important ramification of ensuring the use of the same abrasive material was that the design of the test equipment must be such that degradation of the abrasive by aggressive handling was avoided as much as possible.

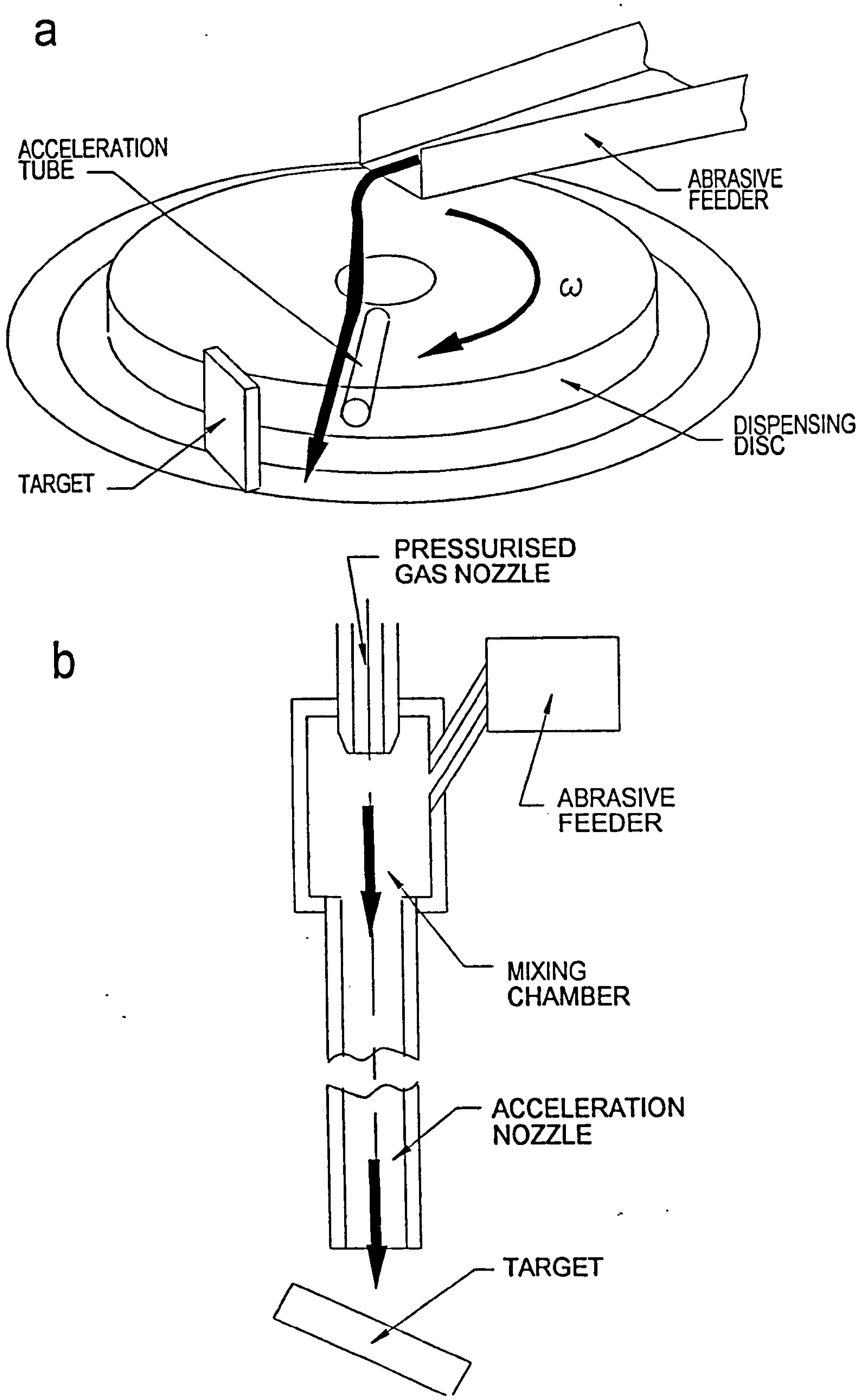
These variables clearly had to be accounted for in the experimental plan, and in the design of the test equipment that was required for the experiments carried out for this project.

3.3 The Choice of the Laboratory Erosion Tester

Advantages and disadvantages of using the various forms of erosion tester are discussed in Appendix 2B. The outcome of the investigations into the suitability of these erosion testers led to a choice between two forms of tester being made. The testers considered were the 'rotating disc accelerator' form of erosion tester and the 'gas blast' form of tester, (schematic views of both forms of tester are given in Figure 3.1). The first of these testers uses a high speed rotating disc to accelerate abrasive particles along radial channels in its structure. A range of targets are arranged around the periphery of the acceleration disc at different angles of orientation. A wide variety of materials and/or impingement angles can be tested under identical conditions simultaneously. In the case of the 'gas blast' form of tester, abrasive particles are mixed with a stream of pressurised gas and projected against a single target whose angle of orientation to the plume of abrasive can be varied.

The erosion tester that was chosen for this project was the 'rotating disc accelerator' form of equipment. The reasons why this form of tester was adopted in preference to the 'gas blast' tester are discussed below.

Figure 3.1 Schematic views of a) the 'rotating disc accelerator' erosion tester, and b) the 'gas blast' erosion tester.



1. The particle velocity vector in the rotating disc accelerator erosion tester is more controllable since the velocity is induced by forces related to the mass of the particles, and gas velocities within the tester tend to be fairly low. In the gas blast type of rig, the shape of the particles greatly affects their velocities since the velocity is induced by drag of the gas on the particles, and the drag coefficients of the particles are a function of their shape. Also because of the nature of this rig the gas velocities within it tend to be high. Particle shape is difficult to quantify whereas in comparison the particle mass can be more easily found. Consequently, the size and shape of the particles will have a more significant effect on the particle trajectories in the 'gas blast' form of tester. This author suggests that because of these facts, the particle velocities in the gas blast tester are more subject to variation than those that occur in the rotating disc accelerator erosion tester [C1,N3,S9], especially since most abrasive materials incorporate a wide range of particle sizes.

2. More than one target can be tested at once under identical impact conditions of particle velocity, particle concentration and angle of impingement. In this way the problems associated with experimental error can be minimised.

3. The method of testing requires a series of mass loss measurements to be taken for each sample used in the tester. This is because the targets arranged at different angles of orientation in the erosion tester will be struck by a different mass of abrasive. The mass of abrasive striking a target per unit time is dependent on its angle of orientation. Because of this, in order for the erosion damage suffered by each target to be comparable, results for a series of tests would be needed so that the damage caused by a fixed mass of abrasive striking the, target irrespective of target orientation, can be found by interpolation. In this way the steady state erosion for the sample concerned could be much more easily found. Therefore, another possible source of experimental error was eliminated. This is not necessarily the case in tests carried out using the 'gas blast' form of tester where individual tests with a fixed mass of abrasive are easily achieved.

4. Since the gas velocity in this form of tester is much less than that which occurs in a 'gas blast' erosion tester the coupling between the gas and the particles is significantly less. Coupling between the particles and the gas can cause significant effects to the particle impact angle because of the presence of the stagnation zone at the surface of the target [D1].

There are several disadvantages to using the rotating disc accelerator form of tester. Most important of these is that not all of the abrasive dispensed by the particle feeding device strikes the surface of all of the target samples placed in the tester. Also, because of the mode of operation of the tester, the erosion process is not continuous since the samples are struck by particles only when the exit nozzle of the acceleration mechanism sweeps across the target surface. This leads to the erosion damage occurring in a cyclic manner. It is not too difficult to account for the mass of abrasive particles striking the sample surface per unit time. However, it is more difficult to assess what effect the cyclic nature of the erosion event has on the erosion process as a whole.

Despite the disadvantages mentioned above, erosion testers of this form have been used successfully in the countries that used to form the Soviet Union [K6], Sweden [S8] and Japan [S5]. A test facility of this type was developed and built specifically for this project.

3.3.1 The Effect that the Choice of Test Variables had on the Design and Use of the 'Rotating Disc Accelerator' Erosion Tester

One major advantage of the 'rotating disc accelerator' test facility is that it was possible to generate a wide range of particle velocities by varying the velocity of the accelerating disc. This was achieved by using a variable speed inverter drive to drive the electric motor rotating the disc. The maximum value of the particle velocity required was 45 m/s; since this was thought to be the maximum possible velocity of the particles that would be expected in a well designed pneumatic conveyor. It was felt that the accuracy of the velocity selection in the tester should be good enough to enable particle velocities to be selected to within ±1.5 m/s at the worst. This range of accuracy was justifiable when it was considered how much the particle velocity in a pneumatic conveyor was likely to vary because of the effects of variations in particle size and the localised flow of turbulent eddies in the gas. It was found that calibration of the rotational velocity of the acceleration disc against that of the particles could be carried out by using readily established techniques. These are discussed in the next Chapter which also describes all of the work carried out on this form of erosion tester for this project.

Experience obtained from making a prototype of this form of erosion tester made it obvious that the abrasive media to be used in the test programme had to be free flowing. The reasons for this were that in this design the abrasive had to flow through quite small contorted passages in the acceleration mechanism. This limited the choice of abrasive materials that could be used. However, it was deduced that the materials that are free flowing generally need to be conveyed in low concentrations in pneumatic conveyors. Consequently, they tend to be the ones that cause most erosive damage when conveyed through such systems.

Obviously the abrasive media that was chosen would largely dictate the materials from which the acceleration mechanism would be made. The components of this mechanism would be subjected to abrasive, i.e. sliding wear, along with a limited amount of erosive wear. Since the test facility was prone to damage by wear, the various components that made up this apparatus had to be easily replaced.

It was essential that the angle of particle impact could be varied throughout a wide range of possible values. The reasons for this were that it was necessary to generate data for a large range of impingement angles. This would assist in the derivation of a predictive model which covered the full range of possible erosion conditions that could occur in a pneumatic conveying system.

Feeding of the abrasive material into the erosion testing device would be very important. The intensity of the particle impact on the surface suffering erosion damage would effect the quantity of damage caused. The system to feed the abrasive material into the tester had to be capable of providing a wide range of feed rates. However, for any given feed rate for a test the chosen rate had to be kept as constant as possible whatever the external conditions.

The design features of the 'rotating disc accelerator' erosion tester developed for this project met these requirements. The essential features of this apparatus are discussed in section 4.2 and the design detailed in Appendix 4A.

3.4 The Pneumatic Conveyor Test Facility

The pneumatic conveyor test facility required for this test work needed to be of an industrial scale. The reasons for this were that, in the past, it had been found very difficult to scale erosion behaviour from results on small scale pipe lines up to industrial scale plant [U2].

3.4.1 The Effect that the Choice of Test Variables had on the Design and Use of the Pneumatic Conveyor Test Facility

The range of operation of the pneumatic conveyor had to include as a first priority the simulation of low concentration, high velocity conveying conditions. It is in cases where these sort of conditions prevail that erosion damage is greatest. The range of conveying conditions that were required for this apparatus ranged from velocities of 10 m/s to a maximum of 45 m/s and particle concentration densities of between 0.25 kg/m^3 and 20 kg/m^3. It is within this range that erosion damage reaches a maximum for pneumatic conveyor bends [M1] (see Figure 2.2).

The particle velocity in erosion studies is a key quantity, as discussed above. It was therefore necessary to allow for the measurement of this variable in detail in the pneumatic conveyor loop, especially at the location at which erosive wear was being studied. Particle velocity measurement has been the subject of many studies [K1,W2,M10]. However, there are two ways in which this can be approached. Firstly, an active measurement technique such as that used by Kliafas *et al.*, Woodhead and McClusky [K1,W2,M10] could be used. Secondly, it has been suggested that by finding the velocity of the conveying gas at the location for which particle velocities are needed, this velocity can be taken as the particle velocity. This technique has been used by workers in the past [M9]. If the length of the pipeline before the measurement location is long enough, the particles will have had sufficient time to accelerate to their terminal velocities in the pipe line. Therefore, provided that a long enough section of pipe is used, the particles will be travelling at much the same velocity as the gas [W2]. It can also be shown that the pressure recovery in the pipeline following the disturbance caused by an earlier bend or obstruction can occur within a finite length of the following straight. The inference from this is that the re-entrainment of the particles has been achieved and the particles are travelling at their terminal velocity for such a situation [B14]. Obviously, the lay out of the test pipeline was affected by these findings since the distance between bends in the pipeline will have to be sufficient to ensure that the particles have reached their terminal velocity. Also, attention to the detail of the way in which the pipeline components are joined was known to be important in ensuring that unwanted disturbances to the flow of the particle-gas suspension by pipe segment misalignment was avoided.

It was essential that the conveying system should give a conveying cycle free from any transients in the mass flow rate of abrasive material through the system. In this way fluctuation in the conveying velocity, (determined by taking measurements of the local air pressure at locations around the test pipe loop), would be avoided. This requirement led to the adoption of feeding equipment that gave a constant feed rate of abrasive material into the pipeline, and very short start and stop transients.

Measurement of the particle concentration within the pipe bore at the site of erosion damage being studied was also required. The major problem in this instance was that of ensuring that there was no disturbance to the two phase flow regimes in the pipeline caused by the intrusion into the pipe bore of the measurement device. The results of previous research have enabled an estimate of the local particle concentration to be obtained [S10,T2,T3,H2]. However, each conveying condition and conveyor system design will lead to changes in the value of this variable. This would make it imperative that the local particle concentration within the pipe bore was measured in some way.

The puncture of the wall of a bend in a pneumatic conveyor indicates that the bend has failed. It was therefore thought that the measurement of the penetration of the bend wall with progressive erosion damage was required. In this way a time-history of the erosive penetration of the bend would be obtained. It was therefore decided that measurements of the local wall thickness had to be made. Account had to be taken for this in the design of the test programme structure and conveyor system hardware.

3.5 The Structure of the Complete Test Programme

From the literature review, identification of the variables in which investigations would be made during this project were decided. The effects that measuring these variables would have on the design of the test equipment required for this project were considered. Conclusions were then reached regarding the structure of the experimental work to be carried out on the test equipment devised for this project.

It was decided that an investigation into the effects of varying the material of the eroding surface, and the particle properties, were not among the main goals for this project. A decision was made that the materials used in the test work would be standardised for tests in both the 'rotating disc accelerator' erosion tester and the pneumatic conveyor test facility. In this way the effects of material properties were eliminated from the project.

The materials that were chosen met all of the criteria detailed above. Throughout the project the material requirements were met by seeking them from the same suppliers at all times. The abrasive material that was selected was an olivine sand and the material that was being eroded was a structural mild steel.

Olivine sand is a free flowing abrasive that shares many properties in common with silica, the main mineral contaminant found in many bulk materials. This sand mainly consists of $(Mg,Fe)_2SiO_4$ with traces of metallic oxides, is irregularly shaped and chemically inert under ambient conditions. The mean particle diameter was 324μm, with the range of size distribution being 10% below 213μm in diameter and 90% being below 455μm in diameter. This material was found to have a particle density of 3280 kg/m^3, (measured using a Beckman air comparison pycnometer), and particles had a hardness that was equivalent to 6.5-7 on the Moh scale.

The mild steel that was used throughout the bulk of the work described in this thesis was a 0.21% Carbon steel made according to Grade 43C / BS EN10210 Parts 1&2 and supplied in the hot rolled condition. Chemical etching and microscopic examination of the microstructure of the steel showed that it consisted of large ferrite grains within which sub-boundaries could be seen. On the sub-boundaries, plate like cementite was formed and there was a small quantity of pearlite clusters contained within the bulk of the material. The bulk hardness of the steel was measured (using Vicker's equipment) to be 126 N/mm^2.

Both materials are discussed in detail in Appendix 3A.

The steel that was used in the construction of the pneumatic conveyor test bend would be used to produce a series of samples for testing in the 'rotating disc accelerator' erosion tester. The experiments that would be carried out on these samples would consist of tests at a range of velocities and particle concentrations within the ranges discussed above for the pneumatic conveyor test facility. The effects of these variables on the erosion of the steel would then be fully analysed. Modelling of these results would be carried out to form a series of general expressions that could be used to predict the erosive damage in the pneumatic conveyor test facility.

The tests on the pneumatic conveyor test rig would consist of measuring the penetration of the wall of a single long radius bend in the pipeline. Long radius bends are commonly used in pneumatic conveying pipelines because there is a general belief that they lead to reduced pressure drops for the flow of the two phase suspension, therefore reducing the power consumption of the conveyor. Determination of the gas velocity and the particle concentration local to the test bend would also be carried out. Comparisons between the erosive damage sustained by the test bend and the damage measured in the 'rotating disc accelerator' test facility could then be made.

Chapter 4

A Description of the Work Carried Out on the 'Rotating Disc Accelerator' Erosion Tester

4.1 Introduction

The literature review described in Chapter 2 enabled a thorough survey to be obtained of the designs of various forms of erosion tester that have been used in the past. The advantages and disadvantages of all of the various erosion tester designs are highlighted in Appendix 2B of this document. It was decided that the rotating disc accelerator form of erosion tester was the better erosion testing device. The reasons for this decision are discussed in section 3.3.

This chapter of this thesis details the design and construction of the rotating disc accelerator erosion tester used in this research project. The results obtained from this device, and their analysis, are also discussed in detail in this chapter.

4.2 Design and Construction of the Rotating Disc Accelerator Erosion Tester

4.2.1 Design of the Rotating Disc Accelerator Erosion Tester

4.2.1.1 Design Features that were Considered for the Construction of the Rotating Disc Accelerator Erosion Tester

The variables that were of interest when the design of the rotating disc accelerator erosion tester was being considered were discussed in Chapter 3 section 3.2. Measurement of these variables had a significant effect on the design and construction of the erosion tester. These variables were:-

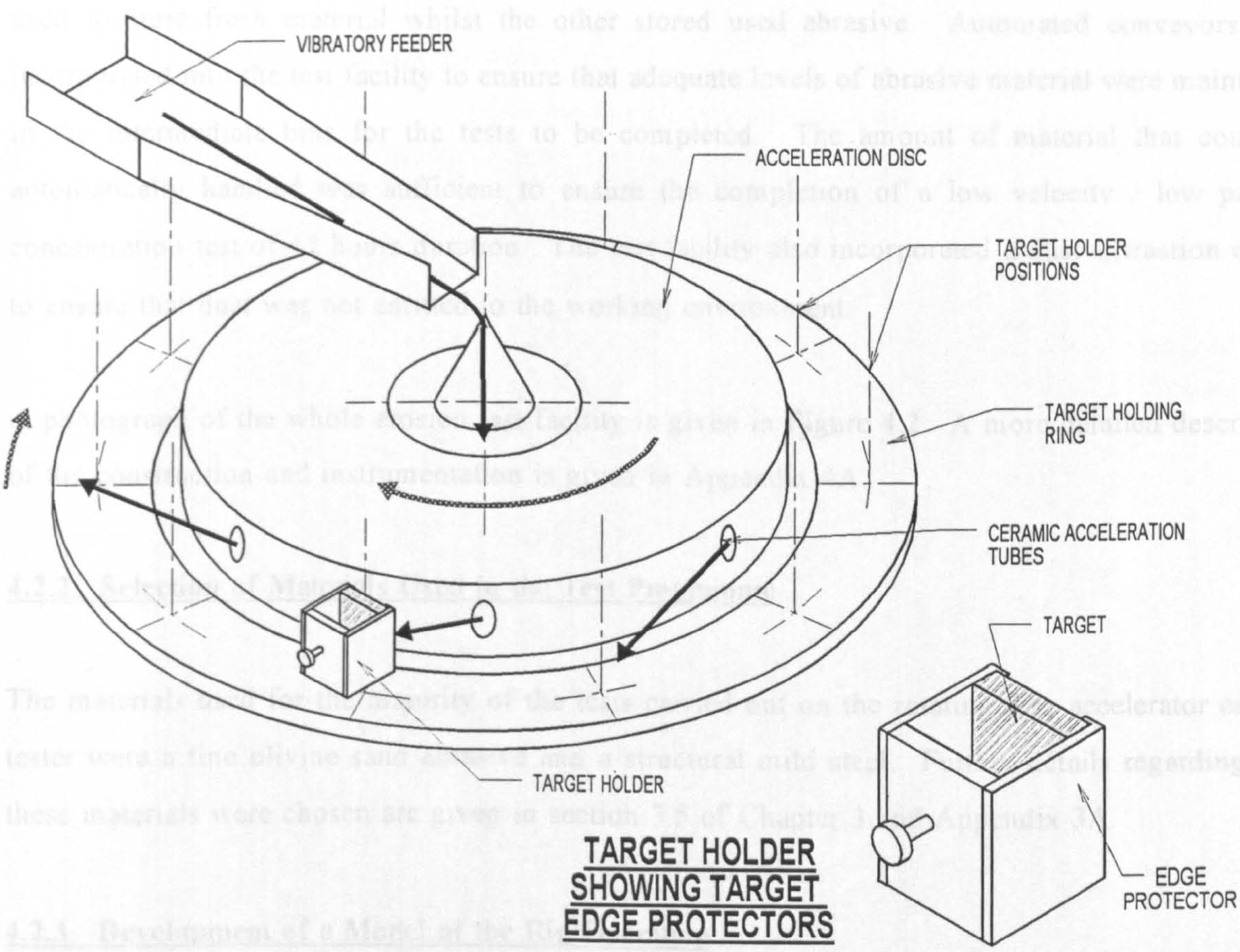
1. The particle velocity (including the angle of impingement), and
2. The particle concentration at the target surface.

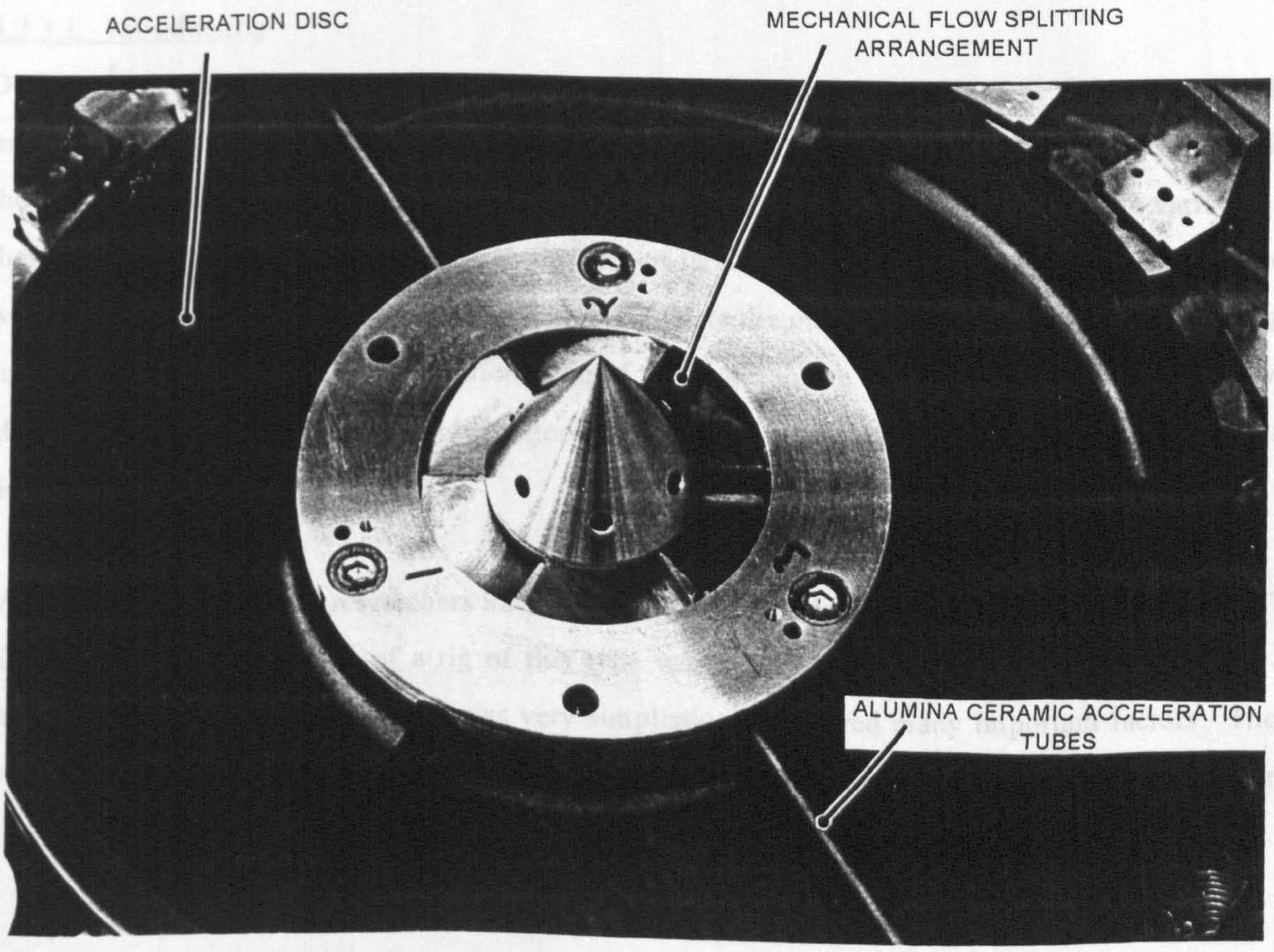
4.2.1.2 A Brief Description of the Rotating Disc Accelerator Erosion Tester

The rotating disc accelerator erosion test facility consisted of a balanced disc whose velocity of rotation in a clockwise direction could be varied continuously between 0 and 6000 rpm, and fixed at any given value. This range of rotational velocities generated particle velocities between 0 and 90 m/s. The rotating disc had a very low inertia and it was possible to select a rotational velocity using a potentiometer set point alone. The disc was 0.12 m in radius and contained six radial channels made from a high quality alumina ceramic. These were 2.6 mm in internal diameter. A mechanical arrangement ensured even splitting of the abrasive flow into the six acceleration tubes (see Figure 4.1). Abrasive particles were fed into the rotating disc system by a vibratory feeder of a type developed by Barnes [B15]. This feeder permitted the selection of a constant feed rate of particles. This was achieved by use of amplitude feedback control to ensure that the amplitude of tray vibration was kept constant despite variations in the load on the feeder tray. The test rig was constructed so that ten targets were utilised per test. The target holders were equally spaced around a ring running concentrically with the acceleration disc. A slow rotation was applied to the target holder ring, to eliminate the effect of any bias in the way in which the rotating disc dispensed abrasive particles. Each target holder could be angled independently to the particle flow in 5° increments for angles of orientation from 5° to 90° to the trajectory of the particles. This was achieved by rotating the target holders in a clockwise direction. The targets were mounted in the vertical plane. Protection was given to both the leading and trailing edges of the targets to prevent erosion taking place at unwanted angles of impingement (see Figure 4.1). A series of automatic and manual mechanical safety interlocks were provided to ensure that entry into the erosion 'centre' while tests were in progress was not possible.

The purpose of the test programme was to simulate the particle impact conditions seen within a pneumatic conveyor. Particle velocities seen in such systems rarely exceed 45 m/s under normal operating conditions. More commonly the particle velocity is limited to values between 15 and 35 m/s. The majority of erosion testing devices have been used to generate particle velocities considerably higher than these values; illustrative of this is Hutchings catalogue of erosion studies carried out prior to 1979 [H5] stating the particle velocities that were used. However, higher particle velocity tests were not employed in this work because there are significant problems that occur if attempts are made to scale results obtained at higher velocities to make predictions of erosion at lower velocities. The reasons for this are that there is considerable debate over the value of the power law exponents applied to velocity terms seen in empirical erosion models [H5]. Due to the low particle velocities being used, test duration times needed to be fairly long to produce a measurable amount of erosion damage. In order for a long enough test time to be used, large quantities of abrasive were needed.

4.1. Illustrations of the rotating disc accelerator erosion tester mechanism.





The abrasive particle storage facility consisted of two 3 m^3 capacity storage bins. One of these was used to store fresh material whilst the other stored used abrasive. Automated conveyors were incorporated into the test facility to ensure that adequate levels of abrasive material were maintained in the intermediate bins for the tests to be completed. The amount of material that could be automatically handled was sufficient to ensure the completion of a low velocity / low particle concentration test of 42 hours duration. The test facility also incorporated a dust extraction device to ensure that dust was not emitted to the working environment.

A photograph of the whole erosion test facility is given in Figure 4.2. A more detailed description of the construction and instrumentation is given in Appendix 4A.

4.2.2. Selection of Materials Used in the Test Programme

The materials used for the majority of the tests carried out on the rotating disc accelerator erosion tester were a fine olivine sand abrasive and a structural mild steel. Further details regarding why these materials were chosen are given in section 3.5 of Chapter 3 and Appendix 3A.

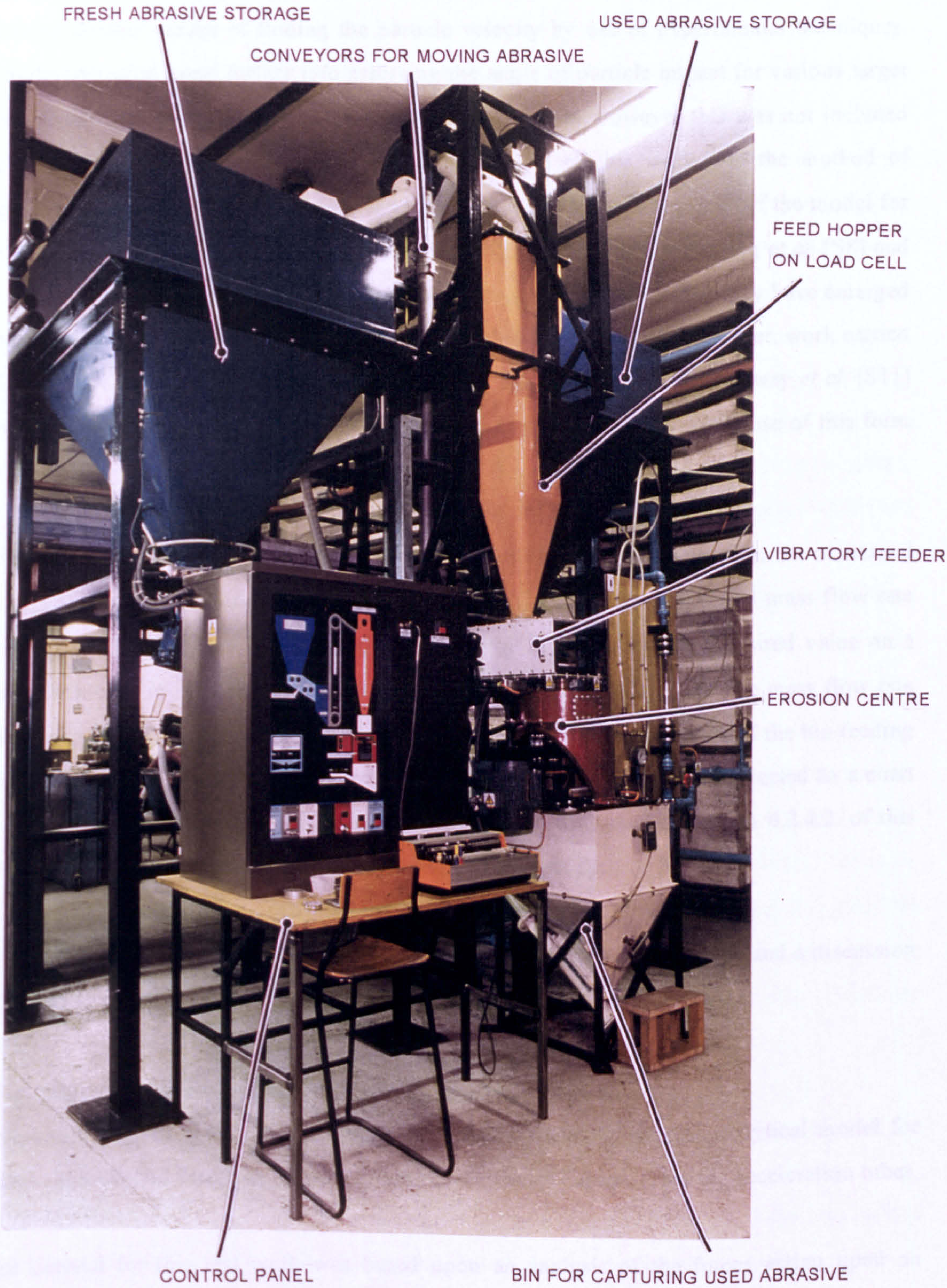
4.2.3. Development of a Model of the Rig Operation

4.2.3.1. Introduction

Owing to the fact that not all of the abrasive material strikes the surfaces of the target samples involved, and that it was necessary to find the angles and velocities of particle impacts, a model for the operation of a rig of this type was required. The model was needed to calculate the variation in the angle of particle impingement across the face of targets arranged at various angles of orientation within the erosion tester. It was also needed to calculate the mass of abrasive that struck each target surface; this was dependent on the orientation of the target to the flow of abrasive particles. It was also essential that this model provided a good estimate of the particle velocity generated by rotating the disc at various speeds.

Various attempts by other researchers have previously been made to carry out these calculations. The first model of the operation of a rig of this type was by Kleis [K6]. This model consisted of an empirically derived expression, but was very simplistic and ignored many important factors. These included variation of the direction of the particle velocity vector with changes in the rotational velocity of the disc. Following on from this work was that carried out by Söderberg *et al.* [S8]. In

4.2. Photograph of the rotating disc accelerator erosion tester.



this model, a simple empirical equation which incorporated a form of friction coefficient was used to determine the velocity of the particles as they emerged from the rotating disc. Shimizu *et al.* [S5] recently derived another means of finding the particle velocity by use of experimental techniques. However, Söderberg *et al.* went further into assessing the angle of particle impact for various target orientations. Dispersion of the particle stream was also mentioned, however this was not included within the model of the system. The most important aspect of this work was the method of calculating the mass of abrasive that strikes a target surface. This important aspect of the model for such a tester was also discussed by Kleis *et al.* in 1969 [K9]. To date only Söderberg *et al.* [S8] and Burnett *et al.* [B13] have suggested that dispersion of the stream of particles after they have emerged from the acceleration mechanism is important when using this form of tester. However, work carried out recently on gas blast forms of erosion tester by Krishnamoorthy *et al.* [K8], Shipway *et al.* [S11] and Chevallier *et al.* [C7] have highlighted the importance that this can have in the use of this form of erosion tester.

Intensity of particle impacts within the tester was modelled by incorporating within the numerical model the results of calibration trials carried out on the vibratory feeder. The actual mass flow rate of abrasive particles flowing into the test rig was found by interpolating for a desired value on a curve of particle mass flow rate versus vibratory feeder potentiometer set point. The mass flow rate was checked during the progress of the test work by measuring the change in mass of the bin feeding abrasive into the vibratory feeder using a load cell. Output of the load cell was directed to a chart recorder. The curve, and the way in which it was derived, are discussed in section 4.2.4.2. of this chapter and Appendix 4C which deals with calibration of the test facility.

A full working listing of the programme of the model (coded in MathCad notation) and a discussion detailing its construction is included in Appendix 4B.

4.2.3.2. Calculation of the Particle Velocity at Exit from the Rotating Disc

For the reasons discussed above it was decided to construct a more general analytical model for finding the magnitude and direction of the particle velocity vector at exit from the acceleration tubes.

The model derived for this test work was based upon an analysis of the forces acting upon an individual particle within an acceleration tube and took the form of a simple finite differencing routine. These forces included the centripetal force caused by the rotation of the acceleration disc; the drag force acting on the particles due to their motion through the air in the acceleration tubes; the force acting to retard the motion of the particle, caused by sliding friction; the coriolis force acting between the particle and the wall of the acceleration tube - this force has a significant effect on the force caused by sliding friction.

Two conditions had to be satisfied before the velocity of the particle had converged to the final value. These were that the value of the radial position of the particle was greater than the actual radius of the rotating disc and that the pressure drop of the air flowing along the tube with the particles was the same as the pressure rise caused by the motion of the particles. This modelling procedure gave a robust and reliable result for the value of the velocity vector for the particles leaving the rotating accelerating disc.

4.2.3.3. Calculation of the Impingement Angles of the Particles on the Target Surfaces

Owing to the finite width of the targets the angle of impingement with which the particles struck the target surface varied with position across the target face. The reasons for this were purely geometrical. Since the full spectrum of impingement angles in 5° increments was needed for the test work contained within this thesis, the calculations required were performed for impingement angles between 5° and 90°. The equations for these calculations were taken from Söderberg *et al.* [S8].

4.2.3.4. Calculation of Mass of Abrasive Particles Striking the Target Surface

The mass of abrasive that struck the target surfaces varied according to the orientation of the target surface to the flow of particles. Each target has a particular aspect ratio for a given target orientation. Values of this ratio were found by using the variation of the impact angle across the face of the targets. This was found to be equivalent to the angle within which each target was eroded. The mass flow rate of the abrasive particles into the erosion tester was used to produce a figure for the mass flow rate per acceleration tube. Combination of these two results permitted the mass of the abrasive striking each target per minute to be found. This technique was similar to that adopted by Söderberg *et al.* [S8].

4.2.3.5. Calculation of the Particle Jet Dispersion and Its Effects on the Particle Dynamics at the Target Surface

The importance of the intensity of impacts in the region of an eroding surface have been highlighted by several researchers [K9,A2,A5]. Numerous methods have been proposed for accounting for these effects. Some of these methods were incorporated into the numerical model for the rotating disc accelerator erosion tester.

McClusky [M10] showed the likely dispersion of particle jets being injected into gas flows by carrying out particle image velocimetry measurement of the emerging particle jet. Extrapolation from data presented by McClusky by carrying out elementary curve fitting has yielded the following equation:-

$$R_j = \left(3.92.10^{-3}\ V_{res} + 0.075 \right) x_d + r \qquad (4.1)$$

Where R_j is the radius of the jet (m), V_{res} is the average particle velocity (m/s), x_d is the distance from the nozzle to the target in meters and r is the radius of the acceleration tube bore (m). The use of this equation enabled a reasonable estimate of the jet dispersion to be undertaken as can be seen from the results shown later in this chapter for the rig calibration.

This equation was used in the calculation of the spread of the jet of particles at each of the edges of the target. Combining the calculation of the actual length of the target suffering erosive damage with the spread of the particle jet at the target edges gave the area of the target being eroded. Once the area experiencing erosion damage was calculated it was possible to calculate a general value of the particle mass flux on the target surface using the following equation:-

$$M_{flux} = \frac{M'_{target}}{A_{eroded}} \qquad (4.2)$$

where M_{flux} is the particle mass flux; M'_{target} is the mass of abrasive striking the target surface per unit time of operation of the test facility and A_{eroded} is the actual area suffering erosion damage.

Further to this general value of the particle mass flux, an instantaneous particle mass flux can also be calculated as suggested by Kleis *et al.* [K9]. These calculations are based on finding the mass of abrasive striking the target surface per traverse of an acceleration tube nozzle and the period of time over which this event takes place.

The instantaneous mass flux, M_{fi} can therefore be found by using:-

$$M_{fi} = \frac{M_{cycle}}{A_{eroded}\ T_{cycle}} \qquad (4.3)$$

where M_{cycle} is the mass of abrasive material striking the target during a single acceleration tube nozzle traverse and T_{cycle} is the time in which this event occurs.

Another way of assessing the effect of the intensity of particle impacts in the region around the eroding surface of the target was also considered. It was thought to be important that a variable related to the spacing of the particles in the free abrasive stream be used. This variable could also be used to describe the homogenous, distributed flow observed in a low particle concentration pneumatic conveying regime. This involved finding the distance between particles in the region in front of the eroding surface of the target in terms of the number of mean particle diameters. This method was originally proposed by Shipway *et al.* [S11]. The distance between particles, L_{bp} is calculated as follows:-

$$L_{bp} = \left(\frac{M_p \; V_{res} \; A_{eroded}}{M'_{target}} \right)^{\frac{1}{3}} \frac{1}{R_p} \qquad (4.4)$$

where M_p is the mass of a single particle of radius R_p (in this case the particles were taken to be spherical), and V_{res} is the particle velocity at exit from the acceleration mechanism. The equations 4.1 to 4.4 were incorporated into a numerical model coded in MathCad syntax. Appendix 4B contains a listing and detailed explanation of this programme.

4.2.4 Calibration of the Test Facility

4.2.4.1 Introduction to the Calibration Methods

The rig needed to be calibrated to ensure that the most important variables affecting the erosion damage were accurately controllable, and measurable within acceptable limits. With the rotating disc accelerator erosion tester three major variables needed to be checked. These were:-

- the accuracy and controllability of the mass flow rate of the abrasive into the tester using the vibratory feeder,
- the accuracy of the velocity vector calculated for the particles emerging from the rotating disc, and
- the amount by which the jet of particles had diverged by the time it reached the target surface.

These three areas are dealt with in turn in the following three sections of this chapter and in much more detail in Appendix 4C.

4.2.4.2 Calibration of the Vibratory Feeder

Calibration of the vibratory feeder was easily achieved. At each incremental position of the potentiometer that controlled the amplitude of the feeder vibrations, a series of measurements were taken for the mass conveyed through the feeder in a given time.

The actual mass flow rate of the abrasive into the erosion tester was measured using a load cell throughout the test programme. This permitted a check to be made on the calculated value. Corrective measures could be undertaken if any significant deviation between the two values was observed.

4.2.4.3 Calibration Tests to Confirm the Accuracy of the Particle Velocity Vector on Exit from the Rotating Disc

The velocity vector was checked by using a static form of the Ruff and Ives slot and displaced wear scar method [R3] (see Figure 4.3 and Appendix 4C). The mean of the offset of the wear scar from the slot was derived from ten test measurements. The tangential velocity of the rotating disc was known, as was the geometry of the system at the time of these tests owing to the mechanical arrangement of the targets within the tester. Consequently, the only information missing was the direction of the particle travel. This was found by using the distance between the positions of the slot and the wear scar. Once this information was available it was possible to find the missing radial velocity component for the particles. This could then be used to calculate the magnitude and direction of the actual particle velocity.

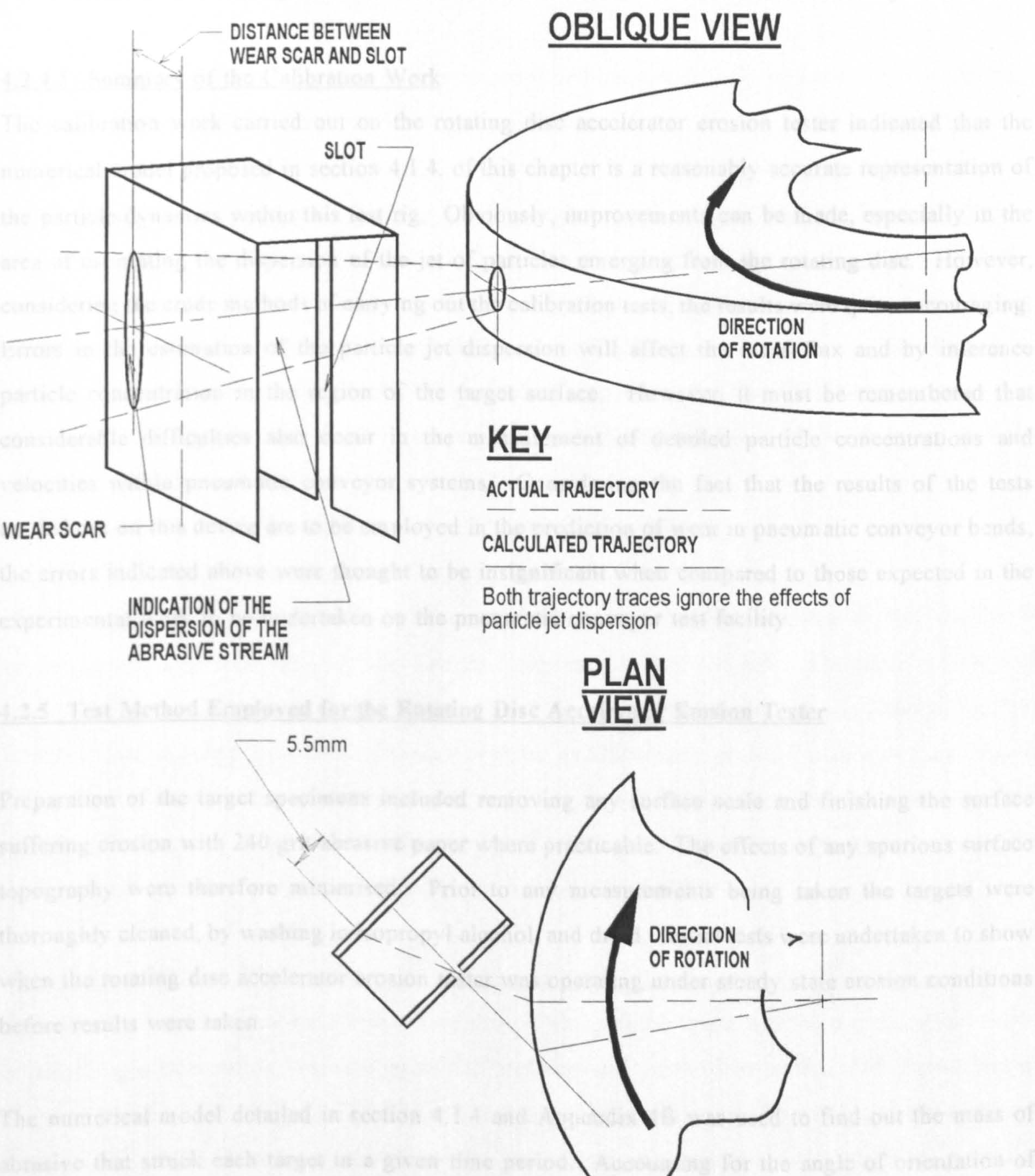
Results from using this form of particle velocity measurement device are given in Appendix 4C; they cover a range from +7% to -9% of the desired value. Considering how crude and simplistic this method is, and that other researchers have previously found the Ruff and Ives method to be in error by ±18% [P6], these results must be viewed as being quite good. The indication was that this erosion tester was capable of generating particle velocities within the range desired and with sufficient accuracy (see section 3.3.1).

4.2.4.4 Calibration Tests for Assessing the Dispersion of the Particle Jet at the Target Surface

It was important to assess the amount by which the particle jet diverged as it travelled away from the rotating disc, since only in this way could the intensity of particle impacts on the target surface be found accurately. This was achieved by covering the surface of a polished mild steel target by a thin layer of engineers marking blue [S11]. The targets were exposed to the abrasive stream at set conditions for a short period. Removal of the marking out dye occurred in the areas subject to particle impact. Manual measurement of the dimensions of the scar in the dye enabled an estimate of the dispersion of the abrasive jet across the surface of the target to be obtained.

