Biofiltration Technology

For

Effective Control of Air Emissions

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- Theory of the Study
- Objectives
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Introduction

- **VOCs ?**

Volatile organic compounds (VOCs)

- **They are found in the waste stream emitted from most processes employing organic or petroleum based solvents.**

Introduction

VOC Emission and Regulation

1. **The passage of the 1990 Amendments to the Clean Air Act:**
   significantly heightened the interest in the development of innovative technologies for VOCs removal.
2. **VOCs are precursors to the formation of ozone, and they have their own toxicity.**
3. **International standard on environmental management (ISS14000):**
   demands the treatment of VOCs emission

Introduction

Wastewater treatment

1. **Source of VOCs to ambient atmosphere**.
   affected by the Clean Air Act Amendments.
2. **Depends on domestic, commercial, and industrial sources**
3. **VOCs are transferred into the air mainly in case of aerated bioreactor.**
   (activated sludge process)

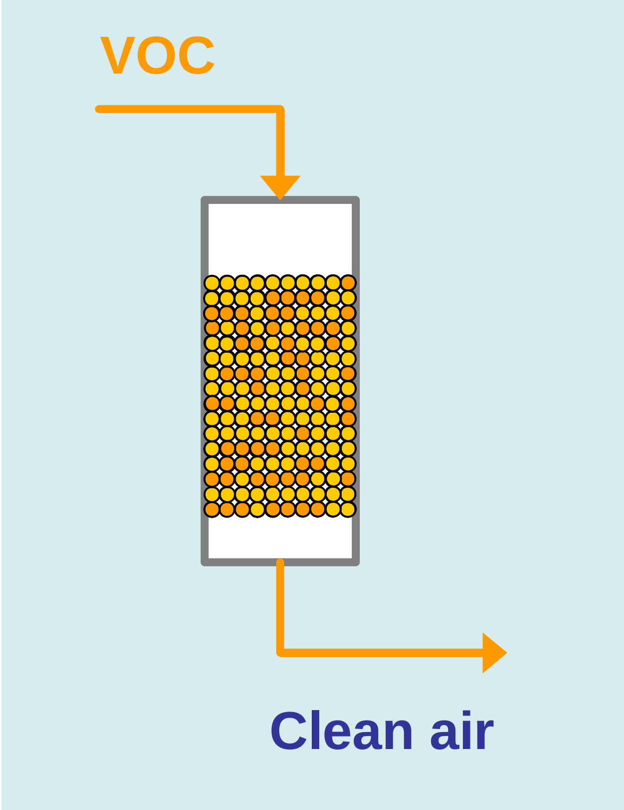
Introduction

VOC Removal technology

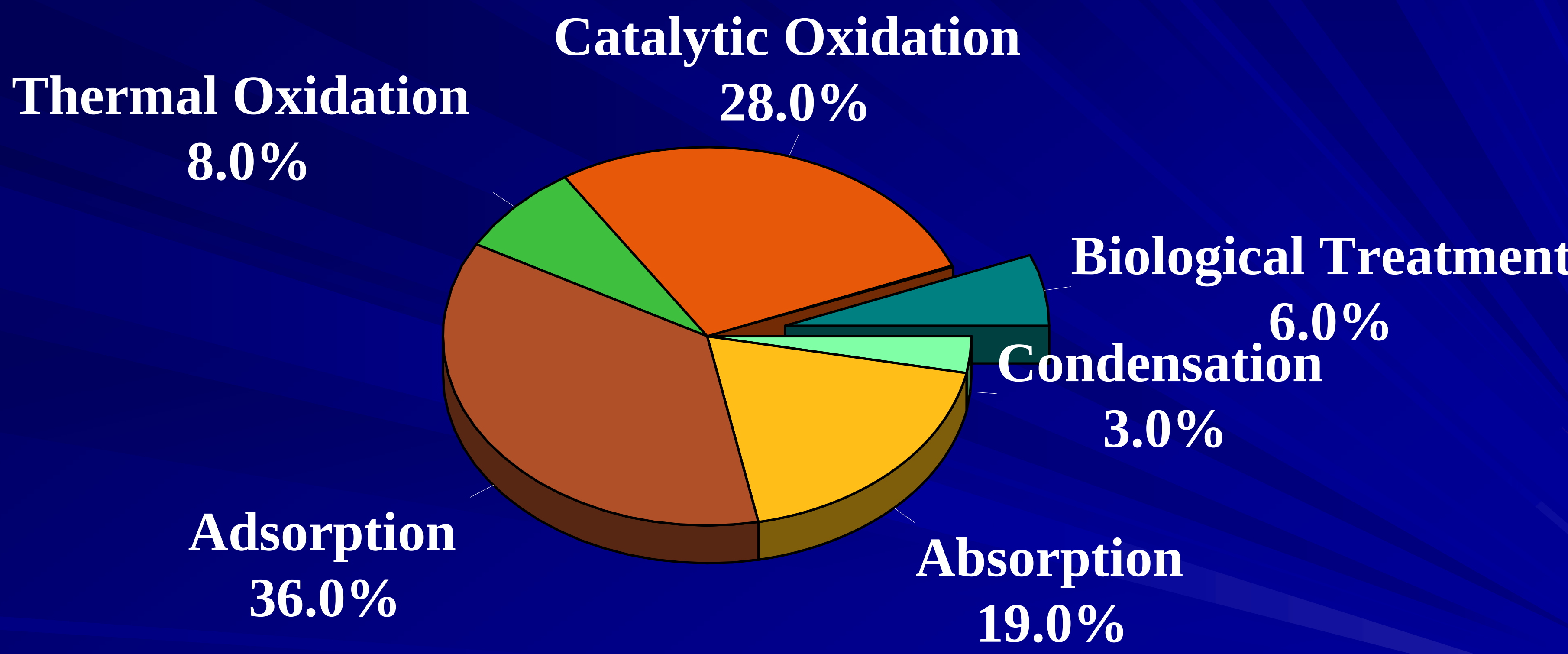
1. **Thermal oxidation, Catalytic oxidation, Condensation, Carbon adsorption, Membrane separation…**

