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Summer School on Mathematical Control Theory

(3 - 28 September 2001)

Wastewater treatment processes: Why is it important to control them and what are the difficulties?

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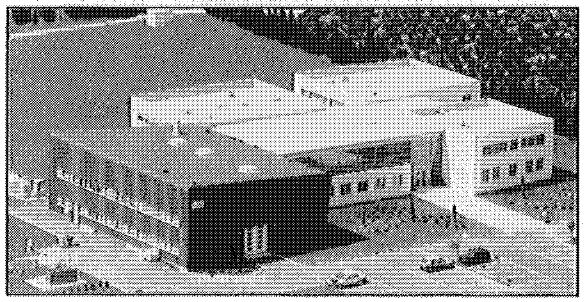
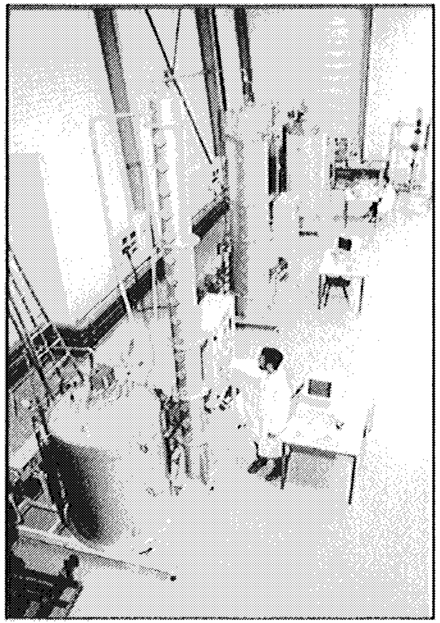




Contents of the Presentation

1) Problem statement

2) Difficulties in Modeling

3) Difficulties in Control

4) An integrated approach

Need for Waste and Wastewater Treatment

- Today, in Europe, **only 43 % of the entire pollution is removed** :
  - ✓ It is better than in the past : 32.5 % in 1981,
  - ✓ But the objective is 65 % in 2002 !...

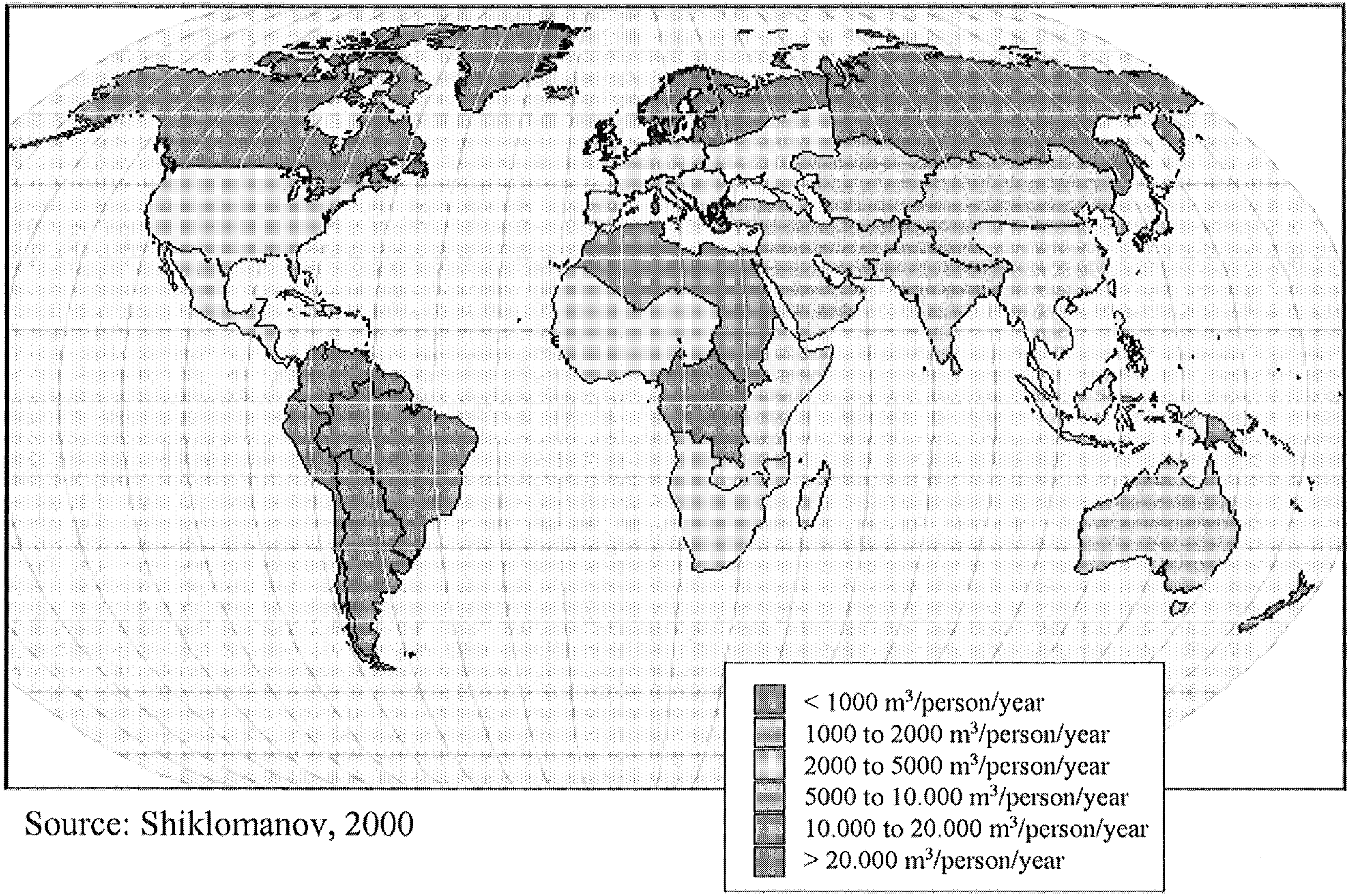
- **Quantities are enormous**, for example :
  - ✓ 40 millions cubic meters of wastewater produced per day in Europe,
  - ✓ 60 billions tons of solid waste produced yearly worldwide, (e.g., the highest point of the US east coast is the NYC landfill deposit, ...)

- **High risks for human health :**
  - ✓ Loss of fertility of living beings (e.g., birds or bees worldwide)
  - ✓ Loss of fertility of soils (i.e., no more plants in 400 years)
  - ✓ Health problems related to the presence of nitrate, heavy metals, pathogens, …

Every year, around 5 million people in developing countries die from waterborne diseases and polluted air !!!

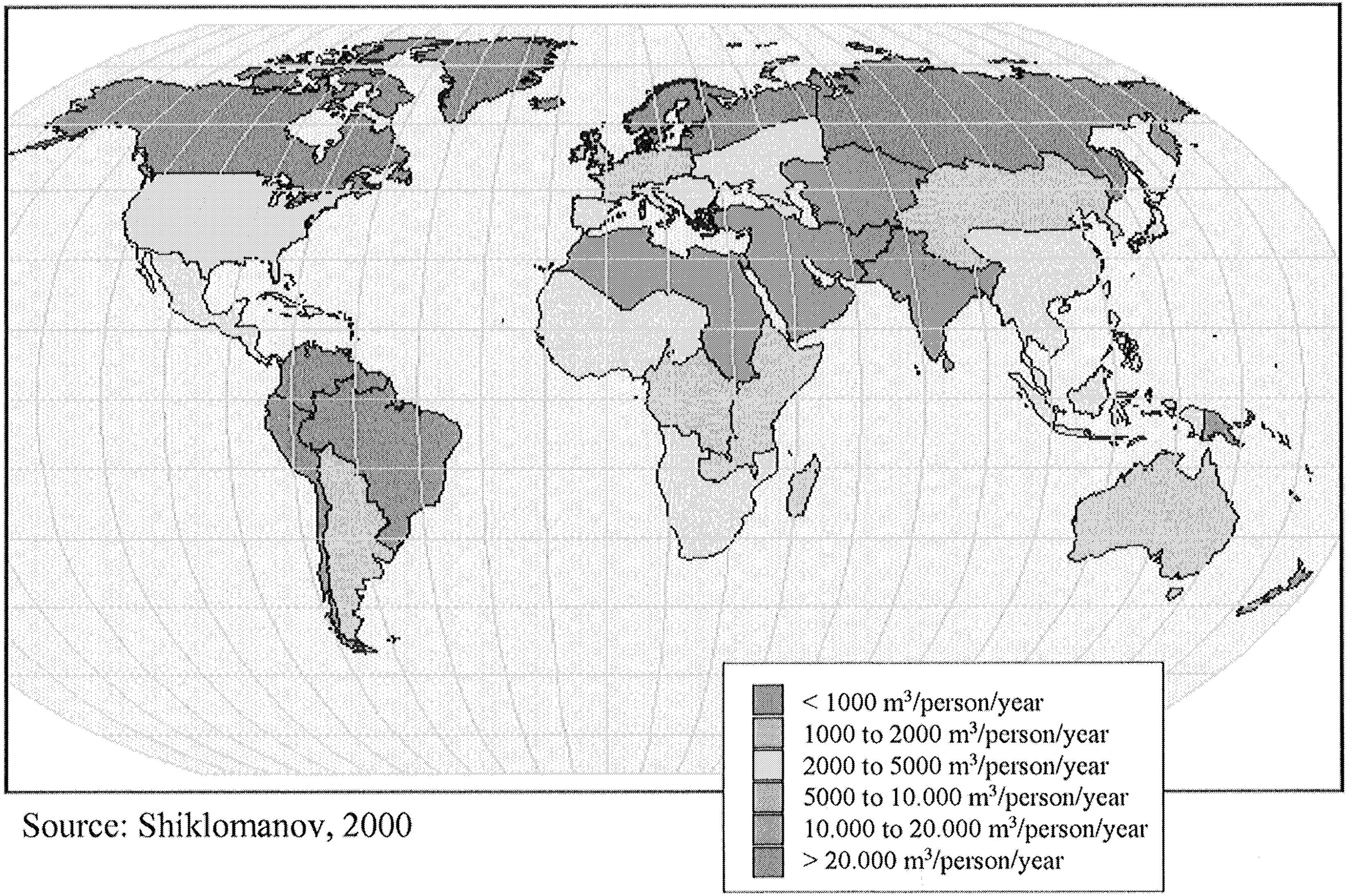
- **Legislation is changing** :
  - ✓ Thresholds (125 mg/l of COD, 10 mg/l of total nitrogen, 2 mg/l of phosphate)
  - ✓ Results within the limits 95 % of the time

Water Availability in 1995



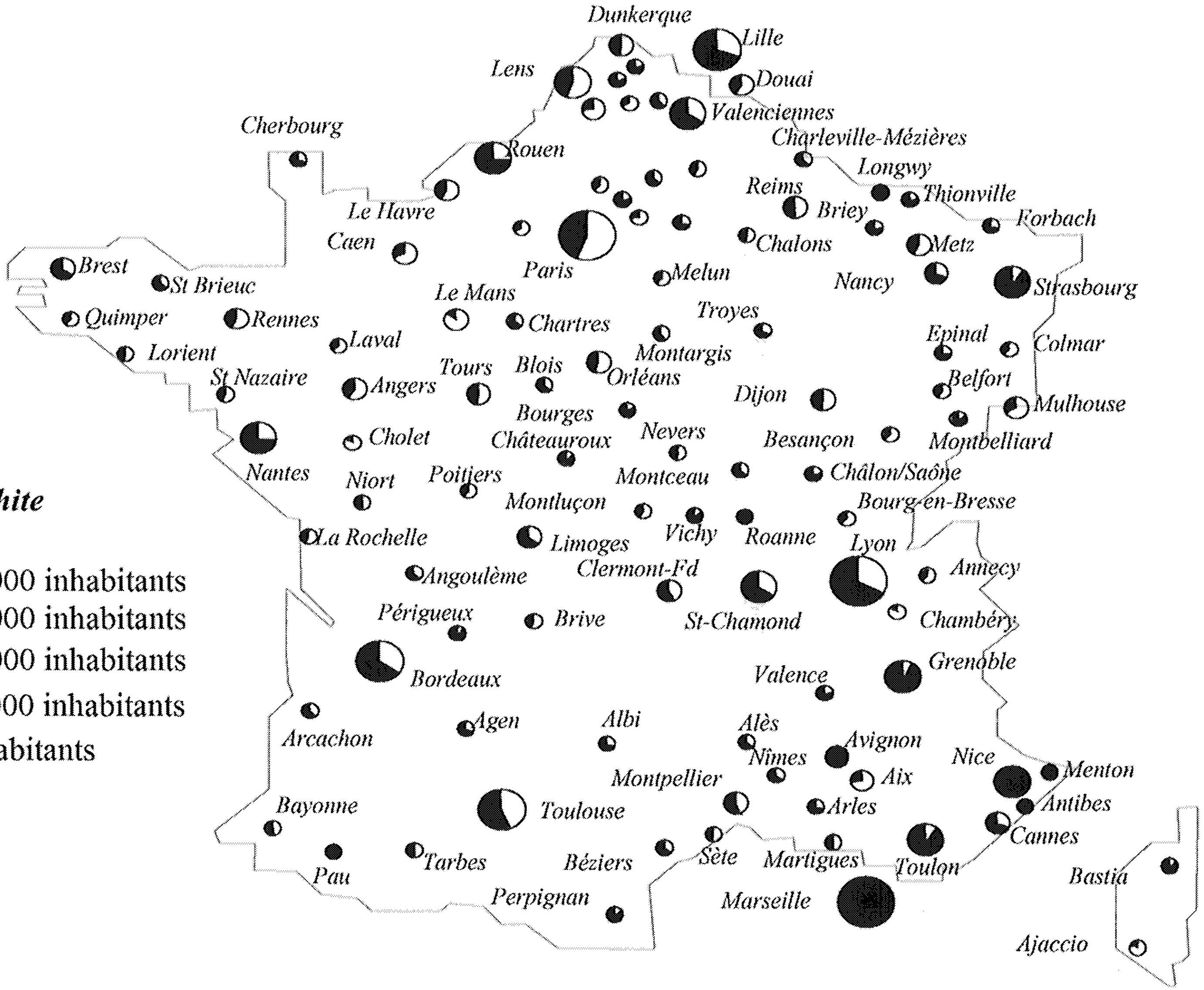
Source: Shiklomanov, 2000

Water Availability Expected in 2025



Source: Shiklomanov, 2000

Performances of urban WWTPs in France



Removal is indicated in white

- From 50.000 to 150.000 inhabitants
- From 150.000 to 300.000 inhabitants
- From 300.000 to 500.000 inhabitants
- From 500.000 to 1.000.000 inhabitants
- More than 1.000.000 inhabitants

As a consequence ...

There is much to be done !...

BUT :

- ✓ Number of aspects ...
- ✓ Number of solutions ...
- ✓ Number of constraints ...

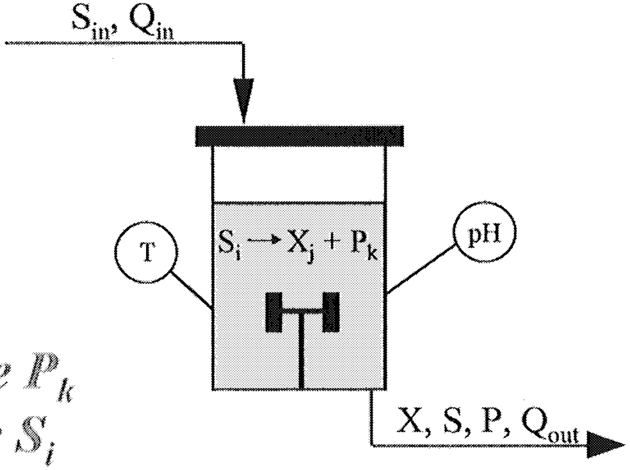
↳ ***Need for pluridisciplinarity !***

Biological Processes : Definition

The growth of the microorganisms (bacteria, yeasts, ...) proceeds by consumption of appropriate nutrients or ***substrates*** (involving carbon, nitrogen, oxygen, ...) provided the environmental conditions (temperature, pH, ...) are favourable. The mass of living microorganisms or living cells is called the ***biomass***.

Associated with cell growth, but often proceeding at a different rate, are the enzyme catalysed reactions in which some reactants are transformed into ***products*** through the catalytic action of intra or extracellular enzymes.

In other words : $S_i \rightarrow X_j + P_k$



Objectives :

For pharmaceutical or food processes : *maximize P_k*

For wastewater treatment processes : *minimize S_i*

Waste and Wastewater Treatment

A biological wastewater treatment processes are one solution among others.

↳ Advantages :

- ✓ Safe for environment,
- ✓ Efficient processes,
- ✓ Economically interesting.

