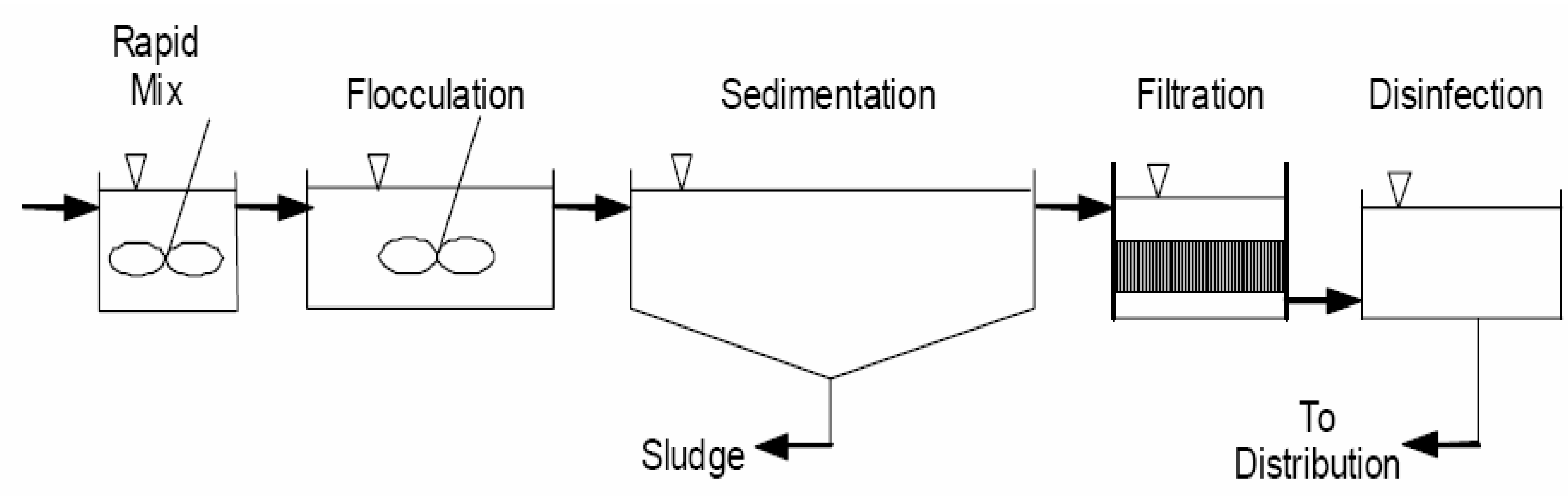
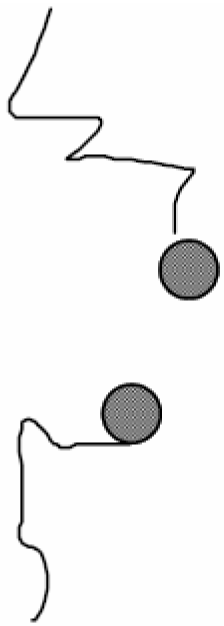
Conventional Surface Water Treatment for Drinking Water



Paddle Flocculators at Everett WTP

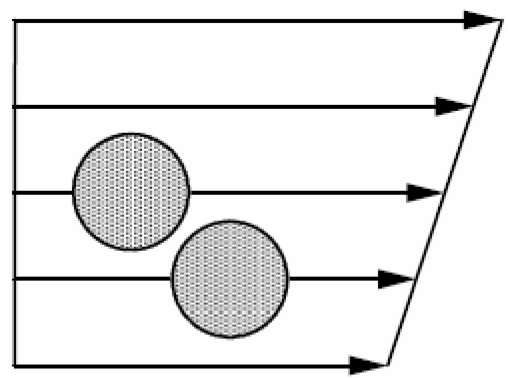
The Rate of Collisions by Each Mechanism Can be Predicted from Theory

$$r_{floc} = \beta_{ij} n_i n_j$$



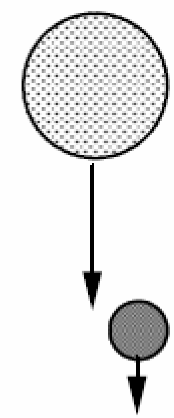
$$^{Br}\beta = \frac{2k_B T}{3\mu}\left(\frac{1}{d_i} + \frac{1}{d_j}\right)\left(d_i + d_j\right)$$

Brownian Motion: Particles Collide Due to Random Motion



$$^{Br}\beta_{ij} = \frac{1}{6} G \left(d_i + d_j\right)^3$$

Fluid Shear: Particles on Different Streamlines Travel at Different Velocities

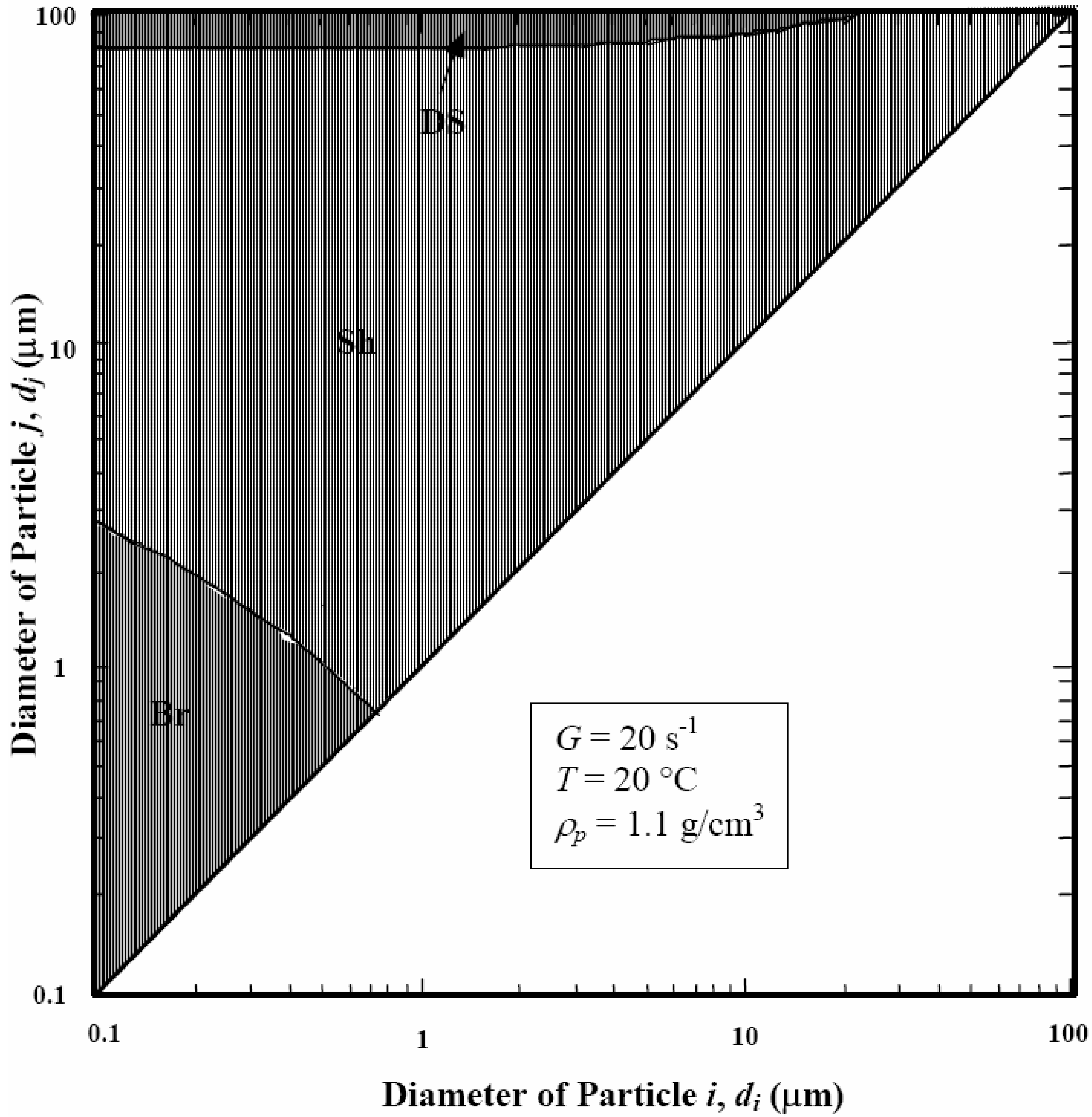


$$^{DS}\beta_{ij} = \left|v_i - v_j\right| \frac{\pi}{4}\left(d_i + d_j\right)^2$$

