THE INFLUENCE OF DESIGN PARAMETERS ON THE EFFICIENCY OF PYRITE FLOTATION IN AIR-SPARGED HYDROCYCLONES

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ABSTRACT

Two batches of ore, A and B, from the reclaimed dumps of ERGO Ltd on the East Witwatersrand were used to investigate the effect of design parameters on the flotation of pyrite in an air-sparged hydrocyclone (ASH). In the ASH, air is sparged radially through the porous cylinder and dispersed by the high velocity of slurry in swirl flow countercurrent to the rising froth phase. The froth overflowing through the vortex finder is loaded with hydrophobic particles, while the tailings flow downward. A spigot where flow is restricted by a horizontal baffle, positioned 30 mm above an orifice, proved to be more successful than a spigot consisting of an annular opening between a pedestal and the cylindrical wall, and a flow restricting orifice below.

Pyrite from both samples A and B was difficult to float efficiently. Sample A, which contained only 0.14 %S, yielded typical sulphur recoveries of 40 % and associated grades of 4 %S in the ASH, while batch flotation yielded recoveries of 65 % and grades of 11 %S. The corresponding results for Sample B with a head grade of 1.42 %S, were 40 % and 7.5 %S in the ASH, and 56 % and 6 %S in batch tests. From a variety of runs, it can be concluded that flotation in the ASH is influenced mainly by the tangential velocity and the hold-up of slurry. Hence, the effective design of an ASH is critically dependent on the dimensions of the cylinder, vortex finder and the spigot. For some ASH designs, flotation performance could be improved noticeably by sealing off the lower part of the porous cylinder.

INTRODUCTION

The inefficient recovery of fine particles in conventional froth flotation results in large quantities of valuable minerals being lost to tailings [1]. Owing to the relatively low intensity of turbulence, the probabilities of collision and attachment in conventional flotation cells are low. Consideration of these constraints led to the development of an air-sparged hydrocyclone (ASH) in the late seventies at the University of Utah [2]. The powerful centrifugal forces developed in a hydrocyclone, together with a high concentration of small bubbles are utilized to achieve effective flotation of fine particles at an increased rate. Bubble attachment phenomena, rather than the rate of collision or air flow, limit the rate of flotation in an ASH [3]. In an ASH, separations can be achieved for residence times of about one second rather than minutes as in conventional flotation cells.

The ASH consists of a vertical porous cylinder with slurry fed tangentially at the top, froth overflowing through the vortex finder, and tailings flowing downward through a spigot. The high velocity of slurry in swirl flow, countercurrent to the rising froth phase, disperses the air which is sparged radially through the porous wall.

Miller and co-workers have proved their concept in the flotation of oil shale [4], fine coal [5], copper sulphide ore [6] and fine gold [7]. They have also conducted fundamental work on the dynamic performance of the ASH [3,8,9]. Burger [10] and Van Deventer *et al.* [11] showed that the ASH could be used successfully for the flotation of a coarse pyritic ore containing 1.74 %S, and investigated the effect of operating variables. Although Miller and co-workers have conducted a wide range of fundamental research on the ASH, it is believed that factors influencing the design of an ASH are still understood poorly.

This paper reports the influence of design variables on the flotation performance of the ASH using two quartzitic gold ores from the Witwatersrand. These ores were of a lower grade and less amenable to flotation than that used by Burger [10]. The effect of the operating parameters such as the head grade and the mass % of solids in the slurry will also be discussed. This paper will be a further advance towards an understanding of the ASH, but will certainly not present a final analysis of the very complex flow patterns in the ASH.

EXPERIMENTAL

Air-Sparged Hydrocyclone (ASH)

Two different air-sparged hydrocyclones, ASH I and ASH II, were used to generate the results presented in this paper.

ASH I consisted of a slurry inlet of 15.8 x 5.4 mm^2, vortex finder of diameter 13.7 mm and length 50 mm, porous ceramic cylinder of internal diameter 50 mm, length 410 mm and porosity 1 micron, and a 44.1 mm diameter pedestal above the spigot with an orifice of diameter 10 or 15 mm. This configuration was similar to that used by Burger [10].

ASH II was fitted with porous sintered bronze cylinders, and a simple horizontal baffle with length equal to the internal diameter of the cylinder, was placed 30 mm above the orifice. The design of ASH II permitted a variety of hydrocyclone configurations as shown in Table I.

TABLE I: DESIGN PARAMETERS USED IN ASH II

Parameter	Dimensions			
Slurry inlet area (mm^2)	15x6	15x9	15x12	
Diameter of vortex finder (mm)	13.7	21.7	27.7	
Length of vortex finder (mm)	50	75	100	
Internal diameter of cylinder (mm)	46	76	96	
Length of cylinder (mm)	300	400	500	
Porosity of cylinder (micron)	2	8	12	18
Diameter of orifice (mm)	10.5	14	22	

(Numbers in **bold** depict the standard dimensions for ASH II. These standard conditions were used, except where mentioned otherwise in the figures.)

Characteristics of the Ores

Two different batches of ore, A and B, obtained from the reclaimed dumps of ERGO Ltd. on the East Witwatersrand, were used. Table II gives the distribution of total mass and sulphur in the particle size fractions. It is clear that ore A was much coarser than ore B. The bulk of the pyrite in ore B was in the -38 micron fraction.

Batch flotation tests were conducted in a 2.5 l Leeds cell. The conditions used were an air flow rate of 6 l/min, a froth height of 12 mm, impeller speed of 1100 r.p.m. and the concentration of both collector and frother was 50 p.p.m.

Results illustrated in Figure 1 show that batch tests at 28.6 mass % solids on ore A yielded an optimal sulphur recovery of 65 % and an associated grade of 11 %S, while the corresponding values for ore B were 56 % and 6 %S respectively. At 50 mass % solids ore B yielded a sulphur recovery of 66 % and a grade of 5 %S.

These results prove that neither of the ores floated easily. Although ore B had a high head grade of sulphur, it was the large percentage of fine pyrite bearing particles that could not be floated.

TABLE II: DISTRIBUTION OF PARTICLE SIZE AND SULPHUR IN ORES A AND B

Size fraction (micron)	Mass %		Mass % of total S in size fraction	
	Ore A	Ore B	Ore A	Ore B
+300	15.9	3.2	6.2	11.3
+212	17.3	3.7	7.7	1.0
+150	23.5	7.7	11.8	1.0
+106	23.6	21.4	19.8	9.2
+ 75	9.2	10.6	16.5	9.5
+ 53	6.9	9.0	24.4	13.3
+ 38	2.2	6.4	8.3	9.9
- 38	1.4	38.0	5.3	44.8
Average mass %S			0.14	1.42

Operating Procedures

A pyrite slurry containing 10 mass % solids was prepared in a 470 l conditioning tank using tap water. The slurry was mixed for 15 minutes before 160 p.p.m. of sodium isobutyl xanthate was added. Another 5 minutes followed before 40 p.p.m. of Dowfroth 250E was added. The slurry was pumped to the ASH 10 minutes after frother addition. Samples of the overflow and underflow were taken simultaneously and weighed. The solids were filtered, dried and assayed for sulphur. Mass and sulphur balances were accurate within 5 %. For ASH I the air flow rate was 200 l/min. The air flow rate for ASH II of length 500 mm and inner diameter 46 mm was 205 l/min, and for other configurations of ASH II the air flow rate was scaled-up on a volumetric basis as shown in Table III.

Experiments were conducted where sections along the length of the ASH were sealed off. The flow of air was maintained at a constant level for a specific ASH system, so that the flux of air increased through the remaining aerated area. For ASH I 25 % of the cylinder was sealed off at different positions, while only the bottom 30 % was sealed off in the case of ASH II.

TABLE III: FLOW RATES OF AIR IN ASH II

Cylinder Length (mm)	Cylinder Diameter (mm)	Air Flow Rate (l/min)
300	46	123
300	96	536
400	46	164
400	96	714
500	46	205
500	76	560
500	96	893

RESULTS AND DISCUSSION

Design of Underflow Outlet

ASH I was used here to improve the design proposed by Burger [10] and Van Deventer *et al.* [11].

The effect of a pedestal, as suggested by Miller and Kinneberg [3], was investigated by feeding slurry A to ASH I. The underflow outlet for ASH I was fitted with a pedestal, which was supported by three baffles spaced at angles of 120°, and followed by an orifice below. In this case the underflow was limited by the orifice below the pedestal, and not by the annular opening between the pedestal and the cylinder. Orifice diameters of 10 or 15 mm were used.

When this pedestal was removed, the recoveries of solids and water changed very little, while the recovery of pyrite increased slightly as illustrated in Figure 2. The concentrate grade changed very little at an orifice diameter of 10 mm, but increased significantly at 15 mm according to Figure 3. Hence, it could be concluded that a pedestal is not required in the ASH.

When the outlet, as mentioned above, was replaced by an orifice without any baffles, it was found that the water recovery at high feed rates of slurry increased, while the sulphur recovery and grade decreased correspondingly as shown in Figures 2 and 3. This could be attributed to the absence of baffles, which decelerated the swirl flow near the bottom of the ASH. A horizontal baffle placed slightly above the orifice is possibly the simplest method by which deceleration of the swirl flow can be achieved. Hence, the spigot for ASH II

consisted of an orifice and a horizontal baffle, placed at a height of 30 mm above the orifice.

It was possible that this deceleration reduced turbulence in the froth phase, which inhibited the entrainment of water. The recovery of pyrite particles, however, would be enhanced in view of the lower shearing forces on particle-bubble aggregates.

Area of Slurry Inlet

Owing to the complex flow patterns in the ASH and the wide range of variables affecting its performance, it is difficult to draw general conclusions from one set of results. Nevertheless, Figures 4 and 5 indicate that the recovery of pyrite decreased generally with an increase in the feed rate of slurry, while the sulphur grade reached a maximum at intermediate feed rates.

The increased centrifugal force associated with an increase in the feed rate caused more particles to report to the underflow. As a result of the low density of the hydrophobic particle-bubble aggregates, relatively more hydrophilic particles than hydrophobic particles were affected in this way. It appeared that the recovery of total solids reached an asymptotic level at higher feed rates owing to the restriction of flow through the vortex finder. The decrease in the sulphur grade at higher feed rates can thus be explained by the decrease in recovery of pyrite relative to the recovery of total solids.

Figure 4 shows that the dimensions of the slurry inlet did not affect the recovery of sulphur substantially. However, the centrifugal velocity associated with the point of maximum sulphur grade in Figure 5 shifted to higher feed rates at larger inlet areas.

Diameter of Vortex Finder

According to Ye *et al.* [12] the concentration of hydrophobic particles decreases radially from a maximum in the centre of the froth phase to a minimum in the slurry layer. When the diameter of the vortex finder is increased, the froth core recovered will increase in diameter. This will result in an increased recovery of hydrophobic particles, but a decrease in concentrate grade [12]. Figures 6 and 7 show that an increase in the diameter of the vortex finder from 13.7 to 21.7 mm confirmed this hypothesis concerning the decrease in grade, but yielded almost no improvement in recovery.

When the diameter was increased to 27.7 mm, the recovery of pyrite in Figure 6 decreased, while the recovery of total solids also decreased. Figure 7 shows that the grade did not

change noticeably at lower feed rates, but increased slightly at higher centrifugal velocities. An explanation for this behaviour could be that the resulting drop in pressure over the length of the ASH had a more pronounced effect than the increase in the diameter of the froth core. Furthermore, the hydrophobic particle-bubble aggregates could have a lower sensitivity to this drop in pressure than have the hydrophilic particles. This would have resulted in a relatively lower recovery of gangue associated with the decrease in recovery of pyrite, and consequently an improvement in the grade.

Length of Vortex Finder

As the vortex finder penetrates deeper into the ASH, it could be expected that the effective length of the froth core will decrease. This will lead to lower recoveries of total solids and pyrite, which corresponds to the results of Figure 8 for the lengths of 75 and 100 mm. When a length of 50 mm was used, the recovery decreased below that of the 75 mm length at low feed rates. A possible explanation for this could be the destabilization of the froth by the highly turbulent region near the slurry inlet. This reversed trend was also observed in the case of a vortex finder diameter of 27.7 mm and a porosity of 2 micron.

It could be assumed that the grade in the froth core increased from the bottom to the top of the ASH. Hence, an increase in the length of the vortex finder will result in lower grades, as illustrated in Figure 9.

Diameter and Length of Porous Cylinder

It was clear that the effects of the diameter and length of the cylinder were interrelated, and should not be discussed independently. As illustrated in Figures 10 to 13, a diameter of 46 mm was most appropriate for an ASH length of 500 mm, while a diameter of 96 mm decreased the performance significantly. This decrease could be explained in terms of the low centrifugal velocity expected near the bottom of the 500 mm x 96 mm ASH, which would destabilize the froth. As shown in Figures 10 and 11, the performance of this ASH could be expected to increase towards higher feed rates for ore A. However, this trend could not be observed for the much finer ore B.

Figures 12 and 13 show that the 500 mm ASH yielded better grades for a diameter of 96 mm, but lower recoveries compared with a diameter of 46 mm. Better recoveries were obtained when using a diameter of 96 mm than 46 mm for lengths of 400 and 300 mm, although the grades did not change much. For the shorter cyclones with a diameter of 46 mm the hold-up of slurry could proportionally be higher than that for a diameter of 96 mm. Hence, the slurry flow layer could be shearing too much on the outside of the froth

phase and thus losing valuable particles to the tailings. In the case of the smaller cyclones, the proportionally higher hold-up of slurry caused the ASH to act primarily as a flow splitter, so that the effect of flotation was inhibited.

Porosity of Cylinder

Ye *et al.* [12] argued that bubble-particle attachment in the ASH occurs by collision contact rather than by sliding contact. Hence, the efficiency of flotation will improve with an increase in the total external surface area associated with the production of smaller bubbles by a lower cylinder porosity. As shown in Figure 14, the recovery of pyrite increased in general with the production of smaller bubbles. Moreover, the higher water recovery associated with lower porosity enhanced entrainment of gangue, which caused a general reduction in the grade as illustrated in Figure 15.

Diameter of Underflow Outlet

If the orifice diameter is increased moderately, it could be assumed that the hold-up of slurry decreased. This would have resulted in a larger contact area between the slurry flow and the froth core, and thus an improvement in the recovery of pyrite (Figure 16). The larger the diameter of the orifice, the lower the recoveries of both water and solids. This was clearly accompanied by an increase in the concentrate grade, as illustrated in Figure 17.

When the orifice diameter was increased even further, the low hold-up, and hence a low pressure difference across the ASH, was not sufficient to support the froth core. Consequently, the recovery of pyrite dropped significantly at lower feed rates, as shown in Figure 16. At higher feed rates, however, the hold-up and pressure increased sufficiently to counteract the effect of the larger spigot diameter, so that the recovery of pyrite increased gradually. The relatively high grades obtained at high slurry feed rates and larger diameters of the orifice show that the latter variable is extremely important in the control of the ASH.

