A Study of factors affecting wear characteristics of asbestos cement pipes used for conveyance of slurries. June 1977.

Author:
Tuck, J. K.

Publication details:
Commissioning Body: James Hardie and Coy.
Report No. UNSW Water Research Laboratory Report No. 149
0858242338 (ISBN)

Publication Date:
1977

DOI:
https://doi.org/10.4225/53/57998b132f17f

THE UNIVERSITY OF NEW SOUTH WALES

water research laboratory

Manly Vale N.S.W. Australia

A STUDY OF FACTORS AFFECTING WEAR CHARACTERISTICS OF ASBESTOS-CEMENT PIPES USED FOR THE CONVEYANCE OF SLURRIES

by

J.K. Tuck

Report No. 149

June 1977.

The University of New South Wales

Water Research Laboratory

A STUDY OF FACTORS AFFECTING WEAR CHARACTERISTICS OF ASBESTOS-CEMENT PIPES USED FOR THE CONVEYANCE OF SLURRIES

by

J.K. Tuck

Report No. 149

June 1977.

---

https://doi.org/10.4225/53/57998b132f17f

BIBLIOGRAPHIC DATA SHEET

1. REPORT No. 149

2. I.S.B.N. O/85824/233/8

3. TITLE AND SUBTITLE

A Study of Factors affecting Wear Characteristics of Asbestos Cement Pipes used for the Conveyance of Slurries.

4. REPORT DATE

June 1977.

5. AUTHOR(S) J.K.Tuck

6. SPONSORING ORGANIZATION

Water Research Laboratory

7. SUPPLEMENTARY NOTES

8. ABSTRACT

A number of factors are known to influence the rate of wear and pattern of wear in asbestos-cement pipes used for the conveyance of slurries. Specifically these factors include: 1. Particle hardness, density, size, shape and concentration; 2. Slurry dynamics; 3. Slurry acidity; 4. Pipe diameter, alignment and hardness. This report investigates the effects of particle size and to a lesser degree the effects of flow velocity, pipe diameter, joint alignment and protective coatings.

Generally rates of wear were found to increase logarithmically with an increase in particle size and varied within the pipe according to proximity to the joint and circumferential position. The epoxy coating was found to reduce wear rates for quartz particle sizes less than 1mm, but to be ineffective for larger sizes.

The mode of particle conveyance, expressed in terms of flow regime and dependent primarily on flow velocity, pipe diameter and particle settling velocity was shown to be a major factor in determining wear characteristics. Operating with a stationary or sliding bed, an increased pipe diameter and a reduced average velocity, the area of maximum wear was displaced from the invert to the juncture of the invert and obvert hemispheres. Wear rates at the juncture were found to be significantly less than the invert wear rates established by heterogeneous conveyance of the same solid material.

9. DISTRIBUTION STATEMENT

Enquiries re purchase of the report should be directed to the Officer-in-Charge, Water Research Laboratory, Universityof N.S.W., King St., Manly Vale, N.S.W. 2093.

10. KEY WORDS Wear, Erosion, Slurry, Asbestos-Cement Pipes, Flow Regimes, Epoxy-lined Pipes, Hydrotransport.

11. CLASSIFICATION

12. NUMBER OF PAGES Approx. 80

13. PRICE

Preface

This study is part of a program to establish the effect of a number of factors on the rate of wear in asbestos-cement pipes used for the conveyance of slurries.

The project was funded by a University grant, established with the support of James Hardie and Coy. Pty. Limited. The work was supervised by Associate Professor D.N. Foster.

D.N. Foster,
Assoc. Professor of Civil Engineering,
Officer-in-Charge.

Abstract

A number of factors are known to influence the rate of wear and pattern of wear in asbestos-cement pipes used for the conveyance of slurries. Specifically these factors include:-

1. Particle hardness, relative density, size and grading, shape and concentration.

2. Slurry dynamics.

3. Slurry acidity.

4. Pipe diameter, alignment and hardness.

As a program to comprehensively test all these factors would be extremely time consuming, it was decided that initially the experimental investigations be concerned with particle size and to a lesser degree the effects of flow velocity, pipe diameter, joint alignment and protective coatings.

Generally rates of wear were found to increase logarithmically with an increase in particle size and varied within the pipe according to proximity to the joint and circumferential position. The epoxy coating was found to reduce wear rates for quartz particle sizes less than 1mm, but to be ineffective for larger sizes.

The mode of particle conveyance, expressed in terms of flow regime and dependent primarily on flow velocity, pipe diameter and particle settling velocity was shown to be a major factor in determining wear characteristics. Operating with a stationary or sliding bed, an increased pipe diameter and a reduced average velocity the area of maximum wear was displaced from the invert to the juncture of the invert and obvert hemispheres. Wear rates at the juncture were found to be significantly less than the invert wear rates established by heterogeneous conveyance of the same solid material.

Table of Contents

List of Figures

List of Figures (cont'd.)

List of Photographs

1. Introduction

The transport of solids by pumping them along pipelines in slurry form is increasing in importance, particularly in the mineral processing industries where the use of long distance pipelines is becoming a more competitive alternative to transportation by road or rail.

Asbestos-cement pipes represent an important segment of the slurry pipeline market. Successful utilisation of A-C pipelines for the transportation of slurry mixtures has been demonstrated at Broken Hill, N.S.W., Mt. Isa, Queensland, and Stradbroke Island, Queensland. However, excessive wall erosion has limited the life of A-C pipes in other instances, particularly where coarse materials were being conveyed.

The failure of the A-C bauxite failings line at Weipa, causing the pipeline to be abandoned and replaced with a steel line, prompted the establishment of the present study in 1970. The objectives of the study were to delineate those conditions under which wear in A-C pipes will be of major concern and investigate methods for reducing pipe wear, such as the use of protective coatings and the implementation of acceptable alternate operational procedures which would extend the life of the piping.

2. The Research Program

The following factors are likely to have an effect on the rate of internal pipe wear in the course of slurry transport.

- (i) Type of pipe and nature of joint
- (ii) Size grading and shape of sediment
- (iii) S.G. and hardness of sediment
- (iv) Sediment concentration
- (v) Flow velocity
- (vi) Pipe diameter
- (vii) Water pH and temperature

As a program to comprehensively test all these factors would be extremely time consuming, it was decided to experimentally investigate in detail the effect of particle size, (item (ii)) and to a lesser degree the items (i), (v) and (vi). All the factors listed above were examined in the light of the available literature on the subject.

The main thrust of the testing program was directed towards the measurement of the rates of wear in 100 mm (4") diameter A-C pipes for several particle sizes when pumped at a velocity of 4 m/s and an average slurry concentration by weight of 25% (maximum normally used in practice). The performances of both standard and epoxy lined A-C pipes were investigated. It was expected that the results of the tests would delineate the critical particle size below which A-C pipes could be recommended without danger of excessive wear. In addition the tests would provide a basis for future testing of other parameters (e.g. velocity) by facilitating the selection of a particle size parameter above the critical for the purpose of minimising the testing time (i.e. by a maximisation of wear rates).

3. The Nature of Wear in A-C Pipes

Bitter (1963) describes two possible types of wear action. In the first instance wear can be caused by repeated deformation during collision between the slurry solids and the pipe wall resulting in a dislodgement of wall material; and in the second instance wear can be the result of a cutting action which tends to occur when particles strike a horizontal surface at an acute angle.

The asbestos-cement pipe is composed of cement particles and asbestos fibres bonded together hydraulically. Bitter states that with a cement surface particles are dislodged in their entirety under a stream of abrasive particles according to the second mechanism rather than the first. No information could be found regarding the exact mechanism of wear for an asbestos-cement composite, however it seems likely that cutting action will predominate.

4. Factors Influencing the Rate of Wear

Both the rate of wear and the pattern of wear in slurry pipelines are influenced by a number of factors. Specifically these factors include:-

1. Particle hardness, relative density, size and grading, shape and concentration.

2. Slurry dynamics.

3. Slurry acidity.

4. Pipe diameter, alignment and hardness.

Some of these factors are interdependent. Details of their effects as found by other investigators are discussed in the following pages. It is evident that some areas require further study.

4.1 Particle Hardness

Wear increases rapidly once the particle hardness exceeds that of the pipe material. A survey by Truscott (1972) suggests, however, that beyond a certain particle hardness the wear rate may become fairly constant. Barker and Truscott (1974) state that the most abrasive slurries appear to be mineral ores and their concentrates (e.g. iron, copper, phosphate, silica) and some mine tailings. Soft materials such as coal, limestone, cement and clay have relatively low abrasivity.

4.2 Particle Density

The particle density in conjunction with the particle size and the fluid density determines the settling velocity of suspended slurry particles. The settling velocity in association with the axial velocity is used to indicate the type of flow regime existing in the pipe during operation. A more detailed discussion of this aspect is given in Section 4.8.2.

4.3 Particle Size and Grading

A number of investigations (Barker and Truscott (1974), Truscott (1972), Cornet (1975)) have found increases in wear rate to be proportional to increases in the average particle size to the nth power. Cornet (1975) offers a value of n between 0.75 and 0.8 for sand in the size range 100 $\mu m < d_{50} < 10mm$. As an example this indicates that the rate of wear of 10mm particles will be approximately 12 times as high as with 0.4 mm particles.

Consideration of the grading of the slurry solids involves the recognition that the initial natural grading of the material will undergo change as the slurry flows along the length of a pipeline. The extent of the change in grading will depend on such factors as the pipeline length, the flow velocity and the hardness of the particles and pipe material. It is possible that for a long pipeline wear rates will gradually decrease along the length due to a gradual reduction in mean particle size. However, it should be noted that the ease of particle size reduction will diminish with decreasing particle size since the energy required to fracture materials is related to the surface area formed which for a given quantity of material increases rapidly as attrition proceeds.

The use of mixtures of distinct particle sizes has been shown to have an inhibiting effect on the rate of wear. Newitt et al (1955) investigating the effects of mixtures, came to the following conclusions:-

1. Suspensions of fine particles reduce the settling velocity of coarse particles so that the distribution of coarse particles becomes more uniform across the pipe section.

2. A more uniform concentration of solids across the pipe section (i.e. a lower concentration of solids near the bottom of the pipe) will tend to reduce friction head losses and pipe wear.

3. There is an optimum composition for each mixture of two sizes which will give a maximum flow rate at a minimum head loss.

4.4 Particle Shape

Little information is to be found on the effect of particle shape on the nature of wear. However, this area of study portends to be extremely complex. Not only will shape affect the area of impact (and hence the force/unit area parameter) but will also affect particle dynamics and thus flow regime (Sections 4.8.1.2 and 4.8.2).

With regard to area of impact, Bitter (1963) notes that the probability of an angular particle striking a surface with an edge or a plane surface is very small in comparison with the probability that it strikes the surface with a point. If the volume of the particle is equated to $4/3\pi R^3$ and the radius of curvature of the point of impact is 'r' then the deformation will be equivalent to that caused by a rounded particle of radius 'r' and a density which is $(R/r)^3$ times as large as the actual density.

4.5 Particle Concentration

The rate of wear tends to increase with an increase in mixture concentration, (Barker and Truscott, 1974). This is due to the higher frequency of contact between the solids and pipe. However, at high concentrations mutual interference between the particles and suppression of turbulence due to their presence will reduce both the frequency of particle-pipe contacts and the velocity of impact. Barker and Truscott state that wear rates may even fall above a certain concentration, being of the order of 20-25% by weight for some slurries.

4.6 Particle and Fluid Velocity

Particle velocities are determined largely by the fluid velocity and the shape of the pipe. A study by Scarlet and Grimley (1974) found particle velocities lagging the mean fluid velocity by 8% at 3 m/s to 13% at 2 m/s. They suggest that for non homogeneous suspensions a large contribution to the apparent slip velocity is due to fluid flowing at high velocity through the 'empty' upper portion of the pipe and that in those regions of pipe in which particles are freely suspended, the difference between mean particle and fluid axial velocities is probably quite modest.

Scarlet and Grimley also examined transverse velocities and found them to be in the order of 0.25 m/s when average axial velocities were of the order of 3 m/s. The transverse velocities aid the suspension of particles particularly if terminal falling velocities are less than transverse velocities. Jenkins (1973) states that a particle will be suspended in an eddy field if the fluid velocity within the eddy field is greater than about 2.7 times the settling velocity of the particle in quiescent fluid.

A number of studies have been directed towards the establishment of a relationship between the average rate of wear and the average fluid velocity (Barker and Truscott (1974), Cornet (1975), Truscott (1972)). In general, the relationship 'rate of wear $\propto$ (velocity)^n' has been adopted. Values for the exponent have been reported to range between 0.85 and 3 (Barker and Truscott, 1974). It is interesting to note that for an exponent of 2.5 the rate of wear at a flow velocity of 3 m/s is almost three times the rate of wear at 2 m/s.

4.7 Particle Flux

Particle flux is the product of velocity and concentration. Scarlet and Grimley (1974) were able to measure particle velocities and concentrations in a glass pipe using high speed cine photography. Referring to Figure 42 it is interesting to note that the maximum flux may be at some distance above the bottom of the pipe.

4.8 Slurry Dynamics

Acquirement of techniques to predict rates of wear and patterns of wear is to a large extent dependent on an understanding of the dynamics of slurry flow. The possibility for computation of trajectories of non-buoyant particles in a field of eddies has been demonstrated to a limited degree by Jenkins (1973). Unfortunately, considerable development in this area is required before this method can be applied to slurry flow. At the present time the determination of flow regime through empirical methods and relating this to wear appears to be a more encouraging area of endeavour.

4.8.1 Particle Dynamics

An excellent dissertation on the forces causing motion of particles in a fluid is given by Jenkins (1973). A short review of these forces is given in the following sections:-

4.8.1.1 Gravitational and Buoyant Forces: Assuming the particle to be denser than the fluid the effective weight of the particle is the vector sum of the gravitational force on the particle and the buoyant force exerted on the particle by the surrounding fluid.

i.e. $$\vec{F}_g = \bar{V}_p(\rho_p - \rho_f)\vec{g}$$

where $\vec{F}_g$ = net gravitational force on the particle

$\bar{V}_p$ = volume of the particle

ρ_p, ρ_f = particle and fluid densities respectively

$\vec{g}$ = gravitational acceleration vector

4.8.1.2 Lifting Forces: These forces act on a particle in a direction perpendicular to the direction of flow. If the particle is located within a velocity gradient and/or subject to rotation, the particle will be subjected to an upward lift due to pressure inequalities between the obvert and invert of the particle.

Cheppil (1961) has determined that for spherical particles, the lift force component is of comparable magnitude to the drag force component only when the particle is in contact with a rigid body. However, if the particle is irregular in shape, the lift forces formed as a result of the "aerofoil effect" may be highly significant, particularly in their effect on flow regime.

Lifting of particles may also occur due to a conversion of some of the horizontal momentum to vertical momentum.

4.8.1.3: Drag Forces: When relative motion occurs between a fluid and a rigid particle, a drag force is exerted on the particle. This force acts in the direction of the fluid motion relative to the particle and is expressed as:-

$$\vec{F}_D = C_D A_p \rho_f \frac{(U_f - U_p)^2}{2}$$

where F_D = the drag force on the particle

C_D = a dimensionless "drag coefficient"

A_p = the cross-sectional area of the particle, projected onto a plane perpendicular to the direction of the velocity of the fluid relative to the particle

$U_f - U_p$ = velocity of the fluid relative to the particle

Although values of the drag coefficient as a function of Reynolds number have been established for steady-state conditions, indications are that these are not necessarily applicable to those situations where the velocity of the fluid relative to the particle is not steady. Jenkins (1973) suggests that the established values of the steady state drag coefficient can be used if the Reynolds number describing the motion of the fluid relative to the particle is less than 0.1, the limit of validity of Stokes Law.

4.8.1.4 Pressure-gradient Forces

In accelerating flow a pressure gradient will, in general, exist in the direction of the acceleration. If the mass of the particle differs from the surrounding fluid the acceleration of the particle will differ from that of the surrounding fluid but it is assumed that the force causing the acceleration will be the same in each case.

Taking into account the mass of an appended volume of fluid the force which will act on a rigid particle within an accelerating fluid due to the pressure gradient within the fluid, may be taken to be:-

$$\vec{F}_p = \bar{V}_p (1 + K) \rho_f \vec{a}_f$$

where K = added mass coefficient

$\vec{a}_f$ = local fluid acceleration

4.8.1.5 The Inertial Reaction of the Particle

A combination of forces as described in Sections 4.8.1.1 to 4.8.1.4 will impart to the particle an acceleration a_p. The resultant inertial force is taken to be

$$\vec{F}_r = m_v \vec{a}_p$$

where m_v is the 'virtual' mass of the particle and is given

$$m_v = \text{mass of particle and appended fluid}$$
$$= \bar{V}_p (\rho_p + K\rho_f)$$

For the particular case of a spherical particle

$$\vec{F}_r = \frac{\pi d^3}{6} (\rho_p + K\rho_f) \vec{a}_p$$

where d = the diameter of the particle

4.8.2 Flow Regime

Wilson (1974) describes the change in flow regime with increasing velocity as follows:-

"At sufficiently low flow rates, the bed remains stationary, with rolling and saltating particles travelling along its top surface. If the flow rate is increased while the input concentration of solids is kept constant, the upper layers of particles are sheared off the top of the bed, increasing the flow area until a new equilibrium condition is attained, with a reduced height of stationary bed. Further increases in flow rate cause progressive reduction in the bed height, but before the deposit is completely eliminated in this fashon there comes a point at which the bed begins to slip at the pipe wall and move en bloc. With additional increase in discharge sliding-bed flow will occur, followed by heterogeneous flow associated with the breakup of the sliding mass."

4.8.2.1 Classification: Newitt et al (1955) have differentiated four flow regimes in the conveyance of solids by a fluid.

(a) Flow with a stationary bed

(b) Flow by saltation or with moving bed

(c) Flow as a heterogeneous suspension (i.e. non-axisymmetric concentration distribution)

(d) Flow as a homogeneous suspension (i.e. a uniform concentration of particles about the pipe axis).

For a pipeline of a given size the flow regime will depend on the relative magnitudes of the flow velocity and the particle settling velocities. The higher the velocity and the smaller the settling velocity the closer the slurry will approach a homogeneous suspension of uniform concentration. A reduction in flow velocity or an increase in sediment size will encourage particles to fall out of suspension to establish one of the flow regimes designated by (a), (b), or (c) above.

The intensity and distribution of energy exchange between the liquid, solid and boundary is dependent on the flow regime. It follows that rates of wear and patterns of wear will be related to the flow regime within the pipe. If the material is conveyed as a fairly homogeneous suspension, the wear will be evenly distributed around the pipe. On the other hand, if the material is conveyed by saltation or as a suspension having a marked concentration gradient, most of the wear will occur on the bottom of the pipe. Where there is a stationary or sliding bed of solids, the bottom of the pipe will be protected from the faster moving particles, although wear rates may be high at points above the bed.

In 1952 Durand and Condolios published the following classification of particles in which each mode of particle transport is associated with a specific range of particle size. The flow regimes given in the classification are those obtained at the lowest velocities consistent with the absence of a bed of solids and relate to material having a specific gravity of 2.65.

1. Particles of a size less than 40 μm: transported as a homogeneous suspension.

2. Particles of a size between 40 μm and 0.15mm: transported as a homogeneous suspension which is maintained by turbulence.

3. Particles of a size between 0.15 and 1.5mm: transported by saltation.

Newitt et al (1955) established relationships defining the transition velocities between the various flow regimes. These relationships are expressed in S.I. units as follows:-

(a) transition from flow as a homogeneous suspension to flow as a heterogeneous suspension.

$$V_1 = 29.6\, D^{1/3}\ w^{1/3}$$

where V_1 = transition velocity - ms^{-1}

D = pipe diameter - m

w = particle fall velocity - ms^{-1}

(b) transition from flow as a heterogeneous suspension to flow by saltation or with moving bed.

$$V_2 = 17w$$

where V_2 = transition velocity - ms^{-1}

w = particle fall velocity - ms^{-1}

(c) transition from flow by saltation to flow with moving bed (commonly known as the Durand equation)

$$V_3 = F_L \ 2gD(s-1)$$

where V_3 = transition velocity - ms^{-1}

F_L = dimensionless ratio which is related to the delivered concentration of solids, and particle diameter, as shown in Figure 40;

D = pipe diameter - m

S = specific gravity of solids

g = gravitational constant (9.8 ms^{-2})

The transitions between the various flow regimes are not marked and the transition velocities given above should be taken only as a guide. The introduction of mixed grain size increases the complexity of defining the flow situation since the settling velocity is affected both by the presence of other solid particles and the additional buoyancy provided by the solid-water mixture. In fact the actual settling velocities may be 2 to 3 times lower in magnitude than determined in the laboratory under conditions of unhindered settling in clear water (Du Plessis and Ansley, (1967), Jenkins (1973)).

4.8.2.2 Pressure Gradient and Flow Regime

Figure 39 shows the type of relationship between the pressure gradient and the mean slurry velocity for different values of solids concentration. The point of minimum head loss represents the lower limit of the heterogeneous flow regime and occurs at a velocity which is usually just slightly less than that found at the limit of solid deposition (Wilson, 1974)). The transition from the heterogeneous to the homogeneous regime is not as well defined although homogeneity is said to occur if a straight line relationship occurs when pressure gradient is plotted against velocity on log-log paper (Thomas, 1975).

4.9 Pipe Corrosion

Corrosion of A-C pipes may occur as a result of the leaching of cement into the transporting fluid or by chemical reaction between the cement and contaminants in the fluid. Camp and Meserve (1973) state that the leaching process itself is too slow to be of significance. Nevertheless it is possible that leaching will increase the porosity of the surface layer such that the resistance of the surface layer to fracturing will be reduced. Chemical attack of the pipe can be severe due to the high porosity of the asbestos-cement composite.

4.10 Pipe Diameter

Bain and Bonnington (1970) state that the frequency of impact between particles and the containing pipe wall can be expected to increase linearly with the mean hydraulic depth of the pipe. Experimental confirmation of this has been obtained by Bergeron (1952), who observed a linear increase of wear rate with pipe diameter.

The explanation for this phenomenon is said to rely on the concept that the larger the pipe diameter, the larger are the associated turbulent eddies which are more capable of supporting large particles than are the smaller eddies (Wilson and Watt, 1974).

4.11 Pipe Alignment

Accelerated wear will occur wherever flow eddies are generated at pipe discontinuities. This will be most evident where mis-alignment of consecutive pipes occurs.

5. Test Rig

The test rig was assembled in the form of a loop and is shown schematically in Figure 1. Recirculation of the slurry was achieved with a 4-3 Warman slurry pump driven by a 20 hp induction motor. Discharge was controlled by varying the speed of the pump using a Dunstan variable speed hydraulic drive, thus eliminating the need for valves in the line. The flow rate was measured using a Fisher Porter electromagnetic flow meter and the slurry concentration was regulated by withdrawing samples from the hopper during testing and measuring the weighted fraction of solids.

6. Experimental Procedure

A number of tests were designed to examine the performance of standard and epoxy lined asbestos-cement pipes over a select range of operating conditions. The significant conditions of each test are as follows:-

Test Series 1: The slurry mixture consisted of 10 mm nom. diameter basalt particles at a concentration of 25% by weight in water. 100 mm dia. A-C and epoxy lined pipes were tested at a flow velocity of 4 m/s.

Test Series 2: Similar conditions as T.S. 1 except particles of 5 mm nom. diameter were used.

Test Series 3: Similar conditions as T.S. 1 except sand particles of 1.6 mm nom. diameter used.

Test Series 4: Similar conditions as T.S. 1 except sand particles of 0.4 mm nom. dia. used.

Test Series 5: The slurry mixture consisted of 5 mm nom. dia. sand at a concentration of 25% by weight in water. 100 and 150 mm dia. A-C pipes were tested at flow velocities of 4 m/s and 2 m/s respectively.

Solids were added during the course of each test to replace fines lost in the overflow. Changes in pipe wall thickness and diameter at the centre and extremities of the test sections were recorded at suitable time intervals.

7. Test Results

Details of test conditions observations and data collected are given in Appendices I, II and III and the associated figures 12 to 38 and photos 1-5. Graphical analyses of these results were undertaken to determine the relationships between the rate of wear and particle size, velocity, locality and alignment. (Figures 2-11).

7.1 Qualitative Description of Wear

Photo 1 shows a typical failure in the upstream end of the asbestos-cement pipe. Photo 2 reveals the extent of the wear on the invert in comparison to that on the obvert for centre sections of pipe. A comparison of the wear in the downstream and upstream ends of the epoxy lined pipe, shown in Photos 3 and 4, reveals a more uniform wear area in the downstream end than in the upstream end. The view into the upstream end of the epoxy pipe shows that the wear along the length of the pipe invert is markedly non-uniform (Photo 5). This form of discontinuous wear pattern which occurs only in the epoxy pipe is disadvantageous. Flow eddies generated in the regions of undulation result in accelerated wear, thus reducing the effectiveness of the protective coating.

7.2 Wear Characteristics as a Function of Particle Size (Figures 2-11)

Four particle sizes ranging from 10mm down to 0.4mm nominal diameter were selected for testing. Details of the size grading of the 10mm material are shown in Figure 2.

Generally rates of wear have been shown to increase logarithmically with increase in particle size. In some instances, particularly in the 5-10mm diameter range, a reduction in rates of wear in the obvert region has been recorded.

The relationships between rate of wear and particle size in the central regions of the A-C and epoxy lined pipes are shown in Figures 3 and 4. Maximum rates of wear occur at positions 1 and 2 for the full range of particle sizes. For particle sizes less than 1 mm dia. a definite wear rate advantage exists in the epoxy lined pipe; however, this advantage diminishes with increasing particle size.

Rates of wear in the joint region of the A-C pipe (Figures 5 and 6) are highly variable. This variability, which increases with increasing particle size, is a result of high turbulence generated at the joint discontinuity. The upstream and downstream zones of wear are similar and lack any definite discriminating characteristics. A comparison of joint wear rates with barrel centre rates (Figure 3) shows that the rate of wear at the joint invert exceeds the wear rate at the invert in the centre of the pipe from 20% for a particle diameter of 0.4mm to 100% for a 10mm diameter particle.

In the epoxy lined pipe the rates of wear upstream from the joint (Figure 7) are up to 15 times higher than corresponding positions in the downstream joint area (Figure 8) and the barrel centre (Figure 4).

Maximum wear rates (regardless of circumferential position and including the highly variable rates in the immediate joint region shown in Figures 10-11) are plotted in Figure 9. It is apparent from this figure that little advantage will be gained by using the epoxy lined pipe with slurry particle diameters greater than 2 mm.

7.3 Wear Characteristics and Pipe Alignment

Vertical displacement of the upstream joint by 0.5cm (see Figures 10 and 11) appears to reduce the rate of wear at the invert in the adjoining downstream joint region, particularly where solids in the 10mm size range are being conveyed.

7.4 Wear Characteristics and Flow Regime

A partial understanding of potential wear may be obtained by evaluating flow regime and particle flux characteristics as described in Test Series 5 and Appendix IV.

In summary -

1. Flow as a homogeneous suspension will distribute particle flux uniformly around the circumference of the pipe, resulting in uniform and reasonably low rates of wear.

2. As particle size increases or velocity decreases flow as heterogeneous suspension will result and particle flux will be greatest at the invert, resulting in maximum wear rates in this area.