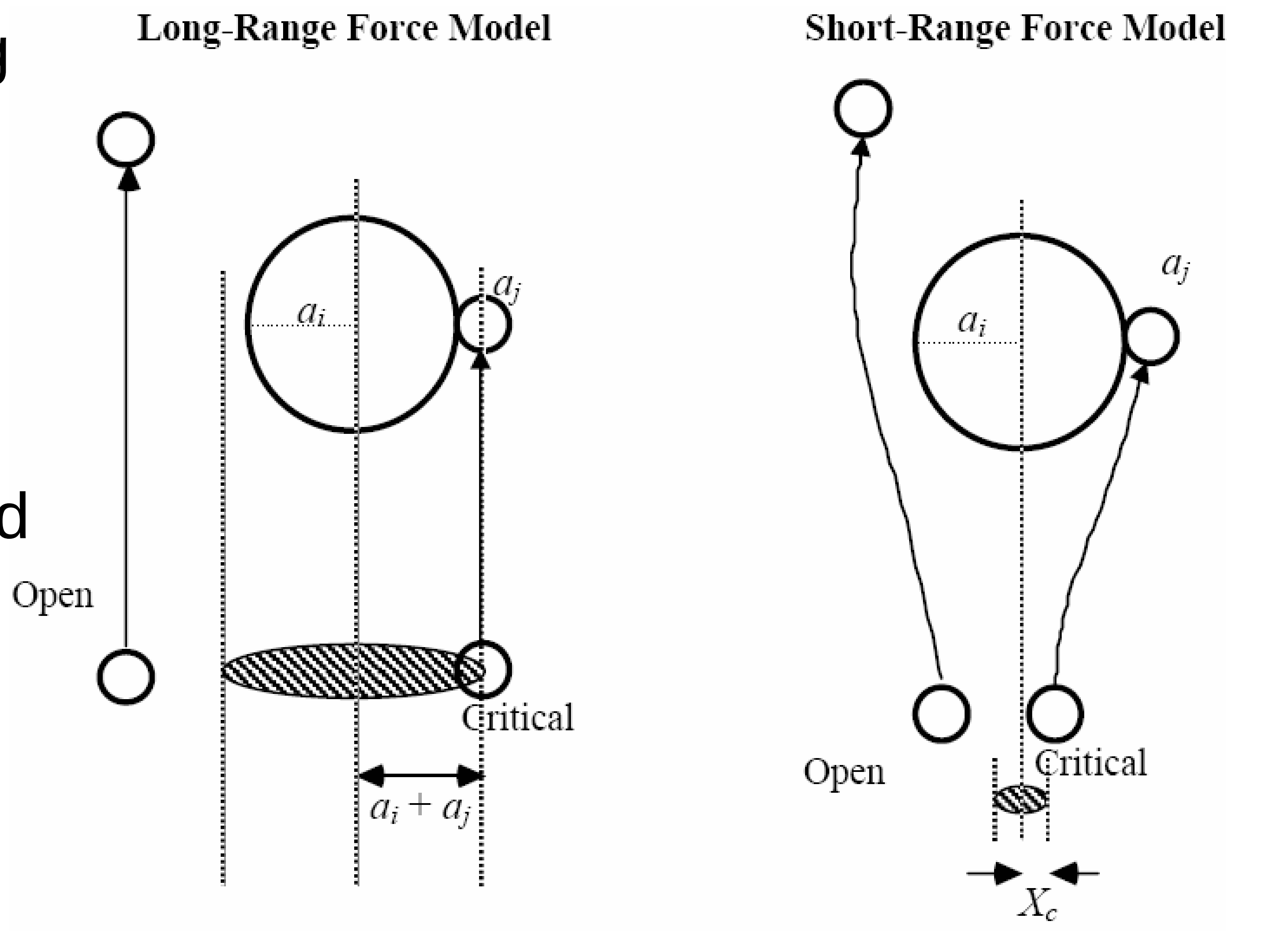
$$= \frac{\pi g}{72\mu}\left(\rho_p - \rho_w\right)\left(d_i + d_j\right)^3 \left|d_i - d_j\right|$$

Differential Sedimentation: Particles Collide Due to Different Terminal Velocities

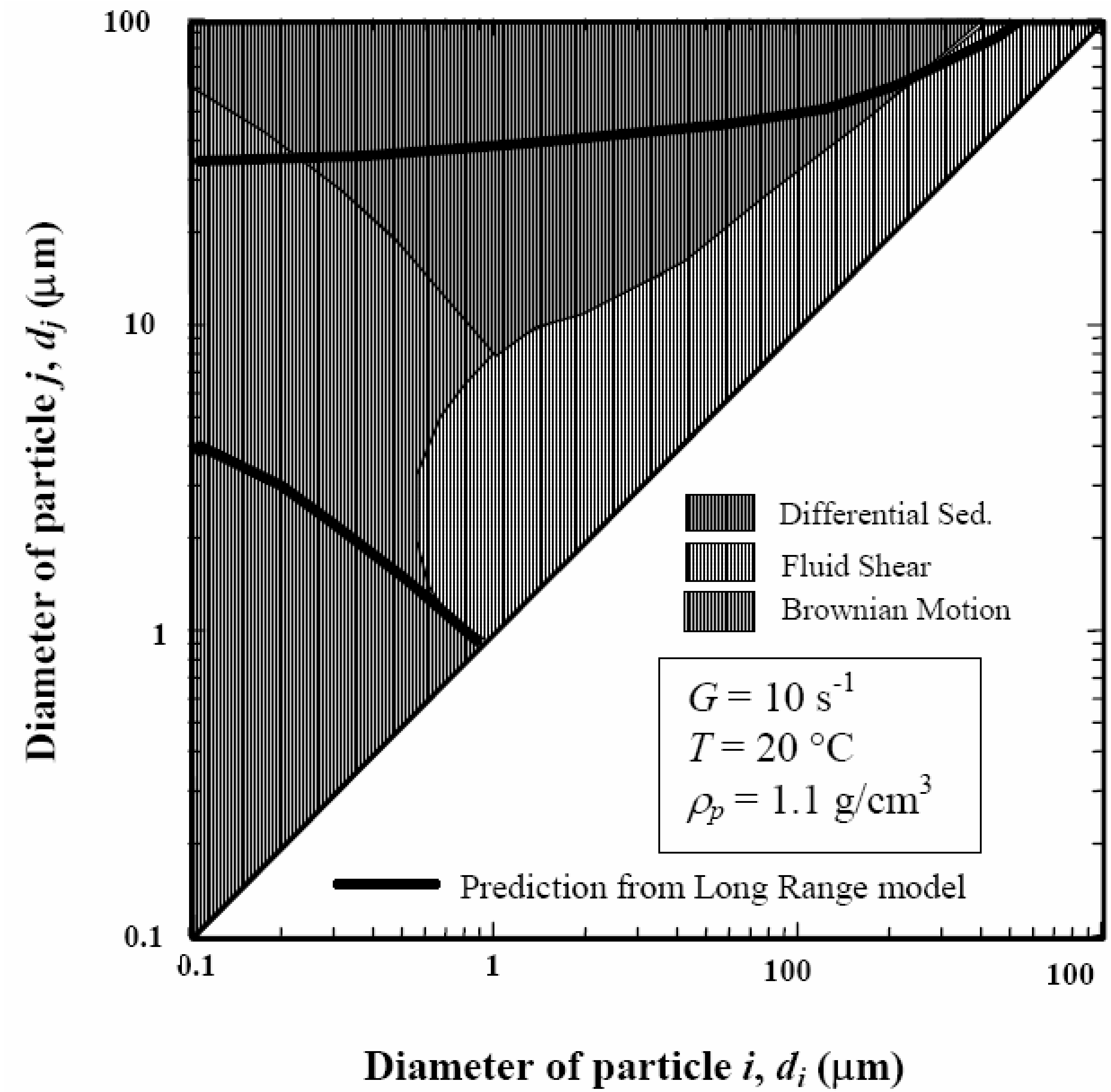
Each mechanism of flocculation is predicted to dominate for certain ranges of particle properties (primarily size)