The results of this calibration work are set out in Table 4C.2 in Appendix 4C; they range from -29% to +11% of the expected value calculated using the expression (equation 4.1) derived from the work

Figure 4.3 Schematic of the static form of the Ruff and Ives technique for measurement of the particle velocity vector [R3].



carried out by McClusky [M10]. Considering how inaccurate the measurement technique was, and the fact that the data provided by McClusky did not cover the full range of particle and gas velocities that occurred in the rotating disc accelerator erosion tester, these results seem tolerably accurate.

4.2.4.5 Summary of the Calibration Work

The calibration work carried out on the rotating disc accelerator erosion tester indicated that the numerical model proposed in section 4.1.4. of this chapter is a reasonably accurate representation of the particle dynamics within this test rig. Obviously, improvements can be made, especially in the area of estimating the dispersion of the jet of particles emerging from the rotating disc. However, considering the crude methods of carrying out the calibration tests, the results were quite encouraging. Errors in the estimation of the particle jet dispersion will affect the mass flux and by inference particle concentration in the region of the target surface. However, it must be remembered that considerable difficulties also occur in the measurement of detailed particle concentrations and velocities within pneumatic conveyor systems. Considering the fact that the results of the tests carried out on this device are to be employed in the prediction of wear in pneumatic conveyor bends, the errors indicated above were thought to be insignificant when compared to those expected in the experimental work to be undertaken on the pneumatic conveyor test facility.

4.2.5 Test Method Employed for the Rotating Disc Accelerator Erosion Tester

Preparation of the target specimens included removing any surface scale and finishing the surface suffering erosion with 240 grit abrasive paper where practicable. The effects of any spurious surface topography were therefore minimised. Prior to any measurements being taken the targets were thoroughly cleaned, by washing in isopropyl alcohol, and dried. Initial tests were undertaken to show when the rotating disc accelerator erosion tester was operating under steady state erosion conditions before results were taken.

The numerical model detailed in section 4.1.4 and Appendix 4B was used to find out the mass of abrasive that struck each target in a given time period. Accounting for the angle of orientation of the target to the flow of abrasive, the time required for an equal mass of abrasive to strike each target was found by the use of this model. The mass loss results were then converted to volume loss values. The time periods derived by the model were then used for interpolation purposes on the time history of the volume loss of each target specimen. This yielded a value for erosion damage in terms of volume loss for an identical mass of abrasive striking each target irrespective of the angle of particle impingement. Erosion performance of the target materials used were presented by simply dividing the volume of material removed from the target by the chosen fixed mass of abrasive striking the target surface. Details of the calculations that were carried out are given in Appendix 4F for a set of test results that were obtained as described later in the next paragraphs.

The method of carrying out the tests on this device is laid out sequentially in Appendix 4D. All tests were carried out on this tester using ten targets simultaneously.

4.2.6 Comparisons Between the Rotating Disc Accelerator and Another Form of Erosion Tester

A test programme was carried out to assess what differences occurred in the results obtained from carrying out tests in a rotating disc accelerator and gas blast type erosion testers. The reasons for carrying out this work, brief details of the test programme, and the conclusions made as a consequence of this work will be discussed in the following sections. A much more detailed description of this work is given in Appendix 4E.

4.2.6.1 The Reasons for Carrying out Comparative Tests

The concept and use of the rotating disc accelerator erosion tester as used in this project is predominately a former Soviet block, Eastern European practice [G1,K6]. The preferred form of erosion tester in Western Europe has been the gas blast erosion tester [D3,A4]. In order to find out whether these erosion testers gave comparable results, a collaborative project between two institutions using these different forms of erosion tester was carried out. It was expected that significant and important differences in the results obtained from these testers would become apparent due to the different way in which particle acceleration was achieved within them.

4.2.6.2 Details Regarding the Design of the Erosion Testers Used in this Work

The rotating disc accelerator erosion tester for these comparative trials was the one described above whilst the gas blast form of erosion tester was provided and operated by staff at The Department of Powder Science Technology (POSTEC) at The Telemark Technological Research and Development Centre (TEL-TEK), Porsgrunn, Norway. The gas blast erosion tester used at POSTEC generally followed the design and operational procedure laid down in the German DIN standard [D3]. Further details are provided in Appendix 4E.

4.2.6.3 Details of the Comparative Test Programme

4.2.6.3.1 Erosion Test Conditions

It has been widely reported in previous research literature that the erosion damage suffered by a material depends predominantly on the velocity of the particle impact. The particle velocities selected were 15, 25 and 35 m/s; it was felt that these accurately represented a suitable range of particle velocities comparable with those seen in pneumatic conveyors.

Reports suggest that erosion damage in pneumatic conveyors is dependent on the concentration of particles in the flowing suspension [M1]. Consequently, the particle concentrations that were selected for this test programme were commensurate with those seen in low particle concentration conveying. Particle concentrations of 1, 4 and 13 kg/m^3 were selected therefore.

Two impingement angles were used during this test programme; 30° & 90°. These angles were selected on the basis of the fact that the tests were designed to compare the erosion testers, not provide a full curve for the erosion damage of the materials plotted against impingement angle.

The test conditions described in this section were used in both of the different types of erosion tester. Calibration of both of the testers to ensure that these conditions were met as closely as possible was also carried out. This is described in Appendix 4C for the rotating disc accelerator erosion tester and Appendix 4E for the gas blast erosion tester.

Further information regarding the reasoning why these test conditions were adopted is contained in Appendix 4E.

4.2.6.3.2 Erosion Test Materials

The abrasive particulate material used in this test programme was the olivine sand described in section 3.5 and Appendix 3A. A series of five target materials were used in this test programme. These were a fused ceramic (HITEC 100 alumina), a cast ceramic (cast basalt, Abresist), a metal (EN3B mild steel), an ultra high molecular weight polyethylene (UHMW PE) polymer (Tivar 100) and an elastomer (nitrile rubber). Each material selected represented a general class of materials that is or could be used in pneumatic conveyor pipe construction. Table 4.1 below gives more information on these materials.

Table 4.1 Erosion Target Material Description.

Material Type	Cast Ceramic	Fused Ceramic	Metal	Elastomer	Polymer
Material Description	Cast Basalt	Fused Alumina	Mild Steel	Rubber	UHMW PE
Trade Name	Abresist	Hitec 100	EN3B	Nitrile Rubber	Tivar 100
Supplier	Kingfisher Ind. Services, Washford East, Redditch, Birmingham, UK.	Morgan Matroc Ltd, Stourport-on-Severn, Worchestershire, UK.	Outlook Metal Stockholders Ltd., Banstead, Surrey, UK.	Arco Holman Nichols Ltd, Orpington, Kent, UK	PoliHi Solidur UK Ltd., Todmorden, Lancashire, UK.
Density (g/cm^3).	2.8	3.73	7.8	0.86	0.94
Hardness (Rockwell).	79C	82C	50C	3.35 N/mm^2 Vickers	64R
Constituents	SiO_2 - 46% Al_2O_3 - 15% Fe_2O_3 - 12% CaO - 11% MgO - 8% K_2O/Na_2O - 6% TiO_2 - 2%	Al_2O_3 - 97% + FILLERS	080A15 specification C - 0.16% Si - 0.09% S - 0.005% P - 0.01% Mn - 0.7%	Butadiene Acrylo-nitrile Co-polymer + FILLERS	Virgin Cross Linked Ultra High Molecular Weight Polyethylene.
Yield Strength (N/mm^2).	30 (in bending)	320 (in bending)	430 (ultimate tensile)	5 (ultimate tensile)	28 (ultimate tensile)

4.2.6.4 Comparative Test Programme Results

Information regarding the test results for this test work is contained within Appendix 4E.

4.2.6.5 Conclusions Drawn from this Comparative Test Programme

The main conclusions drawn from these tests were as follows:-

a) The test results show that the two types of tester provide similar results for the trends in the erosion damage between the materials that were tested. The results suggested also that the testers can be used for the comparative testing of wear resistant materials, and give reliable agreement in qualitative terms. However, there are very significant differences for the erosion damage between the two erosion testers in quantitative terms.

b) Differences in the quantitative results were concluded to be due to changes in the particle flux at impact between the two testers. Particle flux at impact varied considerably during tests on both erosion testers because the abrasive streams in these test facilities were seen to diverge (see Figure 4E.2 in Appendix 4E). The quantity of divergence varied depending on the desired velocity and the particle concentration. It was concluded that divergence of the jets of abrasive particles occurred as a consequence of inter-particulate collisions at exit from the accelerating mechanism nozzle. Also, it was concluded that the gas-blast erosion tester was also much more likely to lead to particle jet divergence as a consequence of coupling between the motion of the gas and the particles; this was as a consequence of the much higher gas velocities that occurred in the use of this form of tester.

A detailed explanation of the analysis of the results obtained from this test programme are contained in Appendix 4E.

4.3 The Detailed Analysis of the Erosion Resistance of a Structural Mild Steel

4.3.1. Reasons for Carrying Out this Test Programme

The main aim of this research project was to find a link between the results of erosion tests carried out on a laboratory erosion tester and see whether they compared favourably with results obtained for the erosion of a pneumatic conveyor test bend. It was essential, therefore, that the steel used to construct the pneumatic conveyor was the same as that used in the laboratory erosion testing rig.

This section of this thesis describes a detailed series of tests carried out on the rotating disc accelerator erosion tester for the structural mild steel that was used to construct the test bend in the pneumatic conveyor described in the next chapter.

4.3.2. Details of the Mild Steel Test Programme

4.3.2.1. Test Conditions in the Rotating Disc Accelerator Erosion Tester

As in section 3.3.1 of Chapter 3 and Appendix 4E the particle velocities and concentrations selected for this test programme were similar to those seen in the low velocity / low particle concentration conveying regimes often used in pneumatic conveyors. The particle velocities selected were 15, 25 and 35 m/s, and at each velocity three particle concentrations were used; these being 1, 4 and 13 kg/m^3. (The particle concentration of 13 kg/m^3 was used because it was the largest particle concentration that it was originally thought that the rotating disc accelerator erosion tester could simulate). Efforts were made to ensure that these particle concentrations were achieved at the target surface rather than at the exit of the rotating disc acceleration tube nozzle. From the collaborative tests described in section 4.2.6, dispersion of the jet was concluded to be of great significance in the simulation of the particle impact conditions in laboratory erosion testers. It was found from carrying out initial trials and calibration tests that it was not possible to simulate impact conditions at 35 m/s and a particle concentration of 13 kg/m^3 simultaneously. This was due to physical limitations in the feed arrangements designed for the rotating disc accelerator erosion tester and the effects of jet dispersion. As a consequence of this, the maximum particle concentration that could be achieved at this velocity was 8 kg/m^3.

The angles of sample orientation to the flow of abrasive material were fixed as follows, 8°, 15°, 24°, 40° & 61°. These angles were selected since the angles of impingement that occur in pneumatic conveyor bends having a long radius (bend radius equal to 14 pipe diameters or greater) tend to be in the range 5° to 30° [Y1]. Three samples were tested at the 8° and 15° impingement angles, two samples at 24° and one at each of the remaining angles. Higher angles of impingement than 30° were used so that a more complete set of data regarding the erosion performance of the material could be generated. It was considered that erosion data for higher angles of impingement could be used for prediction of erosion in pneumatic conveyor pipe bends where the bend radius was small and higher impingement angles could therefore be expected. The increase in the number of samples tested at the lower impingement angles was necessary since scatter in the experimental results at these angles was found to be greater during previous tests carried out on this tester. Calibration tests confirmed the accuracy of the angular placement of the samples (see section 4.2.4 above).

4.3.2.2. Test Materials

The samples used in the erosion tester for this programme were made from the structural mild steel from which the pneumatic conveyor test bend was made. The particulate abrasive used in these tests was the same olivine sand described in section 4.2.2 above. Both of these materials are discussed in more detail in Appendix 3A.

4.3.2.3. Notes on the Test Method Used

The tests were organised so that each one consisted of ten samples at each combination of particle velocity and concentration. These targets were arranged so that the five angles of impingement were set sequentially in the rig, i.e. the three targets at 8° were placed in target holders 1 to 3 and so on. This arrangement was adopted for all of the tests. A series of five exposure times for each target angle were used. The results were taken for a fixed mass of abrasive striking the target surface. This was typically 700 grammes. The test methods employed were otherwise as stated in section 4.2.5 of this chapter.

4.3.3. Results of the Mild Steel Test Programme

Figure 4.4 overleaf is a micrograph of the eroded surface of one sample used in this test programme. Orientation of this target was at approximately 24° and the particle impact conditions were 25 m/s and 4 kg/m^3. The surface of the sample shows typical features seen throughout previous research in this area. These features have been described as being illustrative of the classical form of 'ductile erosive wear' [H7,R4], and is similar to the micrograph shown for the EN3B material used in the collaborative test programme discussed in Appendix 4E. All of the samples indicated much the same form of deformation of the target surfaces.

Figure 4.5 below illustrates the nine curves obtained from the test work for the erosion of the mild steel under the conditions mentioned in section 4.3.2.1 above. (Please note that the curves for particle concentrations of 4 and 13 kg/m^3 at 15 m/s are almost coincident in Figure 4.5). Further information regarding the results obtained during this test work are contained in Appendix 4F. The curves are of volume loss per unit mass of abrasive striking the sample surface, versus angle of impingement. These curves show several interesting trends. The most important of these trends is that the authors of previously published work have always shown a maximum in the erosion data at an impingement angle of between 20° and 30°. In the test work reported in this chapter this behaviour was not observed. Instead, the graph tended to imply that volume loss continued increasing as the angle of impingement approached zero degrees. This is different from previously reported results [K8,E1]. This anomaly is discussed in detail in section 4.3.6 later on in this chapter. It can readily be seen that there are three broad groupings of results, that are dependent on the impact velocity. This echoes the well-reported fact that the primary variable affecting the amount of erosion damage is particle

Figure 4.4 Micrograph illustrating the surface topography of a mild steel (EN3B) target eroded in the rotating disc accelerator erosion tester at a particle velocity of 25 m/s and a particle concentration of 4 kg/m^3.

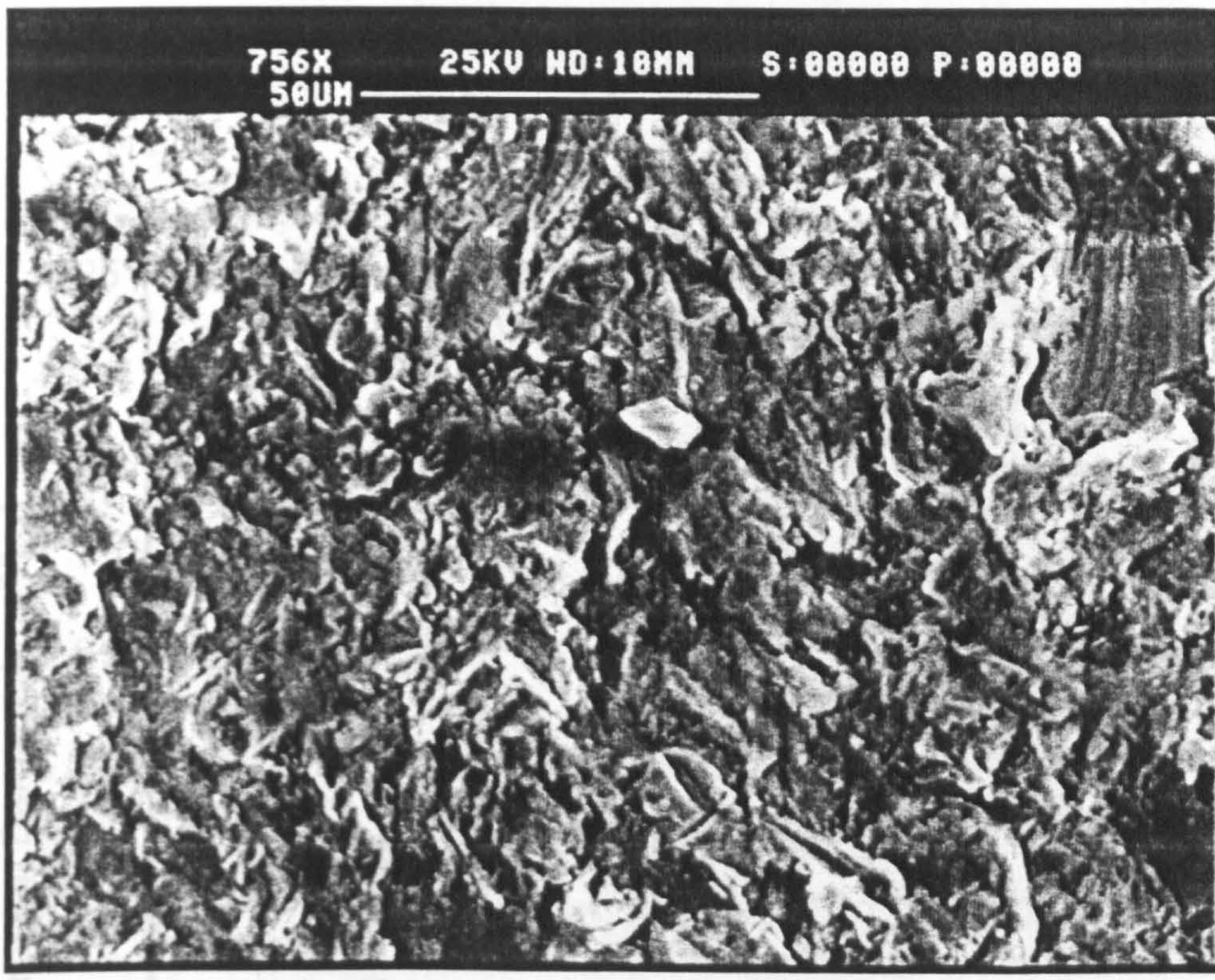
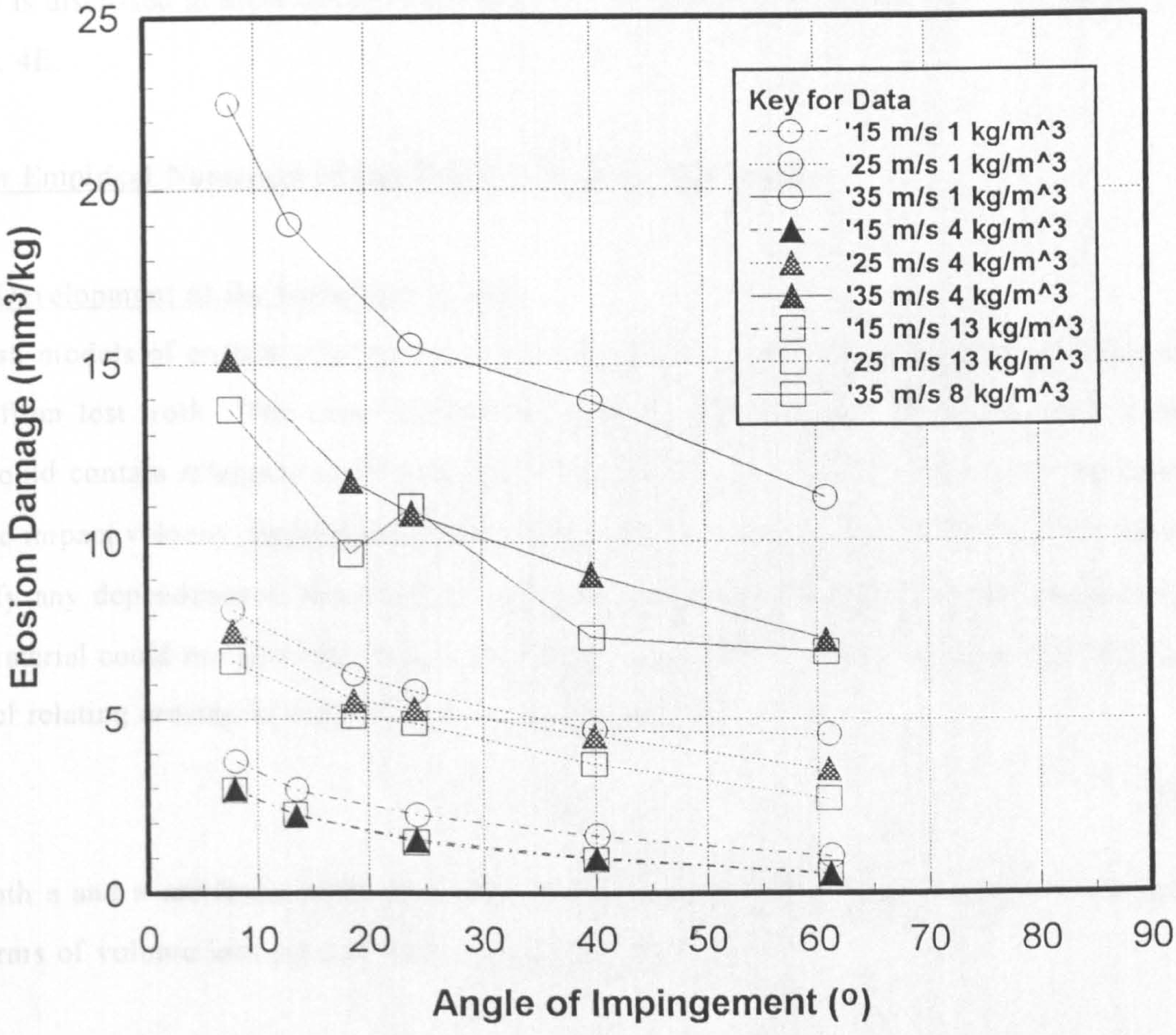


Figure 4.5 Graph of erosion damage versus particle impingement angle for all nine test conditions used in the mild steel test programme.



impact velocity [F2]. This dependency is better illustrated in Figure 4.6 shown overleaf for one group of results obtained for a particle concentration of 1 kg/m³. Two other graphs illustrating families of curves similar to this figure were created for particle concentrations of 4 and 13 kg/m³.

Figure 4.5 suggests that as the particle concentration increases, the erosion damage per unit mass impacting reduces. This effect is most noticeable for the results obtained at an impact velocity of 35 m/s. This could be due to inter-particulate collisions [A2,A5]. The effect of inter-particulate collisions is discussed in more detail in section 4.3.6 of this chapter, section 2.1.1 of Chapter 2, and Appendix 4E.

4.3.4. An Empirical Numerical Model for the Erosion of Mild Steel

4.3.4.1. Development of the Numerical Model

In the past, models of erosion phenomena were obtained by fitting power law curves to the results obtained from test work. The same method was adopted in this work. Obviously, the numerical model should contain reference to the dominant variables in the system. These were interpreted to be particle impact velocity, impingement angle and particle concentration (see Chapter 3). Attempts to quantify any dependence of this form of erosion on material properties for either the abrasive or sample material could not be made, since only one of each of these materials was used. The power law model relating erosion to velocity took the following form: -

$$E = a \ (V_{res})^{n} \tag{4.5}$$

Where both a and n are found empirically, V_{res} is the particle impact velocity and E is the erosion rate in terms of volume loss per unit mass of abrasive striking.

Figure 4.6 below, suggests that if a series of power law curves is fitted to the erosion data versus particle velocity, the impingement angle affects the power and multiplying coefficients of these curves. This method was also used on the data obtained at the other two particle concentrations. Once the power law curves of the above form were fitted to the experimental data, an investigation of the variation of the power law exponents and multiplying coefficients with impingement angle was carried out.

The variations of the power law exponents with impingement angle are shown to follow approximately linear trends (see Figure 4.7). It should be noticed that this graph indicates that as the velocity and particle concentration increase, the scatter in the data increases.

Figure 4.6 Erosion damage plotted against particle velocity for a particle concentration density of 1 kg/m^3.

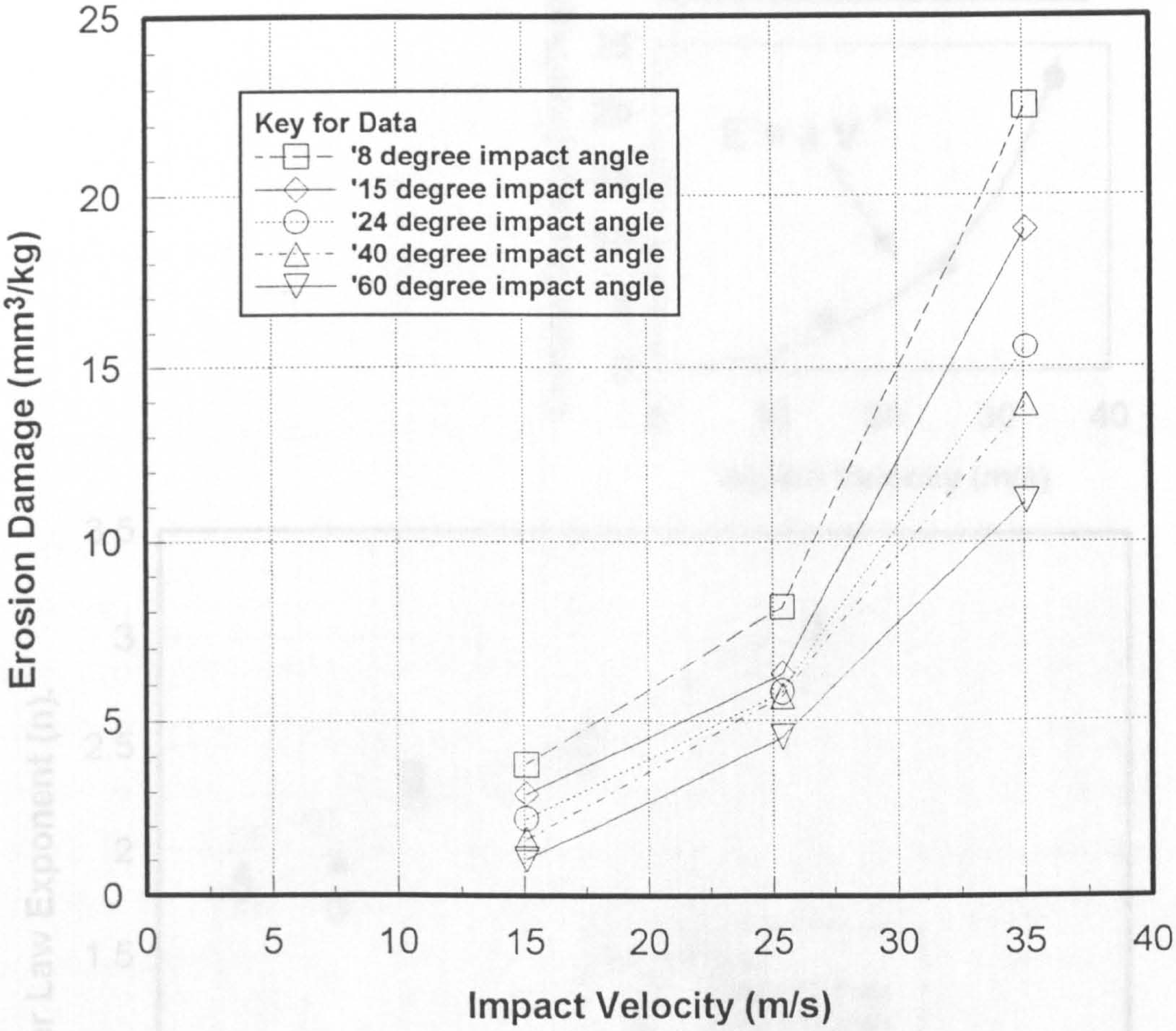
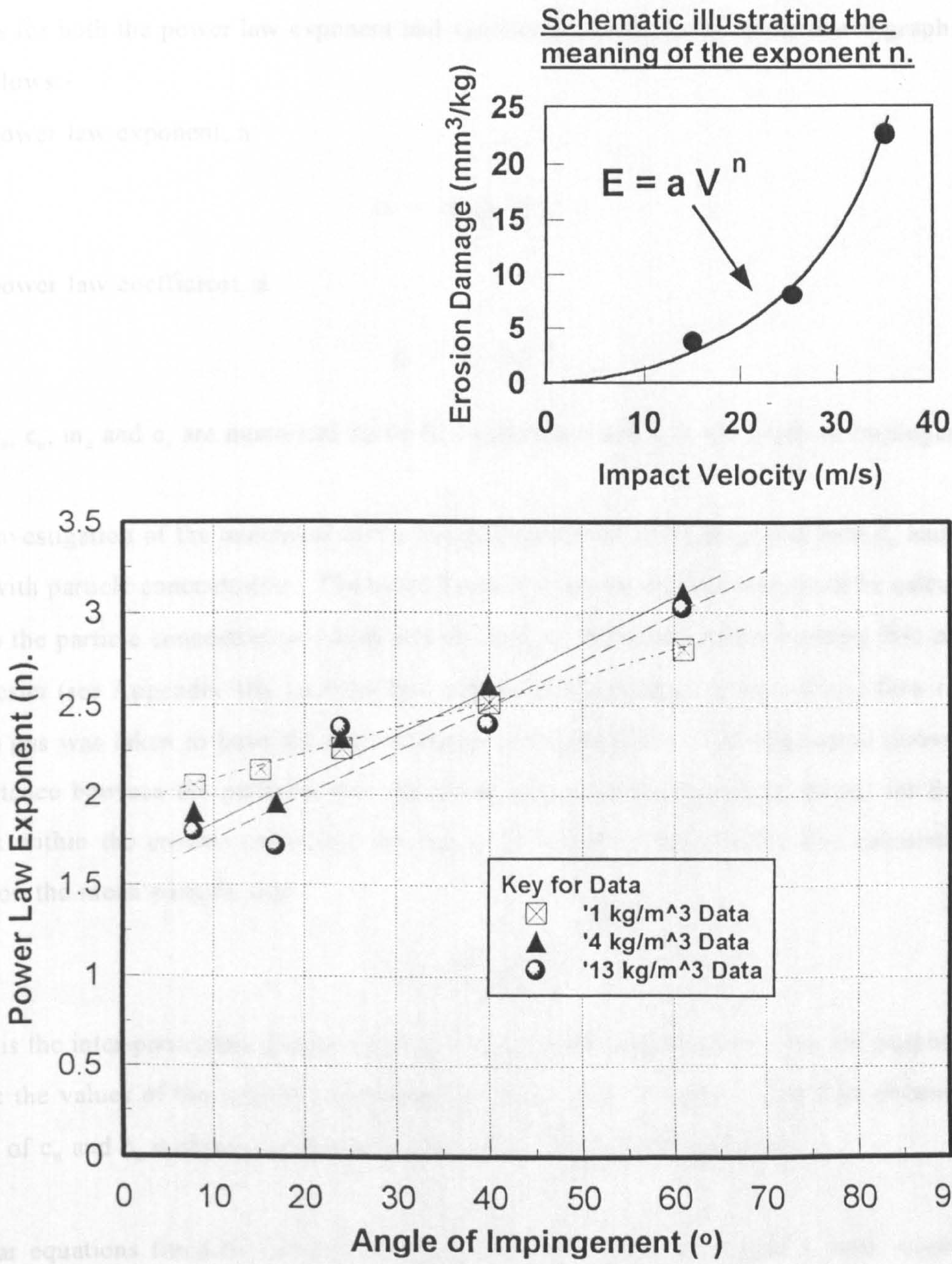


Figure 4.7 Variation of power law exponents.



The power law coefficient (a) for the three series of particle concentration data are shown to vary exponentially with the impingement angle (see Figure 4.8). However, there is a significant amount of scatter in the data for the variation of 'a', especially as the particle concentration increases.

Equations for both the power law exponent and coefficient can be fitted to the above graphs. These are as follows:-

For the power law exponent, n:

$$n = m_n \alpha + c_n \tag{4.6}$$

For the power law coefficient, a:

$$a = c_a e^{m_a \alpha} \tag{4.7}$$

Where m_n, c_n, m_a and c_a are numerical curve fit coefficients and α is the angle of impingement.

Further investigation of the numerical curve fit coefficients led to findings that both c_n and c_a varied linearly with particle concentration. The mean distance between the particles could be calculated and related to the particle concentration which was defined, in the model of the rotating disc accelerator erosion tester (see Appendix 4B), as mass flow rate of solids divided by the volume flow rate of gas when the gas was taken to have the same velocity as the particles. The expression derived for the mean distance between the particles was calculated as part of the numerical model for the particle dynamics within the erosion tester (see section 4.2.3.5. and equation 4.4). The calculations were based upon the mean particle size.

$$D = \frac{69.599}{\rho_s^{0.2865}} \tag{4.8}$$

where D is the inter-particulate distance and ρ_s is the particle concentration. For the purposes of this test work the values of the particle concentrations were 1, 4, 13 kg/m^3. The data obtained for the variation of c_n and c_a is shown on the graphs shown in Figures 4.9 and 4.10.

The linear equations fitted to the data obtained for the variation of c_n and c_a with mean distance between particles, D, are as follows:-

For the intercept for the power law exponent, n;

$$c_n = 0.00988 D + 1.239 \tag{4.9}$$

For the intercept for the power law coefficient, a;

$$c_a = -7.983E{-4} D + 0.0751 \tag{4.10}$$

Figure 4.8 Variation of the power law coefficients.

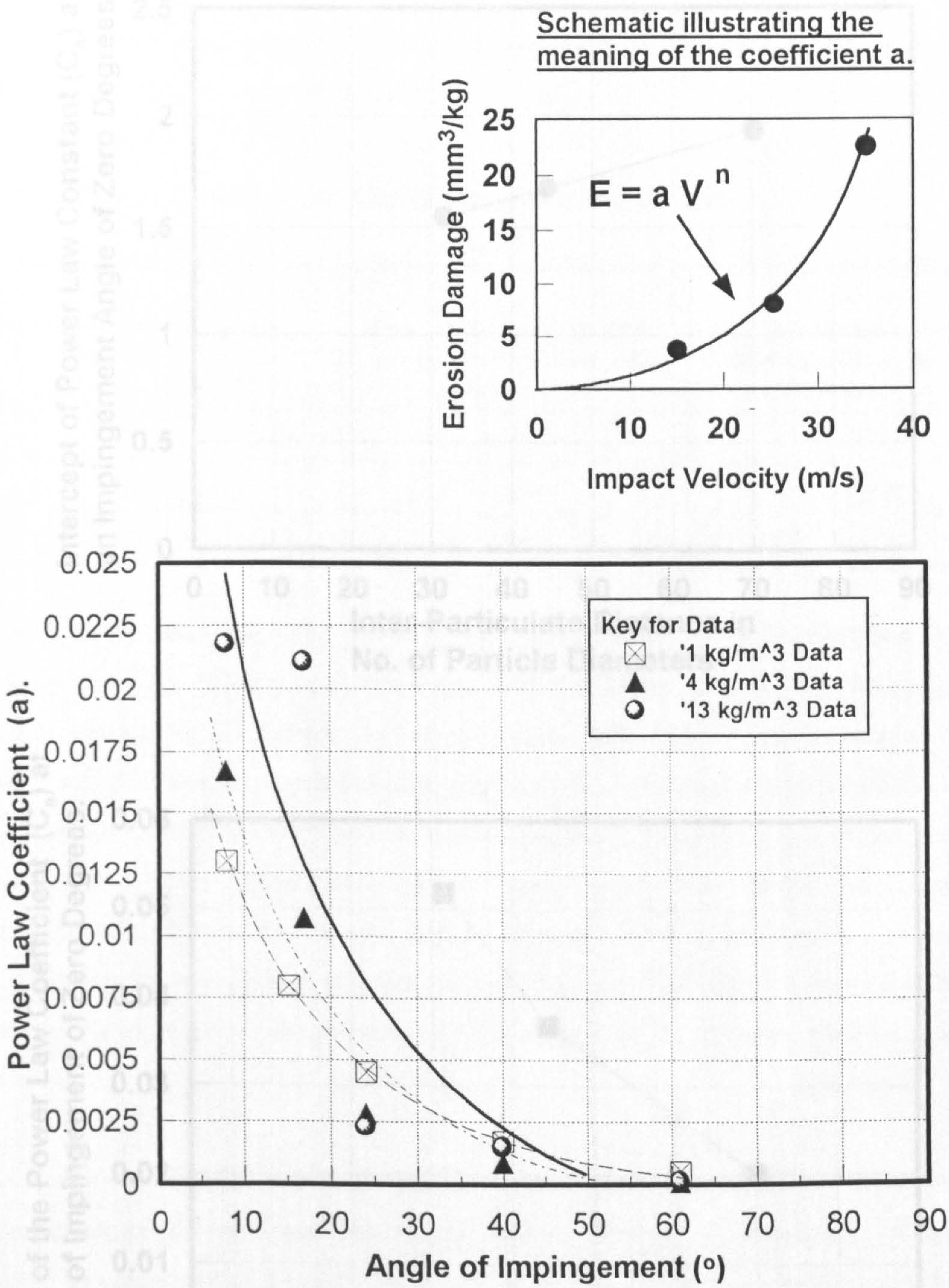
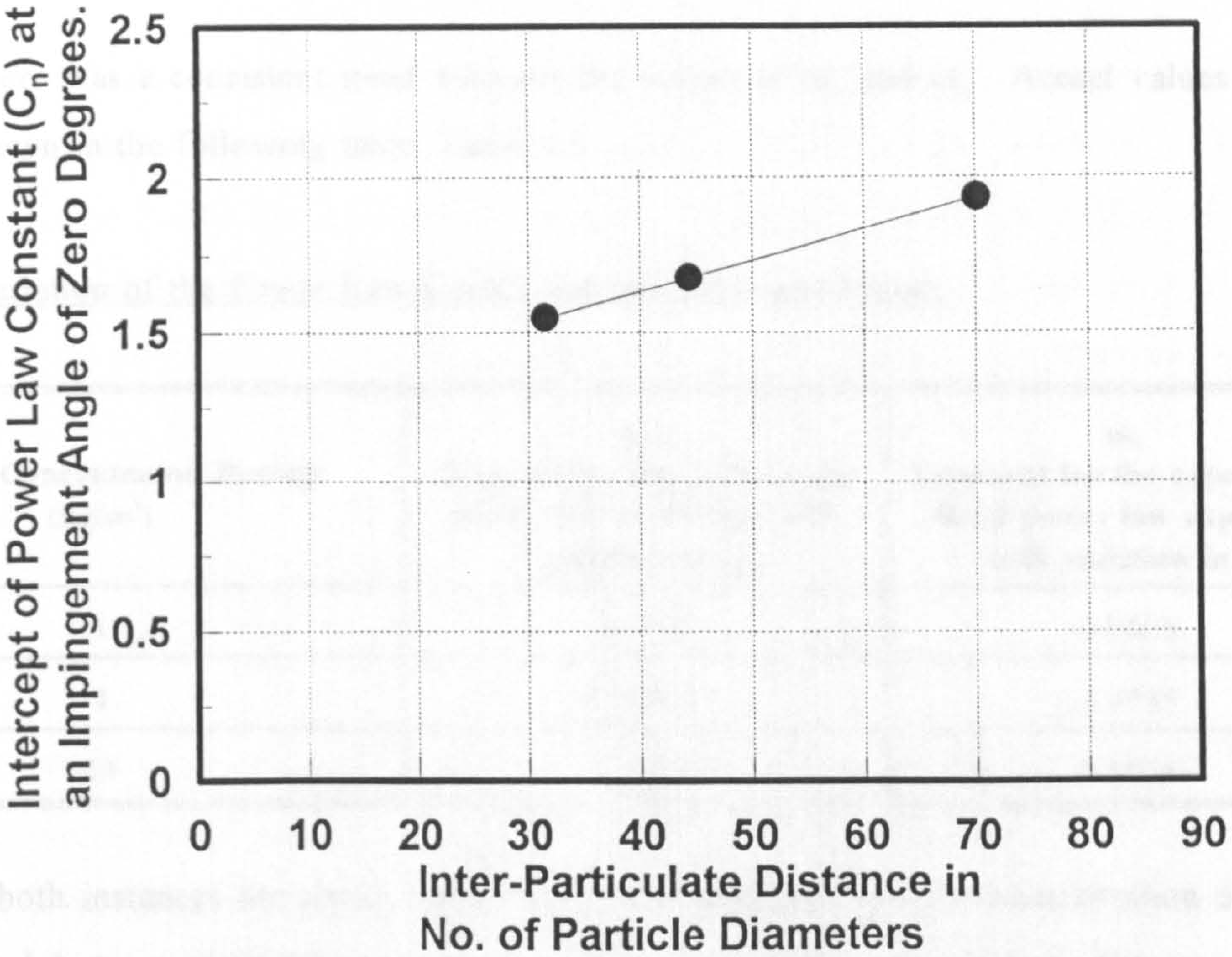
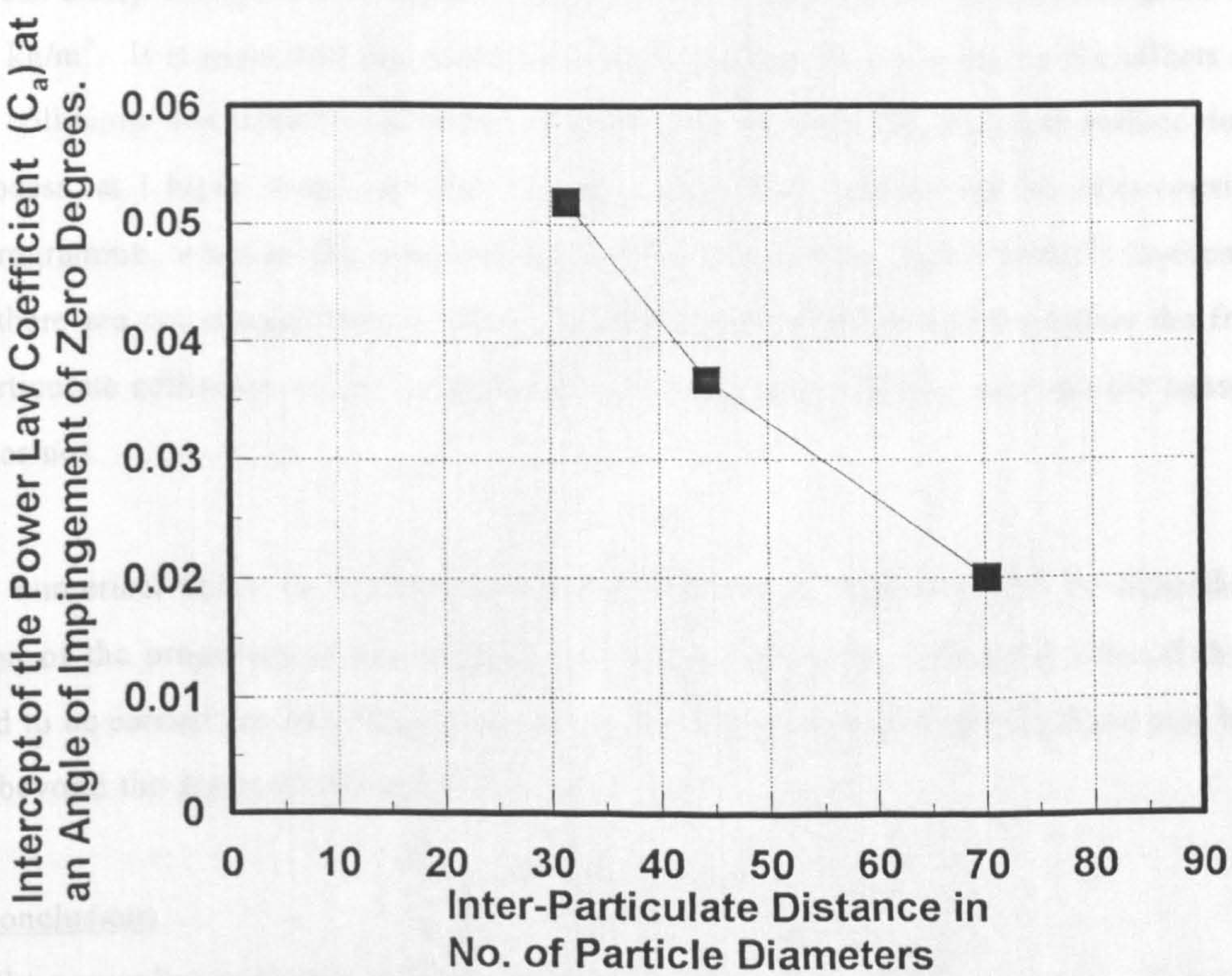


Figure 4.9 Variation of c_n, the power law exponent, with mean distance between particles.

Figure 4.10 Variation of c_a, the power law coefficient, with mean distance between particles.





Fitting equations to the variation of the slopes of the curves fitted to the power law coefficients and exponents proved to be very unreliable. The main reason for this was that there are only three data points for each of the coefficients and exponents.

However, there was a consistent trend between the values of m_n and m_a. Actual values of these slopes are shown in the following table, Table 4.2.

Table 4.2 Variation of the Power Law Coefficient and Exponent Slopes

Particle Concentration Density (kg/m^3)	**m_n Slope of the linear fit of the power law coefficient with variation in α.**	**m_a Exponent for the exponential fit of power law exponent with variation in α**
1	0.0143	-0.0605
4	0.02399	-0.0935
13	0.0238	-0.0955

Note that in both instances the above values are very similar at a particle concentration density of 4 and 13 kg/m^3, but very different at a particle concentration density of 1 kg/m^3. This suggests that there has been a step change in the values of these variables between particle concentration densities of 1 and 4 kg/m^3. It is suspected that this step change in these values is due to the effects of inter-particulate collisions and intensity of particle impacts per unit area on the target surface during the erosion process; at 1 kg/m^3 these variables will have their lowest values for the tests considered in this test programme, whereas the opposite will be the case at the higher particle concentrations. However, there are not enough data to make any definitive statement about whether the frequency of inter-particulate collisions, or the intensity of particle impacts per unit area, are the cause of this behaviour or not.

All of the numerical curve fit coefficients used in the above equations will be dependent on a combination of the properties of the abrasive and sample materials. However, tests of this nature would need to be carried out on a large range of materials to assess what effects these may be. Such work was beyond the scope of this project.

4.3.4.2. Conclusions

Values of the power law exponent have been found to vary with impingement angle. This statement is also applicable to the variation of the power law multiplying coefficient. Observations of this type have been reported before [S5,H18]. In Humphrey's paper [H1] it is suggested that the power law exponent should vary between 2.3 and 2.7 for a ductile metal. However, in this work values seem to vary with impingement angle from approximately 1.55 to 3.7.

