The Sludge Age Concept and the Activated Sludge Process: A 45-Year Historical Review

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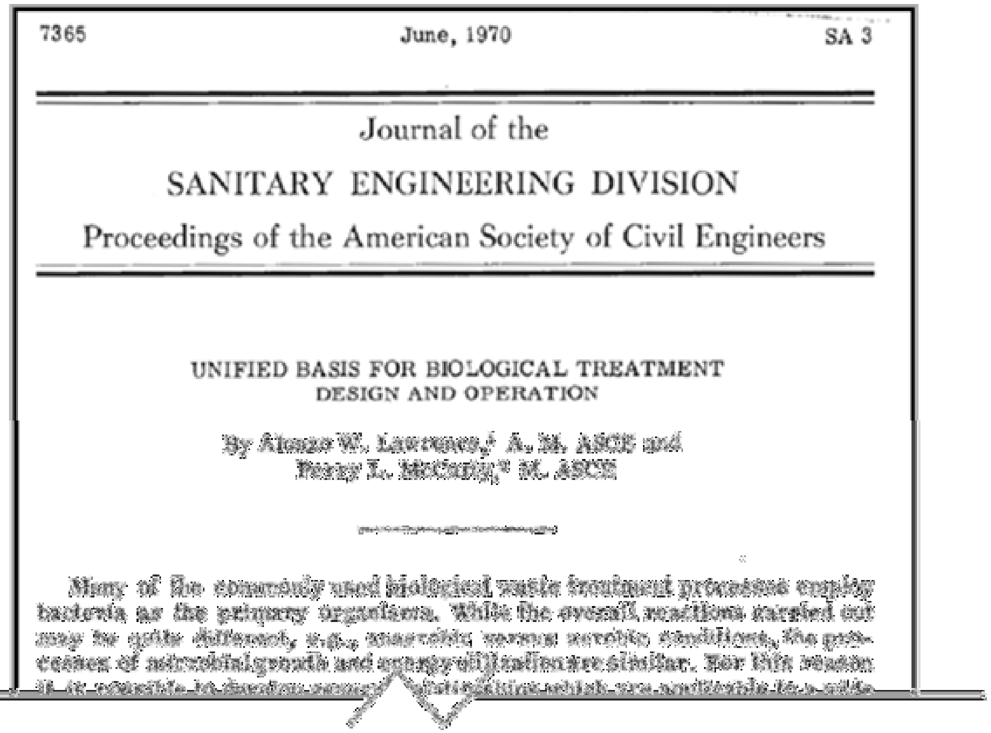
Activated Sludge Process – Circa 1960s

- Plug-flow aerobic, microbial slurry process
- Long, narrow tanks aerated by swing arm diffusers
- Empirical design criteria centered on both:
  - Aeration basin hydraulic retention time (6-10 hours)
  - Organic loading per 1,000 ft^3 aeration volume (15-35 lbs BOD per 1000 ft^3)
- Separate quiescent settling basins with recycle of settled activated sludge typically at 25% of influent flow rate
- "10-State Standards" was the dominant design standard of the day
- Large municipal systems of note: New York City, Chicago, Milwaukee

Activated Sludge Research Highlights of The Decade: 1960-1970

- F/M concept of organic loading as process control parameter
- Mathematics of complete mix activated sludge
- Microbial growth rate control of activated sludge process
- Continuous culture of microorganisms and Monod kinetics
- Rate limiting step methane fermentation process kinetics
- Powdered activated carbon addition to activated sludge (PACT)
- Extended aeration package plants
- Successful treatment of “previously toxic” organics (e.g., phenols)

The Original June 1970 Publication of "Unified Basis For Biological Treatment Design and Operation"



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UNIFIED BASIS FOR BIOLOGICAL TREATMENT
DESIGN AND OPERATION

By Alonzo W. Lawrence,[1] A. M. ASCE and
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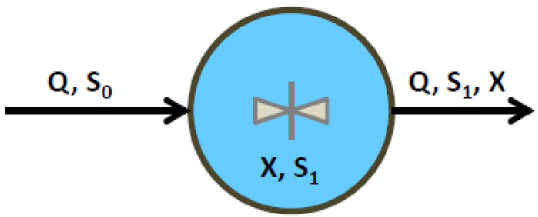
Many of the commonly used biological waste treatment processes employ bacteria as the primary organisms. While the overall reactions carried out may be quite different, e.g., anaerobic versus aerobic conditions, the processes of microbial growth and energy utilization are similar. For this reason

