Practical BM Respirometry
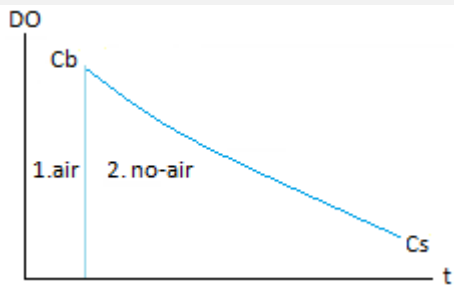# for biological wastewater treatment

BM Respirometry

Three different operation modes

While most of the respirometers on the market offer only one operation mode, the BM respirometers have three different operation modes: OUR mode, Cyclic OUR mode, and R mode. Each mode develops different respirograms for automatic parameters including D.O., Temperature, and pH (in BM-Advance) from where specific applications can be made.

In a single batch reactor, the measuring system can work as LSS and LFS batch respirometry. The system is optimized by a one-sense membrane device, that together with a dividing plate, is able to isolate the measuring chamber and avoid bubbles against the DO sensor.
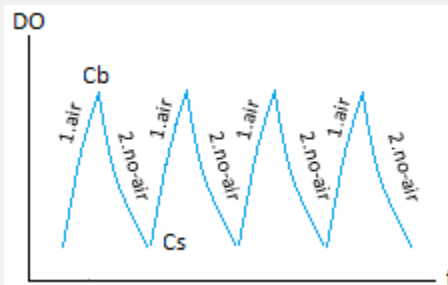
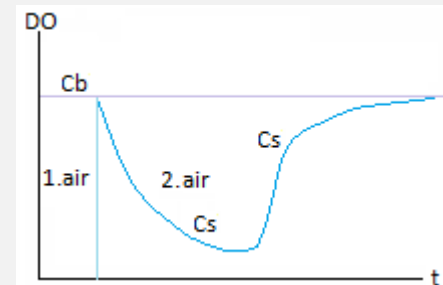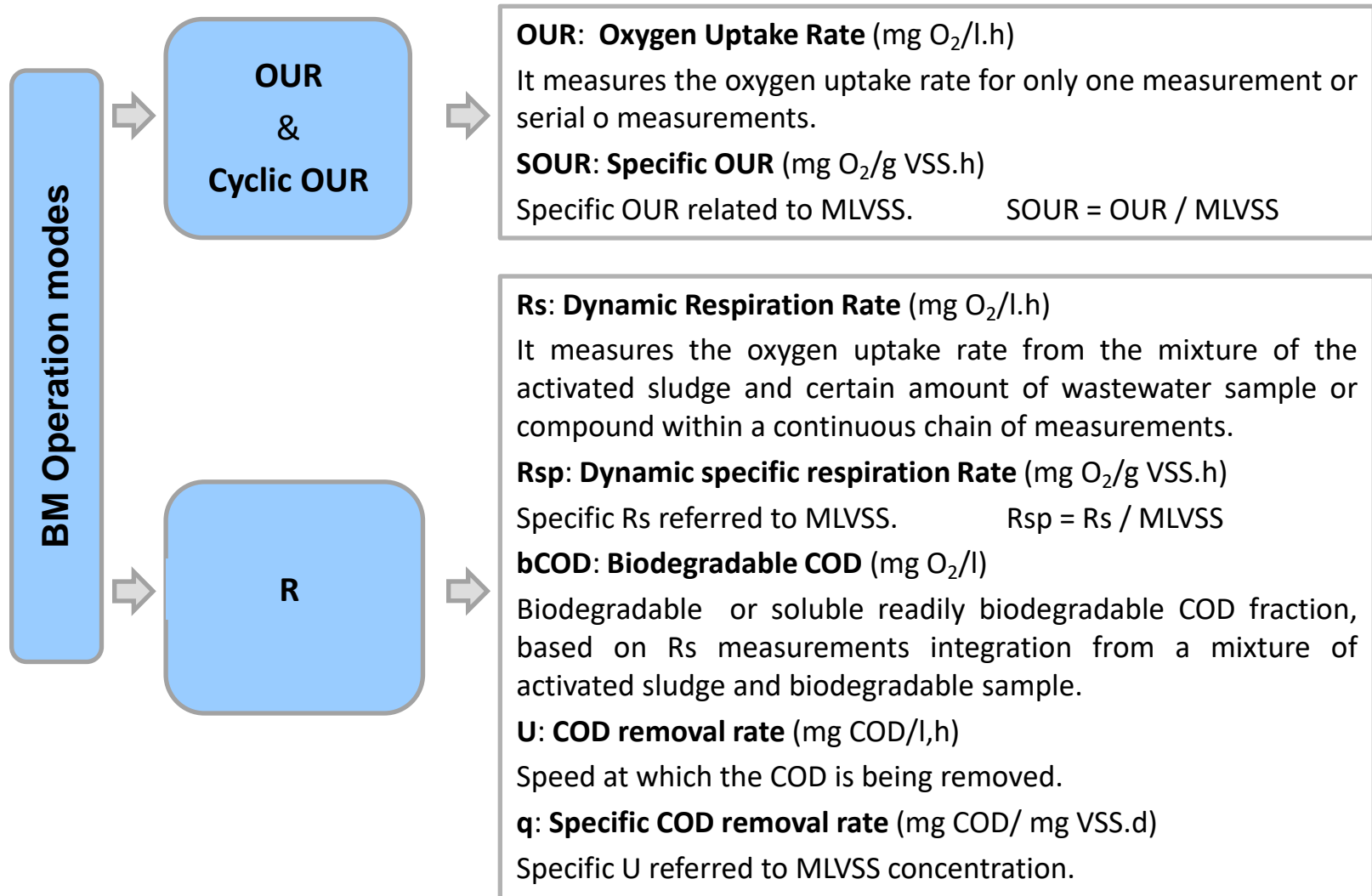| OUR	Cyclic OUR	R
This mode is making use of the LSS respirometry type. The OUR mode consists of a single test to measure the OUR and/or SOUR parameters (by manually setting the MLVSS concentration). It also has the option the get a partial SOUR for any period within the respirogram.	The cyclic OUR mode consists of a progressive sequence of OUR measurements, generated from the DO trajectory when it fluctuates between the DO. Low and DO. High set-points that were set at the start of the test.	The R mode corresponds to a modified LFS respirometry type test. The measuring system can be considered as a completely mixed batch reactor. In this mode, we get the important advantage to work with a small volume of samples in order to minimize the test time for an important package of several simultaneous parameters measurement.

Main automatic parameters in BM respirometer for the different operations modes

BM Operation modes

OUR & Cyclic OUR

OUR: **Oxygen Uptake Rate** (mg O_2/l.h)

It measures the oxygen uptake rate for only one measurement or serial o measurements.

SOUR: **Specific OUR** (mg O_2/g VSS.h)

Specific OUR related to MLVSS.   SOUR = OUR / MLVSS

R

Rs: **Dynamic Respiration Rate** (mg O_2/l.h)

It measures the oxygen uptake rate from the mixture of the activated sludge and certain amount of wastewater sample or compound within a continuous chain of measurements.

Rsp: **Dynamic specific respiration Rate** (mg O_2/g VSS.h)

Specific Rs referred to MLVSS.   Rsp = Rs / MLVSS

bCOD: **Biodegradable COD** (mg O_2/l)

Biodegradable or soluble readily biodegradable COD fraction, based on Rs measurements integration from a mixture of activated sludge and biodegradable sample.

U: **COD removal rate** (mg COD/l,h)

Speed at which the COD is being removed.

q: **Specific COD removal rate** (mg COD/ mg VSS.d)

Specific U referred to MLVSS concentration.

Primary assessment
of the activated sludge process
and biomass health

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👌 Taking the pulse to the activated sludge process

The UNFED SOUR is the SOUR value corresponding to the effluent sludge (end of the aerobic process)

By comparing the UNFED SOUR with the reference value (ref) from a guide table, we can make a primary assessment of how the process is currently performing.

Process type	F/M (BOD/SS.d)	SRT (d)	UNFED SOUR ref (mgO$_2$/gVSS.h)
High loading	> 0.4	4	10 - 15
Medium loading	0.2 – 0.4	4 - 10	7 - 10
Low loading	0.07 – 0.2	10 - 30	3 - 7
Very low loading (extended aeration)	< 0.7		

Actual UNFED SOUR Vs. UNFED SOUR ref. (Table)	Assessment
>> ref	Overloading
= or +/- ref	Good performance
< ref	Low loading
<< ref	Very low loading or Toxicity symptoms

For any activated sludge process were the effluent sludge is not well defined, it also exists the option to perform the UNFED SOUR in a well aerated mixture composed by effluent + aerated returned sludge on equivalent volumes to the effluent flow / RAS flow ratio: [Q (effluent) / Q (RAS) = V (effluent) / V (RAS)]

Endogenous respiration rate

It is about the endogenous oxygen uptake rate test (OUR end) of the activated sludge after being aerated for a sufficient time to eliminate any kind of degradable subtrate.