2. **Biological treatment:**
   economical and ecological technology

3. **Biofiltration**



Air Treatment Processes

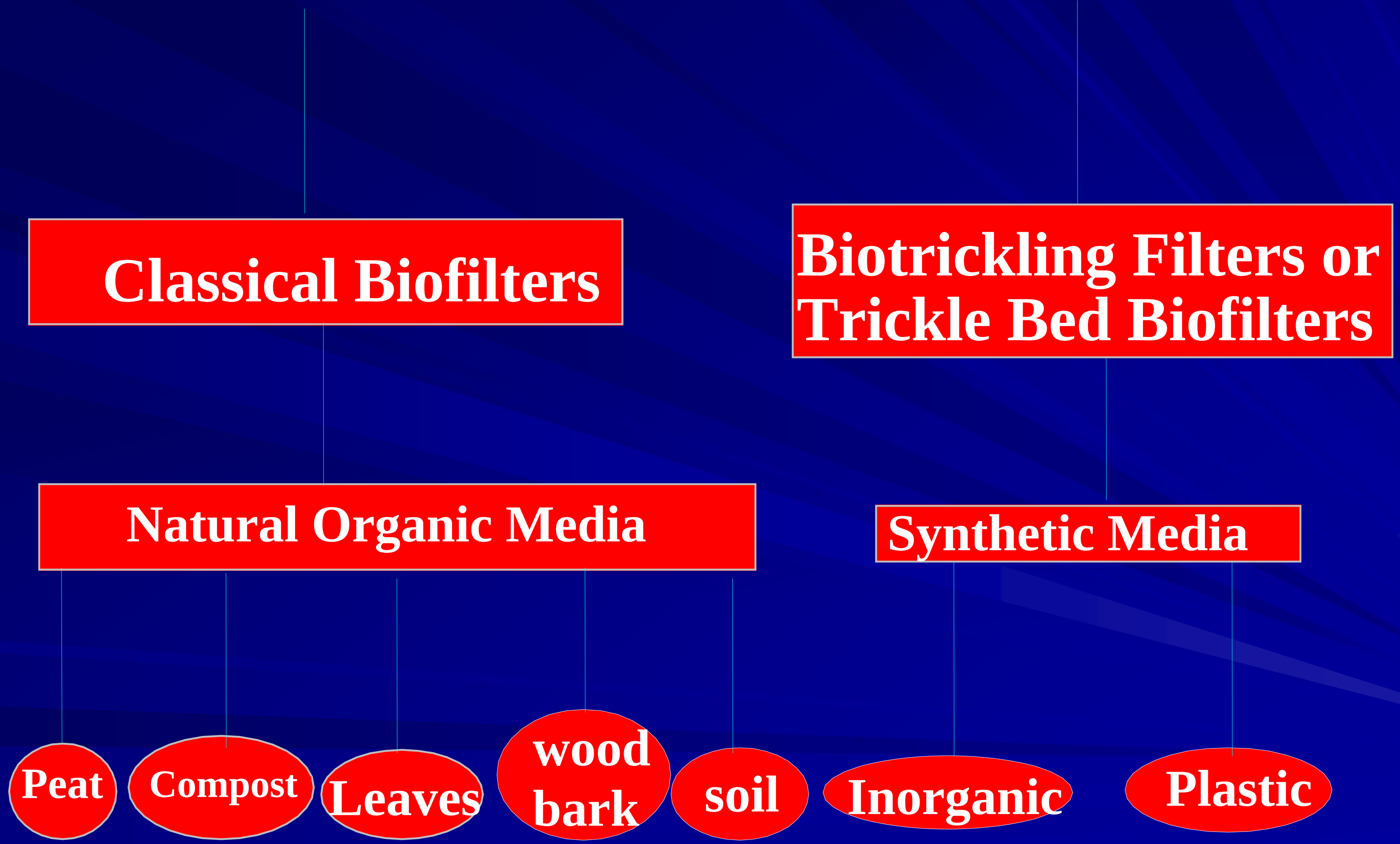


Biofiltration

Basic Design Principles

- Support Media
- Nutrients
- Moisture
- pH Control
- Adequate Oxygen Level
- Temperature

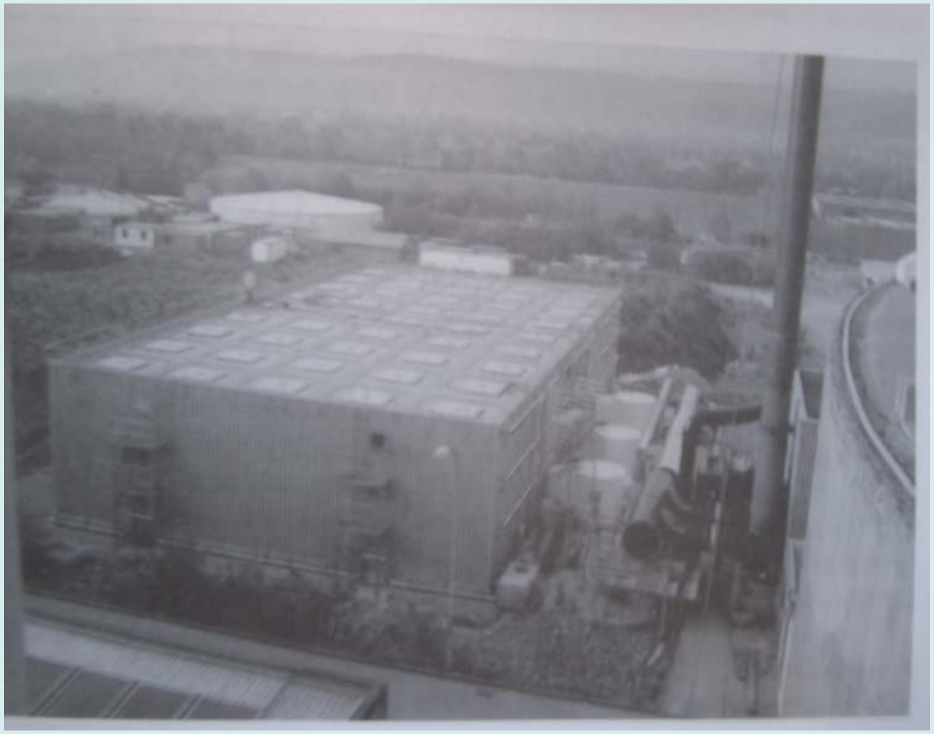
TYPES OF BIOFILTERS



Introduction

Application of biofiltration

1. **Owner and location:**
   Novartis; Basle, Switzerland
2. **Air flow rate:**
   60,000 – 75,000 m^3/h
   (Exhaust air from plant)
3. **Pollutants:**
   toluene, xylene, methanol, isopropanol, chloroform...
   Total conc. : 180 – 500 mg/m^3



