AEROSOL CONTAMINATION OF CLEAN GASES IN TUBES AND VALVES

by: L.D. Arnold B.Sc.

A Master's Thesis submitted in partial fulfilment
of the requirements for the award of
Master of Philosophy
of the Loughborough University of Technology

Date: May 1991

Supervisor: Dr. J.I.T. Stenhouse
Department of Chemical Engineering

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ABSTRACT

Ultra clean process gases containing a very low level of particulate contamination are required in many industrial applications. This is particularly true in the Integrated Circuit industry, where considerable care is taken in the installation of gas delivery systems to clean rooms. However, virtually no quantitative information is available on the release of aerosol particles from the components which comprise such systems. An experimental programme was undertaken to assess the level of particle shedding from tubes and valves.

The extent of particle release from new 'as delivered' tubes was determined first. This will be strongly related to the method of cleaning prior to delivery and will not necessarily reflect the behaviour after purging. To assess longer term behaviour, known quantities of fine particulates were intentionally deposited on the internal tube surfaces. Clean gas was then passed through and the contamination in the outlet measured. The effect of internal surface on aerosol re-entrainment was thus determined. The influence of tube fittings and bends was examined. The quantitative effect of the major operating variables including gas velocity and mechanical shock were measured. The mechanisms responsible for particle re-entrainment are discussed.

It was determined that in the as delivered state that there was less particulate entrainment from the electropolished tubing. However, once particles had been deposited in the tubes there was no detectable difference between the different types of tubing -

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A range of different types of valves, from different manufacturers, was tested when they were fully or partly open. Clean air was passed through them and the level of contamination in the exhaust measured. This reflects the level of cleanliness

this was confirmed by a long term nitrogen test.

A range of surface finished tubes up to a 50μinch RA were examined. Roughness was shown to be a significant factor, sharply increasing in the contamination released for the poorer surfaces examined. However, below a roughness of 10μinch Ra the effect is not significant - the surface finishes used in th integrated circuit industry are typically below this level.

A range of different types of valves, from different manufacturers, was tested when they were fully or partly open. Clean air was passed through them and the level of contamination in the exhaust measured. This reflects the level of cleanliness of the valve in the 'as delivered' state. The effect of repeatedly opening and closing the valves was then determined. The initial test on fully open or partly open valves was then repeated.

The results showed that there were significant differences not only between the design types but also between those produced by different manufacturers, reflecting individual variations in design, cleaning and assembly procedures. Thus it can be concluded that attention to manufacturing processes especially cleaning and clean assembly leads to cleaner components. Also consideration of particulate generation mechanisms during use, such as wear, flexure and a reduction of area exposed to the process gases, should lead to the design of more suitable components.

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ACKNOWLEDGEMENTS

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The author wishes to thank in particular her supervisor, Dr. J.I.T. Stenhouse, for his timely encouragement and for reading this manuscript and providing much helpful advice.

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CHAPTER ONE

INTRODUCTION

The particulate contamination of gases used in the integrated circuit industry, and the control of contamination, forms a very broad and complex topic. A research programme on the entrainment of particulates from new components, the deposition of aerosols into these components and their subsequent re-entrainment was instigated as part of an overall CERCCON programme. CERCCON is the Centre for Engineering Research into Contamination Control and has three research programmes running in parallel. It was set up to provide independent research into how contamination within the semiconductor and biochemical industries could be minimised. The research to be discussed in this thesis concerns the gaseous programme.

1.1 AIMS OF THE RESEARCH

Ultra clean process gases containing a very low level of particulate contamination are required in many industrial applications. This is particularly true in the the Integrated Circuit industry, where considerable care is taken in the installation of gas delivery systems to clean rooms. It is generally considered that high quality components with smoothly finished internal surfaces should be used to achieve this. However, limited quantitative information is available on the effects of either the specific type of finish or the process variables on the level of contamination produced. This thesis

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The research was undertaken in three main sections:

1) As an initial stage of this work a search of the literature has been carried out. It is necessarily limited in its scope to those aspects which are relevant to the project.

2) To assess the effect of internal finish of straight tubes on the production of gas-borne particulate contamination. Electropolished, as drawn and chemically cleaned systems have been tested.

3) To assess the level of particle shedding from a range of valves.

1.2 Experimental Research

1.2.1 Internal Finish of Straight Tubes

The extent of particle release from new 'as delivered' tubes was determined first. The aim of this was to assess the level of particulate contamination in process gases arising from the tubes in their 'as delivered' state prior to installation. This will be strongly related to the method of cleaning prior to delivery and will not necessarily reflect the behaviour after purging.

To assess the longer term behaviour, known quantities of fine particulates were intentionally deposited on the internal tube surfaces. Clean gas was then passed through and the contamination in the outlet measured. It was hoped thus to isolate the effect of internal surface on aerosol pick-up (re-entrainment).

Of necessity, the tests described above were of a short duration. In an attempt to validate the findings and also to simulate closely actual process conditions, ten tubes were exposed to a long term dry nitrogen purge. the tubes were tested individually at monthly intervals for signs of particulate release to determine whether or not the tube characteristics change with time.

1.2.2 Valves

There have been few papers giving quantitative information on the release of aerosol particles from components other than tubes which comprise gas delivery systems. An experimental programme was thus undertaken to assess the level of particle shedding from valves.

A range of different types of valves, from different manufacturers, was tested when they were fully or partly open. Clean air was passed through them and the level of contamination in the exhaust measured. This of course reflects the level of cleanliness in the 'as delivered' state. The effect of repeatedly opening and closing the valves was then determined. The initial test on fully open or partly open valves was repeated.

1.3 CONTENTS

A brief description of the following chapters are included to allow an introductory overview of this thesis.

Chapter 2 contains a review of the available literature. It was necessarily limited in its scope to those aspects which are (re-entrainment).

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A brief description of the following chapters are included to allow an introductory overview of this thesis.

Chapter 2 contains a review of the available literature. It was necessarily limited in its scope to those aspects which are relevant to the project. Sampling or aspiration of aerosols for characterisation purposes is extremely important in any investigation so is reported first. Deposition in tubes, bends and obstructions and aerosol re-entrainment forms the main text of this Chapter.

Chapter 3 explains how the experimental rig and the surrounding clean area were developed.

Chapter 4 includes the experimental details and results of the work carried out on the straight tubes.

Chapter 5 includes the experimental details and results of the work carried out on the valves.

Chapter 6 sets out the conclusions reached from the experimental results on the straight tubing and valves.

CHAPTER TWO

LITERATURE SEARCH

2.1 INTRODUCTION

The particulate contamination of gases used in the integrated circuit industry, and the control of contamination, forms a very broad and complex topic. A research programme on the deposition of aerosols in components and in their re-entrainment was instigated as part of an overall programme. An initial stage of this work involved a review of the literature. It was necessarily limited in its scope to those aspects which are relevant to the investigation. Sampling or aspiration of aerosols for characterisation purposes is extremely important in any investigation so this subject is reported first. Deposition in tubes, bends and obstructions and aerosol re-entrainment forms the main text of this Chapter which is in 4 sections.

2.2 AEROSOL SAMPLING

An aerosol is the name given to a suspension of solid or liquid particles in a gas. The term aerosol includes both the particles and the suspending gas, which is usually air. Particle sizes range from 0.001 to over 100 μm diameter.

A primary aerosol has particles that are introduced directly into the atmosphere whereas a secondary aerosol has particles that are formed in the atmosphere by chemical reactions in gaseous components. Monodisperse aerosols have particles that are all the same size, whereas polydispersed aerosols have a range of particle sizes.

Sampling probes and heads are used to withdraw aerosol samples for analysis. It is necessary to ensure that these samples are representative.

2.2.1 Sampling From A Moving Gas

Sampling is isokinetic when the inlet of the sampler is aligned parallel to the gas streamlines and the gas velocity entering the probe is identical to the free velocity approaching the inlet. If sampling is isokinetic and the head walls are thin there is no particle loss at the inlet regardless of particle size or inertia (Hinds, 1982). However, creation of isokinetic conditions for sampling the flow is not a simple problem (Belyaev, 1974), because:-

a) The sampling nozzle walls have some thickness which is responsible for changes of flow field immediately upstream.

b) For technical reasons, it is very difficult to have exact equality of the two velocities even at low frequency pulsations of the flow.

c) The flow velocity fluctuates due to process variations and turbulence.

Isokinetic sampling in no way ensures that there are no losses between the inlet and the collector, only that the concentration and size distribution of the aerosol entering the tube is the same as that in the flowing stream.

A failure to sample isokinetically (i.e. anisokinetic sampling) may cause a distortion of the size distribution and a misrepresentation of the concentration. The isokinetic condition for a properly aligned probe is

$$U = U_o \tag{2.1}$$

where U = stream velocity
and U_o = velocity in probe.

When the probe is correctly aligned but the probe inlet velocity exceeds the stream velocity, particles with a high inertia originally in the sampled gas volume cannot follow the converging streamlines to enter the probe and are lost from the sample - thus causing an underestimate of the coarse particles in a sample. The reverse is true when the stream velocity exceeds the inlet velocity and thus overestimates the concentration. The maximum error for the above two cases is :

$$C/C_o = U/U_o \quad \text{for Stokes No.} > 6 \tag{2.2}$$

The Stokes number is the ratio of particle stop distance to probe radius and describes the level of particle inertia in the system.

When sampling conditions are such that the Stokes number is less than 0.01 the effect is negligible and $C/C_o = 1$.
For $0.01 <$ Stokes No. < 6 then Durham and Lundgren (1980) produced:

$$C/C_o = 1 + [(U/U_o) - 1]\{1 - 1/[1 + (2 + 0.62\ U/U_o)Stk]\} \tag{2.3}$$

When the sampling flowrate is isokinetic but the probe is misaligned, the concentration will be underestimated and there is an apparent change in the flow characteristics which is due to a reduced projected nozzle diameter.

Belyaev (1974) proposed limitations to the application of isokinetic conditions:

1) At low values of stream velocity, the sample volume can be too small to determine accurately the number of particles in it, even if the stream concentration is high.

2) At high values of the stream velocity, difficulties arise associated with the provision of either an adequate collection efficiency or an adequate air flowrate.

2.3 AEROSOL DEPOSITION

A number of workers have proposed theories for the deposition of aerosol particles in a tube, onto a flat plate and in a vessel of arbitrary shape. This section reviews some of the different theories and compares them with experimental work.

In the absence of thermal gradients, four mechanisms may contribute to the transport of suspended particles to the wall of a tube or duct:

a) gravitation,

b) diffusion,

c) electrostatic forces and

d) inertia.

There are obviously a large number of factors which determine the relative significance of the contributing mechanisms. Theoretical analysis is necessary to isolate the most important parameters.

The theories are applicable for two different flow regimes:

1) laminar flow where $Re < 2100$ and

2) turbulent flow.

2.3.1 Diffusion Mechanisms

2.3.1.1 Brownian Diffusion

a) LAMINAR FLOW

A theoretical equation for the deposition of particles by Brownian diffusion was proposed by Thomas (1967).

The retention is proportionally greater as the particle diameter becomes smaller, the tube diameter having no effect. The particle diffusivity, D, is obtained from the Stokes - Einstein equation:

$$D = KTC_H / 6\pi a \tag{2.4}$$

where C_H = slip correction factor
and K = Boltzmann constant

The above equation has been confirmed experimentally.

b) TURBULENT FLOW

Several theories exist which describe the deposition due to molecular diffusion.

Levich's theory (1962) applies only to fine particles, less than 1 μm in diameter, with a Schmidt number much greater than 1. In his derivation he assumed that the turbulent eddies penetrated the viscous sublayer and died out only at the wall surface. The final equation for the dimensionless deposition velocity is:

$$V^{+} = 0.13337/(Sc)^{-3/4} \qquad (2.5)$$

2.3.1.2 Turbulent Diffusion

The behaviour of larger particles is related to their inertia. Deposition by turbulent diffusion corresponds to an inertial impact of particles projected towards the wall by turbulent eddies.

This mechanism is the one most used to describe the phenomenon of turbulent deposition. After complete radial mixing in the turbulent core, the particles are projected by eddies into the laminar sub-layer. If their stop distance is greater than the thickness of the sub-layer then wall deposition results.

The subject has been very well reviewed by Papervergos & Hedley (1984). It is an important mechanism and a number of theoretical models have been developed. The results of the more notable of these are outlined below:-

1) Friedlander and Johnstone (1957) were among the first to develop a major theory on this subject. The free flight particle velocity, U_{ff}, was assumed to be equal to the root mean square radial fluid velocity, and independent of the position at which a

particle was considered to begin its trajectory within the turbulent core. It is proportional to the friction velocity:

$$U_{ff} = 0.9U' \qquad (2.6)$$

The stopping distance of a particle is calculated by multiplying this free flight velocity by the particle relaxation time. A range of impact velocities is calculated by relating the stop distance to the starting point in the universal velocity profile.

2) Davies (1966) modified the above theory to combine the mechanisms of eddy and molecular diffusion. He proposed that the free flight velocity is equal to the local turbulent fluctuation velocity. The theory consisted of three regimes, diffusive, inertial and transitional, where both mechanisms are present.
i) Brownian diffusion through the viscous sub-layer for submicron particles.
ii) Inertial deposition from turbulent flow for particles of $dp > 1\mu m$.
iii) Deposition in a turbulent flow where both eddy and molecular diffusion are present.

3) Beal's approach (1970) to the theory is similar to that of Davies, the basic difference being in the calculation of the stop distance. According to Beal the free flight velocity was taken to be half of the axial velocity, irrespective of the position of

the particles in relation to the wall. The theory reduces to:

$$V_d = KV'/(K + V') \tag{2.7}$$

where K = mass transfer coefficient
and V' = root mean square velocity
(both are defined in Appendix A).

Montgomery's and Corn's (1970) experimental work on the turbulent flow regime suggests that the theories of Friedlander and Johnstone, Davies and Beal underpredicted the deposition of aerosol particles. Their results were best predicted by Beal's theory but even this does not adequately predict deposition when the influencing parameter changes from particle inertia to particle diffusion. However, Friedlander and Johnstone's theory was found to be adequate when inertial effects were large.

From the above comparisons of theory with experimental results for deposition in a tube, Beal's theory gives the best fit with experimental data. There are, however, many conflicting theories and experimental results and there is a need for further work in this area. There is particular disagreement among authors regarding the mode of transport of particles to the wall in the regime of turbulent inertial deposition which is important with the size of particles typically encountered and is of concern in the integrated circuit industry.

2.3.2 Sedimentation Under The Effect Of Gravity

a) LAMINAR FLOW

The sedimentation of particles, due to gravity, causes a partial retention of these particles in a horizontal tube. If the flow is laminar, the loss can be estimated by the Natanson equation published by Fuchs (1964).

b) TURBULENT FLOW

Fuchs (1964) presented an expression for the efficiency of deposition due to the gravity mechanism. The gravity sedimentation velocity is used in the above expression and deposition takes place across the diameter instead of the total perimeter of the tube:

$$F = 1 - \exp(4V_s L/\pi UD) \qquad (2.8)$$

where V_s = terminal settling velocity
$= \tau g$
τ = relaxation time
$= d_p^2(\rho_p - \rho_a)/18\mu$

2.3.3 Electrostatic Precipitation

Particles in flow streams tend to acquire electrostatic charge as do surfaces upon which they deposit, unless measures are taken to minimise the occurrence of this effect. The rate of particle deposition can be affected by the presence of electrical charge (Montgomery and Corn 1970). This is due to either mutual electrical repulsion between charged particles of the same polarity or by the effect of image forces.

2.3.4 Effect Of Bends On The Deposition Of Particles

Obstructions in a tube deflect the streamline flow and may cause circulation and turbulence resulting in extra deposition due primarily to the inertial forces acting on a particle. The inertia of a particle causes it to impact on to a surface when the flow lines are altered.

Crane and Evans (1977) studied the problem of inertial deposition on the outer wall of a tube bend, theoretically. they calculated the particle trajectories in the bend to determine the impaction efficiency as being a function of Stokes number.

$$E = St\theta_1/2 \qquad (2.9)$$

where E = impaction efficiency
θ_1 = bend angle, radians
St = Stokes number
= $\rho_p d_p^2 u/18\ a$
ρ_p = density of the particles
a = radius of the bend

Two simpler theories have benn presented by Stenhouse and Broom (1979) for deposition in a 90° smooth bend, one for negligible radial mixing (a) and one for predominantly radial mixing (b).

a) Where the centrifugal force in an outward radial direction is equally opposed by Stokes drag, the impaction efficiency is obtained by:

$$E = (\pi/4)St \qquad (2.10)$$

Extending this to a three dimensional case by integration gives:

$$E = St \qquad (2.11)$$

b) Where radial mixing of the aerosol occurs and particles are removed by deposition in the walls of a round tube, a mass balance gives:

$$E = 1 - \exp[-4kL/UD] \qquad (2.12)$$

however the area available for dust collection will be DL rather than the total area of the tube, so

$$E = 1 - \exp(-St) \qquad (2.13)$$

The two theories were confirmed by experimental results, but discrepancies occur at high Stoke's number due to particle bounce.

2.3.5 Effect Of Rough Walls On Deposition

Considerable experimental work has been carried out in the past on deposition of aerosols onto tube surfaces. However, this work has been done mainly with smooth surfaces and the effect of roughness almost ignored. From the work which has been done using rough walled tubes, it is indicated that aerosol deposition increases with roughness.

The theory of El-Shobokshy and Ismail (1980) was developed in an attempt to improve the approach presented by Browne (1974). The effective particle diffusivity was proposed by Liu and Ilori (1973) in which the particle inertia is considered. This removes the deficiency in application of eddy diffusivity of gases for a theory of deposition of solid particles.

It was assumed in Browne's theory that the particle concentration has a maximum value at the centerline of the tube. This theory , however, assumes that the average concentration in the bulk of the flow is maintained at the outer part of the boundary layer, $y_+ = 30$.

From experimental work carried out by El-Shobokshy (1983) it was shown that the above theory predicts the deposition velocity with reasonable accuracy for a particle size range of 1 - 6μm. However, there is a need for experimental work on particles larger than 0.2μm and smaller than 1μm. In an extension of this work El-Shobokshy included the effect of wall roughness.

2.4 ADHESION AND RE-ENTRAINMENT OF PARTICLES

Fine solid particles attach themselves to surfaces and the forces of adhesion determine whether or not they remain. If the adhesive forces are strong enough, then the particle will stay attached to the surface. If they are not strong enough they may fail to adhere on impact which results in particle bounce. Alternatively a failure of adhesion at some subsequent time may occur due to a change in conditions resulting in re-entrainment.

2.4.1 Adhesion Of Particles

The main adhesive forces are van der Waals force, electrostatic force and the surface tension of adsorbed liquid films. These forces are affected by the material, shape and size of the particle, the material roughness and contamination of the surface, relative humidity, temperature, duration of contact and initial contact velocity.

Van der Waals forces decrease rapidly with separation distance between surfaces; consequently their influence extends only several molecular diameters away from a surface. The magnitude of this force is given by:

$$F_{adh} \propto d_p/x^2 \qquad (2.14)$$

where F_{adh} is the resulting force between the particle and a surface of a given material.
and x is the separation distance of the surfaces.

The hardness of the materials involved controls the size of ultimate area of contact and therefore the strength of the adhesive force.

Most particles of 0.1μm diameter or larger carry some small net charge, q, which exerts an attractive force in the presence of an opposite induced charge:

$$F_z \propto q^2/xq^2 \qquad (2.15)$$

where F_z = attractive force in the presence of an opposite charge
q = net charge
and xq = separation distance of opposite charges.

This mechanism may be significant in effecting initial adhesion but the force will rapidly dissipate for other than very high resistivity particles. The van der Waal force may then become dominant. Capillary adhesion forces are normally high but can only be important in the presence of moisture or some other adhesion assisting liquid.

2.4.2 Re-entrainment Of Particles

The force required to detach a particle from a surface can be measured by subjecting particles to a centrifugal force normal to the surface in a centrifuge and determining the rotational speed required to detach the particle.

In general, adhesive forces are proportional to particle diameter while removal forces are proportional to the cube of the diameter for vibration and centrifugal forces or the square of the diameter for air currents. This suggests that as the size of particles decrease it becomes increasingly difficult to remove them from surfaces.

Many measurements of resuspension in the environment indicate that particle removal from a surface is not instantaneous but persists over a period of time (Sehmel, 1980). Several authors (Corn & Stein, 1965) have suggested that this behaviour is evidence of a statistical origin of resuspension intimately associated with the random motion of a fluid close to the surface.

Direct observation of particles near the wall have been reported as long ago as 1932 by Fage & Townsend. They have shown that the motion of individual particles is quite random and unsteady and that the particles often roll along the surface and then suddenly move, almost at right angles, away from the surface into the mean flow. This type of motion has also been recorded by other authors. It has been suggested that this sudden ejection of a particle from the wall may be due to unsteady flow fluctuations. In fact, the visual observations of Kline et al (1967) and Corino and Brodkey (1969) indicate that there are sudden eruptions of fluid normal to the wall. These turbulent bursts are three dimensional and carry away slower moving fluid near the wall to the faster moving turbulent mean flow. Cleaver and Yate's model (1973) for resuspension related the frequency of such events with the resuspension rate itself. This contains an implicit assumption that the resuspension rate is controlled by the frequency of occurrence of an aerodynamic lift force which exceeds the force of adhesion.

In contrast to the above force balance model, the approach of Reeks et al (1988) recognises the influence of turbulent energy transferred to a particle from the resuspending flow. This energy maintains the particle in motion on the surface with a surface potential well. The particle is detached from the surface when it has accumulated enough vibrational energy to escape from the well. These considerations have led the authors to a formula for the rate constant, p, for long term resuspension.

Estimates of p, based on van der Waals adhesive forces for a particle on a surface, indicate that particles can be resuspended more easily from a surface than anticipated on a balance of adhesive and aerodynamic lift forces. The dependence of resuspension on flow and particle size is the same as that observed in practice. Also, resuspension rates from surfaces where there is a spread in adhesive forces are shown to decay almost inversely to the time of exposure to the flow. This has been observed experimentally by Wells et al (1984).

However, no experimental data on the re-entrainment of particles in simulated practical systems such as tubes, valves and fittings could be found. Published fundamental work on idealised systems provides valuable information regarding mechanisms and trends. However, reliable data on re-entrainment of particles from systems found in practice and under practical removal conditions such as vibration and air pulsation is urgently needed.

2.5 CONCLUSIONS

The following general conclusions can be reached as a result of the literature review:

a) Isokinetic sampling is difficult to achieve but is not always necessary. However, the conditions of sampling must be checked and an aspiration coefficient determined.

b) For deposition of aerosols in straight smooth tubes the theory proposed by Beal gives the best fit with existing experimental data.

c) The deposition mechanisms are gravitational sedimentation, electrostatic attraction, diffusional deposition and inertial deposition. The mode of transport of particles to the wall in the turbulent inertial deposition regime is in contention.

d) Deposition is increased by the presence of bends and obstructions in systems. Reliable experimental data on deposition in valves and fittings used in practical systems could not be found.

e) El-Shobokshy and Ismail's theory showed reasonable agreement with El-Shobokshy's experimental work for a particle size range of 1 - 6 μm diameter. However, there is a need for experimental work on particles larger than 0.2 μm and smaller than 1 μm diameter.

f) Re-entrainment of particles becomes more difficult as particle size decreases. Also non-spherical particles re-entrain more easily than spherical particles. Although some fundamental work has been carried out on particle re-entrainment, experimental work on the phenomenon as it effects practical systems is lacking and is urgently needed.

CHAPTER THREE

EXPERIMENTAL DETAILS

The experimental system consists of a source of clean gas, an aerosol generation system, a test circuit and a particle monitoring system. The entire experiment was carried out in a class 1000 clean laboratory.

A source of compressed air was passed through molecular sieve material and activated carbon to minimise the presence of water vapour and hydrocarbons. For particulate control it was passed in series through an ultra high efficiency fibrous filter, a cartridge membrane filter and two flat membranes (0.2μm) retained between 'O' rings. The air could be connected either directly to the units to be tested or to the aerosol generator.

A very fine mist was produced using a Wright nebuliser containing a dilute aqueous suspension of either monodispersed latex particles or fine iron oxide powder. The mist thus produced was passed through a diffusion drier where the water evaporated to leave a finely dispersed dry aerosol. The stream was mixed with dilution air and finally exposed to ionising radiation to neutralise any electrostatic charges on the aerosol particles. The test aerosol is in the size range 0.3 - 1.5 μm diameter.

Two basic types of tests were carried out, first deposition tests and secondly contamination measurement. In the deposition tests the aerosol was sampled alternately before and after passing through the test sections. In the contamination tests clean air was passed through the system and continuously sampled downstream. Sampling chambers were used to ensure representative sampling and particle analysis was by light scattering counters.

The details of the system are described below.

3.1 THE CLEAN ENVIRONMENT

A clean environment was needed to carry out the experimental work, thus a clean room facility was built in two stages. The clean cabinet was constructed initially but this was found to be dependent on contamination from the laboratory. To overcome this problem a clean area was erected to enclose the clean bench cabinet and thus protect it from external contamination.

3.1.1 The Clean Bench Cabinet

The clean bench cabinet consists of a laboratory wall bench where the bench and surrounding walls have been covered with chemically resistant formica. A metal framework surrounds this bench from which I.C.I. Derby curtains hang. Two fans and associated high efficiency particulate air (H.E.P.A.) filters are attached to the top of the framework. These pass clean air into the area above the bench thus creating a positive pressure inside the curtains at all times which helps to minimise external contamination.

3.1.2 The Clean Area

The clean area consists of partitioning and a false ceiling. The dimensions of the clean area are shown in Figure 3.1. The walls of the partitioning are constructed of formica faced wallboards and glass windows. The windows are mainly for viewing purposes but they also allow light out of the clean area into the main laboratory. The false ceiling is a suspended ceiling which is made of formica faced plasterboard.

A filter and fan have been inserted into the partitioning to allow clean make-up air to enter the clean area. The filter has a penetration of 0.002% to BS2938. The fan has the ability to draw in 3.5 m^3 per minute through the filter.

The entrance to the clean room is via the changing area. This room is used as a buffer zone between the laboratory and the clean area; it is where clean room clothing (overalls, hat, gloves etc.) may be put on. There is also a fire exit from the clean area which is kept locked except in the event of an emergency.

A Royco 225 particle counter has been used to monitor the particle count (>0.5μm diameter) in the clean area as well as in the bench cabinet - the results are shown in Table 3.1. It can be seen from these results that the bench cabinet is well within the limits of a Class 10 environment while the outside clean area is Class 1000.

3.2 THE CLEAN AIR SUPPLY

Absolutely clean air is essential for the initial purging and also the re-entrainment experiments - it can also be mixed with the aerosol for dilution purposes.

The compressed air is dried by passing it through a bed of aluminium oxide. It is then passed through a 0.2μm pore size membrane cartridge filter - experimental evidence (Lui et al., 1983) shows that the penetration of particles >0.09μm diameter will be extremely low and certainly within acceptable limits. This stream of compressed air is taken at a controlled and measured rate through a Domnick Hunter filter to remove any hydrocarbon vapour and finally through two back-up membrane filters (0.2μm) to ensure ultra clean conditions. Each of these consist of a flat section media supported on a porous plate and retained by two 'o' rings. Stainless steel high quality fittings are used downstream of this filter to ensure that minimum contamination occurs, as even minor contamination is of vital importance in the clean air system. The length of tubing used after the final filter is minimised also for this reason. The clean air is sampled for 30 minutes at the beginning of each day and analysed using a Royco 225 counter. Testing only proceeds if a zero particle count is obtained.

3.3 AEROSOL GENERATION

It is possible that during operation sections of pipeline could become contaminated from another part of the system. An attempt to simulate this has been to deposit a known aerosol into the test section and then carrying out a re-entrainment test.

Compressed air, which has been dried and filtered may be passed through a 'clean air' line (described in Section 3.2.) or 'aerosol' line (Figure 3.2). The aerosol, which may be diluted to the required concentration by the clean dry air is passed via a hold-up vessel to the test section.

The aerosol generation system consists of the following major items:-

Aerosol nebuliser: A Wright nebuliser is used to generate a fine polydispersed spray of droplets containing salt or iron oxide particles or monodispersed latex particles. The size distribution of the droplets has been measured and the production rate calibrated. Over the operating differential pressure range of 2-20psi the flow increased from 4 to 11l/min.

Aerosol drying: The water is evaporated from the droplets by passing the aerosol through a T.S.I. diffusion dryer. The relative humidity of the aerosol stream leaving the dryer without dilution with dry air was measured and found to be 20% - this is in agreement with the manufacturers data. Subsequent dilution with dry air further reduced the humidity. Adhesion forces will therefore be by London van der Waals forces.

When a saline solution is used a fine polydispersed aerosol of cubic sodium chloride particles results. The size distribution of the aerosol was determined by electron microscopy for a differential pressure of 20psi and a 1% w/w saline. Dried salt aerosol was sampled onto an electron microscope grid using a point to plane electrostatic sampling precipitator manufactured according to the Rochester design (Marcer, 1973). The size distribution was close to log normal with the mean sizes and deviations shown in Table 3.2.

The hold-up vessel: This provides additional residence time for water evaporation. A minimum average hold-up of about 20 seconds is provided which is considerably in excess of that recommended in BS3928 for a similar purpose (1 second). The vessel also provides a concentration smoothing facility.

Ionizing Source: A Krypton 85 β radioactive source was installed to eliminate electrostatic charges on the aerosol which would otherwise effect the deposition and re-entrainment results. It is screwed into the base of a 0.05m internal diameter cylindrical chamber and earthed. The aerosol enters through the side and passes axially 0.1m through the vessel when it is exposed to the source. The vessel is constructed from plastic to prevent the possibility of secondary radiation and it is located under the bench where radiation protection is provide by barium brick and lead shielding. An exhaust system has been installed to pump any aerosol, which may pass through the ionizing vessel, outside the building as an additional safety precaution.

3.3.1 Characterisation of the Generator

Two main areas have been investigated. The dilution ratio required to reduce the aerosol concentration to an acceptable level has been assessed and secondly the time required to purge the system has been measured.

3.4 THE SAMPLING CHAMBERS

Aerosol sampling chambers are located upstream and downstream of the test section. These are constructed from stainless steel with an electropolished internal finish. The aerosol stream enters the end of each 0.05m diameter chamber which has rounded corners to minimise deposition and hence remove the possibility of re-entrainment. The sample for analysis is removed from a location in line with and adjacent to the tapping which leads to exhaust. This ensures that the sample probe is exposed to the same aerosol as that entering or leaving the test section. By reducing the face velocity in the sampling chambers possible sampling errors due to anisokinetic effects are minimised. Calculation shows that the Stokes number for aspiration is very low under these experimental conditions and that consequently the aspiration coefficient is very close to unity.

When purging of the test section is carried out only the outlet chamber is used. This is reasonable as extensive tests have been carried out on the clean air line and it is known that the number of particles can be effectively reduced to zero - the level of contamination is so small that we cannot detect it - so sampling is irrelevant at this point. A reducing union is used to connect the clean air line directly to the test section as a purge gas. This method has been used to bypass the aerosol system without having a t-piece permanently in the test line as this could collect particles and affect the results.

3.5 AEROSOL DETECTION

A P.M.S. LAS-X light scattering particle counter has been used to measure the level of contamination. The aerosol is focused through a laser illuminated sensing zone and the light scattered from single particles is measured using a solid stage photo-detector (Figure 3.3). Since particles are measured individually it is essential that low concentrations are analysed to obviate coincidence errors. Pulse height analysis and comparison with a calibration curve allows complete particle sizing and counting.

The LAS-X operates in four size ranges 0.09μm to >0.2μm, 0.2μm to >0.5μm, 0.5μm to >3μm and 0.09μm to >3μm. The latter size range has been used for the tests. The sizes of the individual channels are shown in Table 3.3.

Initially the maximum count rate for the LAS-X was maintained below one million total particles per minute on the advice of the agents. As a precautionary measure it was decided to investigate this figure by comparing the particle count for a range of known dilutions. The total diluted aerosol flow was constant.

Table 3.4 shows the ratio of indicated to true counts for a number of particle sizes. This shows that although the total count is not affected significantly there is a considerable distortion on an individual channel basis especially for the larger particles. The effect of coincidence is that two small particles appear as one large one, thus the lower channel count will fall as the larger increases. On the basis of these tests the total count level should be kept below about 200,000.

The reproducibility of aerosol analysis, which also indicates the generator stability, when low concentraions are used are shown in Table 3.5. The results are excellent for submicron particles. The concentration of larger particles is insufficient to obtain a statistically representative sample.

To count relatively low concentrations of particulates as in the penetration tests the P.M.S. LAS-X can be used confidently. However, when very low concentrations are being monitored as in the entrainment and re-entrainment tests the number of particles actually counted by the LAS-X at a sampling flowrate of 60cc/min is very low. In an effort to overcome this problem a Royco 225 was used in order that a larger volume of air leaving the test section could be sampled (3l/min) thus reducing considerably the errors associated with the statistics of sampling small numbers. The Royco 225 is a light scattering photometer (Figure 3.4) which has been calibrated down to 0.25μm. This will count the particles sampled in each of five size increments between 0.3 and 5μm.

3.5.1 Comparison of the P.M.S. LAS-X with the Royco 225 Particle Counting Instruments

In a recent publication (Gebhart 1986) it was shown that aerosol particle light scattering counters using white light have a low counting efficiency for sizes less than approximately 6μm diameter. The Royco 225 used in the present work falls into this category. The LAS-X was found to be 100% efficient over the size range of interest. A programme was therefore carried out to measure the counting efficiency of the Royco 225 by calibration with the LAS-X. Monodispersed latex particles ranging between 0.3 and 1.09μm diameter were used.

As the name suggests, the LAS-X uses laser light whereas the Royco 225 uses an incandescent lamp as the light source. Both instruments use the principle of light scattering to detect particles in gaseous media.

The aerosols were produced for each size range using the aerosol generator and samples were taken simultaneously by the two instruments. The counts taken by the LAS-X were scaled up to allow for the same sampling flow as the Royco 225. Figure 3.5 shows the percentage efficiency of the Royco 225 compared with the LAS-X for the particle diameters used. It can be seen that below 0.5μm the particle counting efficiency of the Royco 225 is low. This means that the entrainment and re-entrainment results obtained using the Royco 225 need to be scaled up accordingly.

Table 3.1

PARTICLE COUNTS IN THE CLEAN ENVIRONMENT

Environment	Counts/ft³ >0.5μm	Class
Clean Cabinet	7	10
	0	
	4	
	0	
	2	
	0	
	0	
Clean Area	417	10000
	530	
	490	
	260	

Table 3.2

SIZE DISTRIBUTION OF A SALT AEROSOL

	Number Basis	Weight Basis
Mean Particle Size(μm) (length of side)	0.11	0.53
Geometric Standard Deviation	2.5	1.70
Mean Droplet Size(μm) (diameter)	0.86	4.1

Table 3.3

LAS-X SIZE RANGES

Channel	Size(μm)
LAS-X Size Ranges 0 and 4[1] (0.5 - >3.05μm)	
1	0.50 - 0.67
2	0.67 - 0.84
3	0.84 - 1.01
4	1.01 - 1.18
5	1.18 - 1.35
6	1.35 - 1.52
7	1.52 - 1.69
8	1.69 - 1.86
9	1.86 - 2.03
10	2.03 - 2.20
11	2.20 - 2.37
12	2.37 - 2.54
13	2.54 - 2.71
14	2.71 - 2.88
15	2.88 - 3.05
16	> 3.05
LAS-X Size Ranges 1 and 5[1] (0.20 - >0.5μm)	
1	0.20 - 0.22
2	0.22 - 0.24
3	0.24 - 0.26
4	0.26 - 0.28
5	0.28 - 0.30
6	0.30 - 0.32
7	0.32 - 0.34
8	0.34 - 0.36
9	0.36 - 0.38
10	0.38 - 0.40
11	0.40 - 0.42
12	0.42 - 0.44
13	0.44 - 0.46
14	0.46 - 0.48
15	0.48 - 0.50
16	> 0.50

[1]Cumulative Mode

Table 3.3.(cont'd)

Channel	Size(μm)
LAS-X Size Ranges 2 and 6[1](0.09 - >0.20μm)	
1	0.090 - 0.097
2	0.097 - 0.104
3	0.104 - 0.111
4	0.111 - 0.118
5	0.118 - 0.125
6	0.125 - 0.132
7	0.132 - 0.139
8	0.139 - 0.146
9	0.146 - 0.153
10	0.153 - 0.160
11	0.160 - 0.168
12	0.168 - 0.176
13	0.176 - 0.184
14	0.184 - 0.192
15	0.192 - 0.200
16	> 0.200
LAS-X Size Ranges 3 and 7[1](0.09 - >3.00μm)	
1	0.09 - 0.11
2	0.11 - 0.15
3	0.15 - 0.20
4	0.20 - 0.25
5	0.25 - 0.30
6	0.30 - 0.40
7	0.40 - 0.50
8	0.50 - 0.65
9	0.65 - 0.80
10	0.80 - 1.00
11	1.00 - 1.25
12	1.25 - 1.50
13	1.50 - 2.00
14	2.00 - 2.50
15	2.50 - 3.00
16	> 3.00

[1]Cumulative Mode

Table 3.4

RATIO OF TRUE TO INDICATED COUNTS USING THE P.M.S. LAS-X

	Dilution Ratio		
	0.5:18	1:18	1:13
Total Particle Number Count	231446	407728	620332
Particle Diameter (μm)	Ratio of True to Indicated Counts		
0.1	1.09	1	1.07
0.225	1.04	1	1.2
0.45	0.98	1	1.35
0.9	0.98	1	1.35
Total Particles (all sizes)	1.08	1	1.12

	Dilution Ratio			
	1:18	1:9	1:6	1:3
Total Particle Number Count	333751	686996	948171	1484256
Particle Diameter (μm)	Ratio of True to Indicated Counts			
0.1	1	0.93	0.87	0.86
0.225	1	1.06	1.1	1.23
0.45	1	1.19	1.29	1.48
0.9	1	1.46	1.68	1.59
Total Particles (all sizes)	1	1.08	1.05	0.94

Table 3.5

REPRODUCIBILITY OF AEROSOL ANALYSIS

Particle Diameter (μm)	Number Count Mean/Minute	Standard Deviation	Percentage S.D.
0.1	9968.6	56.7	0.57
0.13	12571.1	60.1	0.48
0.225	2634.5	22.9	0.87
0.35	911.5	7.7	0.84
0.575	95.4	1.45	1.52
0.9	12.1	0.98	8.1

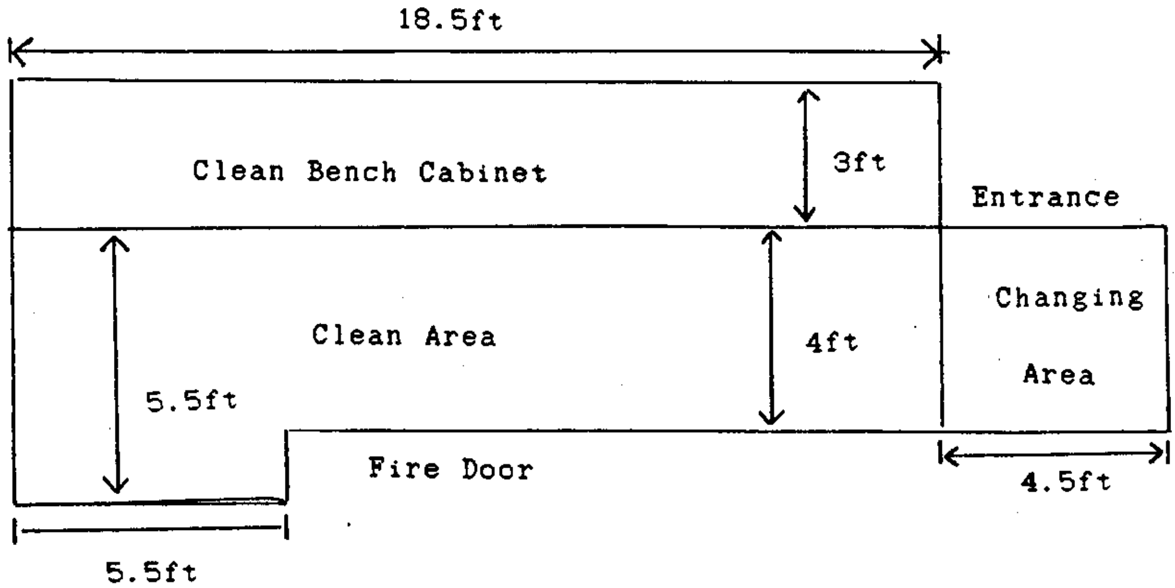

FIGURE 3.1 - DIMENSIONS OF THE CLEAN ROOM

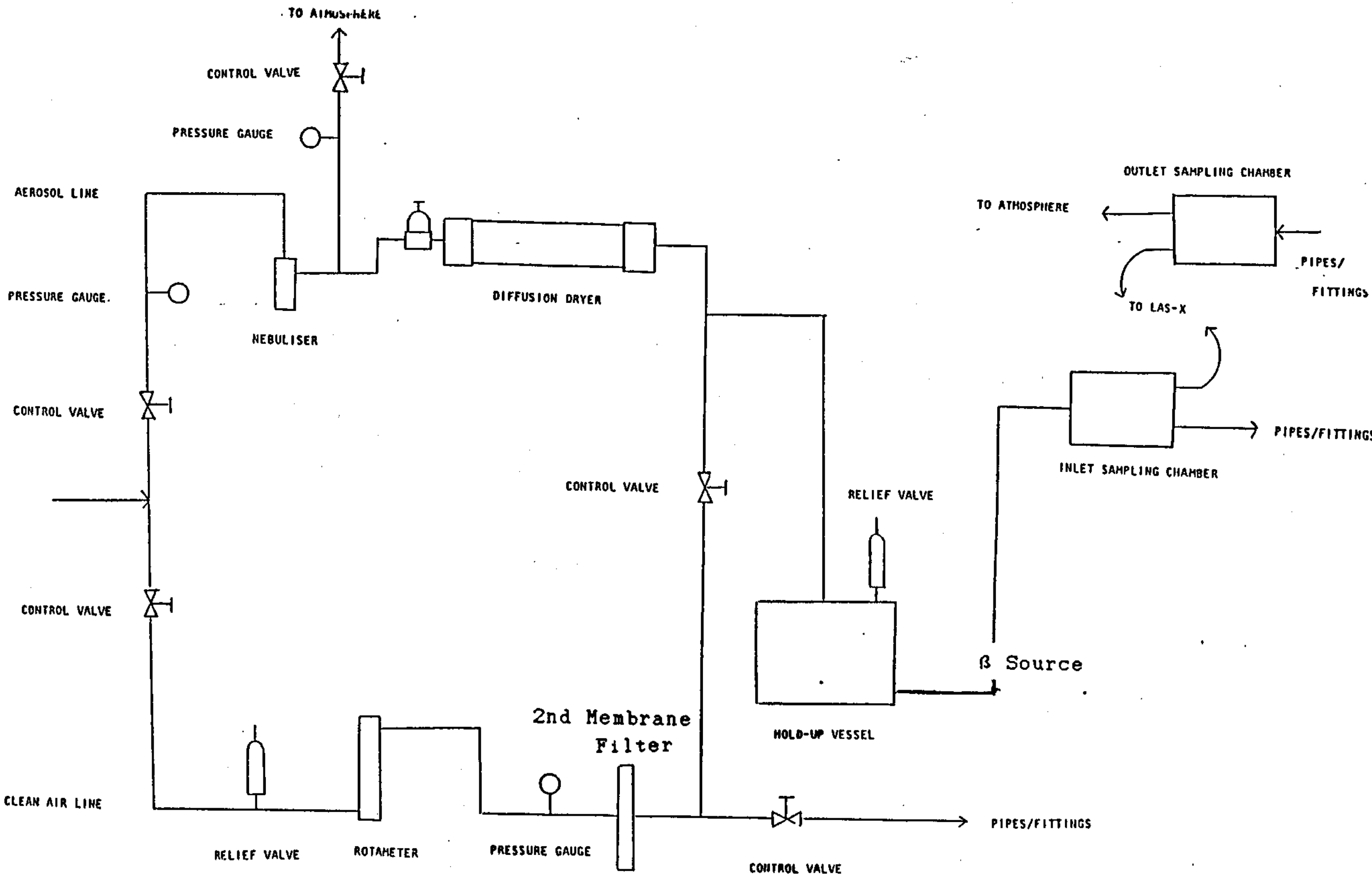

FIGURE 3.2 - THE AEROSOL GENERATION SYSTEM

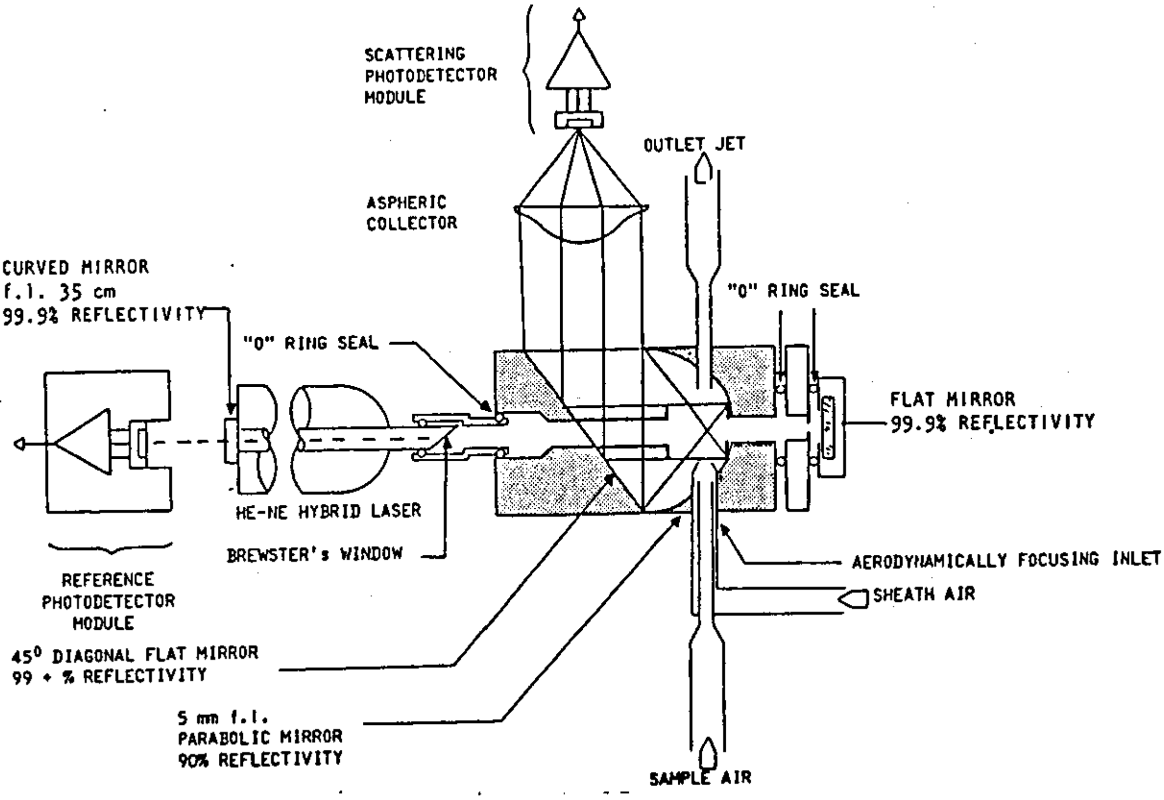

FIGURE 3.3 - OPTICAL SYSTEM DIAGRAM OF THE P.M.S. LAS-X

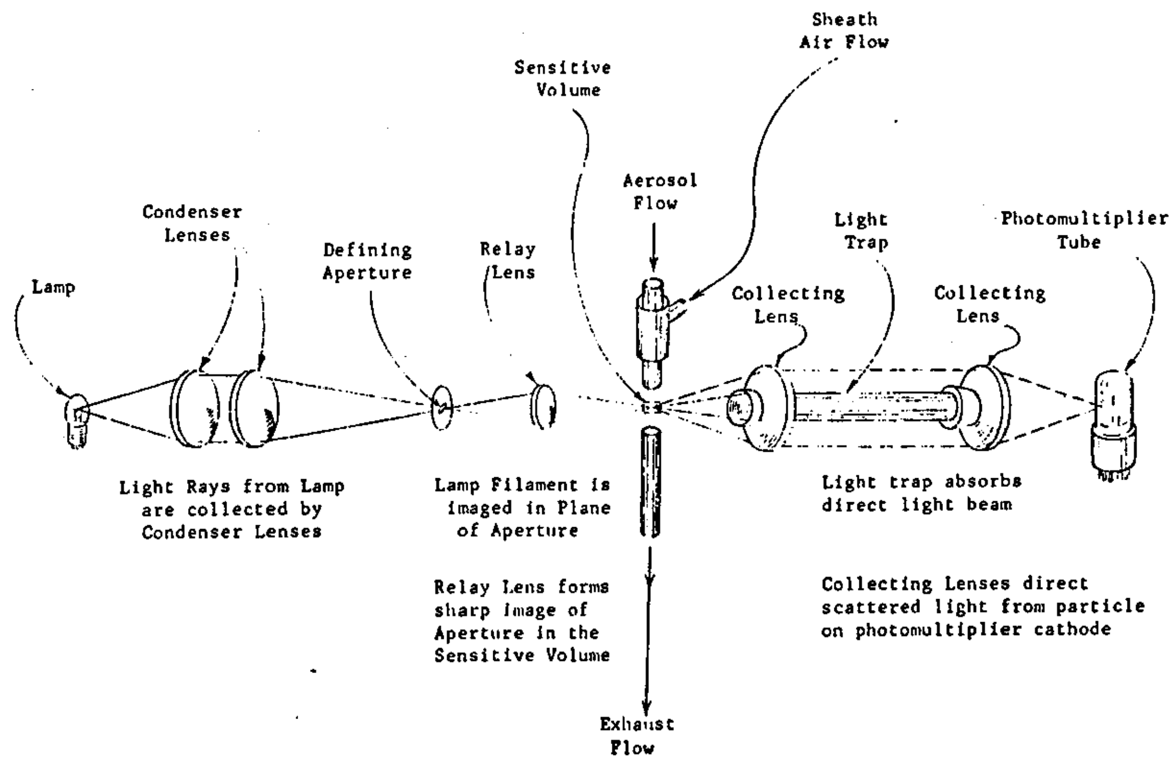

FIGURE 3.4 - OPTICAL SYSTEM DIAGRAM OF THE ROYCO 225

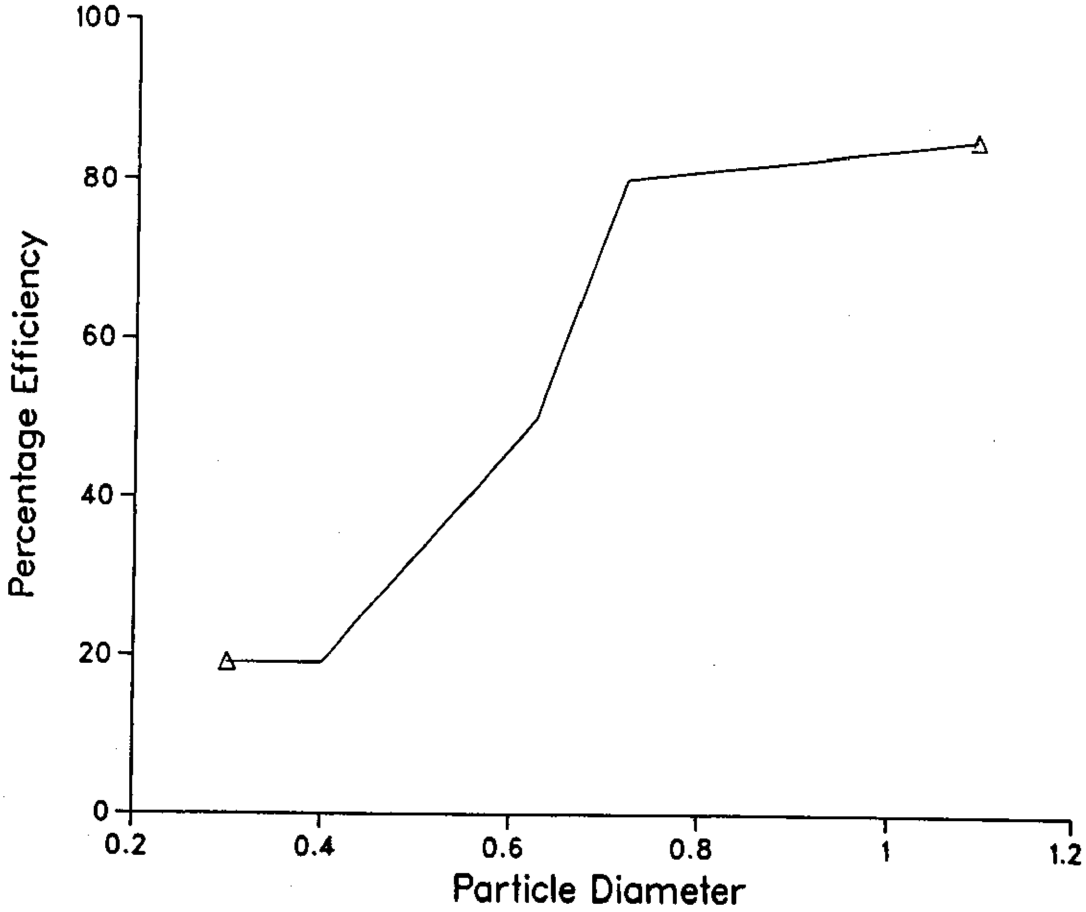

FIGURE 3.5 - PERCENTAGE EFFICIENCY OF THE ROYCO 225 COMPARED WITH THE P.M.S. LAS-X

CHAPTER FOUR

STRAIGHT TUBING, RESULTS AND DISCUSSION

4.1 INTRODUCTION

The objective of this part of the experimental programme was to assess the effect of internal finish of straight tubes on the production of gas-borne particulate contamination. Electropolished, chemically cleaned and as drawn systems have been tested. A detailed description of these terms is given in Appendix I.

The extent of particle release from new 'as delivered' tubes was determined first. The aim of this was to assess the level of particulate contamination in process gases arising from the tubes in their 'as delivered' state prior to installation. This will be strongly related to the method of cleaning prior to delivery and will not necessarily reflect the behaviour after purging.

To assess the longer term behaviour, known quantities of fine particulates were intentionally deposited on the internal tube surfaces. Clean gas was then passed through and the contamination in the outlet measured. It was hoped thus to isolate the effect of internal surface on aerosol pick up (re-entrainment).

Of necessity, the tests described above have been of a short duration. In an attempt to validate the findings and also to simulate closely actual process conditions, ten tubes were exposed to a long term dry nitrogen purge. The tubes were tested individually at monthly intervals for signs of particulate release to determine whether or not the tube characteristics change with time.

4.2 ENTRAINMENT

4.2.1 Experimental Programme

The entrainment experimental programme has involved the use of eighteen test sections, all of 6.35mm (0.25 inches) outside diameter, tested individually:

1) Four 5m lengths of stainless steel tubing which have not been cleaned.
2) Six 5m lengths of 'as drawn' stainless steel tubing (cleaned but not electropolished).
3) Four 4m lengths of 'chemically cleaned' stainless steel tubing (cleaned but not electropolished).
4) Four 5m lengths of electropolished stainless steel tubing.

The entrainment experiments were carried out in two phases by passing clean air (Section 3.2) through each test section and taking samples via the sampling chambers (Section 3.4). The Royco 225 was used in order that a larger volume of air leaving the test section could be sampled. The first phase involved a standard test which was developed in the early part of the experimental programme (described below), while the second phase extended this standard test to use much higher flowrates, flexing the tubes and pulsing the flow.

In the standard test steady flowrates of 5, 20 and 40 litres per minute were passed through three of the uncleaned tubes to find the best purge rate. From these tests (Figures 4.1, 4.2 and 4.3) it could be seen that increasing the flowrate (and thus the pressure through the tubes) increased the number of particles entrained from the tubes. It was thus decided from these results that the highest flowrate should be used as the base of a standard test (i.e. 40 l/min).

The standard test involved passing particle free air through a test section at a steady flowrate of 40 l/min for over three hours. During the period of the test, vibration was applied to the tubes for one hour and a mechanical hammer was used to gently tap the tubes. Vibration and tapping were used in an attempt to dislodge particles. The vibrator uses mains excitation (a frequency of 50Hz) and is in steady contact with the tube - the tube is resting on the vibrator. The mechanical hammer used in the standard test is a swing hammer which is raised to a standard height (determined by a bar release mechanism) to which can be attached different weights.

This standard test was extended in the second phase of the test to involve:-

a) flexing of the tube at a flowrate of 40 l/min,

b) increasing the flow to 60 l/min, flexing the tube and pulsing the air to a flowrate of 70 l/min - a solenoid valve is used for this purpose, and c) increasing the flowrate to 90 l/min, flexing the tube and pulsing the air to a flowrate of 100 l/min.

The purpose of the extended test was to measure the effect of a range of parameters on particle dislodgement which simulate actual process conditions. The effects of step changes in velocity (from 40 l/min to 60 l/min to 90l/min).Tubes are inevitably flexed during installation - in this test the centre of each tube was repeatedly raised about 0.3m and dropped. The flow through the tube was pulsed to simulate the effect of the use of servo mechanisms - in this test the flow was repeatedly stopped then immediately increased again at 15 second intervals during a 10 minute period.

4.2.2 Results of Entrainment Tests on 'As Delivered' Straight Tubing

The results of these tests on one uncleaned, three electropolished, six 'as drawn' and four 'chemically cleaned' tubes are shown in Figure 4.4 - 4.17 in terms of the total number of particles entrained in ten minutes. Tables 4.1 - 4.3 show a typical size distribution of particles entrained from each type of cleaned tube. Results for the total contamination issuing from each tube per cubic foot of air during these tests are summarised in Table 4.4. The contamination relative to the electropolished tubes is shown for comparative purposes (α).

It can be seen from these results that the electropolished tubes are shown to be cleaner than the 'as drawn' or 'chemically cleaned' tubes in the 'as delivered' state. The 'as drawn' and 'chemically cleaned' tubes do not show a great deal of consistency in their results in terms of cleanliness, there being a large variation in the number of particles being entrained.

The effects of vibration at 50Hz, gentle tapping, flexing the tubes, increasing the velocity and pulsing the flow are shown in Table 4.5. It can be seen from this Table that increasing the flowrate of air through the tubes greatly increases the number of particles that are entrained. Figure 4.19 shows the general effect of increasing the velocity in terms of the number of particles entrained/cubic foot of air for each of the three types of tube. This shows that there is a large increase when the flowrate is raised from 40 l/min to 60 l/min and 90 l/min. As expected, pulsing the flow has a similar effect. An increase in pressure in the clean air line is the result of closing the solenoid valve - thus when the valve is opened, the pressure is converted into a higher flowrate.

Vibration, gentle tapping and flexing the tubes all have a slight effect which differs with each type of tube, i.e. there is not always an increase in entrainment.

4.3 PENETRATION

This part of the experimental programme was carried out in two phases and involved the use of eleven test sections (all of 6.35 mm diameter):

1) One 5m length of electropolished tubing.

2) One 4m length of 'chemically cleaned' tubing.

3) One 5m length of 'as drawn' tubing.

4) One T.F.E. lined flexible hose.

5) One 5m length of electropolished tube connected to one 5m length of 'as drawn' tube by a T.F.E. lined flexible hose.

6) As (5).

7) One 5m length of electropolished tube connected to one 4m length of 'chemically cleaned' tube by a T.F.E. lined flexible hose.

8) One 4m length of 'chemically cleaned' tube.

The penetration tests were carried out by passing aerosol through the test sections and taking samples alternately from the inlet and outlet sampling chambers at one minute intervals using the P.M.S. Las-x.

The first phase of this part of the experimental programme was carried out on test sections (1) - (4), to determine accurately the amount of aerosol deposited in each type of surface finished tube. The aerosol used consisted of monosized latex particles (0.369μm and 0.726μm). The total time taken for each penetration test was 30 minutes. The penetration was determined for flowrates of 4 and 13.5 l/min, the experimental conditions are summarised in Table 4.6.

Figures 4.20 and 4.21 show the results of the penetration tests for all of the test sections for flowrates of 4 and 13.5 l/min respectively. Also shown on the figures are the theoretical predictions for a smooth bore tube (Thomas 1967, Beal

1976). The experimental results shown are the average values of many tests (in Table 4.7 the 95% confidence kinetics are shown), the penetration through the flexible hose having been taken into account. As would be expected, the penetration is highest through the flexible hose because of its short length; however there does not seem to be any other trend in the results for the two flowrates. There is reasonably good agreement between these results and the theoretical predictions for smooth walled tubes, although there is a tendency for the penetration to be lower than expected - theory nearly always overpredicts the penetration when quantified in terms of particles collected, this has most significance at the smaller particle sizes. The effect of surface roughness on deposition in tubes has been calculated using the El-Shobokshy and Ismail theory (1986) - Figure 4.22. It can be seen that there is little effect of roughness over the range of surfaces used, or generally considered for use, in the I.C. industry. This agrees with the results for the first three test sections, they are all within 2% of each other - thus for the tubes tested there is no significant difference between the surface finishes.

The second phase of this part of the experimental programme was carried out on tests sections (5) - (8) at flowrates of 4.5 and 11 l/min in order to prepare the tubes for subsequent re-entrainment tests. The time taken to complete each penetration test was varied depending on the number of particles which were required to deposit on to the tube walls.

Three penetration tests were carried out on test section (5) - the aim of this was to increase the internal coverage of the tube walls. The compressed air line was used to generate the aerosol for these three tests, the aerosols being (a) monosized latex (1.09μm), (b) and (c) polydispersed iron oxide (0.2 - 1.5μm). The change in aerosol type was made in order to simulate more closely practical conditions, where an iron oxide aerosol, or similar material, is more likely to be encountered than the artificial latex material.

Since the objective was to simulate the practical situation, efforts were made for the remaining three test sections (6) -(8) to exclude from the experimental system contaminants which would not be present in practice. Since hydrocarbon vapour may contaminate the particle and tube surfaces and effect the adhesion forces this possible contaminant was excluded by using bottled, rather than compressed, air for test sections (6) -(8).

The aerosol is generated by dispersing the particles in water (methanol was used as a dispersing agent) and creating a fine mist from the nebuliser. The water is then dried off in the diffusion drier. The relative humidity of the aerosol stream leaving the drier without dilution with dry air was found to be 20% - in agreement with the manufacturers data. Subsequent dilution with dry air for test section (6) & (7) further reduced the humidity to below the level at which pendular moisture will form. Adhesion forces will therefore be by London van der Waal molecular forces.

In an attempt to remove this water, for test section (8), the aerosol was cooled by passing it through a coiled tube surrounded by solid carbon dioxide; the aerosol was then reheated to the ambient temperature. This resulted in a relative humidity of 2%. This very low relative humidity had no significant effect on the results so it may be assumed that the presence of small amounts of water vapour in these experiments is not important. The experimental conditions and results for all of the test sections are shown in Table 4.8.

The penetration was found to be about 98% for all of the test sections - this is in good agreement with the theoretical predictions and the experimental results obtained in the first phase of the experimental programme.

4.4 RE-ENTRAINMENT

After a penetration test, particles suspended in the air within the tubes have to be allowed time to diffuse/settle onto the walls before a re-entrainment test can be carried out. Figure 4.23 shows the decrease in the apparent re-entrainment of particles the longer they are left before starting the re-entrainment test. These results are in fact caused by "sweep out" of particles which were still suspended in the system following the penetration test.

When a particle is released in air, it quickly reaches its terminal settling velocity, V_{TS},

$$V_{TS} = \rho_p d^2 g C_c / 18 \qquad (4.1)$$

Another mechanism which contributes to the deposition of aerosol particles to the wall of the tube is Brownian diffusion. The particle diffusivity, D, is obtained from the Stokes-Einstein equation:

$$D = KTC_{\infty} / 3\pi a \tag{4.2}$$

The terminal settling velocity of a particle has been calculated using equation (4.1) and the time it takes for a particle to settle is obtained from this. The diffusivity has also been calculated and the time it takes for a particle to diffuse to the wall has been determined (assuming 99% of the particles diffuse)(Perry 5th Edition). The time involved is in the order of hours rather than minutes (Table 4.9); thus the tubes were left overnight after a penetration test was carried out to ensure that the particles were still not suspended in the air.

This part of the experimental programme involved the use of four test sections {described in Section 4.3 as test sections (5) - (8)}.

The experiments were carried out in two phases. The first phase involved the standard test (as described fully for entrainment in Section 4.2.1) - a steady flowrate of 40 l/min with vibration and mechanical tapping applied. While the second phase extended this standard test to a higher flowrate of 60 l/min using bottled air, flexing the tube and pulsing the flow. The flowrate of 60 l/min was chosen as this had been shown to entrain very few particles from the new 'as delivered' tubes after a flowrate of 90 l/min had been used in the entrainment test. The tubes used were thus effectively purged for use up to 60 l/min; this was confirmed experimentally. This should ensure that any particles which were removed from the tubes during a re-entrainment test were particles that had been deposited during a penetration test. The particles were counted using the Royco 225.

