Opening the black box – Improved process design and control with increased understanding of the activated sludge ecosystem

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Successful Activated Sludge Process Design and Operation

- **Selects for** populations of microorganisms that will act on pollutants present in the influent in a manner that will produce an acceptable effluent.
  - Development and retention of an enrichment culture.
- **Selects against** microorganisms that will cause operational problems. (e.g., filaments and foam formers).
- **Provides the appropriate environment(s)** to allow for these populations to perform the desired reactions.
- High degree of reliability and low cost.

What Control Do We Have?

- **Design engineers can control:**
  - Reactor configuration
  - Reactor size
  - Methods of retaining microbes
  - Operational flexibility
- **Operators can control:**
  - Sludge wasting rate
    - Controls solids residence time, MCRT, F/M
  - Aeration rate
    - Controls redox environment
  - Sludge recycle rate and internal recirculation rates
    - Impacts solids concentration in various reactors and mass of solids in clarifier
  - Chemical dosing rates
    - e.g., nutrients, minerals, supplemental carbon, acid/base, polymer

Design and Control to Keep the Microbial Populations Needed and Keep Them Doing What You Want

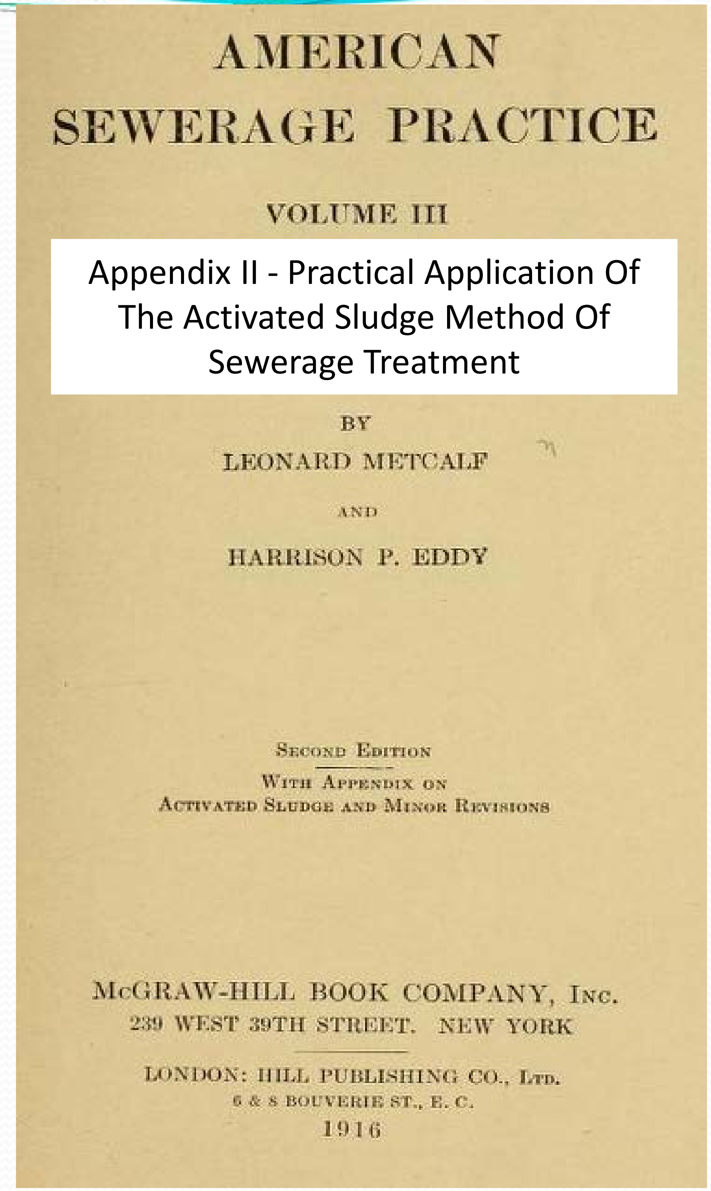
Arden and Lockett, 1914

- The Activated Sludge Process was discovered (or invented) based on the recognition that **retention and reuse of solids formed during aeration of sewage increased the rate of organic carbon oxidation and the conversion of ammonia to nitrate.** It also provided a clarified effluent greatly reduced in solids and active bacteria.
- Arden and Lockett, 1914
  - Goals: Decrease discharge of solids and oxygen demanding contaminants.
  - Approach: **Retain the gravity settled solids** from each subsequent reaction by removing the treated supernatant and adding fresh sewage to the accumulated sludge. (i.e., separate SRT from HRT)
  - Outcome: Development of an "activated sludge" capable of achieving complete oxidation and nitrification of raw sewage in **24 hours** as opposed to the **5 weeks** by aeration of the sewage.
  - Why did it work: The process of feeding, settling and decanting provided selective pressure that resulted in development and accumulation of an **enrichment culture with good settling properties** that was capable of carrying out the desired reactions in a short period of time.

Earliest Guidance on Design and Operation of ASP

Empirical Loading Rates for Fill-and-Draw Operation for Domestic WW.

- Volume of Sewage/Volume of Settled Sludge (typically 4 to 5 parts Sewage to 1 part AS)
- Aeration until nitrification is complete
  (“… 4 to 5 hours aeration with 20% of sludge” - Milwaukee sewage.)
- Air Requirements: 0.5 to 1.75 ft^3/gallon
  0.5 cu. ft./gal (England), 1 cu. ft./gal (Urbana), 1.75 cu. ft./gal (Milwaukee)
- **No mention of problems associated with settling**
- Settled sludge concentrations (30 min to 2 hours) appear to be in the range of 10,000 to 20,000 mg/L for TSS. (Water contents of 98%, 99%.)
- Start-up was time consuming due to need to develop the Activated Sludge.


AMERICAN
SEWERAGE PRACTICE
VOLUME III

Appendix II - Practical Application Of The Activated Sludge Method Of Sewerage Treatment

BY
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AND
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SECOND EDITION
WITH APPENDIX ON
ACTIVATED SLUDGE AND MINOR REVISIONS

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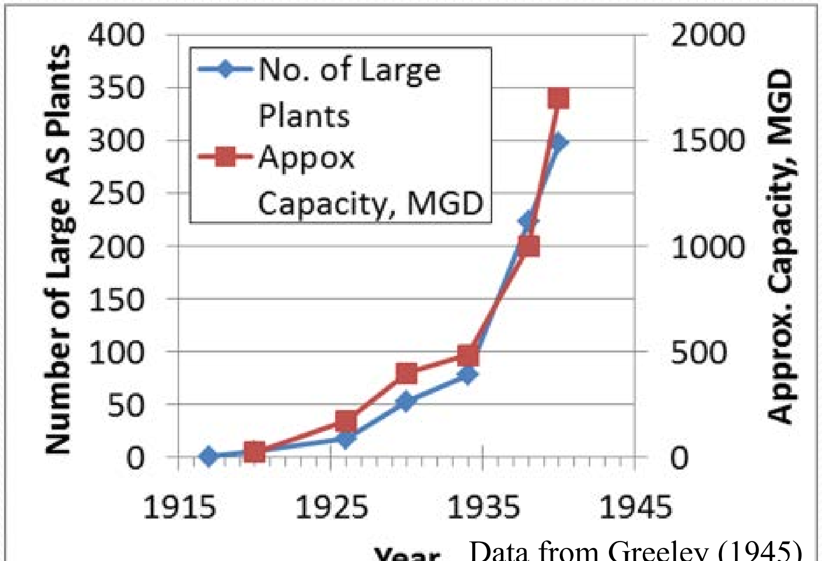
Empirical ASP Design

- Empirical design, experiential control remained the rule for the first 50 years.
- Removal of BOD and Suspended Solids remained primary goals – often with a specific goal of avoiding nitrification (aeration and alkalinity cost).
- Primary design and operation parameters were <u>volumetric loading rate parameters, HRT, and organic loading rate given as BOD or COD per unit volume of the aeration tank</u>.
- Operational problems associated with final clarifiers were common.