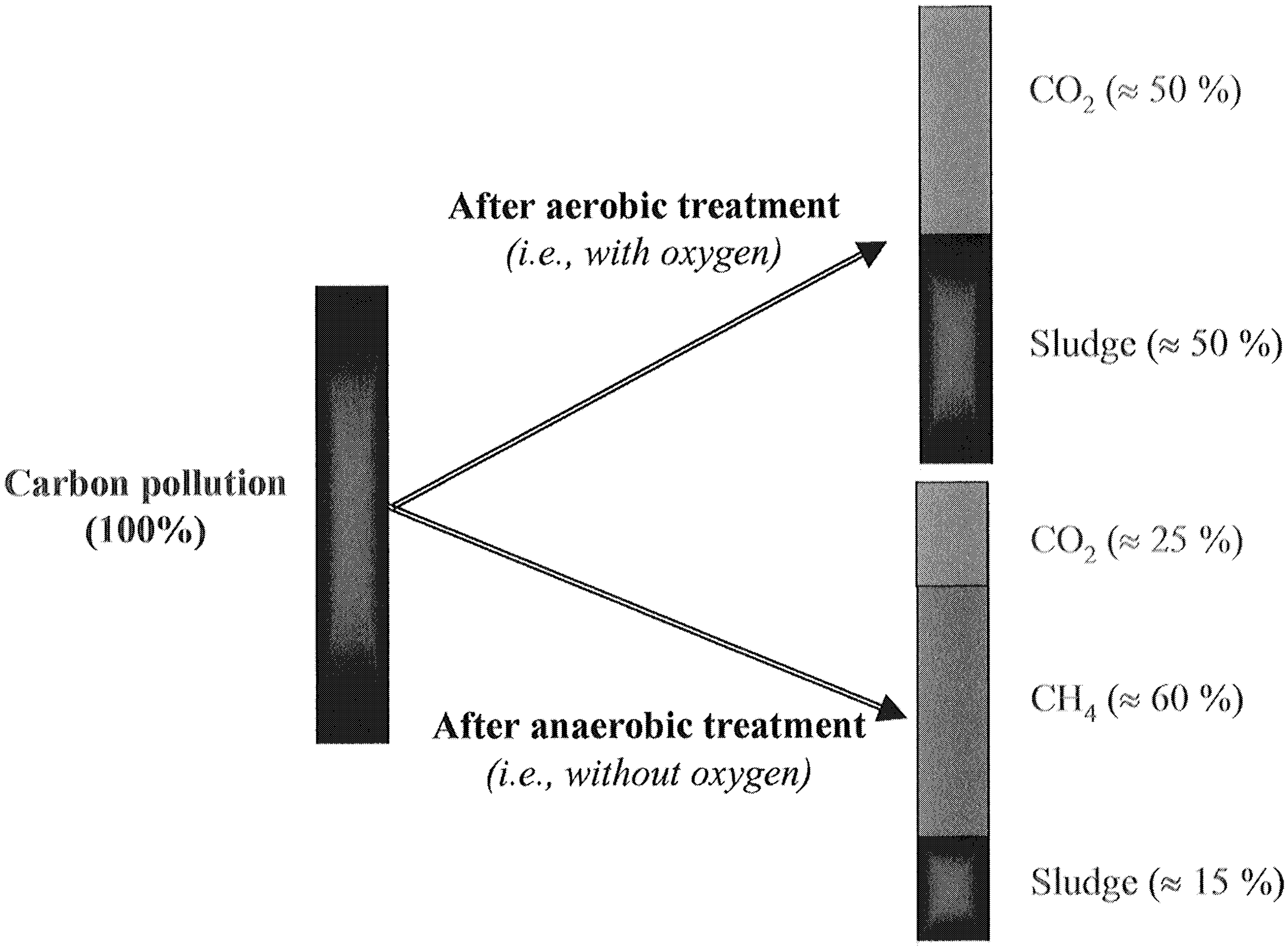
↳ Drawbacks :

- ✓ Very complex pluri-disciplinary systems
- ✓ MIMO non linear systems
- ✓ Difficult to characterize (lack of sensors and actuators)
- ✓ Time delayed systems
- ✓ Time variant systems (non stationary)

Nature of pollutants in water

- Organic matter (OM)
- Suspended solids (SS)
- Nitrogen (ammonia, nitrate,…)
- Phosphorus (phosphates,…)
- Metals (chromium, lead, copper,…)
- Toxic products (cyanide, chlorophenols,…)

Carbon Removal



Carbon pollution (100%)

After aerobic treatment
(i.e., with oxygen)

CO_2 (≈ 50 %)

Sludge (≈ 50 %)

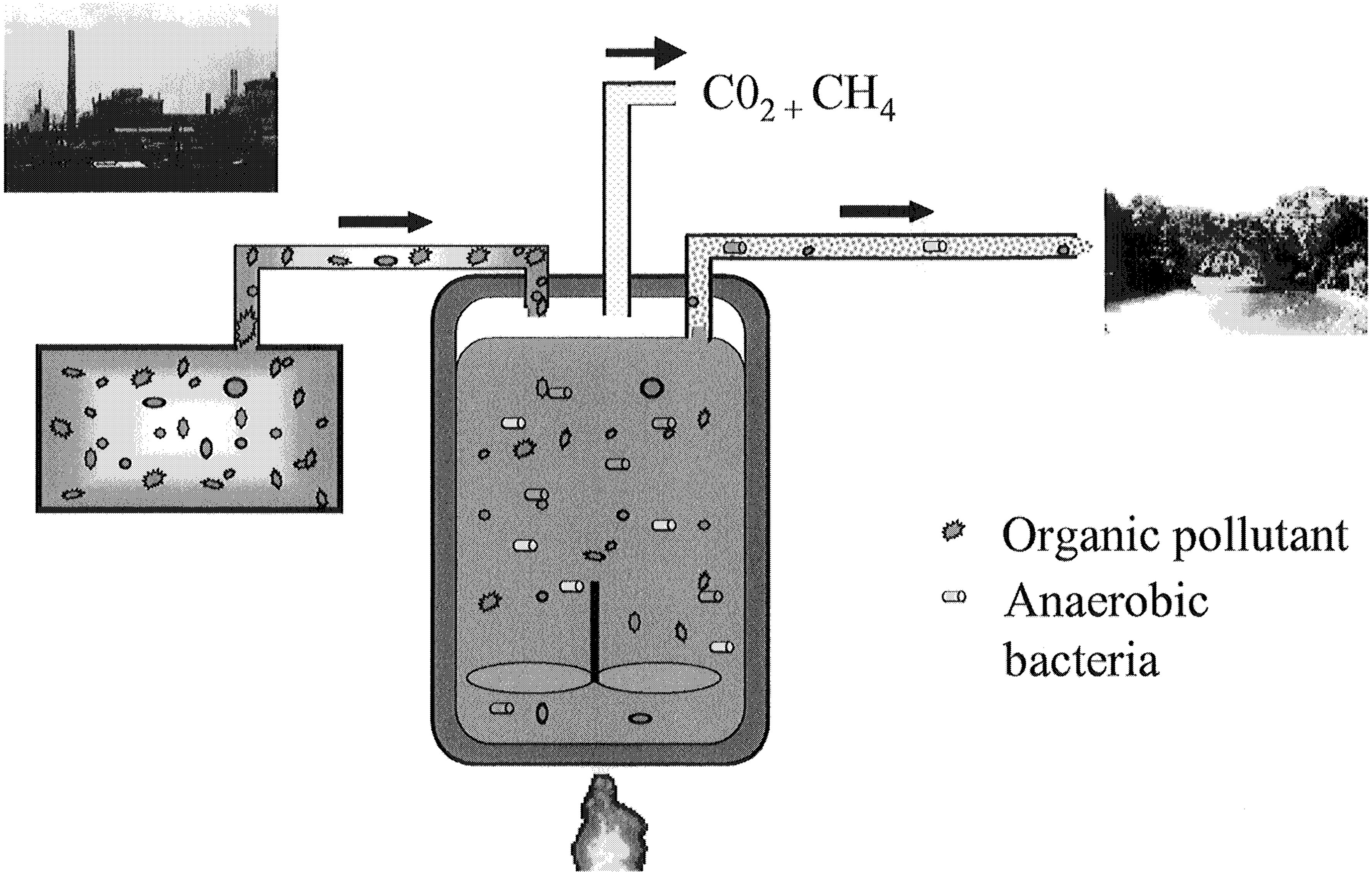
After anaerobic treatment
(i.e., without oxygen)

CO_2 (≈ 25 %)

CH_4 (≈ 60 %)

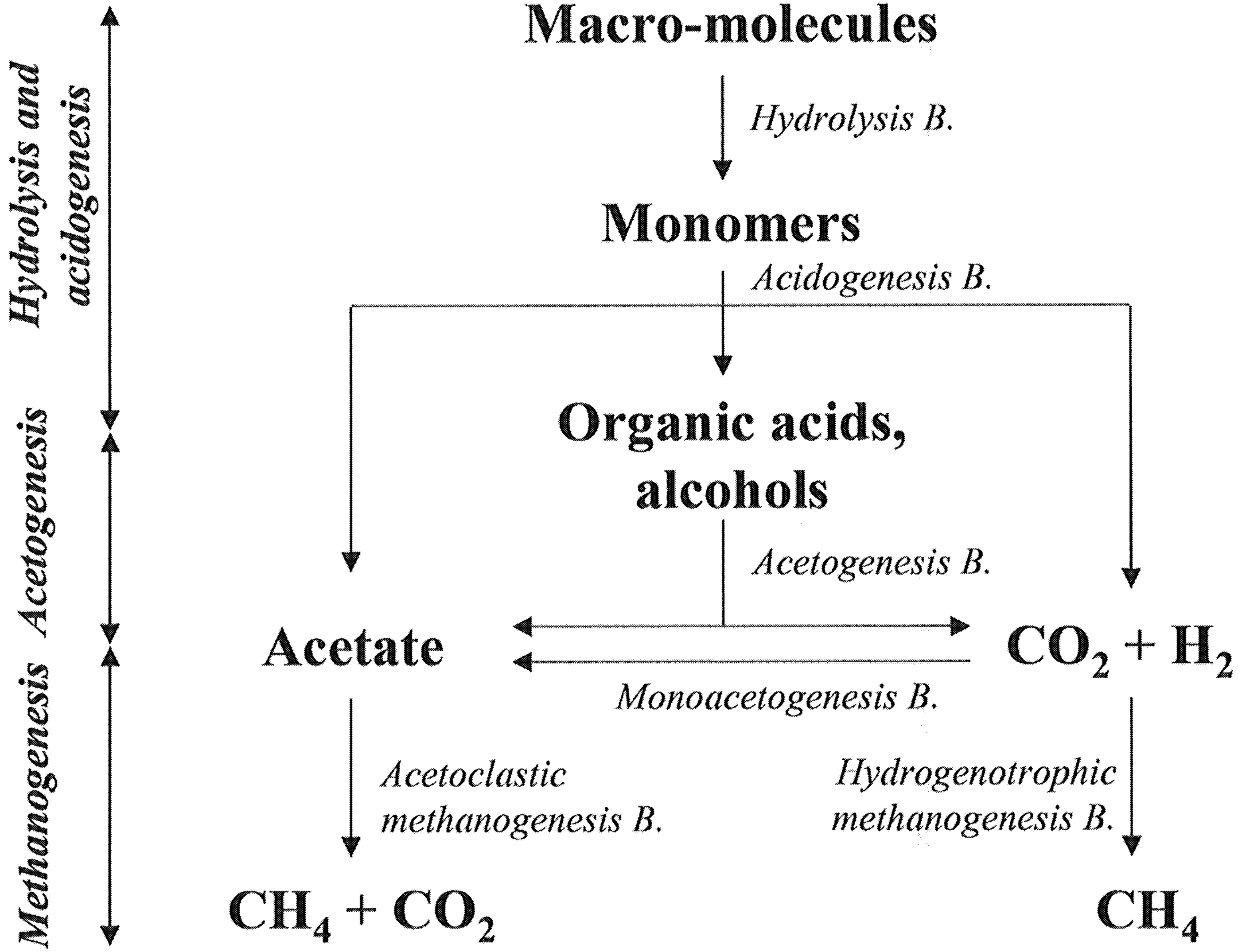
Sludge (≈ 15 %)

Anaerobic Digestion in CSTR


$C0_2 + CH_4$

- ✱ Organic pollutant
- ⊂⊃ Anaerobic bacteria

The Anaerobic Digestion Reaction Scheme



Hydrolysis and acidogenesis

Acetogenesis

Methanogenesis

Macro-molecules

Hydrolysis B.

Monomers

Acidogenesis B.

Organic acids, alcohols

Acetogenesis B.

Acetate

$CO_2 + H_2$

Monoacetogenesis B.

Acetoclastic methanogenesis B.

Hydrogenotrophic methanogenesis B.

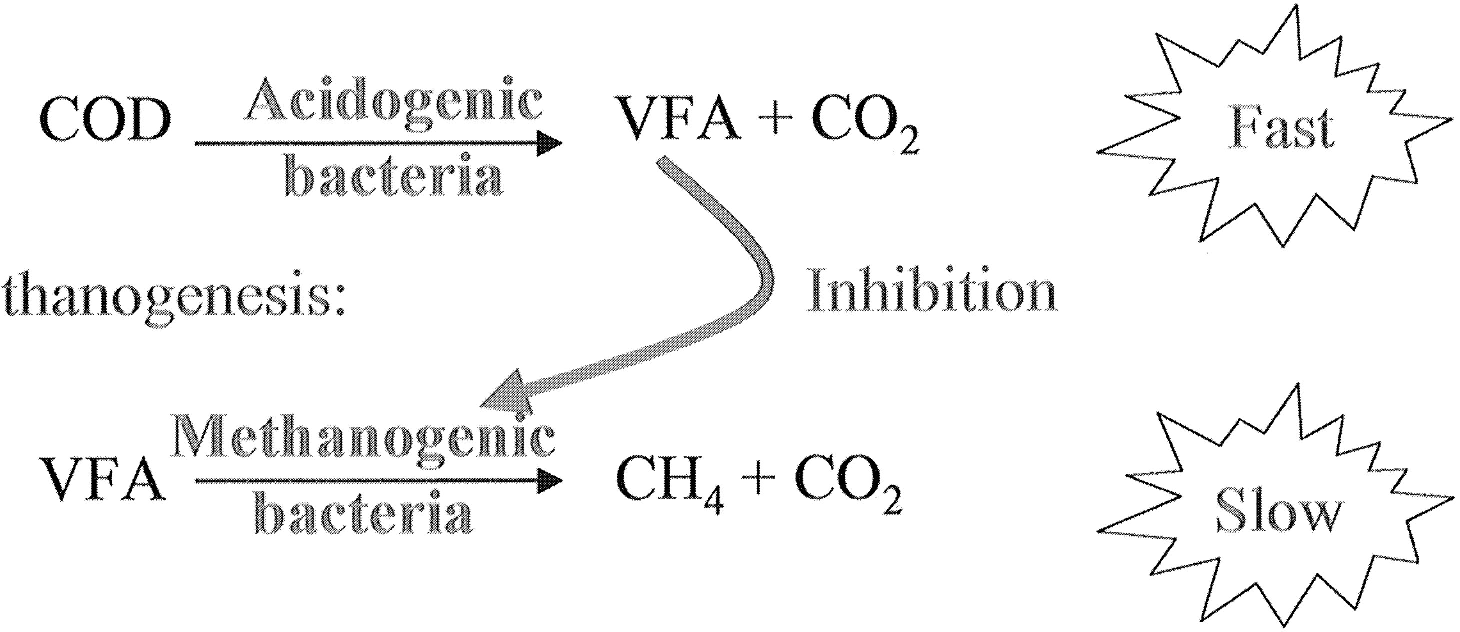
$CH_4 + CO_2$

CH_4

How does it work ?

2 main steps

1) Acidogenesis:



$$\mathrm{COD} \xrightarrow[\text{bacteria}]{\text{Acidogenic}} \mathrm{VFA} + \mathrm{CO_2}$$

Fast

2) Methanogenesis:

Inhibition

$$\mathrm{VFA} \xrightarrow[\text{bacteria}]{\text{Methanogenic}} \mathrm{CH_4} + \mathrm{CO_2}$$

Slow

Nitrogen Pollution

Municipal wastewaters :

- ↳ *30-80 mg/l as organic N (urea)*

Industrial wastewaters :

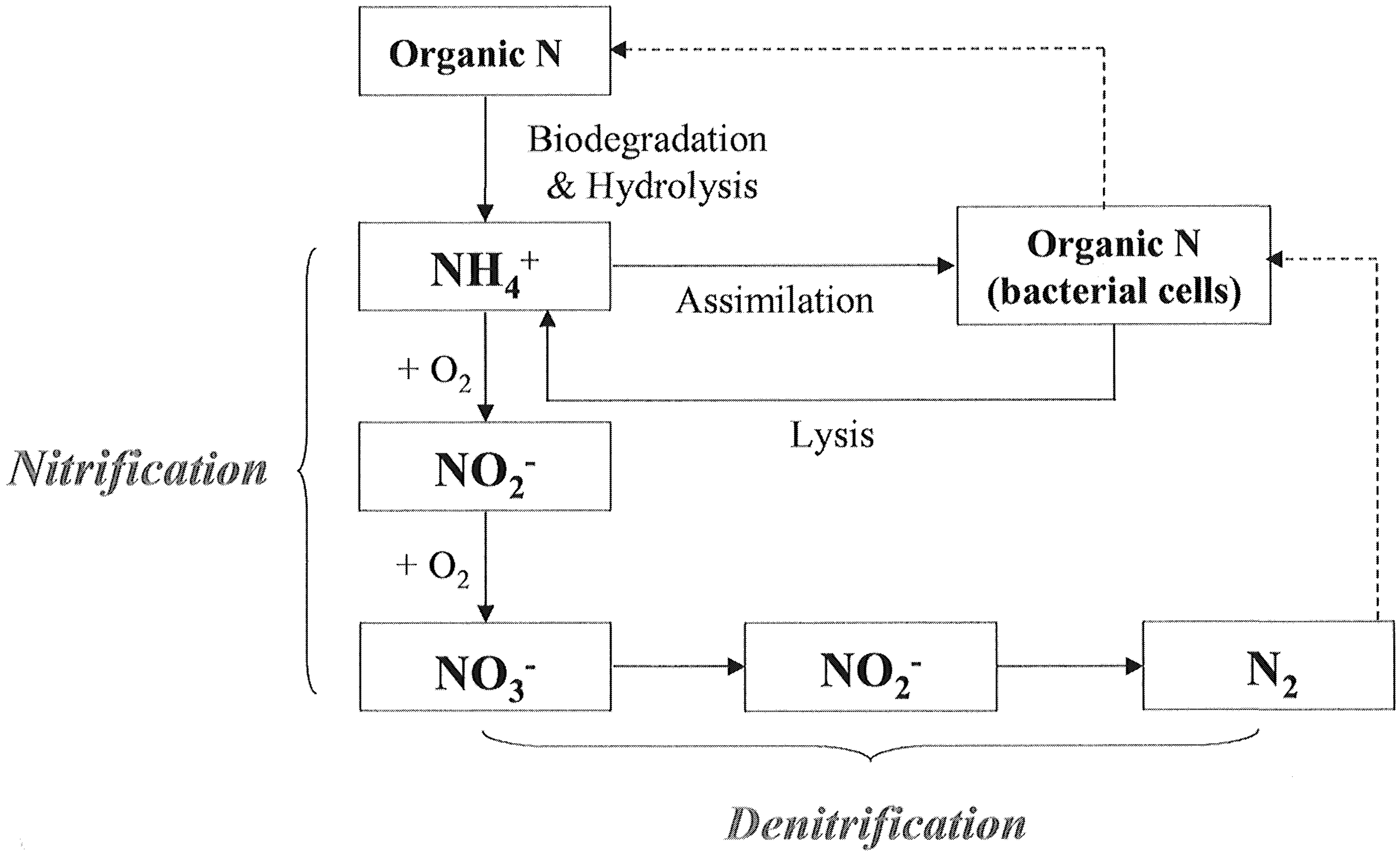
- ↳ *up to several g/l as*
  - ✓ organic N (food industry),
  - ✓ ammonia (cokery, fertilizer, paper,…)
  - ✓ nitrate (explosives, uranium processes, fertilizers)

Problems related to :

- ✓ ***Eutrophication of the receiving water***
- ✓ ***Health : ammonia ⇒ toxic and nitrate ⇒ "methemoglobinemy"***

Nitrogen removal by biological treatment

The Nitrogen Cycle



Organic N

Biodegradation & Hydrolysis

NH_4^+

Assimilation

Organic N (bacterial cells)