Table 4.10 and Figures 4.24 - 4.34 show the results of the re-entrainment tests. They show that the amount of re-entrainment from the internal surface of any of the tubes is very low. Three electropolished, two 'as drawn' and two 'chemically cleaned' tubes have been tested and the results show that there is not a detectable difference between the different types of tube. Four additional experimental tests were carried out to further validate the test procedure and thus results:-

1) A very high concentration was put into the first test section in order to improve the statistical significance of the number of particles counted being re-entrained. The statistical significance of the results is increased by increasing the quantity of deposition.

2) Bottled air was used to remove the effect of any hydrocarbon that may have been present in the compressed air line (a Domnick Hunter filter was later introduced into the compressed air line for this reason). The hydrocarbon may have been increasing the forces of adhesion between the particles and the surface of the tube.

3) A drier aerosol was used to reduce the amounts of water vapour entering the tube. The aerosol was cooled by passing it through a

coiled tube surrounded by solid carbon dioxide; the aerosol was then reheated to ambient temperature. This resulted in a relative humidity of 2%. This was done to test whether the adhesion forces between the particles and the tube wall are effected by the presence of water. The results were negative suggesting it is not important.

4) Heat was applied to the tube wall to examine the effect of temperature (internal surface of about 60°C), and also to dry the aerosol already deposited in the tube. Neither drying the aerosol in this way nor the addition of temperature to the tube were found to effect the results.

Examination of Table 4.10 and comparison of Figures 4.24 - 4.34, show that the precautions in methods (1) -(3) have no significant effect on the results of re-entrainment. It can therefore be concluded that the test procedure normally used is satisfactory.

4.5 MECHANISMS OF PARTICLE ADHESION AND RE-ENTRAINMENT

It is important to consider the mechanism of particle adhesion and re-entrainment to obtain an understanding of the observed phenomena described in Section 4.2 & 4.4. This is the purpose of the following discussion. A particle will be dislodged from a surface if the removal forces are greater than the adhesion forces. The adhesion forces are summarised first and this is followed by a brief analysis of the removal mechanisms.

The three important particle-surface adhesion mechanisms are capillary adhesion, electrostatics and London van der Waals adhesion. The magnitude of these is shown as a function of particle size in Figure 4.35 (Bhattacharya and Mittal, 1978).

Capillary force is largest but this requires pendular moisture between the particle and surface. In the case of contamination with water vapour a monomolecular layer of adsorbed water molecules will form only at about 30% relative humidity. Much higher humidities are required to provide the pendular film of moisture necessary for capillary adhesion to take place. Particle deposition was carried out with relative humidities in the range 2 - 20% so in the present series of experiments this mechanism can be discounted. Electrostatic forces can also be discounted since any charge on the particles was neutralised and the tubes were earthed. It is therefore concluded that the adhesion force is the London van der Waal molecular force.

For smooth spheres on a flat surface the London force is relatively very strong. For 1 μm diameter particles it is 1000 times greater than the gravity force; for 0.1 μm particles it is 100,000 times greater. Since gentle tapping or vibration will only cause a few g's acceleration of the surface, it is not surprising that these actions have only a very small effect on dislodgment. The magnitude of these forces has been calculated assuming an ideal model of the system and as such gives average values which have been confirmed experimentally. However, in real systems there will be a spread of forces about the average of any given particle size. Three factors responsible for the spread are worthy of further consideration:-

a) The presence of molecular contamination: The force is due to intermolecular attraction and moleculaar contamination, such as the presence of a water molecule close to the point of contact, will interfere with the electromagnetic field. It will change the adhesion force, but not by a large amount, and should have little effect on system behaviour.

b) Particle shape: If a particle is non-spherical and has sharp edges the areas of the particle and wall in close proximity may be greatly affected. If these areas were reduced as, for example, in the case of a particle sitting on a sharp edge, the attraction, or adhesion, forces will be greatly reduced.

c) Surface roughness: If the particle or wall surface is rough then the area of close proximity must be affected and the attraction forces reduced. This must be highly dependent on the scale of roughness. If the tube wall roughness is of the order of the particle size it may even cause an increase in adhesion force because two points of contact become possible. If a particle is deposited on the top of a protuberance on the wall then the "sharpness" of that protuberance may be more important than its "height".

There is therefore a spectrum of adhesion forces for any given particle size, the lower end of which may be highly significant in determining the extent of particle re-entrainment. It is those particles with the very low wall attraction forces which may be removed by greater dislodgment forces.

The hydrodynamic forces acting on a particle are as follows:-

a) Steady force: In the current tests the gas is passed through the tubes in turbulent motion with Reynolds numbers in the range 14,000 - 32,000. When the flow flowrate is 40 l/min the laminar sublayer is about 25 μm thick and the velocity parrallel to the tube wall at a distance of 0.5 μm from the surface is about 0.05 m/s. This will be the average velocity causing a drag force on 1 μm diameter particles adhering to the wall. Bhattacharya and Mittal (1978) predicted that about 5 m/s velocity is needed to cause 1 μm diameter particles to roll along the surface. The force in the current tests is thus about 1% of that needed to cause motion. However, even if particles roll along the surface, an upwards lift force is necessary to cause re-entrainment.

b) Transient force: Turbulent bursts, which consist of sudden transient upward flows of gas from the surface through the sublayer, are now known to occur. Cleaver and Yates (1973) showed that these could cause particle re-entrainment from surfaces. The bursts, which are shown diagrammatically in Figure 4.36, live long enough to lift a particle outside the range of the adhesion force so that it may be projected into the turbulent core. For the 40 l/min flow the average area of bursts is in the region of 100 μm across. Calculations of the lift forces experienced by particles due to this mechanism, can only be considered as order of magnitude approximations, but they do suggest that it is the most likely cause of re-entrainment. The bursts are random events and each may cover a relatively large area. There is a wide energy spectrum of turbulence so it must be expected that the energy content of the bursts will vary widely about a mean value, which itself will increase substantially with gas velocity.

When the adhesion force is compared with the mean removal force it is not too surprising that it is difficult to detach particles. However, there is a wide spread of both forces about the mean and it is where the tails of the distributions overlap that re-entrainment occurs, as shown in Figure 4.37.

Large energy bursts will remove weakly adhering particles. Due to the random nature of the bursts the process may continue for a considerable period. The relatively large burst area may be sufficient to encompass several particles. Thus a steady but slowly declining contamination should result from tubes, with an occasional event in which several particles are dislodged simultaneously. If the velocity is suddenly increased the higher energy bursts will rapidly deplete the surface of loosely bound particles until the infrequently occurring high energy tail provides the only removal force. Hence the shape of the two distribution tails will determine the contamination history. These mechanisms are in line with experimental observation.

4.6 ANCILLARY TESTS

4.6.1 Penetration and Re-entrainment using a Dry Aerosol

This part of the experimental programme involved the use of one 5m length of electropolished (6.35 mm) tube.

In order to simulate practical conditions, efforts were made to reduce the amount of water vapour entering the tube with the aerosol. The purpose of this is to test whether the adhesion forces between the particles and the tube wall are affected by the presence of water vapour. In Section 4.4 it was shown that the reduction in relative humidity of the aerosol to 2% did not have a noticeable effect on the subsequent re-entrainment results. This test on the effect of water vapour has now been extended to its limit by using a completely dry aerosol of magnesium oxide, whereas previously the aerosol was formed by evaporating the water from a fine mist of suspension.

The aerosol was formed by igniting a strip of magnesium metal ribbon (using a power source) in dry air to produce a cloud of magnesium oxide aerosol. This aerosol was then passed through the test section at a flowrate of 4 l/min. Table 4.11 shows the experimental conditions and results.

The complete experiment consisted of three stages:-

1) An entrainment test on the 'as delivered' tube was carried out to 60 l/min using clean bottled air. This was to purge the tube and remove any loosely adhering particles.

2) The magnesium oxide aerosol was passed through the tube at a steady rate of 4 l/min to lay down a deposit of particulate contamination.

3) A re-entrainment extended test was carried out using bottled air.

Table 4.12 shows the results of the re-entrainment test. Previous test results are include in the table for comparison. It can be seen from these results that the presence of water vapour does not have a significant effect on the re-entrainment results. Although the percentage re-entrainment is slightly higher, a variation in results is expected because of the small numbers of particles counted and because a different aerosol is used. The differences are not sufficiently great to suggest that the presence of water vapour affected previously reported results.

It is concluded that:

a) The amount of re-entrainment of particulates from all of the tubes is very low - the removal of water vapour introduced into the tube with the air or aerosol has not had a noticeable effect on the results.

b) Once the tubes have been contaminated with aerosol (in the penetration test) there is no detectable difference between any of the different surface finished tubes in terms of particle shedding.

4.6.2 Removal Of Particulates Using Clean Water

This part of the experimental programme involved the use of seven test sections (all of 6.35 mm diameter) as shown in Table 4.13

In the work described in Sections 4.3 and 4.4, aerosol particles were deposited in tubes and then re-entrainment tests were carried out. The extent of particle shedding during these tests was very low. It was therefore decided to water wash the tubes and analyse this water to confirm that particulates had been laid down in the first place.

The CERCCON clean d.i. water system was used for these experiments. Water was passed through the tubes at a flowrate of 0.1 l/min and the number of particles dislodged from the tubes was counted using the PMS laser liquid particle spectrometer (LLPS-X). During the course of the experiment the tube was tapped and vibrated.

The results of these experiments are shown in Table 4.14 and Figures 4.38 - 4.44. It can be seen that there is a large increase in the number of particles being removed from the tubes when water is used.

When water washing the flow in the tubes is laminar so the "turbulent burst" mechanism postulated for particle dislodgement in gas systems is not applicable. Particle drag forces will be increased by a factor of 1000 so it is feasible that particles will roll along the tube wall. If a particle is non-spherical it may be propelled into the fluid stream. The adhesion forces will also be reduced. A combination of these factors result in a much higher proportion of the particles being dislodged.

Comparison of the results of test section (1) with sections (3) & (4) and with (7) & (8) confirms that aerosol had been deposited in the penetration experiments. Many more particles were dislodged from the heavily contaminated tubes. In fact extrapolation of the results indicates a deposit of about 100,000 particles in the size range 0.3 - 0.4 μm diameter per metre length of chemically cleaned tube in its 'as delivered' state. This figure is highly speculative and in any case represents an extremely small fractional coverage of the surface area (5×10^{-7}).

Using water, particle dislodgement from the 'as drawn' tubes is much lower than from the rest, whereas in the tests with air no significant differences could be found. It is suggested that the particle adhesion forces with the 'as drawn' system are such that they are not reduced by the introduction of water i.e. the system is hydrophobic. This may be because the tubes have not been through such an effective degreasing process.

Tapping and vibration have a much more severe effect when water washing than when using gas. Since the particle removal and adhesion forces are much closer, a small change in either will have a more important effect.

It is concluded from this work that:-

a) particles have been deposited during the penetration tests.

b) Water substantially increases particle removal.

c) particles adhere more strongly to the walls of the 'as drawn' tubes.

d) Tapping and vibration both have an effect on the particles being removed in water - this is especially true for the larger particles.

4.6.3 Tube Bends

4.6.3.1 The Effects On Entrainment During Tube Bending

Particle shedding during the process of tube bending has been investigated. This part of the experimental programme has involved the use of three test sections (all 6.35 mm):-

1) One 5m length of clean electropolished tube.

2) One 5m length of clean 'as drawn' tube.

3) One 4m length of clean 'chemically cleaned' tube.

All of the above tubes were purged with clean air at a flowrate of 100 l/min before the tube bending began. This ensured that all of the particles entrained during the experiment had been shed only because of the tubes being bent.

It had been hoped to bend tubes to the smallest radius corresponding to industrial practice. This was to test the most extreme case first - if contamination did not arise then this part of the programme could be curtailed quickly. Unfortunately the constraints imposed by conducting the experiments within the clean cabinet were such that the smallest radius we could practically bend was 1". In the interests of progressing the work we proceeded with this.

The experiments were carried out in two phases. The first phase involved passing clean air at a flowrate of 10 l/min through the tube as it was being bent, and then increasing the flow to 40 l/min and 90 l/min. The initial laminar flow of 10 l/min was chosen so that any particles entrained were due to the tube being bent and not from the effects of turbulence; the higher flowrates of 40 l/min and 90 l/min were used to measure the effects of turbulence. Six bends were put into each tube - one 180° bend and five 90° bends - the bend radius being 1". Tables 4.15 -4.17 show the size distribution of the particulate contamination issuing from each bend and Figures 4.45 - 4.47 show the total contamination above 0.3 μm issuing from each bend in 10 minute periods.

The second phase involved using the standard and extended entrainment tests on each of the tubes when all six bends had been made. The results of these longer term tests are shown in Figures 4.48 - 4.50 in terms of the total particulate contamination above 0.3 μm.

It can be seen from these results that as the tubes are being bent the electropolished tube released the least particulate contamination and the 'as drawn' the most. From the longer term tests, however, it can be seen that all three types of tube release sudden spurts of particles during the course of the experiment.

4.6.3.2 The Effect On Re-entrainment Of Tube Bends

Contamination from another part of the system during the course of the tubes' lifetime is possible. This was investigated by depositing particles onto the tube walls during a penetration test and the subsequent re-entrainment of these deposited particles was investigated.

The penetration tests were carried out by passing an iron oxide aerosol through the test sections at a flowrate of 4 l/min and taking samples alternately from the inlet and outlet sampling chambers at one minute intervals. the penetration of aerosol was found to be 98% for each of the test sections.

An extended re-entrainment test was then carried out on each of the tubes. the results of these tests in terms of the total particulate contamination above 0.3 μm are shown in Figures 4.51 - 4.53. It can be seen from these results that there is little difference in the amount of contamination being re-entrained from each tube. There were ten 90° bends in each 5m length of tube. In any case, the extent of particle re-entrainment is not significantly greater than that from the equivalent straight section.

It must be concluded therefore:

1) The amount of re-entrainment of particulates from all of the bent tubes is very low.

2) Once the tubes have been contaminated with aerosol (in the penetration test) there is not a detectable difference between any of the different surface finishes in terms of particle shedding.

4.6.4 Nitrogen Long-Term Tests

All previous tests in this project have of necessity been carried out over short time periods. A more realistic simulation of operating conditions is to expose the tubes to a dry nitrogen purge over a long period before testing. This work was carried out in parallel with the rest of the programme.

This part of the experimental programme involved the use of ten test sections (all of 6.35 mm) as shown in Table 4.18, which were connected by nine P.T.F.E. lined flexible hoses (Figure 4.54). Nitrogen was passed through all of the tubes in series at a low flowrate (0.75 l/min) for eight hours a day, five days a week. At the end of each month's operation, an hour long entrainment test was carried out on each individual tube - a steady flow of 40 l/min was used - and the tubes are tapped and vibrated. The purpose of testing the tubes at monthly intervals is to determine whether the tube characteristics change with time.

Twelve sets of monthly results have been obtained; Table 4.19 show these results. It can be seen from these results that there are still very few particles removed from the different types of tube, whether they are clean or contaminated. The contaminated as drawn tube, which had released a large number of particles in the early monthly tests, now seems to be comparable to the other types of tubes.

4.7 EFFECT OF PROCESS AND SYSTEMS VARIABLES ON PARTICLE RELEASE

4.7.1 Velocity Effect

In the course of the experimental programme on particle dislodgement the effects of a number of factors were investigated. Tapping, vibrating and flexing the tubes did not have any significant effects on the results, however increasing the velocity and pulsing the flow did have a strong effect. It was decided to investigate the velocity effects further to enable guidelines to be drawn up for tubing installation. Seven test sections have been used for this purpose as shown in Table 4.20.

The re-entrainment tests were carried out by increasing the velocity in stages of 10m/s up to 90m/s for test sections (1)-(3) and (6), in 5m/s stages up to 40m/s for test sections (4) and (5) and 5m/s stages for test section (7).

Tables 4.21 - 4.27 show the results of the re-entrainment tests for all of the test sections at each velocity in terms of the percentage re-entrainment of the deposited iron oxide. The amount of re-entrainment can be seen to be low for each tube size and surface finish.

The results are shown in terms of the total number of particles re-entrained/cubic foot in Figures 4.55 - 4.57 for the 6.35 mm tubes, in Figures 4.58 - 4.59 for the 10 mm o.d. tubes and in 4.63 - 4.64 for the 3.2 mm tubes.

From Figures 4.55 - 4.57 it can be seen that for the new 6.35 mm tubes there is a trend for each of the tubes. At the lower velocities, ie. less than 60m/s, the re-entrainment of particles can be seen to be low; however once 60m/s is reached (Re=18452)the rise in the number of particles being removed is dramatic. This is especially true for the electropolished tube.

With the larger diameter tubes, however, no such trend is observed; the number of particles being removed is quite high and totally random. It may be that a critical velocity (c.f. 60m/s for the 6.35 mm tubes) had not been reached due to the limitations of volume flow on the experiment. The highest velocity achieved with the larger tubes was 40m/s (Re=21220).

Figures 4.60 - 4.61 show the results for the smallest diameter tube (3.2 mm). It can be seen that as the velocity is increased from 10 to 20m/s there is a marked increase in the number of particles removed. This velocity corresponds to the transition from laminar to turbulent flow.

4.7.1.1 Comparison of Different Sized Tubes

Figure 4.62 shows the total number of particles greater than 0.3μm diameter re-entrained/cubic foot of air at each velocity for each size of tube. As stated previously, this shows a critical velocity for the 6.35 mm tube at 60m/s. This velocity could not be reached for the 10 mm o.d. tube due to the constraints of the experimental rig. A sharp rise in the number of particles removed was observed at 20m/s for the 3.2 mm tube.

Figures 4.63 and 4.64 show the results in terms of the cumulative percentage re-entrainment at each velocity for the size ranges 0.3 - 0.5μm and 0.5 - 1.5μm respectively. It can be seen that the re-entrainment is highest from the 3.2 mm tube.

When these same results are plotted against the corresponding Reynold's number (Figure 4.65 and 4.66) it can be seen that for the smallest diameter tube (3.2 mm) the sudden increase occurs around the transition region between laminar and turbulent flow (Re=2100). However for the larger size tubes, particles do not start to be removed until the flow is well into the turbulent regime - the particle dislodgement is so small that it could not be detected at comparably low Reynold's numbers close to transition.

4.7.2 Surface Roughness Effect

In an attempt to determine the reason for the above results, the internal surfaces of a 3.2 mm tube and a 6.35 mm tube were examined using a profilometer. This shows that the internal surface of the 3.2 mm tube has a roughness of 47–50μinch RA, as compared to a 5 - 10μinch RA of an 'as drawn' tube.

To further investigate the effects of surface roughness, two 4m lengths of 12 year old 6.35 mm tube were tested for re-entrainment. These tubes had been used as part of a nitrogen line at British Telecom.

Tables 4.28 and 4.29 show the results of the re-entrainment test for each velocity in terms of the percentage re-entrainment of the deposited iron oxide particles. The amount of re-entrainment is very low and is comparable to previous test results.

Figures 4.67 and 4.68 show the total number of particles re-entrained/cubic foot at each velocity for each 12 year old tube. In contrast with results from earlier tests on new 'as delivered' 0.25" tubes, there does not appear to be a definite velocity at which there is a significant increase of contamination.

Figure 4.69 shows a comparison between these 12 year old tubes and the mean results of the three different sized new tubes (tested previously) in terms of the total number of particles re-entrained/cubic foot of air at each velocity. It can be seen that the results for the 12 year old 0.25" tubes are between those for the new 3.2 mm tube and the new 6.35 mm and 10 mm o.d. tubes. The internal surface of the 12 year old tube has been examined using a profilometer. This shows that the internal roughness of the 12 year old tube has a roughness of 27μinch RA, which also lies between the internal surface roughness values for the 3.2 mm tube (47 - 50μinch) and the new as drawn 6.35 mm tube (5 - 10μinch).

This data covers the range of surface roughness up to 50 μ inch. The work reported earlier in the thesis covered surface finishes, typically used in the I.C. industry, up to a roughness of about 10 μ inch. Clearly roughness is a significant factor, sharply increasing contamination for the poor surfaces examined. Below a roughness of 10 μ inch the effect is not significant.

Table 4.1

ENTRAINMENT RESULTS FROM AN ELECTROPOLISHED TUBE

Sampling Time(mins)	Flow (l/min)	Particle Size (μm) 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
10	40	-	-	-	-	-
10	"	-	-	-	-	-
10	"	-	-	-	-	-
10	"	-	-	-	-	-
10	"	-	-	-	-	-
10	"	-	-	-	-	-
10(add vib'n)	"	-	-	-	-	-
10 "	"	-	-	-	-	-
10 "	"	14	-	-	-	-
10 "	"	14	-	-	-	-
10 "	"	-	-	-	-	-
10 "	"	-	-	-	-	-
10(no vib'n)	"	-	-	-	-	-
10(tap)	"	-	-	-	-	-
10(no tap)	"	-	-	-	-	-
10(tap)	"	14	-	-	-	-
10 "	"	-	-	-	-	-
10(no tap)	"	-	-	-	-	-
10(flex)	"	-	-	-	-	-
10	60	80	60	20	-	-
10(flex)	"	-	-	-	-	-
10(pulse flow)	"	620	60	-	-	-
10	90	1710	990	90	30	30
10(flex)	"	1770	900	60	30	-
10(pulse flow)	"	1260	240	30	-	30
10	"	420	480	-	-	-
10	60	-	-	-	-	-

Table 4.2

ENTRAINMENT RESULTS FROM AN AS DRAWN TUBE

Sampling Time(mins)	Flow (l/min)	Particle Size (μm) 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
10	40	56	28	14	14	-
10	"	14	-	-	-	-
10	"	-	-	-	-	-
10	"	14	-	-	-	-
10	"	-	-	-	-	-
10	"	-	-	-	-	-
10(add vib'n)	"	-	14	-	-	-
10 "	"	14	-	-	-	-
10 "	"	14	28	-	-	-
10 "	"	-	14	-	-	14
10 "	"	-	-	-	-	-
10 "	"	28	-	-	-	-
10(no vib'n)	"	-	-	-	-	-
10(tap)	"	-	-	-	-	-
10(no tap)	"	-	-	-	-	-
10(tap)	"	-	-	-	-	-
10 "	"	14	84	-	-	-
10(no tap)	"	-	-	-	-	-
10(flex)	"	-	-	-	-	-
10	60	20	-	-	-	-
10(flex)	"	60	-	-	-	-
10(pulse flow)	"	20	-	20	-	-
10	90	120	300	60	-	-
10(flex)	"	30	120	-	-	-
10(pulse flow)	"	60	30	120	30	30
10	"	120	210	-	-	-
10	60	20	-	-	-	-

Table 4.3

ENTRAINMENT RESULTS FROM A CHEMICALLY CLEANED TUBE

Sampling Time(mins)	Flow (l/min)	Particle Size (μm) 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
10	40	42	56	42	14	14
10	"	28	-	14	14	-
10	"	14	14	-	-	-
10	"	-	-	-	-	-
10	"	-	-	-	-	-
10	"	-	14	-	-	-
10(add vib'n)	"	14	14	-	-	-
10 "	"	14	-	-	-	-
10 "	"	14	-	-	-	-
10 "	"	-	-	14	-	-
10 "	"	-	-	14	-	-
10 "	"	-	-	-	-	-
10(no vib'n)	"	-	-	-	-	-
10(tap)	"	-	-	-	-	-
10(no tap)	"	-	-	-	-	-
10(tap)	"	-	-	-	-	-
10 "	"	-	-	-	-	-
10(no tap)	"	-	-	-	-	-
10(flex)	"	-	-	-	-	-
10	60	100	180	120	40	-
10(flex)	"	-	-	-	20	-
10(pulse flow)	"	60	60	20	-	-
10	90	180	300	90	-	-
10(flex)	"	120	360	-	-	-
10(pulse flow)	"	150	-	240	-	-
10	"	150	390	30	-	-
10	60	-	20	-	-	-

Table 4.4

TOTAL CONTAMINATION ISSUING FROM EACH TUBE PER CUBIC FOOT OF AIR

Surface Finish of Tube	Total Number of Particles Entrained/cu.ft 40l/min	α	60l/min	α	90l/min	α
Electropolished	0.7		13.5		35.1	
"	0.14		4		47.5	
"	0.525					
Average taken of above 3 to determine α=1	0.455	1	8.75	1	41	1
As Drawn, cleaned	1.26	2.8	18.5	2.24	84	2.05
"	1.4	3.1	2	0.24	10.5	0.26
"	8.96	19.7				
"	8.4	18.5				
"	1.82	4				
"	3.64	8				
Chemically Cleaned	1.82	4	14.5	1.76	23.5	0.59
" "	47.62	105	714	87	250	6.1
" "	6.86	15	165	20	233	5.7
" "	1.39	3	11.5	1.4	10	0.24
As Drawn, uncleaned	35	77				
"	43.4	95				
"	65.8	145				
"	39.2	86				

$\alpha = \dfrac{\text{contamination from tube}}{\text{contamination from electropolished tube}}$

Table 4.5

TOTAL NUMBERS ENTRAINED FROM TUBE IN 10 MINUTES*

	Electropolished	As Drawn	Chem. Cleaned
1) Velocity (40m/s)	6	64	37
" (60m/s)	175	205	1264
" (90m/s)	1230	1410	2670
2) Vibration (40m/s)	11.5	26	17
3) Gentle tap (40m/s)	3.5	14	5.3
4) Flex (40m/s)	-	7	5.3
5) Pulsed Flow	505	960	1649

* Average values over length of run

Table 4.6

EXPERIMENTAL CONDITIONS FOR THE PENETRATION TESTS

Flowrate (l/min)	Velocity (m/s)	Reynold's Number
4	4	1414
13.5	13.5	4774

Table 4.7

RESULTS OF PENETRATION TESTS

Particle Diameter (μm)	No. of Tests	Flow (l/min)	Surface Finish of Tubing	Mean Penetration Results(all within 95% of the mean)
0.369	24	4	Electropolished	96.9 ± 0.7
"	14	"	Chemically Cleaned	97.1 ± 0.26
"	16	"	As Drawn	98.2 ± 0.92
"	8	"	Flexible Hose	99.82 ± 0.014
"		"	Theoretically Smooth Tube	99.43
"	12	13.5	Electropolished	97.2 ± 1.28
"	11	"	Chemically Cleaned	98.1 ± 0.4
"	9	"	As Drawn	97.6 ± 1
"	9	"	Flexible Hose	98.1 ± 0.2
"		"	Theoretically Smooth Tube	98.6
0.726	24	4	Electropolished	97.5 ± 0.74
"	14	"	Chemically Cleaned	96.1 ± 0.09
"	16	"	As Drawn	96.9 ± 0
"	8	"	Flexible Hose	100 ± 0
"		"	Theoretically Smooth Tube	98.9
"	12	13.5	Electropolished	98.7 ± 0.18
"	11	"	Chemically Cleaned	98.21 ± 0.66
"	9	"	As drawn	97.8 ± 0.66
"	9	"	Flexible Hose	97.1 ± 1.52
"		"	Theoretically Smooth Tube	98.7

Table 4.8

EXPERIMENTAL CONDITIONS AND RESULTS FOR THE PENETRATION TESTS

Test Section	Flow (l/min)	Relative Humidity of Aerosol (%)	Aerosol Used	No. of Particles Deposited (98% Penetration) (1)	% Coverage of Internal Surface of Tube Wall (2)
1	4	14	Latex (1.09μm)	170000	1.3×10^{-4}
1	4	14	Iron Oxide (0.2-1μm)	240000	1.9×10^{-4}
1	5	20	" "	350000000	0.28
2	5	20	" "	16000000	0.013
3	5	20	" "	15000000	0.013
4	11	2	" "	32000000	0.063

Note (1) Calculated deposition based on a 2% deposition efficiency.

(2) Calculated on the basis of 1μm diameter particles. The probability of a particle colliding with another on the wall is about 9 times the coverage.

<u>Table 4.9</u>

<u>DIFFUSIONAL AND GRAVITATIONAL SETTLING TIMES OF SUSPENDED PARTICLES</u>

Particle Diameter (μm)	Tube Radius (m)	Diffusivity (m^2/s)	Time for Particle to Diffuse to Tube Wall (secs)	Terminal Settling Velocity (m/s)	Settling Time (secs)
0.369	0.0023	9.75×10^{-11}	37979 = 10 hours	6×10^{-6}	383
0.726	0.0023	4.09×10^{-11}	90538 = 25 hours	19.6×10^{-6}	117

Table 4.10

Test Section	Type of Re-entrainment Test Used	Type of Aerosol Used	Number of Particles Deposited	Number Counted Re-entrained	% Re-entrained	Number Counted Re-entrained	% Re-entrained
				Electropolished Tube		As drawn Tube	
Compressed Air Line Used							
1	Standard 40l/min	Latex	170000	2	1.5×10^{-2}	5	3.7×10^{-2}
1	" "	Iron Oxide	240000	22	1.1×10^{-1}	9	5×10^{-2}
1	" "	" "	350000000	142	6.5×10^{-3}	77	3.5×10^{-3}
Bottled Air Used							
2	Standard 40l/min	" "	16000000	10	8×10^{-4}	18	1.4×10^{-3}
2	Extended 60l/min	" "	"	54	6.8×10^{-3}	33	4.1×10^{-3}
						Chemically Cleaned Tube	
3	Standard 40l/min	" "	15000000	46	4.5×10^{-3}	24	2.4×10^{-3}
3	Extended 60l/min	" "	"	41	6.4×10^{-3}	98	1.5×10^{-2}
4	Standard 40l/min	" "	32000000	-	-	17	6.7×10^{-4}
4	Extended 60l/min	" "	"	-	-	30	2.1×10^{-3}

Table 4.11

EXPERIMENTAL CONDITIONS AND PENETRATION RESULTS USING A DRY AEROSOL

Flowrate (l/min)	Aerosol Used	No. of Particles Deposited(98% Penetration)	% Coverage of Internal Surface of Tube Wall
4	Magnesium Oxide	6980000	0.011

Table 4.12

Re-entrainment Results

Test Section	Type of Re-entrainment Test Used	Type of Aerosol Used	Number of Particles Deposited	Number Counted Re-entrained	% Re-entrained	Number Counted Re-entrained	% Re-entrained
				Electropolished Tube		As drawn Tube	
Compressed Air Line Used							
1	Standard 40l/min	Latex	170000	2	1.5×10^{-2}	5	3.7×10^{-2}
1	" "	Iron Oxide	240000	22	1.1×10^{-1}	9	5×10^{-2}
1	" "	" "	350000000	142	6.5×10^{-3}	77	3.5×10^{-3}
Bottled Air Used							
2	Standard 40l/min	" "	16000000	10	8×10^{-4}	18	1.4×10^{-3}
2	Extended 60l/min	" "	"	54	6.8×10^{-3}	33	4.1×10^{-3}
						Chemically Cleaned Tube	
3	Standard 40l/min	" "	15000000	46	4.5×10^{-3}	24	2.4×10^{-3}
3	Extended 60l/min	" "	"	41	6.4×10^{-3}	98	1.5×10^{-2}
4	Standard 40l/min	" "	32000000	-	-	17	6.7×10^{-4}
4	Extended 60l/min	" "	"	-	-	30	2.1×10^{-3}
5	Standard 40l/min	Magnesium Oxide	6980000	79	1.4×10^{-2}		
5	Extended 60l/min	" "	"	52	1.5×10^{-2}		

Table 4.13

SECTIONS TESTED WITH D.I. WATER

1) One 5m length of electropolished tube (contaminated with 350 million particles of latex and iron oxide).

2) One 5m length of 'as drawn' tube (contaminated with 350 million particles of latex and iron oxide).

3) One 4m length of 'chemically cleaned' tube (contaminated with 32 million particles of iron oxide).

4) One 4m length of 'chemically cleaned' tube (contaminated with 16 million particles of iron oxide).

5) One 5m length of 'as drawn' tube (as delivered).

6) One 4m length of 'chemically cleaned' tube (as delivered).

7) One 4m length of 'chemically cleaned' tube (as delivered).

Table 4.14

PARTICLES REMOVED IN THE FIRST FIVE MINUTES OF WATER WASHING

IN THE SIZE RANGE 0.3 -0.4 μm

	Test No.	Particles Deposited (million)	Particles Removed (million)	Particles Removed/ Particles Deposited
DIRTY TUBES				
Electropolished	1	350	1.28	0.0037
As Drawn	2	350	0.0017	0.0000048
Chem. Cleaned	3	16	0.188	0.0059
" "	4	32	0.117	0.0037
As Drawn	5	16	0.0021	0.00013
CLEAN TUBES				
As Drawn	6	-	0.0017	
Chem. Cleaned	7	-	0.0071	
" "	8	-	0.0055	

Table 4.15

PARTICLE CONTAMINATION ISSUING DURING TUBE BENDING

ELECTROPOLISHED TUBE

Time (mins)	Flow (l/min)	Angle of Bend (°)	No. of Particles 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μm
10	10	180	3	6	6	6	-
10	40	"	-	-	-	14	-
10	90	"	-	-	-	-	-
10	10	90	-	-	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	-	-	-
10	10	90	-	-	-	-	-
10	40	"	14	-	-	-	-
10	90	"	-	-	-	-	-
10	10	90	-	-	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	-	-	-
10	10	90	-	-	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	-	-	-
10	10	90	-	-	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	-	-	-

Table 4.16

PARTICLE CONTAMINATION ISSUING DURING TUBE BENDING

CHEMICALLY CLEANED TUBE

Time (mins)	Flow (l/min)	Angle of Bend (°)	No. of Particles 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μm
10	10	180	147	45	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	-	-	-
10	10	90	45	-	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	32	-	-
10	10	90	12	18	-	-	-
10	40	"	-	-	-	-	-
10	90	"	288	384	32	-	-
10	10	90	63	18	-	-	-
10	40	"	-	14	-	-	-
10	90	"	-	-	-	-	-
10	10	90	84	45	3	-	-
10	40	"	-	-	-	-	-
10	90	"	64	-	-	-	-
10	10	90	9	9	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	1	1	-	-

Table 4.17

PARTICLE CONTAMINATION ISSUING DURING TUBE BENDING

AS DRAWN TUBE

Time (mins)	Flow (l/min)	Angle of Bend (°)	No. of Particles 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μm
10	10	180	408	150	9	-	3
10	40	"	-	-	-	-	-
10	90	"	32	128	32	-	-
10	10	90	228	144	3	-	-
10	40	"	-	-	14	-	-
10	90	"	96	160	96	-	-
10	10	90	33	3	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	-	-	-
10	10	90	185	81	-	-	-
10	40	"	-	-	-	-	-
10	90	"	96	-	-	-	-
10	10	90	63	9	-	-	-
10	40	"	-	-	-	-	-
10	90	"	-	-	-	-	-
10	10	90	36	30	12	-	3
10	40	"	-	-	-	-	-
10	90	"	32	96	-	-	-

Table 4.18

LONG TERM NITROGEN TESTS

1) One 5m length of electropolished tube (as delivered).

2) One 5m length of electropolished tube (as delivered).

3) One 5m length of 'as drawn' tube (as delivered).

4) One 5m length of 'as drawn' tube (as delivered).

5) One 4m length of 'chemically cleaned' tube (as delivered).

6) One 4m length of 'chemically cleaned' tube (as delivered).

7) One 5m length of electropolished tube (contaminated with 16 million particles of iron oxide).

8) One 5m length of 'as drawn' tube (contaminated with 16 million particles of iron oxide).

9) One 5m length of 'as drawn' tube (contaminated with 16 million particles of iron oxide).

10) One 4m length of 'chemically cleaned' tube (contaminated with 16 million particles of iron oxide).

<u>Table 4.19</u>

Long Term Nitrogen Tests

Total number of particles removed during a standard Test at Monthly Intervals

Type of Tube		1mth	2mths	3mths	4mths	5mths	6mths	7mths	8mths	9mths	10mths	11mths	12mths
Electropolished	- Clean	-	28	28	-	28	56	56	42	70	84	28	14
"	- "	14	28	42	28	56	56	70	56	42	84	28	84
"	- Dirty	-	42	14	14	42	28	14	56	56	14	28	56
Chem. Cleaned	- Clean	28	28	14	56	42	84	14	56	42	70	42	28
"	- "	70	42	56	14	28	70	42	56	28	28	56	70
"	- Dirty	70	42	28	-	28	28	42	70	42	84	28	70
As Drawn	- Clean	70	28	14	70	28	70	70	56	42	14	42	42
"	- "	56	14	42	-	70	28	28	56	42	84	56	28
"	- Dirty	1184	700	252	98	70	14	-	56	56	28	56	42
" *	- "	14	14	42	42	42	28	56	42	84	42	28	

Table 4.20

TEST SECTIONS USED TO TEST THE EFFECT OF VELOCITY ON PARTICLE RELEASE

1) One 5m length of Electropolished Tube (6.35 mm)

2) One 5m length of As Drawn Tube (6.35 mm)

3) One 5m length of Chemically Cleaned Tube (6.35 mm)

4) One 4m length of Electropolished Tube (10 mm o.d.)

5) One 4m length of Electropolished Tube (10 mm o.d.)

6) One 6m length of Chemically Cleaned Tube (3.2 mm)

7) One 7m length of Chemically Cleaned Tube (3.2 mm)

Table 4.21

RE-ENTRAINMENT TEST ON 6.35 MM O.D. ELECTROPOLISHED TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
10	3	1.9×10^{-5}
20	-	-
30	-	-
40	-	-
50	54	3.4×10^{-4}
60	84	5.4×10^{-4}
70	200	1.3×10^{-3}
80	171	1.1×10^{-3}
90	800	5.1×10^{-3}
100	2024	1.3×10^{-2}

Table 4.22

RE-ENTRAINMENT TEST ON 6.35 MM O.D. AS DRAWN TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
10	-	-
20	14	8.9×10^{-5}
30	22	1.4×10^{-4}
40	28	1.8×10^{-4}
50	18	1.1×10^{-4}
60	84	5.4×10^{-4}
70	25	1.6×10^{-4}
80	86	5.5×10^{-4}
90	256	1.6×10^{-3}
100	213	1.4×10^{-3}

Table 4.23

RE-ENTRAINMENT TEST ON 6.35 MM O.D. CHEMICALLY CLEANED TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
10	3	2×10^{-5}
20	7	4×10^{-5}
30	11	7×10^{-5}
40	42	2.7×10^{-4}
50	36	2.3×10^{-4}
60	42	2.7×10^{-4}
70	125	8×10^{-4}
80	171	1.1×10^{-3}
90	192	1.2×10^{-3}
100	533	3.4×10^{-3}

Table 4.24

RE-ENTRAINMENT TEST ON 10 MM O.D. ELECTROPOLISHED TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
5	-	-
10	10	1.7×10^{-4}
15	15	2.5×10^{-4}
20	-	-
25	125	2.1×10^{-3}
30	330	5.5×10^{-3}
35	210	3.5×10^{-3}
40	240	4×10^{-3}

Table 4.25

RE-ENTRAINMENT TEST ON 10 MM O.D. ELECTROPOLISHED TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
5	-	-
10	110	1.8×10^{-3}
15	30	5×10^{-4}
20	80	1.3×10^{-3}
25	700	1.2×10^{-2}
30	30	5×10^{-4}
35	210	3.5×10^{-3}
40	240	4×10^{-3}

Table 4.26

RE-ENTRAINMENT TEST ON 3.2 MM O.D. CHEMICALLY CLEANED TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
10	18	4.3×10^{-5}
20	2628	6.3×10^{-3}
30	185	4.4×10^{-4}
40	436	1×10^{-3}
50	350	8.4×10^{-4}
60	1196	2.9×10^{-3}
70	1319	3.2×10^{-3}
80	1516	3.6×10^{-3}
90	2249	5.4×10^{-3}

Table 4.27

RE-ENTRAINMENT TEST ON 2ND 3.2 MM O.D. CHEMICALLY CLEANED TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
5	4	7.8×10^{-6}
10	41	8×10^{-5}
15	4604	9×10^{-3}
20	35334	6.9×10^{-2}
25	4239	8.3×10^{-3}
30	4349	8.5×10^{-3}
35	2299	4.5×10^{-3}
40	6118	1.2×10^{-2}
45	10273	2×10^{-2}
50	8734	1.9×10^{-2}
55	5937	1.2×10^{-2}
60	10304	2×10^{-2}
65	9645	1.9×10^{-2}
70	10133	2×10^{-2}
75	5774	1.1×10^{-2}
80	12132	2.4×10^{-2}
85	8219	1.6×10^{-2}
90	12802	2.5×10^{-2}

Table 4.28

RE-ENTRAINMENT TEST ON 6.35 MM O.D. 12 YEAR OLD TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
5	5	4.5×10^{-6}
10	30	2.7×10^{-5}
20	200	1.8×10^{-4}
30	730	6.6×10^{-4}
40	973	8.8×10^{-4}
50	1750	1.6×10^{-3}
60	820	7.4×10^{-4}
70	2357	2.1×10^{-3}
80	1707	1.6×10^{-3}
90	3840	3.5×10^{-3}

Table 4.29

RE-ENTRAINMENT TEST ON 2ND 6.35 MM O.D. 12 YEAR OLD TUBE

Velocity (m/s)	Total Number of Particles Re-entrained > 0.3μm	% Re-entrained
5	2	6.2×10^{-6}
10	55	1.1×10^{-4}
20	234	4.8×10^{-4}
30	112	2.3×10^{-4}
40	90	1.9×10^{-4}
50	287	5.9×10^{-4}
60	189	3.9×10^{-4}
70	213	4.4×10^{-4}
80	143	3×10^{-4}
90	827	1.7×10^{-3}