- Conventional Design (Greeley, 1945)
  - 15' deep, 25 to 30' wide (PFR)
  - Porous plate fine bubble aeration
  - 3 hour HRT (3 hour at peak hydraulic load)
  - Separate final clarifiers at 1,000 gal/ft^2/day
  - 25 to 50% sludge recycle flow rate
- Loading Rates (Domestic WW):
  - <u>Loading</u>: 25 – 30 lb BOD/1,000 ft^3/day
  - <u>Aeration</u>: 1 – 2 lbs BOD/1,000 ft^3 air
  - <u>Control</u>: MLSS = 1,500 to 2,000 ppm.



Data from Greeley (1945)

Design Based on Stoichiometry & Kinetics

- At the end of the empirical design period the volumetric loading rate approach was being replaced by a food-to-microorganism loading rate approach (F/M as mg BOD or COD/mg VSS/day).
- From 1960s through 1980s advances were made toward development and widespread acceptance of quantitative, kinetics based approaches to design.
  - F/M loading rates still considered but concept of Sludge Age and **design and control based on SRT (MCRT) became the standard approach**.
- Move to demand for removal of BOD/COD, Nitrogen and Phosphorus

Today

- Design using mathematical models based on kinetics and stoichiometry of growth and substrate utilization by <u>multiple populations under multiple environments</u>.
  - Models:
    - IWA ASM1 and ASM3 – Carbon Oxidation and Nitrogen Removal
    - IWA ASM2 and ASM2d – Carbon Oxidation, Nitrogen, and Phosphorous Removal
    - Other Models - Variations on IWA Models - additional substrates and microbial populations
  - Tools:
    - Custom Programs, Spreadsheets, Specific Simulators (e.g, SSSP), Commercial Programs (e.g., ASIM, BioWin, GPS-X, WEST)
- Empirical Values and Experience Are Important
  - Stoichiometry and kinetics
  - Typical loading rate ranges that work
  - Calibration and tuning of the models is important – especially for industrial wastewaters

Operational Control

- Level of sophistication of operational control varies widely.
- Largest and most advanced facilities employ model based control
  - Installation, start-up, and operation of these systems is expensive
    - Model calibration
    - On-line sensor installation and maintenance
- Most smaller systems employ less “advanced” control schemes
  - Traditional operational control (Constant MLVSS, F/M, or SRT).
  - Local knowledge and experience – not detailed model calculations.
  - Why? Limited budgets and less restrictive discharge permits.

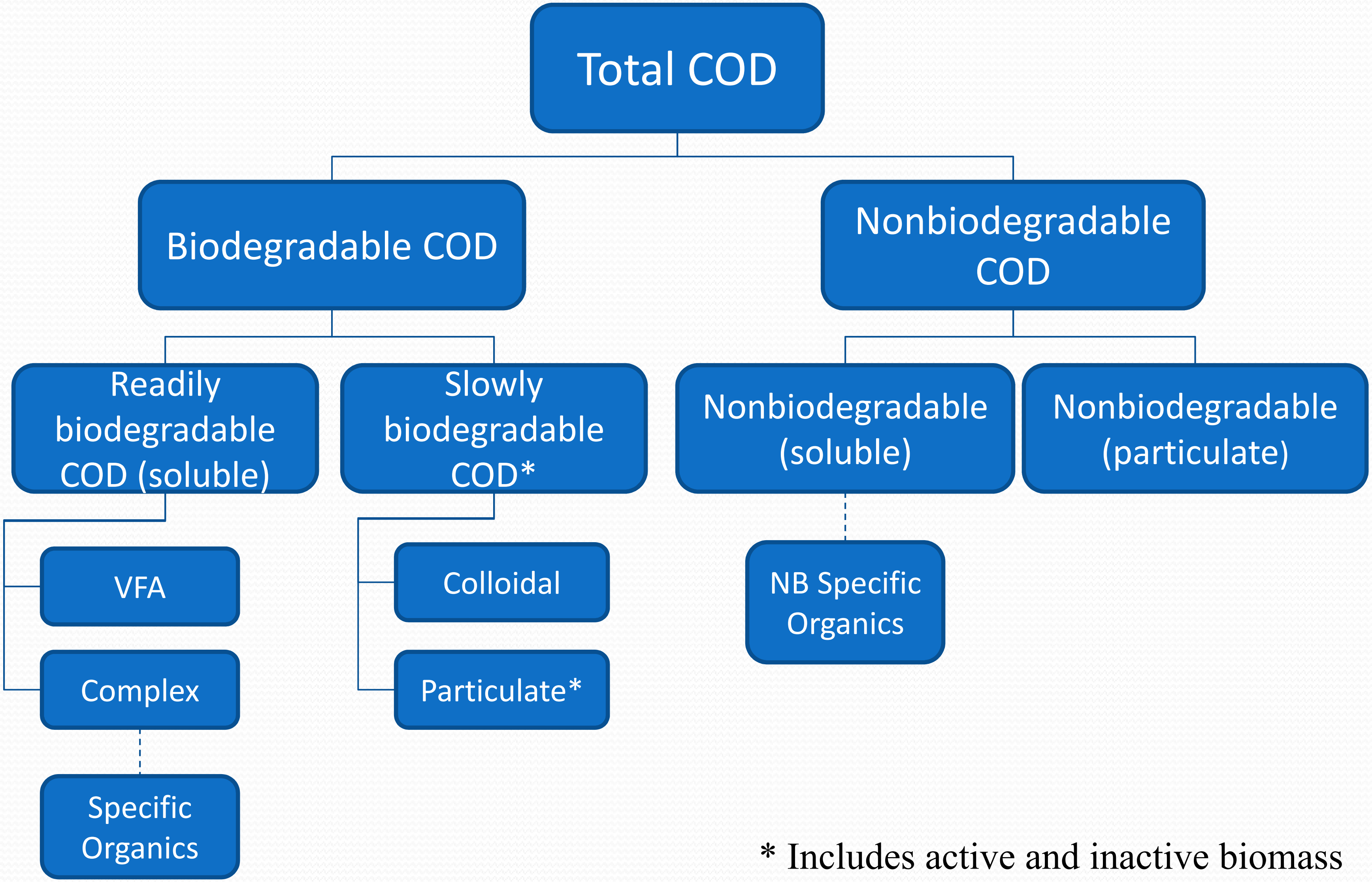
Control Methods

- Improved efficiency and control of smaller facilities (without moving to direct model based control)
  - Develop model based understanding of the ASP for the facility
  - Add of some sensors and feedback control (e.g., DO and ammonia)
  - Implement improved approaches to operational control
    - Constant SRT is better than Constant MLSS or MLVSS
    - COD, N and P fractionation
    - Sludge Quality Approach (usually combined with SRT control)
    - OUR Set-point Control (Constant OUR_{max}) – ML Activity
      - Adjust MLVSS based on changes in biomass activity
      - Activity based on OUR response of ML sample to a standardized feed
      - Accounts for toxicity impacts and accumulation of inactive solids