Normally the endogenous respiration state can be recognized when the oxygen readings are stable within its oxygen saturation level.
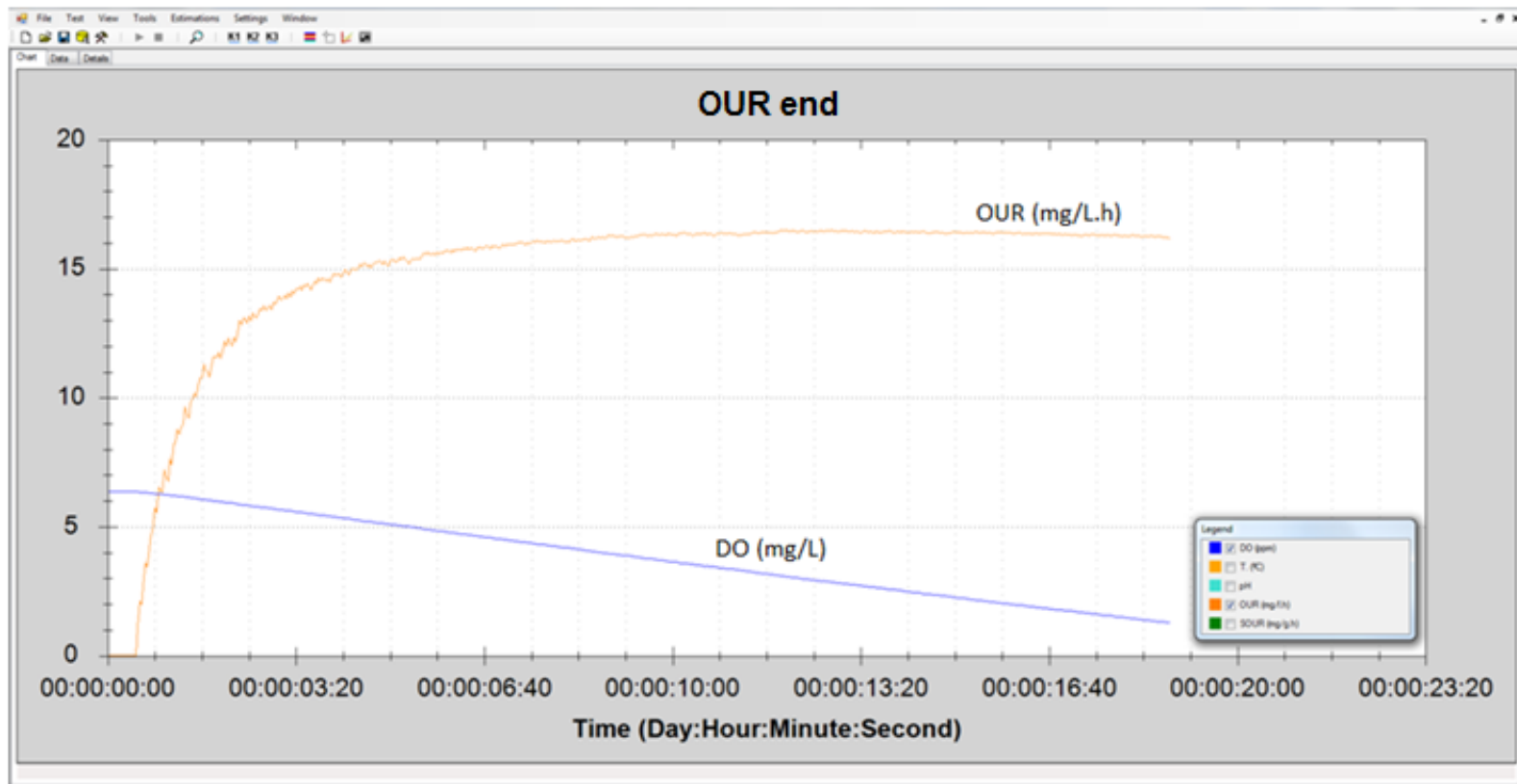
DO and OUR respirogram for OUR end

OUR$_{end}$ assessment

Table guide of usual OUR$_{end}$ values (20 ºC)

MLVSS (mg/l)	OUR$_{end}$ (mg/l.h)
1000	2 – 3.5
1500	3 - 5
2000	4 - 7
2500	5 – 8.5
3000	6 - 10
3500	7 - 12
4000	8 – 13.5
4500	9 – 15.5

Some reasons for which the OUR end value could be below its normal range

1. Low active biomass
2. Toxicity
2. Sludge was too long aerated in its process to get its endogenous respiration state (*)

(*) For high and medium loading process, where the UNFED SOUR is usually in range, the endogenous respiration is normally reached after aerating the effluent sludge for 12 hours. For low and very low loading process, where the UNFED SOUR is also in range, the endogenous state is usually reached after aerating the effluent sludge for 2 ~ 4 hours.
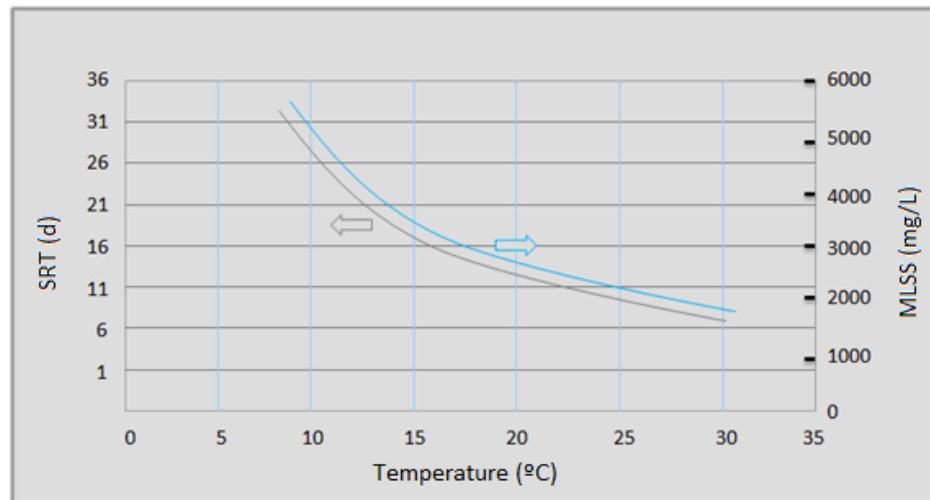
Nitrification

Optimal nitrification conditions

1.

pH	7.3 to 8,3
T	> 15 to 28 ºC
OD	1 a 3 ppm
COD/TKN	< 5
Enough HRT for nitrification in the reactor	
Without any inhibitory or toxic compound	

2. Coherent SRT & MLSS vs Temperature:

Active nitrifier biomass concentration

From the actual nitrification rate of an already existing nitrification process
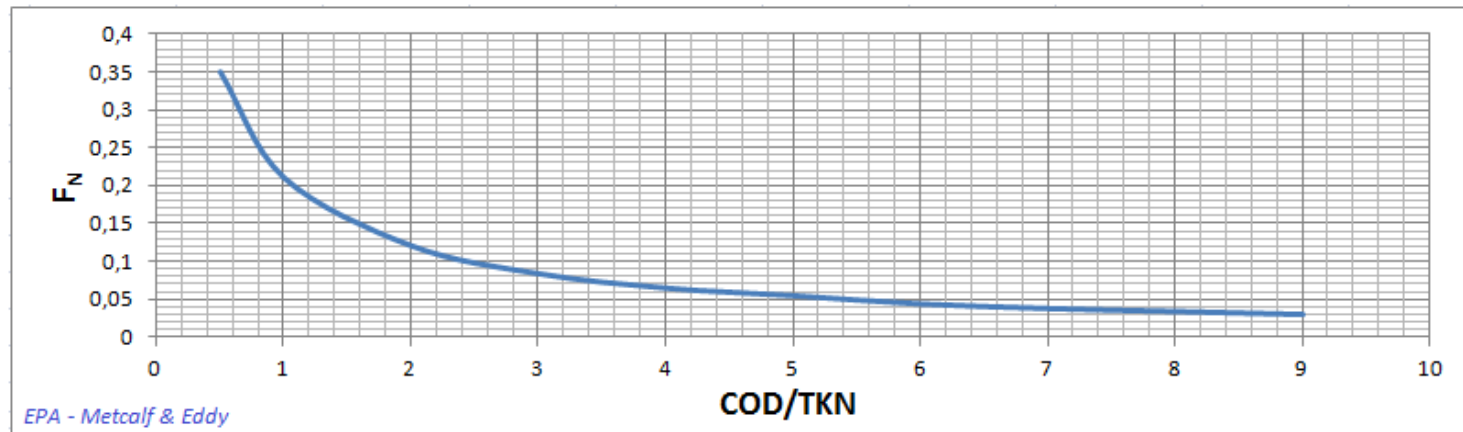
$$X_N = Y_A * 24 * AUR * SRT$$

X_N: Autotrophic biomass concentration (mg/l)
Y_A: Autotrophic yield coefficient ≈ 0.12 (Metcalf & Eddy)
SRT: Actual sludge age on which the process is operating (d)

From standard table

This table should only be applied for a process that is running without any inhibition problems, under an average temperature > 20ºC, pH in between 7 and 8 and DO > 2 ppm.