The minimum exponent value occurs at the boundary of zero degree impingement angle and has a value of approximately 1.55 for tests carried out at a particle concentration density of 13 kg/m^3. It is suggested that the reason the value of the exponent was significantly less than 2, (the figure predicted if the kinetic energy of the particle at impact is considered the prime cause of erosion damage), was due to the effects of particle concentration, therefore causing inter-particulate collisions and changes in particle impact intensity to effect the erosion rate. This is even more likely when it is considered that the frequency of inter-particulate collisions will become greatest when either the impingement angle approaches 90°, or more importantly in this case, 0°. Also, in these instances the number density of particles at the target face reaches maximum values.

Modification to the exponent could be made, according to Humphrey, by adding an extra factor, m. This factor accounts for the fact that the coupling between the gas and particles may cause the particles to strike the target at angles different from those originally intended. Calculations have shown that the olivine sand particles used in the tests described in this paper will suffer very little from these coupling effects due to their comparatively large mass [B13]. Shimizu *et al.* [S5] found a similar trend in the velocity exponent in their work, the reason that these authors give for this behaviour is that the exponents previously derived have been based upon overall suspension velocities. It is stated in Shimizu's work that particle-gas coupling effects are the cause of this. However, this may be true with the smaller particles those researchers used, but as described above it is more likely that collisions between particles and changes in the particle impact intensity per unit area are the cause of this behaviour. It is proposed that the erosion damage could perhaps be modelled in the following manner: -

$$E = a\,k\,(V_{res})^{(2\,n\,m)} \tag{4.11}$$

Where E is the erosion damage in mm^3/kg; V_{res} is the particle velocity in m/s; a & n are numerical coefficients that vary with the angle of impingement and the mean distance between particles as described earlier in this paper; m is a constant that depends upon the level of coupling between the gas and particles, and k is a factor that is dependent on the probability of inter-particulate collisions affecting the erosion rate. Obviously many tests would have to be carried out to establish whether this is a viable method of modelling erosion.

A full discussion of the possible reasons for the peak in the erosion damage versus angle of impingement curve occurring very close to an impingement angle of 0° is discussed in section 4.3.6 below.

4.3.5. The Use of the Semi-Empirical Finnie / Bitter Model for Prediction of Solid Particle Impact Erosion Damage

4.3.5.1. Introduction

It is evident that particle concentration at the target surface has a significant effect on the erosion of the steel being considered here. However, the majority of erosion models suggested to date could not be utilised for the work being carried out in this project [B22,E1,H21,K3,S18,S3,R5,R8]. The reasons for this were that they either failed to account for the effects of particle concentration at all, or did not permit the peak in the curve of erosion damage versus angle of impingement to occur at impingement angles less than 10°. Other reasons why models were not utilised were that they either did not cover the full range of impingement angles being considered in this work, or they required complex experimental work to be carried out to provide values required for some of the constants within the models. Considering these points it was decided that the most appropriate models for use were those that covered the full range of impingement angles and gave the results in terms of the mean mass removed by each particle impact. The most obvious model that could be used in this case was that used by Shimizu *et al.* [S5] which was based on the work of Finnie [F5] and Bitter [B11,B12].

4.3.5.2. A Description of the Finnie / Bitter Erosion Model

In 1958 Finnie [F5] proposed a model for the erosion of ductile metals. This model was based on a theoretical analysis of the mechanisms of kinetic energy exchange during the impact of a single solid particle. This model only accounted for a cutting mechanism of wear and as a consequence it did not allow for erosion damage to occur at an impact angle of 90°, i.e. normal to the eroding target surface. This deficit was corrected by Bitter in 1963 [B11,B12] who suggested that another mechanism, that of deformation wear, acted in conjunction with the cutting wear mechanism proposed by Finnie. The resulting model can be used to predict the mean amount of material removed in one particle impact. It has been stated or implied by other researchers [H11,R5,B16] that single impacts do not always lead to the removal of material from the target surface; it is known that roughening of the surface due to earlier particle impacts is required before material can be removed [B16]. However, the model that can be derived from the combination of the work carried out by Finnie and Bitter has been used successfully in the past to model steady state erosion damage. The most recent use of a model of this form was by Sato *et al.* [S6] and Shimizu *et al.* [S5]. A more detailed examination of this model is given in Appendix 4G.

4.3.5.3. A Discussion Concerning the Empirical Constants Found for the Fitting of the Finnie / Bitter Erosion Model to the Experimental Test Results with Steel

The combined model used by Shimizu involves three major empirical constants, K, C and ε. Both ε and K are reasonably easy to understand; ε is the energy required to remove a unit volume of material from the target by the mechanism of deformation wear. Therefore, this is the empirical constant that can be fitted to ensure that the kinetic energy component incident at 90° can be manipulated to give a volume loss that compares closely with that obtained experimentally at this angle. The value of ε will change with the properties of the target material.

K is the ratio of the vertical to the horizontal force components acting on the particle while the particle and the eroding surface are in contact during impact (therefore, K is equivalent to the inverse of the Coulomb coefficient of dynamic friction [H18]). Finnie [F5] decided to give K a fixed value in his model for any given possible impingement angle. In experimental tests carried out by Finnie using force measurements made during dry grinding tests he found the mean value for this variable to be equivalent to 2. However, in the data presented in Figure 4.5 it can be seen that there is no apparent peak in the curves of erosion plotted against angle of impingement. From the curves shown in this graph a peak in the erosion damage curve is probable somewhere between 0° and 8°. Engel [E2] discussed Finnie's work prior to 1976 and gave the following expression for the angle at which the apex of the erosion damage curve occurs on a graph of erosion damage versus angle of impingement.

$$\alpha_{max} = \frac{1}{2} \tan^{-1}\left(\frac{K}{3} \right) \qquad (4.12)$$

When this expression is used to find the value of K that must be acting in order for the apex in the erosion damage curve to occur at these low impingement angles, it transpires that the values of K range from approximately 0.2 to 0.8. These values are considerably less than the constant value proposed by Finnie. From fitting the Shimizu version of the combined Finnie / Bitter model to the data obtained from testing the structural mild steel, the values of K had a mean value of 1.17 at 15 m/s particle velocity which increased to a mean of 1.43 at 35 m/s. Again this suggests that the value of K cannot be taken to be constant.

The value of C is dependent on a collection of variables. The majority of these variables are functions of the shape of the particle and the material properties in a high strain rate indentation.

Information on the shape of particles and the high strain / high strain rate behaviour of materials is scant and it is unlikely that a more accurate description of C in numerical terms will be possible for some time yet. Work on developing an understanding of the variables that affect C has not progressed since many researchers have decided to derive models for predicting erosion damage from first principles rather than improve these existing models.

4.3.6. A Discussion on the Position of the Apex of the Curve of Erosion Damage Versus Impingement Angle

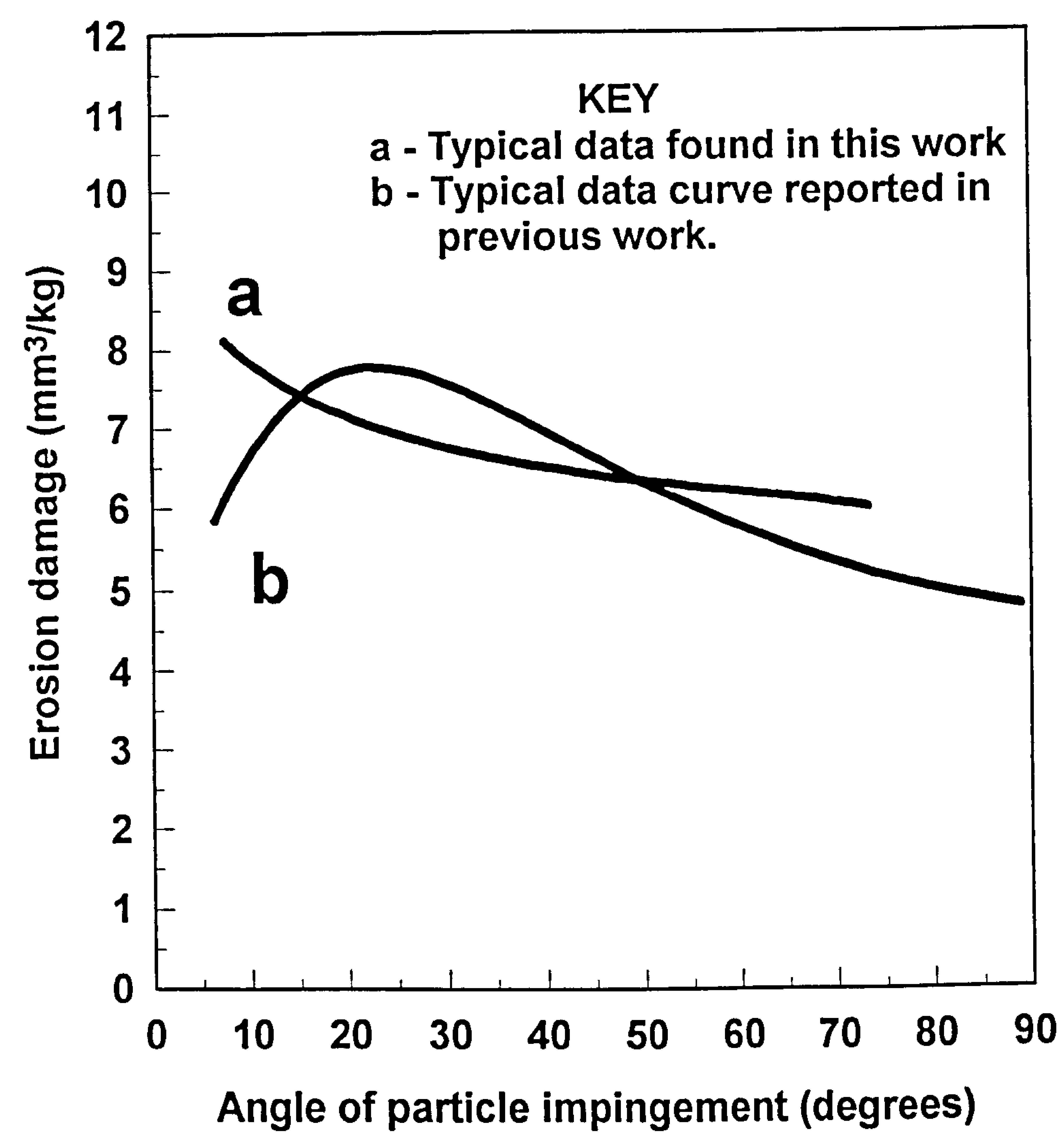
4.3.6.1. Introduction

The majority of work that has been published in the past illustrating curves of erosion damage versus impingement angle have indicated that the maximum erosion damage occurs at an angle between 20° and 30°. Figure 4.5, on page 62, gives the results of the tests carried out on the mild steel. It can be seen that there is no peak visible on any of the curves shown in this figure in this range. However, several other researchers have indicated that the maximum amount of erosion damage occurs at impingement angles less than 20° [B12,F3,F2,S12,N4,A6,M6]. Figure 4.11 below summarises the disparity between the shape of the curves that have been reported as a consequence of this work and in the results of previous research. It would be beneficial if a reason for this behaviour could be found. This section attempts to analyze why this should be the case.

4.3.6.2. A Discussion of Whether Erosion at an Impingement Angle of 0° Has Any Real Significance

This is an important question to address. It may be possible that many of the curves published to date are misleading due to the fact that the author has assumed that no erosion damage occurs at an impingement angle of 0°. This 'false' point may have therefore radically altered the curve fit proposed. Erosion damage by particle impact at an impingement angle of 0° is unable to occur since the particles will not actually strike the target surface. This is because the particles will be travelling parallel to the target surface and therefore cannot strike its surface. However, intuitively, it is possible to conceive of a form of diffuse three body abrasive wear [M11] occurring. In a real system it is possible for a particle of irregular shape, when travelling parallel to the target surface, to strike the surface as a consequence of the effects of particle rotation causing an asperity on the particle to rotate into the target surface and therefore cause damage. It can be expected that the damage caused by such an interaction will be small because the load in the plane normal to the eroding surface will be very low, and therefore, that the amount of erosive wear would be expected to tend towards zero. (Since the actual mass of abrasive particles striking the target surface and the wear that these interactions cause tend towards values of zero, erosion damage in terms of wear per mass of abrasive

Figure 4.11 Sketch of the erosion versus impingement angle curves (traditional and as a consequence of this work).



material striking the target surface becomes indeterminate). Therefore it is possible that a point of zero wear at an impingement angle of 0° may never be reached.

Only in the case of one previous research paper has this behaviour been shown to be a possibility. Wellinger and Uetz in 1957 attempted to link a form of abrasive wear called 'rinsing' with the more commonly accepted form of 'blast' erosive wear for various materials [W3]. These researchers indicated that all of the materials tested suffered some amount of wear at the nominal 0° impingement angle which occurred under the 'rinsing' form of abrasive wear. It must be stated that in the form of tests carried out by these researchers, particle impingements at a variety of angles where the mean was 0° occurred in their tests for 'rinsing' abrasive wear. Therefore, this result indicates the type of behaviour that is prevalent as impingement angles tend towards zero, not at an actual angle of 0°. Since the reporting of this work only two other published documents have mentioned the significance of erosion at 0° impingement angles as far as is known. Walley and Field [W1] stated that the effect of reducing the impingement angle to 0° was not known for the erosive wear of polyethylene, but it was conceded that damage would be caused by 'edge effects, beam spreading and rogue particles..'. Shimizu *et al.* [S5] give some results for erosion at an impingement angle of 0°. They indicate that there is a mass loss at this angle despite the prediction that abrasive particles are in principle unable to strike the target surface. This is not discussed any further in their paper. From the predictive model for the rotating disc accelerator erosion tester described in Appendix 4B it can be seen that there is a range of impingement angles that occur across the face of the target. The implication of this is that it is not possible to ensure that all the particles strike at any given angle of impingement, hence, if the 0° impact angle is being considered, there will always be some particles that will strike the target at a positive angle of impingement and therefore will cause erosive damage. This author believes that the main reason why the majority of erosion studies have indicated no erosion at a 0° impingement angle, is because all of the erosion models produced to date simply imply that this is the case. No evidence to suggest that zero erosion occurs at an impingement angle of 0°, (by carrying out experiments as the impingement angle approaches 0°), has been provided in any of the research supporting the proposed models [B22,E1,H21,K3,S18,S3,R5,R8].

4.3.6.3. What are the Physical Reasons for the Peak in the Erosion Damage Curve Occurring at Impingement Angles Closer to 0°?

There are several avenues that need to be explored in order to discover the answer to this question. These can be divided into three main groups:-

- The effects of particle shape and target microstructure on erosion damage.

- The particle dynamics within the 'rotating disc accelerator' erosion tester and the erosion damage that results from this.
- The effects of the differences in operation between 'gas blast' and rotating disc accelerator erosion testers.

Each of these three broad groupings will be discussed in turn.

4.3.6.3.1. The effects of particle shape and target microstructure on erosion damage

It has been noted in the past that particle shape has a significant effect on the amount of erosion damage that can be caused during multiple particle impact erosion.

Salik and Buckley [S13] found in tests using crushed glass and glass beads of roughly the same size distribution, (the median particle size being 15µm diameter), that the crushed glass in some instances gave an order of magnitude more erosion damage. This difference in the magnitude of erosion damage between spherical and angular particles was also stated as having been observed by Liebhard and Levy [L1]. In this case the damage caused by the crushed glass was approximately three times greater than that caused by the glass beads. However, these results can only be discussed in qualitative terms since the experimental procedure was prone to error. The device used to carry out the tests was an industrial sand blaster, and no mention of the particle velocity was made. In this sort of equipment the particles would have been subject to considerable amounts of jet dispersion due to their small sizes used. Levy and Chik [L5] in tests on mild steel at 80 m/s indicated that the erosion damage caused by steel grit was approximately four times that produced by similar sized steel shot at an impact angle of 30°.

Similar tests were also carried out by Kleis in 1969 [K11] with steel particles. Not only was it observed that there was a large difference in the magnitude of the erosion damage caused, but in the case of the steel grit, the peak in the curve of erosion versus impingement angle was seen to be shifted more towards 0° impingement angle than with the steel shot. A similar observation was made by Cousens and Hutchings [C3].

It was also noted by Cousens and Hutchings that the microstructure of the steels being eroded has a significant effect on the erosion damage caused by particles of different shapes. Salik and Buckley also noted this fact, indicating that the structure of the steel being eroded did not affect the erosion damage caused by angular abrasive particles, whilst the converse was seen with spherical particles. This was only observed during tests carried out on steels which had been heat treated in various ways. Tests involving steels which had been treated by various mechanical means to harden the target surface indicated that work hardening of steels had virtually no effect whatever on their erosion resistance [S13].

The steel used in the tests carried out for this project seems to have had similar properties to the spherodised form of the steel used by Salik and Buckley which had a Rockwell A hardness of 45, i.e. it was fairly soft. The shape of the abrasive particles used in the tests carried out for this project are illustrated in Appendix 3A, and can generally be called angular. In the cases where previous researchers have reported similar trends in the curve of erosion damage versus impingement angle to those reported in this thesis, the majority were found when the target material was soft and the abrasive particles angular [S12,A6].

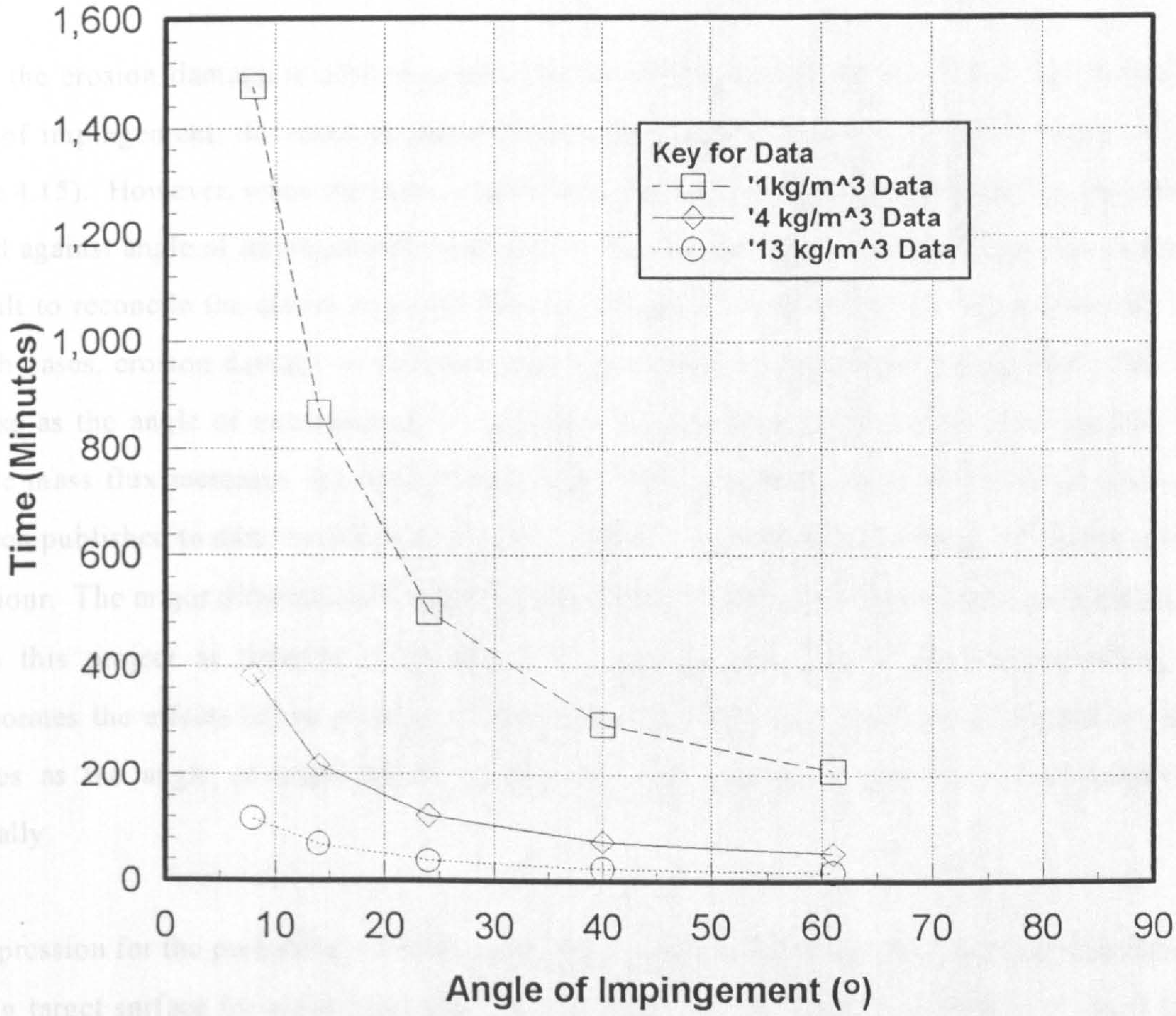
Given that the shape of the particles employed in the test programme were angular and that the steel used was soft and had a microstructure that was susceptible to gross erosion damage, it is possible that these properties of the materials used in the tests combined to cause the peak in the curve of erosion damage versus impingement angle to shift towards 0°.

4.3.6.3.2. The effects of the particle dynamics within the 'rotating disc accelerator' erosion tester and the erosion damage that results from this

Figure 4.12 overleaf shows that as the target angle is reduced it takes a longer time for the same mass of abrasive to strike the target in comparison to those targets orientated to give the higher impingement angles. This leads to the situation where a target orientated at a small angle of impingement to the particle trajectory will not be struck by a sufficient quantity of abrasive to ensure that steady state erosion is occurring. This problem was obviated by increasing the duration of the erosion tests when low impingement angles were being used. As a consequence of this fact the particle flux on the impact area of the target becomes important since it will vary with angle of target orientation, especially when the angle is low.

Two methods of finding values of the particle mass flux were employed in this project. The first of these was a global value of the particle mass flux as described in section 4.2.3.5. by equation 4.2. The second method was derived following recommendations made by Kleis [K9] and is described in section 4.2.3.5. by equation 4.3 which yields a value for the instantaneous particle mass flux. There are major differences between the two methods of calculating the particle flux. For the instantaneous particle mass flux the time for which the target surface is exposed to the stream of particles from a single traverse of an acceleration tube nozzle over the target surface is used. The time of the erosion duration per nozzle traverse varies with the change in the target orientation being

Figure 4.12 Time for 500 g of abrasive to strike a target surface at 25 m/s plotted against impingement angle for the rotating disc accelerator erosion tester.



used. In the case of the global particle mass flux the time base that is used is simply a chosen time unit used to describe the time of operation of the rig; this ignores the fact that for a significant percentage of the time impact on a given target is not taking place whereas for the instantaneous particle mass flux the opposite is the case. As a consequence of these differences the two methods of calculating the particle mass flux give strikingly different results when they are plotted against the angle of impingement being considered (see Figure 4.13 & 4.14).

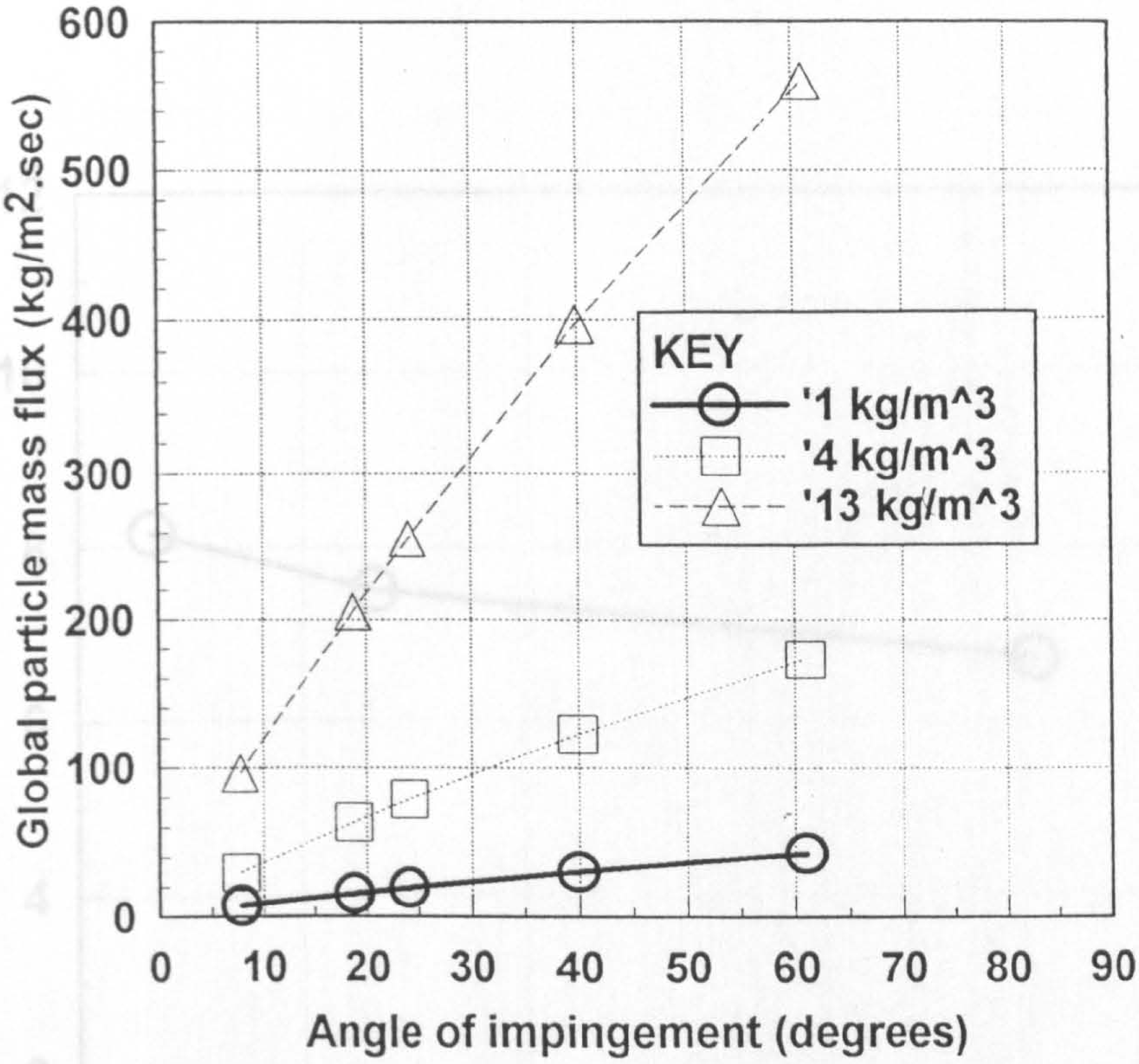
When the erosion damage is plotted against the instantaneous particle mass flux for an individual angle of impingement, the resulting curve follows those discussed in the work by Kleis [K9] (see Figure 4.15). However, when the curves for erosion damage and instantaneous particle mass flux are plotted against angle of impingement measured in the test work described in this chapter, it becomes difficult to reconcile the curves to each other (see Figure 4.5 and 4.13). The reason for this is that in both cases, erosion damage or instantaneous mass flux versus angle of impingement, the values increase as the angle of impingement is reduced. The implications from this work are that as the particle mass flux increases, the erosion increases. This is contrary to all the work on erosion that has been published to date, including that of Kleis [K9]. There must be a logical explanation for this behaviour. The major differences between the equations proposed by Kleis and the modelling carried out in this project as detailed in section 4.2.3. and Appendix 4B is that the modelling work incorporates the effects of the particle jet divergence and the area of the target affected by erosion changes as the angle of impingement is altered. This was not accounted for in Kleis's work originally.

An expression for the probability of inter-particulate collisions occurring in the region adjacent to the eroding target surface for a gas blast type erosion tester was proposed by Anand *et al.* [A5] (shown below in equation 4.13). If the instantaneous particle mass flux is used in this expression, then it can be shown that the probability of these collisions increases as the angle of impingement is reduced (see Figure 4.16 and 4.17).

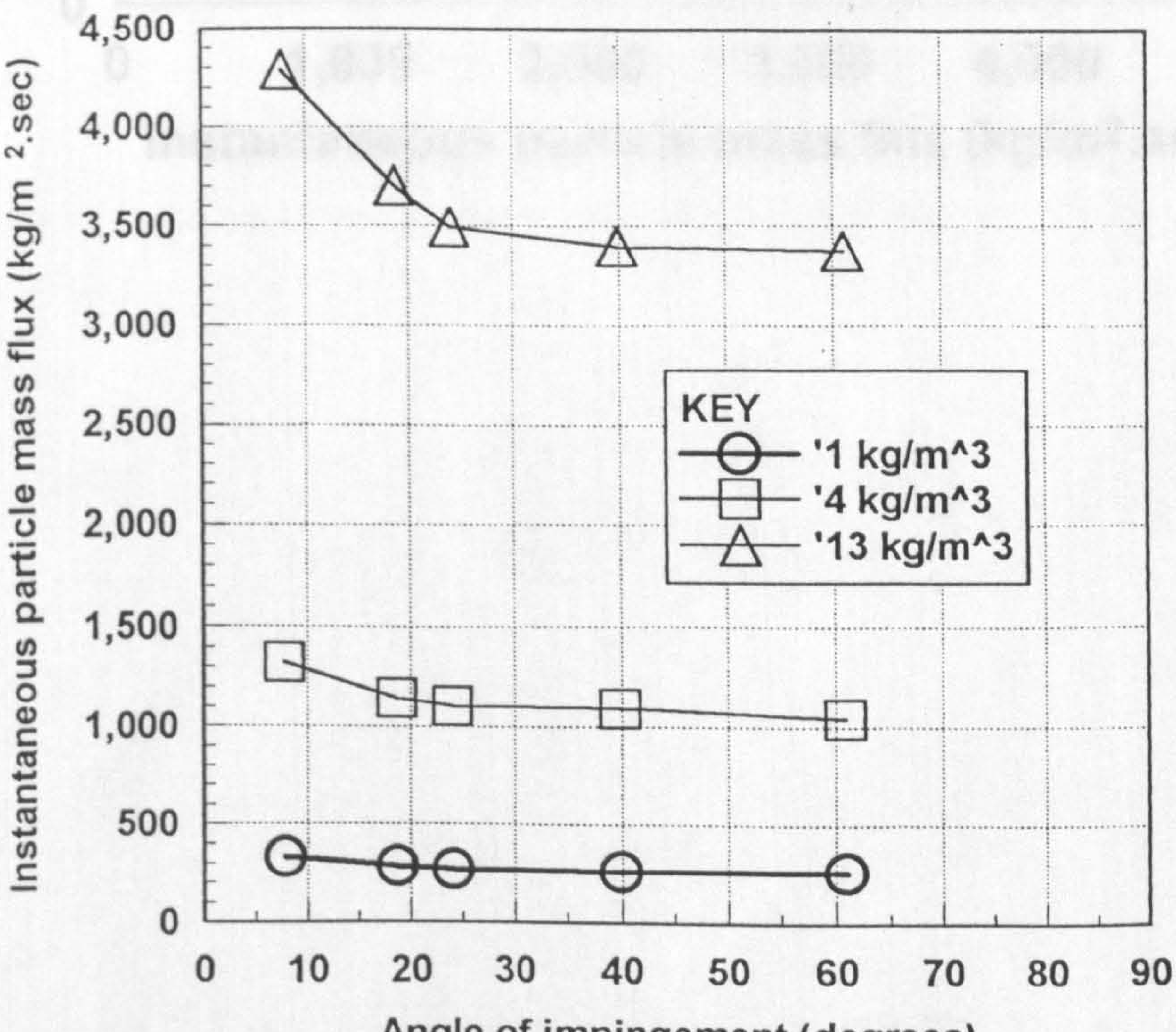
$$P_{col} = 1 - \exp\left(-\frac{Z}{V_{res}} \left[\pi \left(2 R_p \right)^2 \right] \frac{M_{fi}}{M_p} \right) \qquad (4.13)$$

Where Z is the distance that has to be travelled through the debris cloud; R_p is the radius of the mean particle size; M_{fi} is the instantaneous particle mass flux and M_p is the mass of a mean sized particle.

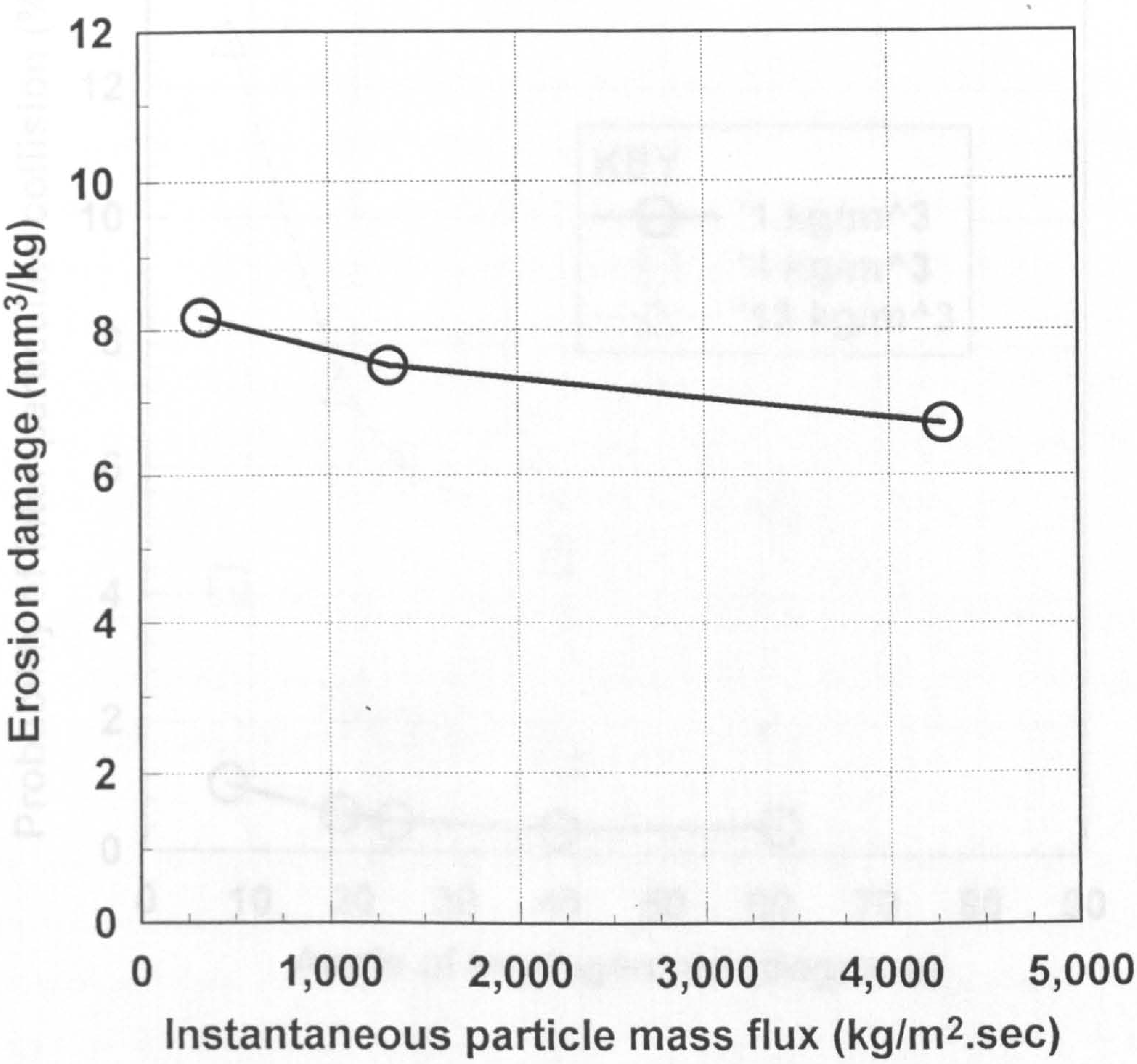
4.13 Variation of the global particle mass flux with angle of impingement at a particle velocity of 25 m/s.



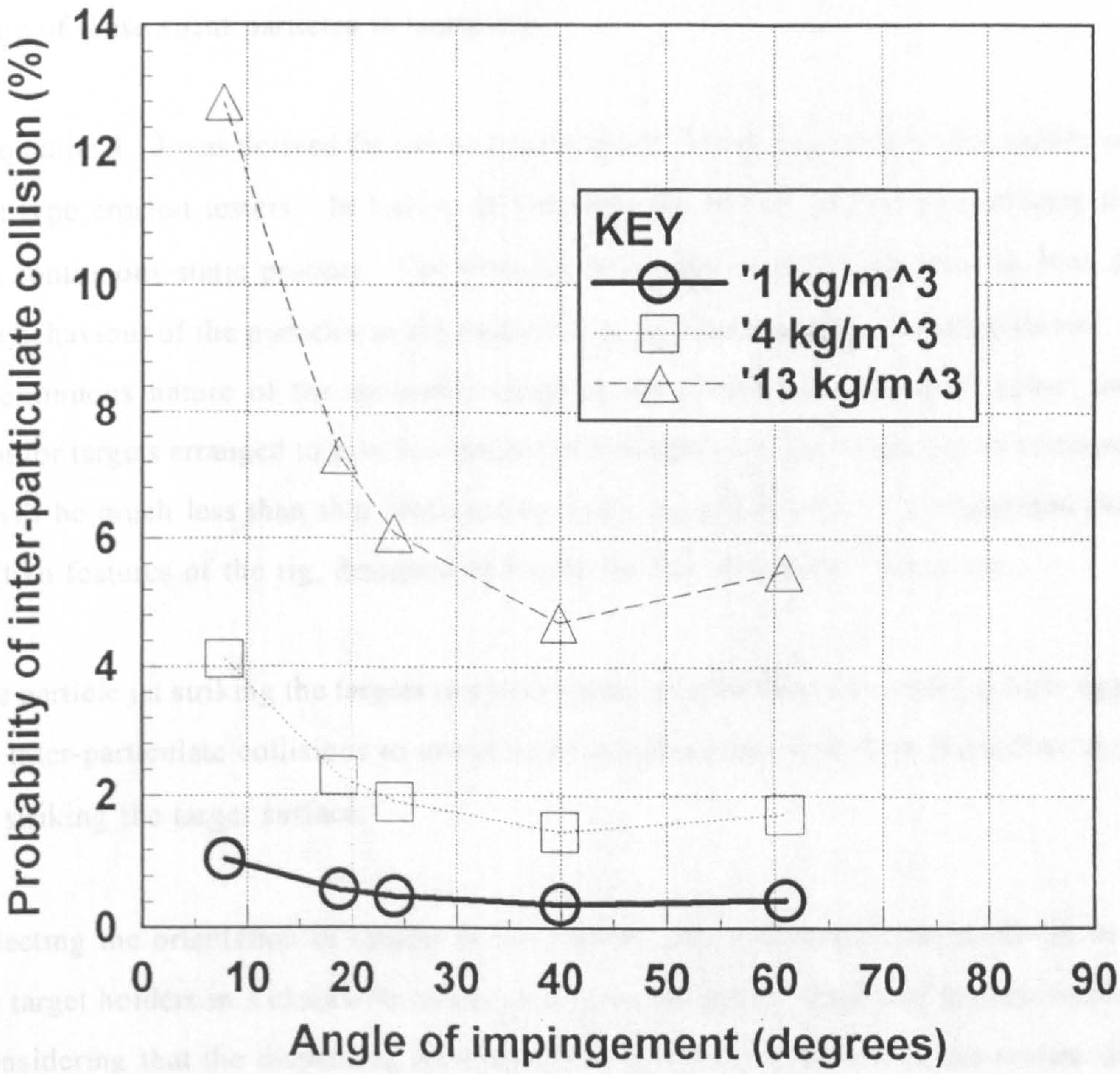
4.14 Variation of the instantaneous particle mass flux with angle of impingement at a particle velocity of 25 m/s.



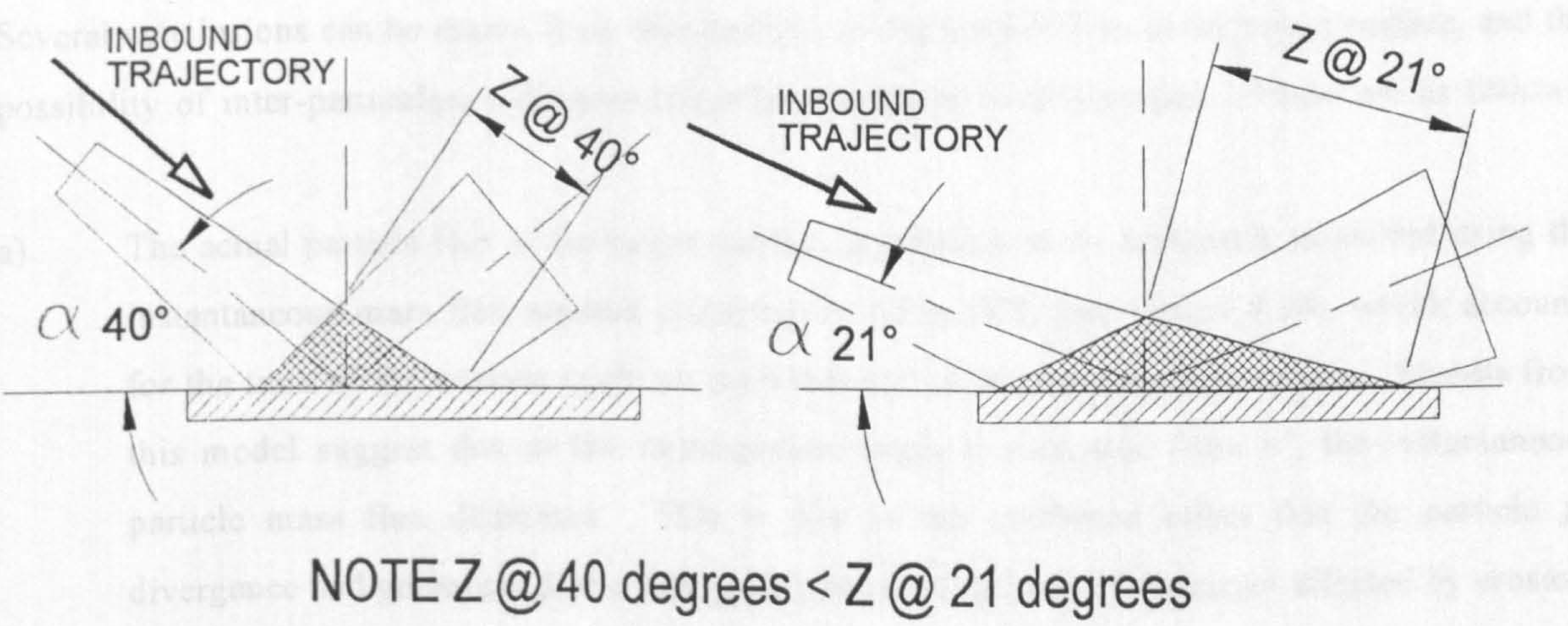
4.15 Erosion damage plotted against instantaneous particle mass flux for an angle of impingement of 8° and a particle velocity of 25 m/s.



4.16 Probability of inter-particulate collisions occurring plotted against angle of impingement (for a gas blast type of erosion tester).



4.17 Illustration of the cloud of erosion debris and the incoming particle stream for a gas blast type of erosion tester.



The reason that this behaviour is predicted is because the distance through which the particles have to travel in a cloud of rebounding particles and erosion debris is increased as the angle of impingement is reduced for any given length of target. Therefore, the chances of inbound particles striking some of these spent particles is increased.

However, equation 4.13 was derived for use in calculating the frequency of inter-particulate collisions in gas blast type erosion testers. In testers of this form the stream of particles striking the target surface is a continuous static process. The question that must be asked therefore is, how does this relate to the behaviour of the particles in the rotating disc accelerator form of erosion tester? Because of the discontinuous nature of the erosion process in the rotating disc form of tester, the author believes that for targets arranged to give low angles of impingement, the frequency of inter-particulate collisions will be much less than that predicted by using equation 4.13. It is suggested that this is because of two features of the rig, designed and used for this test work. These are:-

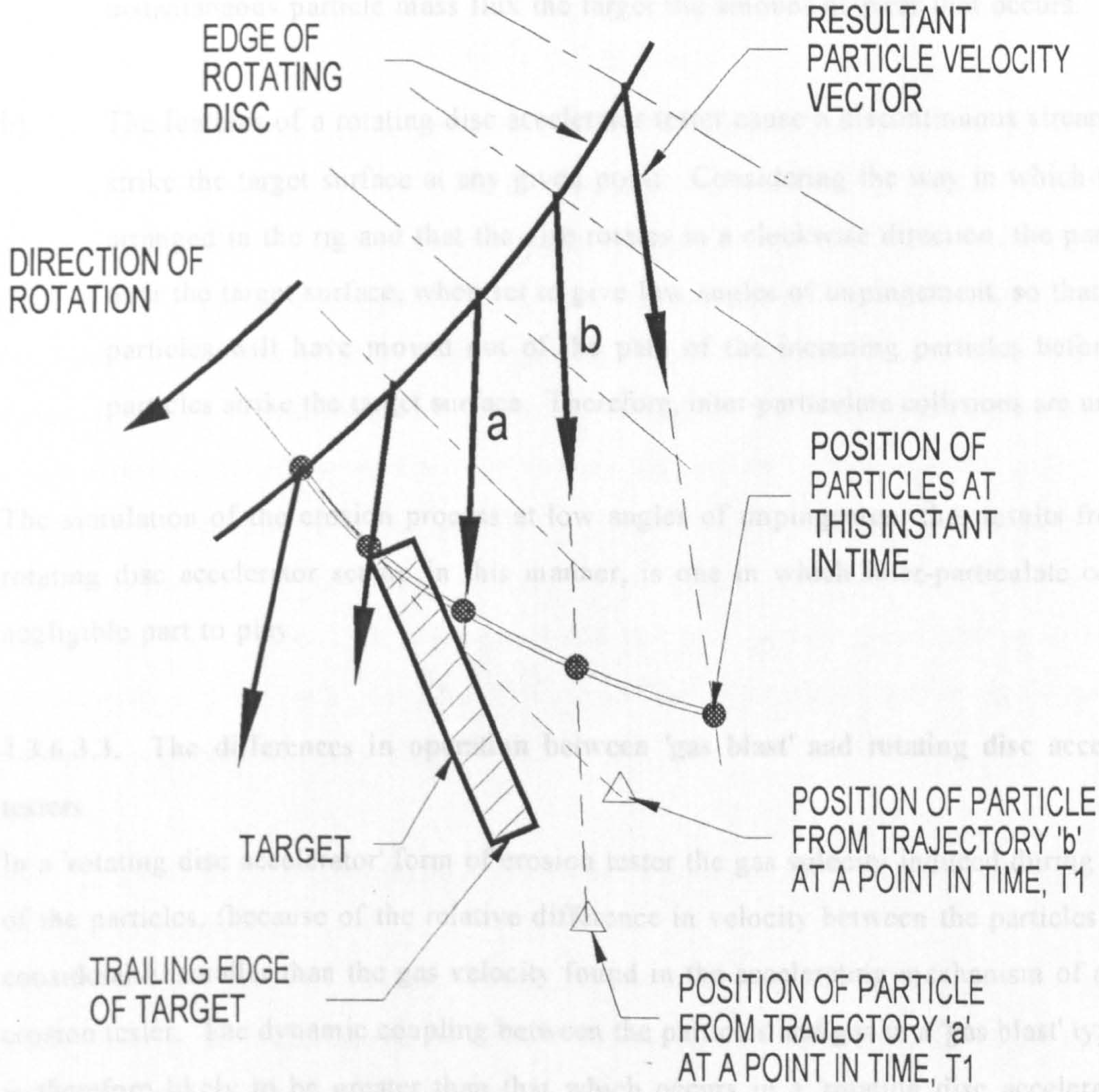
1. The particle jet striking the targets is never stationary, and therefore, there is little opportunity for inter-particulate collisions to occur with particles other than their immediate neighbours on striking the target surface.