Aeration Area of Cylinder

In this section results obtained when sealing off portions of the cylinder, will be presented. As illustrated by Figures 18 and 19, inert sections above the centre of ASH I yielded the highest recovery of sulphur, but did not enhance the grade significantly. Inert sections below the centre of the cylinder yielded a more moderate increase in recovery, but enhanced the grade to levels comparable to that obtained in batch tests. According to

Burger [10], an increase in the flow rate of air as such did not produce similar effects, which means that the efficiency of the ASH was sensitive to the distribution of air along the length of the ASH.

According to Figures 20 to 23 a decrease of 30 % in aeration area was detrimental to recovery and grade for all length-diameter combinations of ASH II, except for the ASH of 400 mm length and 46 mm diameter. This result is surprising, especially in view of the significant enhancement of recovery and grade obtained with two cyclones of about 400 mm x 50 mm.

Figures 22 and 23 suggest that the 500 mm x 96 mm ASH could possibly yield a similar improvement at sufficiently high feed rates. These observations suggest that the fractional hold-up of slurry, the position of the slurry-froth interface, and the pressure drop across the ASH should all be within certain ranges before such improvement could be observed. As stated before, the 300 mm x 46 mm ASH would be expected to have a relatively large hold-up, so that a change in the pattern of aeration did not have a great influence.

Effect of Head Grade

Figures 24 to 27 illustrate results for slurries A and B when enriched artificially with pyrite. Recovery of solids increased to an upper limit, while the recovery of water decreased to a lower limit with an increase in head grade. Figures 24 and 25 illustrate that both the recovery of pyrite and the grade reached a maximum. For head grades exceeding about 1 %S the recovery of pyrite decreased considerably.

Ye *et al.* [12] found that the diameter of the vortex finder controlled the diameter of the froth core entering the overflow. Also, the position of the highest concentration of hydrophobic particles is situated at the mouth of the vortex finder. Hence, it is possible that this diameter could limit the recovery of high concentrations of pyrite from the froth as illustrated in Figure 24. The results shown in Figures 26 and 27 revealed that a larger vortex finder alleviated this restriction at higher flow rates.

Effect of Mass % Solids in Slurry

For 50 mass % solids as opposed to 10 mass % solids in the slurry, the recovery of solids and water increased significantly. Figures 28 and 29 illustrate an increase in the recovery of pyrite and a corresponding decrease in the sulphur grade. At higher feed rates the grades tended to be more or less the same. It is therefore possible to beneficiate relatively concentrated slurries in the ASH without sacrificing efficiency.

CONCLUSIONS AND SIGNIFICANCE

The two batches of ore, A and B, from the reclaimed dumps of ERGO Ltd, were difficult to float efficiently. Sample A, which contained only 0.14 %S, yielded typical sulphur recoveries of 40 % and associated grades of 4 %S in the ASH, while batch flotation yielded recoveries of 65 % and grades of 11 %S. The corresponding results for Sample B with a head grade of 1.42 %S, were 40 % and 7.5 %S in the ASH, and 56 % and 6 %S in batch tests. Despite the poor floatability of the ores, the ASH proved to be a viable alternative to conventional flotation. Slurries containing 50 mass % solids could be used effectively in the ASH.

Contrary to Miller and Kinneberg's [3] suggestion of an annular discharge and a froth pedestal, it was found here that a simple spigot consisting of a horizontal baffle positioned 30 mm above an orifice yielded the best results. From a variety of runs, it can be concluded that flotation in the ASH is influenced mainly by the tangential velocity and the hold-up of slurry. Hence, the effective design of an ASH is critically dependent on the dimensions of the cylinder, vortex finder and the spigot. The diameter of the vortex finder should be increased if it is found to limit the recovery of pyrite from high concentrations in the froth.

Significantly improved performance could be achieved by sealing off the lower part of the porous cylinder if the fractional hold-up of slurry, the position of the slurry-froth interface, and the pressure drop across the ASH are all within certain ranges.

The ASH has potential as a rougher cell in closed circuit with a mill, to produce concentrate as feed to a column flotation cell, and where the higher capital costs of a conventional flotation plant could not be justified. In view of its compactness, the ASH could also be used in mobile plant and in underground processing.

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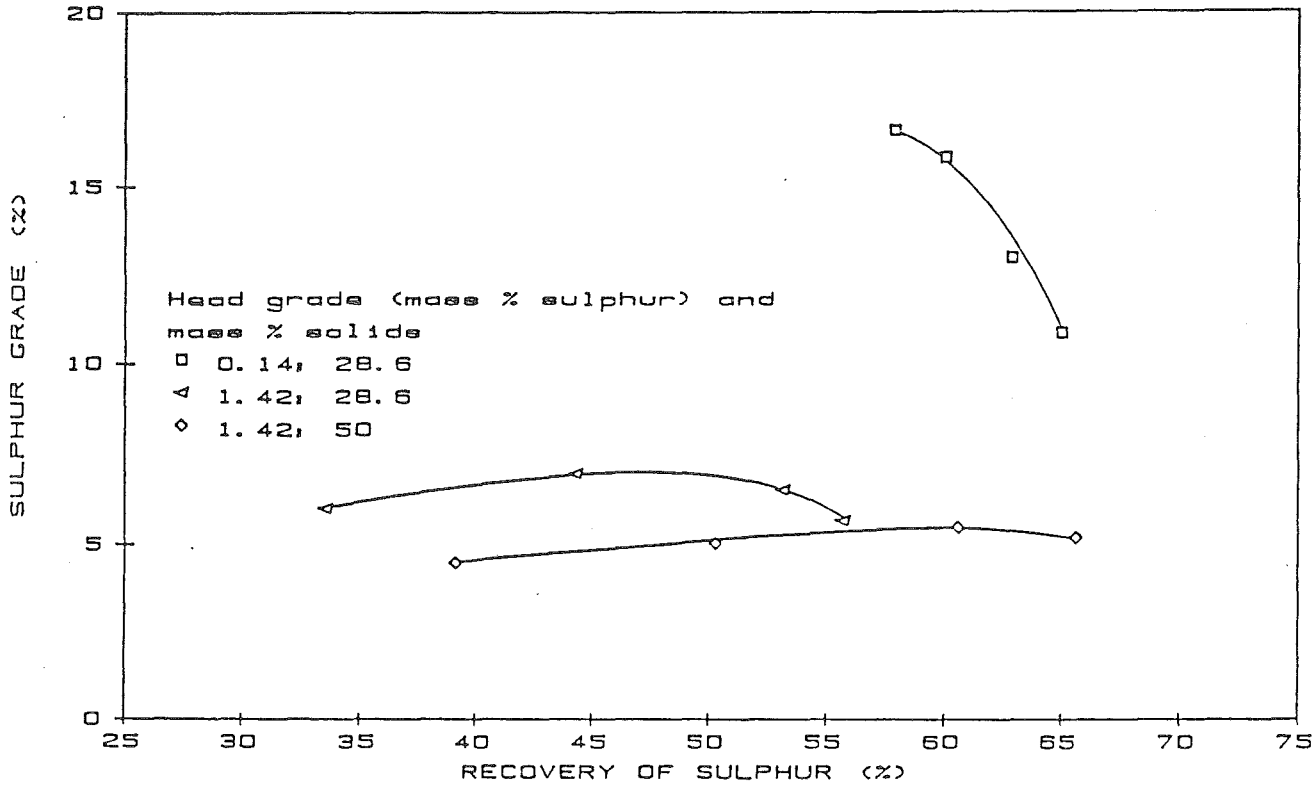

FIGURE 1: Grade-recovery curve for batch flotation with slurry A and slurry B at different mass % of solids.

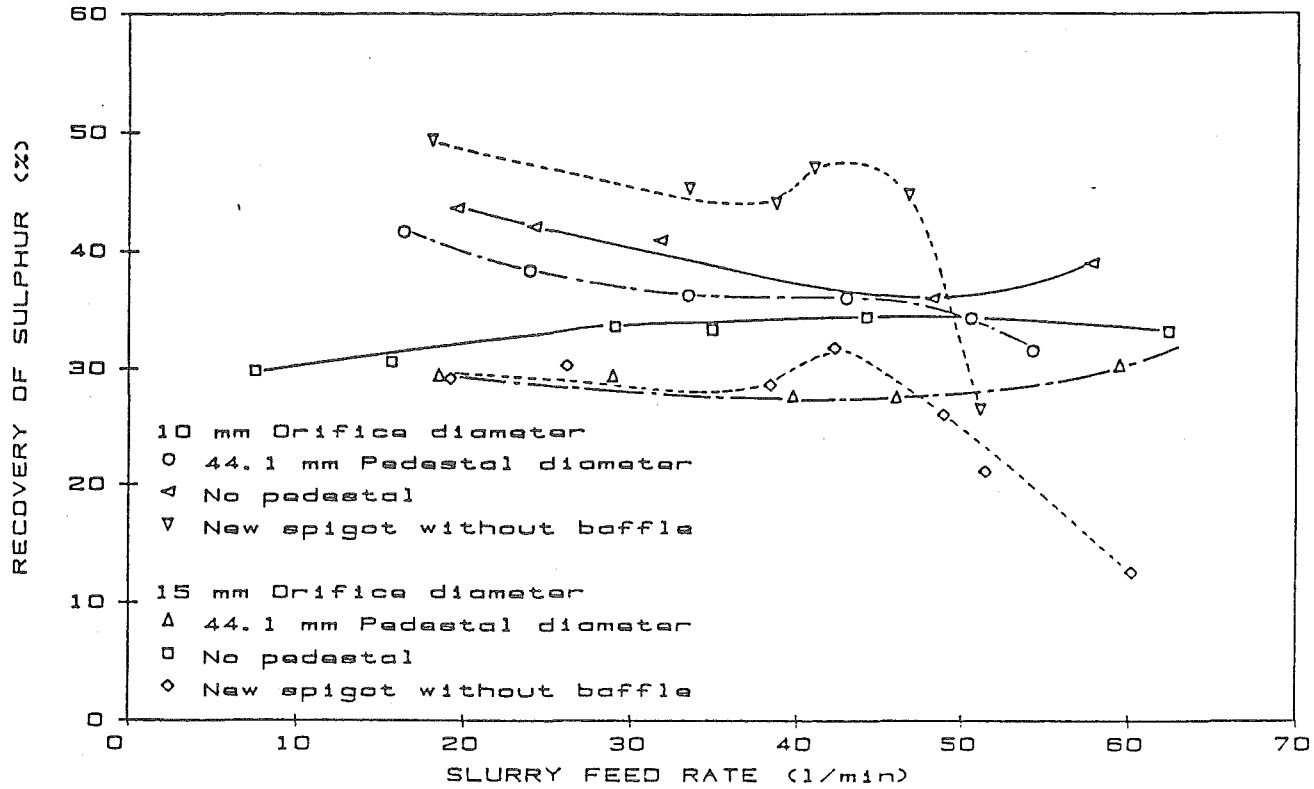

FIGURE 2: Recovery of sulphur for ASH I with slurry A, different underflow outlet configurations and orifices of different diameters.

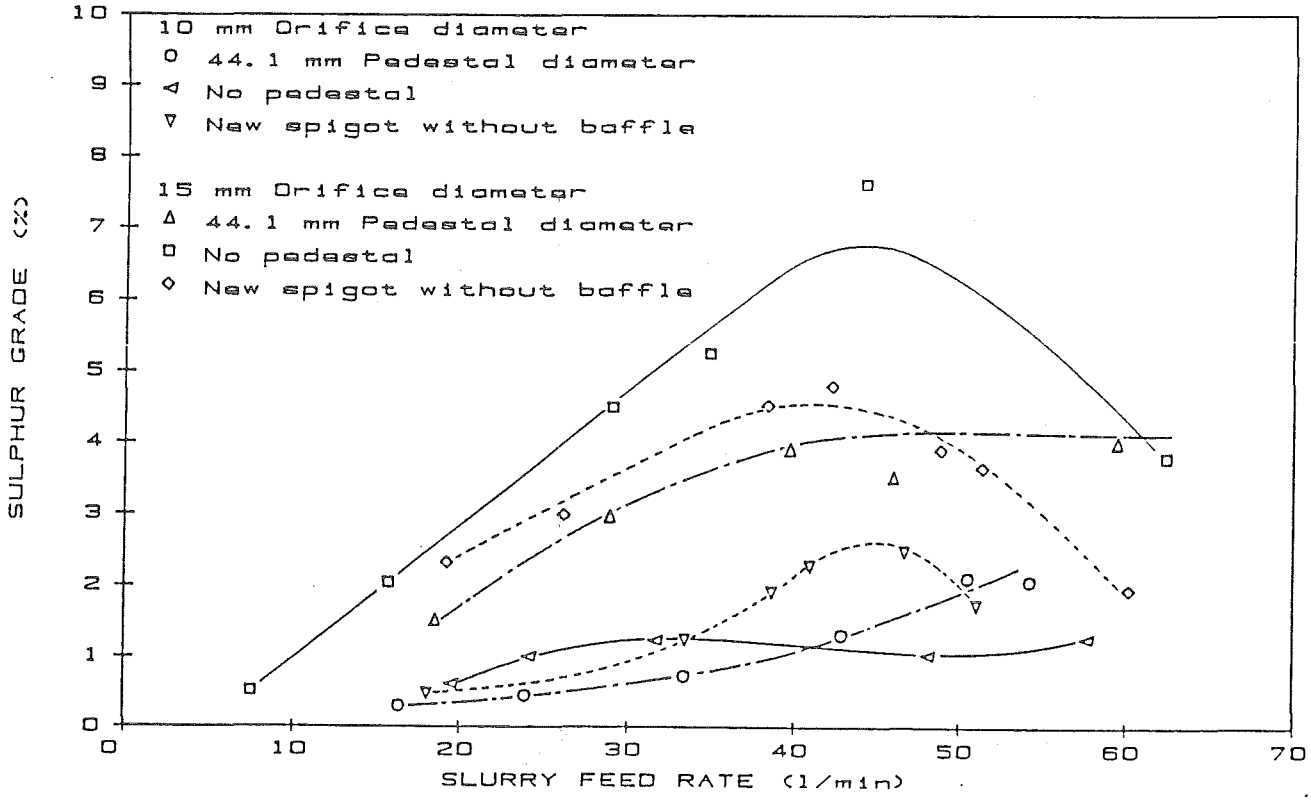

FIGURE 3: Sulphur grade of concentrate for ASH I with slurry A, different underflow outlet configurations and orifices of different diameters.