EPA - Metcalf & Eddy

$$X_A = F_N * X_V$$

Source: Metcalf & Eddy. 1995

Possible reasons from which the actual nitrifier biomass is lower than the reference value in the standard table

1. The process is not operating under one or more correct conditions of DO, pH, Temperature.

2. BOD/TKN > 5

3. BOD/TKN ≥ 5 + Low temperature (< 15ºC) for a long time.

3. Low temperature (< 15ºC) for a long time

4. Presence of toxic compound in the influent wastewater.

5. Nutrients defficiency

6. Others.

Nitrification rate

To get the nitrification rate under optimal oxygen level by means the BM respirometery, we carry out a R test with ammonium chloride on equivalent concentration until reaching the maximum exogenous respiration rate. Then, Allyl Thiourea (ATU) could be added to inhibit the nitrifiers bacteria and get the endogenous sludge ready for organic matter tests where only heterotrophic biomass is acting.
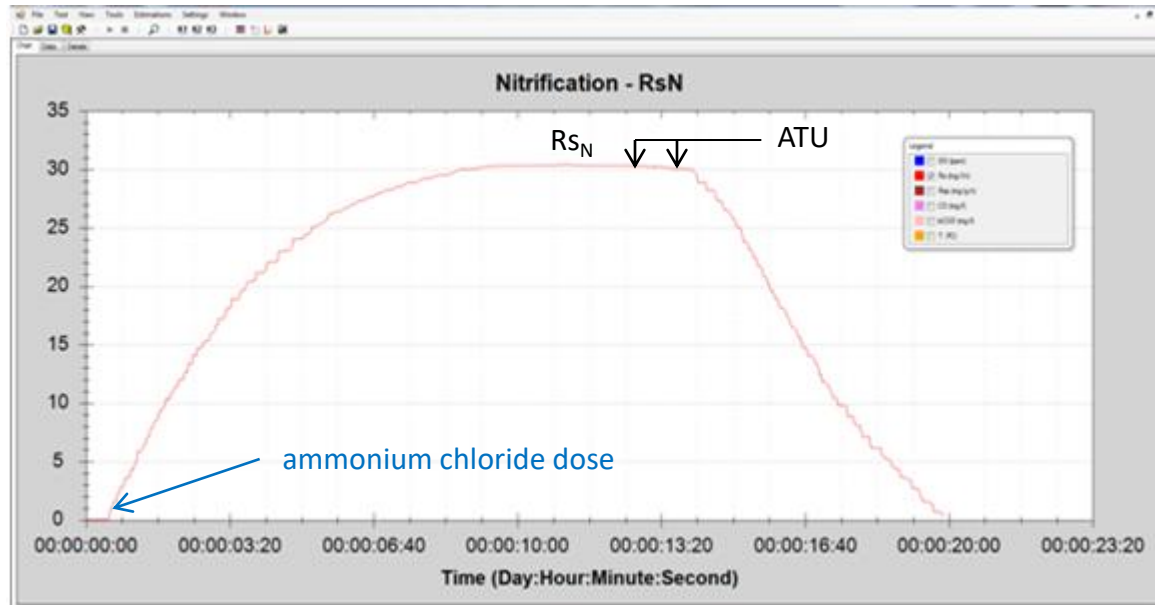
Rs respirogram after adding the NH4Cl dose

$$AUR = (Rs_N / 4.57) * F_{OA}$$

AUR: Nitrification rate (mg /l.h N)

Rs_N: Maximum value of exogenous respiration rate (Rs) due to nitrification

$F_{OA} = DO / (K_{OA} + DO)$ [when DO ≥ 2.5 mg/l → F_{OA} = 1]

DO: Average dissolved oxygen in the actual nitrification process

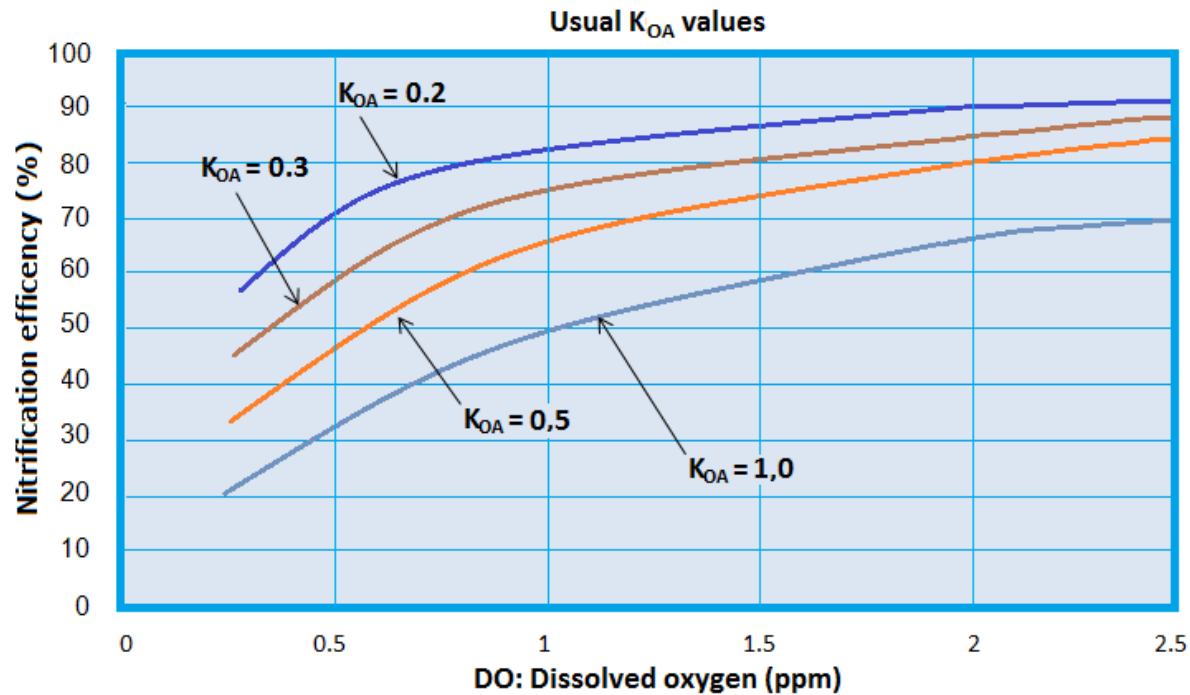K_{OA}: Half saturation coefficient ≈ 0.5 ppm

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Oxygen half-saturation constant for nitrification

$$K_{OA} = DO\ (AUR - N_N / HRT_N) / (N_N / HRT_N)$$

K_{OA}: DO half-saturation constant (mg/l O_2)
DO: Average DO in the nitrification process (mg/l O_2)
HRT_N: Hydraulic retention time for nitrification (h)

Usual default value: K_{OA} = 0.5

Nitrogen for nitrification

Actual nitrogen being nitrified

$$\mathbf{Nn} = TKN_O - TKN_e - N_{sy}$$

Nn: Actual nitrogen concentration that is currently being nitrified (mg/l N)
TKN_O: Influent TKN (mg/l N)
TKN_e: Effluent soluble TKN (mg/l N)
N_{sy}: Nitrogen utilized in the cell synthesis = 0.05 * BOD

Nitrogen that should be nitrified

$$\mathbf{Nn'} = TKN_O - TKN'_e - N_{sy}$$

Nn': Nitrogen concentration that should be nitrified (mg/l N)
TKN_O: Influent TKN (mg/l N)
TKN'_e: TKN that should be in the effluent according to the required nitrification efficiency (mg/l N)
N_{sy}: Nitrogen utilized in the cell synthesis = 0.05 * BOD

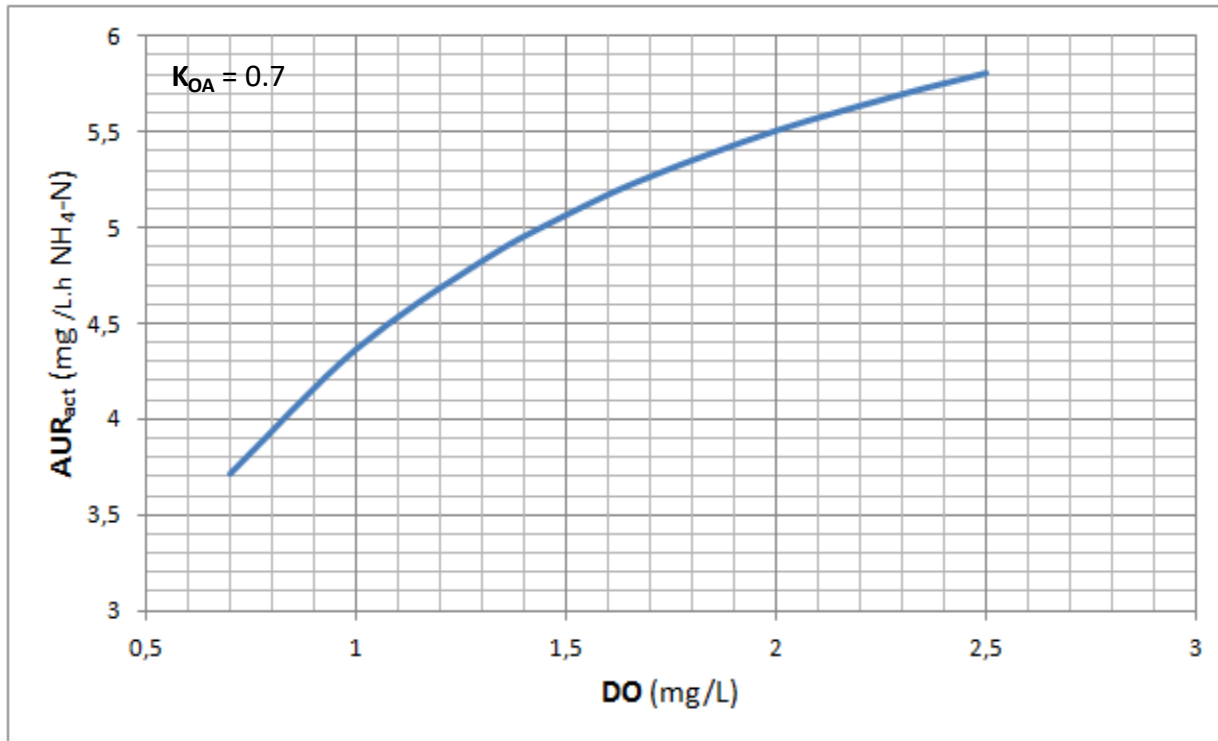# Estimation of the required nitrification rate

$$\mathbf{AUR'} = (Nn' / Nn) * AUR$$

AUR': Nitrification rate to get the required nitrification efficiency (mg /l/h N)