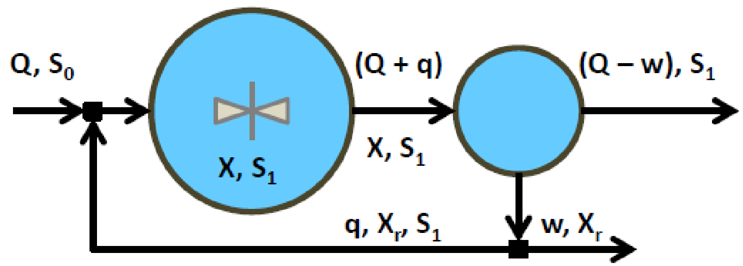
The “Unified Basis…” and the Sludge Age Concept

- The objective of the original paper was to develop a unified basis for design and operation of biological waste treatment systems employing suspensions of microorganisms based on microbial kinetic concepts and continuous culture of microorganisms theory.
- Biological solids retention time (SRT) or sludge age, the average time period a unit of biological mass is retained in the system, was identified as the most useful independent parameter for process design and control.

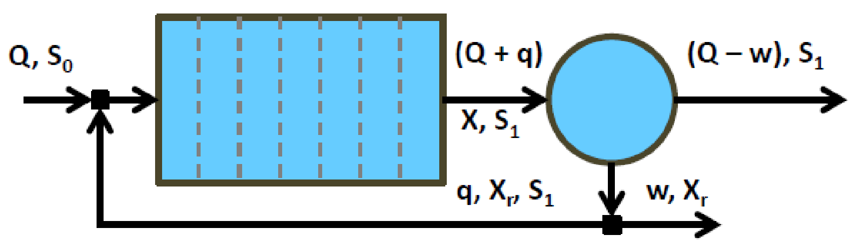
Schematic Representation of Three Continuous Flow Biological Waste Treatment Processes