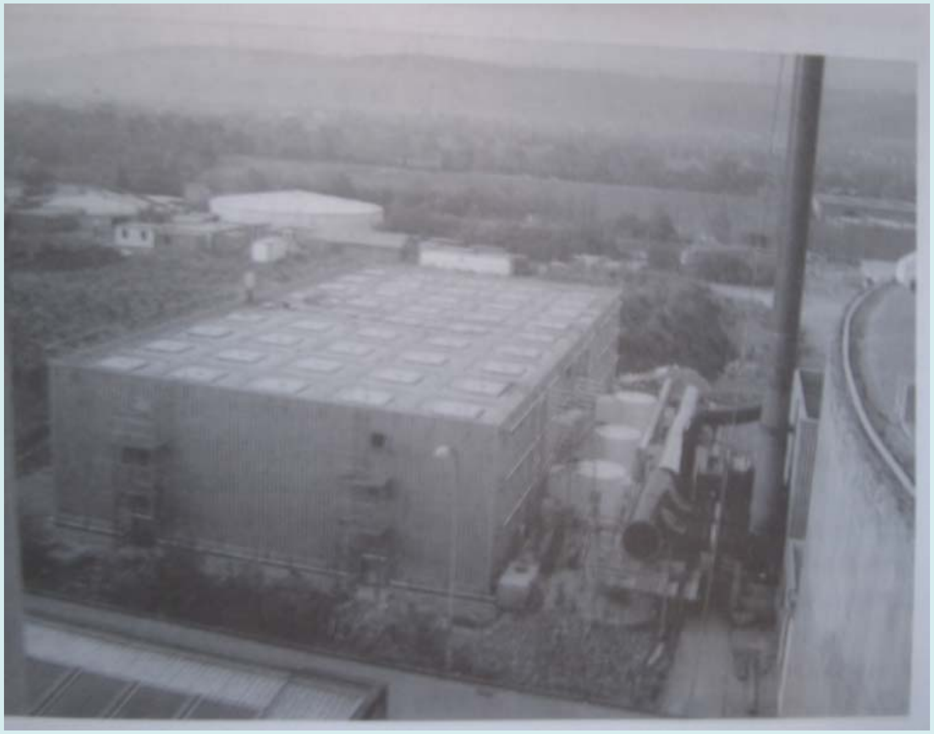
Introduction

Application of biofiltration

4. Biofilter Design
   Investment costs ($2,000,000)
   Treatment costs
   ($1.44 per 1000 m^3 off gas)

5. Biofilter Performance
   Removal: 80 %

   (depends on inlet loading)



CLASSICAL BIOFILTERS

NATURAL ORGANIC MEDIA

Demonstrated Characteristics:

- **Loading limited (degradation rate of the medium is much higher than the VOC degradation rate. The VOC input has minor effect on microbial activity)**

- **Sensitive to moisture content**

- **Very sensitive to temperature**

Biofilter Applications History

Pre 1990: Principally for Nuisance Odor Control

- Sewage Treatment Odors
- Livestock Raising , Processing, and Rendering
- Flavors and Fragrances: Extraction / Processing
- Commercial Composting

Post 1990: Developed for VOC / Volatile Toxics Control

- Groundwater Remediation: Vacuum Extraction Venting
- Fibers Processing: Rayon Fiber
- Industrial Finishing : Painting, Lacquering, Printing
- Commercial Fermentation: Bakeries, Breweries

Biotrickling Filters

Conceptually identical process to the biofilter

- Microbial attachment: Synthetic inorganic or polymeric media
- Intermittent delivery of Nutrient & Buffer to the media

→
- ✓ **Consistent Nutrient & pH control**
- ✓ **Optimizing the waste utilizing kinetics**

↑

Trickle-Bed Air Biofilter (TBAB)

↓

- **Consistent**
- **Long-term**
- **High**

Removal Performance

Biotrickling Filters

for more successful application in industry

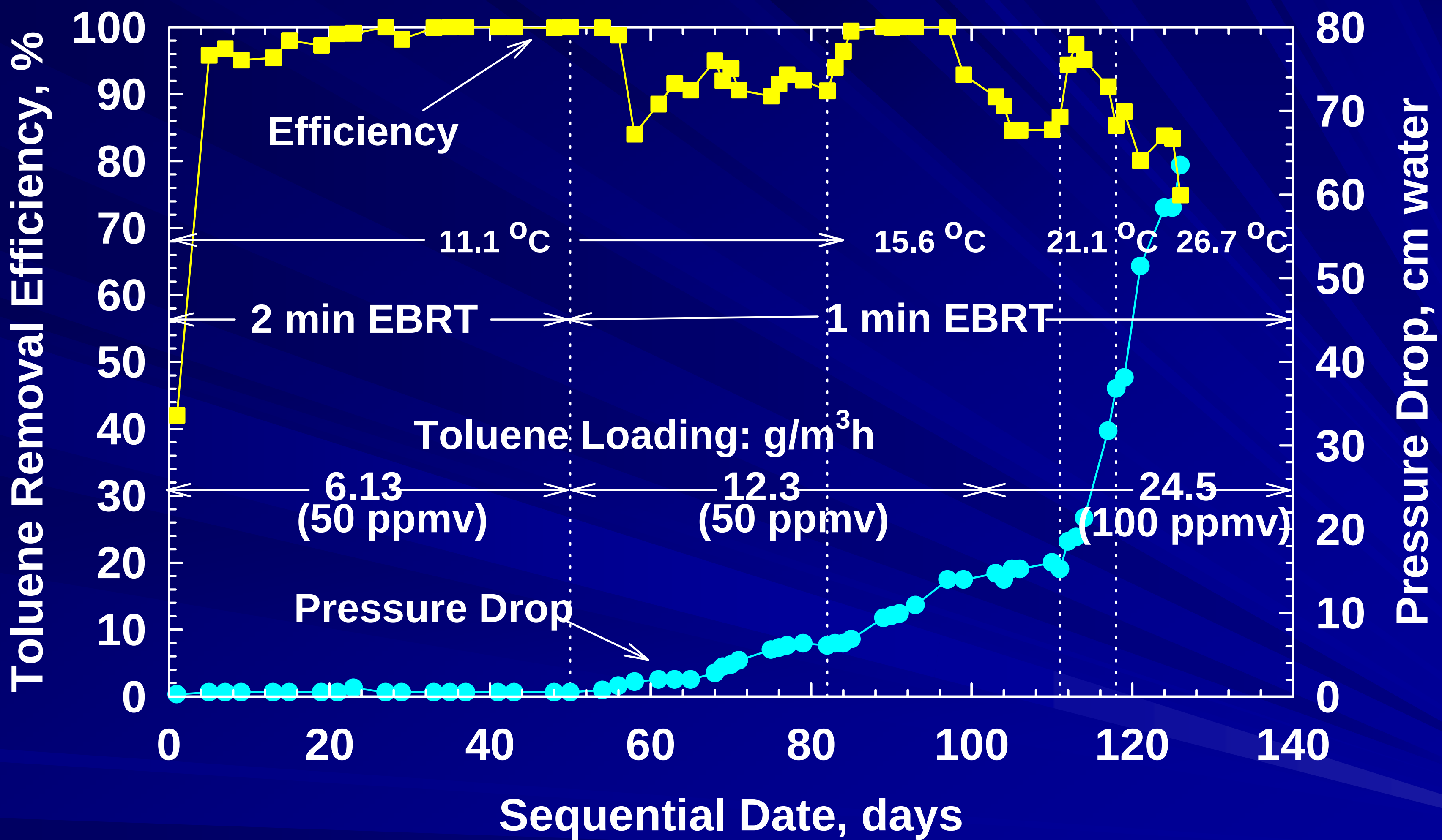
Challenges

Source Characteristics

- Transient loading
- VOCs composition
- Emission mode: non-use periods

Biofilter Maintenance

- Biomass accumulation
- Microbial activity



Performance of Pelletized Biofilter at 1 and 2 Minutes EBRT without Backwashing

Solution

In situ up-flow washing with water, i.e., backwashing at a rate sufficient to fluidize the media and permit rapid removal of excess biomass growth

IMPACT of NUTRIENT-N SPECIES

The relative performance of two biofilters was evaluated by varying the form of nutrient nitrogen

Nitrate-N vs Ammonia-N:

Nitrate-N fed biofilter demonstrated the following advantages:

- **Better steady state performance (overall)**
- **Better recovery after backwash with time**
- **Better removal with depth**
- **Lower microbial yield (about 40% less)**