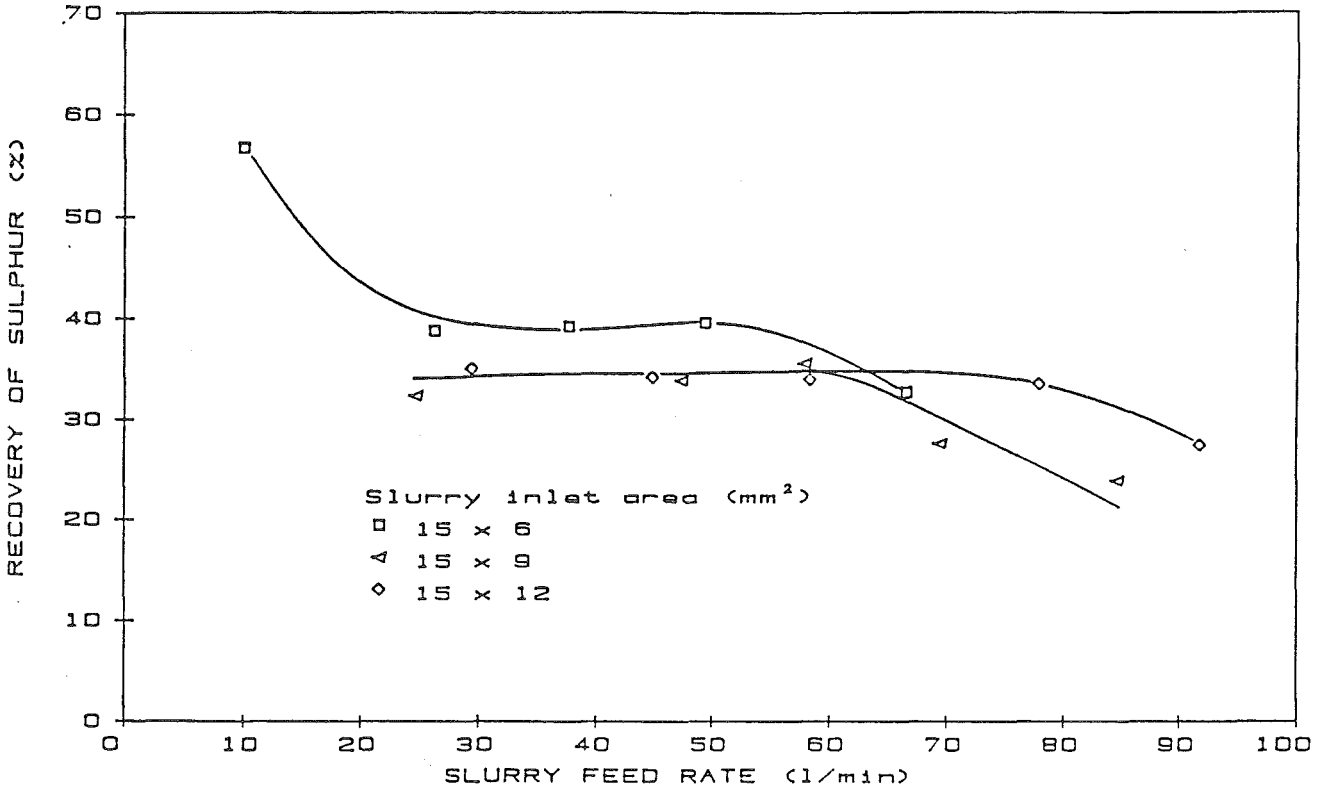

FIGURE 4: Recovery of sulphur for ASH II with slurry A and slurry inlets of different areas.

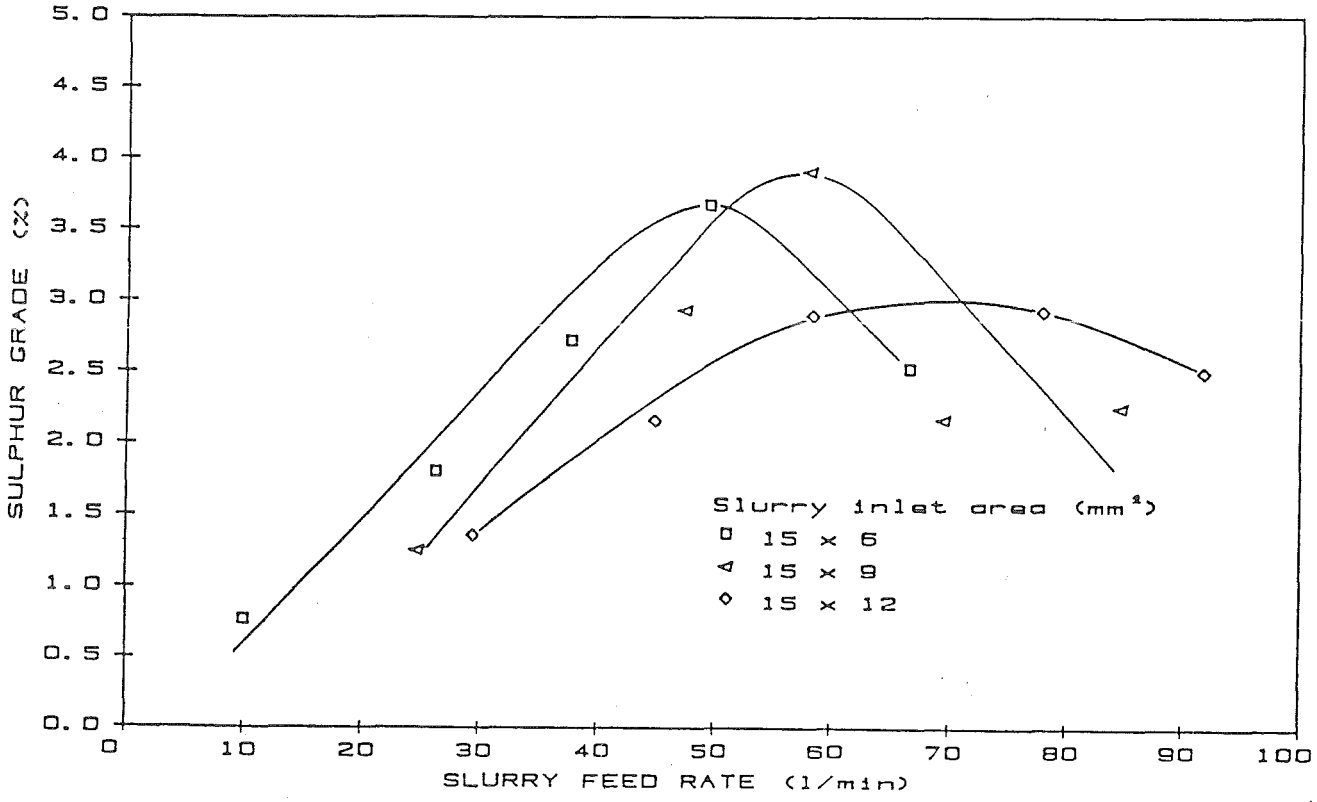

FIGURE 5: Sulphur grade of concentrate for ASH II with slurry A and slurry inlets of different areas.

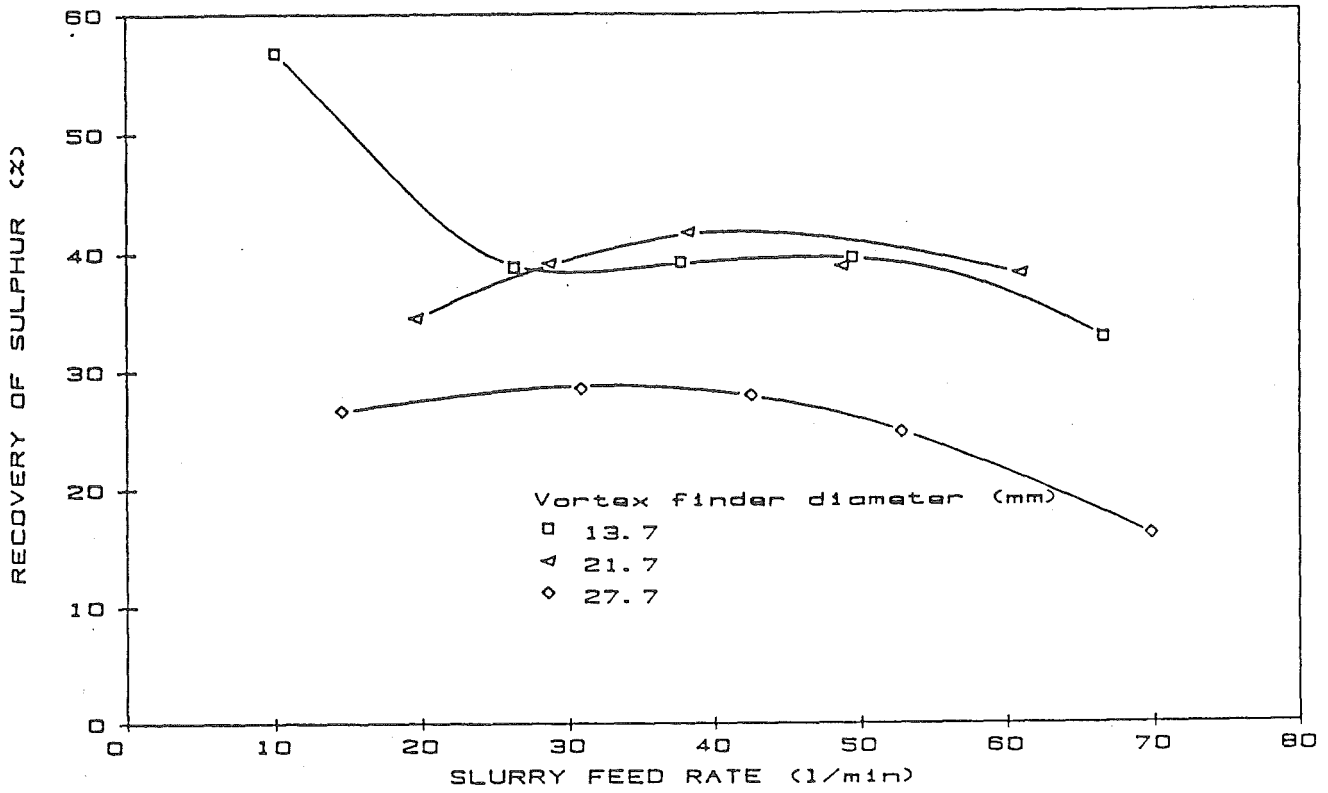

FIGURE 6: Recovery of sulphur for ASH II with slurry A and vortex finders of different diameters.

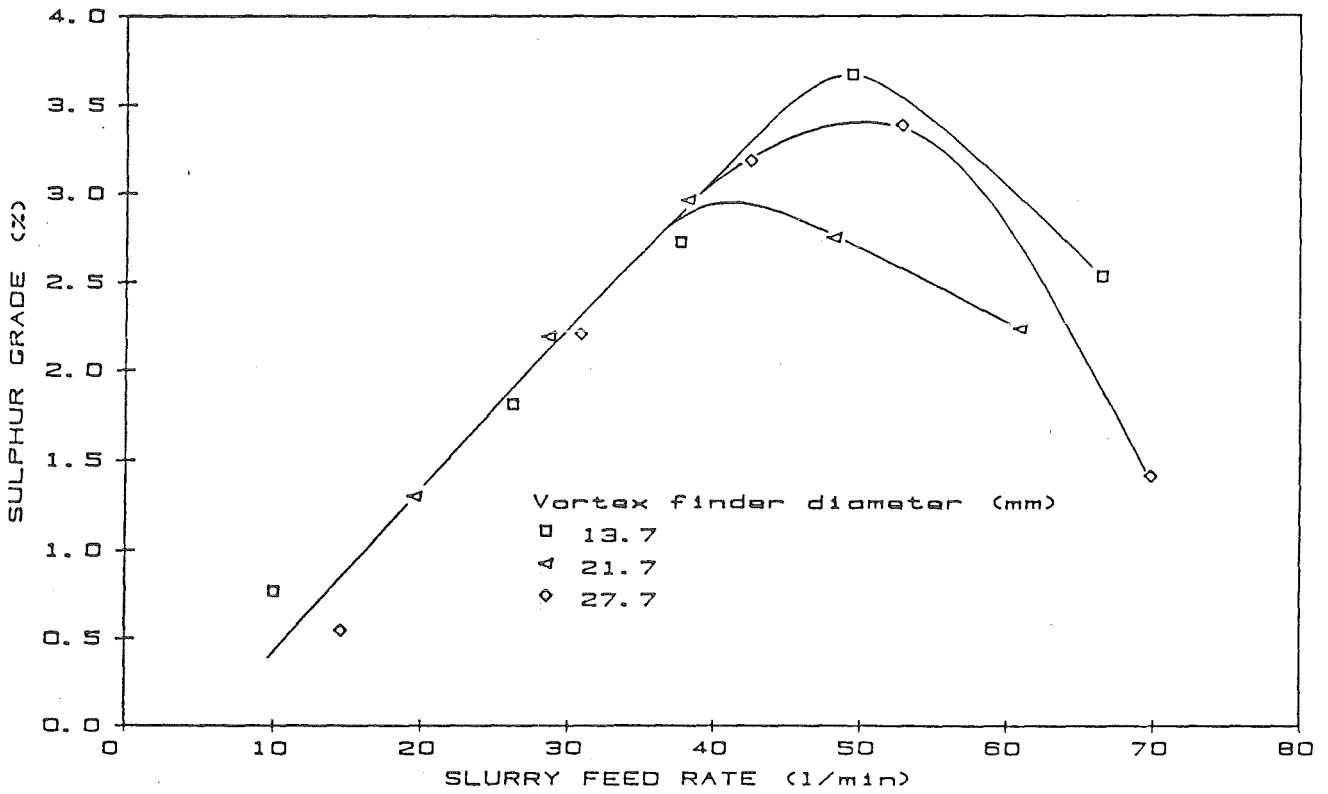

FIGURE 7: Sulphur grade of concentrate for ASH II with slurry A and vortex finders of different diameters.

