o Modifications to the original proposed design.

Initially it was proposed to use vertical gutters of a semi-circular cross-section. This was done to reduce the chances of the formation of any vortices resulting from flow around sharp edges. Such unnecessary turbulence can reduce the settling efficiency of the system. Unfortunately a semi-circular cross-section of the size required was not obtainable and hence a channel section was utilized for the vertical gutters. The corners of the channel were round and hence limited the formation of any vortices.

Since the model tank is constructed of perspex which has a low coefficient of friction for sludge sliding down on it, it was decided to use the spacing between the lower cone and the perspex tank wall as another plate spacing. Hence although 5 cones were installed for d = 40mm, the number of plate spacings was n = 5. Similarly for d = 32mm with 6 cones installed, n = 6. This is not however recommended for concrete lined tanks as sludge will build up on the concrete lined surface due to it's higher coefficient of friction, resulting in eventual blocking of that spacing.

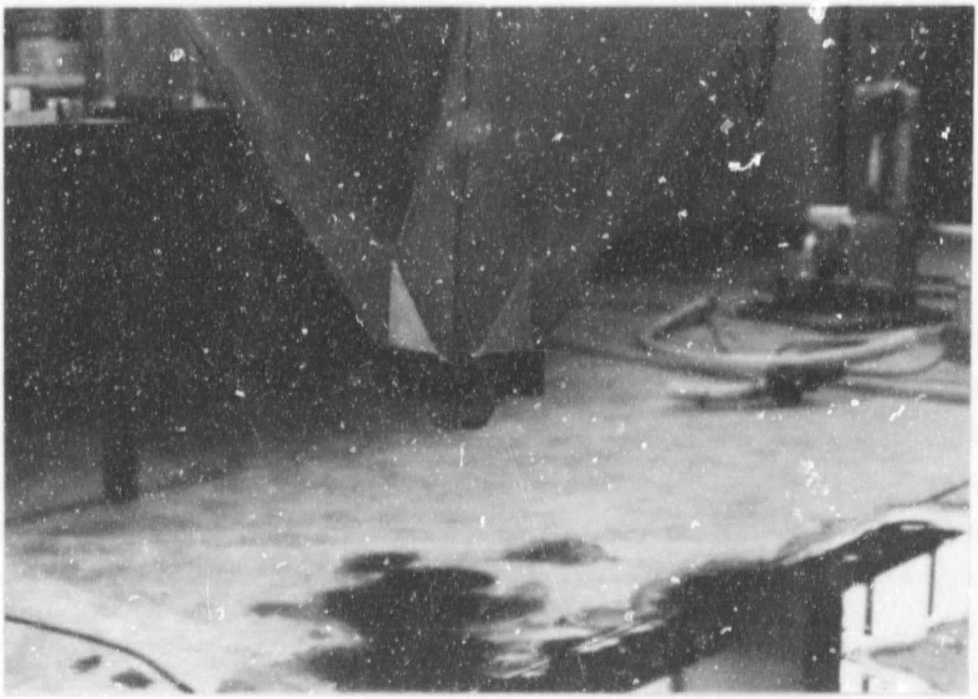

Figure 41. Lower portion of the conical lamella inlet.

Comparing the photographs in figures 41 and 32 it can be seen that the triangular portion between the triangular gutters was closed off with triangular sheet metal sections. This was an intuitive decision and was done to reduce the size of the inlet for the spacing between the lower cone and the tank wall. The results of the conical lamella performance for both plate spacings are given in APPENDIX F.

6.0 COMPARISON BETWEEN THE UPWARD FLOW TANK AND CONICAL LAMELLA PERFORMANCE

6.1 % SS REMOVED

Comparing the curves of conical lamella and upward flow tank performance in APPENDIX G it becomes immediately apparent that the conical lamella settler produces much better effluent qualities, especially at the higher overflow rates. Also the lamella settler is a lot less sensitive to the incoming feed concentration, ie. the % SS removals remain fairly constant over the influent SS concentration range. This is not so for the upward flow tank which produces much reduced % SS removals at the lower feed concentrations. The performance curves of the two types of tanks show that the lamella settler is well suited to operate at high overflow rates. If for example the the influent SS concentration is 3000mg/l, then at an upward flow tank overflow rate of v = 5,6m/h the conventional system will only produce a 40% SS removal. This is a hydraulically overloaded situation and not an acceptable operation of any sedimentation tank. The introduction of cones into the tank however, results in a 77% SS removal which makes the operation of the unit acceptable and more cost effective since a higher flow can be passed through the tank without the effluent qualities falling below the minimum required. Plotting % SS removal vs upward flow tank overflow rate for both types of settlers, and assuming an influent SS concentration of 2000mg/l gives the following figure:

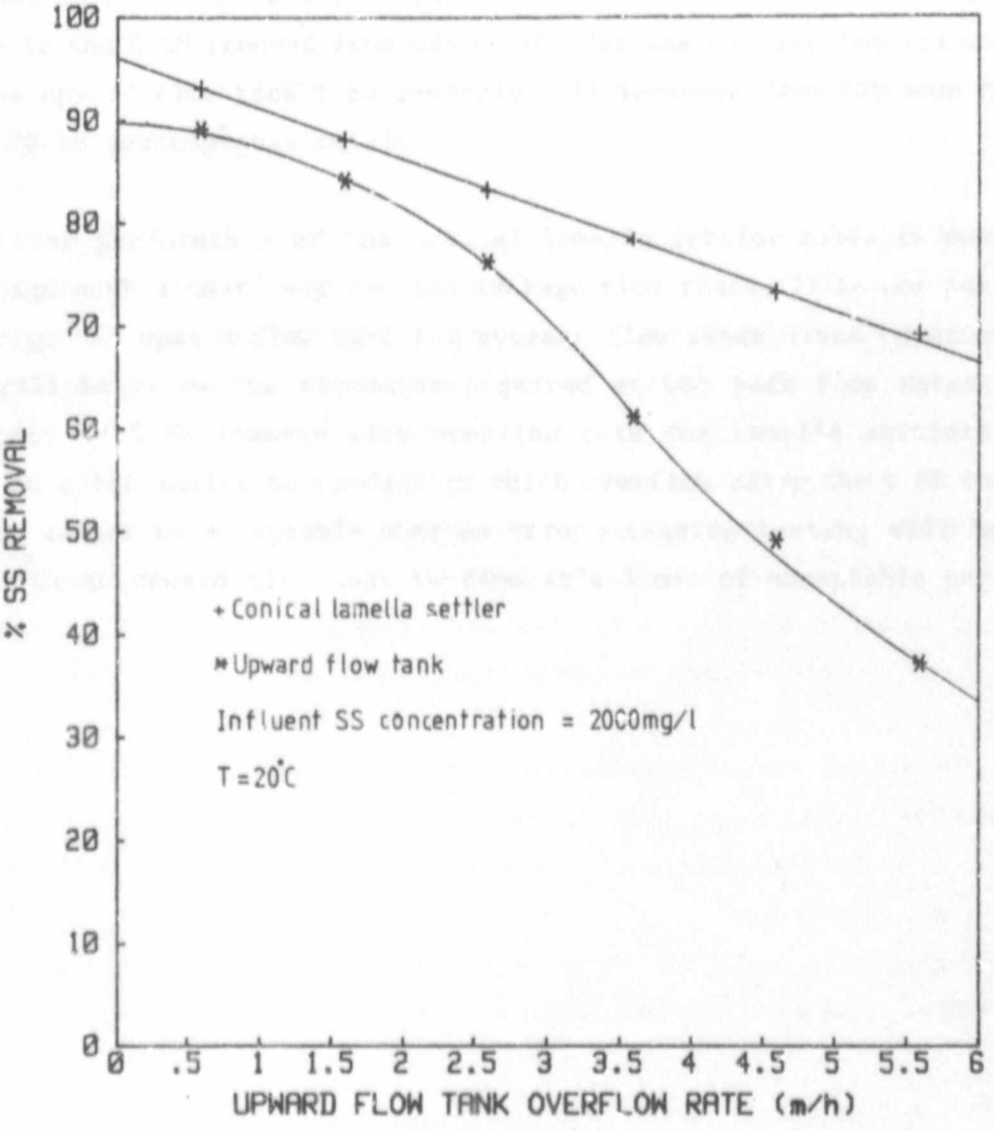

Figure 42. % SS removal vs overflow rate for the upward flow and conical lamella settlers for a feed concentration of 2000mg/l.

Figure 42 shows that the conical lamella settler is fairly insensitive to hydraulic loading and that the relationship between % SS removal and overflow rate is linear. This phenomenon is also experienced in lamella settlers constructed with rectangular plates (see LITERATURE REVIEW). The insensitivity of the conical lamella settler to hydraulic loading is a big advantage if the tank is ever subjected to shock loads. An unforeseen increase in overflow rate from say 1,6m/h to 5,6m/h will result in a decrease in the % SS removed from 88% to 70% for the conical lamella settler whereas upward flow tank % SS removals will decrease from 84% down to 37% which is an unacceptable result.

The better performance of the conical lamella settler makes it possible to design such a unit only for the average flow rates. It is not possible to design the upward flow tank for average flow rates since water qualities will be below the standards required at the peak flow rates. The linearity of % SS removed with overflow rate for lamella settlers also makes it a lot easier to predict at which overflow rates the % SS removed will no longer be acceptable whereas more extensive testing will be required in an upward flow tank to find it's limit of acceptable performance.

6.2 SLUDGE DRAWOFF CONCENTRATIONS

If a mass balance is done across the system used in the laboratory, one will find for the same underflow sludge withdrawal rate ($0{,}45m^3/s$), that the conical lamella settler produces higher sludge concentrations than the upward flow tank. This is because the effluent overflow qualities are better for the lamella settler for the same influent SS concentration, and therefore the balance of the SS from the feed must be discharged with the sludge. The curves of influent SS concentration vs % sludge concentration (found in APPENDIX G), do however not follow this trend at low overflow rates. At an upward flow tank overflow rate of v = 0,6m/h no difference in the % sludge concentrations is discernible whereas for v = 1,6m/h and 2,6m/h the upward flow tank produces denser sludges than the cones. For v ≥ 3,6m/h the theoretical mass balance predictions of % sludge concentrations follow the laboratory results more closely.

Figure 42 shows that the % SS removal differences for v < 2,6m/h are small compared to 3,6 < v < 5,6m/h. This means that the differences in the % sludge concentrations from mass balances for the two systems are also small and the fact that the conical lamella settler should always produce denser sludges for all overflow rates, might be obscured in the scatter of the results for 0,6 < v < 2,6m/h. Only further testing can verify this.

6.3 EFFECT OF THE PLATE SPACING ON THE CONICAL LAMELLA PERFORMANCE

The results of the test runs on the lamella settler for plate spacings d = 40mm and d = 32mm are given in APPENDIX F. They show that there is no difference in the performance for the two plate spacings except at upward tank overflow rates of v = 4,6m/h and 5,6m/h. The difference in % SS removals is some 3% - 5% with d = 40mm producing the better effluent qualities.

The results of % sludge concentration for d = 32mm have considerable scatter in them and no distinct trend is discernible. Generally however, the % sludge concentrations are the same for d = 32mm and 40mm.

7.0 MODIFICATION OF THE EXISTING THEORY FOR SHALLOW DEPTH SEDIMENTATION TO SUIT THE CONICAL LAMELLA SETTLER

7.1 CONTINUOUS SETTLING THEORY

Existing plate settler theory is only valid for tubes and plates of a uniform cross-section. An attempt is made to modify this available theory, mainly from workers such as Yao(1970) and Nakamura and Kuroda(1937). The model is a geometric one and although dynamic models such as given by Leung and Probstein(1983) are more scientifically correct and accurate, they lose their attractiveness because of their complexity which makes them difficult to use in a normal design situation. The design equations proposed by Yao(1970) are much simpler and easier to use in providing a first estimate for the size of a continuous lamella unit. The following nomenclature is used in the development of the model:

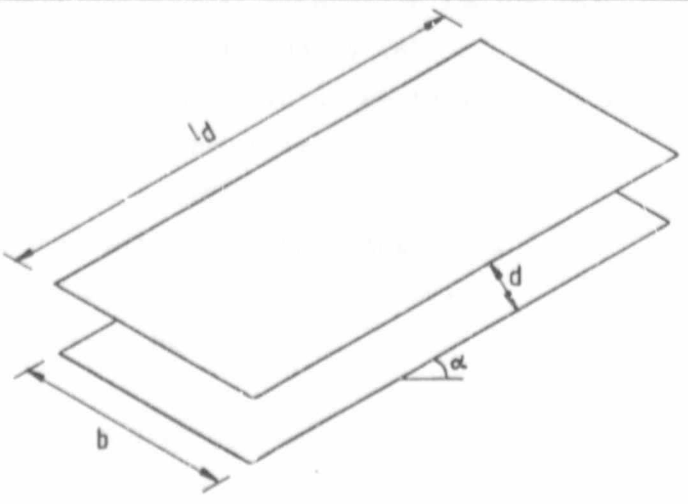

Figure 43. Rectangular plates.