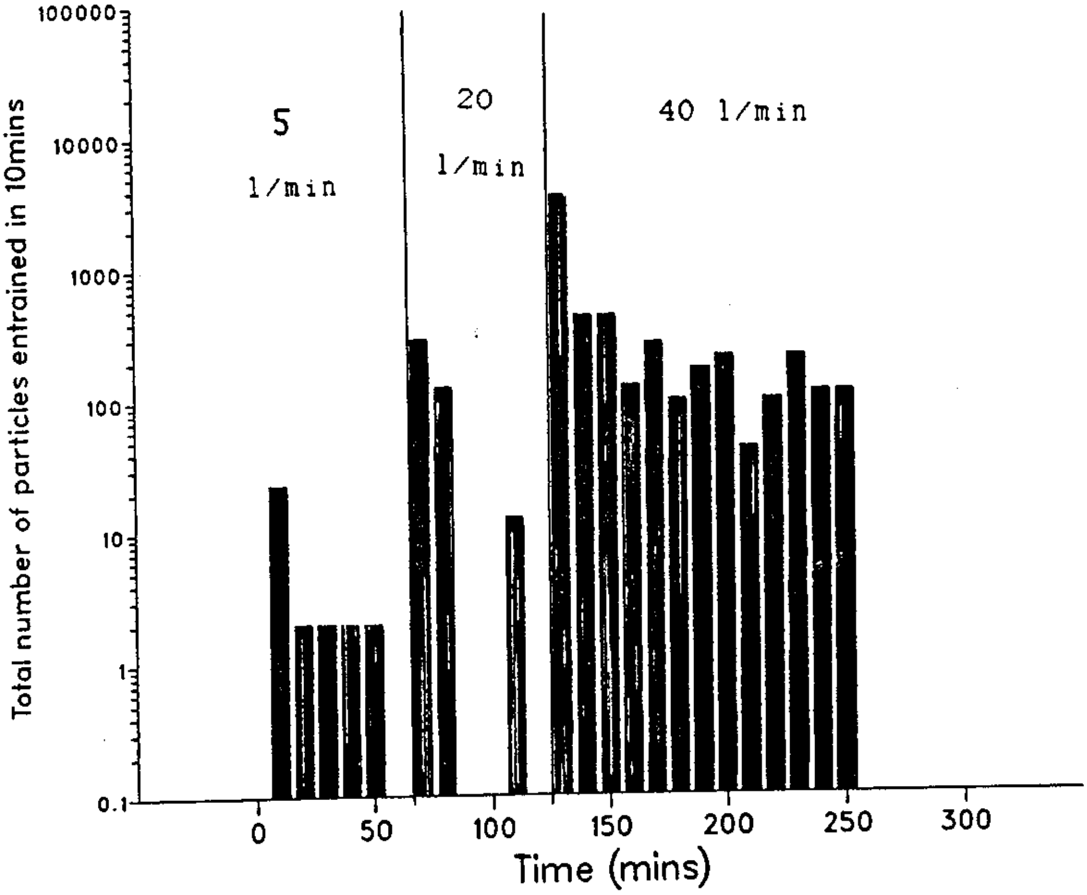

FIGURE 4.1 - ENTRAINMENT TEST ON 1ST UNCLEANED STAINLESS STEEL TUBE

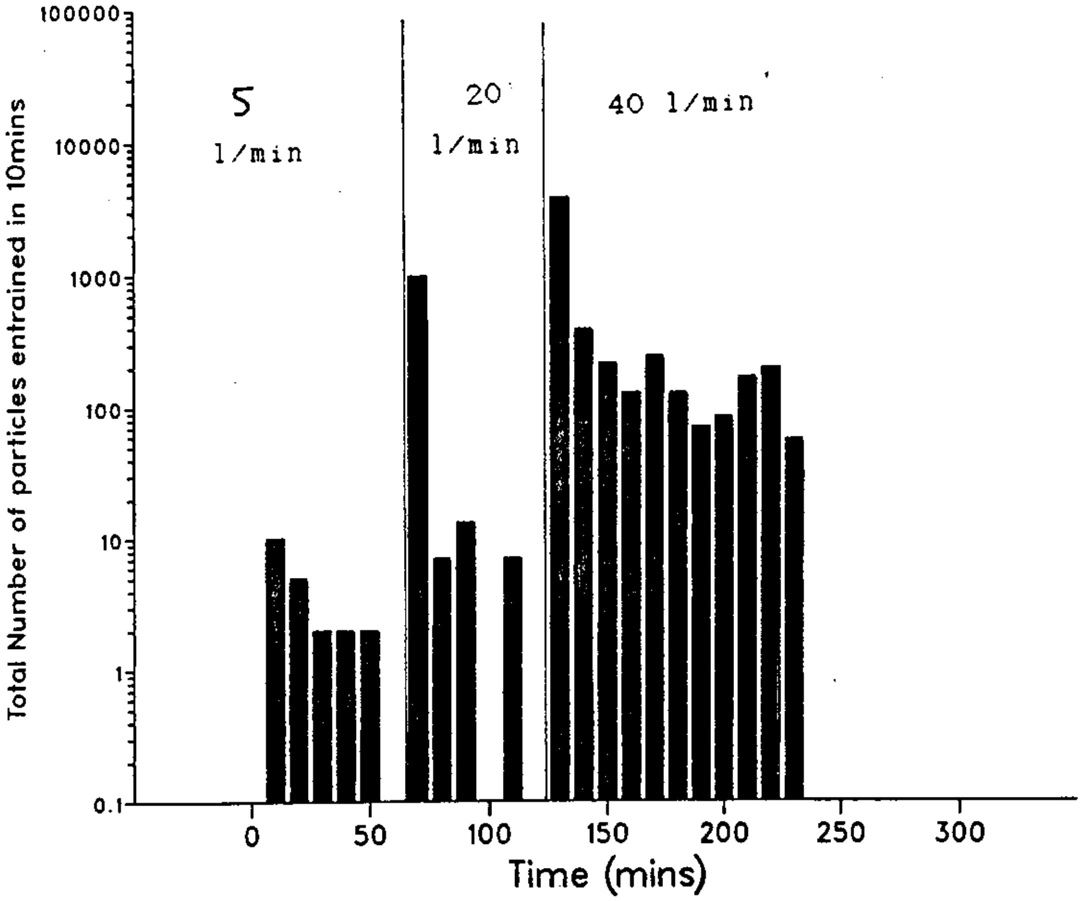

FIGURE 4.2 - ENTRAINMENT TEST ON 2ND UNCLEANED STAINLESS STEEL TUBE

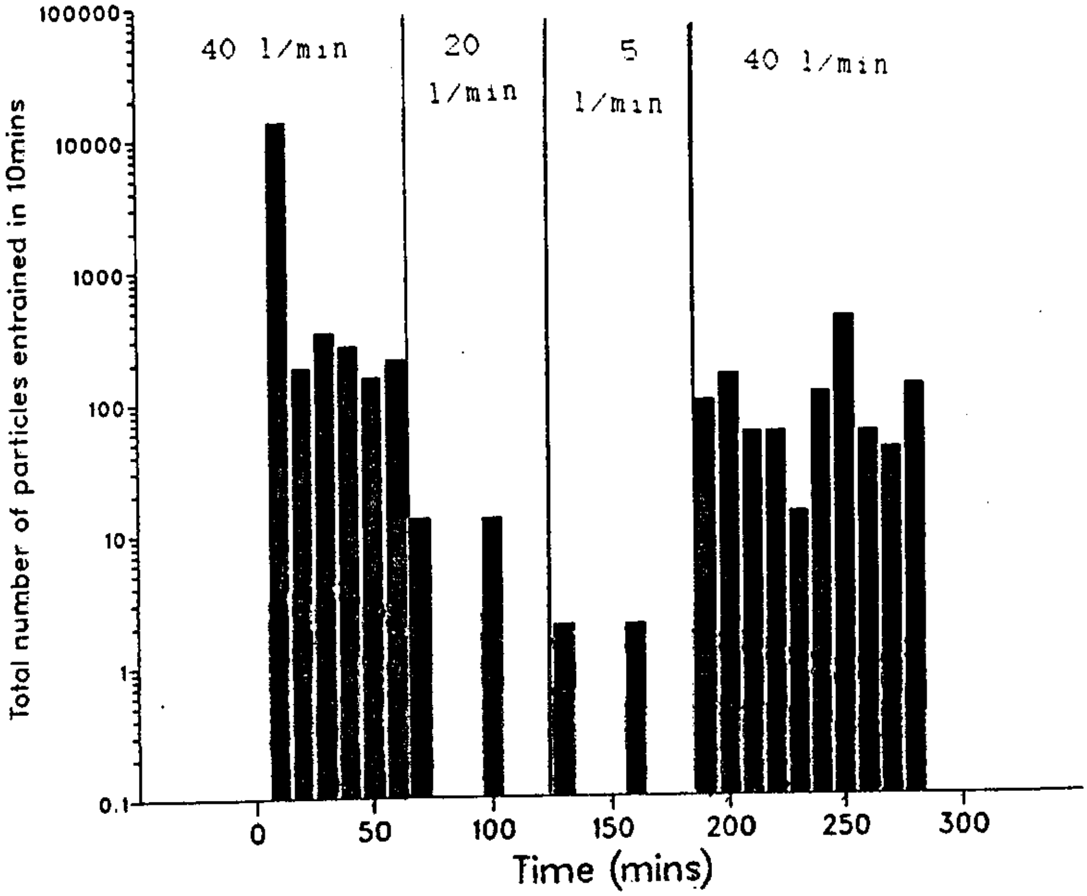

FIGURE 4.3 - ENTRAINMENT TEST ON 3RD UNCLEANED STAINLESS STEEL TUBE

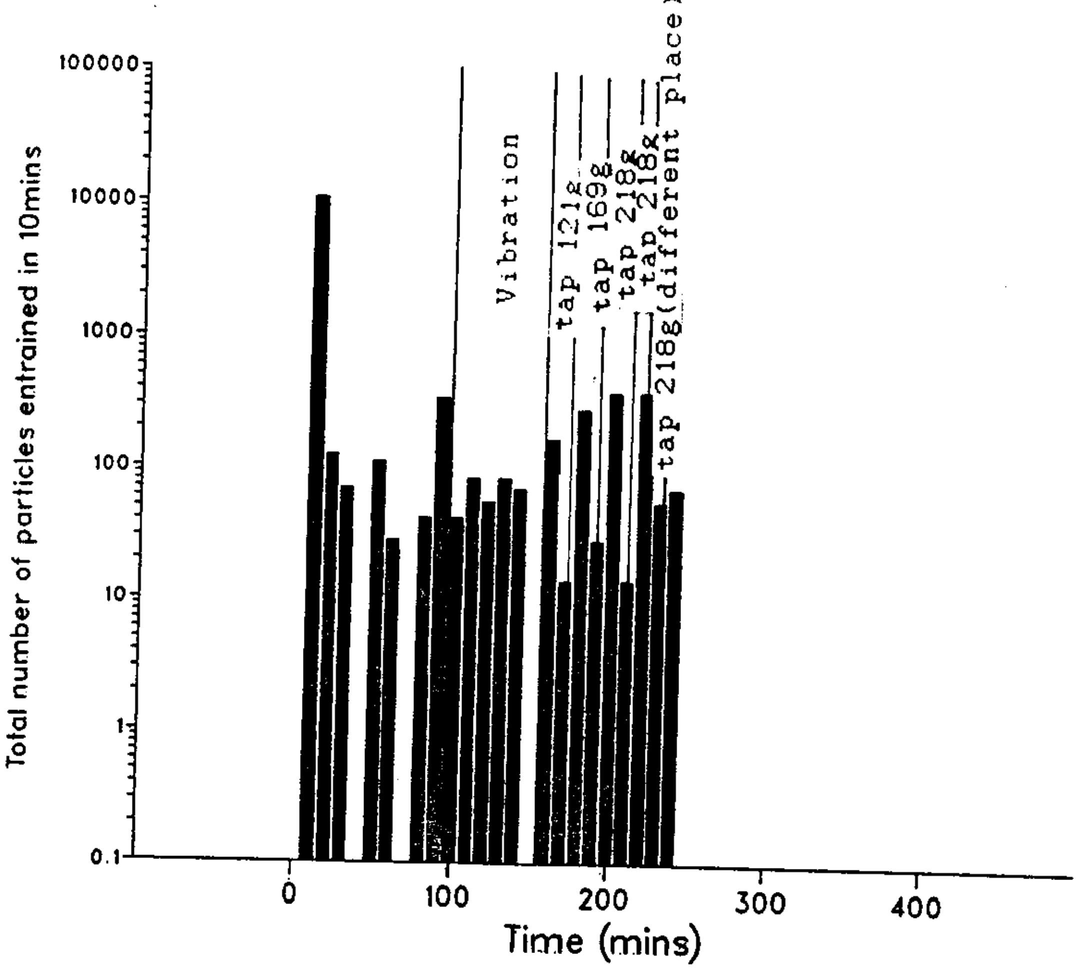

FIGURE 4.4 - ENTRAINMENT TEST ON 4TH UNCLEANED STAINLESS STEEL TUBE

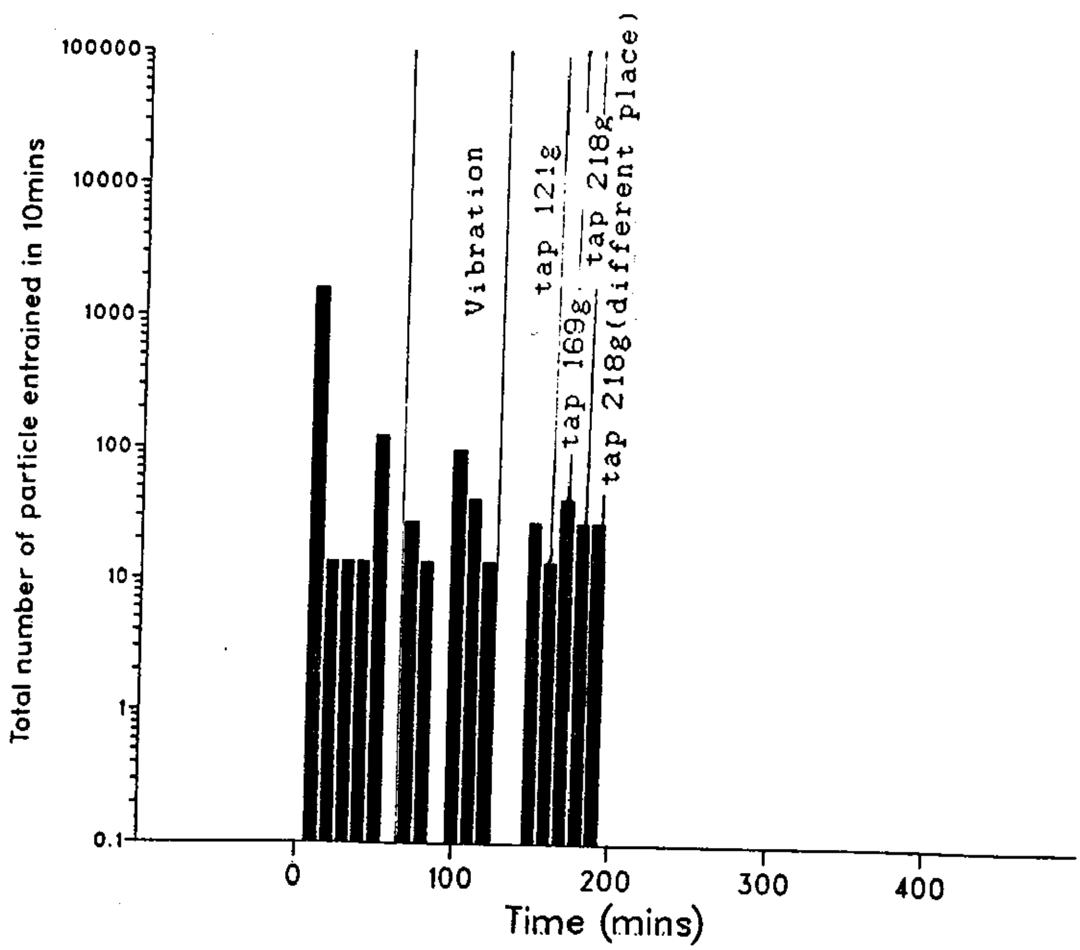

FIGURE 4.5 - ENTRAINMENT TEST ON 1ST AS DRAWN TUBE

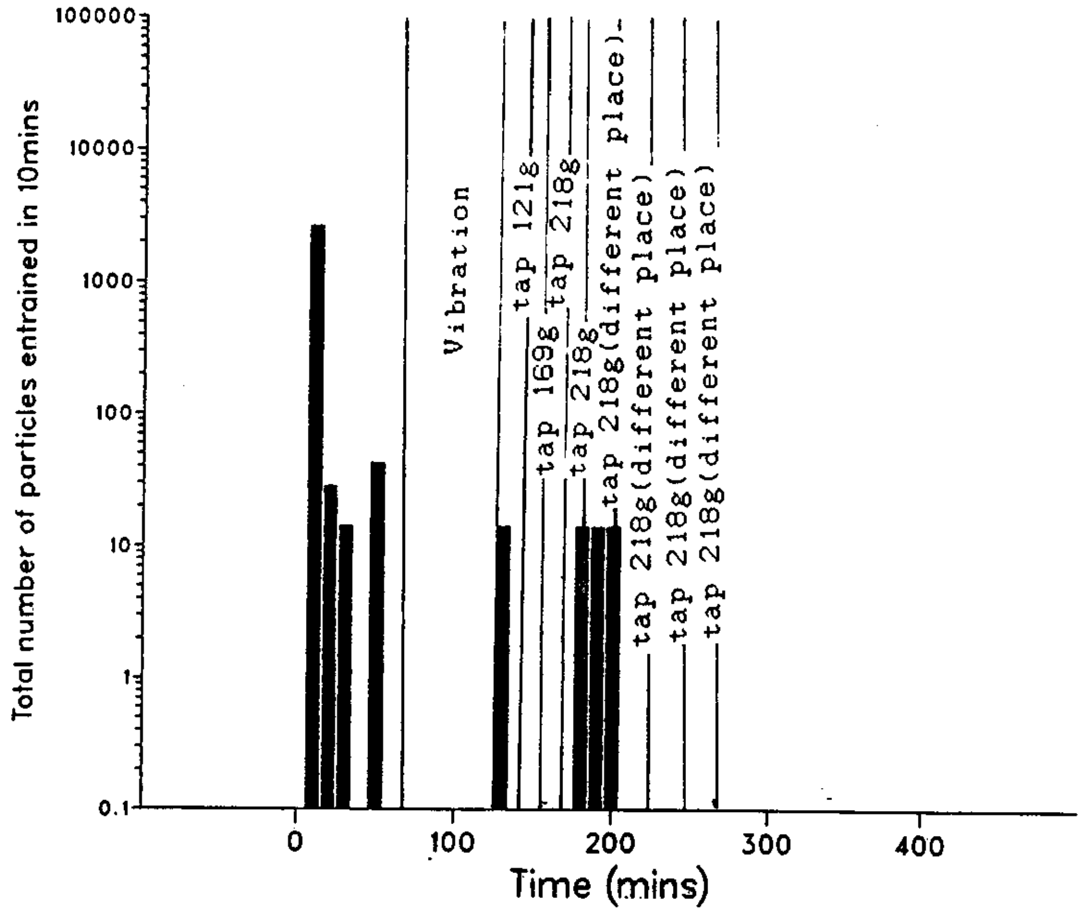

FIGURE 4.6 - ENTRAINMENT TEST ON 2ND AS DRAWN TUBE

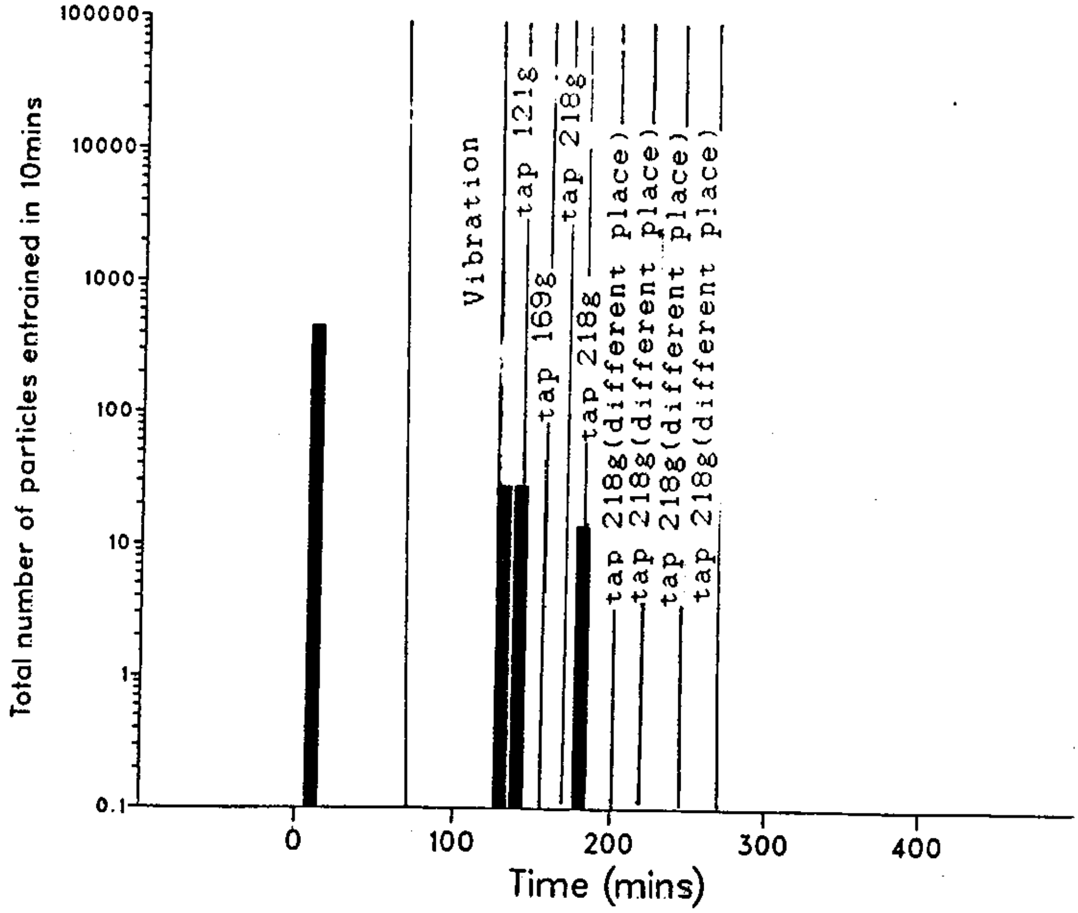

FIGURE 4.7 - ENTRAINMENT TEST ON 3RD AS DRAWN TUBE

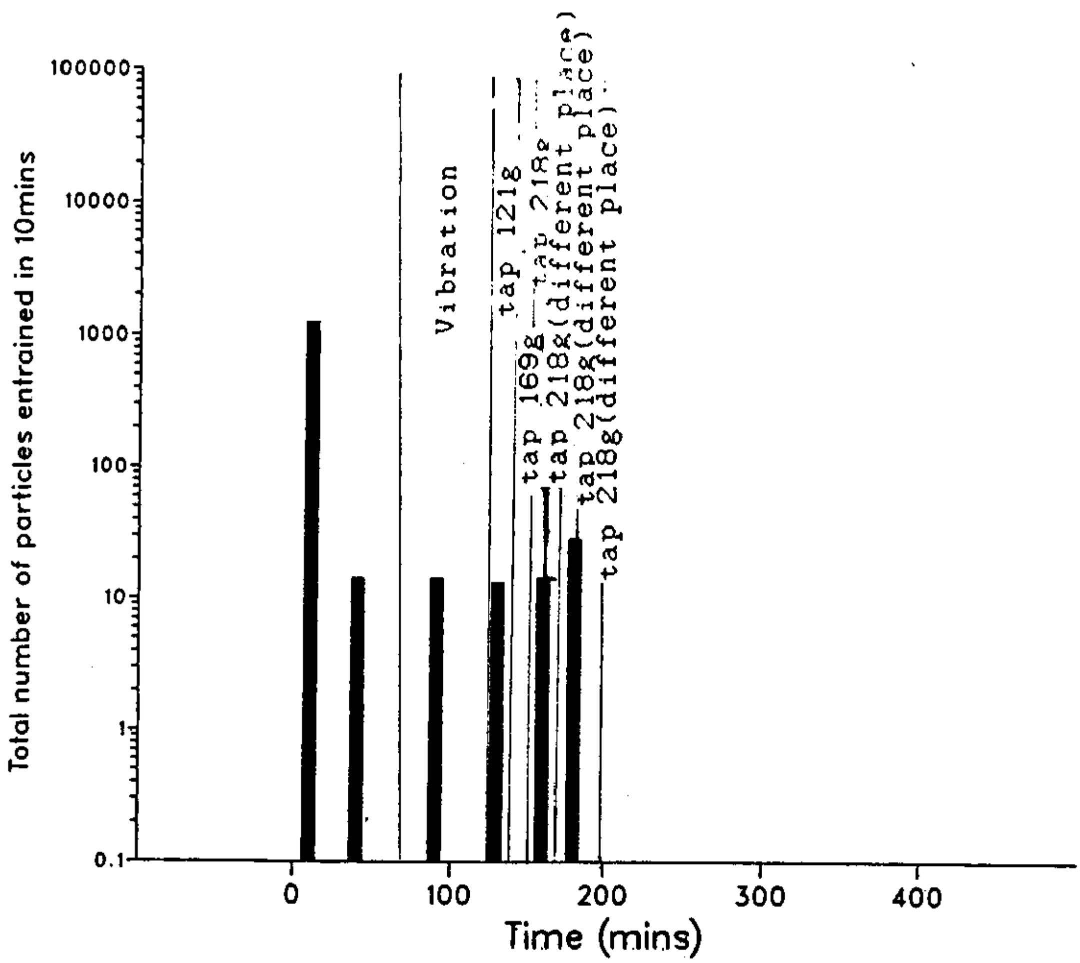

FIGURE 4.8 - ENTRAINMENT TEST ON 4TH AS DRAWN TUBE

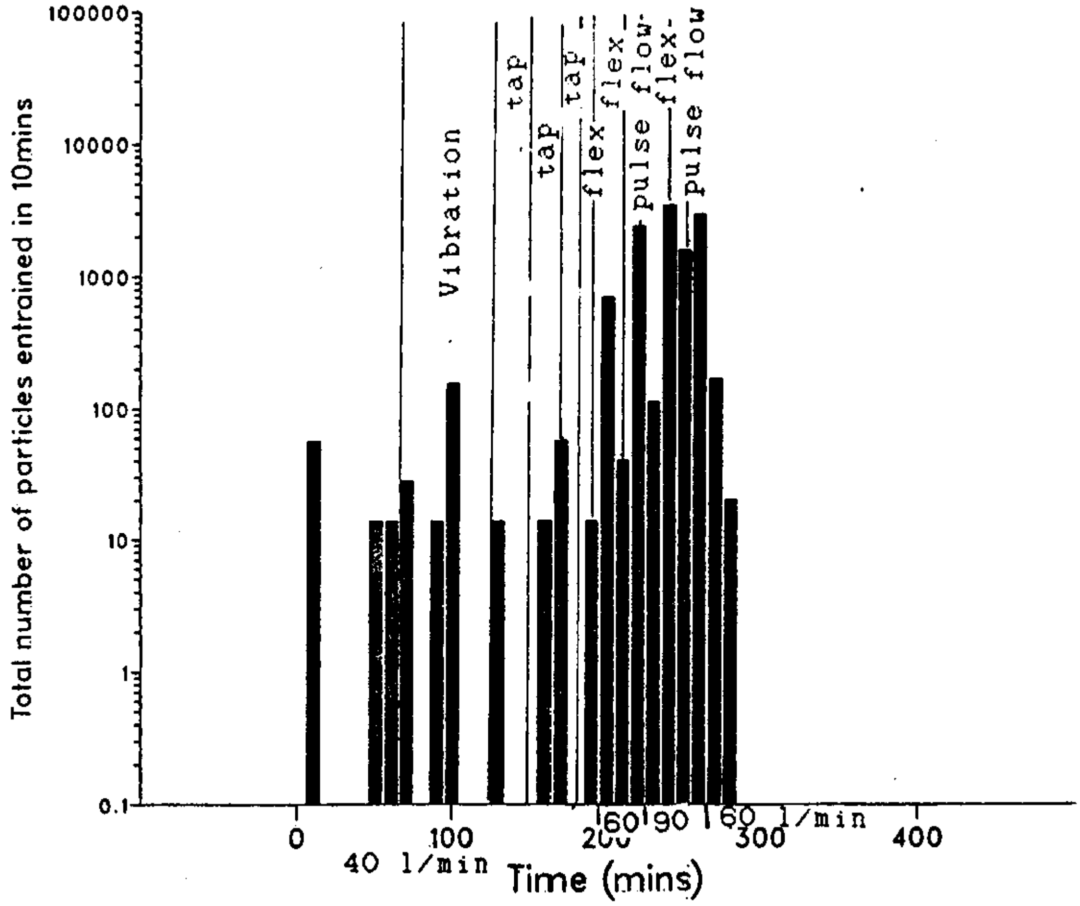

FIGURE 4.9 - ENTRAINMENT TEST ON 5TH AS DRAWN TUBE

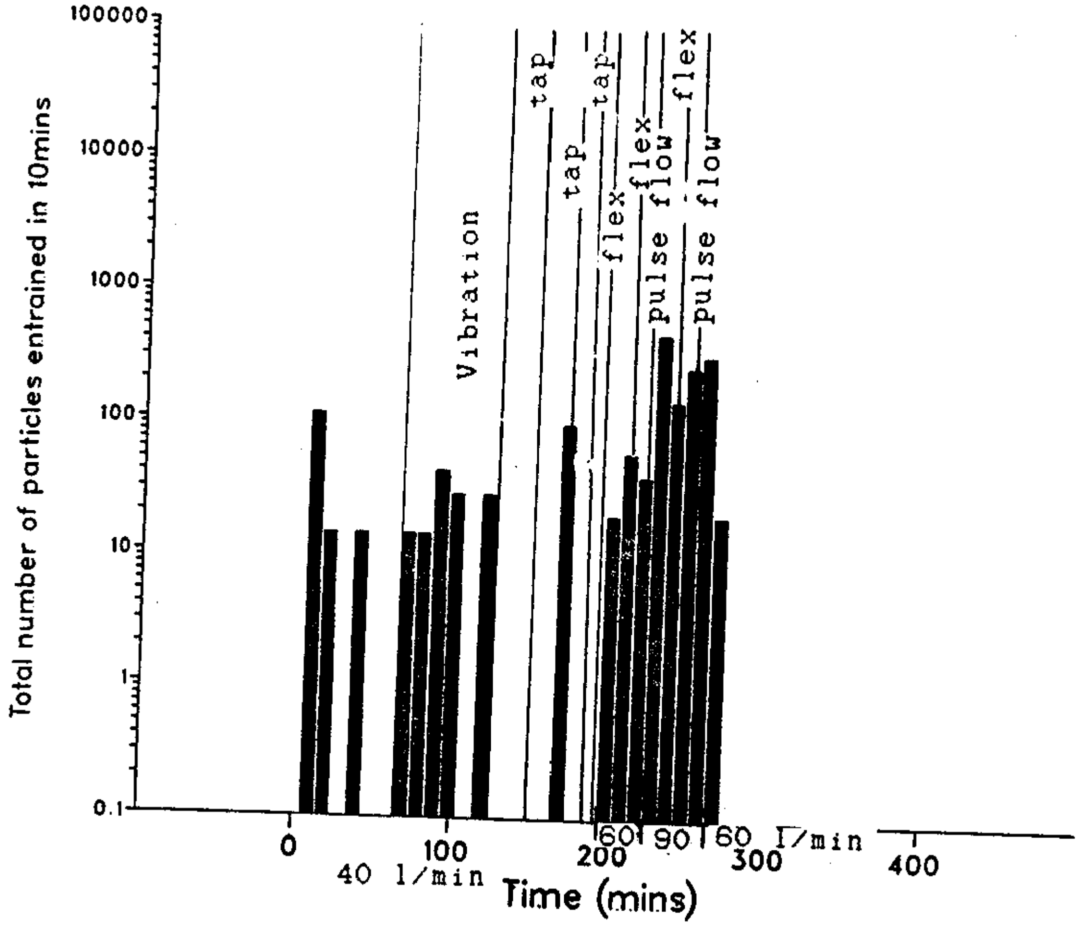

FIGURE 4.10 - ENTRAINMENT TEST ON 6TH AS DRAWN TUBE

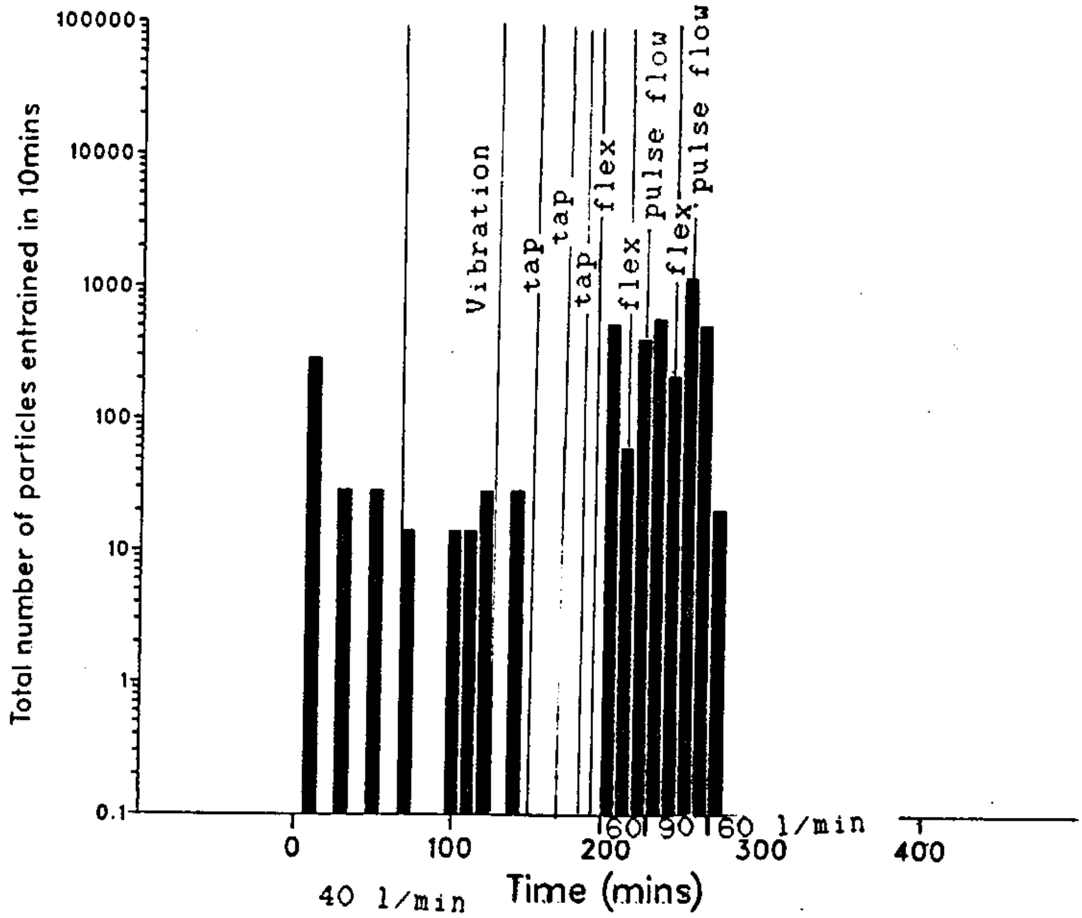

FIGURE 4.11 - ENTRAINMENT TEST ON 1ST CHEMICALLY CLEANED TUBE

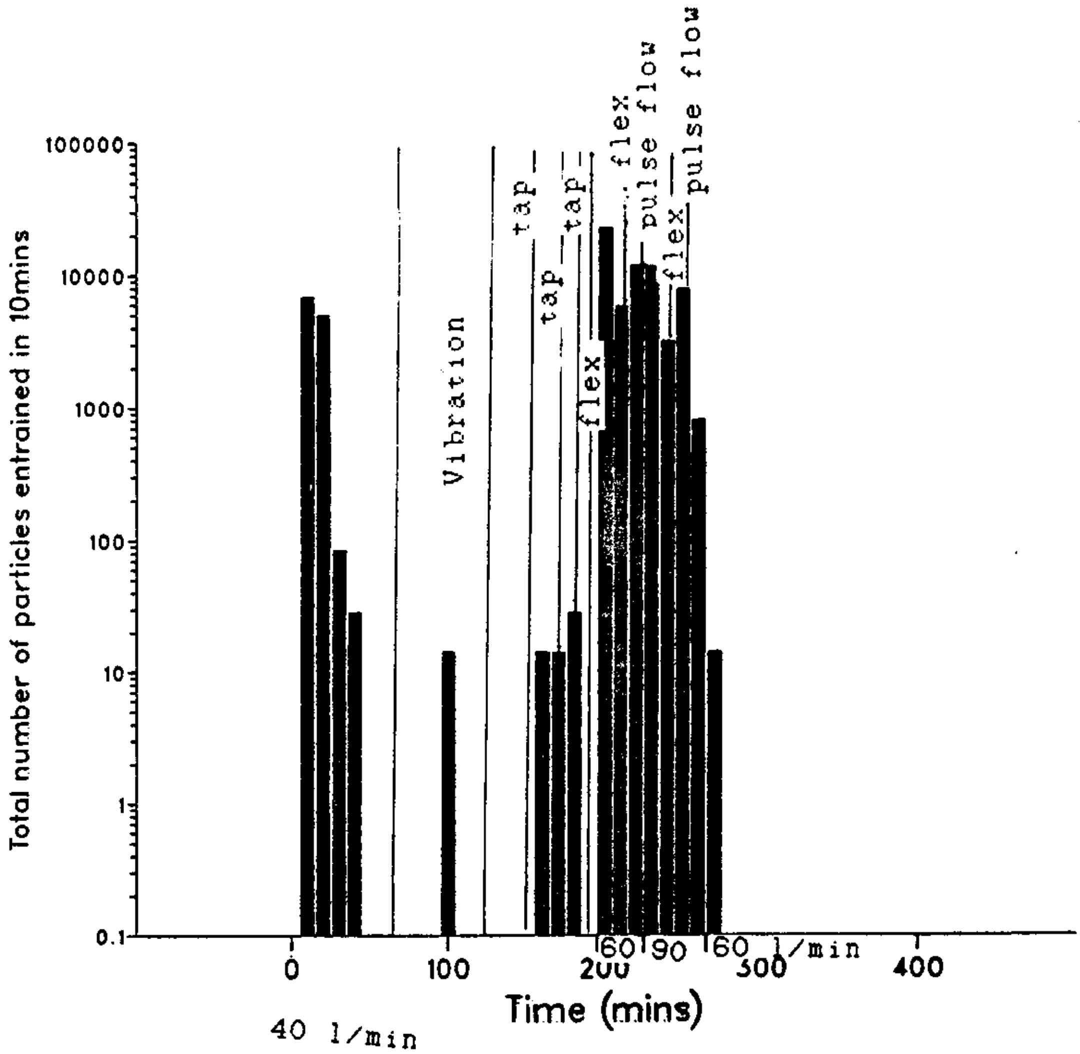

FIGURE 4.12 - ENTRAINMENT TEST ON 2ND CHEMICALLY CLEANED TUBE

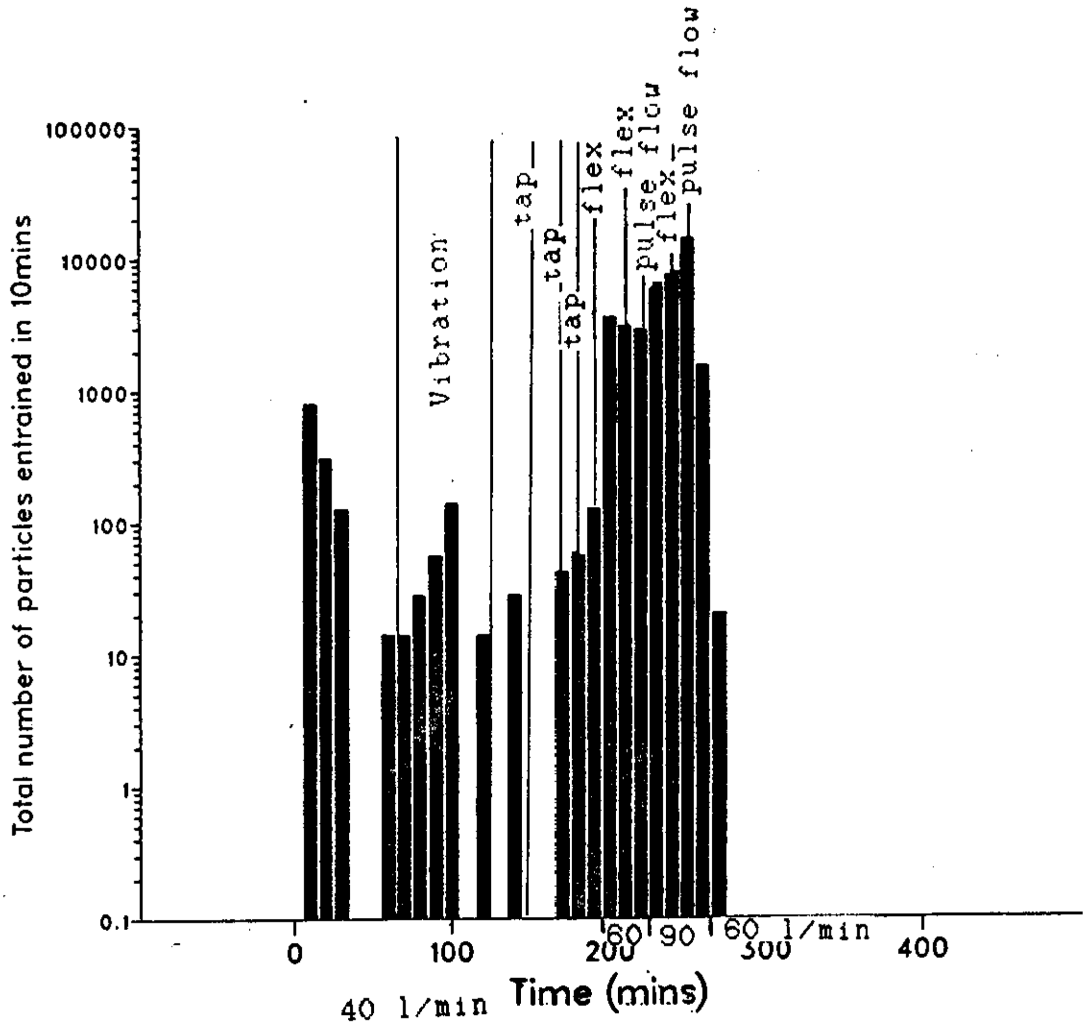

FIGURE 4.13 - ENTRAINMENT TEST ON 3RD CHEMICALLY CLEANED TUBE

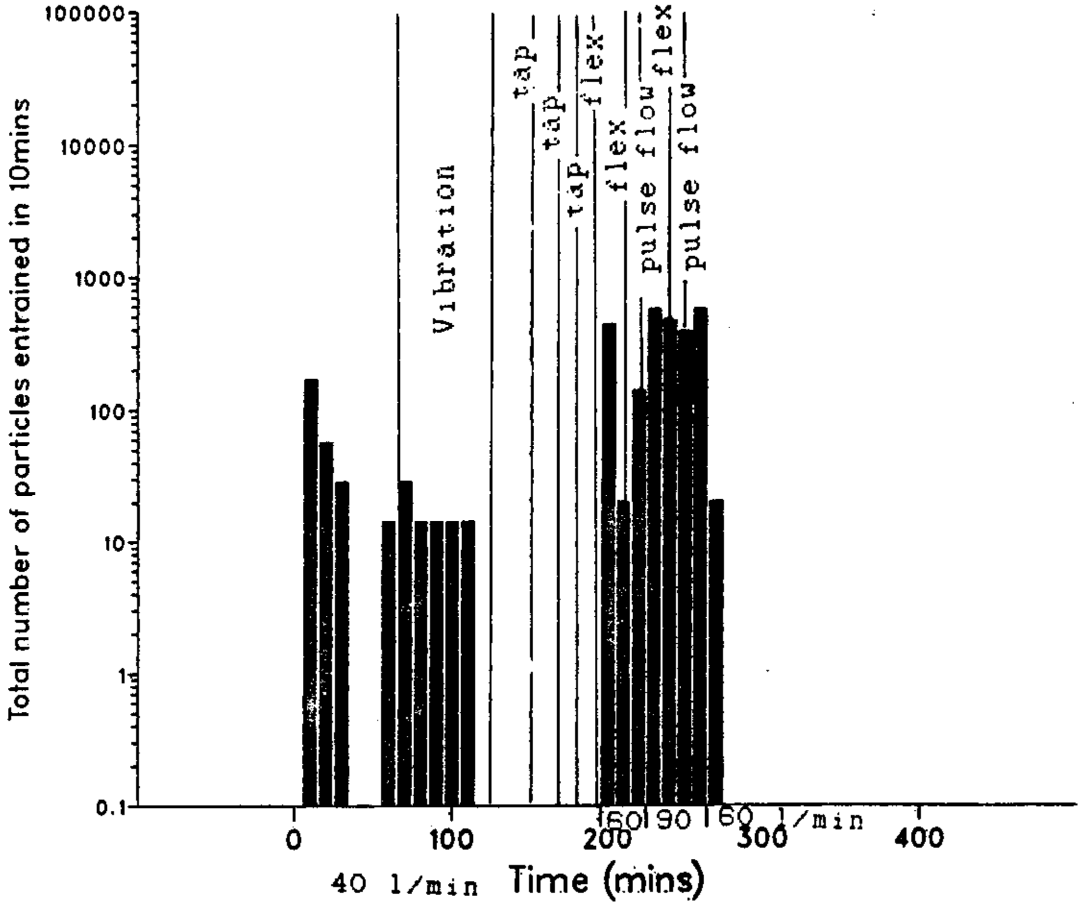

FIGURE 4.14 - ENTRAINMENT TEST ON 4TH CHEMICALLY CLEANED TUBE

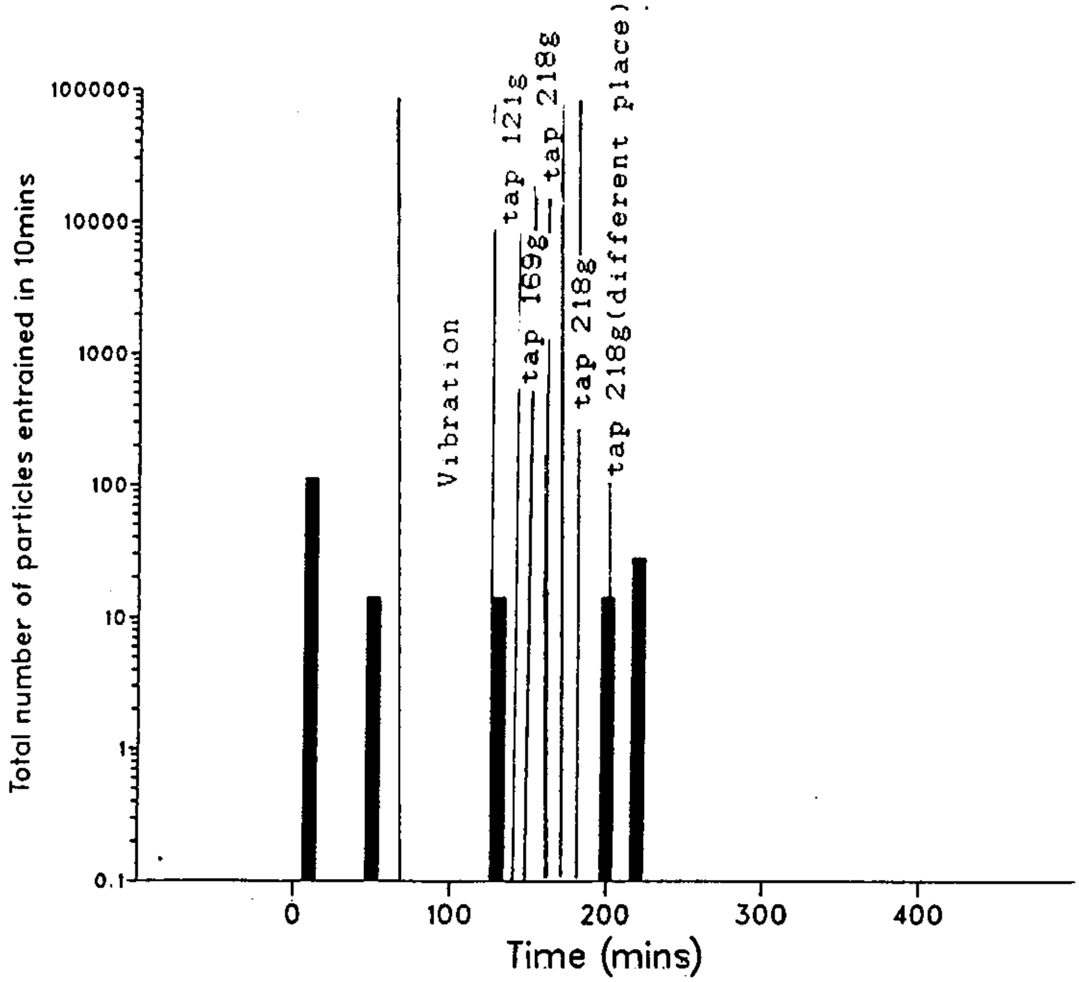

FIGURE 4.15 ENTRAINMENT TEST ON 1ST ELECTROPOLISHED TUBE

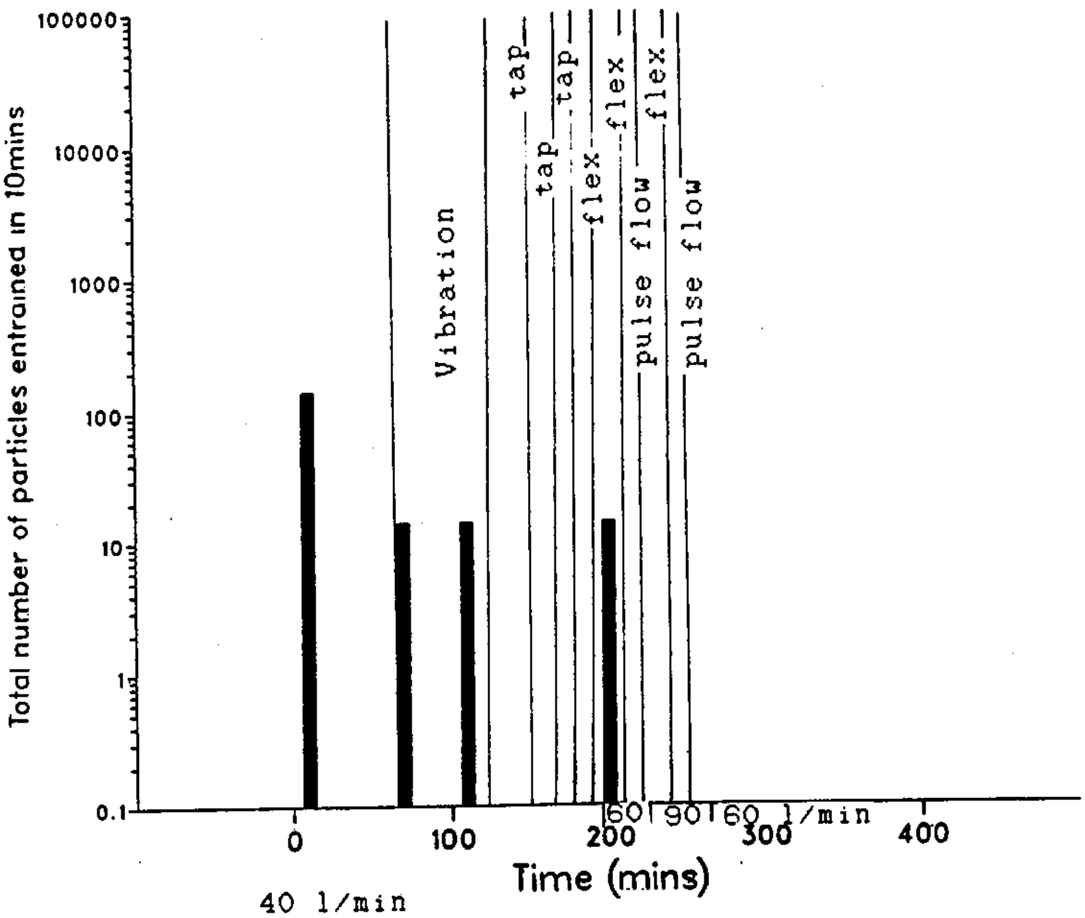

FIGURE 4.16 - ENTRAINMENT TEST ON 2ND ELECTROPOLISHED TUBE

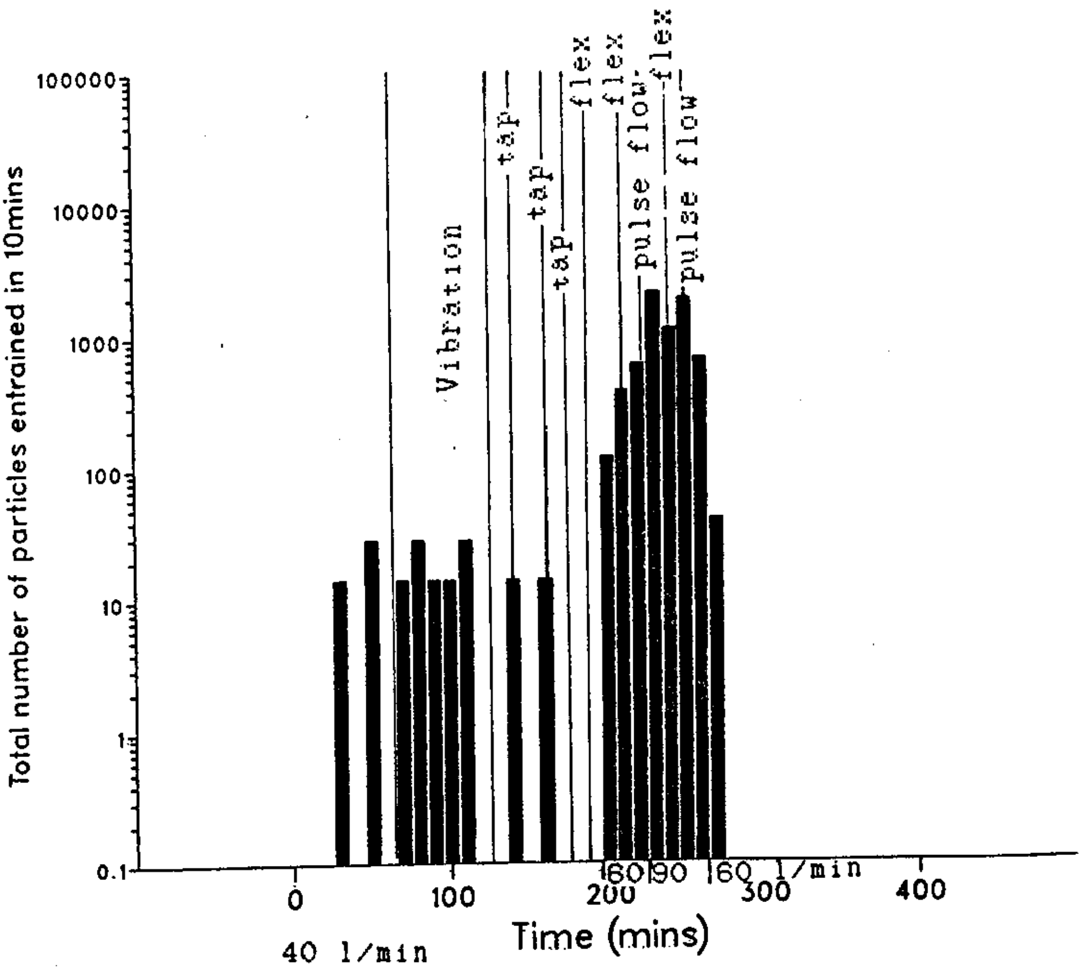

FIGURE 4.17 - ENTRAINMENT TEST ON 3RD ELECTROPOLISHED TUBE

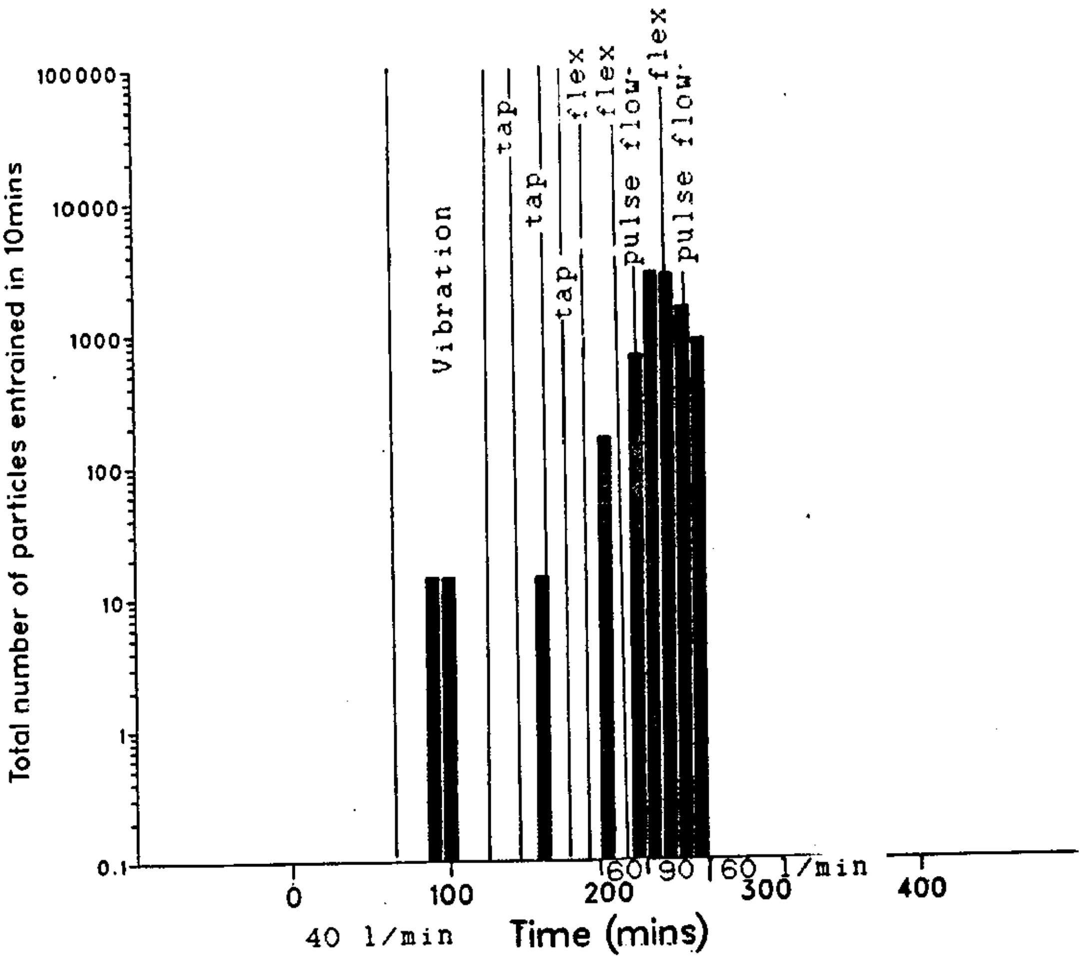

FIGURE 4.18 - ENTRAINMENT TEST ON 4TH ELECTROPOLISHED TUBE

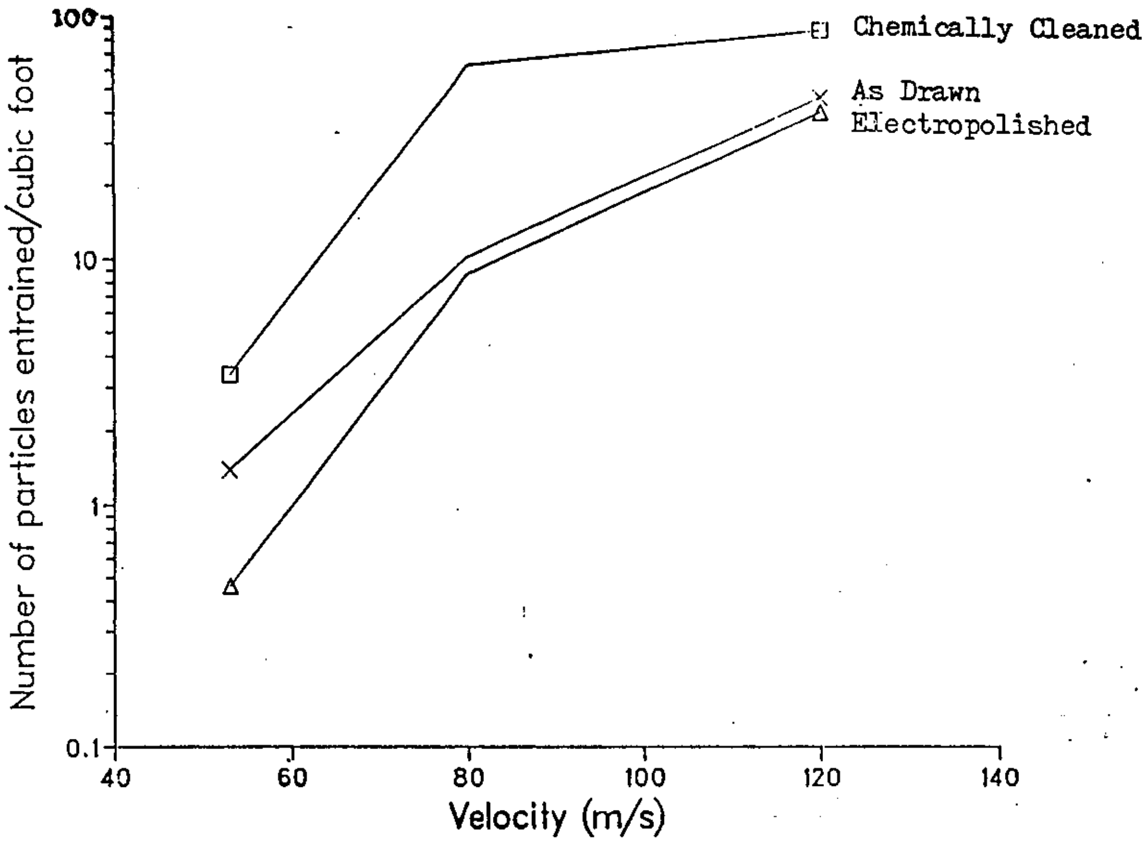

FIGURE 4.19 - EFFECT OF VELOCITY ON ENTRAINMENT OF PARTICULATES

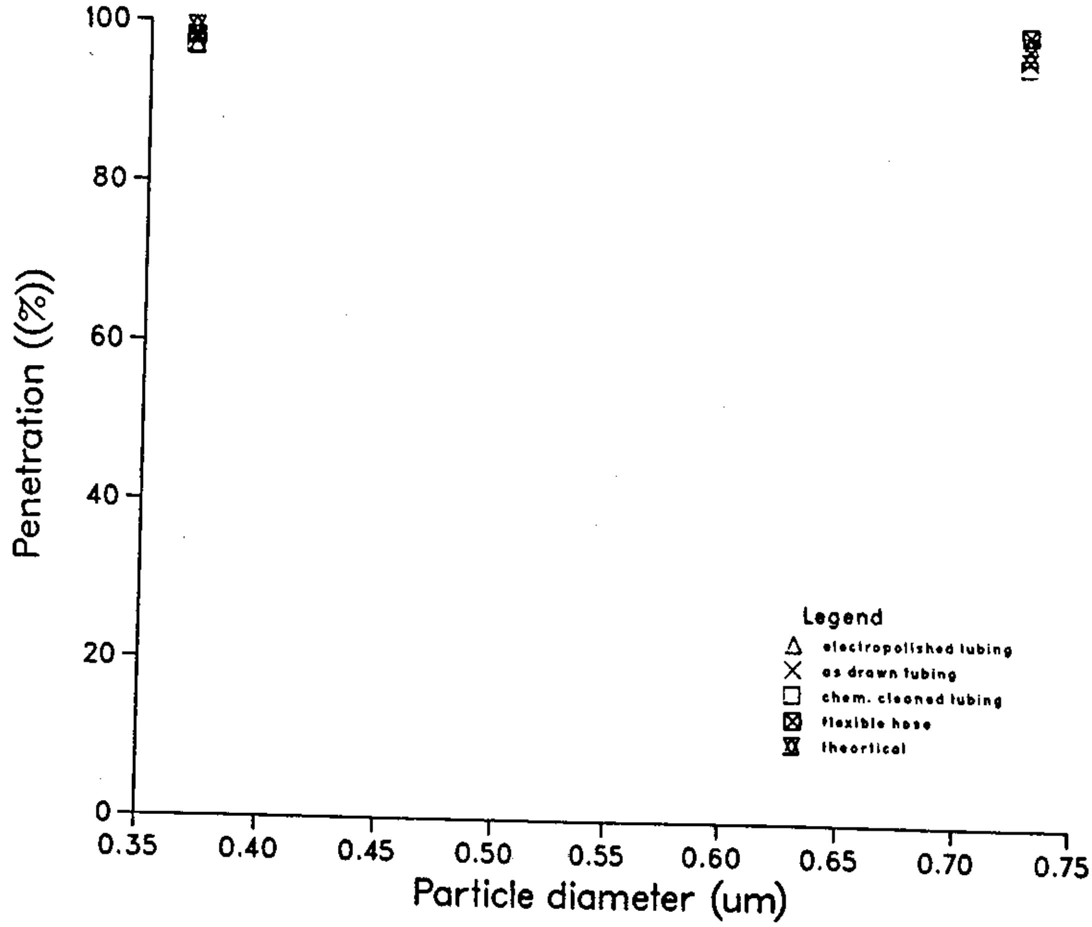

FIGURE 4.20 - PENETRATION TESTS AT A FLOWRATE OF 4L/MIN

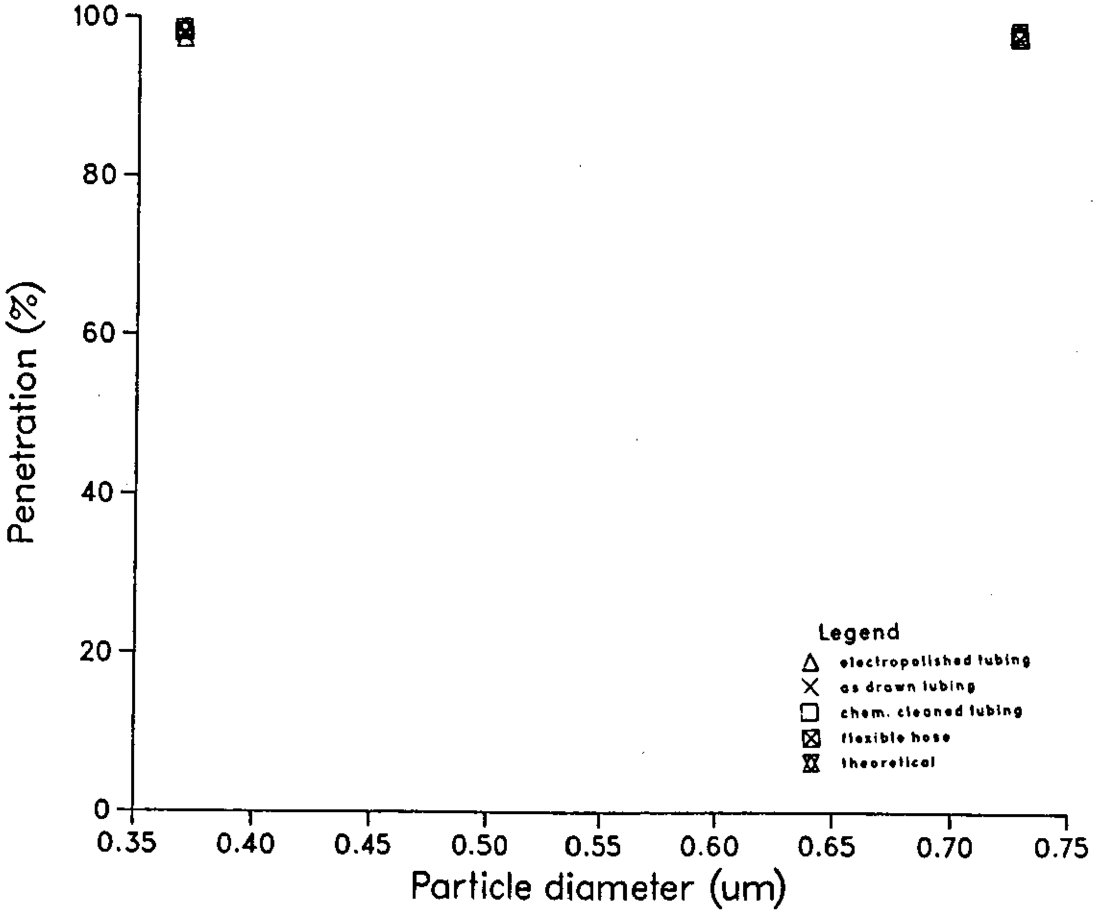

FIGURE 4.21 - PENETRATION TESTS AT A FLOWRATE OF 13.5L/MIN

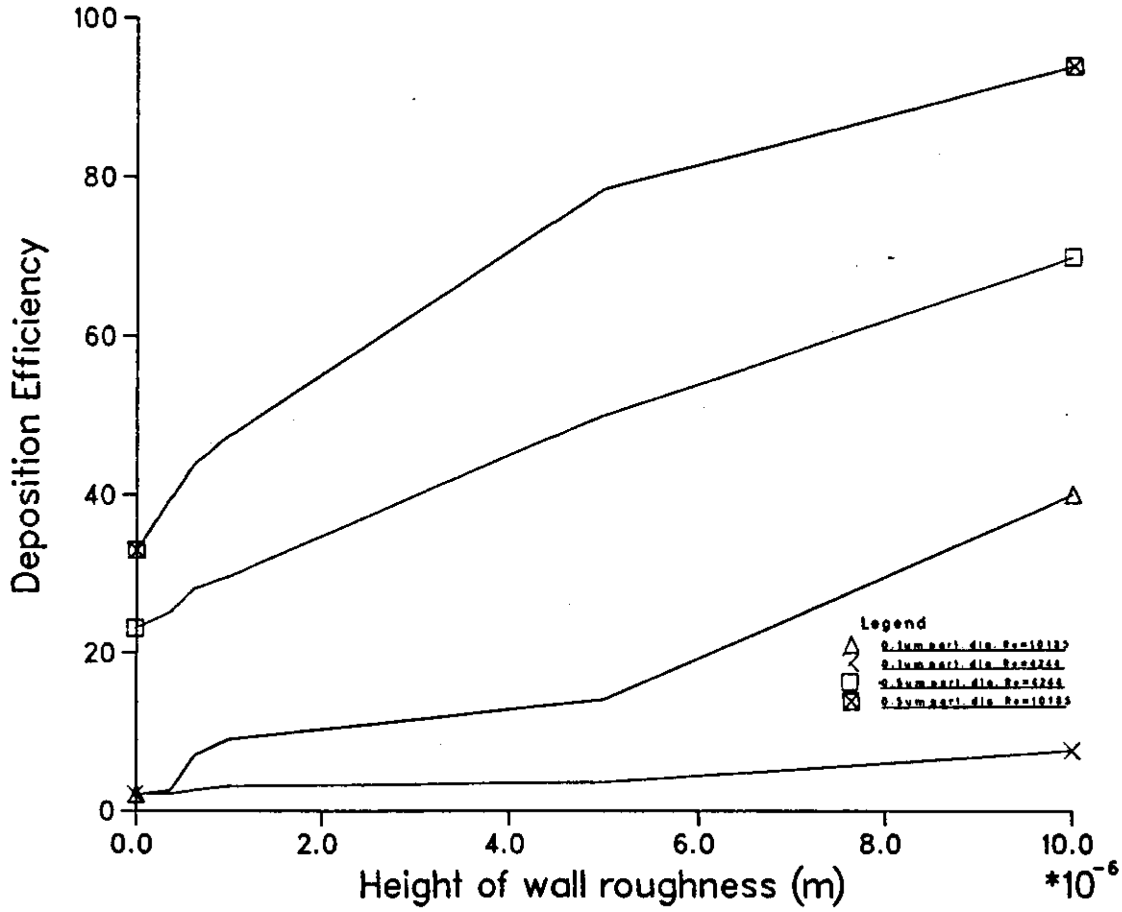

FIGURE 4.22 - EFFECT OF SURFACE ROUGHNESS - PREDICTION BY EL-SHOKSHY AND ISMAIL

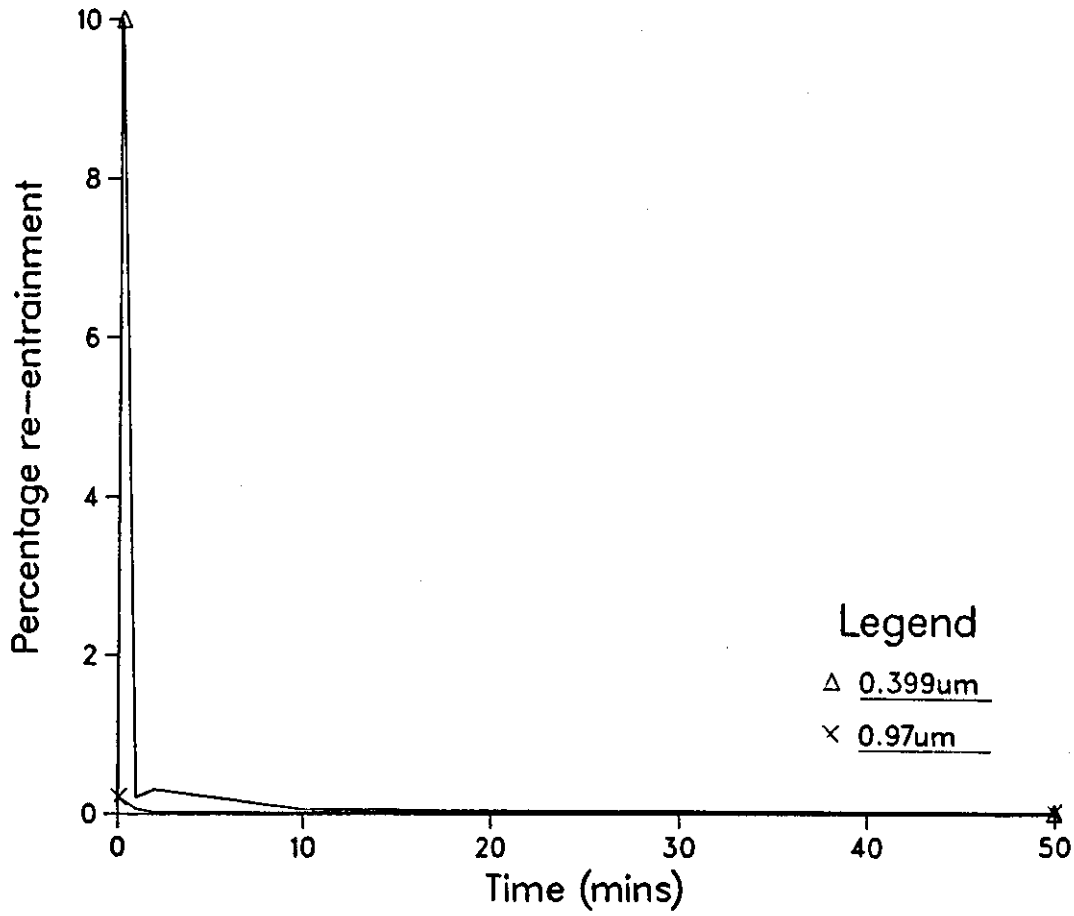

FIGURE 4.23 - EFFECT OF TIME DELAY ON RE-ENTRAINMENT

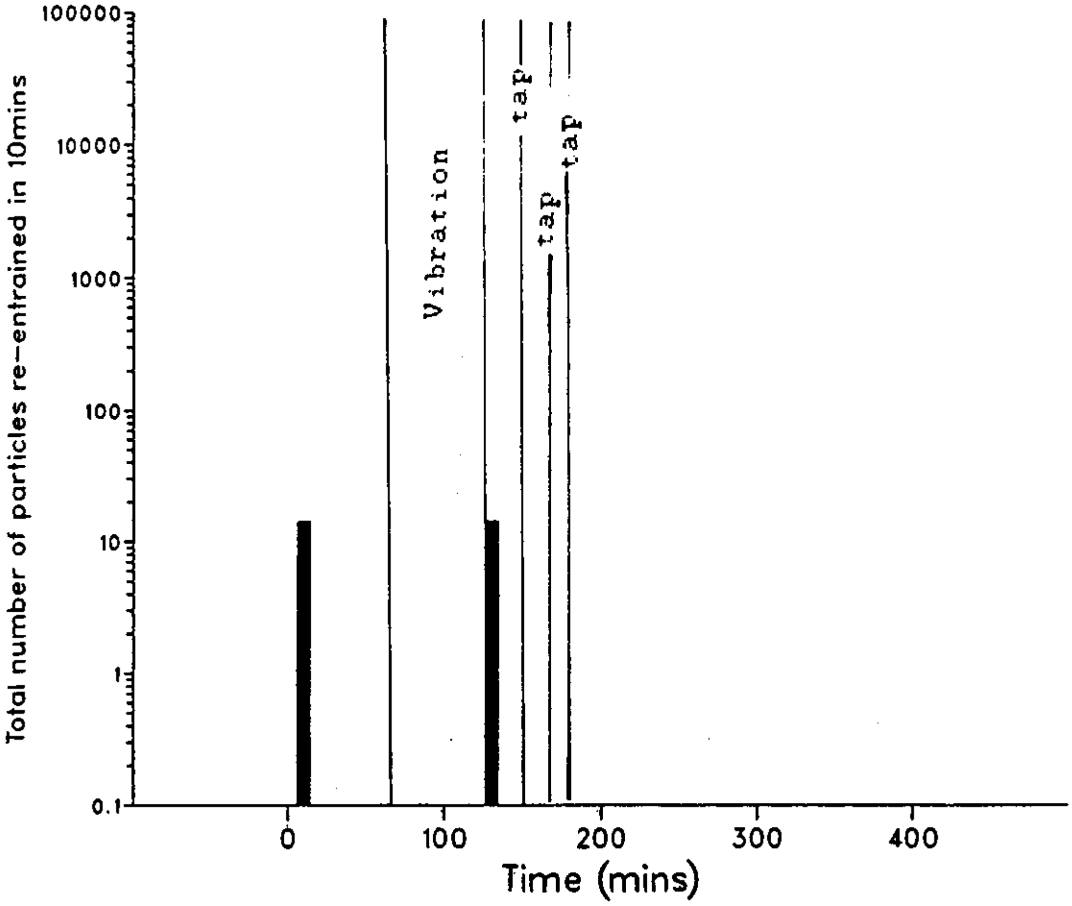

FIGURE 4.24 - RE-ENTRAINMENT TEST ON ELECTROPOLISHED TUBE (17000 PARTICLES OF LATEX DEPOSITED)

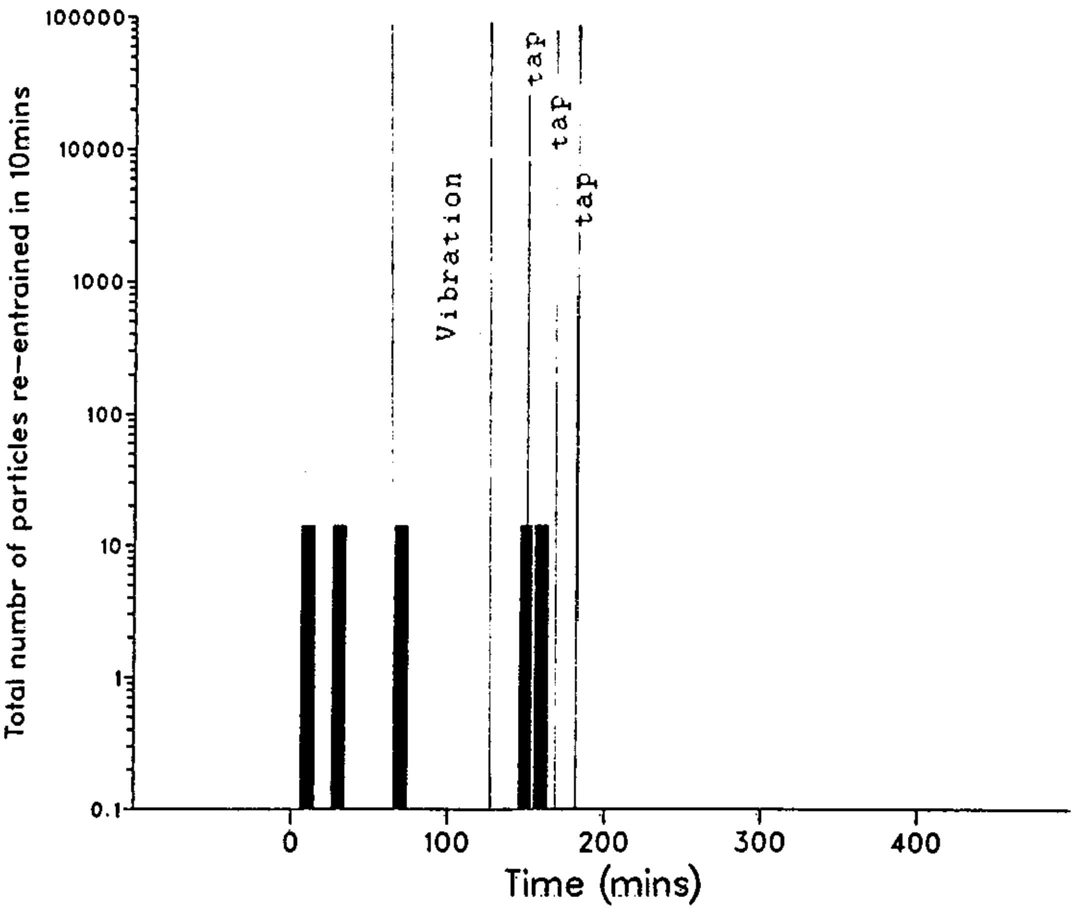

FIGURE 4.25 - RE-ENTRAINMENT TEST ON AN AS DRAWN TUBE (17000 PARTICLES OF LATEX DEPOSITED)

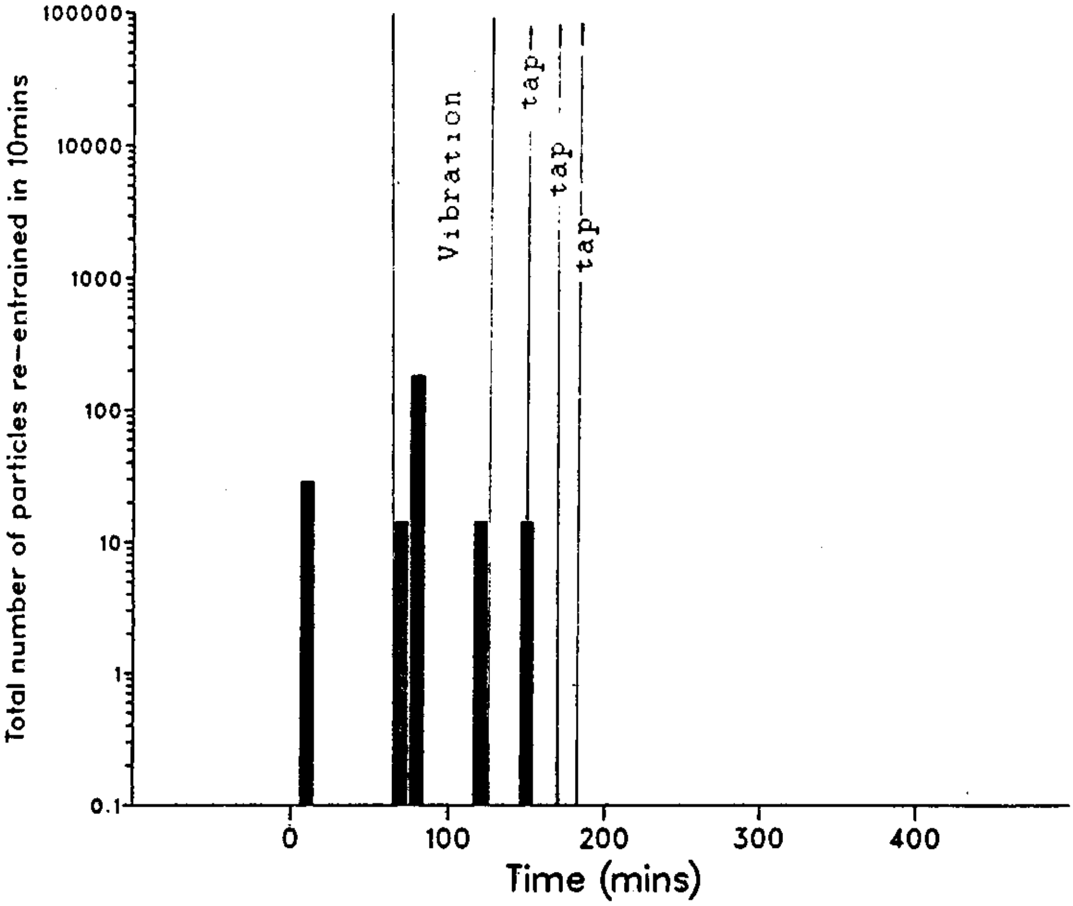

FIGURE 4.26 - RE-ENTRAINMENT TEST ON AN ELECTROPOLISHED TUBE (24000 PARTICLES OF IRON OXIDE DEPOSITED)

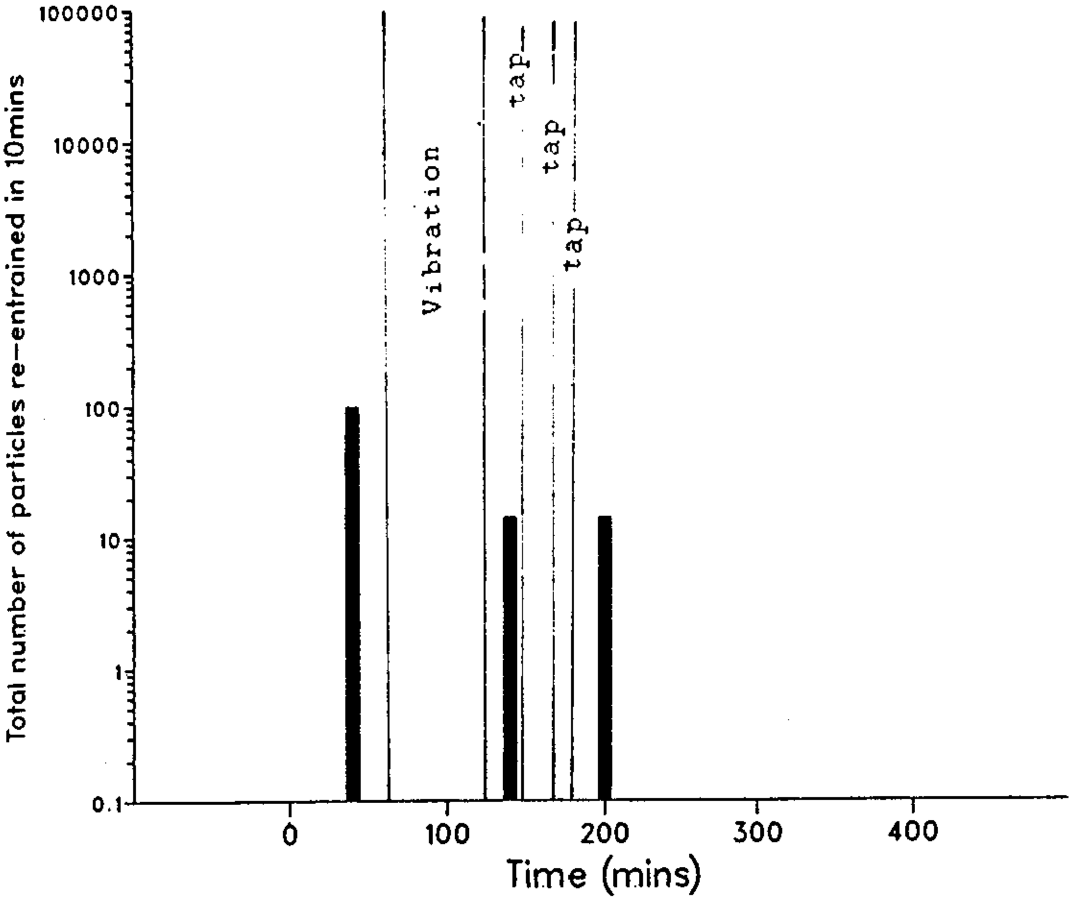

FIGURE 4.27 - RE-ENTRAINMENT TEST ON AN AS DRAWN TUBE (24000 PARTICLES OF IRON OXIDE DEPOSITED)