3. A further increase in particle size or reduction in average flow velocity to form a saltating/stationary or moving bed regime displaces the area of maximum wear from the invert to the juncture of the invert and obvert hemispheres. Wear rates at the juncture were found to be significantly less than the invert wear rates established by heterogeneous conveyance of the same solid material at a higher average velocity.

8. Conclusions

Figure 9 may be used as a guide to the life of an AC pipe pumping sand slurries.

For the range of tests undertaken, wear was concentrated at the invert of the pipe and pipe life can be significantly increased by rotating the pipe to obtain more uniform wear.

The maximum allowable rate of wear will basically depend on economic considerations outside the scope of this report. Nevertheless it is reasonable to assume that rates of wear (without pipe rotation) resulting in a pipe life of less than 12 months of continuous operation (i.e. 1.5×10^{-5} mm/hr for a 100mm dia. pipe of 13mm wall thickness, and 2.2×10^{-3} mm/hr for a 150 mm dia. pipe of 19 mm wall thickness) will be unacceptable for normal operation.

Based on this assumption reference to Figure 9 reveals that for the transportation of a 25% sand slurry at a flow velocity of 4 m/s the particles should not be larger than 0.1mm in diameter for the 100 mm A-C pipe, and not larger than 0.3mm in diameter for the 100 mm epoxy lined pipe. Increasing the A-C pipe diameter to 150 mm and reducing the average flow velocity (i.e. Q/A) to 2 m/s reduces the maximum wear rate to a level which, according to the 12 month criterion and an arbitrary extrapolation of the data will allow the satisfactory conveyance of sand particles of less than 0.5mm in diameter.

The above size limits may be used as a guide to the viability of conveying as a slurry other minerals of hardness equal to or greater than that of sand. It must be emphasised that for harder or more angular materials the rates of wear may exceed those recorded for sand resulting in size limits less than those quoted.

9. Recommendations for Future Testing

Although a large number of avenues for further study are available, the long periods of testing involved make it desirable to limit current objectives. The most productive areas for future investigations of A-C pipe utility are considered to be:-

(i) the determination of rates of wear and size relationships associated with granulated materials of soft and intermediate hardness (e.g. coal, limestone, fly ash, bauxite);

(ii) further investigation of the relationships between flow velocity and rates of wear for a range of solid hardnesses;

(iii) the testing of various mixtures of coarse and fine particles to determine whether lower and more uniform wear rates can be achieved by a more uniform distribution of coarse particles.

The observation of flow regime using glass pipe sections and glass joints would be an essential part of the above studies.

10. References

1. Bain, A.G. and Bonnington, S.T., The Hydraulic Transport of Solids by Pipeline, Pergamon Press, 1970.

2. Barker, M.L. and Truscott, G.F., The Development and Operation of a Test Facility for Pipeline Abrasive Wear Measurement, Hydrotransport 3 (1974).

3. Bergeron, P., Consideration of the Factors Influencing Wear due to Hydraulic Transport of Solid Materials, Proc. 2nd Conf. Hyd. Transport and Separation of Solid Materials, 1952.

4. Bitter, J.G.A., A Study of Erosion Phenomena, Part 1 (pp 5-21) and Part 2 (pp 169-190) Wear, 6 (1963).

5. Camp, T.R. and Meserve, R.L. Water and its Impurities, Reinhold Publishing Corp. 1973, pp. 214-223.

6. Cheppil, W.S., The Use of Spheres to Measure Lift and Drag on Wind - eroded Soil Grains, Soil Science Soc. of America, Proc. v.25, 1961.

7. Cornet, R., Wear in Dredges, The Dock and Harbour Authority, May, 1975.

8. Du Plessis and Ansley, Settling Parameter in Solids Pipelining, Journal Pipeline Div., Proc. A.S.C.E. July, 1967.

9. Durand, R. and Condolios, E., The Hydraulic Transportation of Coal and other Materials in Pipes, Proc. Colloq. on Hydraulic Transportation, National Coal Board, London (1952).

10. Jenkins, B.S. Studies of the Flow of a Fluid with Density Differences caused by Turbidity, Water Research Laboratory, Report No. 133, August, 1973.

11. Mih, W.C., Chen, C.K. and Orsborn, J.F., Bibliography of Solid-Liquid Transport in Pipelines, College of Engineering, Washington State University, 1971.

12. Newitt et al., Hydraulic Conveying of Solids in Horizontal Pipes, Trans. Inst. Chem.Eng. Vol. 33, 1955.

13. Scarlett, B. and Grimley, A., Particle Velocity and Concentration Profiles during Hydraulic Transport in a Circular Pipe, Hydrotransport 3 (1974).

14. Thomas, A.D., Scale-up Methods for Pipeline Transport of Slurries. Accepted for Publication by the Int. Journal of Mineral Processing, 1975-76.

15. Truscott, G.F., A Literature Survey on Abrasive Wear in Hydraulic Machinery, Wear, 20 (1972).

16. Wilson, K.C., Co-ordinates for the Limit of Deposition in Pipeline Flow, Hydrotransport 3 (1974).

17. Wilson, K.C. and Watt, W.E., Influence of Particle Diameter on the Turbulent Support of Solids in Pipeline Flow, Hydrotransport 3, (1974).

Rates of Wear Details

I.1 Test Series 1. (Figures 12-14)

Test conditions were as follows:-

Particle size:	10mm (3/8") nom. dia. basalt
Solids concentration	25% by weight
Flow velocity:	Approx. 4 m/s (12-14 ft/s)
Pipe diameter (I.D.):	100mm (4")
Wall thickness	13mm (0.5")
Type of pipe:	A-C and epoxy lined (Class 'D')

Thirteen pipes were placed in line in the test loop. Six of the pipes were epoxy lined and seven were standard A-C pipes. Several of the pipes were displaced vertically by 0.5 cm so that the effect of misalignment in the joint region could be assessed.

Failure in the pipe network occurred after 17 hours pumping. Observations and measurements were made and it was found that:-

1. Maximum wear occurred at the invert of the pipe.

2. The superior wear characteristics of the epoxy pipe as indicated by the rates of wear in the barrel of the pipe (Figure 12) are not maintained in the joint region. A comparison of Figures 13 and 14 shows that in terms of rates of wear at the invert in the joint region the epoxy lined pipe is only marginally better than the standard A-C pipe.

3. In the joint region rates of wear were considerably lower in the obvert hemisphere. In the case of the A-C pipe the downstream obvert wear rates were relatively higher than corresponding upstream values.

4. Where a pipe was located downstream of a bend, wear tended to be intensified as a result of turbulence induced by the bend.

5. Vertical displacement of the upstream joint appeared to reduce the rate of wear at the invert significantly (Figure 10).

6. The reliability of test results should be taken into account when drawing conclusions. Figures 10 and 11 indicate that for identical testing conditions variations in wear rate may be 50% or more of the mean value (also confirmed in Figure 19).

I. 2 Test Series 2 (Figures 15-18)

Test conditions were as follows:-

Particle size:	5mm (3/16") nom. dia. basalt
Solids concentration:	25% by weight
Flow velocity:	Approx. 4 m/s (12-14 fps)
Pipe diameter (I.D.):	100 mm (4")
Wall thickness:	13mm (0.5")
Type of pipe:	A-C and epoxy lined (Class 'D')

The pipe layout was the same as for Test Series 1. Comprehensive pipe wear measurements were taken after 26 and 80 hours of slurry transport.

Figure 15 shows the mean absolute wear and range of wear for the two pipe types. The rates of wear as a function of circumferential position are shown in Figures 16-18.

In general the pattern of wear was similar to that observed in Test Series 1. The rates of wear were somewhat lower with the finer material. This was particularly so for the standard A-C pipe where the rate of wear was almost half the value of Test Series 1.

Vertical displacement of the upstream joint did not appear to reduce rates at the invert of the joint region to the same extent as was observed with the larger particle size (compare Figures 10 and 11).

I. 3 Test Series 3 (Figures 19-22)

Test conditions were as follows:-

Particle Size:	1.6mm (1/16") nom. dia. sand
Solids concentration:	25% by weight
Flow Velocity:	Approx. 4 m/s (12-14 fps)
Pipe diameter (I.D.):	100 mm (4")
Wall thickness:	13 mm (0.5")
Type of pipe:	A-C and epoxy lined (Class 'D').

The test layout was modified so that slurry was transported through three A-C and three epoxy lined pipes, the alignment being as straight as possible. Measurements of the rate of change of the pipe wall thickness and diameter in the joint and central regions were taken on the central pipe in each triad.

After 183 hours of testing, failure of the A-C pipe occurred (Test 3a, Figure 19). Replacement with a new A-C pipe allowed the extension of testing on the epoxy lined pipe to 390 hours (Figure 20) and the opportunity to assess the variability of the results by comparative testing of the A-C pipe (Test 3b, Figure 19).

I.3.1 Rates of Wear in the Pipe Barrel

Wear rates at the mid point of the A-C and epoxy pipes were measured at regular intervals. Different rates of wear were found at each of three points, the greatest rate occurring at the invert of each pipe (Figures 19 and 20). The rate of wear at the invert of the asbestos-cement pipe was more than twice the rate at the invert of the epoxy lined pipe. All rates were constant over the 183 hours of pumping except the rate at the epoxy invert which, due to a breach of the lining increased sharply after 120 hours of pumping.

The comparison of corresponding A-C tests (3a and 3b) reveals some scatter in the results. The magnitude of this scatter is significant and could interfere with the establishment of some of the more subtle trends between pipe wear and associated parameters.

The extension of the epoxy pipe data from 180 to 390 hours of testing (Figure 20) reveals a continuation of the erosion of the lining around the circumference with the breach in the lining at position 2 occurring at 240 hours.

I.3.2 Rates of Wear at the Pipe Joints

Wear measurements for the A-C pipe are expressed as a function of circumferential position in Figure 21. Maximum wear rates in the 183 and 204 hour tests are of the same order of magnitude. However, wear rates at individual points, particularly on the obvert are variable.

Figure 22 shows rates of wear in the vicinity of the joints of the epoxy pipe. Wear tends to be greatest on the invert immediately downstream of the joint. Substantially less wear is evident at a distance of 30 cms than in the immediate area of the joint, where the rates are comparable to those found in the A-C pipe.

I.4 Test Series 4 (Figures 23-25)

Test conditions were as follows:-

Particle Size:	0.4mm (1/64") nom. dia. sand
Solids concentration:	25% by weight
Flow velocity:	Approx. 4 m/s (12-14) fps)
Pipe diameter (I.D.):	100 mm (4")

Wall thickness	13mm (0.5")
Type of pipe:	A-C and epoxy lined (Class 'D')

I.4.1 Rates of Wear in the Pipe Barrel

Wear rates for the 0.40mm particle size were found to be considerably less than those observed with larger sized materials. Referring to Figure 23 the invert wear rate for the A-C pipe is at least half the corresponding rate of wear with the 1.6mm particle size (Figure 19). Rates of wear for the epoxy lined pipe, shown on the same figure, are from five to ten times less than corresponding A-C values. No measurable difference between the epoxy invert and horizontal wear rates was detected.

I.4.2 Rate of Wear at the Pipe Joints

Figure 24 shows the rate of wear in the A-C pipe as a function of circumferential position. The wear rate pattern is typical except for the "immediately" downstream location where an exceptionally high rate of wear was recorded at the 4 o'clock position (E).

The epoxy lined pipe was found to reduce the rates of wear substantially. Rates of wear in the immediate joint area are shown to vary in an oscillatory fashion around the circumference of the pipe, possibly as a result of unintentional misalignment (Figure 25).

I.5 Test Series 5 (Figures 26-28)

The data collected in Test Series 1 to 4 were sufficient to establish the effect of particle size on wear. Flow velocity was considered to be the next most important parameter worthy of investigation. Rather than reduce the flow through the pipe system a 150mm dia. A-C pipe was inserted in the position formerly occupied by the 100mm epoxy lined pipe.

Test conditions were as follows:-

Particle size	5 mm (3/16") nom. dia. sand
Solids concentration:	25% by weight
Flow velocity:	Approx. 4 m/s in the 100 mm A-C line
	Approx. 2 m/s in the 150mm A-C line
Pipe diameters:	100mm (4") and 150mm (6")
Wall thickness:	13 mm (0.5") and 19 mm (0.75")
Type of pipe:	A-C (Class 'D')

Measurements were taken as in previous tests. Failure of the 100 mm pipe occurred within 60 hours of start-up. Replacement of this pipe allowed the testing of the 150mm line to be extended to 160 hours.

I.5.1 Rates of Wear in the Pipe Barrel

Figure 26 shows that a reduction in flow velocity from 4 m/s to 2 m/s, attained by enlargement of the pipe diameter from 100mm to 150mm, reduces the wear at the invert dramatically. However, wear at the horizontal location (Position 3) is increased substantially.

I.5.2 Rates of Wear at the Pipe Joints

Figure 27 shows that the rates of wear in the 100mm pipe increase in the usual manner from low values at the obvert to high values at the invert.

For the 150mm pipe the rates of wear in the joint area are shown in Figure 28. Maximum values are lower than observed in the 100mm pipe and occur in the horizontal locations B, C, D and E rather than the invert. Reference to Appendix IV and Figure 41 shows that the flow regime is now one of particle saltation along a stationary bed. Although the average or calculated flow velocity is 2 m/s the velocity above the bed will be significantly higher than this value.

Appendix II

Wall Thickness and Diameter Profiles

II.1 Wall Thickness Profiles (Figures 29-32)

Figures 29 and 30 show the longitudinal variation in wall thickness of two 100mm dia. A-C pipes after failure. The pipe used to convey the coarser material (5mm dia. sand) has irregular invert thickness profiles similar to those created by the finer material (1.6mm dia. sand). It is interesting to note that slightly more obvert wear has occurred with the finer material, reflecting the trend towards homogeneity as particle size is reduced.

The wall thickness profile for the 150mm dia. A-C pipe (Figure 31) shows the severe erosion at the point of separation of the obvert and invert hemispheres.

A comparison of Figures 30 and 32 indicate that the epoxy lining offers effective protection against severe wear. However it is apparent that when the epoxy lining is breached (in this case at the invert point D) the rate of wear at this point is increased to the normal A-C level producing a gouging effect.

II.2 Internal Diameter Profiles (Figures 33-36)

The rates of change of internal diameter in the 100mm A-C pipe approach uniformity with decreasing particle size (compare Figures 33 and 34).

Reducing the flow velocity to where a protective moving bed was formed resulted in an expanding horizontal diameter (corresponding with the maximum rates of wear) in the 150mm A-C pipe (Figure 35).

The diameter of the 100mm epoxy lined pipe used to carry 1.6mm dia. solids at 4 m/s velocity expanded for the most part along the vertical axis although immediately downstream from the joint excessive wear had expanded the diameter in all directions (Figure 36).

Appendix III

Particle Attrition

The degree of particle size reduction that occurs during testing is shown in Figures 37 and 38. Attrition of the 1.6mm particles is slow and thus unlikely to affect wear rates significantly. On the other hand, attrition of the 5mm particles occurs rapidly, with the mean diameter being reduced from 5 mm to 3mm after 16 hours pumping.

Addition of make-up material to counteract solid losses through the overflow was a frequent requirement which tended to restore the particle size distribution. However attrition is so severe for 5mm particles (and presumably particle sizes larger than this) that size degradation needs to be considered in the overall evaluation of the test results (see Figure 41).

Appendix IV

Theorized Wear Profiles

An understanding of the wear profile or pattern of wear expected during slurry transportation may be obtained by evaluating flow regime and particle flux characteristics.

Experimental determination of the relationships between pressure gradient and flow velocity for a number of particle concentrations (shown in general form by Figure 39) is one method for flow regime assessment (see Section 4.8.2.2).

The divisions between flow regime for both the 100mm diameter and 150mm diameter pipe may also be determined according to the established relationships of Newitt et al (1955) and are shown by Figure 41.

By transferring velocity and known size grading characteristics of each test (Figure 2) the following conclusions are reached.

1. A homogeneous flow regime will occur with the 0.4mm diameter particles flowing at 4 m/s through the 100mm pipe (Test Series 4).

2. Predominantly heterogeneous flow regimes will occur with the 1.6mm and 5mm diameter particles flowing at 4 m/s through the 100 mm pipe (Test Series 2, 3, 5).

3. A mixture of heterogeneous and saltating flow will occur with the 10mm particles flowing at 4 m/s through the 100mm pipe (Test Series 1).

4. Saltating flow with a stationary bed will occur with the 5mm diameter particles flowing at an average velocity of 2 m/s through the 150mm pipe (Test Series 5).

The hypothetical particle concentration and velocity profiles, shown in Figure 42 were deduced from general hydrodynamic principals, and represent the three main types of flow regime. The particle flux profiles are the product of velocity and concentration profiles. It is proposed that rates of wear in the pipe will be related to a plot of this type. Since previous investigators have indicated that wear is more likely to be logarithmically related to associated parameters than linearly related it seems reasonable to suggest that the relationship wear $\propto$ (concentration)^n (velocity)^m may provide the basis for future wear analyse The concentration profile will be dependent on a number of factors, the most significant being the size range and specific gravity of the solid material.

For the purpose of illustration values of $n = 0.8$ and $m = 2.5$ have been selected. The theorized wear profiles shown in Figure 42 predict (a) an even wear rate around the pipe circumference for homogeneous suspension; (b) wear rates increasing to a maximum a short distance above the invert for heterogeneous suspension and (c) no wear at the invert but a maximum at the juncture of the invert and obvert hemispheres for saltating/stationary bed flow. It should be noted that the magnitude of the wear rates associated with each profile will depend on the gamut of factors outlined in Section 4.

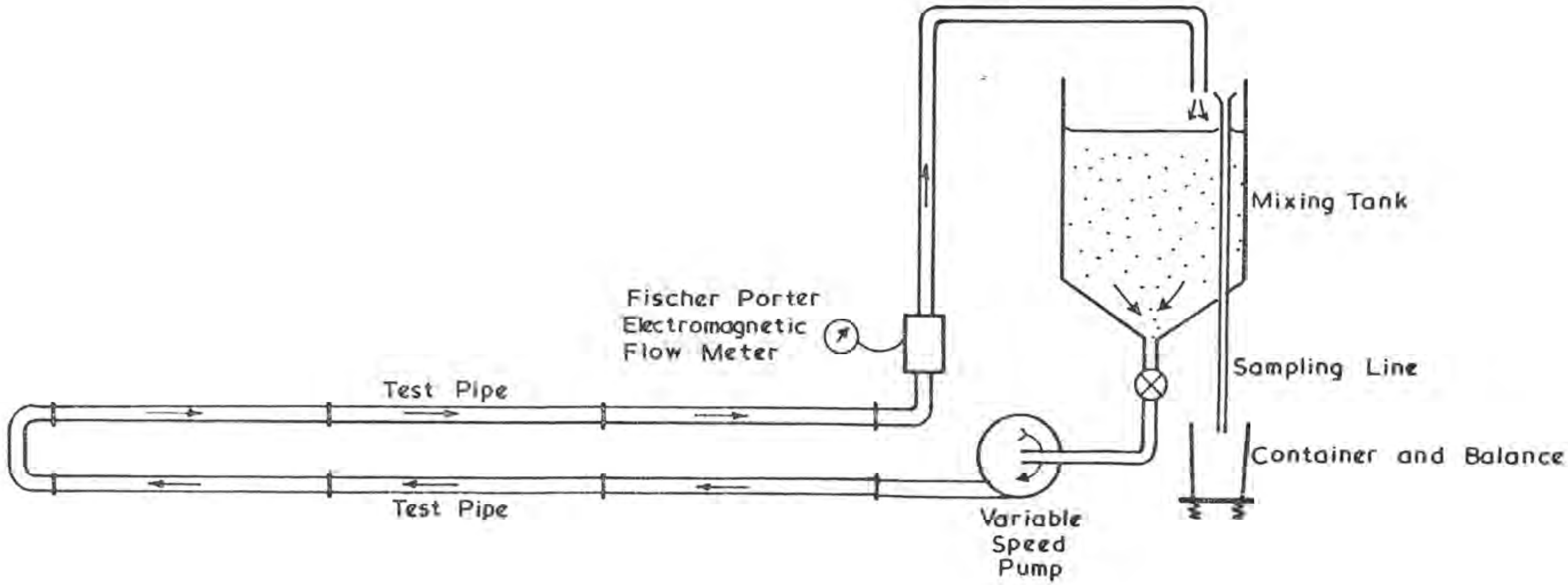
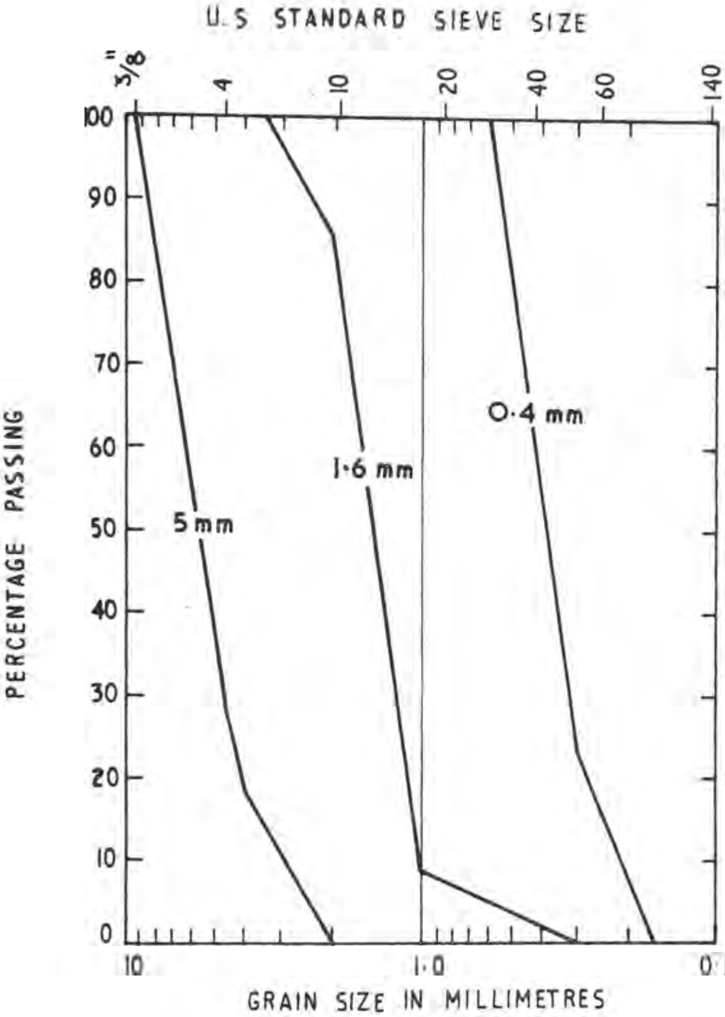


FIGURE 1 : SCHEMATIC ARRANGEMENT OF SLURRY TEST RIG



Gravel	Sand		
fine	coarse	medium	fine

FIGURE 2 : SIZE GRADINGS

BASIC WEAR CHARACTERISTICS

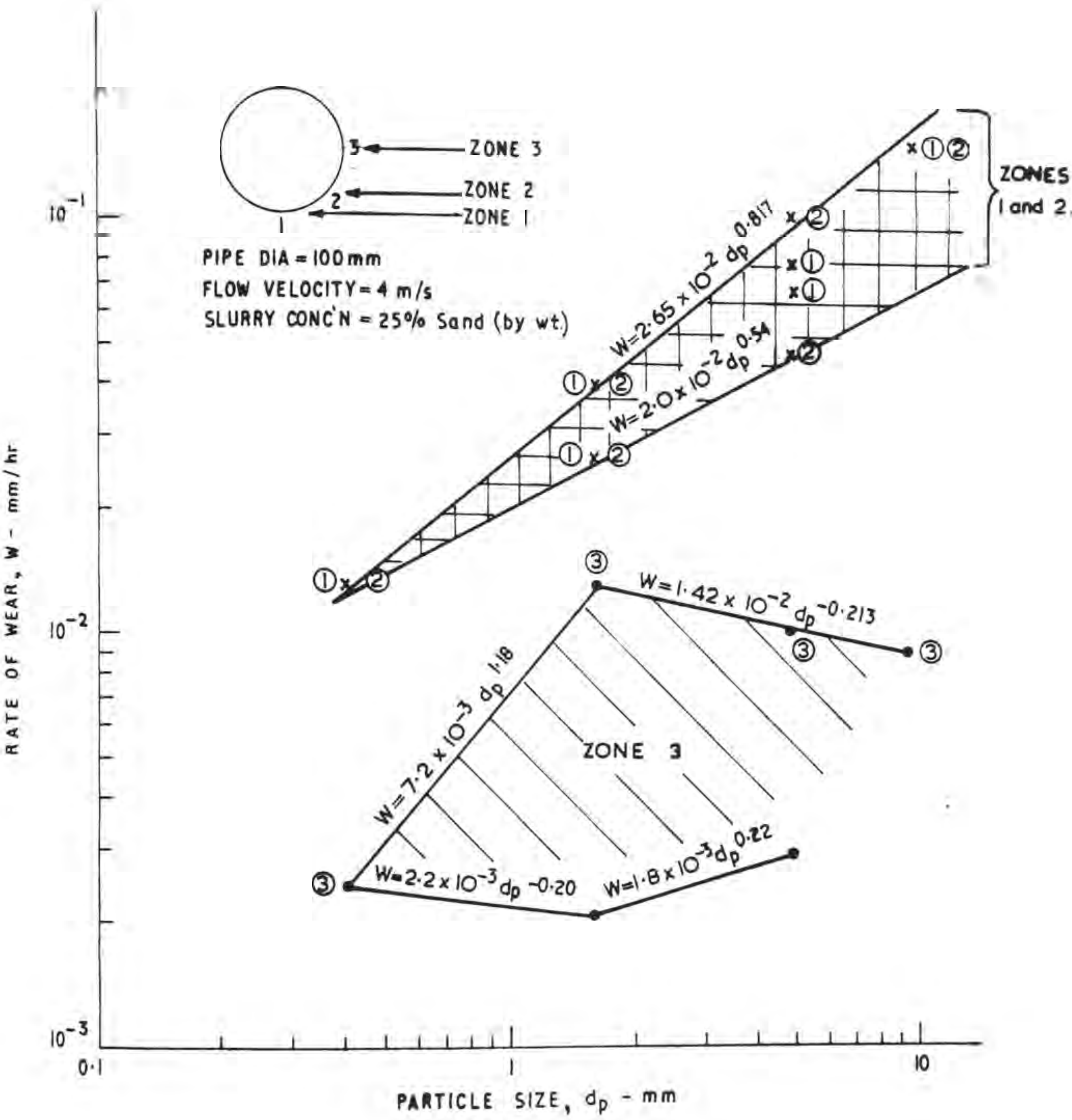


FIGURE 3: RATE OF WEAR IN THE CENTRE OF THE A-C PIPE BARREL AS A FUNCTION OF PARTICLE SIZE.