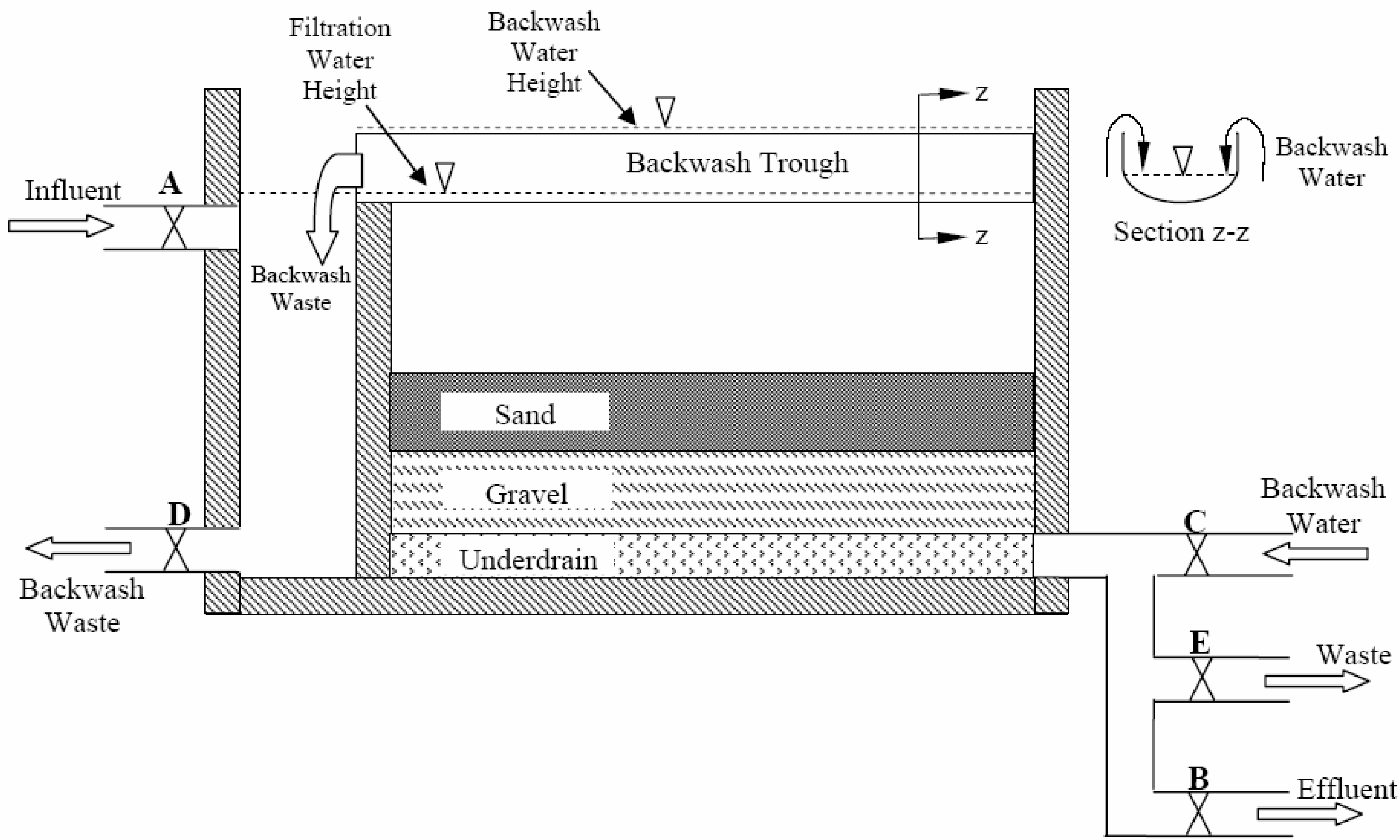


Considering the short-range interactions leads to a decrease in the predicted flocculation efficiency



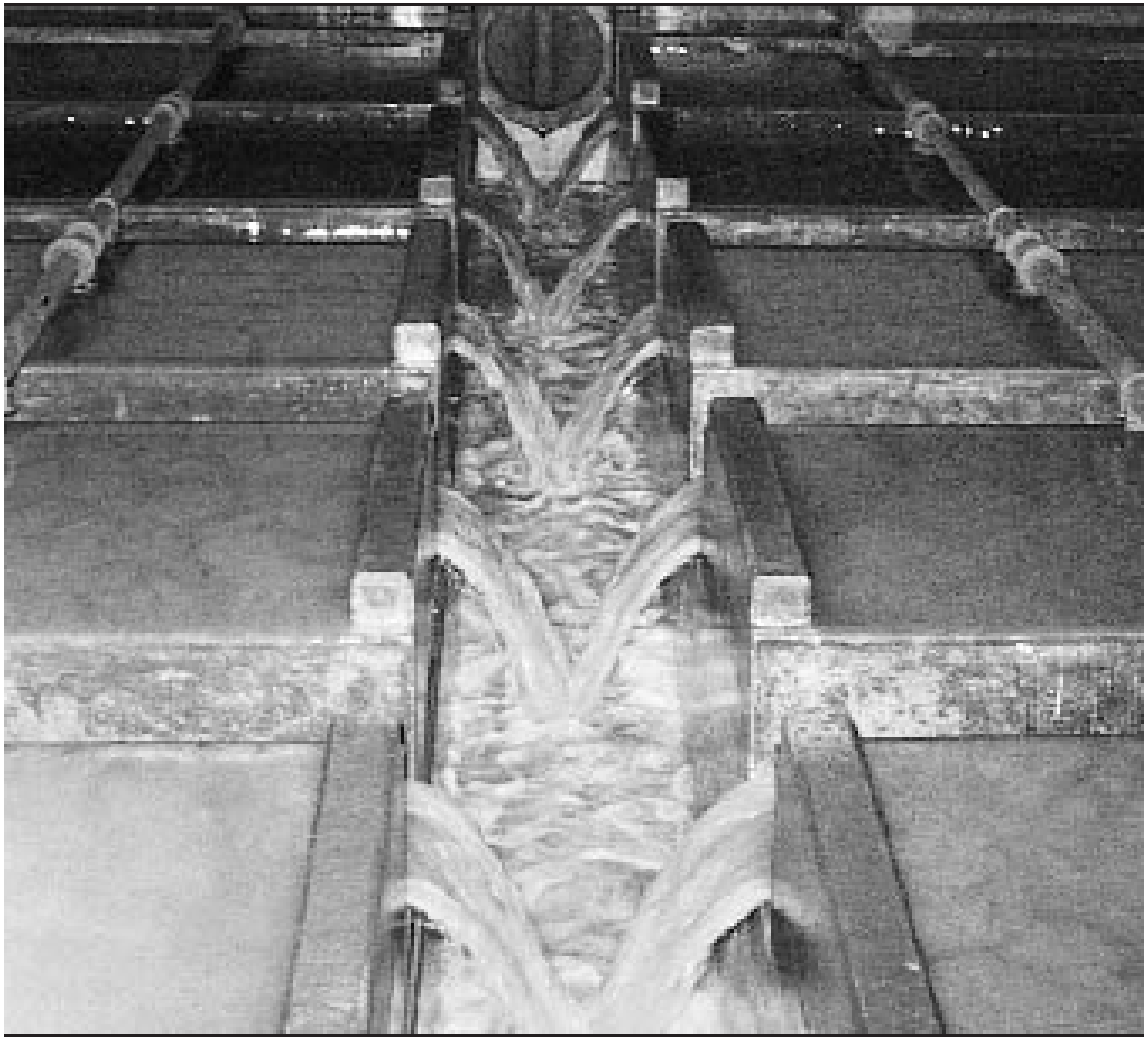
Short-range forces are predicted to reduce the effectiveness of shear as a mechanism of flocculation more than the other mechanisms