Completely Mixed – No Solids Recycle



Completely Mixed – Solids Recycle



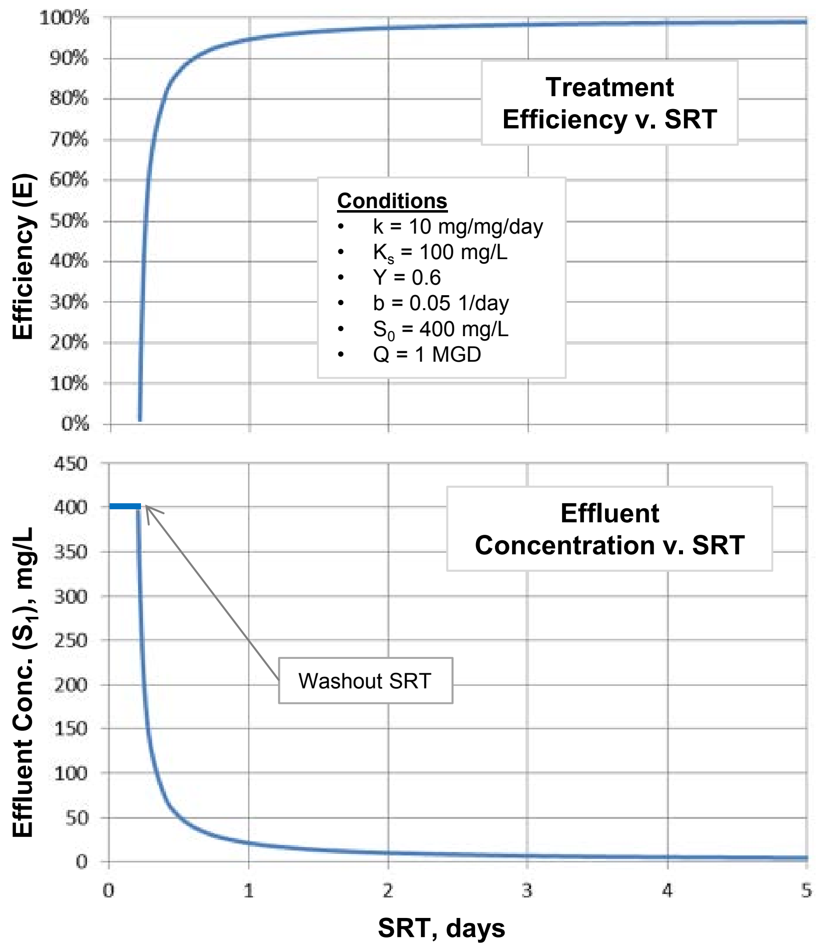
Plug Flow – Solids Recycle

Summary of Steady State Relationships for Biological Waste Treatment with Suspensions of Microorganisms

Characteristic	Complete-Mix System: Without Recycle	Complete-Mix System: With Recycle	Plug Flow System With Recycle [1]
Specific Efficiency	$E_s = \frac{100\,(S_0 - S_1)}{S_0}$	$E_s = \frac{100\,(S_0 - S_1)}{S_0}$	$E_s = \frac{100\,(S_0 - S_1)}{S_0}$
Effluent Waste Concentration (M/L^3)	$S_1 = \frac{K_s\,(1 + b(SRT))}{SRT\,(Yk - b) - 1}$	$S_1 = \frac{K_s\,(1 + b(SRT))}{SRT\,(Yk - b) - 1}$	[2]
Microorganism Conc. in Reactor (M/L^3)	$X = \frac{Y\,(S_0 - S_1)}{1 + b(SRT)}$	$X = \frac{Y\,(S_0 - S_1)}{1 + b(SRT)}\left(\frac{SRT}{HRT}\right)$	$\bar{X} = \frac{Y\,(S_0 - S_1)}{1 + b(SRT)}\left(\frac{SRT}{HRT}\right)$
Excess Microorganism Production Rate (M/T)	$P_x = \frac{YQ\,(S_0 - S_1)}{1 + b(SRT)}$	$P_x = \frac{YQ\,(S_0 - S_1)}{1 + b(SRT)}$	$\bar{P}_x = \frac{YQ\,(S_0 - S_1)}{1 + b(SRT)}$
Hydraulic Retention Time (T)	$HRT = \left(\frac{V}{Q}\right) = SRT$	$HRT = \left(\frac{V}{Q}\right) \neq SRT$	$HRT = \left(\frac{V}{Q}\right) \neq SRT$
Recycle Ratio	not applicable	$r = \left(\frac{q}{Q}\right)$	$r = \left(\frac{q}{Q}\right)$
Recycle Sludge Conc. (M/L^3)	not applicable	$X_r = \frac{X\,(1 + r - \frac{HRT}{SRT})}{r}$	$X_r = \frac{\bar{X}\,(1 + r - \frac{HRT}{SRT})}{r}$
<u>Solids Retention Time (T)</u>			
General	$SRT^{-1} = \frac{YkS_1}{K_s + S_1} - b$	$SRT^{-1} = \frac{YkS_1}{K_s + S_1} - b$	$SRT^{-1} = \frac{Yk\,(S_0 - S_1)}{Ks\,ln\left(\frac{S_0}{S_1}\right) + (S_0 - S_1)} - b$ [3]
Limiting Minimum	$SRT_{lim} = (Yk - b)^{-1}$	$SRT_{lim} = (Yk - b)^{-1}$	[4]

[1] For a situation in which reactor microbial mass concentration (X) is assumed constant
[2] No explicit solution for SRT
[3] For situation in which recycle ratio (r) is less than one
[4] Not mathematically defined for this system