Influence of dissolved oxygen on the actual nitrification rate

Once the K_{OA} is determined, we can plot the values of the actual nitrification rate (AUR_{act}) for different DO values and estimate the nitrification eficiency for some specific conditions
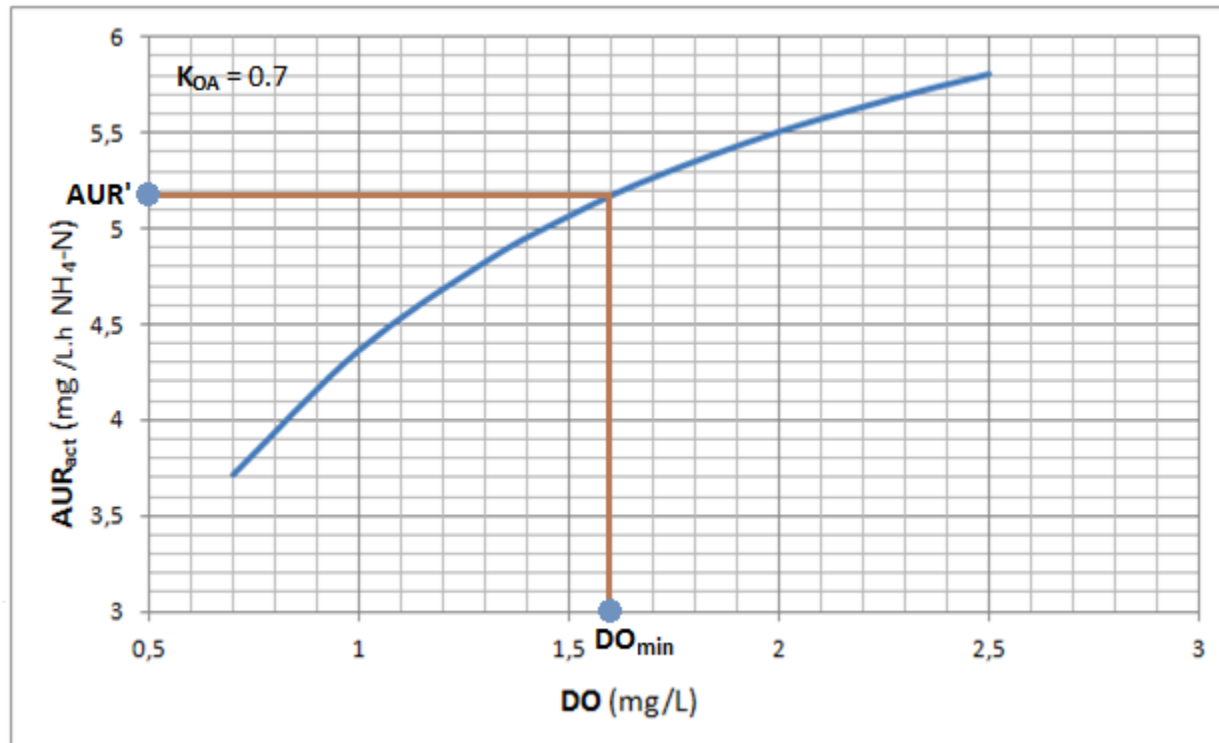
$$AUR_{act} = AUR * DO / (K_{OA} + DO)$$

Minimum oxygen for a specific nitrification eficiency

From the curve AUR vs DO, the minimum DO (DO_{min}), on which the nitrification could operate, can be figured out for a specific nitrification performance where the estimated required nitrification rate should be AUR'.

$$DO_{min} = K_{OA} / (AUR / AUR' - 1)$$

Possible reasons for which the actual nitrification rate could be less than the required nitrification rate

1. The process is not operating under one or more correct conditions of DO, pH, Temperature.

2. The sludge age (SRT) is lower than the one on which the process should be operating.

3. The concentration of the active nitrifier biomass is too low.
   This could be because of
   - . BOD/TKN > 5
   - . Conditions are out of normal range
   - . Inhibition effect

5. Toxicity

6. Others

Nitrifier biomass growing rate

$$\mu_A = 24 * AUR * Y_A / X_A$$

μ_A : Nitrifier biomass growing rate (d^{-1})

Y_A: Yield coefficient ≈ 0,12 (Metcalf & Eddy)

Minimum sludge age for nitrification

$$SRT_{min} = 1 / (\mu_A - b_A)$$

SRT_{min}: Minimum sludge age for nitrification (d)

Temp	Death & Decay Rate b_A (days^{-1})
10°C	0.02
15°C	0.03
20°C	0.04
25°C	0.05

Source: EPA – Long Island. Sound Study, NY - 2000

Sludge age condition for nitrification   →   SRT ≥ SRT_{min}

Practical operation protocol for the nitrification under energy optimization frame

In this protocol we asume the temperature and pH conditions are within the normal range and the process has the capability to control the DO level under the approach of its minimum range.
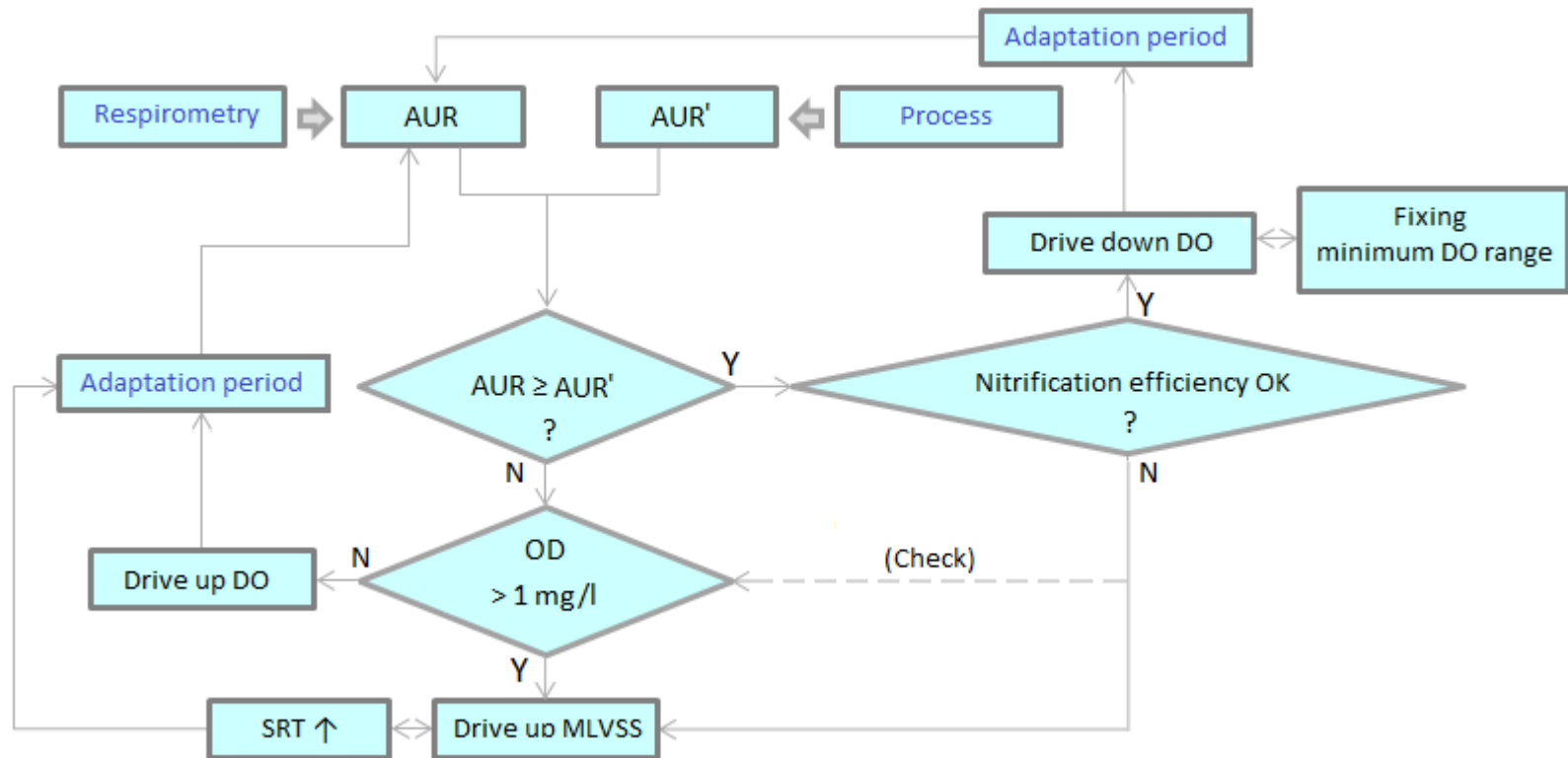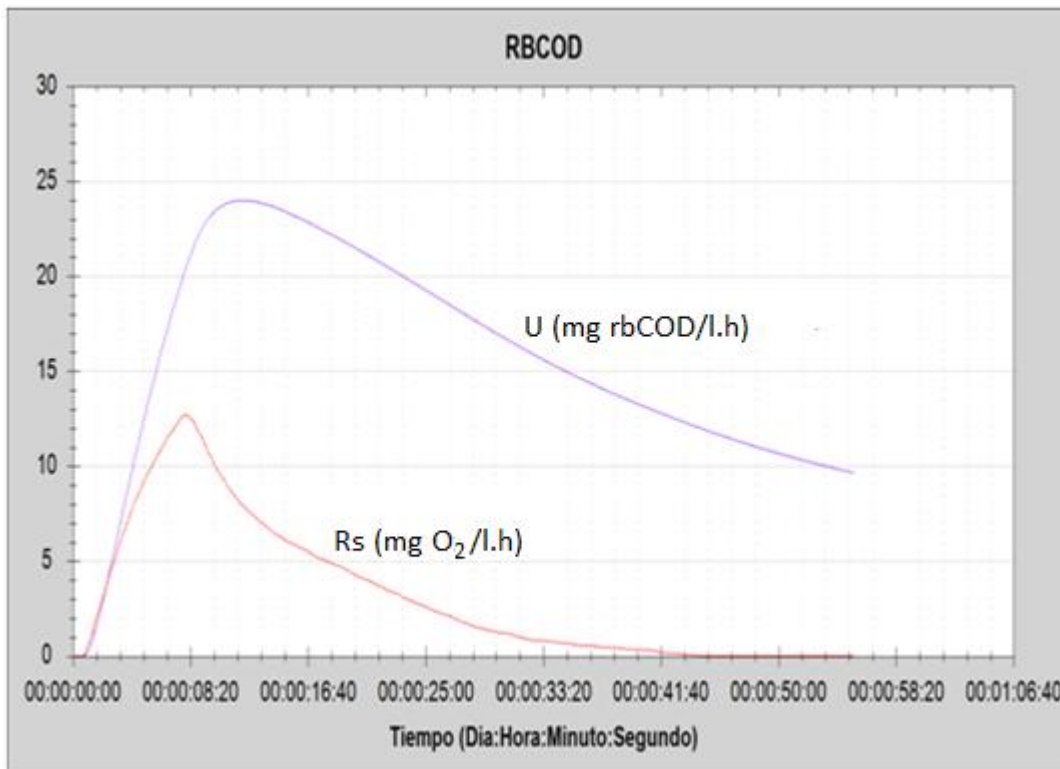
Denitrification optimization