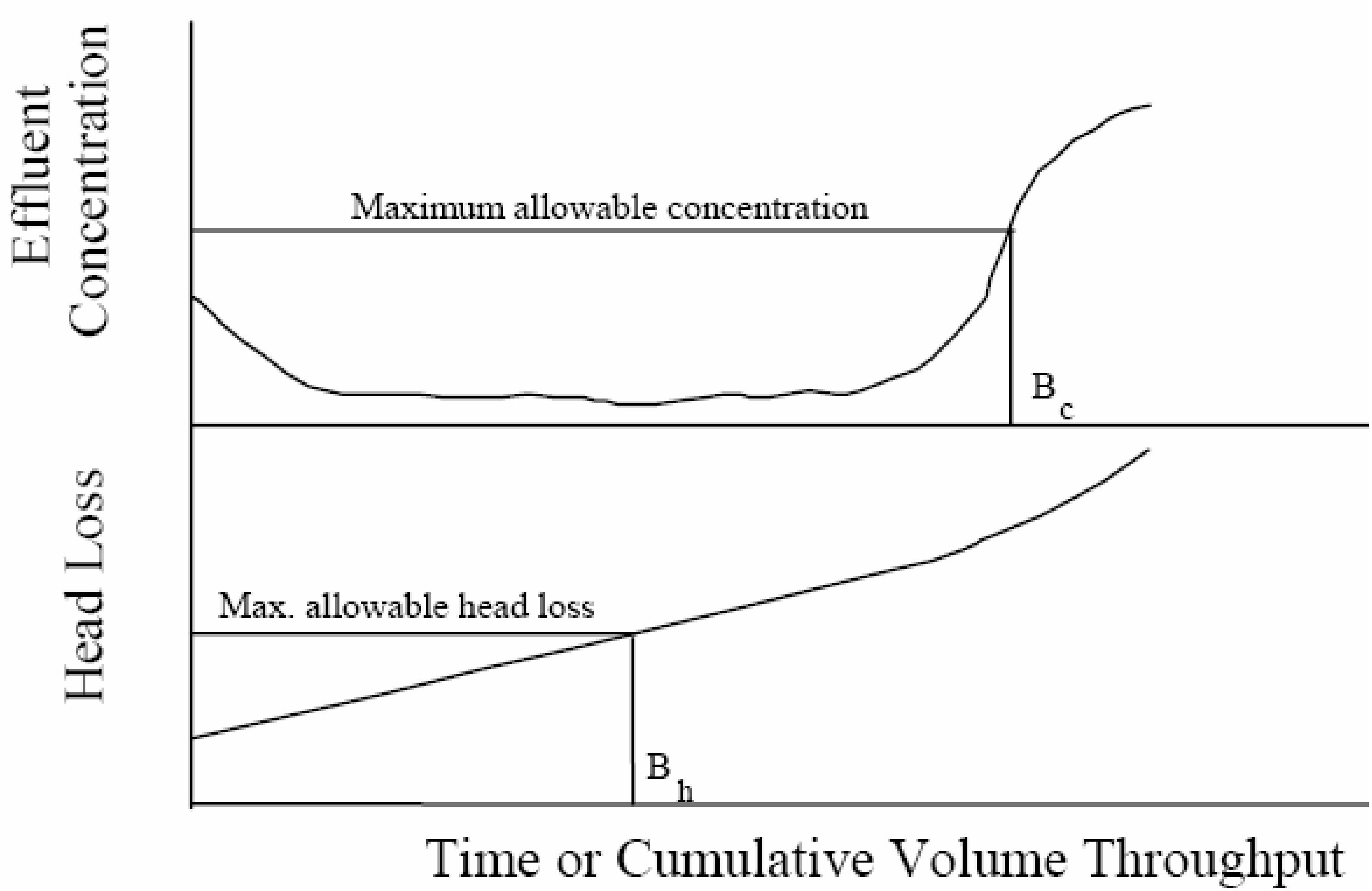


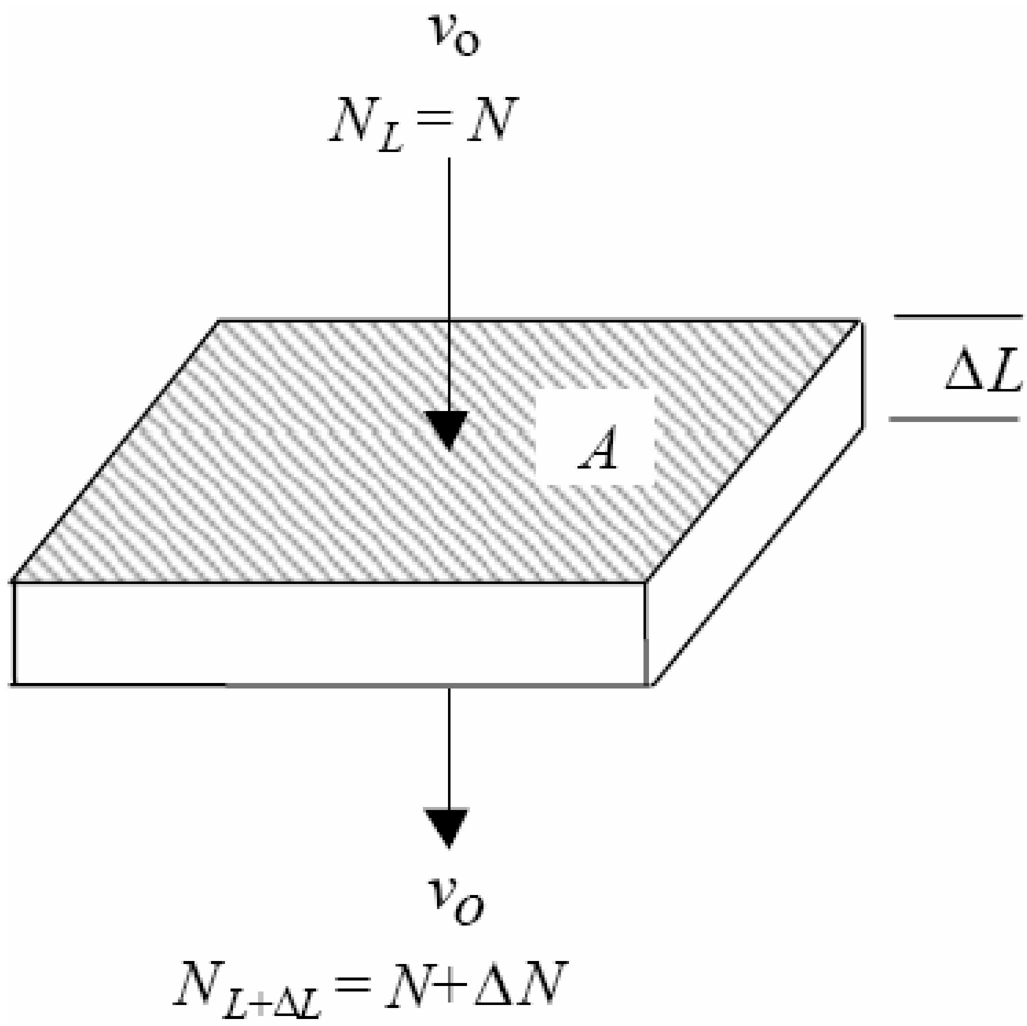
Filtration
Water
Height
Backwash
Water
Height
z
z
Backwash Trough
Backwash
Water
Section z-z
Influent
A
Backwash
Waste
Sand
Gravel
Underdrain
D
Backwash
Waste
Backwash
Water
C
E
Waste
B
Effluent


The Everett Water Filtration Plant utilizes 8 filters, each with a surface area of 1530 ft², to remove over 95% of the suspended particulates from our source water.
After extensive testing, the media was replaced in 1993 to improve performance and efficiency. The profiles for the old and new filter media are shown here at full scale.
The original multi-media filter is on the left. There are layers of anthracite coal, silica sand, and garnet sand. This type of filter uses progressively smaller void sizes between the top and bottom of the filter to ensure that all particulates are removed during filtration. These filters provided excellent filtration, but were limited in how fast they could process water.
The new mono-media filter is on the right. After 3 years of testing, the old filter media was replaced with a deep bed of coarser anthracite coal. Because the media bed is larger in volume, it can hold a greater amount of material before becoming fully loaded, and so needs to be cleaned less often. Also, the media doesn't have smaller void sizes near the bottom, so there is less flow restriction. This allows for increased filtration rates.
Changing the filter media along with many other improvements allow the City of Everett to produce some of the highest quality drinking water in the world.
Anthracite Coal
Depth: 22"
Effective Size: 0.96-1.10 mm
Silica Sand
Depth: 11"
Effective Size: 0.40 - 0.50 mm
Garnet Sand
Depth: 3"
Effective Size: 0.20 -0.35 mm
Support Gravel
Underdrain Block
Anthracite Coal
Depth: 52"
Effective Size: 1.25 -1.35mm
Support Gravel
Underdrain Block
2003 2 5



(From Opflow, June 2000)


Effluent Concentration
Maximum allowable concentration
B c
Head Loss
Max. allowable head loss
B h
Time or Cumulative Volume Throughput



v_o
$N_L = N$
A
ΔL
v_o
$N_{L+\Delta L} = N + \Delta N$

[Rate of change of number of particles in suspension in the volume element] = [Rate at which particles enter the volume element] − [Rate at which particles leave the volume element] − [Rate of removal of particles from suspension by attachment to filter grains]

$$\frac{d\left(NV_{L,\mathrm{CV}}\right)}{dt} = QN - Q\left(N + dN\right) + V_{L,\mathrm{CV}}r_p$$

Assume pseudo-steady state, so $\frac{d\left(NV_{L,\mathrm{CV}}\right)}{dt} = 0$

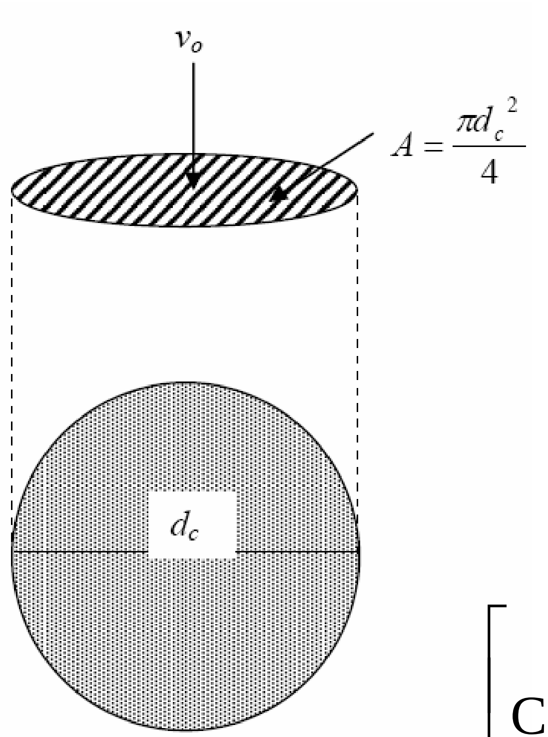
$$Q = Av_0$$

$$0 = -Av_0 dN + V_{L,\mathrm{CV}}r_p$$

$$Av_0 dN = V_{L,\mathrm{CV}}r_p$$

$$V_{L,\mathrm{CV}} r_p = -\begin{bmatrix}\text{Rate of Removal of Particles}\\ \text{by a Single Collector}\end{bmatrix}\begin{bmatrix}\text{Number of}\\ \text{Collectors in Layer}\end{bmatrix}$$