Objective

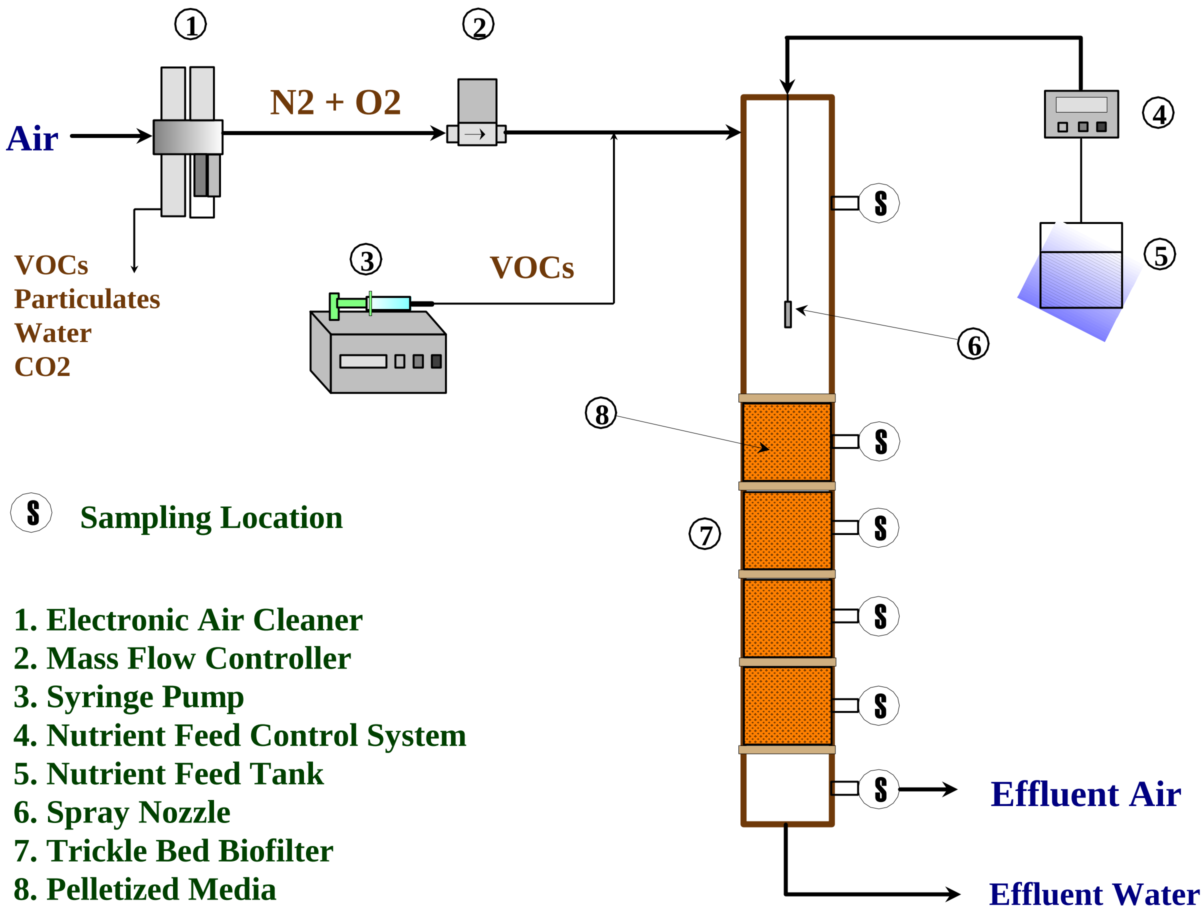
Characterization of TBAB performance

- Effect of step-change in influent concentration (Phase I)
- Effect of non-use periods (Phase I)
- Effect of interchanging the feed VOCs (Phase II)
- Effect of Varying VOCs composition (Phase III)

Materials and Methods

- Reactor : Independent lab-scale TBAB
- Media: pelletized biological support media

Materials and Methods



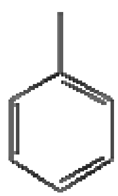
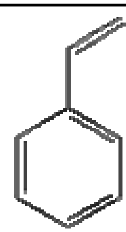
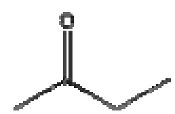
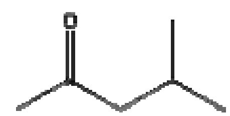
1. Electronic Air Cleaner
2. Mass Flow Controller
3. Syringe Pump
4. Nutrient Feed Control System
5. Nutrient Feed Tank
6. Spray Nozzle
7. Trickle Bed Biofilter
8. Pelletized Media

Characterizing TBAB Performance

- Determination of critical loading
- Impact of non-use periods on performance

Materials and Methods

- **Feed VOCs**

	Hydrophobic compounds		Hydrophilic compounds	
	Toluene	**Styrene**	**Methyl ethyl ketone** (MEK)	**Methyl isobutyl ketone** (MIBK)
				
K'_H	0.280	0.109	0.00194	0.00062
Log K_{ow}	2.58	3.16	0.28	1.09

K'_H = dimensionless Henry's law constant, *K_{ow} = Octanol-water partition coefficient*

Phase I: Biofilter Study

- **Experimental Conditions**

	Toluene	Styrene	MEK	MIBK
Inlet Conc., *ppmv*	50 ~ 500	50 ~ 330	50 ~ 500	50 ~ 250
Loading rate *kg COD/m^3·day*	0.7 ~ 7.03	0.64 ~ 3.17	0.7 ~ 7.03	1.09 ~ 5.43
EBRT, *min*	1.23	1.51 ~ 2.02	0.76	0.76

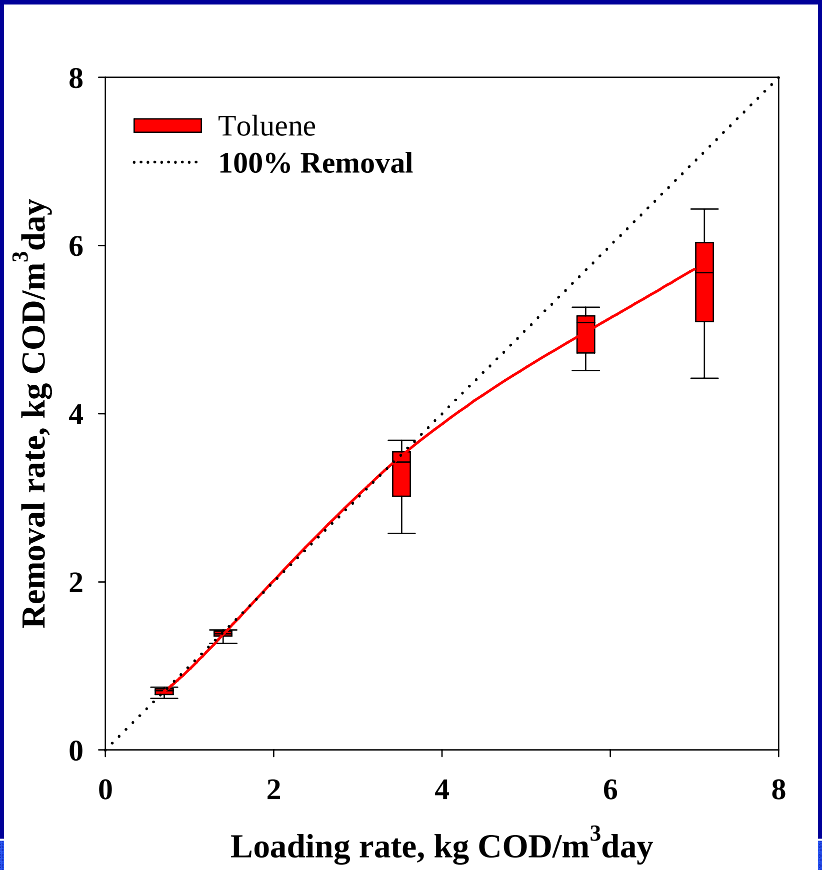
Phase I: Biofilter Study

- Results – VOC removal capacity (Backwashing)