Where l_d - design length of rectangular plate (m) b - width of rectangular plate (m)

α - angle of inclination of plates

d - plate spacing (m)

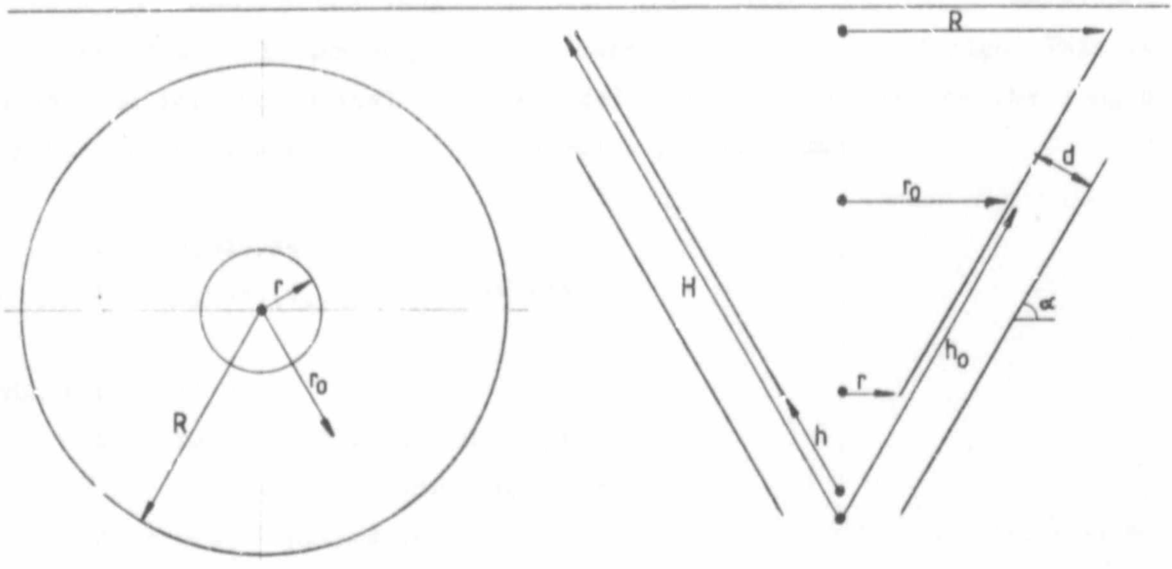

Figure 44. Conical plates.

Where r - inner horizontal truncation radius (m)

R - outer horizontal radius (m)

r_0 - some arbitrary radius where $r \le r_0 \le R$ (m)

h - inner cone radius (m)

H - outer cone radius (m)

h_0 - cone radius corresponding to r_0 (m)

α - angle of inclination of cones

d - cone spacing (m)

Because of the reduction of the hydraulic radius with the introduction of plates into the flow path of the water, laminar flow conditions are developed between the plates. At the entrance of the settler however there exists a transition region in which the turbulent flow is gradually changed to laminar flow. Yao(1970) presumes that the flow in this transition region is a mixture of of laminar and turbulent flow and approaches something more closely resembling uniform flow. Yao(1970) showed that the performance of high rate settlers is comparable or better under uniform flow conditions than laminar flow conditions. This would mean that the transition region should not significantly affect the SS removal efficiencies of the system. He suggested however, that the transition length should be added to the length of the plate based on fully developed laminar flow. This would provide a safety factor in the design. This is also done for the conical lamella model. Yao(1970) estimates the length of the transition region for rectangular plates from:

$$L' = 0{,}058.Re$$
$$L' = 0{,}058.(v_0.d)/\nu \qquad ---(15)$$

where $L' = l'/d$

L' - relative transition length

l' - actual transition length (m)

d - plate spacing (m)

Re - Reynolds number

ν - kinematic viscosity (m^2/s)

v_0 - average velocity through the plates (m/s)

The above equation was developed by Langhaar(1942) for circular pipes and it is found that this theoretical formula agrees well with observation.

Pipe flow convection correlations are however only approximately valid for ducts of non-circular cross-sections provided the diameter in the Re number is replaced with an "effective hydraulic diameter", defined as follows:

$$d_e = 4\times(\text{flow cross-sectional area})/(\text{wetted perimeter})$$

where d_e - effective hydraulic diameter

Applying the above approximation to flow between parallel plates:

$$d_e = 2.b.d/(b+d) \qquad ---(16)$$

The average velocity between one rectangular plate v_0 is given by:

$$v_0 = Q/(n.b.d) \quad ---(17)$$

where Q - total volumetric flow rate through the entire lamella unit (m^3/s)

n - number of plate spacings

For a conical configuration v_0 will however decrease with increasing radius of the cone, ie.

$$v_0 = Q/(n.b'.d) \quad ---(18)$$

where $b' = 2\pi(r_0)$

In both equations (17) and (18) d can be reduced to include the sludge thickness. Sludge thickness on the plates will however vary with overflow rate, influent SS concentration and local eddies and will therefore at the present be neglected. Hilligardt(1985) however recommends that d be reduced to $\approx 1/3.d$, ie. 2/3 of the depth on the plate is occupied by sludge which is sliding down. Such thick sludge layers were never experienced on the conical lamella which were never more than 2 - 3mm after a 3 week continuous run.

Substituting equations (16) and (17) into (15) for rectangular plates ($\parallel$l plates) gives:

$$L' = 0,116.Q/(\nu.n.(b+d)) \quad \text{for } \parallel\text{l plate settlers} \quad ---(19)$$

Now consider two $\parallel$l plate lamella settlers each with incoming flow rate Q and the width of one $b_1 = b$ and the other $b_2 = 2b$. For n and d equal the transition length of the respective settlers using equation (15) is:

$$(L')_1 = 0,058.Q/(n.b.\nu)$$

and $(L')_2 = 0,058.Q/(n.2b.\nu)$

then $(L')_1/(L')_2 = 2$

ie. the volume occupied by the transition length for the two plates is equal although the actual length varies:

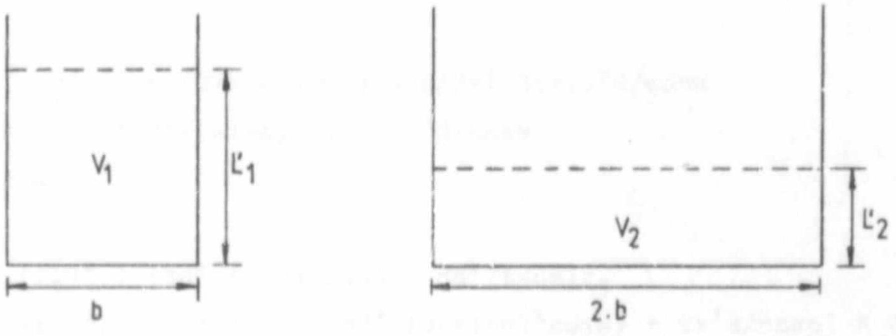

Figure 45. Volume occupied by the transition length of two different rectangular plate sizes.

where $V_1 = V_2 = 2(L')_2.b.d^2$

V - volume occupied by the transition length (m^3)

It is this approach that is used to obtain the relative transition length for a conical lamella settler. The above was obtained by using d instead of d_e (equation (16)). Using equation (16) instead of the above, results in a less accurate approach, however the difference is small since d is small (usually 0,04m) and b is large in comparison (typically 1,2m).

Hence the volume occupied by the transition length of a ‖l plate (rectangular plate) with the same entrance area and flow rate as that of a conical lamella settler is given by equation (20) where $b = 2\pi r$, ie.

$$V = L'.b.\ d^2 \qquad ---(20)$$

$$V_{plate} = 0{,}116.Q/(\nu n.(2\pi r+d))\times 2\pi r\times d^2 \quad ---(21)$$

and the volume between two conical plates:

$$V_{cone} = \pi\tan\alpha/3\times\{\ 3(r_0)^2 d/\sin\alpha + 3r_0 d^2/(\sin\alpha)^2 + d^3/(\sin\alpha)^3\ \} - \pi r^2 d/\cos\alpha - \pi r_0 d^2/\tan\alpha \quad ---(22)$$

See APPENDIX I for the derivation of V_{cone}. Noting the above reasoning of equal volumes and hence equating equations (21) and (22) and solving for r_0 gives:

$$0{,}232.Q.\pi.r.d^2/(\nu.n.(2\pi r+d)) = \pi\tan\alpha/3\times\{\ 3(r_0)^2 d/\sin\alpha + 3r_0 d^2/(\sin\alpha)^2 + d^3/(\sin\alpha)^3\ \} - \pi r^2 d/\cos\alpha - \pi r_0 d^2/\tan\alpha$$

$$[\pi d/\cos\alpha].(r_0)^2 + [\pi d^2/(\sin\alpha\cos\alpha) - \pi d^2/\tan\alpha]r_0 - [0{,}232.Q\pi r.d^2/(\nu n(2\pi r+d)) - \pi d^3/(3(\sin\alpha)^2\cos\alpha) + \pi r^2 d/\cos\alpha] = 0$$

ie. $A.(r_0)^2 + B.r_0 - C = 0$

$$r_0 = \{\ -B + \sqrt{(B^2 + 4.A.C)}\}/2A \quad ---(23)$$

Only the positive root is chosen since a negative r_0 is not possible. Solving equation (23) for the laboratory model values of $d = 0{,}04$m, $\alpha = 55°$, $n = 5$, $\nu = 1{,}01\times 10^{-6}m^2/s$, calculating the relative length of the transition for the cones from equation (24);

$$L'_{cone} = (h_0-h)/d$$
$$= (r_0-r)/(d\cos\alpha) \quad ---(24)$$

defining $Q' = Q/n$, ie.the total flow rate between two plates only and using equation (19) for L'_{plates}, the following graph can be plotted for varying r:

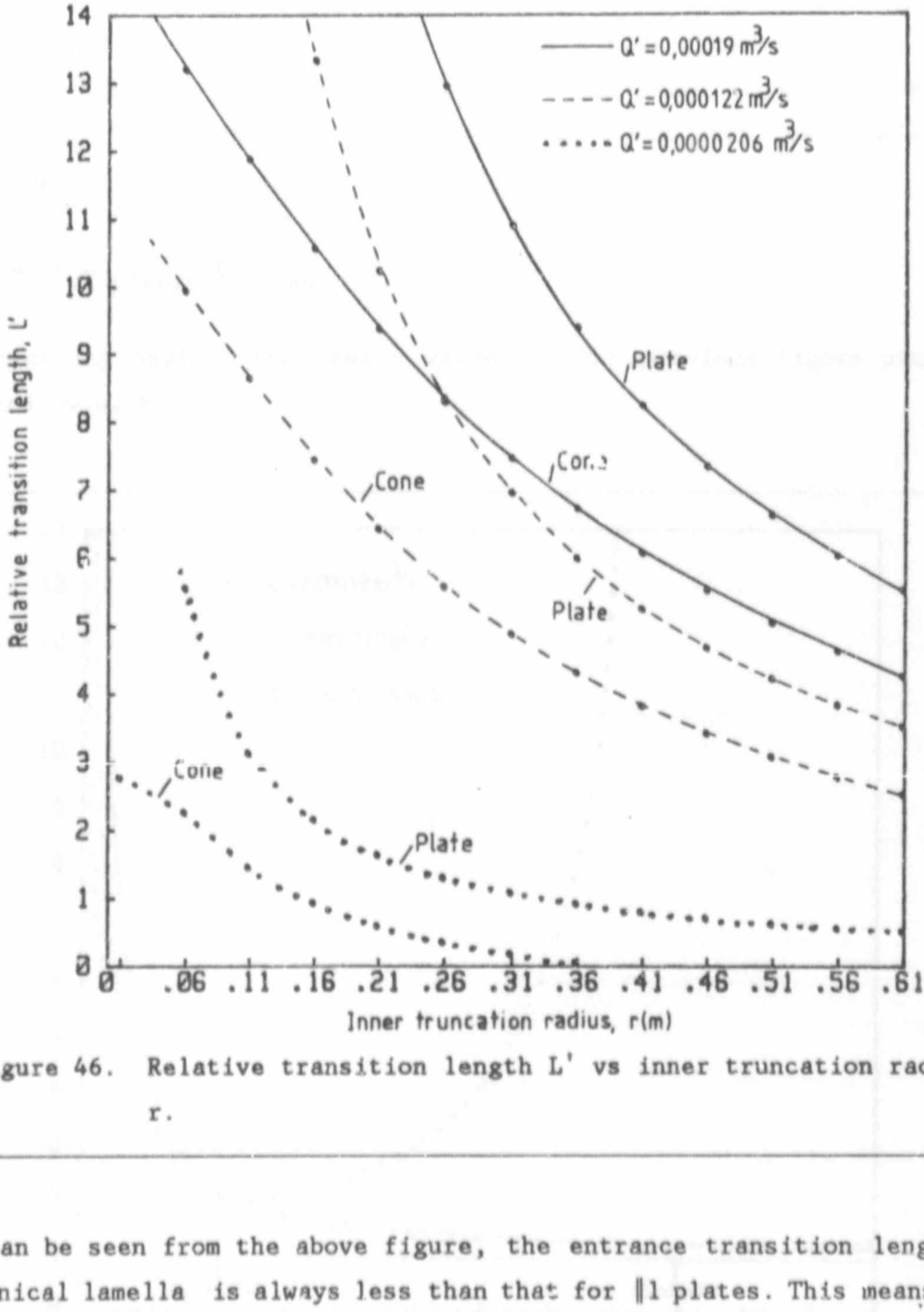

Figure 46. Relative transition length L' vs inner truncation radius r.