$$= -\begin{bmatrix}\text{Rate of Approach of}\\ \text{Particles to a Collector}\end{bmatrix}\begin{bmatrix}\text{Removal Efficiency of}\\ \text{a Single Collector}\end{bmatrix}\begin{bmatrix}\text{Number of}\\ \text{Collectors in Layer}\end{bmatrix}$$



$$\begin{bmatrix}\text{Rate of Approach of}\\ \text{Particles to a Collector}\end{bmatrix} = N v_0 \frac{\pi d_c^2}{4}$$

$$\begin{bmatrix}\text{Removal Efficiency of}\\ \text{a Single Collector}\end{bmatrix} \equiv \eta$$

$$\begin{bmatrix}\text{Number of}\\ \text{Collectors in Layer}\end{bmatrix} = \frac{\begin{bmatrix}\text{Total Volume of}\\ \text{Collector Media}\end{bmatrix}}{\begin{bmatrix}\text{Volume of a}\\ \text{Single Collector}\end{bmatrix}} = \frac{AdL(1-\varepsilon)}{\pi d_c^3/6}$$

$$V_{L,\text{CV}} r_p = -\begin{bmatrix} \text{Rate of Approach of} \\ \text{Particles to a Collector} \end{bmatrix} \begin{bmatrix} \text{Removal Efficiency of} \\ \text{a Single Collector} \end{bmatrix} \begin{bmatrix} \text{Number of} \\ \text{Collectors in Layer} \end{bmatrix}$$

$$= -\left[N v_0 \frac{\pi d_c^2}{4} \right] [\eta] \left[\frac{AdL(1-\varepsilon)}{\pi d_c^3 / 6} \right]$$

"Single Collector Removal Efficiency"

$$= -\frac{3}{2} \frac{(1-\varepsilon)\eta}{d_c} N v_0 AdL$$

$$A v_0 dN = V_{L,\mathrm{CV}} r_p$$

$$\cancel{A v_0}\, dN = -\frac{3}{2}\frac{(1-\varepsilon)\eta}{d_c} N\, \cancel{v_0 A}\, dL$$

$$\frac{dN}{N} = -\frac{3}{2}\frac{(1-\varepsilon)\eta}{d_c} dL = -\lambda dL$$

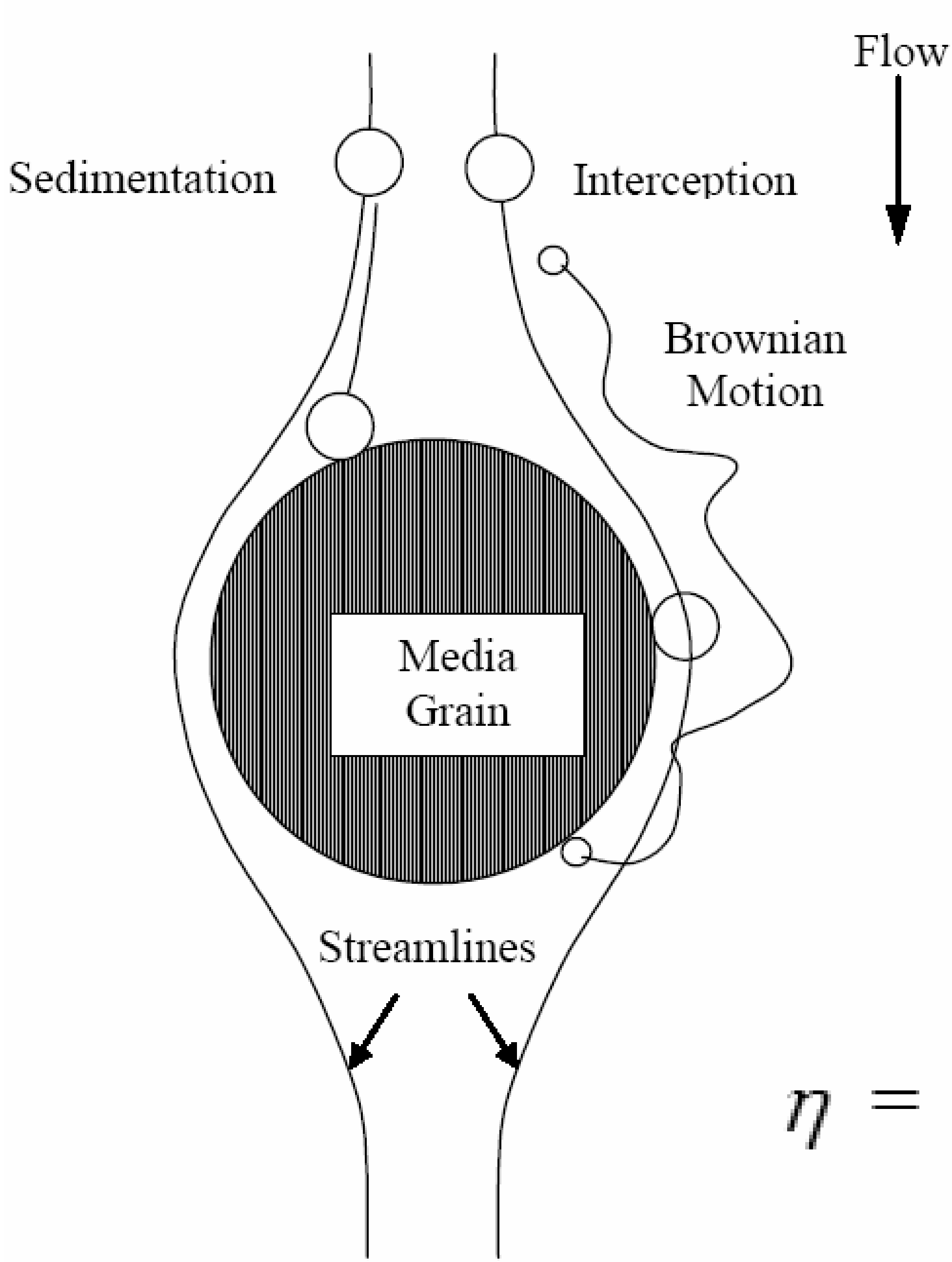
"Filter coefficient"

$$\ln\frac{N_{out}}{N_{in}} = -\lambda L$$

$$N_{out} = N_{in}\exp(-\lambda L)$$

Summary: Mass Balance Analysis of Particle Removal in a Granular Filter

- Based on relative sizes of particles and collectors, sieving is unimportant and removal can be modeled based on interactions with isolated “collector” grains
- Assuming pseudo-steady state, concentration of any given type of particle is expected to decline exponentially with depth
- Each type of particle has a different coefficient for the exponential loss rate
- If we could predict η for a given type of particle, we could predict N_{out}/N_{in} for that particle