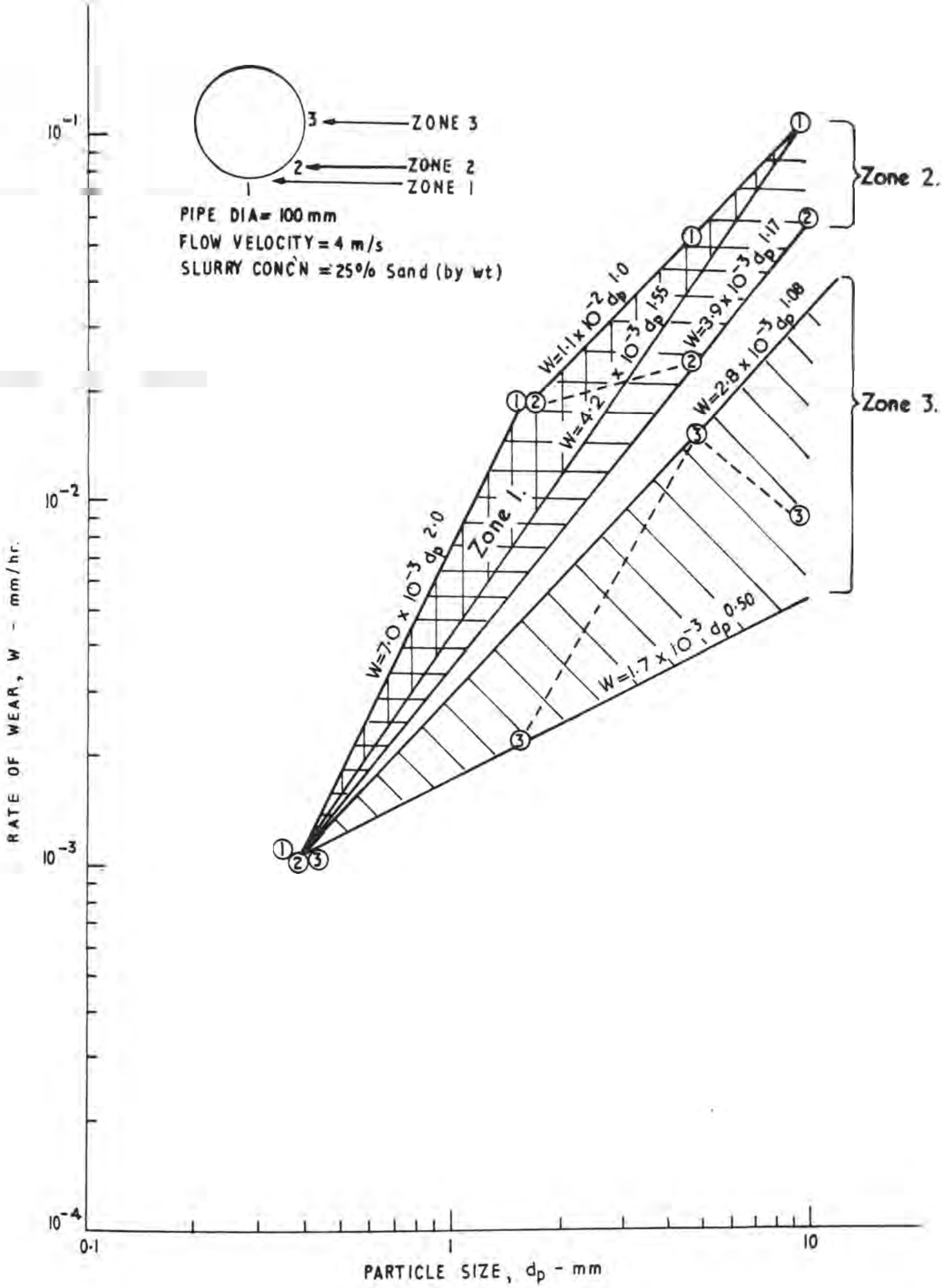


FIGURE 4 : RATE OF WEAR IN THE CENTRE OF THE EPOXY PIPE BARREL AS A FUNCTION OF PARTICLE SIZE.

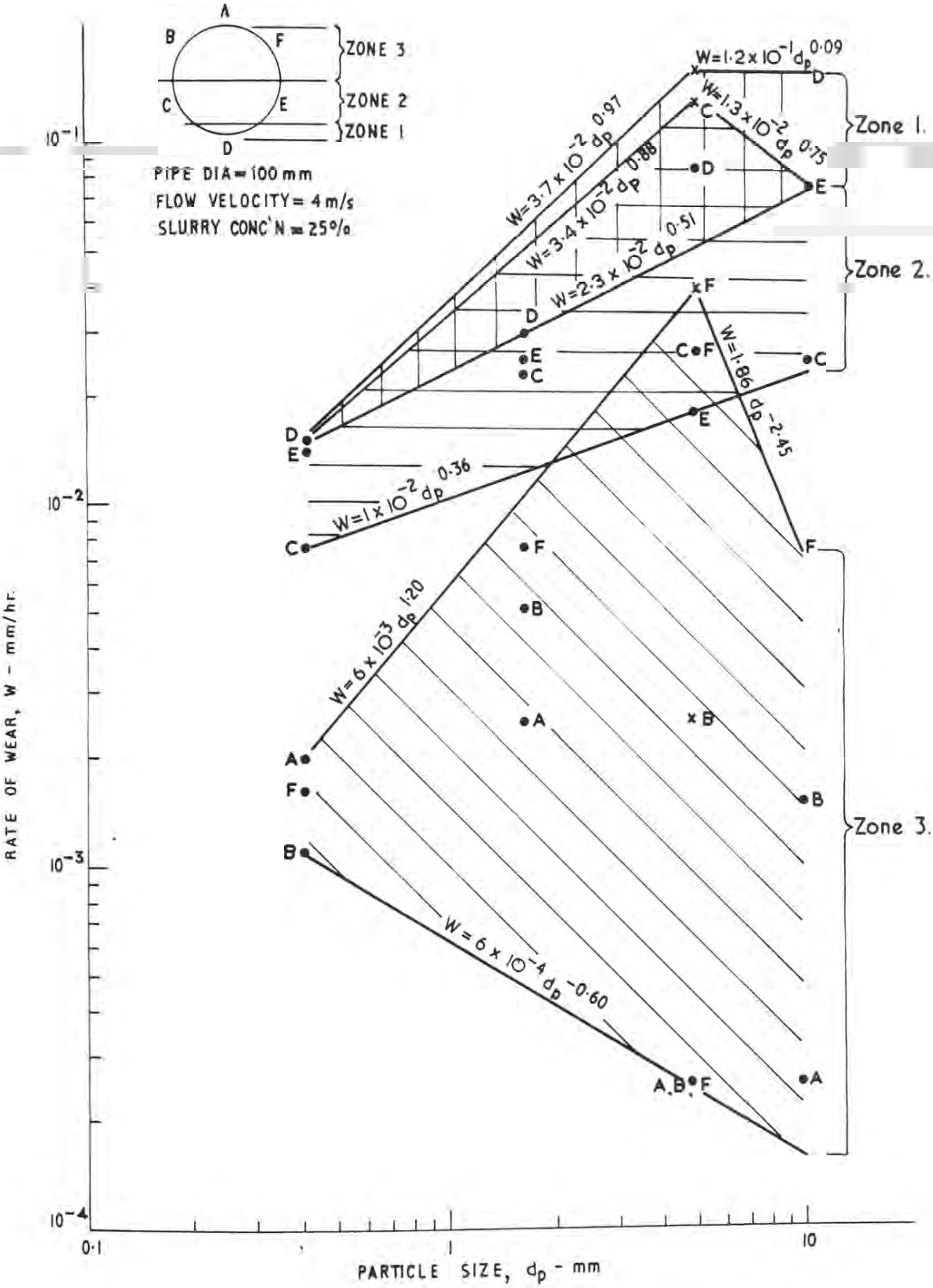


FIGURE 5 : A-C PIPE - RATE OF WEAR 30cms UPSTREAM FROM THE JOINT AS A FUNCTION OF PARTICLE SIZE.

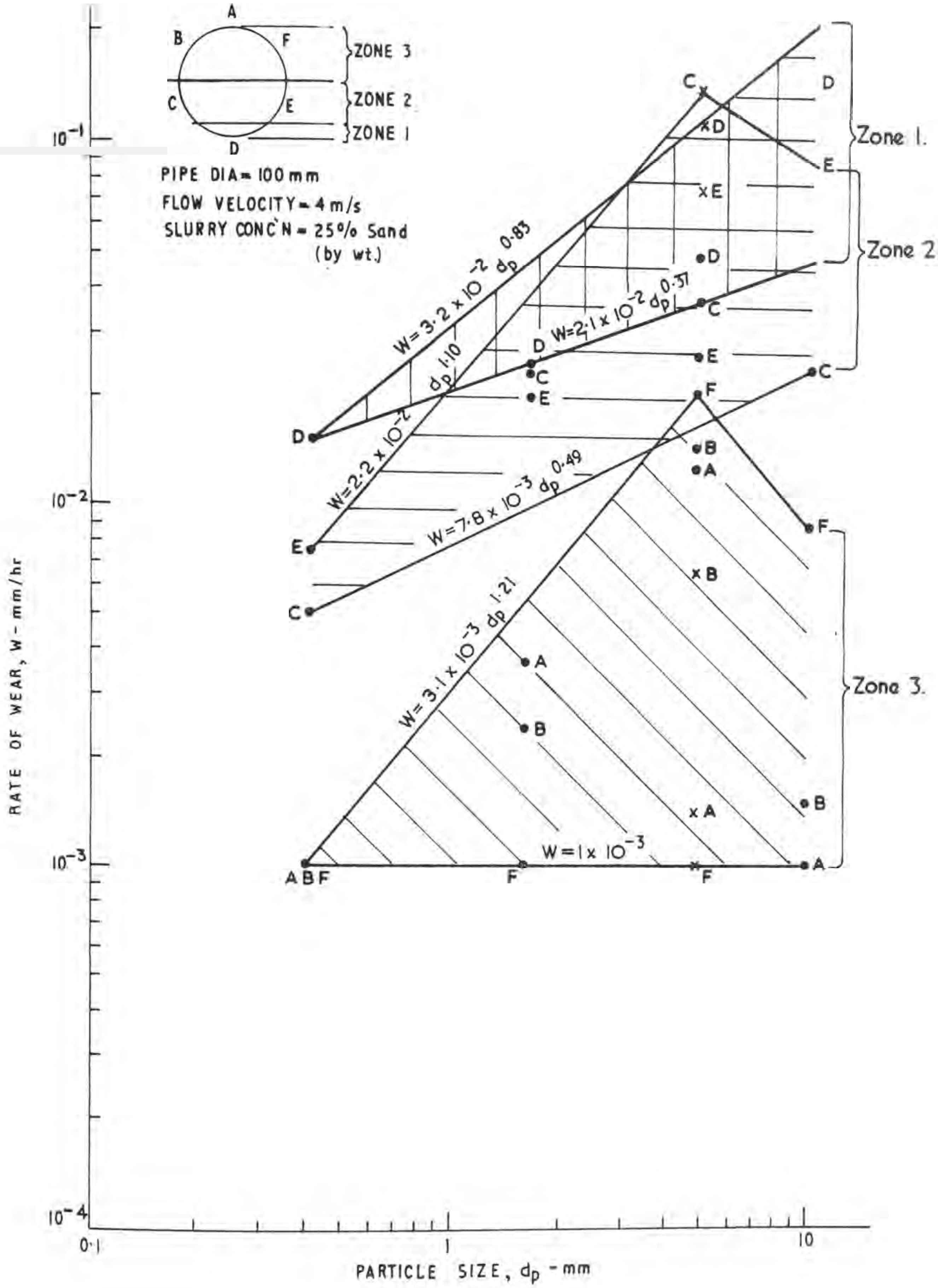


FIGURE 6 : A-C PIPE - RATE OF WEAR 30cms DOWNSTREAM FROM THE JOINT AS A FUNCTION OF PARTICLE SIZE.

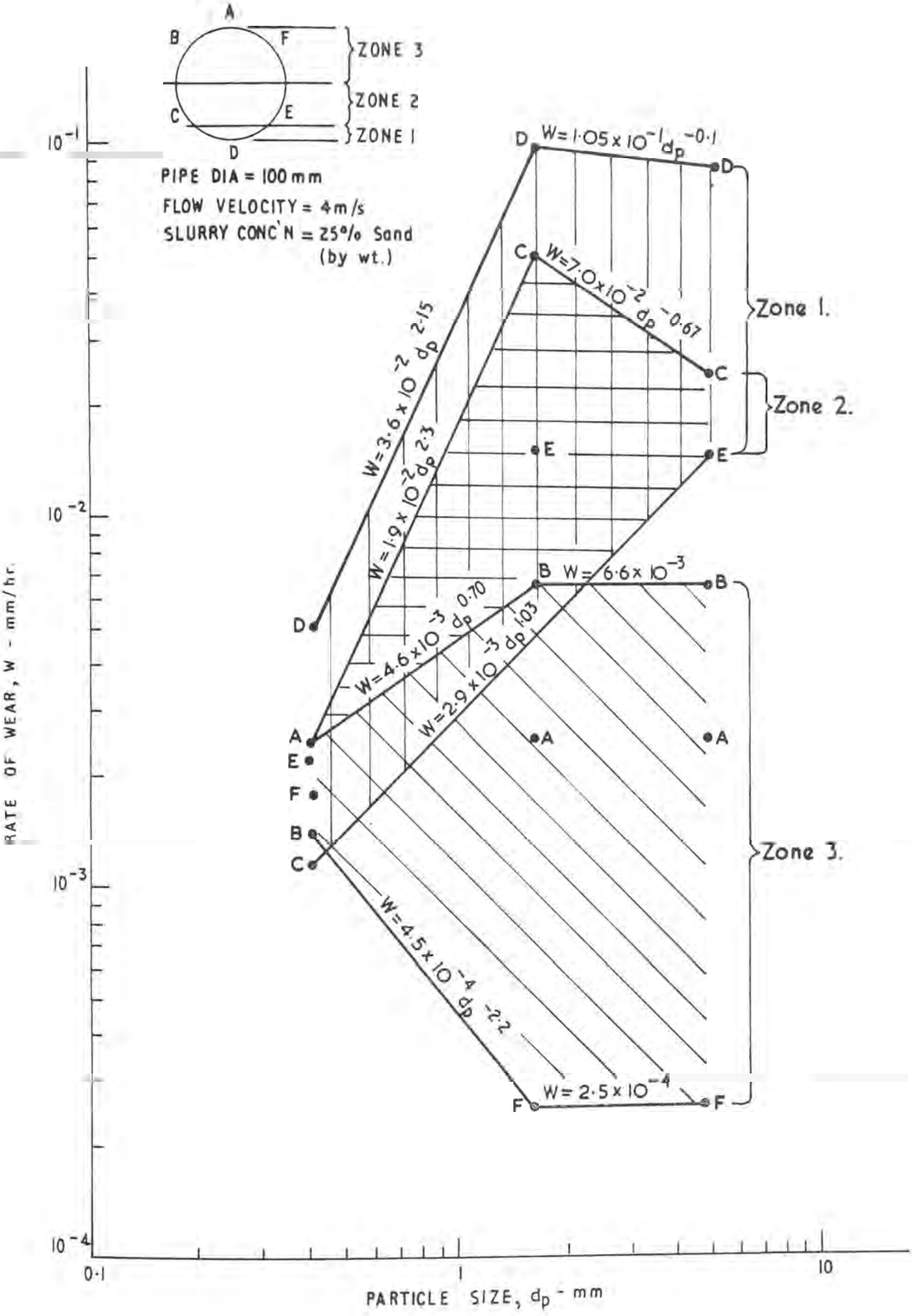


FIGURE 7: EPOXY PIPE - RATE OF WEAR 30cms UPSTREAM FROM THE JOINT AS A FUNCTION OF PARTICLE SIZE.

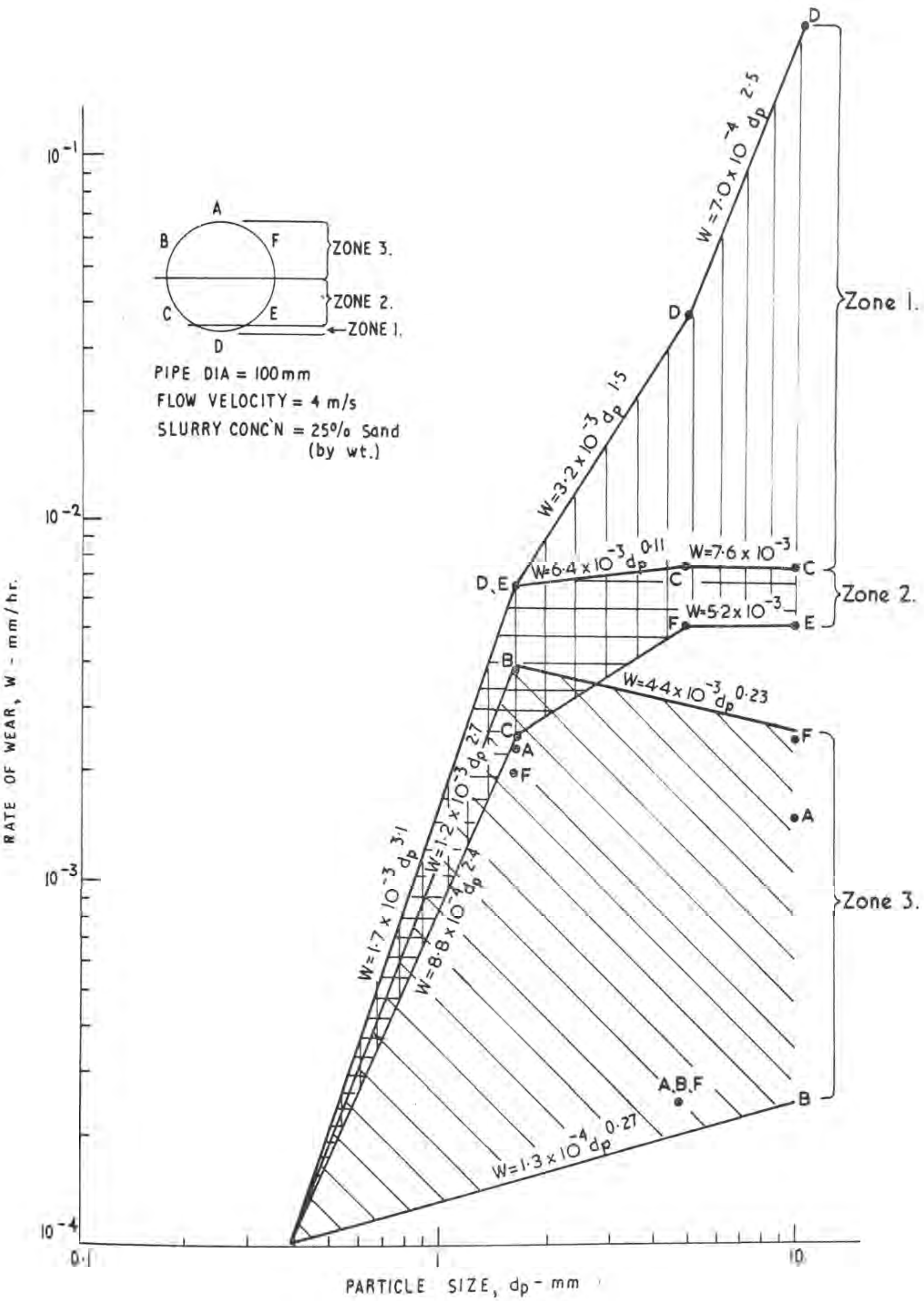


FIGURE 8: EPOXY PIPE - RATE OF WEAR 30cms DOWNSTREAM FROM THE JOINT AS A FUNCTION OF PARTICLE SIZE.

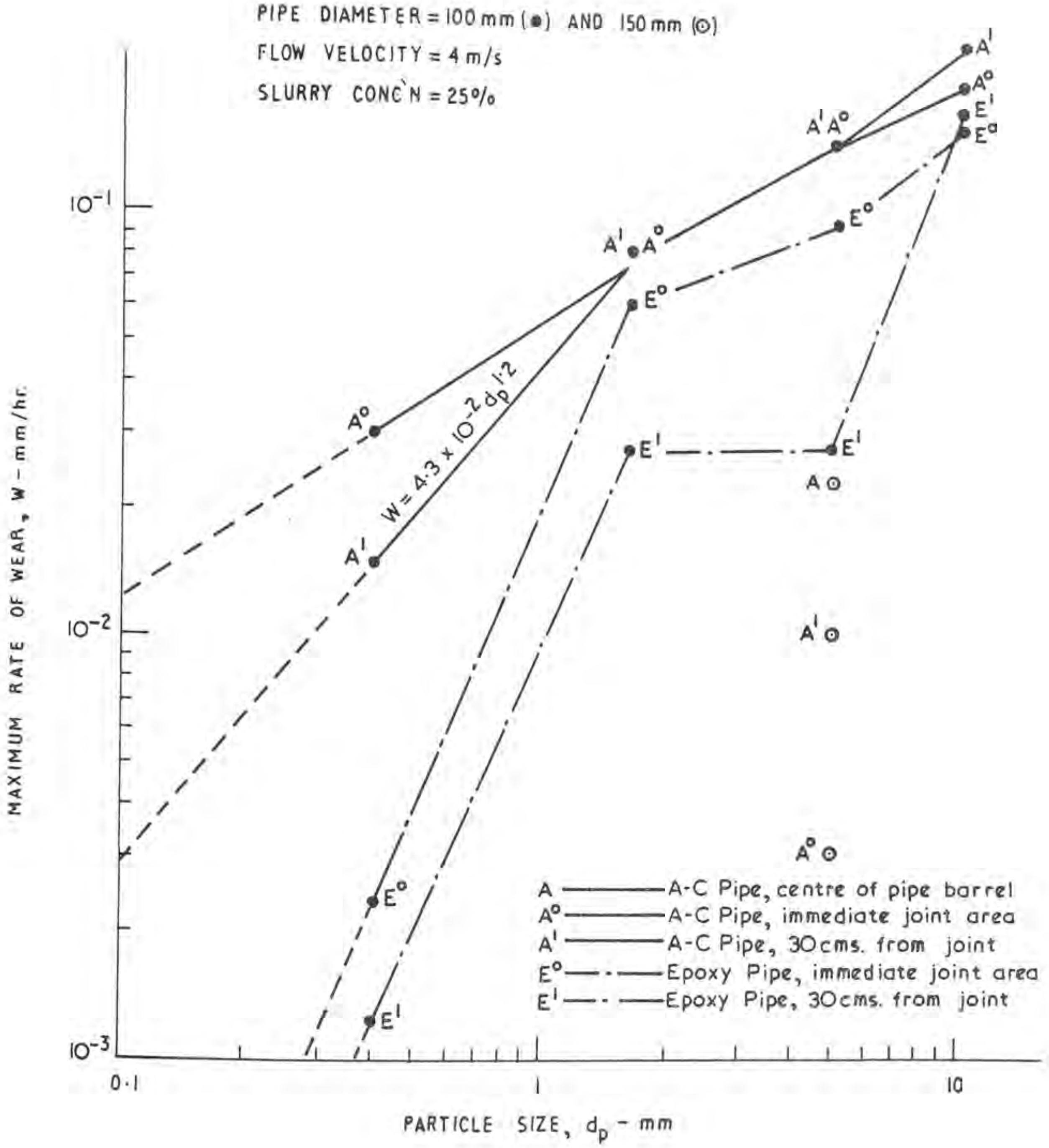


FIGURE 9: MAXIMUM WEAR RATE IN THE JOINT AREA AS A FUNCTION OF PARTICLE SIZE.

SUPPLEMENTARY DATA

(Details in Appendices I to IV)

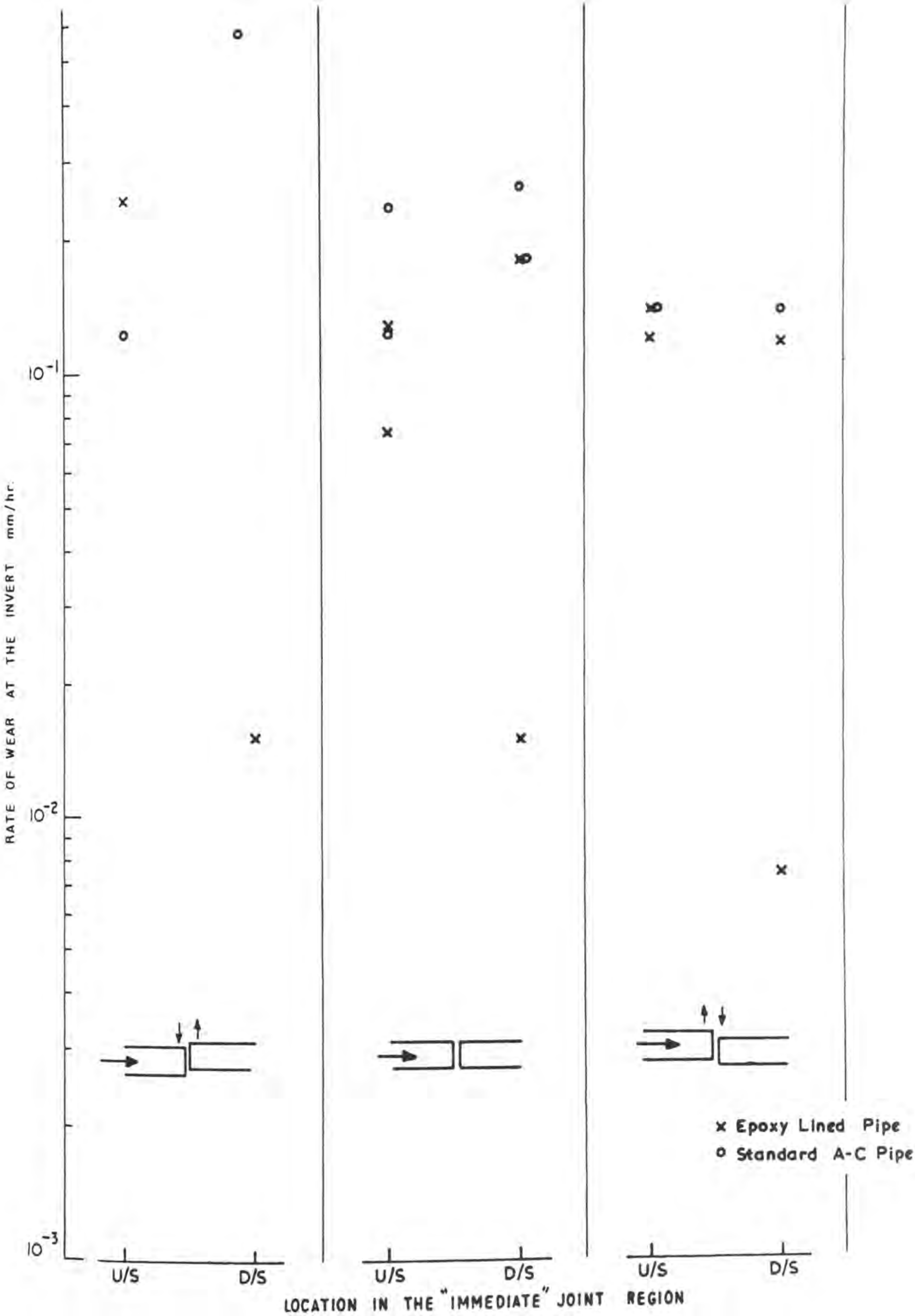


FIGURE 10: RATES OF WEAR AT THE INVERT FOR DIFFERENT JOINT ALIGNMENTS (10 mm. dia. Solids)
TEST SERIES 1.