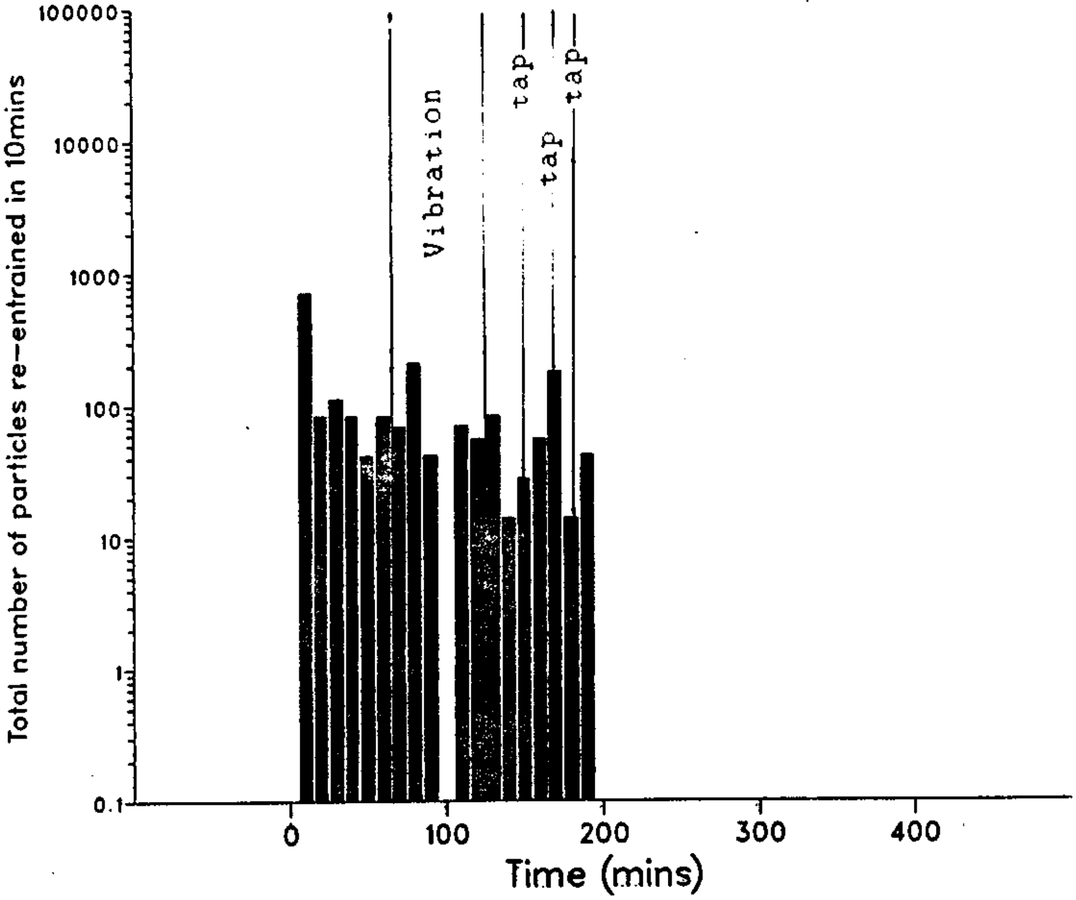

FIGURE 4.28 - RE-ENTRAINMENT TEST ON AN ELECTROPOLISHED TUBE (350 MILLION PARTICLES OF IRON OXIDE DEPOSITED)

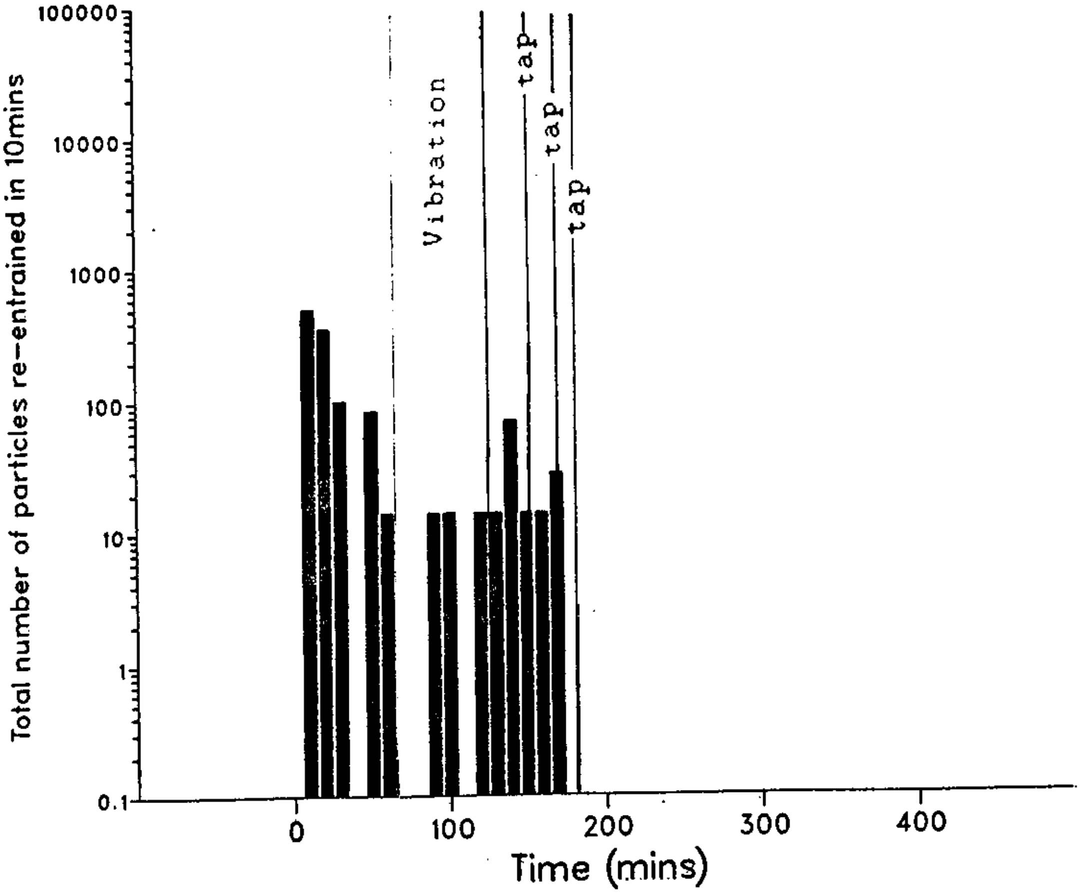

FIGURE 4.29 - RE-ENTRAINMENT TEST ON AN AS DRAWN TUBE
(350 MILLION PARTICLES OF IRON OXIDE DEPOSITED)

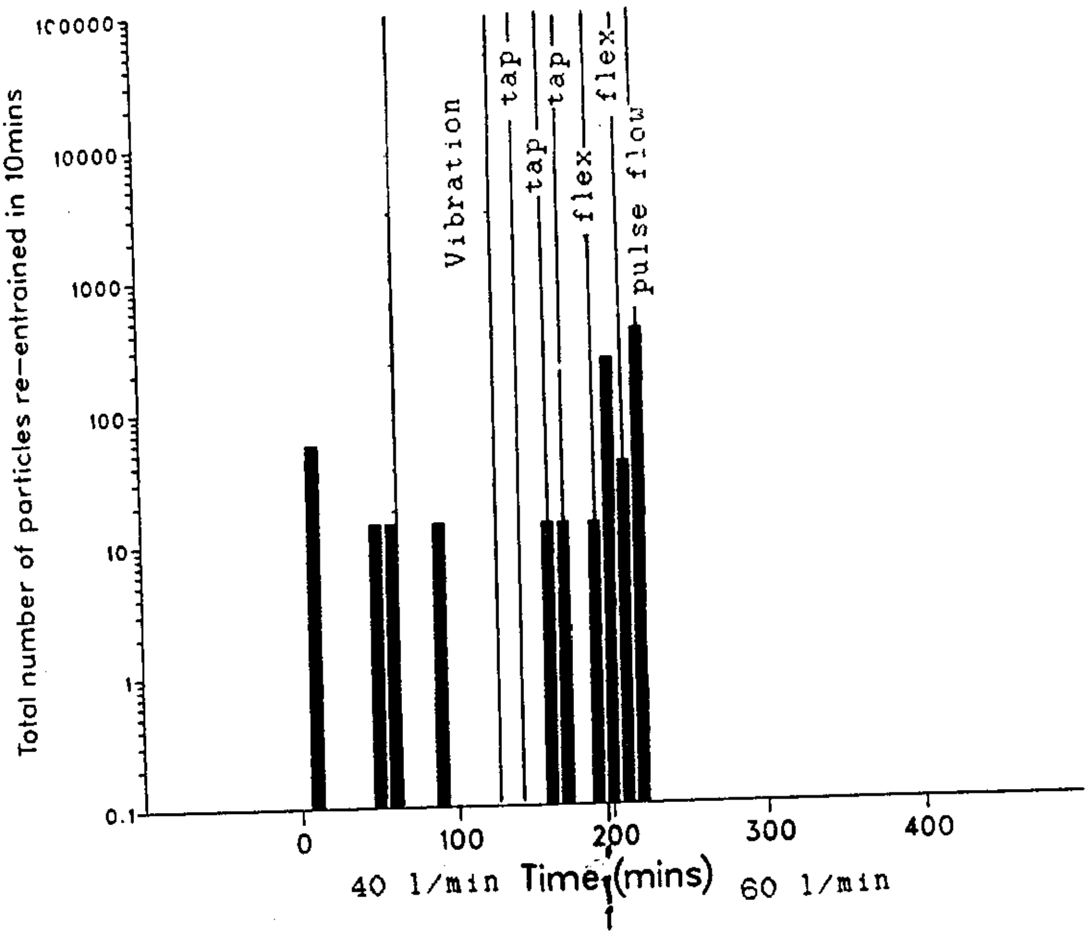

FIGURE 4.30 - RE-ENTRAINMENT TEST ON AN ELECTROPOLISHED TUBE
(16 MILLION PARTICLES OF IRON OXIDE DEPOSITED)

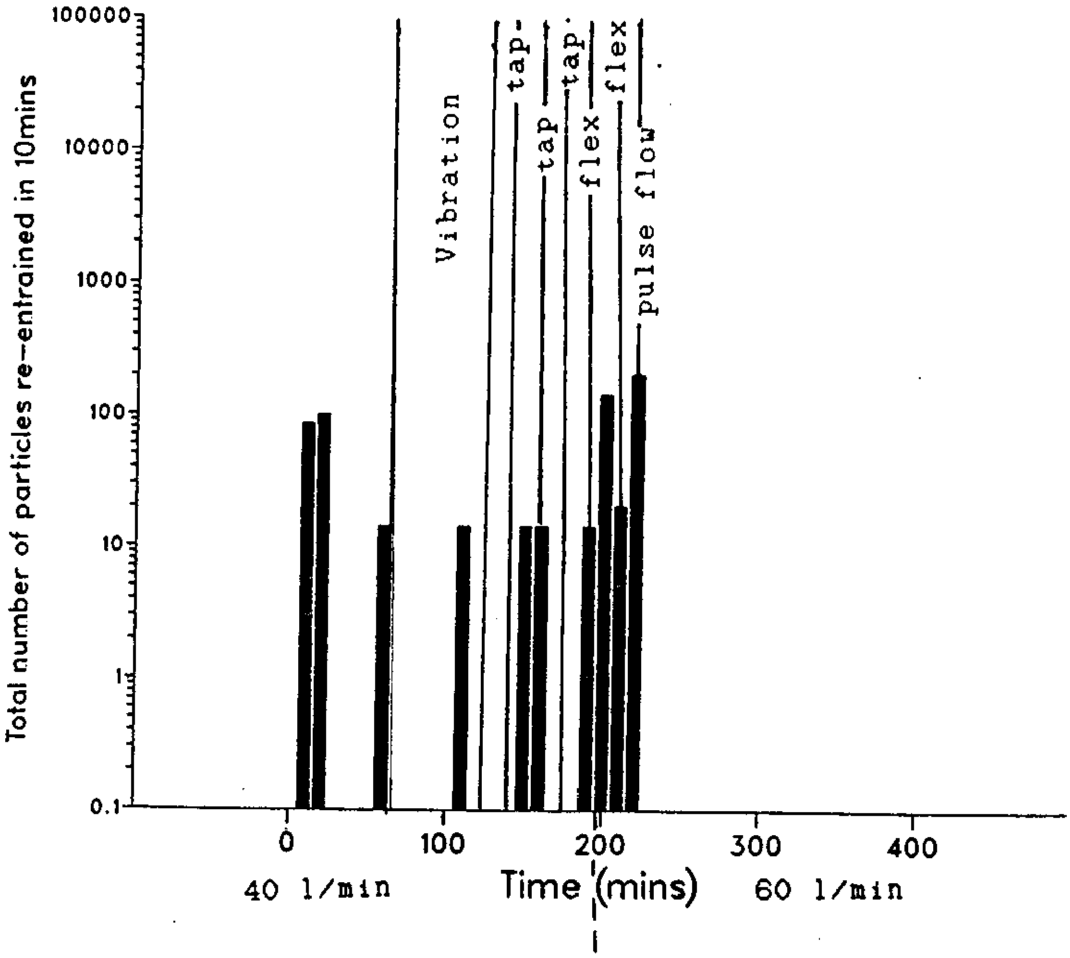

FIGURE 4.31 - RE-ENTRAINMENT TEST ON AN AS DRAWN TUBE
(16 MILLION PARTICLES OF IRON OXIDE DEPOSITED)

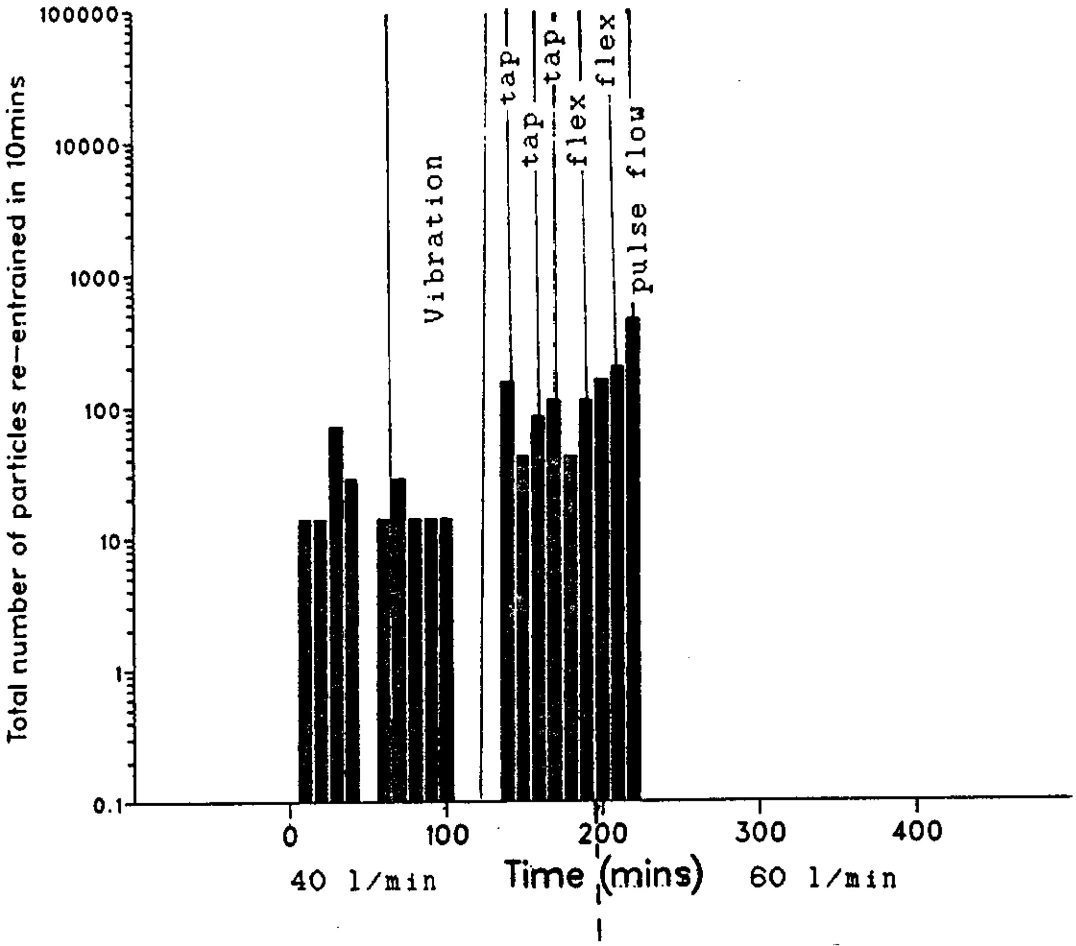

FIGURE 4.32 - RE-ENTRAINMENT TEST ON AN ELECTROPOLISHED TUBE (15 MILLION PARTICLES OF IRON OXIDE DEPOSITED)

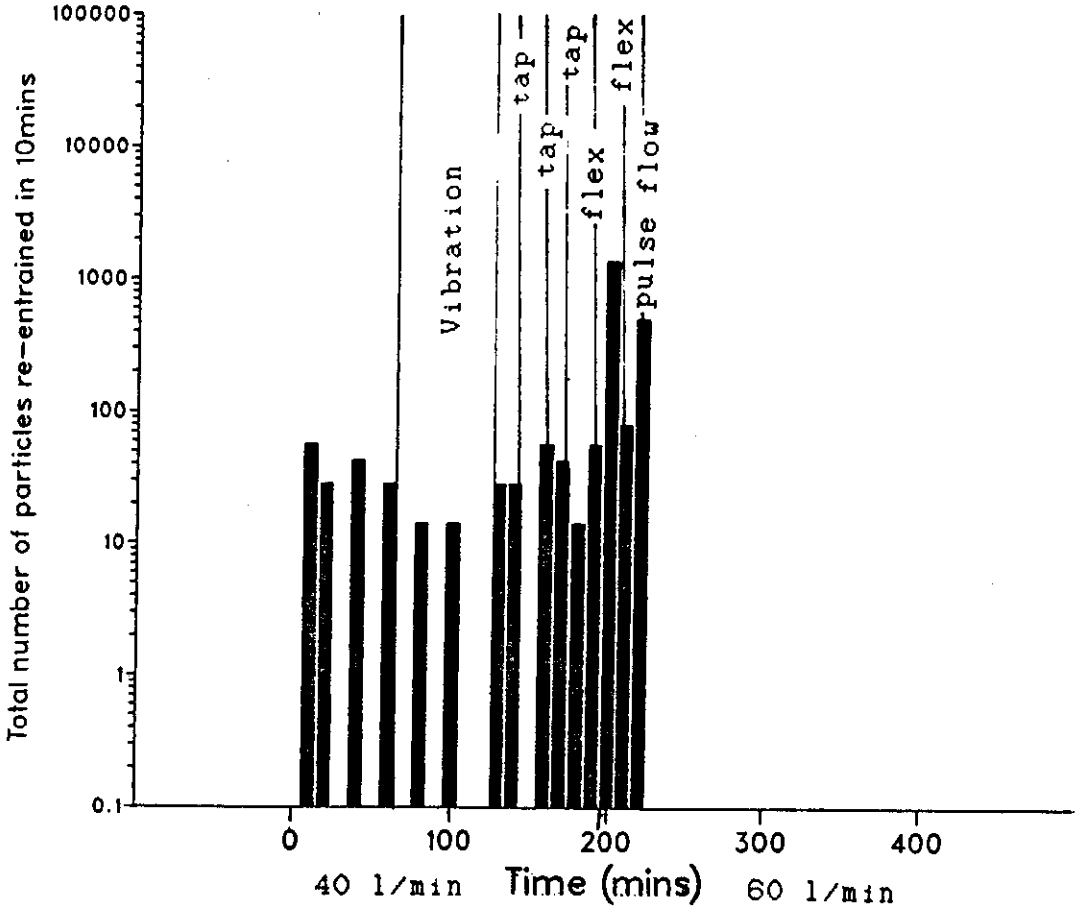

FIGURE 4.33 - RE-ENTRAINMENT TEST ON A CHEMICALLY CLEANED TUBE (15 MILLION PARTICLES OF IRON OXIDE DEPOSITED)

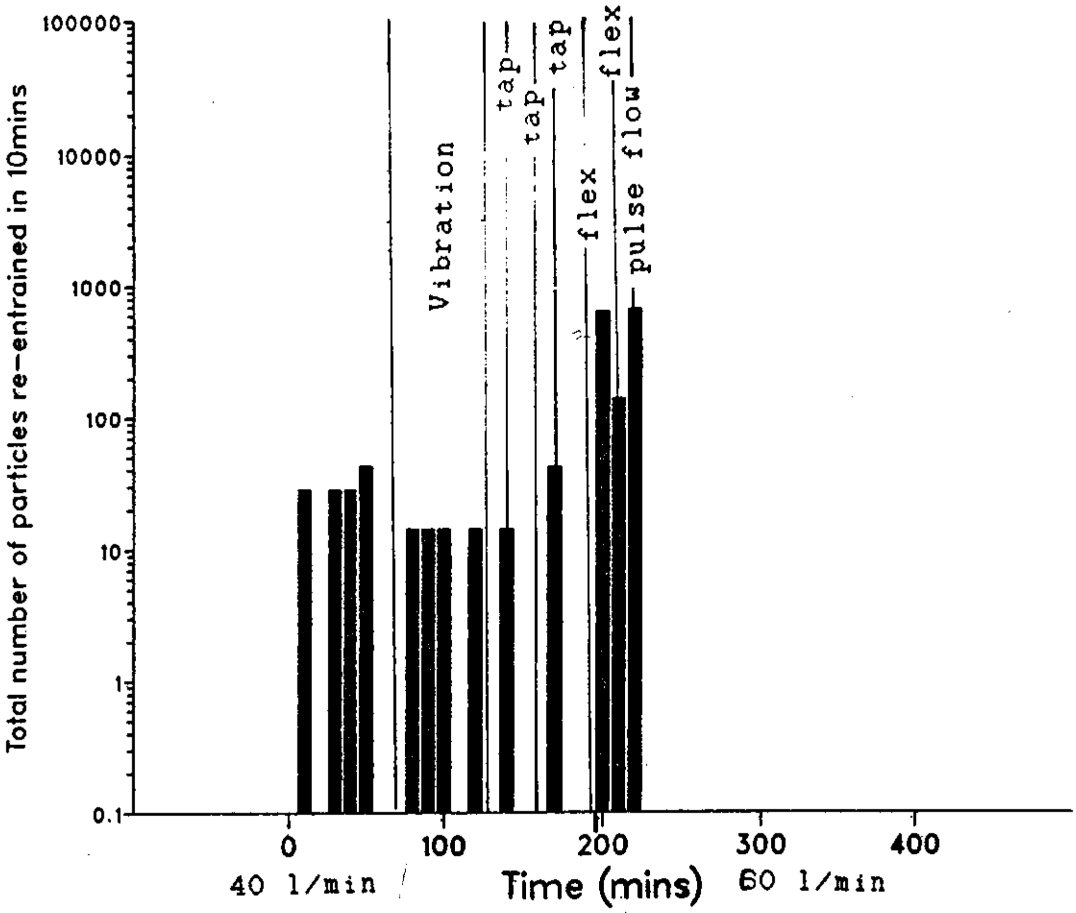

FIGURE 4.34 - RE-ENTRAINMENT TEST ON A CHEMICALLY CLEANED TUBE (32 MILLION P[ARTICLES OF IRON OXIDE DEPOSITED)

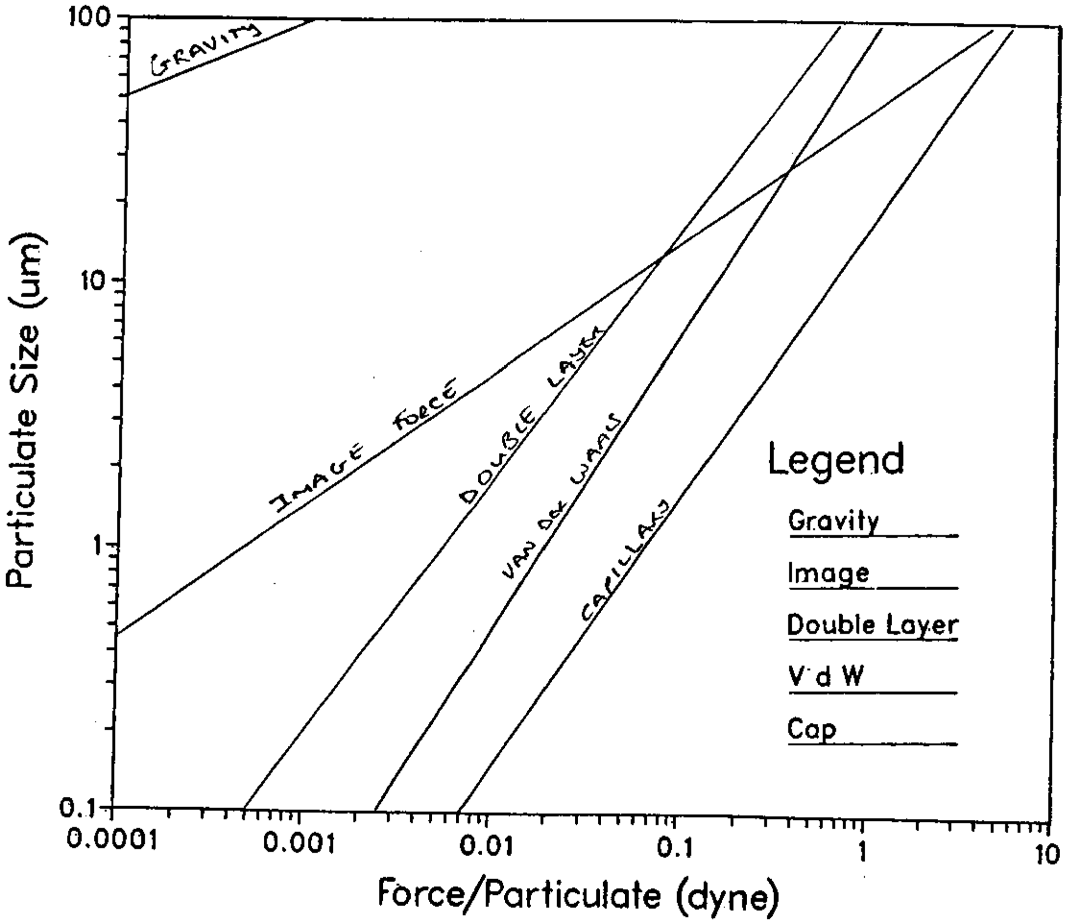

FIGURE 4.35 - SUMMARY OF THE ADHESION FORCES

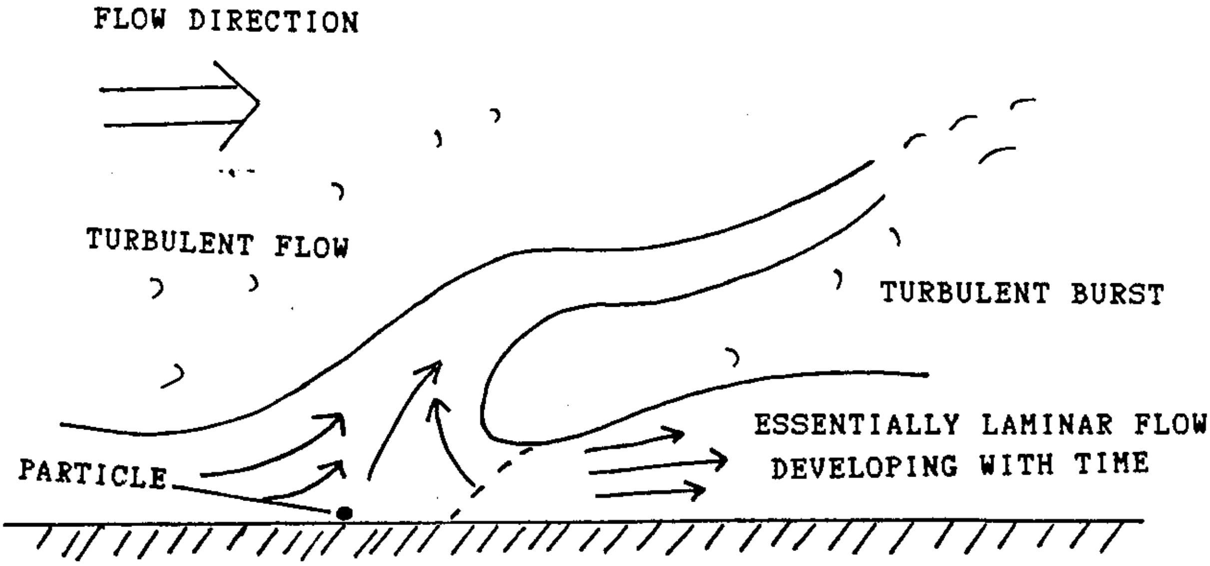

FIGURE 4.36 - SCHEMATIC DIAGRAM OF A TURBULENT BURST IN THE WALL REGION

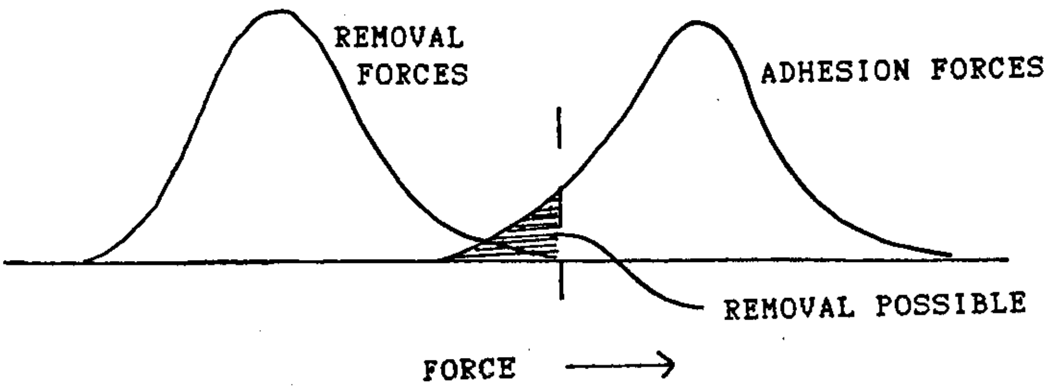

FIGURE 4.37 - PROBABILITY DISTRIBUTION OF FORCES

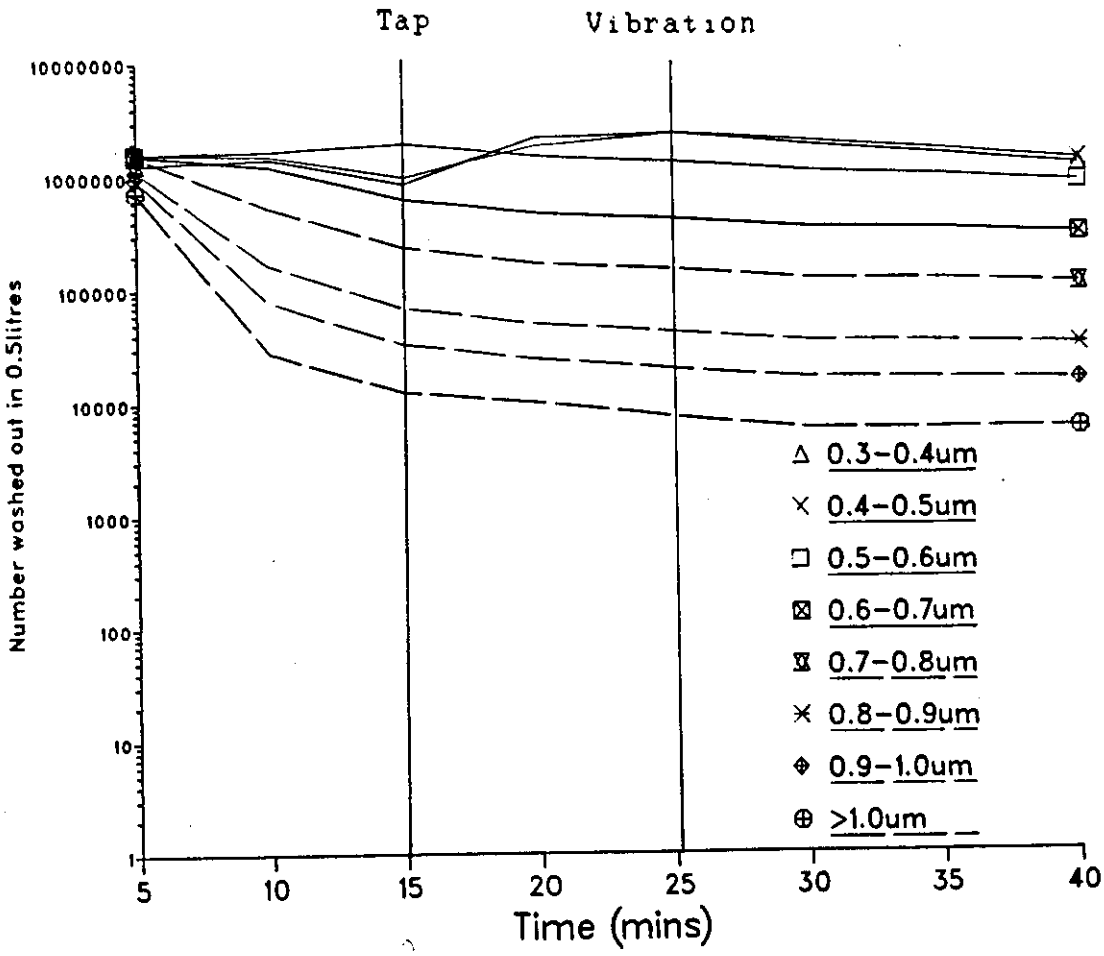

FIGURE 4.38 - CONTAMINATION ARISING FROM CONTINUOUS WATER WASHING (ELECTROPOLISHED TUBE - 350 MILLION PARTICLES DEPOSITED)

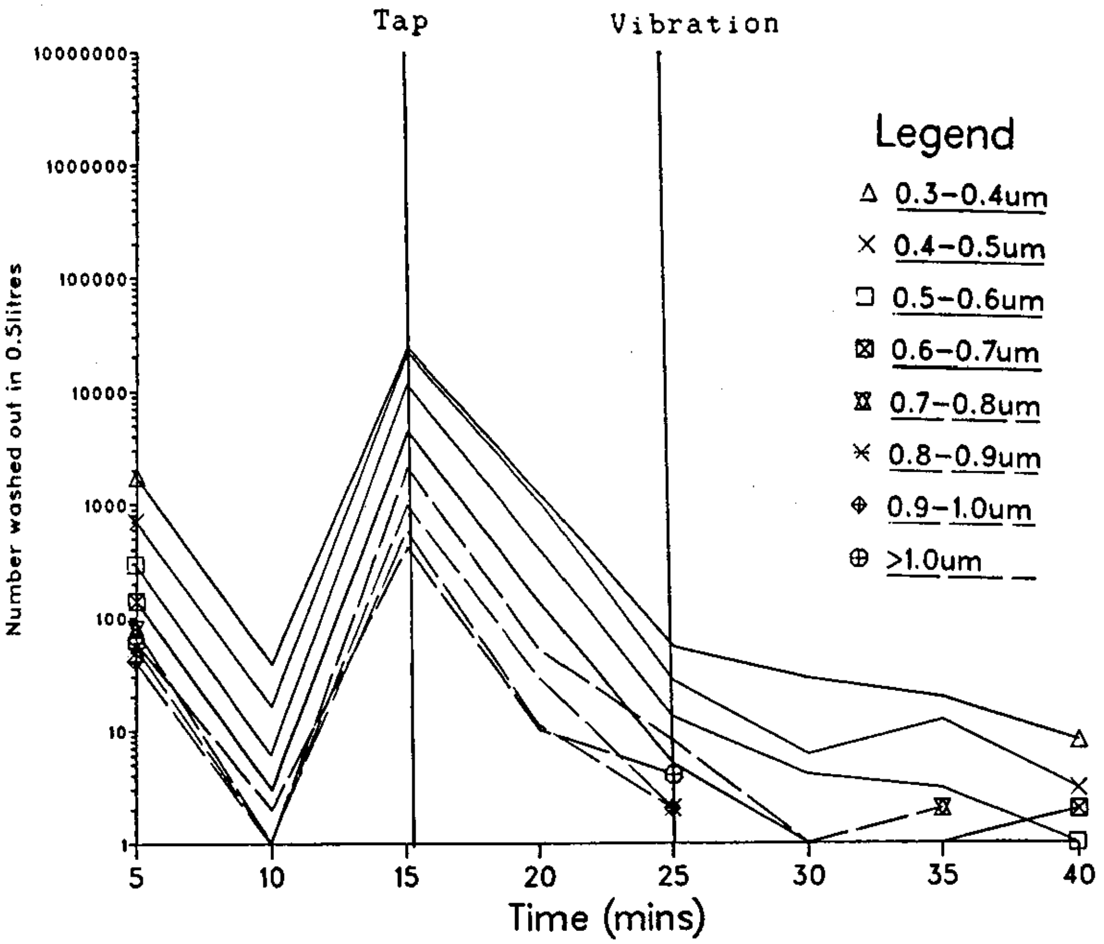

FIGURE 4.39 - CONTAMINATION ARISING FROM CONTINUOUS WATER WASHING (AS DRAWN TUBE - 350 MILLION PARTICLES DEPOSITED)

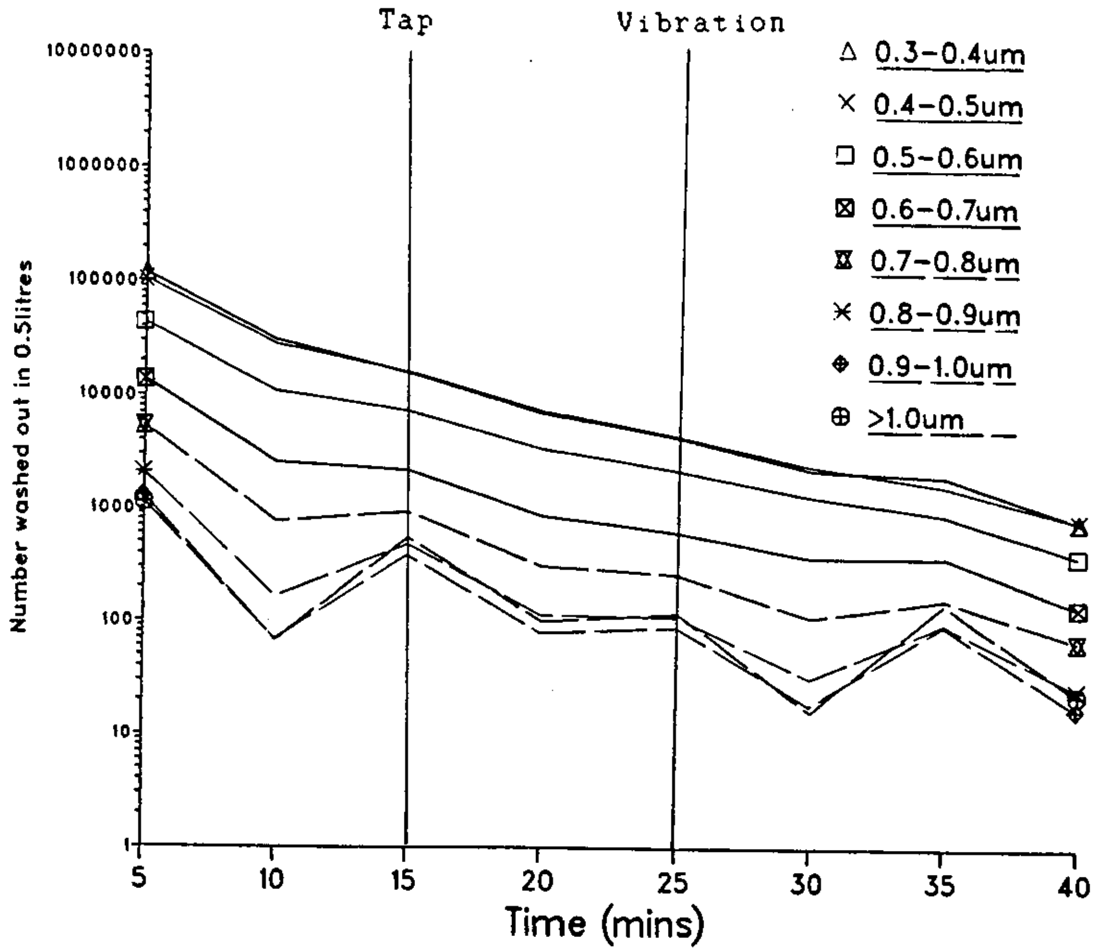

FIGURE 4.40 - CONTAMINATION ARISING FROM CONTINUOUS WATER WASHING (CHEMICALLY CLEANED TUBE - 32 MILLION PARTICLES DEPOSITED)

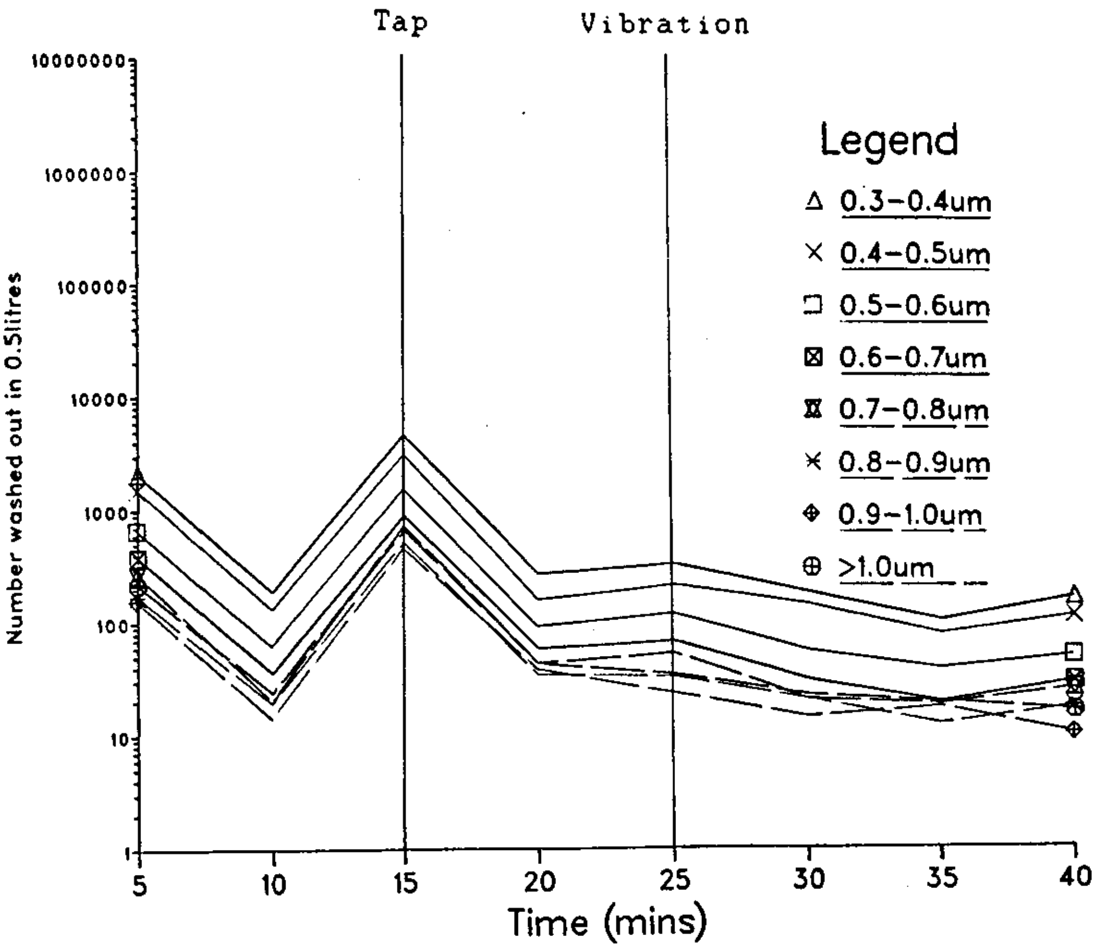

FIGURE 4.41 - CONTAMINATION ARISING FROM CONTINUOUS WATER WASHING (AS DRAWN TUBE - 16 MILLION PARTICLES DEPOSITED)

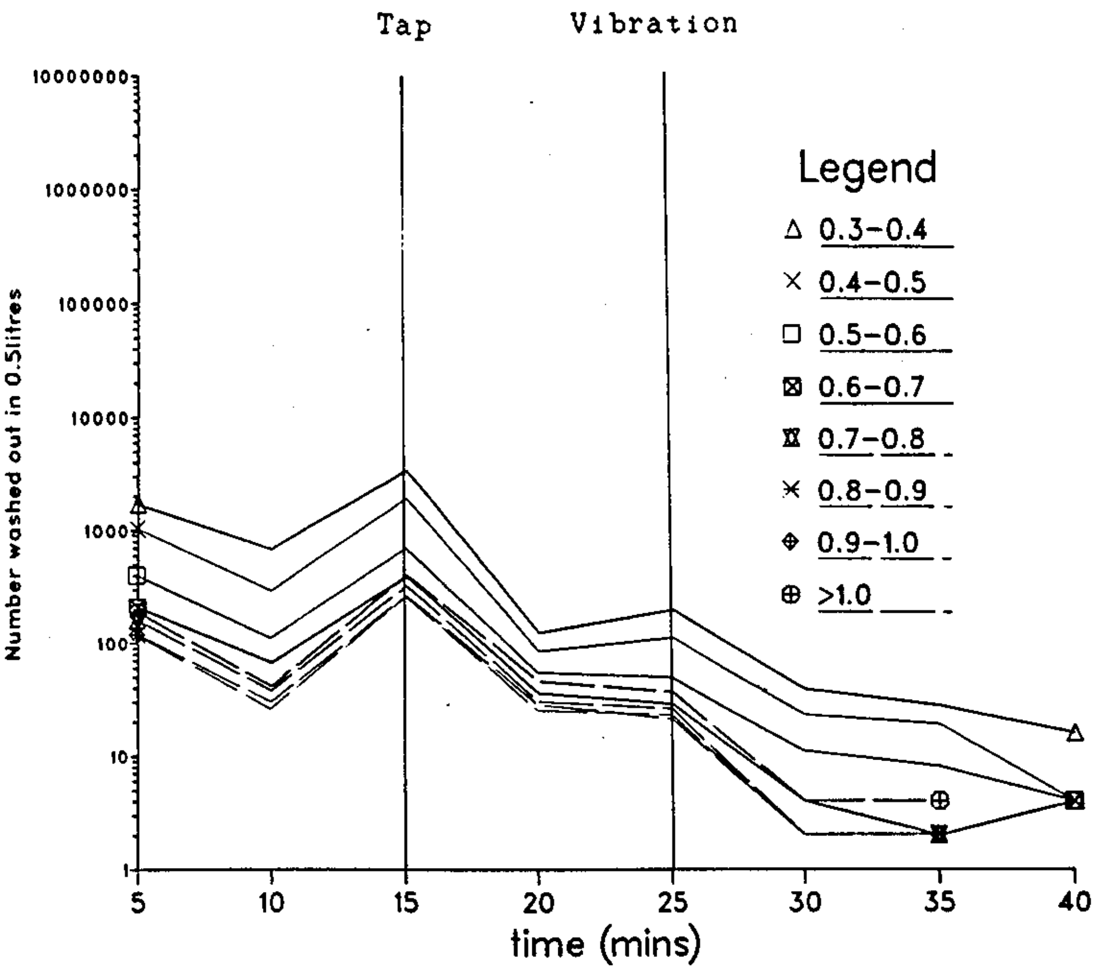

FIGURE 4.42 - CONTAMINATION ARISING FROM CONTINUOUS WATER WASHING (AS DRAWN TUBE - NO PARTICLES DEPOSITED)

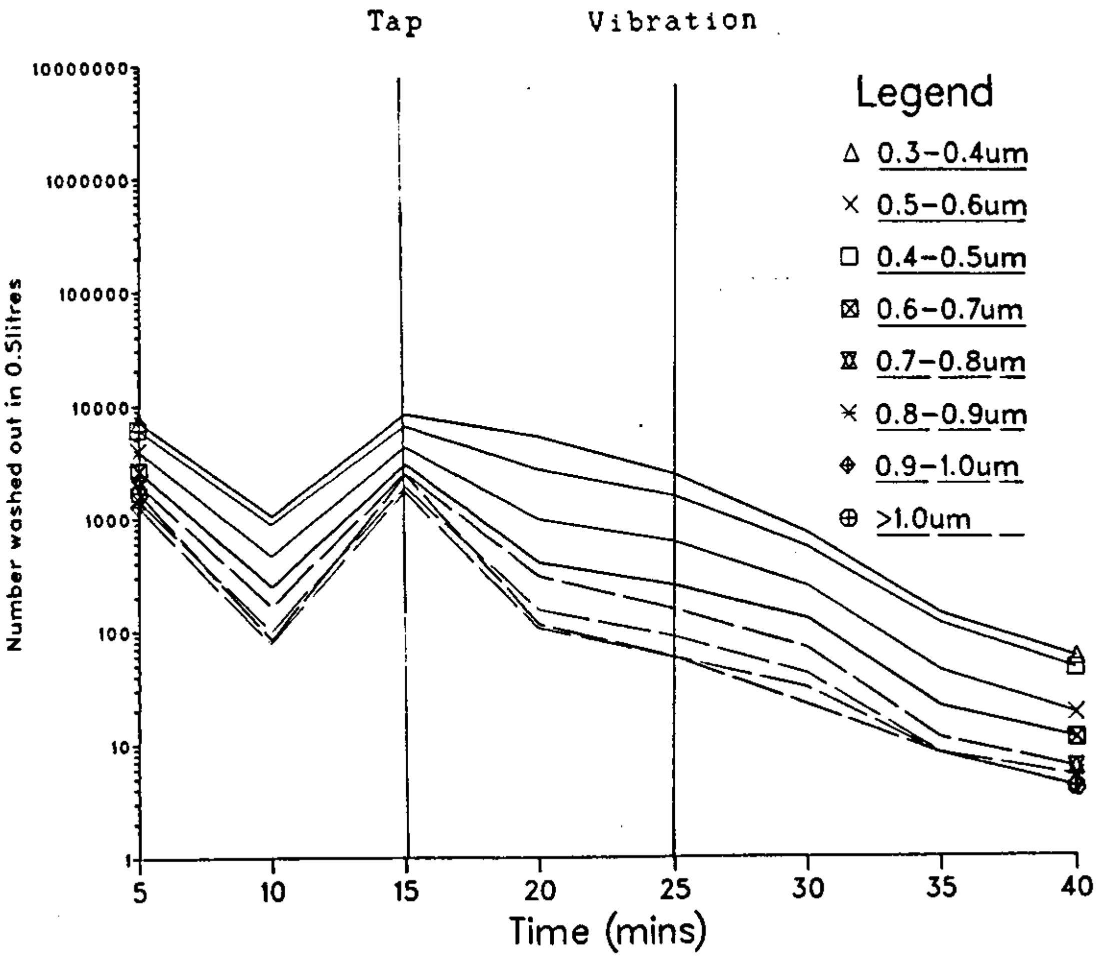

FIGURE 4.43 - CONTAMINATION ARISING FROM CONTINUOUS WATER WASHING (CHEMICALLY CLEANED TUBE - NO PARTICLES DEPOSITED)

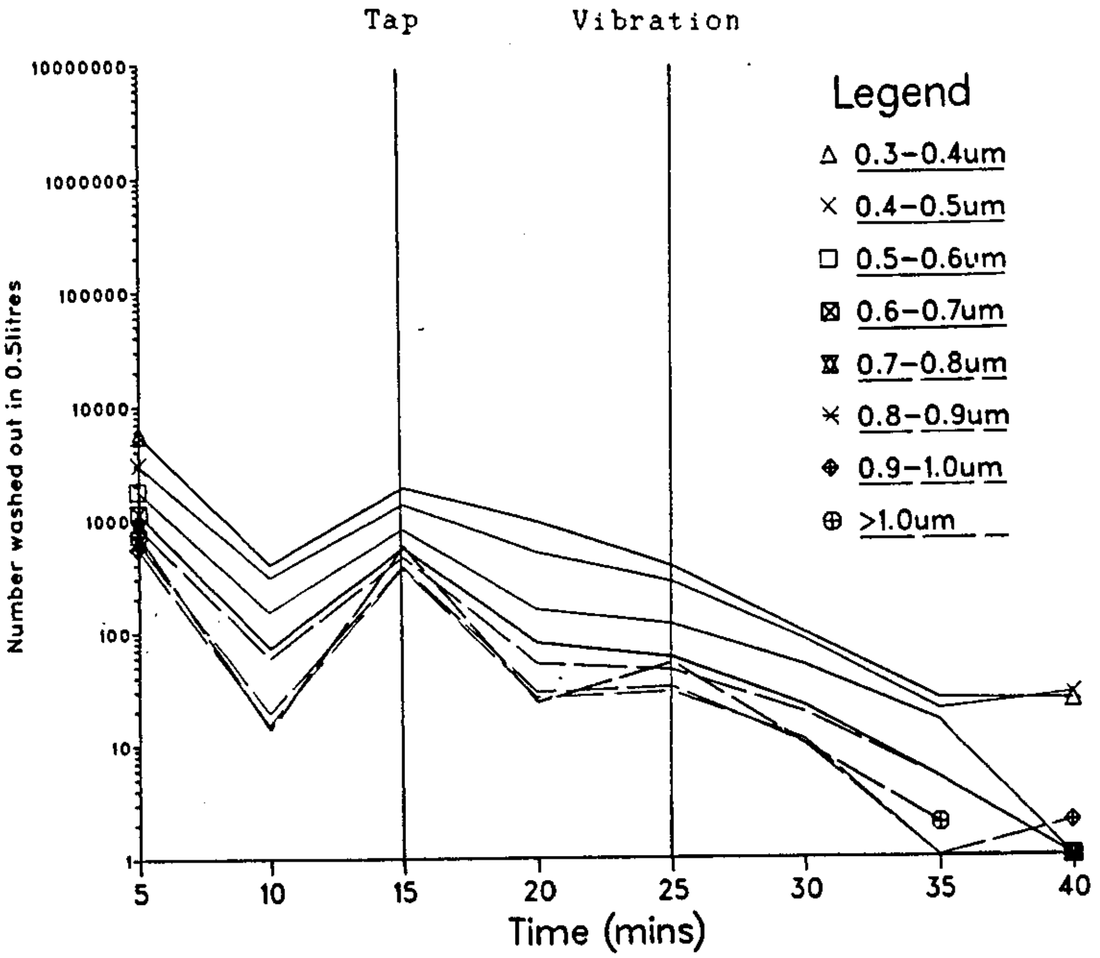

FIGURE 4.44 - CONTAMINATION ARISING FROM CONTINUOUS WATER WASHING (CHEMICALLY CLEANED TUBE - NO PARTICLES DEPOSITED)