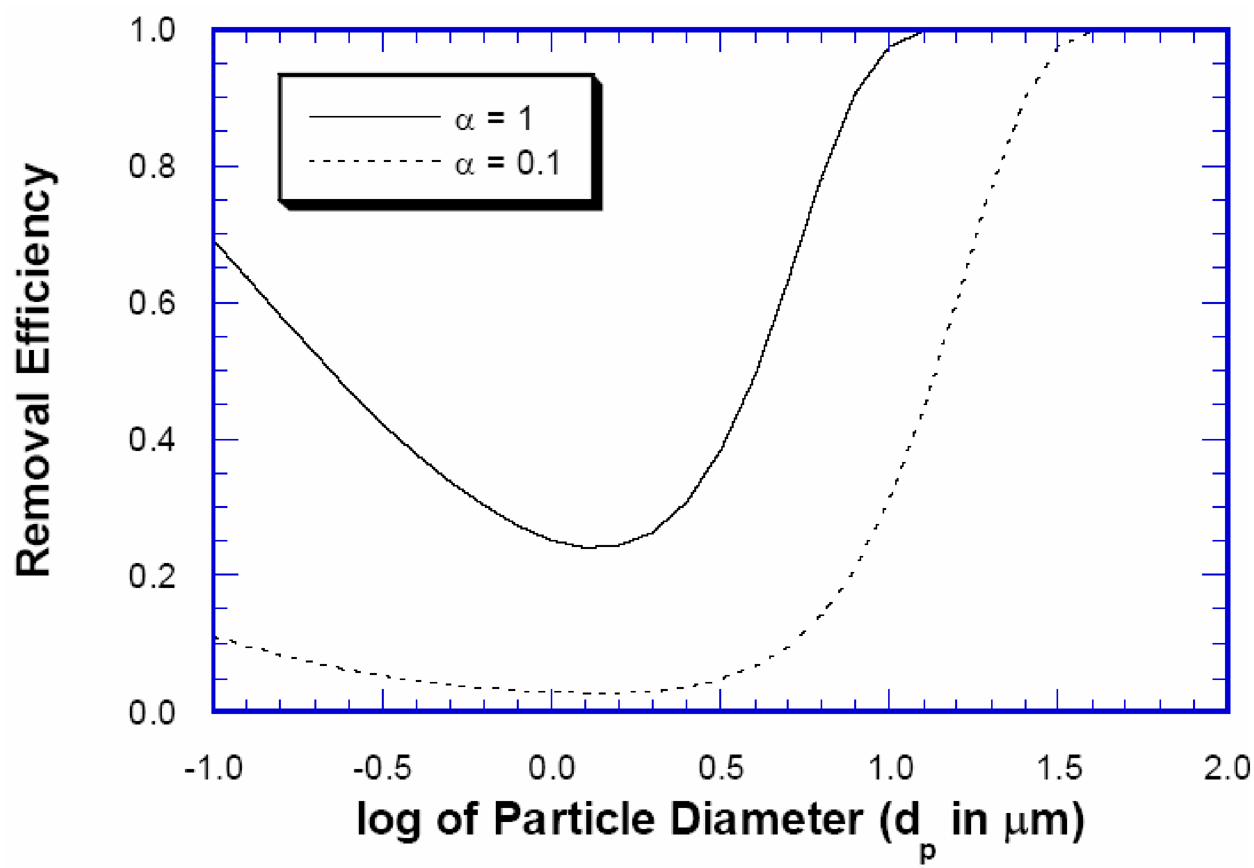


$$\eta_I = \frac{3}{2}\left(\frac{d_p}{d_c}\right)^2$$

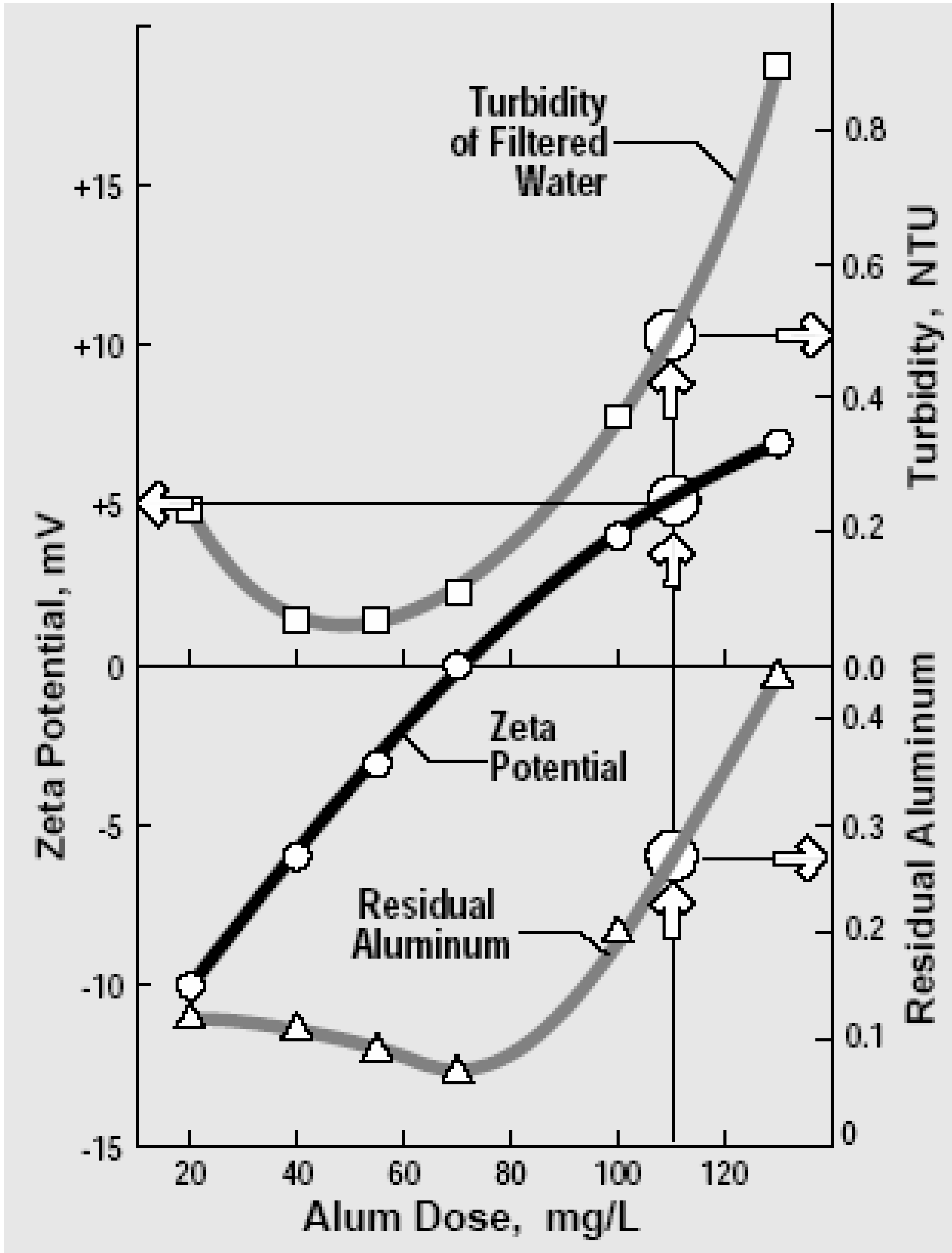
$$\eta_g = \frac{v_s}{v_o} = \frac{(\rho_p - \rho_L) g d_p^{\ 2}}{18 \mu v_o}$$

$$\eta_{Br} = 0.905\left(\frac{k_B T}{\mu d_c d_p v_0}\right)^{2/3}$$

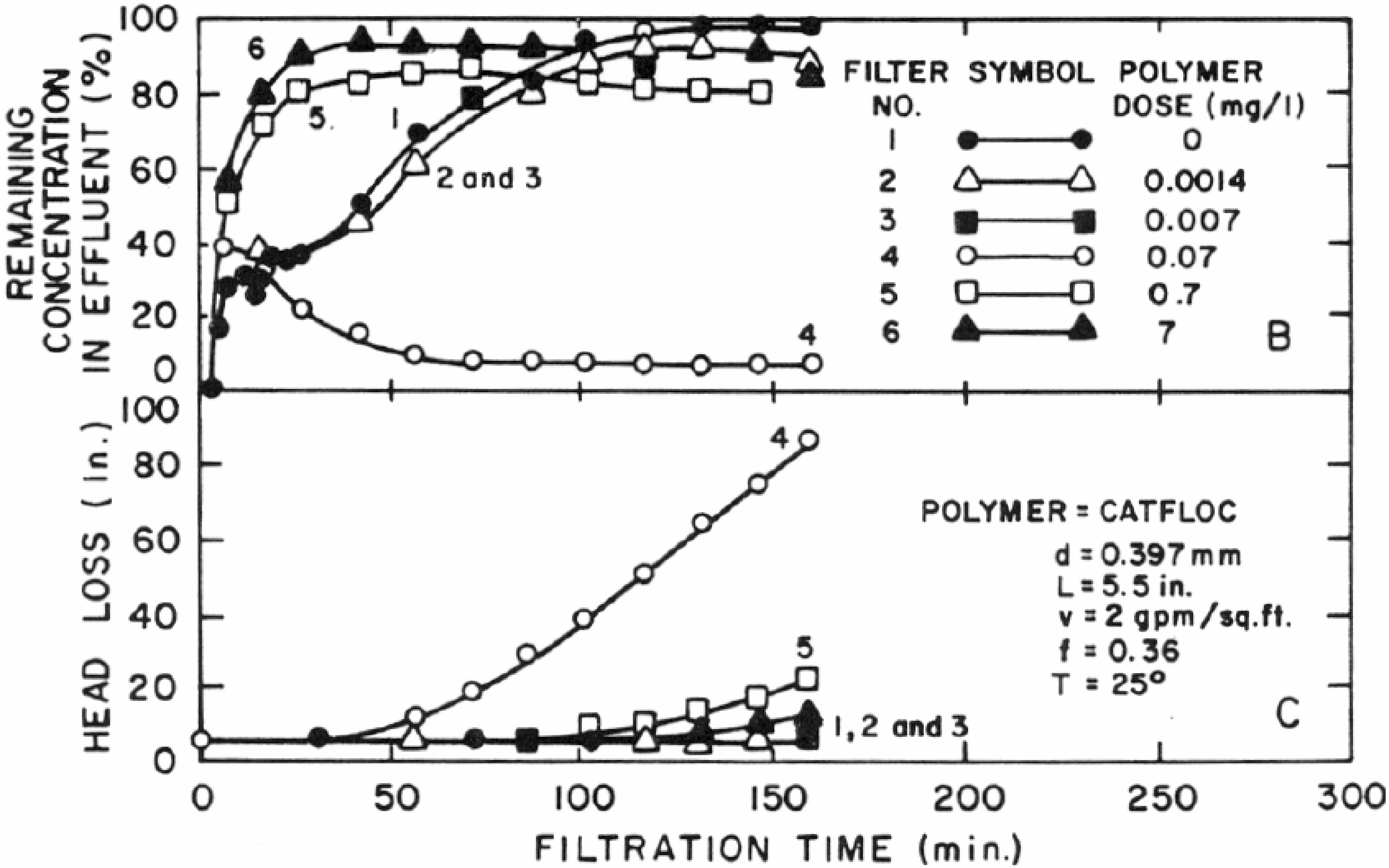
$$\eta = \eta_I + \eta_g + \eta_{Br}$$



α = 1
α = 0.1
Removal Efficiency
0.0
0.2
0.4
0.6
0.8
1.0
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
log of Particle Diameter (dp in μm)