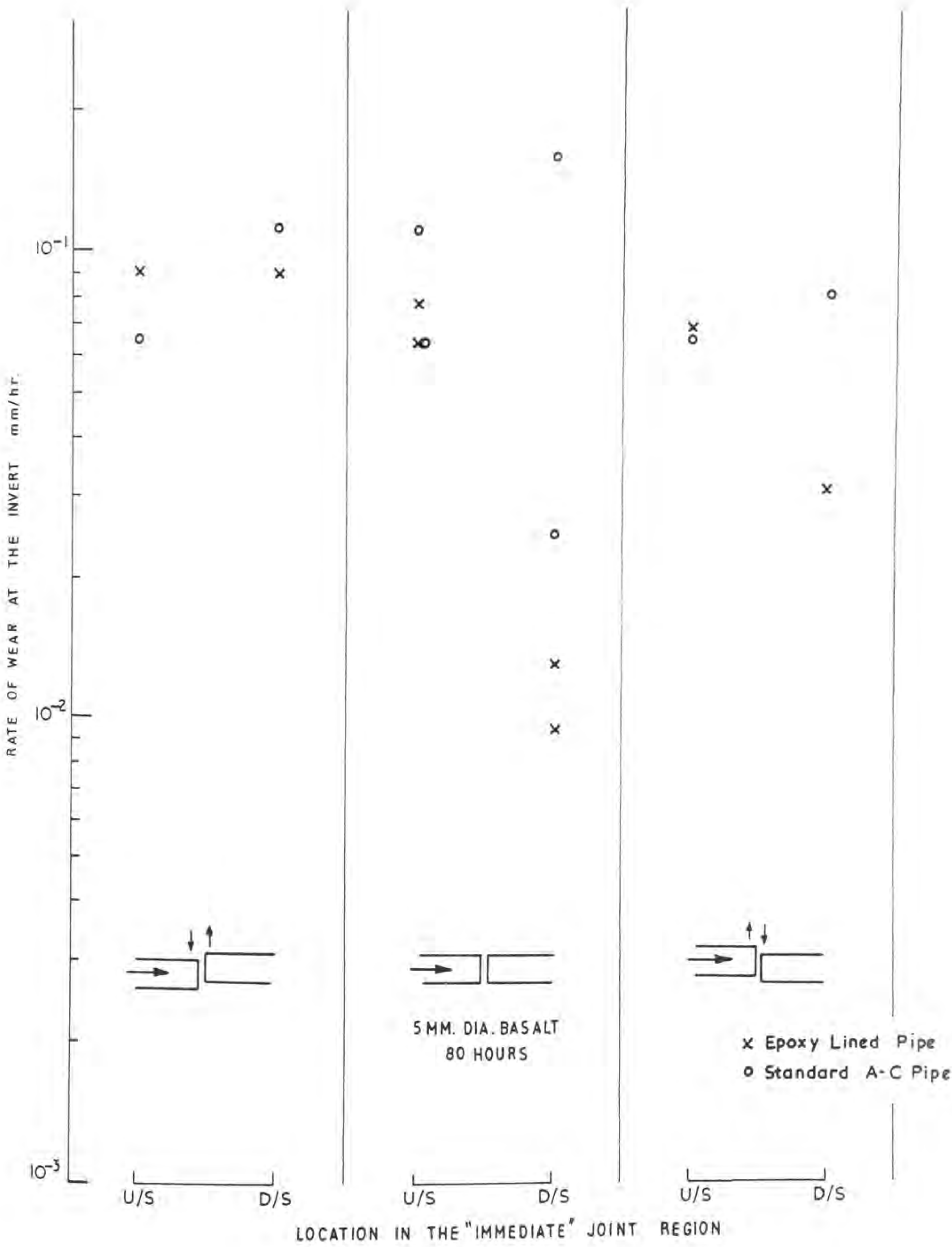
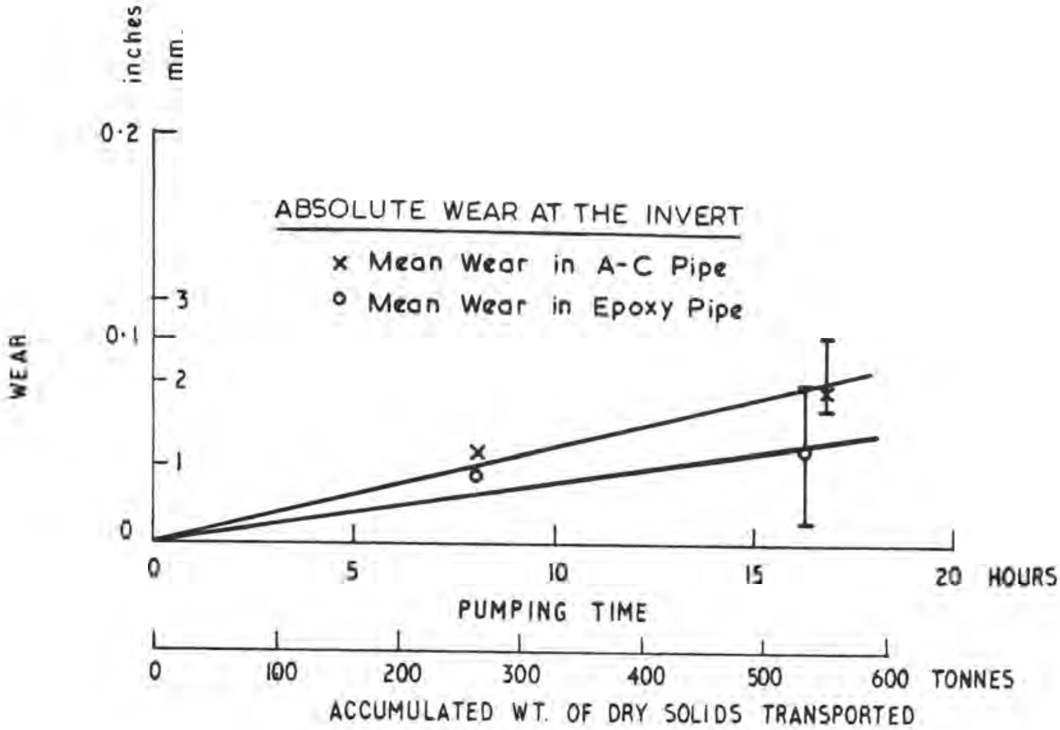


FIGURE 11 : RATES OF WEAR AT THE INVERT FOR DIFFERENT JOINT ALIGNMENTS (5 mm dia. Solids)

TEST SERIES 2.



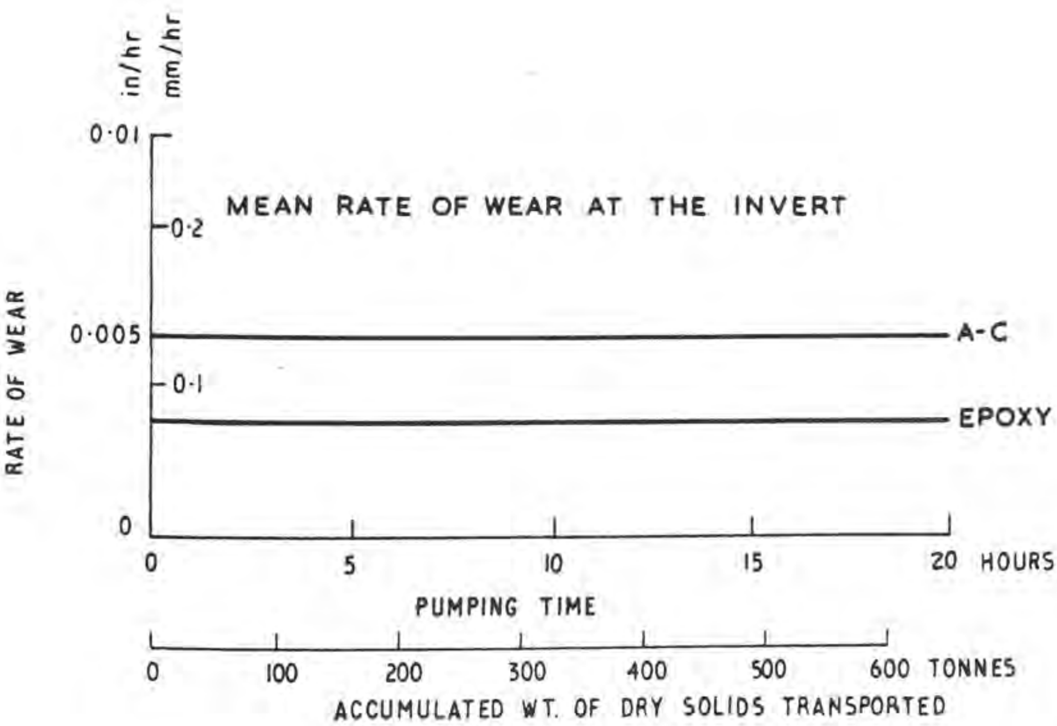


FIGURE 12: ABSOLUTE WEAR AND RATE OF WEAR IN A-C AND EPOXY-LINED PIPE (10 mm (3/8") dia Solids)

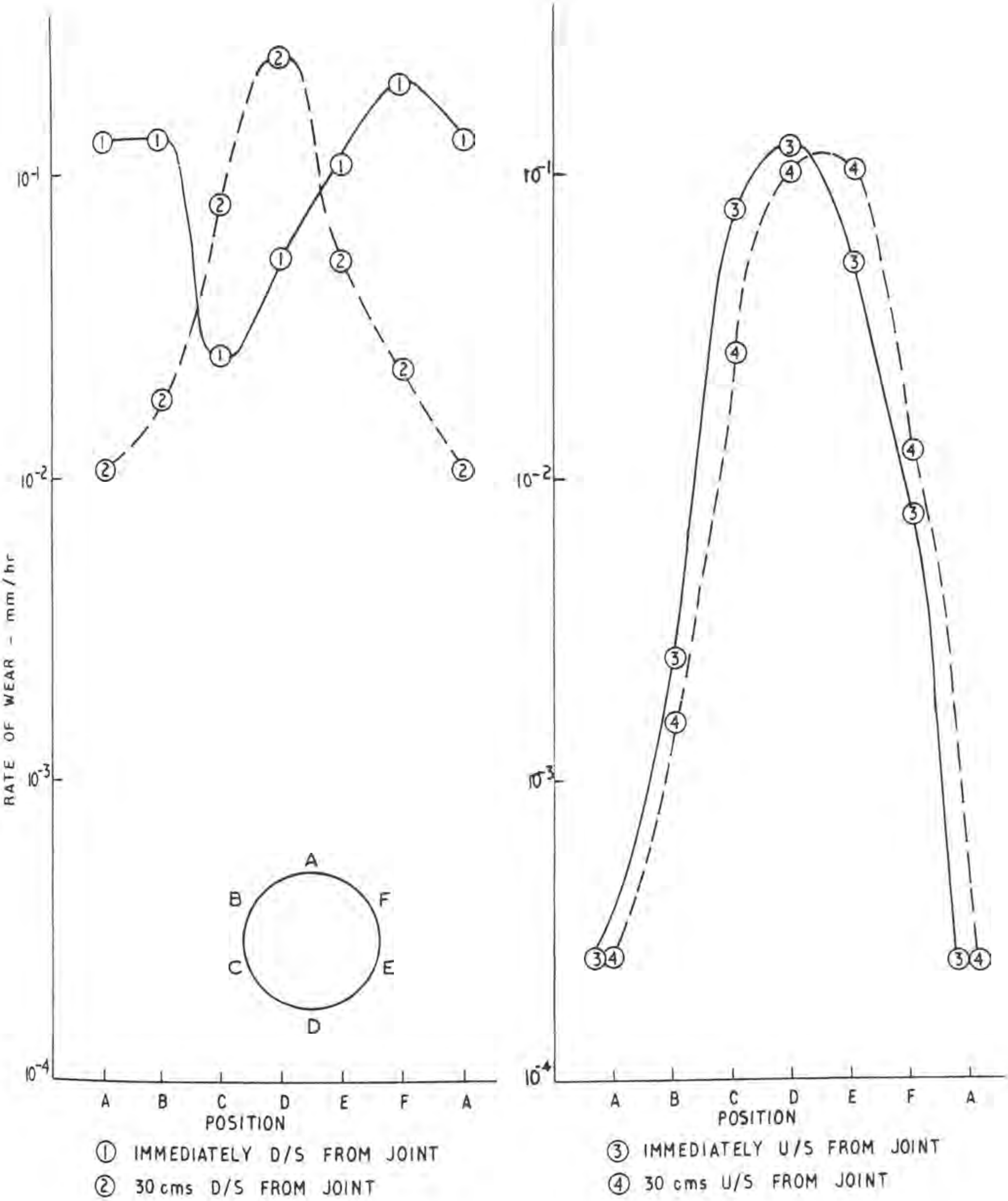


FIGURE 13 : A - C PIPE

RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT (10 mm. dia. Solids)

TEST SERIES 1

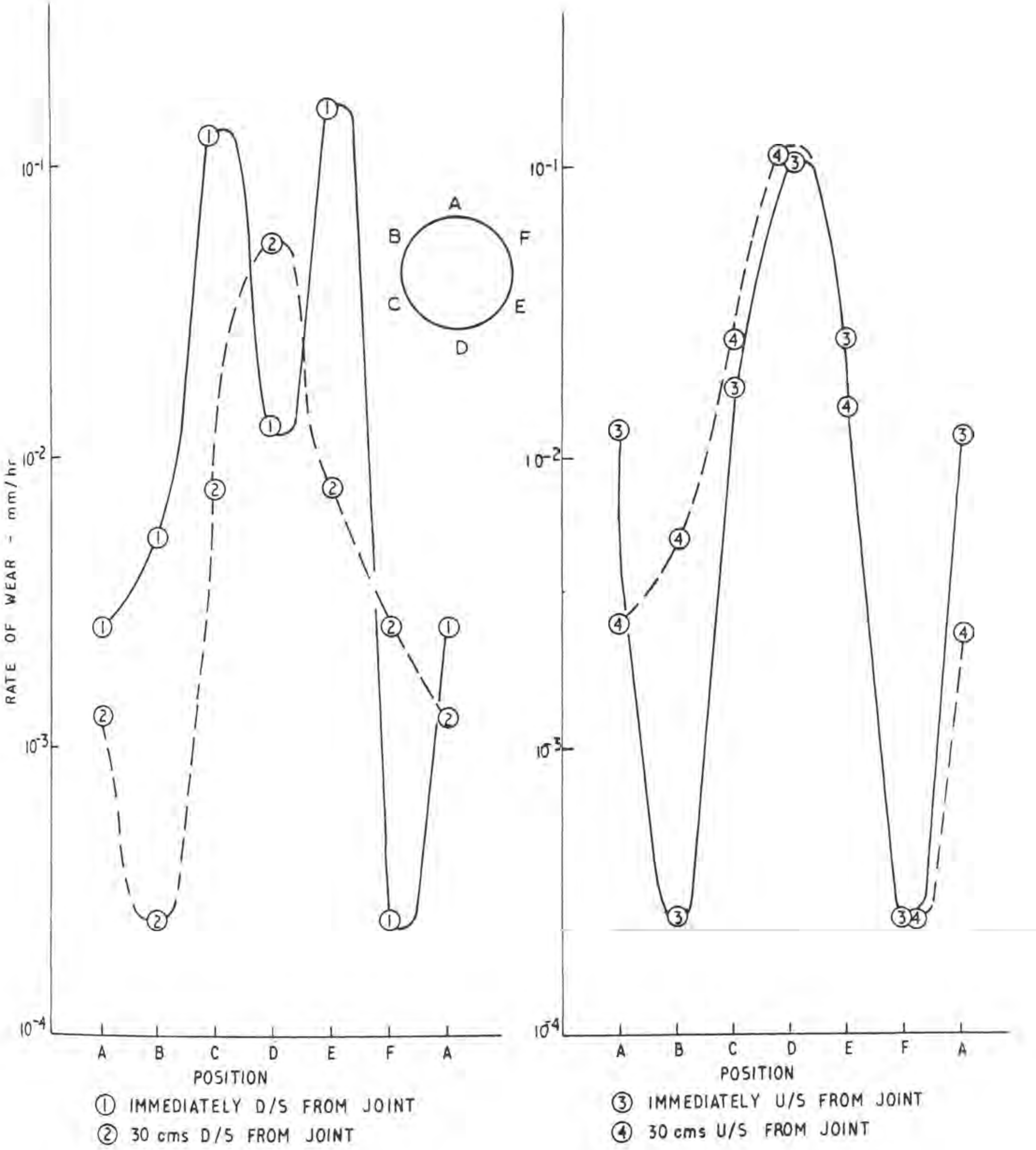
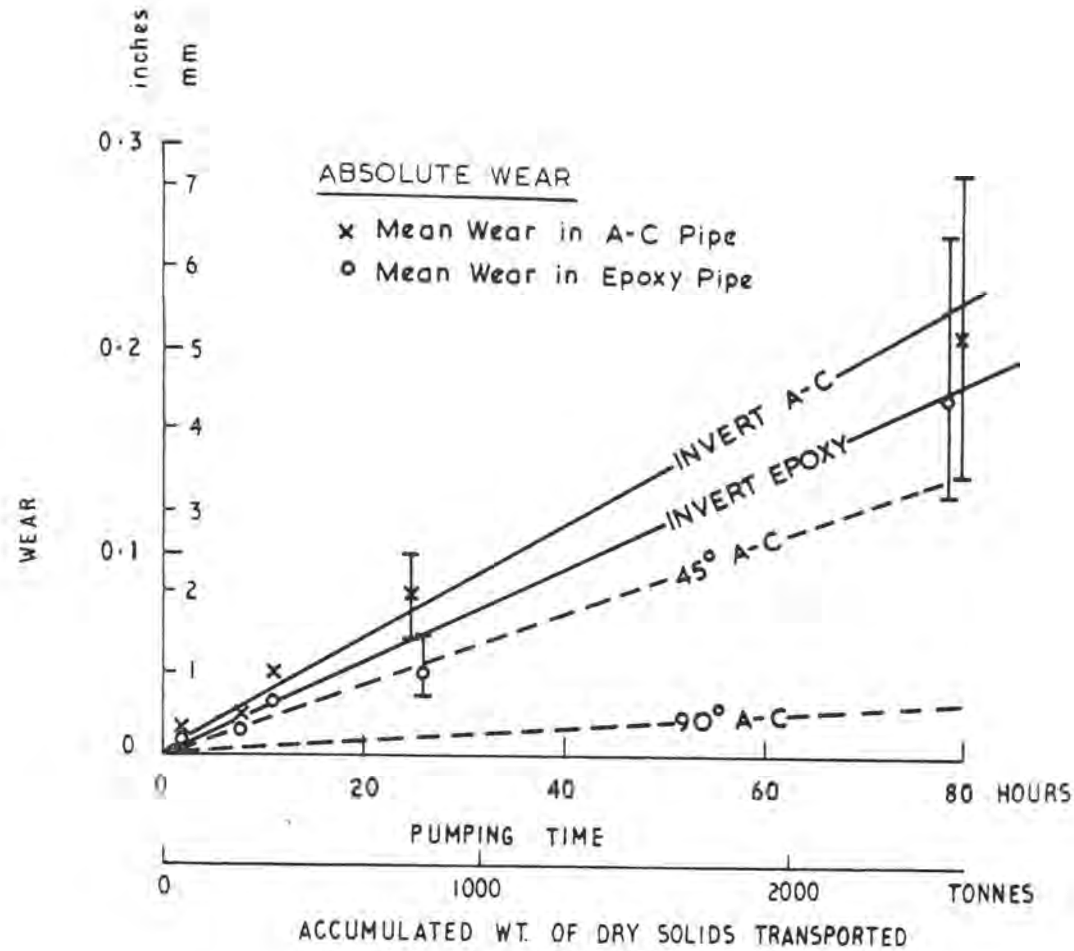


FIGURE 14 : EPOXY PIPE

RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT (10 mm dia. Solids)

TEST SERIES 1



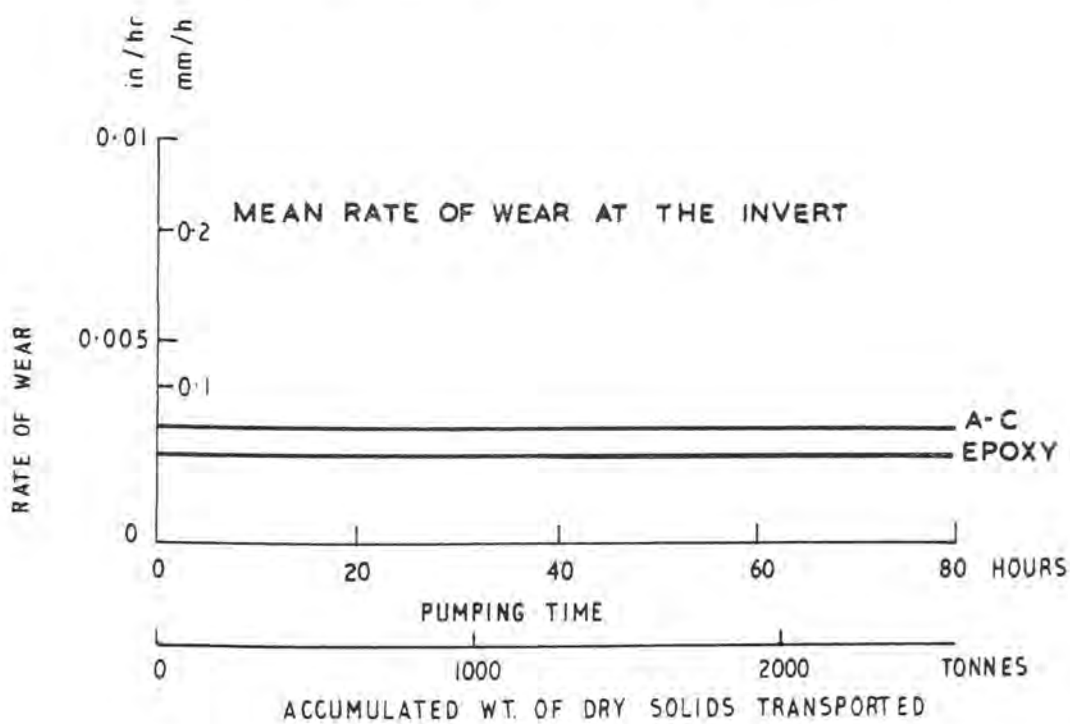


FIGURE 15: ABSOLUTE WEAR AND RATE OF WEAR IN A-C AND EPOXY-LINED PIPE (5mm ($3/16''$) dia. Solids)

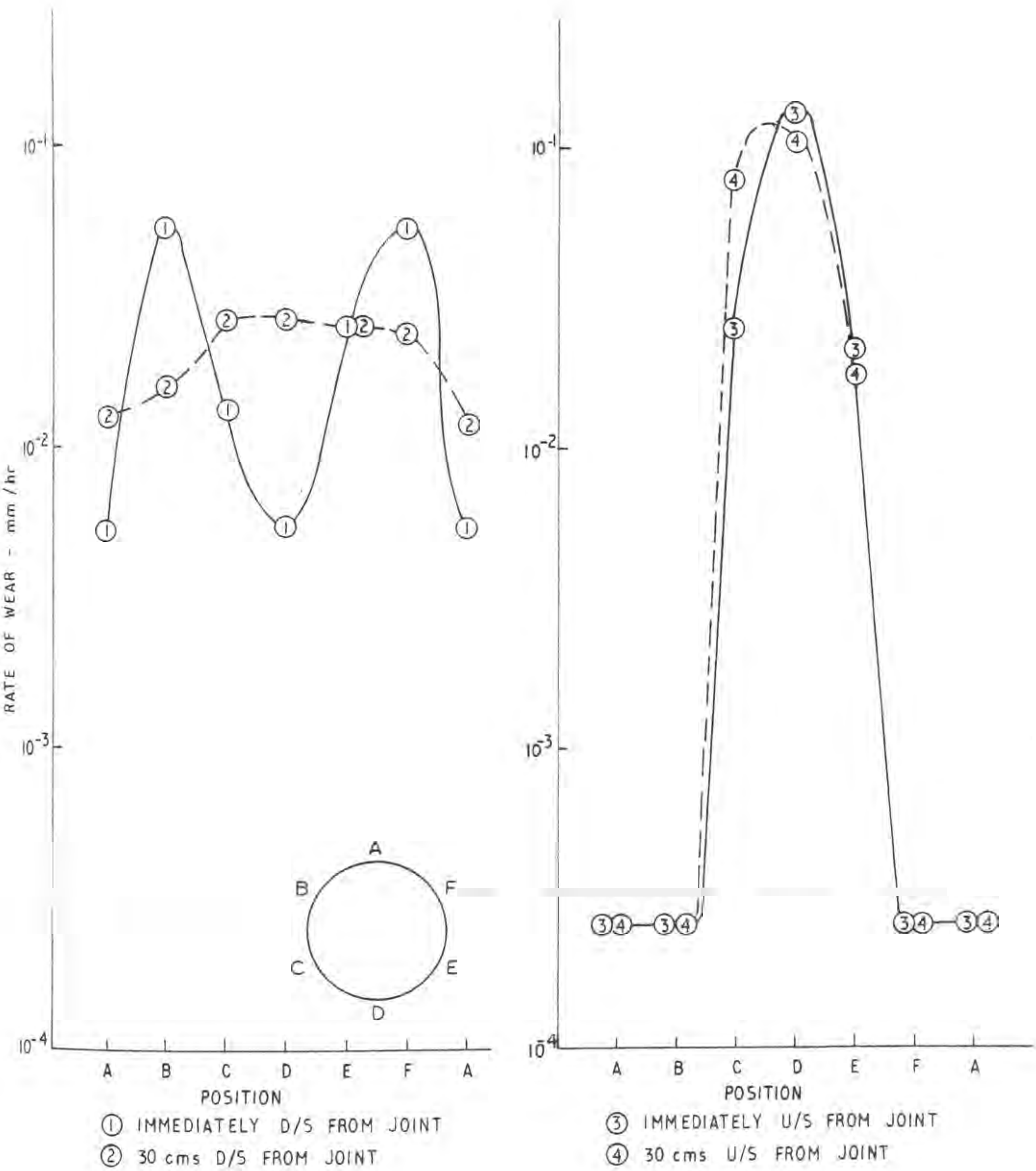


FIGURE 16 : A - C PIPE

RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT (5mm dia. Solids)