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Conditions for denitrification process

Conditions	
pH	6.5 a 8 (optimal)
BOD/TKN	2.5 to 5
Soluble biodegradable COD/N-NO$_{3.DN}$	≥ 2.83
DO	< 0.3 ppm
Denitrification zone with enough HRT to perform the process	
Without any inhibitor nor toxic compounds	

RBCOD for denitrification and soluble substrate uptake rate

Denitrification needs the readily biodegradable COD for its performance.

With a BM respirometer we can automatically obtain the RBCOD of the influent to the anoxic zone and the uptake rate on which it is being eliminated.

U average is the efective value to be taken into account

Carbonaceous matter utilized in denitrification

Consumed oxygen / Nitrate ratio to denitrify

$$C O \, / \, [N\text{-}NO_{3.DN}] \geq 2.86$$

RBCOD required in the denitrification

$$RBCOD_{DN} \geq 2.86 * [N\text{-}NO_{3.DN}] * (1 - Y_{HD})$$

Total COD required in the denitrification

$$COD_{DN} \geq (COD/rbCOD) * rbCOD_{DN}$$

[N-NO$_{3.DN}$]: Nitrate to denitrify (mg /l N-NO$_3$)

Denitrification rate estimation

$$NUR = [U\,(1 - Y_{HD.O2})\,/\,2{,}86] * K'_O\,/\,(K'_O + OD_{DN})$$

NUR: Denitrification rate (mg /l.h N-NO$_3$)
U: rbCOD uptake rate (mg /l.h DQOs) - Automatically calculated in a BM respirometer together with RBCOD -
$(1 - Y_{HD.O2})$: Consumed oxygen from the soluble COD (rbCOD) destinated to the heterotrophic biomass growing ≈ 0,85 * Y$_H$
K'$_O$: Inhibition coefficient due to oxygen in the anoxic zone = 0,2 (mg/l) - Habitual value –
DO$_{DN}$: Dossolved oxygen in the denitrification zone (mg /l O$_2$)

Sources1: US-EPA, Henze et al 1987
Source2: Illinois Institute of Technology – Andrew Robert Shaw; Heather M. Phillips - Black & Veatch Corporation (WEFTEC10)

Specific denitrification rate estimation

$$SDNR = 0{,}024 * NUR\,/\,X_V$$

SDNR: Specific denitrification rate (mg N-NO$_3$/g VSS.d)

Estimated Specific Denitrification Rates

Temp ° C	Estimated SDNR	Temp ° C	Estimated SDNR
10	0.035	18	0.076
12	0.042	20	0.091
14	0.052	22	0.110
16	0.063	24	0.132

Possible reasons for which the actual specific denitrification rate could be less than the reference table value

1. The process is not operating under one or more correct conditions range.

2. The concentration of the readily biodegradable COD is too low (soluble organic cabonaceous matter)

3. Anoxic zone is not gathering the anoxic condition (oxygen < 0.3 ppm)

4. The hidraulc retention time in the denitrification zone is too short (it has not enough volume)

5. Presence of inhibitor or toxic compounds in the wastewater.

6. Others

COD fractions

Yield coefficient of heterotrophic biomass (I)

Heterotrophic yield coefficient (Y_H) is a fundamental parameter for the automatic COD fractions determinations throughout the R mode
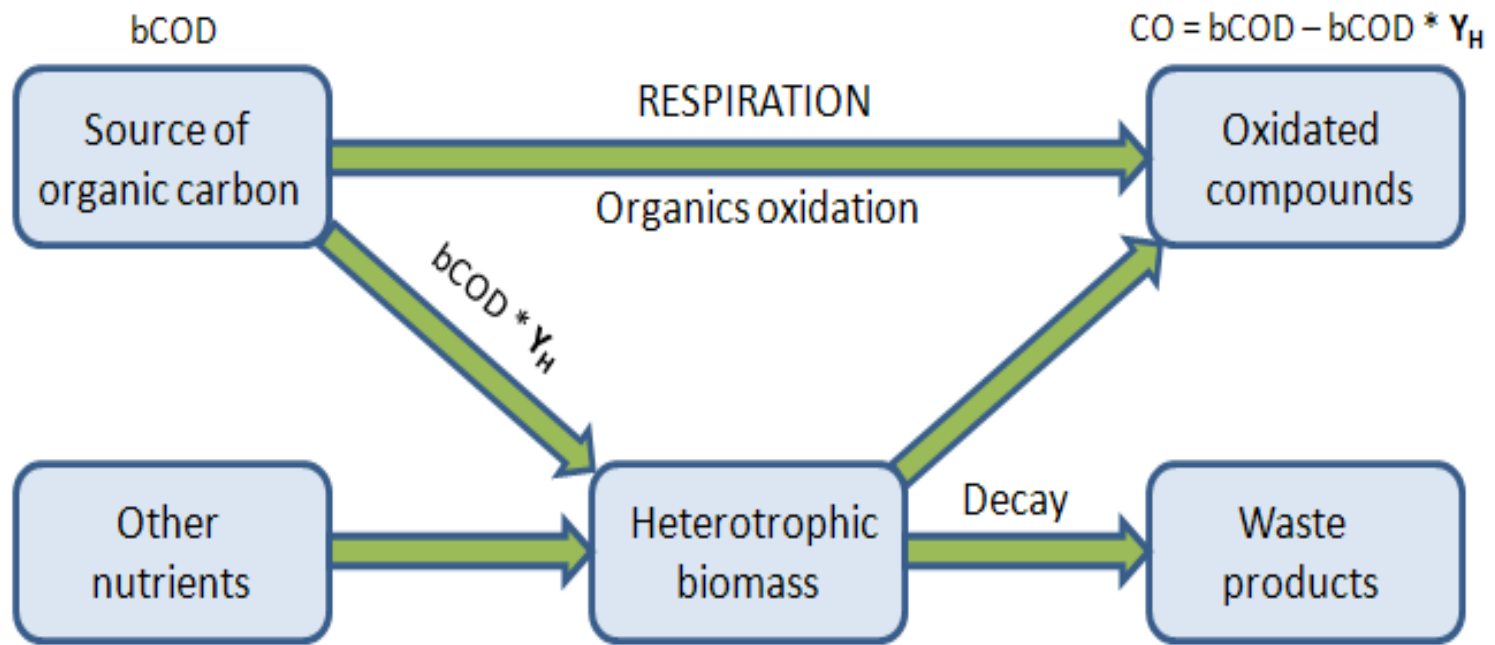
$$\text{bCOD} = CO / (1 - Y_H)$$

Heterotrophic yield coefficient (II)

Yield coefficent is determined by means a single R test, by making use a sodium acetate solution sample of known COD (COD_{ac}). In that test, the BM software will automatically give out the cosumed oxygen result (CO), and then the yield coefficient is calculated from CO and CODac.
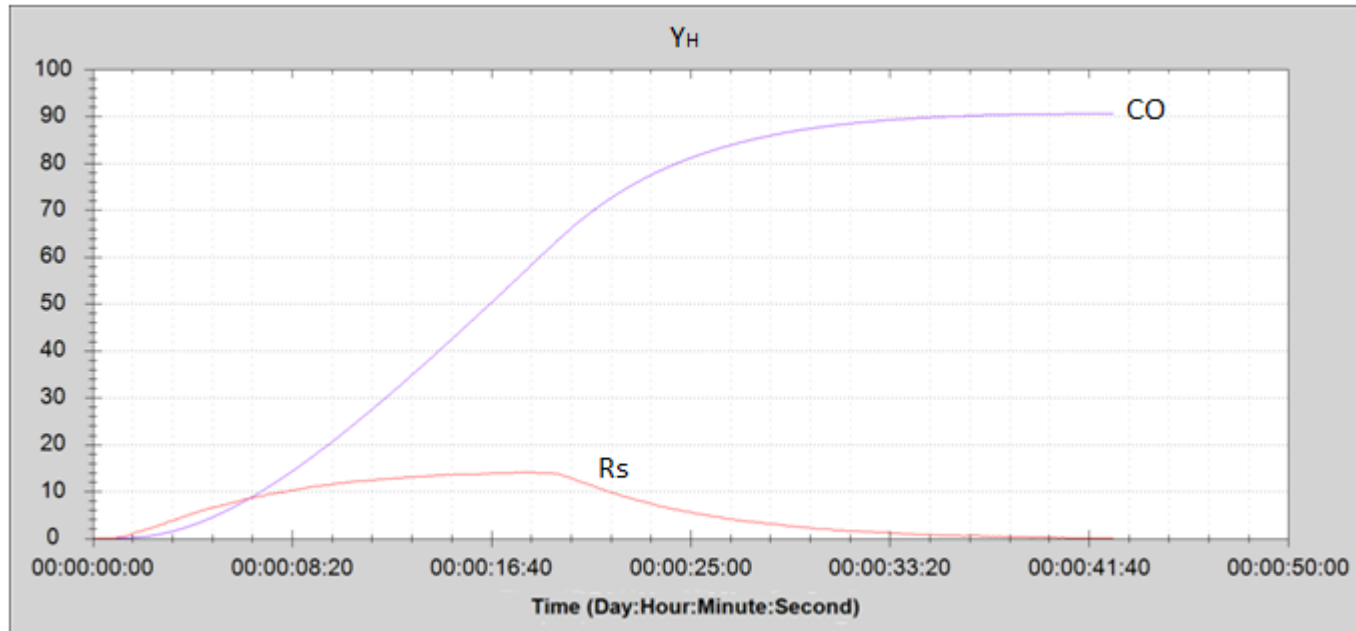
Rs Respirogram for Y_H