Aromatic compounds

Toluene

- Critical loading
  - 3.5 kg COD/m^3·day
  - (46.6 g/m^3·hr)
- Maximum removal capacity
  - 6.0 kg COD/m^3·day
  - (79.9 g/m^3·hr)



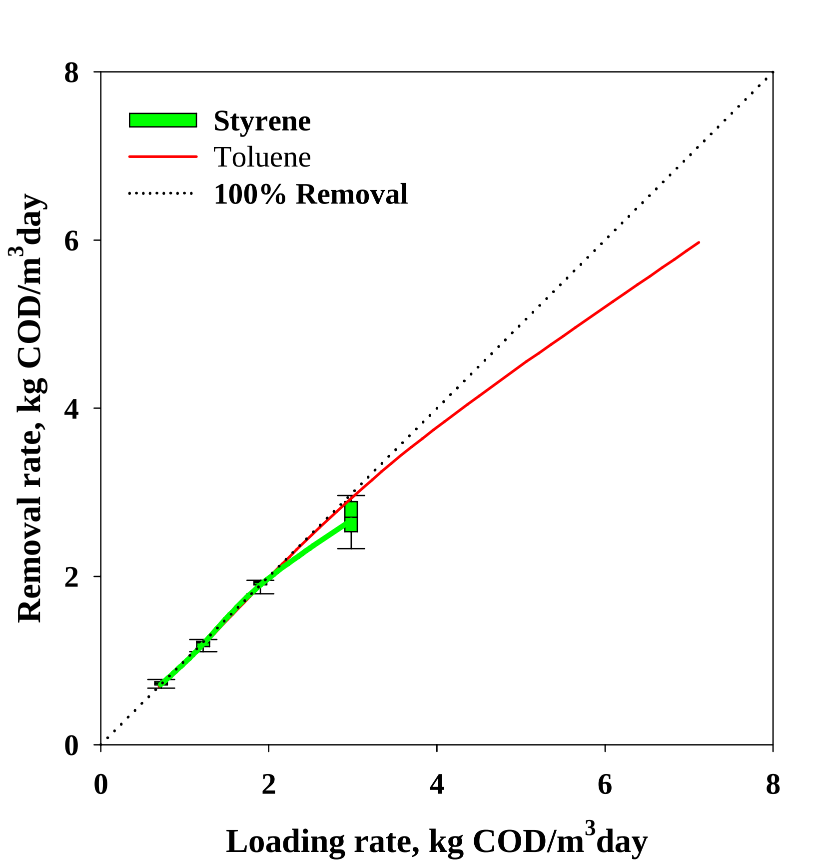
Phase I: Biofilter Study

- Results – VOC removal capacity (Backwashing)

Aromatic compounds

Styrene

- Critical loading
  1.9 kg COD/m^3·day
  (25.8 g/m^3·hr)
- Maximum removal capacity
  2.7 kg COD/m^3·day
  (36.6 g/m^3·hr)



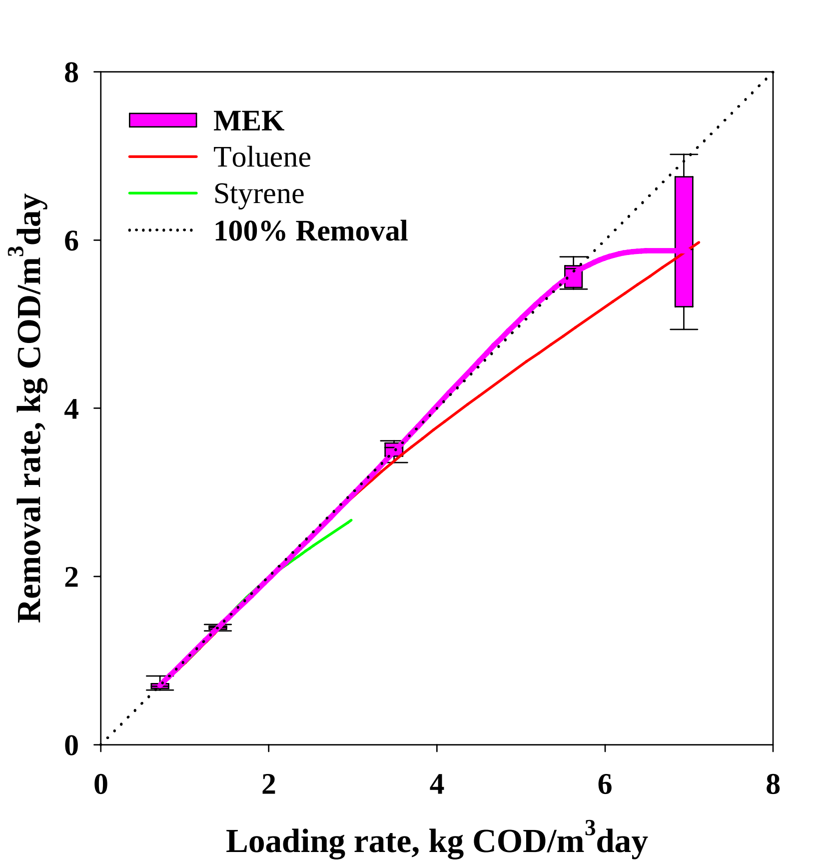
Phase I: Biofilter Study

- Results – VOC removal capacity (Backwashing)

Oxygenated compounds

MEK

- Critical loading
  5.6 kg COD/m³·day
  (95.6 g/m³·hr)
- Maximum removal capacity
  5.9 kg COD/m³·day
  (100.7 g/m³·hr)