Lysis

$+ O_2$

NO_2^-

$+ O_2$

NO_3^-

NO_2^-

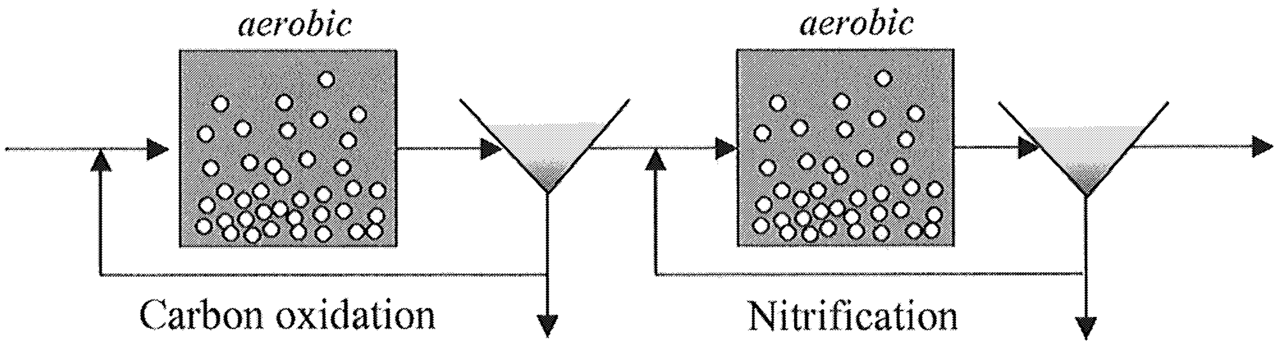
N_2

Nitrification

Denitrification

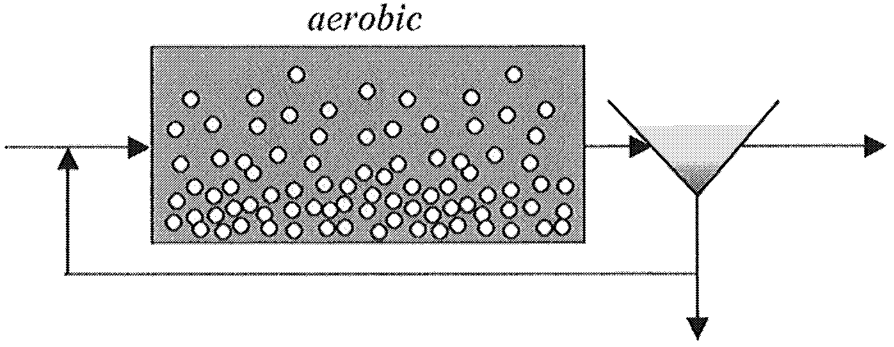
1) Nitrification Processes

Separate-stage nitrification



Single-stage carbon oxidation and nitrification

(high HRT and low loading rate)



2) Denitrification

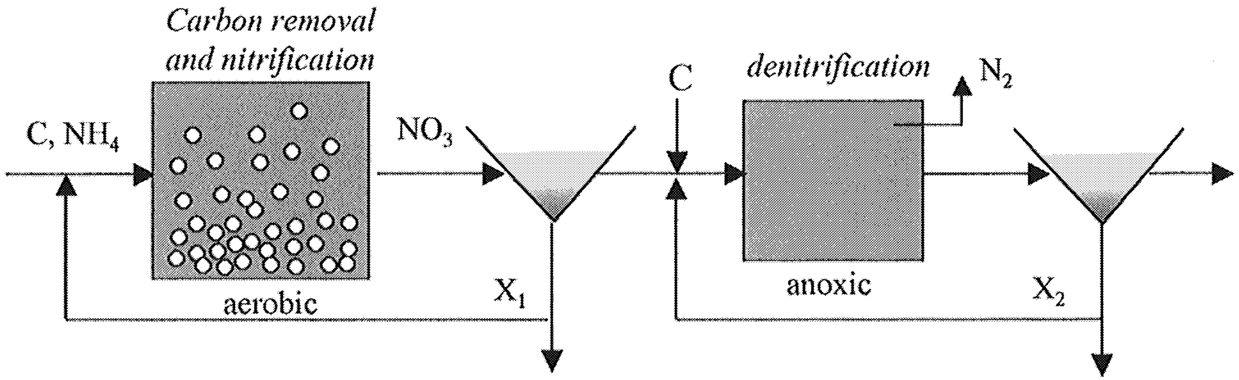
Denitrification is nitrate respiration ***in anoxic conditions*** by a wide range of bacteria using an organic carbon source as an electron donor :

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2$$

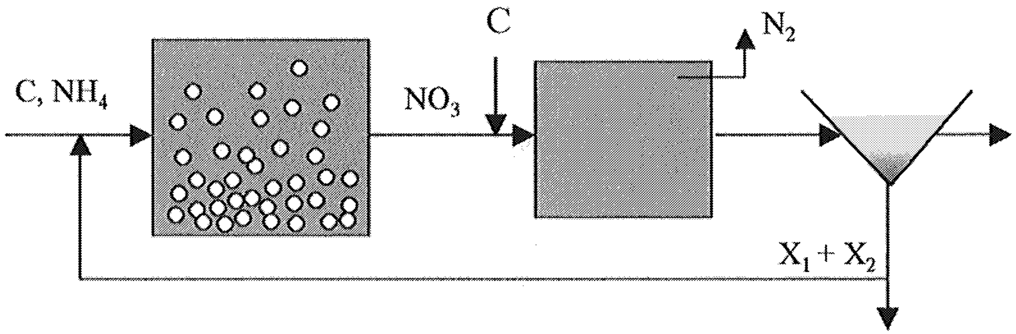
Minimum carbon required : 2.86 mg COD / mg N-NO_3

Carbon and Nitrogen Removal

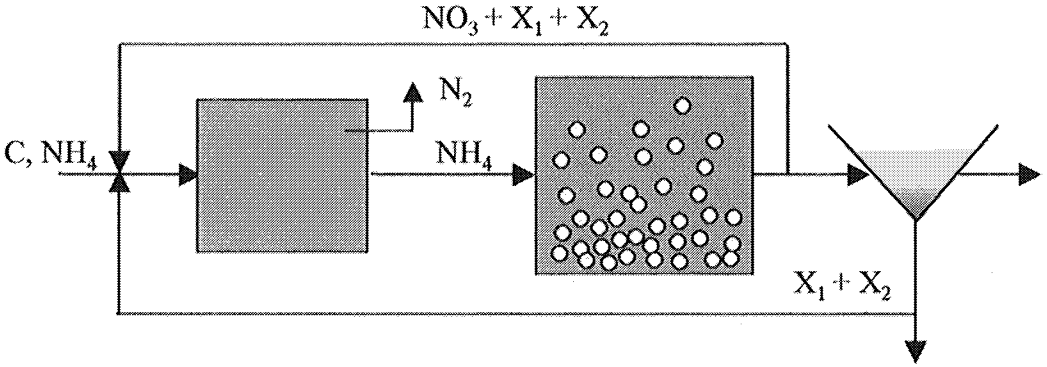
Two-stage biological nitrogen removal



With alternative carbon addition (same biomass)



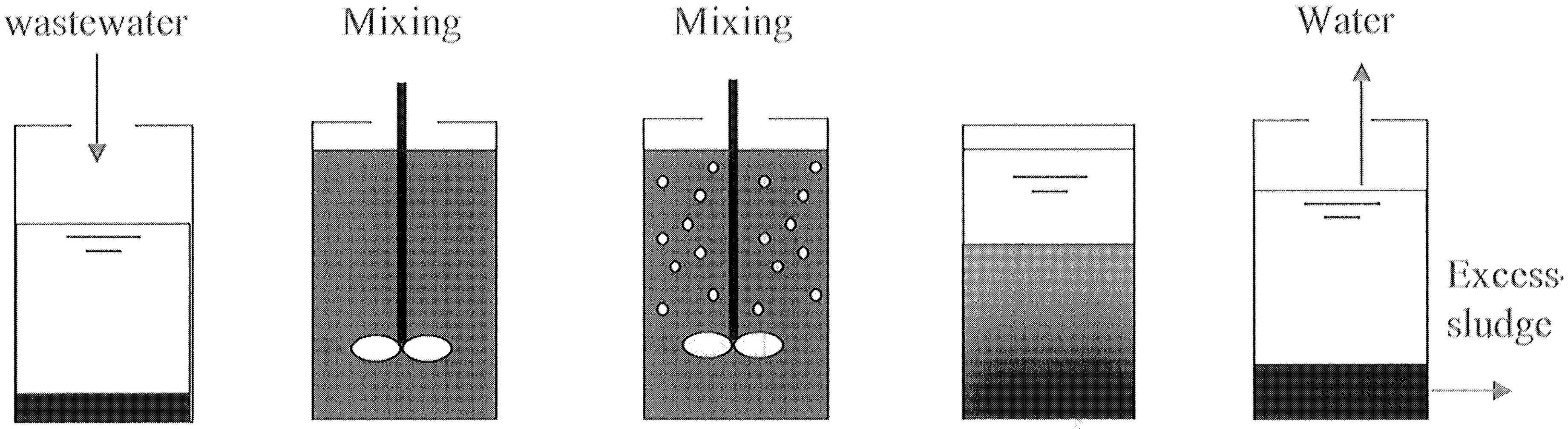
Denitrification using the carbon of the wastewater (*i.e.,* Ludzack-Ettinger configuration)



Biological nitrogen removal in SBR

SBR : Sequencing Batch Reactor

(i.e., separation in time vs. space)



Fill

Denitrification (no aeration)

Nitrification (aeration)

Settle

Draw

Phosphorus Pollution

Municipal wastewaters : 6-25 mg/l as orthophosphate

Industrial wastewaters : Food industry,
Chemical industry,
Surface treatment, …

Problem related to eutrophication of the receiving water

Phosphorus removal :

- ✓ ***Chemical treatment by precipitation***
- ✓ ***Biological treatment***

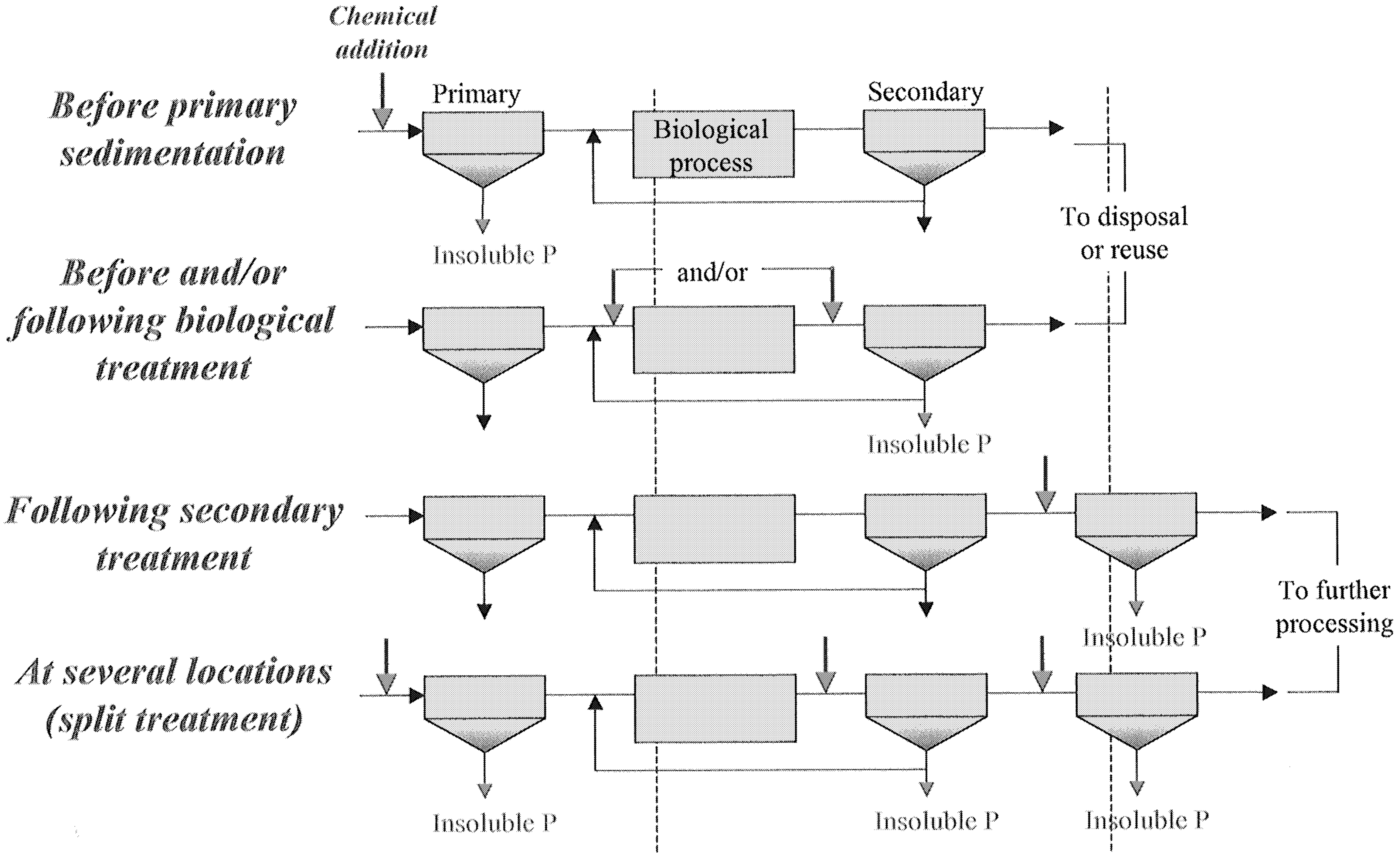
Chemical phosphorus removal

Use of a cation to precipitate phosphate :

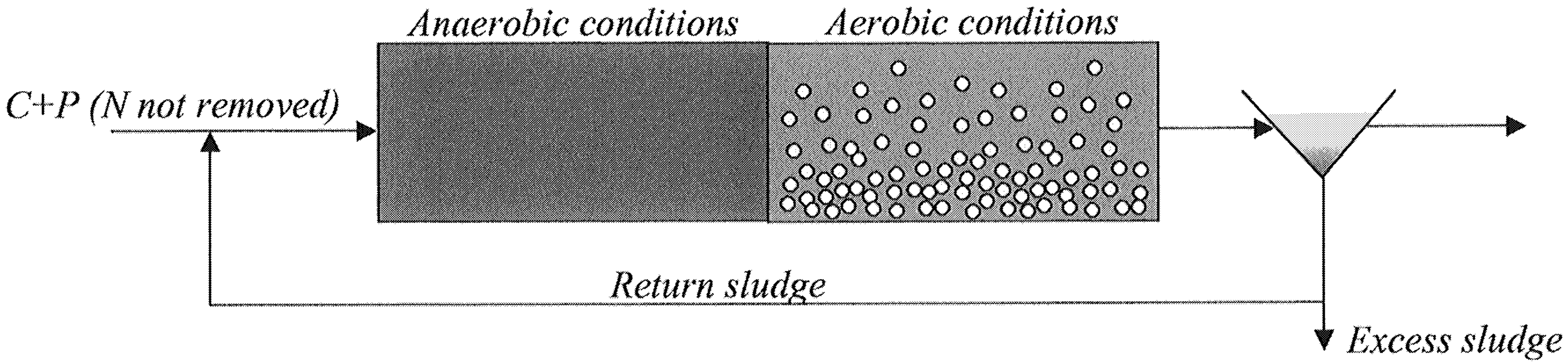
$$M^{3+} + PO_4^{3-} \rightarrow MPO_4$$

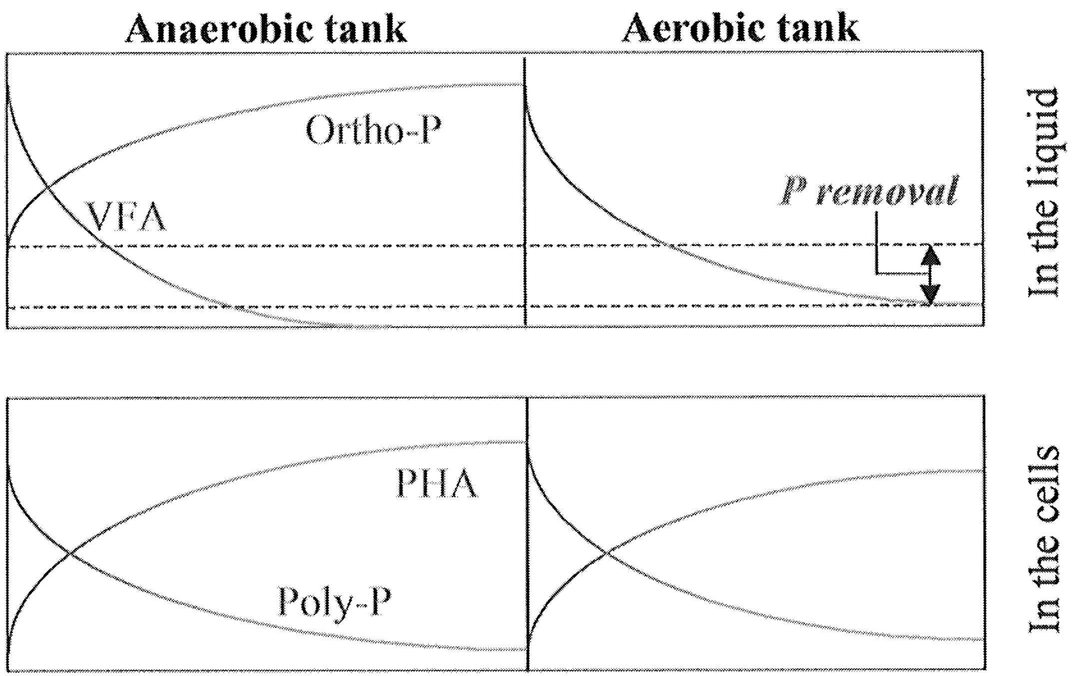
Chemicals used :	aluminium salts	(→ $Al(OH)_3 + AlPO_4$)
	iron salts	(→ $FePO_4 + Fe(OH)_3$)
	lime	(→ $Ca_5(PO_4)_3OH + CaCO_3$)

Chemical phosphorus removal



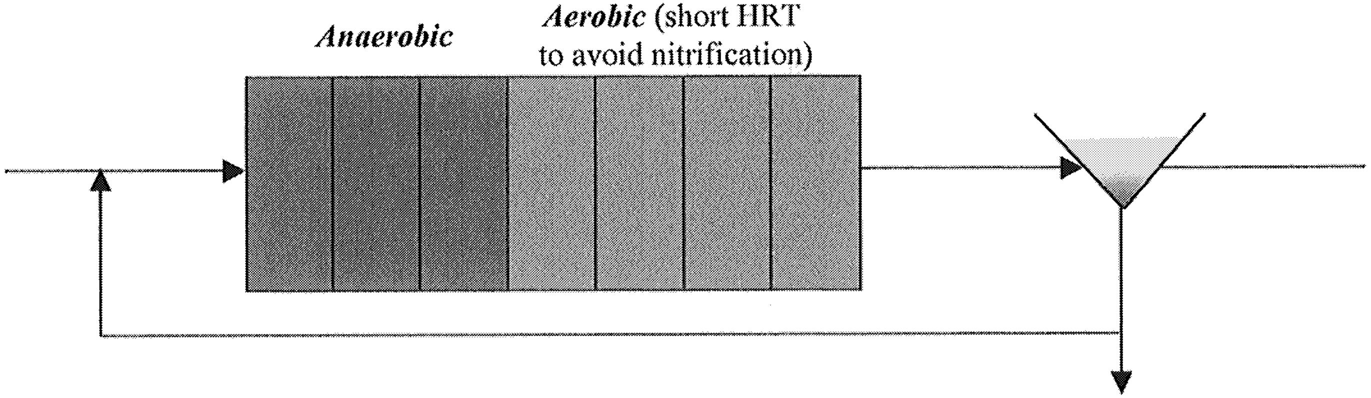
Biological Phosphorus Removal





Biological phosphorus removal

A/O process

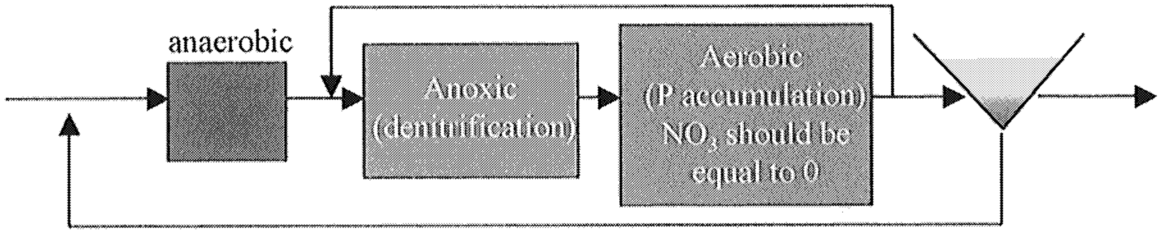


Anaerobic

Aerobic (short HRT to avoid nitrification)