$$\mathbf{Y_{H.02}} (O_2/COD) = 1 - CO / COD_{ac}$$

$Y_{H.O2}$: Yield coefficient refrered to O_2 consumption (O_2/COD)
COD_{ac}: COD of the sodium acetate sample = 270 - 320 mg/L)
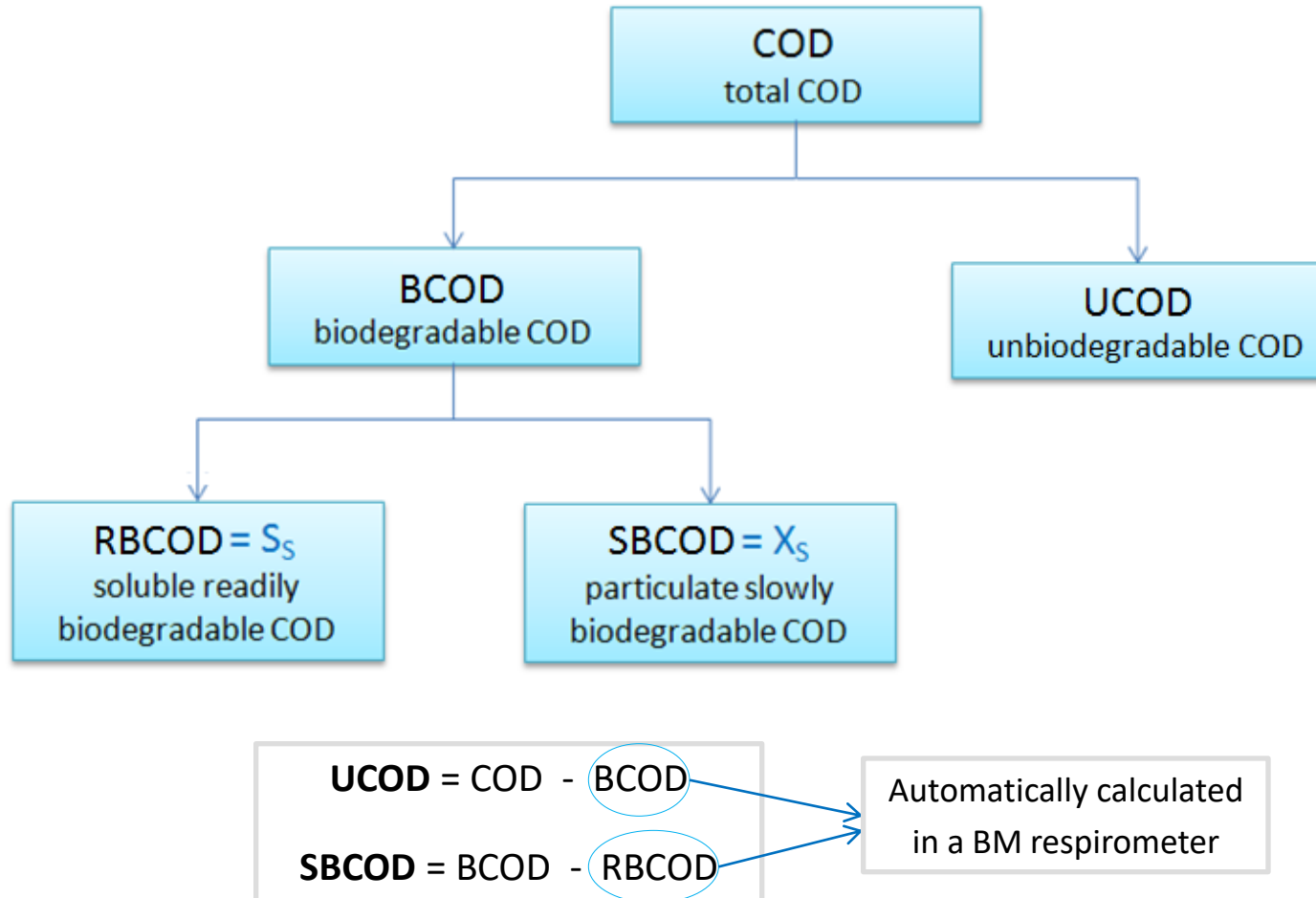
Complete COD fractions

From some test performed on R mode, the BM respirometer can automatically calculate the total biodegradable COD (BCOD), soluble biodegradable COD (S_B), Soluble readily biodegradable COD (S_{SB}) Also, from endogenous sludge, it can be estimated the heterotrophic biomass COD. Then from all these parameters, it is possible to calculate the rest of the main COD fractions.
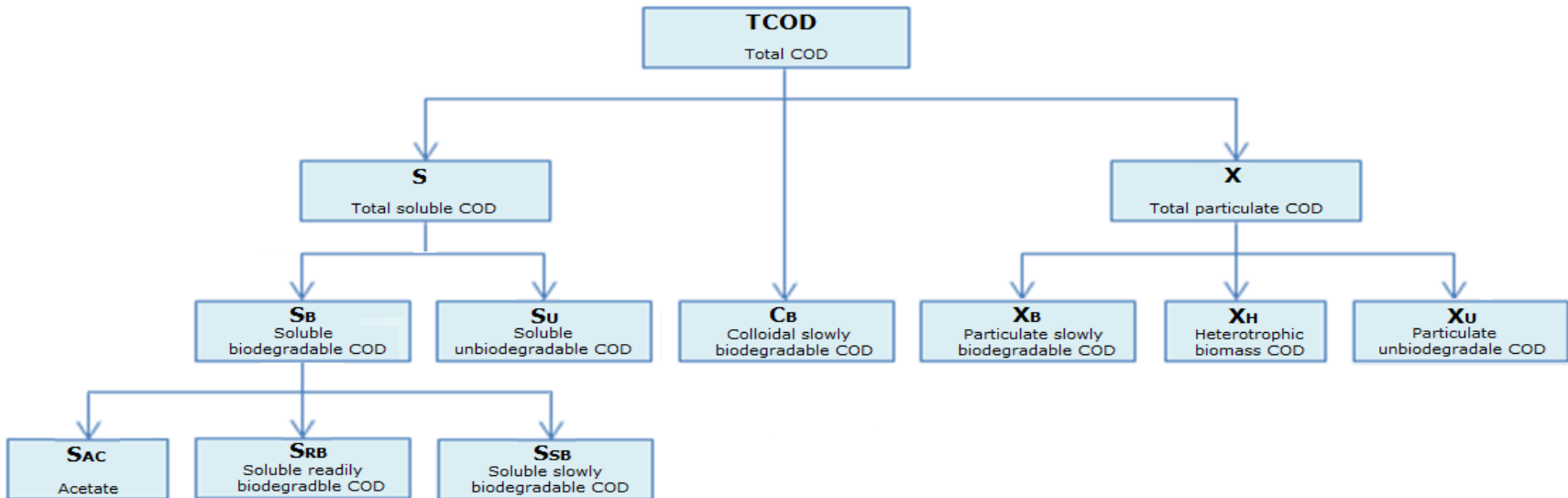
|			
BCOD	Total biodegradable COD	S_{SB}	$S_{SB} = S_B - S_{RB}$
S	Soluble COD	C_B	$C_B = S_B - S_{RB}$
X	Total particulate COD	C_U	$C_U = FFCOD - C_B$
FCOD	1 x filtered COD (1.2 µm)	X_S	$X_S = BCOD - S_{RB}$
FFCOD	2 x filtered COD (1.2-0.45 µm)	X_B	$X_B = BCOD - C_B - S_{RB}$
S_U	$S_U = S - S_{RB}$	X_U	$X_U = X - X_B$

Critical COD fractions

For a wastewater treatment control, most of the times only the critical COD fractions are taken into account.