As can be seen from the above figure, the entrance transition length of a conical lamella is always less than that for ‖l plates. This means that settling under laminar flow conditions is liable to occur sooner between conical plates than ‖l ones. Also the smaller the truncation radius r of the cones the longer the transition length, hence it would be advantageous to design a conical lamella settler with a large as possible inner radius to capitalise on the greater reduction of the transition length with increasing r. The above figure also shows that the transition length increases with increasing flow rate through a single plate spacing which is to be expected since L' is directly proportional to the average velocity v_0. Theoretically L' can even be zero for very low flow rates. Defining:

$$L'' = L'_{plates} + L'_{cones}$$

and plotting against the same r values as the previous figure produces the following plot:

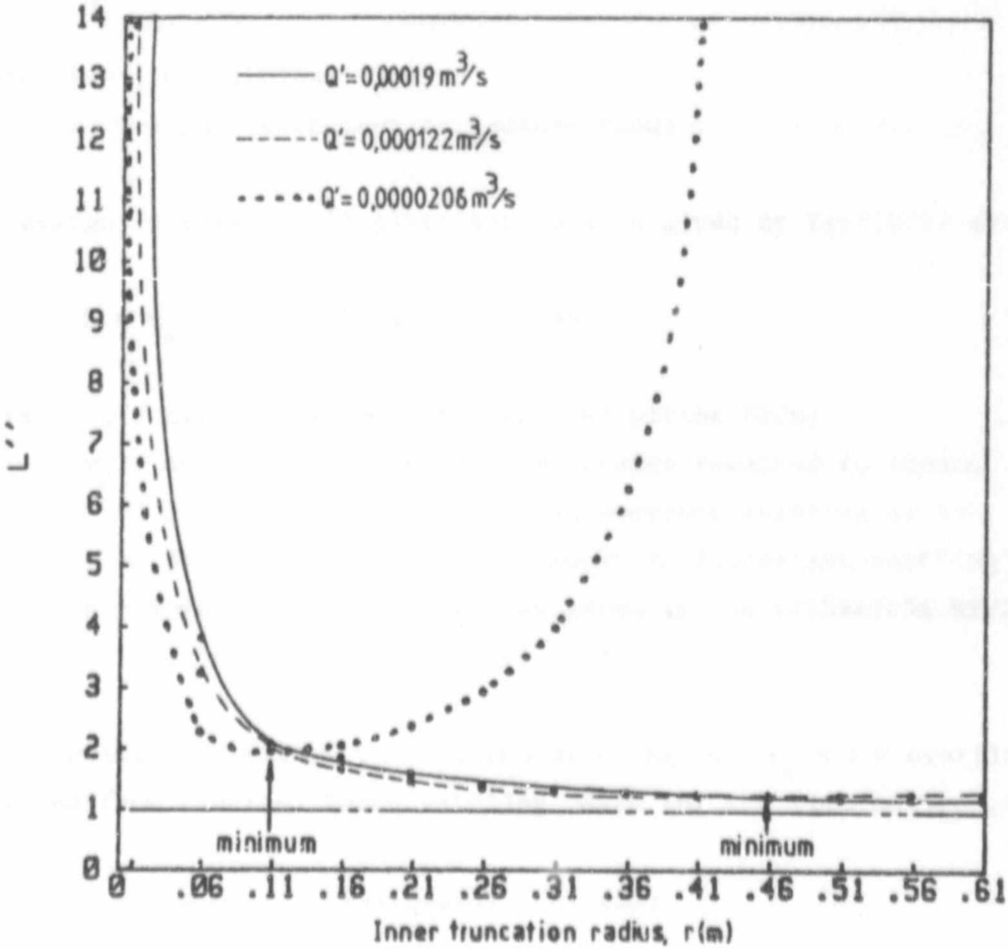

Figure 47. L" vs inner truncation radius r.

Since L" is a function of r^2 a series of parabola are formed for different Q'. It should be noted that L" never falls below 1 meaning that a reduction in the transition length due to the geometry of the cones is always possible, however small it may be. The plot also highlights the advantages of using cones over ∥l plates at small r values since this is where the reduction of L' is the greatest.

Yao(1970) recommends that the relative transition length L' be added to L (relative length of fully developed laminar flow) to obtain the design relative length. Therefore the design relative length L_d is given by:

$$L_d = L+L' \quad ---(25)$$

where $L = l/d$ (laminar flow)

$L' = l'/d$ (turbulent to laminar flow)

The design formula for ∥l plate settlers is given by Yao(1970) as:

$$S = v_s/v_0 \times (\sin\alpha + L\cos\alpha) \quad ---(26)$$

where v_0 - average velocity between the plates (m/s)

v_s - overflow rate in inclined plates required to remove a certain particle size in discreet settling or to obtain a certain % SS removal in flocculant settling (m/s)

S - S-value (Numerical values given in the LITERATURE REVIEW. For plate configurations, S = 1.)

Substituting equation (17) for v_0 and assuming that v_s = v = overflow rate obtained from vertical batch settling tests for the time being, gives:

$$S = n.b.d.v/Q \times (\sin\alpha + L\cos\alpha) \quad ---(27)$$

Now consider two ∥l plate lamella settlers with $b_1 = b$ and $b_2 = k.b$ and Q, n, d, α and v being equal for both units and k some constant. Then:

$$S = n.v.d.b/Q\times(\sin\alpha + L_1\cos\alpha) \quad \text{for unit 1} \quad \text{---(28)}$$

$$S = n.v.d.kb/Q\times(\sin\alpha + L_2\cos\alpha) \quad \text{for unit 2} \quad \text{---(29)}$$

Dividing (28) by (29):

$$k = (\sin\alpha + L_1\cos\alpha)/(\sin\alpha + L_2\cos\alpha) \quad \text{---(30)}$$

For L large (Yao(1970) recommends between 20 and 40), and $\alpha = 55°$ (typically) gives $\sin\alpha = 0{,}819$ and $11{,}5 \leq L\cos\alpha \leq 23$. Hence $L\cos\alpha \gg \sin\alpha$, and equation (30) becomes approximately:

$$k = L_1/L_2$$

Then the volume V occupied between two parallel plates for the laminar flow region in terms of L_1 for both units is:

$$V_1 = L_1.b.d^2$$

$$V_2 = (L_1/\kappa).kb.d^2$$

$$V_2 = L_1.b.d^2$$

Hence the two volumes are equal (for equal v, n, Q, and d) and it is this approximation which will be used in formulating L for the conical plates.

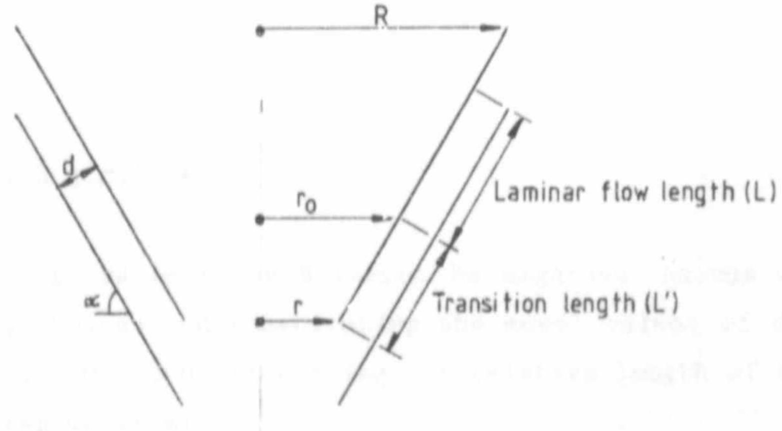

Figure 48. Flow regimes between the conical plates.

The volume between r_0 and R is given by (derivation in APPENDIX I):

$$V_{cone} = \pi\tan\alpha\{ R^2d/\sin\alpha - R.d^2/(\sin\alpha)^2 - r_0d^2/(\sin\alpha)^2 - (r_0)^2d/\sin\alpha \} + \pi d^2r_0/\tan\alpha + \pi d^2(R-d/\sin\alpha)/\tan\alpha \quad ---(31)$$

The volume of the laminar flow region between rectangular plates is:

$$V_{plate} = L.b.d^2$$

and $L = S.Q/(n.b.d.v.\cos\alpha) - \tan\alpha \quad ---(32)$

hence $V_{plate} = \{S.Q/(n.b.d.v.\cos\alpha) - \tan\alpha\}.b.d^2 \quad ---(33)$

Then equating equations (31) and (33) and putting $b = 2\pi r_0$ for equal entrance widths to the laminar flow region:

$$S.Q.d/(n.v.\cos\alpha) - 2\pi r_0d^2\tan\alpha = \pi\tan\alpha\{ R^2d/\sin\alpha - R.d^2/(\sin\alpha)^2 - r_0d^2/(\sin\alpha)^2 - (r_0)^2d/\sin\alpha \} + \pi d^2r_0/\tan\alpha + \pi d^2(R-d/\sin\alpha)/\tan\alpha$$

$$[\pi d/\cos\alpha]R^2 + [\pi d^2/\tan\alpha - \pi d^2/(\sin\alpha\cos\alpha)]R - [S.Q.d/(n.v.\cos\alpha)$$

$- 2\pi r_0 d^2 \tan\alpha + \pi r_0 d^2/(\sin\alpha\cos\alpha) + \pi(r_0)^2 d/\cos\alpha - \pi d^2 r_0/\tan\alpha$
$\pi d^3/(\tan\alpha\sin\alpha)] = 0$

ie. $A.R^2 + B.R - C = 0$

$$R = \{ -B + \sqrt{(B^2 + 4.A.C)}\}/2A \quad ---(34)$$

Only the positive root is valid since R cannot be negative. Assume v = 0,000377m/s (arbitrary choice) and substituting the model values of d = 0,04m, $\alpha = 55°$, S = 1, n = 5 and calculating the relative length of the conical laminar flow region from:

$$L_{cone} = (H-h_0)/d$$

$$= (R-r_0)/(d\cos\alpha) \quad ---(35)$$

and also plotting equation (32) for varying r_0, produces figure 49.

As can be seen from figure 49, the relative length of laminar flow required for cones is less than that for rectangular plates, but only up to a point after which the rectangular relative plate length is less than that required for cones. Yao(1970) recommends a L of about 20 to 40 for ‖1 plates and from the above figure it can be seen that to satisfy this requirement and still have $L_{plates} > L_{cones}$, a very large r_0 will be required. The width of the ‖1 plate, $b = 2\pi r_0$, should however not be too large since the problem arises in trying to distribute the flow evenly across the entire plate. For this reason the width is limited to 1 - 1,2m in practice. This practical limitation results in only a small portion of the graph (shaded area in the above figure) in which L for cones is bigger than L for plates. The stipulation that $20 \leq L \leq 40$ and $r_0 < 0,19$m will completely exclude this area of design and hence L for cones is very much less than L for plates in a practical situation. Figure 49 is only valid if L' = 0.