TEST SERIES 2

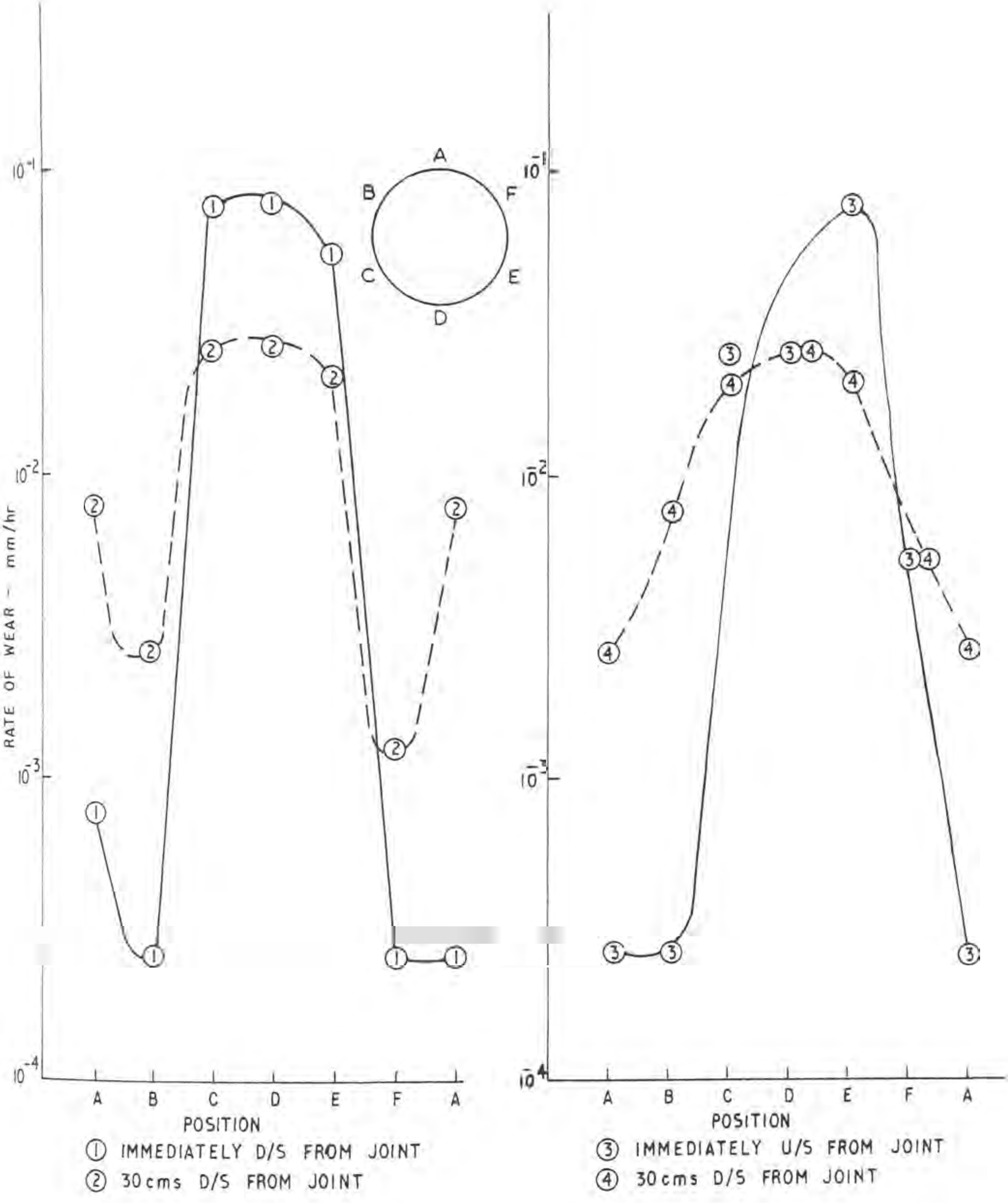


FIGURE 17 : EPOXY PIPE

RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT (5 mm dia. Solids)

TEST SERIES 2

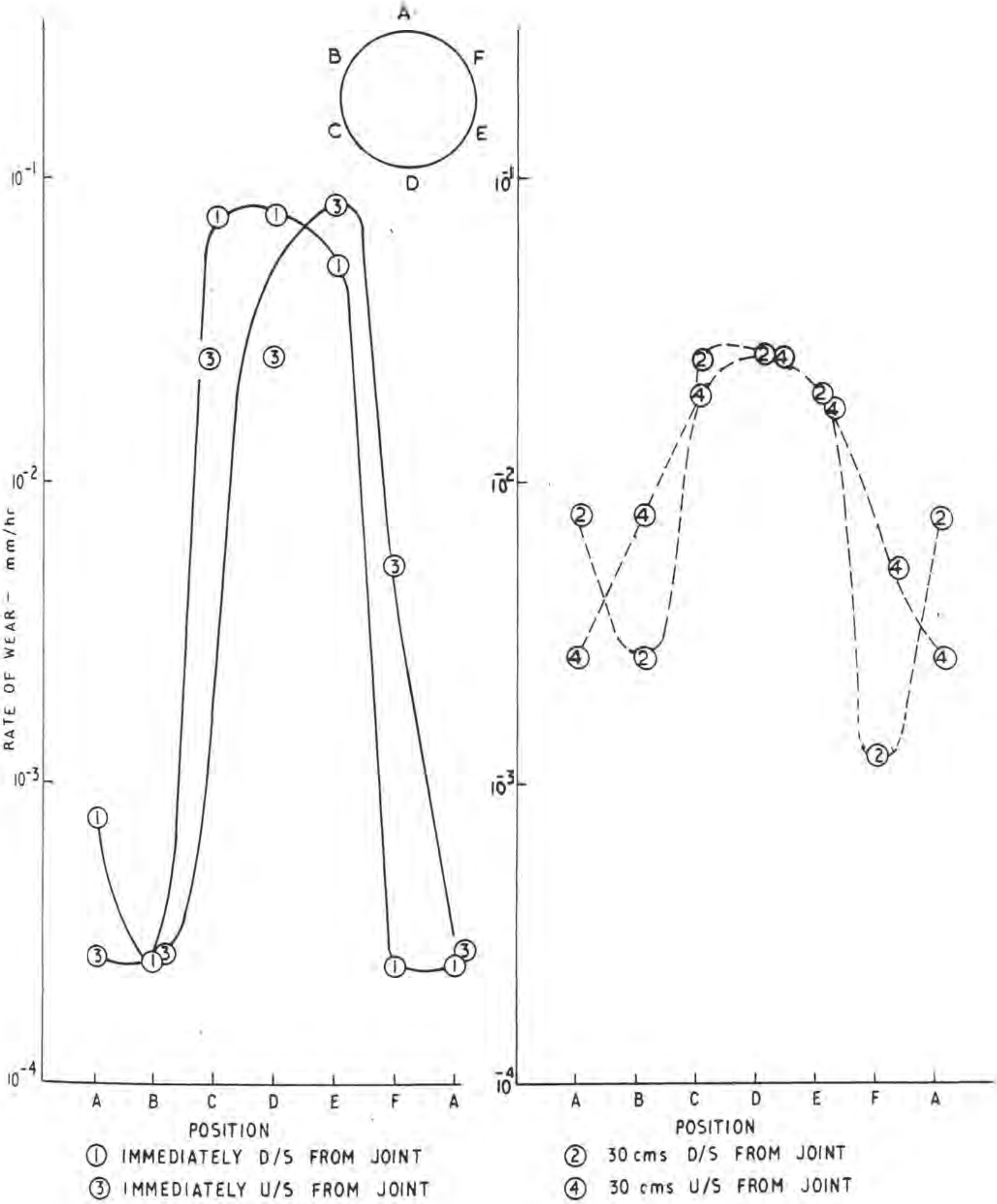


FIGURE 18 : EPOXY PIPE

RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT (5 mm dia. Solids)

TEST SERIES 2

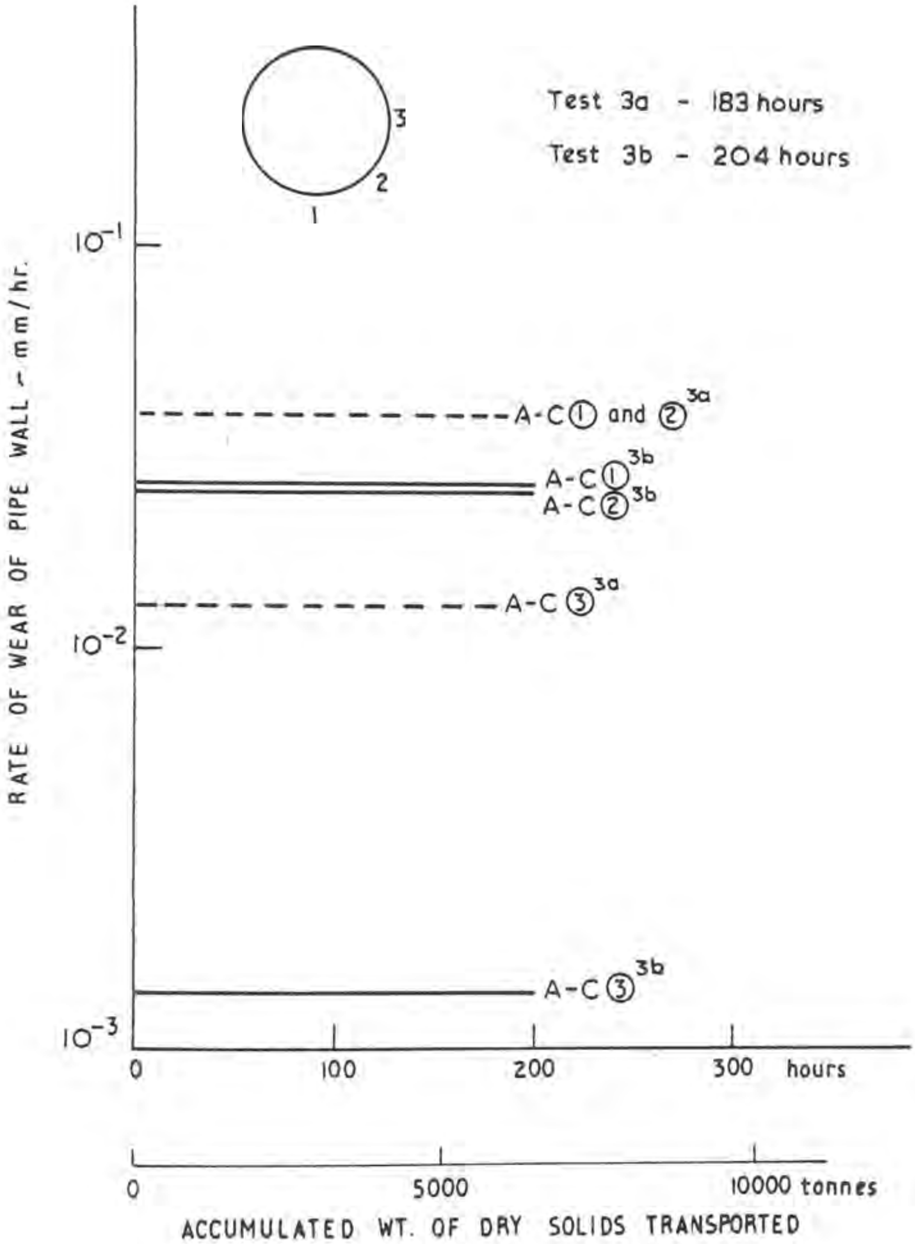


FIGURE 19 : A-C PIPE
RATE OF WEAR IN THE BARREL OF THE PIPE. (1·6mm. dia. Solids)

TEST SERIES 3.

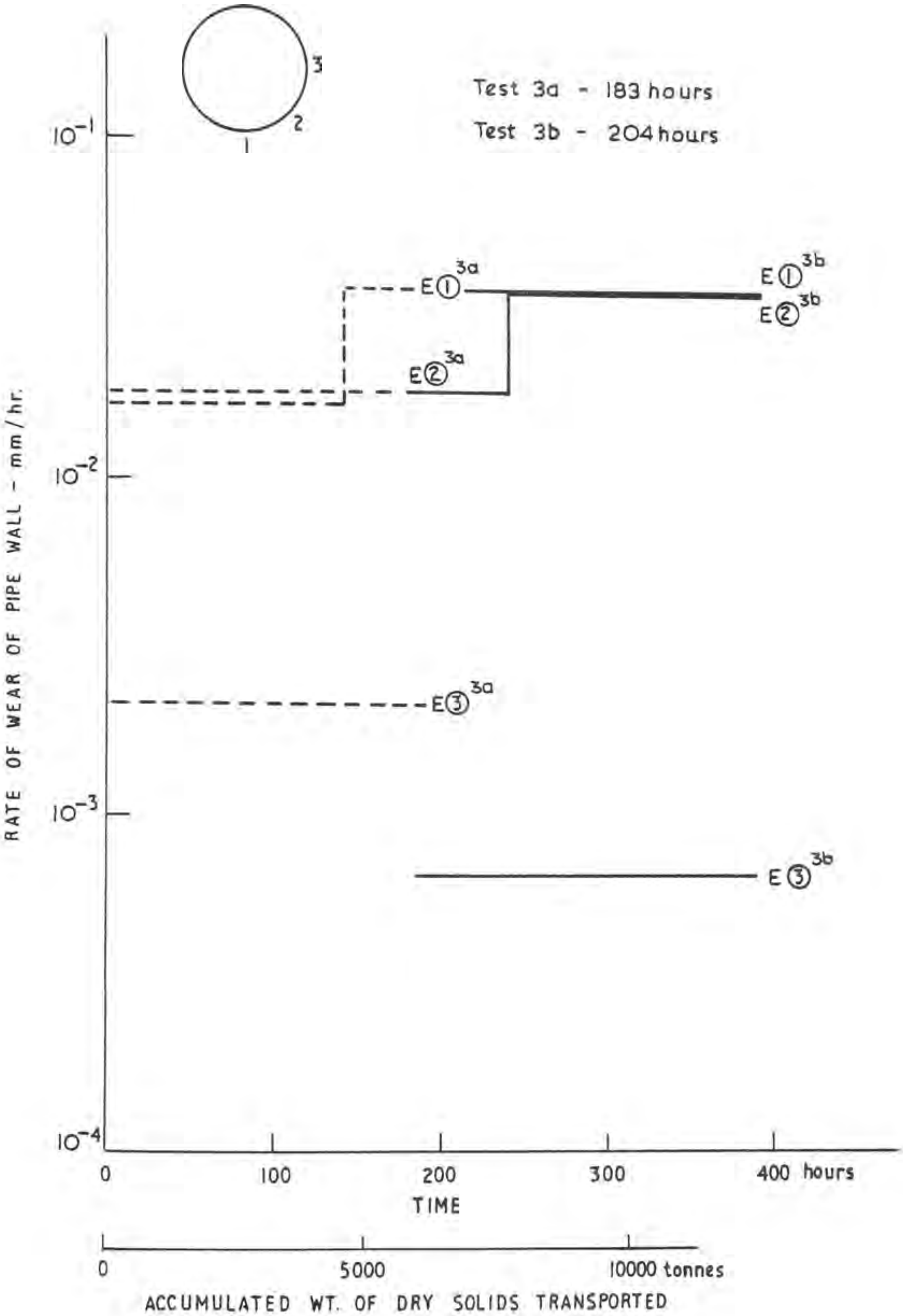


FIGURE 20: EPOXY PIPE
RATE OF WEAR IN THE BARREL
OF THE PIPE. (1·6mm. dia. Solids)

TEST SERIES 3.

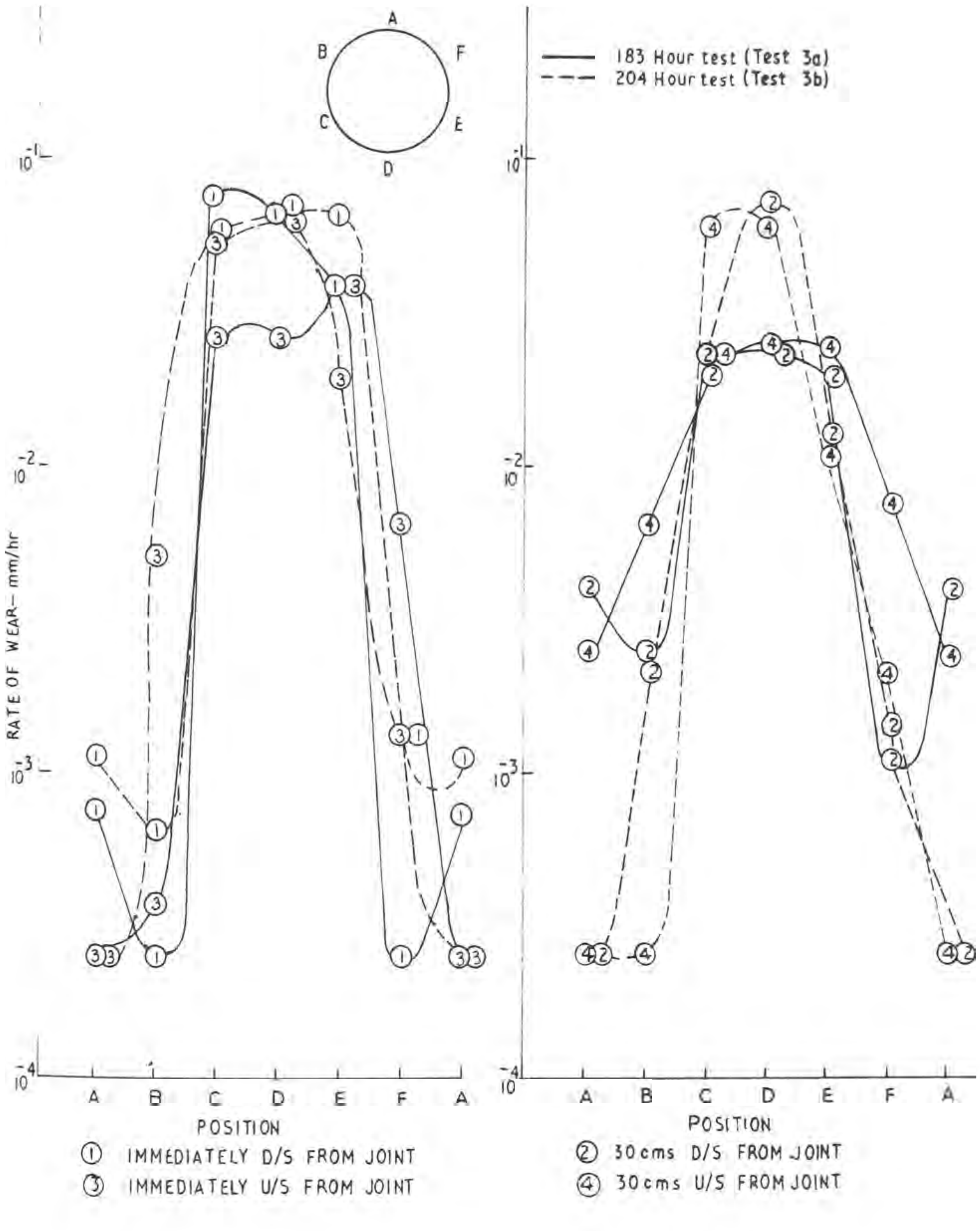


FIGURE 21 : A-C PIPE
RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT (1.6mm dia. Solids)

TEST SERIES 3

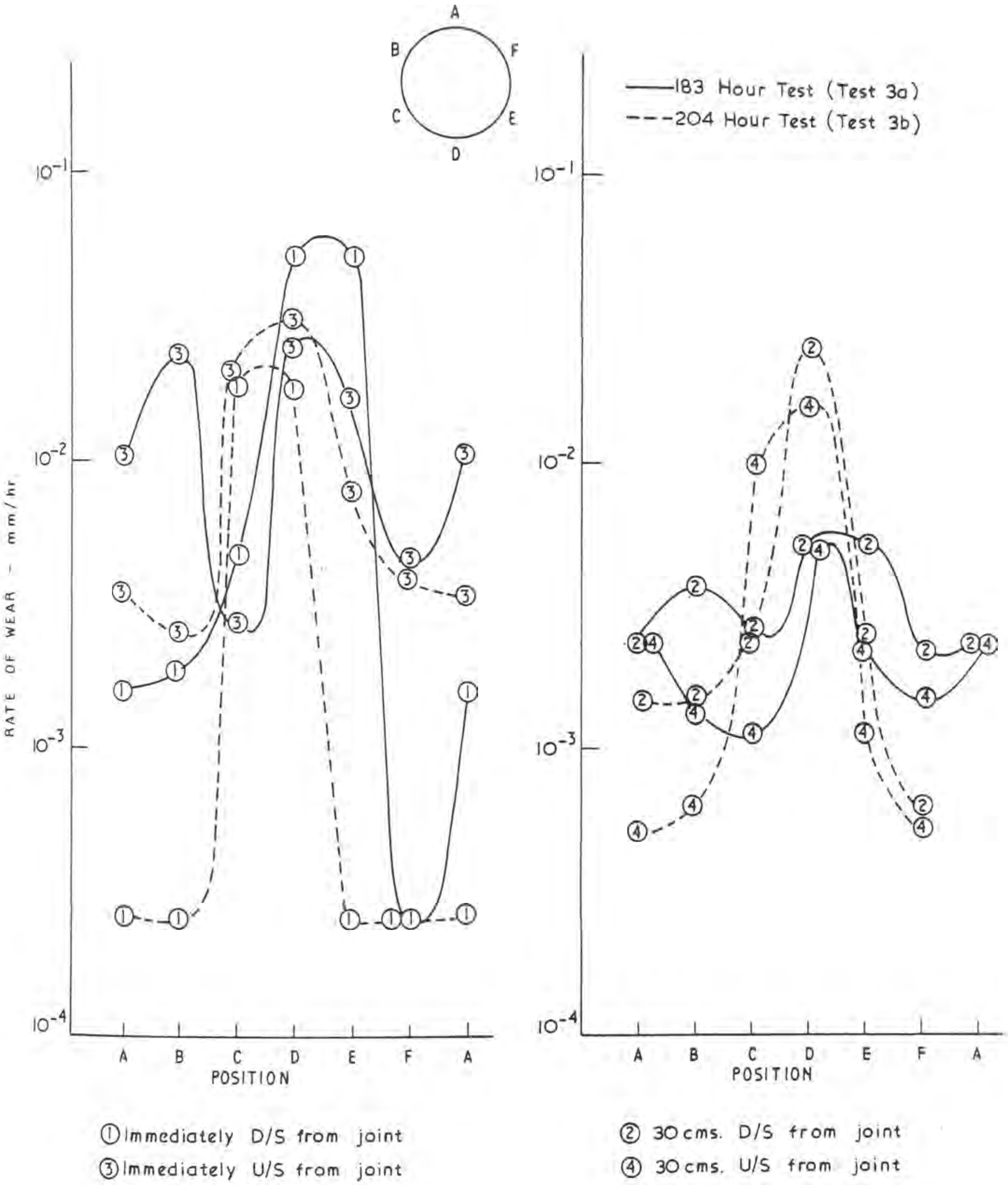


FIGURE 22: EPOXY PIPE
RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT. (1·6 mm. dia. Solids)

TEST SERIES 3.

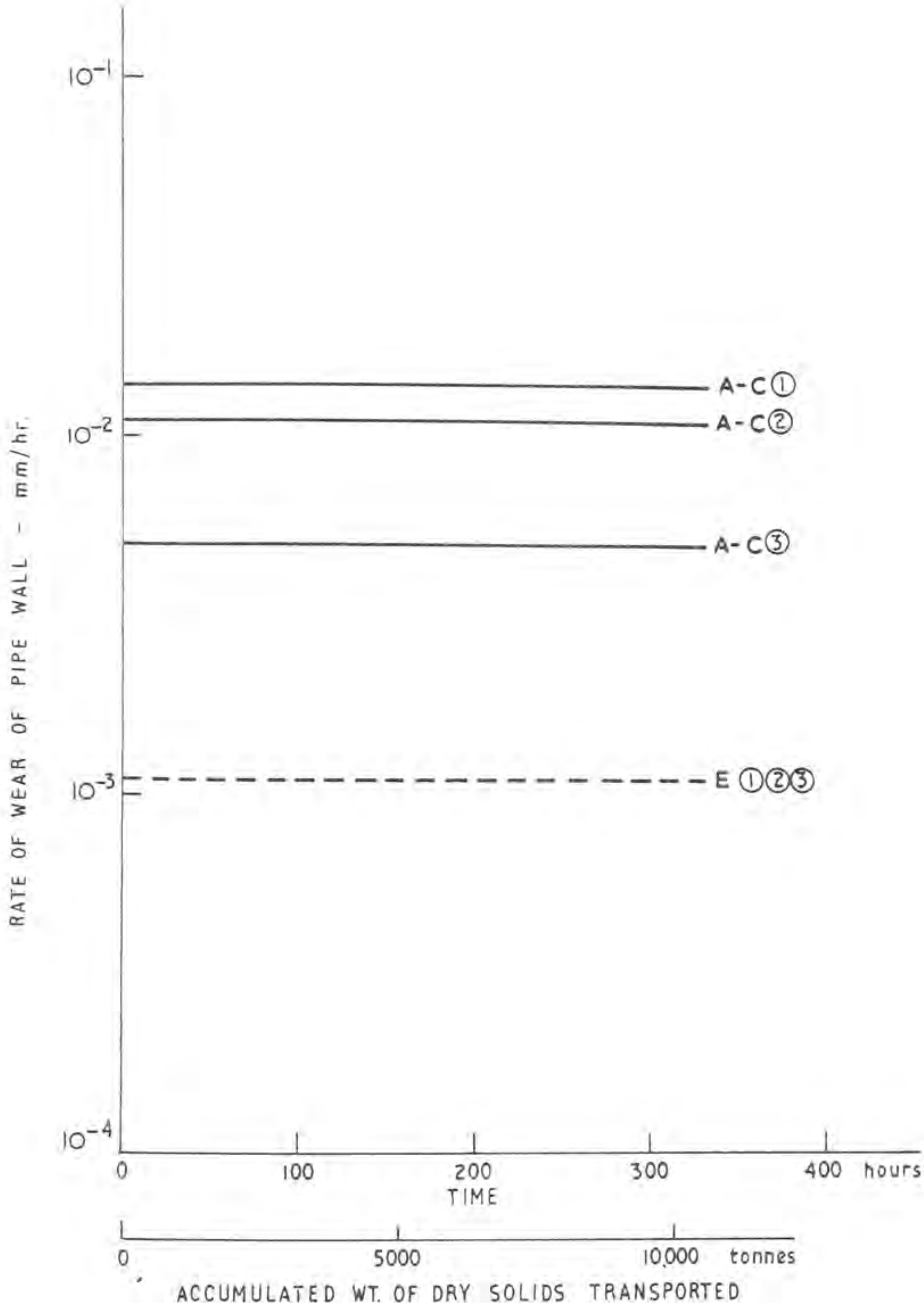


FIGURE 23: A-C AND EPOXY PIPES
RATE OF WEAR IN THE BARREL
OF THE PIPE (0·4mm. dia. Solids)

TEST SERIES 4.