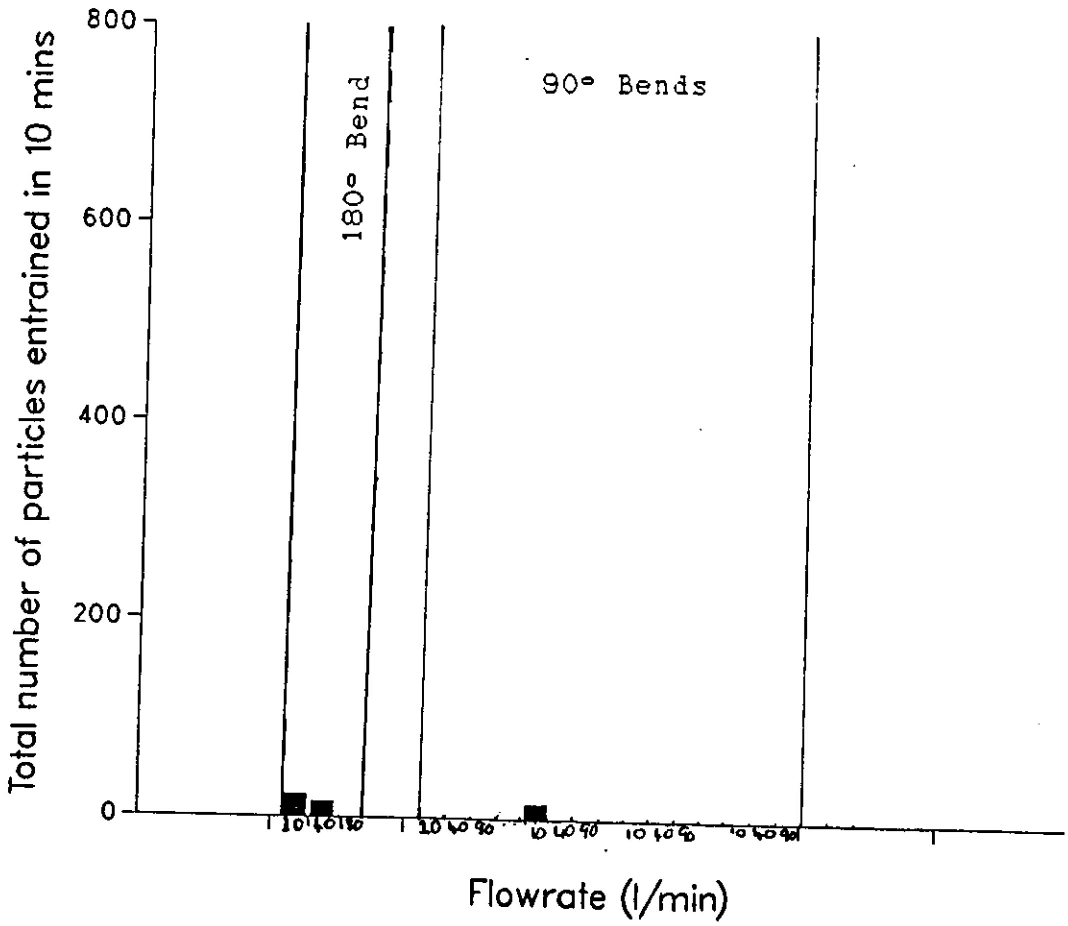

FIGURE 4.45 - THE EFFECT ON ENTRAINMENT OF BENDING AN ELECTROPOLISHED TUBE

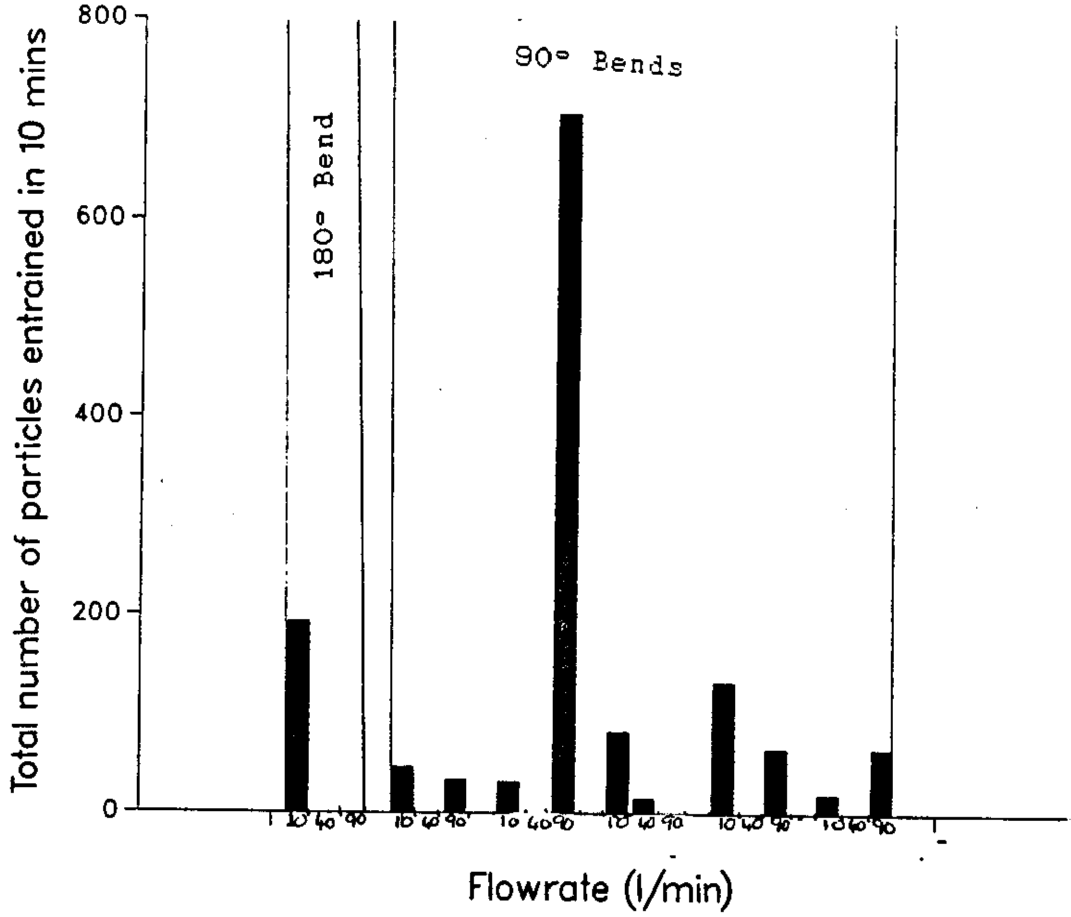

FIGURE 4.46 - THE EFFECT ON ENTRAINMENT OF BENDING A CHEMICALLY CLEANED TUBE

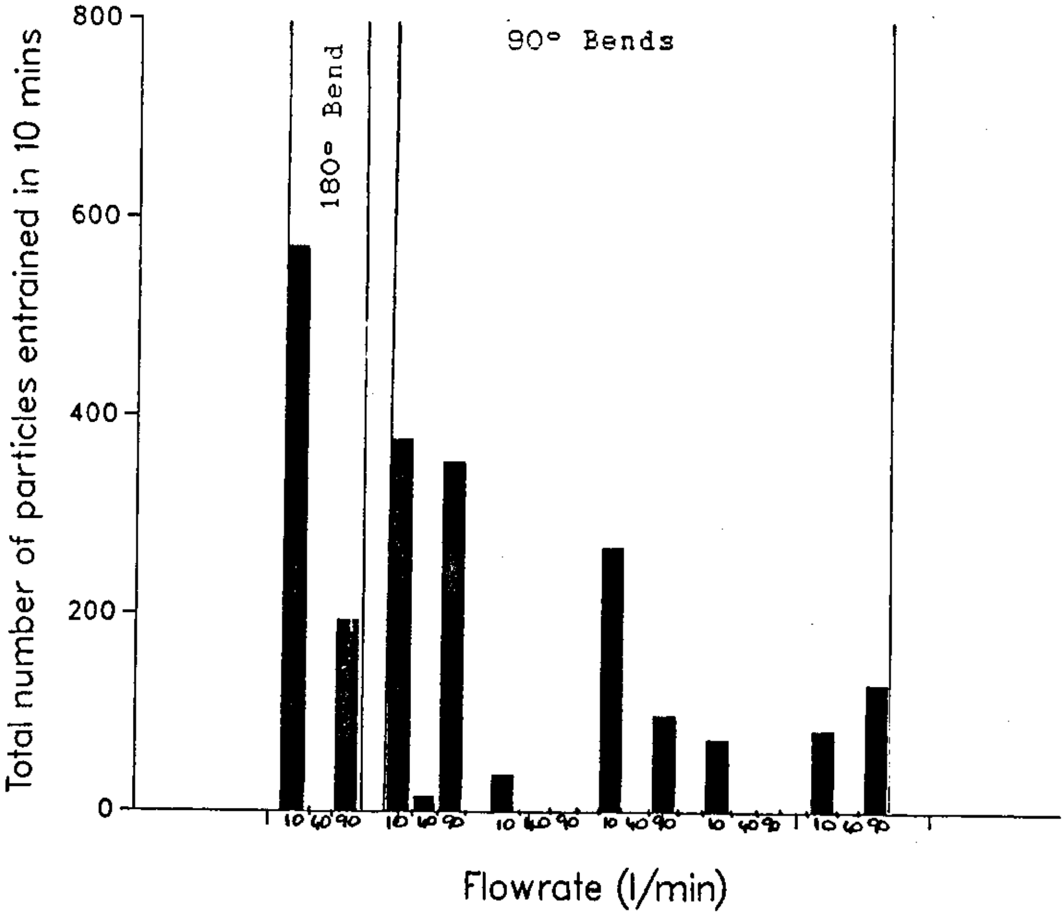

FIGURE 4.47 - THE EFFECT ON ENTRAINMENT OF BENDING AN AS DRAWN TUBE

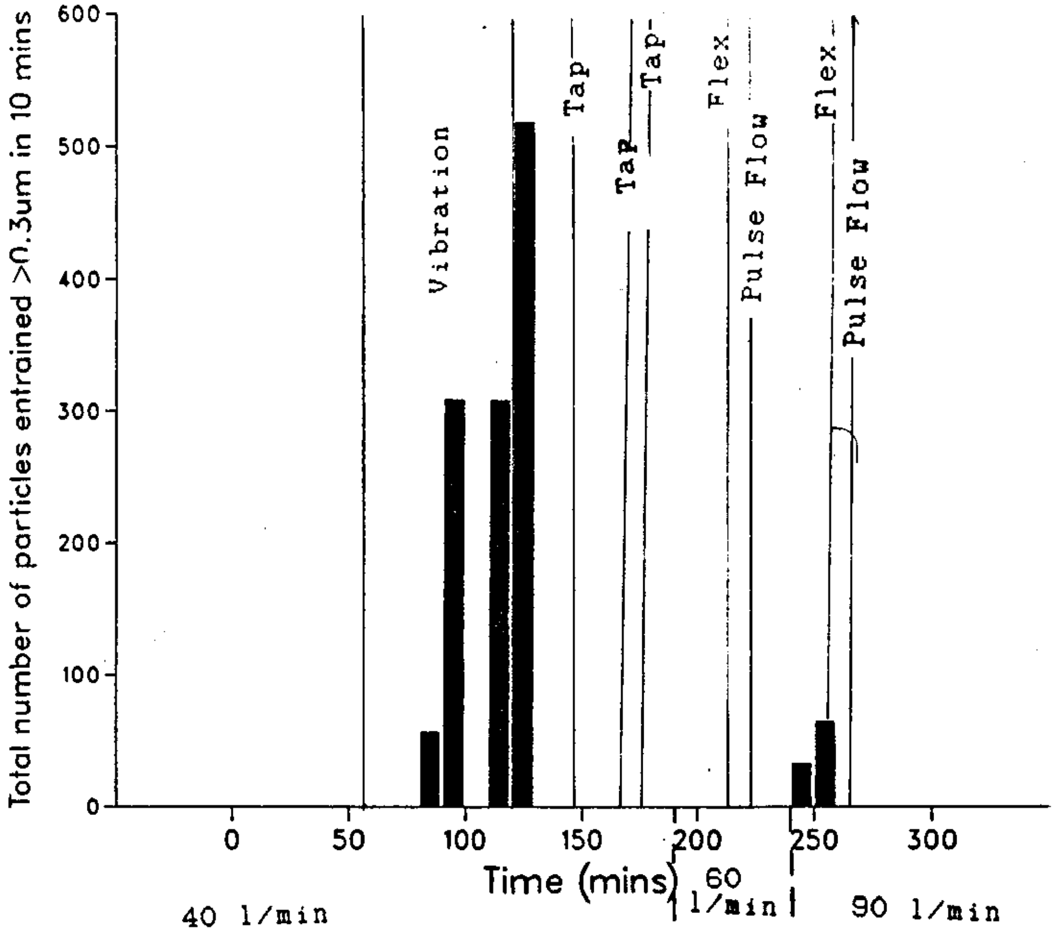

FIGURE 4.48 - ENTRAINMENT TEST ON A BENT ELECTROPOLISHED TUBE

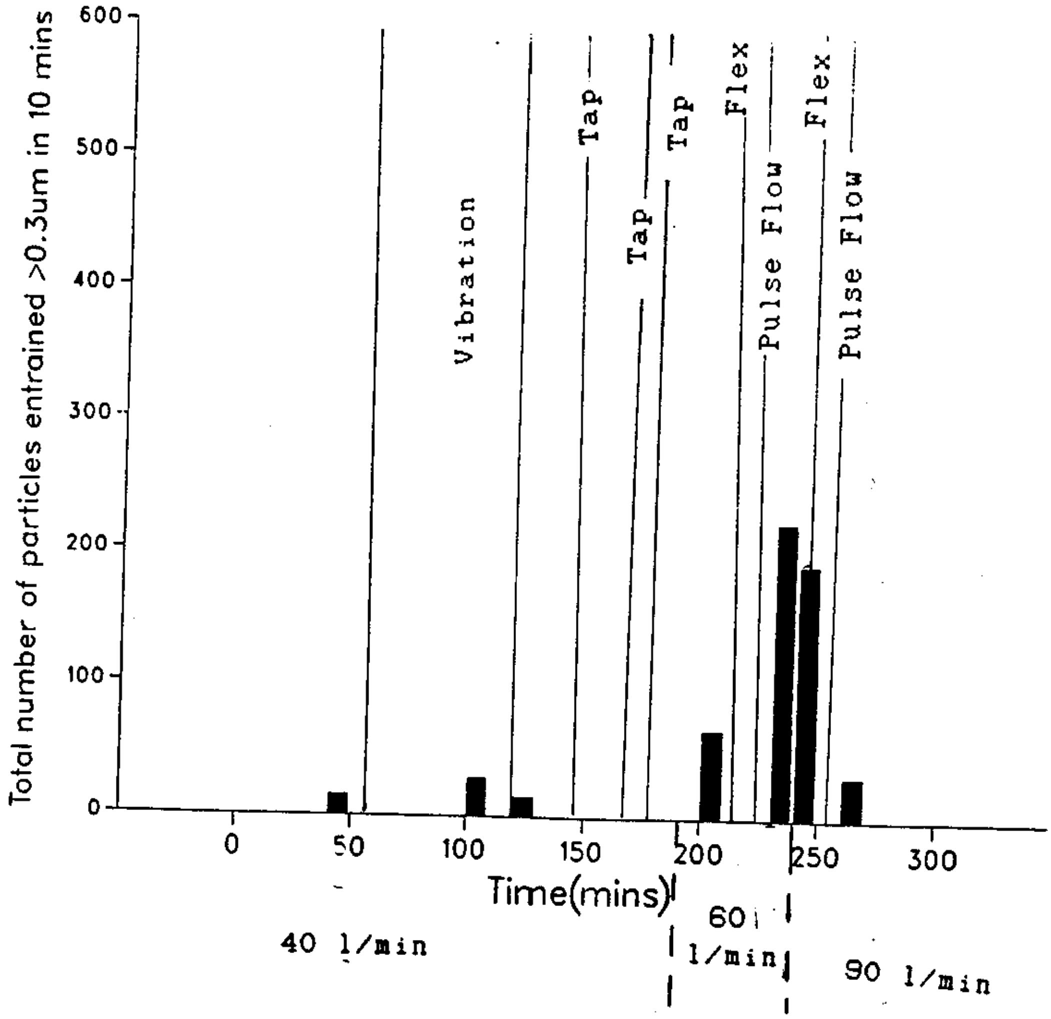

FIGURE 4.49 - ENTRAINMENT TEST ON A BENT CHEMICALLY CLEANED TUBE

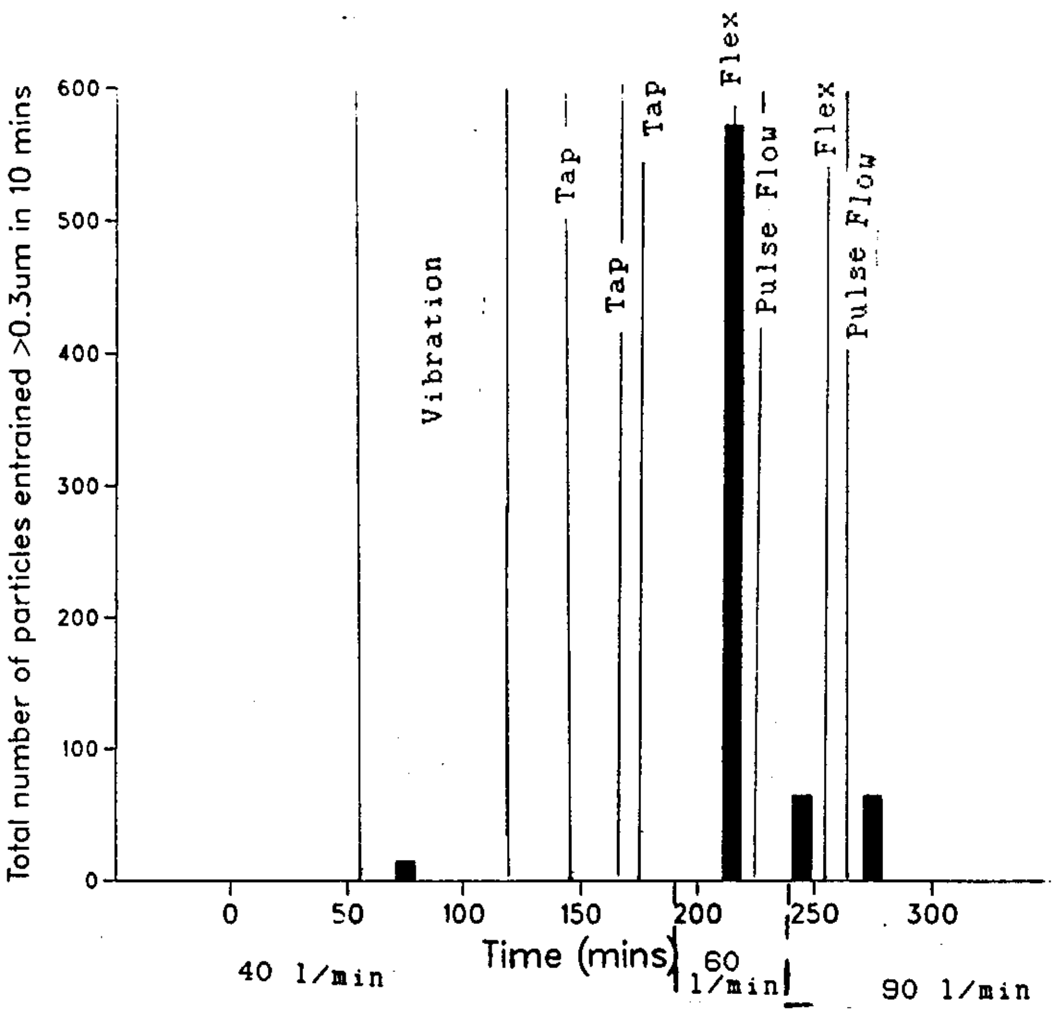

FIGURE 4.50 - ENTRAINMENT TEST ON A BENT AS DRAWN TUBE

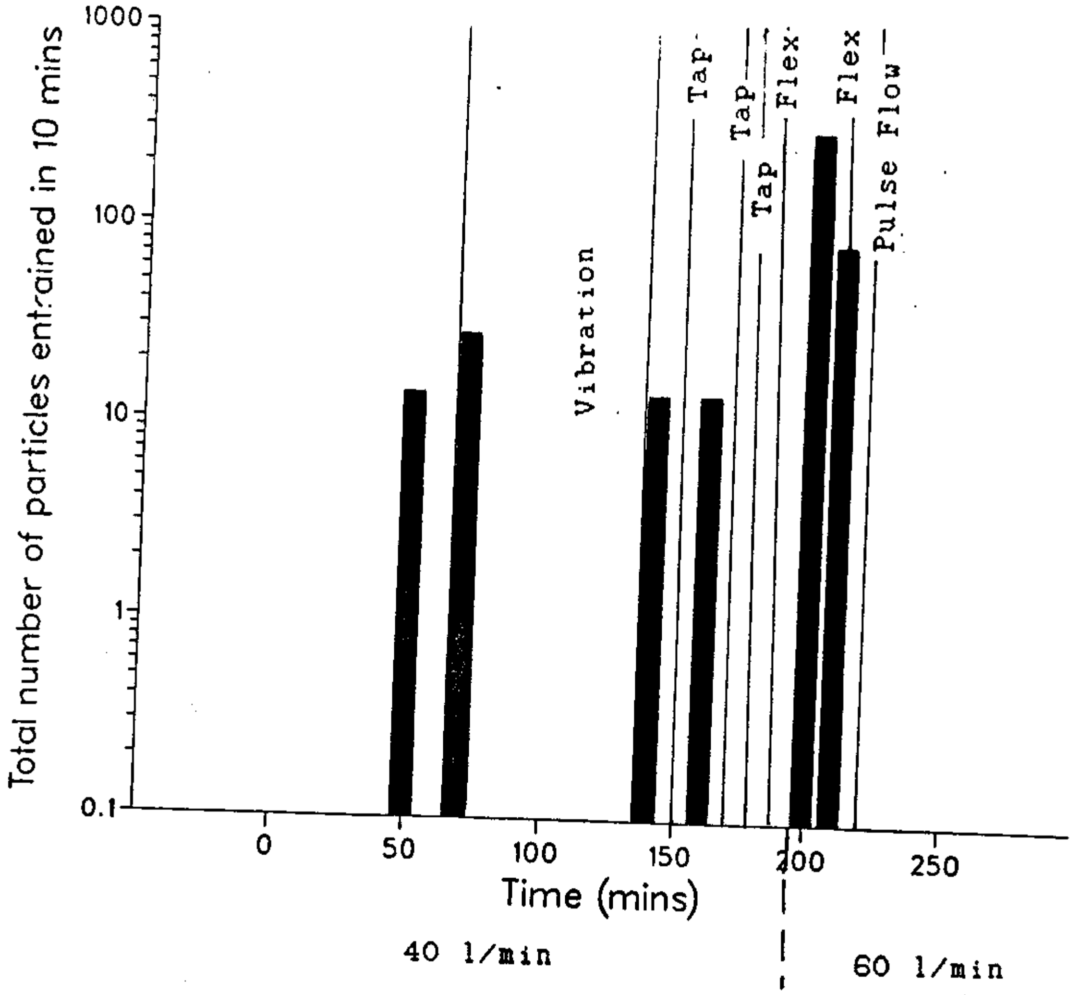

FIGURE 4.51 - RE-ENTRAINMENT TEST ON A BENT ELECTROPOLISHED TUBE

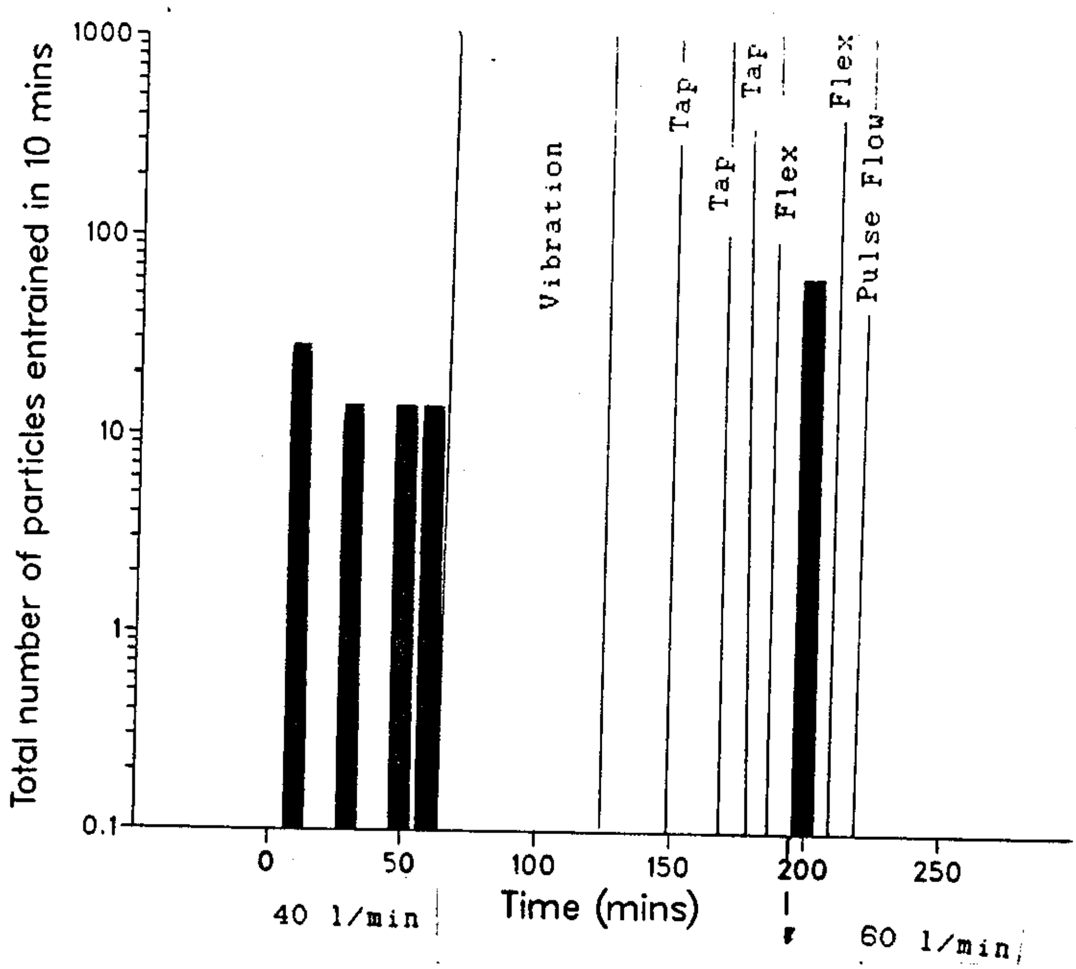

FIGURE 4.52 - RE-ENTRAINMENT TEST ON A BENT CHEMICALLY CLEANED TUBE

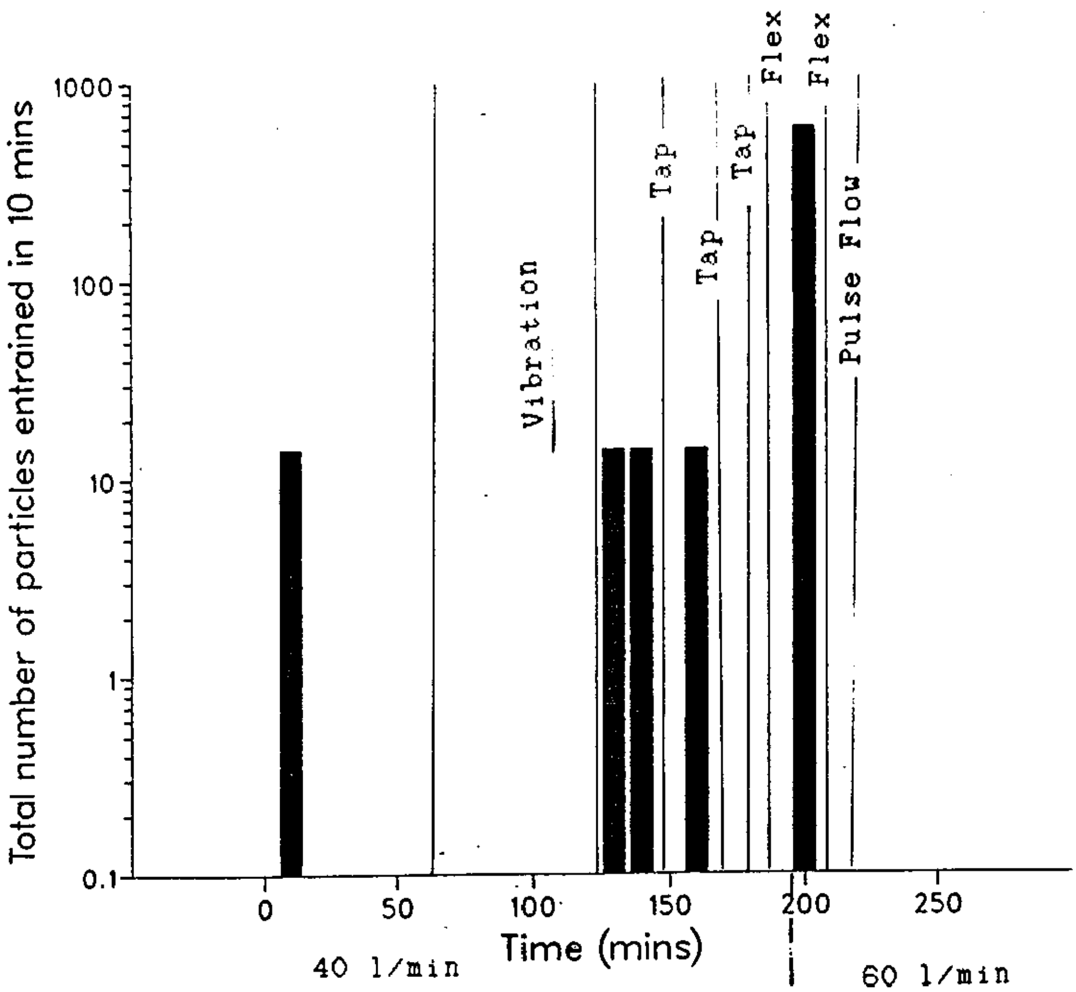

FIGURE 4.53 - RE-ENTRAINMENT TEST ON A BENT AS DRAWN TUBE

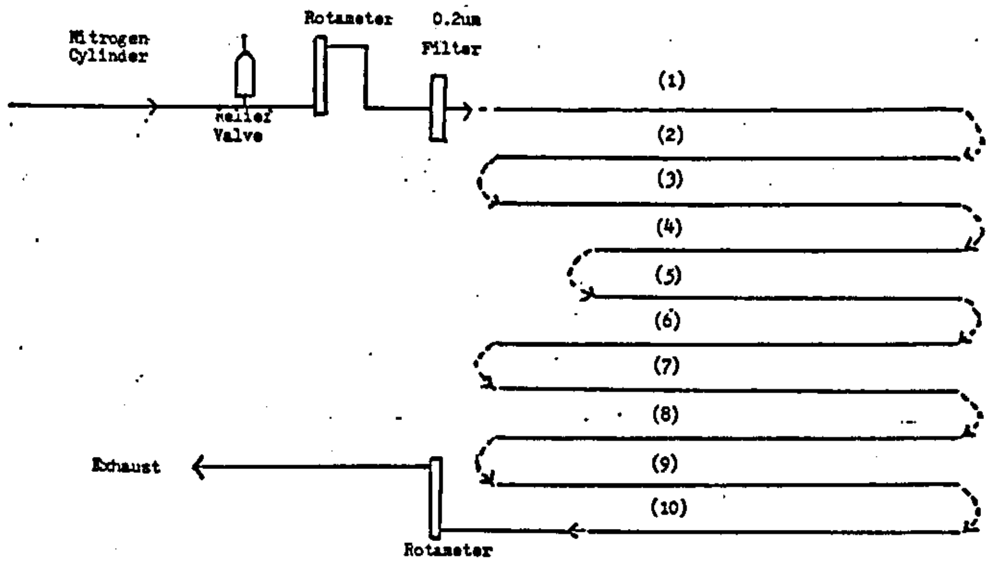

FIGURE 4.54 - LONG TERM NITROGEN TEST SYSTEM

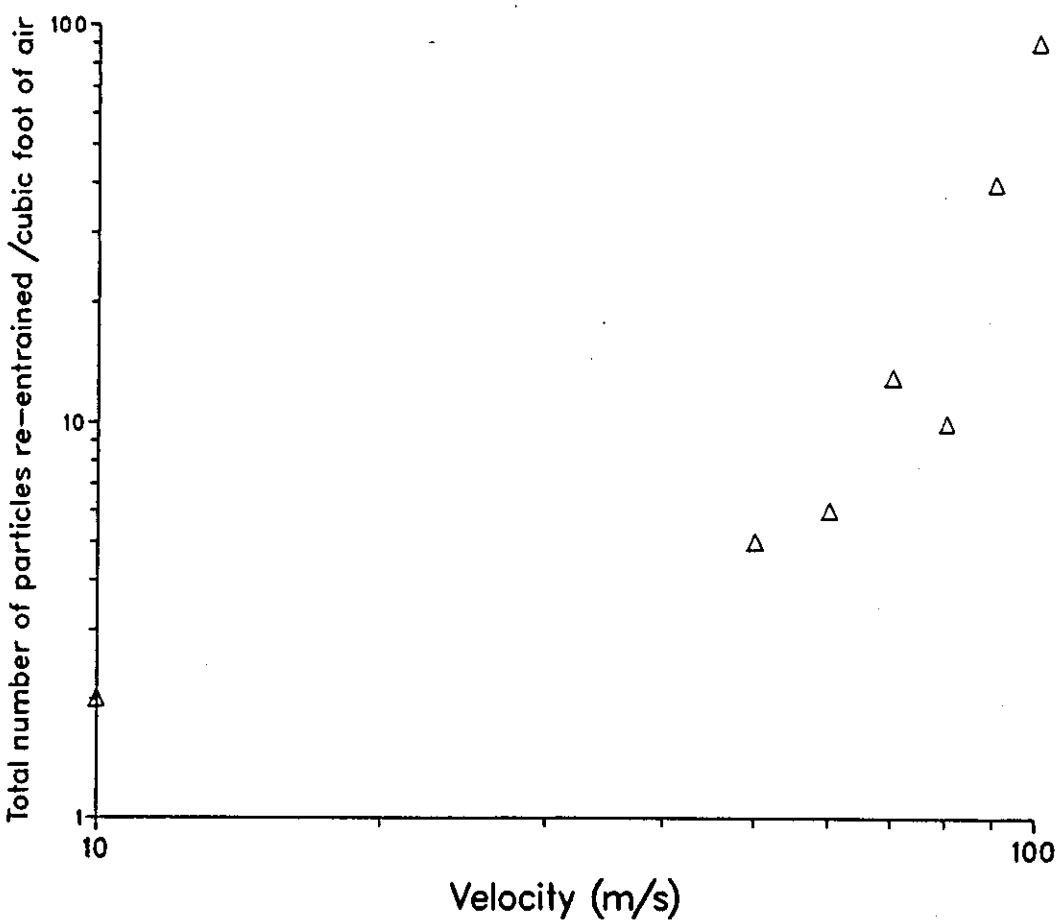

FIGURE 4.55 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM AN ELECTROPOLISHED TUBE

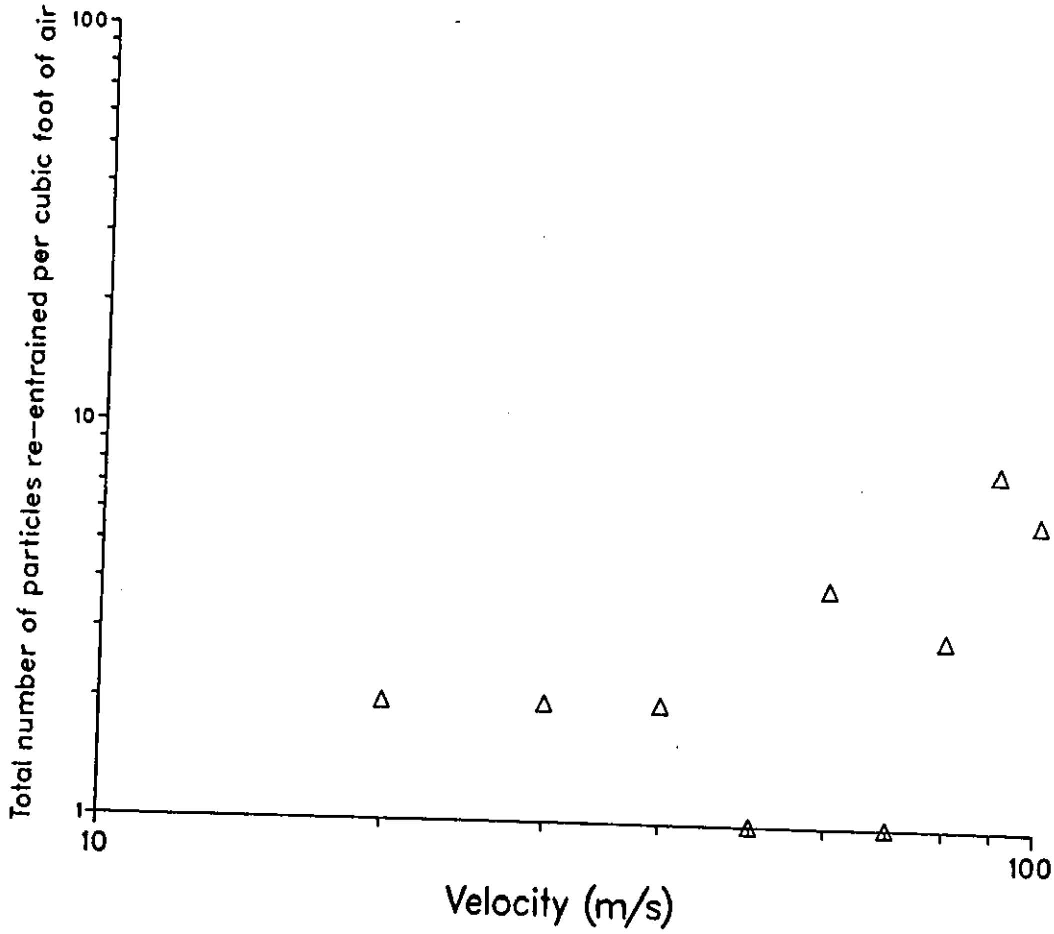

FIGURE 4.56 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM AN AS DRAWN TUBE

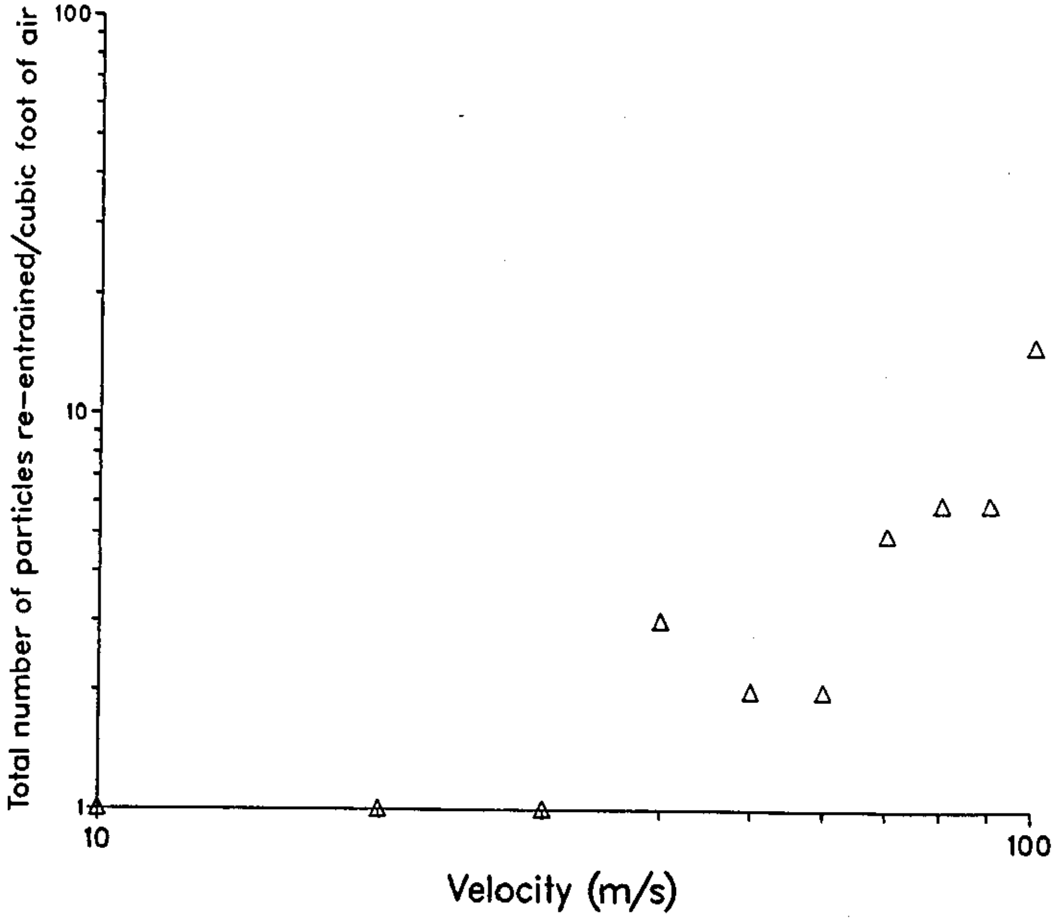

FIGURE 4.57 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM A CHEMICALLY CLEANED TUBE

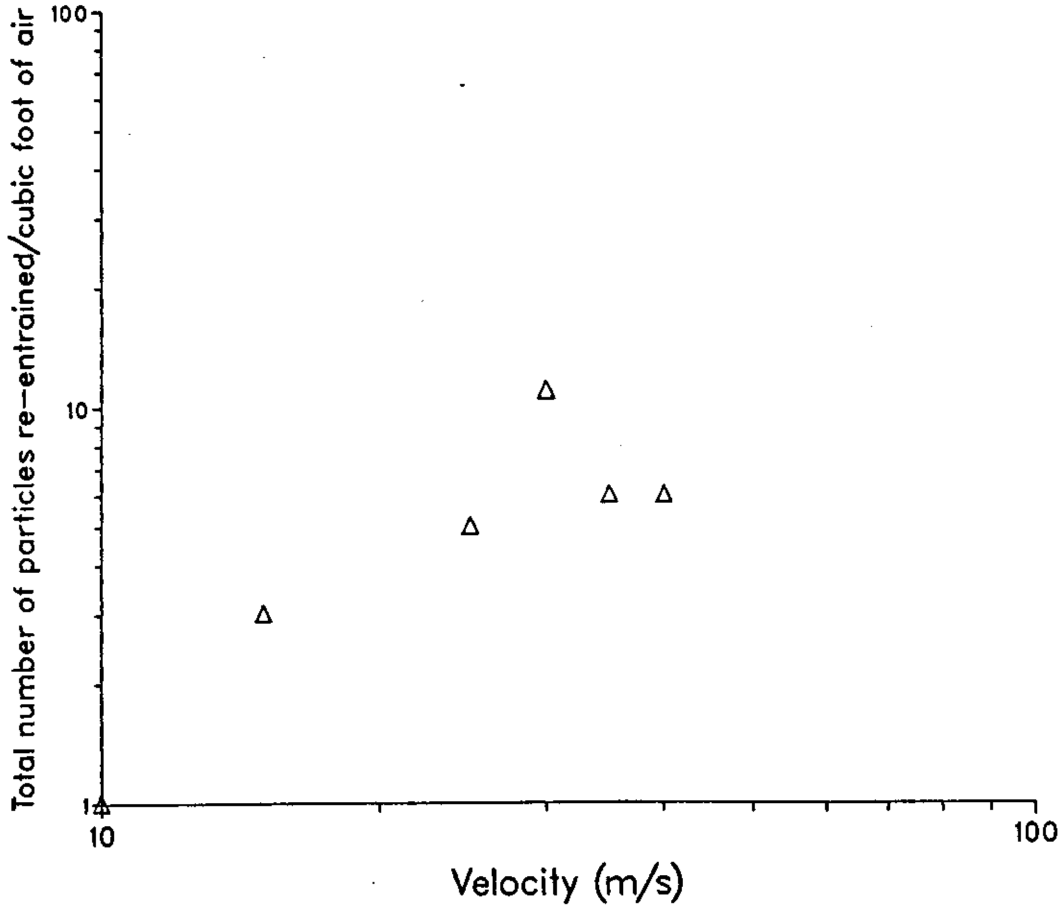

FIGURE 4.58 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM A 10MM O.D. ELECTROPOLISHED TUBE

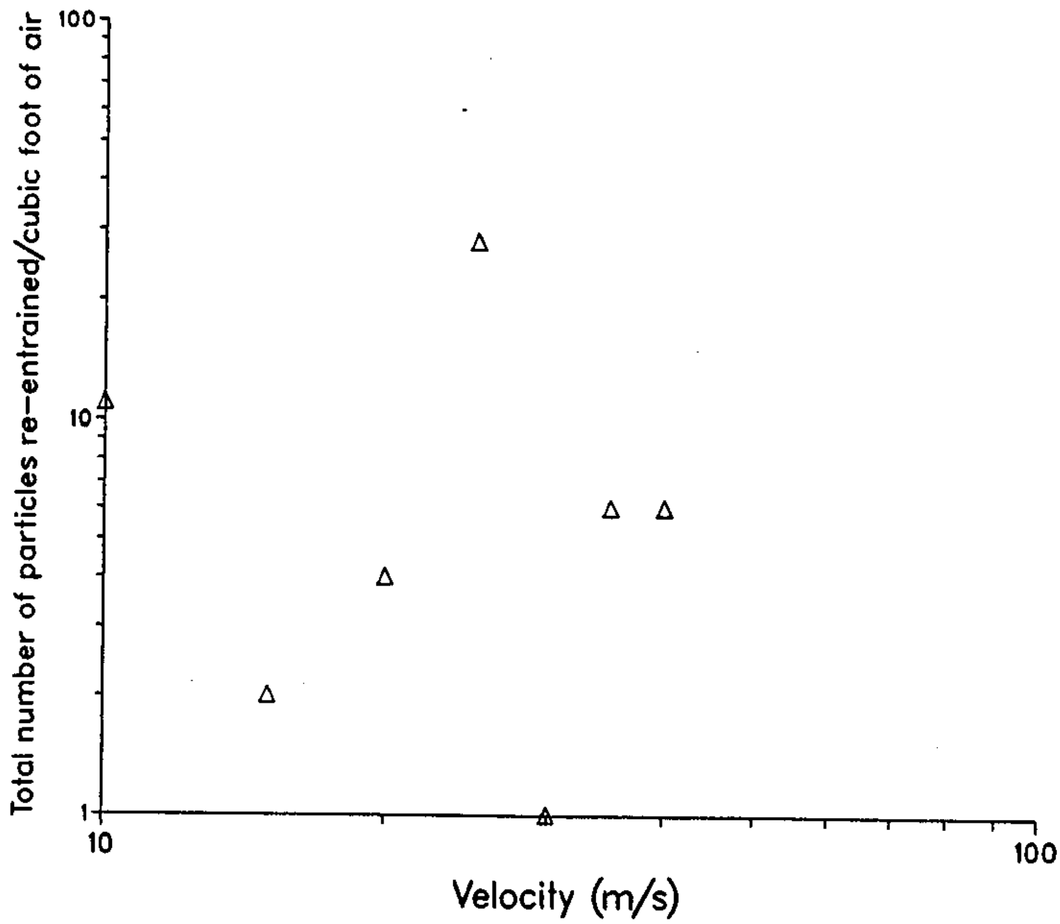

FIGURE 4.59 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM A 2ND 10MM O.D. ELECTROPOLISHED TUBE

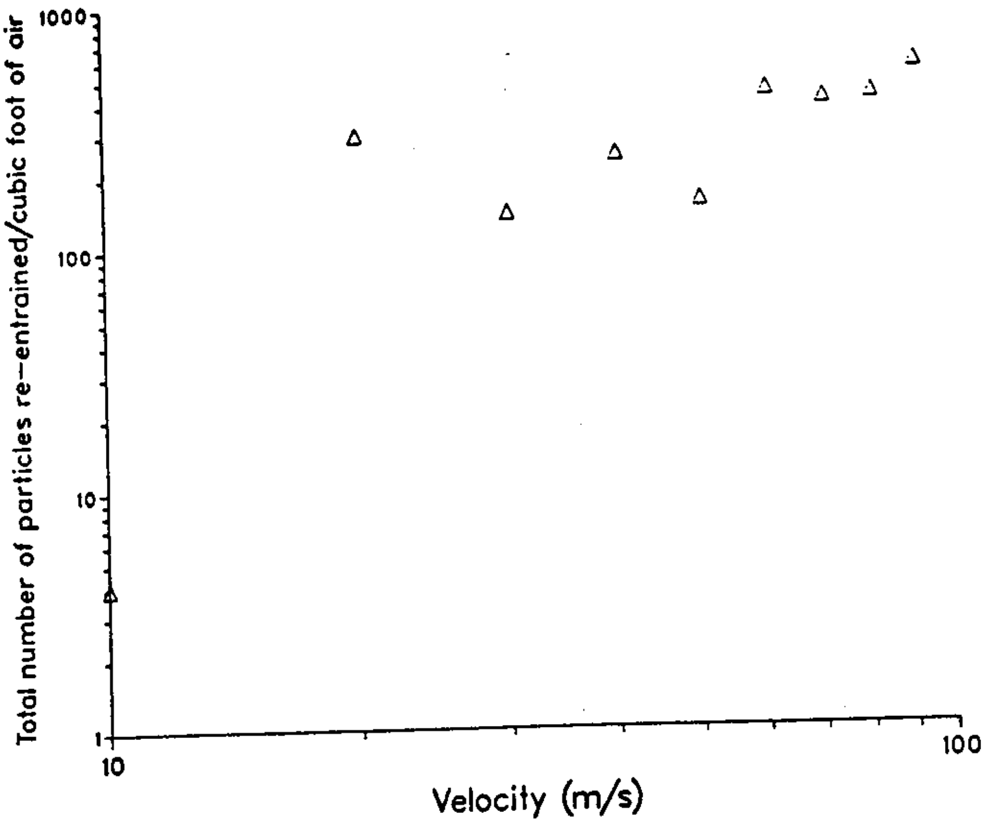

FIGURE 4.60 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM A 3.2MM O.D. TUBE

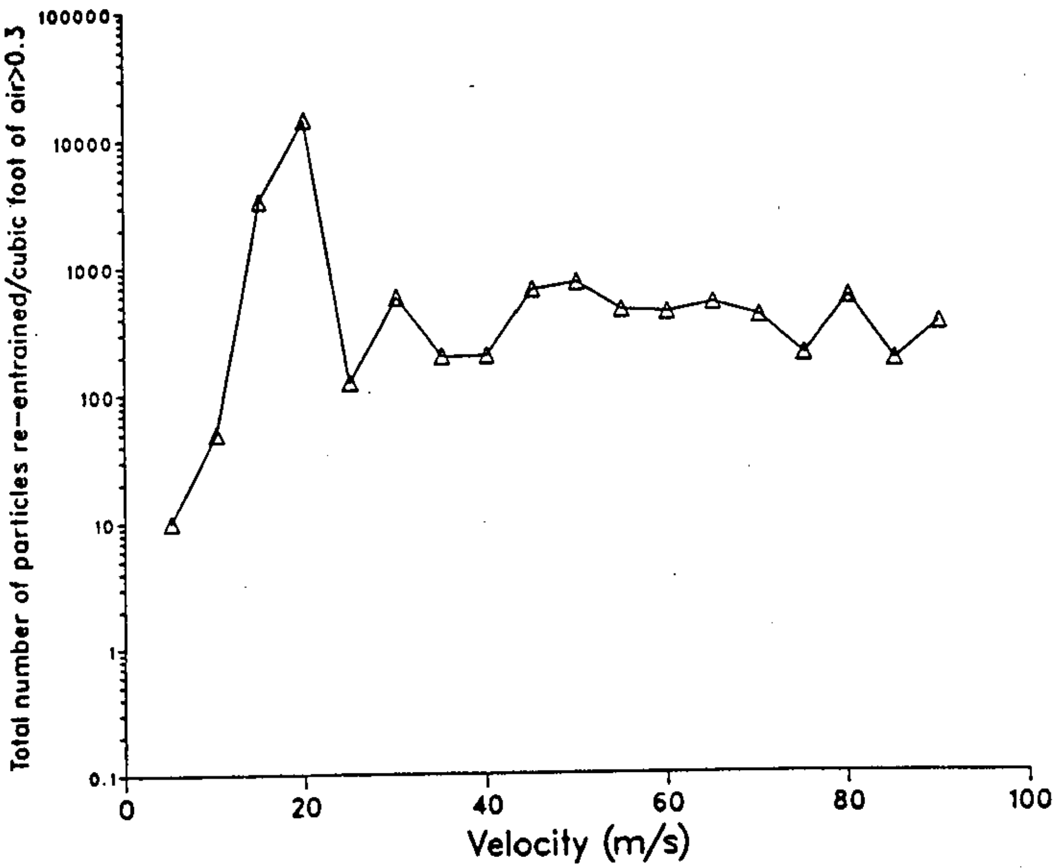

FIGURE 4.61 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM A 2ND 3.2MM O.D. TUBE

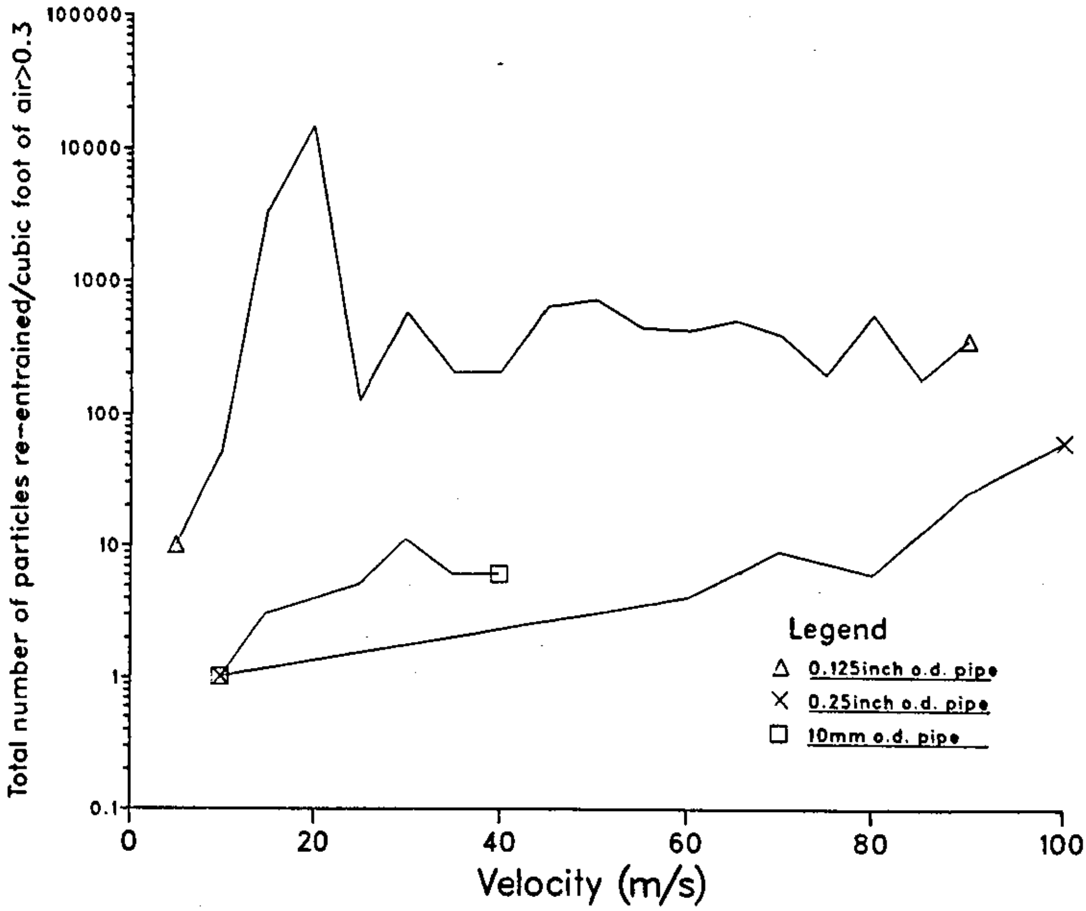

FIGURE 4.62 - COMPARISON OF THE TOTAL NUMBER OF PARTICLE >0.3µm DIAMETER RE-ENTRAINED FOR EACH SIZE OF TUBE

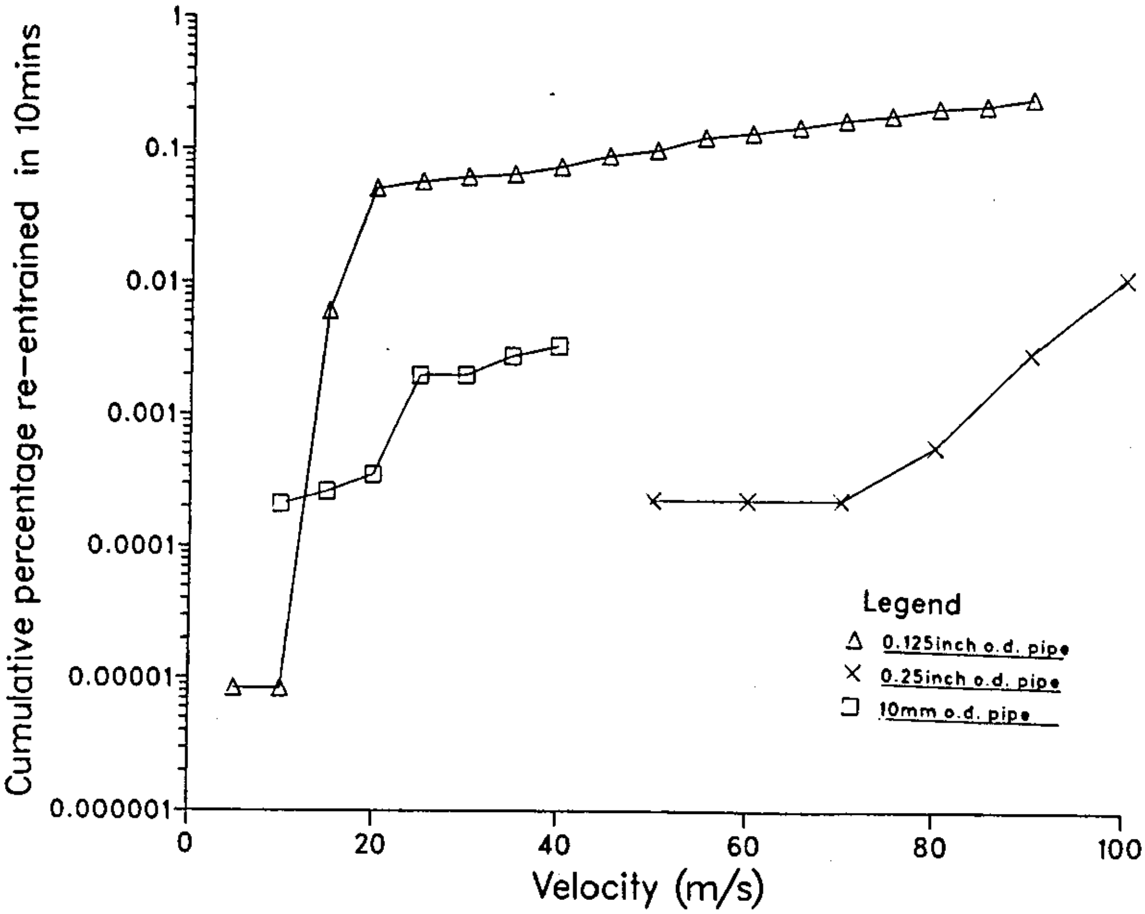

FIGURE 4.63 - EFFECT OF VELOCITY ON THE CUMULATIVE PERCENTAGE RE-ENTRAINMENT OF PARTICLES IN THE SIZE RANGE 0.3 - 0.5μm DIAMETER

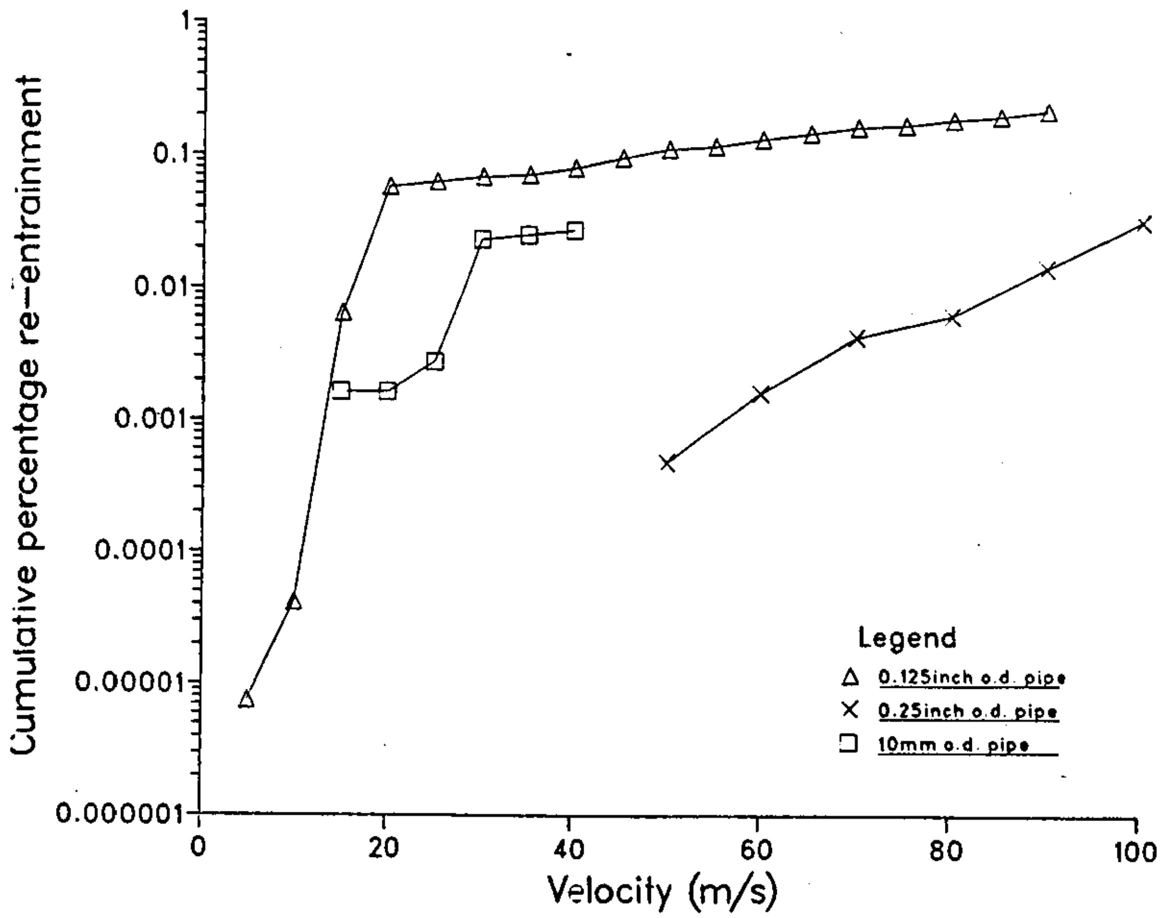

FIGURE 4.64 - EFFECT OF VELOCITY ON THE CUMULATIVE PERCENTAGE RE-ENTRAINMENT OF PARTICLES IN THE SIZE RANGE 0.5 - 1.5μm DIAMETER

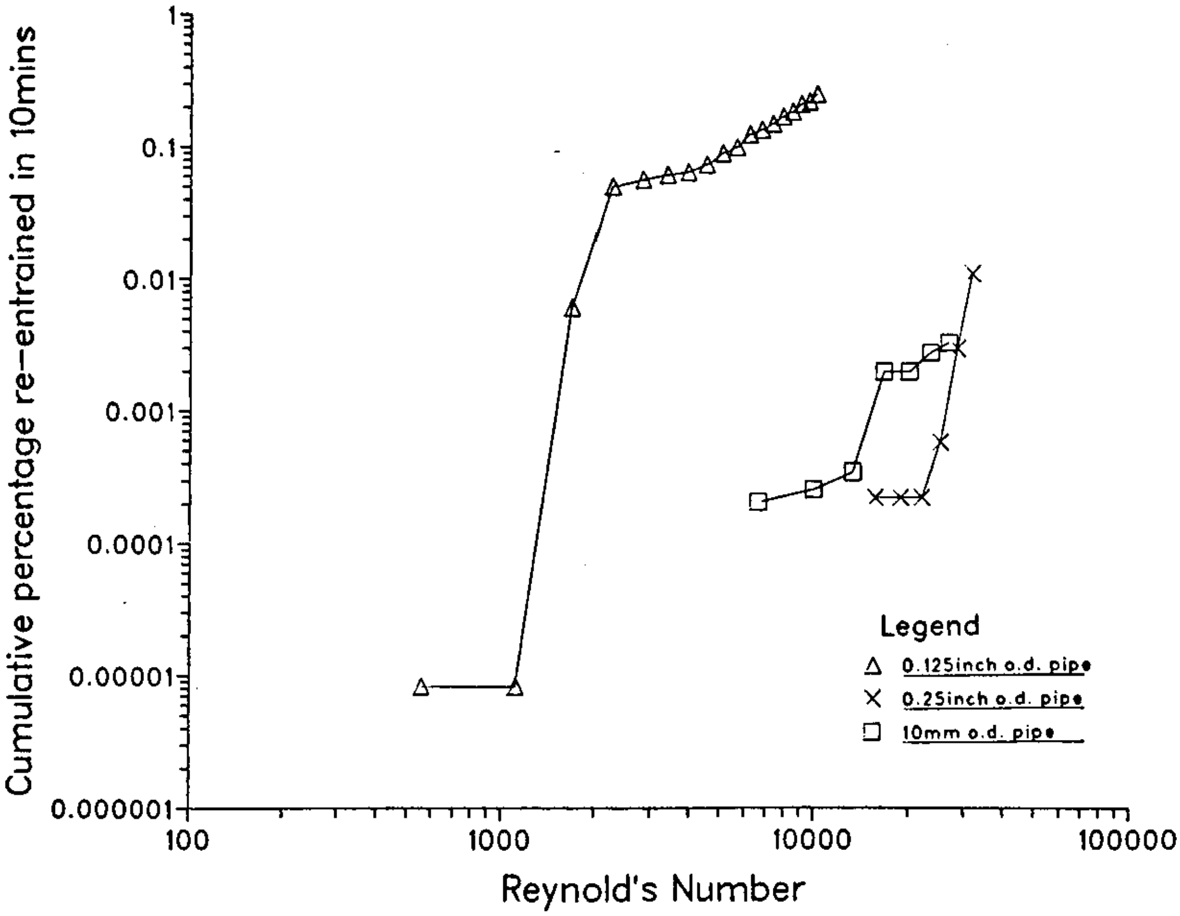

FIGURE 4.65 - CUMULATIVE PERCENTAGE RE-ENTRAINMENT OF PARTICLES AT THE CORRESPONDING REYNOLD'S NUMBER FOR THE SIZE RANGE 0.3 - 0.5μm DIAMETER

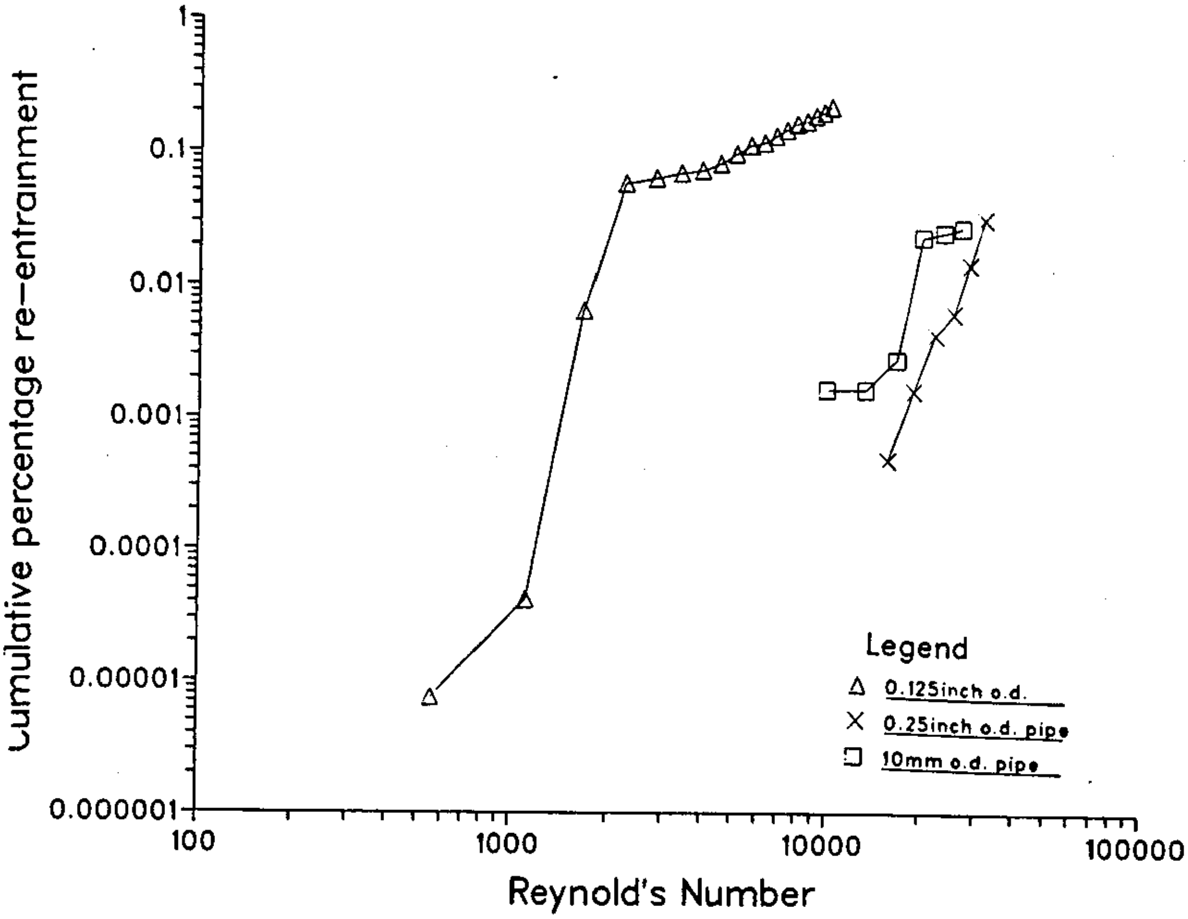

FIGURE 4.66 - CUMULATIVE PERCENTAGE RE-ENTRAINMENT OF PARTICLES AT THE CORRESPONDING REYNOLD'S NUMBER FOR THE SIZE RANGE 0.5 - 1.5μm DIAMETER

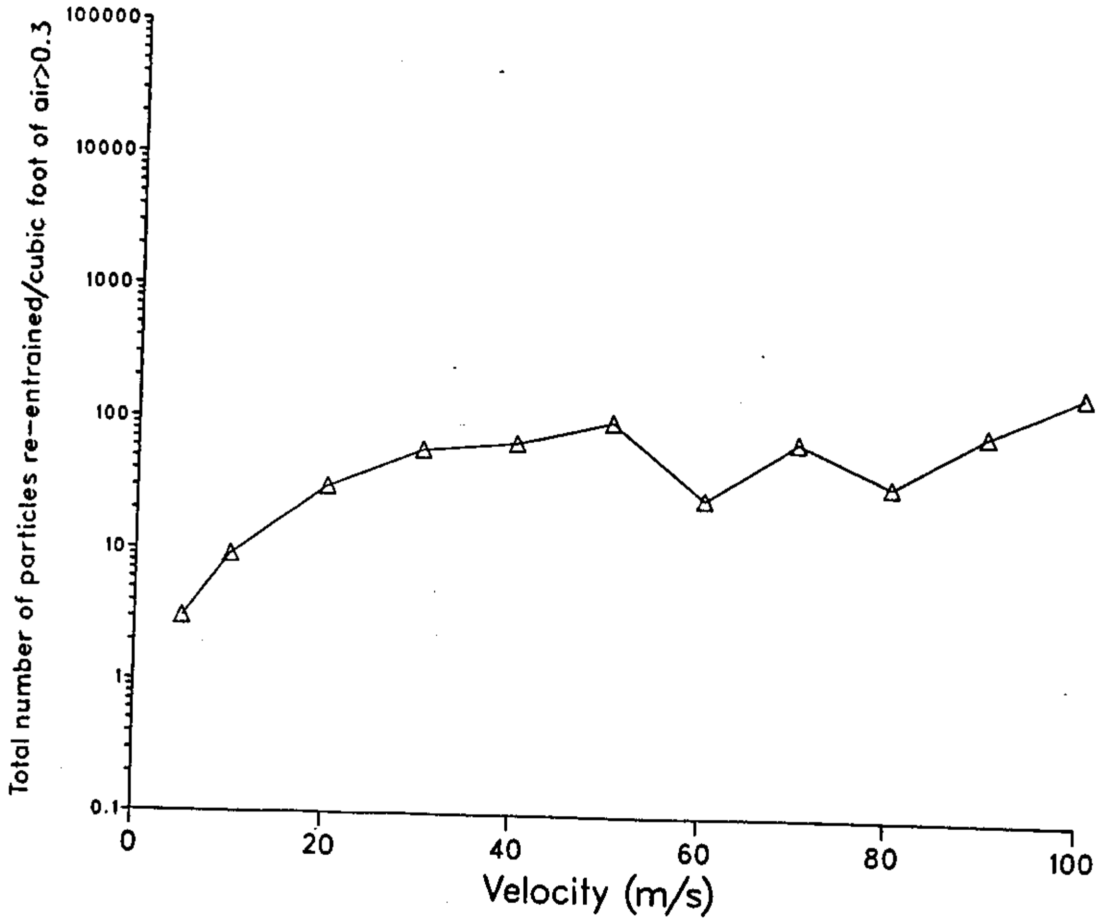

FIGURE 4.67 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICLES FROM A 12 YEAR OLD TUBE

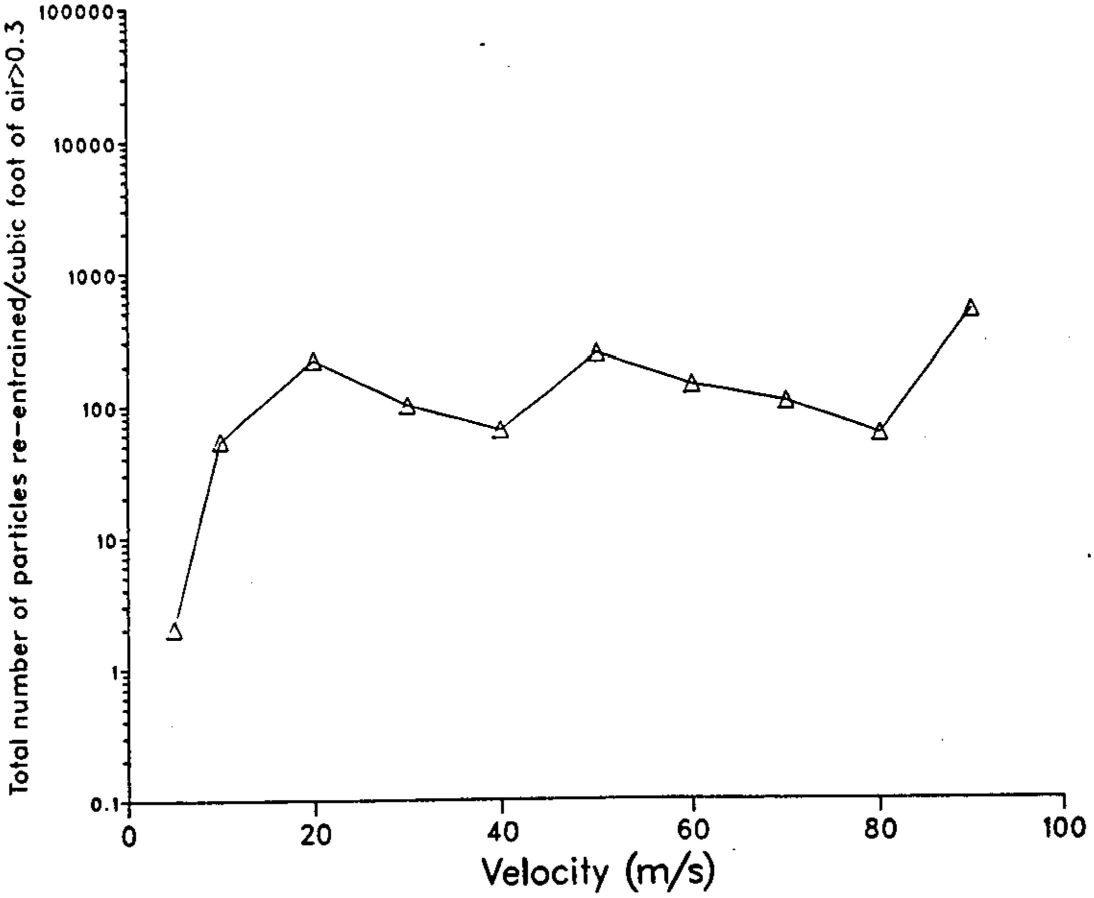

FIGURE 4.68 - EFFECT OF VELOCITY ON RE-ENTRAINMENT OF PARTICULATES FROM A 2ND 12 YEAR OLD TUBE

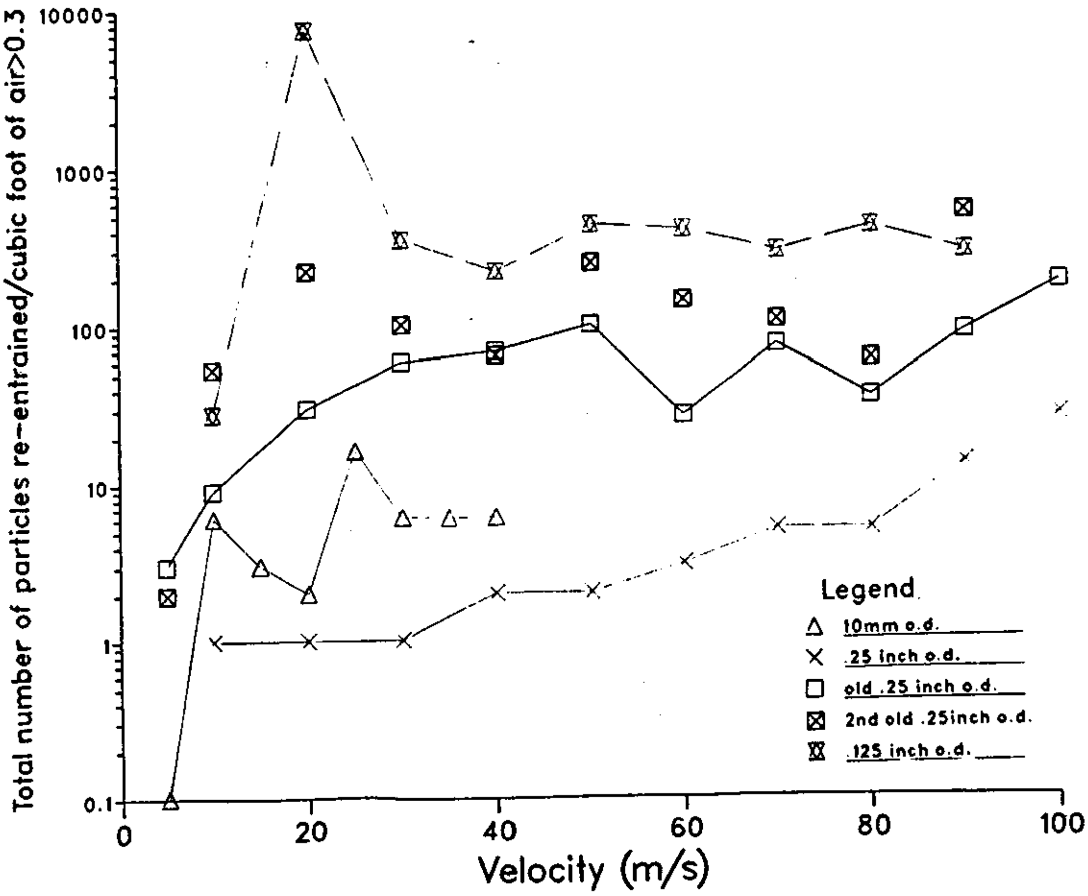

FIGURE 4.69 - MEAN RESULTS OF THE DIFFERENT SIZED TUBES

CHAPTER FIVE

VALVES, RESULTS AND DISCUSSION

5.1 INTRODUCTION

Ultra clean process gases containing a very low level of particulate contamination are required in many industrial applications. This is particularly true in the Integrated Circuit industry, where considerable care is taken in the installation of gas delivery systems to clean rooms. Three different types of surface finished tubes have been investigated for their effect on particulate contamination as described in Chapter 4. However, there is virtually no quantitative information on the release of aerosol particles from other components which comprise such systems. An experimental programme was thus undertaken to assess the level of particle shedding from valves. This Chapter descibes the programme and the results obtained.