For that, the BM respirometer will automatically calculate the BCOD and RBCOD, from which the UCOD and SBCOD will also be calculated.

```
                              ┌─────────────────┐
                              │      COD        │
                              │    total COD    │
                              └────────┬────────┘
                  ┌────────────────────┴──────────────────┐
        ┌─────────────────────┐              ┌──────────────────────────┐
        │       BCOD          │              │         UCOD             │
        │  biodegradable COD  │              │  unbiodegradable COD     │
        └──────────┬──────────┘              └──────────────────────────┘
        ┌──────────┴───────────┐
┌────────────────────┐  ┌─────────────────────┐
│   RBCOD = Ss       │  │    SBCOD = Xs       │
│   soluble readily  │  │   particulate slowly│
│  biodegradable COD │  │  biodegradable COD  │
└────────────────────┘  └─────────────────────┘
```

$$\textbf{UCOD} = COD - BCOD$$

$$\textbf{SBCOD} = BCOD - RBCOD$$

Automatically calculated in a BM respirometer

Total biodegradable (BCOD) & Redily biodegradable COD (S$_{SB}$)

The biodegradable COD (from normal ww sample) or r$_{ead}$ily biodegradable COD (from soluble ww sample) is automatically obtained from R test each. In this test is important to take into account that nitrifier biomass must inhibit the nitrifier biomass (in case the process includes nitrification), before the test, by adding the corresponding inhibitor dose to the endogenous sluge (3 – 4 mg ATU / g VSS) and allowing enough time for inhibition.
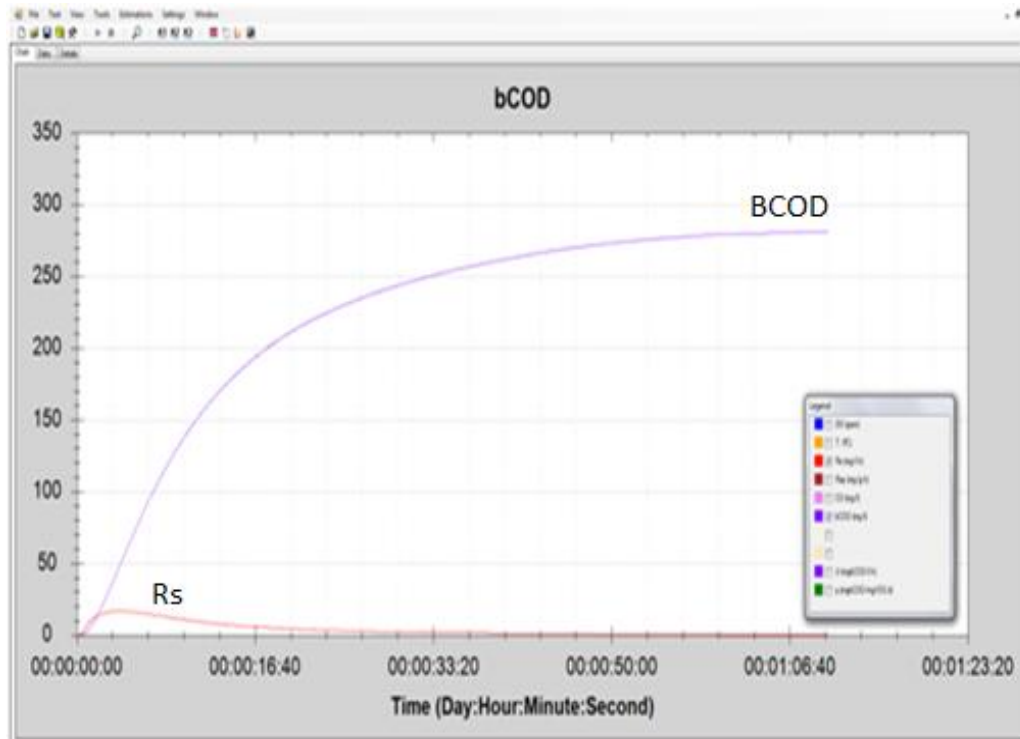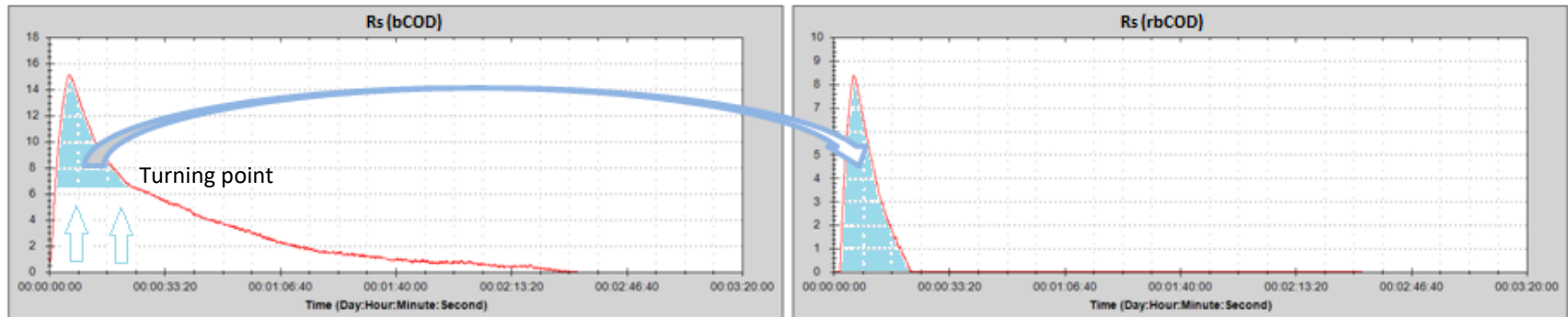

Rs and BCOD Respirograms
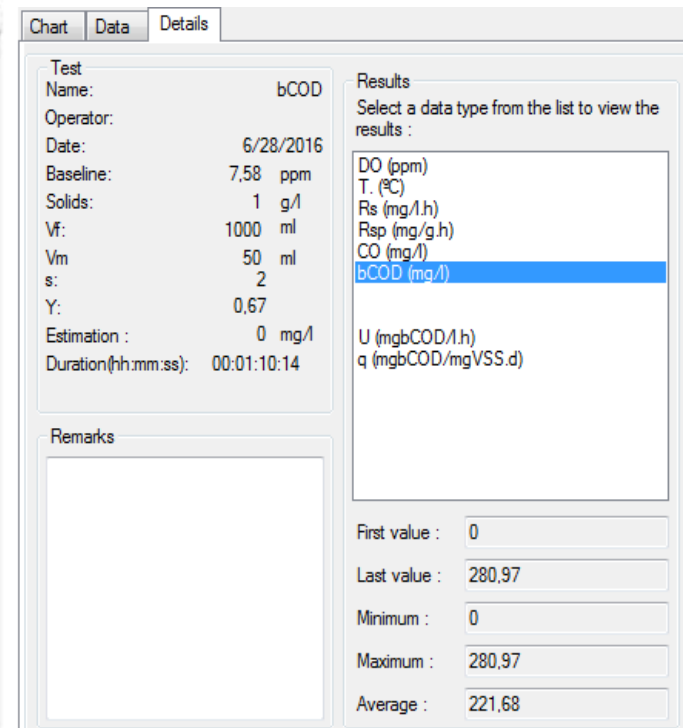
BCOD final result

BCOD and S_{SB} in one single R test

Wherever possible to distinguish the readily biodegradable part in the Rs respirogram for bCOD, in the settings board we can make use of the option "Force Cb" to raise the base-line to the turning point.
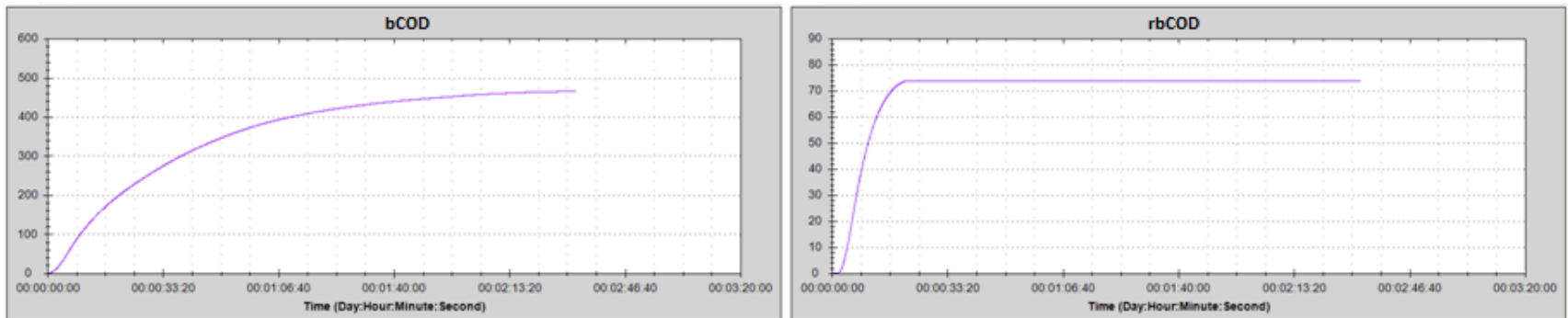
In this way, we can cut the Rs respirogram, convert the turning point level as a new base-line, and automatically create a new respirogram corresponding to the readily biodegradable COD.