2. Selecting the orientation of targets in the rotating disc accelerator was achieved by rotating the target holders in a clockwise direction to give decreasing angles of particle impingement. Considering that the dispensing disc rotated in a clockwise direction, the stream of particle jet sweeps over the target surface when set to give low angles of impingement, so that the rebounding particles escape from the path of the incoming particles before the inbound particles arrive (see Figure 4.18).

Several conclusions can be drawn from this analysis of the particle flux at the target surface, and the possibility of inter-particulate collisions occurring contained in this section. These are as follows:

a) The actual particle flux at the target surface is probably more accurately modelled using the instantaneous mass flux method proposed by Kleis [K9] (see Figure 4.14), which accounts for the time of the erosion cycle on each traverse of accelerating tube nozzle. Results from this model suggest that as the impingement angle is increased from 0°, the instantaneous particle mass flux decreases. This is due to the combined effect that the particle jet divergence and geometry of the test facility have on the area of the target affected by erosion. In the rotating disc accelerator, as the angle of impingement was reduced towards 0° the area

Figure 4.18 Illustration indicating the fact that rebounding particles will have moved out of the path of incoming particles before they arrive at the target surface.



of the target affected by erosion was bought closer to the accelerating disc, therefore, the intensity of particle impacts per unit area at lower angles of impingement is greater than that which occurs at larger angles of impingement. It is instructive to note that the data shown in Figure 4.14 follow the same trends as that shown in Figure 4.5, i.e. the greater the instantaneous particle mass flux the larger the amount of wear that occurs.

b) The features of a rotating disc accelerator tester cause a discontinuous stream of particles to strike the target surface at any given point. Considering the way in which the targets were arranged in the rig and that the disc rotates in a clockwise direction, the particle jet sweeps over the target surface, when set to give low angles of impingement, so that the rebounding particles will have moved out of the path of the incoming particles before the incoming particles strike the target surface. Therefore, inter-particulate collisions are unlikely to occur.

The simulation of the erosion process at low angles of impingement that results from the use of a rotating disc accelerator set up in this manner, is one in which inter-particulate collisions have a negligible part to play.

4.3.6.3.3. The differences in operation between 'gas blast' and rotating disc accelerators erosion testers

In a 'rotating disc accelerator' form of erosion tester the gas velocity induced during the acceleration of the particles, (because of the relative difference in velocity between the particles and the gas), is considerably smaller than the gas velocity found in the accelerating mechanism of a 'gas blast' type erosion tester. The dynamic coupling between the particles and gas in a 'gas blast' type erosion tester is therefore likely to be greater than that which occurs in a 'rotating disc accelerator' form of rig [B13]. In testing in a 'gas blast' type tester with small, low momentum particles there is an increased possibility that some particles will fail to strike the eroding surface. This is because the small particles have motions that are more closely coupled to that of the gas. It is more likely, however, that they will strike at an impact angle different from that which was intended [H1]. If the small particles miss the target completely, the mass of abrasive striking a sample in such a tester will be smaller than the mass of abrasive projected at it. Therefore, the erosion damage expressed in terms of volume of target surface removed per mass of abrasive striking the target surface will be incorrect.

Another reason the results are so different could be attributed to particle jet divergence, which is different with different particle acceleration mechanisms [H1]. As the sample orientation alters towards the lower impingement angles the area of the sample subjected to erosion damage will increase. Also, both the particle jet and target are stationary in tests carried out on a gas blast tester. Therefore, there will be a decrease in the intensity of particle impact in the area undergoing erosion. Consequently, despite the change in the intensity of particle impacts with impingement angle due to jet divergence, inter-particulate collisions will have more chance to establish themselves, especially at low angles of impingement.

The major problem in trying to find the source of the apparent inaccuracy of the erosion test results obtained previously on gas blast types of erosion tester, is that the authors have rarely described the experimental methods that they adopted whilst carrying out the tests. It makes it impossible therefore to confirm the assertions made above. In the standards pertaining to the use of the gas blast form of erosion tester no mention is made regarding ensuring that the particle mass flux is constant with changes in target orientation [D3,A4]. Only one research group has made a mention of the necessity of adjusting the particle mass flow rate to keep the particle mass flux at the impact site constant as the angle of impingement is changed [W1]. However, these researchers were using a gas blast type erosion tester which, when low impingement angles are used, is prone to an increase in inter-particulate collisions. It is proposed that this may be the reason why no difference was seen in the position of the peak of the curve of erosion damage versus angle of impingement; the peak in the curve occurred at approximately 25°.

4.3.6.4. Conclusions Regarding the Position of the Apex in the Curve of the Erosion Damage versus Angle of Impingement

The most likely reasons why the results illustrated in section 4.3.3. Figure 4.5 seem to have no pronounced peak in the curve of erosion damage versus impingement angle around 20-30° (as reported in other work) are as follows:-

1/ The fact that the particle jet sweeps over the target surface in a rotating disc accelerator set up in the manner used in these tests, causes erosion in which inter-particulate collisions have a much reduced part to play. It is suggested that the reduction in the frequency of inter-particulate collisions is the main reason why no peak in the curve of erosion damage versus angle of impingement is seen.

2/ The peak in the curve of erosion damage versus angle of impingement may be shifted towards an impingement angle of 0° because of the effect of the using relatively sharp particles against what is a relatively soft material. However, in the available research, while it is suggested that the peak in the curve of erosion damage versus angle of impingement will shift towards an angle of impingement of 0°, the peak will still be present as a consequence of using sharp particles and a soft target.

3/ It is possible that no peak is observed because it has been shifted very close to 0° because of the rinsing form of erosion damage that is prevalent at low angles of impingement [W3]. This may be more pronounced with softer target materials. Unfortunately, there seems to be no test results available for a range of metallic materials being subjected to this form of diffuse three body abrasive wear.

4.4. Conclusions Drawn from the Experience of Using the 'Rotating Disc Accelerator' Erosion Tester

The results obtained from the 'rotating disc accelerator' erosion tester have indicated that this form of testing device is capable of providing good qualitative and quantitative results (within the same order of magnitude) for the erosion behaviour of materials in comparison with the more common gas blast erosion tester. This can be seen in the results presented in Appendix 4E concerning the collaborative test work in which the results from the two major forms of erosion tester were compared. Careful numerical modelling of the processes occurring within the tester is essential, especially in the areas of calculating the particle velocity, the particle impingement angles and the particle mass flux on the target surface. The collaborative tests carried out with The Department of Powder Science Technology (POSTEC) in Norway highlighted the importance of the particle mass flux on the erosion process.

This fact can also be seen in the results obtained from tests carried out on the structural mild steel used in the pneumatic conveyor, which will be described in Chapter 5. One most unusual aspect of the results observed, was that the peak in the curve of erosion damage versus angle of impingement, which has been reported in other work to occur between 20° and 30°, did not occur at all in the range of impingement angles tested in this project (8°-60°). Instead, the erosion damage continued to increase as the angle of impingement was reduced towards 0°. The main reason why this was felt to occur was because of the manner in which erosion damage was simulated by using the rotating disc accelerator built for this project. This is because the geometry of the target holders, and the fact that the particle jet sweeps over the target, therefore causing erosion to occur with minimal inter-particulate collision affects. In comparison, with a gas blast form of erosion tester inter-particulate collisions can be shown to become more significant as the angle of impingement is reduced towards

0°, and since the erosion process is continuous in this form of tester these collisions tend to have more effect. Also, previous research indicated that using quite sharp particles in conjunction with a relatively soft target material in erosion studies tended to result in the peak in the curve of erosion damage versus impingement angle shifting towards an impingement angle of 0°. However, this will not lead to the absence of a peak, therefore, this may be viewed as a contributory factor only to the observed behaviour

Two models were utilised to describe the erosion results obtained for the structural mild steel tested. One of these was a simple power law model that was fitted empirically to curves of erosion damage versus angle of impingement. The importance of the angle of impingement, and the particle concentration on erosion at the low velocities considered, was emphasised by the use and development of this model. Modifications to the form that previous power law models have taken were proposed. The other model that was utilised was that attributable to Finnie and Bitter which was based on a balance of kinetic energy versus work done on the eroding surface. This is a semi-empirical model that uses three empirical constants to enable it to be fitted to erosion test results. The Finnie / Bitter model was used because it enables an estimate to be made of the material removed from a surface per particle impact. This makes this model more easily useable when it is required to combine erosion models and particle trajectory models such as is described in Chapter 6. Both of these models will be used in the work concerning the prediction of the life of a pneumatic conveyor bend which is contained in Chapter 6.

Chapter 5

A Description of the Work Associated with the Pneumatic Conveying Test Facility

5.1 Introduction

It has been stated previously in this text that it is generally in the relatively high particle velocity / low particle concentration conveying regimes in pneumatic conveyors where erosion damage is greatest. This fact affected the design of the pneumatic conveying test facility considerably. Owing to the problems of scaling for particle velocity and general conveying conditions, (see section 3.4 chapter 3 and section 4.2.3.1 chapter 4) the tests that were carried out were designed to simulate conditions seen in pneumatic conveyors in industry. Effectively, only one test was carried out on the pneumatic conveying test facility. The reason for this was that the main aim of this project was to see if a link could be found between results from the rotating disc accelerator rig and the single test on the pneumatic conveyor, rather than a general examination of erosion behaviour in pneumatic conveyors.

This chapter describes the design, construction and use of a pneumatic conveyor so that these conditions were met as closely as possible. The analysis of the results obtained from this test facility are also discussed in this chapter.

5.2 Design and Construction of the Pneumatic Conveying Test Facility

5.2.1 Design Features that were Considered for the Construction of the Pneumatic Conveying Test Facility

Several variables were of interest and were considered to be of prime importance to the measurement of the erosive wear of a bend in a pneumatic conveyor. They are discussed in section 3.4 chapter 3. The measurement of these variables has a significant bearing on the design and construction of the test facility. The variables that had to be measured were:-

1. The particle velocity,
2. The particle concentration, and
3. The penetration of the bend wall at a variety of points around the bend.

The control of the first two variables mentioned above was of primary importance to the design of the pneumatic conveying test facility. The third was controlled by the design of the bend and the location of the wall thickness measurement positions.

5.2.1.1 A Brief description of the Pneumatic Conveying Test Facility

A pneumatic conveying facility was designed so that the three main variables discussed above could be measured in detail. A schematic of the whole pneumatic conveying test facility is given in Figure 5.1. Much more detail regarding the design and construction of this test facility is given in Appendix 5A and the design options available were discussed briefly in Chapter 3.

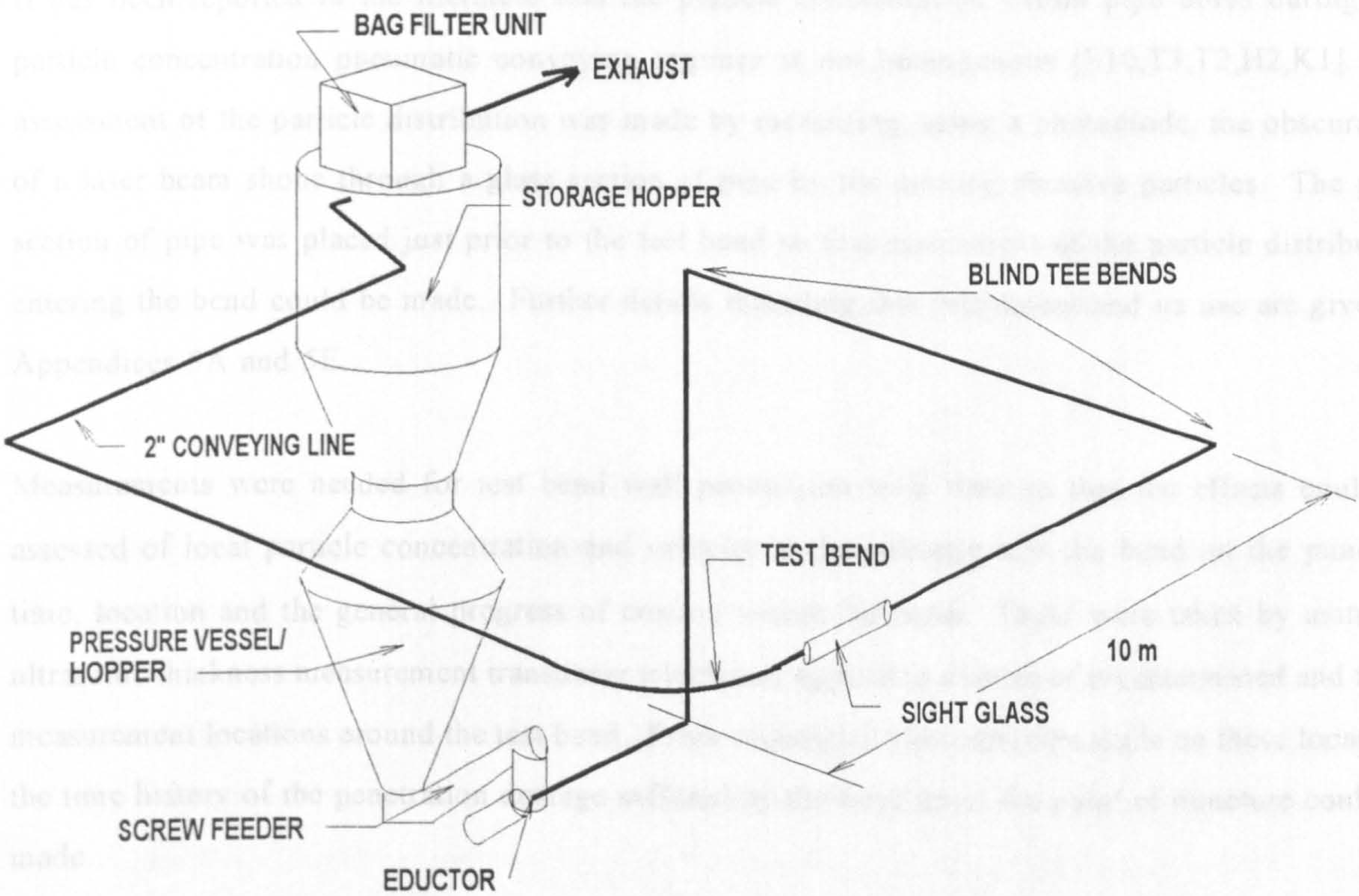
It was concluded that only one test bend was required for the purposes of comparing erosion results obtained from the pneumatic conveyor and the 'rotating disc accelerator' erosion tester. The design of test bend that was chosen was a long radius bend (R/d = 14.15, 53 mm bore, 750 mm radius) of the type that would commonly be used in the construction of pneumatic conveyors in industry. Generally, radiused bends tend to suffer quite severely from erosion damage as a consequence of their geometry.

To establish the particle velocity it was assumed that this was the same as the local gas velocity entering the test section of the pipeline. This was only justifiable provided the length of straight pipe containing undisturbed flow prior to the test section was long enough to ensure the particles had reached their terminal velocity. Because of this, the design of the conveying pipeline was such that the straight lengths were sufficiently long enough to ensure that the particles were at their steady terminal velocity. The local gas velocity was found by measuring the local gas pressure and using the equation of state for a perfect incompressible gas and the known pipe bore geometry.

A choked flow nozzle with a constant upstream air pressure was used to introduce a constant mass flow rate of gas into the pipeline. With a device of this type the mass flow rate of gas is constant whatever the pressure drop in the conveying line. This ensured that the gas velocity around the pipe line was maintained at a constant level for any point within the line. The adoption of this system of gas feed into the conveying line helped ensure that the chosen conveying conditions were kept as steady as possible.

The functions of a blow tank, venturi ejector and a screw feeder were combined to give a steady and consistent flow of abrasive material into the pipeline. Measurement of the mean mass flow rate of abrasive was carried out by measuring the change in mass of the receiving hopper and its contents

Figure 5.1 Schematic of the overall pneumatic conveying test facility.



with time during a test. This form of measurement gives values that are not dependent on slip in velocity between the particles and the gas surrounding them. Operation of a feeding system of this design could lead to an additional volume of air being added to that in the pipe line. To account for this it was necessary to measure the total amount of air flowing through the pipe. This was achieved by using a pitot-static tube and temperature measurement transducer in the gas exhaust line from the test rig.

It has been reported in the literature that the particle concentration within pipe bores during low particle concentration pneumatic conveying regimes is not homogenous [S10,T3,T2,H2,K1]. An assessment of the particle distribution was made by measuring, using a photodiode, the obscuration of a laser beam shone through a glass section of pipe by the moving abrasive particles. The glass section of pipe was placed just prior to the test bend so that assessment of the particle distribution entering the bend could be made. Further details regarding this instrument and its use are given in Appendices 5A and 5E.

Measurements were needed for test bend wall penetration with time so that the effects could be assessed of local particle concentration and velocity at the entrance into the bend on the puncture time, location and the general progress of erosion within the bend. These were taken by using an ultrasonic thickness measurement transducer which was applied to a series of predetermined and fixed measurement locations around the test bend. From sequential measurements made on these locations the time history of the penetration damage suffered by the bend up to the point of puncture could be made.

A discussion of the design of the test facility is given briefly in Chapter 3 and in more detail in Appendix 5A.

5.2.2 Specification of the Materials Used During The Tests

The materials used during the tests carried out on the pneumatic conveyor test facility were the same as those used in the rotating disc accelerator erosion tester. The olivine sand was the abrasive material and the pipe bend was made from the structural mild steel used in the test work carried out on the rotating disc accelerator. Detailed information regarding these materials is given in Appendix 3A.

5.2.3 Calibration of the Instrumentation Used on the Pneumatic Conveyor Test Facility

The calibration of the transducers used in the instrumentation on the pneumatic conveyor test facility will be discussed in the following section. More details regarding the number and type of the transducers used on this rig are given in Appendix 5A. Detailed indications of how the calibration was carried out are given in Appendix 5B.

The transducers used to obtain information regarding the conveying conditions included a pressure transducer just before the test bend; a pressure transducer on the blow tank; a temperature measurement transducer and pitot static tube on the gas exhaust duct; a group of three load cells designed to weigh the contents of the receiving hopper, and a choked flow nozzle through which the main conveying air was supplied. All of these devices were calibrated against known standards or using devices whose calibration could be traced to suitable standards. All of these transducers were connected to a computer based data acquisition system.

The measurement of the bend wall penetration was carried out by using a hand held ultrasonic thickness measurement transducer. Calibration of this device was made against a segment of steel of known thickness.

The only calibration test that could be carried out on the optical obscuration sensor used to assess the particle distribution, was that of checking for the linearity of the variation of the signal obtained from the photodiode with light obscuration. This was achieved by using a neutral density filter. Relating the readings taken using this device directly to the particle number concentration is not possible for the following two reasons; First the sampling rate of the data acquisition system was not fast enough to distinguish between the obscuration caused by individual particles. Secondly, it is possible that a situation where two particles pass through the light beam simultaneously may occur. In this case the light will be obscured by one of the particles only and the passage of the second particle will remain undetected. It is possible to estimate the probability of this occurring. In conclusion, the device used in this project can only be used to obtain a time averaged mean obscuration caused by the passage of the particles. More information relating to this device and its use is presented in Appendix 5A and 5E.

5.2.4 Test Method Employed During Conveying Tests

The tests carried out on the pneumatic conveyor test facility can be separated into three phases. These are 1) the main conveying trials, 2) measurement of the bend penetration and 3) assessment of the particle concentration. Effectively 1) and 2) are related and were carried out using the same test runs. However, the assessment of the particle concentration formed a completely different set of tests and consequently will be discussed separately. Both groups of tests, and the methods employed to carry them out, are described in more detail in Appendix 5C.

5.2.4.1 Method of Carrying Out Conveying Characteristic and Bend Penetration Measurements

Since the measurement of the progression of penetration with time under fixed conveying conditions was required, a series of detailed measurements of the bend wall thickness had to be undertaken. Tests of this type for 45 measurement locations (see Appendix 5A section 5A.6) took considerable time. It was therefore necessary to stop the conveying cycle periodically to undertake the necessary measurements. From commissioning trials, it was found that the measurement of the pipe wall penetration was best carried out over a number of conveying runs, each of which consisted of the conveying of 250 kg of olivine sand. These conveying runs were continued until bend wall puncture occurred.

With the unusual feeding arrangement attached to the bottom of the blow tank, considerable control could be exercised over the conveying cycle. A conveying run was normally initiated by starting the pressurisation of the blow tank, the rotation of the screw feeder at the required velocity, and the supply of the air to the conveying line via the venturi feeder. Once all of these systems were running in their correct manner the butterfly valve on the base of the blow tank was opened, and the olivine sand was allowed to flow into the screw feeder, beginning the conveying run.

Owing to the careful design and operational procedure adopted for the test facility, the start up and shut down transients normally seen in pneumatic conveyor operations were minimised. Hence, the effects of such transients on the erosion process by frequent stopping and starting of the conveyor were not seen.

The data acquisition system was used to register the values of the variables important in the assessment of the conveying conditions. After 250 kg of abrasive had been conveyed, detailed measurements of the bend penetration at the predetermined measurement locations was carried out and the results logged by hand. This sequence of events was then repeated for the passage of another 250 kg of abrasive.

5.2.4.2 Method of Carrying out Particle Distribution Assessment Using the Laser Obscuration Technique

The use of the laser obscuration technique for the measurement of the particle distribution required the use of the data acquisition equipment normally used to assess the conveying conditions of the test. However, the experience gained using the test facility indicated that once the relevant valve and control settings had been made the repeatability of the test process was reasonably good. Good enough to justify the removal of the data acquisition equipment from its first task, that of measurement of the major conveying variables involved, to allow it to be redeployed to assessment of the particle distribution in the pipeline cross-section.

Tests without abrasive material being conveyed through the line were undertaken using the light obscuration sensor to enable calibration measurements to be taken. Particle distribution assessment tests required starting the conveying system in the manner as described above. Conveying continued whilst manual positioning of the sensor, and assessment of the particle distribution at various points across the glass pipe section bore, was undertaken. This was repeated several times for sensor traverses in both vertical and horizontal orientations.

5.2.5 Test Conditions

In order to ensure that the behaviour of the pneumatic conveying erosion trials could be predicted it was obvious that the conditions for the erosion to take place must be within the range of simulated conditions used in the rotating disc accelerator. To this end the rotational speed of the screw feeder, the blow tank pressure and the mass flow rate of the air supplied to the conveying pipe line were adjusted to give a local air velocity of approximately 25 m/s, and a particle concentration density of as close to 4 kg/m^3 as possible. It was found to be quite difficult to generate conveying conditions where the particle concentration density was 4 kg/m^3. However, the value that was obtained was reasonably close to this figure. The reason why this was the case was that the screw feeder was too small, and therefore, the amount of material that could be passed through it was lower than that required.

5.3 Test Results

The tests on the pneumatic conveyor were carried out on a single bend at a single set of conveying conditions. However, there were three sets of results that were obtained from these tests. These were the mean conveying conditions, the progress of bend wall penetration and the assessment of the particle distribution in the pipe bore. Each will be discussed in turn.

An important result for the erosion of a bend of this one geometry was that the bend punctured after 22 test runs during which approximately 5475 kg of material had been conveyed through it.

5.3.1 Results Obtained for the General Conveying Conditions

These results were obtained from the 22 sets of data obtained from the instrumentation on the pneumatic conveyor test facility. This included the load cells, two pressure transducers, the pitot-static tube and the temperature measurement transducer. The information derived from these measurements included:-

a) the local gas velocity in the test bend (which was, for the purposes of this work, taken to be the particle velocity on approach to the bend),
b) the mass flow rate of solids in units of kg/s,
c) the particle concentration density (suspension density) in units of kg/m^3, and
d) the solids loading ratio in units of kg of solids / kg of air.

This information was obtained from the data gathered by the data acquisition system from each conveying run, by selecting the data readings where the blow tank pressure could be considered to be constant. Once these readings had been selected the conveyor could be said to be operating under steady state conditions. The mean of the calculated readings for the local gas velocity determined using equation 5A.2 section 5A.5.2 Appendix 5A was obtained and was taken, by inference, to be the particle velocity approaching the test bend. The mass flow rate of the abrasive material was obtained for each test series by calculating the difference in the mass of the receiving hopper and contents within a certain time period during a test. The calculation of both the particle concentration density and the solids loading ratio were derived from these two values.

An example of the typical data obtained from the data acquisition system is contained within Appendix 5D. A full set of the results for these variables is also given in tabular form in Appendix 5D.

The final mean values obtained for the conveying conditions during the tests carried out on the pneumatic conveyor test facility are contained in Table 5.1 below.

Table 5.1 Mean Values for the Conveying Conditions Obtained for the Tests Carried out on the Pneumatic Conveyor Test Facility

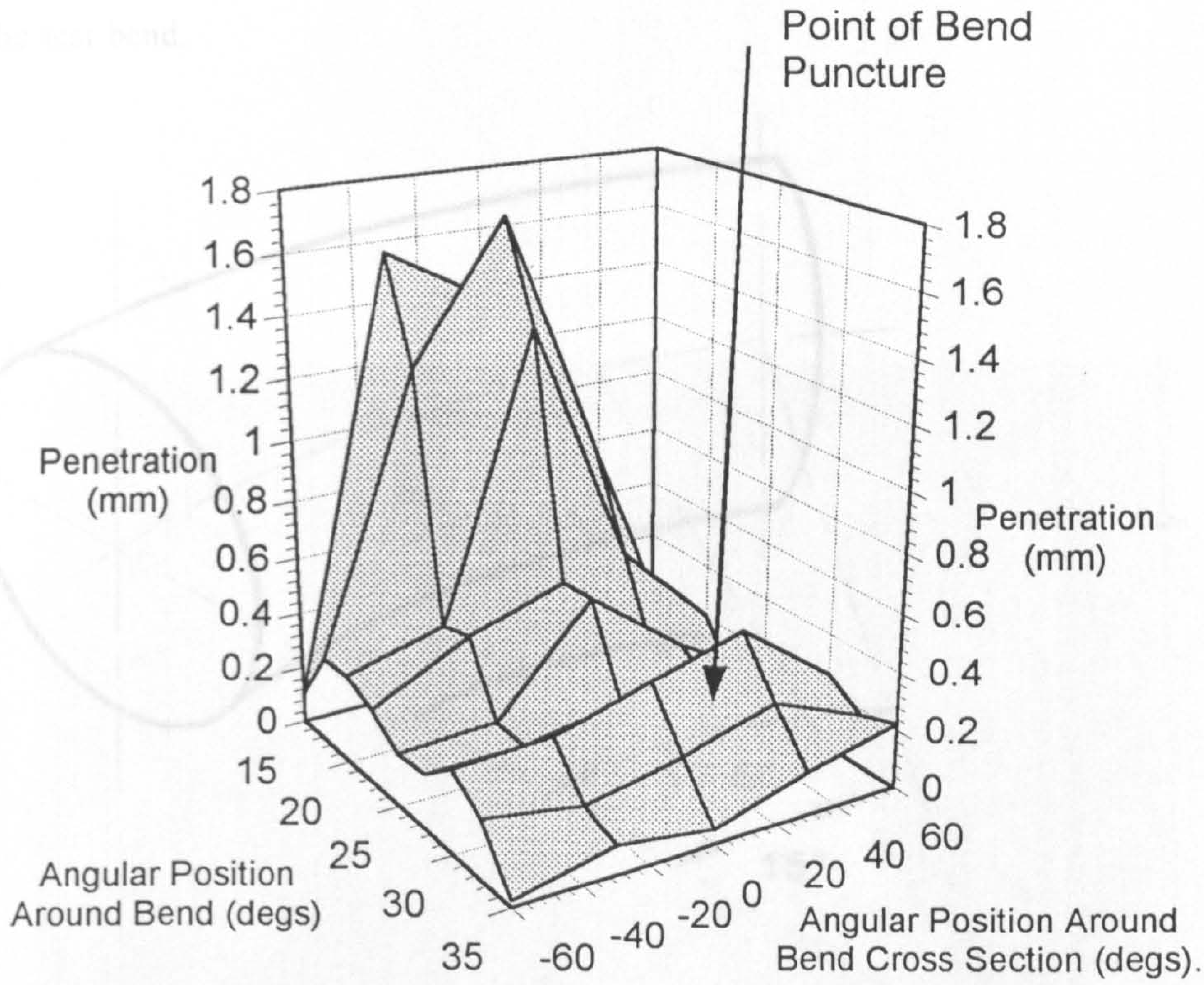
Mass Flow Rate of Abrasive (kg/s)	**Particle Concentration Density or Suspension Density (kg/m^3)**	**Solids Loading Ratio (kg/kg)**	**Local Gas Velocity / Particle Velocity (m/s)**
0.2594 (0.0085)	3.5 (0.12)	2.93 (0.1)	25.6 (0.15)

(Note: The values in brackets in the table above are the standard deviations of the test results for all 22 test runs).

5.3.2 Results Obtained for the Bend Wall Penetration

Twenty-two sets of 45 readings for the bend wall thickness were taken during conveying, before the test bend punctured. The complete set of data for all of the measurements is given in Appendix 5D. The data for the bend penetration at the point at which failure of the test bend occurred is shown in Figure 5.2. Also included on this graph is an indication of the point at which bend puncture actually occurred; puncture occurred at a point approximately 28.5° around the bend radius and 15° around the pipe bore circumference where the origin is taken as shown in Figure 5.3. As can be seen from Figure 5.2 the major wastage of the bend wall material occurred in the regions where the thickness measurement locations were between 15° and 20° around the bend radius, there being a distinct difference in the position of the puncture point and the mean position of the region of gross material wastage. A photograph taken up the bend (Figure 5.4) after it had been removed from the conveying line at the end of the test programme indicates that the erosion damage becomes more and more focused until a point is produced in the erosion damage profile at which puncture of the bend wall occurs. The reasons as to why this behaviour may occur are discussed after the presentation of all of the results and their analysis in section 5.3.4.

Figure 5.2 Penetration data in surface and contour plot format



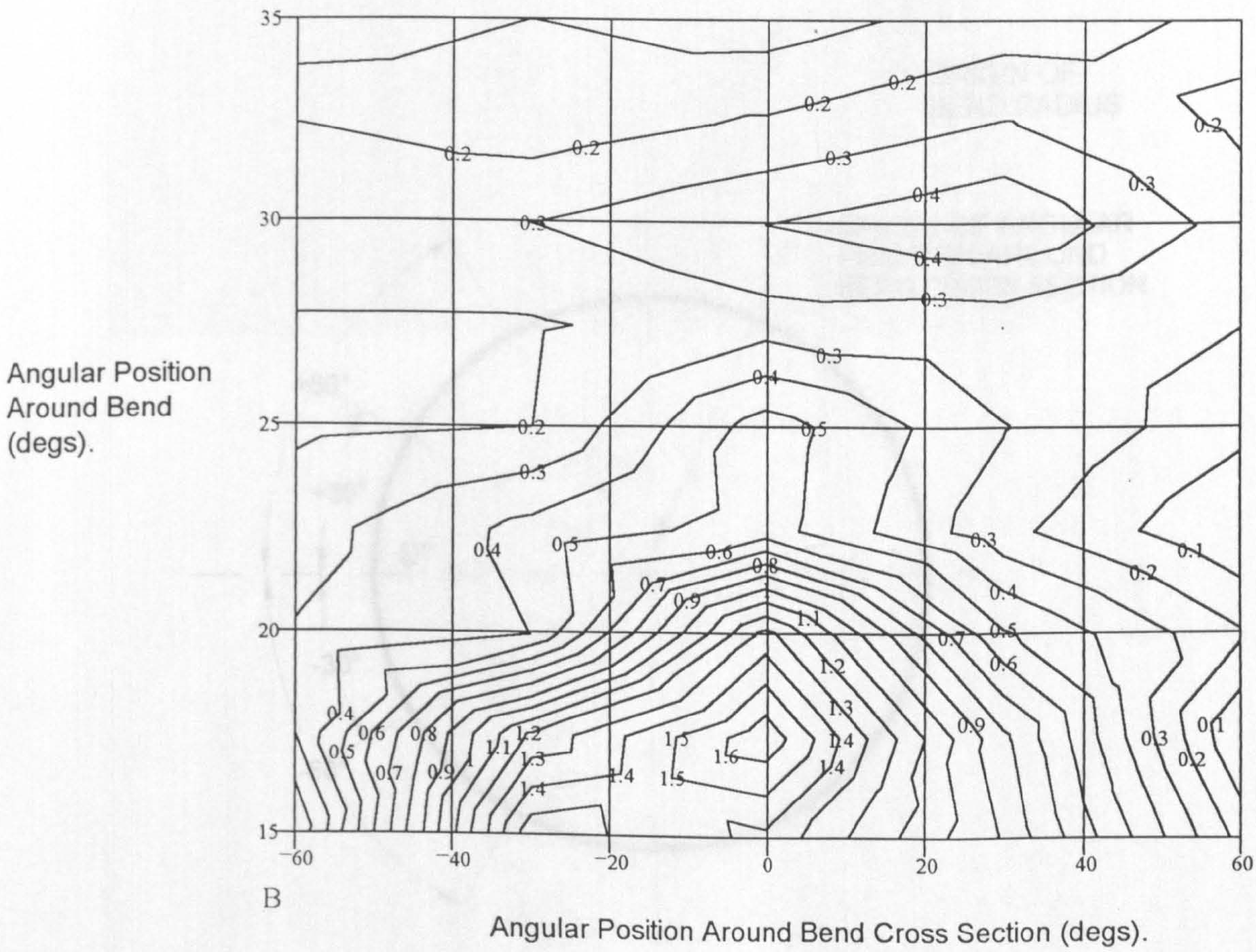


Figure 5.3 Orientation of zero of the toroidal coordinate system taken for the analysis of the results seen in the test bend.

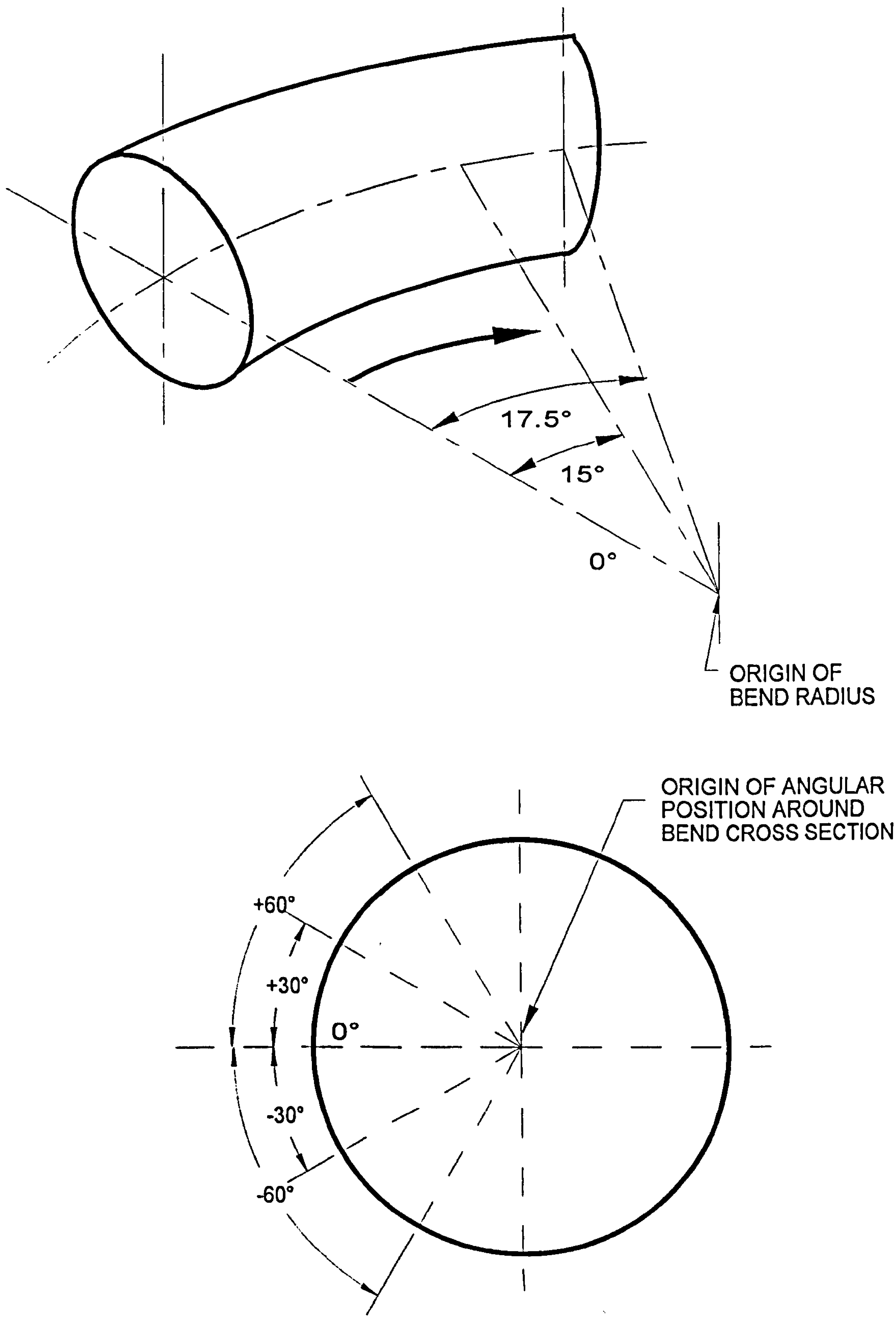


Figure 5.4 Photograph of the punctured bend.

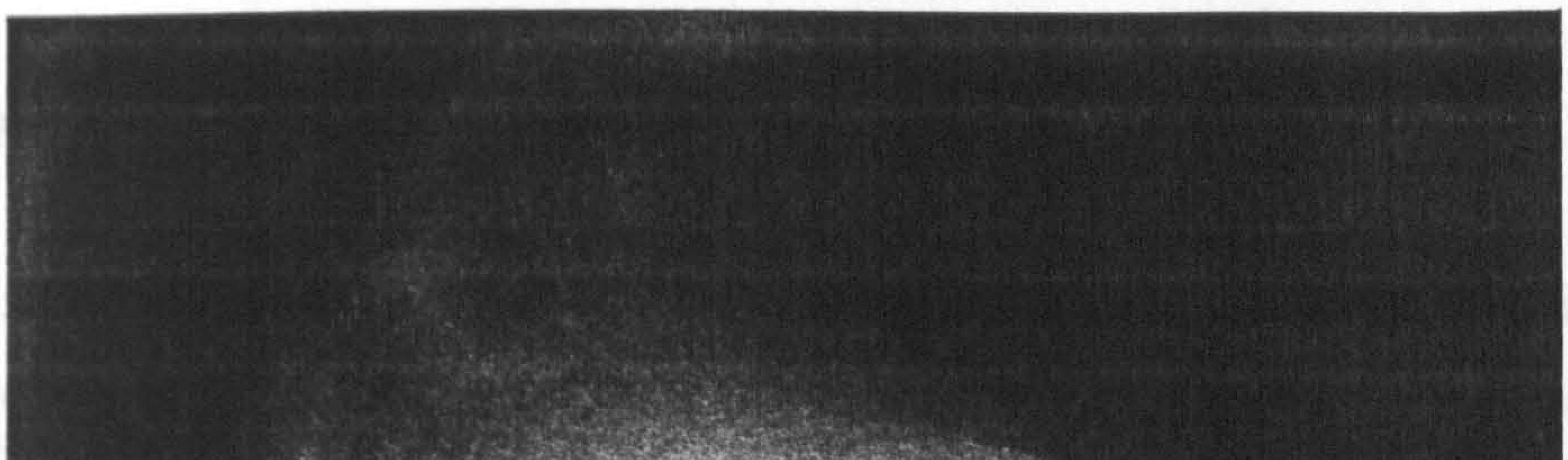


Figure 5.5 shows the variation of the thickness of the pipe bend wall with the mass of abrasive that has been conveyed. This indicates that erosion damage at some points in the bend wall sloweddown during the erosion process. It is suggested that this is a direct consequence of the effect that the changing profile of the bend wall has on the impingement angles of the particles on the wall surfaces. In addition, the erosion resulted in the formation of a rippled surface on the surfaces of the bend wall. The ripples can be seen clearly in Figure 5.4.

5.3.3 Results Obtained from the Laser Obscuration Tests for Particle Distribution

The laser obscuration device was used to assess the distribution of abrasive particles across the pipeline cross-section on approach into the test bend. More information regarding the set-up, calibration, use and analysis of results obtained from this device are contained in Appendices 5A and 5E.

It can be seen from Figure 5.6 that the data set for the scan in the horizontal plane using the vertically orientated laser beam is generally symmetrical about the centre line of the glass pipe section. In the case of the data obtained from the scan in the vertical plane using the horizontally orientated laser beam this is not the case. The majority of the area under the curve in this data set occurs below the bore centre line. Reasons why this should be the case are discussed in the sections that follow.

Diffraction of the laser beam on passage through the glass pipe section may be the cause of the shoulder like features that can be seen on the normalised light obscuration curves. When the laser crosses the glass / air interfaces it is diffracted from the nominal assumed chord length that is based upon the initial first contact position of the laser on the outside wall of the glass pipe section (see Figure 5.7) [B21]. The length and orientation of the section of laser beam within the pipe bore will therefore deviate from the notional chord length as the position of the laser with respect to the glass pipe section changes. As a consequence of this, the scaling for chord length carried out as described above may be slightly in error. Because of the change in orientation of the laser beam within the glass pipe bore, some shift in the actual distance across the pipe bore at which the particle distribution is being assessed, as shown on the horizontal axis in Figure 5.6, may also occur. This change will become more pronounced as measurements close to the edges of the pipe bore occur. However, these effects will be symmetrical around the axis of the bore and were considered to have been alleviated to a large extent by carrying out the calibration measurements before conveying was undertaken. The reason for this assertion is that the maximum amount of laser light incident on the photodiode during

Figure 5.5 Graph of the variations of the bend wall thickness with mass of material conveyed for selected measurement locations.

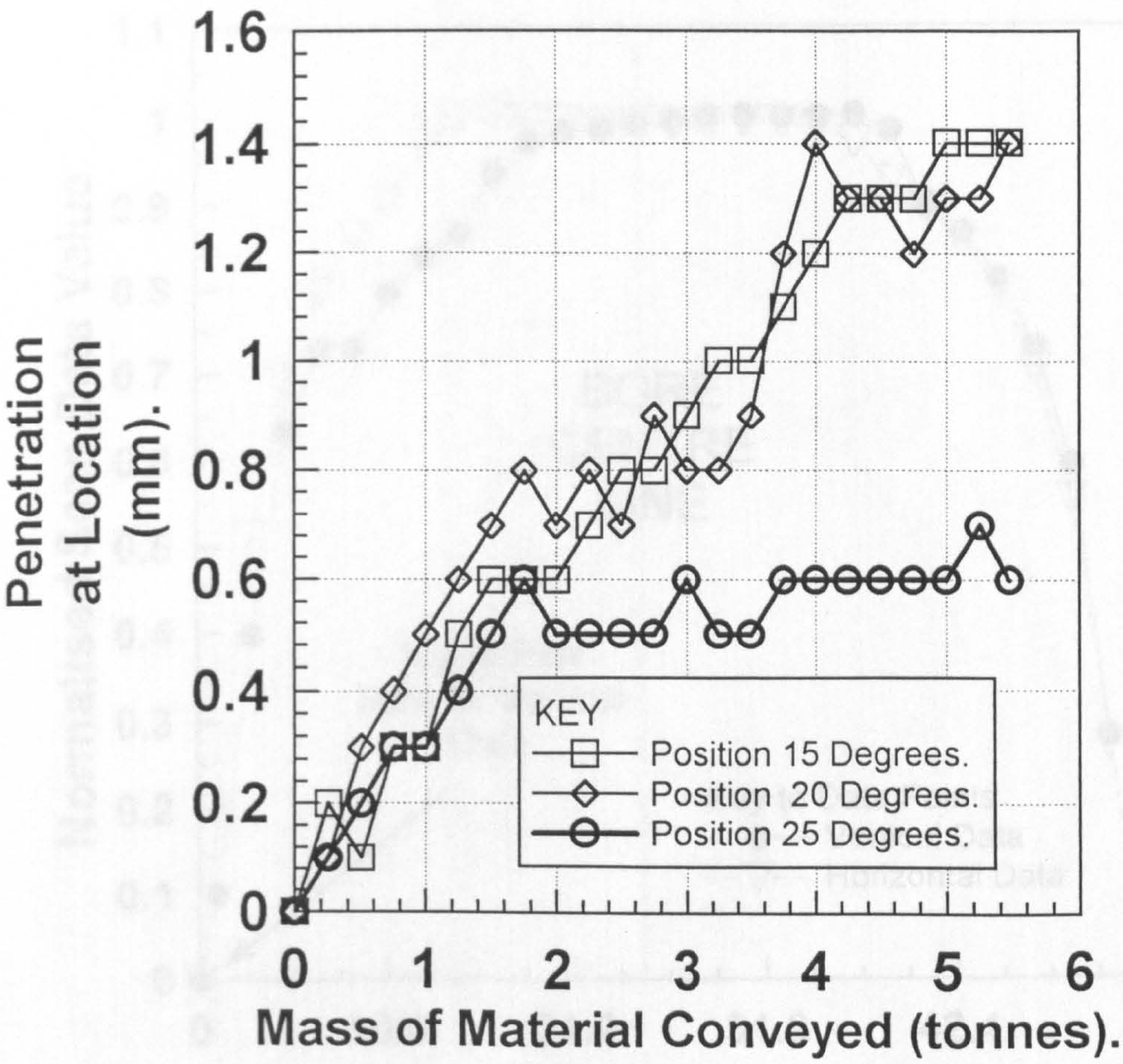


Figure 5.6 Graph of the mean results of the data bits plotted against distance across the pipe bore for both measurement orientations.