Future – Improved Understanding of F&M

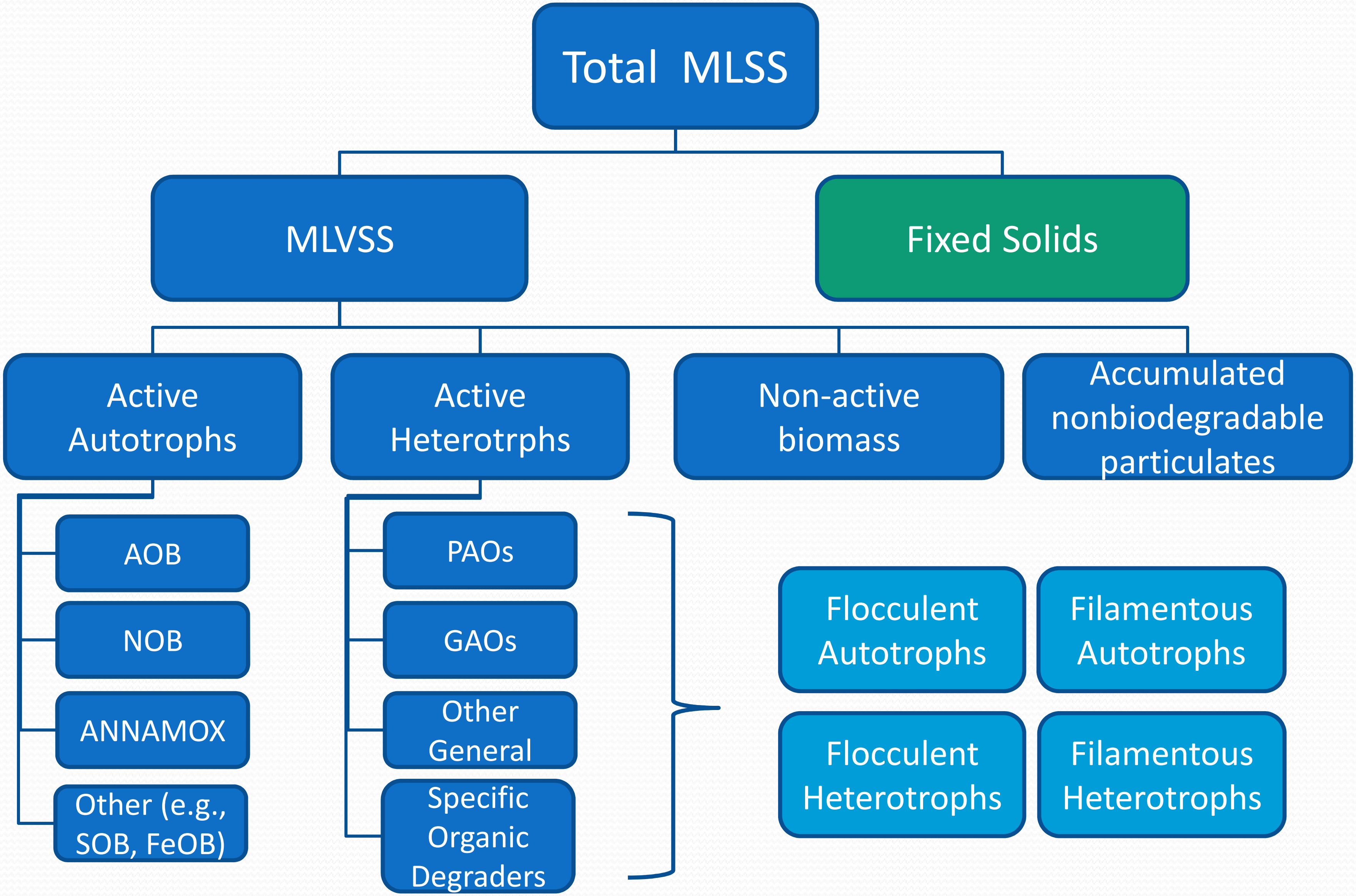
- The history of ASP includes increasing segmentation of the food and the microorganisms.
- Detailed characterization of COD, nitrogen, and phosphorus in a wastewater.
  - Increasingly common today
  - Future - more frequent monitoring, more specific compounds
- Detailed characterization of microbial populations
  - Models increasingly account for more functional population
  - Tools are needed to make it easier to measure presence and activity
  - Molecular tools show promise for presence and abundance
  - Respirometry and other techniques are needed to evaluate reaction rates and activity

COD Fractionation



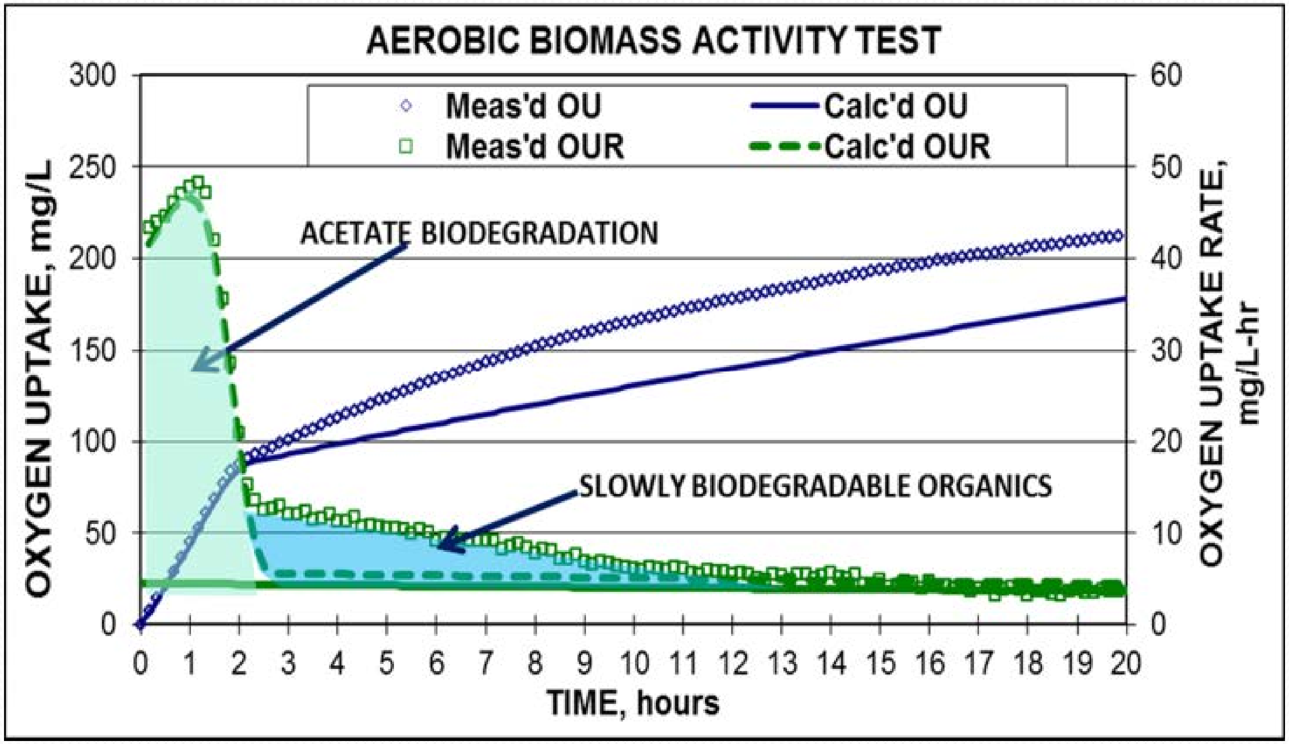
* Includes active and inactive biomass

Mixed Liquor Fractionation



Mixed Liquor Activity - Aerobic

- Measurement of OU in the presence of acetate typically provides a reliable means for determining aerobic carbonaceous reaction **biomass activity.**
- The oxygen uptake data are analyzed using a kinetic model.
- The results, coupled with other diagnostic tests, provide a basis for maintaining and improving process performance of ASP.