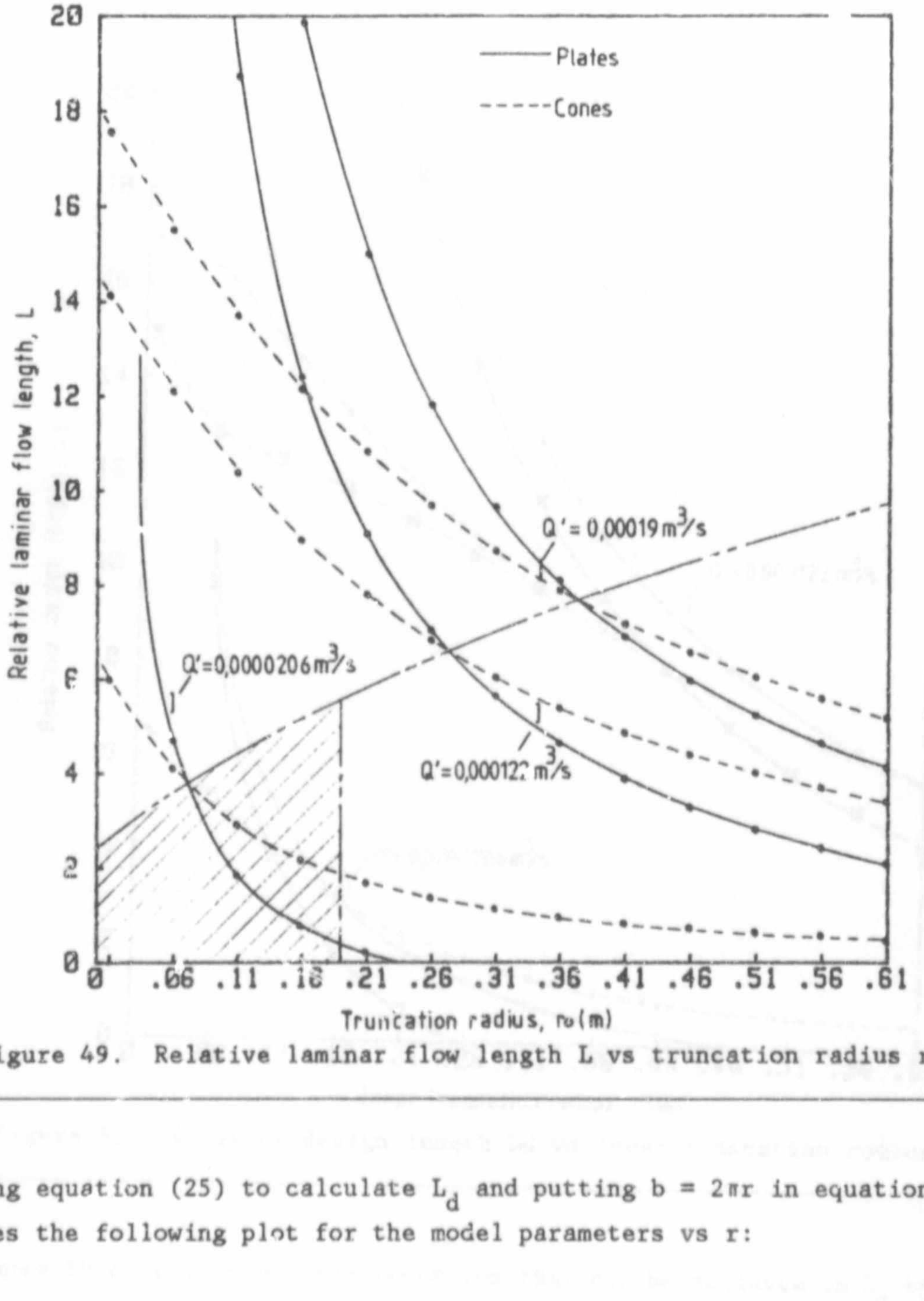

Figure 49. Relative laminar flow length L vs truncation radius ro.

Using equation (25) to calculate L_d and putting $b = 2\pi r$ in equation (32) gives the following plot for the model parameters vs r:

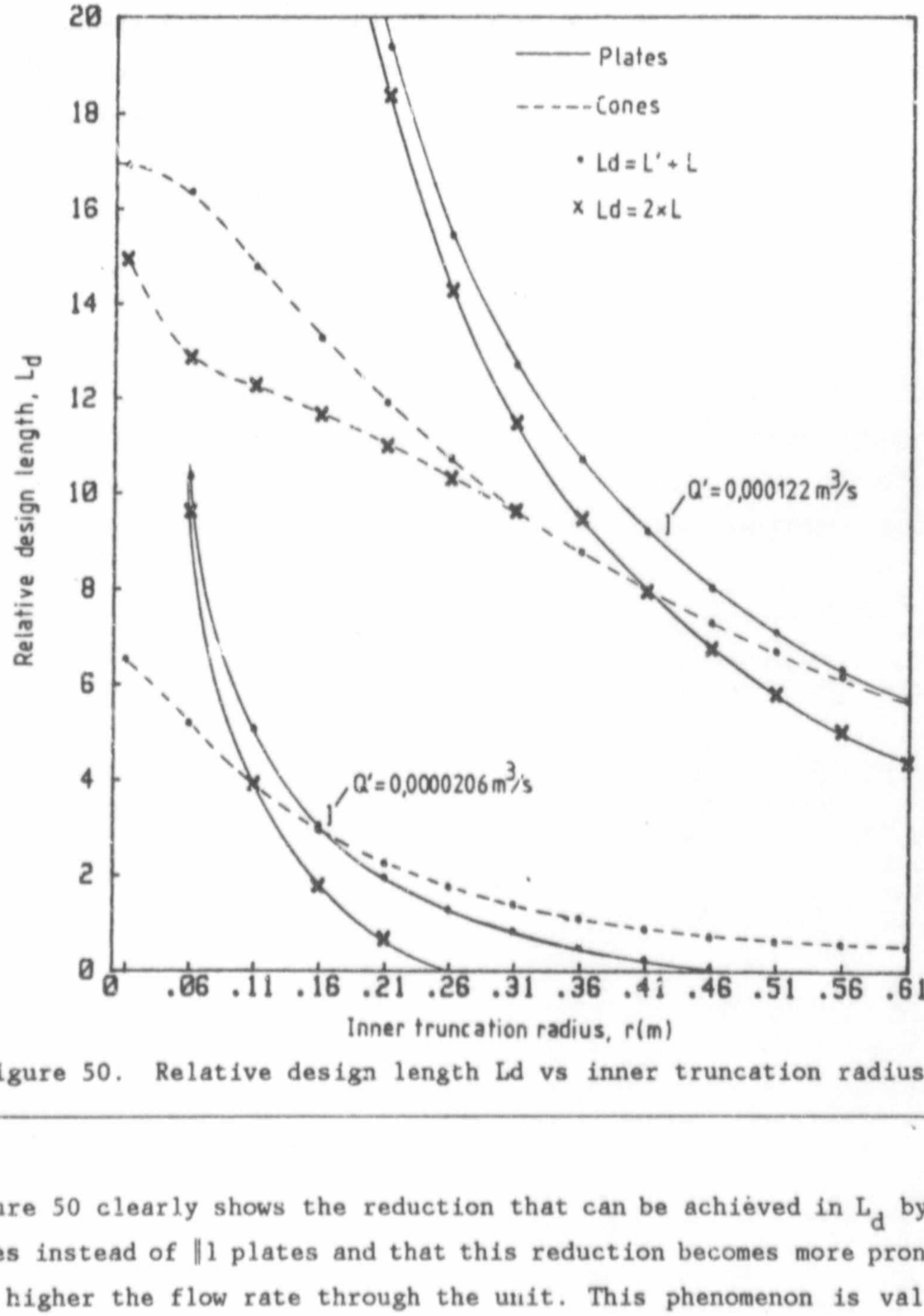

Figure 50. Relative design length Ld vs inner truncation radius r.

Figure 50 clearly shows the reduction that can be achieved in L_d by using cones instead of ‖l plates and that this reduction becomes more pronounced the higher the flow rate through the unit. This phenomenon is valid for all the practical design considerations of $20 \leq L \leq 40$ and $r < 0{,}19$m. Yao(1970) also recommends that if $L' > L$ a value of $L_d = 2L$ be used instead of $L_d = L+L'$. If this statement is incorporated in the above plot, an L_d adjusted as shown above is obtained. This constraint results in an even greater reduction for L_d in the practical design region for conical settlers whereas L_d is reduced for plates only at large *r* which are not advisable since a uniform velocity distribution over the inlet becomes difficult to achieve.

7.2 MODIFICATION OF THE BATCH SETTLING OVERFLOW RATE FOR USE IN THE CONICAL LAMELLA SETTLER

The enhancement of the settling rate under inclined surfaces is well known and Nakamura and Kuroda(1937) developed a simple model to express this phenomenon in mathematical terms (see LITERATURE REVIEW). Arcivos and Herbholzheimer(1979) showed that this theory should be adequate for the design of both continuous and batch settling tanks as a first approximation and an upper limit, and is hence used to approximate the initial settling velocity under the inclined surface of a cone. Consider the following two cones with a suspension between them, initial height k_0:

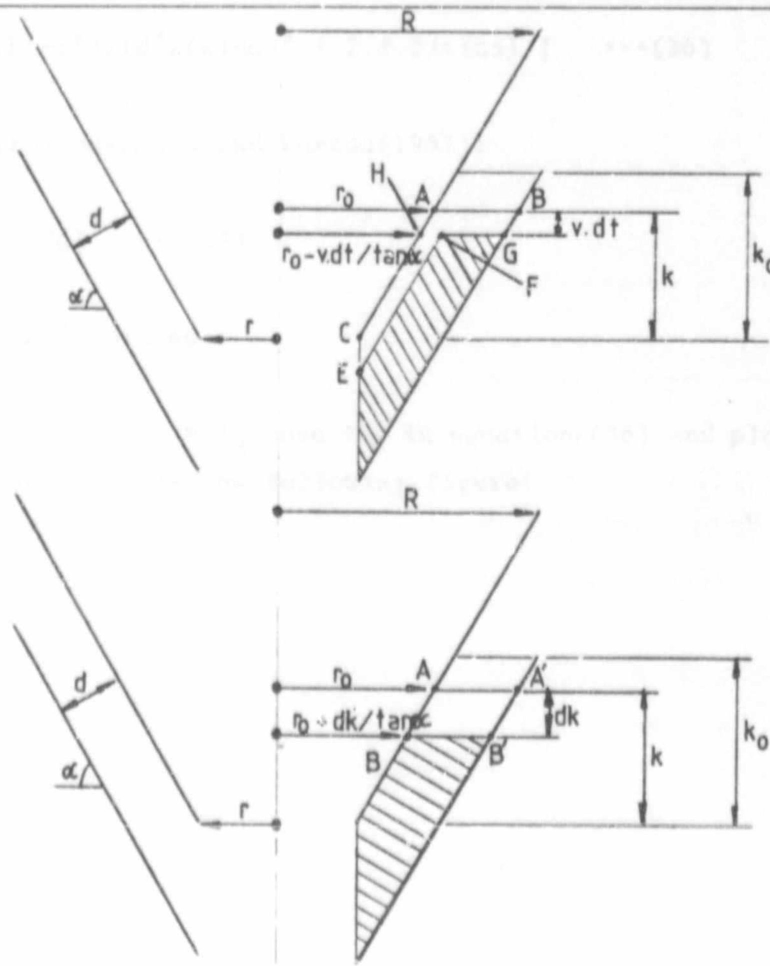

Figure 51. Nakamura model for a suspension between conical plates.

For reasons explained in the LITERATURE REVIEW, the volume ABA'B' = volume ABGFEC (see APPENDIX I for the derivation of the volumes). Equating the two volumes gives:

$$(dk).\{ \pi d^2/(\sin\alpha)^2 + 2\pi r_0 d/\sin\alpha \} = (v.dt).\{ (\pi d^2/(\sin\alpha)^2 + 2r_0\pi d/\sin\alpha + (\pi(r_0)^2 - \pi r^2) \}$$

and $(dk)/(dt) = v_s$ the overflow rate in quiescent conditions under the inclined surfaces of the cones. For k_0 the initial height of the suspension, $r_0 = R$ and hence the ratio of the settling velocity in a tilted conical tube (v_s) to the sedimentation velocity in a vertical tube (v), is:

$$v_s = v.[\ 1 + (R^2-r^2)/(d^2/(\sin\alpha)^2 + 2.R.d/\sin\alpha)\ ] \quad ---(36)$$

For a square tube from Nakamura and Kuroda(1937):

$$v_s = v.[1+k_0\cos\alpha/d] \quad ---(37)$$

where $k_0 = l_d\sin\alpha$ for $\|$l plates.