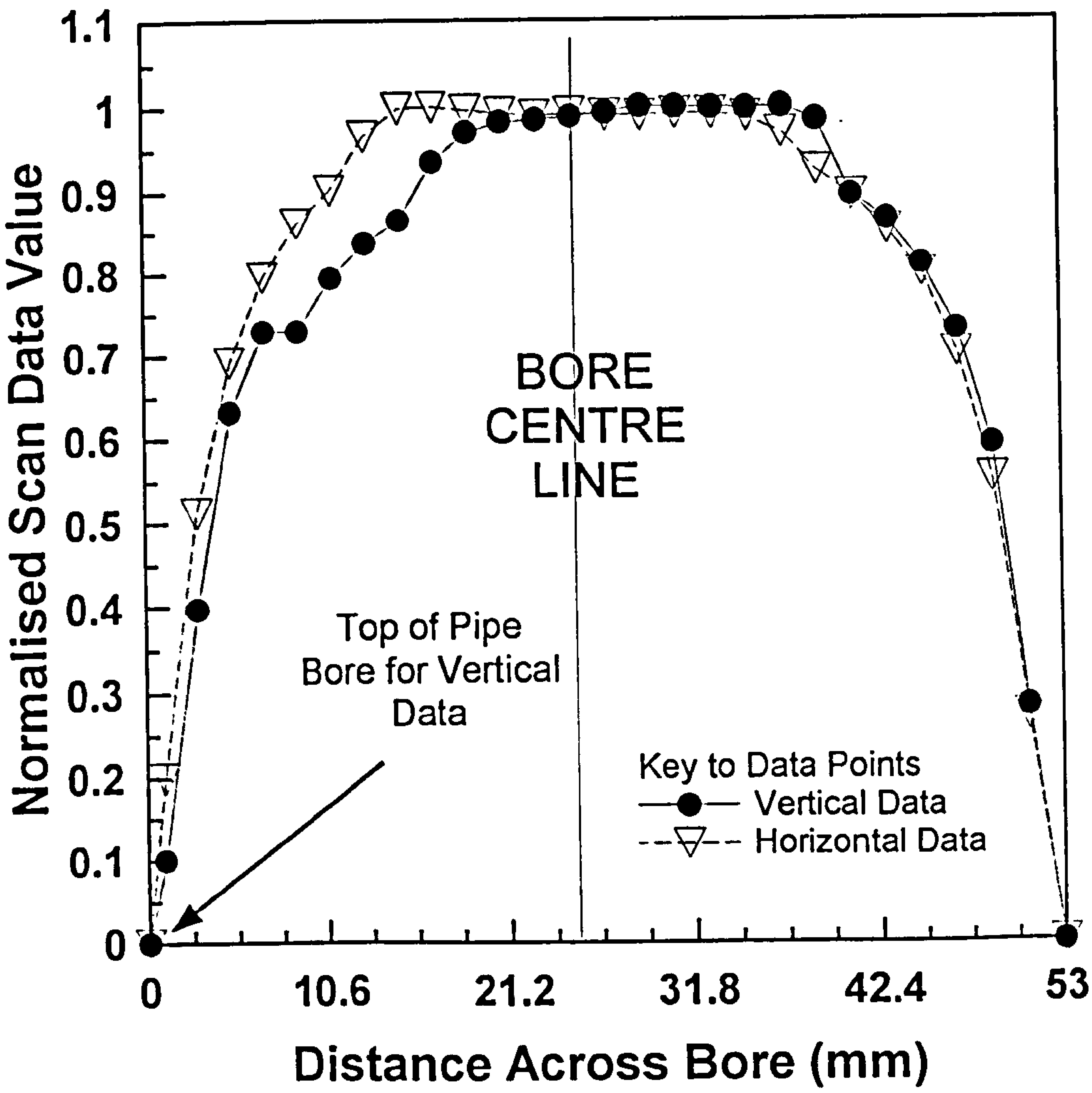
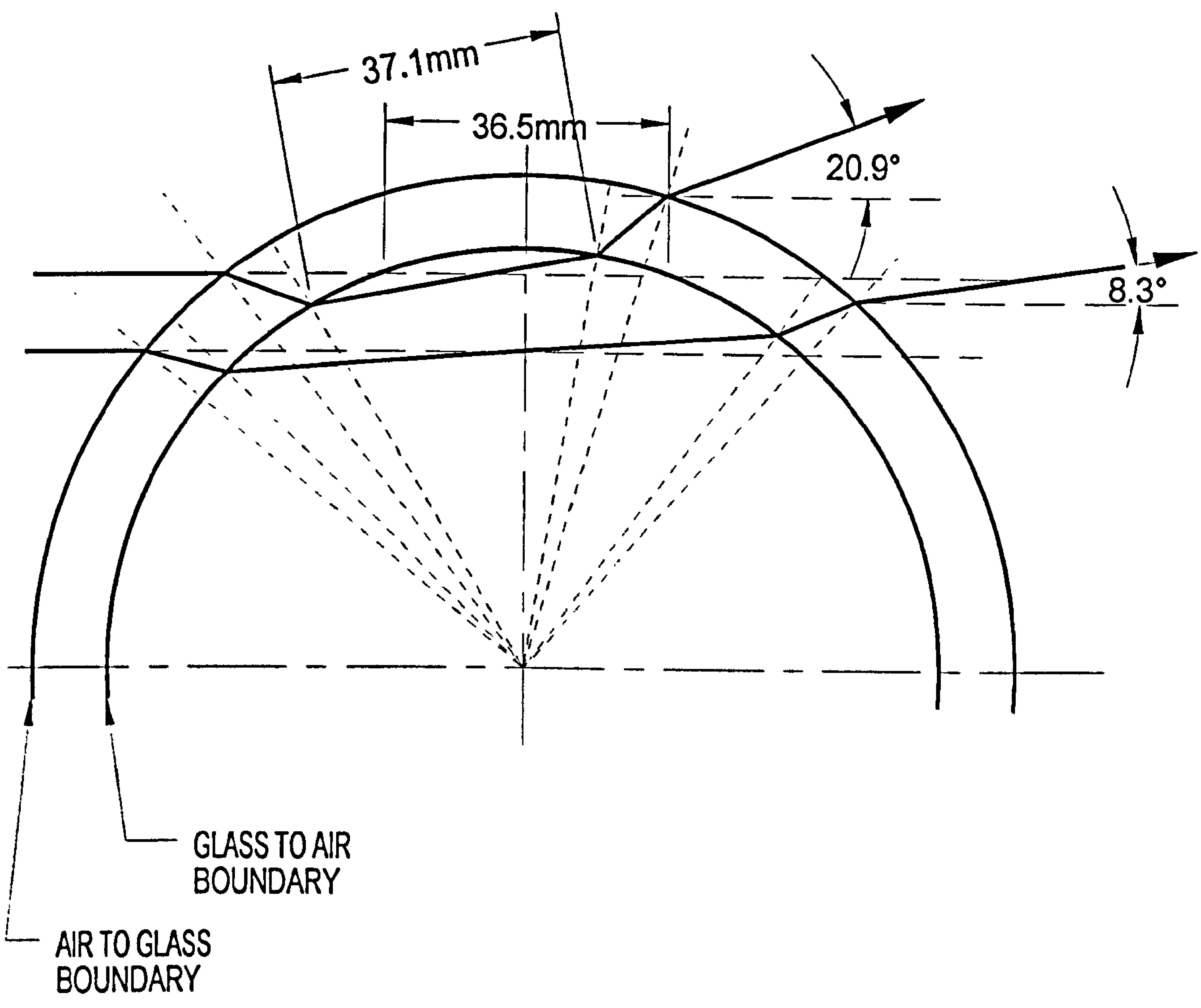


Figure 5.7 Path of laser through the glass pipe section and its comparison with the assumed chord length [B21], (the effect has been exaggerated by using a larger refractive index of 1.5: the refractive index of the glass used in the tests was 1.273).



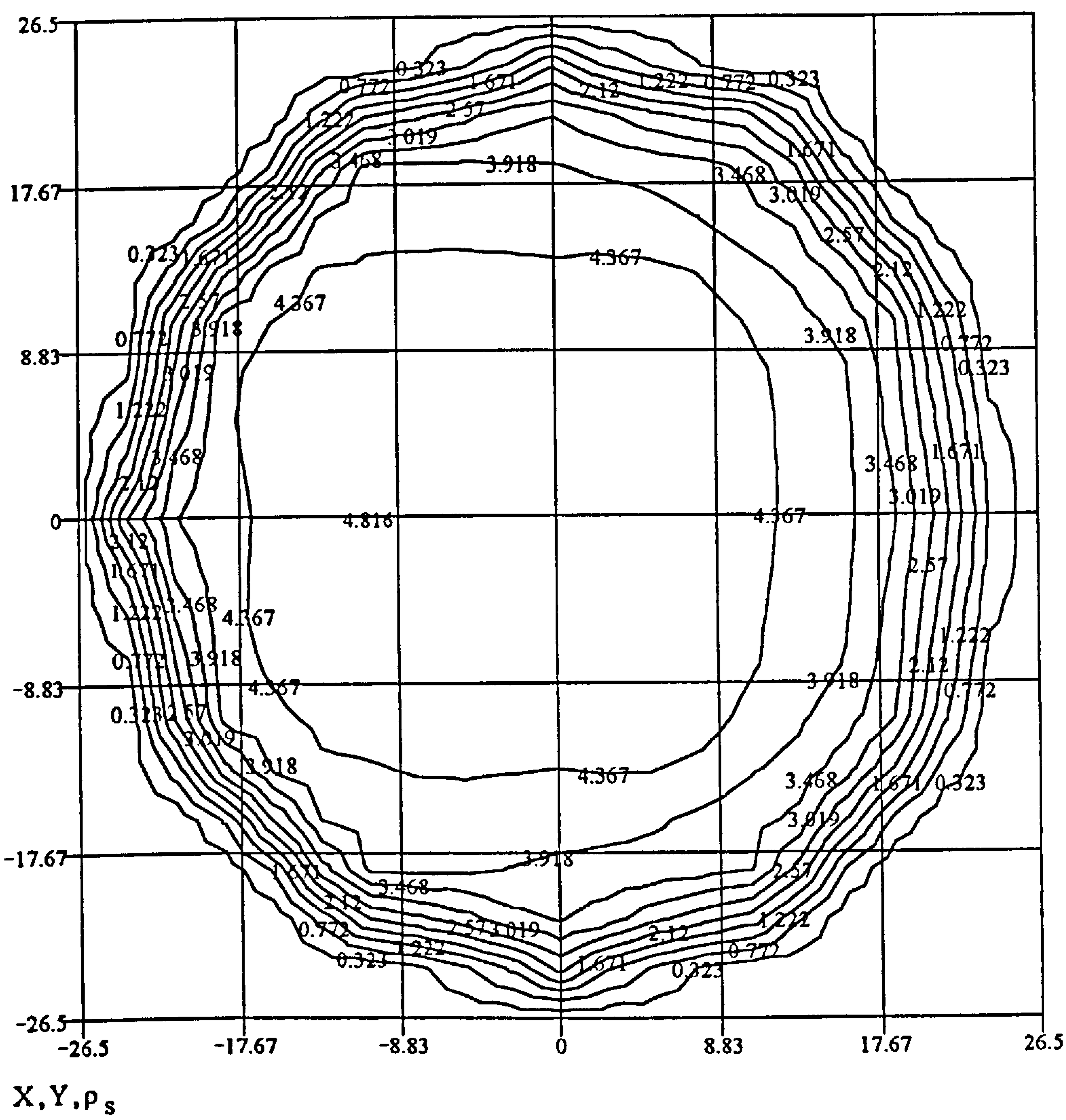
calibration will be affected by the diffraction caused by the curvature of the glass pipe segment walls. Since these results were used as the maxima of each measurement at every scan position, the effect of diffraction was accounted for in the scaling of the raw data obtained from the photodiode during the conveying trials.

These two data sets were utilised to generate a three dimensional surface plot of the particle distribution within the pipe segment being examined. Strictly this is not correct since the data values obtained were not measures of the particle concentration at a point but of those along a chord length across the pipe bore. However, since no other means of assessing the particle distribution was available for the project the following method was the only possible way in which a three dimensional plot of the particle distribution could be derived.

The data set obtained from the horizontally orientated measurements was scaled to the correct chord length and multiplied by interpolated values of the vertical data set. This data set consisted of a matrix of values, twenty nine values square. The volume under the surface that could be drawn through the data set was calculated and equated to the particle concentration density (suspension density) of particles in the pipe line. This volume could not be equated to any variable involving a rate or velocity, since the measurement technique employed gave results that were independent of velocity. Interpolation on the surface plot for a specific position within the pipe bore for local values of the abrasive particle concentration density could then be made. (Further information pertaining to the two dimensional interpolation routine is also given in Appendix 5E). The resulting surface plot of particle concentration density of abrasive against a two dimensional grid positioned over the pipe bore can be seen in Figure 5.8.

It must be realised that the presence of the particles may have a significant effect on the air velocity distribution. Experimental evidence suggests that as the number of particles in any given part of the flowing mixture increases, there will be a corresponding reduction in the air velocity in this region with a corresponding increase in the air velocity elsewhere in the pipe bore [L2,K1,T2]. Therefore, as a consequence of the greater concentration of particles in the lower half of the pipe bore, the air velocity distribution is likely to be skewed so that its peak occurs in the upper half of the pipe bore. Since no means of measuring the local air velocities occurring in the pipe bore during conveying was available, effort to model the skewed air velocity distribution using existing information was made. The slope on the peak of the normalised particle distribution curve in the vertical plane was found, and used to bias, in proportion, an air velocity distribution which would be expected for turbulent single phase air flow only [P2]. It was presumed that the air flow distribution would be symmetrical

Figure 5.8 Particle concentration density distribution of abrasive within the pipe bore.



The top of the pipe bore is to the right hand side of this image.

about the horizontal plane as was the particle concentration distribution. Data obtained from the skewed Prandtl function was scaled so that the mean calculated air velocity in a vertical plane in the pipe bore was the same as the value of air velocity inferred from measurement of the local pressure and overall air mass flow rate in tests carried out in the pneumatic conveyor. The details of how this was achieved are discussed in Appendix 5E. The final skewed air velocity distribution is shown in Figure 5.9.

5.3.4 Conclusions and Discussions Regarding the Results of this Test Work

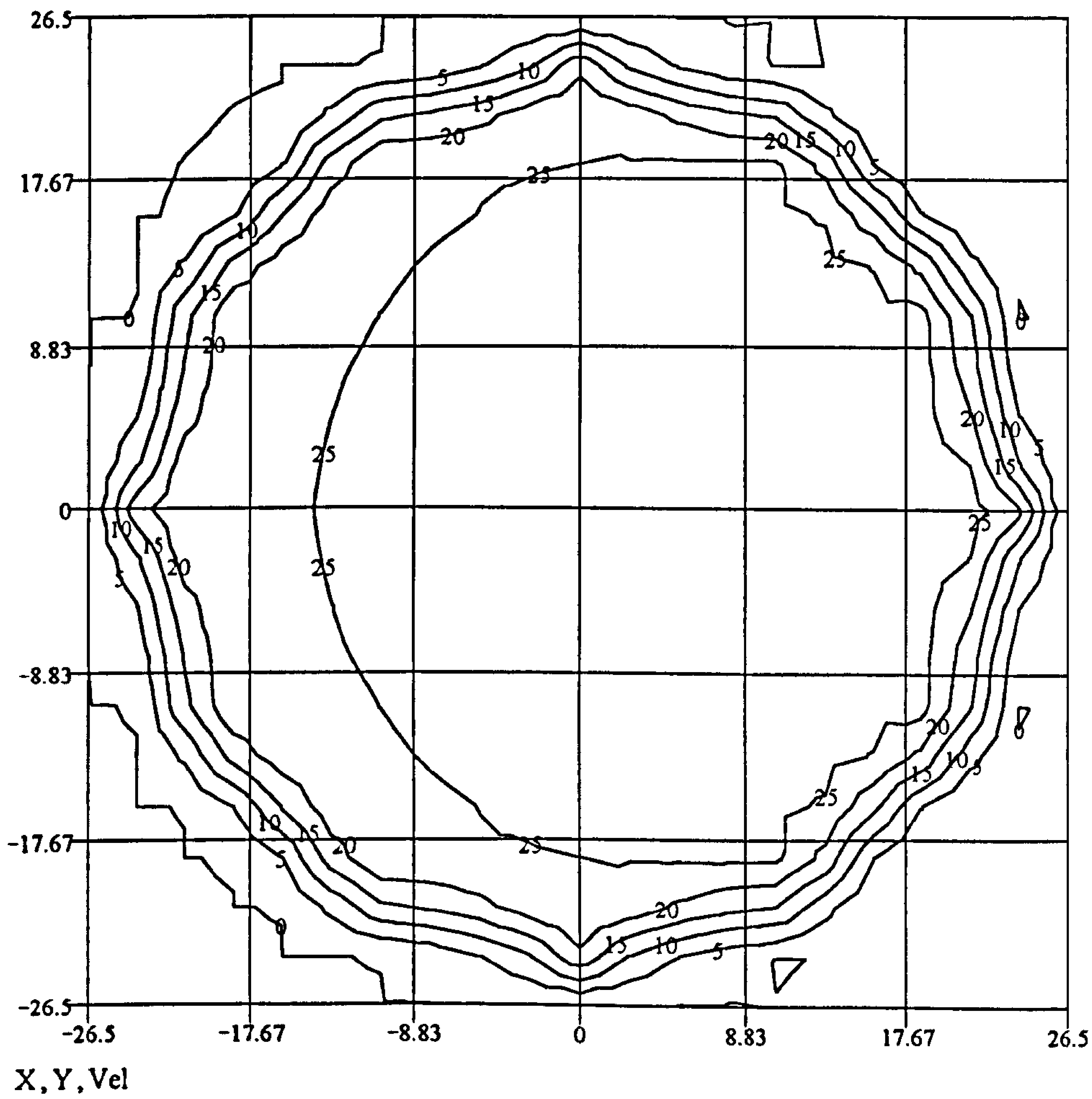
This section gives a descriptive account of the way the various measurements taken inter-relate.

Numerical modelling of the particle trajectories possible in the pipe bend was carried out using the model derived by Yeung [Y1] and commercial computational fluid dynamics software (see Appendix 5F). The purpose of this work was to aid the understanding of the author of the behaviour of the particles as they travelled through the bend. From calculations carried out for this conveying situation, the particle velocity seemed to be constant within certain limits (see Appendix 5F). It was therefore concluded that the distribution of the particles within the pipe bore dictated to a large extent the location of the puncture in the bend wall.

5.3.4.1 A Discussion Regarding the Reasons Why an Asymmetrical Particle Distribution in the Pipe Bore Occurs

The particle density distribution given in Figure 5.8 has been derived using methods that are not strictly correct as described earlier (see section 5.3.3. and Appendix 5E). However, the distribution seen from this analysis compares well with the results reported in other researchers' work on this subject [S10,T3,T2,H2,K1]. Soo *et al.* [S10], Tsuji *et al.* [T2] and Huber and Sommerfeld [H2] suggest that the effects of gravity are the reason why the majority of particles are present below the pipe bore centre line. However, there are several effects that have a bearing on the particle distribution. The reasons for the particles being maintained in suspension are described as being due to a balance between particulate diffusion and particle electrostatic attractive forces [S14]; the effects of particle / wall collisions which are caused by the particle shape effects [T3,T2,H2,O1]; the turbulence in the gas causing mixing of the particles; and, finally, the effects of asymmetry in the gas velocity within the pipe [H2].

Figure 5.9 Estimated skewed air velocity distribution in the pipe bore.



The top of the pipe bore is to the right hand side of this image.

5.3.4.1.1 The Effects of Electrostatic Attractive Forces on the Particle Concentration Distribution

The arguments of Soo concerning the effects of the balance between attractive electrostatic and diffusive hydrodynamic forces acting on the particles [S14] tend to imply that the particle concentration density distribution will be symmetrical about the centre of the pipe bore. This has not been observed in this test work. The hydrodynamic forces acting on the particles give them high momentums and when a comparison is made to the magnitude of the electrostatic attractive forces that can be expected, the electrostatic forces are negligible. The reason for this is that the size of a particle does not affect the saturation charge that a particle can hold; it only affects its rates of charge and discharge which are dependent on the surface area of the particle [A1]. Since the saturation charge is fixed, if all the conditions remain the same and the particle size is sequentially increased the effects of the electrostatic forces between particles will become increasingly small compared with their inertial forces. If this argument is sustained, then the electrostatic attractive forces occurring in the two phase flow are of negligible importance in the case discussed within the frame work of this thesis.

5.3.4.1.2 The Effects of Particle Collisions Against the Pipe Walls on the Particle Concentration Distribution

Since the effect of gravity will lead to the particles congregating towards the bottom of the pipe bore, it has been suggested that suspension flow can only be maintained by a combined effect of the particle's shape and inertia affecting its rebound trajectory after a collision [T5,B5]. The shape of a particle has been shown theoretically to have a very significant effect on the particle motion in a two phase flow [T5,B5]. The hypothesis is that individual particles will drift towards the bottom of the pipe under the effect of gravitational forces whereupon they will collide with the pipe wall. At this point the dynamic forces acting on the particles will cause them to rebound from the surface with a wide range of possible trajectories that depend on the shape of the particles and their orientation at impact. Those particles with a high enough inertia prior to the collision can easily have a rebound trajectory that will take them beyond the central axis of the pipe. The effect of particle shape has been used to explain the particle distributions in dilute gas-solid flows by several authors [T3,T2,H2,K1].

5.3.4.1.3 The Effects on the Particle Distribution Caused by the Hydrodynamic Forces Acting on the Particles

Very careful measurements of gas-solid flows made by Huber and Sommerfeld [H2] have indicated other important effects that have not been noticed previously in the study of such phenomena. One of these effects is that gravitational effects will tend to cause a size segregation of the particles in the flowing suspension with the larger particles tending towards the lower half of the pipe bore. The presence of the heavier particles in this section of the pipe bore causes the gas to be slowed as the energy required from the flowing gas in this section of the pipe to keep the large particles moving is greater. Lighter particles will tend to be present in the upper part of the pipe bore. This is because their response to forces caused by particle rotation, (Magnus forces), and fluid shear, (Saffman forces), will be much greater than that of the heavier particles owing to the reduced dominance of gravity on their motion. Since the energy required from the gas in this region is less than that in the lower half of the pipe bore due to the reduced inertia of the particles, the gas velocity in this part of the bore will tend to be greater than that present in the lower half of the pipe. As a consequence of this behaviour the gas velocity profile within the pipe bore will be asymmetric (as discussed in section 5.2 and in more detail in Appendix 5E). Another factor affecting the particle velocity in this region of the pipe is that since the particles in the upper half of the bore tend to be those that are from the smaller end of the size distribution these particles are more affected by gas-particle coupling effects. This is because their momentums are low and they are therefore, more likely to follow the path taken by the gas [H1]. However, owing to the fact that the smallest size fraction of the size distribution of particles used in this test work was still quite large, (i.e. above 100 μm in diameter (see Appendix 3A)), the majority of the particles will tend to be present in the lower half of the pipe bore.

5.3.4.2 The Effects of the Skewed Particle Concentration Distribution on the Bend Wall Penetration

The particle concentration distribution shown in Figure 5.8 indicates that the peak in the distribution occurs in the lower two quadrants of the pipe bore. This would explain why the majority of the wear seen in the pipe bend occurs on the bend wall in the lower left quadrant of the pipe when looking in the direction of travel of the particles (see Figure 5.4). After all, it is in this area where the primary impact location of the particles occurs and consequently, this is where a large proportion of the material wastage should occur. However, this reasoning does not assist us in understanding why the actual puncture location is further around the bend radius.

There are two effects that combine to make the puncture location occur at the point observed in these studies. These are best explained by adopting two different approaches; the first of these is by discussing what is likely to happen to an individual particle as it travels through the pipe bend, and the second is by superimposing the effect of inter-particulate collisions in conjunction with a discussion of the likely intensity of impacts on to this single particle trajectory theory.

5.3.4.2.1 A Description of Individual Particle Trajectories in a Pipe Bend

From the view point of an individual particle it is possible to suggest that the main reason why puncture occurs at a point is because the curvature of the internal walls of the pipe bend will tend to direct any rebounding particles towards the plane of the bore axis, therefore, concentrating the wear into a smaller area. Since, in this instance, the particles are relatively unaffected by the motion of the gas, they have trajectories that are approximately straight (see Appendix 4E and Appendix 5F). Because of this, the behaviour of the particles can be likened to the incidence of light on a cylindrically concave mirror, forming a curve of aberration for such a mirror but within a toroidal coordinate system (see Figure 5.10) [B19]. The distance around the pipe bore that the particles travel before they strike the bend wall is also dependent on the bend geometry. Modelling of many single particle trajectories that are dispersed across the pipe cross-section on approach to the bend will lead to the observation that all will be seen to pass through a small region of the pipe bore cross-section after rebound (see Figure 5.11). It is in this small region where there will be a large concentration of particles, and by inference, a greater frequency of particle impacts against the bend wall bordering this region. Because of this, an increase in the wear of the wall surface in this area will occur above that observed in the primary impact area.

The reason why the erosion caused by particles that have struck the pipe wall surface once can still be effective enough to cause penetration of the pipe wall at the second impact location is that the amount of kinetic energy lost in the initial impact is small. If a particle strikes at a low angle of impingement, such as is the case in this work, the component of the impinging kinetic energy normal to the pipe wall that the particle has at impact is low. The friction effects between the particle and the pipe wall will be greater at these low impingement angles than those that occur at higher impact angles because the contact time is suspected to be higher in this case. However, if the dynamic friction coefficient between the particle and pipe wall is low, in overall terms, the amount of energy lost as a consequence of the first impact at low angles of impingement may be small. Therefore, it is quite possible for the particles to retain enough kinetic energy to cause significant wear at their second and possibly even third impact locations.

5.3.4.2.2 The Effect of Inter-Particulate Collisions on the Point of Bend Wall Puncture

There are two reasons why the actual puncture point occurs above the pipe bore axis centre line. First, the puncture point may lie above the axis of symmetry of the pipe bore because of inter-particulate collisions. From the laser obscuration scan results it has been suggested that the majority of the particles reside below the axis of the pipe bore. Once they strike the wall of the bend for the first time they will tend to rebound in an upwards direction, heading around the bend radius, with all

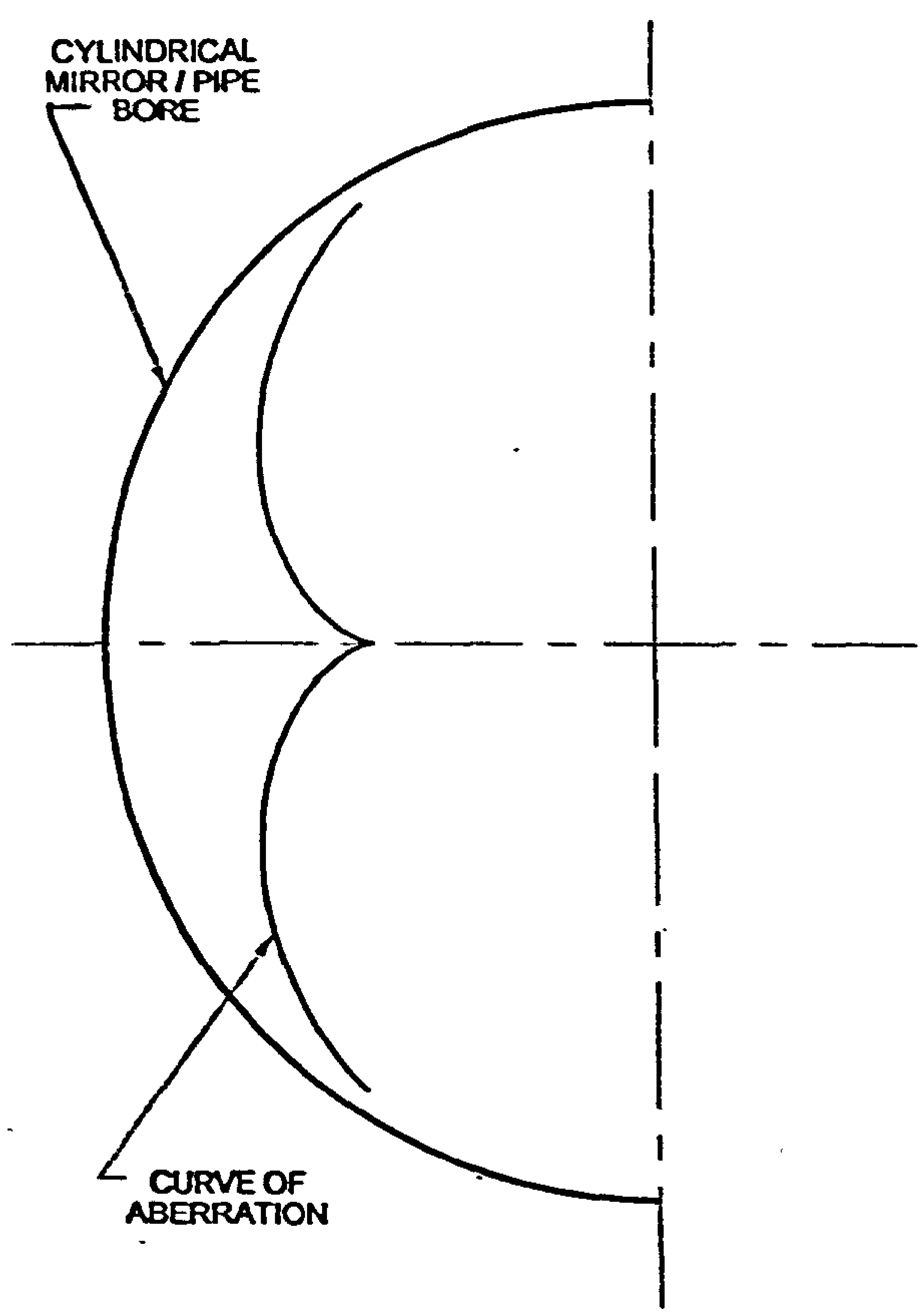

CYLINDRICAL
MIRROR / PIPE
BORE
CURVE OF
ABERRATION

Figure 5.10 Curve of aberration for a cylindrical mirror superimposed upon a photograph of the damaged pipe bore.

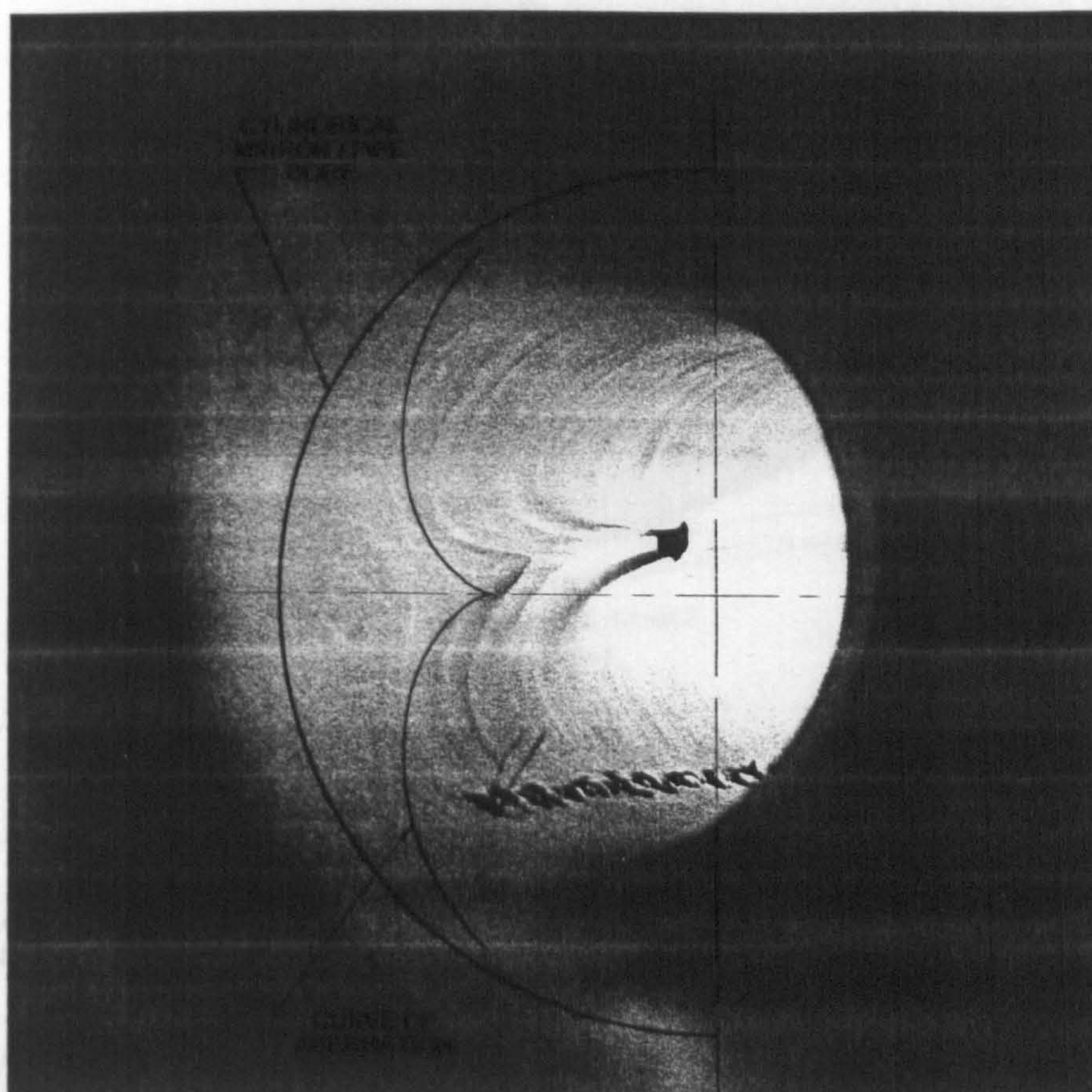
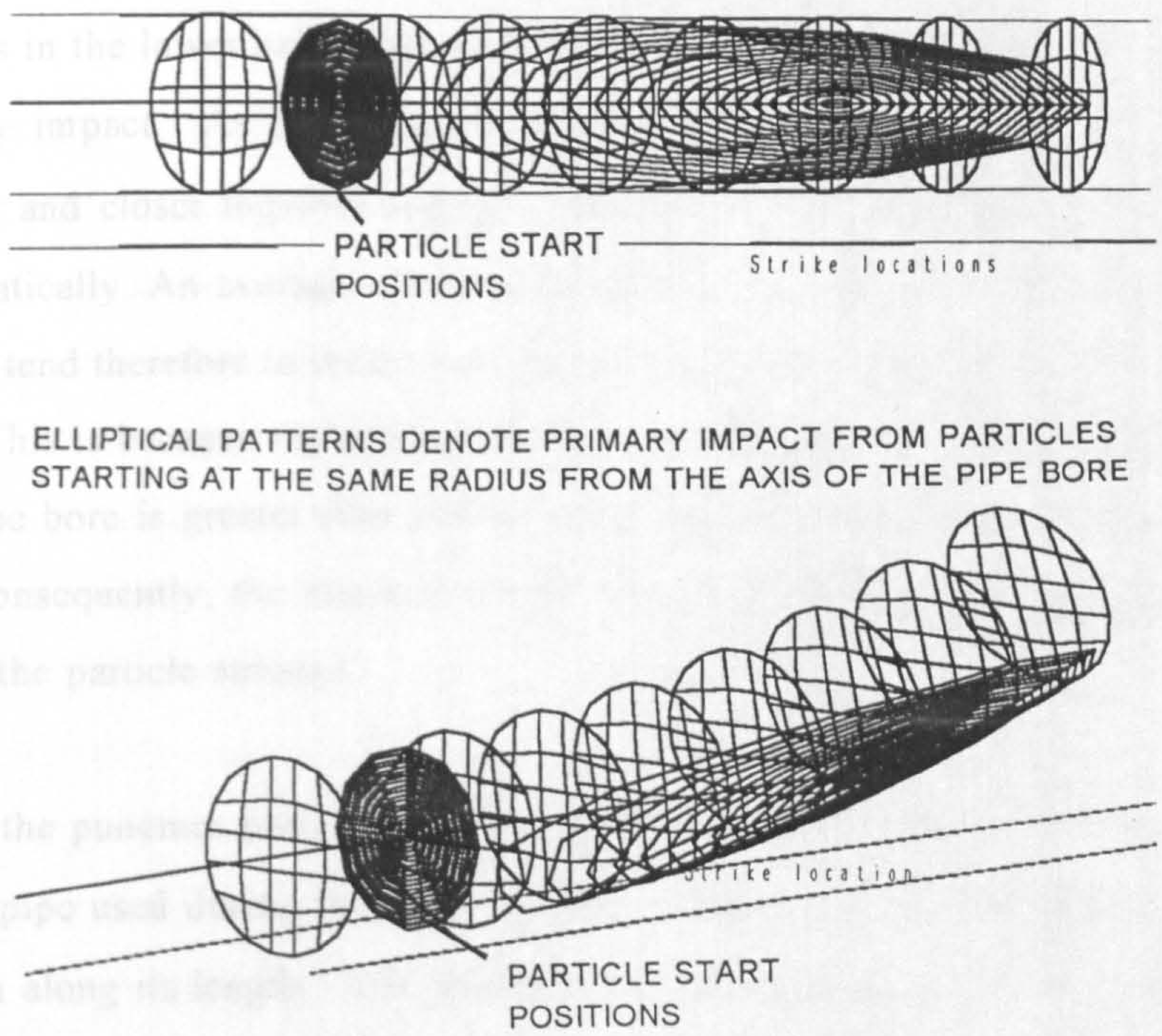
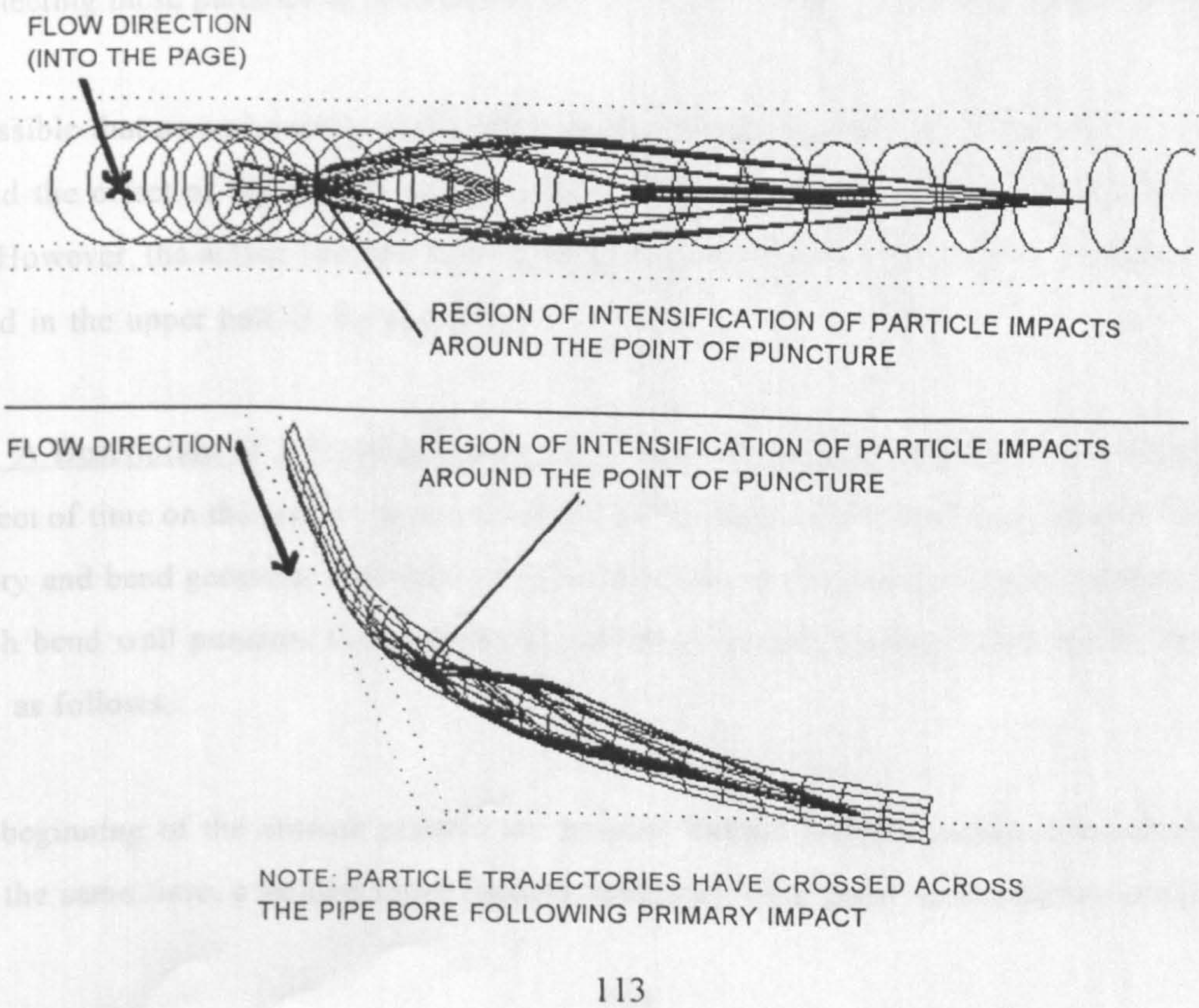


Figure 5.11 PHOENICS / GENTRA (computational fluid dynamics) particle tracking analysis results for (a) the primary, and (b) the secondary impact positions assuming that the particles were perfectly elastic [P5] (see Appendix 5F for further information) [P5].

a)



b)



the particles becoming closer together as they are directed inwards towards the plane of the pipe bore axis. A similar series of particle trajectories will be seen for the particles that reside above the plane of the pipe bore axis, however, from Figure 5.8 there are either fewer particles in this part of the pipe bore or they are smaller [H2]. Whatever the reasons for this particle distribution, the momentum flux of the particles in the lower half of the pipe bore will tend to be greater than those in the upper half before primary impact. As both sets of particles approach the second impact location they will become closer and closer together and the probability of inter-particulate collisions occurring will increase dramatically. An average inter-particulate collision between particles from each half of the pipe bore will tend therefore to result in both sets of particles striking the pipe wall in the upper half of the bore. This is because the momentum flux of the particles travelling upwards from the lower part of the pipe bore is greater than that of those travelling downwards from the upper part of the pipe bore. Consequently, the result is a nett upwards vertical component of momentum after the interaction of the particle streams.

Alternatively, the puncture point may lie above the axis of symmetry of the pipe bore because of a feature of the pipe used during the tests; the pipe material used to fabricate the test bend contained a welded seam along its length. It is possible that some of the particles travelling in the lower half of the pipe bore may have struck this seam at their first impact. Prediction of the rebound trajectories of these particles then becomes almost impossible; the abnormally rebounding particles may have caused a major disruption to the flow of the remaining particles, by crossing through their trajectories and deflecting these particles by interparticulate collisions to strike higher up in the bore of the pipe.

It is possible that a combination of the differences in the momentum of the particles across the pipe bore and the effect of the welded seam may be the reason why the puncture point occurred where it did. However, the author favours the former explanation for why the position of the puncture point occurred in the upper half of the pipe bore.

5.3.4.3 A Description of a Possible History of Erosive Penetration in a Pneumatic Conveyor Bend

The effect of time on the erosion process is more subtle than the effect of the aforementioned particle trajectory and bend geometry variables. If it is accepted that the second impact location is the point at which bend wall puncture occurs then the pattern of erosion damage sustained by the bend wall may be as follows.

At the beginning of the erosion process the primary impact location suffers a lot of erosive wear. But, at the same time, a smaller more focused secondary wear point occurs further around the bend radius which is suffering erosion damage at a similar rate to that occurring in the primary impact area, (evidence of this behaviour can be seen in Figure 5.5). This is due to the effect of the internal curvature of the pipe to direct particles towards the axis of symmetry of the pipe bore. This behaviour causes a greater intensity of impacts to occur in this area.

As time progresses, wear in the primary impact area changes the contours of the internal bend surfaces. This tends to affect the rebound trajectories of the particles so that they form tighter and tighter wear scars in the secondary impact area; (Evidence of this behaviour can again be seen in Figure 5.5, where erosive penetration with mass of abrasive conveyed at a point close to the final puncture point was seen to reduce dramatically after approximately 1.7 tonnes of material had been conveyed. This fact indicates that the wear is being directed to a smaller area). Consequently, the penetration of the secondary impact location is increased by the increase in the concentration of particles, and therefore, intensity of particle impacts, in this location. Whilst this behaviour is evident in the area surrounding the locations of secondary impact, the erosion damage in the area of the primary impact will continue unchanged (see Figure 5.5). This behaviour is one of the main reasons why the erosion at the second impact location overtakes that which occurs at the primary impact location. This offers a good explanation of why puncture at the primary wear point was not seen.

In conclusion the penetration of the pneumatic conveyor bend tested for this project can be described in two main steps. These are as follows:-

1/ The erosion process begins with erosive damage occurring in the primary and secondary impact locations at a similar rate. This behaviour can be described under the heading of running, or wearing in.