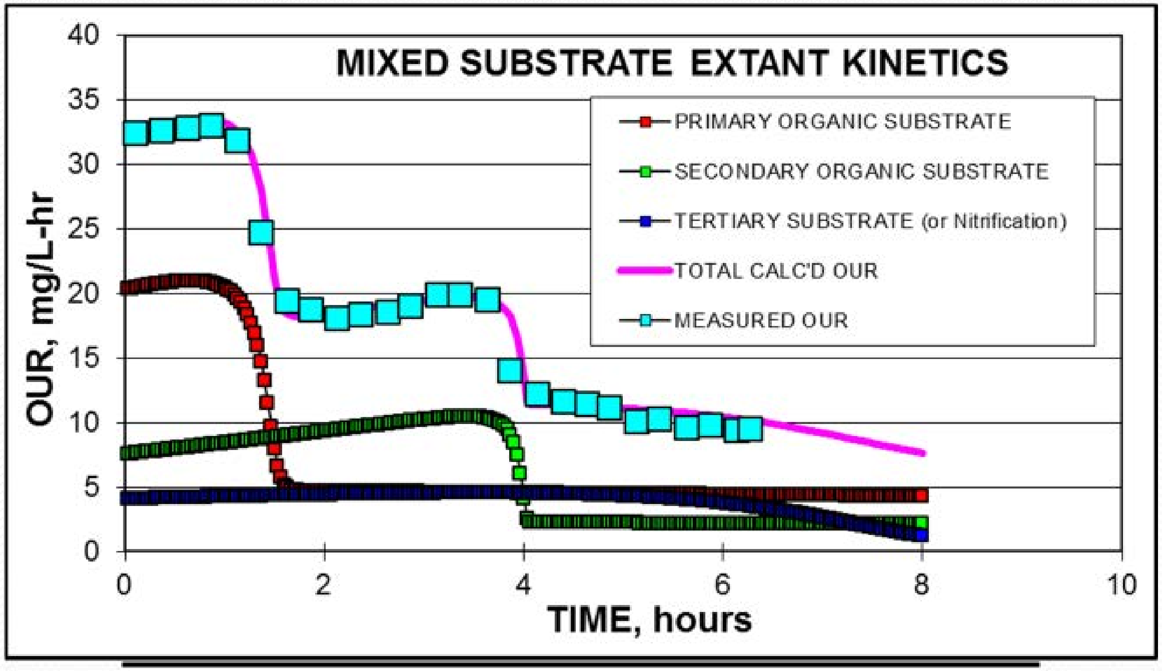


Normal Activity at a Poultry Processing Plant

- 14.5% active
- SRT ~ 15 days

Extant Kinetics - OUR Fingerprints

- Respirometry performed at similar F/M used at full scale
- Multiple substrate model used to regress kinetic parameters and estimate active biomass
  - MLVSS = 2000 mg/L
  - Active Biomass: 12%, 4.25%, 0.35% of the MLVSS



Parameter	S1	S2	S3
Yo, mg VSS/mg CODr =	0.5	0.5	0.5
So, Initial COD, mg/L =	77	100	8.0
Xao, Active Biomass, mg/L =	235	85	7.0
q, mg COD/mg VSS/d =	6.0	6.0	4.0
Ks, mg COD/L =	4.0	1.0	1.0
Kd, mg VSS/mg VSS/d =	0.30	0.30	0.30
SMP, % of CODr =	0	0	0

Importance of Settling Behavior

- Until introduction of membranes for use in retaining biomass gravity separation was only method available for separating SRT from HRT.
- Thus, nature of the flocculent solids has always played large role in determining successful design and operation.
- Early systems run based on fill-and-draw operation (SBRs) provided optimal conditions for this:
  - Tended to select for populations with good settling behavior
  - Provided an ideal environment for settling
  - e.g., Bartow and Mohlman (1915) **SVI = 27 mL/g** for a fill-and draw system (Urbana, IL)
- Unfortunately poorly settling sludge did not take long to show up.
  - e.g., Bushwell (1923) as poor as **SVI = 667 mL/g** for an internal clarifier CMAS system (Urbana, IL)

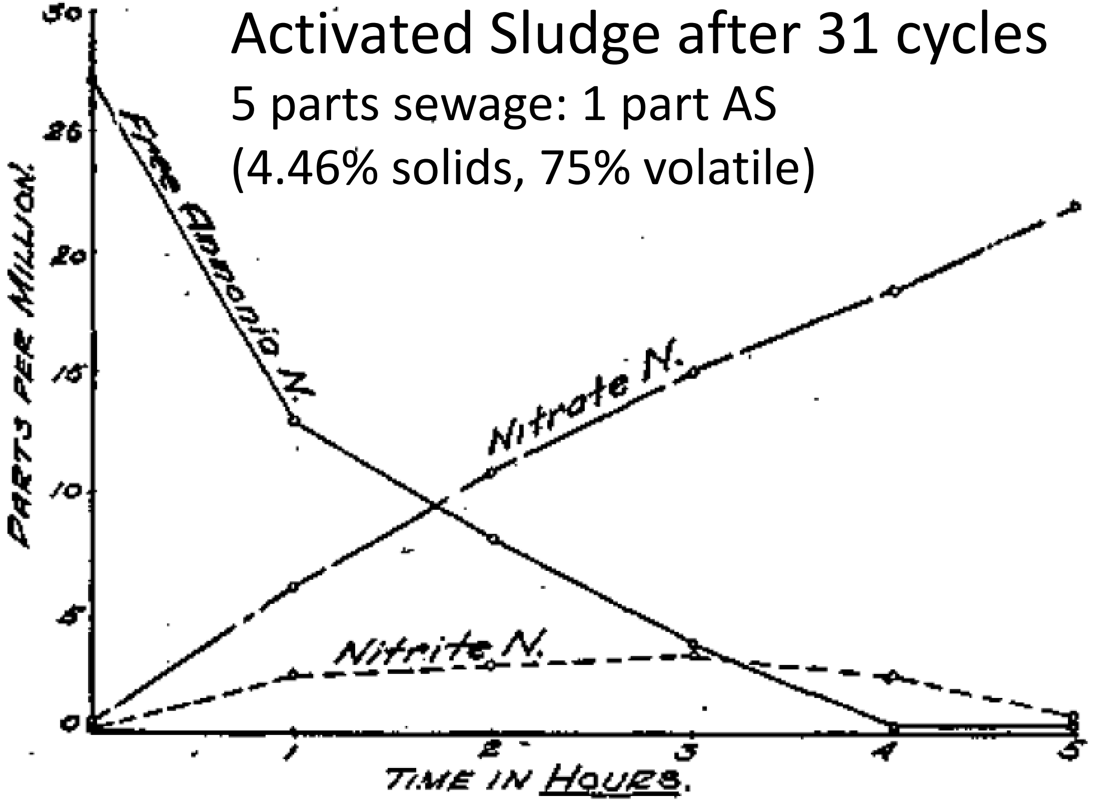
Bartow and Mohlman, 1915 (ISWS)