A range of different types of valves, from different manufacturers (referred to as "A","B","C" and "D"), was tested when they were fully or partly open.Clean air was passed through them and the level of contamination in the exhaust measured. This of course reflects the level of cleanliness of the valve in the 'as delivered' state. The effect of repeatedly opening and closing the valves was then determined. The initial test on fully open or partly open valves was repeated.

5.2 EXPERIMENTAL

The experiments were carried out in the Class 10 clean cabinet (described in Chapter 3) located in the Class 1000 clean laboratory. Clean air, which was monitored daily for 30 minutes, was supplied from the clean air line (Chapter 3). The experimental set-up is shown in Figure 5.1. The clean air entered the valve under test through a Tee-piece and left via a sampling chamber. When the valve was closed the plug was removed from the other line out of the Tee and the flow diverted. This procedure was followed so that the valve was not under any pressure when it was re-opened and any particles that were entrained came from the opening/closing motion of the valve rather from a high pressure air flow. The particle entrainment was measured using the Royco 225 particle counter.

The experimental work was carried out in three stages:-

a) When the valves were fully or partly open the particle entrainment was measured over a range of flowrates. These are static tests in that the valves were not moved mechanically.

b) The valves were opened and closed a set number of times and the amount of particle entrainment was measured over a range of flowrates.

c) The fully open or partly open throttling test was repeated.

The valves were tested at four flowrates for the three parts of the test. In the majority of the valves tested, the flowrates were 20 l/min, 40 l/min, 60 l/min and finally 90 l/min. At each flowrate, the valve was purged for at least one hour or until no more particles were seen to be released.

The results of parts (a) and (c) of the test are shown in terms of the total number of particles entrained in ten minutes. The histogram of part (c) of the test is situated immediately below the histogram of part (a). However, the results of the opening and closing test (part (b)) are shown in tabular form.

The experimental work can be categorised into two sections - manual valves and air-operated valves.

5.3 MANUAL VALVES

The experimental programme undertaken on manual valves can be further categorised into the different types of valves tested. Four types of manual valves, produced by different manufacturers, 'A','B','C' and 'D' were tested, these are as follows:

1) Ball valves (Figure 5.2)
2) Needle valves (Figure 5.3)
3) Bellows valves (Figure 5.4)
4) Diaphragm valves (Figure 5.5).

5.3.1 Ball Valves

Four "A" and three "B" ball valves were tested in this part of the experimental programme.

The results of parts (a) and (c) of the tests are shown in

Figures 5.6 - 5.12 in terms of the total number of particles entrained in 10 minutes. Both makes of ball valve could only be tested in the fully open position. It can be seen from these Figures that there was not a significant difference between the two sets of results. However, all of the valves release high contamination in the 'as delivered' state.

The results of the opening and closing tests (part (b)) are shown in Tables 5.1 - 5.7. Both makes of valve were found to release random numbers of particles, which increased as the flow through the valve increased.

5.3.2 Needle Valves

Four "A" needle valves were tested in this part of the experimental programme. However, two of these needle valves were found to release such a large number of particles it was not considered worthwhile to continue the tests.

The results for parts (a) and (c) of the test for the remaining two needle valves are shown in Figure 5.13 & 5.14. The needle valves were tested in the fully, 3/4, 1/2 and 1/4 open positions. Again, there is not a significant difference between the two parts of the test, large numbers of particles are released in both parts of the throttling test.

The results of part (b) of the test are shown in Tables 5.8 & 5.9. The needle valve was found to release large numbers of particles, which increased as the flow through the valve was increased.

5.3.3 Bellows Valves

One "C" and five "B" bellows valves were tested in this part of the experimental programme.

The results of parts (a) and (c) of the test are shown in Figures 5.15 - 5.19 for the "B" valves and Figure 5.20 for the "C" valve. One of the "B" valves tested was a toggle bellows valve, and could thus only be tested in the fully open position. All the other bellows valves were opened and closed by a handwheel and were also tested in the 3/4, 1/2 and 1/4 open positions. The results show that for the four handwheel bellows valves there is not a significant difference in the two sets of results. However, Figures 5.19 and 5.20 show the results for the toggle "B" and handwheel "C" bellows valves, for both of these valves there are significantly more particles released in the 'as delivered' state (i.e. for part (a) of the test) than in part (c) of the test. This suggests that the valves cleaned up with use.

The results of the opening and closing tests are shown in Tables 5.10 - 5.15. The majority of the bellows valves tested (including the toggle bellows valve) released very small amounts of contamination while being opened and closed. However, one of the handwheel bellows valves released a very large number of particles throughout this test. This does suggest that in the main the bellows valves are amongst the cleanest of all the different types of valves tested in this way - however, we should be aware that a 'rogue' valve could slip through the quality control net.

5.3.4 Diaphragm Valves

5.3.4.1 Valves Tested Up To 40l/min

Three diaphragm valves have been tested in this part of the experimental programme, these consist of one "B" valve, one "C" valve and one "D" valve. The flowrates used for these valves were 10 l/min, 20 l/min, 30l/min and 40 l/min.

The results of parts (a) and (c) of the tests are shown in Figures 5.21 - 5.23 for the "B", "C" and "D" valves respectively. All three valves were tested in the fully open position only. It can be seen from these Figures that there is not a significant difference between the two sets of results for the "B" and "C" valves; if anything there are less particles removed in part (c) of the test than in part (a). However, at the highest flowrate for the "D" valve there is quite a large difference between the two sets of results. There are a great deal more particles released in part (c) of the test than in part (a). The "D" valve also released the highest amount of contamination in the 'as delivered' state.

The results of the opening and closing tests are shown in Tables 5.16 - 5.18. All of the valves are found to release random amounts of particles, which increased as the flow through the valve was increased. Of the three types of valve, the "D" diaphragm valve released the most contamination. However, one test of each make of diaphragm valve is not enough to get a truly representative picture

5.3.4.2 Valves Tested Up To 90l/min

Four "B" diaphragm valves were tested in this part of the experimental programme and these are as follows:

1) 1/4 turn diaphragm valve (NC-55)[1]

2) 1/4 turn diaphragm valve

3) 1½ turn diaphragm valve

4) 1½ turn diaphragm valve (NC-55).

The results of parts (a) and (c) of the tests are shown in Figures 5.24 - 5.27. Valves (1) & (2) were tested in the fully open position only, whereas valves (3) & (4) were also tested in the 3/4, 1/2 and 1/4 open positions. It can be seen from these Figures that there is not a significant difference between the two sets of results. In the 'as delivered' state, valves (1) and (4) released the least contamination - this as was expected as they had been processed under clean room conditions.

The results of the opening and closing tests are shown in Tables 5.19 - 5.22. All four diaphragm valves were found to release random amounts of particles, which increased as the flow through the valve was increased.

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[1]NC-55 refers to the special cleaning process used for these valves which are processed under a Class 100 clean tunnel.

5.4 AIR OPERATED BELLOWS VALVES

The air operated valves can be further categorised into two different types of valve:

1) Normally open valve - one which is usually kept in the fully open position.
2) Normally closed valve.

As far as possible the same experimental procedure was used on the air driven valves. Parts (a) and (c) of the test were carried out only on the normally open valve in the fully open position. Part (b) was carried out as normal on both types of valve.

5.4.1 Normally Open Bellows Valve

One "B" normally open air operated bellows valve was tested in this part of the experimental programme.

The results of parts (a) and (c) of the test are shown in Figure 5.28 in terms of the total number of particles entrained in 10 minutes. A significant difference can now be seen between the large number of particles entrained at the start and the low number at the end of the run.

The results of the opening and closing test are shown in Table 5.23. It can be seen that the normally open bellows valve released a large number of particles in this test.

5.4.2 Normally Closed Bellows Valve

One "C" and three "B" (one of which had been cleaned under a class 100 clean tunnel) normally closed bellows valves were tested in this part of the experimental programme.

The opening and closing part of the test was carried out on these types of valves only, the results are shown in Table 5.24 - 5.27. It can be seen from these results that the first "B" valve released a large number of particles. However, there is not a significant difference between the other three valves tested - they were all found to release small random amounts of particles.

5.5 COMPARISON OF THE DIFFERENT TYPES OF VALVE

Before discussing the results it is pertinent to consider the likely sources of particulate contamination arising from the use of valves. These may be summarised as follows:-

i. Entrainment from the internal surfaces of particulates left over from the manufacturing and assembly processes. This is a reflection of the effectiveness of cleaning prior to delivery.

ii. Particle entrainment due to flexure of diaphragms, springs and the surfaces of bellows during operation. Contamination of gases during tube bending has certainly been observed (Stenhouse and Arnold 1988); however, it is difficult to determine whether this is due to the entrainment of adhering particles or the generation of new particles arising from surface breakage.

iii. Surface wear caused by mechanical action.

iv. Generation from grease etc. left over from manufacture.

Figure 5.29 is typical of a purge test - the total number of particles greater than 0.3 μm diameter entrained over 10 minute periods are shown. The valve was purged at 20 l/min until contamination ceased; then the purge rate was increased to 40 l/min, then 60 l/min and finally 90 l/min. Clearly residual contamination from the manufacturing process was being removed. Obviously turbulent entrainment increases with flowrate.

Particulate contamination over the purging period is shown for a range of types of valve in Table 5.28. The figures shown are an integral over the purging period and represent the averages of several valves for each type tested. There are significant differences between the design types but within these are also significant differences between those produced by different manufacturers, reflecting individual variations in design and cleaning and assembly procedures.

The effect of opening and closing the valves 100 times is shown in Table 5.29. When the ball valves, for example, which had previously been operated in an opening/closing test at 60 l/min, were opened and closed 100 times at 90 l/min, they released on average 1,845 particles per cubic foot during the 10 minute duration of the test. Mechanical action in the ball valve, and especially in the needle valve, caused substantial contamination.

Tests on two needle valves were discontinued because of obvious breakdown of the seating. In the diaphragm valves tested the spring was located in the process gas stream, where its movement caused heavy contamination. If this were not in contact with the process stream the contamination would be greatly reduced.

Following these tests the purge sequence was repeated. Although the contamination was generally less, it was of a similar order to the contamination initially measured. This suggests that some of the contamination generated during operation is relocated on the internal surfaces, where it can be re-entrained by the turbulent action of the process gas.

It can be concluded that:

1) Attention to manufacturing practices, especially cleaning and clean assembly, leads to cleaner components.
2) Consideration of particle generation mechanisms during use, such as wear and flexure and a reduction of area exposed to the process gases, should lead to the design of more suitable components.

Table 5.1

1ST 'A' BALL VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	7	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	7	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	14	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	-	-	-
1	" "	-	-	-	-	14
1	" "	-	-	-	-	-
1	" "	42	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	40	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	20	-	20
1	" "	-	-	-	-	-
1	90 open/close once	-	-	60	-	-
1	" "	-	-	-	-	-
1	" "	30	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	60	-	-	-	-
1	" "	90	90	30	-	-
1	" "	-	90	-	30	-
1	" "	-	-	-	-	-
1	" "	-	30	-	-	-
10	90 open/close 100t.	90	240	150	90	60
10	90 open/close 100t.	210	210	240	30	60

Table 5.2

2ND 'A' BALL VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	21	14	21	-	-
1	" "	14	7	7	-	-
1	" "	-	14	-	-	-
1	" "	7	-	7	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	7	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	14	-	-	-
1	" "	14	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	14	-	14	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	60 open/close once	20	40	60	20	20
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	20	-
1	" "	-	20	-	-	-
1	" "	-	20	20	-	20
1	" "	-	-	-	-	-
1	" "	20	-	-	-	-
1	" "	-	20	20	-	-
1	" "	-	-	-	-	-
1	90 open/close once	90	60	60	-	-
1	" "	-	-	60	-	-
1	" "	60	90	-	-	30
1	" "	120	180	240	-	-
1	" "	-	60	30	-	-
1	" "	30	30	60	30	-
1	" "	-	-	-	-	-
1	" "	-	60	60	-	-
1	" "	-	60	-	-	-
1	" "	-	60	30	-	-
10	90 open/close 100t.	3450	4590	1170	90	180
10	90 open/close 100t.	14550	4350	3390	1170	1230

Table 5.3

3RD 'A' BALL VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	812	1022	161	7	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	14	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	280	580	60	-	-
1	" "	-	-	-	-	-
1	" "	21	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	150	180	-	-	-
1	" "	-	-	30	-	-
1	" "	-	-	30	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	30	-	-	-
1	" "	-	-	-	-	-
1	" "	30	-	-	-	-
1	" "	-	-	-	-	-
10	20 open/close 100t.	7	7	-	-	-
10	40 open/close 100t.	28	56	28	42	28
10	60 open/close 100t.	220	340	20	-	-
10	90 open/close 100t.	1050	1800	450	30	30

Table 5.4

4TH 'A' BALL VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	30	60	60	-	-
1	" "	-	30	-	-	-
1	" "	30	-	-	-	-
1	" "	30	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	30	-	-	-
1	" "	-	-	-	-	-
1	" "	90	60	-	-	-
10	20 open/close 100t.	21	14	-	-	-
10	40 open/close 100t.	28	56	84	-	-
10	60 open/close 100t.	220	300	180	20	-
10	90 open/close 100t.	1230	1650	480	-	-

Table 5.5

1ST 'B' BALL VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)		Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once		-	14	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	40 open/close once		-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	60 open/close once		20	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	90 open/close once		-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	30	-	-	-
1	"	"	-	-	-	-	-
1	"	"	60	30	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
10	20 open/close 100t.		-	-	7	-	-
10	40 open/close 100t.		14	14	-	-	-
10	60 open/close 100t.		-	20	-	-	-
10	90 open/close 100t.		210	30	60	-	-

Table 5.6

2ND 'B' BALL VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5µ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	7	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	14	-	-
1	" "	-	-	14	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	-	-	30	30	-
1	" "	30	30	-	-	-
1	" "	30	30	30	-	-
1	" "	-	-	-	-	-
1	" "	-	-	30	-	-
1	" "	-	-	-	-	-
1	" "	-	60	-	-	-
1	" "	-	60	-	-	-
1	" "	-	-	-	-	-
1	" "	60	30	-	-	-
10	20 open/close 100t.	7	14	7	-	-
10	40 open/close 100t.	-	42	-	-	-
10	60 open/close 100t.	60	40	-	-	-
10	90 open/close 100t.	210	390	180	60	-

Table 5.7

3RD 'B' BALL VALVE - OPENING/CLOSING TEST

Time	Flow	Total number of particles entrained				
(mins)	(l/min)	0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	7	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	14	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	-	30	-	-	-
1	" "	-	30	-	-	-
1	" "	-	-	-	-	-
1	" "	30	30	-	-	-
1	" "	-	-	-	-	-
1	" "	-	30	-	-	-
1	" "	-	30	-	30	-
1	" "	30	30	-	-	-
1	" "	30	30	-	-	-
1	" "	-	30	-	-	-
10	20 open/close 100t.	-	7	-	-	-
10	40 open/close 100t.	56	28	42	-	-
10	60 open/close 100t.	200	140	20	-	-
10	90 open/close 100t.	570	990	300	30	-

Table 5.8

1ST 'A' NEEDLE VALVE - OPENING/CLOSING TEST
(CLEANED FOR O_2 SERVICE)

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	28	21	-	-	-
1	" "	-	21	-	-	-
1	" "	7	-	-	-	-
1	" "	-	21	-	-	-
1	" "	7	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	7	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	7	-
1	" "	-	7	-	-	-
1	40 open/close once	28	84	84	14	-
1	" "	-	42	14	-	-
1	" "	-	70	14	-	-
1	" "	14	56	28	14	-
1	" "	14	238	28	-	-
1	" "	14	14	14	-	-
1	" "	-	14	-	14	-
1	" "	-	14	28	-	-
1	" "	-	14	-	-	-
1	" "	-	28	-	14	-
1	60 open/close once	40	80	80	20	20
1	" "	100	80	40	20	-
1	" "	-	80	60	20	40
1	" "	40	140	80	40	20
1	" "	20	100	60	-	-
1	" "	80	40	40	20	-
1	" "	-	100	60	40	-
1	" "	-	20	60	20	20
1	" "	100	260	140	60	20
1	" "	-	180	20	60	-
1	90 open/close once	1260	4530	990	210	-
1	" "	210	1320	390	30	30
1	" "	780	2430	780	30	30
1	" "	1290	3120	780	-	-
1	" "	690	1800	270	-	30
1	" "	210	450	180	-	30
1	" "	120	660	300	30	30
1	" "	240	660	270	150	-
1	" "	90	360	120	-	-
1	" "	330	720	360	-	-
10	20 open/close 100t.	14	35	21	14	49
10	40 open/close 100t.	42	280	238	196	112
10	60 open/close 100t.	480	1560	1080	540	360
10	90 open/close 100t.	3060	6390	4920	1290	570

Table 5.9

4TH 'A' NEEDLE VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	7	7	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	14	168	28	14	-
1	" "	14	308	84	-	-
1	" "	-	-	-	-	-
1	" "	56	224	70	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	1640	4440	1500	20	-
1	" "	540	2680	760	-	-
1	" "	80	520	420	-	-
1	" "	40	-	-	-	-
1	" "	1140	3220	1200	-	-
1	" "	960	2680	900	20	-
1	" "	120	120	60	-	-
1	" "	-	20	-	-	-
1	" "	1060	3120	1140	-	-
1	" "	620	1900	780	-	-
1	90 open/close once	810	3150	930	60	-
1	" "	3900	11790	2370	-	-
1	" "	6990	17910	4950	-	-
1	" "	8100	24390	6030	-	-
1	" "	1050	3060	990	-	-
1	" "	720	1320	390	-	-
1	" "	3540	10290	2520	30	-
1	" "	2190	4680	990	30	-
1	" "	510	1260	360	-	-
1	" "	10890	35250	9600	30	-
10	20 open/close 100t.	28	63	21	-	-
10	40 open/close 100t.	42	364	168	-	14
10	60 open/close 100t.	20	80	40	-	-
10	90 open/close 100t.	150	150	90	60	90

Table 5.10

1ST 'B' BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	49	42	-	-	7
1	" "	42	77	7	-	-
1	" "	56	84	7	-	-
1	" "	77	119	14	7	-
1	" "	98	105	-	-	-
1	" "	28	56	7	-	-
1	" "	77	56	49	-	-
1	" "	91	42	14	-	-
1	" "	105	84	21	-	-
1	" "	133	77	21	7	-
1	40 open/close once	518	560	70	28	-
1	" "	490	364	28	-	-
1	" "	364	392	28	-	-
1	" "	336	210	28	-	-
1	" "	532	308	14	14	-
1	" "	504	224	-	-	-
1	" "	420	364	42	-	-
1	" "	308	280	-	-	-
1	" "	364	308	70	-	-
1	" "	266	252	14	-	-
1	60 open/close once	800	600	40	40	-
1	" "	880	700	60	-	-
1	" "	480	600	60	-	-
1	" "	380	300	20	-	-
1	" "	680	460	20	40	-
1	" "	540	540	40	20	-
1	" "	620	260	-	-	-
1	" "	480	180	-	-	-
1	" "	420	260	-	-	-
1	" "	540	180	60	-	-
1	90 open/close once	1950	1200	180	-	-
1	" "	1350	720	60	-	-
1	" "	900	540	60	-	-
1	" "	1410	390	-	-	-
1	" "	990	540	30	-	-
1	" "	1050	750	30	-	-
1	" "	810	420	-	-	-
1	" "	660	420	-	-	-
1	" "	360	180	30	-	-
1	" "	840	360	30	-	-
10	20 open/close 100t.	3857	3367	357	7	7
10	40 open/close 100t.	44296	25844	784	42	-
10	60 open/close 100t.	120320	63600	1580	60	-
10	90 open/close 100t.	207030	103350	3900	210	90

Table 5.11

2ND 'B' BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	-	-	-
1	" "	14	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	56	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	-	30	-	-	-
1	" "	30	30	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	30	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	60	-	-	-
1	" "	60	-	-	-	-
1	" "	-	30	-	-	-
1	" "	-	-	-	-	-
10	20 open/close 100t.	-	-	-	-	-
10	40 open/close 100t.	14	-	-	-	-
10	60 open/close 100t.	160	80	60	20	60
10	90 open/close 100t.	90	210	60	-	-

Table 5.12

3RD 'B' BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	20	-	-	-
1	" "	-	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	-	-	-	-
1	" "	20	-	-	-	-
1	90 open/close once	30	-	-	-	-
1	" "	-	30	30	-	-
1	" "	-	-	-	-	-
1	" "	30	-	-	-	-
1	" "	-	-	-	30	30
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	60	90	-	-	-
10	20 open/close 100t.	-	-	-	-	-
10	40 open/close 100t.	96	-	-	-	-
10	60 open/close 100t.	-	60	-	-	-
10	90 open/close 100t.	240	360	60	-	-

Table 5.13

4TH 'B' BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)		Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20	open/close once	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	40	open/close once	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	14	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	42	-	-	-
1	"	"	14	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	60	open/close once	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	90	open/close once	-	60	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
1	"	"	-	-	-	-	-
10	20	open/close 100t.	-	-	-	7	-
10	40	open/close 100t.	14	-	14	-	-
10	60	open/close 100t.	-	-	-	-	-
10	90	open/close 100t.	210	270	90	-	-

Table 5.14

'B' TOGGLE BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	28	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	14	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	20	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	30	-	90	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
10	20 open/close 100t.	7	-	-	-	-
10	40 open/close 100t.	14	-	-	-	-
10	60 open/close 100t.	-	80	-	-	-
10	90 open/close 100t.	30	30	30	-	-

Table 5.15

'C' BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	-	-	14
1	" "	-	-	28	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	20	-	-
1	" "	20	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	-	-	-	20
1	" "	-	40	-	-	-
1	90 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	30	-	-
1	" "	30	-	30	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	30	-	-	30	-
1	" "	-	-	30	-	-
10	20 open/close 100t.	7	-	-	-	7
10	40 open/close 100t.	14	42	84	-	-
10	60 open/close 100t.	60	40	60	-	-
10	90 open/close 100t.	90	90	210	30	30

Table 5.16

'B' DIAPHRAGM VALVE (MAX. 40 L/MIN) - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained				
		0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	10 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	7	-	-	-	-
1	" "	7	-	-	-	-
1	" "	-	-	-	-	-
1	30 open/close once	10	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	10	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	10	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	14	14	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	14	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	14	14	28	-	-
1	" "	-	-	-	-	-
10	10 open/close 100t.	3	-	3	-	-
10	20 open/close 100t.	140	175	105	21	-
10	30 open/close 100t.	820	1580	610	120	20
10	40 open/close 100t.	16870	28574	9338	420	14

Table 5.17

'C' DIAPHRAGM VALVE (MAX. 40 L/MIN) - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	10 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	3	-	-	-	-
1	" "	3	3	-	-	-
1	" "	-	-	-	-	-
1	" "	3	-	-	-	-
1	" "	-	-	-	-	-
1	20 open/close once	-	-	-	-	-
1	" "	-	-	14	-	-
1	" "	7	-	7	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	7	-	21	-	-
1	" "	-	-	-	-	-
1	" "	7	7	7	-	-
1	" "	-	7	14	-	-
1	" "	-	-	14	-	-
1	30 open/close once	-	70	-	-	-
1	" "	10	-	-	-	-
1	" "	-	30	10	-	-
1	" "	-	10	-	-	-
1	" "	-	20	-	-	-
1	" "	-	20	10	-	-
1	" "	-	20	10	-	-
1	" "	-	10	10	-	-
1	" "	-	10	-	-	-
1	" "	-	50	10	-	-
1	40 open/close once	14	-	28	28	14
1	" "	28	14	14	-	-
1	" "	14	28	42	-	-
1	" "	14	-	14	-	-
1	" "	42	-	28	-	-
1	" "	28	-	-	-	-
1	" "	28	28	-	-	-
1	" "	42	28	14	-	-
1	" "	14	-	14	-	-
1	" "	14	14	42	-	-
10	10 open/close 100t.	6	-	-	-	-
10	20 open/close 100t.	126	112	119	21	14
10	30 open/close 100t.	130	240	180	20	-
10	40 open/close 100t.	1260	2156	1610	196	140

Table 5.18

'D' DIAPHRAGM VALVE (MAX. 40 L/MIN) - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5µ
1	10 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	7	-	-	-
1	" "	-	3	-	-	-
1	" "	3	-	3	-	-
1	" "	3	3	3	3	-
1	" "	-	-	-	-	-
1	" "	-	-	3	-	-
1	" "	-	12	3	3	-
1	" "	-	-	-	-	-
1	20 open/close once	28	7	21	7	7
1	" "	42	42	14	-	7
1	" "	56	49	49	14	-
1	" "	35	63	49	21	-
1	" "	35	21	56	21	-
1	" "	35	14	28	7	-
1	" "	28	49	56	7	14
1	" "	49	56	56	21	-
1	" "	77	168	91	7	-
1	" "	70	98	84	7	-
1	30 open/close once	60	50	50	-	-
1	" "	190	410	170	30	-
1	" "	250	310	150	10	10
1	" "	130	90	90	-	-
1	" "	40	70	20	10	-
1	" "	160	200	100	10	-
1	" "	180	310	140	-	-
1	" "	110	140	50	10	-
1	" "	30	60	60	10	-
1	" "	110	110	30	-	-
1	40 open/close once	294	504	238	14	-
1	" "	238	364	154	14	-
1	" "	196	238	182	14	-
1	" "	322	420	210	14	-
1	" "	266	476	140	-	-
1	" "	308	560	252	-	-
1	" "	252	378	252	-	-
1	" "	434	350	140	28	-
1	" "	392	462	266	28	-
1	" "	266	378	140	-	-
10	10 open/close 100t.	831	1629	777	57	9
10	20 open/close 100t.	18067	31353	7196	378	84
10	30 open/close 100t.	75280	116170	21190	680	150
10	40 open/close 100t.	115024	189294	35042	1176	266

Table 5.19

1/4 TURN 'B' DIAPHRAGM VALVE (NC-55) - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	-	14	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	20	40	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	20	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	30	30	-	-
1	" "	-	30	-	-	-
1	" "	30	30	-	-	-
1	" "	-	30	-	-	-
10	20 open/close 100t.	1553	3127	847	53	7
10	40 open/close 100t.	33292	56490	5628	168	28
10	60 open/close 100t.	35460	45780	3660	80	-
10	90 open/close 100t.	64590	73440	5280	240	

Table 5.20

1/4 TURN 'B' DIAPHRAGM VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5µ
1	20 open/close once	7	7	7	-	-
1	" "	7	20	-	-	-
1	" "	-	13	13	-	-
1	" "	7	7	-	-	-
1	" "	-	20	13	-	-
1	" "	27	27	20	-	-
1	" "	13	-	7	-	-
1	" "	-	27	-	-	-
1	" "	7	20	7	7	-
1	" "	-	7	-	-	-
1	40 open/close once	14	-	-	-	-
1	" "	-	70	14	-	14
1	" "	-	14	-	-	-
1	" "	112	84	84	-	-
1	" "	28	-	14	-	-
1	" "	-	42	-	-	-
1	" "	14	14	-	-	-
1	" "	28	56	56	-	-
1	" "	14	-	-	-	-
1	" "	-	28	14	-	-
1	60 open/close once	40	80	60	-	-
1	" "	-	40	20	-	-
1	" "	200	300	80	-	-
1	" "	80	160	40	-	-
1	" "	120	100	60	-	-
1	" "	220	160	20	-	-
1	" "	20	20	40	-	-
1	" "	80	140	40	-	-
1	" "	40	80	-	-	-
1	" "	120	220	-	-	-
1	90 open/close once	360	750	180	-	-
1	" "	420	390	60	-	-
1	" "	240	300	120	-	-
1	" "	120	300	60	30	-
1	" "	210	180	90	30	-
1	" "	120	300	90	30	-
1	" "	240	180	30	-	-
1	" "	270	330	180	-	-
1	" "	90	210	60	-	-
1	" "	180	360	30	-	-
10	20 open/close 100t.	1680	7127	1173	100	7
10	40 open/close 100t.	110110	188510	19152	616	56
10	60 open/close 100t.	333560	494920	45520	1420	80
10	90 open/close 100t.	712320	866640	66300	1830	150

Table 5.21

1½ TURN 'B' DIAPHRAGM VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	7	7	-	-	-
1	" "	7	7	13	-	-
1	" "	-	20	7	7	-
1	" "	13	60	27	7	-
1	" "	27	33	53	7	-
1	" "	20	73	47	-	7
1	" "	73	147	60	7	-
1	" "	53	113	40	-	-
1	" "	73	100	20	13	7
1	" "	7	20	13	7	-
1	40 open/close once	140	364	126	14	14
1	" "	70	112	98	7	-
1	" "	154	210	84	14	-
1	" "	70	56	56	14	-
1	" "	70	84	28	-	-
1	" "	210	434	112	28	-
1	" "	154	140	126	-	-
1	" "	182	182	84	-	-
1	" "	126	140	98	-	-
1	" "	126	154	112	-	-
1	60 open/close once	480	700	280	60	-
1	" "	280	180	-	20	-
1	" "	300	220	120	-	-
1	" "	380	540	100	-	-
1	" "	280	240	120	-	-
1	" "	200	340	80	-	-
1	" "	200	320	40	-	-
1	" "	180	300	100	-	-
1	" "	560	600	200	-	-
1	" "	80	160	100	-	-
1	90 open/close once	210	360	210	-	-
1	" "	510	660	600	60	120
1	" "	1260	1080	420	-	-
1	" "	300	510	90	-	-
1	" "	420	510	300	-	-
1	" "	390	450	150	-	-
1	" "	600	480	30	-	-
1	" "	570	660	30	-	-
1	" "	210	120	150	-	-
1	" "	420	570	210	30	-
10	20 open/close 100t.	2393	6993	2227	113	-
10	40 open/close 100t.	21532	39452	7882	350	84
10	60 open/close 100t.	79100	116440	17220	680	120
10	90 open/close 100t.	207420	265500	24330	600	90

Table 5.22

1½ TURN 'B' DIAPHRAGM VALVE (NC-55) - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5µ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	27	13	13	7	-
1	" "	20	7	13	-	-
1	" "	27	27	13	7	-
1	" "	27	40	7	13	-
1	" "	47	53	27	13	-
1	" "	53	27	13	7	-
1	" "	7	27	27	-	-
1	40 open/close once	98	14	28	-	-
1	" "	70	196	98	-	-
1	" "	168	196	-	-	-
1	" "	42	112	28	-	-
1	" "	168	252	56	-	14
1	" "	98	140	42	-	-
1	" "	98	56	-	14	-
1	" "	56	70	70	-	-
1	" "	56	126	28	14	-
1	" "	98	182	70	-	-
1	60 open/close once	200	260	60	-	-
1	" "	180	140	60	20	-
1	" "	180	140	100	-	-
1	" "	160	260	60	20	-
1	" "	200	260	80	-	-
1	" "	160	120	60	-	-
1	" "	340	360	120	20	-
1	" "	240	240	80	-	-
1	" "	160	320	80	-	-
1	" "	140	160	40	-	-
1	90 open/close once	420	300	180	-	-
1	" "	210	210	90	-	30
1	" "	300	300	30	30	-
1	" "	420	690	60	-	60
1	" "	210	420	30	-	-
1	" "	210	300	60	-	-
1	" "	240	150	300	-	-
1	" "	330	570	-	-	-
1	" "	120	120	-	-	-
1	" "	360	330	150	-	-
10	20 open/close 100t.	2467	6060	1093	73	13
10	40 open/close 100t.	15610	27930	3808	210	70
10	60 open/close 100t.	29400	47840	5900	120	20
10	90 open/close 100t.	67170	88470	8250	210	240

Table 5.23

'B' NORMALLY OPEN AIR OP. BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	35	28	7	-	-
1	" "	7	14	7	-	7
1	" "	7	56	28	-	7
1	" "	14	28	35	-	-
1	" "	28	7	14	-	-
1	" "	-	-	-	-	-
1	" "	7	35	7	-	7
1	" "	-	-	7	-	-
1	" "	7	7	7	-	-
1	" "	7	-	7	-	-
1	40 open/close once	98	252	140	28	-
1	" "	-	14	14	-	-
1	" "	98	182	112	14	-
1	" "	-	-	-	-	-
1	" "	-	28	-	-	-
1	" "	14	14	-	-	-
1	" "	-	-	-	-	-
1	" "	14	-	-	-	-
1	" "	-	-	14	-	-
1	" "	14	14	-	-	-
1	60 open/close once	168	63	105	-	21
1	" "	42	42	21	-	-
1	" "	21	-	-	-	21
1	" "	42	-	21	-	-
1	" "	105	63	42	-	-
1	" "	42	84	21	-	-
1	" "	84	21	-	-	-
1	" "	42	42	21	-	-
1	" "	84	42	-	-	-
1	" "	-	-	21	-	21
1	90 open/close once	320	768	544	96	-
1	" "	192	352	160	-	-
1	" "	320	384	192	-	-
1	" "	96	160	128	-	32
1	" "	-	64	64	-	-
1	" "	64	32	-	-	-
1	" "	64	96	-	-	-
1	" "	96	192	192	32	-
1	" "	32	96	96	-	-
1	" "	-	96	32	-	-
10	20 open/close 100t.	14	42	28	21	-
10	40 open/close 100t.	84	140	56	28	-
10	60 open/close 100t.	588	756	189	63	21
10	90 open/close 100t.	1856	1728	544	256	64

Table 5.24

'C' NORMALLY CLOSED AIR OP. BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	21	7	42	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	7
1	" "	7	7	-	7	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	14	14	14	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	" "	-	14	-	-	-
1	60 open/close once	60	120	80	20	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	20	-	-	-
1	" "	20	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	20	-	-	-
1	" "	-	20	-	-	-
1	" "	20	-	-	-	-
1	" "	20	-	-	-	-
1	90 open/close once	30	180	150	60	-
1	" "	60	30	30	-	-
1	" "	-	60	-	-	30μ
1	" "	-	-	-	-	-
1	" "	60	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	60	30	-	-
1	" "	30	-	-	-	-
10	20 open/close 100t.	21	28	-	-	-
10	40 open/close 100t.	14	-	14	-	-
10	60 open/close 100t.	-	40	-	-	20
10	90 open/close 100t.	90	60	30	-	-

Table 5.25

1ST 'B' NORMALLY CLOSED AIR OP. BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	105	147	126	7	21
1	" "	21	35	7	7	28
1	" "	42	56	42	-	-
1	" "	-	-	-	-	-
1	" "	-	7	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	420	994	420	42	28
1	" "	-	28	28	-	-
1	" "	28	98	28	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	14	28	-	-	-
1	60 open/close once	714	1617	399	63	21
1	" "	546	693	126	21	-
1	" "	42	63	-	-	-
1	" "	42	63	-	-	-
1	" "	105	42	63	21	-
1	" "	21	105	-	-	-
1	" "	21	21	21	-	21
1	" "	42	42	-	-	-
1	" "	63	126	-	-	-
1	" "	21	42	-	-	-
1	90 open/close once	1504	1984	544	96	-
1	" "	192	160	32	-	-
1	" "	192	352	32	-	32
1	" "	224	320	128	-	-
1	" "	64	32	96	-	-
1	" "	224	384	96	-	-
1	" "	160	64	32	-	-
1	" "	64	384	64	32	-
1	" "	160	256	96	-	-
1	" "	64	96	32	-	-
10	20 open/close 100t.	-	14	-	7	-
10	40 open/close 100t.	28	-	-	-	-
10	60 open/close 100t.	987	2142	273	-	-
10	90 open/close 100t.	5888	4896	1664	224	-

Table 5.26

2ND 'B' NORMALLY CLOSED AIR OP. BELLOWS VALVE - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	7	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	7	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	-	14	-	14	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	20	-	-	-
1	" "	20	60	120	-	20
1	" "	-	40	-	-	-
1	" "	-	20	20	-	-
1	" "	-	-	-	-	-
1	" "	-	20	-	-	-
1	" "	-	-	-	-	-
1	" "	-	40	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	90 open/close once	180	150	90	-	30
1	" "	30	30	-	30	-
1	" "	-	60	-	-	-
1	" "	-	-	-	30	-
1	" "	60	-	-	-	-
1	" "	30	-	-	-	-
1	" "	-	-	30	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
10	20 open/close 100t.	33	20	20	-	-
10	40 open/close 100t.	14	42	-	-	-
10	60 open/close 100t.	100	-	40	-	-
10	90 open/close 100t.	330	270	90	60	-

Table 5.27

3RD 'B' NORMALLY CLOSED AIR OP. BELLOWS VALVE (NC-55) - OPENING/CLOSING TEST

Time (mins)	Flow (l/min)	Total number of particles entrained 0.3-0.5	0.5-1.5	1.5-3	3-5	>5μ
1	20 open/close once	-	-	-	-	-
1	" "	-	7	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	40 open/close once	42	56	28	-	-
1	" "	-	14	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	14	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	60 open/close once	-	-	40	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	60	80	60	-	-
1	" "	-	-	-	-	-
1	" "	20	80	20	20	-
1	" "	40	60	40	-	-
1	" "	20	-	-	-	-
1	" "	-	40	-	-	-
1	" "	-	20	-	-	-
1	90 open/close once	60	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
1	" "	-	-	-	-	-
10	20 open/close 100t.	20	-	7	-	-
10	40 open/close 100t.	-	-	28	-	-
10	60 open/close 100t.	-	-	-	-	-
10	90 open/close 100t.	180	60	-	-	-

Table 5.28

RESULTS OF STATIC PURGING TESTS

Type of Valve	Particle Entrainment/ft^3 (>0.3μm dia.) 40 l/min	90 l/min
Ball	3.9	15.1
Needle	57.5	54467
Bellows	6	14.2
Diaphragm	2.7	4.8
Bellows(Air Op.)	3028	236

Table 5.29

PARTICLE CONTAMINATION DUE TO VALVE OPERATION

Type of Valve	Particle Entrainment/ft^3(>0.3μm dia.) 40 l/min	90 l/min
Ball	109	1845
Needle	728	8944
Bellows	58.6	440
Diaphragm	131395	613343
Bellows(Air Op.)	308	4448

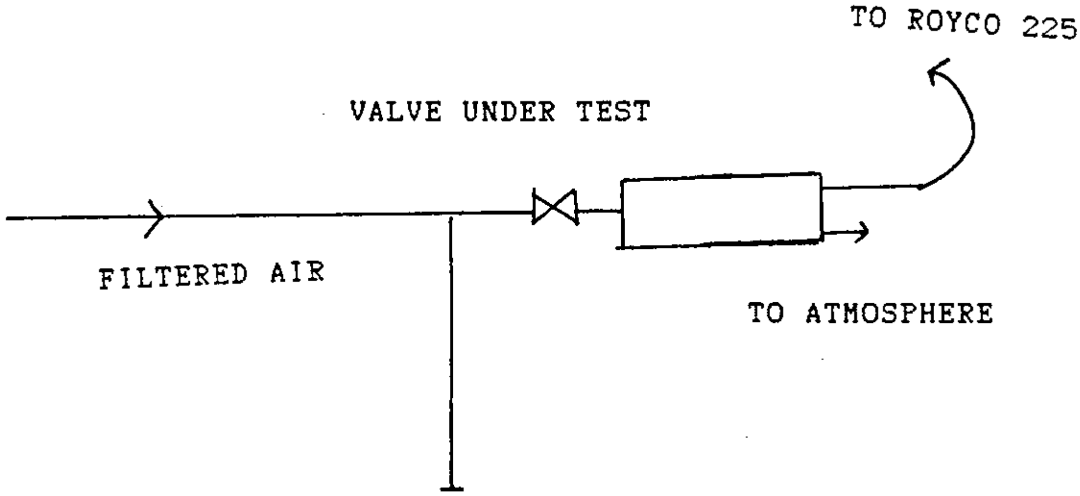


FIGURE 5.1 - VALVE TEST-RIG

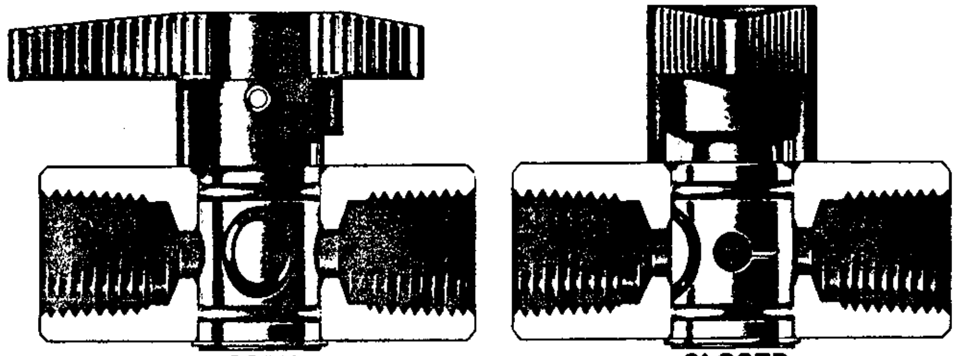


FIGURE 5.2 - BALL VALVE

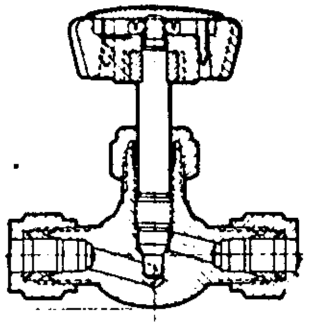


FIGURE 5.3 - NEEDLE VALVE

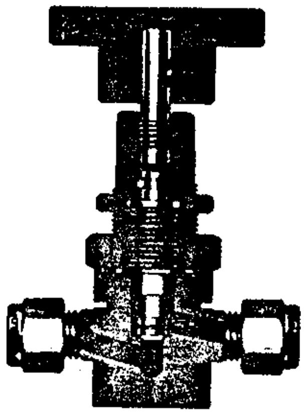


FIGURE 5.4 BELLOWS VALVE

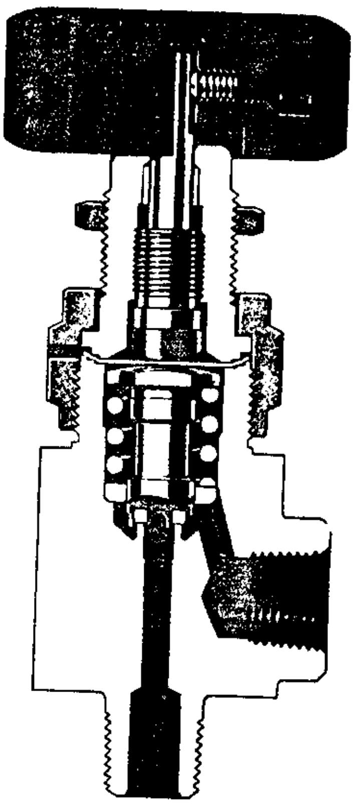


FIGURE 5.5 - DIAPHRAGM VALVE

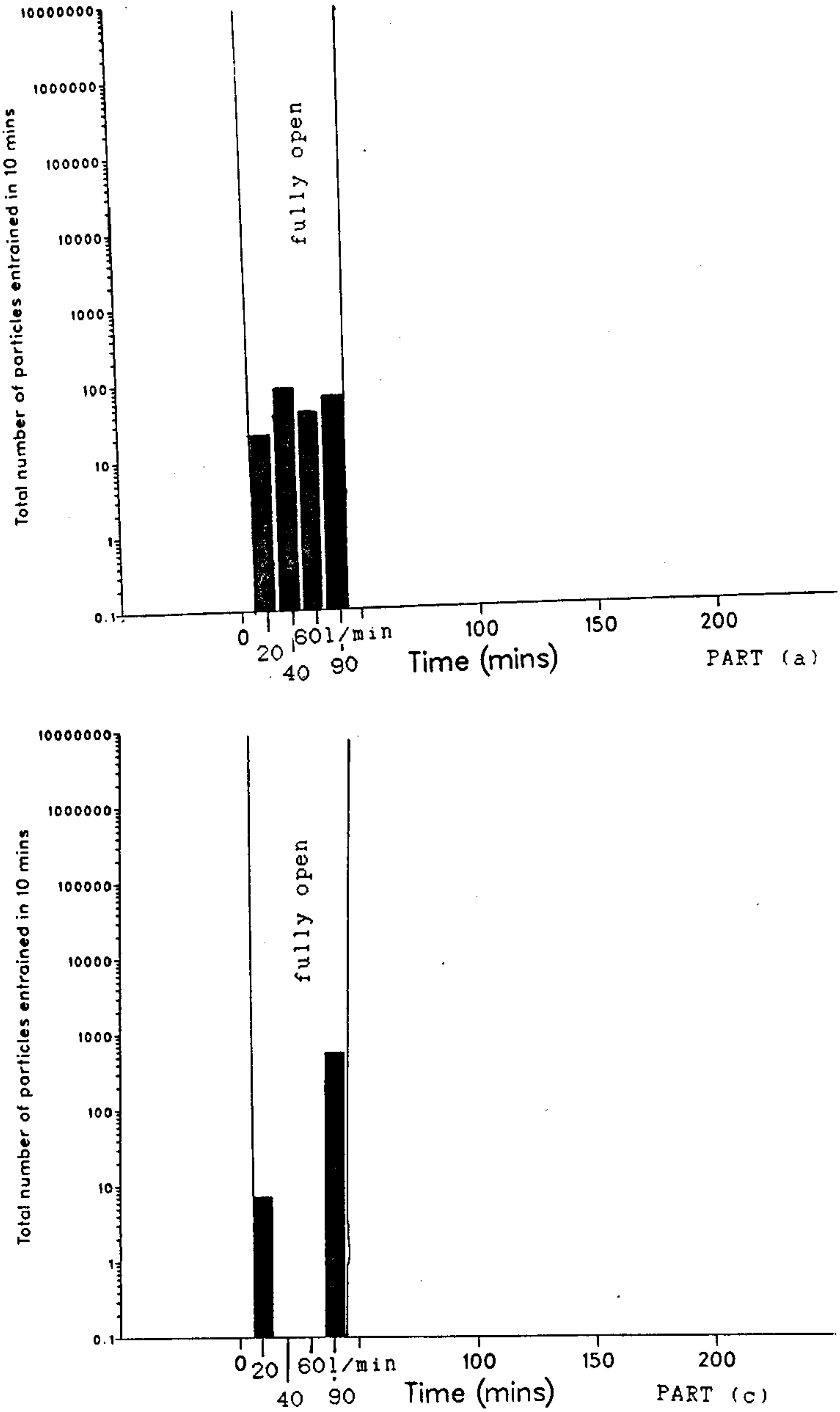
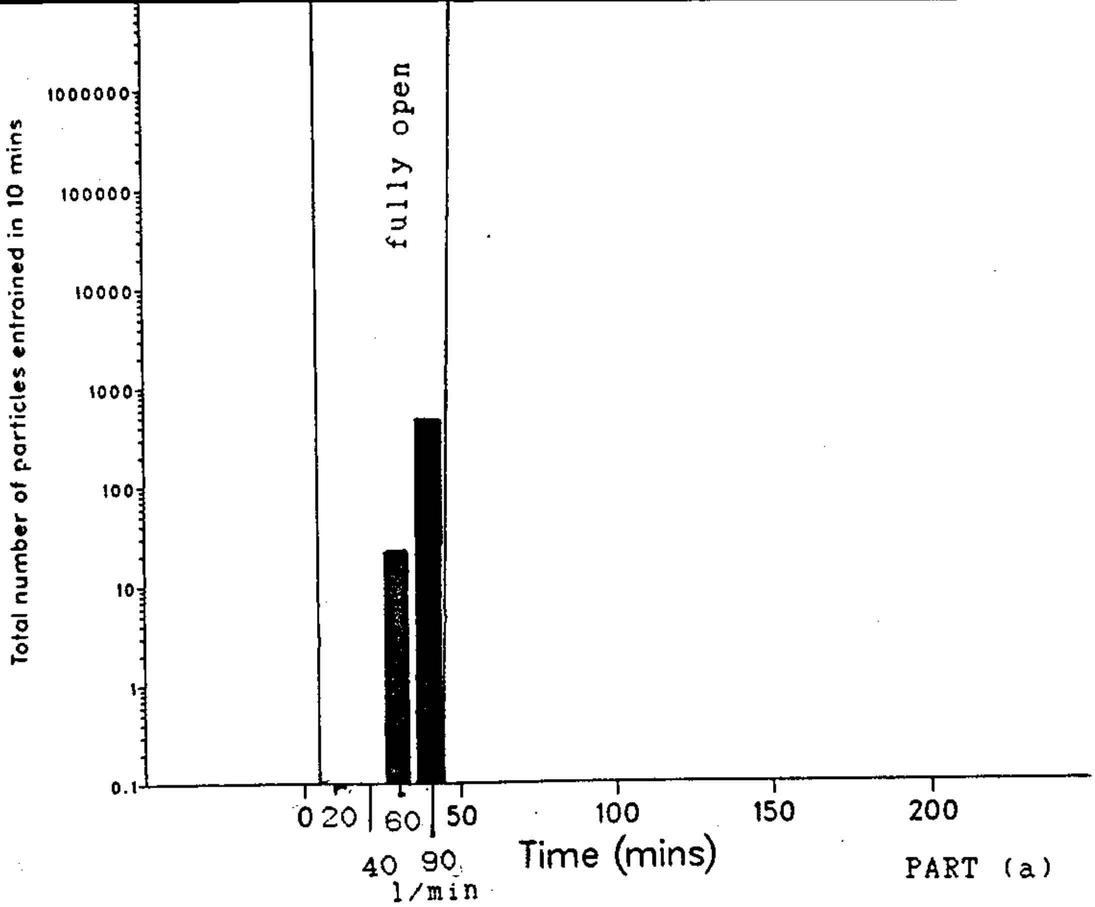


FIGURE 5.6 - THROTTLING TEST ON 1ST 'A' BALL VALVE



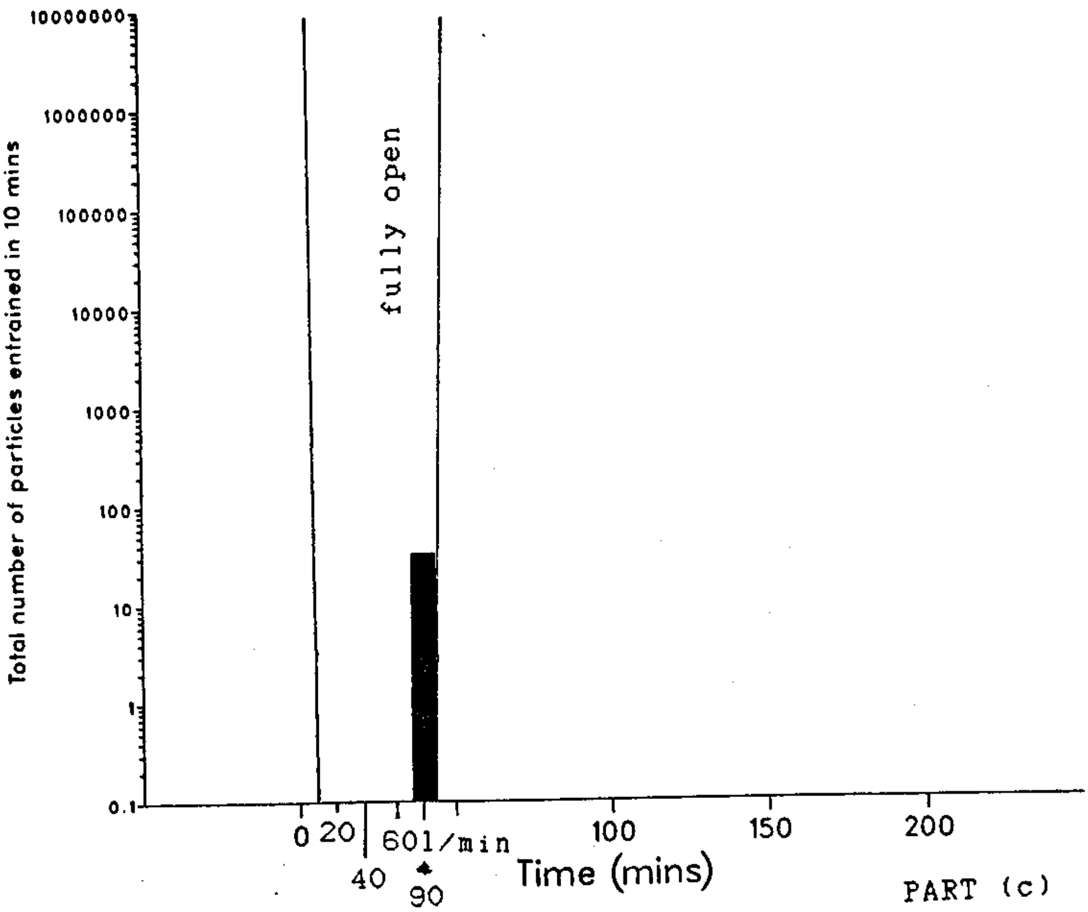
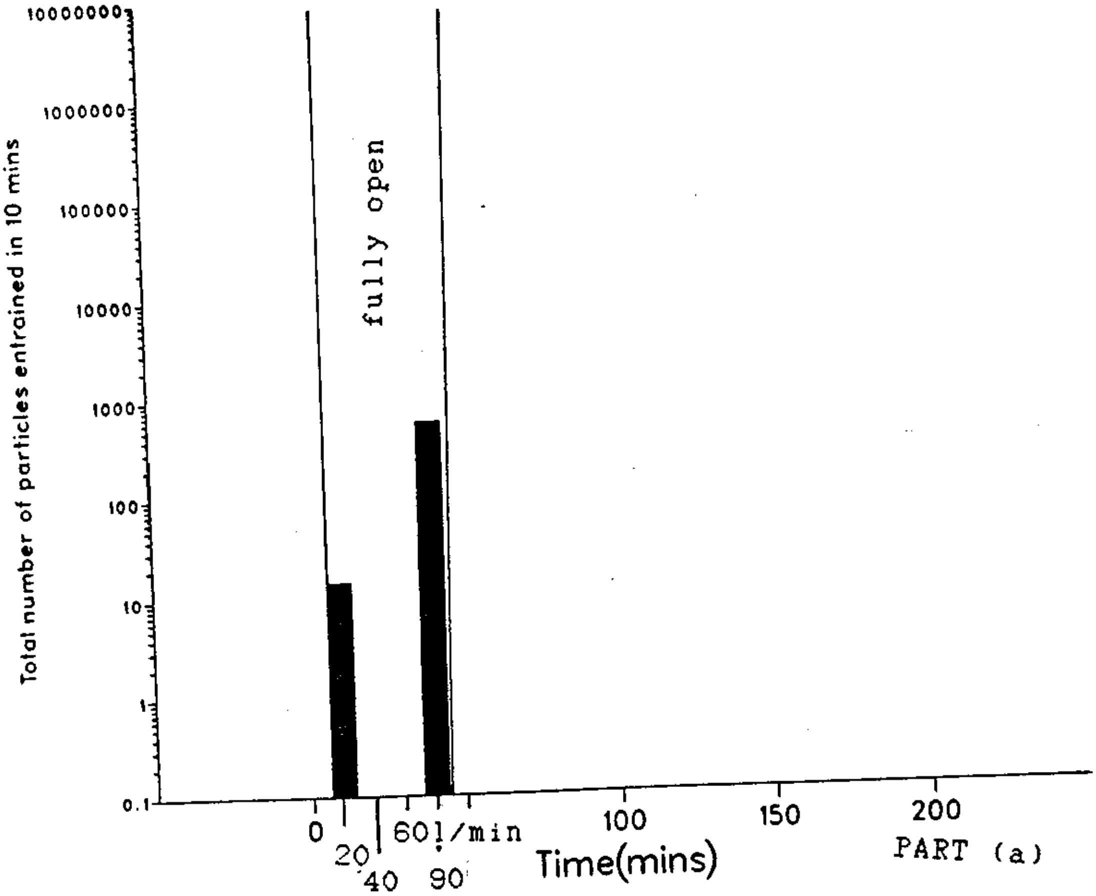


FIGURE 5.7 - THROTTLING TEST ON 2ND 'A' BALL VALVE



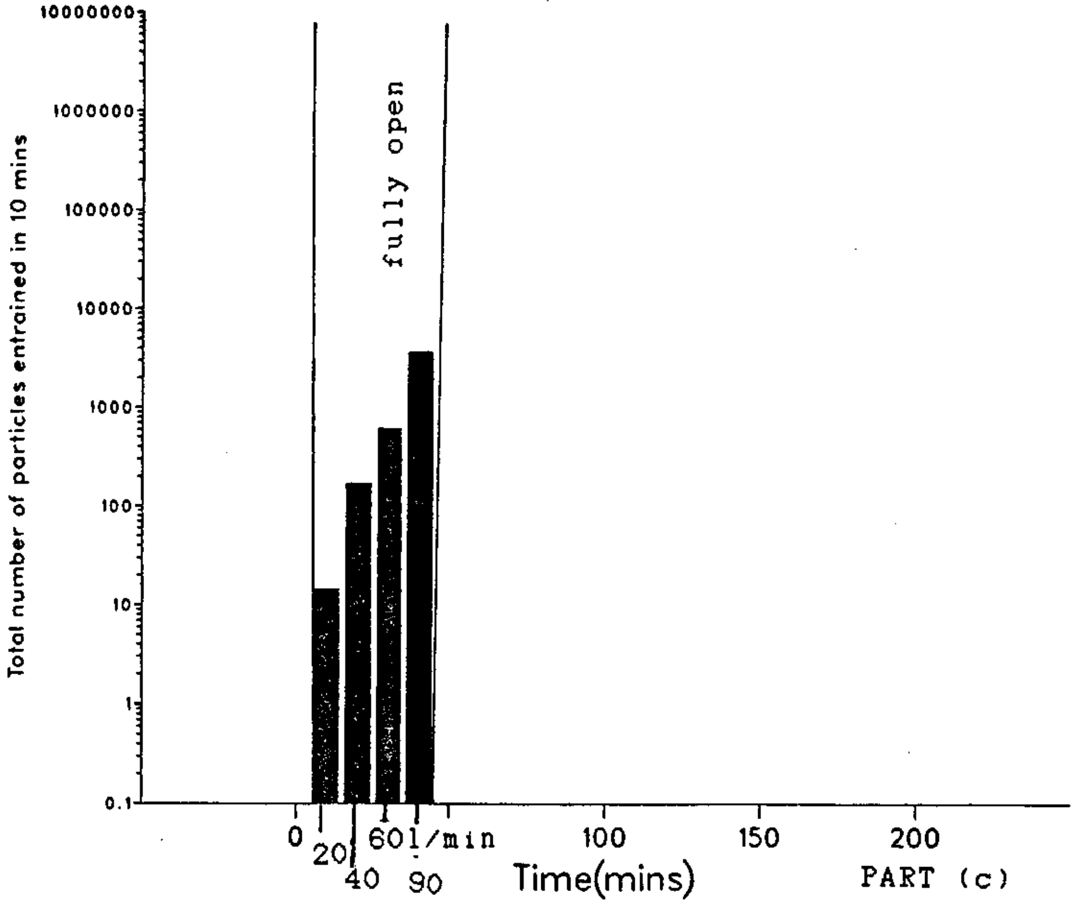
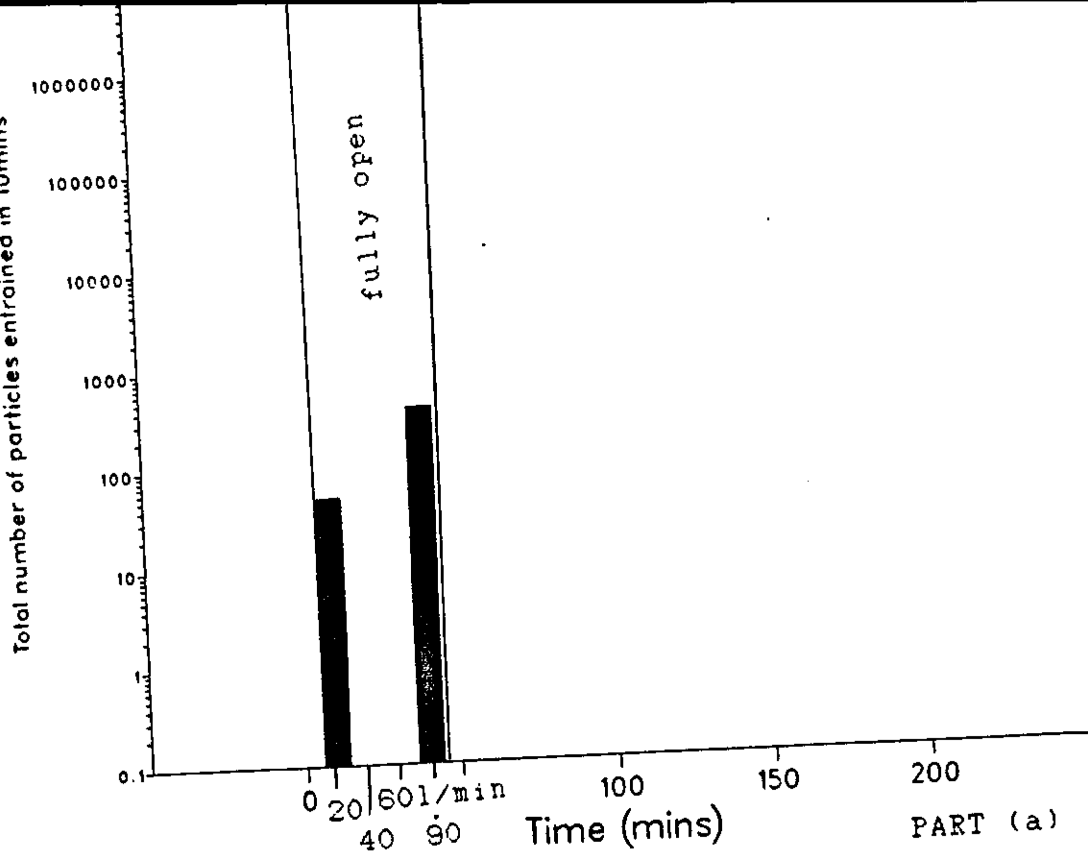