Putting $\alpha = 55°$, d = 0,04m, $R = l_d.\cos\alpha + r$ in equation (36) and plotting v_s/v vs r for various l_d gives the following figure:

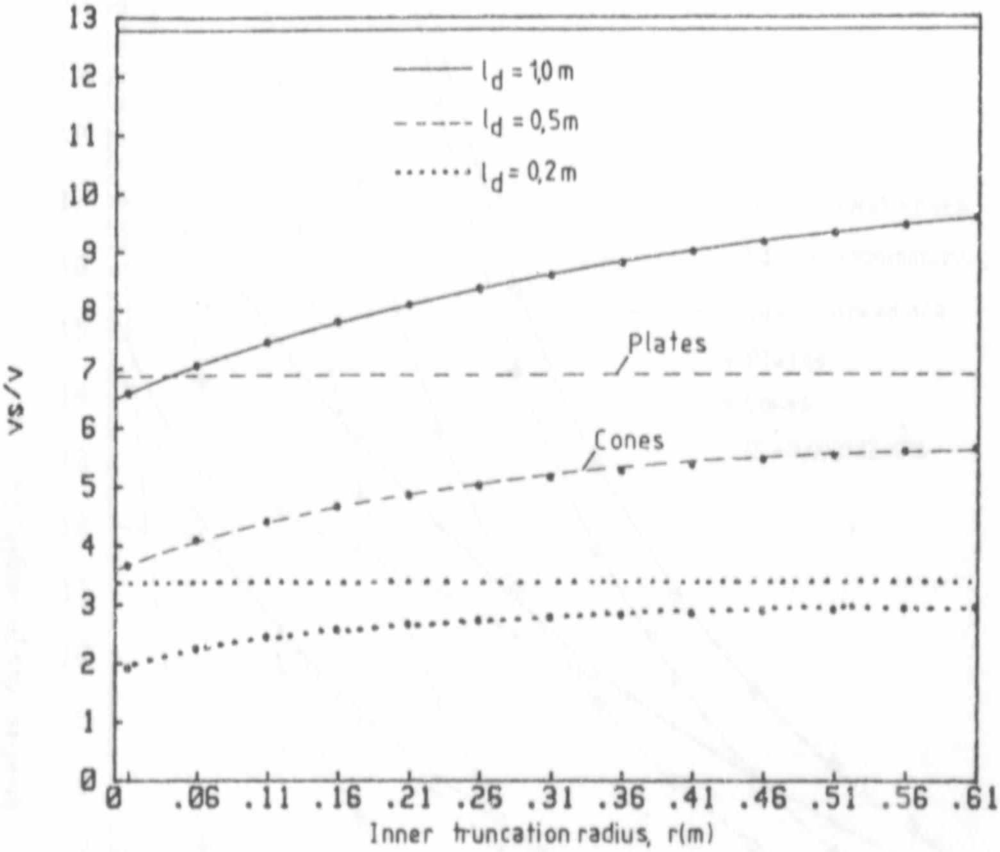

Figure 52. vs/v vs inner truncation radius r for various values of ld.

As can be seen from the above figure v_s/v for ‖l plates is a theoretical constant for a specific value of l_d. The value of v_s/v for cones however increases with increasing r but is less than that for ‖l plates.

Equations (36) and(37) can be incorporated into the design formulae (32) and (34) where v is replaced by v_s, the adjusted batch settling overflow rate. This requires an iterative procedure to solve for l_d, the final design length. Substituting $\alpha = 55°$, $n = 5$, $Q = 0{,}000611 m^3/s$, $v = 0{,}00038 m/s$, $d = 0{,}04 m$ and $\nu = 1{,}01\times10^{-6} m^2/s$, the following curves are obtained for the various approaches to the design of rectangular and conical lamella settlers:

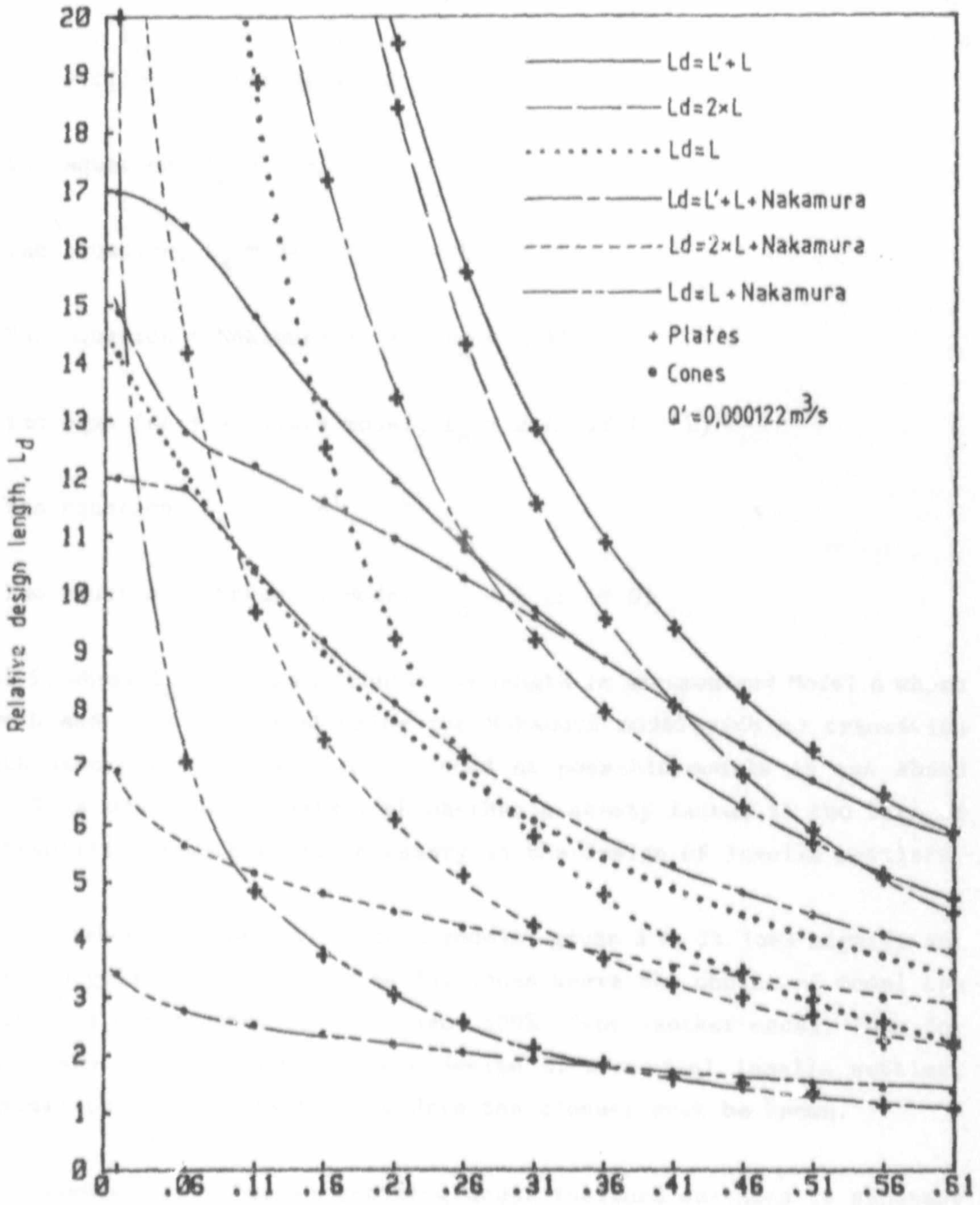

Figure 53. **Relative design length Ld vs inner truncation radius r for different approaches to the design of continuous lamella settlers.**

The above figure clearly shows the differences in the final relative design length L_d caused by differences in the approach to the design of a lamella settler. Essentially there are the following approaches:

1. Yao equation, $L_d = L'+L$

2. Yao equation, $L_d = 2 \times L$ (if $L' > L$)

3. Yao equation + Nakamura model, $L_d = L'+L$

4. Yao equation + Nakamura model, $L_d = 2 \times L$ (if $L' > L$)

5. Yao equation, $L_d = L$ ($L' = 0$)

6. Yao equation + Nakamura model, $L_d = L$ ($L' = 0$)

Model 5, where $L_d = L$ and no transition length is assumed and Model 6 where $L_d = L$ and v is increased using the Nakamura model with no transition length incorporated, are also included as possible models in the above plot. This was done to establish whether a safety factor in the form of the transition length L' is necessary in the design of lamella settlers.

The differences between the various models, given a r, is less significant for rectangular plates than that for cones where the choice of model can result in a discrepancy of more than 500% from another model. Thus for an accurate first estimate in the design of a conical lamella settler, the model type that fits the raw data the closest must be known.

The phenomenon of enhanced settling under inclined surfaces is apparent in the dramatic drop of L_d from Models 1 to 3, 2 to 4 and 5 to 6. Also the geometry of cones allows for a much more significant drop in L_d than for rectangular plates. Thus as the theory progresses from Models 1 through to 6, the greater the reduction in L_d for cones as compared to ‖l plates.

Finally it must be emphasised that the preceding equations, especially the ones concerning ‖l plates, are strictly theoretical and require empirical data to substantiate them. It is for this reason that an attempt is made to fit one of the various models to the empirical data obtained in the laboratory for the conical lamella model settler. This is done in the next chapter.

8.0 APPLICATION OF LAMELLA SETTLING THEORY TO RESULTS OBTAINED FROM THE CONICAL LAMELLA SEDIMENTATION TANK

8.1 LAMELLA SPACING D = 0,04M

The dimensions of the cones inserted into the perspex tank are as follows (see APPENDIX E):

$\alpha = 55°$
$r = 0{,}11m$
$R = 0{,}3975m$
$n = 5$
$\nu = 1{,}01\times10^{-6}m^2/s$ (T = 20°C)
$d = 0{,}04m$
$L_d = 12{,}53$

The dimensions of the cones were chosen as such due to the physical constraints of the perspex model tank (outer radius = 0,4475m). Total flow rates passing through the lamella pack (adjusted to T = 20°C) were as follows:

$Q = 0{,}000103m^3/s$
$= 0{,}000272m^3/s$
$= 0{,}000442m^3/s$
$= 0{,}000611m^3/s$
$= 0{,}000778m^3/s$
and $= 0{,}00095m^3/s$

Since the physical dimensions of the conical lamella are fixed, the only variable appearing in the design equations in the previous chapter is v - the overflow rate required for a certain percentage SS removal. Hence the equations describing the various models will be solved for this variable for the different Q. The effect the gutters will have on the theoretical results is not considered since it is not quantifiable and hence the lamella will be treated as perfect cones.

The batch settling results carried out in the vertical settling column (see APPENDIX A) are evaluated for a settling depth of $h' = d/\cos\alpha$ since this is the maximum vertical distance a particle has to settle between the cones for the particle to be removed. (For the model $h' = 0{,}07$m). This is done for the range of concentrations tested. From the graph of % SS removal vs overflow rate obtained from batch settling data, the % SS removals for the v values calculated from the design equations are read off for the range of concentrations tested and plotted together with the curves of % SS removal vs concentration for the conical lamella model settler. A comparison between theory and practice is then made.

The theoretical batch settling overflow rates (v) expressed in m/h, plotted vs Q give the following curves for the various models:

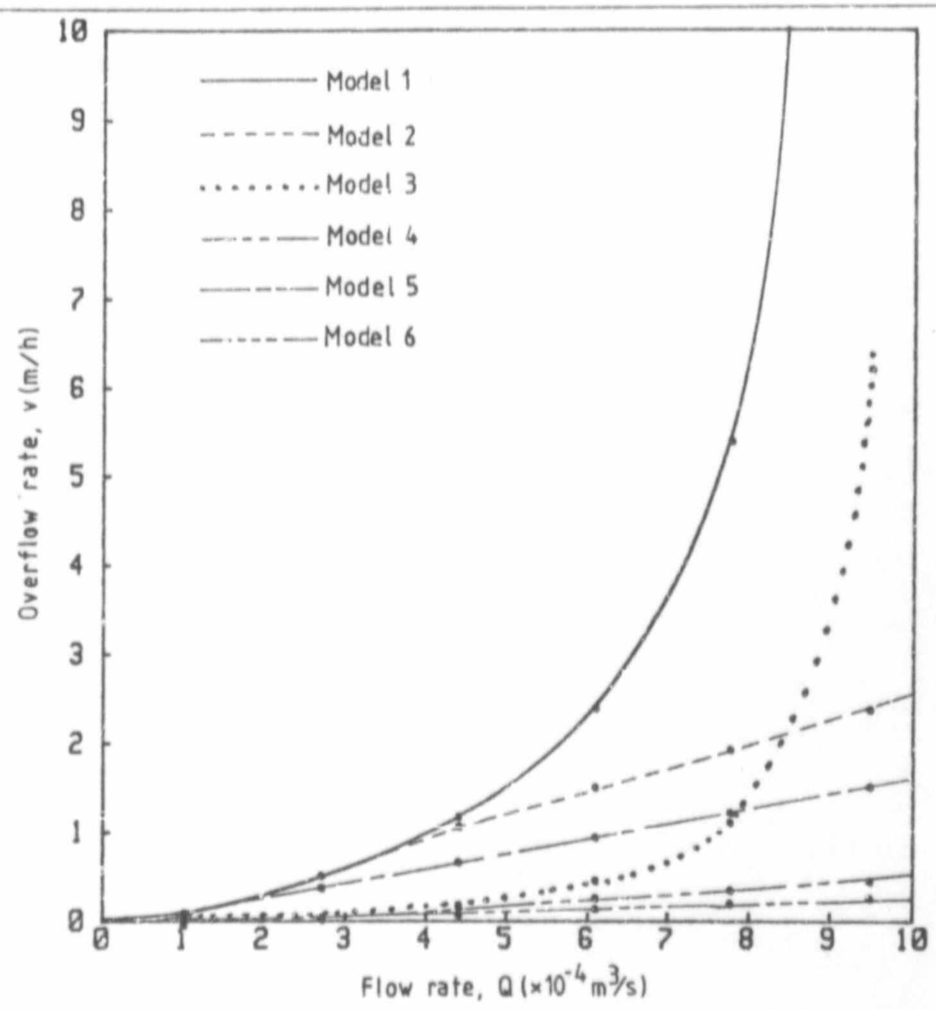

Figure 54. Overflow rate v vs total flow rate Q for the various theoretical models.