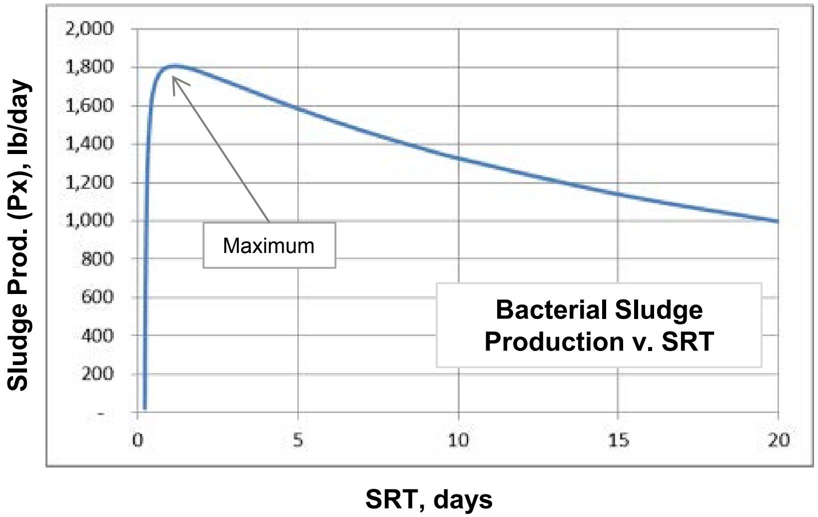
Graphical Representation of Relationship Between SRT and Treatment Efficiency and Effluent Concentration for Completely Mixed Recycle System

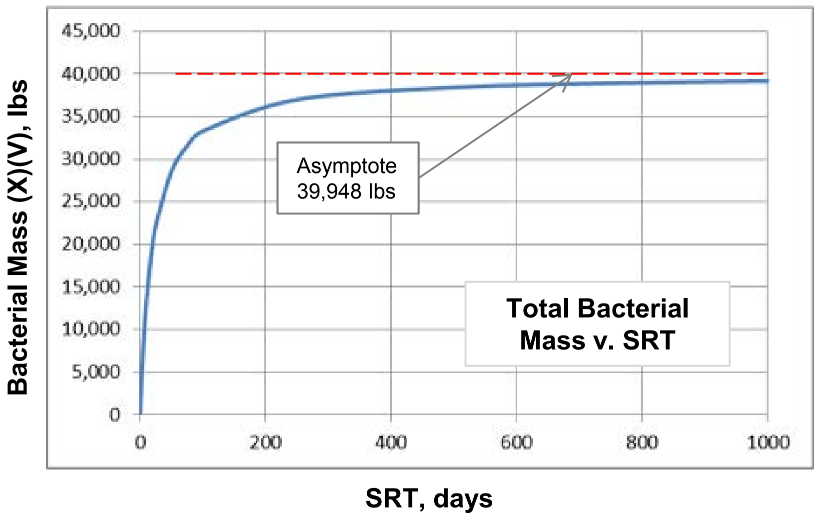


Graphical Representation of Relationship Between SRT and Bacterial Sludge Parameters for Completely Mixed Recycle System

Conditions
- k = 10 mg/mg/day
- K_s = 100 mg/L
- Y = 0.6
- b = 0.05 1/day
- S_0 = 400 mg/L
- Q = 1 MGD

Long SRT systems were found to be especially applicable to industrial waste treatment.