2/ Erosion damage in the region of the primary impact location steadily increases. As it does so, the 'focusing' that the particles undergo after rebound from the primary impact area increases, causing the particles to be directed into a smaller and smaller volume of the pipe bore close to the bend wall in the area of secondary impact. Wall puncture occurs in this region because of the increased intensity of particle impacts per unit area of wall surface. Therefore, damage in this region is increased in magnitude over that occurring at the primary impact area.

Consequently, if the velocity of the particles and the particle and pipe line materials are assumed to be constant for the situation being discussed, the geometry of the test bend, the consequences of inter-particulate collisions and the intensity of particle / wall impacts are the next most significant variables. These variables have values which change with the damage caused on the internal surfaces of the pipeline. It is the interaction of these variables that cause the large range of variation that can be seen in the duration of the life of a bend in a pneumatic conveyor.

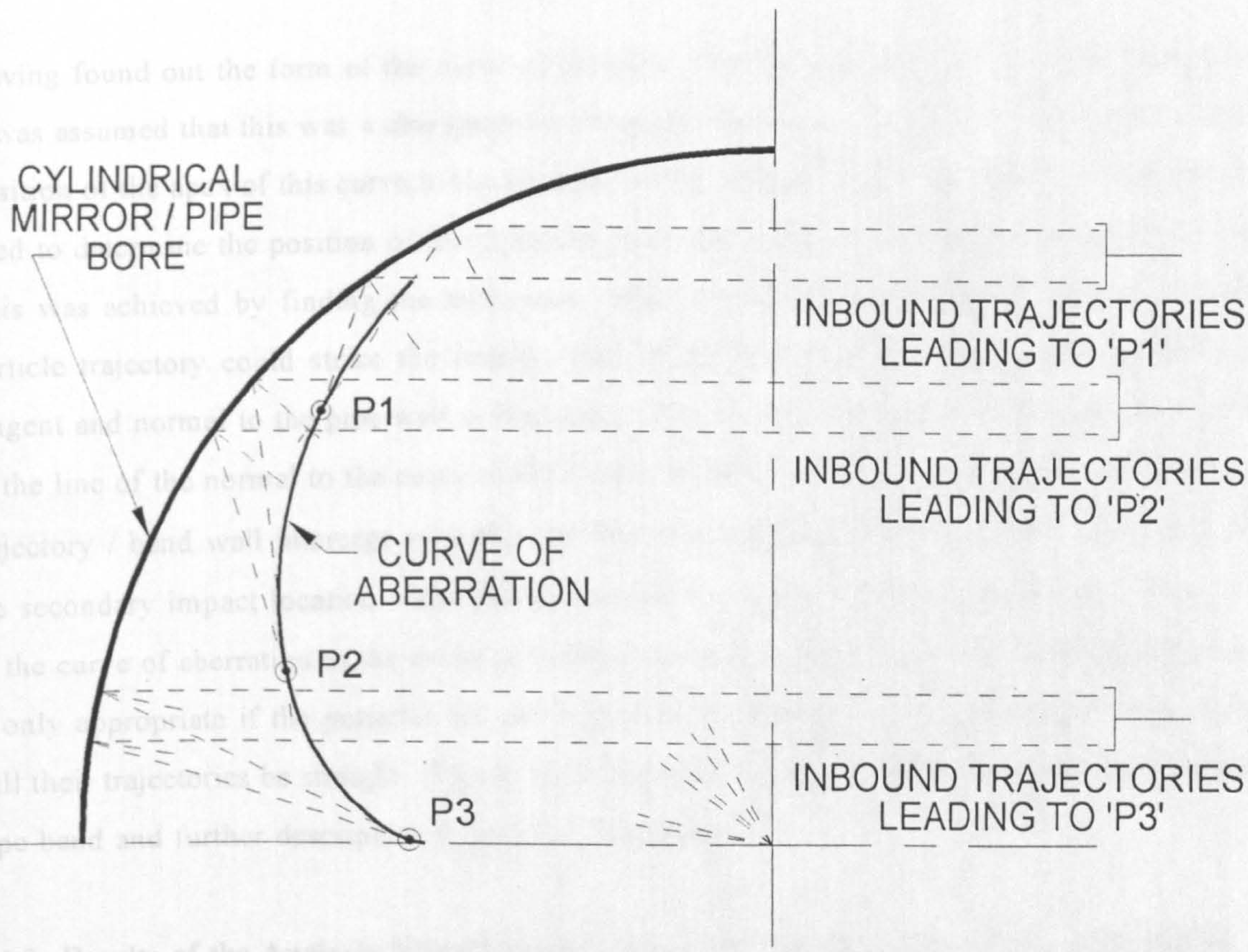
5.4 Prediction of the Location of the Puncture Point in a Bend Using a Model Based Upon the Curve of Aberration for a Cylindrical Mirror

It was observed that the internal surfaces of the worn out test bends had rippled surfaces. The ripples were formed so that they seemed to resemble optical curves of aberration for a cylindrical concave mirror (see Figure 5.10). It was suggested that the modelling of this curve and its relationship to the geometry of the bend may serve to provide designers of pneumatic conveyor equipment with a quick and easy way of finding the location of the puncture point in bends of the type used in this work [B19]. This method is based upon straight line trajectories of the particles, in the same manner that light follows straight rays. With the relatively heavy and massive particles used in this test work this is not a problem, although for smaller particles that have high degrees of dynamic coupling with the carrying gas this may not be the case. (For the particles used in this work, significant effects caused by coupling between the particles and the gas flow would be observed if the particle size were less than 50μm in diameter). Use of the model that is proposed in the following sections would not be appropriate for particles of this size.

5.4.1 A Brief Description of the Method of Generating the Curve of Aberration for a Cylindrical Mirror

The generation of the curve of aberration for a cylindrical mirror was carried out using a series of straight line trajectories traced towards the curved internal surface of a cylinder of the diameter of the pipe bore before wear had occurred. Coordinates of the intersection of each of these trajectories with the pipe wall was found and the normal and tangent lines to each of these points was calculated. Angles of impingement of the trajectory lines and the normals to the pipe wall at each impact location were found. The line of each trajectory was mirrored in the line of the normal at each impact location (see Figure 5.12). Once the rebound trajectory direction was fixed the interception point of neighbouring rebound trajectories were found. Points were obtained in this manner to form the profile of the curve of aberration. A cubic spline curve with cubic ends was fitted to the data points so obtained (this was a built in function within MathCad). The most important feature of the

Figure 5.12 Schematic illustrating the method used to construct the curve of aberration of a cylindrical mirror



curve was its apex which lay on the horizontal plane containing the axis of the pipe line. The distance of the apex point from the axis of symmetry of the pipe bore, as well as the distance from the apex to the radial extremity of the pipe bore surface, were taken as being fixed for the geometry of the bend used in the tests. Details of the calculations that were carried out are contained in Appendix 5G.

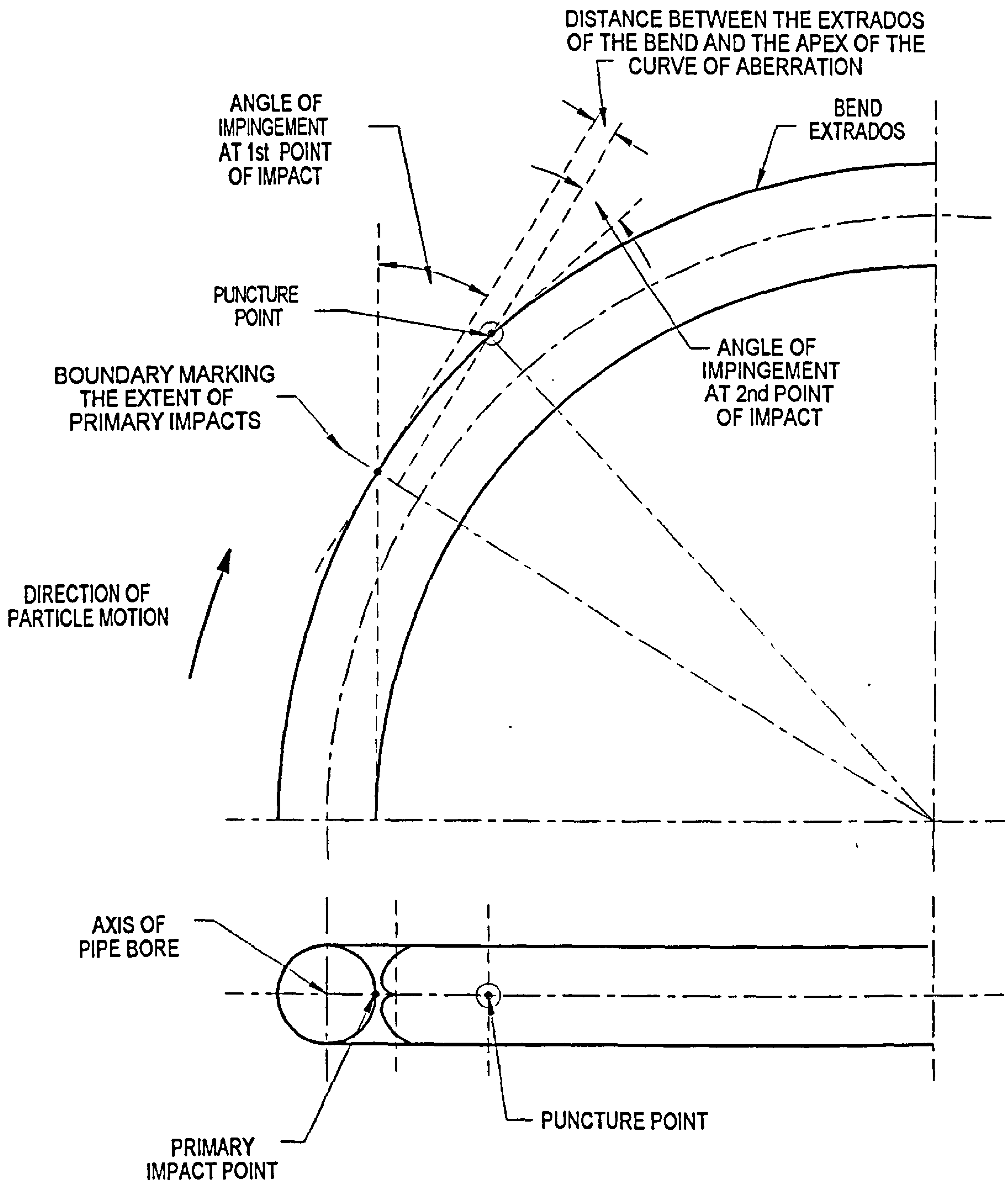
5.4.2 Predicting the Point of Bend Wall Puncture

Having found out the form of the curve of aberration for the pipe bore geometry being considered, it was assumed that this was a characteristic feature of the bend. An attempt was made to relate the position of the apex of this curve to the location of the puncture point. A series of calculations were used to determine the position of the puncture point that occurs in the region of secondary impacts. This was achieved by finding the maximum radius around the bend that the primary impact of a particle trajectory could strike the outside wall of the bend, and calculating the equations of the tangent and normal to the pipe wall at this point. The incoming trajectory was taken to be mirrored in the line of the normal to the curve of the bend a distance along the normal from the first point of trajectory / bend wall intercept such that the mirrored trajectory intercepted the bend wall close to the secondary impact location. The distance selected was equivalent to the distance from the apex of the curve of aberration to the extrados of the pipe bore. Again it must be stated that this analysis is only appropriate if the particles are not significantly affected by the gas motion, since only then will their trajectories be straight. Figure 5.13 illustrates the layout of the trajectory model within the pipe bend and further description is given in Appendix 5G.

5.4.3 Results of the Analysis Based Upon the Curve of Aberration for a Cylindrical Mirror

The angle of traverse around the test bend at which puncture occurred was approximately 28.5° and as a consequence of using the proposed model, the puncture point is predicted to occur at approximately 31.9° around the bend radius (see Appendix 5G). This is a 11.9% error. When it is considered how crude this model is, this margin of error is surprisingly good. The attractive aspect of this model is that the puncture location can be found using simple geometrical features of the bend only, provided that relatively large particles are being conveyed. Attempts to link this model to the actual penetration rate will be discussed in Chapter 6.

Figure 5.13 Layout of the curve of aberration trajectory model within the test bend



The position of the apex of the curve of aberration is fixed for any pipe bore, however the angles of the tangent and normal of the maximum primary trajectory intercept position will change as the ratio of bend radius over bore diameter, R/d, changes. Therefore, it will be necessary to carry out further tests to ascertain whether this model holds true for all values of R/d, since the relationship between position of the apex of the curve of aberration and the angles of the tangent and normal may not change linearly.

Obviously, particle impact location positions will change as the internal pipe wall surface profile changes with increasing amounts of erosion damage. This will alter the position of the second impact location, and may be the cause for the error in the location reported above. Accounting for this shift in the secondary impact point with erosion damage would be very difficult to model using this method.

5.5 Conclusions and Discussion Regarding the Pneumatic Conveying Test Work and the Analysis of Results Obtained From It

The pneumatic conveying test facility that was designed and constructed for this project allowed the detailed measurement of the gas pressure local to the test bend, the particle distribution on entering the bend, and the penetration damage of the bend measured on a time basis. From these results it was evident that the puncture point did not occur in the primary impact area, but in the area of secondary impact. Clearly the internal curvature of the pipe bend surfaces served to direct the particles to a point at which puncture occurred. Rippling of the worn surface of the pipe bore was clearly visible.

Puncture occurred in the upper half of the pipe bore. This was due to a combination of two possible effects. The distribution of particles entering the test bend was found to be asymmetrical, with the majority of particles being present in the lower half of the pipe bore. It is suggested that after primary impact occurred the upwards momentum flux of the particles in the lower part of the pipe bore overcame the downwards momentum flux of the particles present in the upper half of the bore in the region of increased interparticulate collision activity on the plane of the bore centre line. This biased the secondary impacts of the particles to occur in the upper half of the pipe bore. Alternatively, the presence of the weld seam in the lower half of the pipe bore may have deflected some of the particles in an upward direction forcing the mean impact area into the upper part of the pipe. Either of these two options, or a combination of both, are possible causes of this behaviour.

Failure of the bend was judged to have occurred once the bend had punctured. The penetration of the bend with time was measured so that changes in the erosion damage suffered by various points within the pipe bore could be assessed as the internal bend surface profile changed. Several researchers in the field of erosion in pneumatic conveyor bends have used the location of the primary impact location of a particle starting into the bend from the bend intrados as the point of puncture for their erosion models. However, the point at which bend puncture occurred, as described above, did not occur at this location but in the region of secondary impacts which were further around the bend radius than this previously assumed point of puncture. In depth analysis of the test bend penetration and particle distribution have not been carried out before. Evidence to support the reasoning behind the descriptive model for erosion damage behaviour in a long radius bend as given above has been found, but otherwise the results and conclusions drawn from the experimental work form what is, in the opinion of this author, new work.

One of the most interesting findings of this work, was that the focal point reached at the puncture point, and the rippling of the bend surface, tended to indicate features that seemed to resemble the curve of aberration for a cylindrical concave mirror. Using a model based upon this curve for the pipe bore before erosion damage had altered its profile, enabled the position of the puncture point to be located quite accurately. If this model can be improved to include an estimate of the duration of erosion the bend wall would have to suffer before puncture occurred, it may prove to be a reasonably straight forward way of assessing the life of a long radius pneumatic conveyor bend. Attempts to carry out these improvements to this model will be undertaken in Chapter 6.

Chapter 6

Predicting the Erosion of the Pneumatic Conveyor Test Bend

6.1 Introduction

The information contained within this chapter is concerned with the prediction of the erosion damage seen in the pneumatic conveyor test bend using models derived from tests carried out on the rotating disc accelerator erosion tester.

Essentially this chapter is divided into four main sections. The first of these is a discussion of previous models for prediction of bend puncture. Comparisons are made between results obtained from the use of these models, and the results obtained from the test work described in Chapter 5. Secondly, the results obtained for the penetration of the bend wall in the region of primary particle impact in the pneumatic conveyor test work are compared against predicted penetration figures. This is achieved by utilising the features of the trajectory model derived by Yeung [Y1] (see Appendix 5F) and combining this with the erosion models that were fitted to the results obtained from the rotating disc accelerator (as described in Chapter 4 sections 4.3.4 and 4.3.5).

As mentioned in Chapter 5, puncture of the bend wall does not occur in the region of primary particle impact, but is concluded to occur in the area where the particles strike the bend wall for the second time. The trajectory model based upon the curve of aberration for a cylindrical concave mirror is further developed to model the erosion damage. This is discussed in the third part of this chapter. Finally, conclusions related to the accuracy of the modelling techniques are given.

6.2 Predictions Using Previously Derived Models for Erosion of Pneumatic Conveyor Bends

Several models have been derived in the past to predict the life of a bend in a pneumatic conveyor. These works have been described in Chapter 2 section 2.2.

From all of these works three groups can be distinguished. The first of these is the work carried out by Bikbaev *et al.* [B8]. The second group follows the influential work of Mills and Mason *et al.* [M1] and includes the work of Shimoda and Yukawa [S4]. Finally, all those works that combine particle trajectory and erosive wear models form the last group. These include the works of Yeung [Y1], Hoadley and Johnson [H8,J1,H9,J2], Flemmer *et al.* [F4] and Sato and Shimizu *et al.* [S5,S6]. It was decided that a representative model from each group should be used and compared with the actual measured bend penetration that was observed in the test work described in Chapter 5. To this end, the predictive models of Bikbaev *et al.* [B8], Shimoda and Yukawa [S4], and Mason and Mills [M13] were used, and are described in the following sections. A model of the combined particle trajectory and erosion model type is described in section 6.3 of this Chapter.

6.2.1 Use of the Bikbaev Model

The model reported by Bikbaev *et al.* [B8] was derived empirically from the results of tests carried out in a pneumatic conveyor test facility. Expressions are given for the mean wear rate in mm/hour, the wear rate at any point around the bend radius in mm/hour and the location of the zone of maximum wear. All these expressions are based upon the use of variables that describe the geometry of the bend, i.e. bend radius and pipe bore, the local particle velocity (assumed to be the same as the local gas velocity) and the concentration of solids in the flowing suspension described in terms of mass flow rate of solids / mass flow rate of gas. The result of using this model is given in a MathCad document in Appendix 6A.

Table 6.1 Comparisons Between the Actual Bend Puncture Rate and Angle at which Puncture Occurred Against the Results Obtained from the Bikbaev Model

	Angle Around Bend Radius of Puncture Point (°)	Mean Wear Rate in Bend (mm/hour)
Actual Experimental Results	28.5	0.408
Bikbaev Predictions	14.9	1.448

As can be seen from the above table the expressions derived by Bikbaev *et al.* [B8] overestimated the mean wear rate by 3.55 times, and the predicted zone of maximum wear, i.e. puncture was also significantly different from that actually observed.

It is believed that the effects of three main areas of fundamental difference between the tests carried out by Bikbaev *et al.* [B8] and those described in Chapter 5 are the cause of these discrepancies. The first major difference is that the expressions of Bikbaev *et al.* were derived from results obtained from wear observed in bends whose maximum radius of curvature was 360 mm; approximately half that of the bends used in this test work. There was also a difference in the properties of the materials used in the tests carried out by Bikbaev; both the particles being conveyed and the material used to form the bends were different from those used during this project. Finally, the concentrations of particles used in the tests carried out for this project were greater than those used by Bikbaev *et al.* These three facts could combine to give the errors stated above.

6.2.2 Use of the Mills and Mason Type Bend Erosion Models

Mills and Mason have produced the largest volume of work on the wear of pneumatic conveyor bends to date. The approach that these researchers adopted was that of using large amounts of experimental data to produce empirical power law based predictive models. Several expressions were produced by these researchers which related the various measurable conveying characteristics such as gas velocity, the ratio of mass flow rate of solids to mass flow rate of gas and the bend geometry, to the erosion rate. In this section one of the early expressions derived by Mills and Mason [M13], and the work of Shimoda and Yukawa [S4] are used and compared to the actual measured results obtained in this project.

Mills and Mason [M13] derived an expression for the mass of abrasive material that can be conveyed through a bend before puncture occurs. This was as follows:-

$$M_s = 0.756 \times 10^6 \; V_p^{-3.5} \qquad (6.1)$$

where M_s is the mass of abrasive material conveyed before failure occurs and V_p is the particle velocity (assumed in this work to be equivalent to the local gas velocity). Use of this equation with a particle velocity of 25.5 m/sec leads to the prediction that failure of the bend by puncture will occur after 9.03 tonnes of material had been conveyed. In the tests carried out on the pneumatic conveyor used in this project puncture occurred after 5.475 tonnes of olivine sand had been conveyed. The prediction was 1.65 times larger than the actual result.

Use of this expression in the case being considered, for the prediction of the mass throughput before puncture of the bend, is suspect for similar reasons to that expressed for the models of Bikbaev *et al.* above: Basically, the test conditions used to develop the empirical relationship and the materials used were different from those used in the work described in this thesis.

The expression derived by Shimoda and Yukawa [S4] was based upon a more extensive series of tests than those carried out by Mills and Mason for the above expression. The Shimoda expression is as follows:-

$$E \propto V_p^{2.8} \mu_s^{-0.6} d H_v^{-0.4} \qquad (6.2)$$

where E is the erosion rate in mm/tonne; V_p is the particle velocity (which is considered to be the same as the local gas velocity); μ_s is the particle concentration expressed as mass flow rate of solids over the mass flow rate of gas; d is the mean particle diameter and H_v is the Vickers hardness of the bend wall material. Using the following values for these variables: V_p = 25.5 m/sec; μ_s = 3; d = 0.32 x 10^{-3} m and H_v = 150 (kg/mm^2) a value of E of 0.194 mm/tonne was found. For 5475 kg of material being conveyed, the model of Shimoda and Yukawa predicts that the amount of bend wall penetration will be 1.06 mm. This value is 63% of the actual penetration.

Again, the conveyed material used in the test work that was used to derive the model described in equation 6.2 was distinctly different from that used in the work described in this document. This is one of the most difficult system variables to account for and will have a significant effect on the erosion rate that occurs.

6.3 Predicting the Erosion Damage Seen in the Region of Primary Impact by Combining Particle Trajectory and Erosion Models

This section of this chapter deals with the use of the Yeung trajectory model [Y1] and its combination with the erosion models derived in Chapter 4 of this document.

There is a limit in the application of the Yeung trajectory model used in this work. This occurs when the particle trajectories intersect with the pipe wall for the first time and rebound trajectories need to be predicted. Owing to the difficulty of accounting for particle shape and properties, the behaviour of a particle during impact with the pipe wall and the resulting trajectory are very difficult to predict. Because of this, the Yeung trajectory model could only be used up to the point of initial impact with the pipe bend wall and no further. Hence, it cannot be used to predict the life of a pneumatic conveyor bend. However, it was found to be instructive to use this model in conjunction with the erosion models described in section 4.3 of Chapter 4. This is because it is possible that an indication of the concentration of particles at various locations in the primary impact zone can be obtained by this means.

6.3.1 Use of the Yeung Trajectory Model and its Combination with Erosion Models

It was found that the particle trajectory model of Yeung [Y1], despite its simplicity, gave results that were not too dissimilar to those found using a more complex commercial computational fluid dynamics programme (see Appendix 5F). It was suggested that the reason this occurred was due to the relatively large size of the abrasive particles and, therefore, the particle motion was largely unaffected by the presence of the turbulent gas flow. Because of this observation, it was decided that this simplistic model of the particle trajectory would be sufficient for calculating the necessary trajectories.

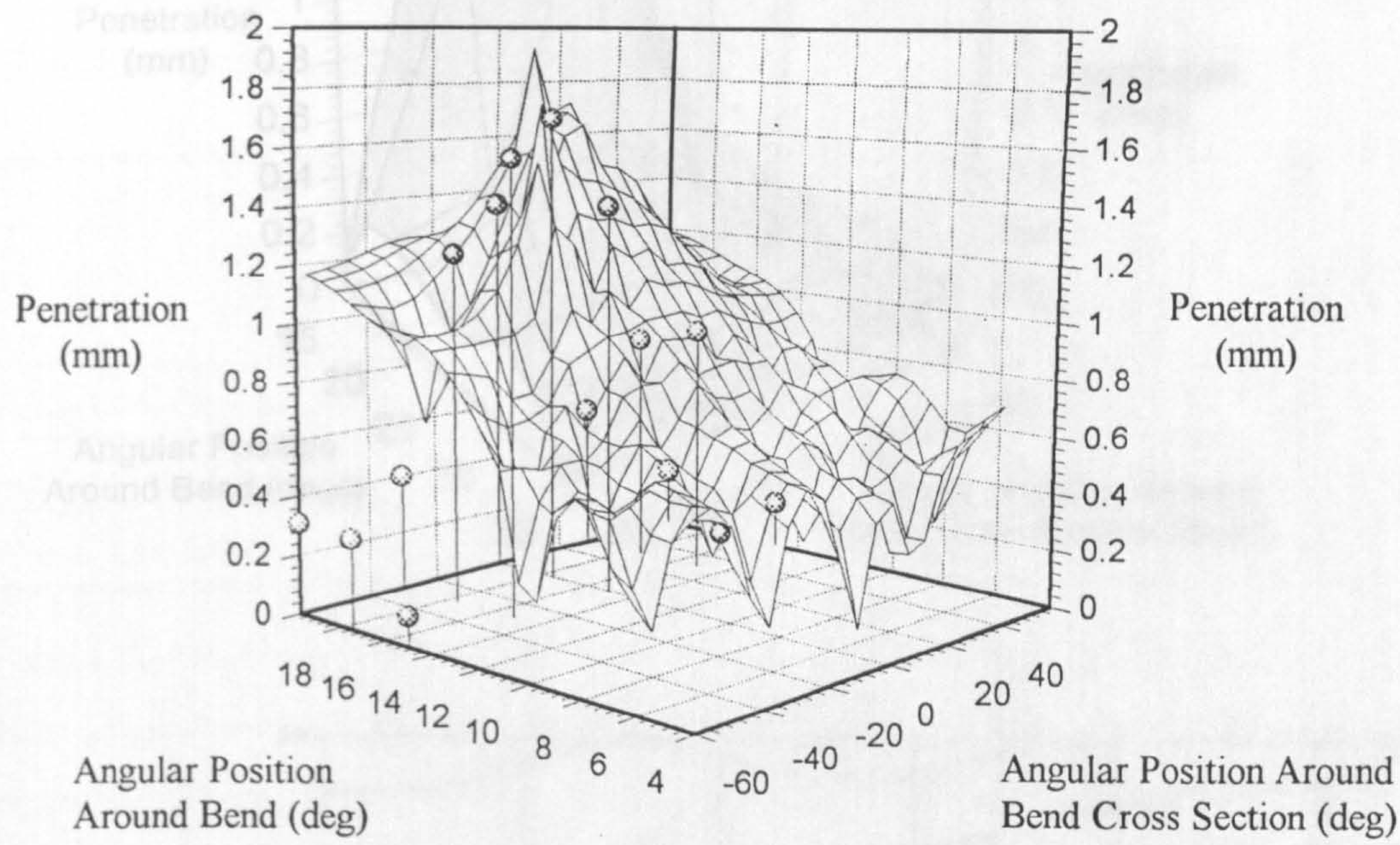
The method in which the Yeung trajectory model was used, was to calculate the trajectories of ninety six particles whose initial positions were fixed in the bore of the pipe at the entrance to the bend. At each of the initial positions, a corresponding value of estimated air velocity and particle concentration density were interpolated from the data presented in Figures 5.9 and 5.8 respectively. Each of these interpolated values, in conjunction with the value of the impingement angle determined by the trajectory model, were used as key input variables for the erosion models described in Chapter 4 section 4.3.4 (empirical power law erosion model derived during this project) and Chapter 4 section 4.3.5 (the Finnie / Bitter erosion model). Details of the combined trajectory & erosion models used to predict the erosive penetration in the region of primary impacts is given in Appendix 6B. The results of this series of calculations are expressed in the graphs shown in Figure 6.1 which also show data points that illustrate experimental results. The graph of the actual measured erosive penetration of the bend wall plotted against position within the bend is repeated in Figure 6.2 to enable a comparison to be made.

6.3.2 Observations Related to the Predictive Capability of the Combined Trajectory & Erosion Models

In comparison to the actual measurements of bend wall penetration obtained from the pneumatic conveying test work, it is interesting to note that the greatest amount of penetration of the bend wall in the primary impact area occurs at between 16° and 18° around the sweep of the bend from its entrance (see table 6.3). This is very close to that calculated using either of the erosion models combined with the Yeung trajectory model mentioned above.

Figure 6.1 Prediction of the erosion damage caused in the primary impact area by a) the Yeung trajectory model in conjunction with the Finnie / Bitter erosion model and b) the derived power law model in conjunction with the Yeung trajectory model; (data points for some of the experimental results obtained are included on both graphs). (Please note that the corrugations in the fitted surface are caused by the smoothing routine used in the graph plotting program).

a)



b)

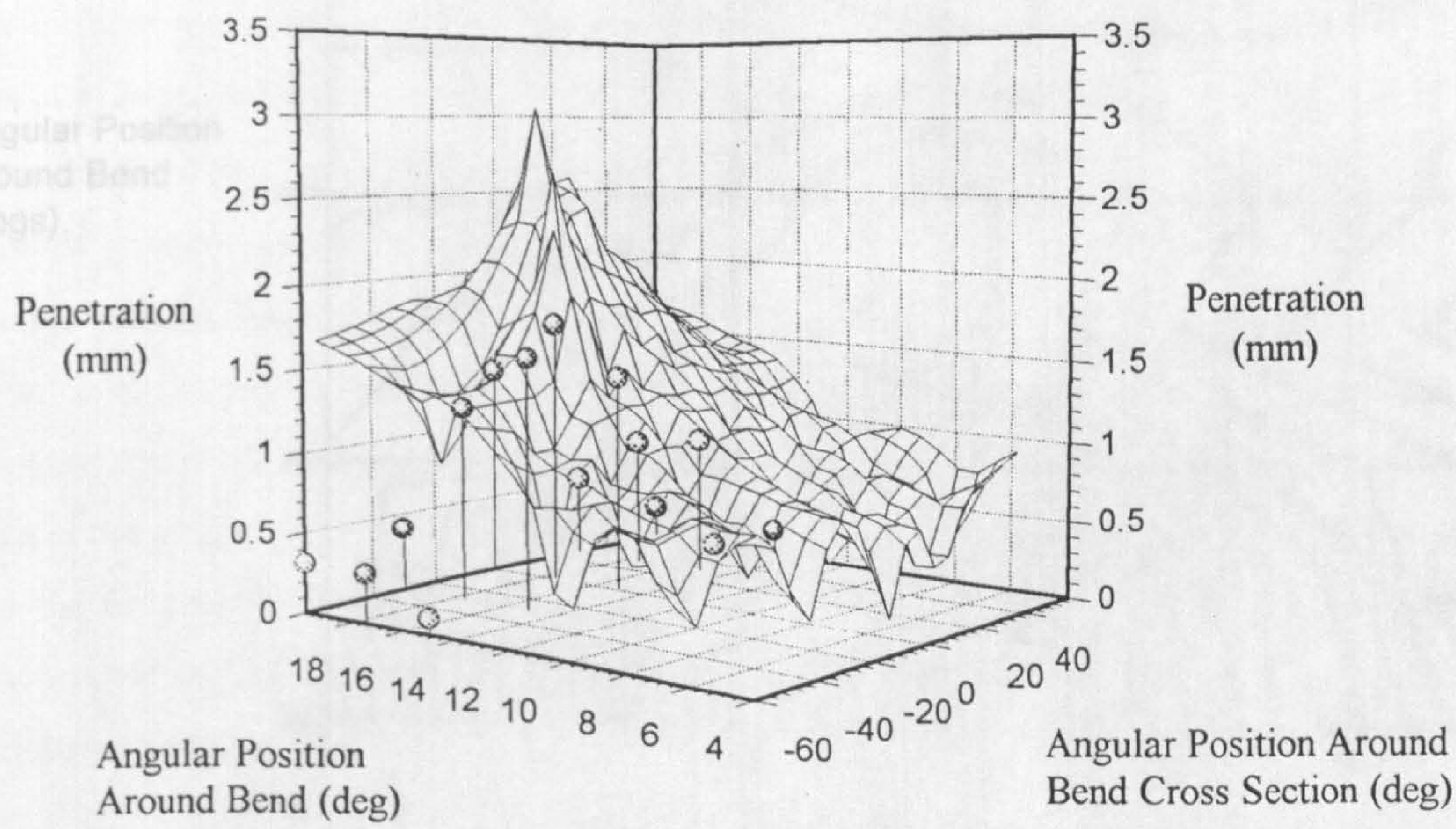
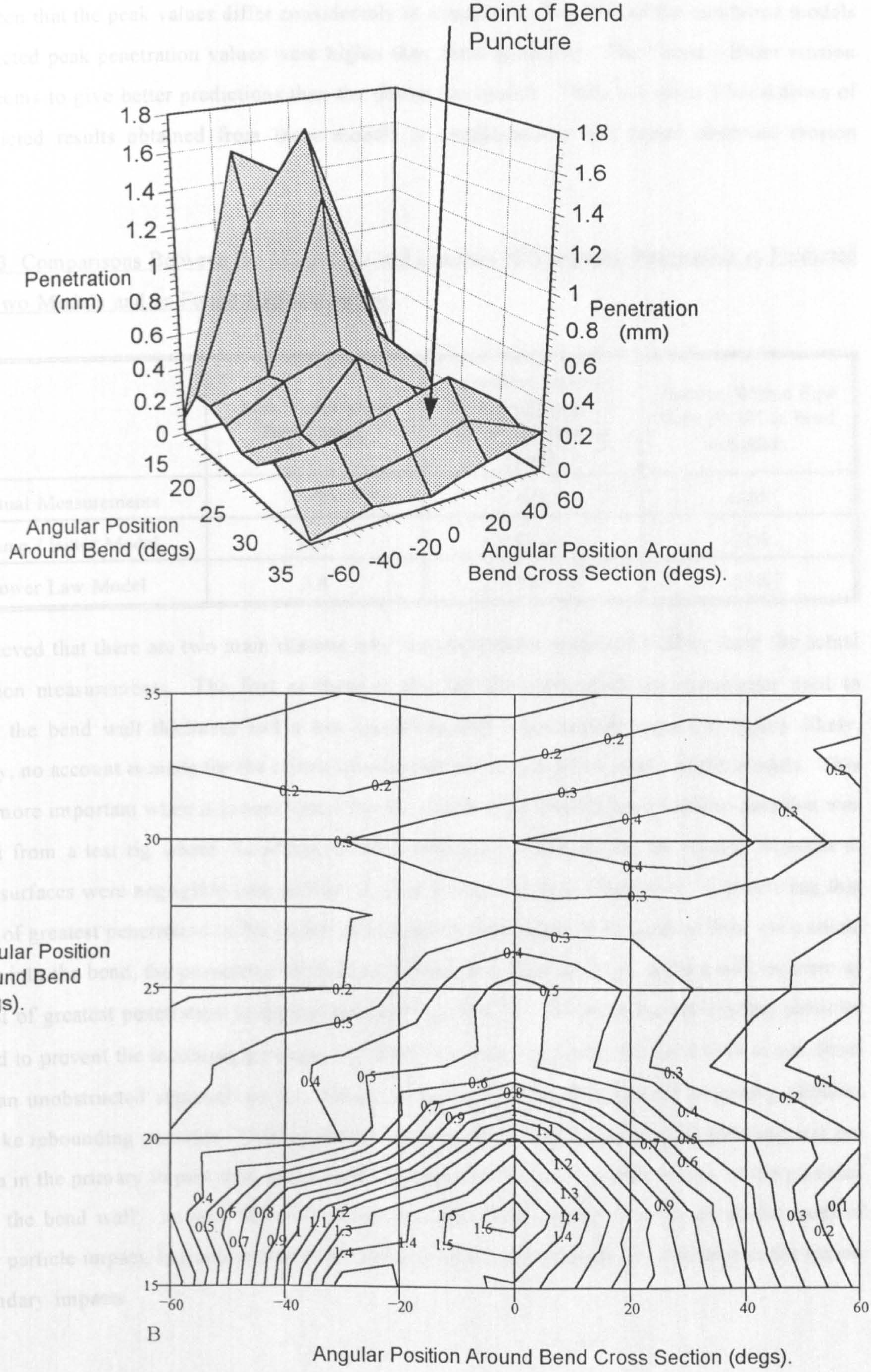


Figure 6.2 Surface and contour plots of the actual measured erosive penetration of the bend.



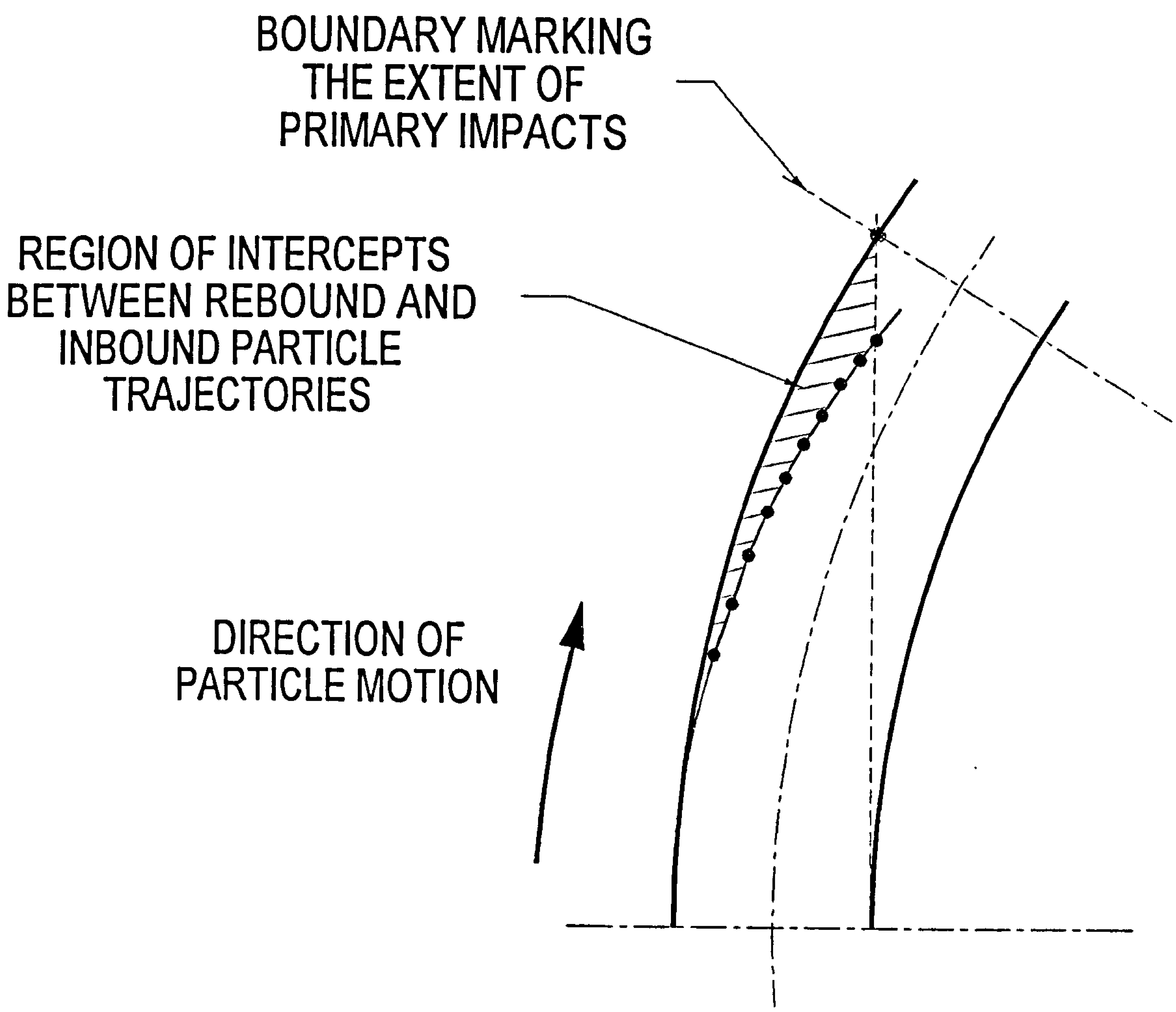
However, when the predicted penetration profiles are compared to the actual penetration profile, it can be seen that the peak values differ considerably in magnitude. For both of the combined models the predicted peak penetration values were higher than those measured. The Finnie / Bitter erosion model seems to give better predictions than the power law model. Table 6.3 gives a breakdown of the predicted results obtained from these models in comparison to the actual observed erosion damage.

Table 6.3 Comparisons Between the Magnitude and Location of Maximum Penetration as Predicted by the Two Models and as Found Experimentally

	Max. Penetration Depth (mm)	Position Around Radius of Bend (°) (0° at entrance to bend)	Position Within Pipe Bore (°) (0° at bend extrados)
Actual Measurements	1.674	≈16	≈-15
Finnie / Bitter Model	2.36	14.4	-23.6
Power Law Model	3.8	14.4	-23.6

It is believed that there are two main reasons why the penetration predictions differ from the actual penetration measurements. The first of these is that the ultrasonic thickness transducer used to measure the bend wall thickness had a low resolution and experimental error was highly likely. Secondly, no account is made for the effects of inter-particulate collisions in any of the models. This is even more important when it is considered that the two erosion models were fitted to data that was obtained from a test rig where the effects of inter-particulate collisions in the regions adjacent to erosion surfaces were negligible (see sections 4.3.6.3.2 and 4.3.6.4 in Chapter 4). Considering that the area of greatest penetration in the region of primary impacts tends to be furthest from the particle entrance into the bend, the proportion of particles rebounding from the bend surface will increase as the point of greatest penetration is approached (see Figure 6.3). Therefore the rebounding particles will tend to prevent the incoming particles, i.e. those that have not struck the bend wall as yet, from having an unobstructed approach to the eroding surface. It is possible that the incoming particles may strike rebounding particles. This will lead to a lessening of the intensity of particle impacts per unit area in the primary impact area, and a small reduction in the mean kinetic energy of the particles striking the bend wall. In turn, this will reduce the amount of erosion that occurs in the areas of primary particle impact, but will increase the intensity of particle impacts per unit area in the region of secondary impacts.

Figure 6.3 Illustration of the region of increased inter-particulate collisions in the region of primary impact.



6.3.3 Conclusions Relating to these Predictions

The major difference between the Finnie / Bitter erosion model and the derived power law model is that the actual amount of erosion predicted by the Finnie / Bitter model in each individual particle impact is invariant with the local particle concentration. In the case of the derived power law model different behaviour is shown, i.e. the erosion damage caused reduces with an increase in the local particle concentration (see Figure 4.11).

Both of the erosion models have been fitted to erosion data obtained from a test rig in which inter-particulate collisions are believed to be negligible (see sections 4.3.6.3.2 and 4.3.6.4 in Chapter 4). Therefore, these models are not capable of accounting for the effects of these collisions. These models will need to be altered to account for inter-particulate collisions before they are capable of accurate prediction of the bend wear. It is suggested that it is the effect of these collisions, and as a consequence of their occurrence, changes in the intensity of particle impact per unit area, that caused the differences between the predicted and actual results given above.

6.4 The Combined Model Based Upon the Curve of Aberration for a Cylindrical Mirror and the Power Law Erosion Model

This section describes a model based upon that used to empirically determine the point of puncture in the bend used in the test work described in Chapter 5 section 5.4. Erosive penetration is predicted using the empirical power law model derived from the tests carried out on the rotating disc accelerator as described in Chapter 4 section 4.3.4. A brief description of the combined model is given in the following paragraph, with more detailed information being given in Appendix 6C.

6.4.1 Construction of the Model Based Upon the Curve of Aberration for a Cylindrical Mirror and the Power Law Erosion Model

The curve of aberration for a cylindrical mirror, was used empirically to find the position of puncture in a bend [B19] (see section 5.4 in Chapter 5 and equation 5.1). A straight line particle trajectory was used to find the position of primary impact of a particle that was furthest around the bend radius; this occurred when a particle track was taken to start from the bend intrados at the entrance to the bend. Reflection in the normal at the point of impact of this single particle track was used to find the slope of the trajectory that goes from the first to the second impact position. (The primary particle pipe wall contact was presumed to be perfectly elastic, i.e. the coefficient of restitution was taken to be 1). However, the start position of this second trajectory was adjusted by using a distance along the normal to the pipe wall at the primary trajectory impact that was equivalent to the distance of the apex of the curve of aberration from the bend extrados. A value of erosion rate, predicted using the power law erosion model, was required. The mean values of the local gas velocity, (and therefore the particle velocity), and particle concentration density were obtained from Table 5.1 section 5.3.1 in Chapter 5. These values were used as input into the erosion model. Penetration at the predicted puncture location was calculated and compared to the actual penetration observed in the test bend for this point.

6.4.2 Observations on the Use of this Model

The penetration actually predicted for the predicted puncture point using the power law erosion model was 0.61 mm after 5.475 tonnes of olivine sand had been conveyed. At the point of bend failure, the actual penetration had to be 2.39 mm to ensure bend wall puncture. In this case, the model predicted approximately 25.6% of the actual value.

For this model to give penetration results of the same order as that measured for the puncture point during the conveying trials two complimentary effects must be considered,

a) either the frequency of particle impacts in the region of the point of puncture must be more than that predicted by using the measured data for particle concentration density, or

b) the damage is caused by an increased number of individual particle impacts, which, on an individual basis, cause an amount of damage that is not substantially changed from that which occurs in their first impact with the pipe wall.

Each of these options is now discussed.

An accumulation of particles against the extrados of the pipe bend has been observed by several researchers in the past [M4,B9,S4,J3]. The reason for this behaviour is that the curvature of the pipe walls causes the particles to be directed towards the axis of the pipe bore, and this is why the use of the curve of aberration for a cylindrical mirror can be justified. The consequence of this behaviour is to cause an increase in the number of inter-particulate collisions in this area. Inter-particulate collisions will tend to scatter the particle impacts over a wider area. Scattering of the particles will tend to act in opposition to the increased intensity of particle impacts per unit area caused by the particle accumulation effect due to the geometry of the internal bend surfaces. However, it is felt that the effects of an increase in the number of particle impacts per unit area of the pipe wall will be greater than the dispersive effect that the inter-particulate collisions will have [A2,A5].