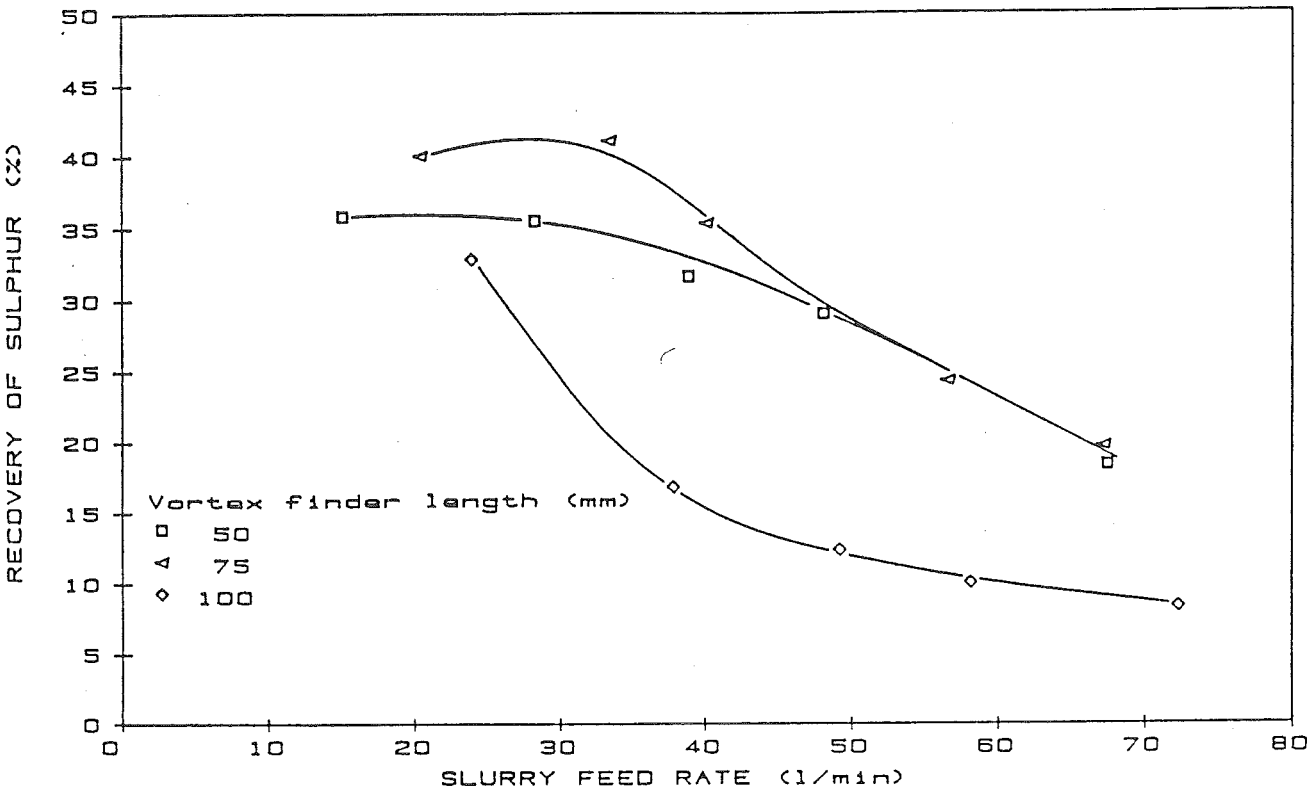

FIGURE 8: Recovery of sulphur for ASH II with slurry A, a cylinder porosity of 18 micron and vortex finders of different lengths.

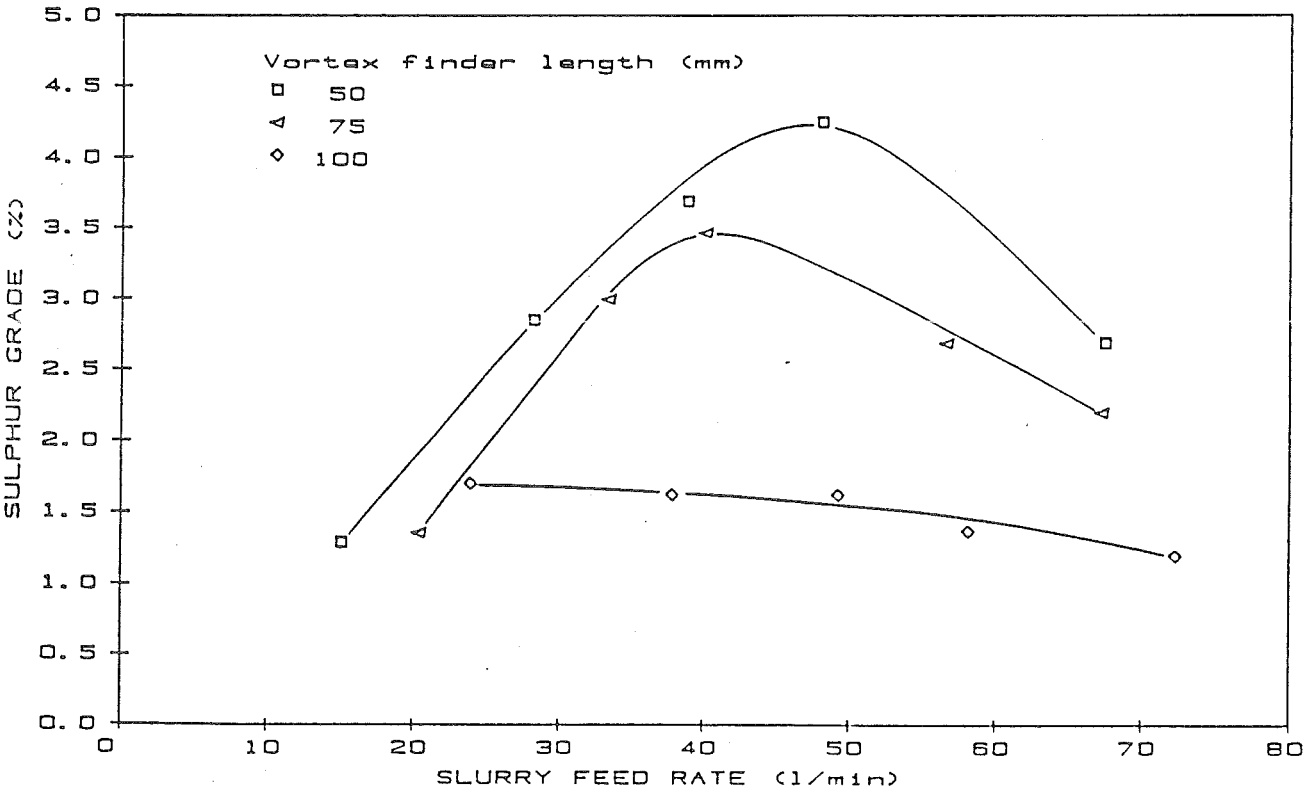

FIGURE 9: Sulphur grade of concentrate for ASH II with slurry A, a cylinder porosity of 18 micron and vortex finders of different lengths.

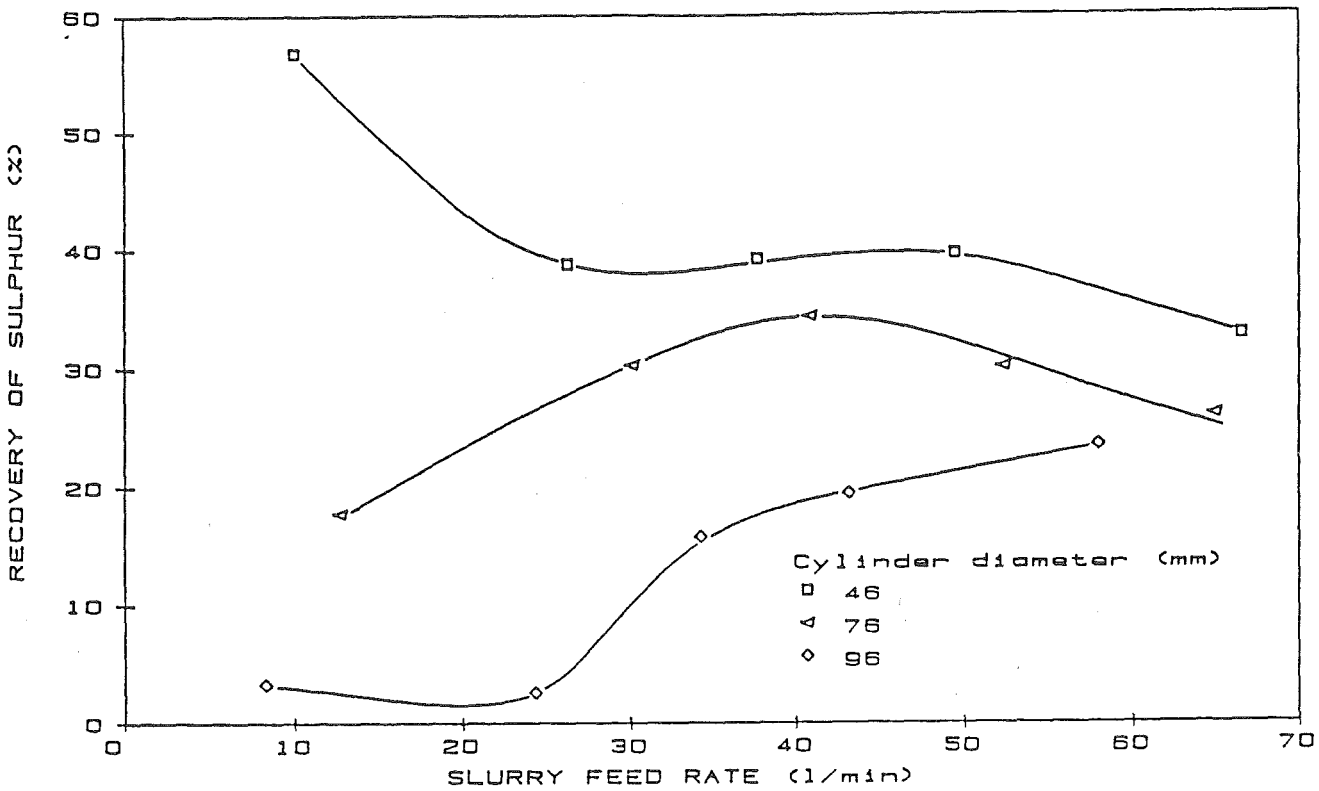

FIGURE 10: Recovery of sulphur for ASH II with slurry A and cylinders of different inner diameters.

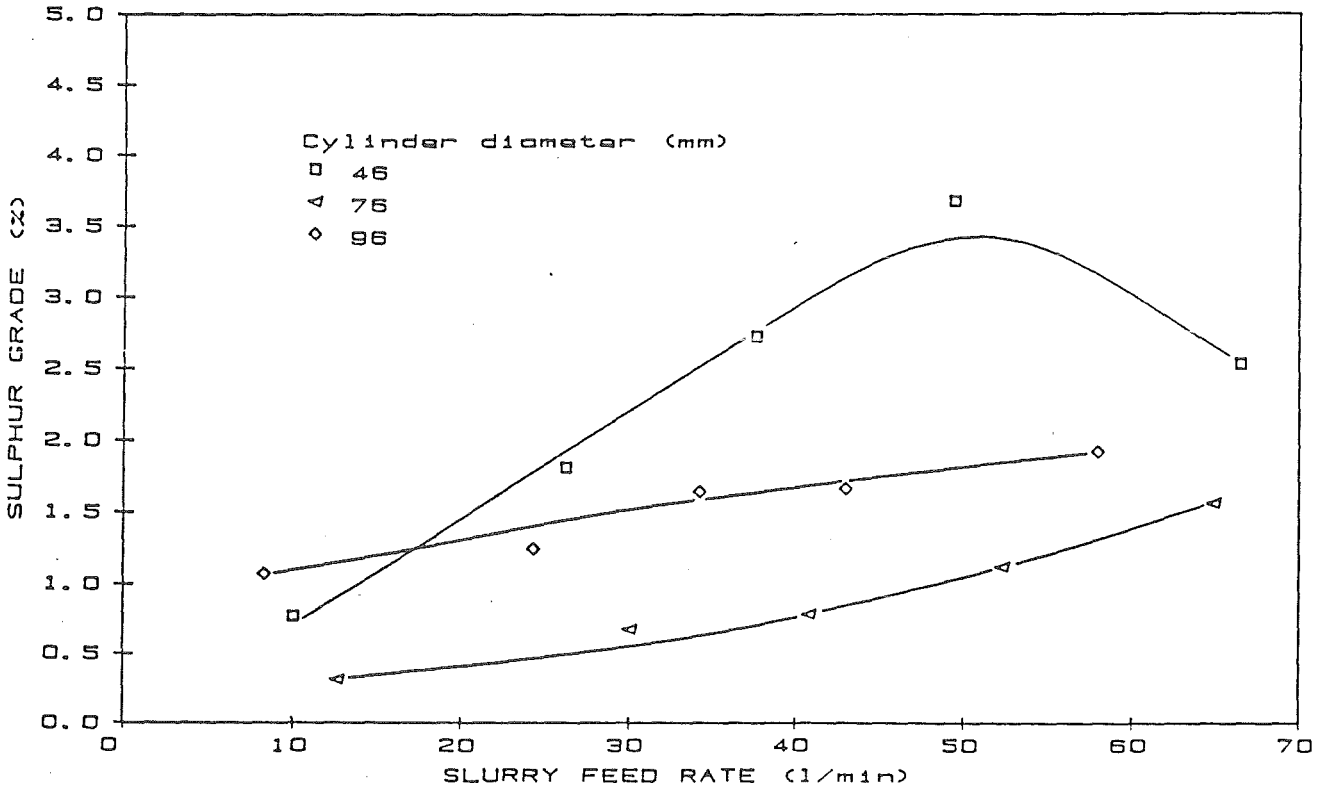

FIGURE 11: Sulphur grade of concentrate for ASH II with slurry A and cylinders of different inner diameters.

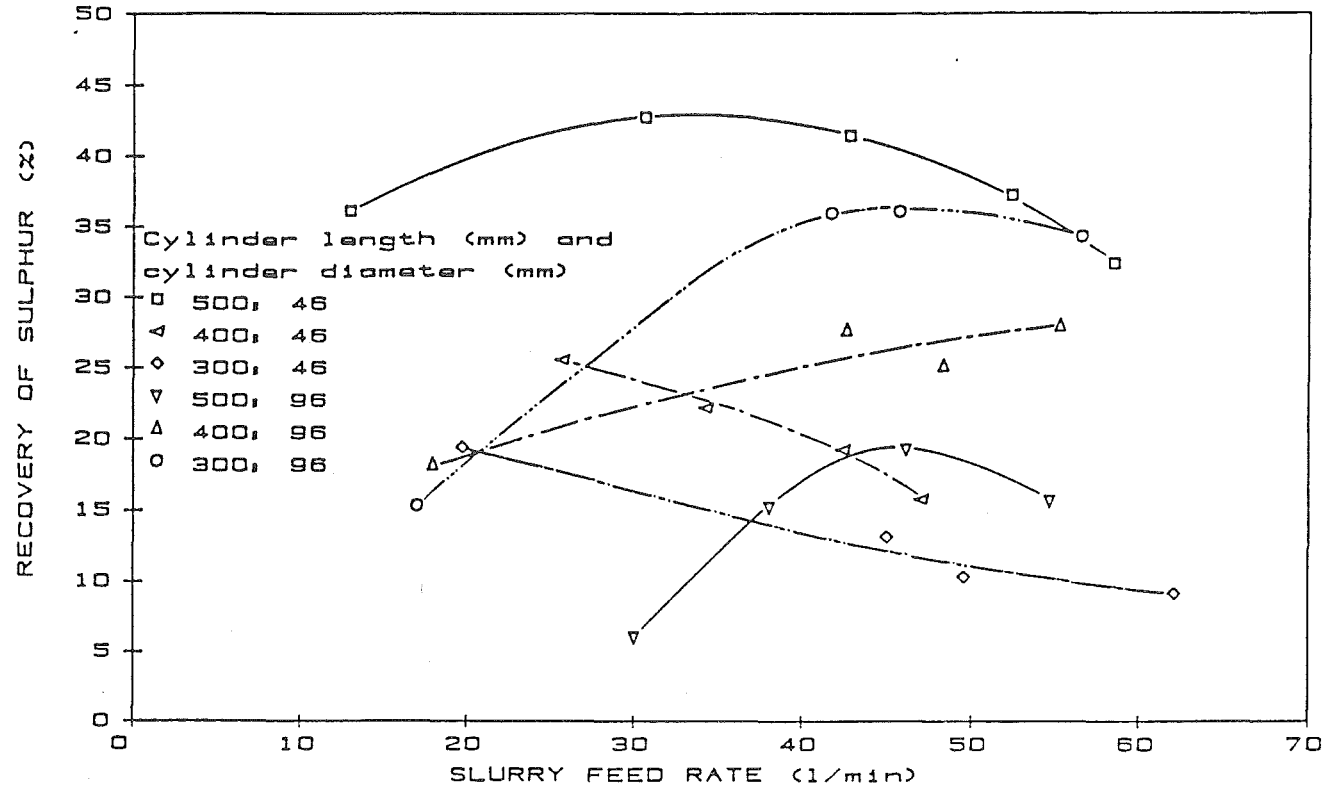

FIGURE 12: Recovery of sulphur for ASH II with slurry B and cylinders of different inner diameters and lengths.