FIGURE 5.8 - THROTTLING TEST ON 3RD 'A' BALL VALVE



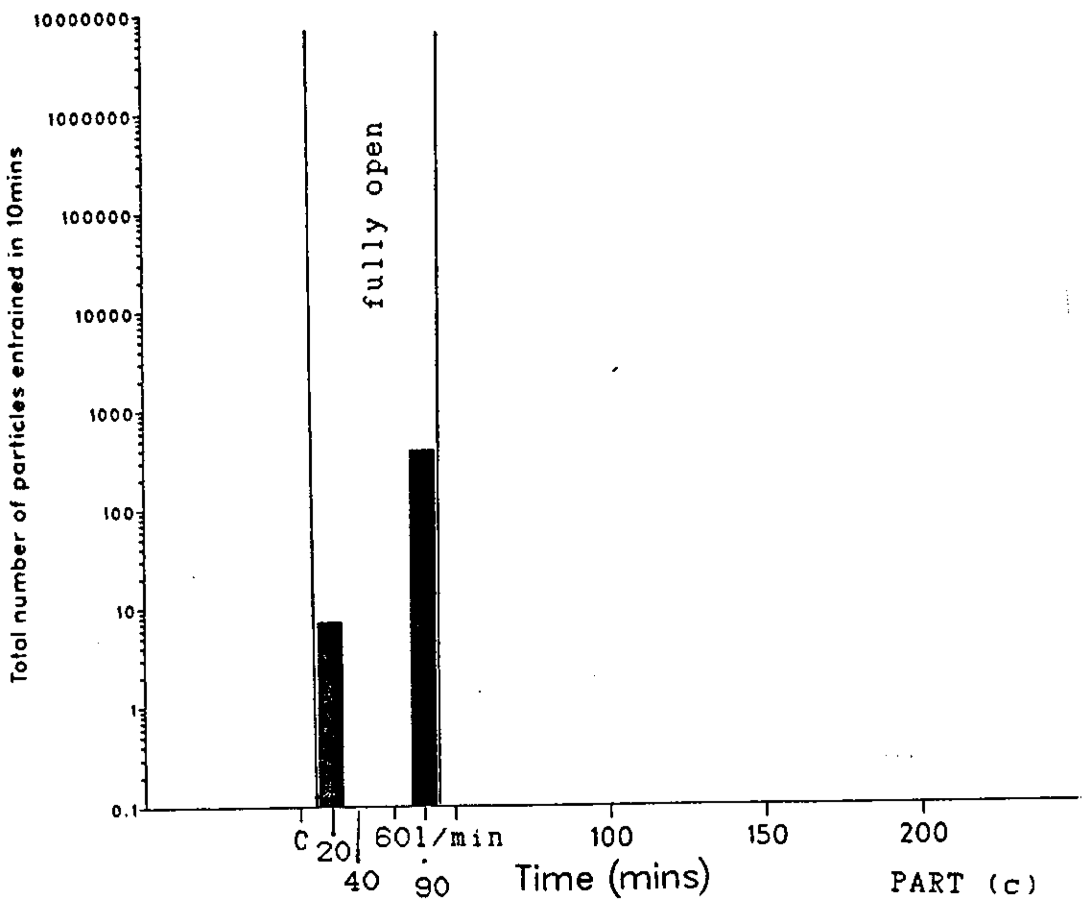
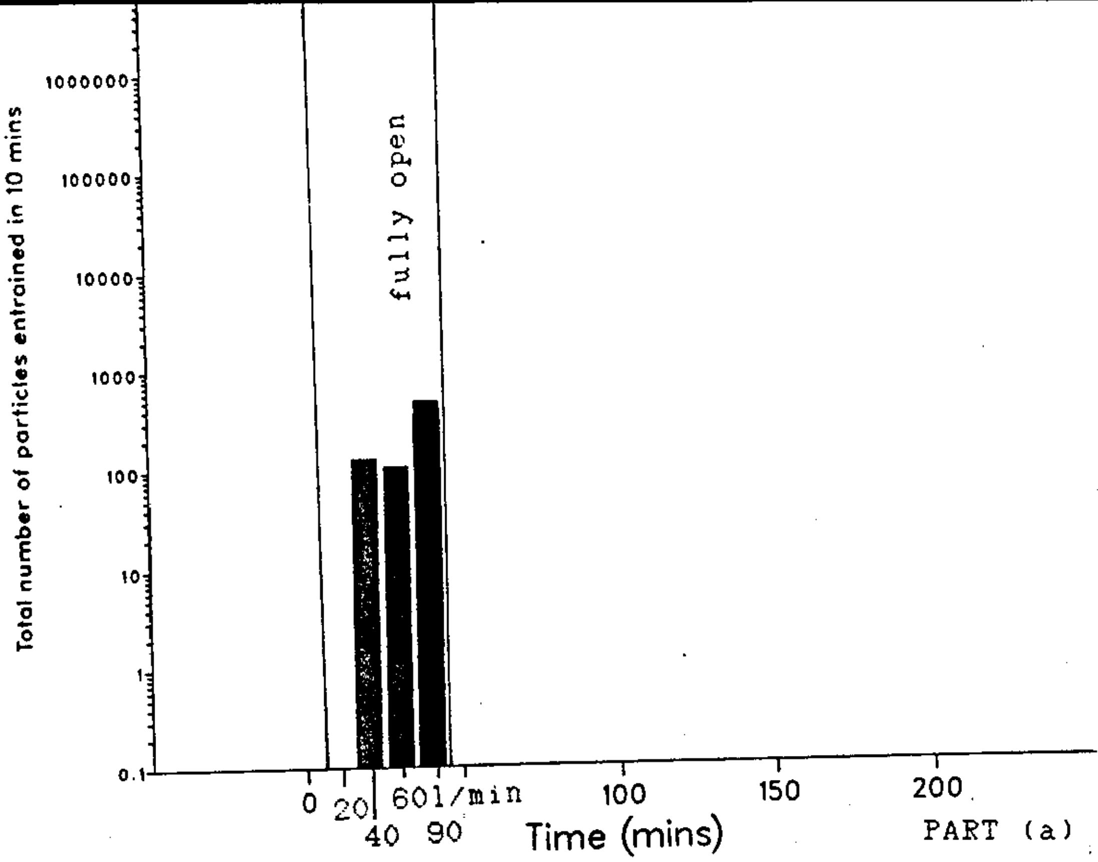


FIGURE 5.9 - THROTTLING TEST ON 4TH 'A' BALL VALVE



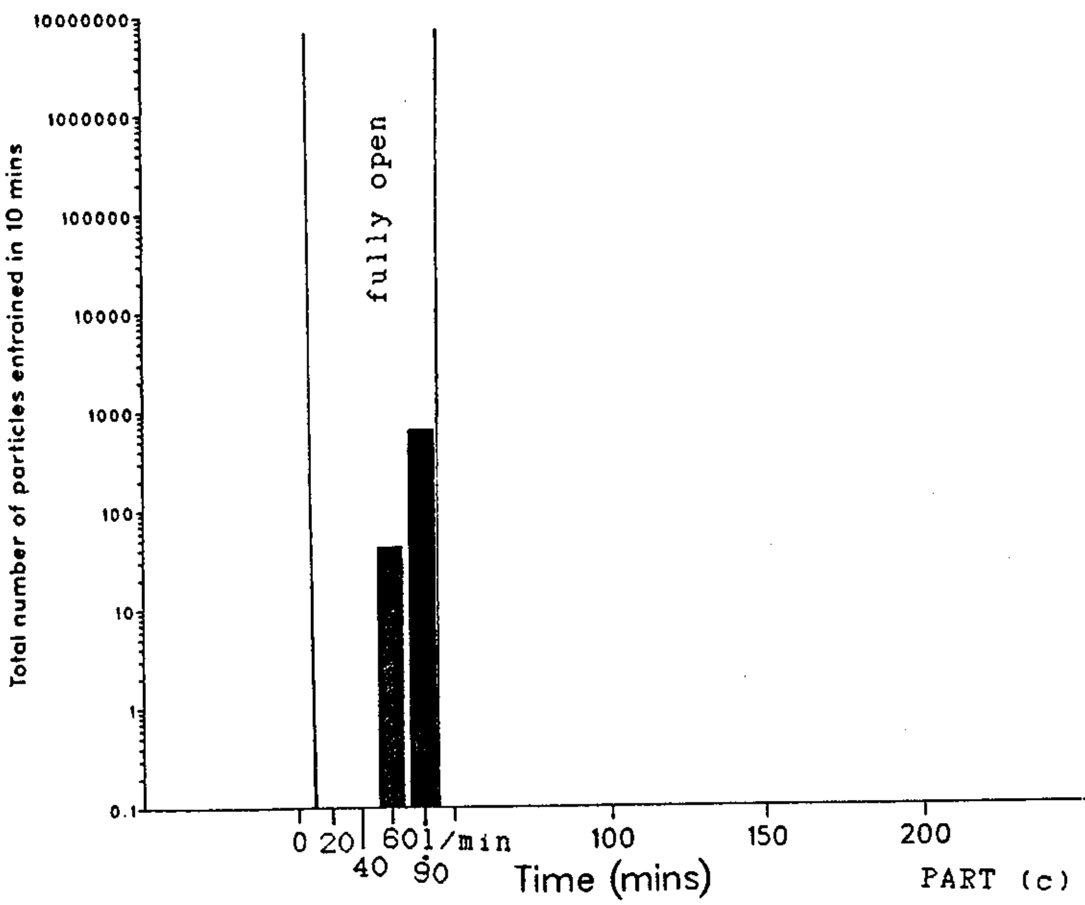
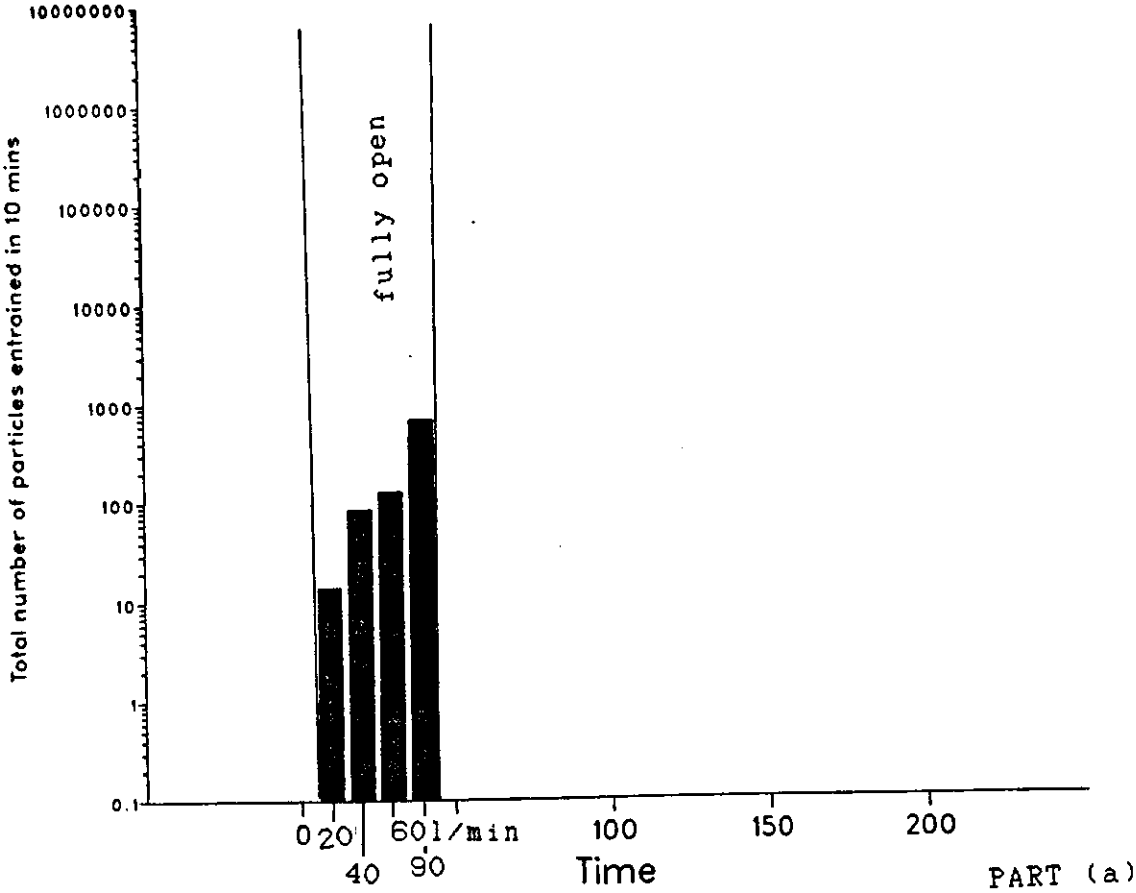


FIGURE 5.10 - THROTTLING TEST ON 1ST 'B' BALL VALVE



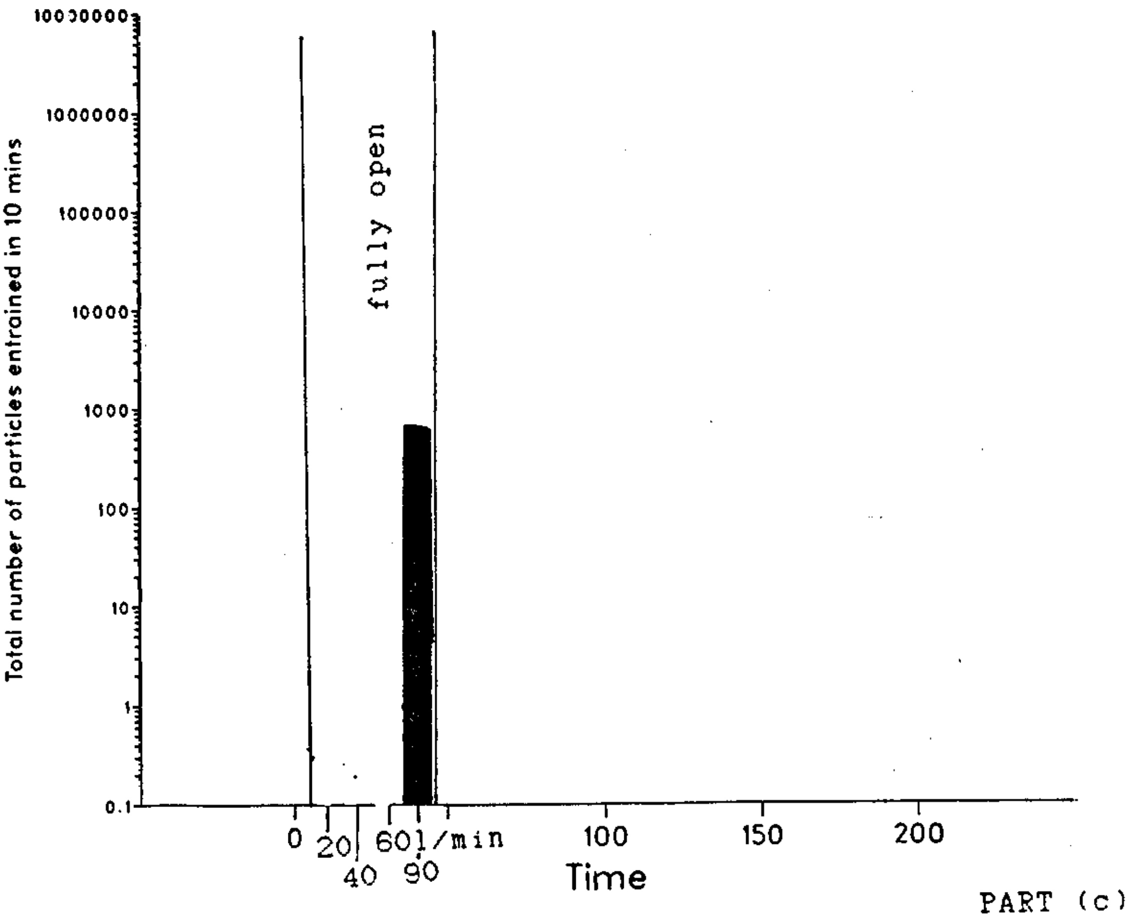
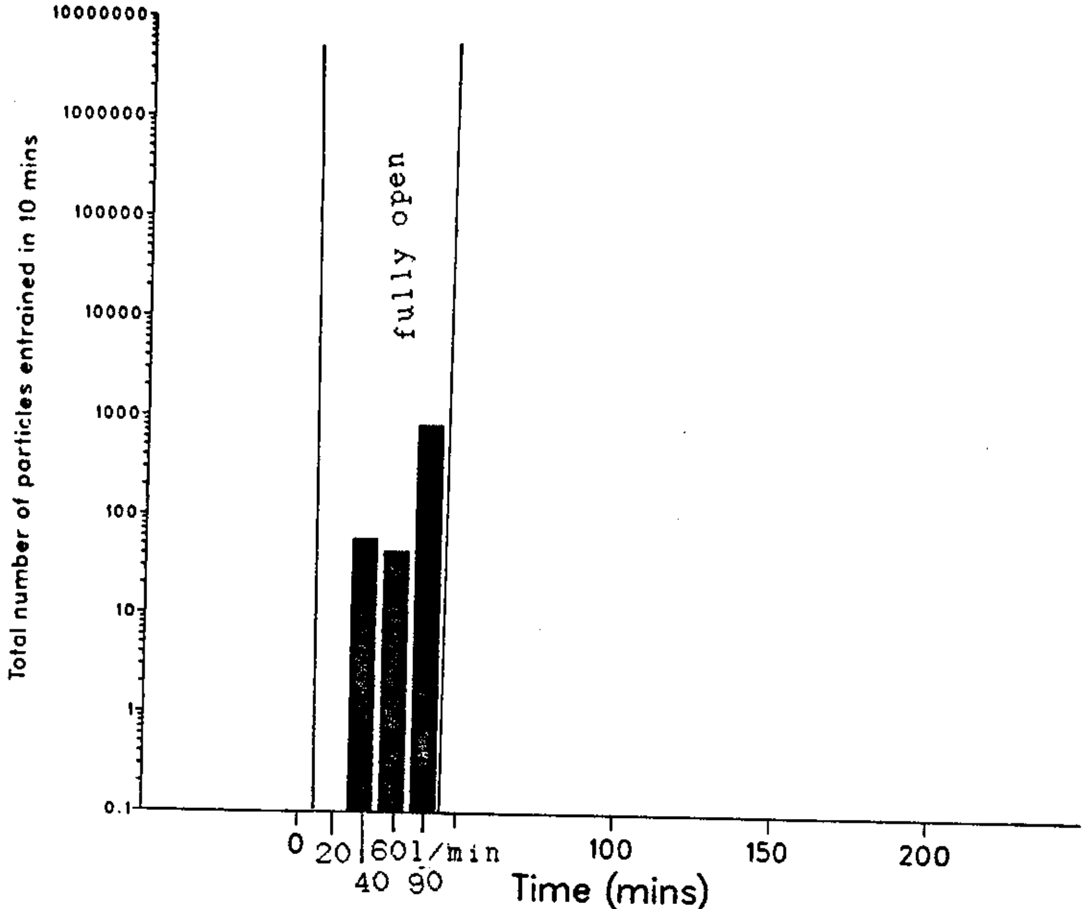
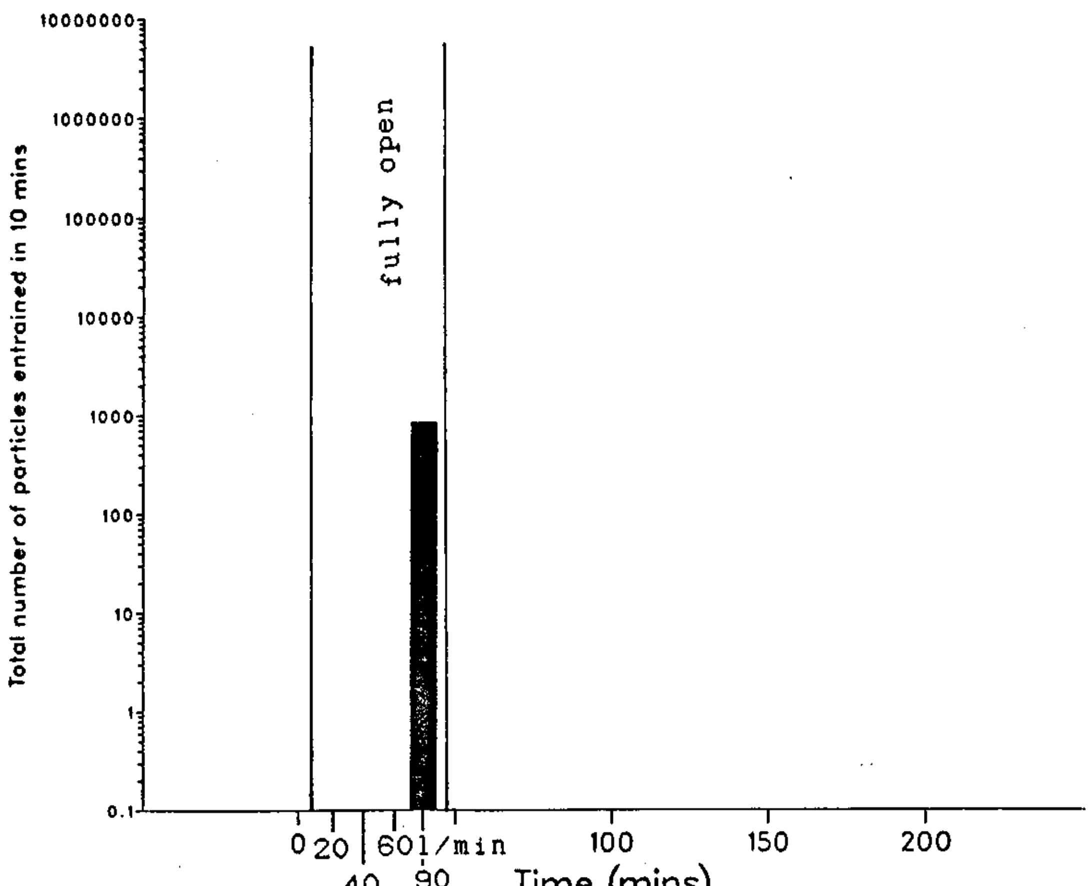


FIGURE 5.11 - THROTTLING TEST ON 2ND 'B' BALL VALVE

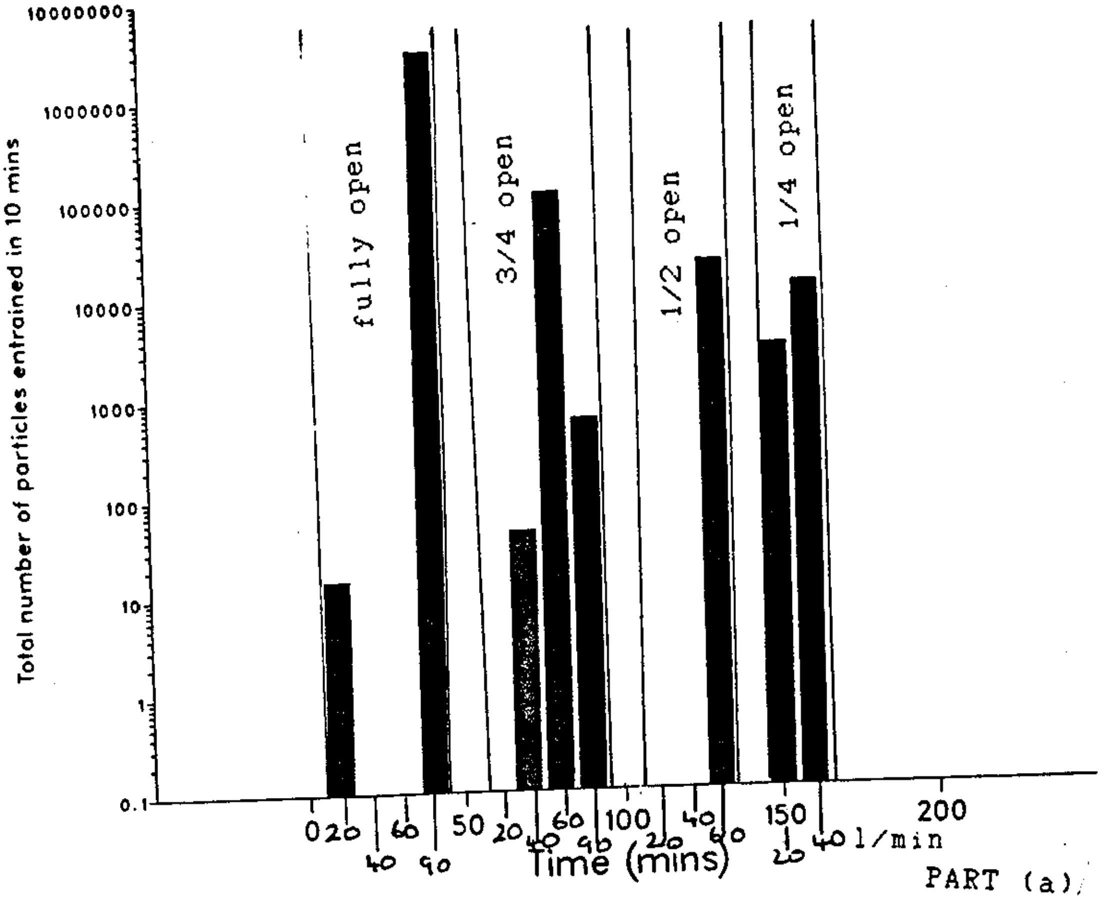


PART (a)



PART (c)

FIGURE 5.12 - THROTTLING TEST ON 3RD 'B' BALL VALVE



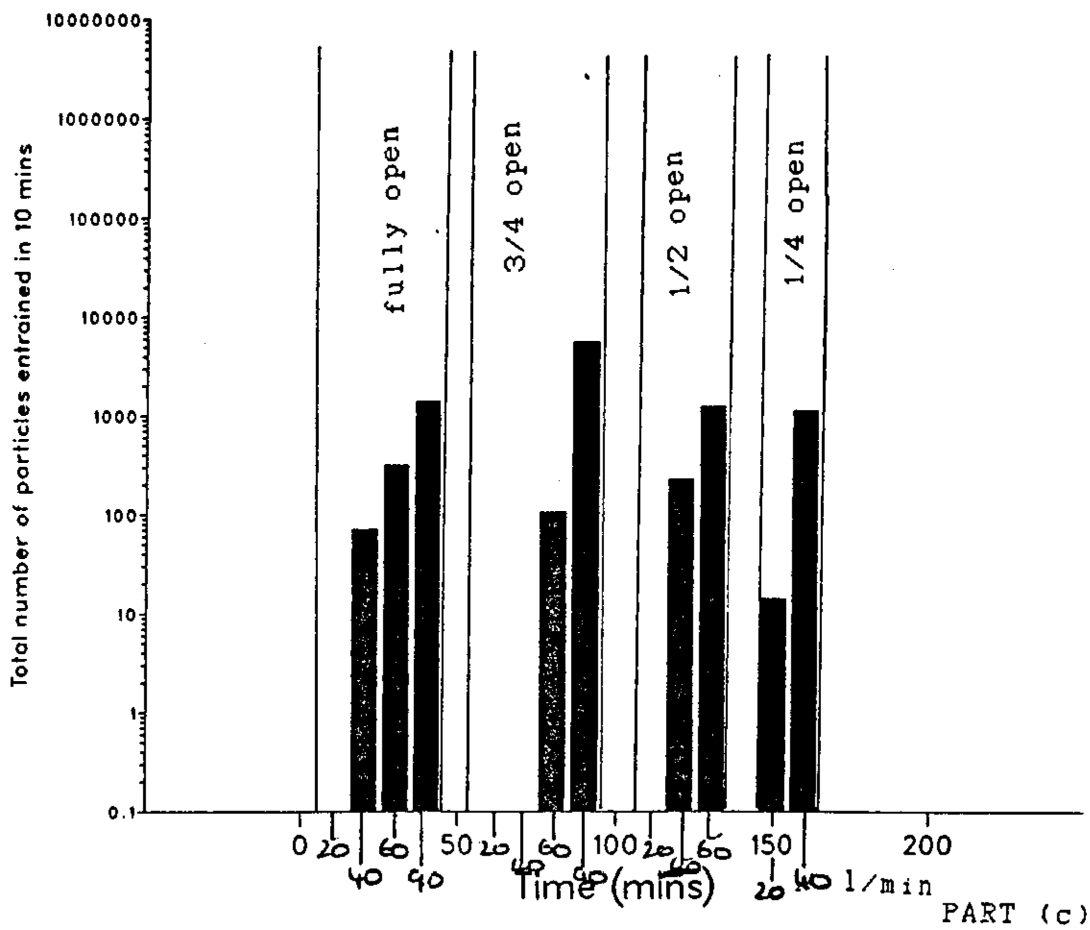
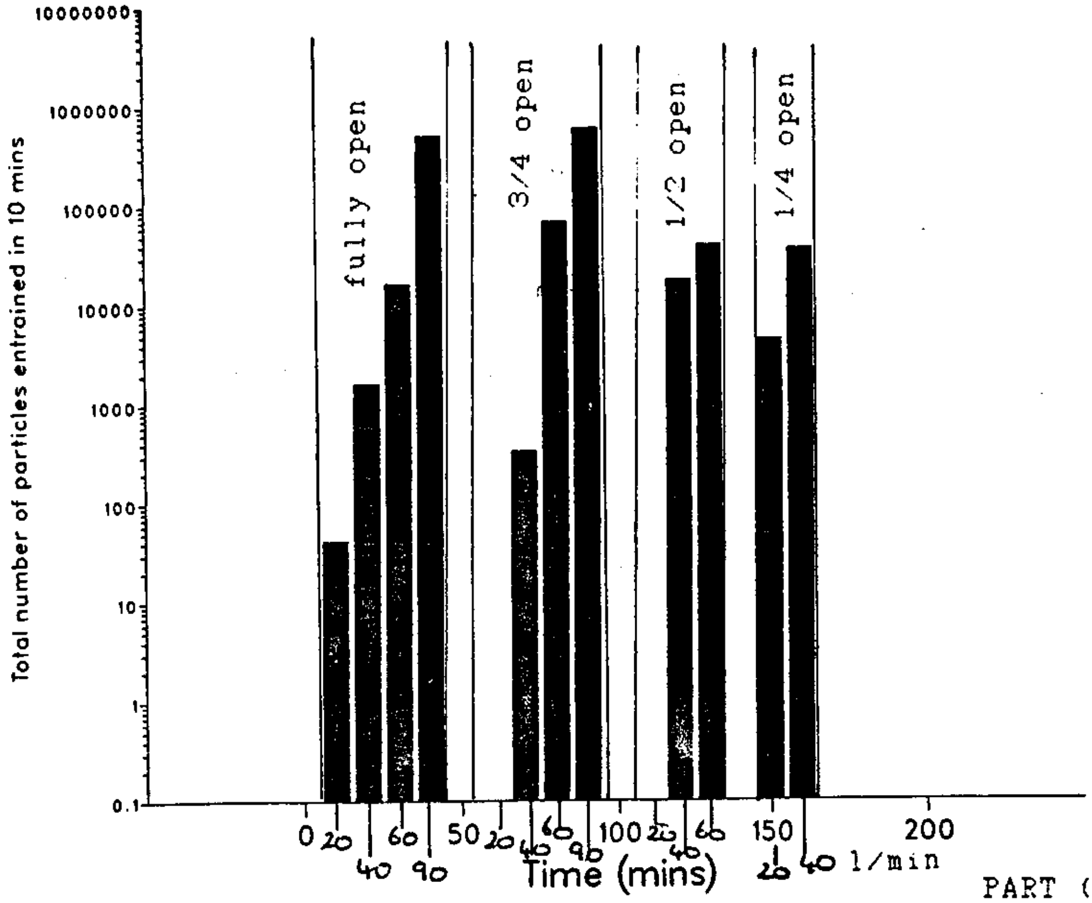


FIGURE 5.13 - THROTTLING TEST ON 1ST NEEDLE VALVE



PART (a)

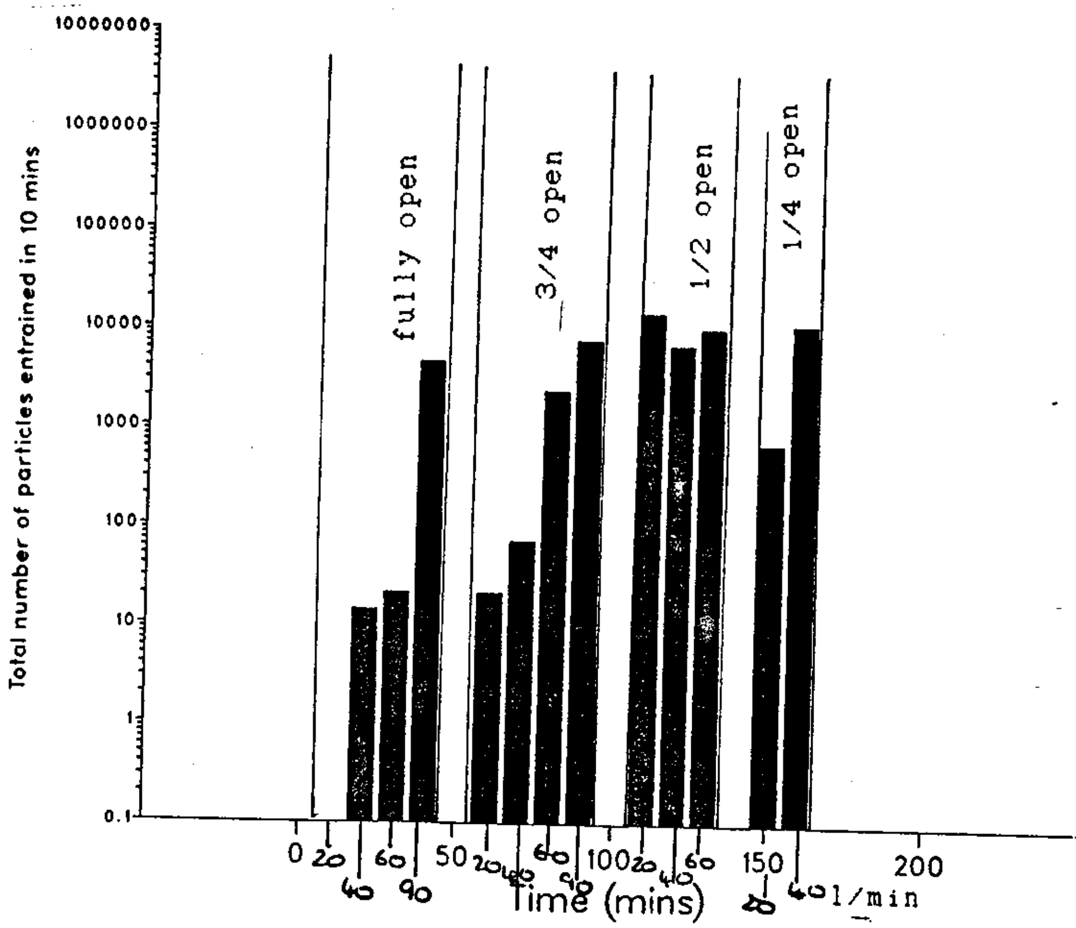


FIGURE 5.14 - THROTTLING TEST ON 4TH NEEDLE VALVE PART (c)

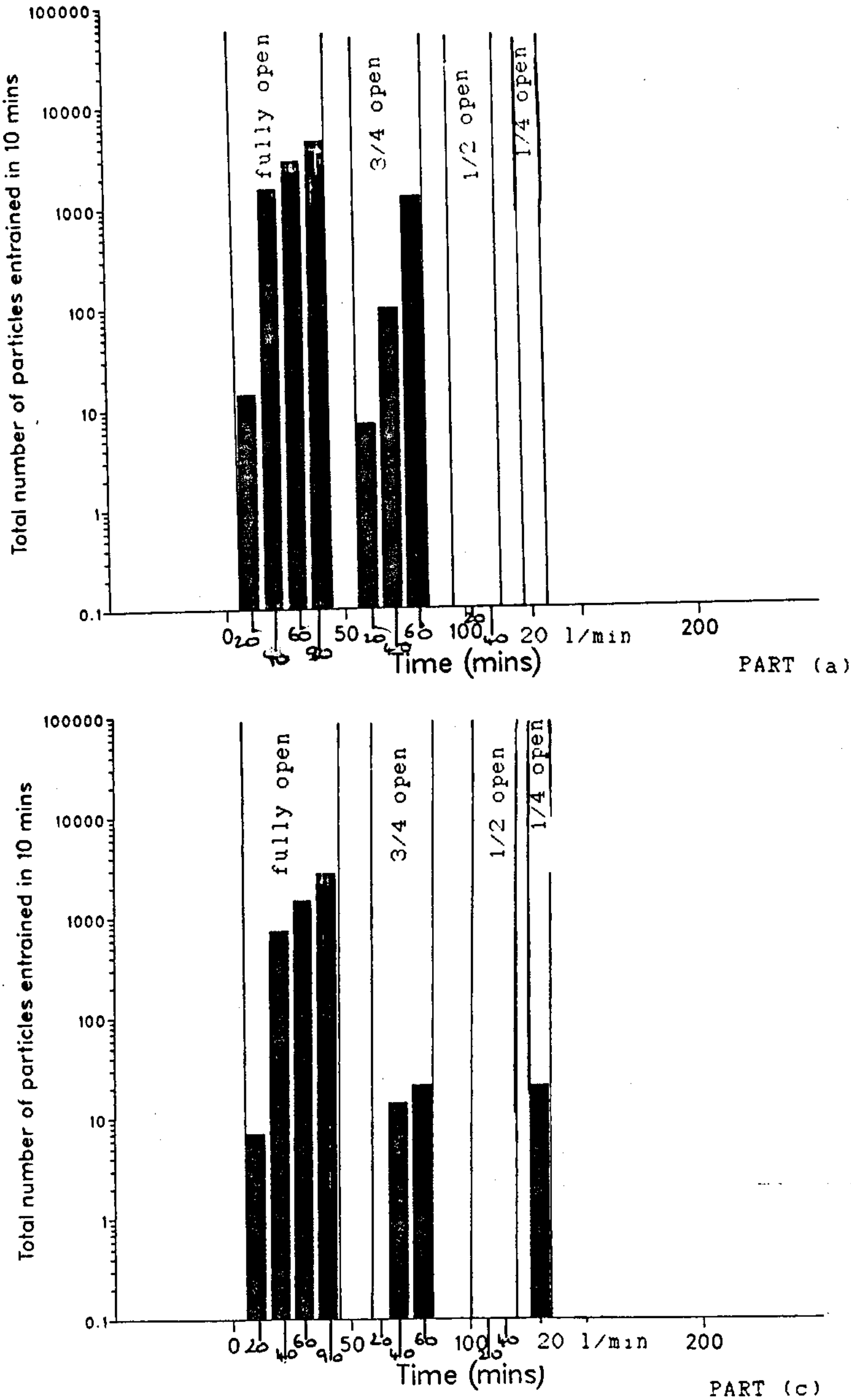
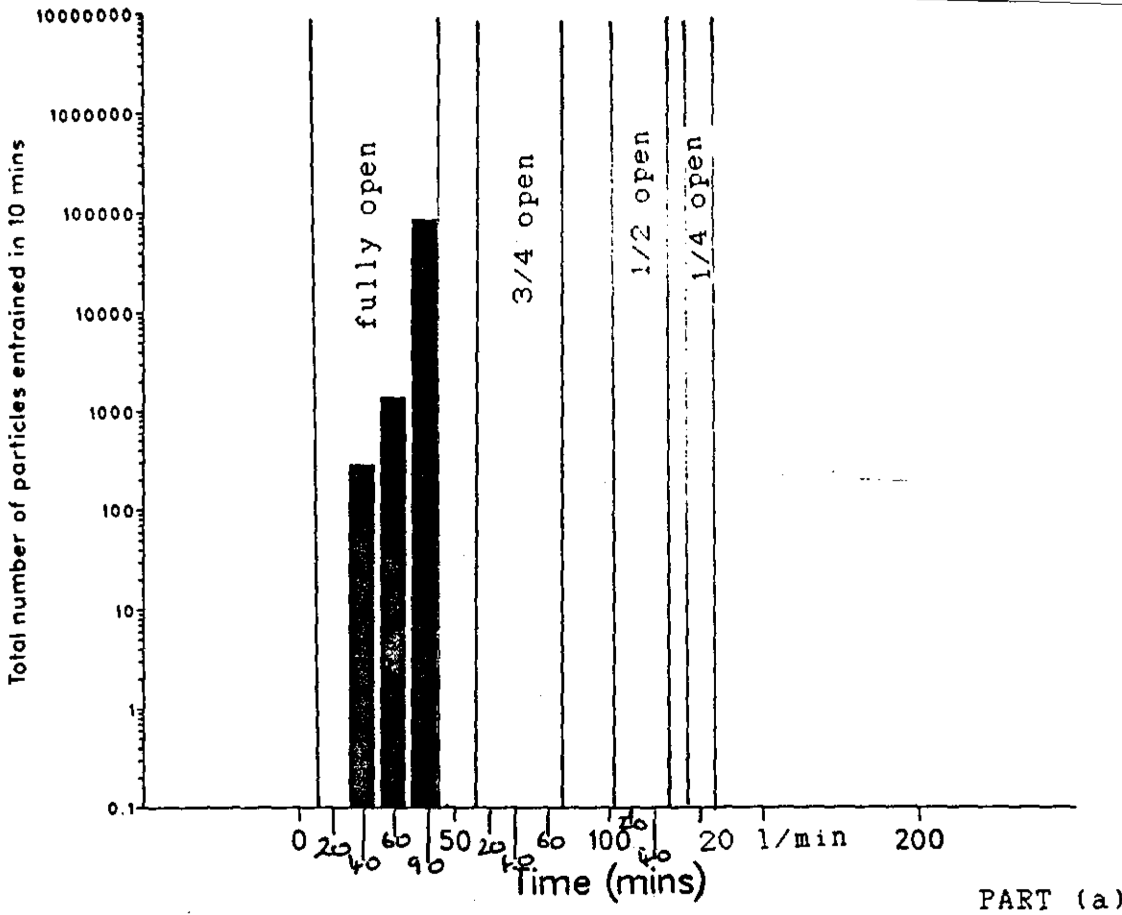
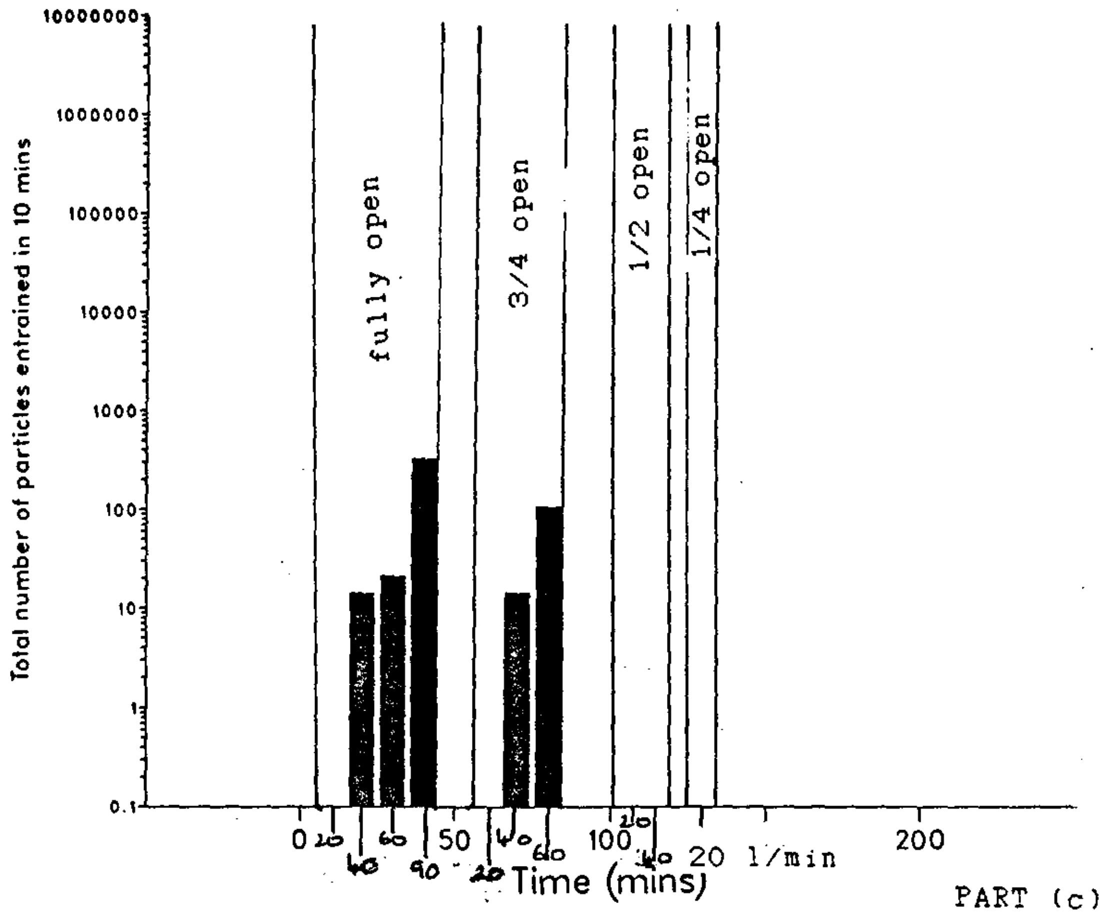


FIGURE 5.15 - THROTTLING TEST ON 1ST 'B' BELLOWS VALVE

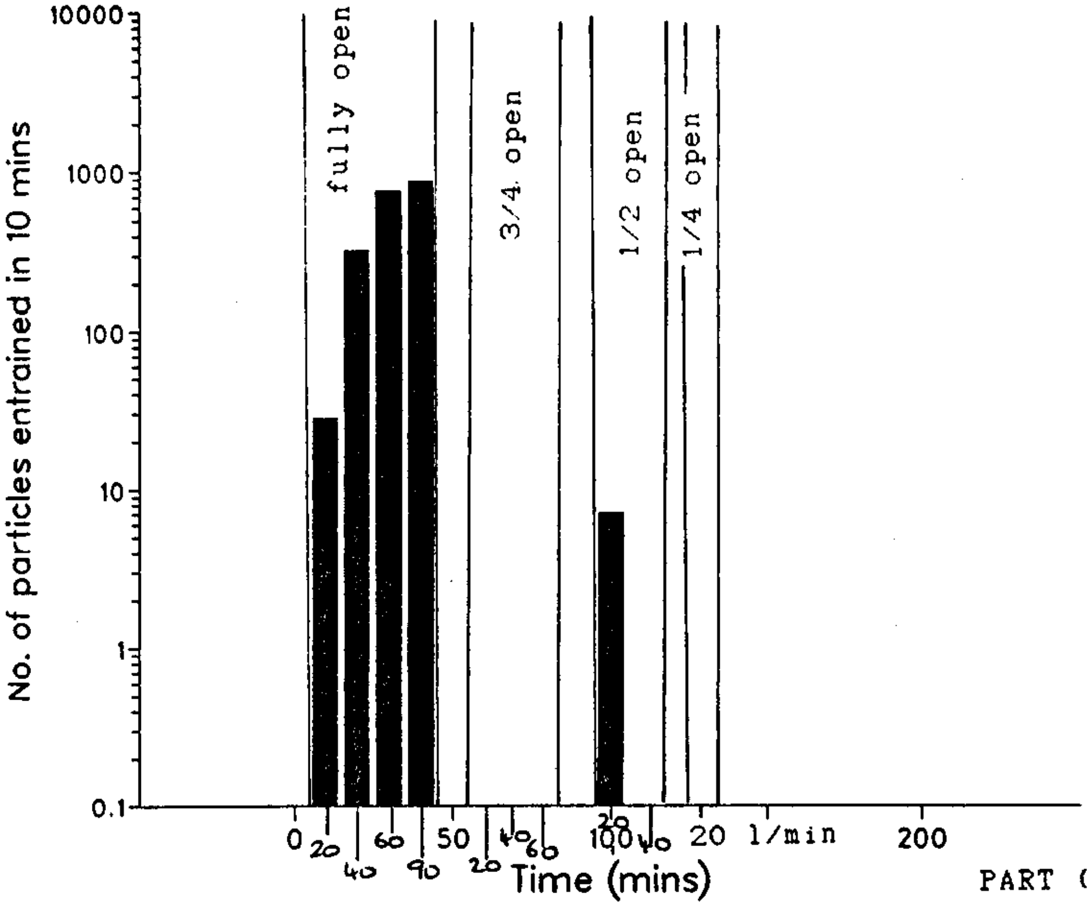


PART (a)

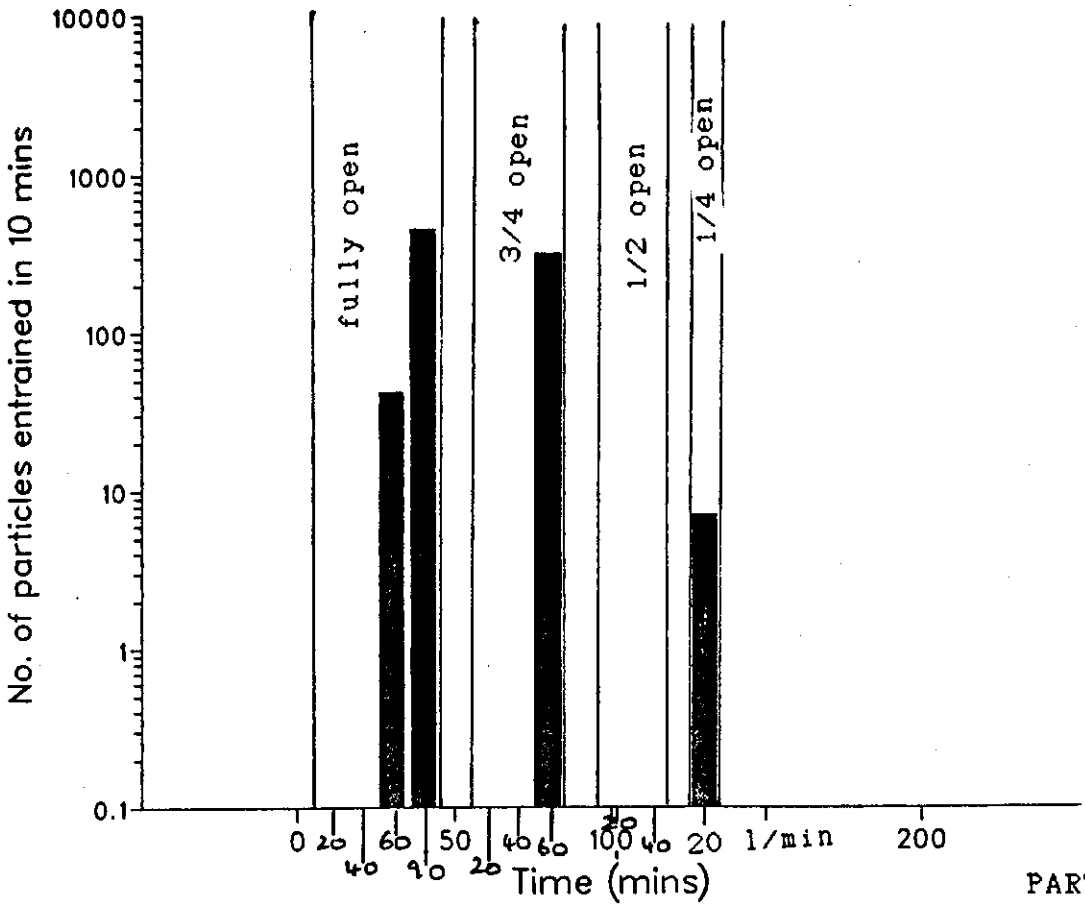


PART (c)

FIGURE 5.16 - THROTTLING TEST ON 2ND 'B' BELLOWS VALVE

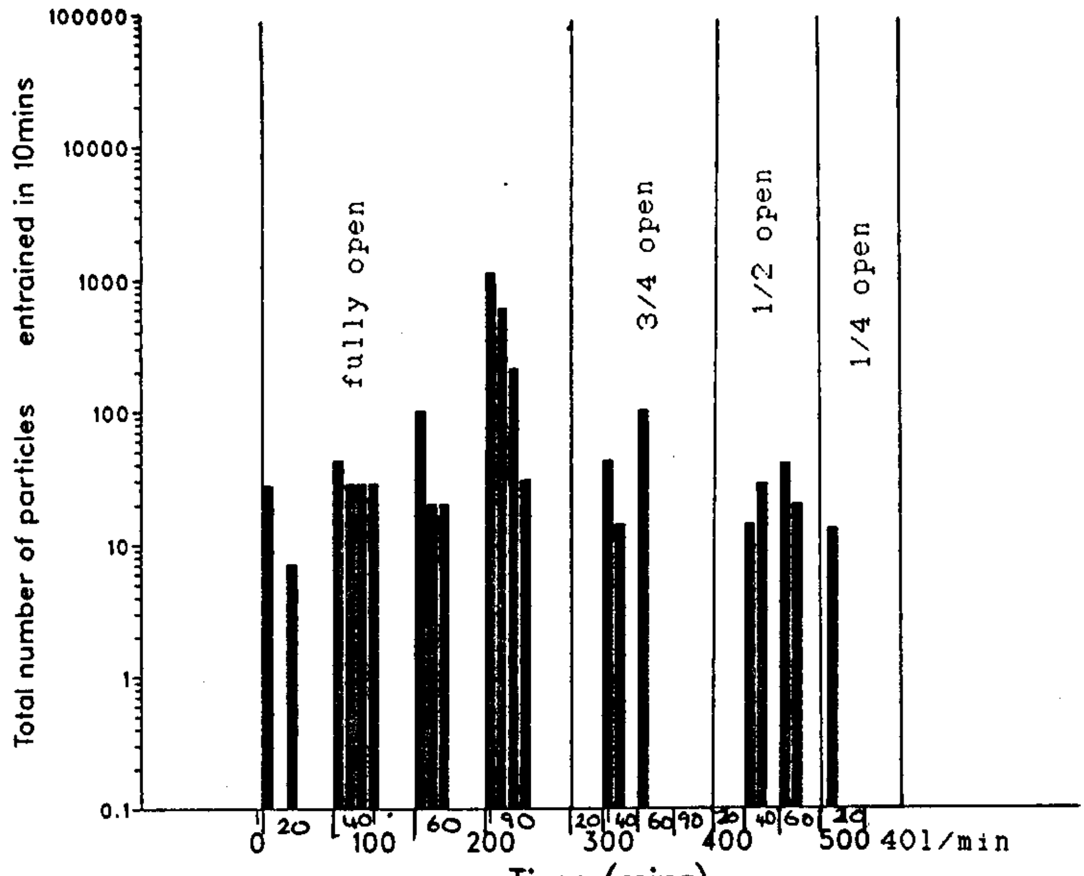


PART (a)

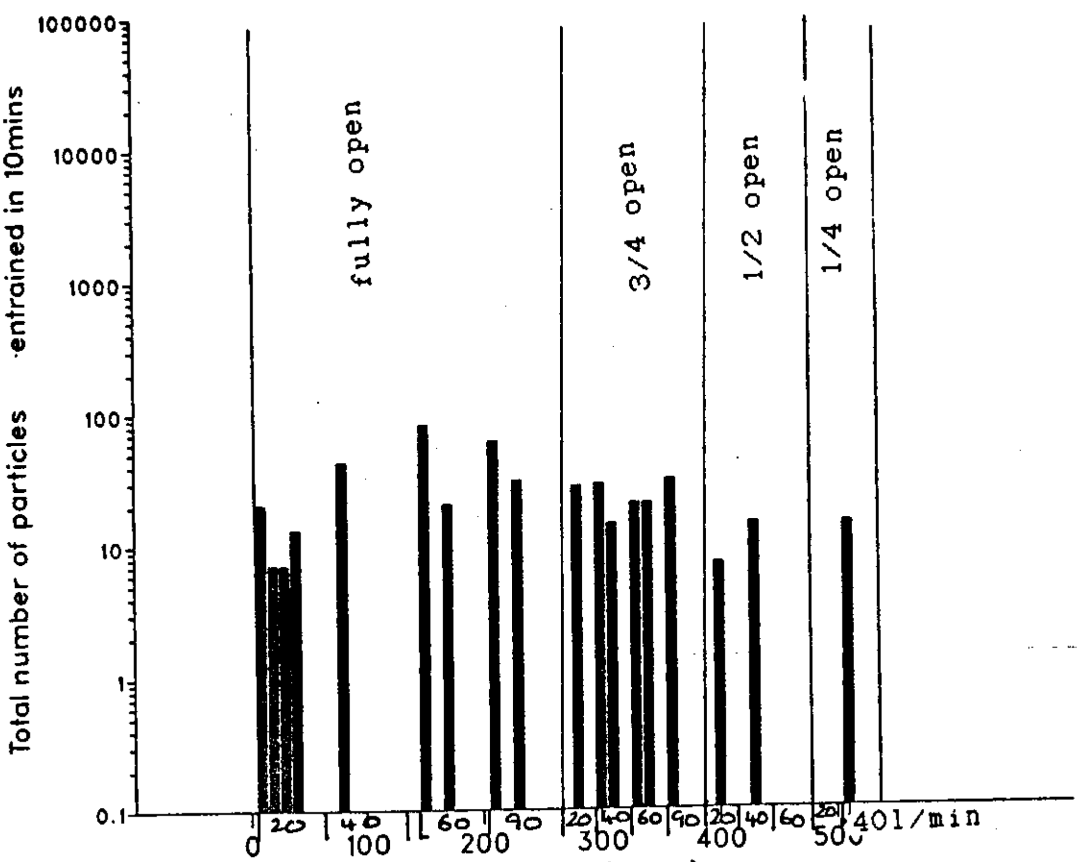


PART (c)

FIGURE 5.17 - THROTTLING TEST ON 3RD 'B' BELLOWS VALVE

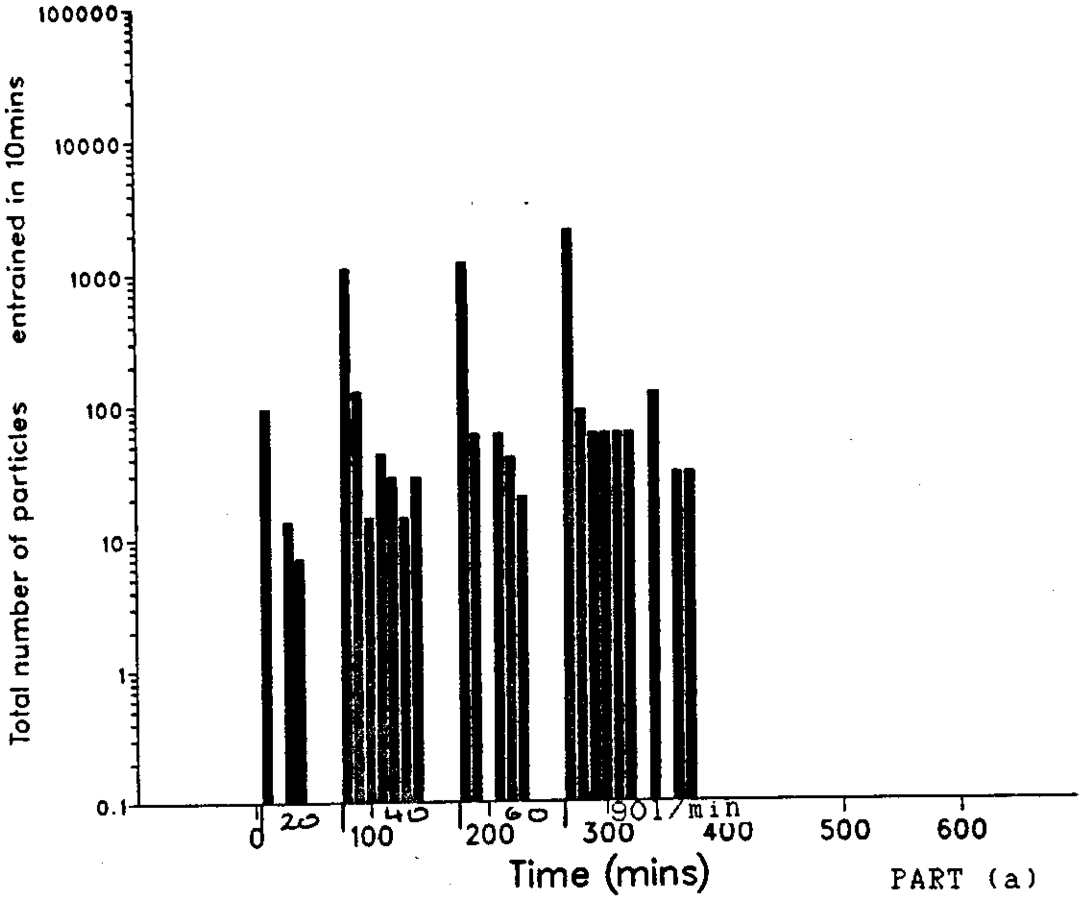


PART (a)



PART (c)