Sufficient information to estimate an SVI = 27 mL/g for a fill-and draw system (Urbana, IL)

Activated Sludge after 31 cycles

5 parts sewage: 1 part AS

(4.46% solids, 75% volatile)



Settled solids:

TSS = 44,600 mg/L

VSS = 33,450 mg/L

SSV_{60} = 200 mL/L

Mixed Liquor:

TSS = 7,433 mg/L

VSS = 5,575 mg/L

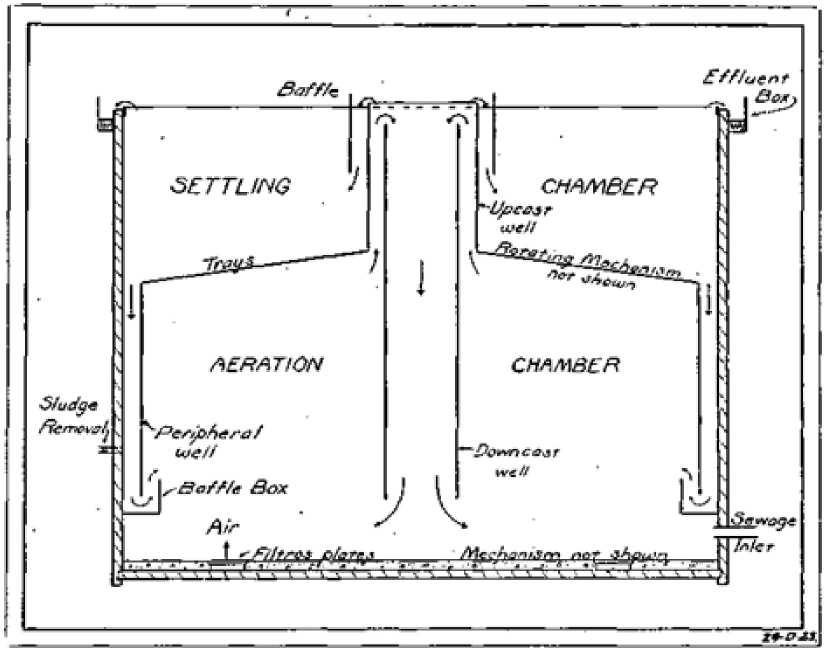
SVI = 27 mL/g

Bushwell, 1923 (ISWS)

Evidence of bulking sludge - CMAS

- "light and feathery"
- TSS of settled sludge averaging 2,622 mg/L (high variability)
- Worst case SSV_{60} = 70% with 1,500 mg/L TSS (**SVI = 667 mL/g**)
- Microscopy based descriptions:
  - "zoogleal masses' intermixed largely with filamentous bacterial and occasional zoogleal ramigera"
  - **"It appears that filamentous forms overwhelmingly predominate the sludge."**

Dorr-Peck Tanks at ISWS



Process Problems – Past

- **Did not recognize that there were several different problems**
  - Did not know the specific cause
  - Limited tools for diagnosis
- **Solutions found by trial and error**
  - Solutions might not be reproducible
  - Inadequate appreciation for microbial diversity

Causes of Sludge Bulking (Greeley, 1945)

1. Causes associated with the character of the raw sewage:
   a. Septic (or aged) sewage
   b. Excessive organic load
   c. Low inorganic content
   d. Presence of trade wastes
   e. Presence of mineral oil
   f. High fat content
   g. High iron content
   h. Abnormal pH value
   i. Low temperature
   j. Greatly fluctuating sewage flow
   k. Presence of hydrogen sulfide
   l. Excessive carbonaceous content.
2. Causes associated with the operation of the aeration tanks:
   a. Underaeration
   b. Overaeration
   c. Incorrect aeration period
   d. Excess suspended solid content
   e. Absence of dissolved oxygen
   f. Poor mixture of activated sludge and sewage
   g. Retarded biological activity
   h. Short-circuiting through aerators
   i. Excessive growths of filamentous organisms.
3. Causes associated with the operation of the final sedimentation tanks:
   a. Maintaining excessive depth of sludge
   b. Permitting sludge to become septic:
      Production of carbon dioxide
   c. Production of nitrogen gas in a highly nitrified effluent.

Process Problems - Present

- Recognize different problems and their causes; for example:
  - **viscous bulking** (excess exocellular polymer) - very high F/M, nutrient imbalance and/or mineral limitation
  - **filamentous bulking** (excessive filaments) – many causes where filaments outcompete floc formers
  - **pin floc** (inadequate filaments)
  - **foaming** - *Nocardia*-like filaments
  - **dispersed growth** - high growth rate / toxicity
  - **rising sludge** – denitrification in clarifier

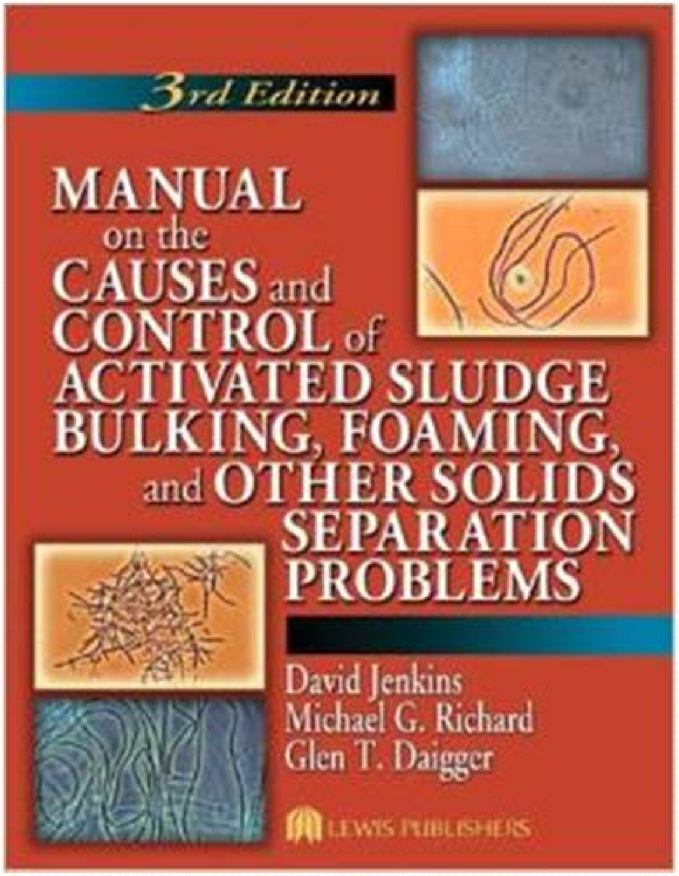
Solutions to Process Problems

Solutions - based on proper analysis of the cause

- Analysis of cause of the problem can be difficult
  - Filamentous bulking - diversity
- Most appropriate solution - Eliminate the root cause

  Examples:

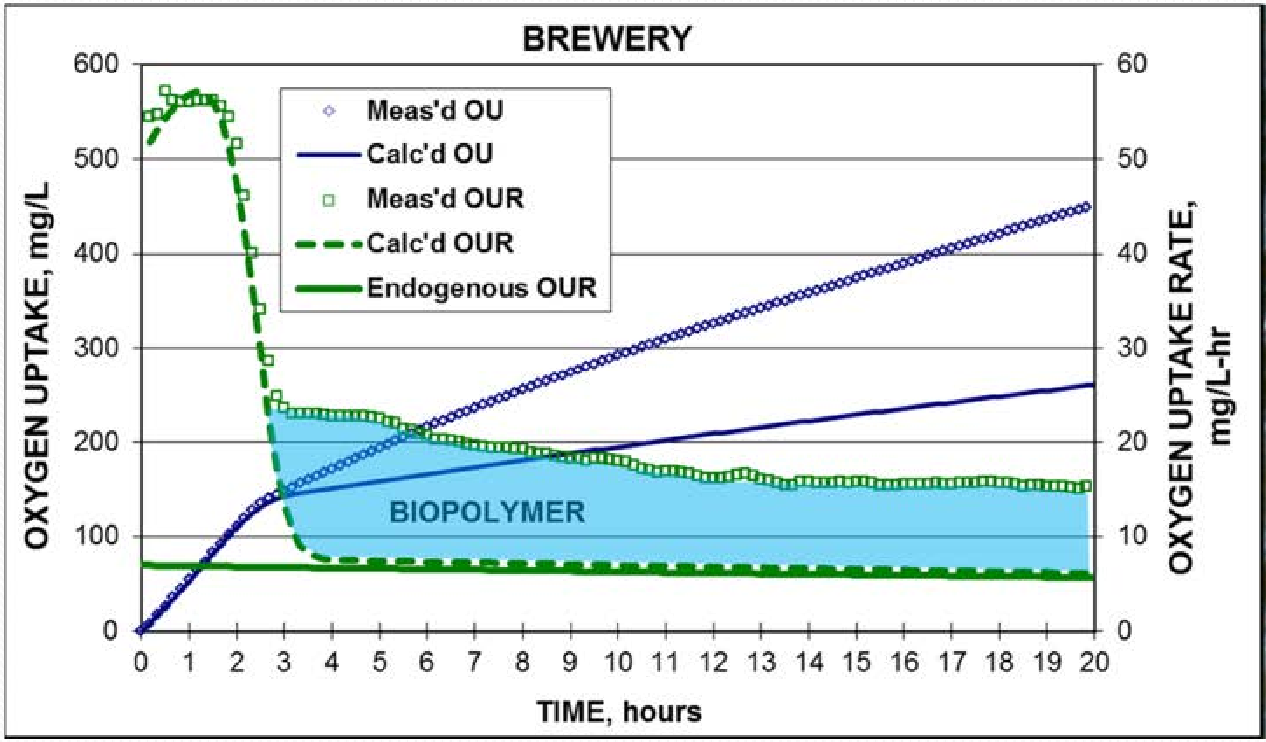
  - Nutrient Limitation – Add Nutrients
  - Filamentous Bulking – Provide Selective Pressure
  - Nocardia-like Foaming – Selective Removal



Example: Nutrient Limitation

- Nutrient and mineral analysis of the WW and ML.
- Microscopic analysis of the mixed liquor.
- Respirometric analysis using an activity test.

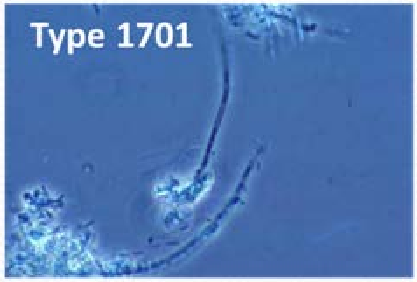
SOLUTION = provide missing nutrients/minerals

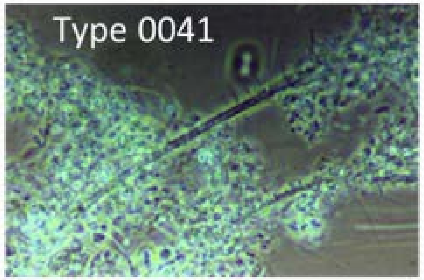


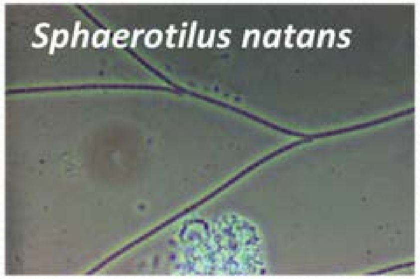
Example: Causes of Filamentous Bulking

- Filamentous bulking occurs when conditions allow filamentous organisms to outcompete floc formers for resources.
- Various conditions allow for this to occur.
- Identifying which filamentous organisms are present and their abundance can help identify the likely cause and suggest solutions.

Kind of Bulking	Indicative Filament Type
Major (commonly occurring)	
Low organic load (Low F/M)	0041, 0092, *M. parvicella*, 0581, 0803
Low DO	1701, 021N, *S. natans*, 1863
Minor (infrequently occurring)	
Low pH	Fungi
Sulfides	*Thiothrix*-like, *Beggiatoa*
Low N (or P)	? (*S. natans*)







Limitation of ID by Microscopy

- Identification of filaments by microscopy is uncertain
  - Type 021N probably at least 3 different species
  - May be favored by different conditions

Overcoming Limitation

- Use of Molecular Tools
  - Improve identification of filaments by microscopy (FISH)
  - Fingerprinting techniques (DGGE, T-RFLP)
  - Quantitative real-time PCR (QRT-PCR)
  - Pyrosequencing of 16S rRNA

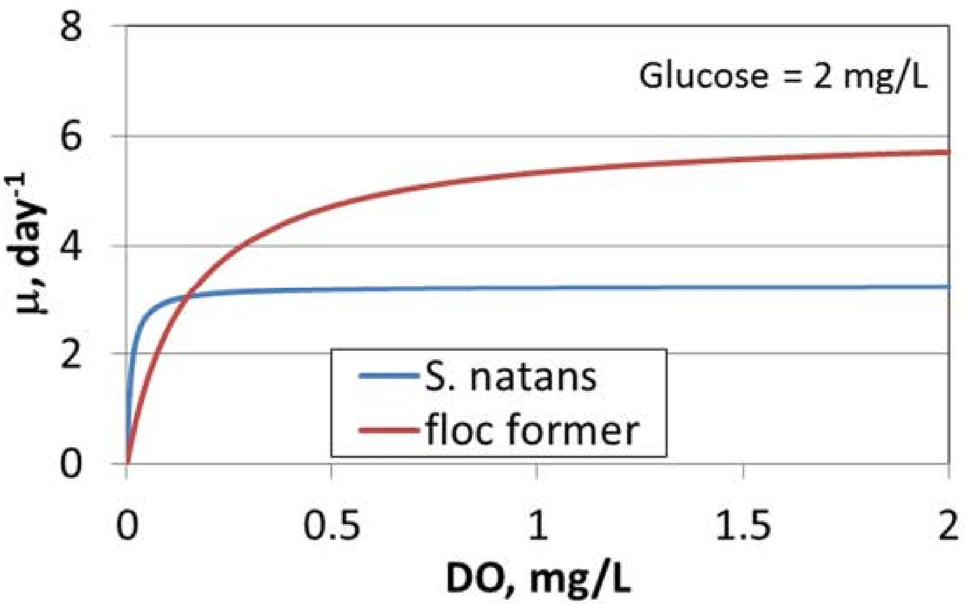
Corrective Actions

- Appropriate corrective actions depend on identified causes
- Several theories exist which are helpful
  - Diffusion Based Selection (low F/M bulking)
  - Kinetic Selection Theory (low F/M and low DO bulking)
  - Storage Selection Theory
  - Nitric oxide hypothesis (low F/M bulking in BNR systems)