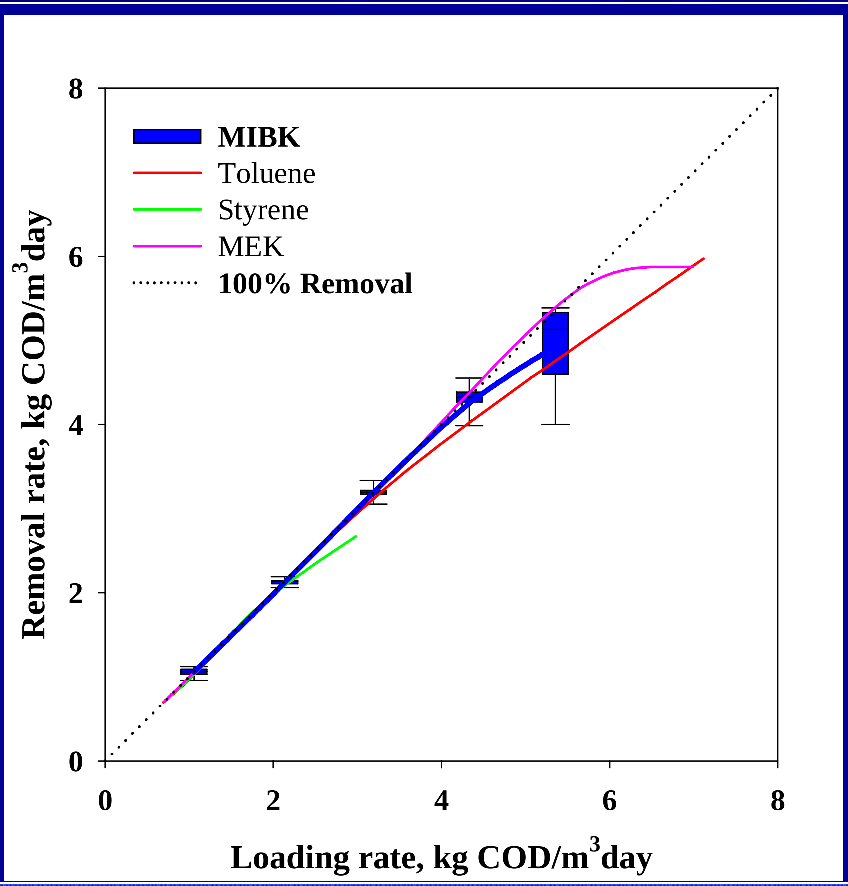
Phase I: Biofilter Study

- Results – VOC removal capacity (Backwashing)

Oxygenated compounds

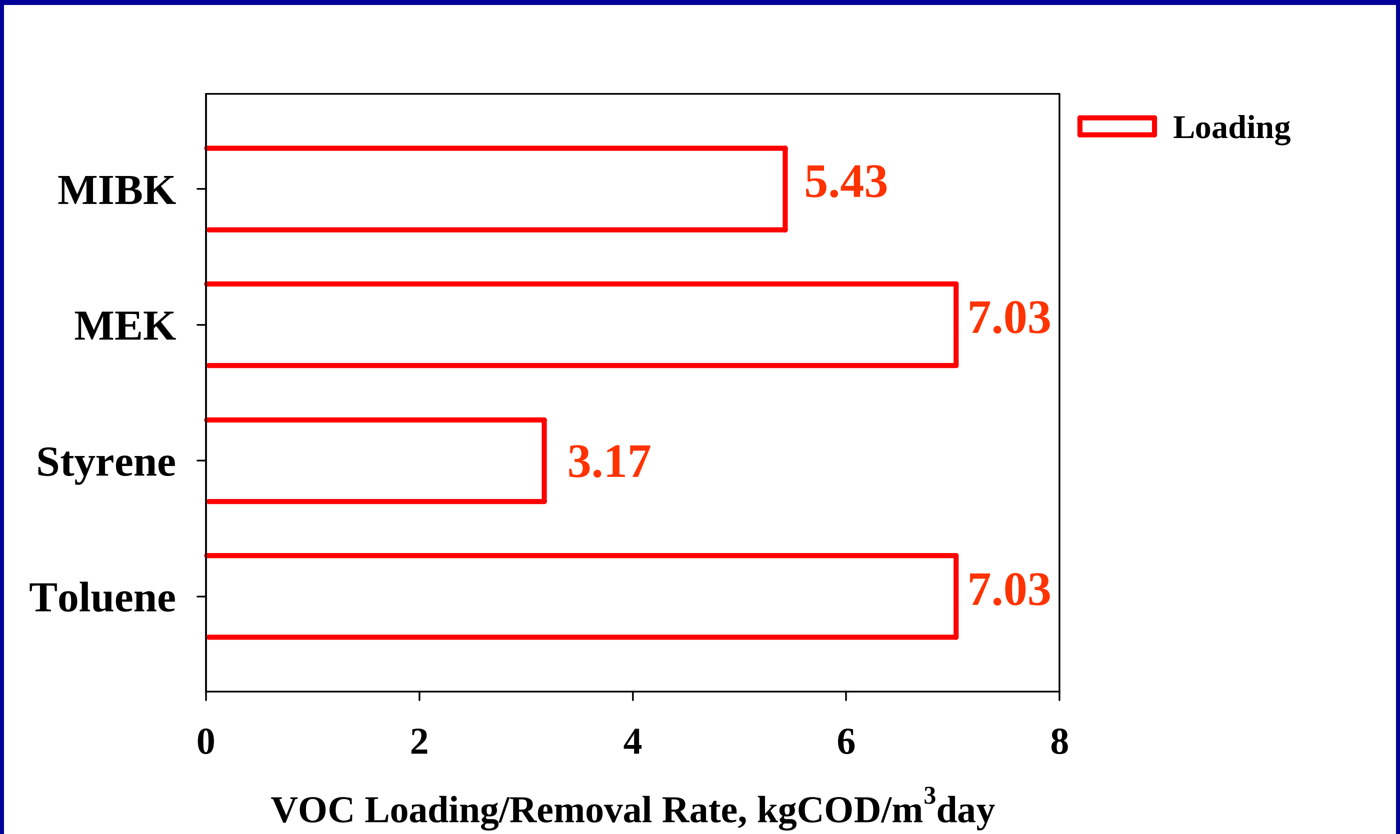
MIBK

- Critical loading
  - 4.3 kg COD/m³·day
  - (65.9 g/m³·hr)
- Maximum removal capacity
  - 4.9 kg COD/m³·day
  - (75.1 g/m³·hr)