The above figure clearly highlights the lack of correlation between the various approaches to the design of lamella settlers.

The graphs of % SS removal vs v(m/h) for various concentrations are given in APPENDIX H and are derived from the same figures of % SS removed vs time and depth given in APPENDIX A for a settling depth of 70mm. To avoid cluttering of the next lot of graphs, Model 6 is not elaborated on since it predicts the lowest v values of all the models (see figure 54). The corresponding % SS removals for these v values are hopelessly too high for any accurate prediction of the conical lamella performance and therefore Model 6 is discarded right at the onset. Figures of influent SS concentration vs % SS removal for various Q' depicting both the experimental results and the theoretical data for Models 1 to 5 follow:

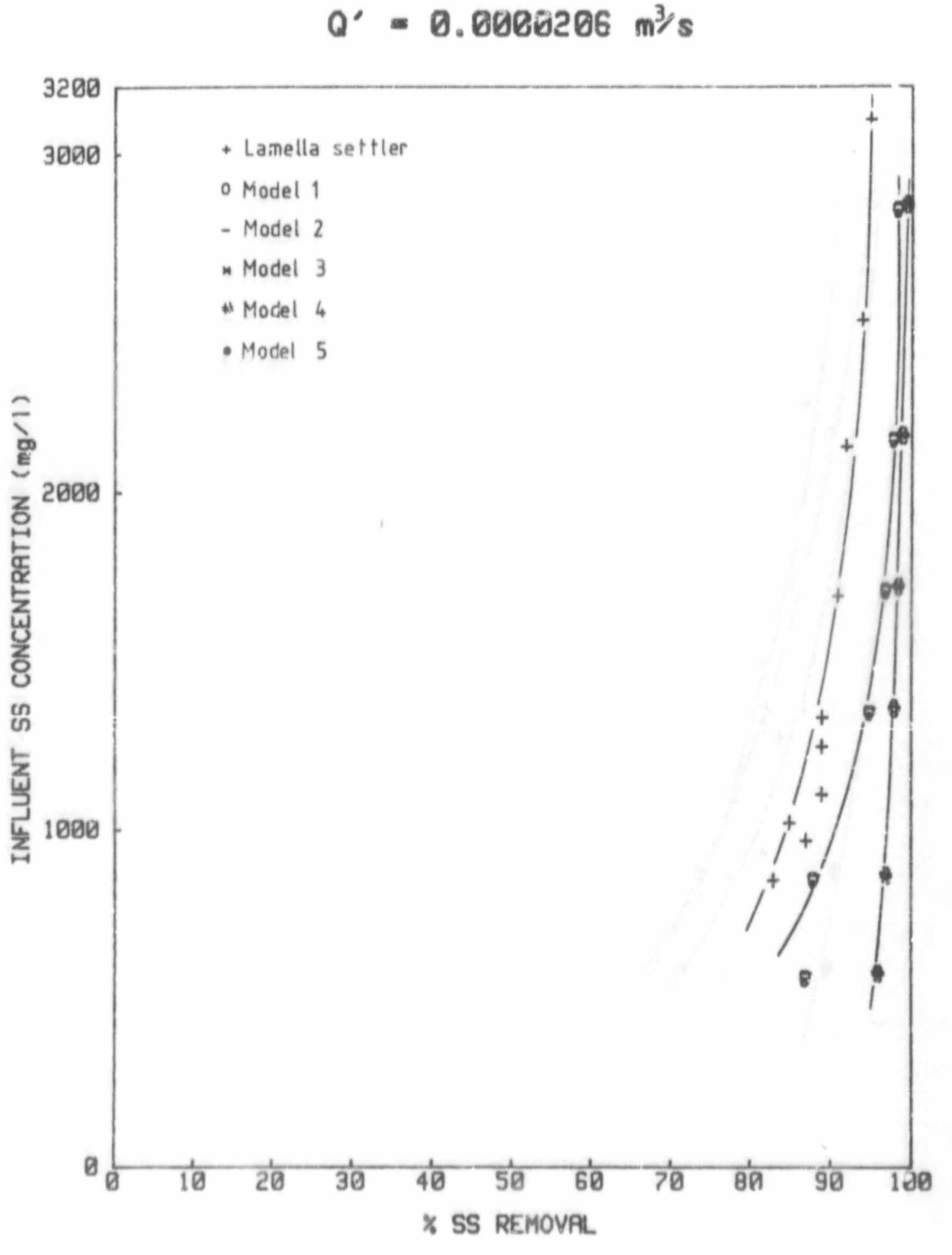

Figure 55. Influent SS concentration vs % SS removal. Q' = 0,0000206m³/s.

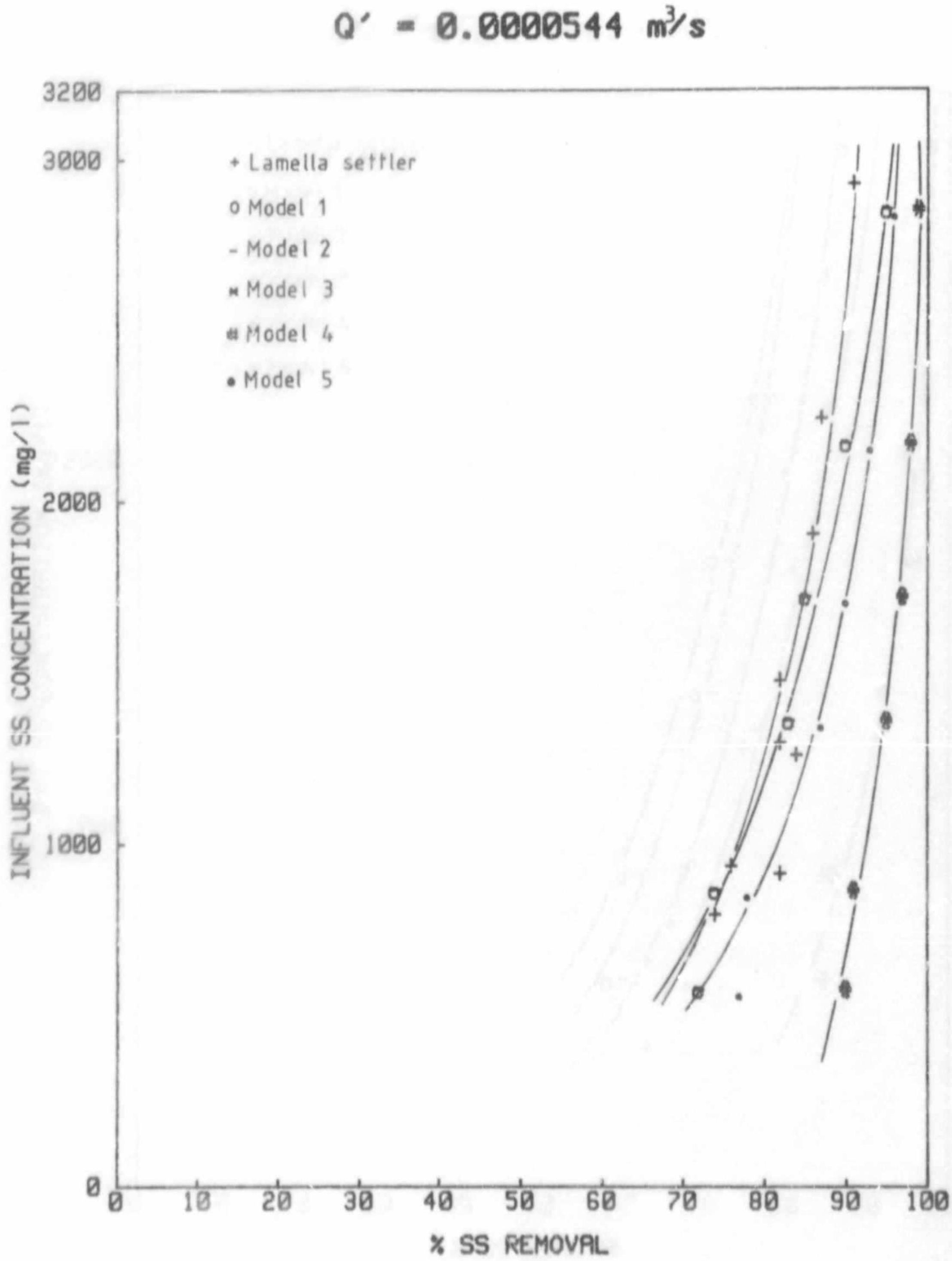

Figure 56. Influent SS concentration vs % SS removal. Q' = 0,0000544m³/s.

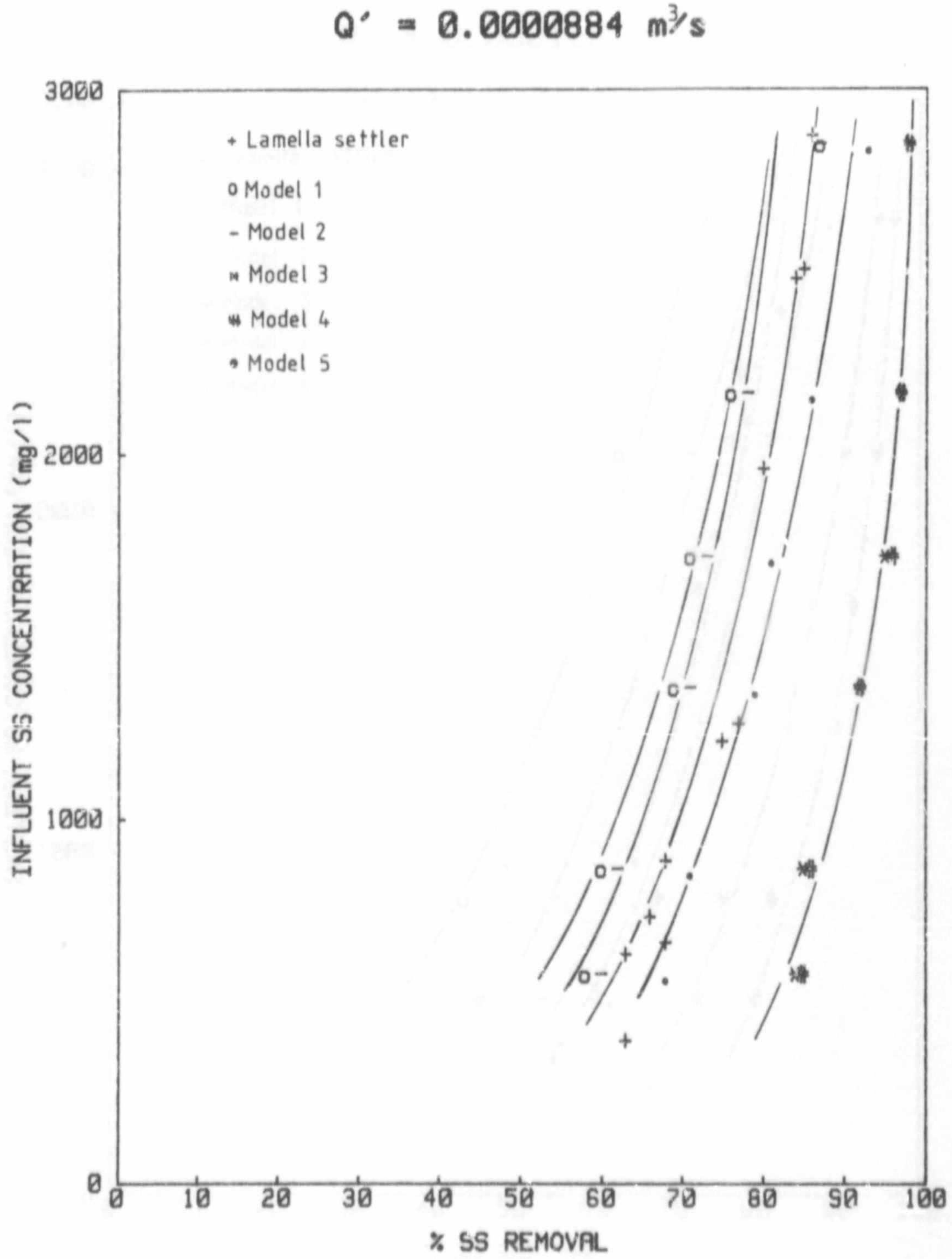

Figure 57. Influent SS concentration vs % SS removal. Q' = 0,0000884m³/s.