Low DO Bulking - Kinetic Selection

		S. natans	floc former
μ_{max}	day^{-1}	6.5	9.2
K_S	mg COD/L	10	5
K_{O2}	mg/L	0.01	0.15

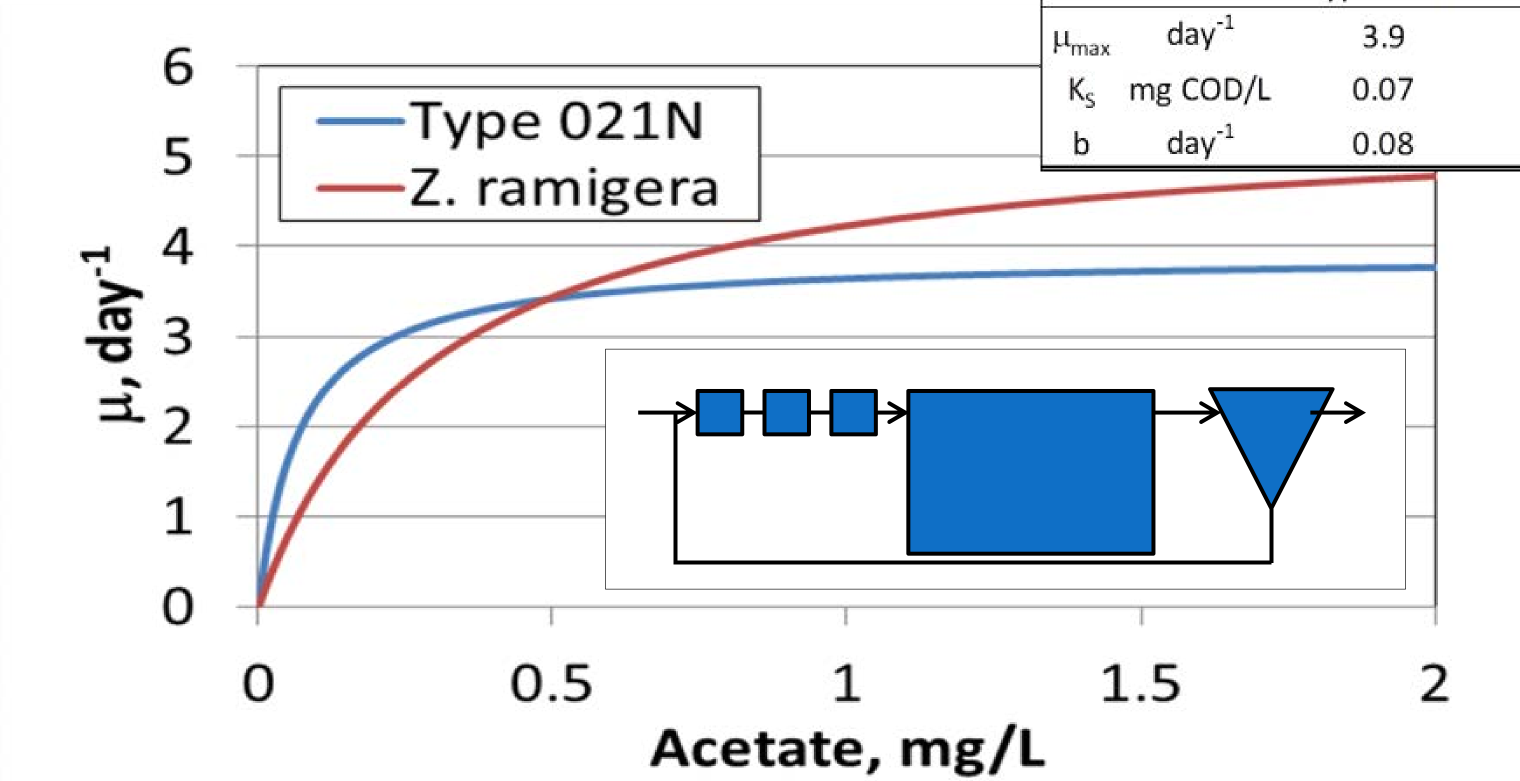
Values from: Lau, Strom, Jenkins (1984)



Corrective Actions – Filamentous Bulking

- Example: Use of Selectors for Low F/M Filamentous Bulking
  - Use of selectors was introduced by Chudoba et al. (1973+)
  - Chudoba's contribution included the kinetic selection theory.
  - This concept works particularly well for CMAS

		Type 021N	Z. ramigera
μ_{max}	day^{-1}	3.9	5.5
K_S	mg COD/L	0.07	0.3
b	day^{-1}	0.08	0.03



Kinetic values from: Van Niekerk, AM, Jenkins D, Richard M. (1987)

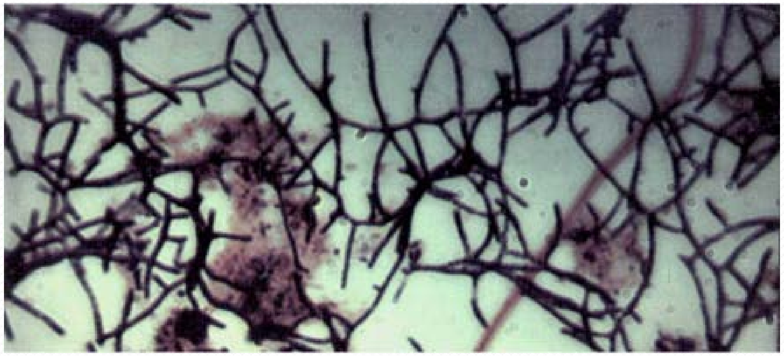
Foaming

- **Foaming can be caused by:**
  - Poorly biodegradable surfactants
  - *Nocardia* and nocardia like organisms with hydrophobic cell walls
- **Control of foaming due to *Nocardia*-like organisms:**
  - Apply selective pressure against these organisms
  - Limit their ability to accumulate:
    - Avoid subsurface discharge from aeration basins
    - Avoid recycle of foam
    - Install classifying selectors for selective foam wasting (Parker et al, 2003)

      (i.e., apply selective pressure through removal of undesired microbes)

Mild *Nocardia* Foam

***Nocardia*-like Foaming Filaments**



Other Examples of Selection

- Competition for Substrate
  - Enhanced Biological Phosphorous Removal
    - PAOs outcompete other heterotrophs
    - Requires cyclic anaerobic and aerobic conditions.
    - Requires influent with good VFA content
    - Problems can occur under conditions where GAOs outcompete PAOs.
- Selective retention of desired microbes
  - Shortcut Nitrogen Removal
    - ANNAMOX bacteria are retained by growing them under conditions where they grow as granular sludge.
    - High-rate clarifiers (ANAMMOX® Granulated Sludge Reactor) or hydrocyclones (DEMON® Sequencing Batch Reactor) are used to retain these slow growing organisms to allow them to compete against AOB and NOBs.
  - Aerobic Granular Sludge*
    - Intense selective pressure through wash-out of non-granular biomass selects for dense granular biomass.