FIGURE 5.18 - THROTTLING TEST ON 4TH 'B' BELLOWS VALVE



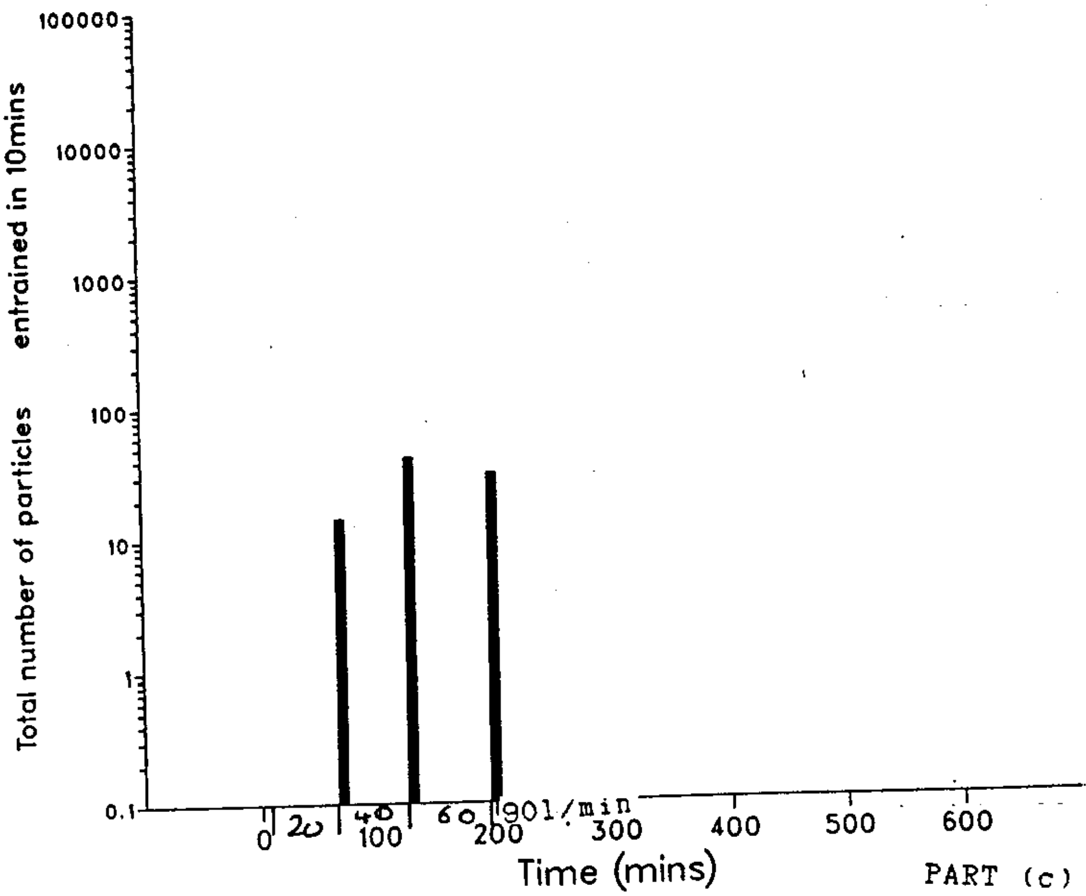


FIGURE 5.19 - THROTTLING TEST ON 'B' TOGGLE BELLOWS VALVE

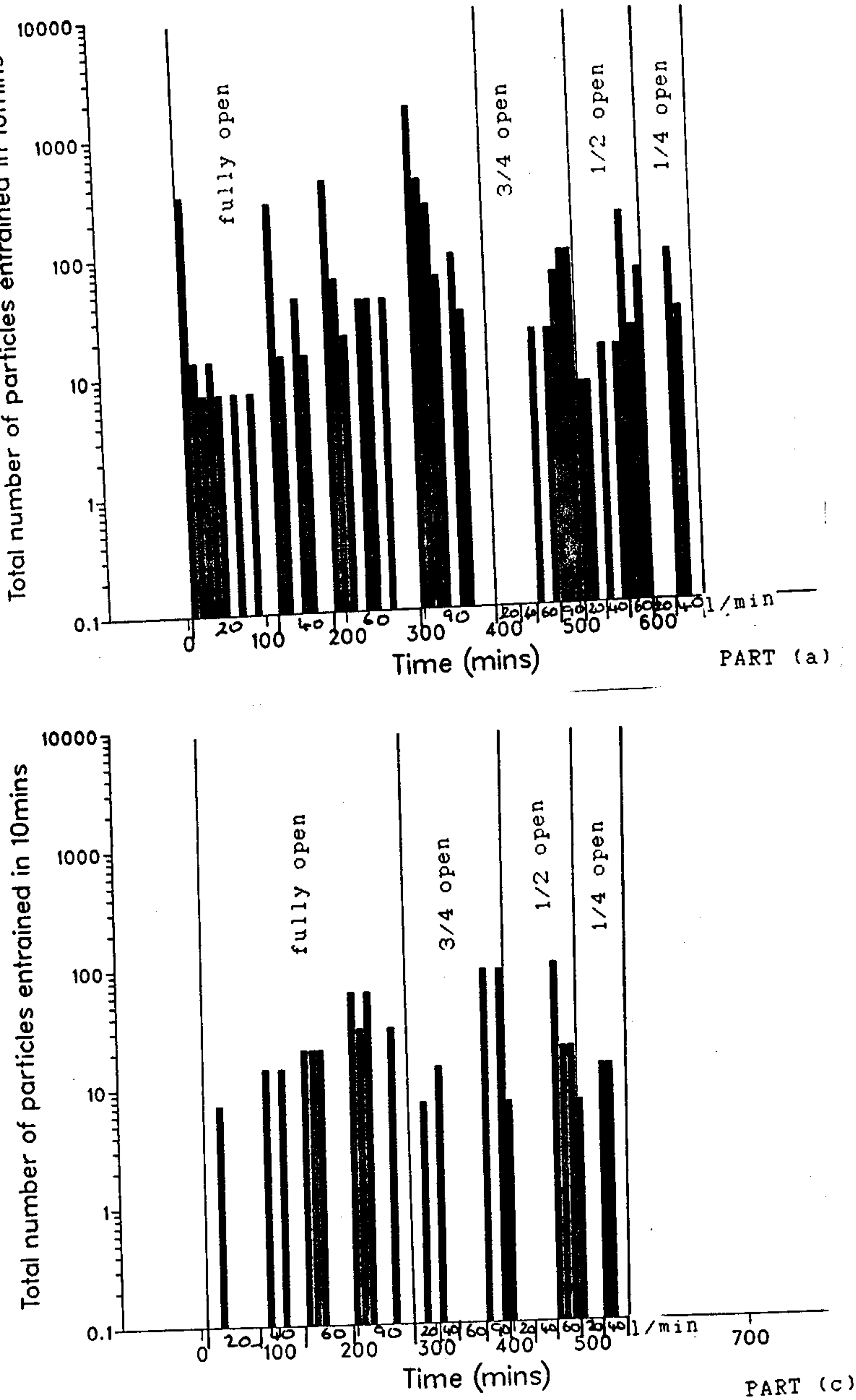
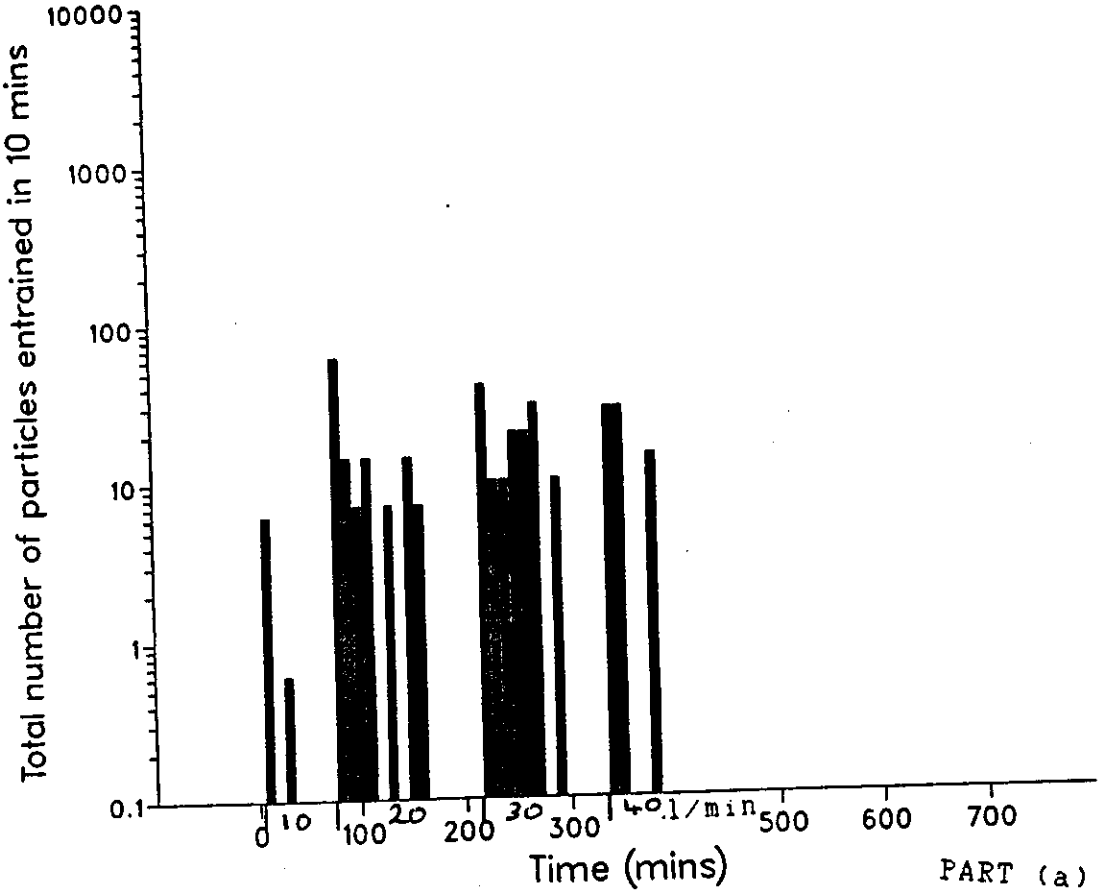


FIGURE 5.20 - THROTTLING TEST ON 'C' BELLOWS VALVE



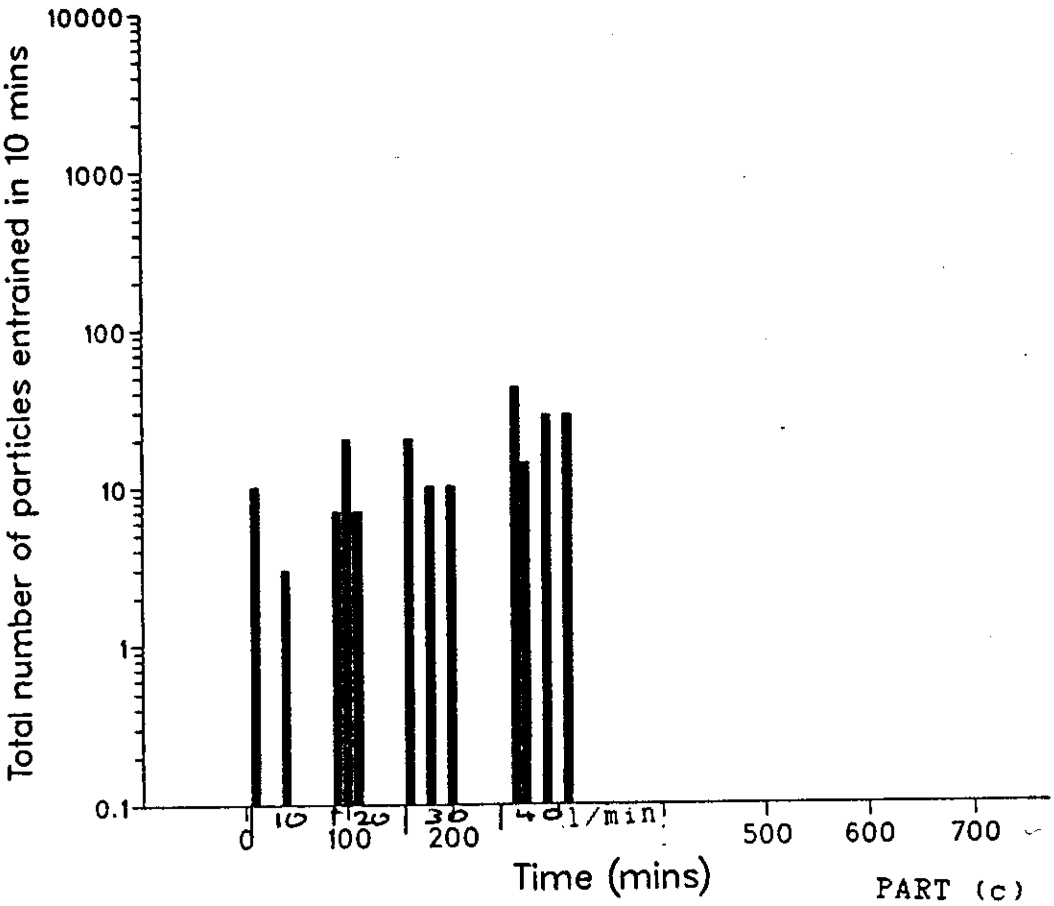
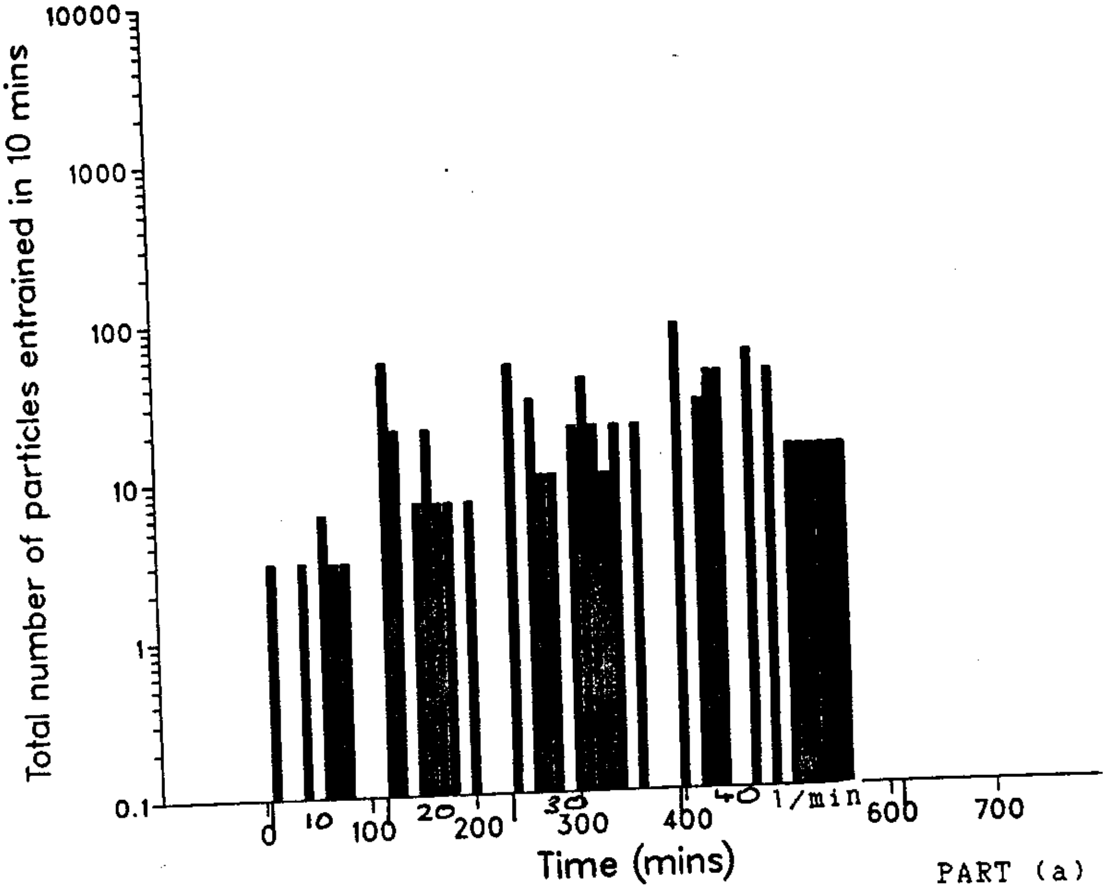


FIGURE 5.21 - THROTTLING TEST ON 'B' DIAPHRAGM VALVE



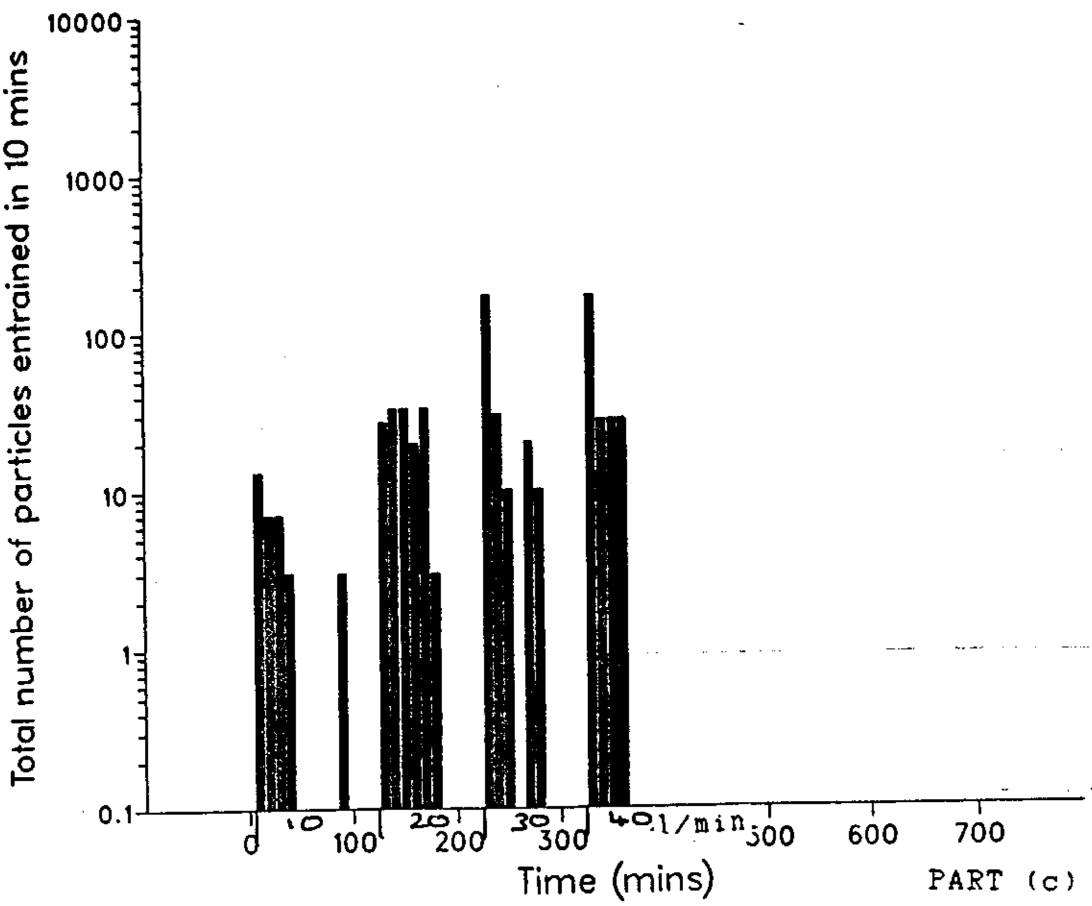
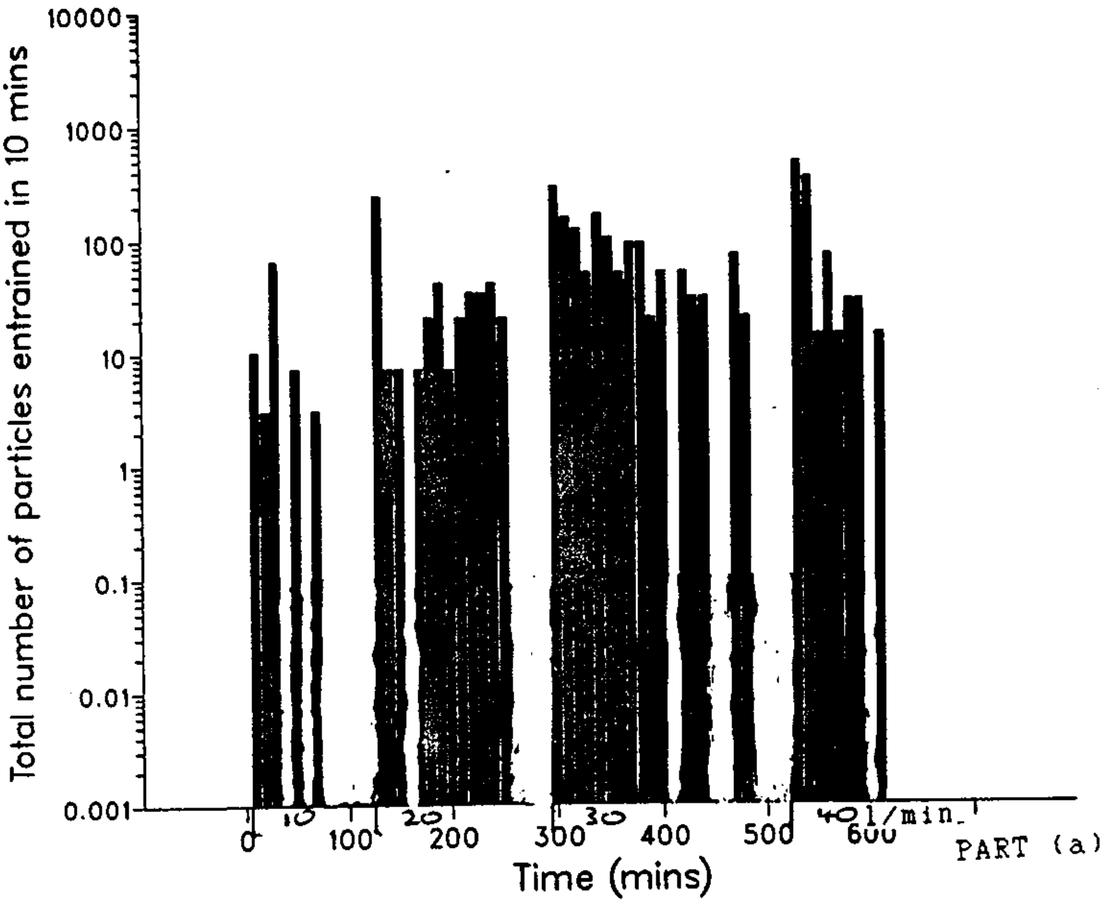


FIGURE 5.22 - THROTTLING TEST ON 'C' DIAPHRAGM VALVE



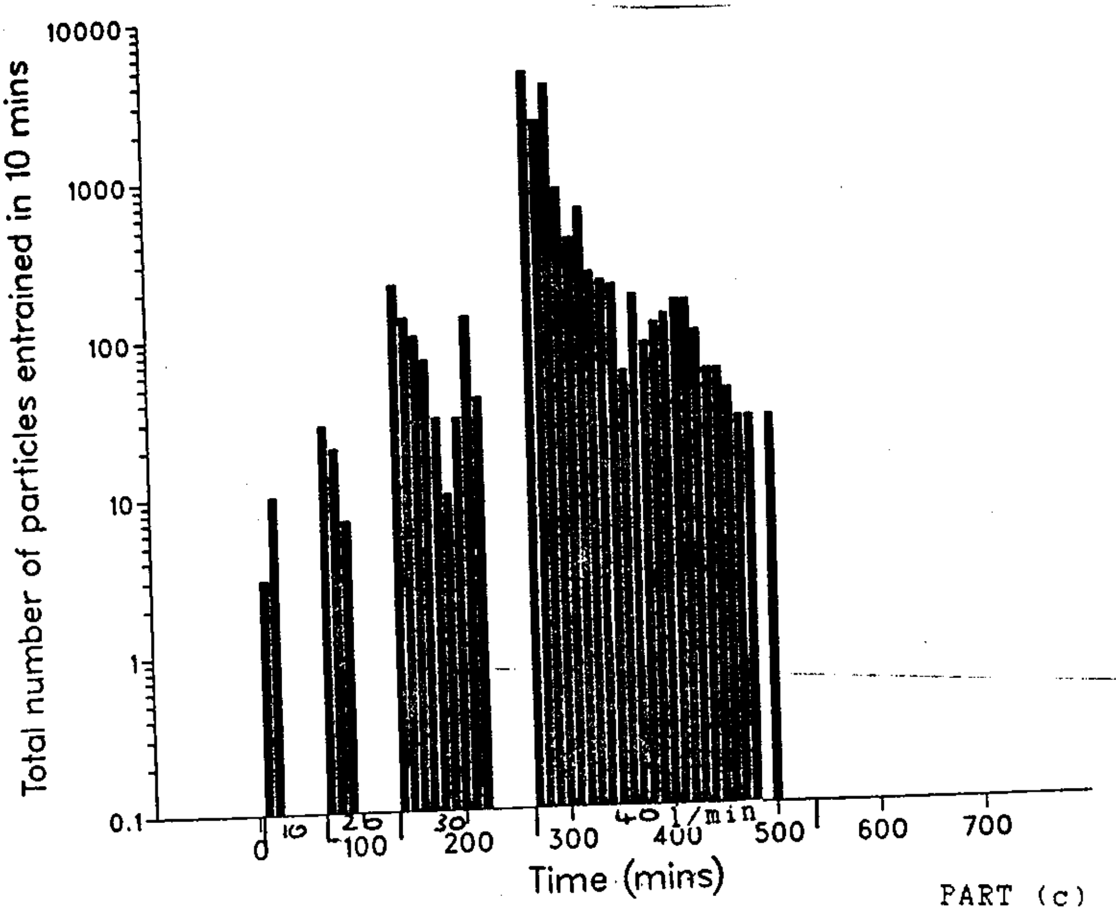
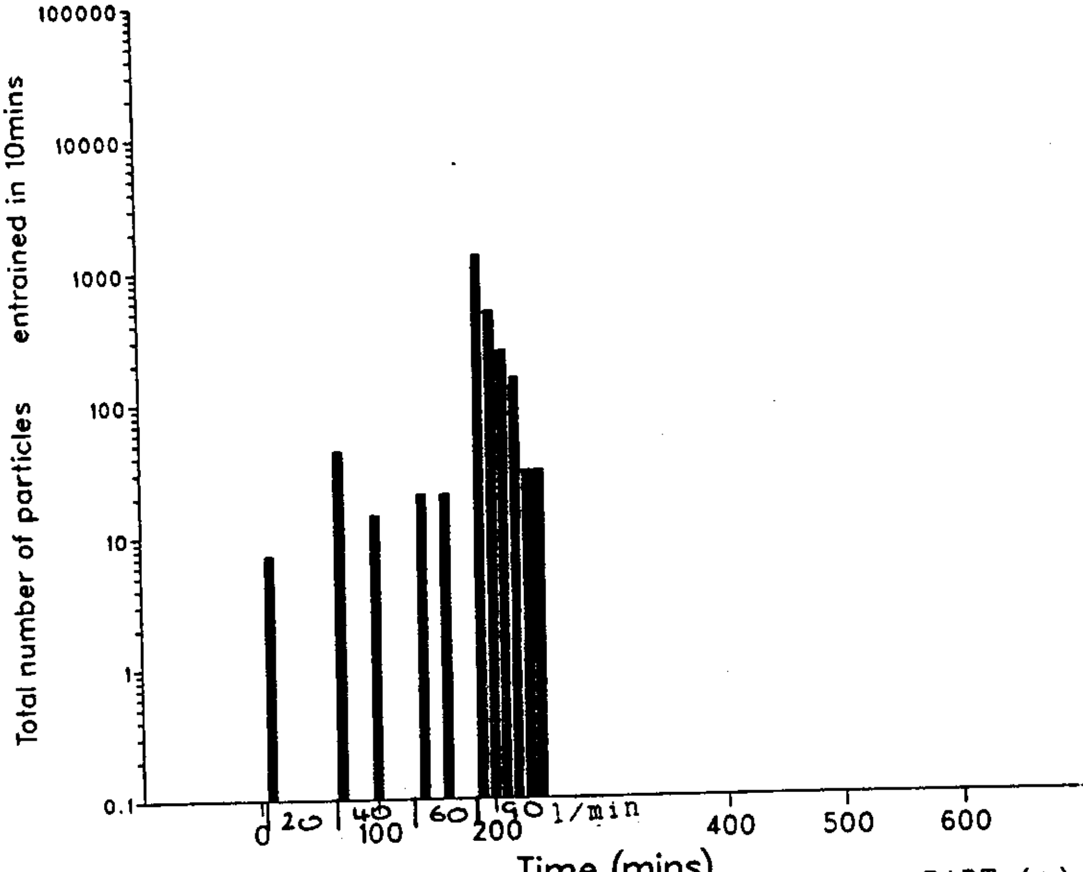
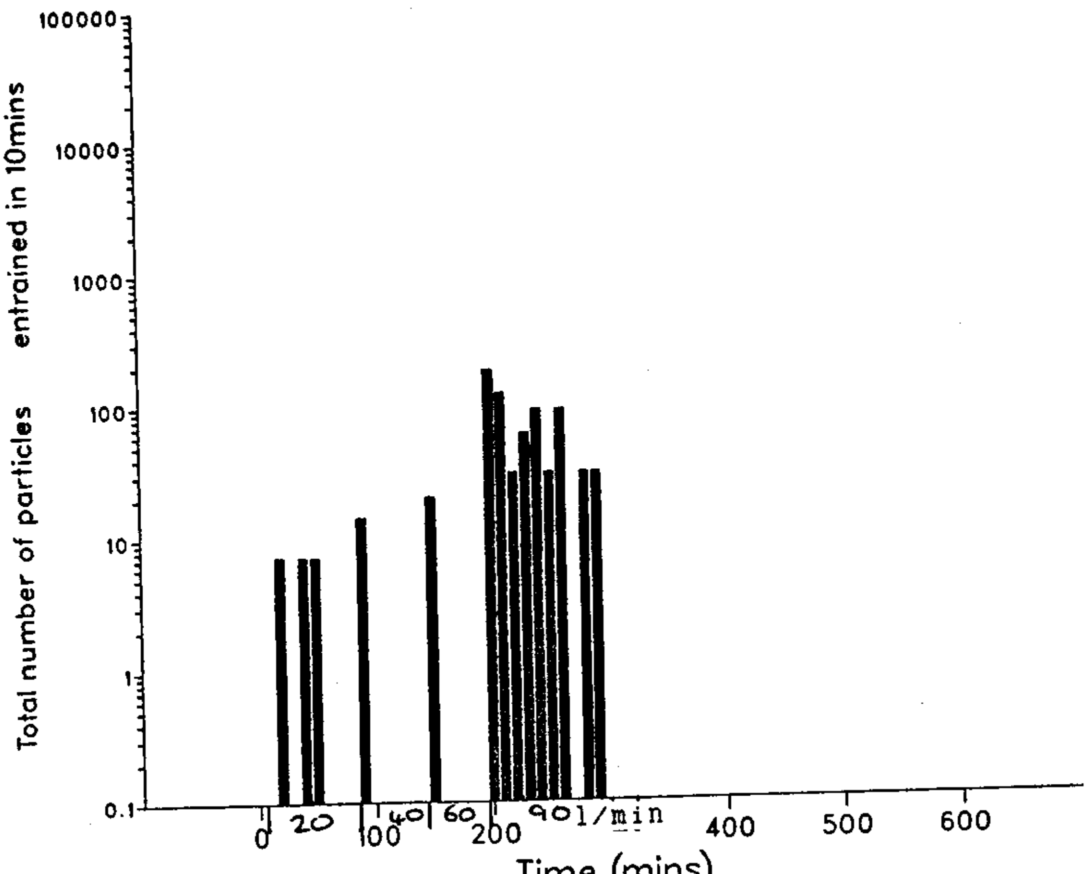


FIGURE 5.23 - THROTTLING TEST ON 'D' DIAPHRAGM VALVE

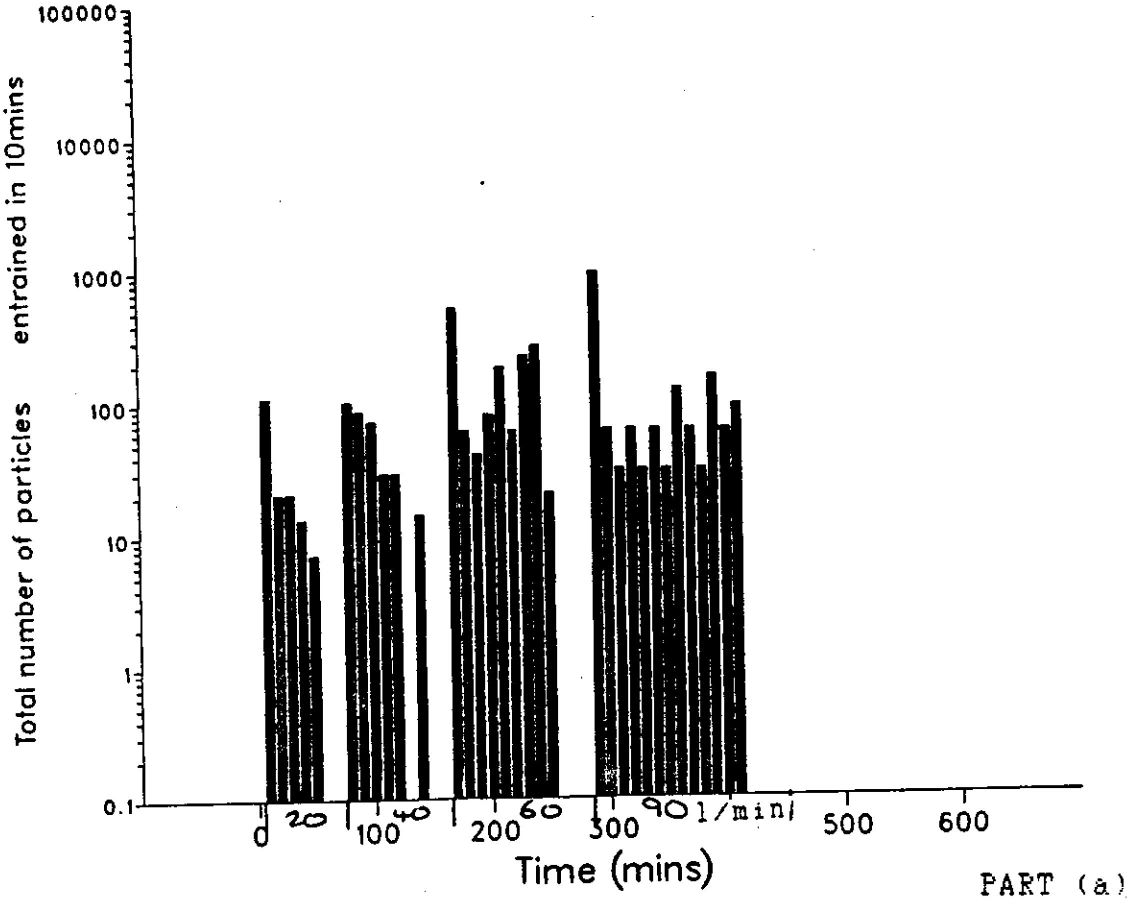


PART (a)



PART (c)

FIGURE 5.24 - THROTTLING TEST ON 'B' 1/4 TURN DIAPHRAGM VALVE (NC-55)



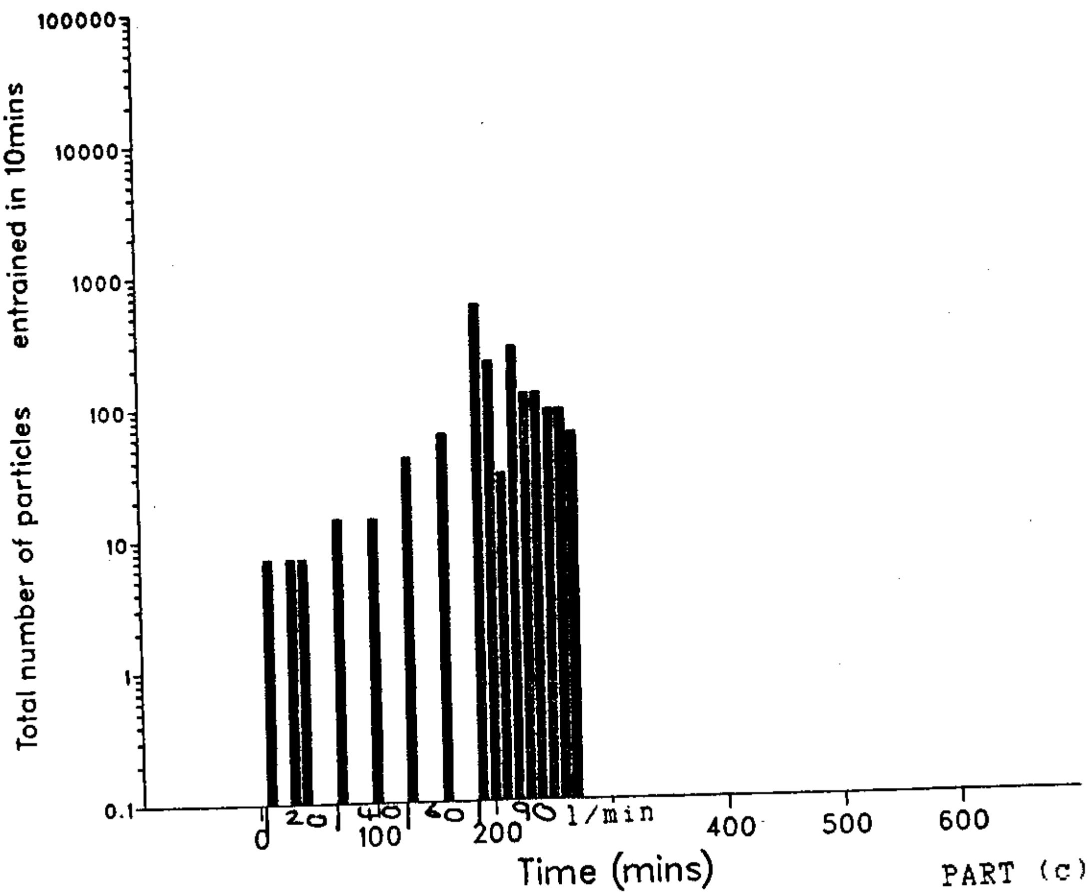
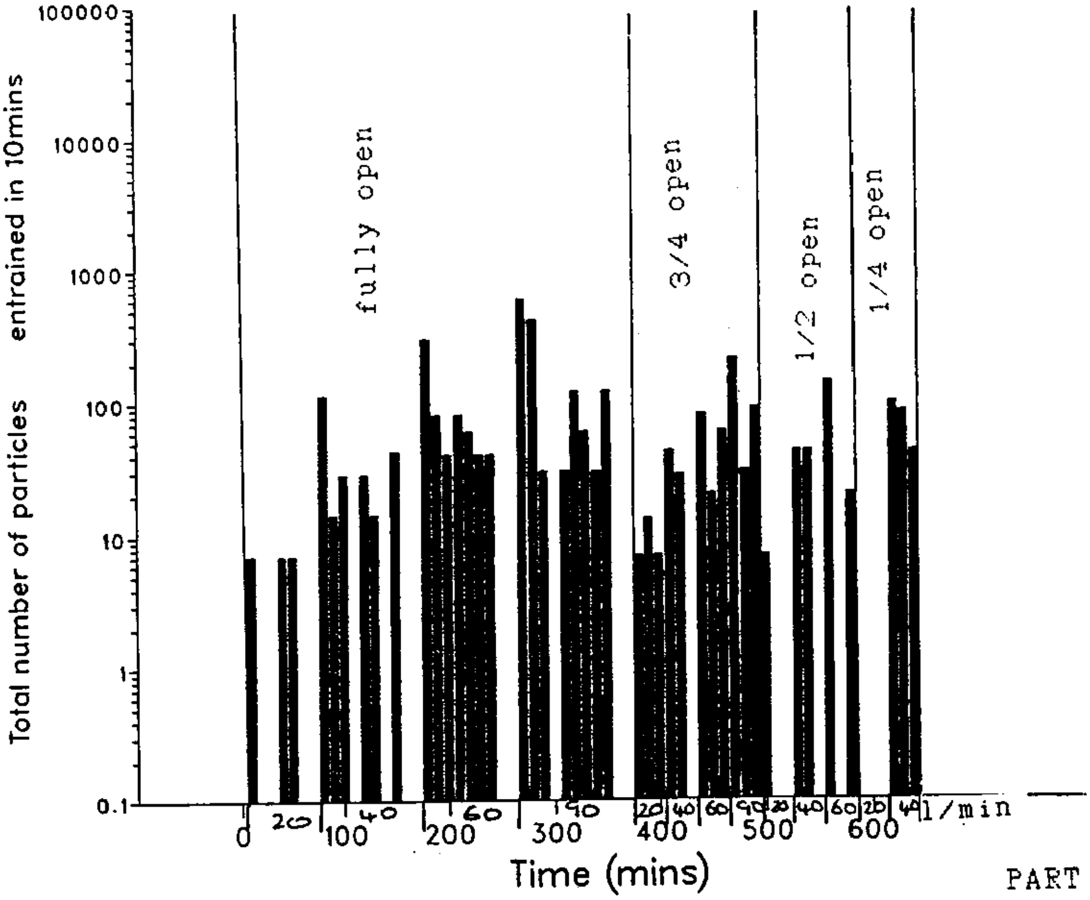
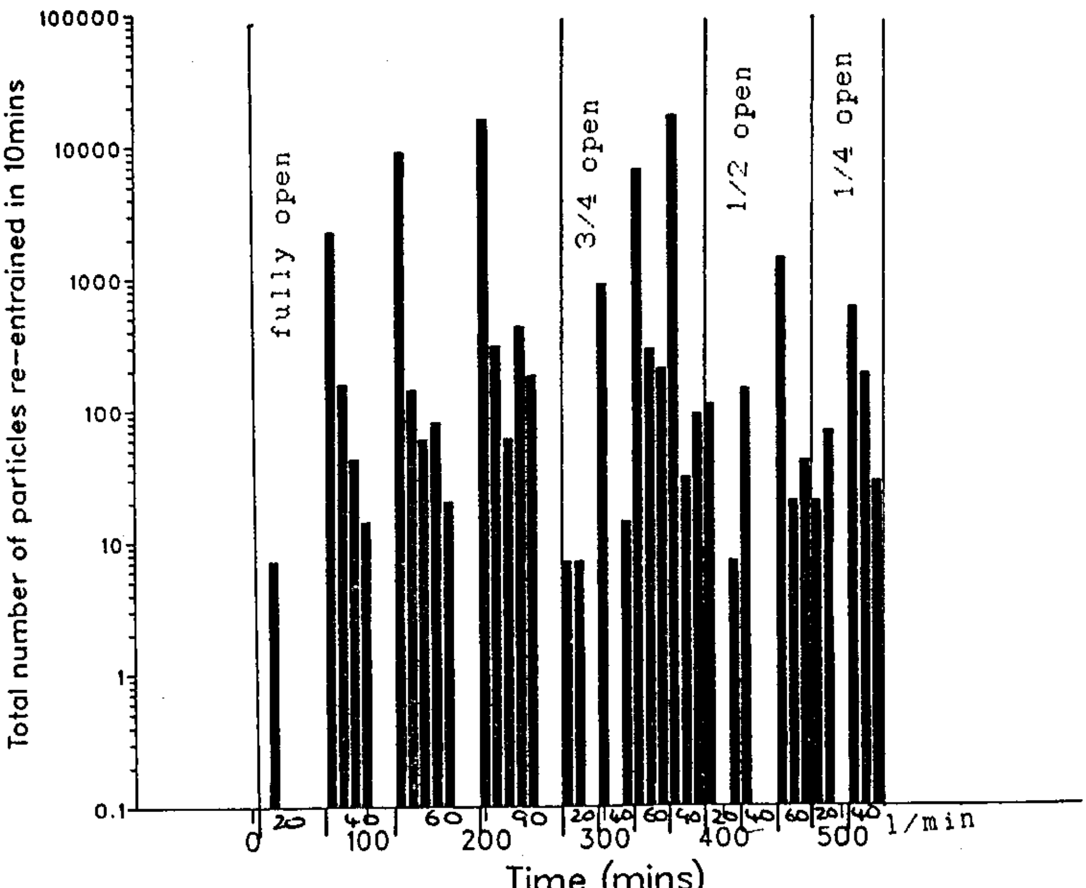


FIGURE 5.25 - THROTTLING TEST ON 'B' 1/4 TURN DIAPHRAGM VALVE



PART (a)



PART (c)

FIGURE 5.26 - THROTTLING TEST ON 'B' 1 1/2 TURN DIAPHRAGM VALVE

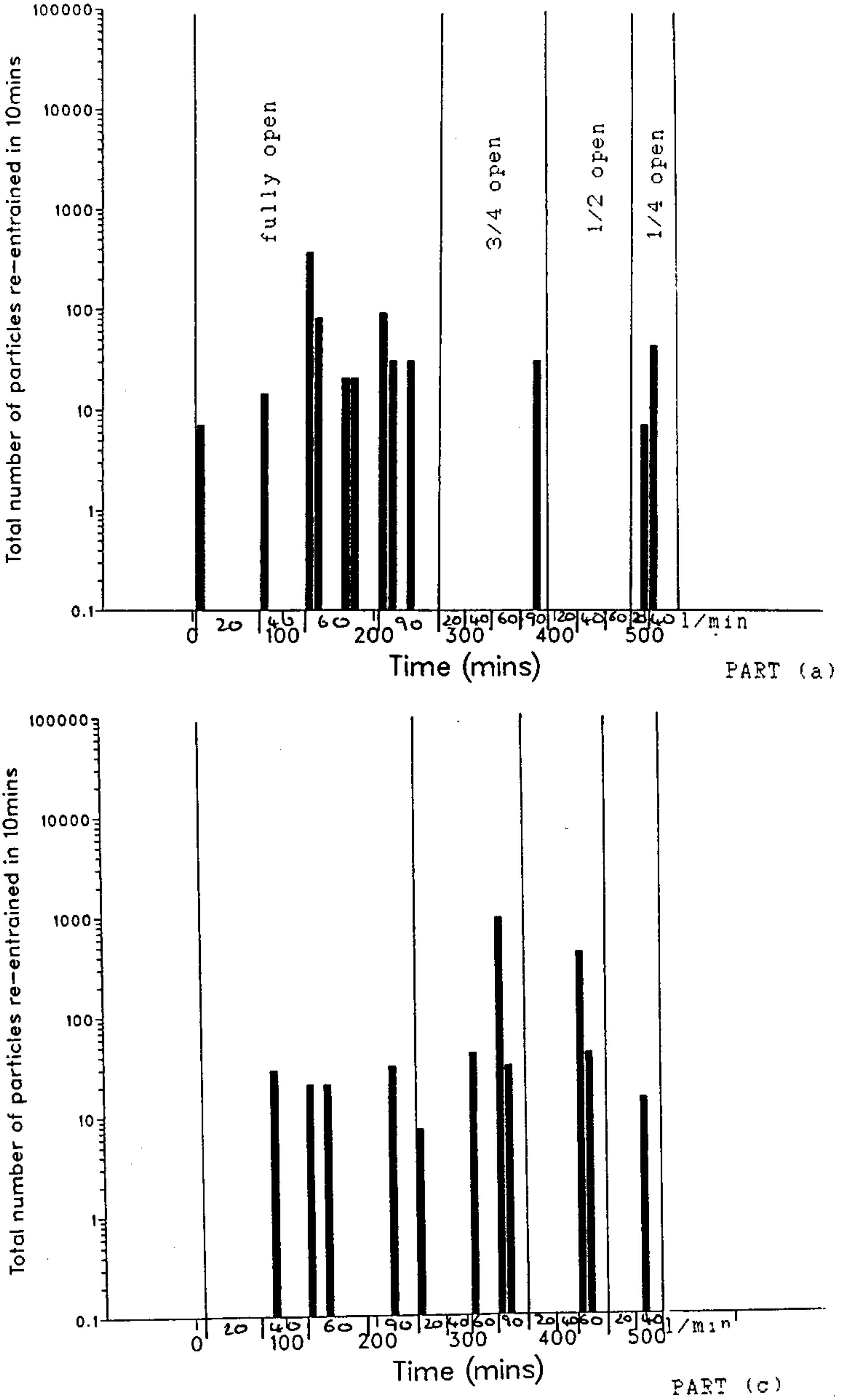
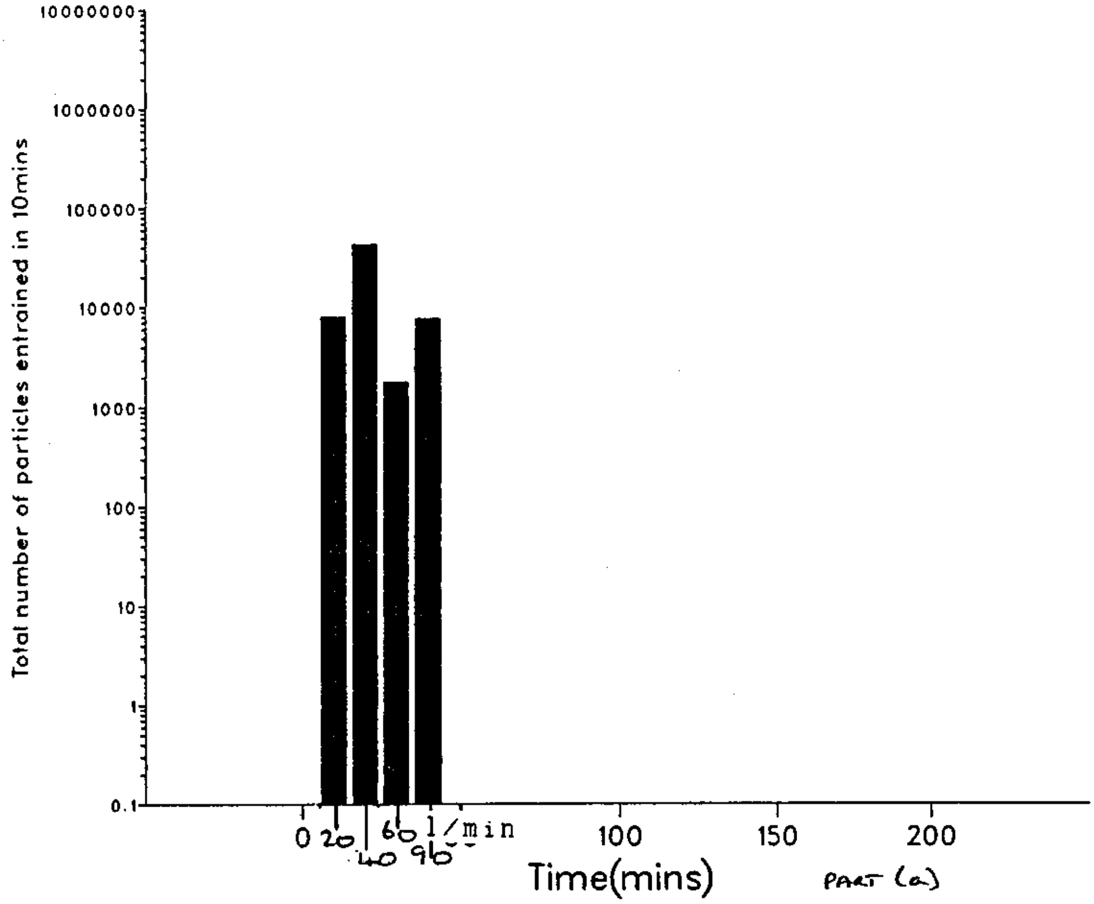


FIGURE 5.27 - THROTTLING TEST ON 'B' 1 1/2 TURN DIAPHRAGM VALVE (NC-55)



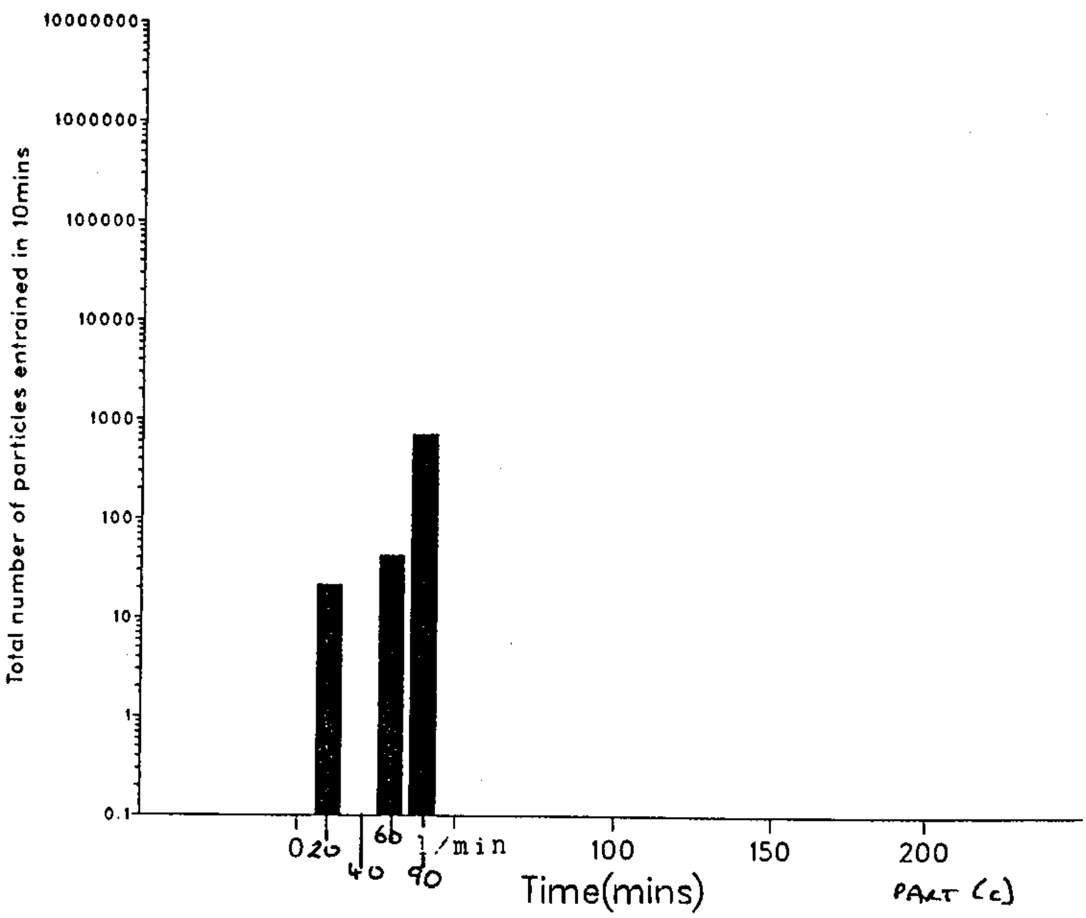


FIGURE 5.28 - THROTTLING TEST ON 'B' NORMALLY OPEN AIR OPERATED BELLOWS VALVE

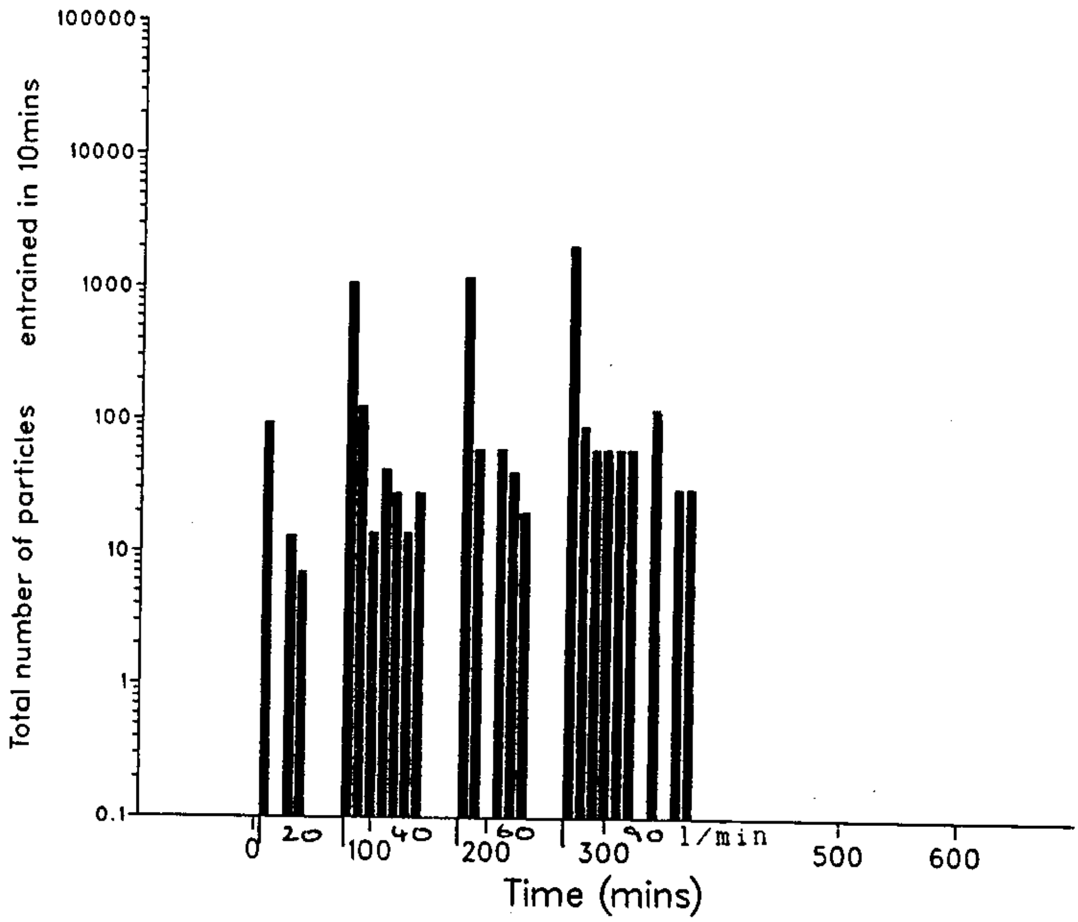


FIGURE 5.29 - TYPICAL PURGE TEST ON A VALVE

CHAPTER SIX

CONCLUSIONS

6.1 STRAIGHT TUBING

6.1.1 Entrainment Of Particulate Contamination From Straight Tubes

It was observed from the results (Section 4.2.2) that the electropolished tubes were shown to be cleaner than the 'as drawn' or 'chemically cleaned' tubes in the 'as delivered' state. The 'as drawn' and 'chemically cleaned' tubes did not show a great deal of consistency in their results in terms of cleanliness, there being a large variation in the number of particles being entrained.

The effects of vibration at 50Hz, gentle tapping, flexing the tubes, increasing the velocity and pulsing the flow were also investigated. Increasing the flowrate of air through the tubes greatly increased the number of particles being entrained. As was expected, pulsing the flow had a similar effect. Vibration, gentle tapping and flexing the tubes all had a slight effect which differed with each type of tube, i.e. there was not always an increase in entrainment.

6.1.2 Penetration Of Aerosol Particles

There was found to be reasonably good agreement between the results and the theoretical predictions for smooth walled tubes. The effect of surface roughness on deposition in tubes was also calculated using the El-Shoboksby and Ismail theory (1986). It could be seen that there is little effect of roughness over the range of surfaces used, or generally considered for use, in the I.C. industry. This agreed with the results for the test sections, they were all within 2% of each other - thus for the tubes tested there is no significant difference between the surface finishes.

Since the objective was to simulate the practical situation, efforts were made to exclude from the experimental system contaminants which would not have been present in practice. Hydrocarbon vapour was excluded by using bottled air. The relative humidity was reduced to 2% which is well below the level at which pendular moisture will form. This had no significant effect on the results so it may be assumed that the presence of small amounts of water vapour in these experiments is not important.

The penetration was found to be about 98% for all of the test sections.

6.1.3 Re-entrainment Of Aerosol Particles

The time it takes for a particle to diffuse to the tube wall was calculated. The tubes were thus left overnight after a penetration test was carried out to ensure that the particles were not still suspended in the air.

It was found that the amount of re-entrainment from the internal surface of any of the tubes is very low, i.e. there is not a detectable difference between the different types of tube. Further ancillary tests which were carried out validated the test procedure and thus the results (Section 4.6). These particularly showed that the presence of the small amount of water vapour in the tests did not effect the results.

6.1.3.1 Tube Bending

In the installation of clean room systems tubes have to be bent it was therefore decided to determine the particulate release from tubes during the process of tube bending and also the re-entrainment from bent tubes deliberately contaminated with aerosol particles.

It could be seen from the results that as the tubes are being bent the electropolished tube released the least particulate contamination and the 'as drawn' the most. However,it was also concluded that the amount of re-entrainment of particulates from all the bent tubes is very low i.e. once the tubes have been contaminated with aerosol (in the penetration test) there is not a detectable difference between any of the different surface finishes in terms of particle shedding.

6.1.3.2 Long-Term Nitrogen Tests

All of the previous tests were of necessity carried out over short time periods. A more realistic simulation of operating conditions was to expose the tubes to a dry nitrogen purge over a long period before testing.

Twelve sets of monthly results were obtained and it could be seen from the results that there were still very few particles removed from the three different types of tube. It can be concluded from this that the results obtained during the short term tests are validated.

6.1.3.3 Effect of Internal Surface Roughness

It was decided to investigate the effects of velocity on re-entrainment for three sizes of tubing to enable guidelines to be drawn up for tubing installation.

The results showed that a critical velocity for the 0.25" (6.3 mm) o.d. tube was reached at about 60m/s. This velocity could not be reached for the 10mm o.d. tube due to the constraints of the experimental rig. A sharp rise in the number of particles being removed was observed at 20m/s for the 3.2 mm (0.125") o.d. tubing. When comparing this critical velocity with the equivalent Reynold's number, it can be seen that for the smallest diameter tube this sudden increase occurs around the transition region between turbulent and laminar flow. However for the larger sized tubes, particles do not start to be removed until the flow is well into the turbulent regime - the particle dislodgement being so small that it could not be detected at comparably low Reynold's numbers close to transition.

In an attempt to determine the reason for the above results, the internal surfaces of a 3.2 mm o.d. tube and a 6.35 mm o.d. tube were examined using a profilometer. This shows the internal surface of the 3.2 mm o.d. tube has a roughness of 47-50 μinch (1.19 - 1.27 μm) RA, as compared to a 5-10μinch (0.13 - 0.26 μm) RA of an 'as drawn' tube.

To further investigate the effects of surface roughness, two twelve year old 6.35 mm (0.25") o.d. tubes were tested for re-entrainment. From this it could be seen that the results for the 12 year old tubes are between those for the 3.2 mm o.d tubes and the 6.35 mm o.d. and 10mm o.d. tubes. The internal roughness of the 12 year old tube was 27μinch (0.69 μm) RA, which also lies between the internal surface roughness values for the 3.2 mm o.d. and the new 6.35 mm o.d. tubes. This data covers the range of surface roughness up to 50μinch RA. The work reported earlier in this thesis covered surface finishes, typically used in the Integrated Circuit industry, up to a roughness of about 10μinch (0.26 μm). Clearly roughness is a significant factor, sharply increasing contamination for the poorer surfaces examined. Below a roughness of 10μinch the effect is not significant.

From a mechanistic point of view the results are consistent with the discussion in Section 4.5. Turbulent bursts and the higher end of the energy distribution will remove particles adhering at the lower end of the adhesion energy distribution. This will be strongly affected by roughness of the substrate if this is greater than the particle size.

6.2 Valves

The experimental procedure carried out on the different types of valves involved passing clean air through a new 'as delivered' valve, opening and closing this valve and finally repeating the first part of the experiment.

The results showed that there were significant differences not only between the design types but also between those produced by different manufacturers, reflecting individual variations in design and cleaning and assembly procedures.

The effect of opening and closing the valves was investigated on the different types of valve. Mechanical action in the ball valve, and especially the needle valve, caused substantial contamination. In the diaphragm valves tested the spring was located in the process gas stream, where its movement caused heavy contamination. If this were not in contact with the process stream the contamination would be greatly reduced.

It can be concluded that:

1) Attention to manufacturing practices, especially cleaning and clean assembly, leads to cleaner components.

2) Consideration of particle generation mechanisms during use, such as wear and flexure and a reduction of area exposed to the process gases, should lead to the design of more suitable components.

NOMENCLATURE

a	Radius of particle
a^+	Dimensionless radius of particle
A	Hamaker's constant
B	Dynamic mobility
C	Concentration in probe
C_c	Slip correction factor
C_o	Concentration in stream
c^+	Dimensionless concentration
C_o^+	Dimensionless concentration at a distance from the wall
d_a	Aerodynamic diameter of particle
d_p	Diameter of particle
d_{ar}	Davies' dimensionless stop distance of particle
D	Molecular diffusion coefficient
D_p	Diameter of tube
e	Coefficient of restitution
e^+	Dimensionless displacement in origin of velocity profile
E	Impaction efficiency
f	Fanning friction factor
F	Retained fraction
F_{adh}	Resulting adhesive force between the particle and a surface
F_p	Penetration fraction
F_z	Attractive force in the presence of an opposite charge
g	Acceleration due to gravity

k	Unit normal vector in the vertical direction
k'	Zimmer and Dahneke's rate constant
K	Average height
K'	Boltzmann constant
K"	Kinetic energy required for particle bounce to occur
K^+	Dimensionless average height of wall roughness
L	Length of section
m	Mass of particle
n	Numerical density of the particles/unit volume of gas
N	Concentration of surface borne particles
N(x)	Unit normal to the surface
p	Rate constant for long term resuspension
P	Fractional penetration through individual section
<PE>	Average potential energy of a particle in a well
q	Net charge
Q	Sampling flow rate
Q'	Height of surface adhesive potential well
R^+	Dimensionless tube radius
Re	Reynold's number
S	Schmidt number
St	Stoke's number
S^+	Dimensionless stop distance
t	Staying time
t^+	Dimensionless staying time
t_p^+	Dimensionless stopping time of particle
T	Absolute temperature

U	Stream velocity
U_o	Gas velocity in probe
U'	Friction velocity
U^*	Average fluid velocity
V	Volume of vessel
V_c	Critical velocity at which bounce will occur
V_d	Deposition velocity of particle
V_n	Normal resolute of the turbulent velocity
$V.$	Root mean square particle velocity
V_{TS}	Terminal settling speed
V^+	Dimensionless deposition velocity
V_n^+	Dimensionless normal resolute of turbulent velocity
w	Wind velocity
x	Separation distance
xq	Separation distance of opposite charges
y	Particle surface separation
y^+	Dimensionless particle surface separation
Z_b	Outer boundary condition where zero particle concentration is maintained
β	Deposition coefficient/unit volume of vessel
β_2	Constant that depends on material and geometry
δ^+	Dimensionless turbulent boundary layer thickness
$^+$	Dimensionless capture distance
ϵ	Fluid eddy diffusivity
ϵ_o	Permittivity
ϵ_p	Effective particle diffusivity
ϵ_p^+	Dimensionless particle diffusivity

η	Viscosity of fluid
θ_1	Bend angle
θ'	Angle of probe misalignment
	Kinematic viscosity
ρ_p	Density of particle
σ_{k+}	Dimensionless standard deviation of average height of wall roughness
τ	Relaxation time
τ^+	Dimensionless relaxation time
ϕ_0	Potential minimum
ϕ_1	Potential maximum
ω	Curvature of the barrier
ω_0	Typical frequency of vibration

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APPENDIX I

STANDARD DEFINITIONS

Chemically Cleaned Tube	- Tube which has undergone an acid pickling treatment.
As Drawn Tube	- A non-pickled tube which has had some cleaning.
Electropolished Tube	- A tube which has been electropolished in order to obtain a smoother internal finish.
Entrainment	- Particulate contamination arising from 'clean' tubes, in the "as delivered" conditic
Penetration	- The fraction of aerosol particles which pass through a tube without depositing onto the tube wall.
Re-entrainment	- The extent of particle dislodgement from tubes which have been well purged after installation but contaminated during use.
Standard Test	- A steady flowrate of 40 l/min of clean air is passed through the test section; vibration and mechanical tapping are applied.
Entrainment Extended Test	- The flowrate of clean air is increased to 60 l/min and then 90 l/min, the flow is pulsed and the tube is flexed at both flowrat
Re-entrainment Extended Test	- The flowrate of clean air is increased to 60 l/min, the flow is pulsed and the tube flexed.