Combined biological carbon, nitrogen and phosphorus removal

Modified Phoredox

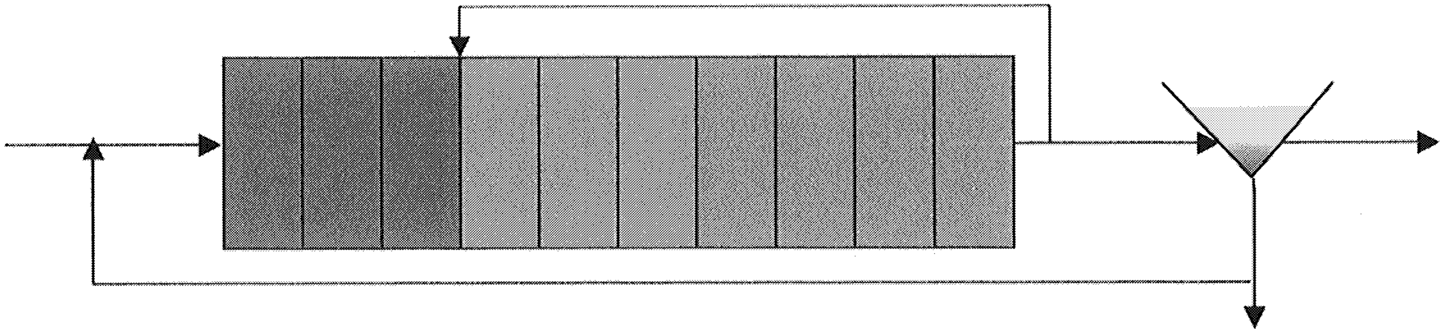


anaerobic

Anoxic (denitrification)

Aerobic (P accumulation) NO_3 should be equal to 0

A_2/O



About Biological Treatment ...

➩ Biological carbon and nitrogen removal is widely adopted.

➩ Phosphorus removal by chemical precipitation is well established and reliable. Biological P-removal processes seem less stable, partly because of a lack of knowledge.

➩ Actual development of high rate processes :

- Biofilm reactors : biofilters, fluidized bed reactors,
- Membrane bioreactors.

➩ Need of monitoring and control, especially for P removal processes.

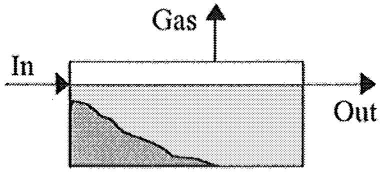
➩ Actual problems to be solved :

- Sludge management,
- Availability of carbon sources for denitrification and enhanced biological phosphorus removal.

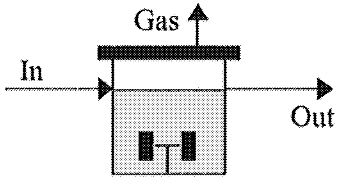
Characteristics of WWT Processes

First generation

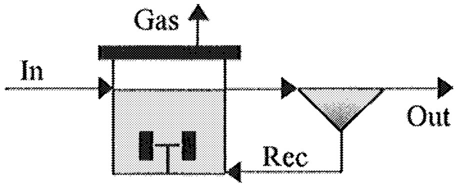
Lagoon



Continuous Stirred Tank Reactor

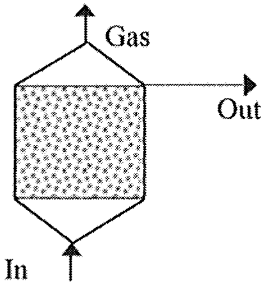


Contact Reactor

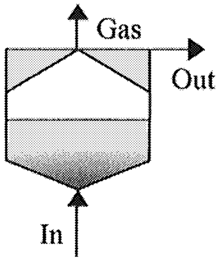


Second generation

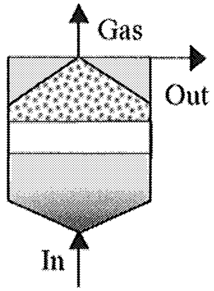
Fixed Bed



UASB

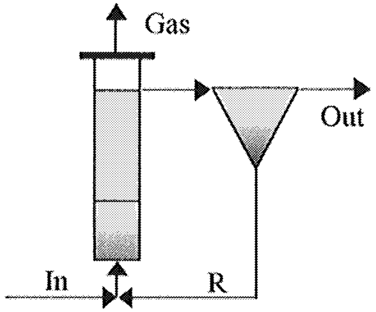


UBF

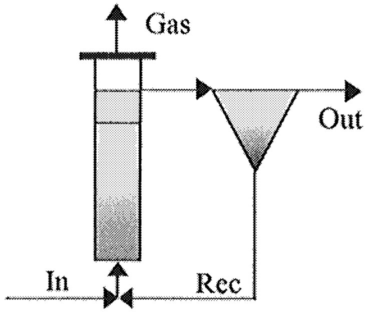


Thrid generation

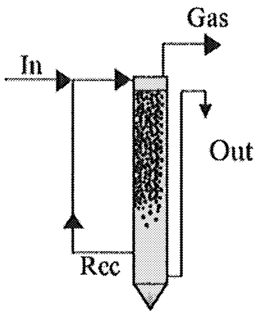
Expanded Bed



Fluidized Bed

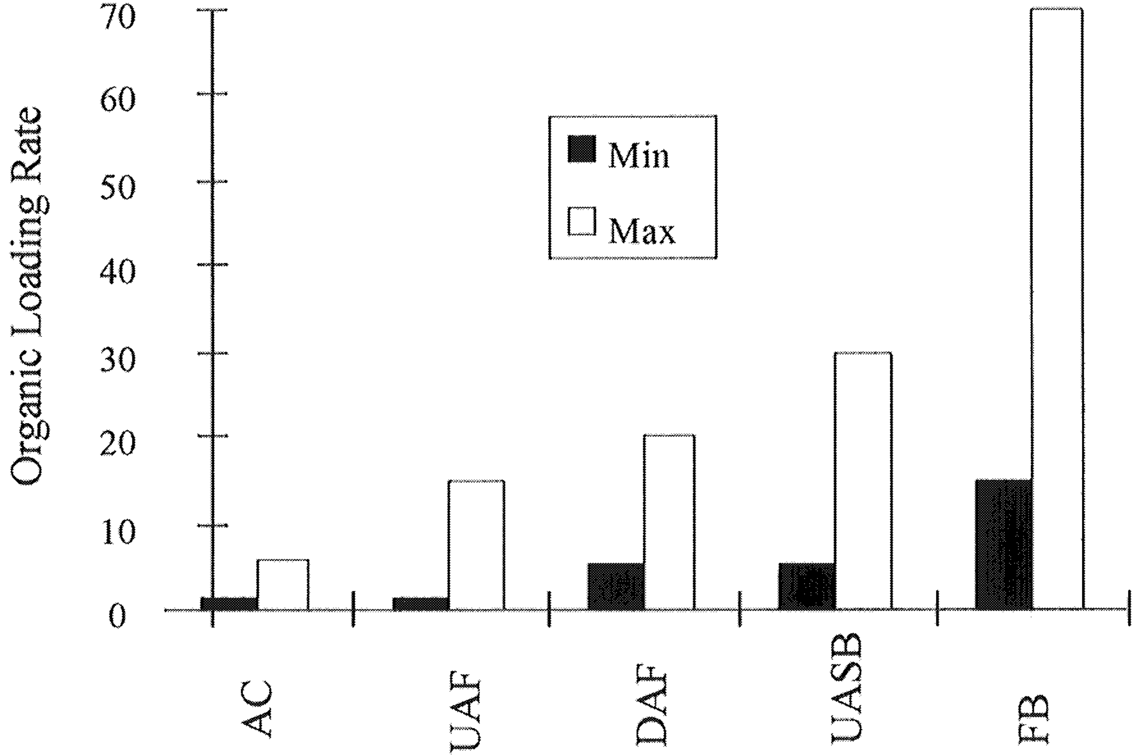


Inverse Fluidized Bed



Performances of Anaerobic Digestion Processes (from the literature)

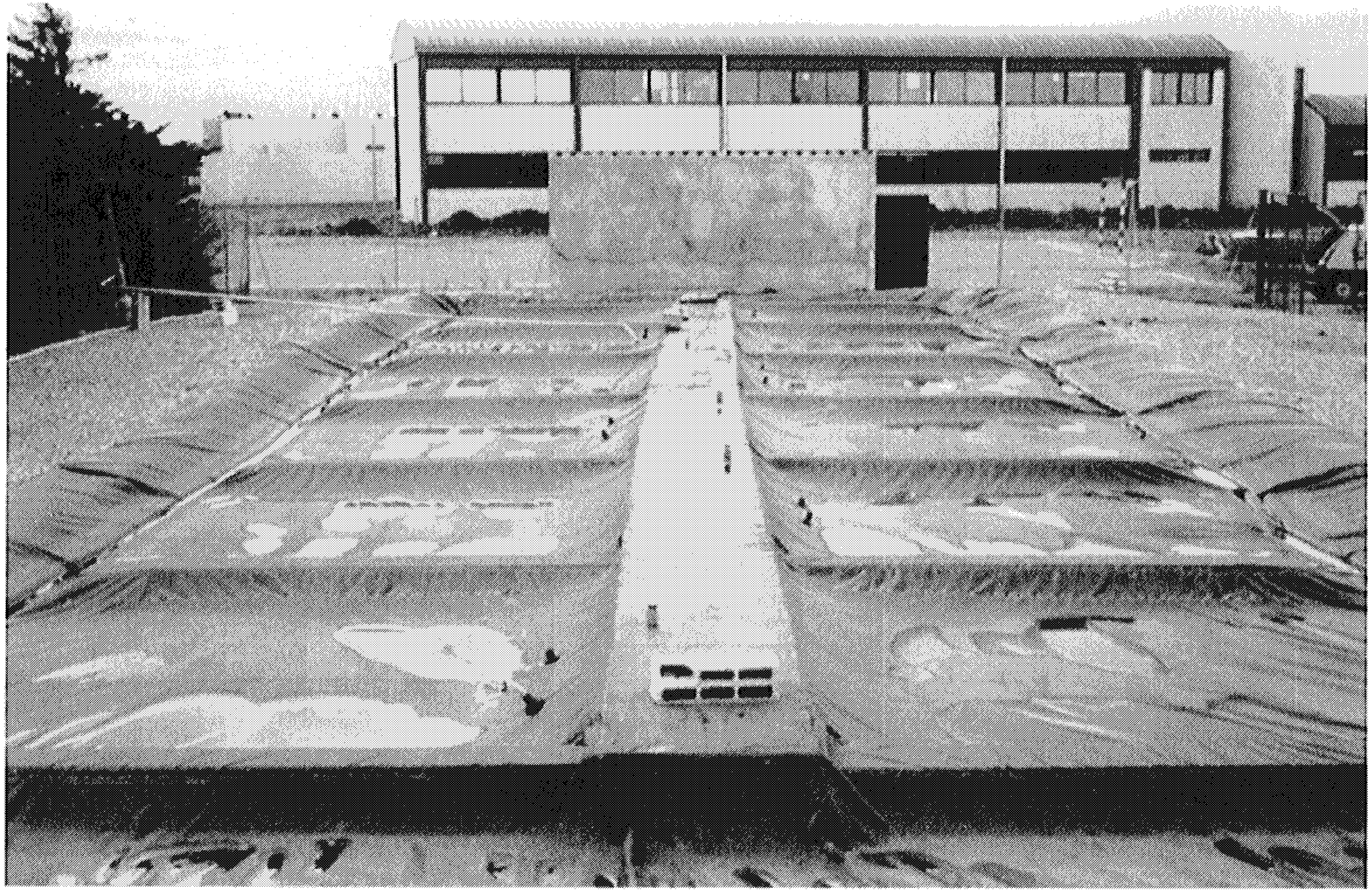
Organic Loading Rate : kg COD/m^3/d



AC	: Anaerobic Contactor	UASB	: Up-flow Anaerobic Sludge Blanket
UAF	: Upflow Anaerobic Filter	DAF	: Down-flow Anaerobic Filter
FB	: Fluidized Bed		

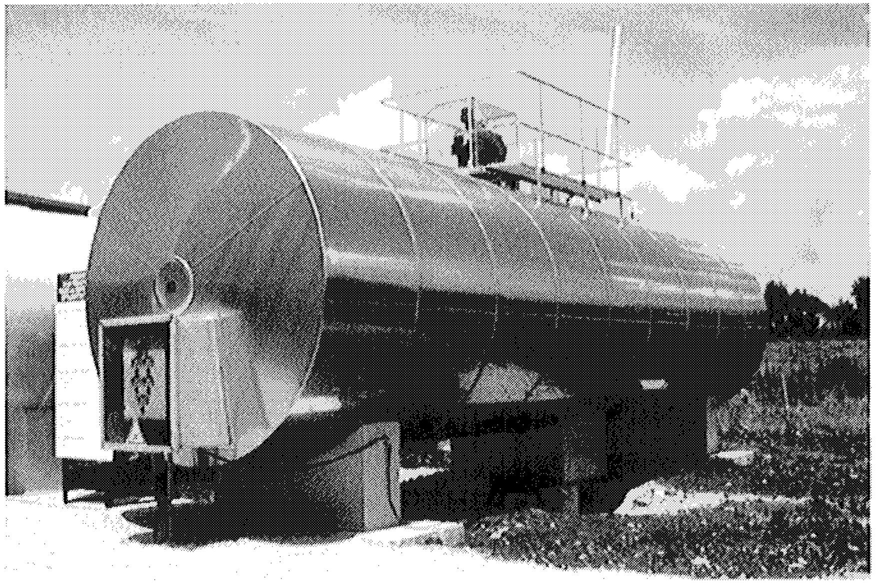
Anaerobic Lagoon

(LBE-INRA, Narbonne)



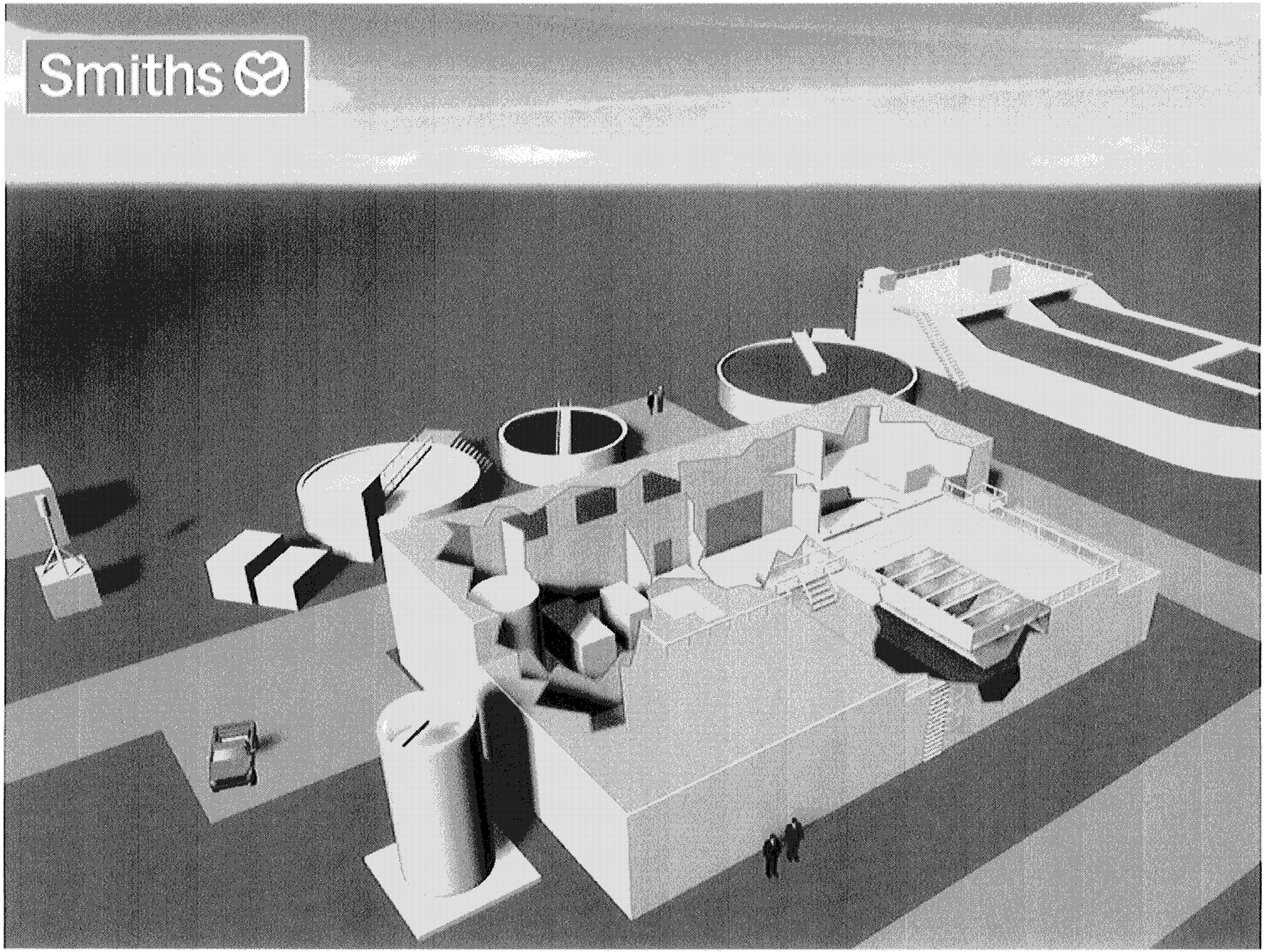
Sequencing Batch Reactor

(Narbonne and Le Fied, France)