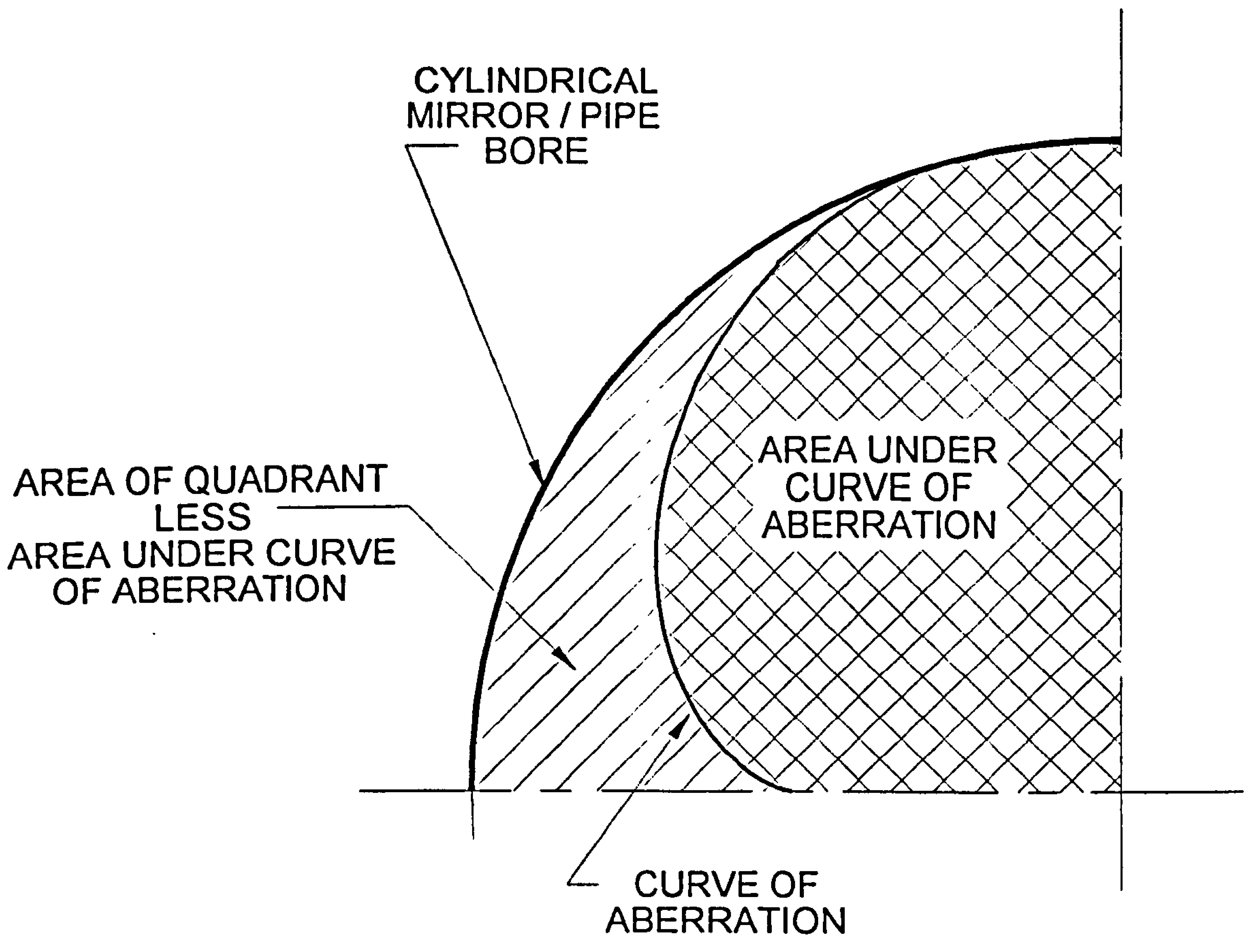
In order for the erosion in the secondary impact area to be large enough to cause puncture, the kinetic energy of the particles after their first impact with the pipe wall must remain quite high. In the case of the erosion of the long radius bend used in this work, the angles of impact that occurred tended to be low. As a consequence of this, the coefficient of restitution acting during the impact, (which acts on the component of the particle velocity normal to the pipe wall at the point of impact), will have only a small effect in reducing the kinetic energy of the particle. More effective in this instance may be the coefficient of friction that occurs between a particle and the pipe wall surface during contact. However, it is possible to conceive of a rotating angular particle striking the surface of the pipe wall such that one of the projections on its surface may rotate into the bend wall and effectively push the particle away. Behaviour of this type will lead to the particles being in contact with the pipe wall for short periods of time. If this form of behaviour predominates, it can be argued that since the particles will spend small amounts of time in contact with the pipe wall, the coefficient of friction may have a negligible effect in reducing the kinetic energy of the particles. With both the coefficients of friction and restitution having a minimal effect on reducing the particle kinetic energy, the particles could retain enough energy to cause significant damage during successive impacts.

The ratio of actual penetration to the predicted penetration can be used to imply that the number of particle impacts in the region of bend puncture must be about four times that suggested from the results of this model. It is interesting to note that the shape of the curve of aberration for a cylindrical mirror can be used to predict this increase in particle impact intensity. By calculating the area beneath the half of the curve of aberration fitted to a quadrant of the pipe bore, (described in section 5.4.1, Appendix 5G, Appendix 6C and see Figure 6.4), it has been found that an empirically derived factor based upon the ratio of this area to that of the quadrant being considered can be used to give account of the reduction in erosion damage seen. The factor is as shown below:-

$$F_c \propto \frac{\pi R_p^2}{2\left(A_{quadrant} - A_{aberration}\right)} \qquad (6.3)$$

Where F_c is a factor that is related to the increase in the intensity of particle impacts; R_p is the radius of the pipe bore; $A_{quadrant}$ is the area of the quadrant of the pipe bore being considered and $A_{aberration}$ is the area under the curve of aberration for a cylindrical concave mirror fitted in the same quadrant.

Figure 6.4 Illustration of the areas being considered for the determination of the factor, F_c.



For the bend tested in this project, equation 6.3 predicts that the factor will have a value of 4.33. The ratio of the predicted erosive penetration at the puncture point to the actual erosive penetration is 3.907. These two values are not that dissimilar being within 10.8% of each other.

This is an interesting and encouraging finding, however, more experimental results for bend puncture are required to validate this model.

6.4.3 Conclusions Related to the Use of The Model Based Upon the Curve of Aberration for a Cylindrical Mirror and the Power Law Erosion Model

In summary, because of the combined effects of the accumulation of particles against the outer wall of the bend, and the small (perhaps minimal) reduction of the kinetic energy of the particles after their first contact with the bend wall, there will be an increase in the amount of erosive penetration above that which is predicted that takes place in the secondary impact region by the power law erosion model (see Chapter 4 section 4.3.4). An empirically determined expression, derived from the properties of the curve of aberration for a cylindrical mirror, may be used to predict a value for a factor that will correct for the reduction in the predicted erosion damage for the region around the puncture point.

This model has a good physical basis and with further development may prove to be the basis of a simple model for predicting the life of pneumatic conveyor bends. More information regarding the use and development of this model is given in Chapter 7.

6.5 Conclusions Relating to the Accuracy of the Pneumatic Conveyor Bend Wear Models Used in this Work

The following table summarises the results obtained from using the various models for predicting wear in a pipe bend discussed in this chapter. Please note that if the ratio of the actual value over the predicted value is greater than 1, the predicted penetration rate of the bend wall is slower than that which actually occurred. The converse is also true.

Table 6.3 Comparisons of the Results Obtained from all of the Predictive Models Used in this Chapter

Type of Bend Wear Model: Location of Point being Considered	Ratio of Actual Value over Predicted Value
Bikbaev [B8]: puncture point	0.28
Mills and Mason [M13]: puncture point	0.61
Shimoda and Yukawa [S4]: puncture point	2.25
Investigation of Wear in Area of Primary Impacts	
Yeung [Y1] + Finnie / Bitter [S5,S6]: maximum penetration value in the area of primary impact.	0.71
Yeung [Y1] + Power Law Model [Section 4.3.4]: maximum penetration value in the area of primary impact.	0.44
Model Formed Using the Curve of Aberration for a Cylindrical Mirror [Sections 5.4 and 6.4] & Power Law Erosion Model [Section 4.3.4]	
Secondary impact location (without accounting for inter-particulate collisions).	0.26
Secondary impact location with model of curve of aberration for a cylindrical mirror.	1.11

6.5.1 Comments Relating to Models Proposed by Other Authors

In the case of the models proposed by other authors, the tests upon which the models were based were too narrow in scope to encompass either the values of the conveying conditions, or the geometry of the bends used in this work. All of these models predicted that the penetration point would occur in the region of primary impact, whereas the experimental results obtained in this project indicate that puncture occurs well beyond the primary impact area. For these reasons the results from these models were felt to be untrustworthy. Despite this difficulty, and the fact the models were derived from tests at conditions, and using materials, quite different from those used in this work, the results obtained from using these models are surprisingly good. It is suspected that this is because all of the models utilise the particle velocity as one of their primary input variables. This is, without doubt, the most important variable in determining the amount of erosion damage that occurs. Any model including this variable will tend to give results within the correct order of magnitude at least.

6.5.2 Comments Relating to Combined Erosion / Trajectory Models

Both combined erosion / trajectory models used to investigate the erosive penetration in the area of primary impacts predicted that the damage would proceed faster than that which actually occurred. At least this is a conservative result. There are two main reasons why this should be the case. These are as follows:-

a) Inter-particulate collisions between particles that have not struck the bend wall and those that have, cause a reduction in the intensity of particle impacts per unit area in the primary impact region. This is because the area of the bend wall affected by the primary impact of particles is increased with an increase in the frequency of the inter-particulate collisions. A reduced penetration rate of the bend wall, when compared to the predicted value, occurs as a consequence of this. Neither of the models account for the effects of inter-particulate collisions. The curvature of the internal surfaces of the bend do not significantly affect the wear in this part of the bend. This is because the particles have to have struck the pipe wall before any projection towards the bore axis can take place.

b) It is possible that the 'rotating disc accelerator' erosion tester did not adequately simulate the particle motion conditions occurring in the pneumatic conveyor bend. Obviously, this would have an effect on the data used to find the empirical constants utilised in the erosion components of the models described above. One of the features of the rotating disc accelerator rig, is that the erosion of any given target is a discontinuous process. Another is that the arrangement of the targets within the tester in conjunction with the particle jet dynamics used in this work led to a situation where inter-particulate collision effects were minimised. It is possible that these two facts led to inaccuracies in the simulation of inter-particulate collisions in the region of the target surface for any given conditions of particle impact, and therefore, by inference, a poor simulation of particle impact intensity on the target surface as well. This behaviour can be viewed as an advantage when the accurate simulation of erosion without the effects of inter-particulate collisions is required.

It seems as though predictions for impact locations closer to the entrance to the bend are better than those for impact points that occur further around the bend radius (see Figure 6.1). This fact tends to support the above assertions.

6.5.3 Comments Relating to the Model Based Upon the Curve of Aberration for a Cylindrical Mirror and the Power Law Erosion Model

Prediction of the bend wall penetration by the curve of aberration for a cylindrical mirror model in the secondary impact area (as described in Appendix 6C) is slightly greater than that which actually occurs. Any differences are attributed to two factors. These are that the curvature of the internal surfaces of the bend will tend to direct the particles to strike for a second time at a point very close to the actual point of puncture in the bend. This accumulation of particles causes the intensity of inter-particulate impacts in the region of puncture to increase substantially. Also, the loss of kinetic energy of the particles in the first impact is small and will tend not to reduce the amount of damage that is caused. Importantly, the properties of the curve of aberration can be used to empirically estimate a value of the increase in the intensity of particle impacts necessary to cause the amount of erosion observed at the puncture point.

Considering the simplicity of the model based upon the curve of aberration and the power law erosion model, it is shown that, for the combination of flow and material conditions under discussion, this model gives the most accurate prediction of bend puncture rate out of all of the models considered in this chapter. Further tests on bends of different radii and under different conveying conditions are required to establish the validity of this model. However, despite its simplicity this model has a good physical basis. Further development of this model will be discussed in Chapter 7.

Chapter 7

Structure and Development of a Bend Erosion Model Based Upon the Curve of Aberration for a Cylindrical Mirror

7.1 Introduction

This chapter will discuss the development of a model suitable for predicting the erosive penetration of a long radius pneumatic conveyor bend wall. The model is based on the curve of aberration for a cylindrical concave mirror. Details of how the model used in this thesis has been developed so far, and suggestions as to how further improvements can be made, will be given.

7.2 A Description of the Basic Technique that was Adopted

The primary goal of the work described in this thesis was to find a way of predicting the life of a long radius pneumatic conveyor bend by using results from erosion tests carried out on a laboratory scale erosion tester.

It was decided, as a consequence of the results of the literature survey, that the main variables that affected the erosion resistance of a material, aside from the material properties for both the abrasive particles and the material suffering erosion, were the particle velocity, the angle of impingement of the particles against the eroding surface, and the intensity of particle impacts per unit area of the eroding material (which was directly related to the concentration of particles in the flowing suspension). Tests on a laboratory erosion tester were carried out to determine the effects of these three variables on the erosion observed for a selected abrasive and target material.

Observations from actual pneumatic conveying trials using identical materials to those used in the laboratory erosion tester yielded some interesting findings. Most important of these were that the penetration of the bend wall occurred in the region of secondary particle impacts, and that the curvature of the bend walls tended to direct the particles to concentrate near the bend extrados following their first impact against the wall of the bend. The shape of ripple patterns formed on the internal surfaces of the pipe bend following erosion suggested the use of the curve of aberration for a cylindrical mirror as the basis of the bend erosion model discussed in this Chapter was not unreasonable [B19] (see Chapter 5 Figure 5.11). However, due to the optical basis of this model it was apparent that this model was only applicable to erosive wear situations where the particles were large enough not to be influenced significantly by the turbulent gas flow surrounding them.

From the results obtained from the rotating disc accelerator the erosive penetration of the targets could not be used to model the penetration of a pneumatic conveyor bend without modification. The reason for this was that it was concluded that erosion in the rotating disc accelerator erosion tester occurred in a discontinuous manner such that it did not accurately simulate the effect of inter-particulate collisions on the frequency of particle impacts on the eroding surface, and therefore, erosion of the surface being struck. However, the concentration effect caused by the curved internal surfaces of the pipe bend following primary particle impacts had to be accounted for in the model. It was proposed that an empirically determined coefficient be used to carry this out, and serve to simulate an increase in the frequency of particle impacts at the point of puncture in the bend. It was decided that erosive damage predictions made from results obtained from the rotating disc accelerator erosion tester would therefore be multiplied by this coefficient as shown in equation 7.1.

$$\begin{bmatrix} \text{Penetration rate at} \\ \text{the point of puncture} \end{bmatrix} = \begin{bmatrix} \text{Erosion rate prediction} \\ \text{at given values of V, } \alpha \\ + \dot{m}_{flux} \end{bmatrix} \times \ldots \begin{bmatrix} \text{Coefficient of} \\ \text{intensification} \\ \text{of particle} \\ \text{impacts} \end{bmatrix} \quad (7.1)$$

7.3 The Model of the Curve of Aberration for a Cylindrical Mirror

Use of the curve of aberration for a cylindrical mirror of the same dimensions as the bore of the pipeline has been used to locate the puncture position, (Chapter 5 section 5.4 and Appendix 5G), to determine the input variables for the power law erosion model (described in section 4.3.4 of Chapter 4), and to determine a coefficient that can account for the intensification of particle impacts in the region of the puncture point, (Chapter 6 section 6.4 and Appendix 6C). A brief repetition of how the model was used in each of these instances is given below.

7.3.1 Construction and Use of the Curve of Aberration of a Cylindrical Mirror to Find the Location of the Puncture Point in the Bend

7.3.1.1 Construction of the Curve of Aberration for a Cylindrical Mirror

The generation of the curve of aberration for a cylindrical mirror was carried out using a series of straight line trajectories traced towards the curved internal surface of a cylinder of the diameter of the pipe bore before wear had occurred. Coordinates of the intersection of each of these trajectories with neighbouring rebound trajectories were found (see Figure 7.1). Points were obtained in this manner to form the profile of the curve of aberration. The most important feature of the curve was its apex which lay on the horizontal plane containing the axis of the pipe line. The distance of the apex point from the radial extremity of the pipe bore surface was taken as being fixed for the geometry of the bend used in the tests. Details of the calculations that were carried out are contained in Appendix 5G.

7.3.1.2 Finding the Location of the Point of Bend Wall Puncture

A series of calculations were used to determine the position of the puncture point that occurs in the region of secondary impacts. This was achieved by finding the maximum radius around the bend that the primary impact of a particle trajectory could strike the outside wall of the bend, and calculating the equations of the tangent and normal to the pipe wall at this point. The incoming trajectory was taken to be mirrored in the line of the normal to the curve of the bend a distance along the normal from the first point of trajectory / bend wall intercept such that the mirrored trajectory intercepted the bend wall close to the secondary impact location. The distance selected was equivalent to the distance from the apex of the curve of aberration to the extrados of the pipe bore. Again it must be stated that this analysis is only appropriate if the particles are not significantly affected by the gas motion, since only then will their trajectories be straight. Figure 7.2 illustrates the layout of the trajectory model within the pipe bend and further description is given in Chapter 5 section 5.4 and Appendix 5G.

The angle of traverse around the test bend at which puncture occurred was 28.5° and as a consequence of using the proposed model, the puncture point is predicted to occur at 31.9° around the bend radius (see Appendix 5G and Chapter 6 section 6.4.2). This is an 11.9% error. Considering the simplicity of the model used, this was thought to be a good agreement.

Figure 7.1 Schematic illustrating the method used to construct the curve of aberration of a cylindrical mirror

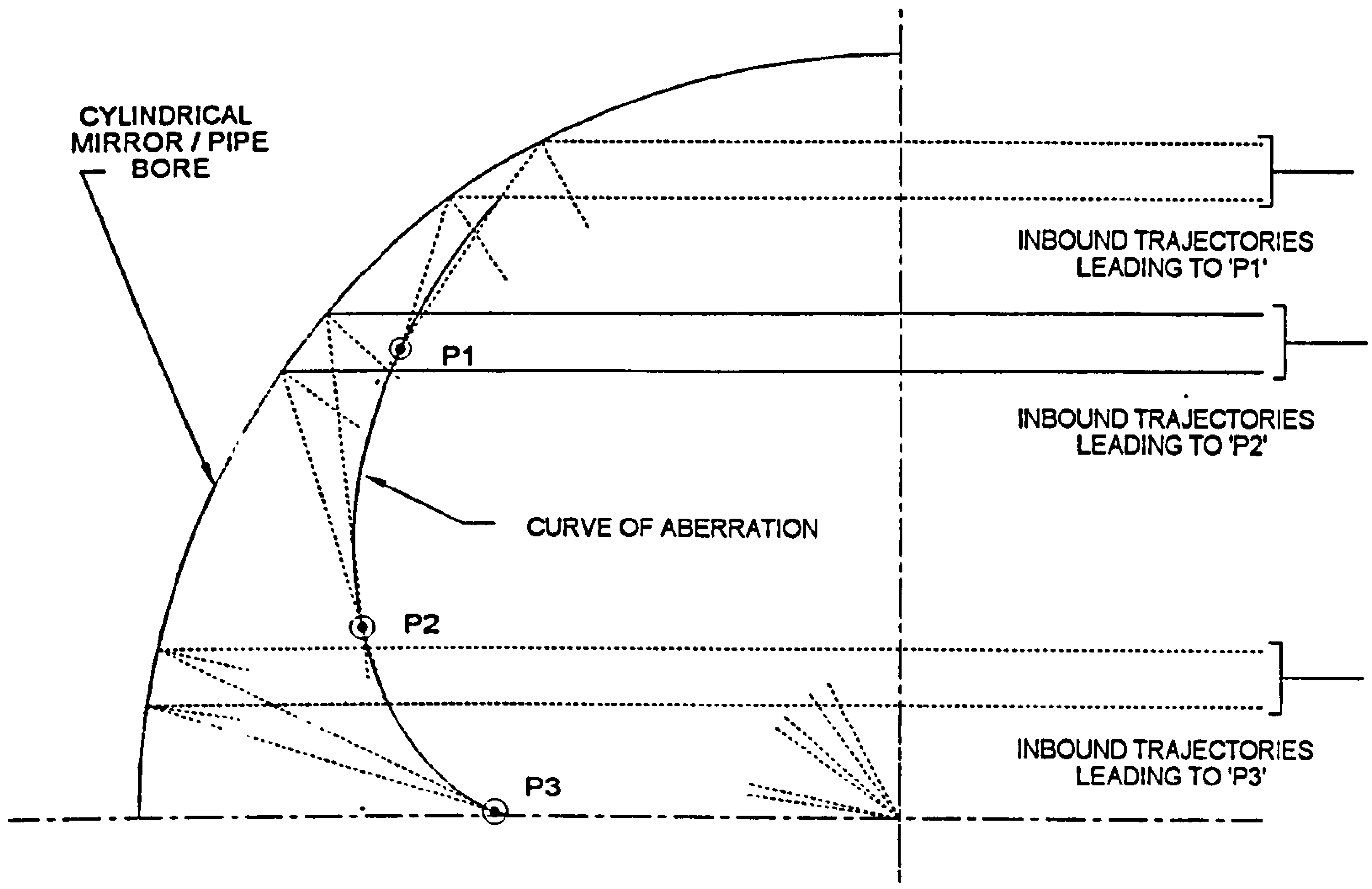
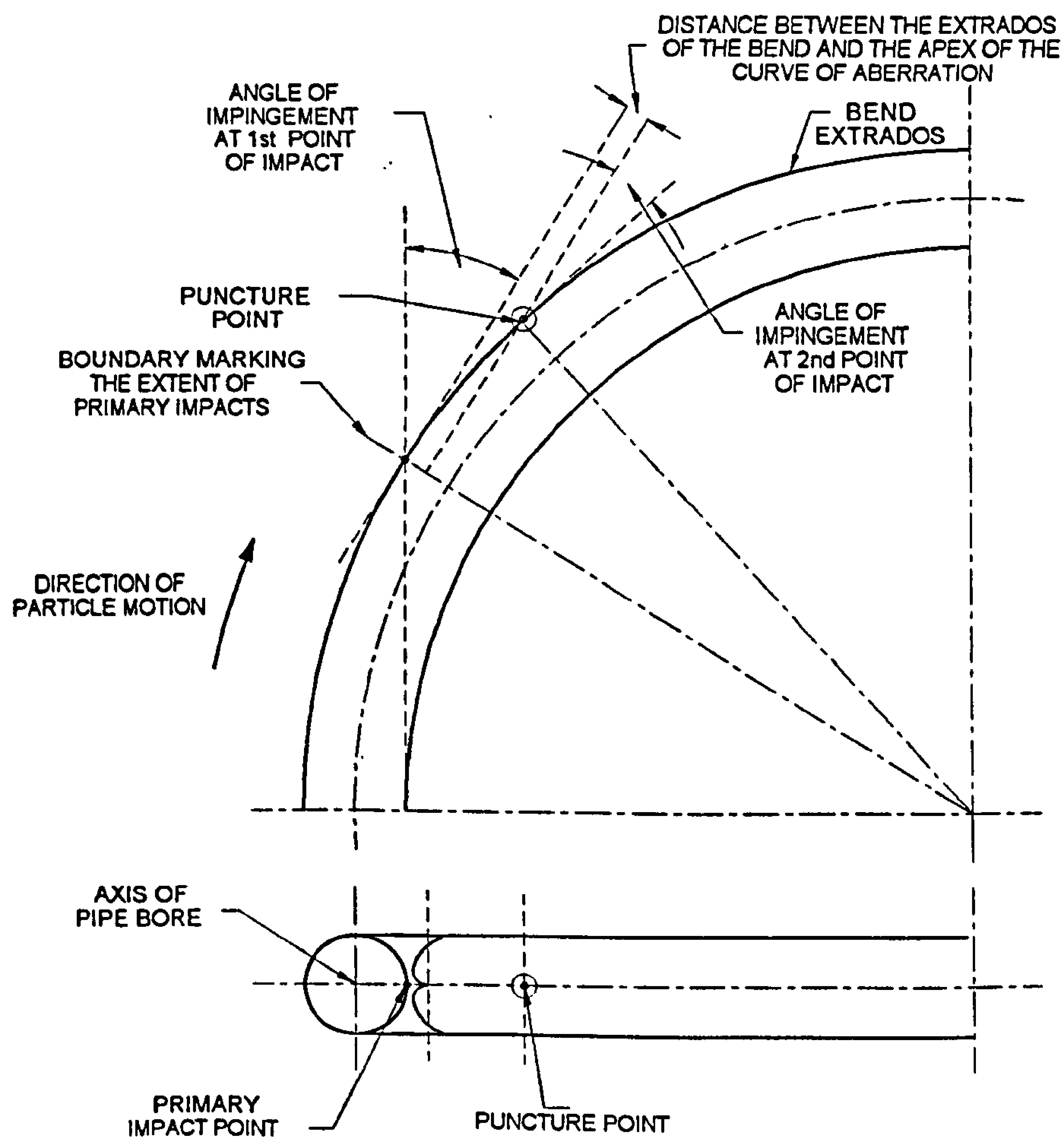


Figure 7.2 Layout of the curve of aberration trajectory model within the test bend



7.3.2 Linking the Curve of Aberration for a Cylindrical Mirror to the Power Law Erosion Model

Using the particle trajectory model that was briefly described above and illustrated in Figure 7.2, it was possible to arrive at an estimate of the angle of particle impact against the bend wall in the region of the puncture point. This value was used as input into the erosion model, called the power law erosion model (see Chapter 4 section 4.3.4). The erosion model was described using the following equation:-

$$E = a\ V^n \tag{7.2}$$

where E is the erosion rate in mm^3/kg (i.e. volume lost per unit mass of abrasive striking the target surface); V is the particle velocity (taken to be the superficial gas velocity at entry to the bend), and a and n are empirical coefficients that are dependent on both α, the angle of particle impingement and ρ_s, the suspension density of the particles in the flowing gas (which has units kg/m^3). A full description of the derivation of this model is given in Chapter 4 section 4.3.4. The values of V and ρ_s used in this model were taken to be the mean global values of these variables as determined from the pneumatic conveying trials, see Table 5.1 Chapter 5 section 5.3.1. Since the value of the erosion rate, E is not dependent on the area of the target suffering erosive wear, selection of an arbitrarily sized flow channel was used to model the extent of the actual area of the pipe bend wall which suffered particle impingement (see Figure 7.3 for a graphical explanation). Use of this flow channel permitted the erosion rate to be derived in terms of penetration of the bend wall per unit mass of abrasive striking the actual area of the bend wall (i.e. in units of mm/kg).

When results from this model were compared to the actual penetration results obtained from the pneumatic conveying trials described in Chapters 5 and 6, the predicted penetration rate was only approximately 25% of that which actually occurred. Corrections to account for this are discussed in the next section of this chapter.

7.3.3 Determining a Particle Impact Intensification Factor from the Model Based Upon the Curve of Aberration

It was concluded that the disparity between the predicted and actual penetration rates was caused by an intensification in the frequency of particle impacts in the region of secondary impact. This was concluded to be due to the effect that the shape of the bend wall had on concentrating the particles at the extrados of the bend following rebound from the primary impact position. Section 6.4.2 of

Chapter 6 discussed the reasoning behind this conclusion in more detail, however, to recapitulate it was concluded that:-

a) Collisions between inbound and rebounding particles in the region of secondary impact to cause 'shielding' of the eroding surface from direct high speed particle impacts was unlikely to occur because the concentration of particles in the flowing suspension was too low for this to occur.

b) Loss of kinetic energy in the primary impact of a particle in the long radius bend used in this study was minimal because of the low angles of impingement that were likely to occur. Energy losses due to the restitution effects would therefore be small. Any effect due to the friction between the particle and the pipe wall was also concluded to be small due to the possibility of the particle rolling on contact and the short contact times that were expected to occur.

It was observed that the geometry of the curve of aberration could be used to estimate the increase in intensity of particle impacts surrounding the puncture point that occurs in the pneumatic conveyor bend. To this end the ratio of the area of a single quadrant of the pipe bore over the area under the curve of aberration was used in an empirical expression to describe the intensification of particle impacts in the region of the pipe wall surrounding the puncture point (see Figure 7.4). The expression was as follows:-

$$F_c \propto \frac{\pi R_p^2}{2\left(A_{quadrant} - A_{aberration}\right)} \tag{7.3}$$

where F_c is the intensification factor; R_p is the radius of the pipe bore; $A_{quadrant}$ is the area of a quadrant of the pipe bore, and $A_{aberration}$ is the area under the curve of aberration when fitted to one quadrant of the pipe bore. This expression gave a value of approximately 4.3 which predicted an erosion rate within 11% of the actual erosion rate discussed above. The use of the model described above and by equation 7.1 is discussed further in Chapter 6 section 6.4 and Appendix 6C.

Figure 7.3 Diagram of the arbitrary sized flow channel used in the erosion model

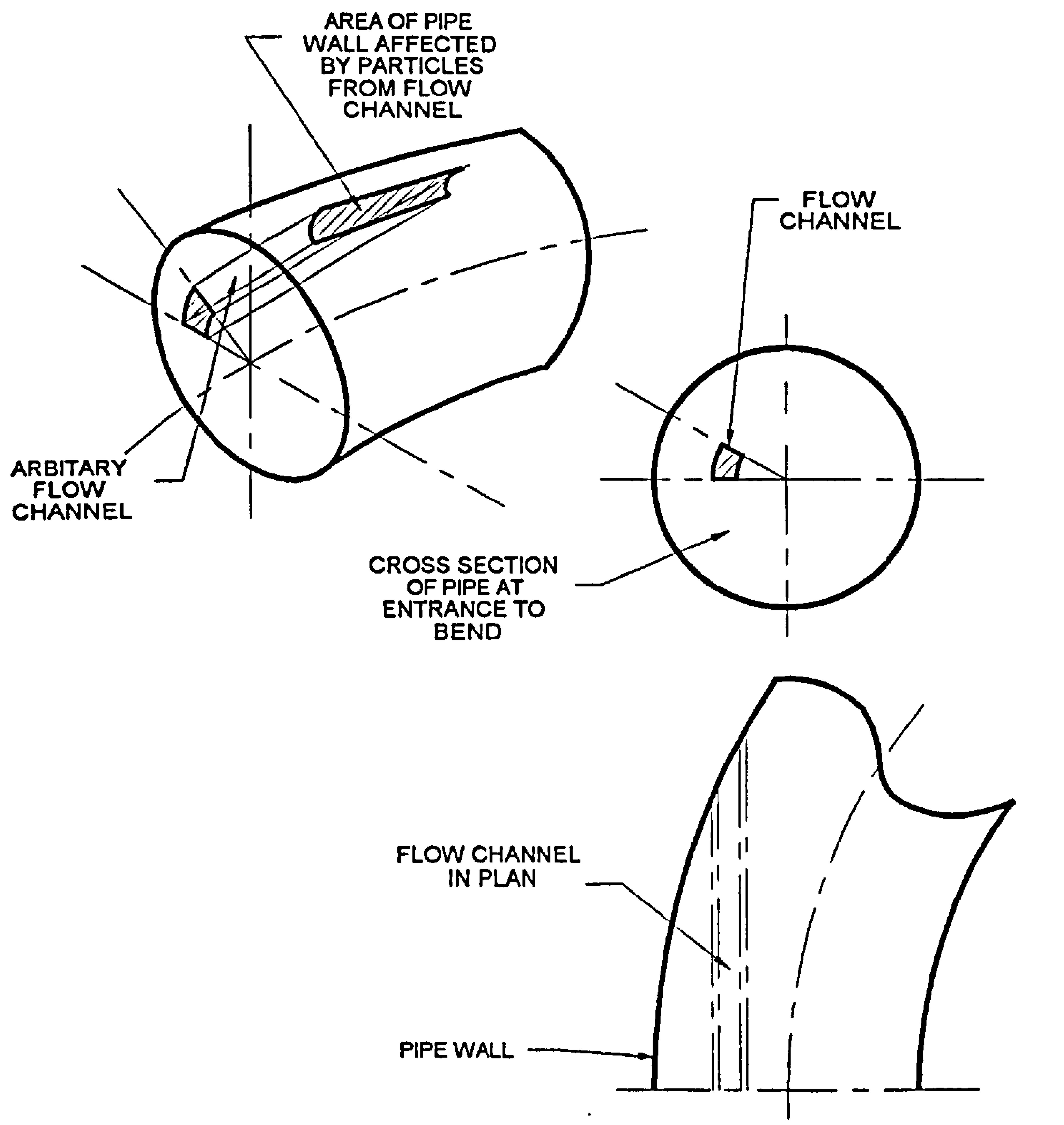
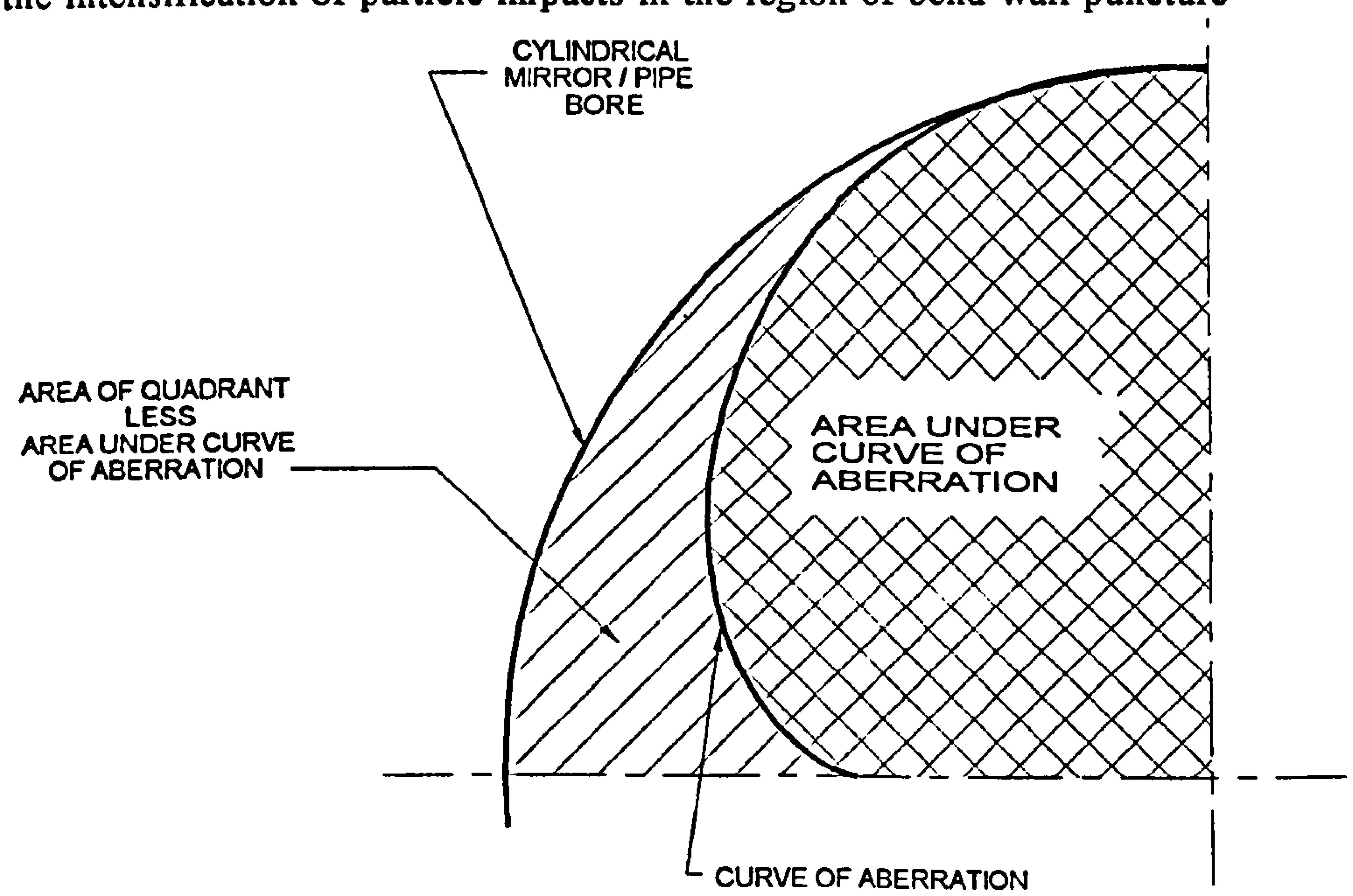


Figure 7.4 Illustration of the areas being considered for the determination of the factor to account for the intensification of particle impacts in the region of bend wall puncture



7.4 Further Development of the Model for Predicting the Life of a Long Radius Pneumatic Conveyor Bend Using the Curve of Aberration

The model discussed above that includes the coefficient of intensification of particle impacts in the region of the puncture point was in error by +10.8% when compared with the actual results obtained from the pneumatic conveying trials discussed in Chapter 5. In an industrial application of this model, this degree of accuracy would be sufficient to give a prediction of whether wear resistant linings need to be used in the pipeline bends or not. It is felt that work to check the applicability of the model to bends of different geometries is more important than refining the existing model to reduce this margin of error. To this end, it is suggested that the curve of aberration for a toroidal mirror is used to form the basis of an improved model should the model described above prove not to be generally applicable.

However, the concepts introduced in the following section will focus on the refinement of the existing model based upon the curve of aberration for a cylindrical mirror with the goal of reducing the amount of error.

7.4.1 The Addition of Further Correcting Coefficients

It was possible to conceive of several reasons why this positive error has occurred between the predicted and actual amounts of penetration in the pneumatic conveyor bend. These were as follows:-

- A small number of inter-particulate collisions between inbound and rebounding particles in the region of the point of bend wall puncture would have a tendency to reduce the amount of erosion damage that occurs. The probability of inter-particulate collisions occurring for any given suspension density will decrease with an increase in the size of the particles. This is due to the reduction in the number of particles in a selected segment of the pipe bore.

- If some of the particles in the distribution of particles being conveyed are small enough, they may begin to be affected by the motion of the turbulent gas flow that surrounds them. This would tend to alter the point at which they strike the wall of the bend and, consequently, would lead to a reduction in the amount of erosion because of the greater area of the bend wall over which impacts occur. The effect of increased levels of interaction between the gas and the particles would be affected dramatically by the range of particle sizes and the velocity at which they are travelling. For the material used in this work a very small percentage of the olivine sand had mean particle diameters below 100µm (see Appendix 3A). When the particle size is of the order of 60µm mean particle diameter the motion of the particles begins to be affected by the gas surrounding them.

- With increases in the thickness of the bend wall there would be an increase in the life of a bend before puncture occurred, however, because of the increased damage that would occur before puncture disturbance to the flow of the particles would also be increased. Particle impact positions would change as the internal pipe wall surface profile changed with increasing amounts of erosion damage. This would mean that as the amount of erosion damage increases, the position of the puncture point would move back towards the region of primary impacts, and the intensity of particle impacts over the parts of the surface of the bend wall would increase at the point of puncture.

The basic model described in section 7.3 above dealt with the majority of the major effects noted during the results of the pneumatic conveying tests (see Chapter 5). The three factors discussed above, are more likely to have a small effect on the outcome of the predictions obtained from the model. Because of this, it is suggested that the easiest way to account for their effect is by using further empirically derived coefficients. Therefore, further refinement of the model may result in equation 7.1 being modified to the following form:-

$$\left[\begin{array}{c}\text{Penetration rate at}\\ \text{the point of puncture}\end{array}\right] = \left[\begin{array}{c}\text{Erosion rate prediction}\\ \text{at given values of } V,\ \alpha\\ +\ \dot{m}_{flux}\end{array}\right] \times \ldots$$

$$\left[\begin{array}{c}\text{Coefficient of}\\ \text{intensification}\\ \text{of particle}\\ \text{impacts}\end{array}\right] \times \left[\begin{array}{c}\text{Coefficient of}\\ \text{interparticulate}\\ \text{collisions}\end{array}\right] \times \left[\begin{array}{c}\text{Coefficient of}\\ \text{gas-particle}\\ \text{coupling}\end{array}\right] \times \ldots$$

$$\left[\begin{array}{c}\text{Wall thickness}\\ \text{coefficient}\end{array}\right] \times \left[\begin{array}{c}\text{other}\\ \text{coefficients}\end{array}\right]$$

(7.4)

A considerable amount of test work would have to be carried out to find values for each of these coefficients, and when this has been achieved it may become apparent that there are other, as yet, unnoticed behaviour patterns that may affect the predictive capabilities of the model. However, these unnoticed affects may be accounted for by adding yet further coefficients to the model.

7.4.2 Further Work

Aside from the large quantity of further work required to obtain values for the coefficients mentioned in section 7.4.1 and equation 7.4, other investigations will be required. The most important of these concerns the effects of changes in bend geometry on the accuracy of the model predicting the life of a conveyor bend.

Several researchers in the past have indicated that puncture occurs in the region of primary impacts for bends whose radii are smaller than that tested in this work [M1,S4,B8, etc]. The position of the apex of the curve of aberration is fixed for any pipe bore, however, the angles of the tangent and normal of the maximum primary trajectory intercept position will change as the ratio of bend radius over bore diameter, R/d, changes. Therefore, it will be necessary to carry out further tests to ascertain whether this model holds true for all values of R/d, since the relationship between position of the apex of the curve of aberration and the angles of the tangent and normal may not change linearly. It is worth considering expanding the model based upon the curve of aberration into a third dimension. This can be achieved by considering the curve of aberration for a toroidal mirror. It is possible that a model based on the geometry of a toroidal mirror may be better able to model the effect of varying the bend radius on the erosion damage that occurs.

7.5 Conclusions

This chapter describes the model that has been developed to predict the life of a long radius pneumatic conveyor bend using the properties of the curve of aberration for a concave mirror and a basic power law erosion model. The approach adopted for the development of the model, its state at the end of the work described in this thesis, and the scope for further development have been discussed.

The combination of the simplicity and accuracy of the model should recommend the adoption of the model for practical use in the prediction of the lives of pneumatic bends in industry, but before this occurs more work is required to clarify the scope of applicability of this model.

Chapter 8

Conclusions and Further Work

8.1 Introduction

Results of the work undertaken during this project will be discussed in the light of the project objectives set out in section 1.2 of Chapter 1. Also included in this chapter is a discussion regarding further work that should be carried out to improve the understanding of particle impact erosion when applied to the wear that occurs in pneumatic conveyor bends.

8.2 Results of the Work Carried Out to Meet the Subsidiary Goals Detailed in Chapter 1

The goals outlined in Chapter 1 necessitated undertaking the following:-

i) a literature review,

ii) planning and designing the test rigs,

iii) assessing the performance of the 'rotating disc accelerator' erosion tester in comparison to that of a gas blast type tester,

iv) measuring the resistance to erosion of a mild steel commonly used in the construction of pneumatic conveyor bends in the 'rotating disc accelerator' erosion tester,

v) measuring the progress of erosion, and the factors affecting the erosion, of a bend in an industrial scale pneumatic conveyor,

vi) developing a means of predicting the life of a pneumatic conveyor bend by using data obtained from the 'rotating disc accelerator' erosion tester.

Each of these areas is covered, in turn, below.

8.2.1 Results of the Literature Review

The results of the literature review carried out to ascertain the current state of knowledge regarding erosive wear are as follows:-

1/ Very little work had been carried out concerned with linking the results obtained from laboratory erosion testers to bend wear rates seen in pneumatic conveyors. As a consequence of this, research into the separate areas of (a) erosive wear in pneumatic conveyors, and (b) erosion studies using laboratory erosion testers, was carried out.

2/ Early investigations of the life of pneumatic conveyor bends carried out by other researchers, modelled bend life empirically using values of measurable variables obtained from large scale pneumatic conveyor rigs. Later on erosion models derived from work carried out in laboratory erosion testers were combined with particle trajectory models for the gas-solid flows occurring in the pneumatic conveyor bends. Very little notice was taken of changes in particle concentration in the wear of the conveyor bends in these models.

3/ All of the erosion models proposed for pneumatic conveyor bends dictated that puncture occurred in the area of pipe wall in which the particles entering the bend struck for the first time.

4/ Several different laboratory erosion testers were found to have been used in previous work. The design and operation of these testers was assessed to see which one would be best for simulating the erosion conditions seen in pneumatic conveyors whilst operating in the most efficient manner.

8.2.2 Planning and Building the Test Rigs

As a consequence of this literature work, it was decided that the rotating disc accelerator form of erosion tester would best fill the requirement for a laboratory erosion tester. Specifications for the construction of the industrial scale pneumatic conveyor and laboratory erosion tester were derived on the basis of the understanding of erosion in pneumatic conveyors obtained from the literature. Construction of these two forms of test equipment was therefore carried out.

8.2.3 Comparing the Rotating Disc Accelerator Erosion Tester to the Gas Blast Erosion Tester

The accuracy of simulation of solid particle impact erosion in the rotating disc accelerator was compared to that of another form of erosion tester, the gas blast rig. Results from the comparisons made, indicated the importance of the frequency of inter-particulate collisions on the erosion process. In retrospect, the results obtained from this work were a forewarning of further difficulties that were to be experienced with the use of the chosen erosion testing equipment in simulating erosion processes.

8.2.4 Results from Using the Rotating Disc Accelerator Erosion Tester

Further tests on the steel that was used to form the pneumatic conveyor test bends in the rotating disc accelerator highlighted several important facets of erosion testing that had not been widely appreciated at the time these studies were begun. These were as follows:-

a) Erosion at impact angles close to 0° is the subject of dispute. It had always been assumed that erosion does not occur at an impact angle of 0°. While it is understood that the erosion rate at this angle reduces to a minimum, efforts to experimentally prove this are very few in number. Erosion rate is indeterminate at an impact angle of 0° when it is described in terms of mass or volume loss per unit mass of abrasive striking the target surface. This is because, in theory, no material strikes the target surface at this angle. Therefore, assuming an erosion rate of zero at 0° impact angle is fundamentally flawed and may have led to incorrect curve fitting occurring in previous work.

b) Results obtained from the work carried out on the rotating disc accelerator indicated the importance of intensity of particle impacts per unit area on erosion rate. Intensity of particle impacts is much more difficult to control in erosion testers than is particle velocity. This is because of the effects of the divergence of the particle jet emerging from the acceleration mechanism used. Jet divergence was found to occur as a result of impact of the particles against components of the erosion tester, and/or other particles.

c) The curves of erosion damage versus angle of impingement obtained for the structural mild steel showed no peaks. This was not what had been observed in tests carried out with similar materials by other researchers. Despite the fact that the materials used in this project would tend to shift the maxima in these curves closer to 0° than other materials, it was suggested that the main reason that no peak was seen was because of the particle dynamics occurring within the test rig used for this project.