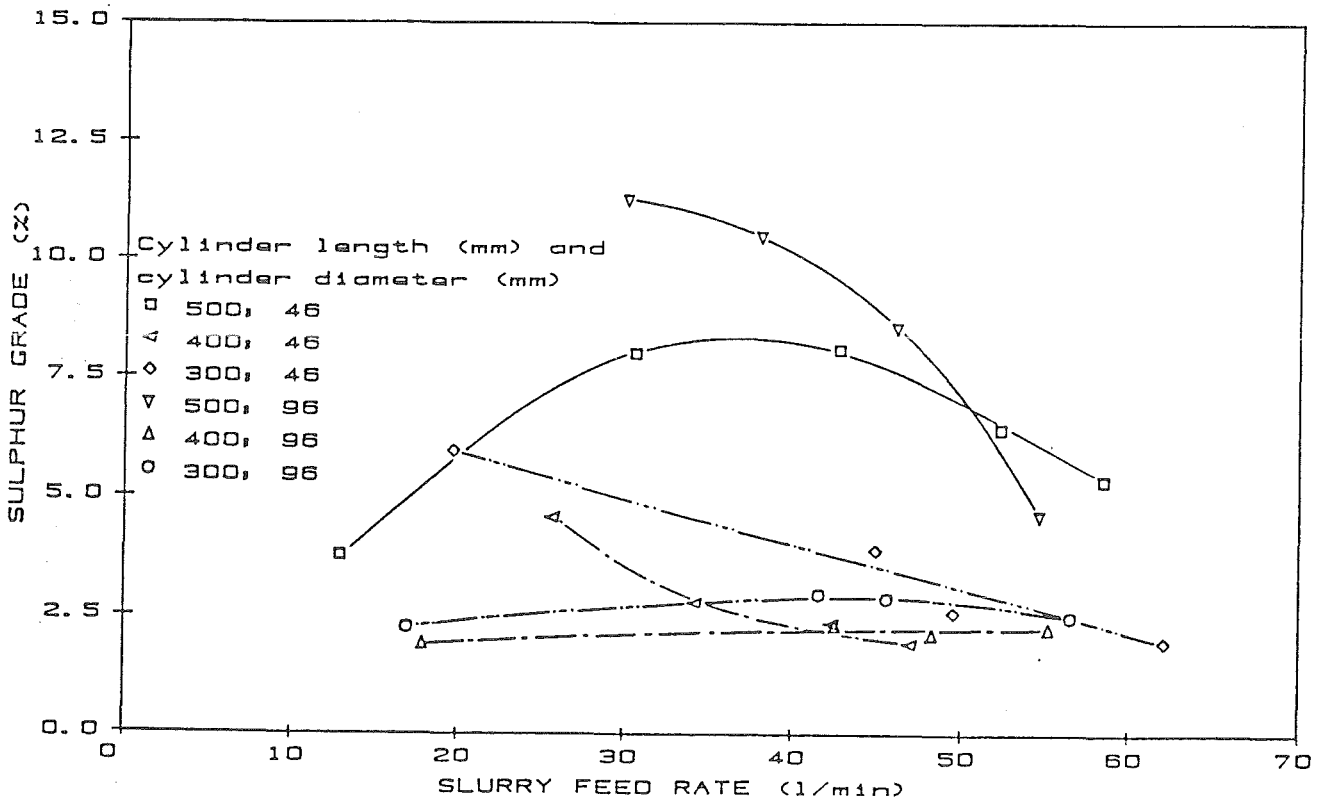

FIGURE 13: Sulphur grade of concentrate for ASH II with slurry B and cylinders of different inner diameters and lengths.

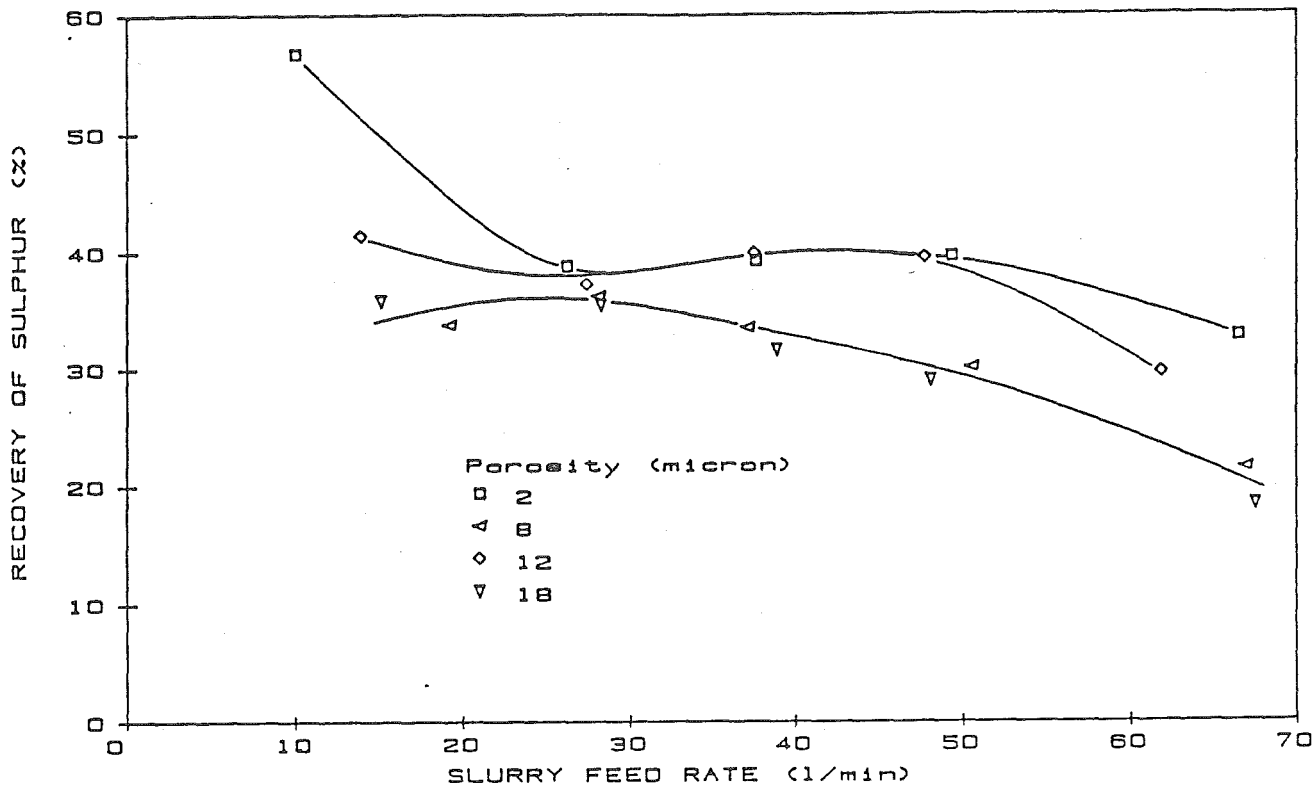

FIGURE 14: Recovery of sulphur for ASH II with slurry A and cylinders of different porosities.

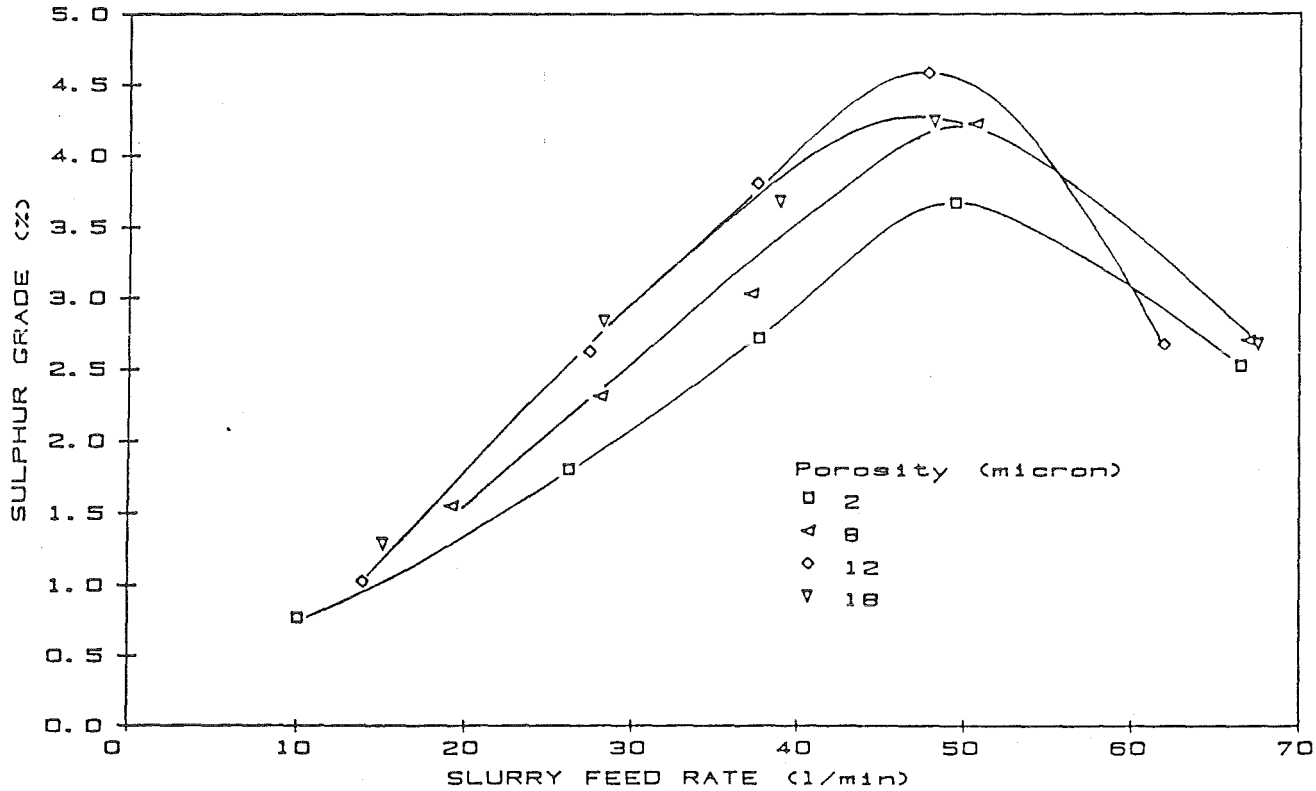

FIGURE 15: Sulphur grade of concentrate for ASH II with slurry A and cylinders of different porosities.

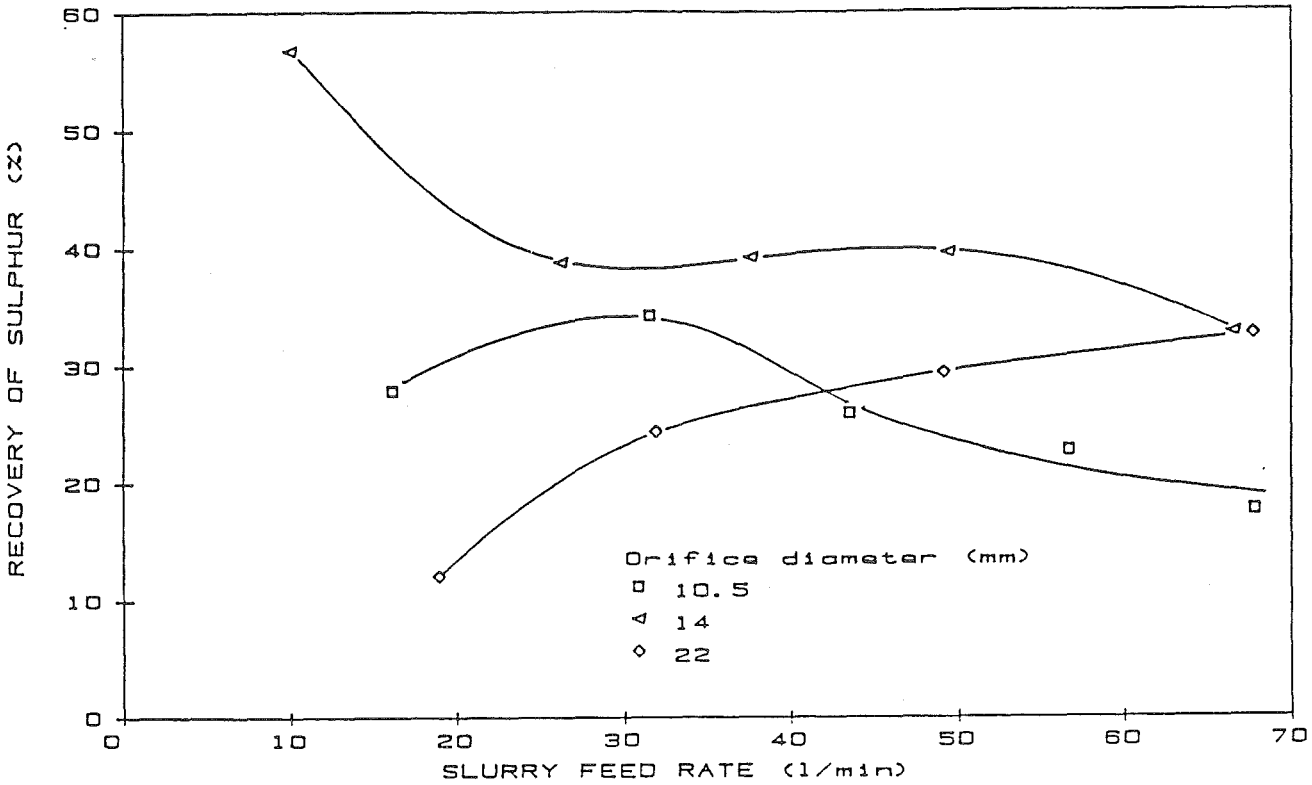

FIGURE 16: Recovery of sulphur for ASH II with slurry A and orifices of different diameters.