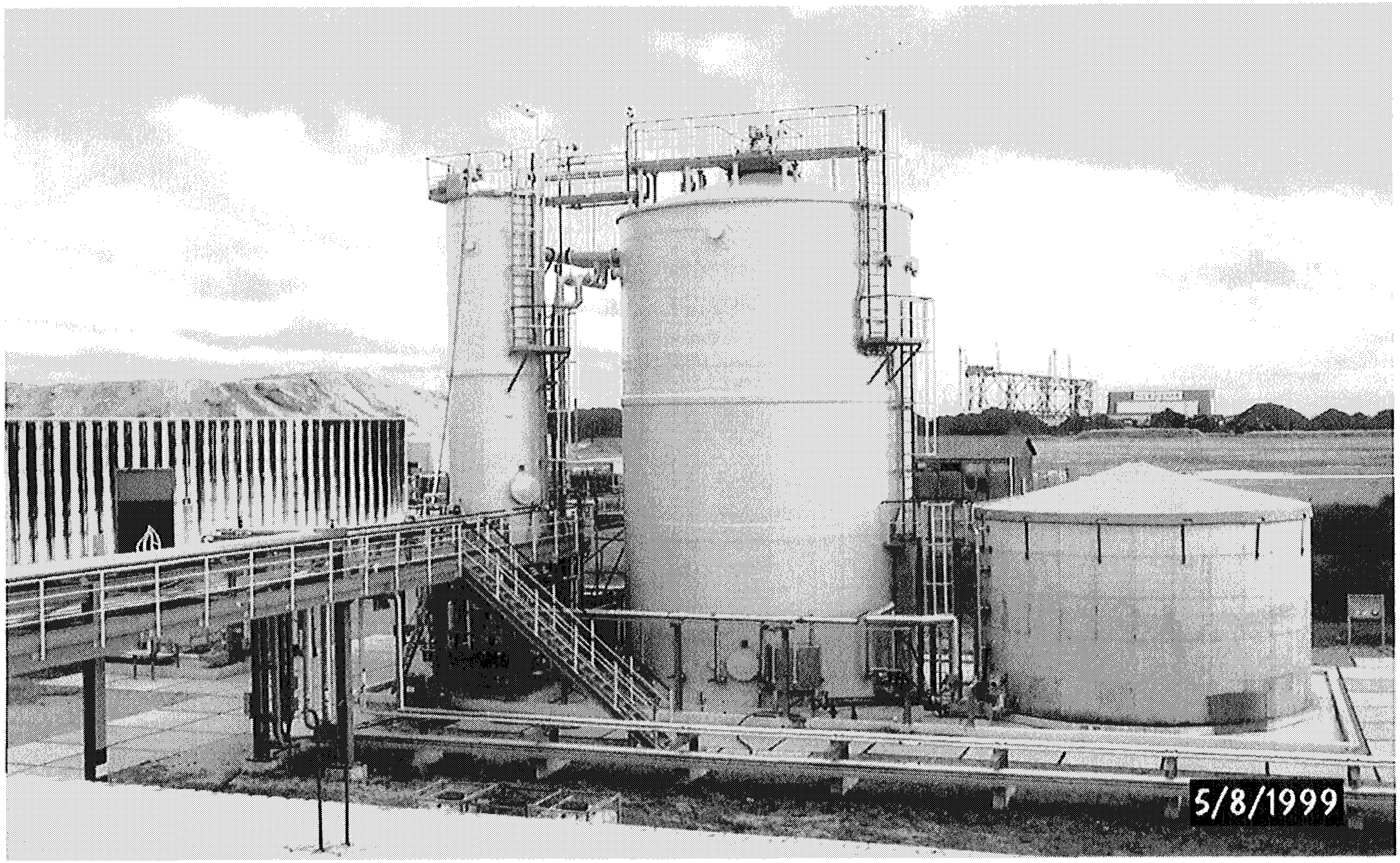
For cheese making wastewater

For wine distillery wastewater



KoSa, Vlissingen

(BIOTHANE Systems International)



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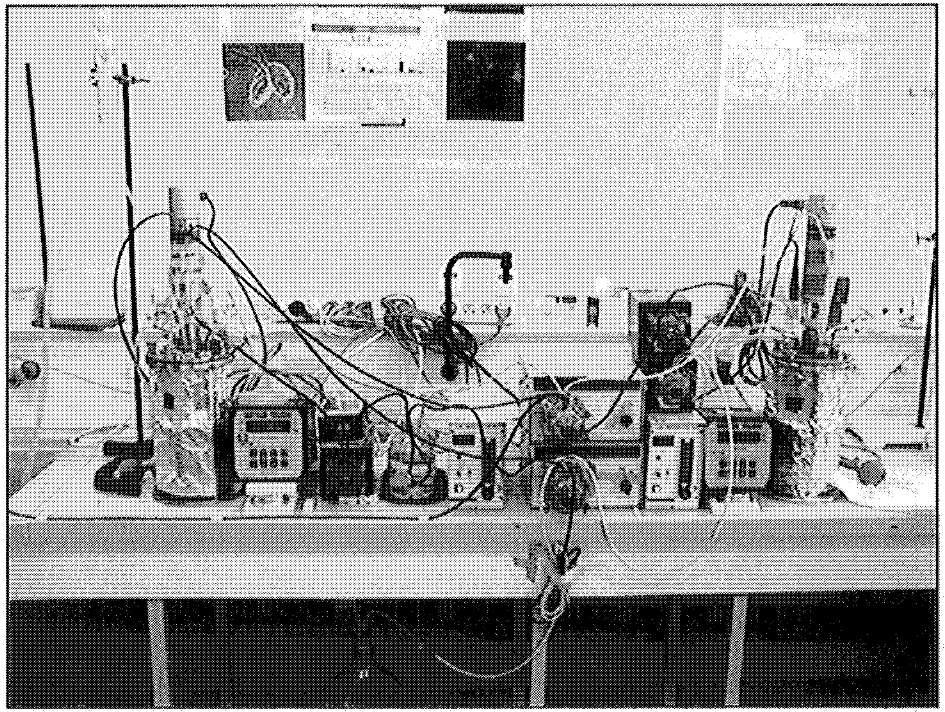
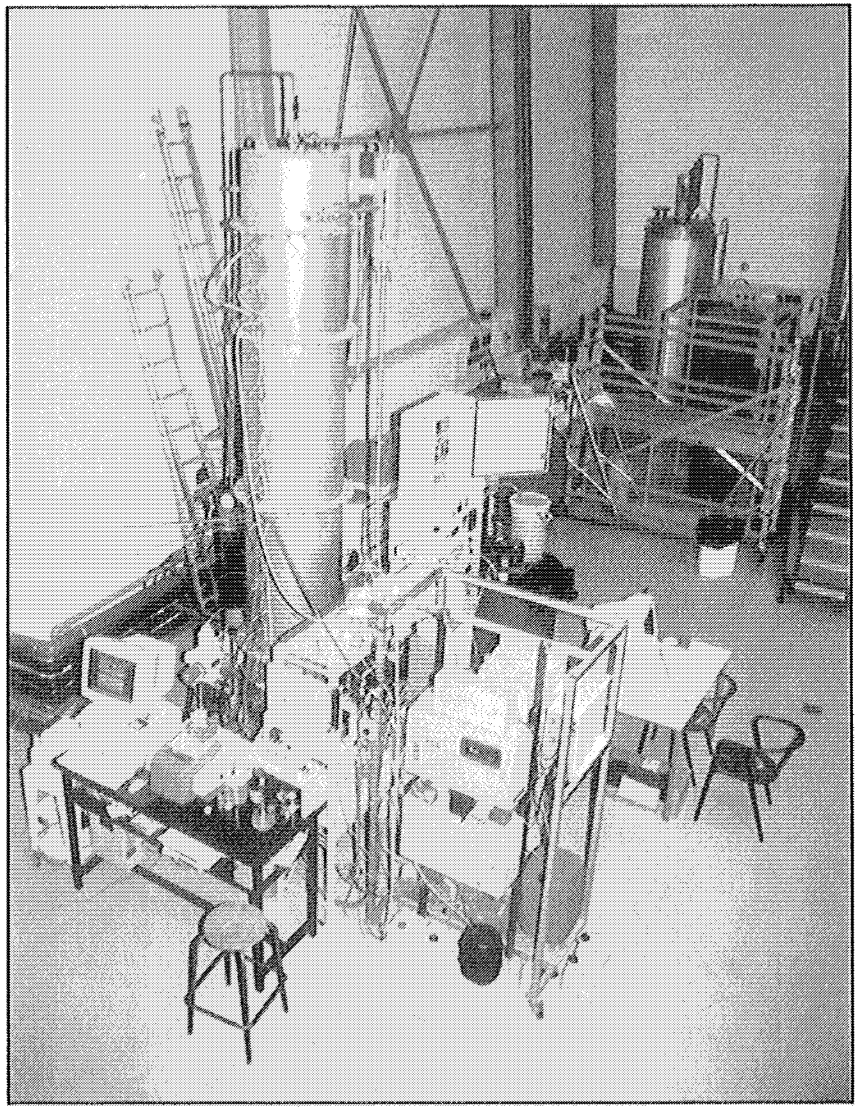
At the Laboratory Scale

(LBE-INRA, Narbonne)



Lab Scale

Pilot Scale



Contents of the Presentation

1) Problem statement

2) Difficulties in Modeling

2.1) Problem Statement
2.2) An Experimental Illustration

3) Difficulties in Control

4) An integrated approach

Bioprocess Modeling : When ? Why ? How ?

Model structure and model complexity can only be defined according to the objective we want to achieve :
To elaborate a model without refering to its goal is a nonsense ...

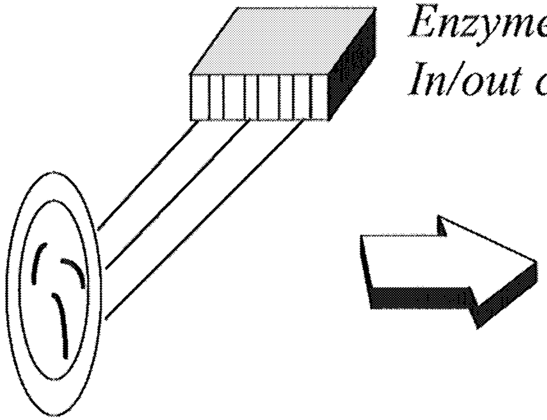
Among other advantages, mathematical modeling is useful and helpful :

- To minimize the number of experiments to be run,
- To improve the process design,
- To optimize process operations,
- To test and validate different control strategies.

⇨ ***Need of pluridisciplinarity in order to get closer to micro-organisms just knowing what happens in their surrounding***

"Ideal" measurements are not always available

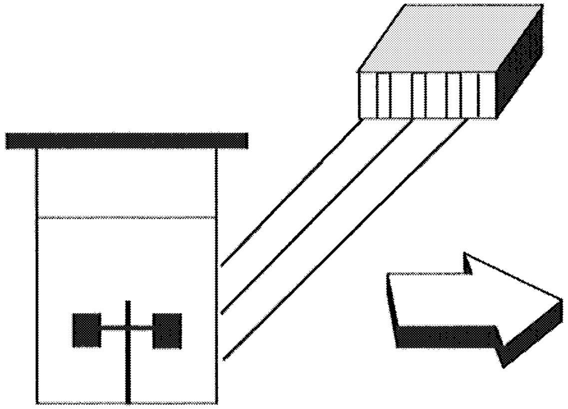
In reality :



Enzymes synthesis,
In/out cell transfers, ...

REGULATION

In practice :



gas, pH, temperature, ...

ESTIMATION
&
CONTROL

Mass Balance Modeling of Bioprocesses

Variation of the quantity in the reactor

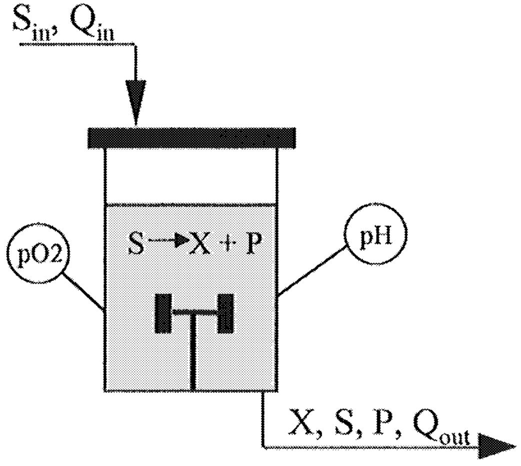
=

input - output + production - consumption

Biological Reaction Scheme :

$$S \rightarrow X + P$$

In a CSTR :



Structure of the model

From :

$$\begin{cases} \dfrac{d(XV)}{dt} = 0 \quad -Q_{out}X \quad +r_X V \quad -0 \\ \dfrac{d(SV)}{dt} = +Q_{in}S_{in} \quad -Q_{out}S \quad +0 \quad -r_S V \\ \dfrac{dV}{dt} = +Q_{in} \quad -Q_{out} \end{cases}$$

To :

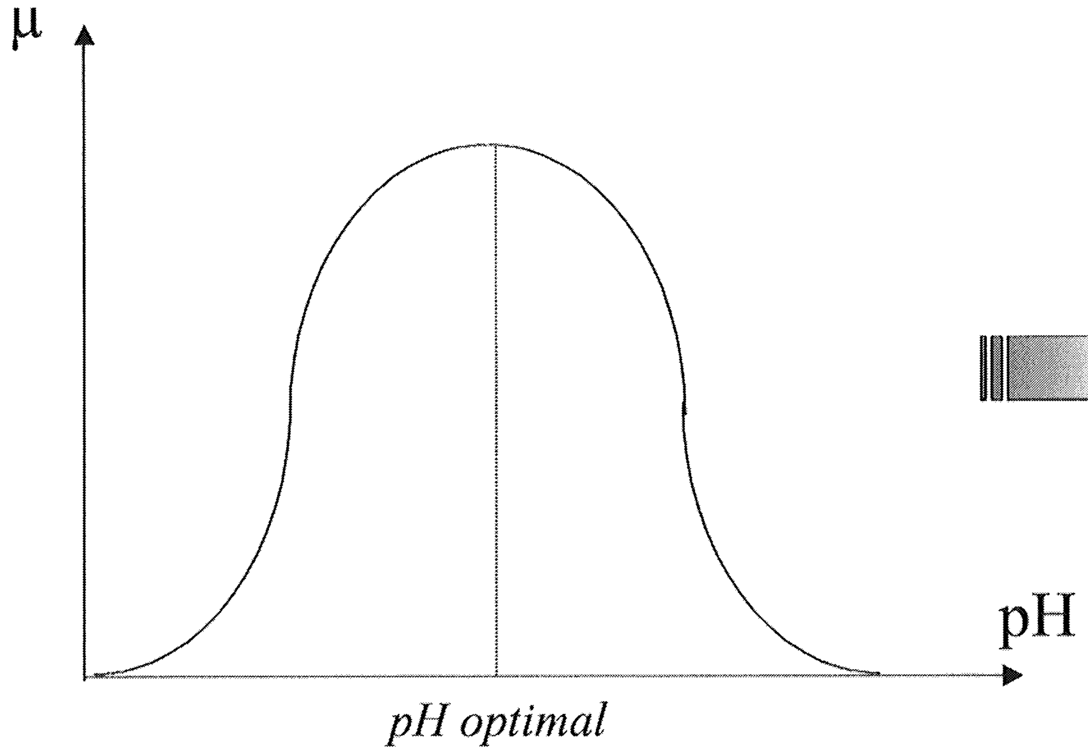
$$\begin{cases} \dfrac{dX}{dt} = (\mu - D)X \\ \dfrac{dS}{dt} = -\dfrac{\mu X}{Y_{X/S}} + D(S_{in} - S) \\ \dfrac{dV}{dt} = Q_{in} - Q_{out} \end{cases}$$

With D : dilution rate, $Y_{X/S}$: yield coefficient
and μ : specific growth rate

$$\mu = \frac{1}{XV}\frac{d(XV)}{dt} \quad \Rightarrow \quad \mu = f(X, S, P, T, pH, \ldots)$$

Modeling of the Specific Growth Rate

Specific Growth rate : $\mu = f(X, S, P, T, pH, \ldots)$



Regulation at pH optimal

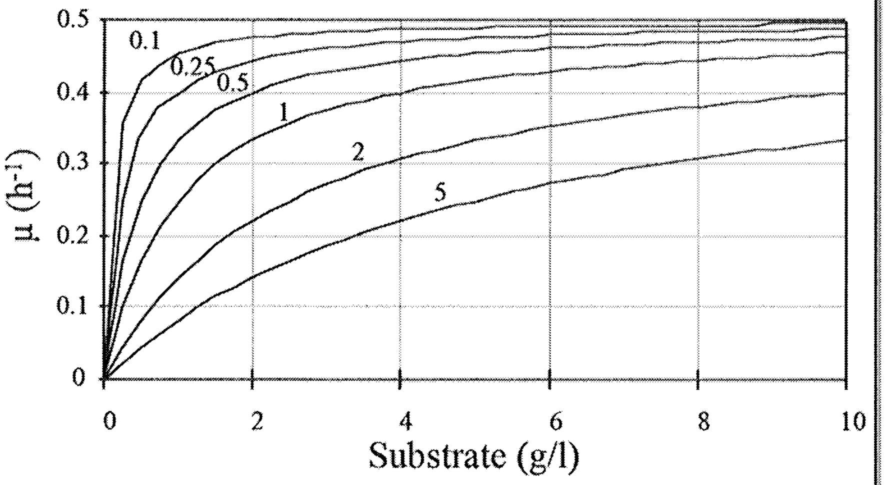
$\mu = f(X, S, P, T, pH, \ldots)$ *is usually restricted to* $\mu = f(S)$

Modeling of the Specific Growth Rate

When $\mu = f(X, S, P, T, pH, \ldots)$ is restricted to $\mu = f(S)$

With only limitation by the substrate : the Monod law

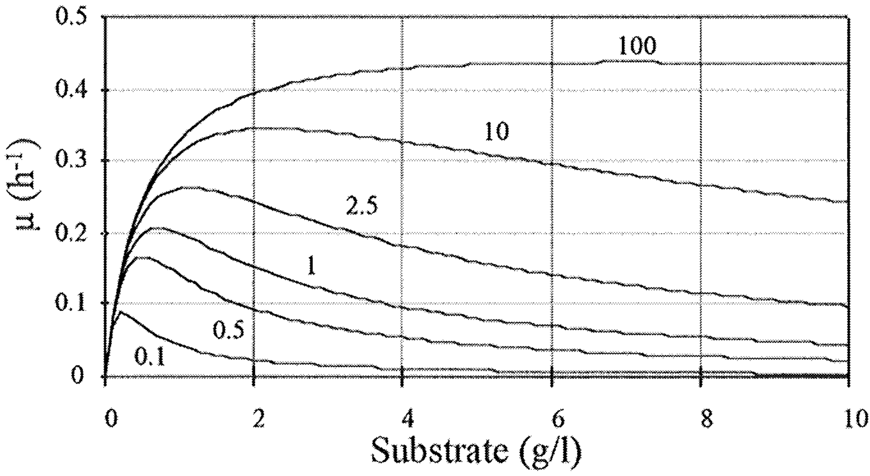
$$\mu = \mu_{\max} \frac{S}{K_S + S}$$



Example with $\mu_{max} = 0.5\ h^{-1}$ and $K_S \in [0.1, 5]$

With limitation and inhibition : the Haldane law

$$\mu = \mu_{\max} \frac{S}{K_S + S + \dfrac{S^2}{K_I}}$$



Example with $\mu_{max} = 0.5\ h^{-1}$, $K_S = 0.5$ g/l and $K_I \in [0.1, 100]$ g/l

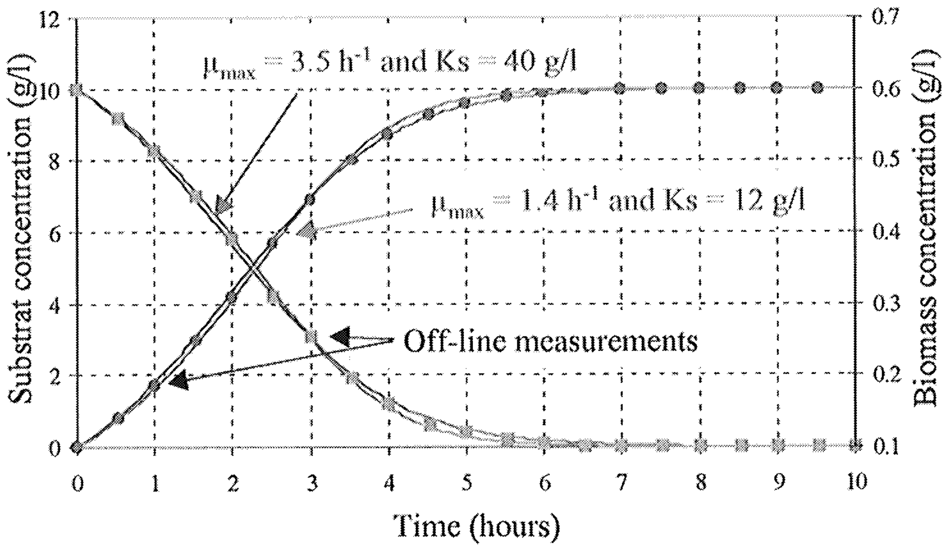
On identifiability of kinetic constants ...