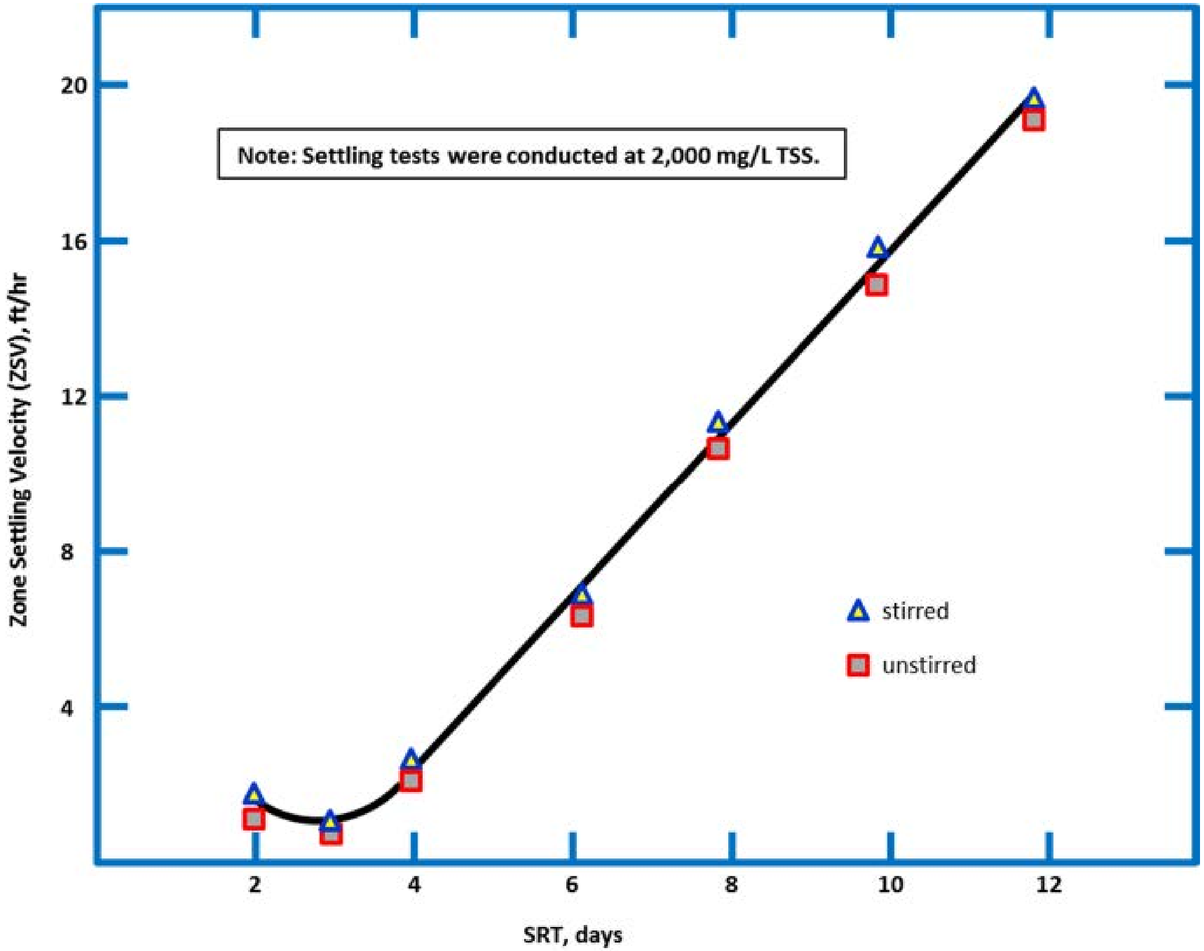




Importance of Activated Sludge Settling To Overall System Performance

- Effective secondary clarifier performance is essential to attaining satisfactory activated sludge system performance.
- Zone settling velocity (ZSV) is the system specific critical parameter for secondary clarifier design (Bisogni and Lawrence 1971).
- Clarifier design is based on selecting the larger surface area of that required for clarification or sludge thickening.
- Clarifier surface area required for sludge thickening is determined by incorporating the zone settling velocity (ZSV) into the batch flux method as described by R. I. Dick (1970).

Zone Settling Velocity as a Function of SRT after Bisogni and Lawrence (1971)



Activated Sludge Least Cost Design Studies (Middleton and Lawrence – 1970s-80s)

- New Systems
  - SRT independent variables:
    - SRT
    - HRT (hydraulic retention time)
    - r (recycle ratio)
  - Allowed least-cost design of new system as a function of these variables:

    Min NPV = Capital Cost + NPV of Operating Cost

    subject to:

    effluent permit limitations
    equipment limitations
    process limitations

    (Minimum volume techniques were also developed as alternative to least cost design)

- Existing Systems
  - Least cost operation of existing system

    Min Operating Cost

    subject to:

    effluent permit limitations
    variable influent conditions
  - Least cost capacity increase of existing system

    Min NPV = Capital Cost of Additional Equipment + NPV of Additional Operating Cost

    subject to:

    effluent permit limitations
    new hydraulic and constituent loadings
    equipment limitations
    process limitation

The Sludge Age Model allowed mathematical solutions of these optimization formulations.

The Sludge Age Concept and the Activated Sludge Process: Today and Tomorrow

Simply stated, the idea of identifying microbial net specific growth rate (μ) and its reciprocal, SRT (sludge age) as the independent steady-state design variable allows design and control of the activated sludge process by the daily wasting of the net accumulation of activated sludge mixed liquor suspended solids regardless of their origin:

- Active microbial mass;
- Microbial cell debris;
- PAC; or,
- Inorganic components of the wastewater.