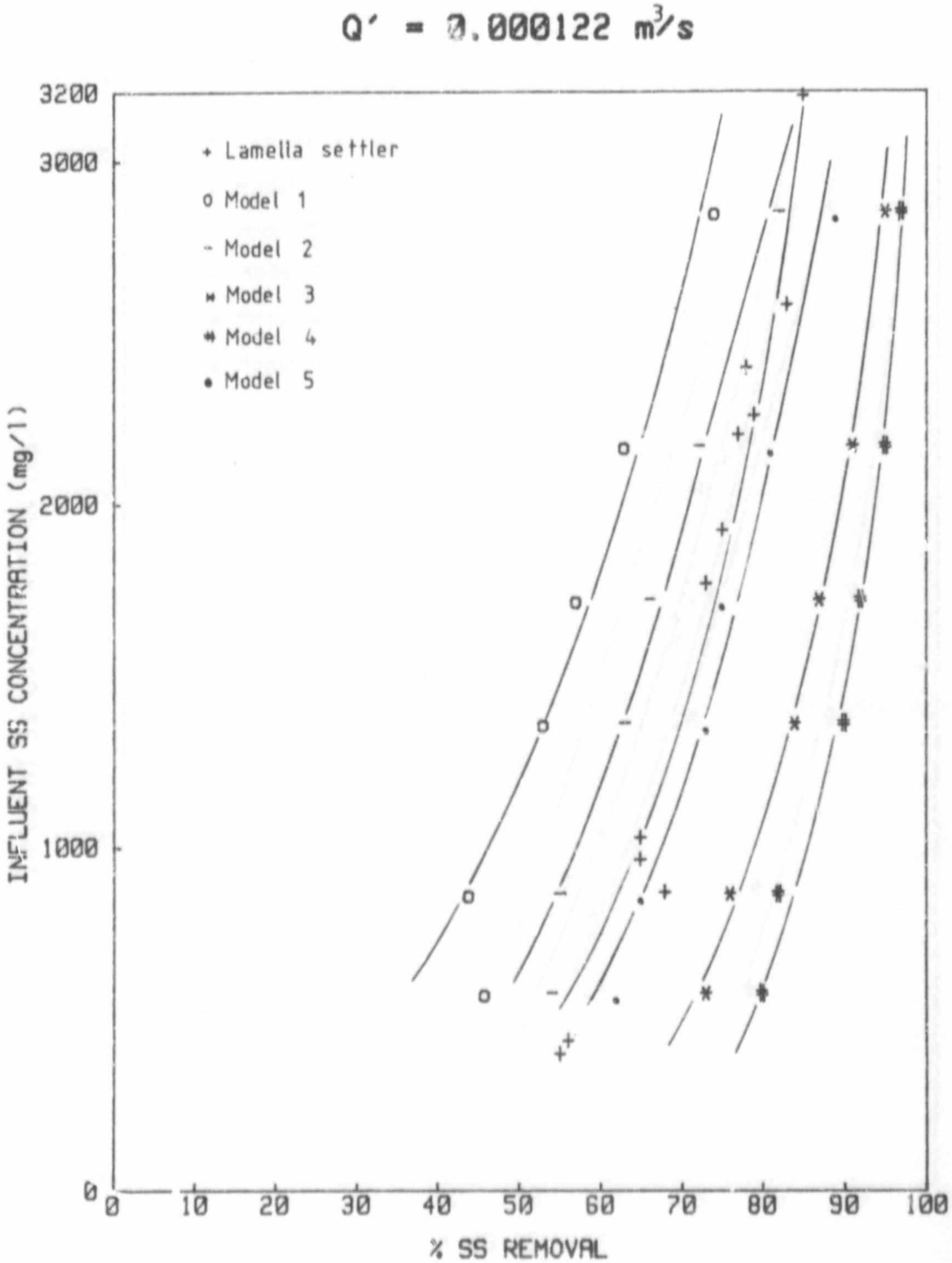

Figure 58. Influent SS concentration vs % SS removal. Q' = 0,000122m³/s.

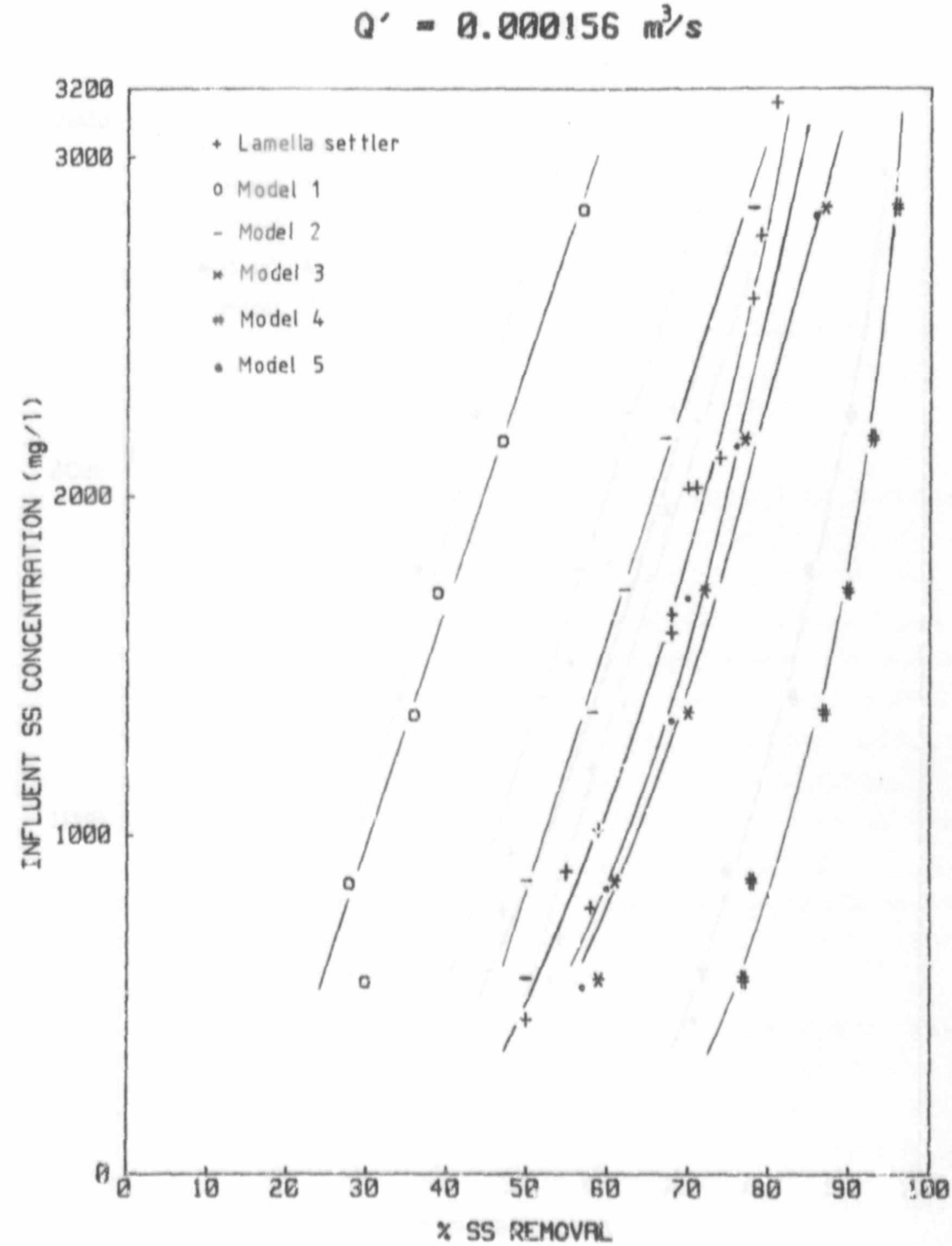

Figure 59. Influent SS concentration vs % SS removal. Q' = 0,000156m³/s.

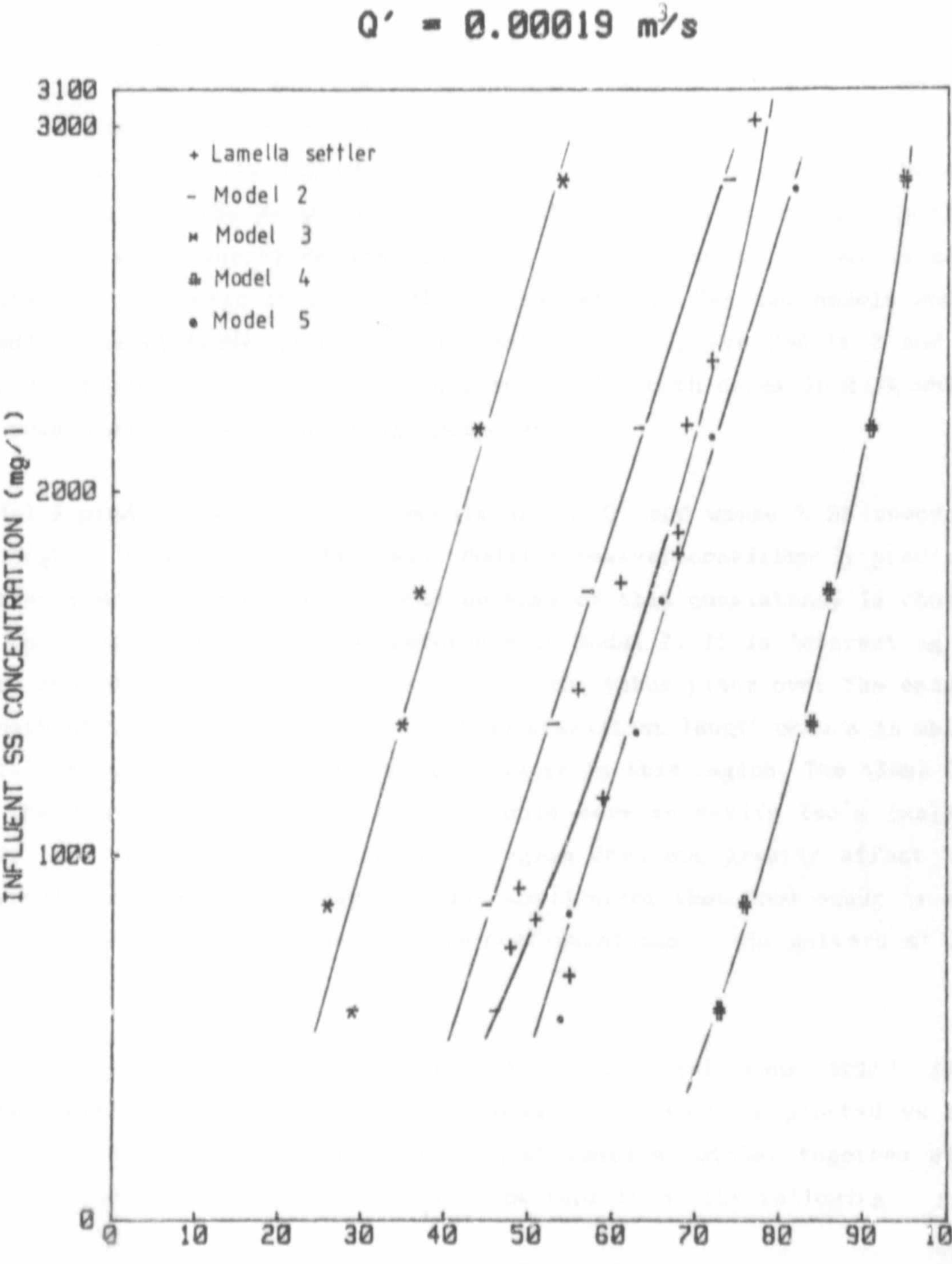

Figure 60. Influent SS concentration vs % SS removal. Q' = 0,00019m³/s.

The preceding figures show that Model 1, 3, and 4 do not predict effluent qualities accurately and that discrepancies vary from almost 0% to 20% for the same model. Hence these models are discarded as impractical for design. It is interesting to note that the models which include the adjustment of v by the Nakamura theory (Models 3, 4, and 6) are also in this group. It would therefore seem that the Yao equation on its own is adequate for the design of a conical lamella settler. The two models which predict the effluent qualities the most accurately are Models 2 and 5. The discrepancy between theory and practice for both cases is ± 5% which is more than adequate for design purposes.

Model 2 predicts better % SS removals at low Q' and worse % SS removals at high Q' (see previous figures). Model 5 however consistently predicts better removals than practice and because of this consistency is chosen as the final design model in preference to Model 2. It is interesting to note that Model 5 assumes that sedimentation takes place over the entire length of the conical plate and that no transition length occurs in which settling is prevented due to the turbulence in this region. The close fit of the data to Model 5 (< 5% error), would seem to verify Yao's feeling that the existence of a transition region does not greatly affect the removal efficiencies of a system. The small error that does occur is ascribed to disturbances caused by the configurations of the gutters at the inlet.