*see work of van Loosdrecht and others and commercialization as Nereda Technology

The Challenge of Emerging Contaminants

- BIODEGRADABILITY
- LOW CONCENTRATIONS
  - Insufficient loading of a biodegradable organic compound can lead to the inability to maintain a viable population capable of degrading it – even at SRTs > SRT_{min}

$$S_{min} = \frac{K_S b}{\hat{\mu} - b}$$

- Example: 1,4-dioxane

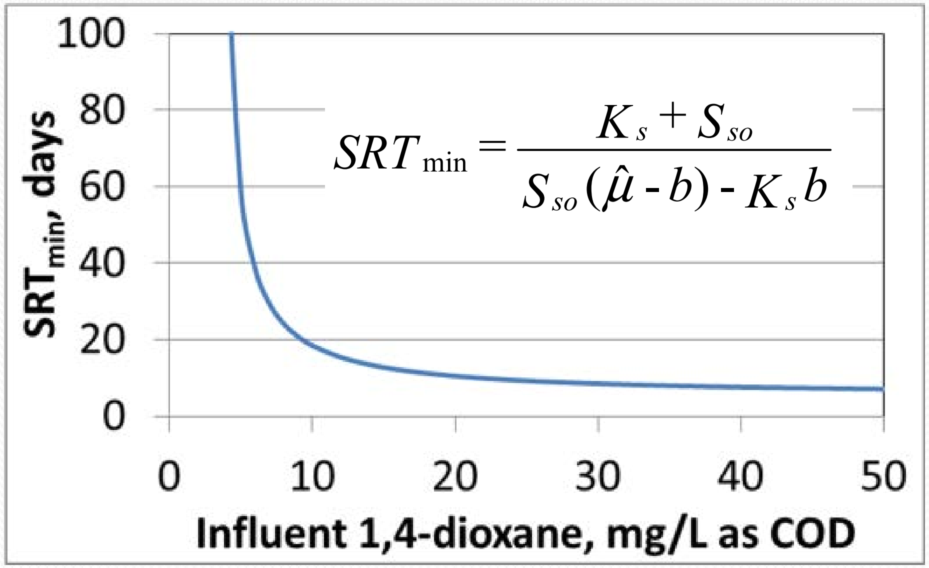
Y_g = 0.33 mg biomass COD/mg COD

$\hat{\mu}$ = 0.010 hr^{-1}

K_S = 13.5 mg/L as COD

b = 0.002 hr^{-1}

S_{min} = 3.375 mg/L (at 25^{o}C)

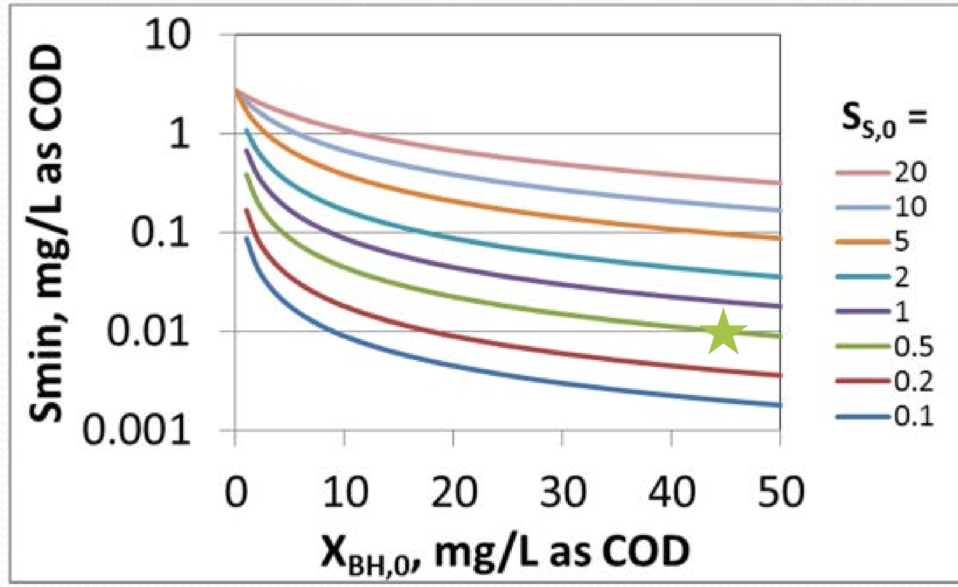


Kinetic values from: Grady, Cowan, and Sock (1997)

Overcoming Low Concentration Challenge

- **Provide active capable degraders (biosupplement)**

$$S_{min} = \frac{K_S\, b_H}{\hat{\mu}_H \left(1 + \dfrac{X_{B,H0}}{Y_H \cdot S_{S0}}\right) - b_H}$$



Example: 1,4-dioxane

<u>Assume:</u>

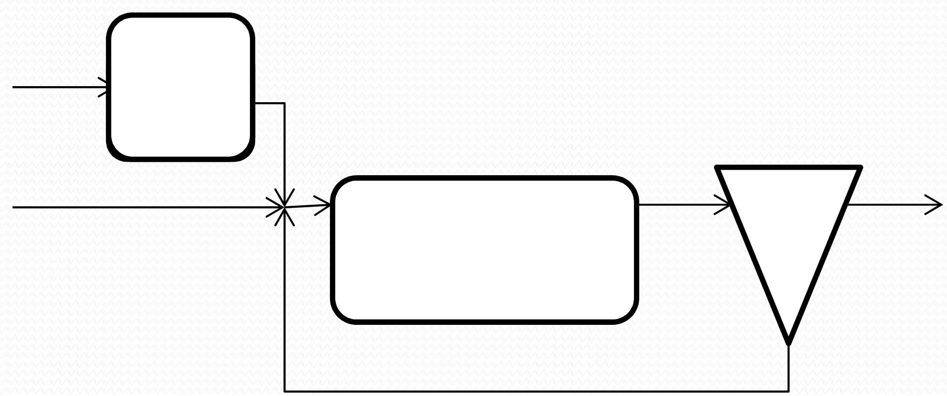
Influent = 0.5 mg/L

Effluent Limit = 10 ppb

<u>Requires:</u>

45 mg/L active supplement

at SRT→ ∞



- Easy if there is a concentrated sidestream available
- Potentially expensive if there is not

Grady, Cowan, and Sock (1997)

Overcoming Low Concentration Challenge

- **Rely on Cometabolism, Example: Use of AOBs**
  - Cometabolism of emerging contaminants by AOBs shows reasonable promise.
  - AOBs use a fairly non-specific ammonia monooxygenase (AMO).
  - AMO can act on other compounds.
  - The ability to take advantage of this in a controlled manner is complex due to:
    - Understanding of the kinetics of cometabolism is still limited.
    - Competitive inhibition – the presence of the emerging contaminants can negatively impact ammonia oxidation.
    - The metabolites formed during cometabolism may still be of environmental concern.

<u>A few recent examples of work contributing to growth in this area</u>:
Sathyamoorthy, Chandran, Ramsburg (2013) ES&T, 47, 12835-12843.
Fernandez-Fontina, Omil, Lema, Carballa (2012) Water Research, 46, 5434-5444.
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THANK YOU!
Questions?

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