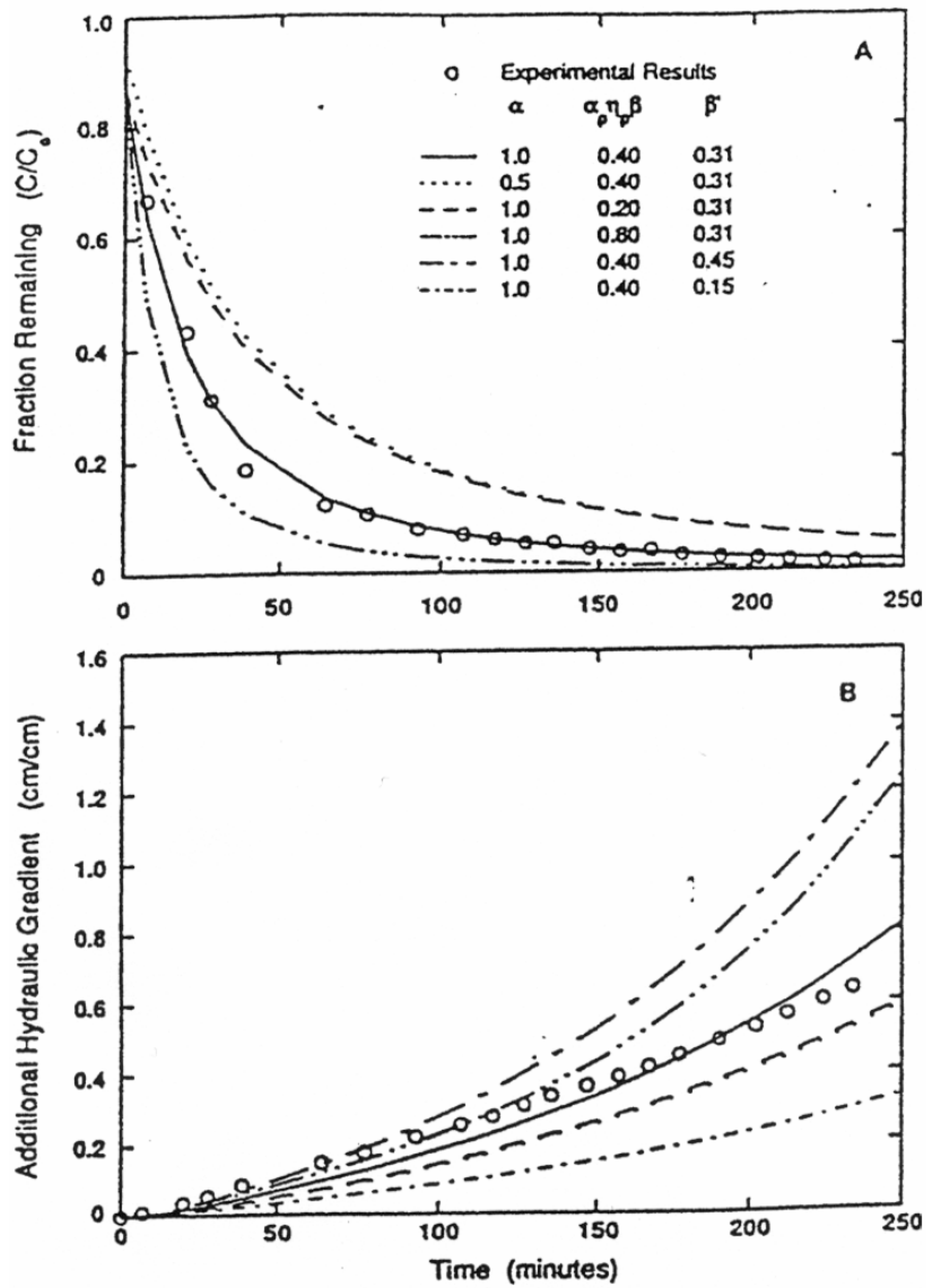


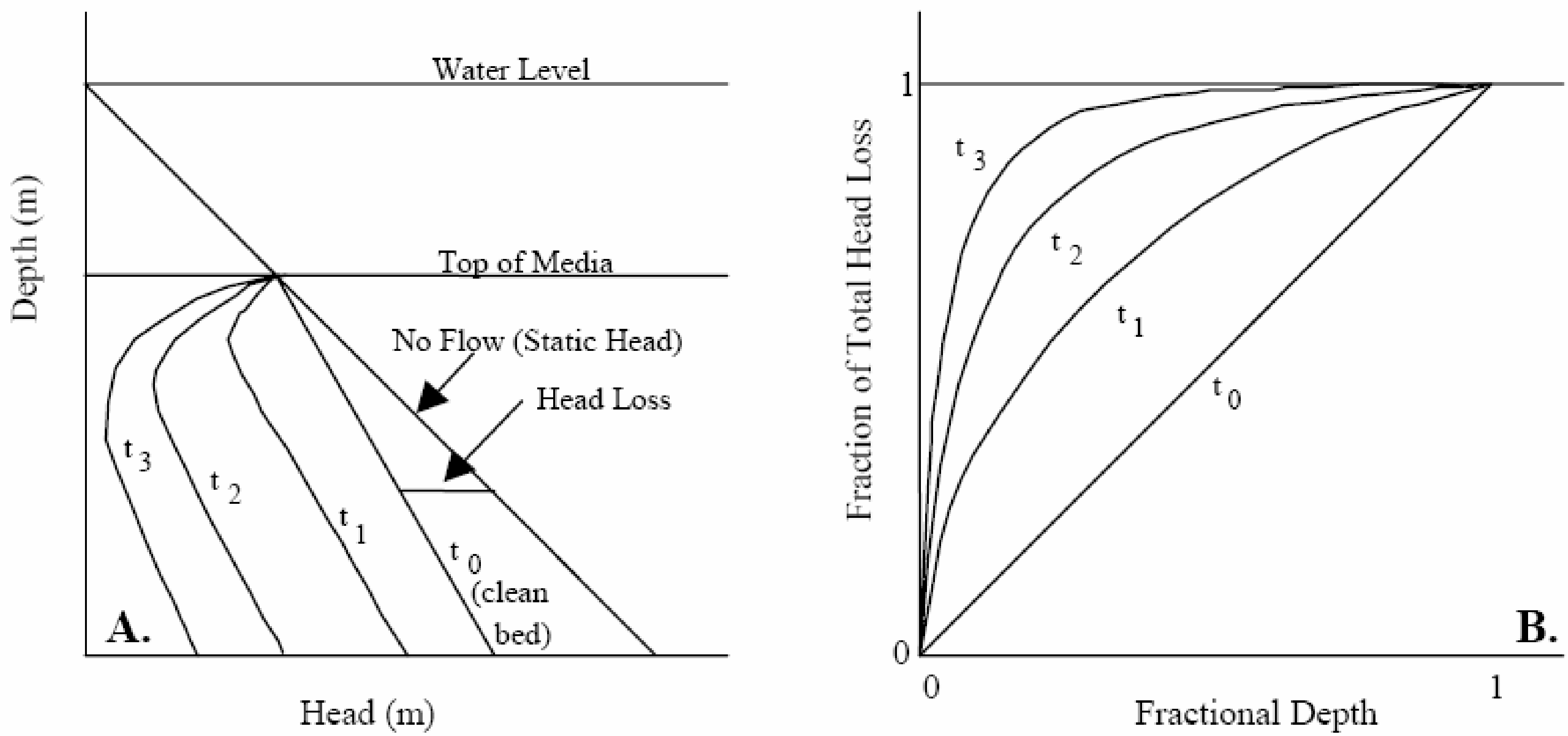
Turbidity
of Filtered
Water
Zeta
Potential
Residual
Aluminum
Zeta Potential, mV
+15
+10
+5
0
-5
-10
-15
20
40
60
80
100
120
Alum Dose, mg/L
Turbidity, NTU
0.8
0.6
0.4
0.2
0.0
Residual Aluminum
0.4
0.3
0.2
0.1
0