If the upscale factor (ratio of batch to model tank total flow rate/overflow rate), for a 70% SS removal efficiency is plotted vs the influent SS concentration for the conical lamella settler together with the upscale factors for the upward flow tank then, the following figure is obtained:

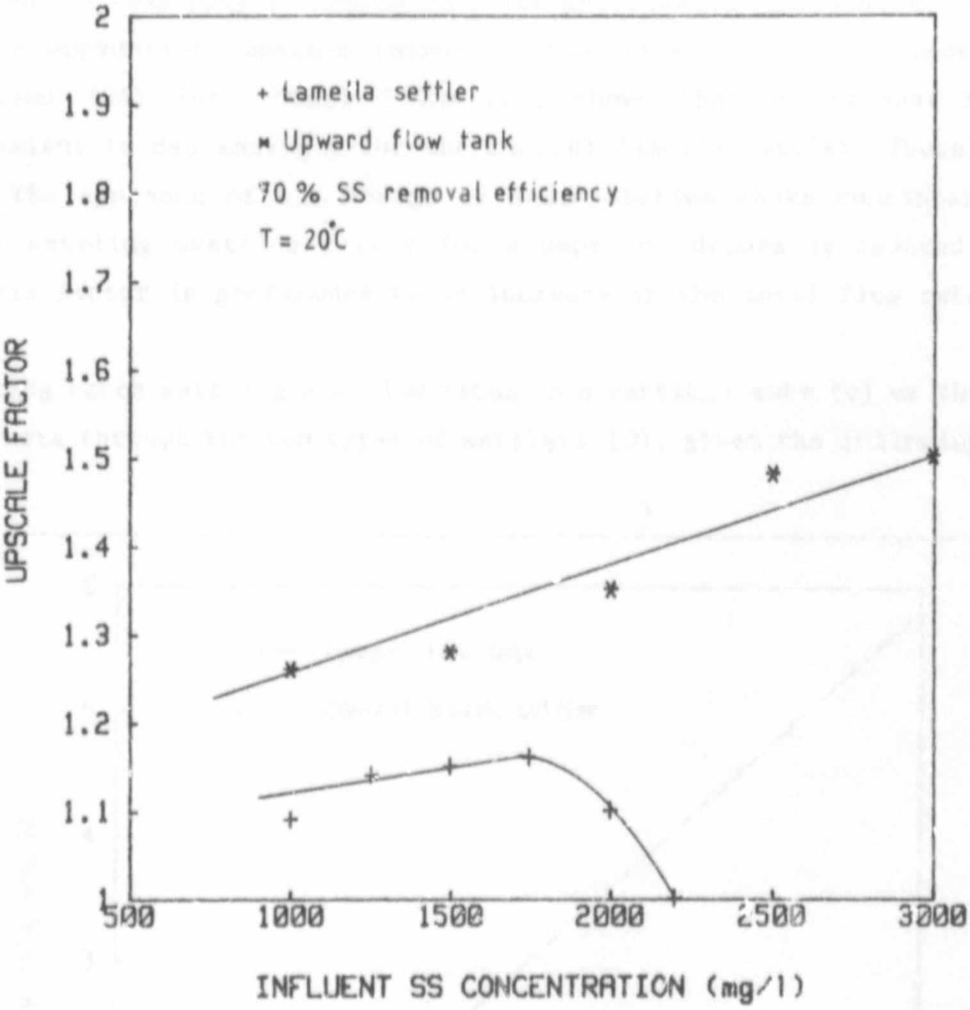

Figure 61. Upscale factor vs influent SS concentration.

The figure clearly shows that the discrepancy between theory and practice is far less for the lamella settler than for the upward flow tank. This can be ascribed to flow stability resulting from the flow of water between the parallel plates. Also an upscale factor is no longer required at an influent SS concentration of 2200mg/l since a 70% removal efficiency is achieved at this point. This indicates that the conical lamella settler produces a much more efficient form of settling than a conventional system does. It must however be remembered that the upscale factor for the lamella settler is calculated from the ratio of the batch to model tank total flow rate (Q), while for the upward flow tank the overflow rate (v) is used for this purpose. Hence in a design situation Q would be increased by the appropriate upscale factor in the lamella settler. Looking at equation (34) for Model 5 however, shows that an increase in Q is equivalent to decreasing v for the conical lamella settler. Therefore to keep the approach of the design of sedimentation tanks consistent, the batch settling overflow rate v for a depth of $d/\cos\alpha$ is reduced by the upscale factor in preference to an increase in the total flow rate Q.

Plotting batch settling overflow rates in a vertical tube (v) vs the total flow rate through the two types of settlers (Q), gives the following plot:

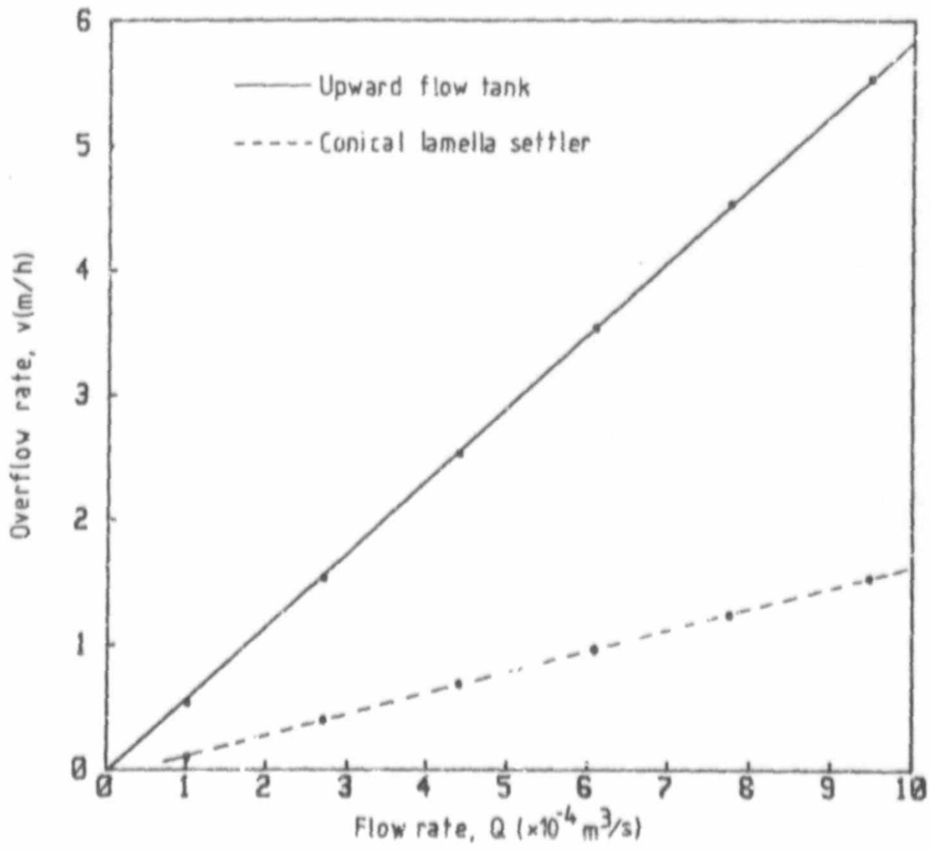

Figure 62. Overflow rate v vs total flow rate Q for both the upward flow and the conical lamella settlers.

The increase in overflow rate with an increase in Q for the conical lamella settler is 3,5 times less than that for the upward flow tank. Hence a sudden surge of Q through an upward flow tank will result in a very rapid hydraulic overloading whereas the introduction of cones into such a tank will reduce the chances of such a failure since the increase of v with Q is much more gradual if this type of up-rating is introduced.

8.2 LAMELLA SPACING D = 0,032M

Substituting d = 32mm, n = 6, α = 55°, r = 0,11m, R = 0,3975m, and ν = $1{,}01\times10^{-6}m^2/s$ into the equation of Model 5, results in a theoretical prediction of the conical lamella performance as shown in APPENDIX E. The figures show a fairly good correlation between theory and practice and the discrepancy in the % SS removals ranges from 5% at low Q to 10% at high Q. The consistency in the discrepancies which exists for a plate spacing of d = 40mm (constant 3 - 4%) is therefore not present for the d = 32mm plate spacing. The upscale factor (ratio of theoretical to laboratory overflow rate) is higher for d = 32mm as compared to d = 40 mm since the differences between theory and practice are higher for the d = 32mm case.

Theoretically the bigger the n, and the lower the d, the more efficient the settling between the plates should be, ie. v decreases for the same Q which means that a higher % SS removal is theoretically achievable (compare v Model 5 for d = 32mm and 40mm in APPENDIX H). This theoretical performance is however not borne out in the laboratory results (APPENDIX F). In fact the conical lamella results at d = 32mm produce some 5% lower % SS removals than d = 40mm at the two highest Q.

The average velocity over the circular inlet for one plate spacing of the cones is given by:

$$v_0 = Q/(2\pi n.r.d) \qquad ---(38)$$

Plotting v_0 vs Q for d = 32mm and d = 40mm gives the following figure:

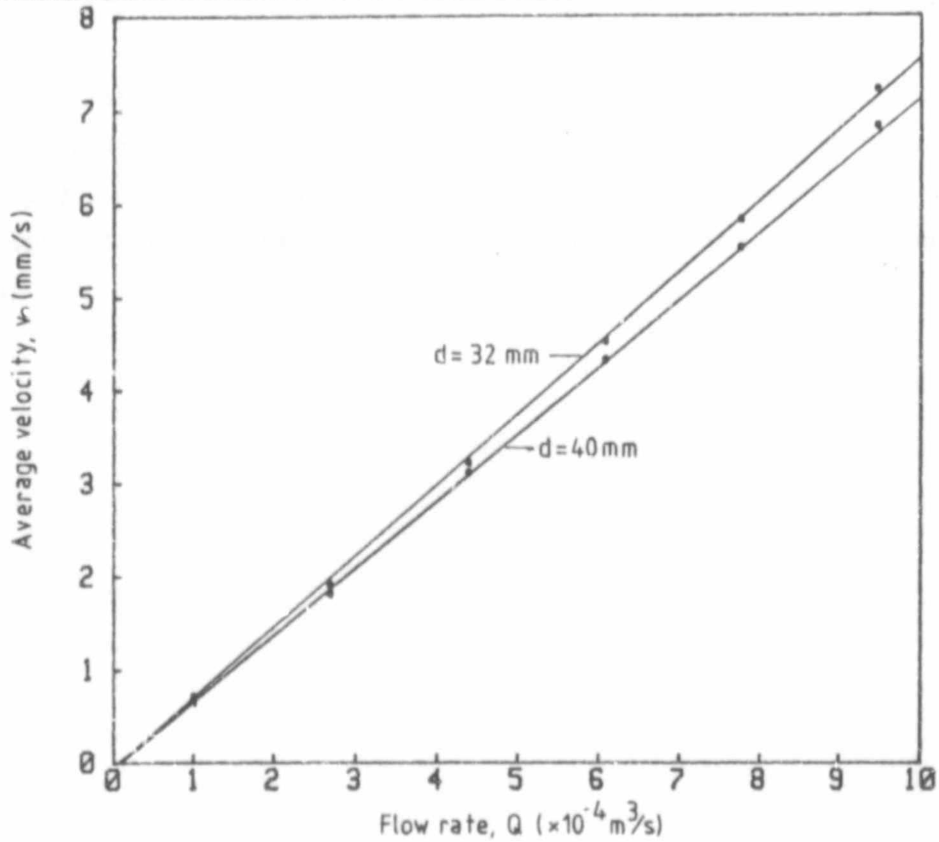

Figure 63. Average velocity at inlet between two plates vo vs total flow rate Q.

The above figure shows that v_0 for d = 32mm is higher than for d = 40mm. This is important in that high inlet velocities can re-suspend the settled floc at the entrance since this is where the volume of sludge is critical. The lamella distance must be large enough so that the incoming suspension and settled sludge run as two independent loads. The optimum plate spacing is therefore dependant on the ratio between sludge and water volume in the lamella cell and will vary from sludge to sludge. Also the ability of the sludge to slide down the inclined surface is an important factor determining plate spacing. Some sludges, especially sludges forming a network, slide down very slowly and result in a solids retention time in the unit that is very much longer than the liquid retention time. It is the above variables that make it difficult to calculate the optimum plate spacing theoretically. Hence the optimum plate spacing can only be determined by trial and error. For a sludge with the same characteristics as used in the laboratory, a plate spacing of d = 40mm produces the better effluent qualities even though smaller plate spacings should theoretically perform better. The distance d = 40mm must also be close to the optimum, a fact borne out by the consistency of the laboratory results. The exact optimum however, can only be determined by further experimentation.