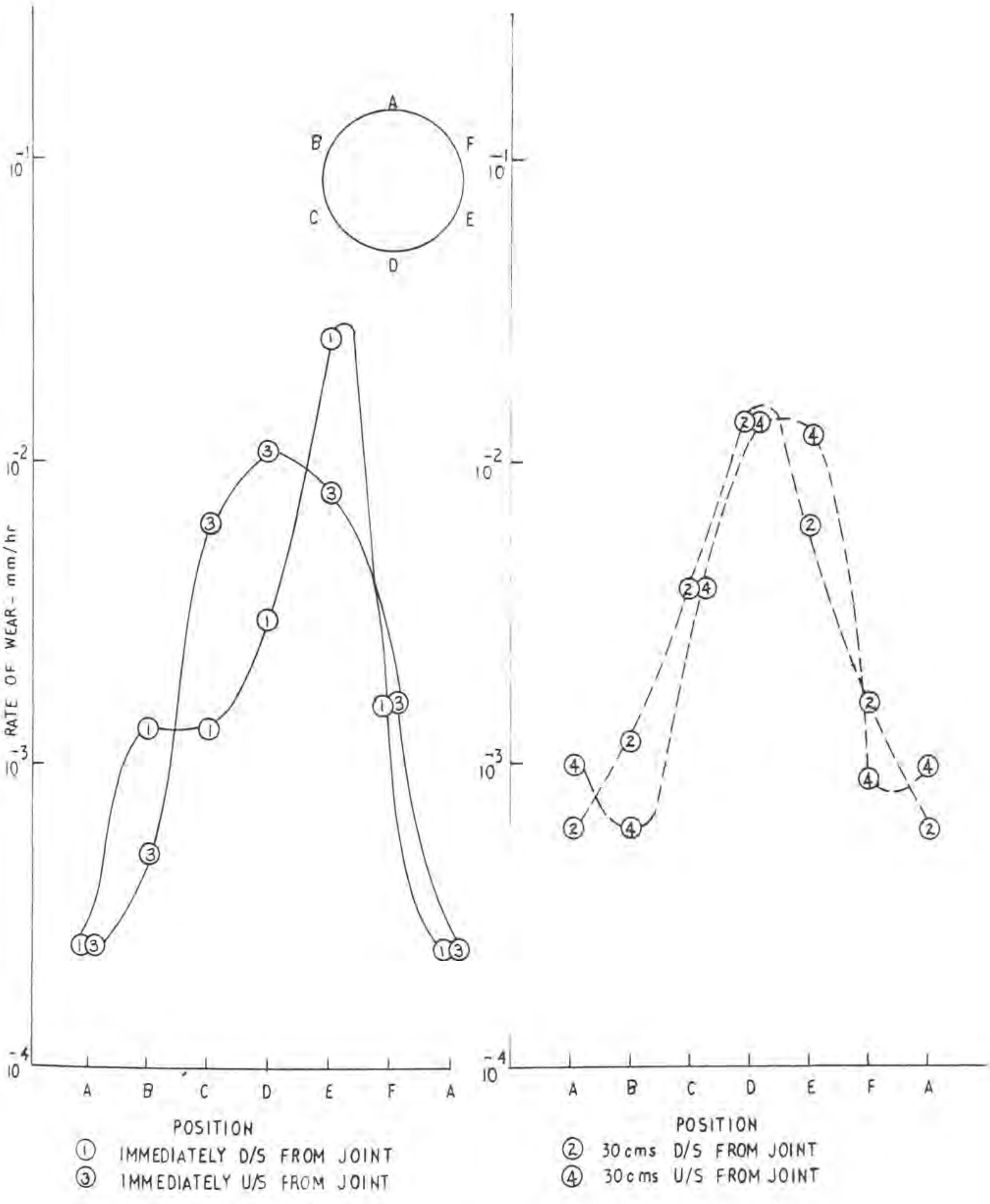


FIGURE 24 : A-C PIPE

RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT. (0.4 mm dia. Solids)

TEST SERIES 4

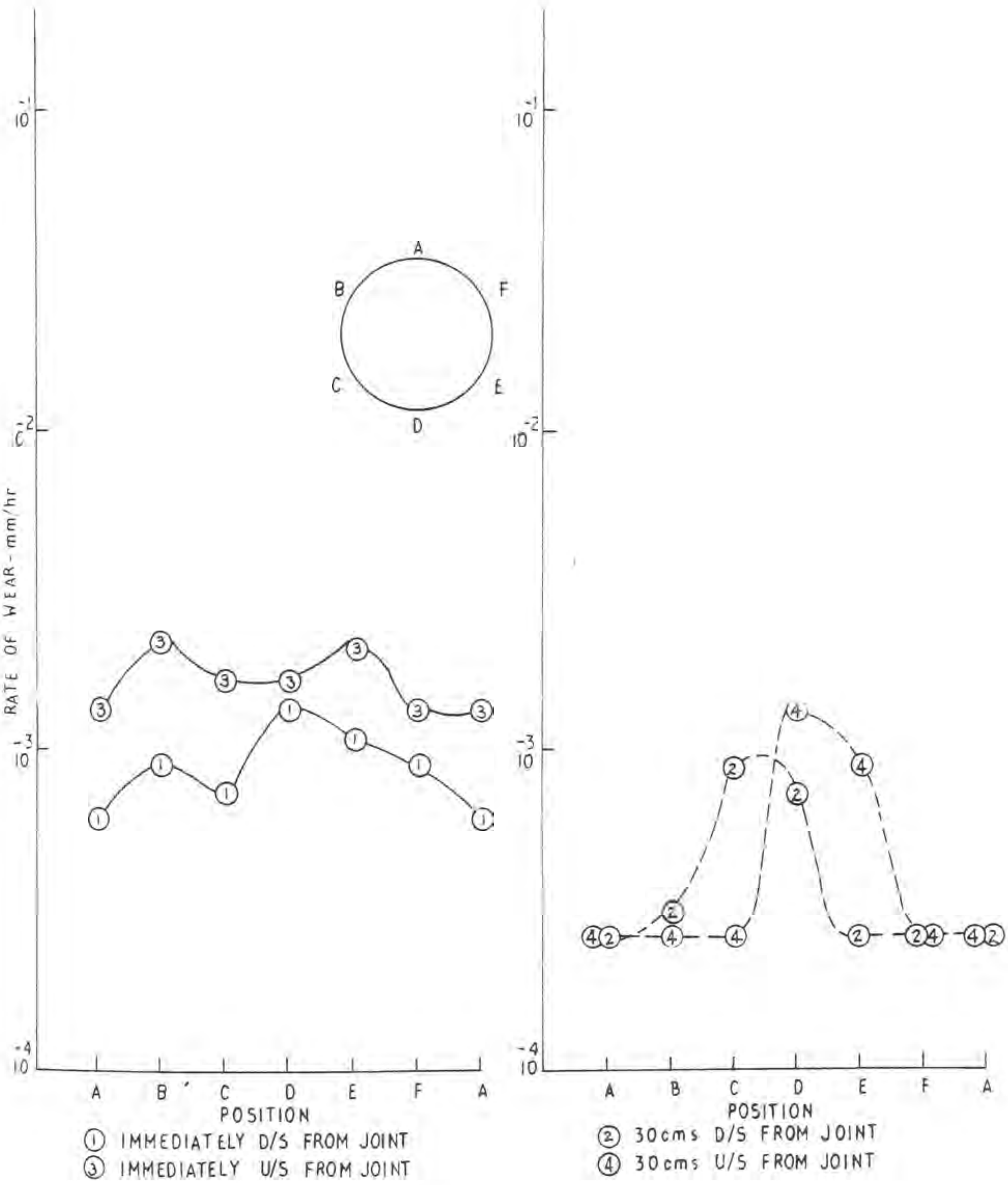


FIGURE 25 : EPOXY PIPE

RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT (0.4 mm dia. sand)

TEST SERIES 4

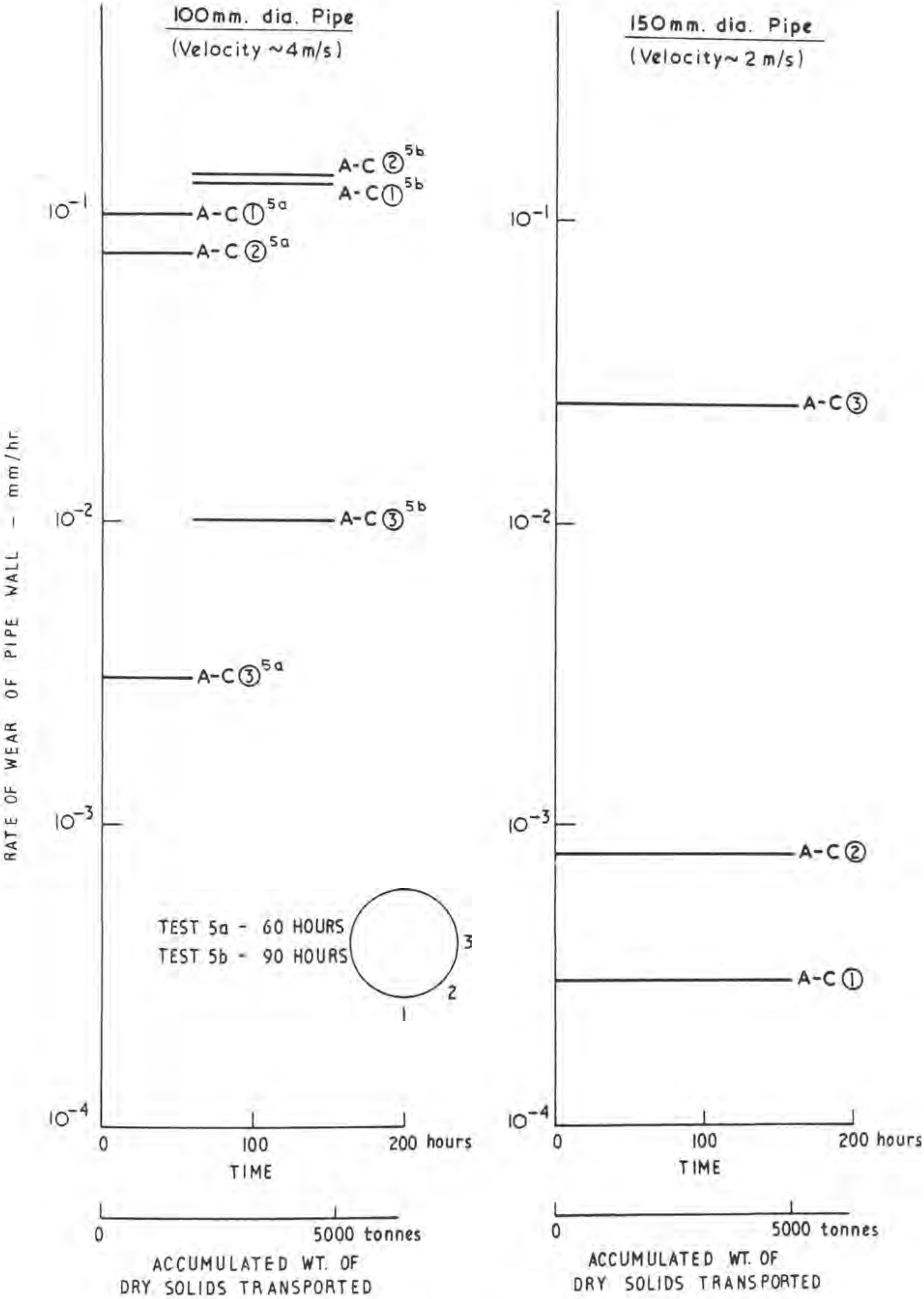


FIGURE 26 : 100mm. AND 150mm. DIA. PIPE
RATE OF WEAR IN THE BARREL OF THE PIPE
(5mm. dia. Solids)

TEST SERIES 5.

100MM. DIA. A-C PIPE

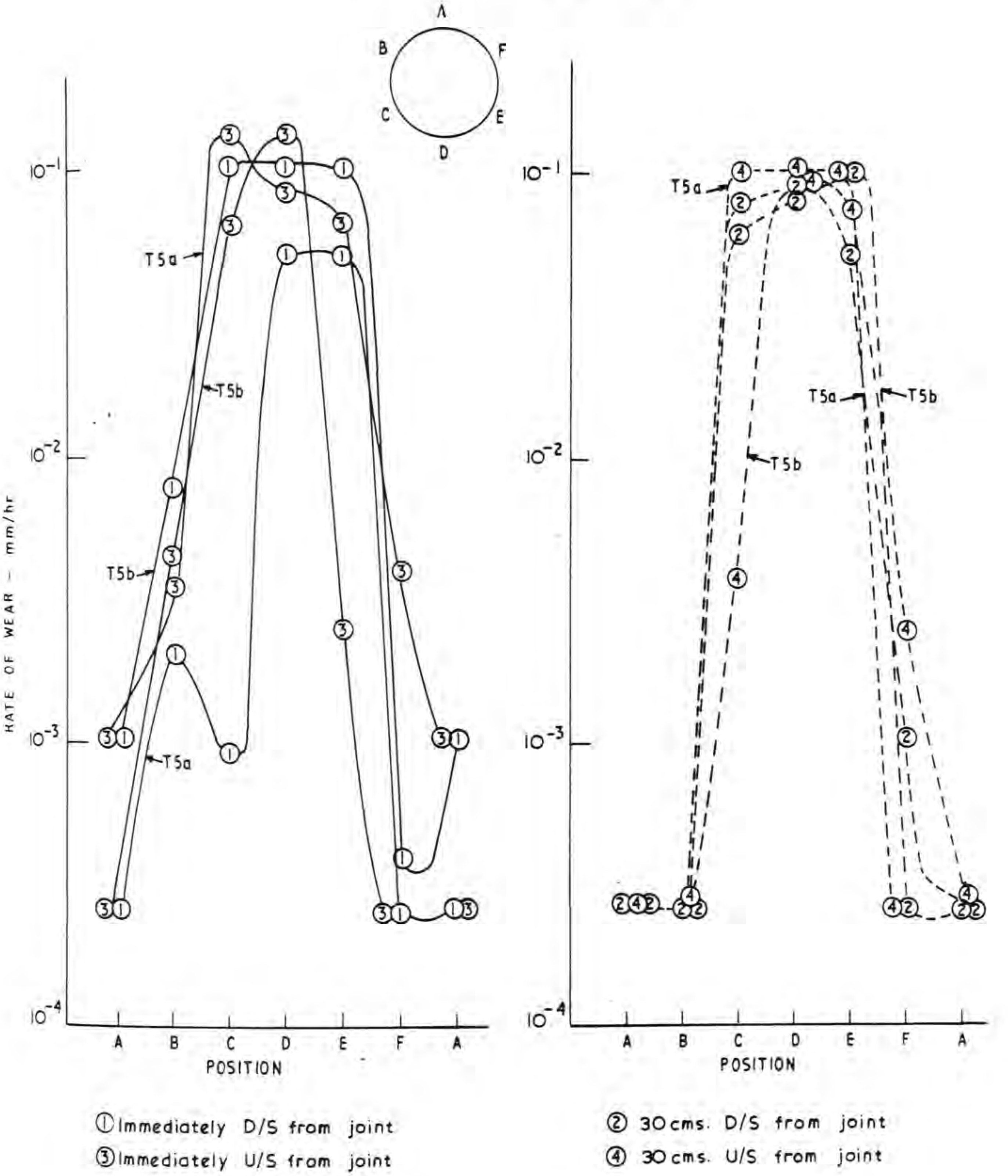


FIGURE 27: A-C PIPE
RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT. (5mm dia. Solids)

TEST SERIES 5.

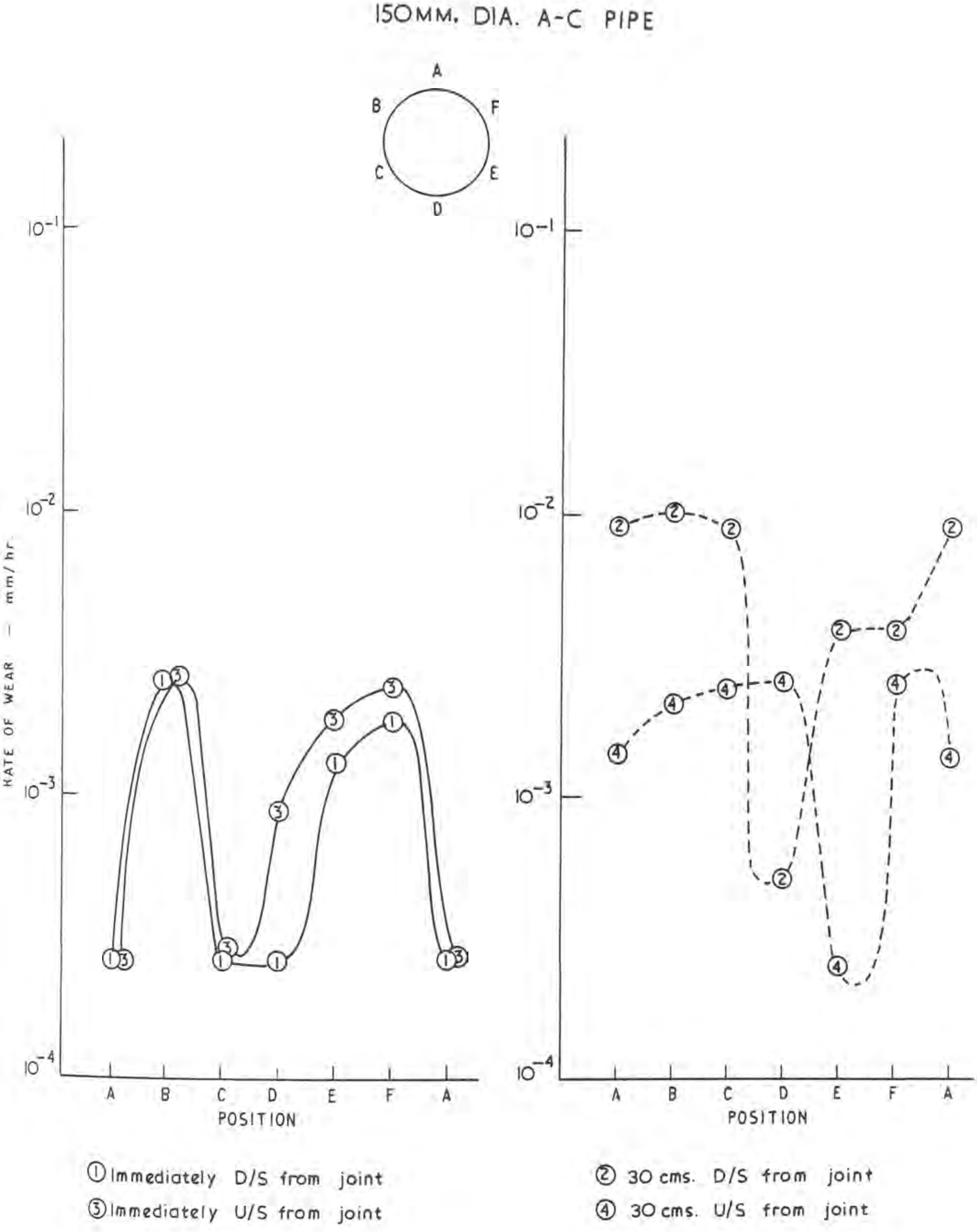


FIGURE 28: A-C PIPE
RATE OF WEAR AS A FUNCTION OF CIRCUMFERENTIAL POSITION IN THE REGION OF THE JOINT. (5mm dia Solids)

TEST SERIES 5.

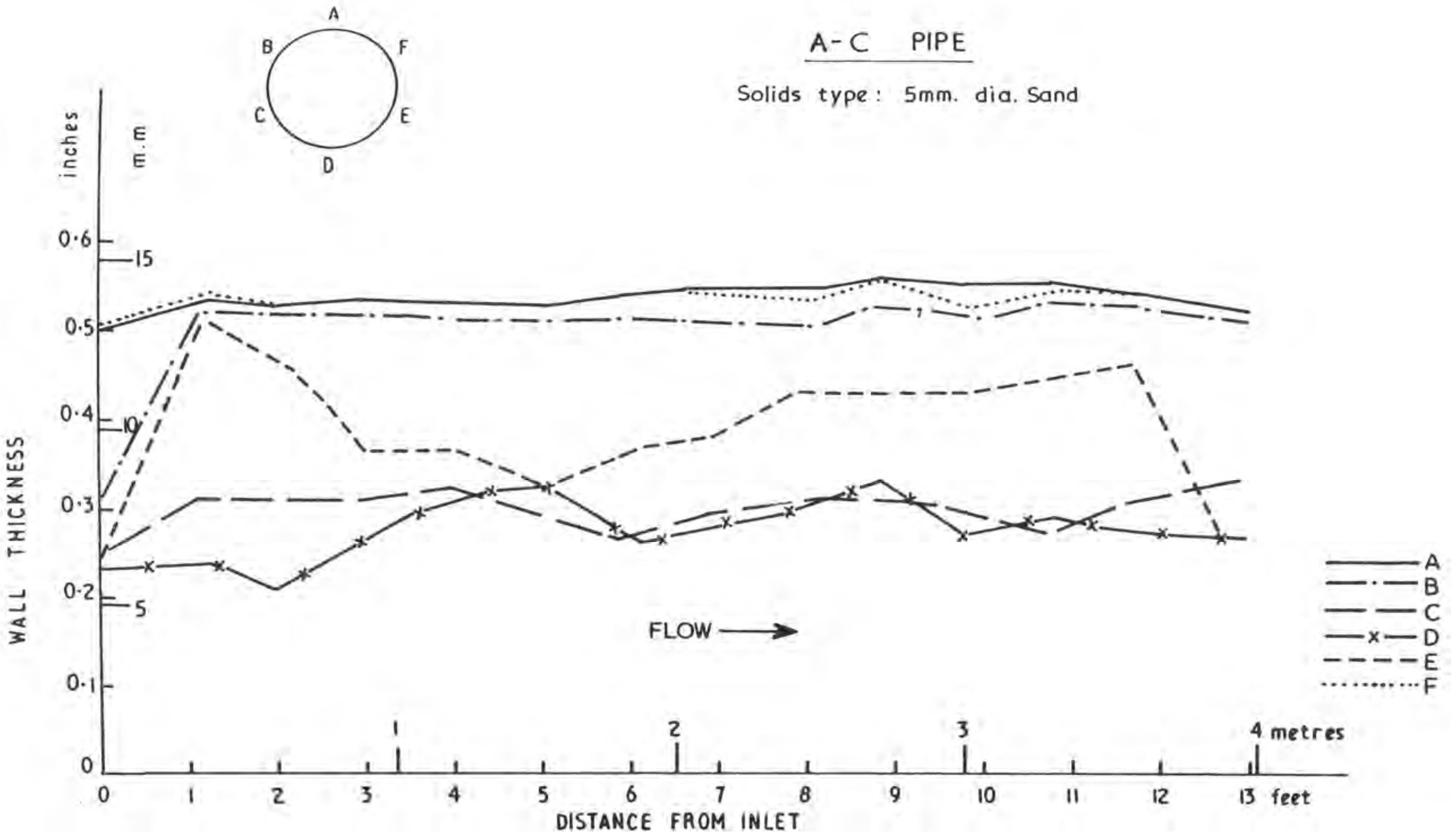


FIGURE 29: A C PIPE
WALL THICKNESS ALONG THE LENGTH OF THE PIPE AFTER 60 HOURS OF PUMPING.

TEST SERIES 5.

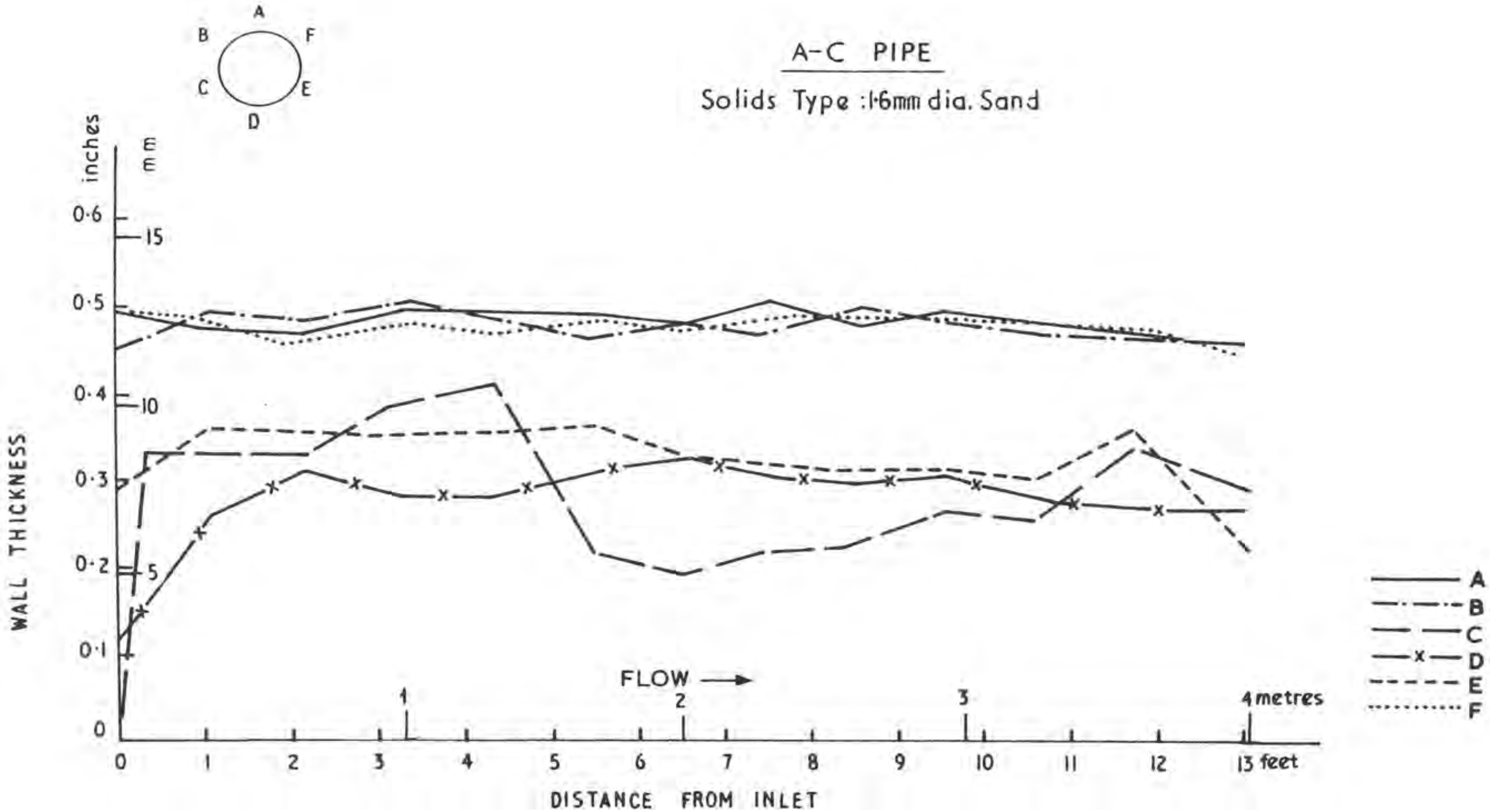


FIGURE 30: A-C PIPE - WALL THICKNESS ALONG THE LENGTH OF THE PIPE AFTER 183 HOURS OF PUMPING

TEST SERIES 3

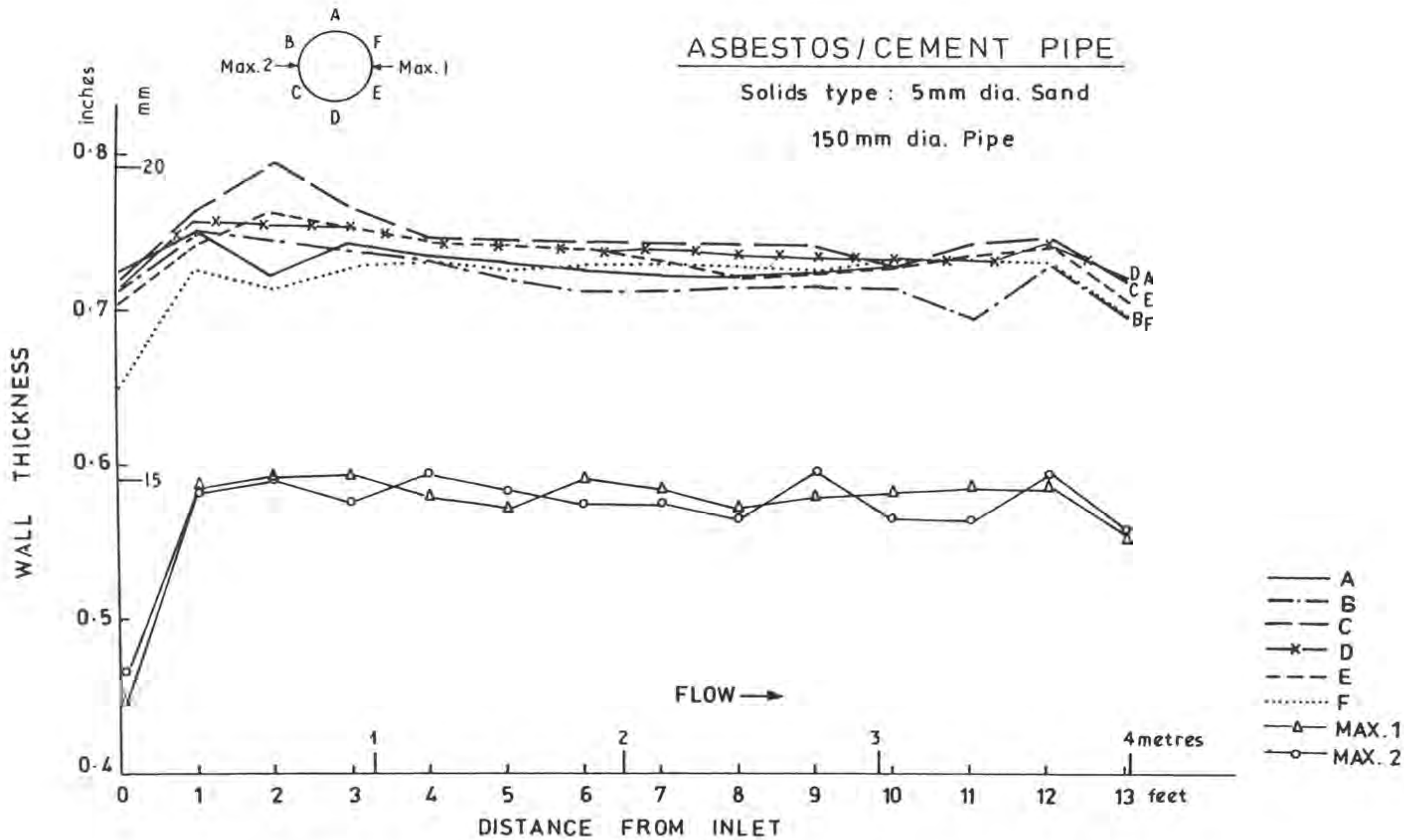


FIGURE 31: A/C PIPE - WALL THICKNESS ALONG THE LENGTH OF THE PIPE AFTER 160 HOURS OF PUMPING.