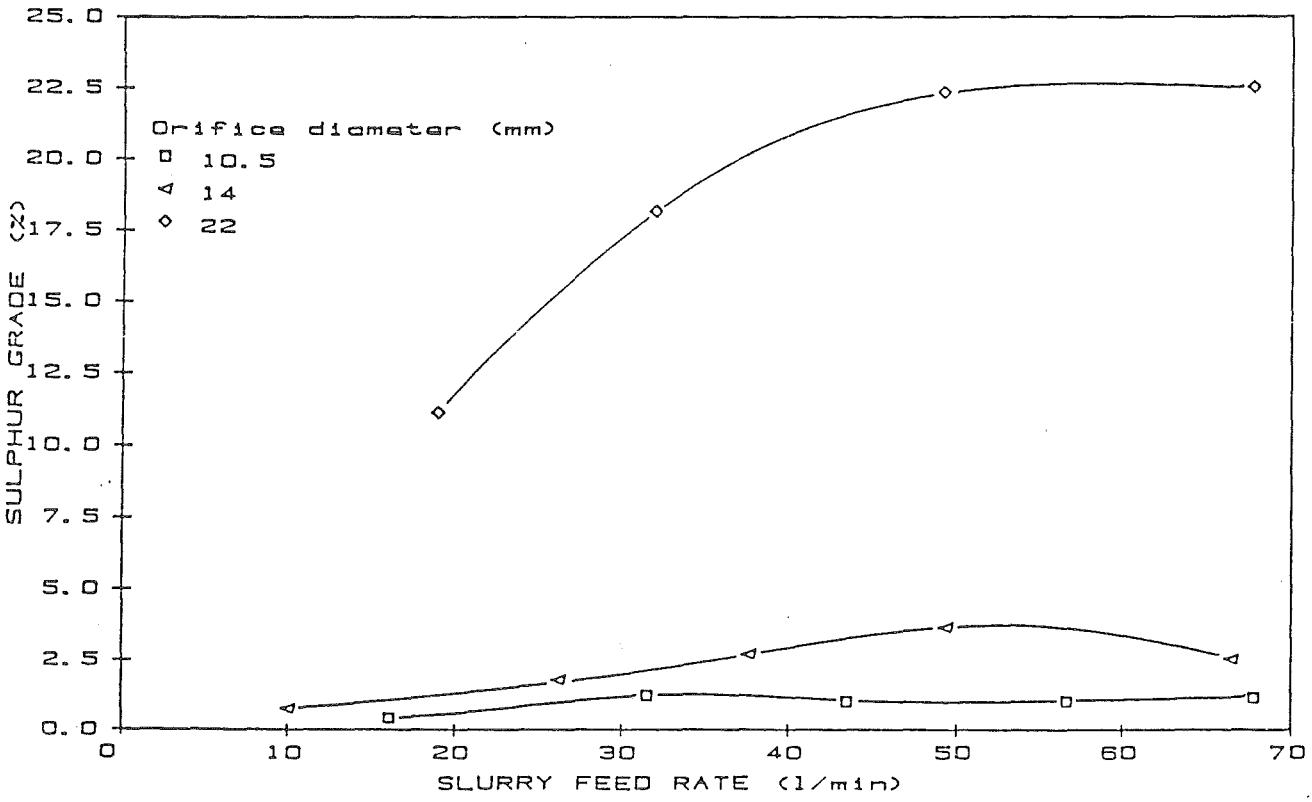

FIGURE 17: Sulphur grade of concentrate for ASH II with slurry A and orifices of different diameters.

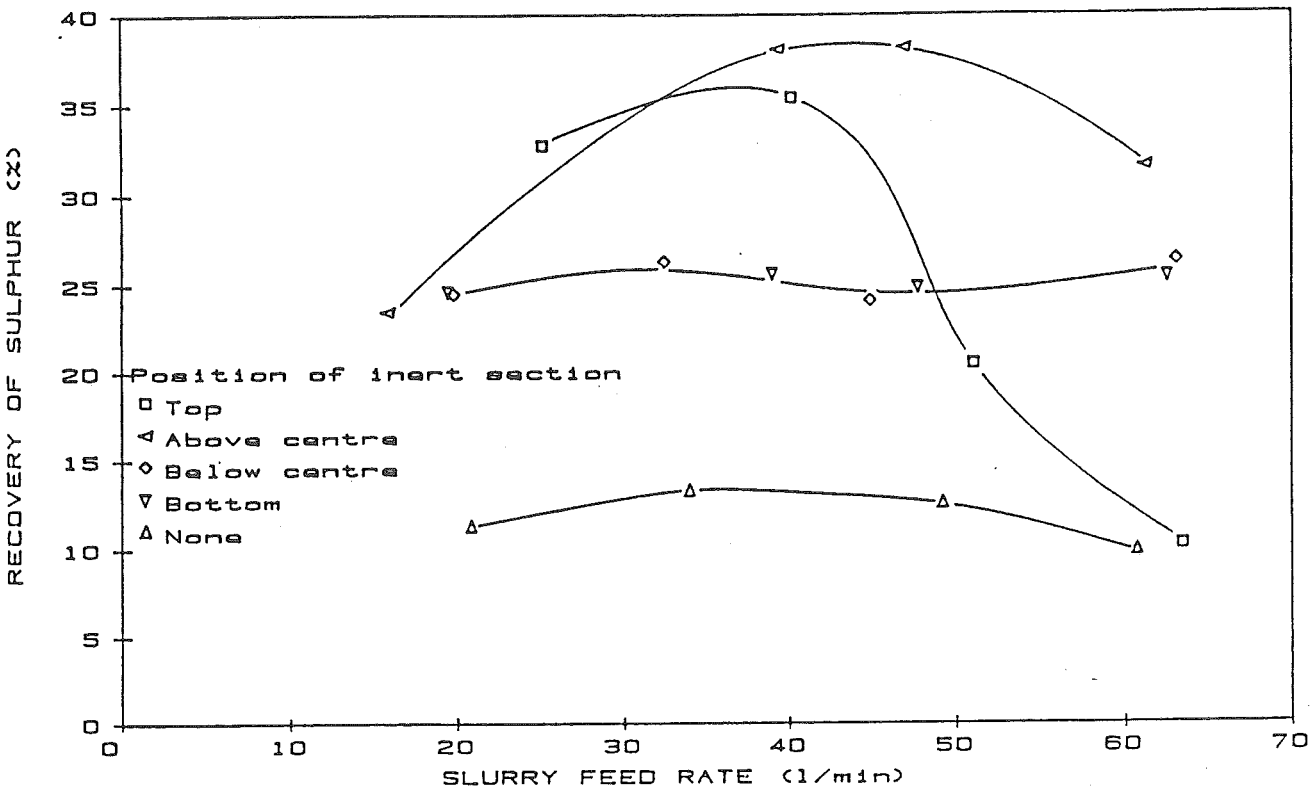

FIGURE 18: Recovery of sulphur for ASH I with slurry A, an orifice diameter of 15 mm and different positions of the inert sections along the length of the ASH.

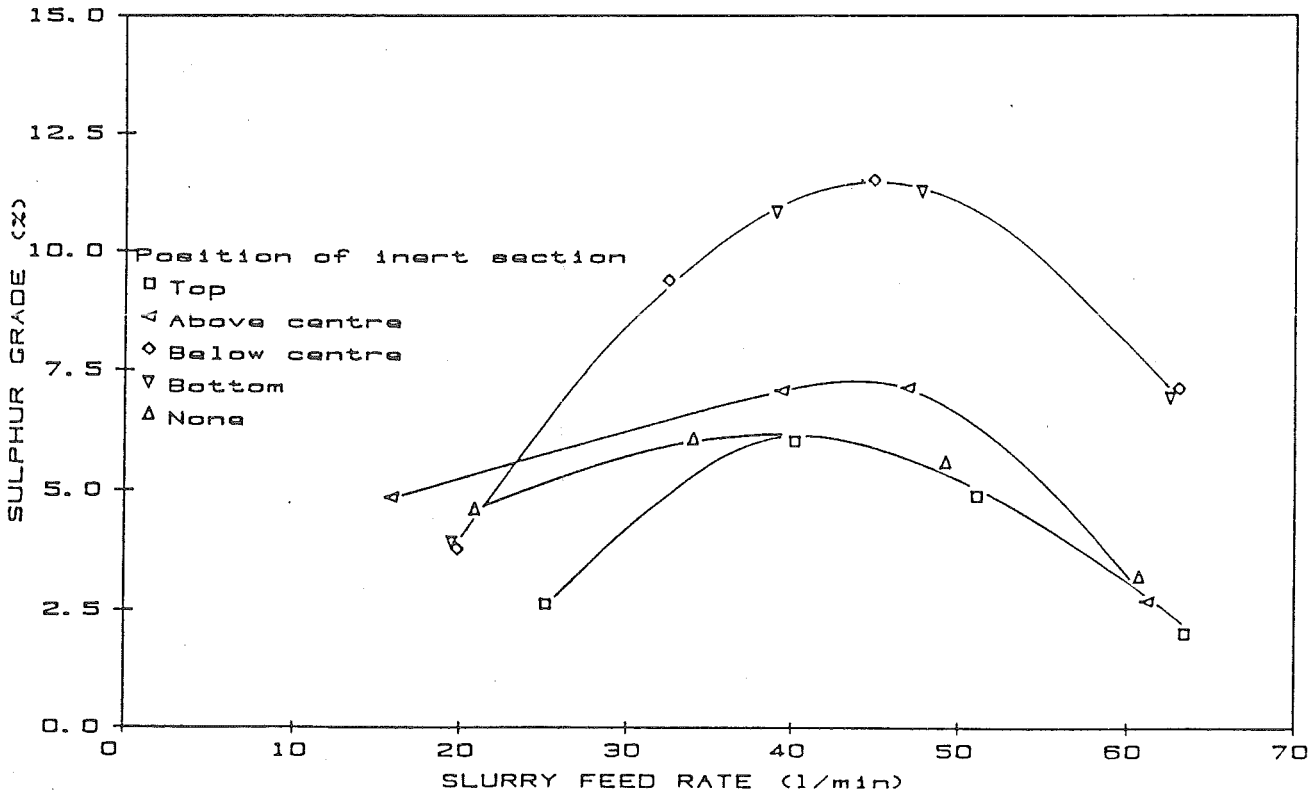

FIGURE 19: Sulphur grade of concentrate for ASH I with slurry A, an orifice diameter of 15 mm and different positions of the inert sections along the length of the ASH.

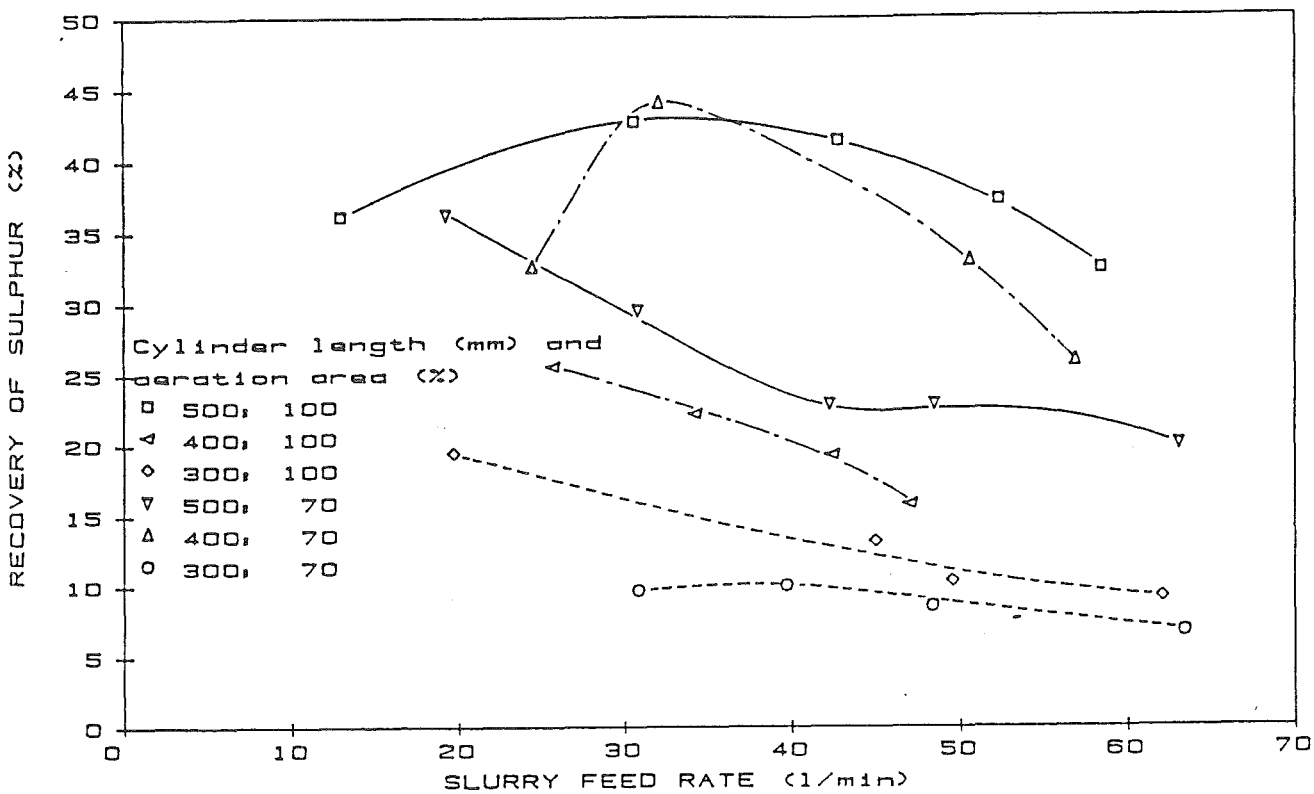

FIGURE 20: Recovery of sulphur for ASH II with slurry B, cylinders of different lengths and different areas of aeration.