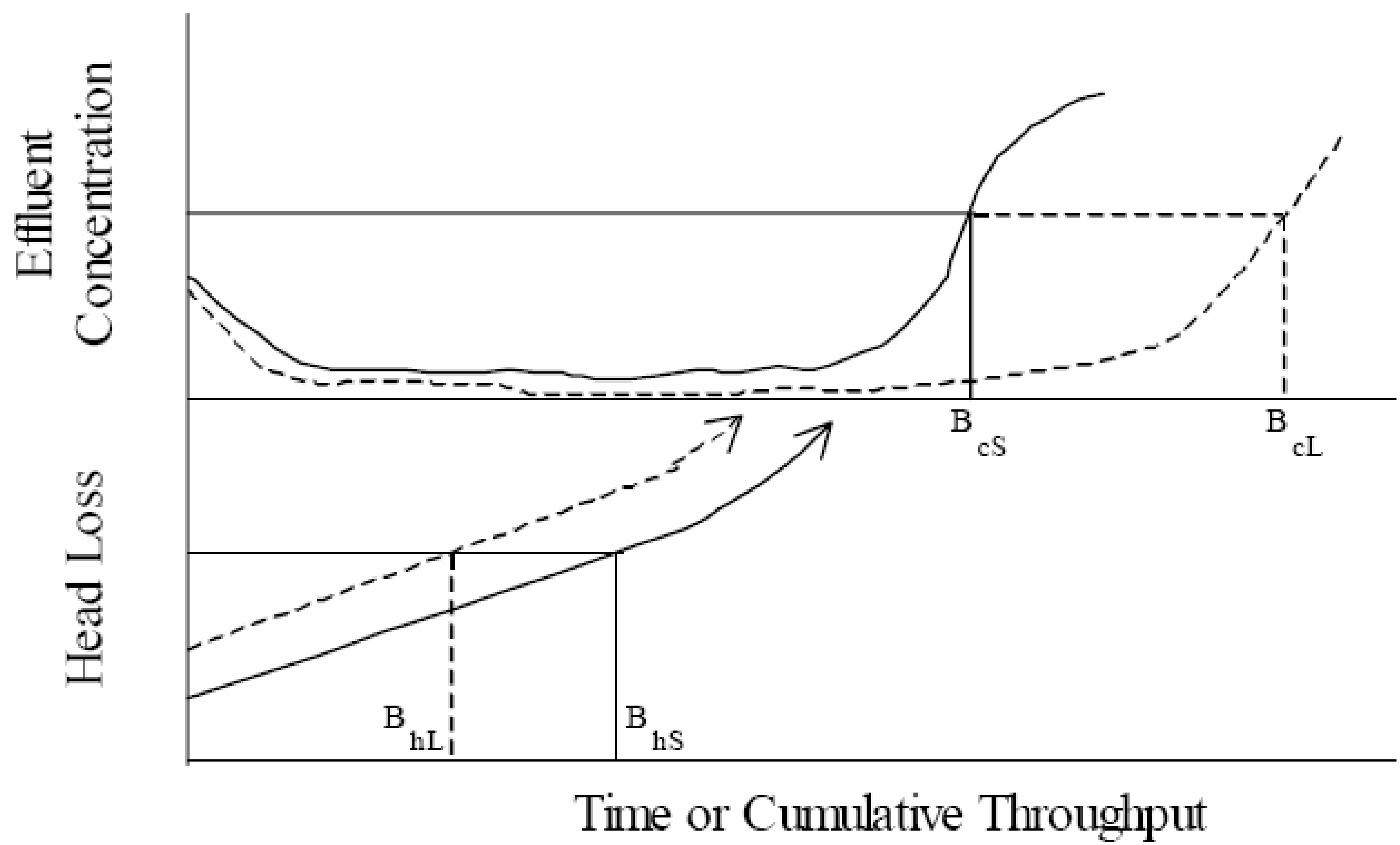


REMAINING CONCENTRATION IN EFFLUENT (%)
100
80
60
40
20
0
6
5.
1
2 and 3
4
FILTER NO.
SYMBOL
POLYMER DOSE (mg/l)
1
0
2
0.0014
3
0.007
4
0.07
5
0.7
6
7
B
HEAD LOSS (in.)
100
80
60
40
20
0
4
5
1,2 and 3
POLYMER = CATFLOC
d = 0.397 mm
L = 5.5 in.
v = 2 gpm/sq.ft.
f = 0.36
T = 25°
C
0
50
100
150
200
250
300
FILTRATION TIME (min.)

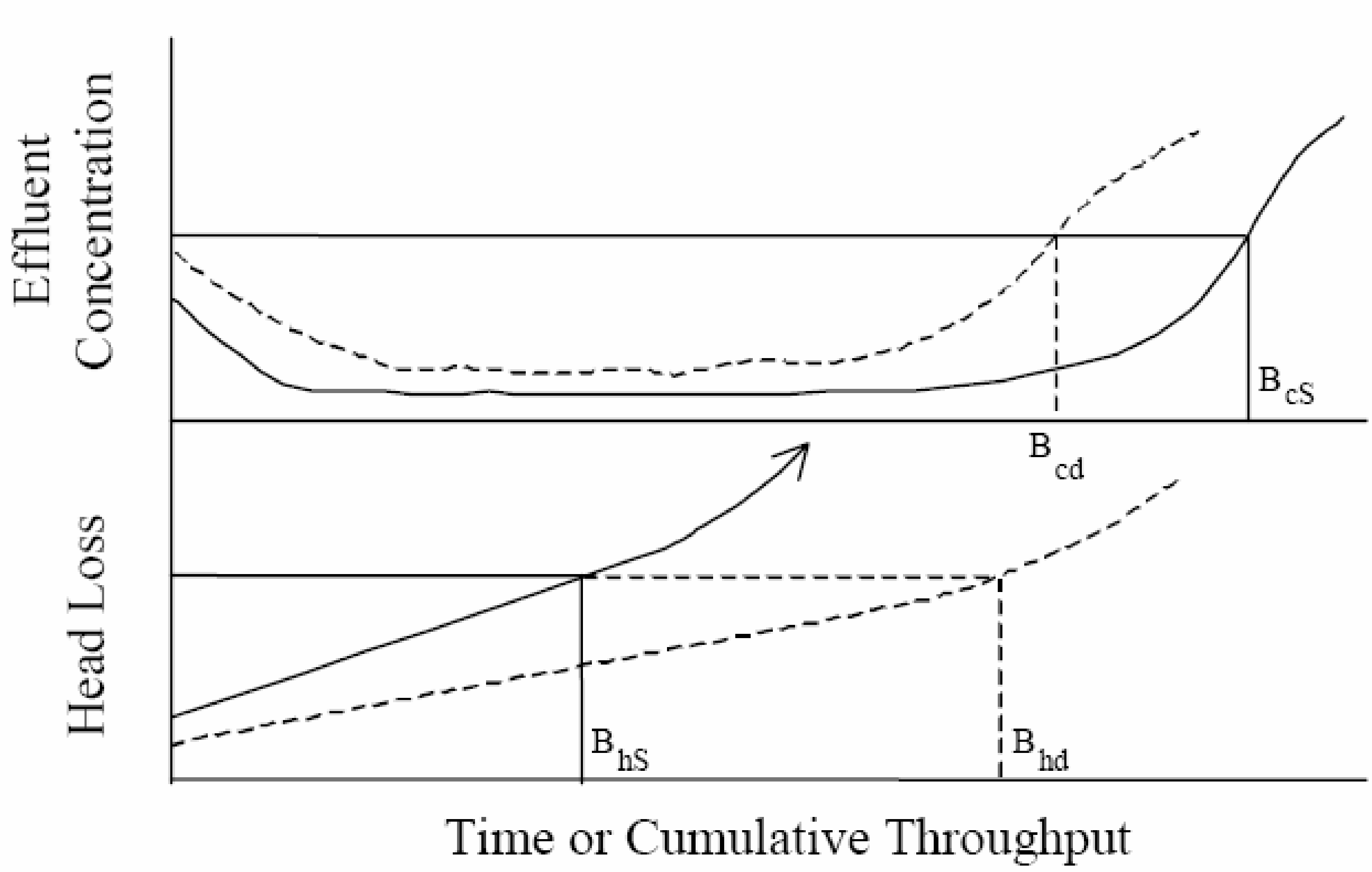
"Filter Ripening"




Water Level
Top of Media
No Flow (Static Head)
Head Loss
Depth (m)
Head (m)
t 3
t 2
t 1
t 0
(clean
bed)
A.
1
0
Fraction of Total Head Loss
Fractional Depth
0
1
t 3
t 2
t 1
t 0
B.



S=Standard case; L=longer bed;
c=concentration; h=headloss



S=Standard case; d=larger diameter grains;
c=concentration; h=headloss