In practice, the identifiability of the kinetic is far from being guaranteed !...

For example : $\mu = \mu_{max} \dfrac{S}{K_s + S}$

Cultivation	Initial substrate So (g/l)	Estimated Kinetic Coefficient	
		μ* (h-1)	Km (g/l)
1	11.6	1.0 +/- 2.0	16.8 +/- 22.3
2	7.0	1.1 +/- 0.8	1.8 +/- 2.2
3	18.2	0.7 +/- 0.2	12.9 +/- 14.6
4	25.0	0.3 +/- 0.2	7.0 +/- 11.9

Identification results of the kinetic coefficient μ* and Km



Simulation with two different sets of kinetic coefficients

From A. Holmberg (1983) : *On the accuracy of estimating the parameters of models containing Michaelis-Menten type nolinearities*, in G.C. Vansteenkiste and P.C. Young (Eds.), Modelling and Data Analysis in Biotechnology and Medical Engineering, North-Holland

IWA Activated Sludge Model #2 on C,N,P Removal

Hydrolysis

- $K_h \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
- $K_h \eta_{NO_3} \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_{NO_3}}{K_{NO_3}+S_{NO_3}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
- $K_h \eta_{fe} \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \frac{K_{NO_3}}{K_{NO_3}+S_{NO_3}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$

Heterotrophic Organisms

- $\mu_H \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_F+S_A} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \frac{S_{PO_4}}{K_P+S_{PO_4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
- $\mu_H \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_F+S_A} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \frac{S_{PO_4}}{K_P+S_{PO_4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
- $\mu_H \eta_{NO_3} \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_F+S_A} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \frac{S_{NO_3}}{K_{NO_3}+S_{NO_3}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{S_{PO_4}}{K_P+S_{PO_4}} X_H$
- $\mu_H \eta_{NO_3} \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_F+S_A} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \frac{S_{NO_3}}{K_{NO_3}+S_{NO_3}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{S_{PO_4}}{K_P+S_{PO_4}} X_H$
- $q_{fe} \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \frac{K_{NO_3}}{K_{NO_3}+S_{NO_3}} \frac{S_F}{K_{fe}+S_F} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
- $b_H X_H$

Phosphorus Accumulating Organisms

- $q_{PHA} \frac{S_A}{K_A+S_A} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PP}/X_{PAO}}{K_{PP}+X_{PP}/X_{PAO}} X_{PAO}$
- $q_{PP} \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_{PO_4}}{K_{PS}+S_{PO_4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} \frac{K_{MAX}-X_{PP}/X_{PAO}}{K_{IPP}+K_{MAX}-X_{PP}/X_{PAO}} X_{PAO}$
- $\mu_{PAO} \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{S_{PO_4}}{K_P+S_{PO_4}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} X_{PAO}$
- $b_{PAO} X_{PAO} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$
- $b_{PP} X_{PP} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$
- $b_{PHA} X_{PHA} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$

Autotrophics Nitrifying Organisms

- $\mu_{AUT} \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \frac{S_{PO_4}}{K_P+S_{PO_4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_{AUT}$
- $b_{AUT} X_{AUT}$

Simultaneous Precipitation of Phosphorus with $Fe(OH)_3$

- $k_{PRE} S_{PO_4} X_{MeOH}$
- $b_{RED} X_{MeP} \frac{S_{ALK}}{K_{ALK}+S_{ALK}}$

Contents of the Presentation

1) Problem statement

2) Difficulties in Modeling

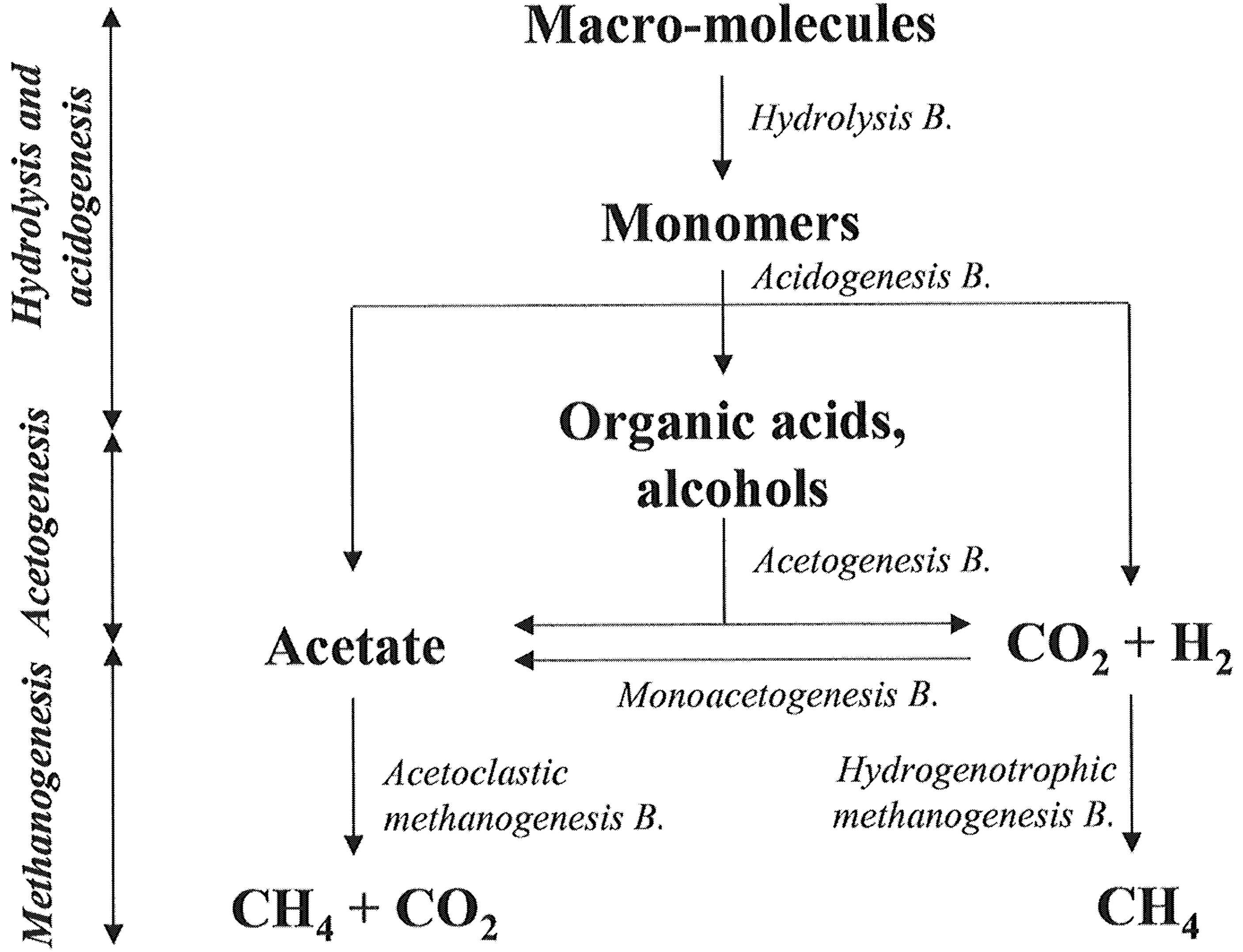
2.1) Problem Statement

2.2) An Experimental Illustration

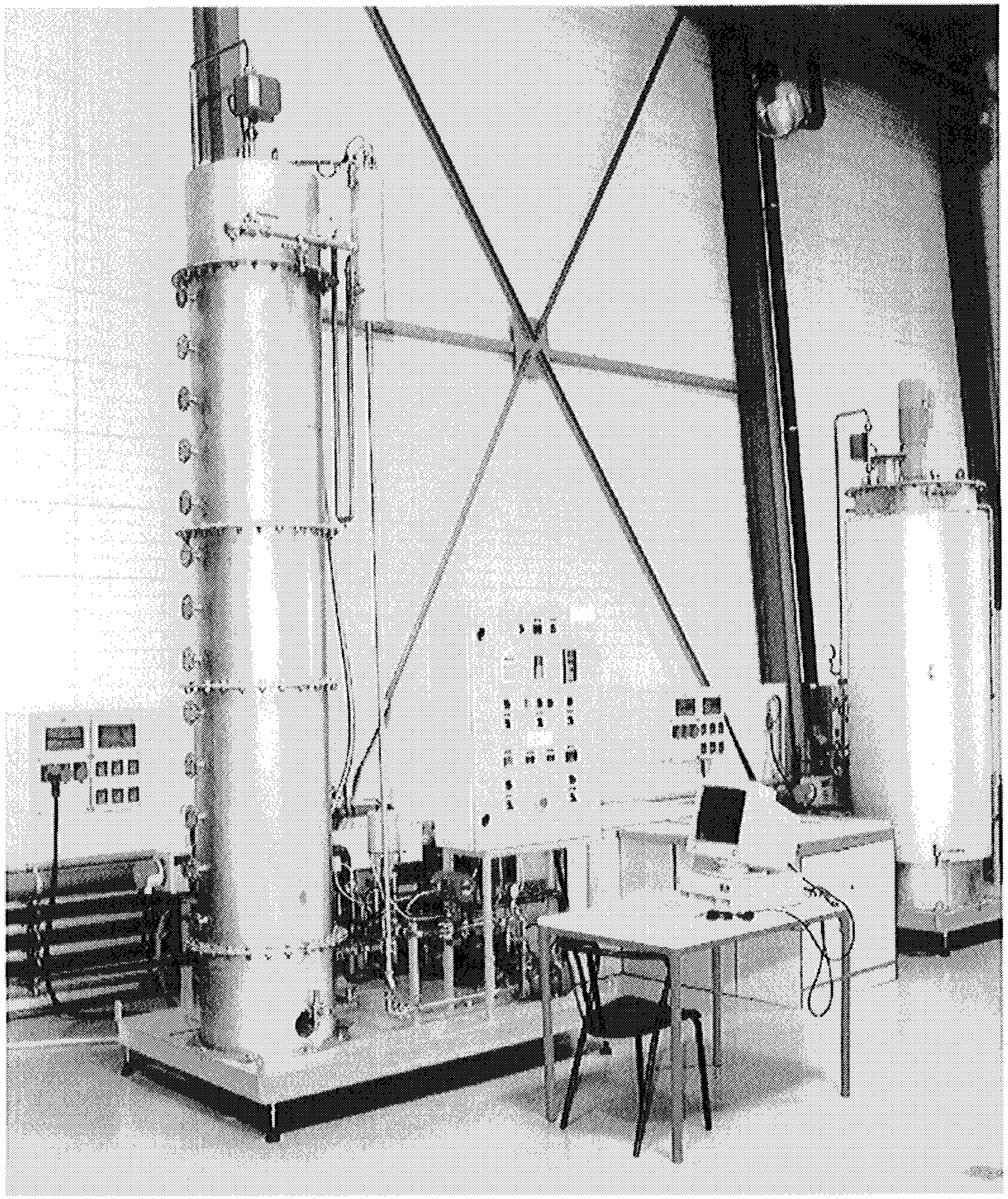
3) Difficulties in Control

4) An integrated approach

The Anaerobic Digestion Reaction Scheme



The process used in Narbonne



Influent : **Raw industrial distillery vinasses**

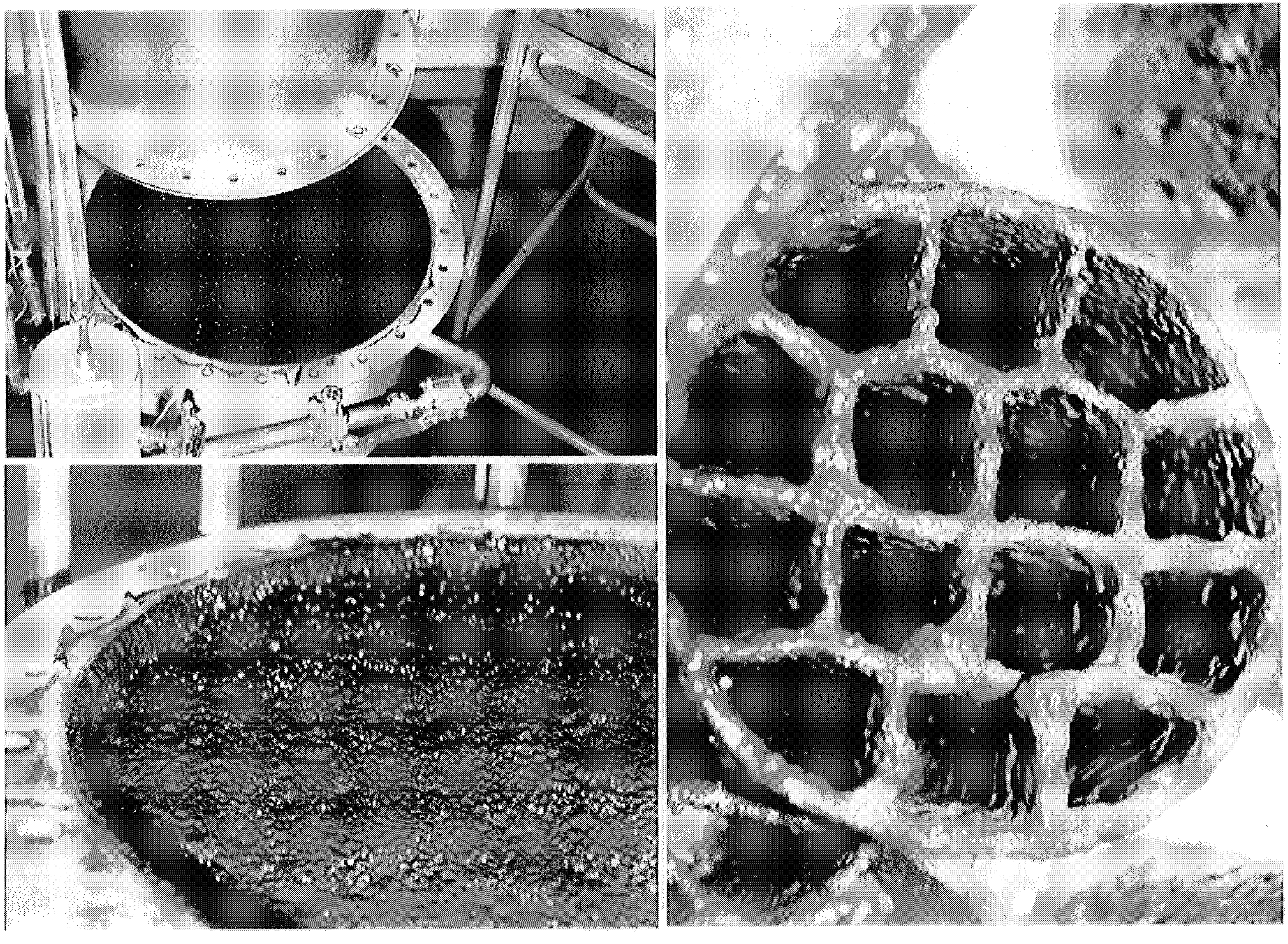
Reactor : **Circular column**
Up-flow fixed bed reactor
- 3.5 m height,
- 0.6 m diameter,
- 982 liters of total volume.