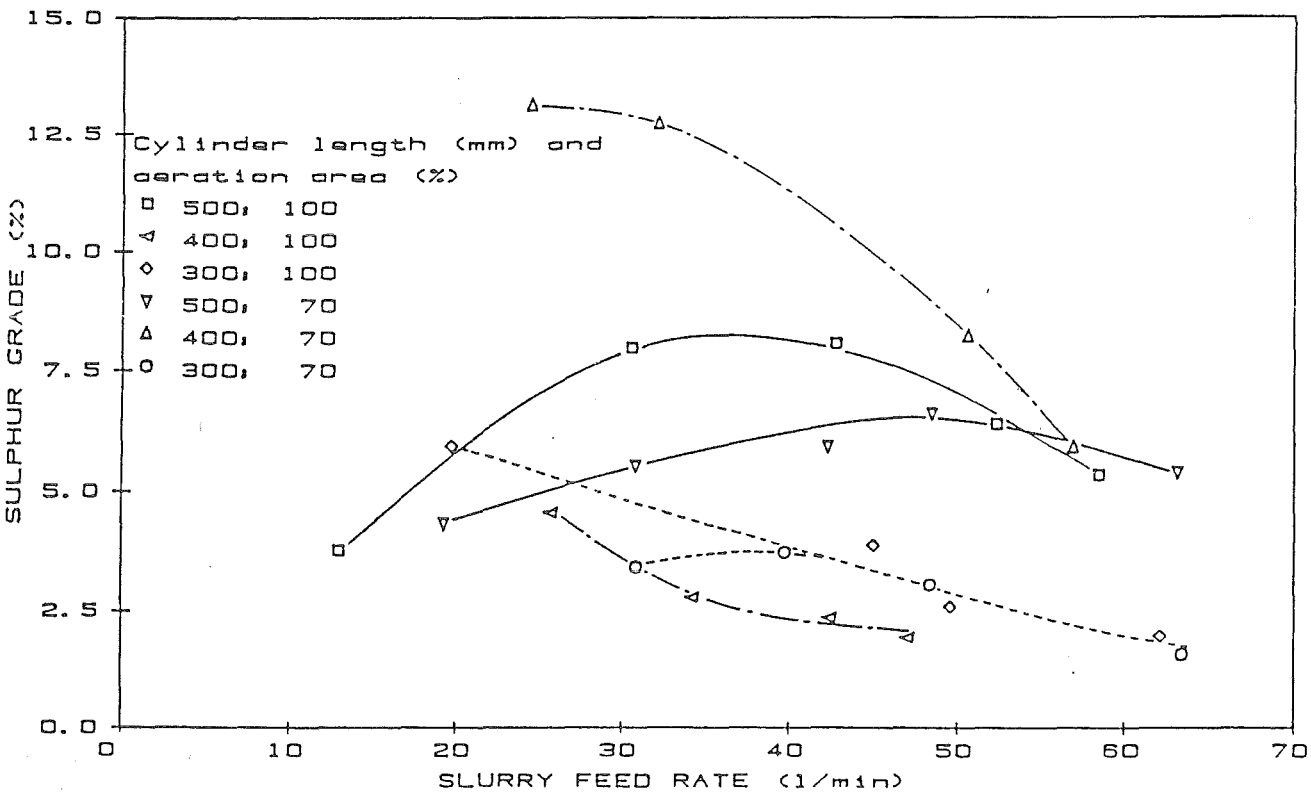

FIGURE 21: Sulphur grade of concentrate for ASH II with slurry B, cylinders of different lengths and different areas of aeration.

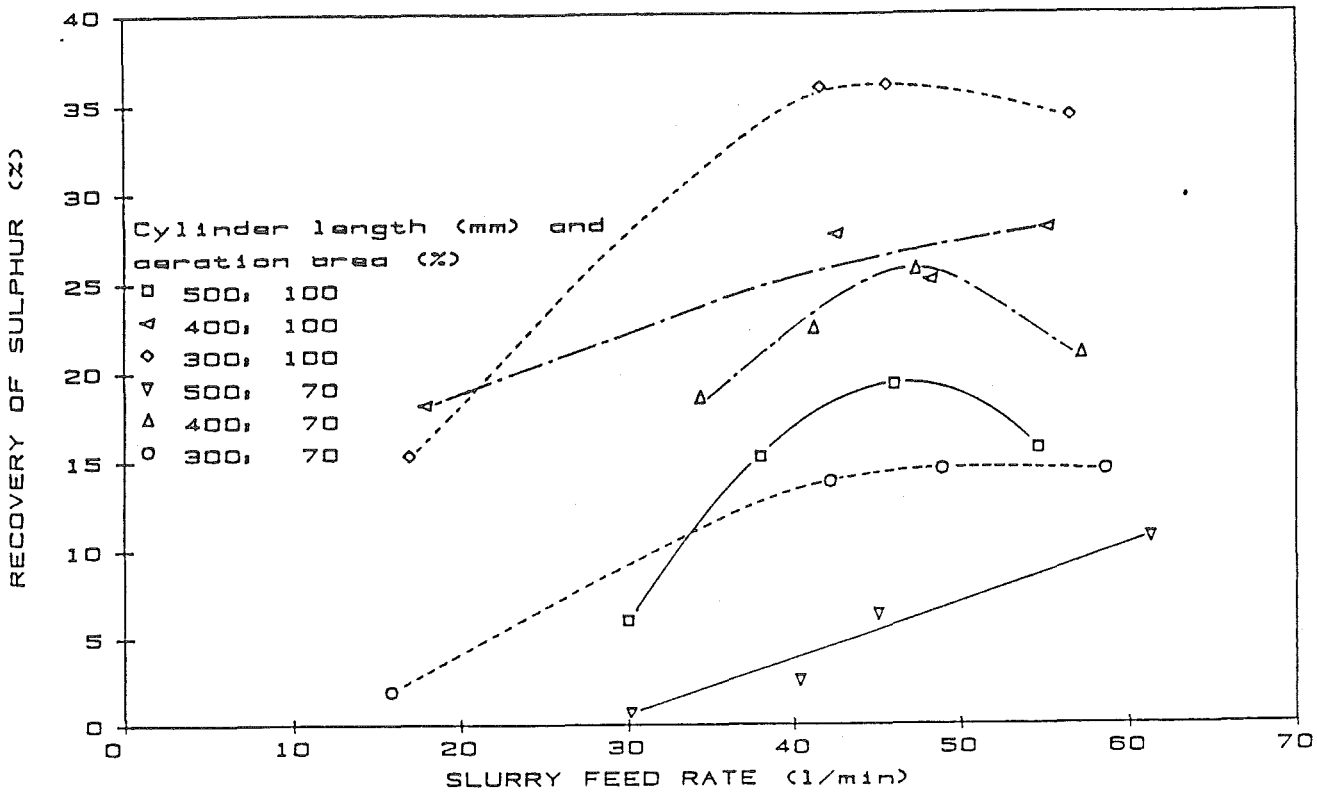

FIGURE 22: Recovery of sulphur for ASH II with slurry B, a cylinder diameter of 96 mm, cylinders of different lengths and different areas of aeration.

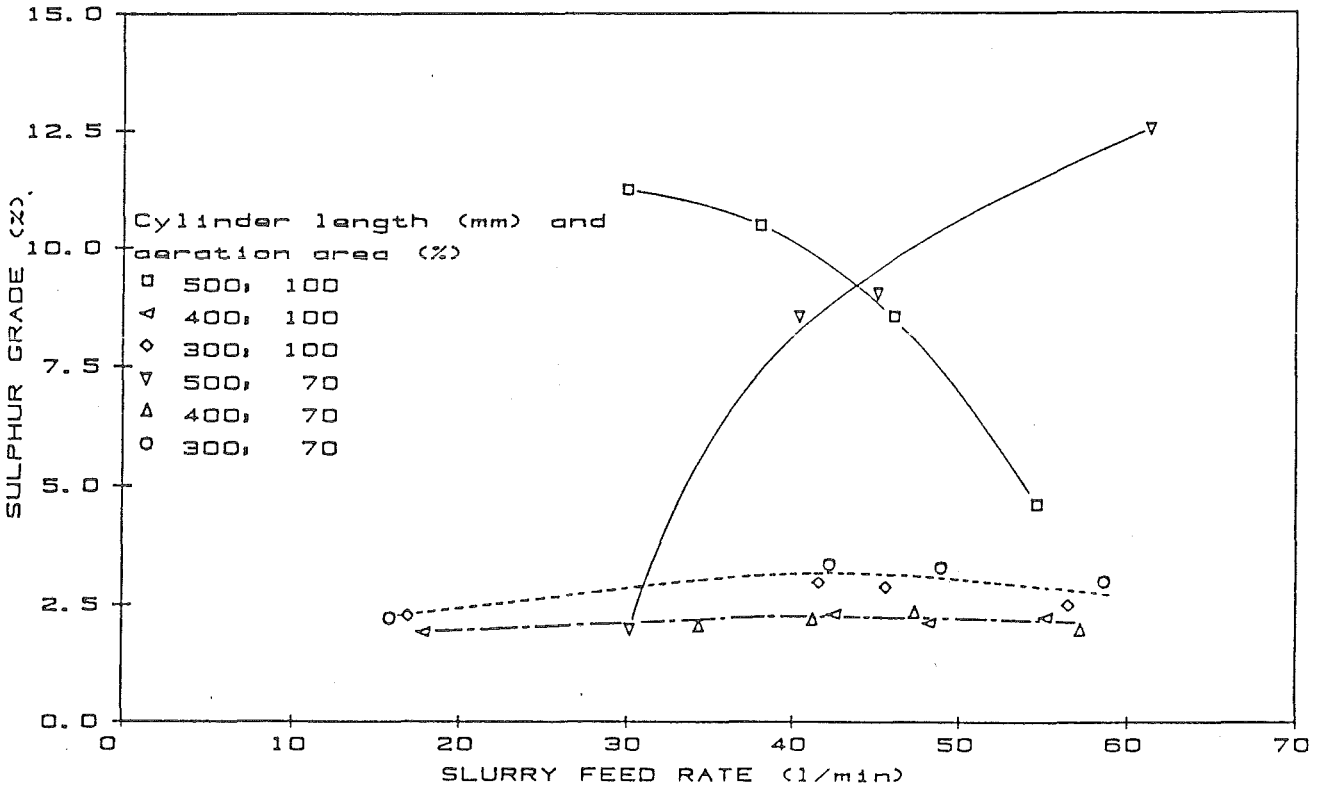

FIGURE 23: Sulphur grade of concentrate for ASH II with slurry B, a cylinder diameter of 96 mm, cylinders of different lengths and different areas of aeration.

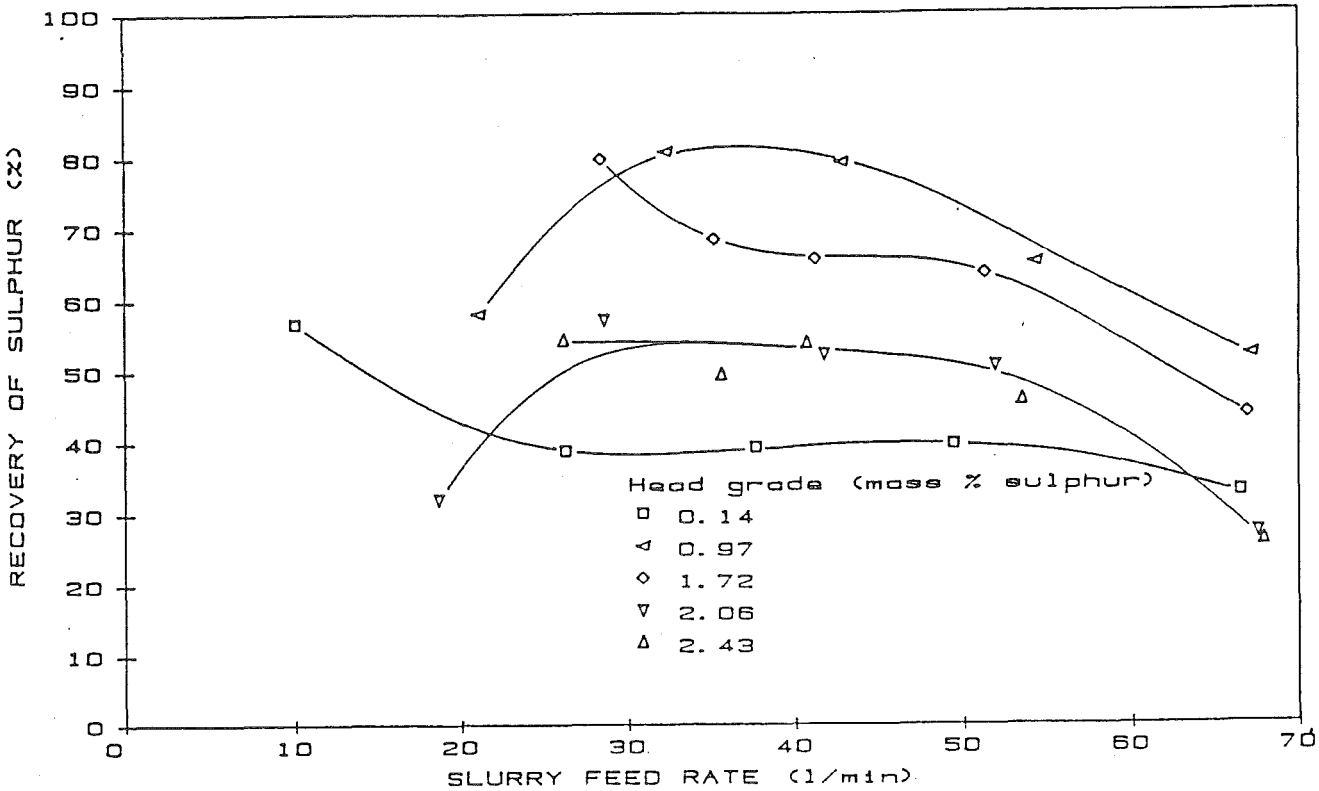

FIGURE 24: Recovery of sulphur for ASH II with slurry A at different head grades of sulphur (artificially enriched).

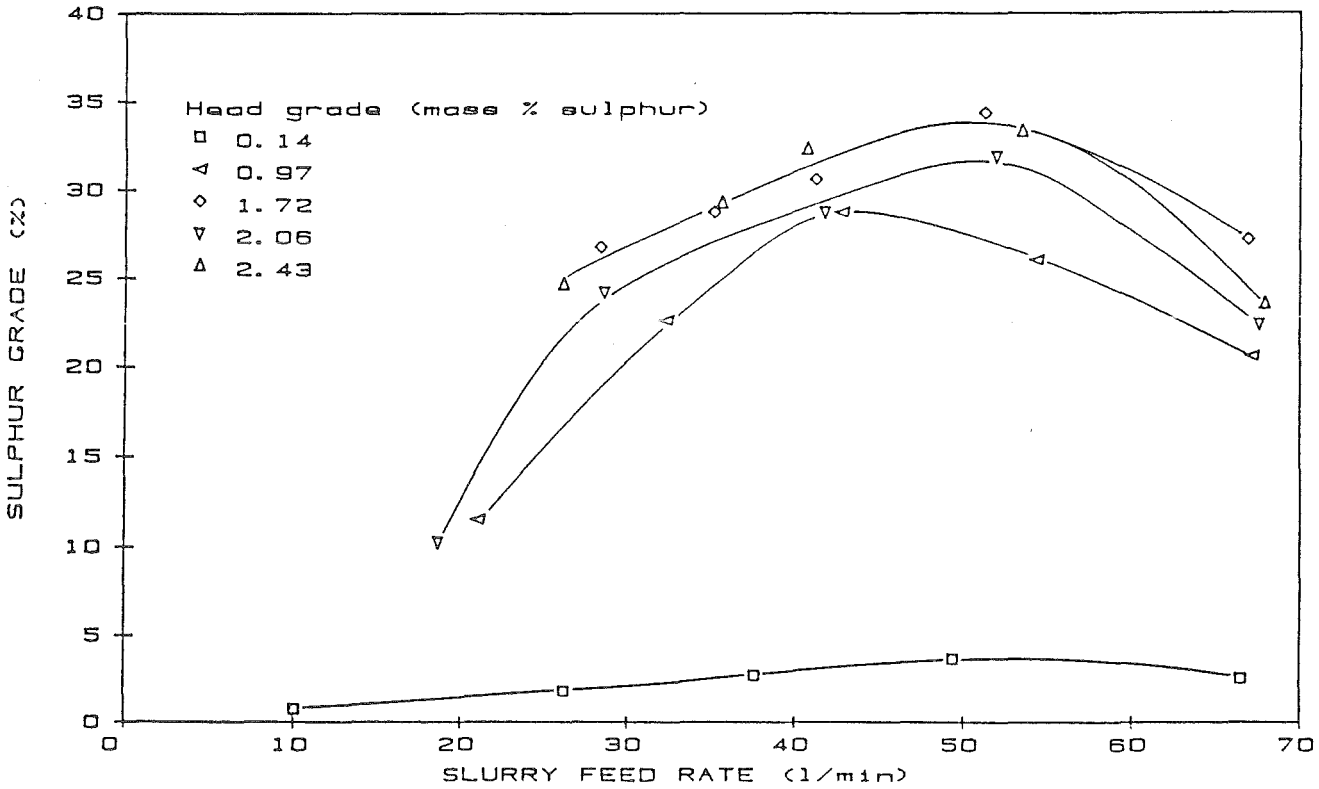

FIGURE 25: Sulphur grade of concentrate for ASH II with slurry A at different head grades of sulphur (artificially enriched).