Erosion of each target within this type of tester occurs in short cycles. During each cycle minimal inter-particulate collisions were suspected to occur because the particles rebounding from the target surface did not cross the paths of the incoming particles, especially at low angles of impingement. Inter-particulate collisions still occurred at high angles of impingement.

However, doubts concerning the actual erosion / particle conditions in the regions close to the surface of eroding targets in this rig still exist.

8.2.5 Findings From the Industrial Scale Pneumatic Conveying Test Facility

Experimental work carried out on the industrial scale pneumatic conveying facility yielded several very interesting results. As far as the author was aware, this was the first time that such a detailed investigation of the erosion of a bend in a pneumatic conveyor had been carried out. Three main conclusions were reached as a consequence of this work:-

a) Puncture of the long radius bend used in this project appears to occur in the region where particles strike the bend wall for the second time. This is in opposition to previous research which states that penetration occurs in the region of primary impacts. The reason that this should be so is that the curved internal surfaces of the conveyor bend direct the particles towards a second impact area that is much smaller in area than the region of primary impacts. This increases the intensity of particle impacts per unit area and therefore the amount of erosion that occurs in this region. The penetration of the bend wall in the region of secondary impact therefore proceeds at a faster rate than that in the primary impact area, leading to puncture at the secondary impact location as observed experimentally.

b) When the scar of erosion damage in the primary impact region of a long radius bend is studied in detail, a strong dependence on the distribution of penetration damage in the primary wear scar area with local particle distribution in the flowing suspension is observed.

c) The distribution of the particles within the pipe bore prior to entry into the bend was observed to be eccentric with the majority of the particles being present in the lower half of the pipe bore. This was felt to be due to the effects of gravity and particle shape and size on the rebound trajectories of particles after collisions with the pipe wall and / or other particles. Previous research indicates that eccentricity in the particle distribution within the pipe bore leads to a corresponding eccentricity of the local gas velocity. These facts are suspected to have a serious effect on the amount and position of erosion damage that occurs in a pneumatic conveyor bend.

8.2.6 Prediction of the Bend Life from the Laboratory Erosion Tester Results

Three groups of models were used to try and predict the life of the bend tested in the pneumatic conveyor. The findings obtained from using these models is as follows:-

a) The older empirical models are severely limited in use, simply because they are not capable of accounting for all of the variables (e.g. the geometric and material properties of the particles and the properties of the bend wall material) that are required when attempting to predict the life of pneumatic conveyor bends. This occurs because it is too time consuming and costly to carry out a wide enough series of tests to ensure that any empirical model derived from the results of these tests is generally applicable.

b) With the combined erosion / particle trajectory models used in this work, it was felt that the errors in predictive capability seen were due to the effects of inter-particulate collisions altering the intensity of particle impacts per unit area. The reason that this assertion is made is because it is suspected that the erosion models were empirically fitted to data that did not include the effects of inter-particulate collisions. However, until models of this type are modified to account for the these collisions, particle rebound and changes in the shape of the eroding surface, it is unlikely that significant progress with these models will be made.

c) Due to the fact that the particles used in this test work were insensitive to the turbulence in the gas flow surrounding them, the particle trajectories were modelled in a similar manner to light beams. As a consequence of this, it was found that some features of the wear scars observed in the test bends were similar in shape to a curve of aberration for a cylindrical mirror. From this observation, a model was derived based upon the curve of aberration for the diameter of the pipe bore. The features of this curve were used empirically to accurately predict the position of the puncture point within the secondary impact area. It was found that the combination of the model based upon the curve of aberration, and the power law erosion model derived from the results of carrying out erosion tests on the structural mild steel, could be used to predict accurately the amount of penetration damage caused in the secondary impact area for puncture to occur. Prediction of the wear rate at the puncture point was complicated by the focusing of particles caused by the internal curvature of the pipe bend. Direction of particles towards the region in which puncture was to occur led to an increase in particle impact intensity per unit area in this region. However, it was found that an estimate of the increase in particle impact intensity above that which was predicted to occur in the region of primary impact could be made using further properties of the fitted curve of spherical aberration.

8.3 Has the Work Carried Out Achieved the Goal Originally Set for this Project?

The major goal for this project was to derive a means of accurately predicting the wear life of a bend in an industrial scale pneumatic conveyor by using results obtained from a laboratory erosion tester.

A simple, easily used, means of assessing the life of a pneumatic conveyor bend, based around the curve of aberration for a cylindrical mirror, has been proposed. This method can be described as a suitable predictive tool and meets the main goal of this project. However, the amount of experimental work was limited to carrying out tests with a very specific group of materials and, as a consequence of this, much further work is required to assess the accuracy of the suggested method. Following the completion of this further work, should the proposed predictive method fail to be generally applicable, suggestions have been made in this thesis for modifying existing particle tracking / computational fluid dynamics computer programmes to improve their predictive capabilities.

8.4 Further Work

There are three areas in which further work is recommended. These are:-

1. The effects of the change in particle impact intensity on erosion rate in laboratory erosion testers needs to be investigated. Impact intensity is significantly affected by inter-particulate collisions, (i.e. a particle flux effect), particle jet divergence and the method by which the particles are accelerated in the erosion tester. Because of this, it is recommended that the particle dynamics in erosion testers are investigated in much more detail than has been carried out to date. Only when further knowledge in this area has been obtained will it be possible to simulate reliably the particle dynamics seen in the erosion of a pneumatic conveyor bend.

2. Further research in an industrial scale pneumatic conveyor at one conveying condition is recommended. The work required includes detailed examinations of the variation of local particle concentrations, particle velocity distributions and corresponding air velocity

distributions for various positions around the radius of the bend. Only by acquiring data of this sort can mathematical models of the particle dynamics in this type of bend in a pneumatic conveyor be developed further. This will enable the prediction of the erosive penetration in specific areas in the bore of the bends to be improved.

3. Erosive penetration tests on bends of different geometries using the same conveying conditions used in the work described in this project, can be used to prove the accuracy of the model of bend wear based upon the curve of aberration for a cylindrical mirror. It is suggested that this model lends itself most to use by practising engineers owing to its simplicity. However, if the model in its current form fails to be generally applicable, improvements that include modelling the curve of aberration for a toroidal mirror and using this as the basis of a predictive model have been suggested.

The investigation of wear in pneumatic conveyors should be further expanded to include the following:-

a) tests under different conveying conditions,

b) tests on various materials used to construct conveyor bends, and

c) tests with different abrasive materials.

This short list describes a large number of permutations of test options that are available for further research. Only by carrying out, and analysing results from tests for a large number of the permutations described in this list, will it be possible to economically predict the life of any given pneumatic conveyor bend.

References

[A1] Private Communication, Armour-Chelu D., University of Greenwich, London, UK, 1995.

[A2] Andrews D.R., Horsfield N., 'Particle Collisions in the Vicinity of an Eroding Surface', J. Phys D: Applied Physics, 16, (1983), 525-538.

[A3] Aghajanain M.K., Breval E., Jennings J.S. and MacMillan N.H., 'The Erosion of Abresist' , Materials Science and Engineering, 91 (1987), 257-264.

[A4] ASTM G76-83 (Reapproved 1989), 'Standard Practice for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets', American Society for Testing and Materials, 1916 Race St., Philadelpia, Pa., 19103, USA available from ANSI, 4130, Broadway, New York, NY, 10018, USA.

[A5] Anand, K., Hovis, S.K., Conrad, H. and Scattergood, R.O., 'Flux effects in solid particle erosion', Wear, 118, (1987), 243-257.

[A6] Abramov, Yu. I., 'Collision of hard dust particles with an elasto-plastic barrier', Trenie i Iznos, Vol.8, No. 1, 83-94, 1987, (UDC 620.178.3:620.178.16:669-018).

[A7] Arnold J.C. and Hutchings I.M., 'The Mechanisms of Erosion of Unfilled Elastomers by Solid Particle Impact', Wear, 138, (1990), 33-46.

[A8] Arnold J.C. and Hutchings I.M., 'A Model of the Erosive Wear of Rubber at Oblique Impact Angles', J. Phys. D: Applied Physics, 25, (1992), A 222-229.

[B1] Burnett A.J., Bingley M.S. and Bradley M.S.A, 'An Investigation of the Low Velocity/ Low Concentration Solid Particle Erosion of a Structural Mild Steel Using a Centrifugal Erosion Tester'; 5th Int'l Conf. on Bulk Materials Storage Handling and Transportation, The University of Newcastle, Australia, 10-12 July 1995, 191-198, published by The Institution of Engineers, Australia, 11 National Circuit, Barton, ACT, June 1995, ISBN 0 85825 627 4.

[B2] Bradley M.S.A., 'Pressure Losses Caused by Bends in Pneumatic Conveying Pipelines: Effects of Bend Geometry and Fittings', Powder Handling and Processing, Vol. 2, No. 4, November 1990, 315 - 321.

[B3] Buttle D.J. and Scruby C.B., 'Characterisation of Particle Impact by Quantitative Acoustic Emission', Wear, 137 (1990), 63-90.

[B4] Bahadur S. and Badruddin R., 'Erodent Particle Characterisation and the Effect of Particle Size and Shape on Erosion', Wear, 138 (1990), 189-208

[B5] Brach R.M., 'Impact Dynamics with Applications to Solid Particle Erosion', International Journal of Impact Engineering, Vol. 7, No. 1, 37-53, 1988

[B6] Brauer H. and Kreigel E., 'Verschleiss an Rohrleitungen bei hydraulischer Forderung von Festoffen Stahl und eisen, Vol. 84, October 1964, 1313-1322. Translation available: 'Wear on pipes in the hydraulic transport of solid materials', CEGB. Trans. No. 3879.

[B7] Brauer H. and Kreigel E., 'Verschleiss von rohrkrummern bein pneumatischen und hydraulischen festofftransport', Chemie-Ing-techn., Vol. 37, March 1965, 265-276.

[B8] Bikbaev F.A., Krasnov V.I., Maksimenko M.Z., Berezin V.L., Zhilinski I.B. and Otroshko N.T., 'Main Factors Affecting Gas Abrasive Wear of Elbows in Pneumatic Conveying Pipes', UDC [621.643:539.538]:621.547, translated from Khimicheskoe i Neftyanoe Mashinostroenie, No. 1, 35-36, January 1973.

[B9] Bikhaev F.A., Maksimenko V.L., Berezin V.L., Krasnov V.I. and Zhilinskii I.B., 'Wear on branches in pneumatic conveying ducting', Chemical and Petroleum Engineering, Vol. 8, May 1972, 465-466.

[B10] Burnett A.J., 'Wear in Pneumatic Conveyors: A Review of Past and Present Work', paper presented at the Proceedings of the International Symposium Attrition and Wear in Powder Technology, 12-14 October 1992, Utrecht, The Netherlands, 231-242 also published in Powder Handling and Processing, Vol. 5, No. 2, June, 1993, 123-128

[B11] J.G.A. Bitter, 'A Study of Erosion Phenomena, Part I', Wear, 6 (1963), 5-21.

[B12] J.G.A. Bitter, 'A Study of Erosion Phenomena, Part II', Wear, 6 (1963), 169-190.

[B13] Burnett A.J., De Silva S.R. and Reed A.R. 'Comparison between 'Sand Blast' and Centripetal Effect Accelerator' Erosion Testers', Proceedings of the 8th Int. Conf on Erosion by Liquid and Solid Impact, (ELSI VIII), Cambridge, UK, 4-8th September 1994, published in Wear, 186-187 (1995), 168-178.

[B14] Bradley, M.S.A. and Reed, A.R., 'An improved method of predicting pressure drop along pneumatic conveying pipelines', Powder Handling and Processing, Vol. 2, No. 3, September 1990, 223-227 ISSN 0934-7348.S20268F.

[B15] R.N. Barnes, 'Resonant Vibratory Feeders', Proc. 4th IEAust Int. Conf. on Bulk Solids Material Handling and Transportation & 7th IFPS Int. Symp. on Freight Pipelines, Wollongong, NSW, Australia, 6-8 July, 1992, 321-326, published by The Institution of Engineers, Australia, 11 NAtional Circuit, Barton, ACT, June 1992, ISBN 85825 5545.

[B16] Bellman, R. and Levy, A.V., 'Platelet mechanism of erosion of ductile metals', Wear of Materials 1981, eds. S.K. Rhee, A.W. Ruff and K.C. Ludema, 564-576, Proceedings of the Int. Conf. on Wear of Materials, San Francisco, California, March 30-April 1, 1981, The American Society of Mechanical Engineers, United Engineering Centre, 345, East 47 th St., New York, N.Y., 10017, USA

[B17] Beckmann, G. and Gotzmann, J., 'Analytical Model of the blast wear intensity of metals based on a general arrangement for abrasive wear', Wear, 73, (1981), 325-353.

[B18] BS1042: Part 2A: 1973, Pitot tubes, 2A, Class A accuracy, British Standards Institution, UDC 532.57:681.121.8 + 532.574.2:681.121.843.

[B19] Bradley M.S.A., Private Communication, University of Greenwich, London, UK, 1995.

[B20] Bradley M.S.A., PhD Thesis, 'Prediction of Pressure Losses in Pneumatic Conveying Pipelines', Thames Polytechnic, London, UK, 1990.

[B21] Barnes R.N., Private Communication, University of Greenwich, London, UK, 1995.

[B22] Bahadur S., 'The Structure of Erosive Wear Models', in 'Tribological Modelling for Mechanical Engineers', editted by Ludema K.C. and Bayer R.G., published by ASTM, Philadelphia, USA, STP 1105, 1991, 33-50.

[C1] Clift R., Grace J.R. & Weber M.E., 'Bubbles, Drops and Particles', Academic Press, New York, 1978

[C2] Campbell J.D., 'Dynamic Plasticity: Macroscopic and Microscopic Aspects', Materials Science and Engineering, 12 (1973), 3-21.

[C3] Cousens A.K. and Hutchings I.M., 'Influence of Erodent Particle Shape on the Erosion of Mild Steel', Proc. 6th Int'l Conf. on Erosion by Liquid and Solid Particle Impact, Paper 41, 5-8 Sept 1983, Cambridge, UK, ed Field J.E. and Corney N.S., Cavendish Laboratory, Cambridge, UK.

[C4] Clark H. McI., 'A Comparison of Particle Impact in Gas-Solid and Liquid-Solid Erosion', Proceedings of the 8th Int. Conf on erosion by liquid and solid impact, (ELSI VIII), Cambridge, UK, 4-8th September 1994, published in Wear, 186-187 (1995), 465-472.

[C5] Clark H. McI. and Wong K.K., 'Impact Angle, Particle Energy and Mass Loss in Erosion by Dilute Slurries', Proceedings of the 8th Int. Conf on erosion by liquid and solid impact, (ELSI VIII), Cambridge, UK, 4-8th September 1994, published in Wear, 186-187 (1995), 454-464.

[C6] Cundall P.A. and Strack O.D.L., 'A discrete numerical model for granular assemblies', Geotechnique, Vol. 29, No. 1, 47-65, (1979).

[C7] Chevallier P. and Vannes A.B., 'Effects on a Sheet Surface of an Erosive Particle Jet Upon Impact', Wear, 184 (1995), 87-91.

[C8] Cousens A.K. and Hutchings I.M., 'A Critical Study of the Erosion of an Aluminum Alloy by Solid Spherical Particles at Normal Impingement', Wear of Materials 1983: Proceedings of the International Conference on Wear of Materials, 1983, ASME, New York, NY, USA, 186-187.

[D1] Dosanhj S. & Humphrey J.A.C., 'The Influence of Turbulence on Erosion by a Particle-laden Fluid Jet', Wear, 102, (1985), 309-330.

[D2] Doyle R.A. and Ball A., 'On Thermomechanical Effects During Solid Particle Erosion', Wear, 151, (1991), 87-95.

[D3] DIN 50332, Strahlverschleiß-prűfung, DIN, Berlin, 1984, ('Solid Particle Erosion Test; Basic Rules'.)

[E1] Ellermaa R.R.R., 'Erosion Prediction of Pure Metals and Carbon Steels', Wear, 162-164 (1993), 1114-1122.

[E2] Engel, P.A., 'Impact Wear of Materials', Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, 1976, 106-111.

[E3] Evans A.G., 'Impact Damage Mechanics: Solid Projectiles', Treatise on Materials Science and Technology, edited by Preece C., published by Academic Press, New York, USA, 1979, Vol. 16, 1-67.

[E4] Etter D.M., 'Fortran 77 with Numerical Methods for Engineers and Scientists', Benjamin / Cummings Publishing Co. Inc., 390, Bridge Parkway, Redwood City, California 94065, USA, 1992 ISBN 0-08053-1770-8, 538-540.

[F1] Flemmer C.L., Flemmer R.L.C., Johnson E.K. and Means K.H., 'Roping Paths in Elbows', ASME Pressure Vessels and Piping Division Publication PVP v. 193, 'Damage Assessment, Reliability and Life Prediction of Power Plant Components, 1990, Pressure Vessels and Piping Conference, Nashville, TN, USA, June 17-21, 1990, Published by ASME, New York, NY, USA, 1990, 105-109.

[F2] Finnie I., 'Erosion of Surfaces by Solid Particles', Wear, 3 (1960), 87-103.

[F3] Finnie I., Stevick G.R. and Ridgely J.R., 'The Influence of Impingement Angle on the Erosion of Ductile Metals by Angular Abrasive Particles', Wear, 152 (1992), 91-98.

[F4] Flemmer C.L., Flemmer R.L.C., Means K. and Johnson E.K., 'The Erosion of Pipe Bends', ASME Pressure Vessels and Piping Conference, Pittsburgh, June 1988, 139/193-98, 1745.2079, v 138, 1988.

[F5] Finnie I., 'The Mechanism of Erosion of Ductile Metals', ed. R.M. Haythornewaite, U.S. National Congress of Applied Mechanics, Providence, RI, USA, June, 1958, 527-532.

[F6] Fox, J.A., 'An Introduction to Engineering Fluid Mechanics', 2nd edition, MacMillan, London, 1985, 198.

[F7] Finnie I., 'Some Observations on the Erosion of Ductile Metals', Wear, 19, (1972), 81-90.

[G1] GOST 23201.078 (Standard of the former soviet union appertaining to centripetal accelerator erosion testers), Russian Federation State Commitee for Standardization, Metrology and Certification, Leninsky Prospekt 9, Moskva 117049, Russia.

[G2] Goodwin J.E., Sage Miss W. and Tilly G.P., 'Study of Erosion by Solid Particles', Proceedings of the Institution of Mechanical Engineers, 1969-70, Vol. 1984, Part 1, 279-292.

[H1] Humphrey J.A.C., 'Fundamentals of Fluid Motion in Erosion by Solid Particle Impact', Int'l J. of Heat and Mass Transfer, Vol 11, No 3, Sept 1990

[H2] Huber N and Sommerfeld M., 'Characterisation of the cross-sectional particle concentration distribution in pneumatic conveying systems', Powder Technology, 79, (1994), 191-210.

[H3] Hutchings I.M., 'Strain Rate Effects in Microparticle Impact', Journal of Physics D: Applied Physics, Vol. 10, 1977, 151 onwards, L179-L184.

[H4] Hutchings I.M., 'Mechanisms of Wear in Powder Technology', Keynote lecture, Proceedings of the International Symposium on Attrition and Wear in Powder Technology, 12th-14th October 1992, Utrecht, The Netherlands, 1-17.

[H5] Hutchings I.M., 'Mechanical and Metallurgical Aspects of the Erosion of Metals', Proceedings of the Corrosion-Erosion of Coal Conversion Systems, EM Materials Conference, 1979, NACE, Houston, Texas, USA, 393-428.

[H6] Hutchings I.M., 'Prediction of the Resistance of Metals to Erosion by Solid Particles', Wear, 35 (1975), 371-374.

[H7] Hutchings I.M and Levy A.V., 'Thermal Effects in the Erosion of Ductile Metals', Wear, 131 (1989), 105-121.

[H8] Hoadley D. and Johnson T.D., 'The Influence of Flow and Particle Size on Pipe Work Erosion', Paper presented to the EPRI Coal Pulveriser Symposium, 13-15, November 1985, Denver, Colorado, USA.

[H9] Hoadley D. and Johnson T.D., 'A practical method for assessing the wear life of pipe bends', Proc. 7th Int. Conf. on Erosion by Liquid and Solid Impact, 1983, Cambridge, UK, paper 76.

[H10] Hilgraf P. and Cohrs H., 'The Practicability of the YPG Erosion Tester for the Determination of Erosion in Pneumatic Conveying Systems', Powder Handling and Processing, Vol. 4., No. 2, June 1992, 189-197.

[H11] Hutchings, I.M. and Winter, R.E., 'Particle Erosion of Ductile Metals: A Mechanism of Material Removal', Wear, 27, (1974), 121-128.

[H12] Horowitz P. and Hill W., 'The Art of Electronics', 2nd Edition, Published by Cambridge University Press,, 32 East 57th St., New York, NY 10022, USA, 1989.

[H13] Hutchings I.M. and Winter R.E., 'The Erosion of Ductile Metals by Spherical Particles', Journal of Physics D: Applied Physics, Vol. 8, 1975, 8-14.

[H14] Hutchings I.M., 'Mechanisms of the Erosion of Metals by Solid Particles', 'Erosion Prevention and Useful Applications', edited by Adler W.F., ASTM, Philadelphia, USA, Special Technical Publication 664, 1979, 59-76.

[H15] Hutchings I.M. and Winter R.E., 'Particle Erosion of Ductile Metals: A Mechanism of Material Removal', Wear, 27 (1974), 121-128.

[H16] Hutchings I.M, ' A Model for the Erosion of Metals by Spherical Particles at Normal Incidence', Wear, 70 (1981), 269-281.

[H17] Hammarsten Å., Söderberg S. and Hogmark S., ' Study of Erosion Mechanisms by Recovery and Analysis of Wear Fragments', Wear of Materials 1983: Proceedings of the International Conference on the Wear of Materials, 1983, 373-381, published by ASME, New York, NY, USA.

[H18] Hutchings I.M., 'Tribology: Friction and Wear of Engineering Materials', Edward Arnold Publishers, London, UK, 1992, ISBN 0-340-56184-X.

[H19] Hockey B.J. and Weiderhorn S.M., 'Erosion of Ceramic Materials: The Role of Plastic Flow', Proceedings of the 5th Int. Conf. on Erosion by Liquid and Solid Impact, (ELSI V), Cambridge, UK, 3-6th Sept 1979, paper 26, published by the Cavendish Laboratory, Cambridge, UK.

[H20] Hutchings I.M., 'Transistions, Threshold Effects and Erosion Maps', 'Erosion of Ceramic Materials', Edited by Ritter J.E., TransTech Publications, Switzerland, Key Engineering Materials Series, Vol 71, (1992), 75-92.

[H21] Hashish M., 'An Improved Model of Erosion by Solid Particle Impact', Proceedings of the 7th Int. Conf. on Erosion by Liquid and Solid Impact, (ELSI VII), Cambridge, UK, 7-10th Sept 1987, paper 66, 1-8, edited by Field J.E. and Dear J.P., published by Cavendish Laboratory, Cambridge, UK.

[H22] Hitt R.J., PhD Thesis, 'An Investigation into Low Velocity Pneumatic Conveying', Thames Polytechnic, London, UK, 1985.

[J1] Johnson T.D., Low M.B.J., Parry M. and Wall D.J., 'Pulverised fuel system erosion', Paper presented to the EPRI Coal Pulveriser Symposium, 13-15, November 1985, Denver, Colorado, USA.

[J2] Johnson T.D., Low M.B.J., Parry M.T. and Wall D.J., 'Erosion in pulverised fuel distribution systems: materials selection and plant performance', Proc. 7th Int. Conf. on Erosion by Liquid and Solid Impact, 1983, Cambridge, UK, paper 74.

[J3] Jakobsen M.L., McClusky D.R., Easson W.J., Glass D.H. and Greated C.A., 'Pneumatic Conveyance in Pipe Bend: Simultaneous Two Phase PIV Measurements of the Slip Velocity Between the Air and the Particle Phases', 7th International Symposium on the Application of Laser Techniques to Fluid Mechanics, 1994, Lisbon, Portugal, 31.4.1 - 31.4.5.

[K1] Kliafas Y., Holt M., 'LDV Measurements of a Turbulent Air-Solid Two-Phase Flow in a 90° Bend', Experiments in Fluids 5, 73-85, 1987.

[K2] Kosel T.H., 'Improved Model for Impact of Spherical Particles on Metals', 1987, contact author at University of Notre Dame, Notre Dame, IN, USA.

[K3] Kosel T.H., Kotteyil M., Anand K. and Sundararaman V, 'A Model for the Impact of Angular Erodent Particles', presented at the 8th Int. Conf. on Erosion by Liquid and Solid Impact, (ELSI VIII), Cambridge, UK, 4-8th September 1994.

[K4] Kriegel E., 'Der strahlverschleiss von Werkstoffen', Chemie-Ing-Techn., Vol. 40, 1968, 31-36

[K5] Kreigel E., 'Druckverlust unf verschleiss in rohrkrummern bei pneumatiscehn transport', Verfahrens Technik, Vol. 4, August 1970, 333-339. Title Translation:- 'Pressure loss and wear in pipe bends during pneumatic conveying'.

[K6] Kleis I.R., Uuemois H.H., Uksti L.A. and Pappel T.A., 'Centrifugal Accelerators for Erosion Research and Standard Wear Testing', Proceedings of the International Conference on the Wear of Materials, Dearborn, Michigan, April 16th-18th, 1979, ASTM, 212-218.

[K7] Krishnamoorthy P.R. and Seetharamu S., 'The wear life of pipe bends and other components under pulverised coal erosion', Proceedings of the Workshop on Wear and Erosion of Materials in Thermal Power Stations, December, 7-8th 1989, Central Power Research Institute, Prof. Sir C.V. Raman Rd., Bangalore -560 012, India, paper 2G, pages 1-9.

[K8] Krishnamoorthy P.R., Seetharamu S. and Sampathkumaran P., 'Influence of the mass flux and impact angle of the abrasive on the erosion resistance of materials used in pulverised fuel bends and the other components in thermal power stations', Wear, 165 (1993), 151-157.

[K9] Kleis, I.R. and Uuemois, H.H., 'A critical analysis of erosion problems that have been little studied', Wear, 31, (1975), 359-371.

[K10] Kosel, T.H. and Anand, K., 'An optoelectronic erodent particle velocimeter', in V. Srinivasan and K. Vedula (eds.), Corrosion and Particle Erosion at High Temperature, The Minerals, Metals and Materials Society, 1989, 349-368.

[K11] Kleis, I., 'Probleme der bestimmung des strahlverschleisses bei metallen', Wear, 13, (1969), 199-215, (in German).

[K12] Koller D.W. MacMillan N.H., 'Hardness Measurements Adjacent to Eroded Surface of Ductile Ferrous Alloys', Materials Characterisation, Vol. 24, (1990), 115-134.

[L1] Leibhard M. & Levy A.V., 'The Effect of Erodent Particle Characteristics on the Erosion of Metals', Proceedings of the Int'l Conf. on the Wear of Materials, ASME, New York, NY, USA, 1991, 123-127, edited by Ludema K.C. and Bayer R.G.

[L2] Lourenco L.M., Riethmuller M.L. & Essers J.A., 'The Kinetic Model for Gas-Particle Flows and its Numerical Implementation', International Conference on the Physical Modelling of Multi-Phase Flow, Coventry, UK, April 1983, Edited by Stephens H.S., and Stapleton C.A., Cranfield, BHRA, Fluid Eng., 1983.

[L3] 'The 1st Special Report on: Abrasion-Resistant and Low Friction Linings', Loadstar Publications, 77a, High Rd., Willesden Green, London, NW10 2SU, 1988.

[L4] Levy A.V., 'The Effect of Material Properties on Erosion Behaviour', Mechanical Properties and Phase Transformations in Engineering Materials, Earl R. Parker Symposium on Structure Property Relationships, eds. Antolovich S.D., Ritchie R.O. and Gerberich W.W., AIME TMS AGM, New Orleans, March 1986.

[L5] Levy, A.V. and Chik, P., 'The effects of erodent composition and shape on the erosion of steel', Wear, 89, (1983), 151-162.

[L6] Levy A.V., 'The Effect of Materials Properties on Erosion Behaviour', Mechanical Properties and Phase Transformations in Engineering Materials, Earl R. Parker Symposium on Structure Property Relationships, edited by Antolovich S.D., Ritchie R.O. and Gerberich W.W., ASME TMS AGM, New Orleans, March 1986, ISBN 0-87339-012-1.

[L7] Li J. and Hutchings I.M., 'Resitance of Cast Polyurethane Elastomers to Solid Particle Erosion', Wear of Materials 1989; Proceedings of the International Conference on Wear of Materials, 1989, published by ASME, New York, NY, USA, ed. Ludema K.C., 109-114.

[M1] Mills D., 'Erosive Wear Problems in Industry with Particular Reference to Process Plant, Power Stations and Bulk Solids Handling Systems', Workshop Notes, presented at the SOLIDEX 86 conference and exhibition, Harrogate, June, 1986.

[M2] Mi B. & Wypych P., 'Pressure Drop Prediction in Low-Velocity Pneumatic Conveying', Powder Technology, 81 , (1994), 125-137.

[M3] Mason J.S., PhD Thesis, Liverpool Polytechnic, Liverpool, UK, 1972.

[M4] Mason J.S. and Smith B.V., 'The Erosion of Bends by Pneumatically Conveyed Suspensions of Abrasive Particles', Powder Technology, Vol. 6, 1973, 323-335.

[M5] Mason J.S and Smith B.V., 'Pressure Drop and Flow Behaviour for the Pneumatic Transport of Fine Particles Around Ninety Degree Bends', Proceedings of Pneumotransport 2., BHRA Conference, Guildford, Surrey, 1973, Paper A2.

[M6] Mason J.S., Arundel P.A., Taylor I.A., Dean W. and Doran T.E., 'The Rapid Erosion of Various Pipe Wall Materials by Stream of Abrasive Alumina Particles', Proceedings of Pneumotransport 2., BHRA Conference, Guildford, Surrey, 1973, Paper E1.

[M7] Mills D. and Mason J.S., 'The Erosive Wear of Hardened and Tempered Steels in Pneumatic Conveying System Pipelines', Proceedings of the 7th Int. Conf on Erosion by Liquid and Solid Impact, 7-10 Sept 1987, Cambridge, UK, paper 81, 1-6, ed. Field J.E. and Dear J.P., published by Cavendish Laboratory, Cambridge, UK.

[M8] Mills, D., Mason, J.S., and Tong, K.N., 'The Role of Penetrative Wear in the Erosion of Pipe Bends', Proc. 6th Int. Conf. on Erosion by Liquid and Solid Impact, Paper 58, 5th-8th Sept 1983, Cambridge, UK, ed. Field J.E. and Corney N.S., published by Cavendish Laboratory, Cambridge, UK.

[M9] Mills, D. and Mason, J.S., 'The Influence of Velocity on the Erosive Wear of Pipe Bends in Pneumatic Conveying Systems', Proc. Int. Conf. on Powder and Bulk Solids Handling and Processing, Philadelphia, Pennsylvania, USA, 1986.

[M10] McClusky, D.R., 'An Optical Investigation of Air Particle Flows', PhD Thesis, University of Edinburgh, Scotland, UK, 1992.

[M11] Misra A. & Finnie I., 'An Experimental Study of Three-Body Abrasive Wear', Wear of Materials 1981, edited by S.K. Rhee, A.W. Ruff and K.C. Ludema, 426-431, Proceedings of the Int. Conf. on Wear of Materials, San Francisco, California, March 30-April 1, 1981, The American Society of Mechanical Engineers, United Engineering Centre, 345, East 47 th St., New York, N.Y., 10017, USA.

[M12] Moffat J, Malin M.R. and Pericleous K.A., 'A Users Guide to "GENTRA", A General Particle Tracking Program, Part 1: Regular Grids', CHAM Internal Report TR/211a, March 1989, CHAM Ltd., 40, High St., London, SW 19 8AU, UK.

[M13] Mills D. and Mason J.S., 'Conveying Velocity Effects in Bend Erosion', Journal of Pipelines, 1, (1981), 69-81.

[M14] Mark's Standard Engineering Handbook for Mechanical Engineering, edited by Avallone E.A. and Baumeister III T., McGraw Hill Publishers, New York, NY, USA, 1987, ISBN 0-07-004127-X, table 3.2.1 page 3-26.

[M15] Marei A.I. and Izvozchikov P.V., 'Determination of the Wear of Rubbers in a Stream of Abrasive Particles', Abrasion of Rubber, published by McLaren , London, 1967, 274-280.

[N1] Mainwaring N.J., 'The Effect of the Physical Properties of Bulk Solid Materials on Modes of Dense Phase Pneumatic Conveying', PhD Thesis, Thames Polytechnic, Woolwich, London, UK, 1988.

[N2] Neilson J.H. and Gilchrist A., 'An Experimental Investigation into Aspects of Erosion in Rocket Tail Nozzles', Wear, 11, (1969) 123-143.

[N3] Ninham, A.J. and Hutchings, I.M, 'A Computer Model for Particle Velocity Calculation in Erosion Testing', Proc. 6th Int. Conf. on Erosion by Liquid and Solid Impact, Cambridge, UK, 5th-8th Sept 1983, paper 50, ed. Field J.E. and Corney N.S., published by Cavendish Laboratory, Cambridge, UK.

[N4] Neilson, J.H., and Gilchrist, A., 'Erosion by a stream of solid particles', Wear, 11, (1968), 111-122.

[O1] Oesterle B. and Petitjean A., 'Simulation of particle-to-particle interactions in gas-solid flows', International Journal of Multiphase Flow, Vol. 19, No. 1, 199-211, (1993).

[P1] Peterson B., Rishel D.M., Birks N., and Pettit F.S., 'The Development of Surface Features on Nickel During Erosion-Corrosion', ELSI VIII, Proceedings of the 8th International Conference on Erosion by Liquid and Solid Particle Impact, 4th-8th September 1994, Cambridge, UK, Published in Wear, 186-187 (1995), 56-63.

[P2] Prandtl L., 'Essentials of Fluid Dynamics; With Applications to Hydraulics, Aeronautic, Metrology and Other Subjects', Authorized Translation, Blackie and Son Ltd., London, UK, 1952.

[P3] Patankar S.V. and Spalding D.B., 'A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-Dimensional Parabolic Flows', International Journal of Heat and Mass Transfer, Vol. 15, 1787-1806, (1972).

[P4]. Patankar S.V., 'Numerical Heat Transfer and Fluid Flow', Hemisphere Publishing Corporation, New York, NY, USA, (1980).

[P5] Patel M.K., Private Communication, University of Greenwich, London, UK, 1995.

[P6] Ponnaganti V., Stock D.E. and Sheldon G.L., 'Measurement of Particle Velocities in Erosion Processes', Symposium on Polyphase Flow and Transport Technology, edited by Bajura R.A., ASME, New York, NY, USA, Century 2 - Engineering Technology Conferences, 1980, 217-222.

[R1] Raask E., 'Erosive Wear in Coal Utilisation Plants', published by Hemisphere, New York, USA, 1988.

[R2] Ratner S.B. and Styller E.E., 'Characteristics of Impact Friction and Wear of Polymeric Materials', Wear, 73 (1981), 213-234

[R3] Ruff, A.M. and Ives, L.K., 'Measurement of solid particle velocity in erosive wear', Wear, 35, 1975, 195-199.

[R4] Ruff, A.W. and Weiderhorn, S.M., 'Erosion by solid particle impact', Treatise on Materials Science and Technology, Vol. 16., edited by Preece C., Academic Press, New York, 1979, 69-126.

[R5] Rickerby, D.G. and MacMillan, N.H, 'Erosion of aluminium and magnesium oxide by spherical particles', Wear of Materials 1981, eds. S.K. Rhee, A.W. Ruff and K.C. Ludema, 548-563, Proceedings of the Int. Conf. on Wear of Materials, San Francisco, California, March 30-April 1, 1981, The American Society of Mechanical Engineers, United Engineering Centre, 345, East 47 th St., New York, N.Y., 10017, USA.

[R6] Rosten H.I. and Spalding D.B., 'The PHOENICS Beginners Guide', CHAM TR/200, CHAM Ltd., 40, High St., London, SW 19 8AU, UK, (1987).

[R7] Ruff A.W., ' Debris Analysis of Erosive and Abrasive Wear', Proceedings of the International Conference on Tribology, MIT, Cambridge, Massachusset, MA, USA, June 19-22, 1978, 877-885.

[R8] Rickerby D.G. and MacMillan N.H., 'On the Oblique Impact of a Rigid Sphere Against a Rigid Plastic Solid', International Journal of Mechanical Science, Vol. 22, Pergammon Press Ltd., UK, 491-494.

[S1] Svarovsky L., 'Solid and Liquid Separation', 2nd ed., Butterworths, London, UK, 1986, ISBN 0-408-70943-X.

[S2] Schuster T., Bradley M.S.A and Reed A.R. 'The Dependence of Power Consumption of Pneumatic Conveying Systems Upon Bulk Materials Properties, Pipeline Bore and Routing, and Mode of Flow', Proceedings of the Institution of Mechanical Engineers; Part E: Journal of Process Mechanical Engineering, 1995, Vol. 209, No. E1, 69-75, published by MEP, Edmunds, England.

[S3] Sundarajan G., 'A Comprehensive Model for the Solid Particle Erosion of Ductile Materials', Wear, 149 (1991), 111-127.

[S4] Shimoda K. and Yukawa T., 'Erosion of Pipe Bend in Pneumatic Conveyor', Proc. 6th Int. Conf. on Erosion by Liquid and Solid Impact, Cambridge, UK, 5th-8th Sept 1983, paper 59, ed. Field J.E. and Corney N.S., published by Cavendish Laboratory, Cambridge, UK.

[S5] Shimizu A., Yagi Y., Yoshida H. and Yokomine T., 'Erosion of Gaseous Suspension Flow Duct due to Particle Collision (I), Experimental Determination of Erosion Rate by Individual Collision', Journal of Nuclear Science and Technology, 30 (9), 881-889, September 1993.

[S6] Sato. S, Shimizu A. and Yokomine T., 'Numerical Prediction of Erosion for Suspension Flow Duct', Presented at the 8th International Conference of Erosion by Liquid and Solid Impact, Cambridge, England, Sept. 4-8 1994, published in Wear, 186-187 (1995), 203-209.

[S7] Salman A.D., Gorham D.A. and Verba A., 'A Study of Solid Particle Failure under Normal and Oblique Impact', Presented at the 8th International Conference of Erosion by Liquid and Solid Impact, Cambridge, England, Sept. 5-8 1994, published in Wear, 186-187 (1995), 92-98.

[S8] Söderberg S., Hogmark S., Engman U. and Swahn H., 'Erosion Classification of Materials Using a Centrifugal Erosion Tester', Tribology International, 14 (6), December, 1981, 333-343.

[S9] Stevenson, A.N.J., and Hutchings, I.M., 'Scaling Laws for Particle Velocity in the Gas-Blast Erosion Test', Wear, 181-183, (1995), 56-62.

[S10] Soo, S.L. and Regalbuto, J.A., 'Concentration Distribution in Two-Phase Pipe Flow', The Canadian Journal of Chemical Engineering, October, 1960, 160-166.

[S11] Shipway, P.H., and Hutchings, I.M., 'A Method for Optimising the Particle Flux in Erosion Testing with a Gas-Blast Apparatus', Wear, 174, 1994, 169-175.

[S12] Sheldon, G.L., 'Similarities and Differences in the Erosion Behaviour of Materials', presented at the Winter Annual Meeting of the Metals Engineering Division, Los Angeles, California, November 16-20, 1969, Transactions of the American Society of Mechanical Engineers, Paper No.69-WA/Met-7, Journal of Basic Engineering, September 1970, 619-626.

[S13] Salik, J. and Buckley, D.H., 'Effect of Mechanical Surface and Heat Treatments on Erosion Resistance', International Conference on the Wear of Materials, 1981, eds. S.K. Rhee, A.W. Ruff and K.C. Ludema, 592-596, Proceedings of the Int. Conf. on Wear of Materials, San Francisco, California, March 30-April 1, 1981, The American Society of Mechanical Engineers, United Engineering Centre, 345, East 47 th St., New York, N.Y., 10017, USA.

[S14] Soo S.L., 'Fluid Dynamics of Multiphase Systems', Blaisdell Publishing Company, Waltham, Massachussets, USA, 1967, 162 - 180.

[S15] Selves T.P., 'Analysis and Control of Splitting Ratios of Particulate Materials at Bifurcation's in Pneumatic Conveying Pipelines', PhD Thesis, University of Greenwich, London, UK, 1995

[S16] Sundararajan G., 'The Differential Effect of the Hardness of Metallic Materials on their Erosion and Abrasion Resistance', Wear, 162-164 (1993), 773-781.

[S17] Sparks A.J. and Hutchings I.M., 'Transistions in the Erosive Wear Behaviour of a Glass Ceramic', Wear, 149 (1991), 99-110.

[S18] Sriram T.S. and Kosel K.H., 'Computer Modelling of the Rebound Characteristics of Spherical Erodent Particles', Proceedings of the 7th International Conference on Erosion by Liquid and Solid Particle Impact (ELSI VII), Cambridge, UK, 10th-17th, September 1987, paper 67, 1-7.

[S19] Swallowe G.M., Field J.E. and Horn L.A., 'Measurements of Transient High Temperatures During the Deformation of Polymers', Journal of Materials Science, 21 (1986), 4089-4096.

[T1] Tilly G.P., 'A Two Stage Mechanism of Ductile Erosion', Wear, 23 (1973), 87-96.

[T2] Tsuji Y., Morikawa Y., Tanaka T., Nakatsukasa N. and Nakatani M., 'Numerical Simulation of Gas-Solid Two-Phase Flow in a Two-Dimensional Horizontal Channel', International Journal of Multiphase Flow, Vol. 13, No. 5, 671-684, 1987.

[T3] Tsuji Y., Shen N.Y. and Morikawa Y., 'Lagrangian Simulation of Dilute Gas-Solid Flows in a Horizontal Pipe', Advanced Powder Technology, Vol. 2, No. 1, 63-81, 1991.

[T4] Timoshenko, S. and Goodier, J.N., 'Theory of Elasticity', (3rd ed.), (1970), McGraw-Hill Book Publishers, New York, USA, 409.

[T5] Tsuji Y., Shen N.Y. and Morikawa Y., 'Numerical Simulation of Gas-Solid Flows. I - Particle-to-Wall Collision', Technology Reports of the Osaka University, Vol. 39, No. 1975, (October, 1989), 233-241.

[T6] Tsuji Y., 'Discrete Particle Simulation of Gas-Solid Flows (from Dilute to Dense Flows)', KONA, No. 11, (1993), (Powder and Particle, The Council of Powder Technology of Japan), 57-68.

[T7] Tirupataiah Y., Venkataranain B. and Sundararajan G., 'The Nature of Elastic Rebound of a Hard Ball Impacting on Ductile, Metallic Target Materials', Materials Science and Engineering, A124 (1990), 133-140.

[T8] Trilok S., Tiwari S.N. and Sundararajan G., 'Room Temperature Erosion Behaviour of 304, 316 and 420 Stainless Steels', Wear 145 (1991), 77-100.

[T9] Tilly G.P., 'Erosion Caused by Impact of Solid Particles', Treatise on Materials Science and Technology, Vol. 13, edited by Preece C., Academic Press, New York, USA, 1979, 287-319.

[U1] Uetz H. and Gommel, 'Temperaturerhöhung und elektrische aufladung beim stoss einer stahlkugel gegen eine stahlplatte', Wear, 9 (1966), 282-296, (in German).

[U2] Pneumatic Conveying Short Course Notes, University of Greenwich, London, UK, 1995.

[V1] Veerabhadra Rao P., Young S.G. and Buckley D.H., 'Morphology of ductile metals eroded by a jet of spherical particles impinging at normal incidence', Wear, 85, (1983), 223-237.

[V2] Vaughan R.A. and Ball A., 'The Effect of Hardness and Toughness on the Erosion of Ceramic and Ultra-Hard Materials', Proceedings of the International Conference on Wear of Materials, 1991, Orlando, Florida, USA, 7th-11th April 1991, published by ASME, New York, USA, 71-75.

[W1] Walley S.M. and Field J.E., 'The Erosion and Deformation of Polyethylene by Solid Particle Impact', Philosophical Transactions of the Royal Society London, A 321, 277-303, (1987).

[W2] Woodhead, S.R., 'The Measurement of Particle Velocity and Suspension Density in Pneumatic Coal Injection Systems', PhD Thesis, The University of Greenwich, London, UK, 1992.

[W3] Wellinger, K. and Uetz, H., 'Gleit-, Spül -, und Strahlverschleiss-prüfung', Wear, Vol. 1, (1957/58), 225-231, (in German).

[W4] Walton O.R., 'Numerical Simulation of Inelastic Frictional Particle-Particle Interactions', Chapter 25, 884-911, 'Particulate Two-Phase Flow', edited by M.C. Roco, Butterworth Heineman, 80, Montvale Avenue, Stoneham, Boston, MA, 02180, USA, (1993).

[W5] Walley S.M., Field J.E. and Yennadhiou, 'Single Solid Particle Impact Erosion Damage on Polypropylene', Wear, 100 (1984), 263-280.

[W6] Walley S.M., Field J.E., Scullion I.M., Heukensfeldt-Jansen F.P.M. and Bell D., 'Dynamic Strength Properties and Solid Particle Erosion Behaviour of a Range of Polymers', Proceedings of the 7th Int. Conf. on Erosion by Liquid and Solid Impact (ELSI VII), 7-10 Sept 1987, ed. Field J.E. and Dear J.P., published by Cavendish Laboratory, Cambridge, UK.

[Y1] Yeung W.S., 'Erosion in a Curved Pipe', Wear, 55 (1979), 91-106.

[Y2] Yang Z.Y., Preistman G.H. and Boysan H.F., 'Internal Flow Modelling of Vortex Throttles', Proceedings of the Institution of Mechanical Engineers, Vol. 205, No. C6, 1991, 405-513.