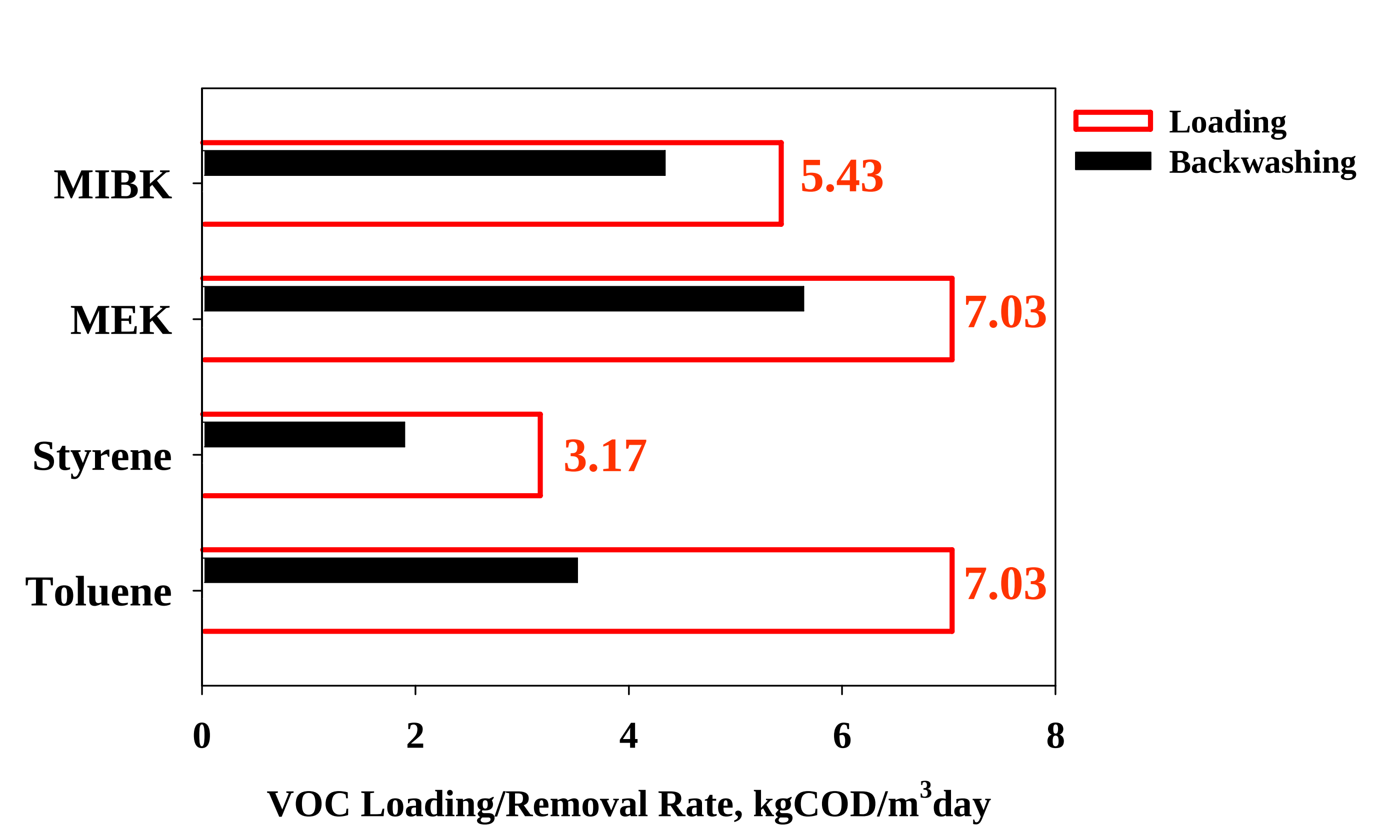
Phase I: Biofilter Study

- Results – Comparison of VOC removal capacity



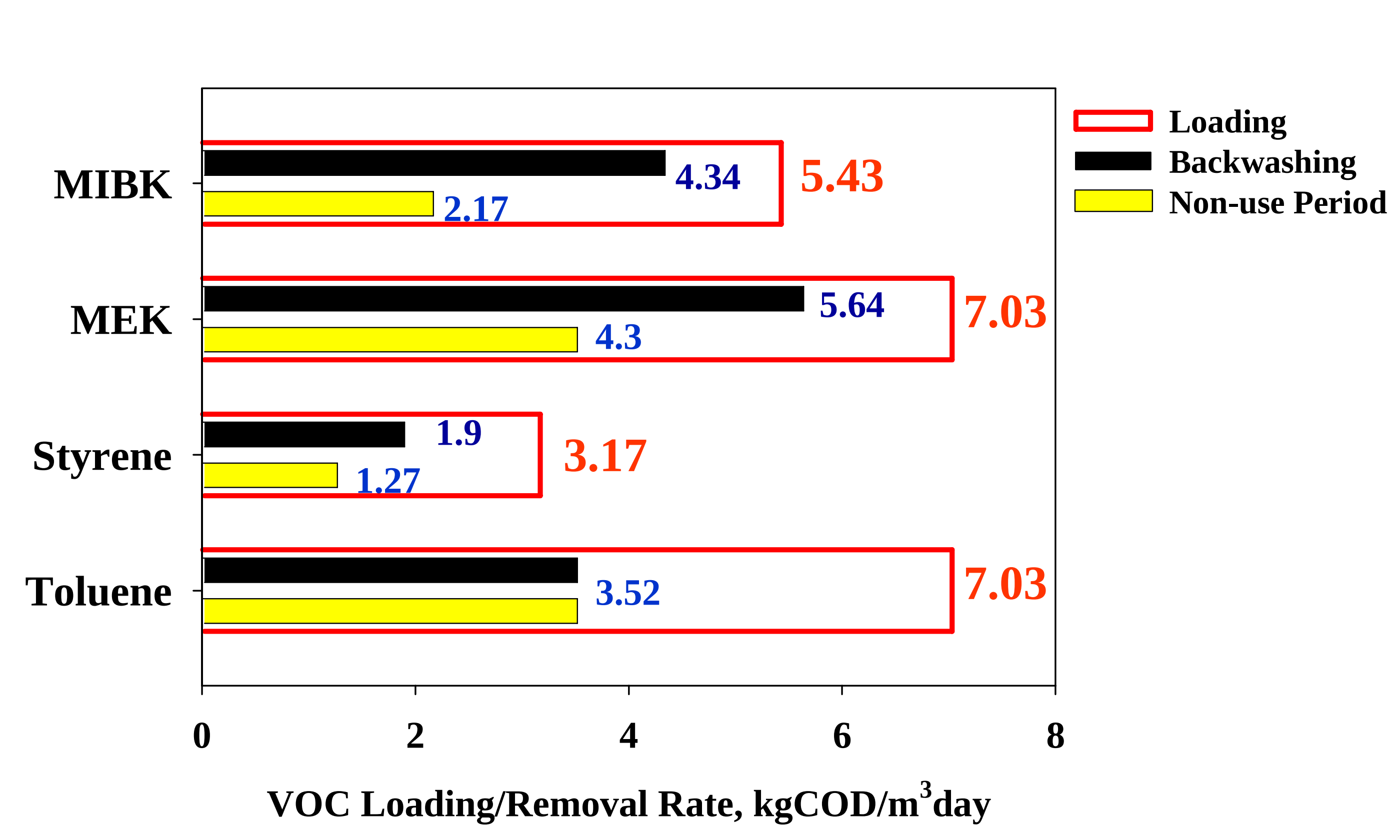
Phase I: Biofilter Study

- Results – VOC removal capacity



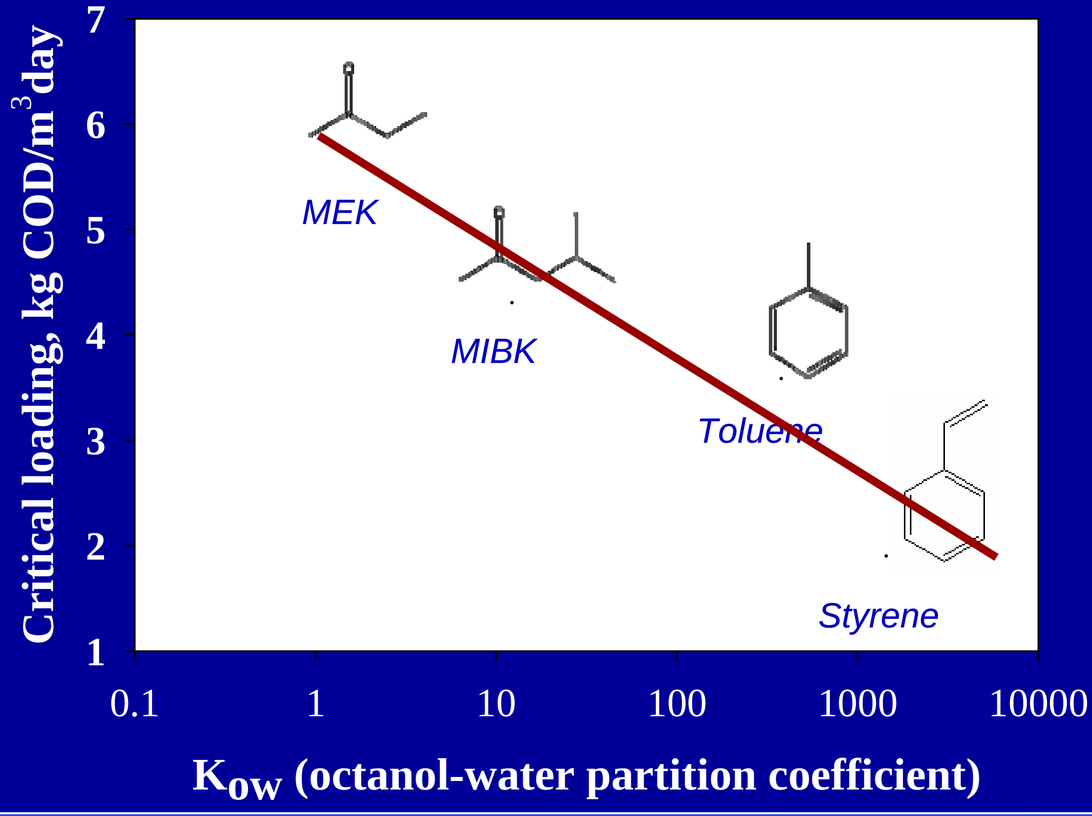
Phase I: Biofilter Study

- Results – VOC removal capacity



Phase I: Biofilter Study

- Results – Critical loading vs. Kow



Phase I: Biofilter Study

Summary

Experimental findings supported the handling limitation of performance of the current biofiltration system

1. Up to the critical VOC loading rate, the backwashing was effective biomass control to attain consistently high removal performance.

2. Non-use periods can be considered as another means of biomass control at lower VOC loading rate.