TEST SERIES 5.

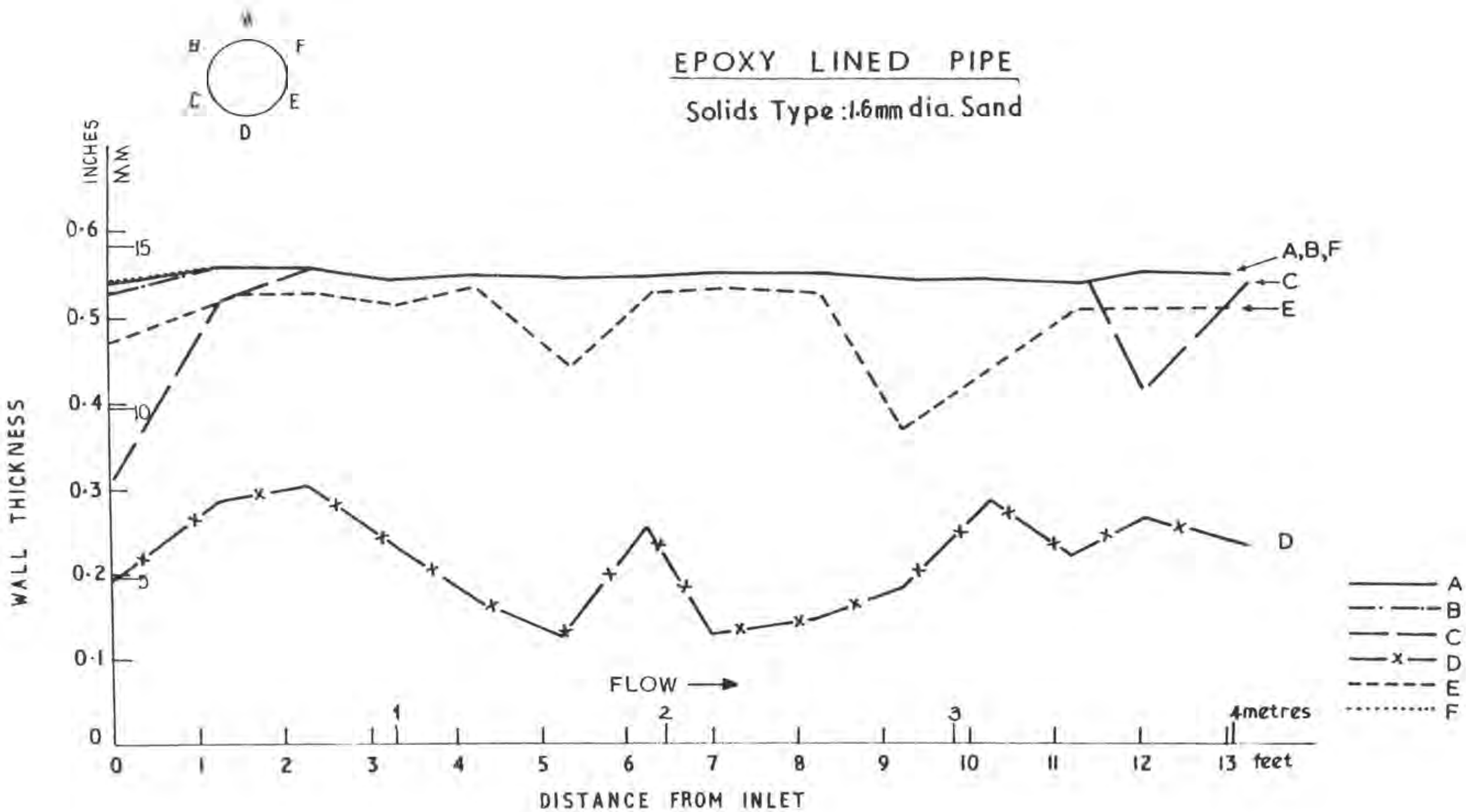


FIGURE 32: EPOXY LINED PIPE - WALL THICKNESS ALONG THE LENGTH OF THE PIPE AFTER 388 HOURS OF PUMPING.

TEST SERIES 3.

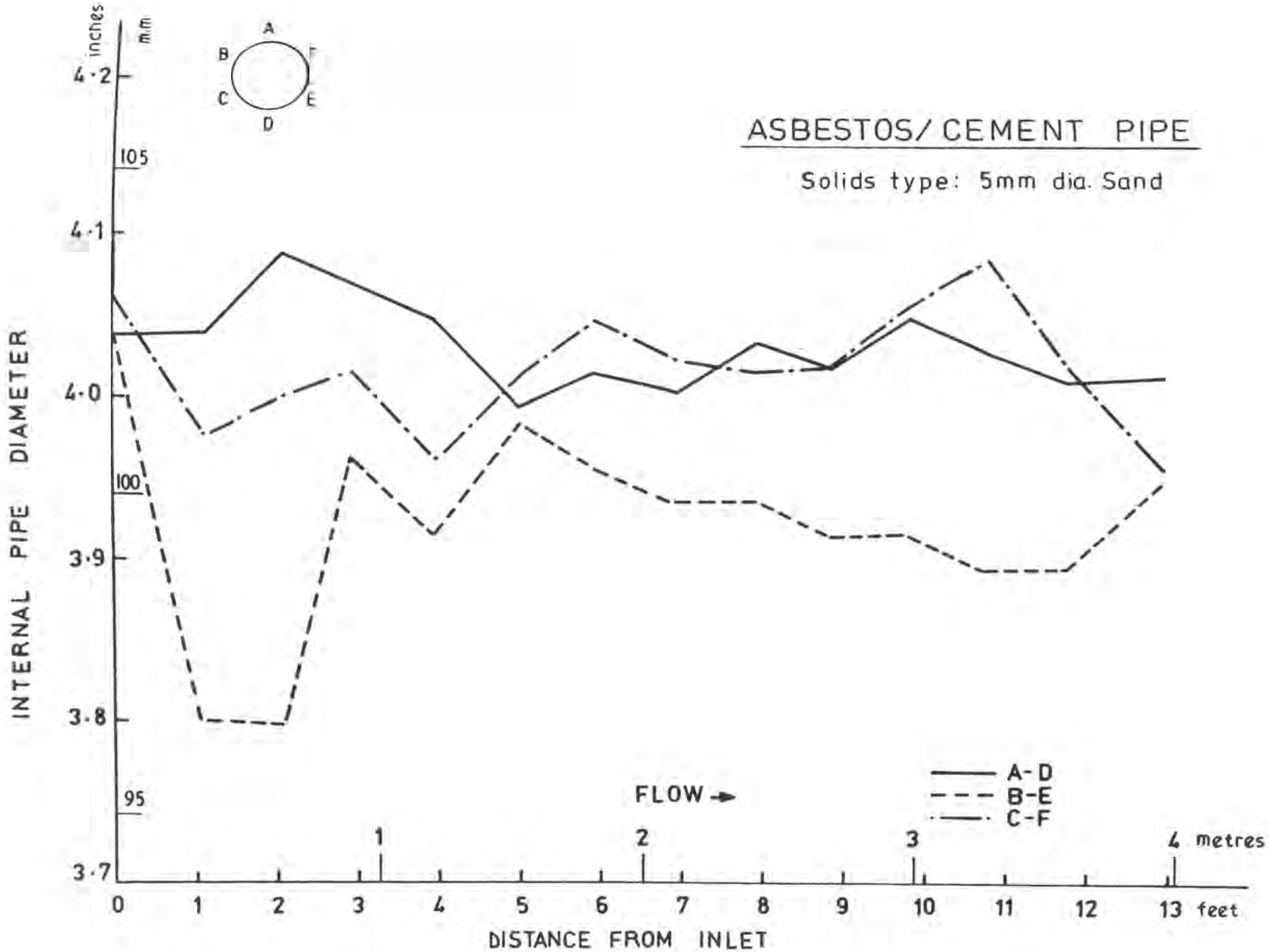


FIGURE 33: A/C PIPE-INTERNAL DIAMETER ALONG THE LENGTH OF THE PIPE AFTER 60 HOURS OF PUMPING.

TEST SERIES 5

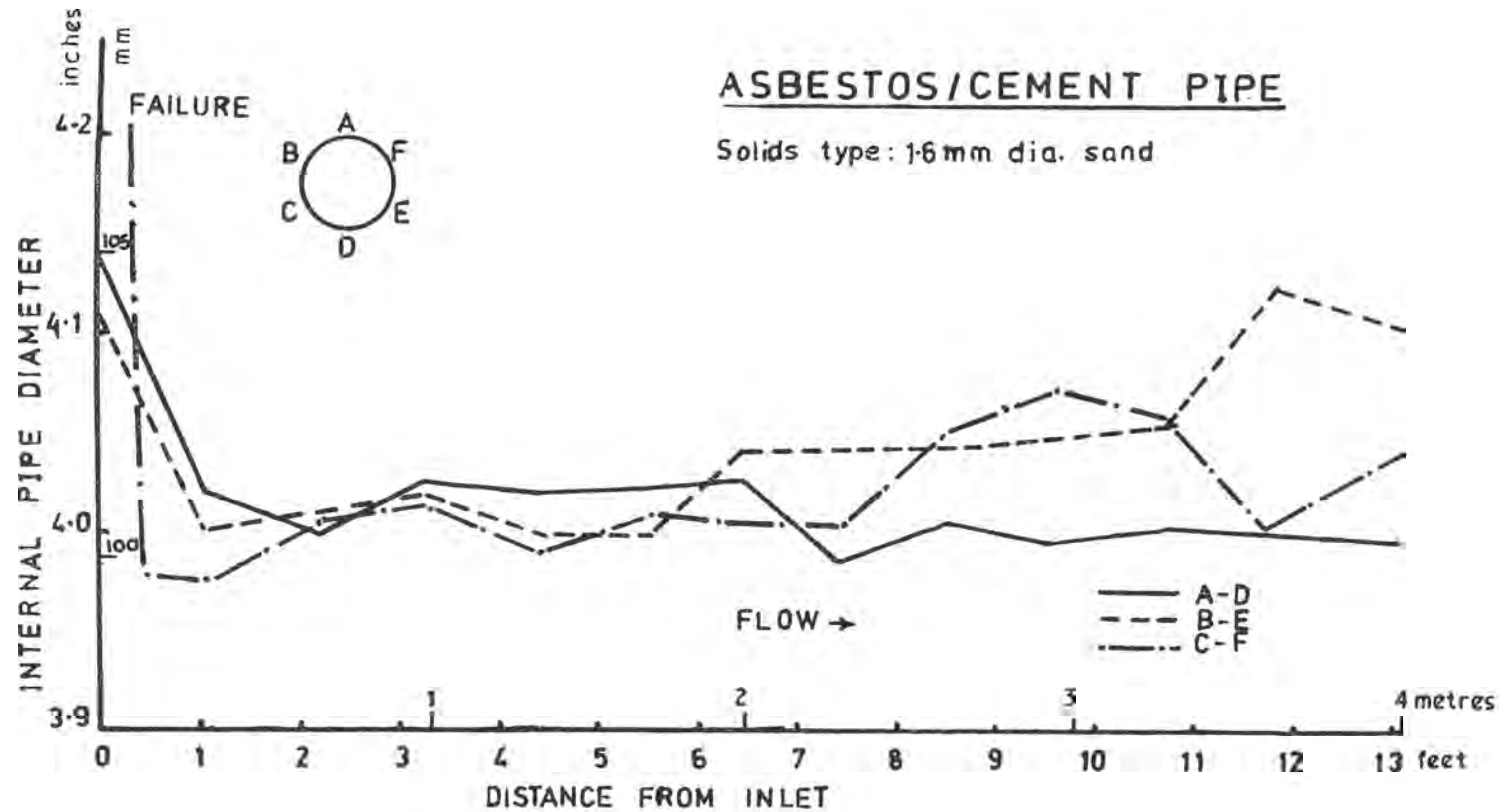


FIGURE 34: A/C PIPE-INTERNAL DIAMETER ALONG THE LENGTH OF THE PIPE AFTER 183 HOURS OF PUMPING

TEST SERIES 3

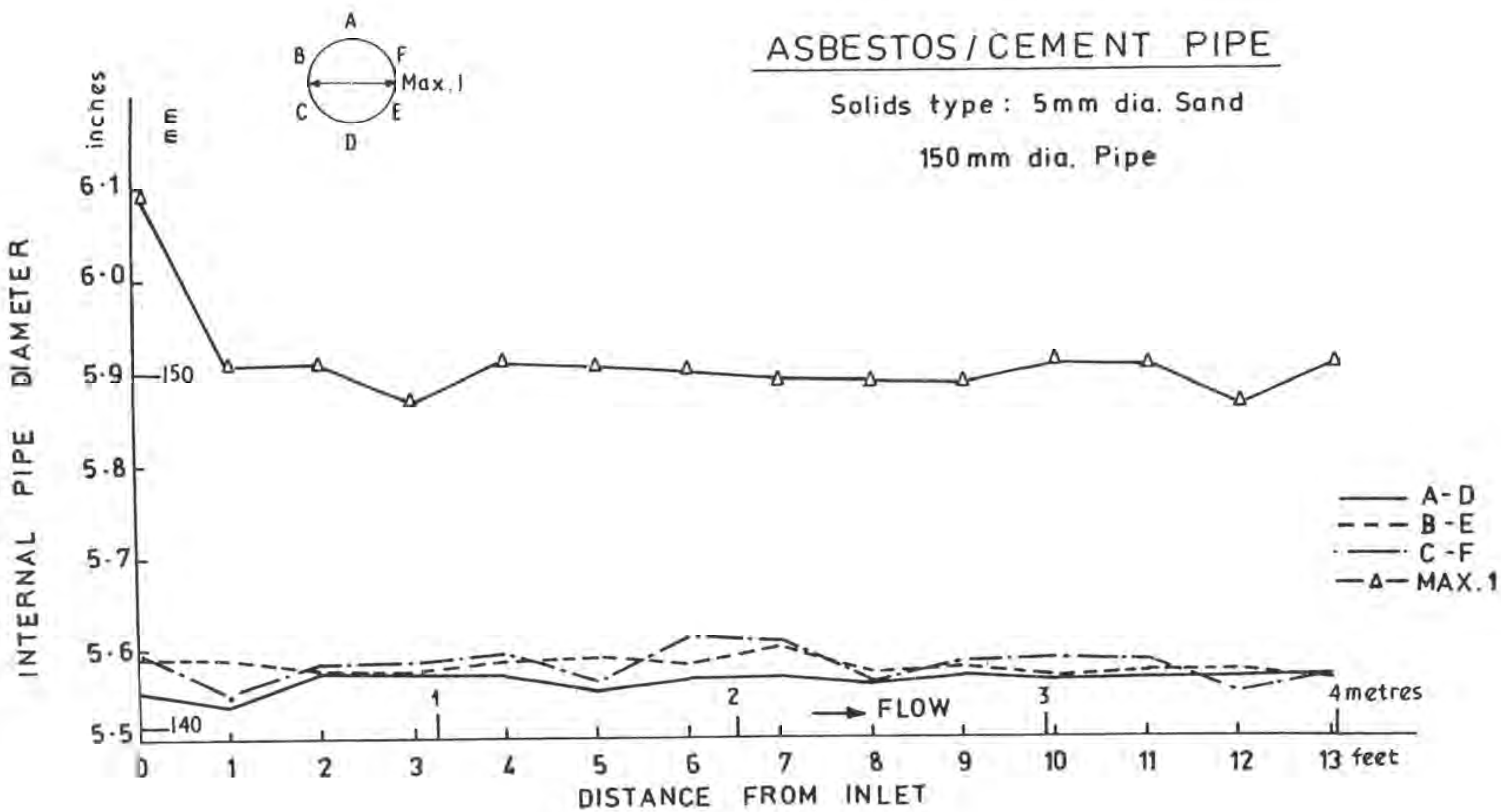


FIGURE 35: A/C PIPE - INTERNAL DIAMETER ALONG THE LENGTH OF THE PIPE AFTER 160 HOURS OF PUMPING.

TEST SERIES 5

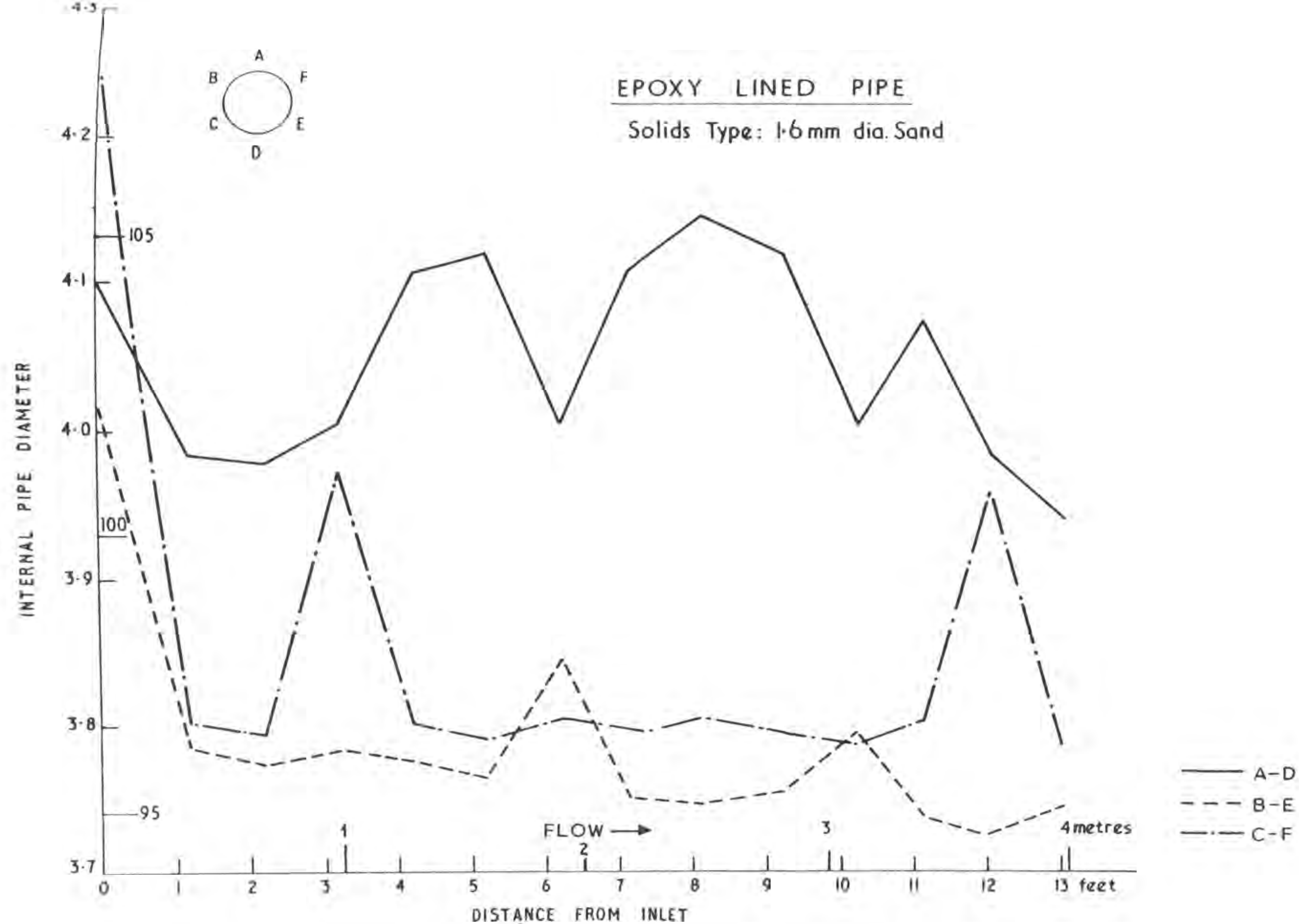
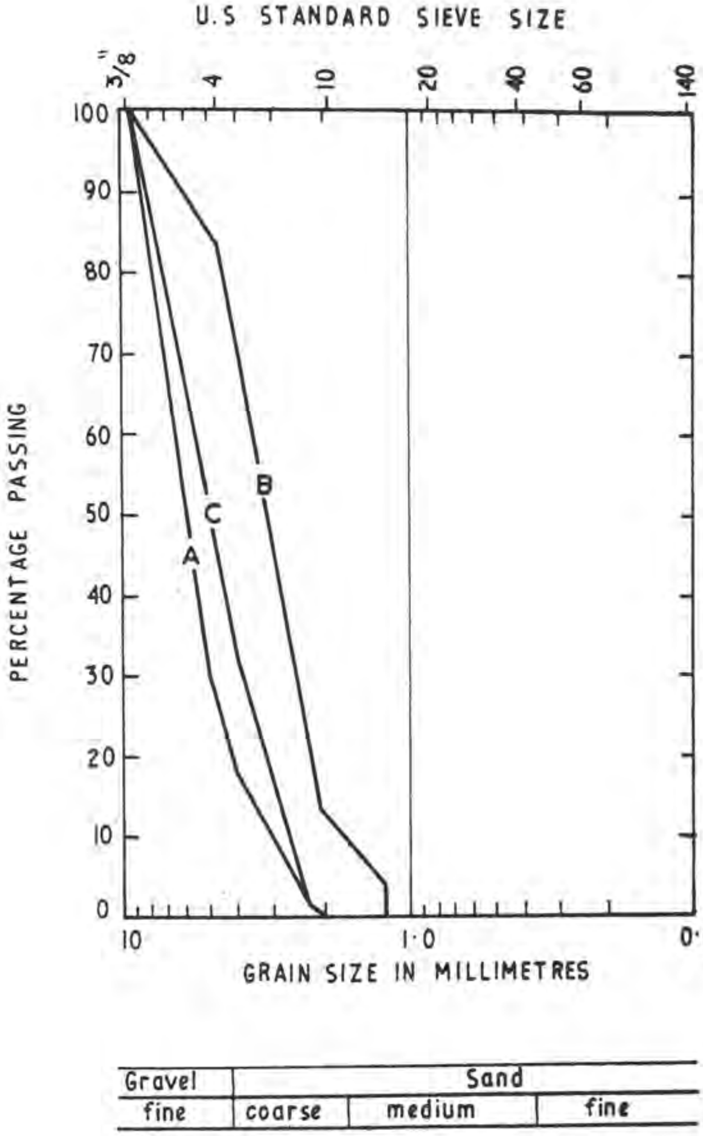


FIGURE 36: EPOXY LINED PIPE – INTERNAL DIAMETER ALONG THE LENGTH OF THE PIPE AFTER 388 HOURS OF PUMPING. TEST SERIES 3



Attrition of 5mm dia. Particles

A - initial grading

B - after 16 hours

C - after 16 hours with make-up

FIGURE 37: SIZE REDUCTION OF SLURRY PARTICLES (5mm Nom. Size)

TEST SERIES 5.

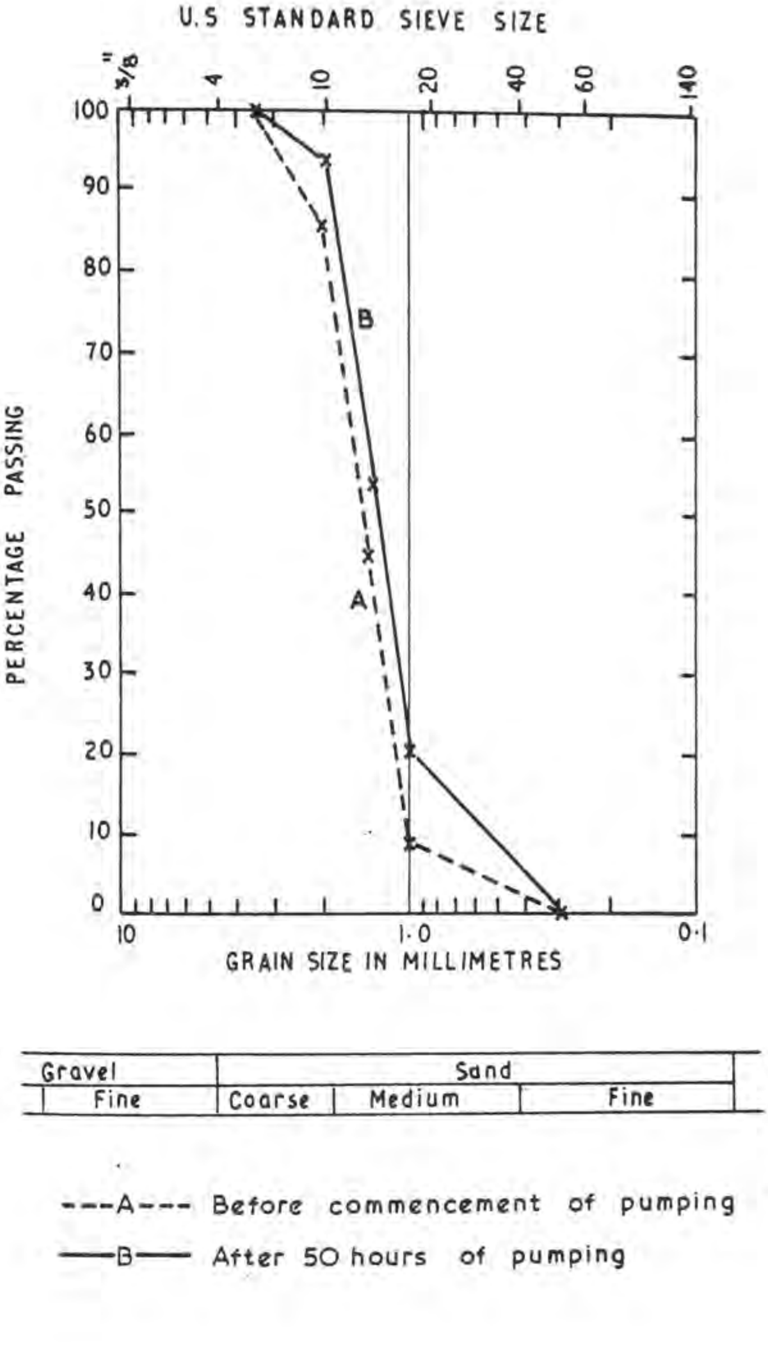


FIGURE 38: SIZE REDUCTION OF SLURRY PARTICLES (1·6 mm Nom. Size)

TEST SERIES 3.