Media : **Cloisonyl**

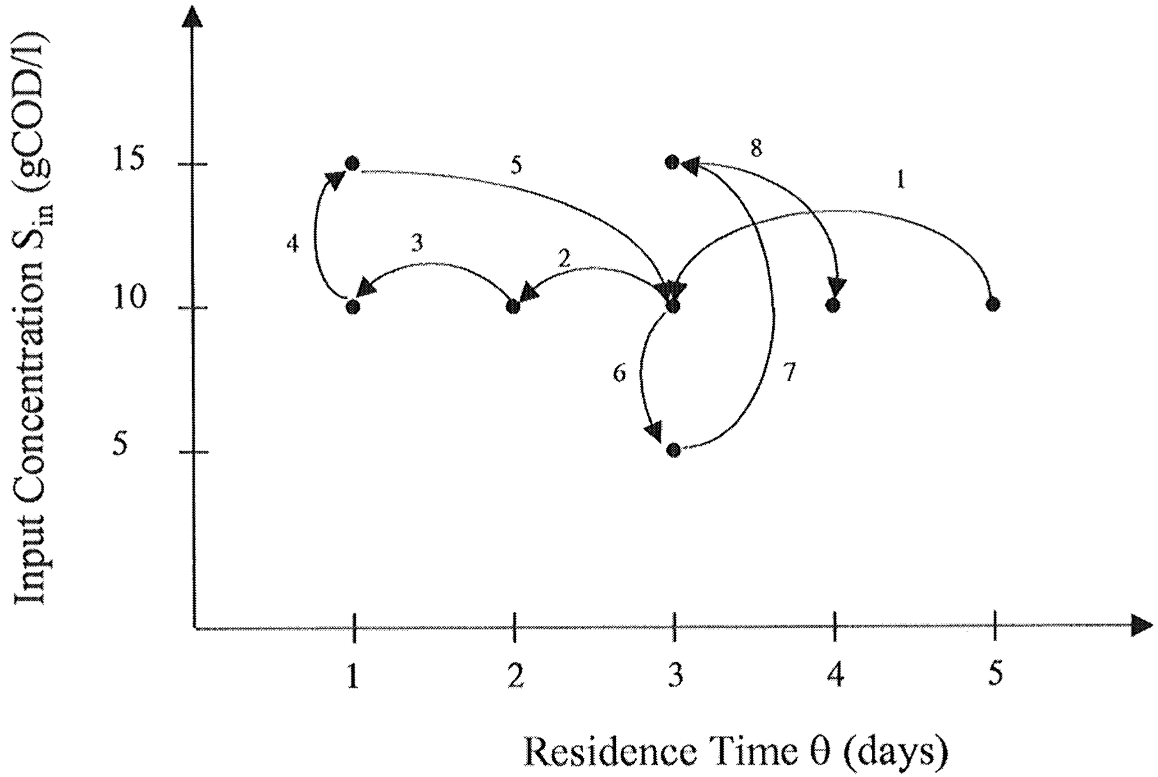
- Specific surf.	: 180 m^2/m^3
- Volume	: 33.7 liters

Total effective volume : **948 liters**

Media for Microorganisms (Cloisonyl)



Experimental Protocol for the Modeling of the Process



8 transient changes and ... 1 year of heavy experimental work !

Dynamical Model of the Anaerobic Digestion

- Starting point : reaction network

organic matter

Acidogenesis : $S_1 \rightarrow X_1 + S_2 + CO_2$

Methanization : $S_2 \rightarrow X_2 + CO_2 + CH_4$

volatile fatty acids

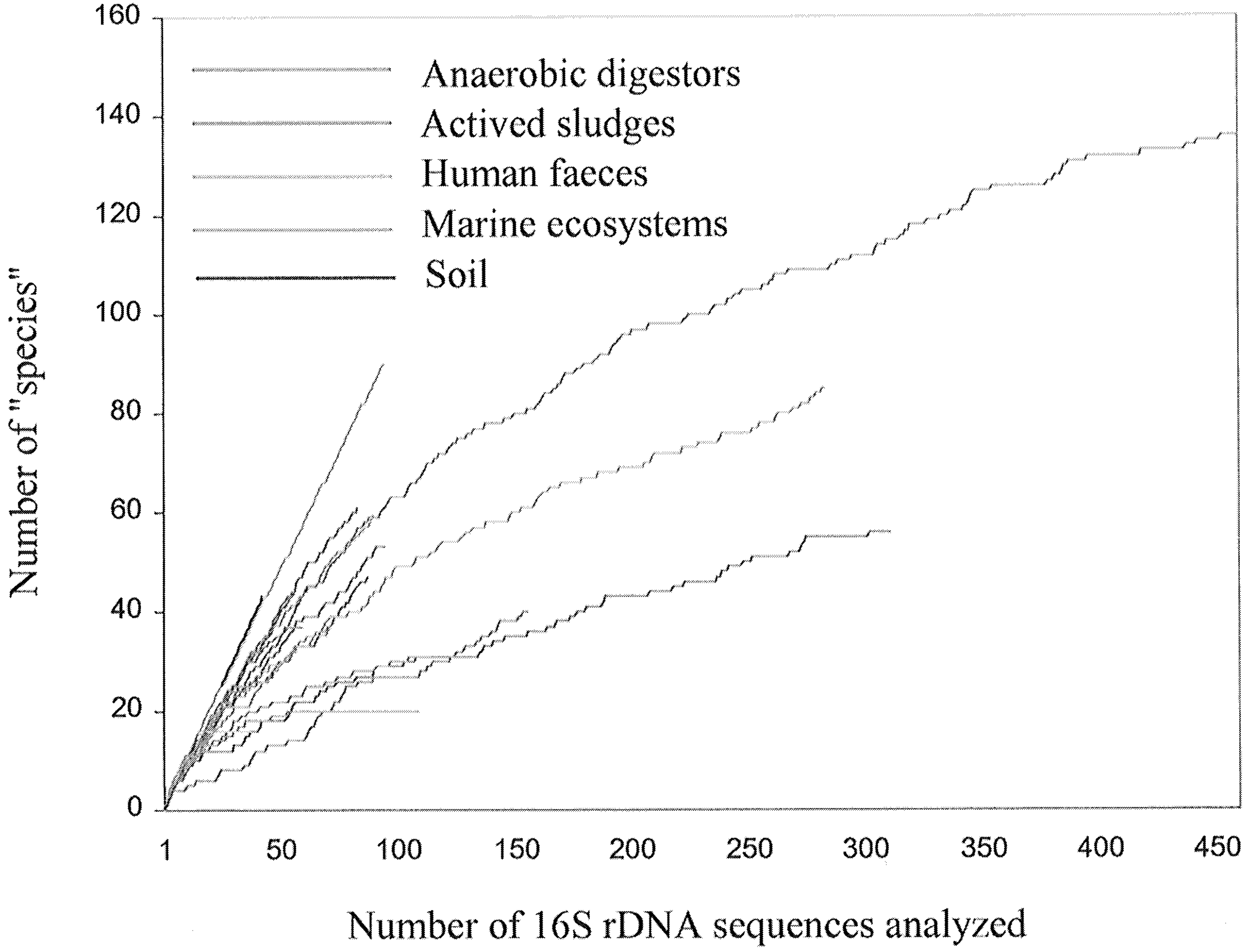
- Alkalinity assumptions : $6 \leq pH \leq 8$ and temperature $\approx$ 38 C

Total organic carbon : $C_{TI} = CO_2 + B$

Total alkalinity : $Z = B + S_2$

bicarbonate

Anaerobic Digestion is a Complex Ecosystem



The "AMOCO" Anaerobic Digestion Model
(EU FAIR Project CT 1198)

From Mass Balance

$$\begin{cases} \dot{X}_1 = (\mu_1 - \alpha D) X_1 \\ \dot{X}_2 = (\mu_2 - \alpha D) X_2 \\ \dot{Z} = D(Z^i - Z) \\ \dot{S}_1 = D(S_1^i - S_1) - k_1 \mu_1 X_1 \\ \dot{S}_2 = D(S_2^i - S_2) + k_2 \mu_1 X_1 - k_3 \mu_2 X_2 \\ \dot{C}_{TI} = D(C_{TI}^i - C_{TI}) + k_7 (k_8 P_{CO_2} + Z - C_{TI} - S_2) + k_4 \mu_1 X_1 + k_5 \mu_2 X_2 \end{cases}$$

With $\mu_1 = \mu_{\max 1} \dfrac{S_1}{K_{S_1} + S_1}$ (*i.e.*, limitation by organic matter)

and $\mu_2 = \mu_{\max 2} \dfrac{S_2}{K_{S_2} + S_2 + \left(\dfrac{S_2}{K_{I_2}} \right)^2}$ (*i.e.*, limitation and inhibition by VFA)

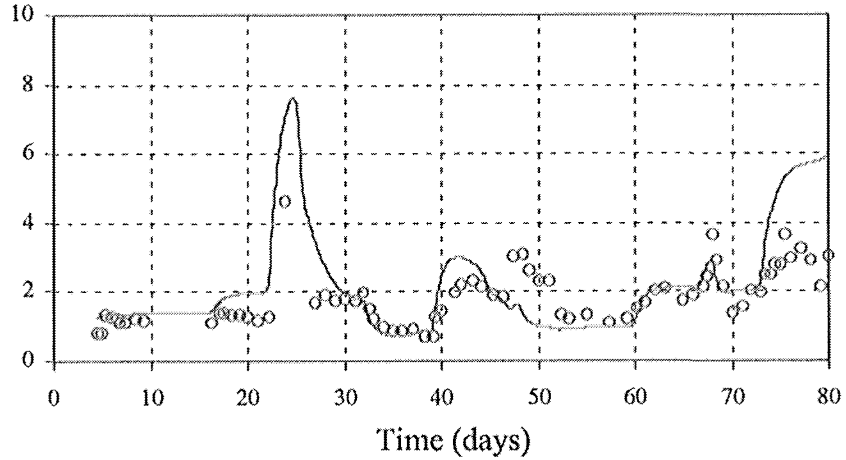
INRA

Process parameters of the "AMOCO" model

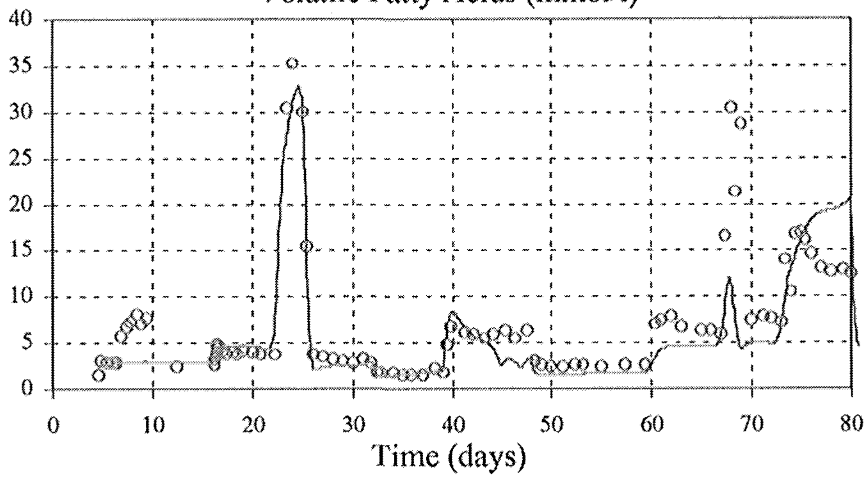
Parameter	Meaning	Value
k_1	Yield coefficient for COD degradation	6.6 kg COD/kg X_1
k_2	Yield coefficient for fatty acid production	7.8 mol VFA/kg X_1
k_3	Yield coefficient for fatty acid consumption	611.2 mol VFA/kg X_2
α	Proportion of dilution rate for bacteria	0.5
μ_{max1}	Maximum acidogenic biomass growth rate	1.2 day^{-1}
μ_0	Maximum methanogenic biomass growth rate	0.69 day^{-1}
K_{S_1}	Saturation parameter associated with S_1	4.95 kg COD/m^3
K_{S_2}	Saturation parameter associated with S_2	9.28 mol VFA/m^3
K_{I_2}	Inhibition constant associated with S_2	20 $(mol\ VFA/m^3)^{1/2}$

Dynamic simulations vs. experimental data

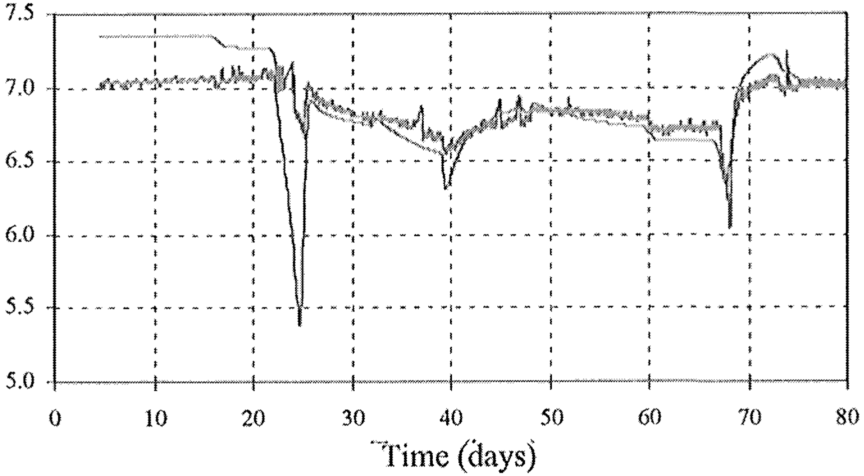
Chemical Oxygen Demand (g_{COD}/l)



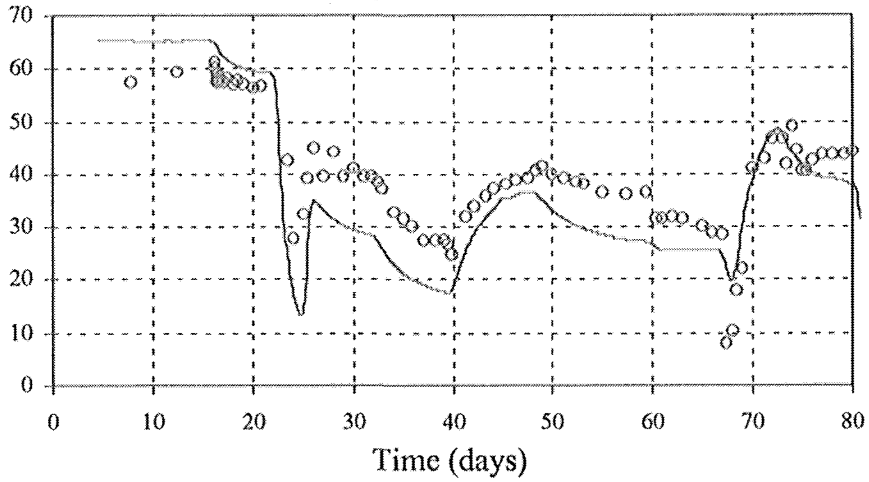
Volatile Fatty Acids (mmol/l)



pH (UpH)



Total Inorganic Carbon (mmol/l)



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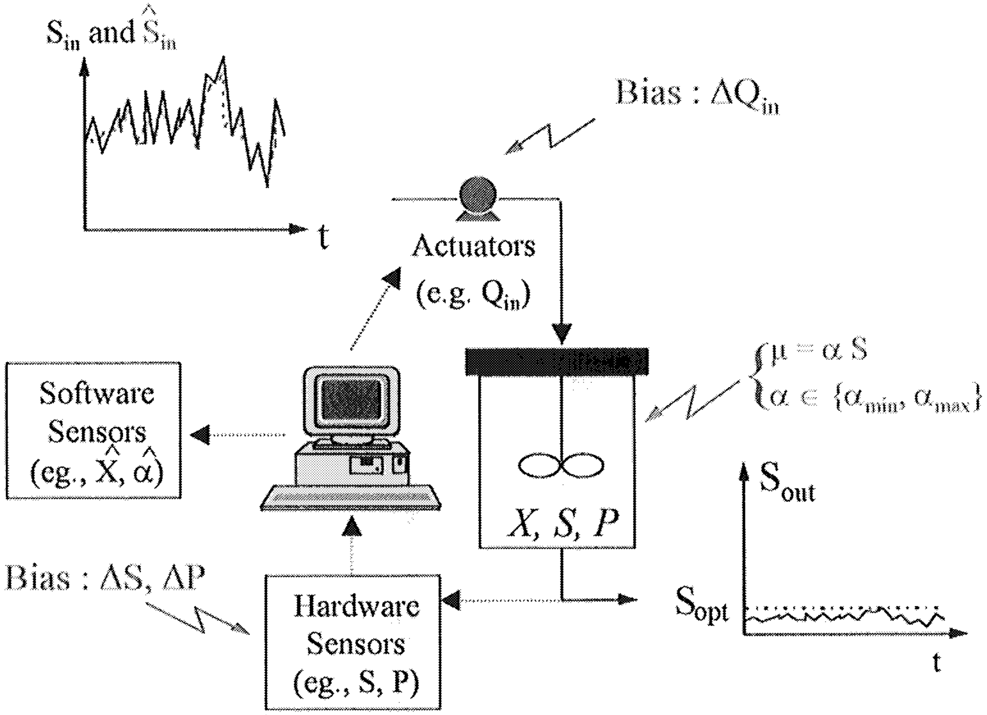
Main Requirements for Process Control

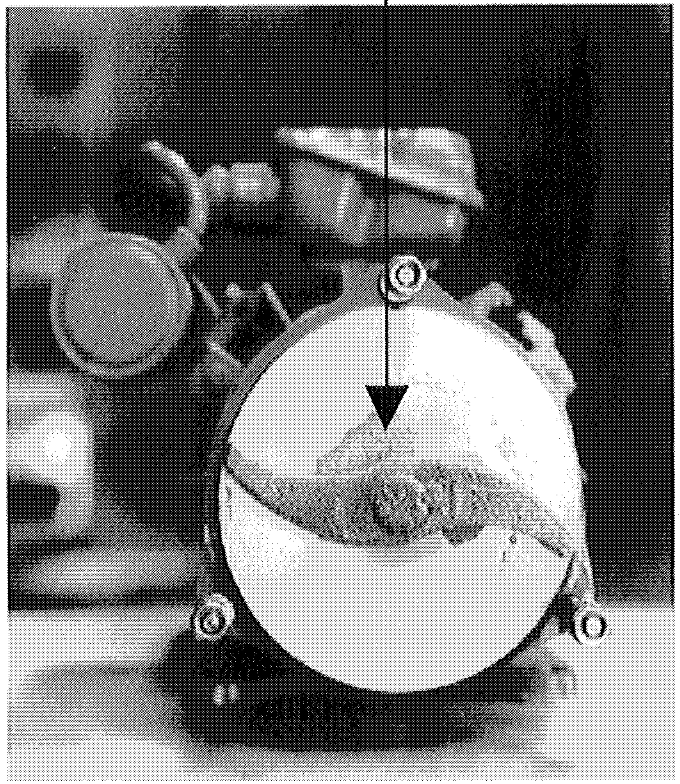
- ✓ Insensitivity to unmodeled or approximated phenomena,
- ✓ Insensitivity to variations of model parameters,
- ✓ Both short and long time scale disturbances rejection,
- ✓ Handling of constraints for state and control variables.