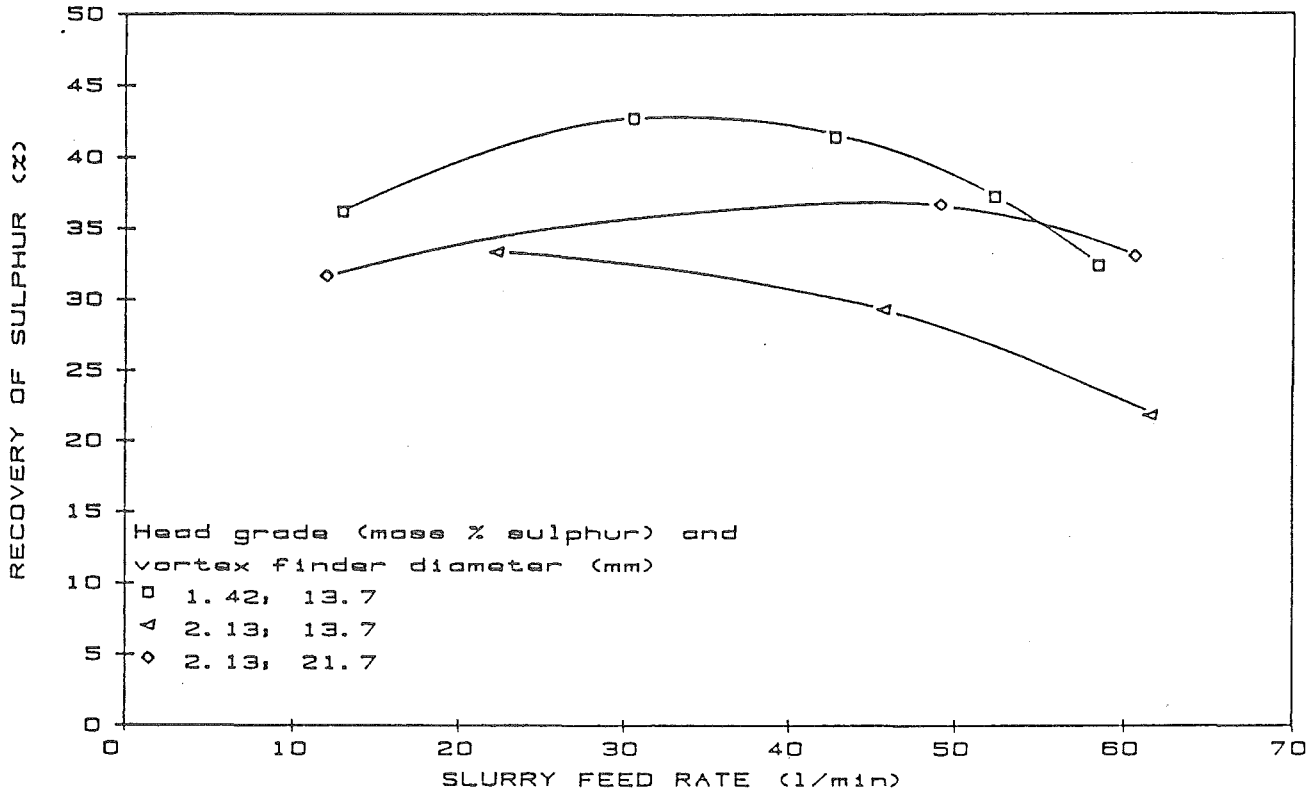

FIGURE 26: Recovery of sulphur for ASH II with slurry B at different head grades of sulphur (artificially enriched) and vortex finders of different diameters.

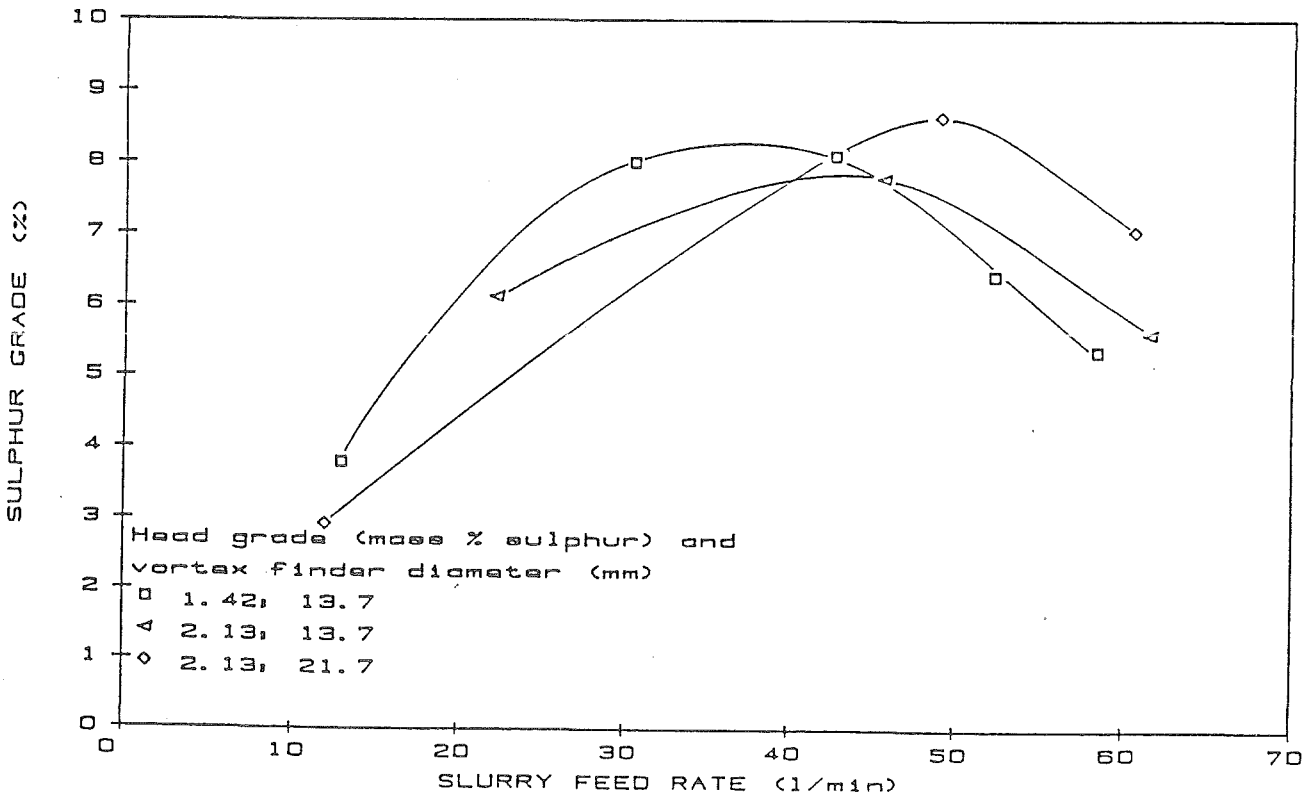

FIGURE 27: Sulphur grade of concentrate for ASH II with slurry B at different head grades of sulphur (artificially enriched) and vortex finders of different diameters.

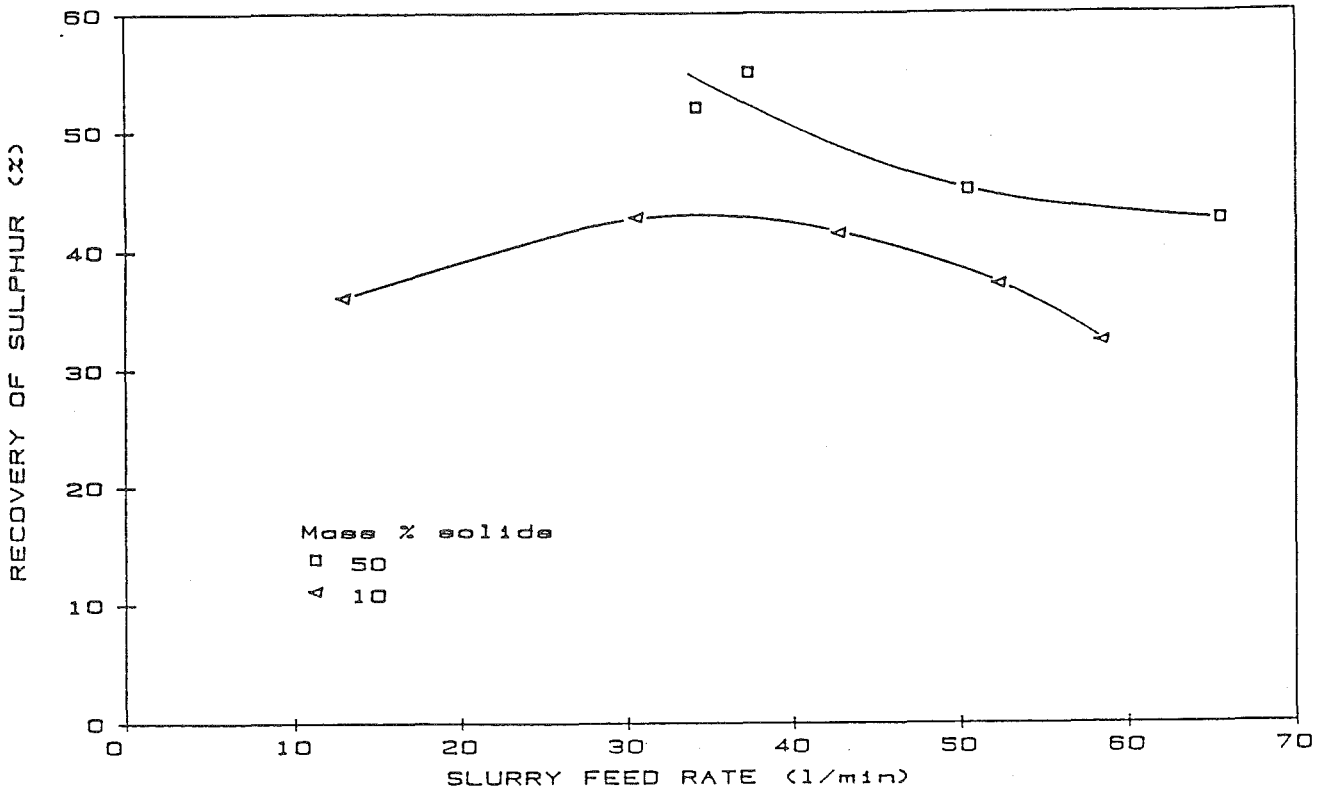

FIGURE 28: Recovery of sulphur for ASH II with slurry B at different mass % of solids.

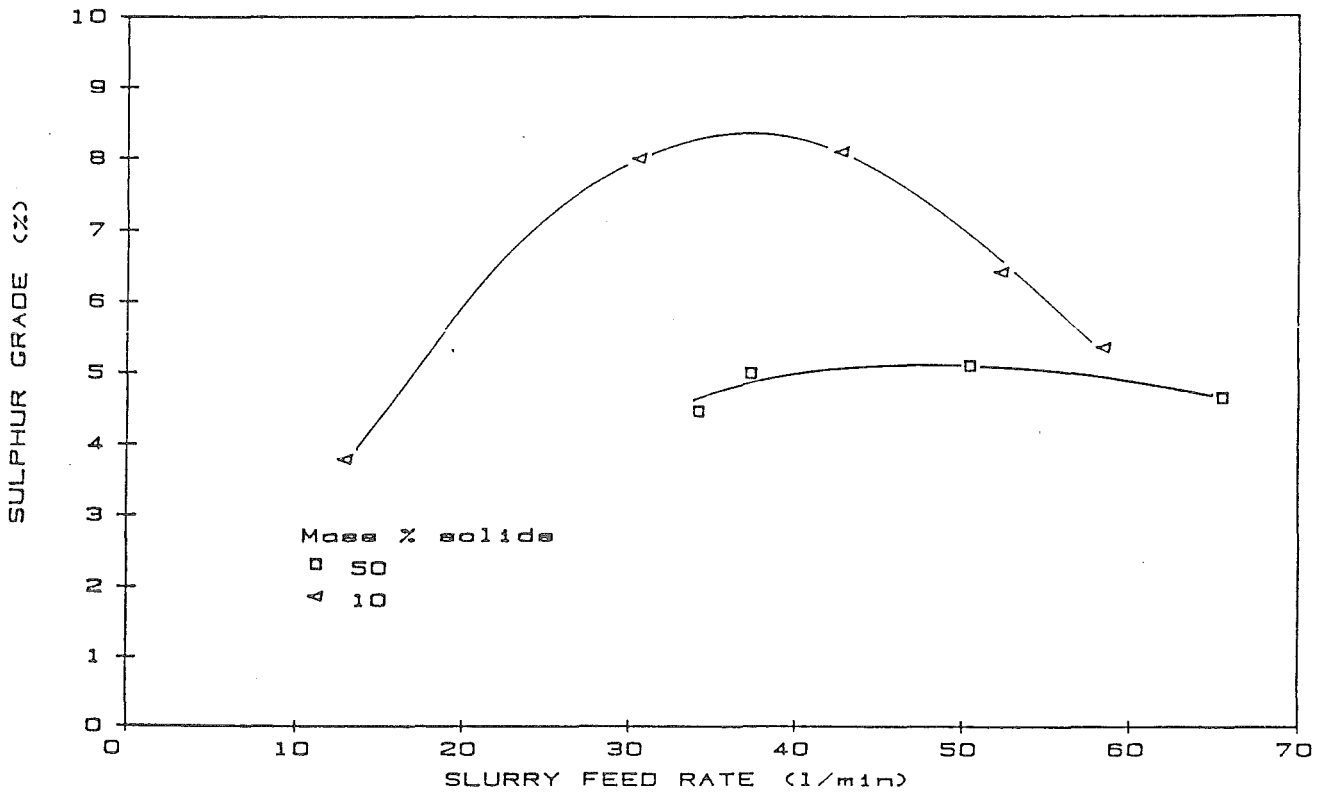

FIGURE 29: Sulphur grade of concentrate for ASH II with slurry B at different mass % of solids.