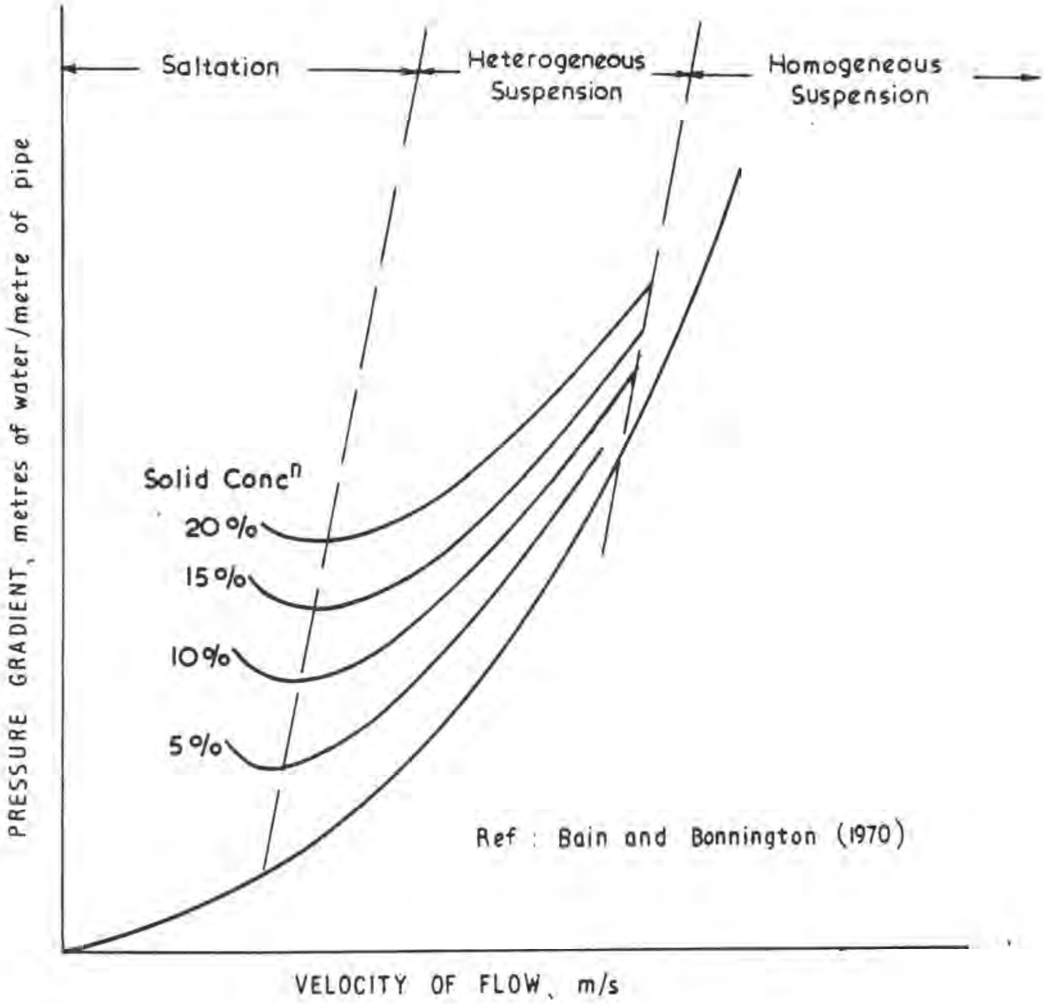


FIGURE 39: PRESSURE GRADIENT AND FLOW REGIME

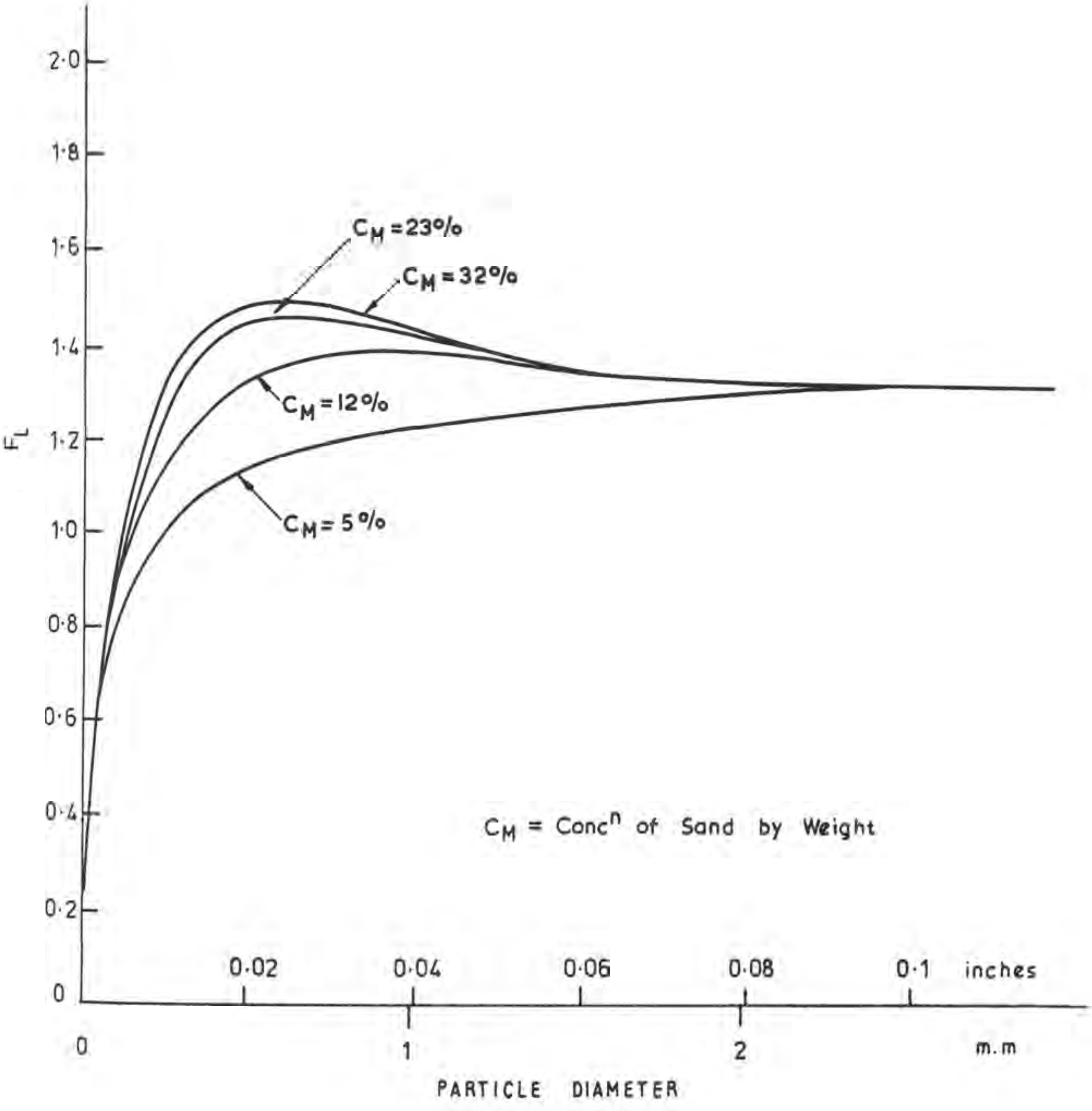
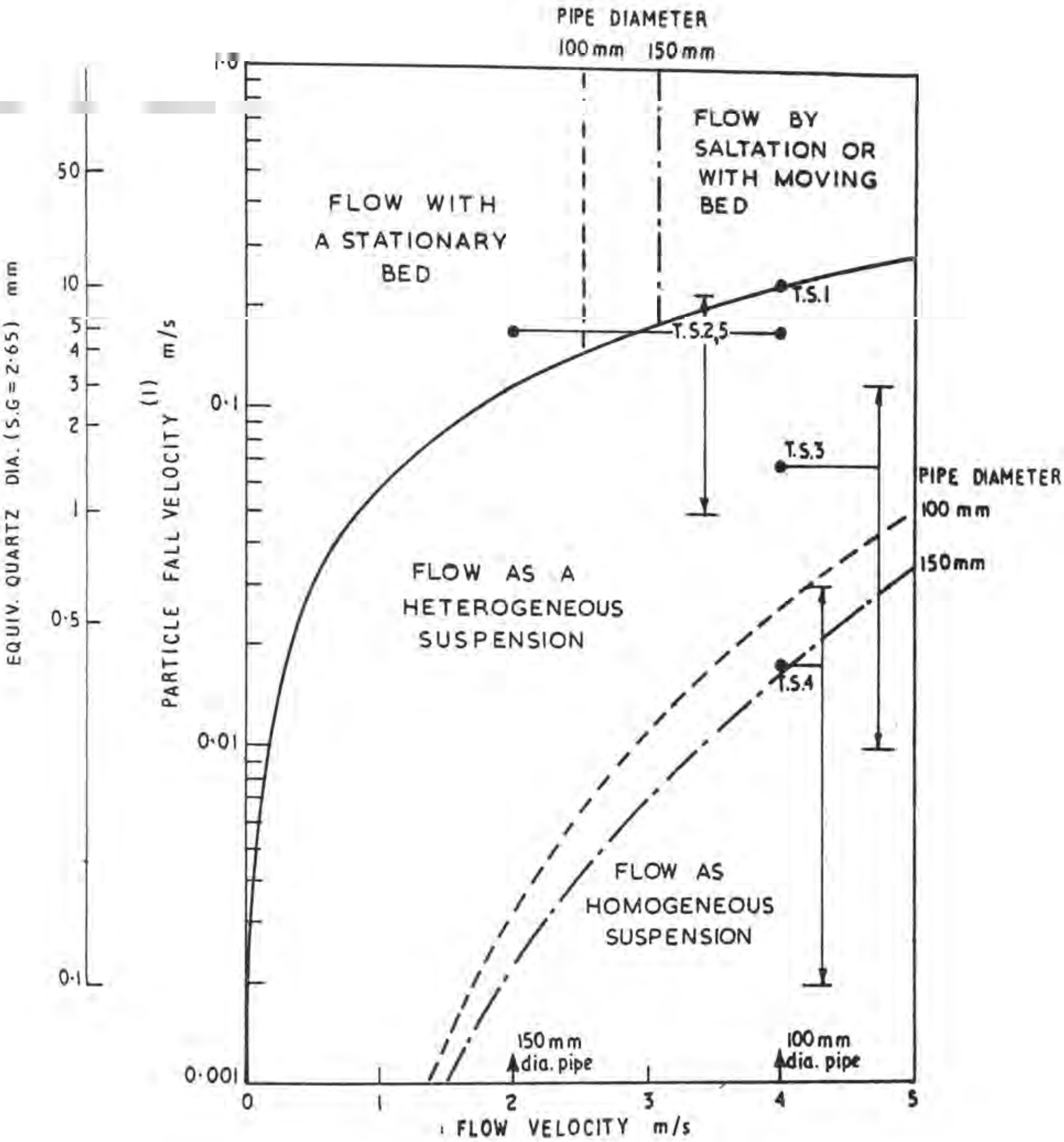


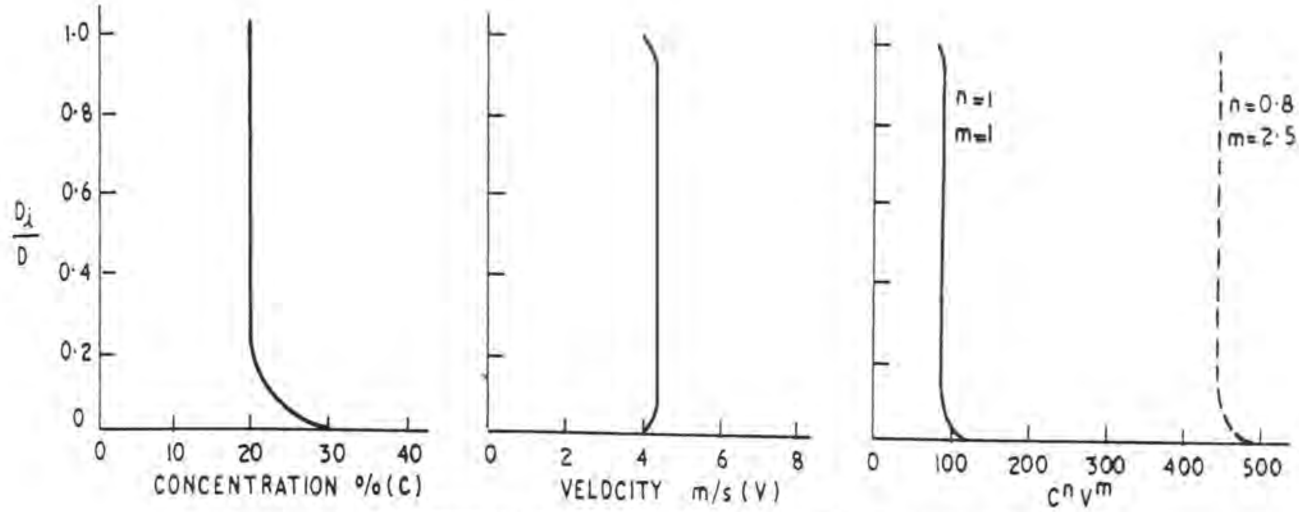
FIGURE . 40 : F_L AS A FUNCTION OF PARTICLE DIAMETER AND CONCENTRATION.
(After Durand and Mih)



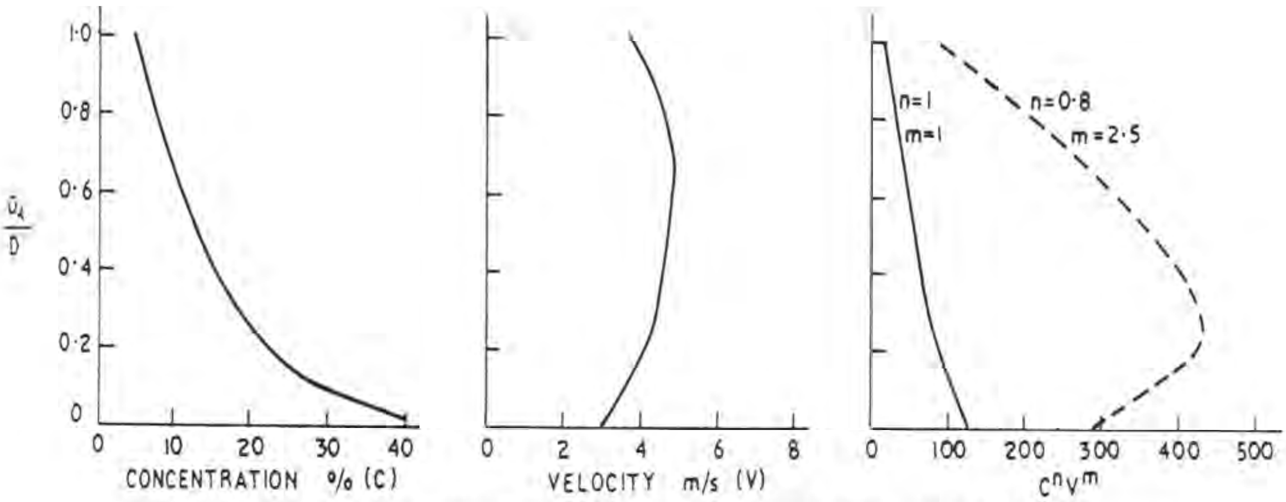
Note:

(i) Fall velocities taken to be one third of clear water values (after Du Plessis and Ansley (1967))

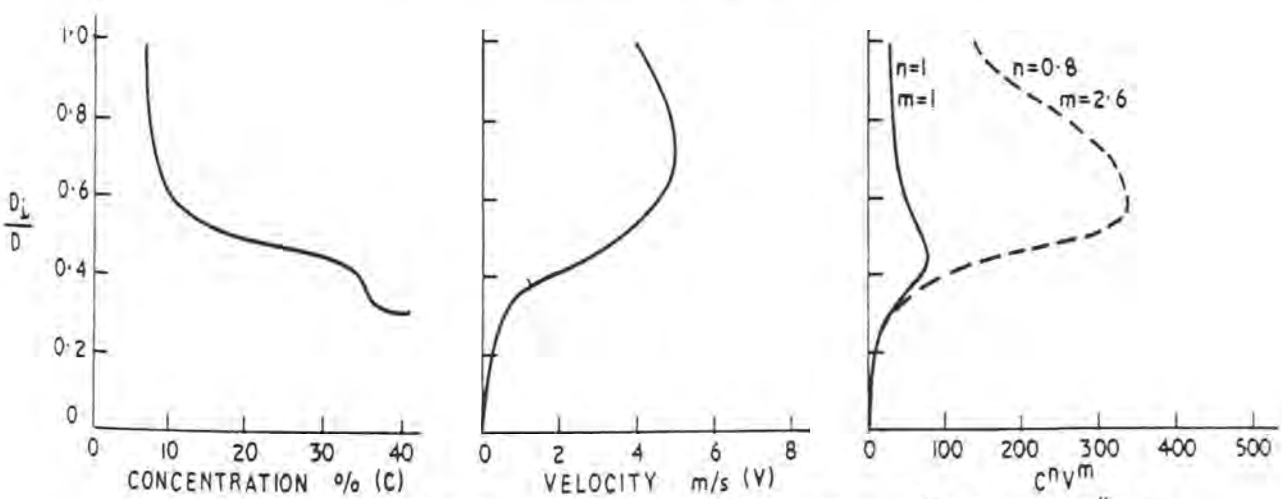
FIGURE 41: FLOW REGIME DIAGRAM FOR 100 MM AND 150 MM DIA. PIPES



(i) PREDOMINANTLY HOMOGENEOUS SUSPENSION
(Corresponding to T.S.4)



(ii) PREDOMINANTLY HETEROGENEOUS SUSPENSION
(Corresponding to T.S.3)



(iii) PREDOMINANTLY SALTATION WITH A "STATIONARY" BED
(Corresponding to T.S.5, Vavg.= 2 m/s)

FIGURE 42: POSSIBLE PARTICLE FLUX PROFILES FOR DIFFERENT FLOW REGIMES

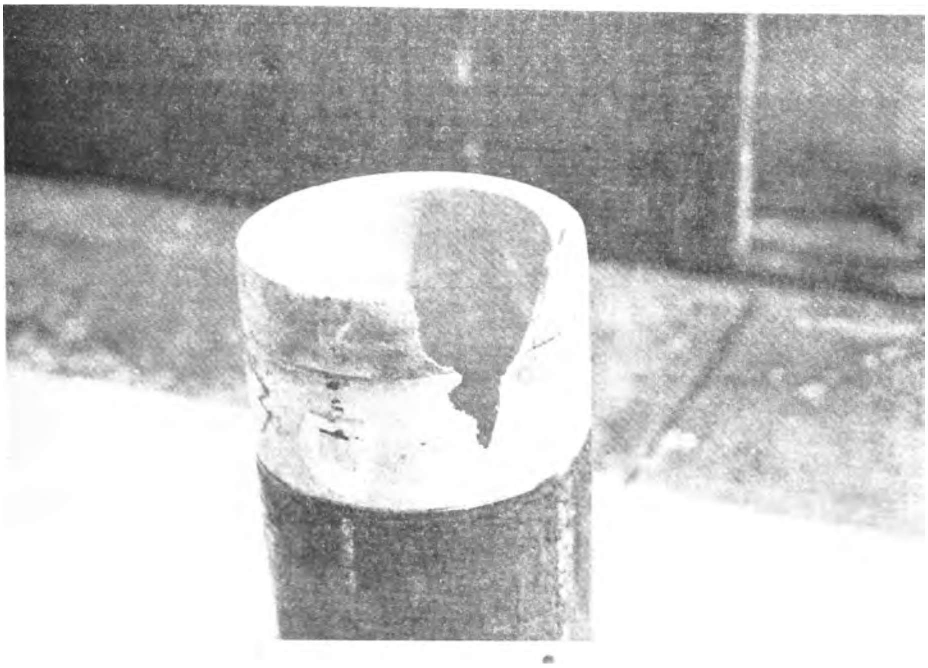


Photo 1: Failure in the upstream end of the asbestos pipe (Test 3)

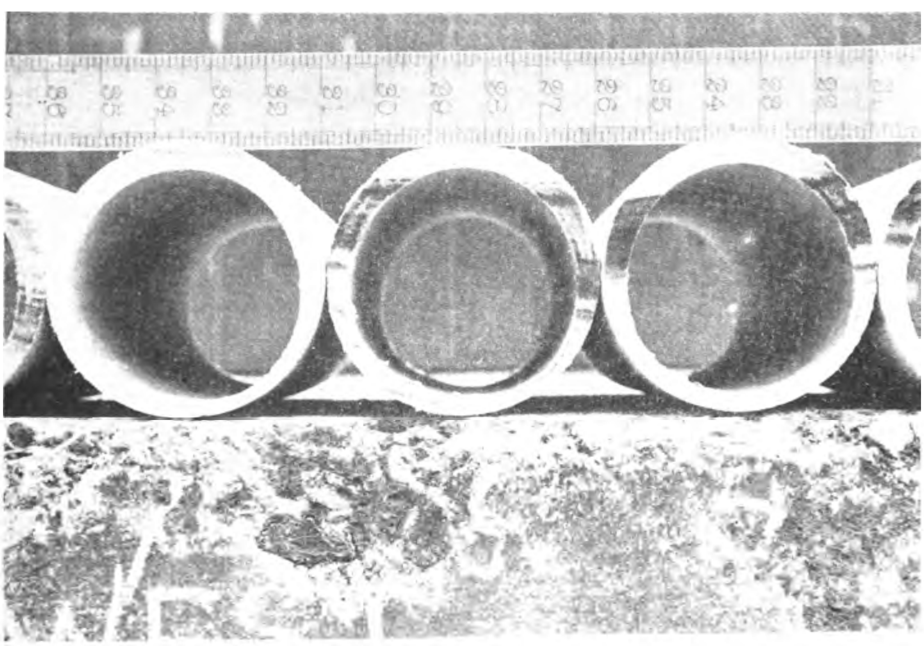


Photo 2: The asbestos pipe in sections for post failure measurements (Test 3)

Photo 3: Breach of the Lining in the Downstream end of the Epoxy Pipe (Test 3).

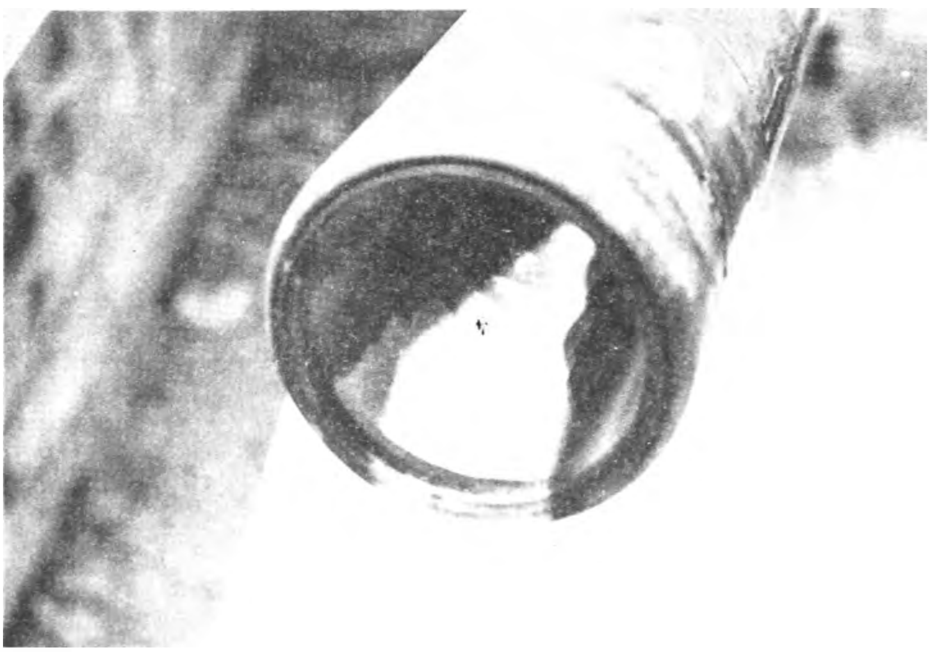


Photo 4: Breach of the lining in the upstream end of the Epoxy Pipe (Test 3).

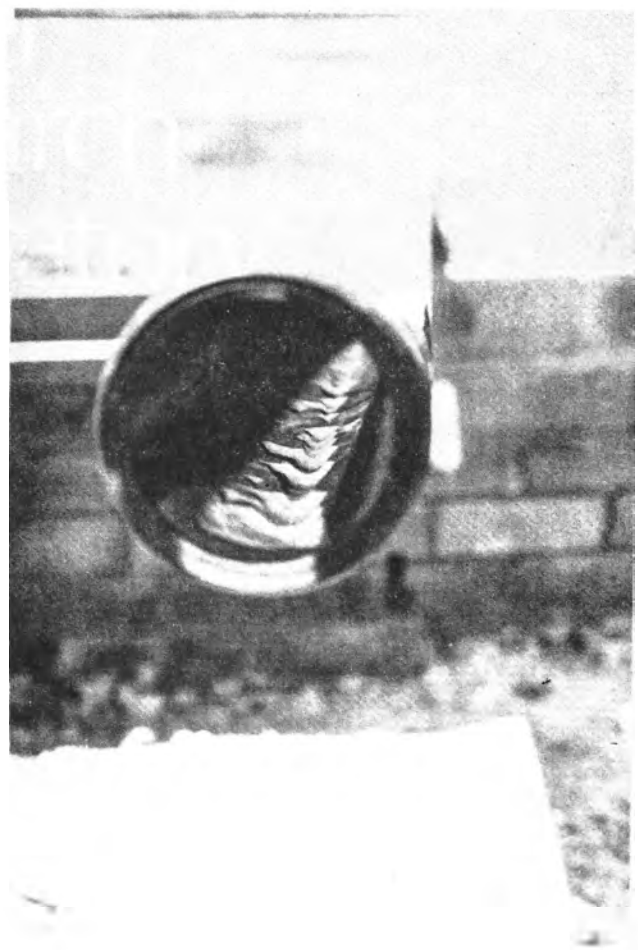


Photo 5: View into the Upstream end of the Epoxy Pipe showing erosion along the Invert (Test 3)