Objectives :

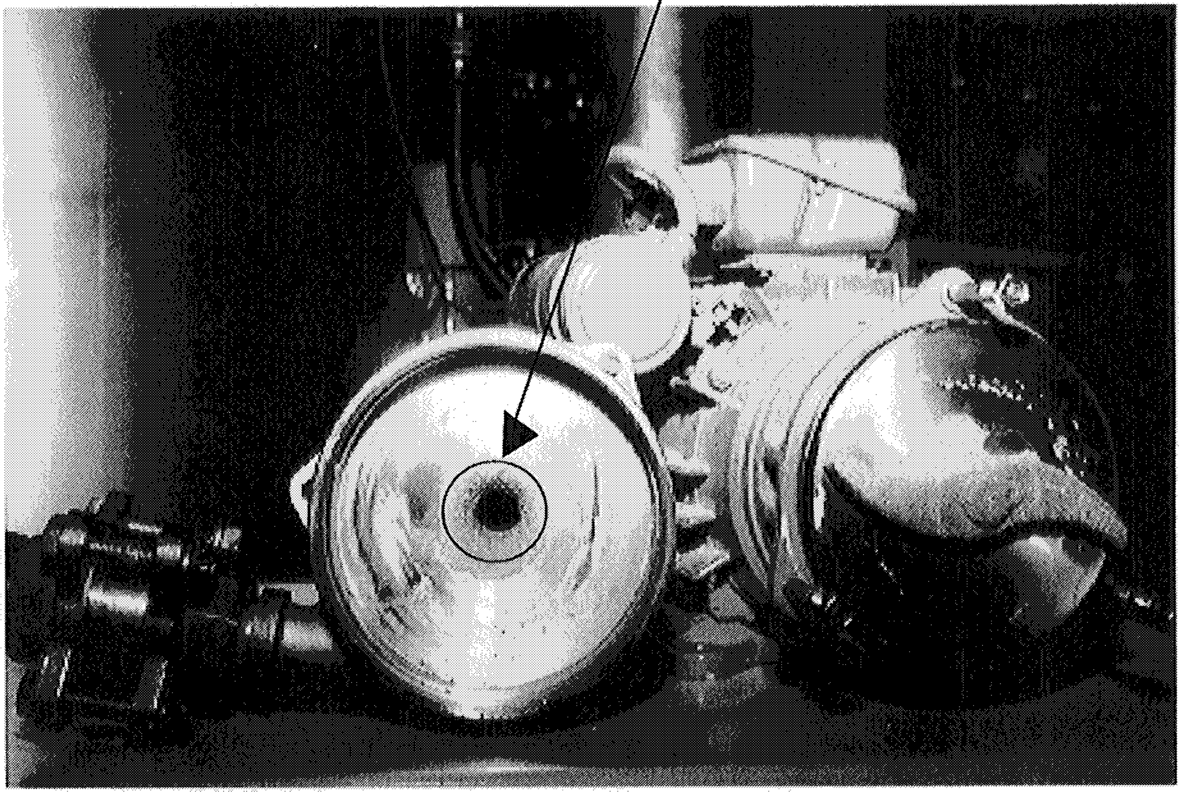
Process regulation in the presence of internal/external disturbances and uncertainty



There are also Technical Problems



Pure Struvite appears on the pump

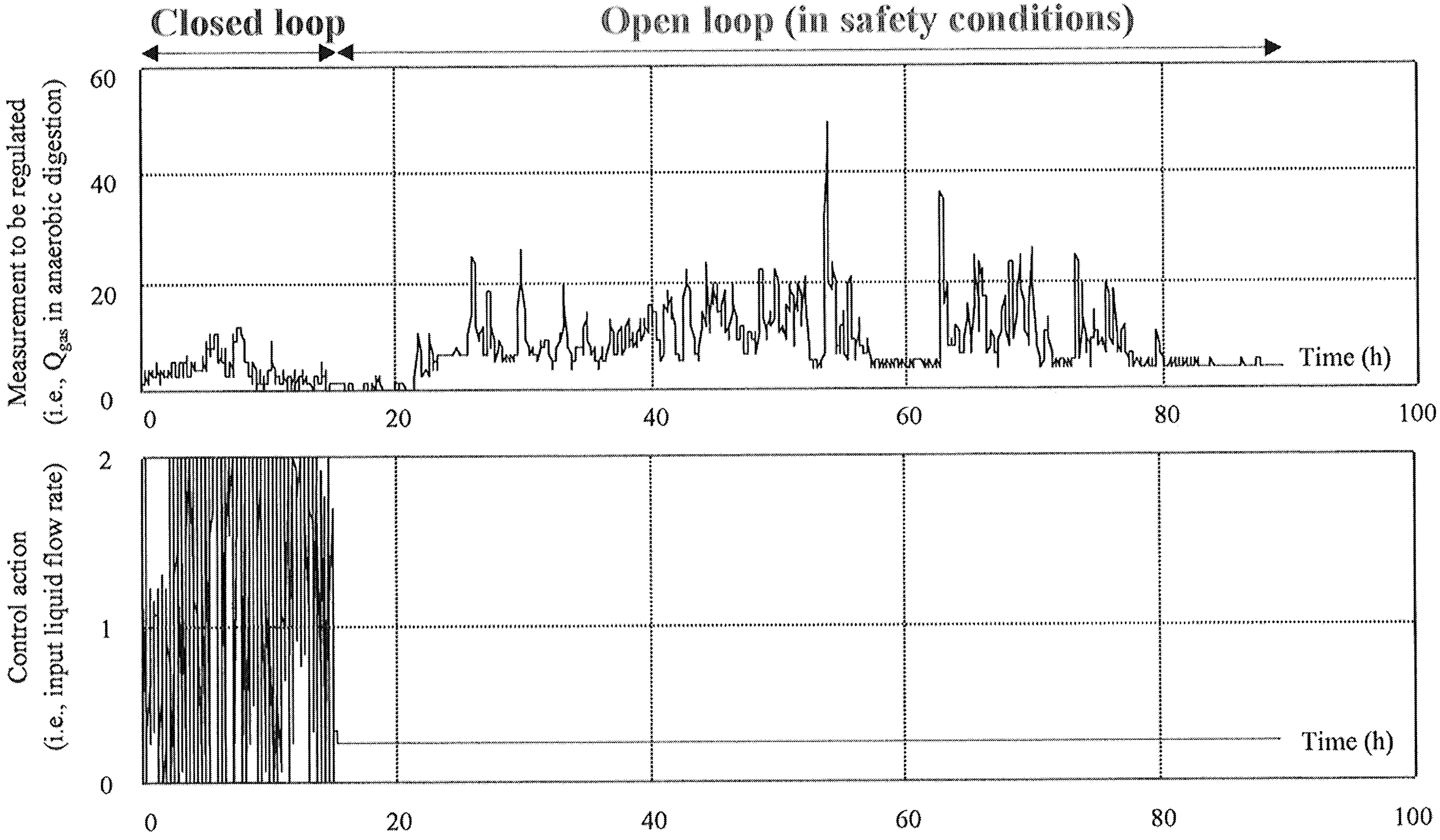


Original hole for the pipe

Pipe Clogging due to Struvite Formation

(and pumps are very often used as main actuators)

Consequences of the Unappropriate Tuning of a Control Law



It took more than a week for the process to recover
(i.e., during this time, the wastewater was not treated !...)

Consequences of a Technical Problem

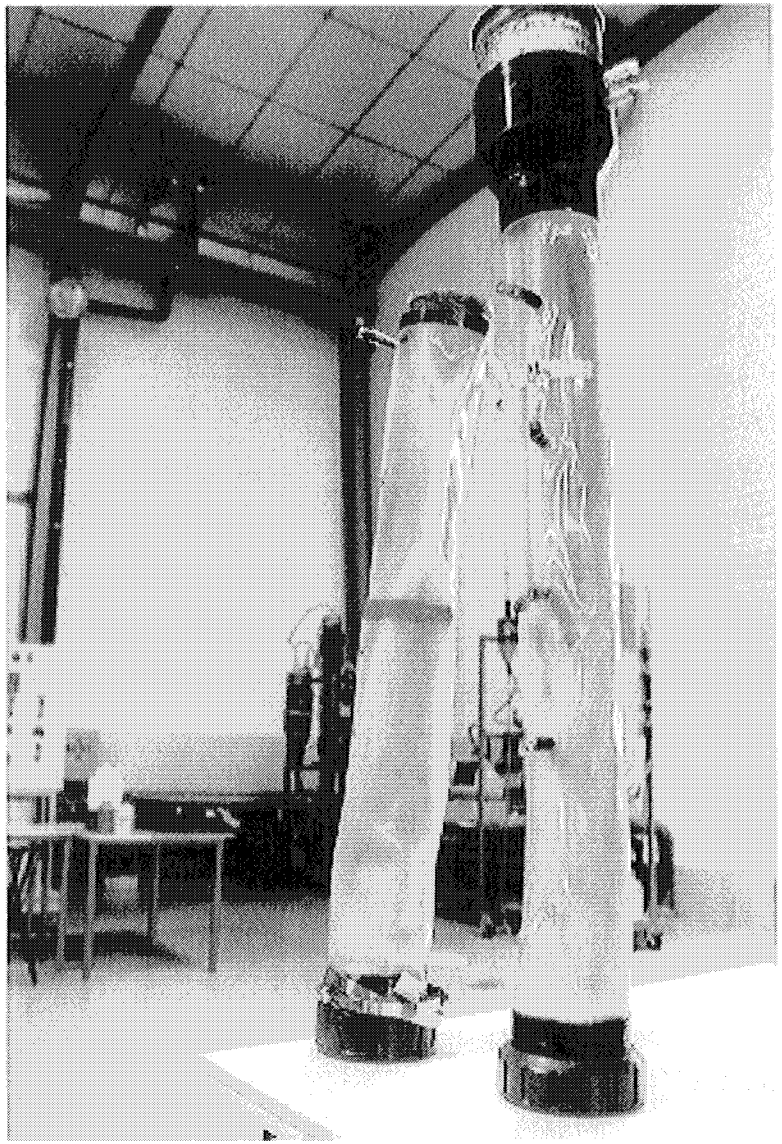
Birds on wires

Electricity shutdown

Problem with temperature regulation (boiling water in the jacket)

Melted reactors !!!

Everything is lost ...



INRA

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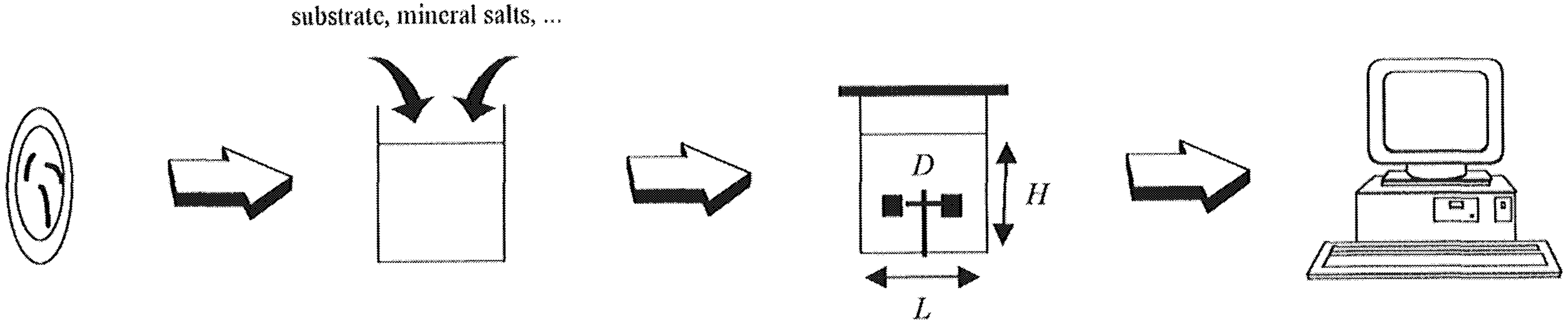
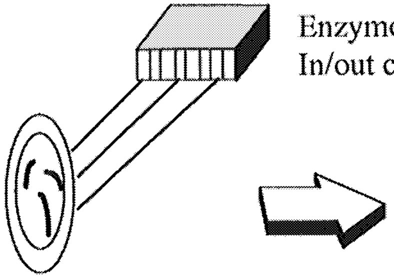
Bioprocesses from the process control "point of view"

- Process control is usually assumed to be helpful *at the end* of the bioprocess

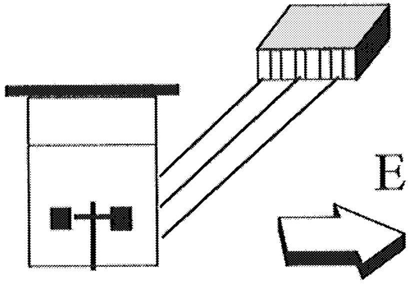


Genetic engineering
Microbiology
Process engineering
Process control

- "Ideal" measurements are not always available


Enzymes synthesis,
In/out cell transfers, ...

REGULATION


gas, pH, temperature, ...

ESTIMATION
&
CONTROL

On the usual design of a bioprocess

Step 1 ***: Selection of the microorganism(s)***

⇨ **GENETIC ENGINEERING**

- What are the most appropriate species ?
- Change (if possible) of the genetics of the cells

Reactor size : the cell

On the usual design of a bioprocess

Step 2 : Choice of the optimal conditions

MICROBIOLOGY

- What substrates should be used ?
- What are the best conditions (pH, temperature, ...) ?

Reactor size : 1 ml to 10 liters

On the usual design of a bioprocess

Step 3 : Analysis of the hydrodynamics

PROCESS ENGINEERING

- What is the best appropriate reactor design ?
- How to improve the mass transfer ?

Reactor size : 1 liter to few cubic meters

On the usual design of a bioprocess

Step 4 : Monitoring of the process

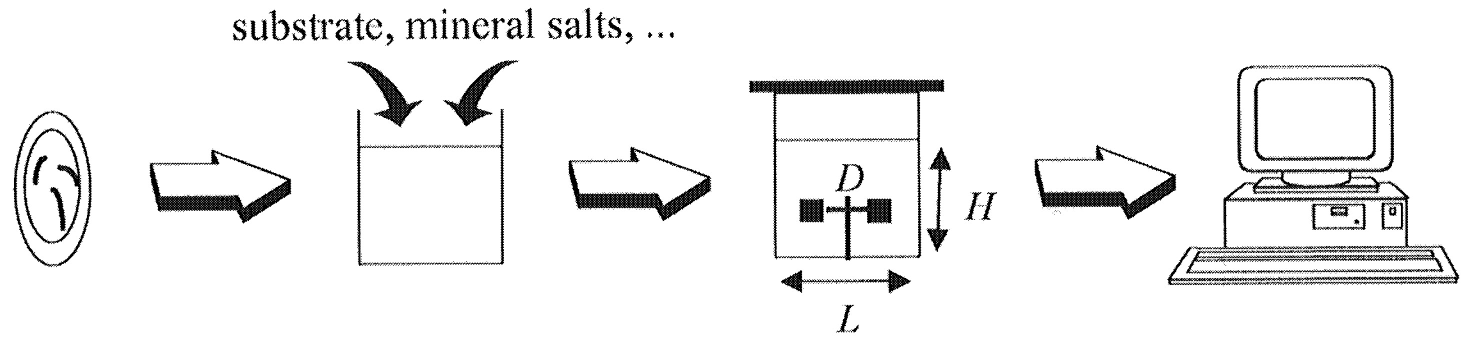
⇨ **PROCESS CONTROL**

- How to improve the available measurements ?
- What is the control law to be applied ?

Reactor size : several liters to few cubic meters

The usual design of a bioprocess is ...

... an "open loop" process



Genetic engineering

Microbiology

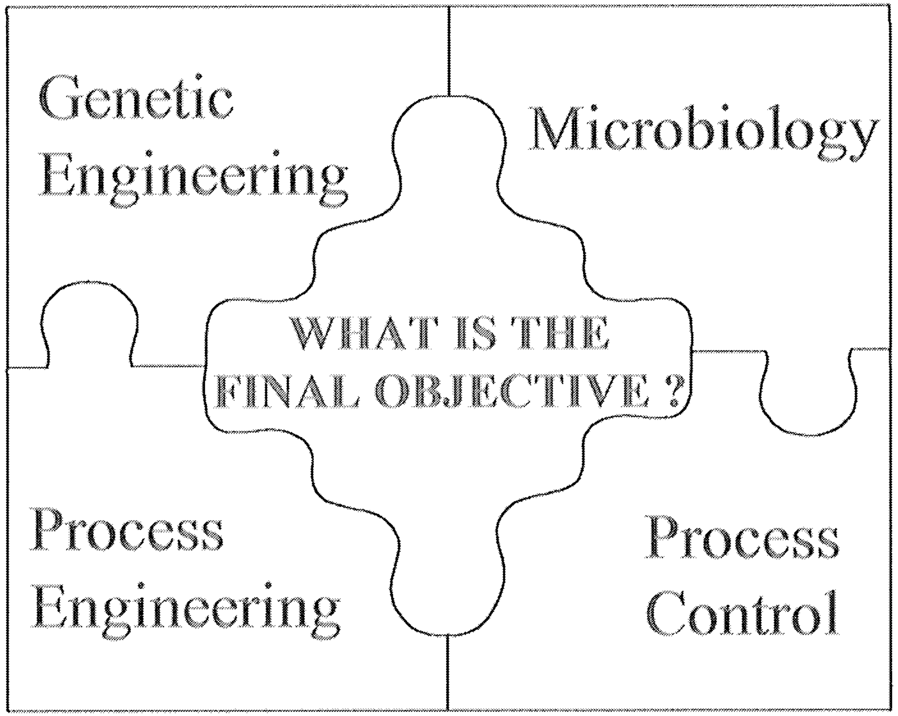
Process engineering

Process control

THIS IS FAR FROM BEING OPTIMIZED !...

On a better way to design a bioprocess ...

Every step is of equal importance and should be done accordingly (i.e., in "closed loop")



Genetic Engineering

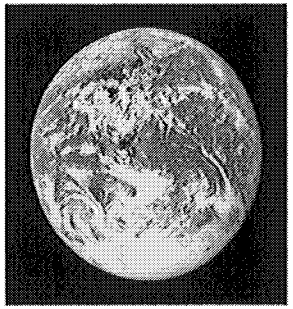
Microbiology

WHAT IS THE FINAL OBJECTIVE ?

Process Engineering

Process Control

Need for pluridisciplinarity !

d 

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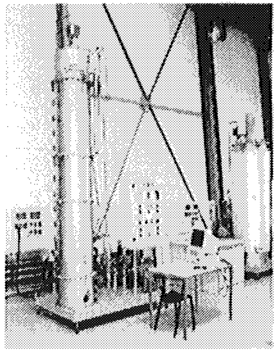
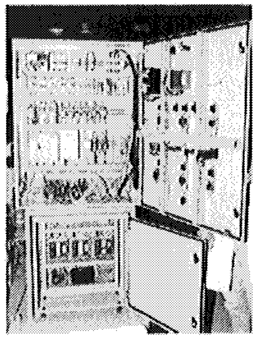
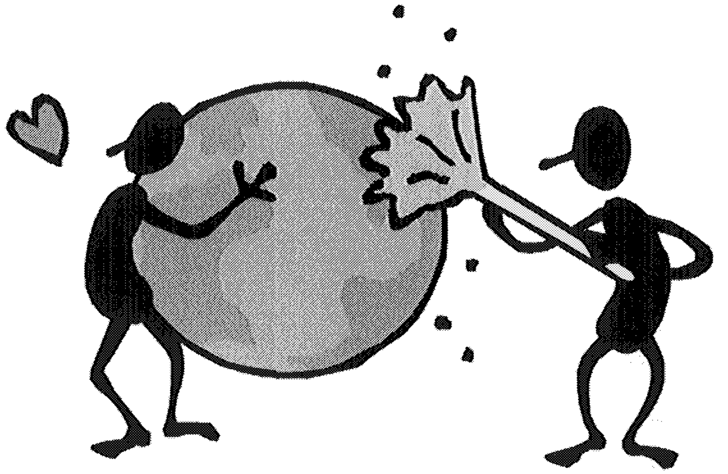
= F ( ,  ,  , t)

Thank you very much for your attention !



I will be very happy to answer your questions