Thus, the biodegradable and readily biodegradable COD are figured out from one single test

Rs respirogram for BCOD

Rs respirogram for RBCOD (S_{RB})

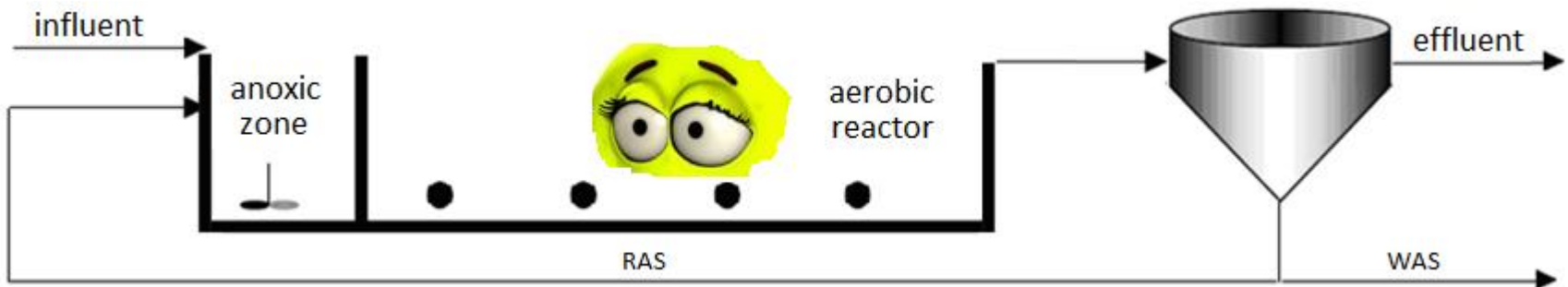BCOD respirogram

RBCOD (S_S) respirogram

Source: Influent fractionation using a respirometric method for the characterization of primary sedimentation
Ellen Vanassche, 2014 - Faculty of Bioscience Engineering – UNIVERSY OF GENT (Belgium)
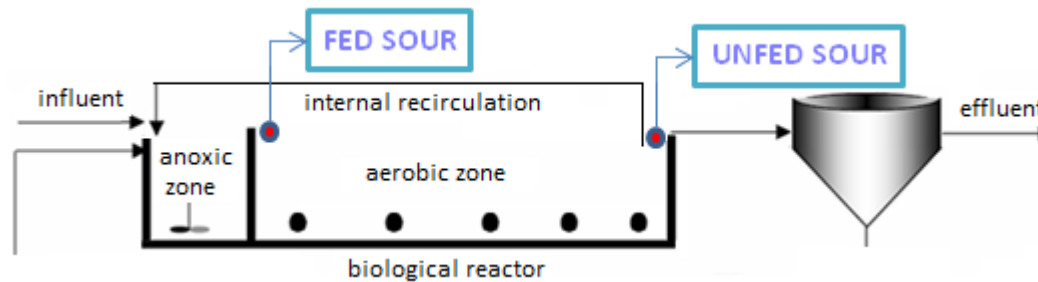
Toxicity

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Two situations for toxicity

1. Toxicity already present in the activated sludge process


2. Toxicity in the influent wastewater or compound

Symptoms for a toxicity already present in the activated sludge process detected by respirometry

Respirometry	Symptom
UNFED SOUR	<< Reference values in the **Table UNFED SOUR vs SRT** (page 9)
FED SOUR / UNFED SOUR	< 1.3
OUR_{end}	<< Reference values in Table OURend vs MLVSS (page 11)

Short term toxicity

The method is based on one R test (using endogenous RAS sludge) where its added a readily biodegradable standard substrate (e.g. sodium acetate) with sufficient concentration to get its maximum respiration and, once this has been achieved, adding sucessive doses of sample to compare the respiration rate in progress with the maximum respiration rate reached in the test (reference)
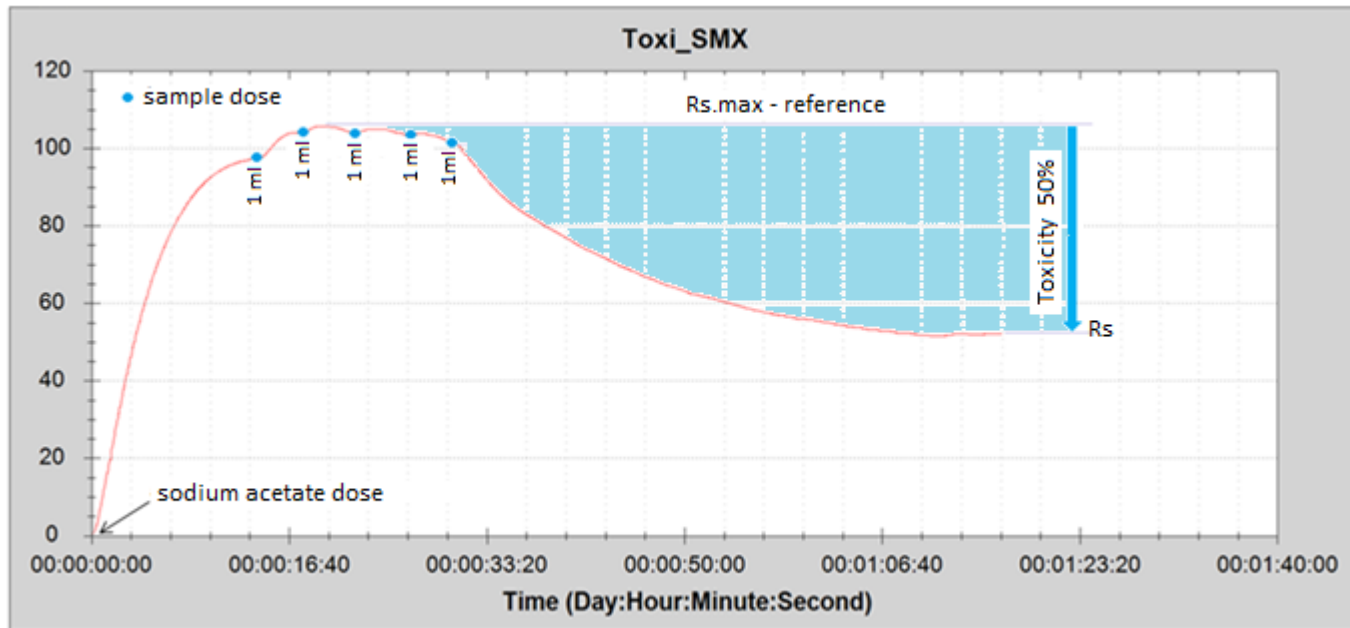
Rs respirogram for short term toxicity

Toxicity (%) = 100 * (Rs.max – Rs) / Rs.max

Additional calculations from short term toxicity

Sample / Sludge ratio for a determined toxicity in the ASP

$V_{m.tox} / V_{RAS}$ = Σ sample doses (ml) / RAS sludge in respirometer reactor (1000 ml)

$V_{m.tox}$: Sample volume from which the toxicity effect is starting
V_{fRAS}: Returned activated sludge volume

Minimum sample flow in the ASP for toxicity

$Q_{i.tox}$ = Q_{RAS} * ($V_{m.tox} / V_{RAS}$)

$Q_{i.tox}$: Minimum influent flow of the sample in the activated sludge process to start toxicity effect (m^3/h)
Q_{RAS} : Returned activated sludge flow (m^3/h)

Minimum F/M in the ASP

F/M_{min} = $Q_{i.tox}$ * BOD / (V * MLVSS)

F/M_{min} : Minimum loading rate (F/M) to start toxicity (BOD /VSS.d)

All the above calculations can also be applied for a determined accepted % of toxicity

Toxicity for global biomass or specific for nitrifiers

This method is based on the preparation of one mixed-liquor with RAS sludge and distilled water (reference) and one o several more mixed-liquor with RAS sludge and sample/s to be analyzed.

Condition for the mixed-liquors: [sample or disitilled water volume / RAS sludge volume] = [Influent flow / RAS flow]

The prepared mixed-liquors are passed into endogenous respiration state to carry out R tests for each one, by adding the same amount of estándar (sodium acetate or ammonium chloride or both) until achieving the maxium respiration rate (Rs.max). The possible toxicity is then assessed by comparing the Rs.max from the reference with the Rs.max corresponding to the samples to analyze.
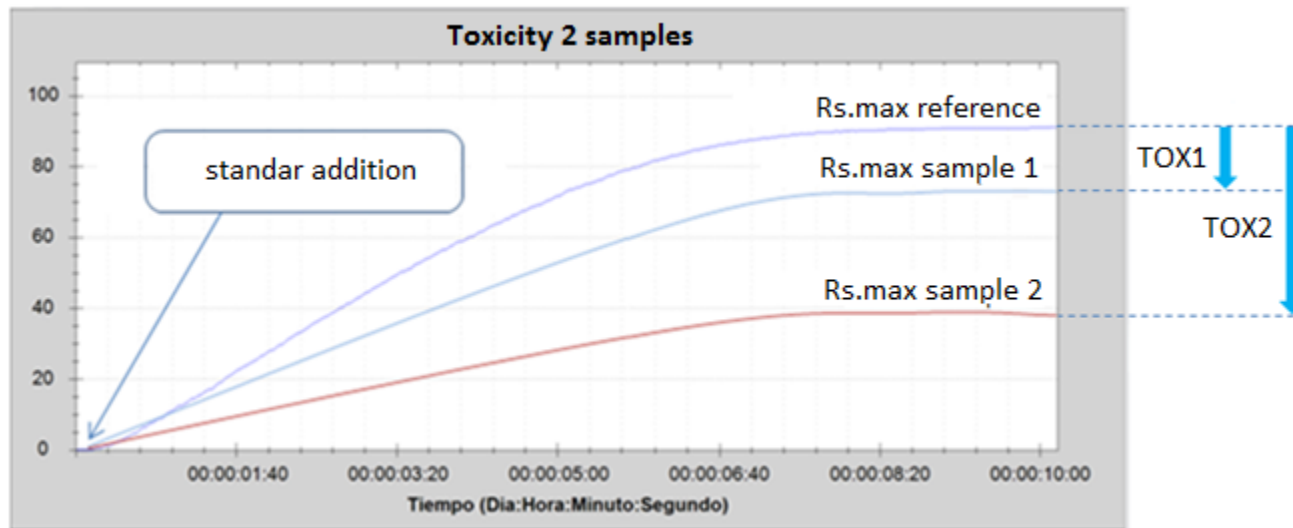
Combined Rs respirograms to asses 2 samples toxicity

Toxicity (%) = 100 * (Rs.max ref. – Rs sample) / Rs.max ref.

This method is valid both to analyze a global toxicity (by adding sodium acetate) or a specific toxicity for nitrification (by adding ammonium chloride)

SURCIS, S.L.

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