3. Reacclimation was a critical factor in biofilter peformance. After non-use periods, the active biomass affects biofilter response.

Impact of Interchanging VOCs on the Performance of Trickle-Bed Air Biofilter

Phase II

Interchanging VOCs

➢ **Operating Condition**

- **Sequence of Feed VOCs**

  Styrene → MEK → Toluene → MIBK → Styrene

- **Inlet concentration of feed VOCs**

  50 ppmv ~ the maximum allowable inlet concentration

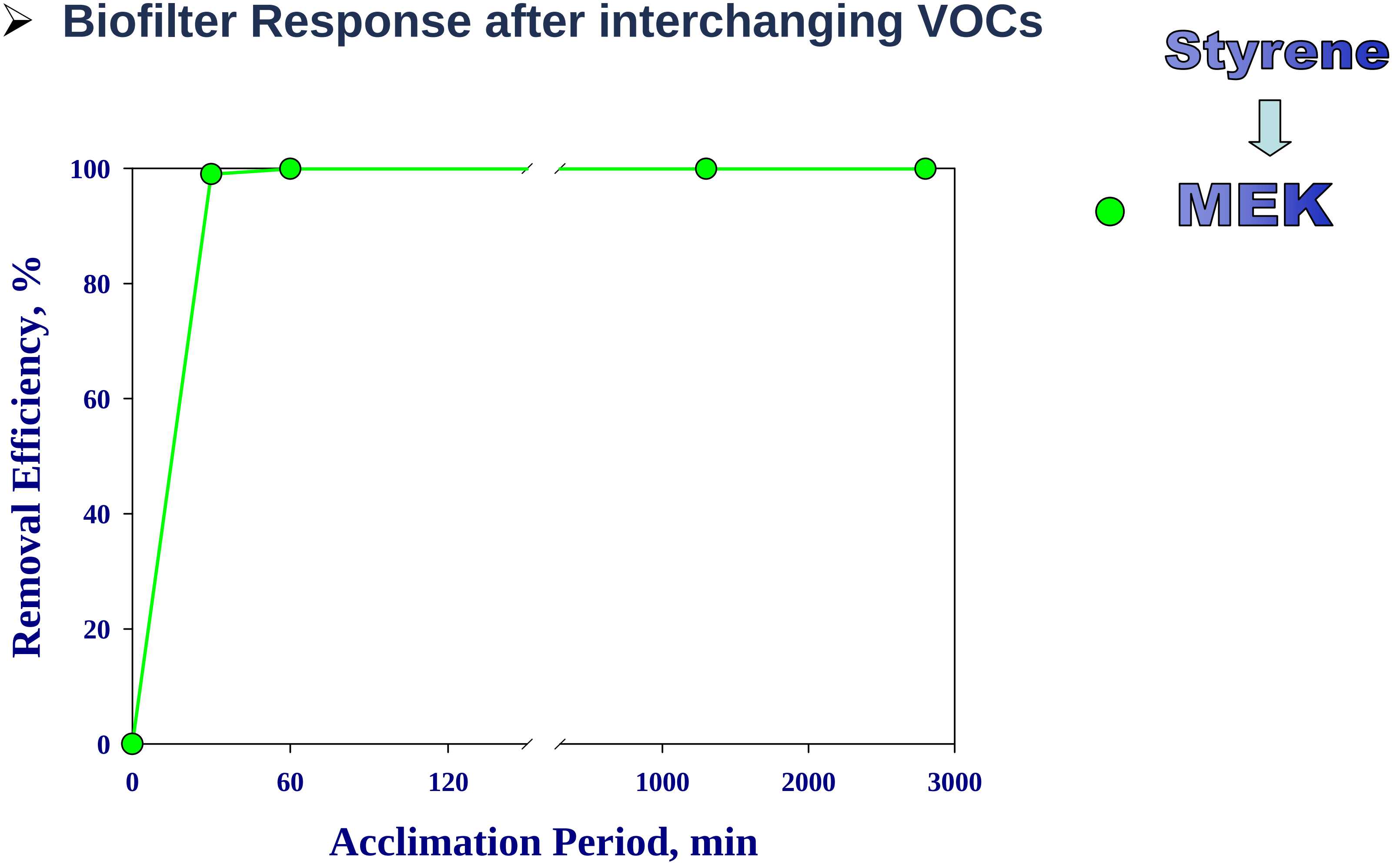
- **Flow rate**
  - **Nutrient solution: 1.5 L/day**
  - **Air: 1.35 L/min (EBRT = 2.02 min)**

- **Biomass control : Periodic in-situ backwashing**

  Frequency: 1 hour of duration / a week

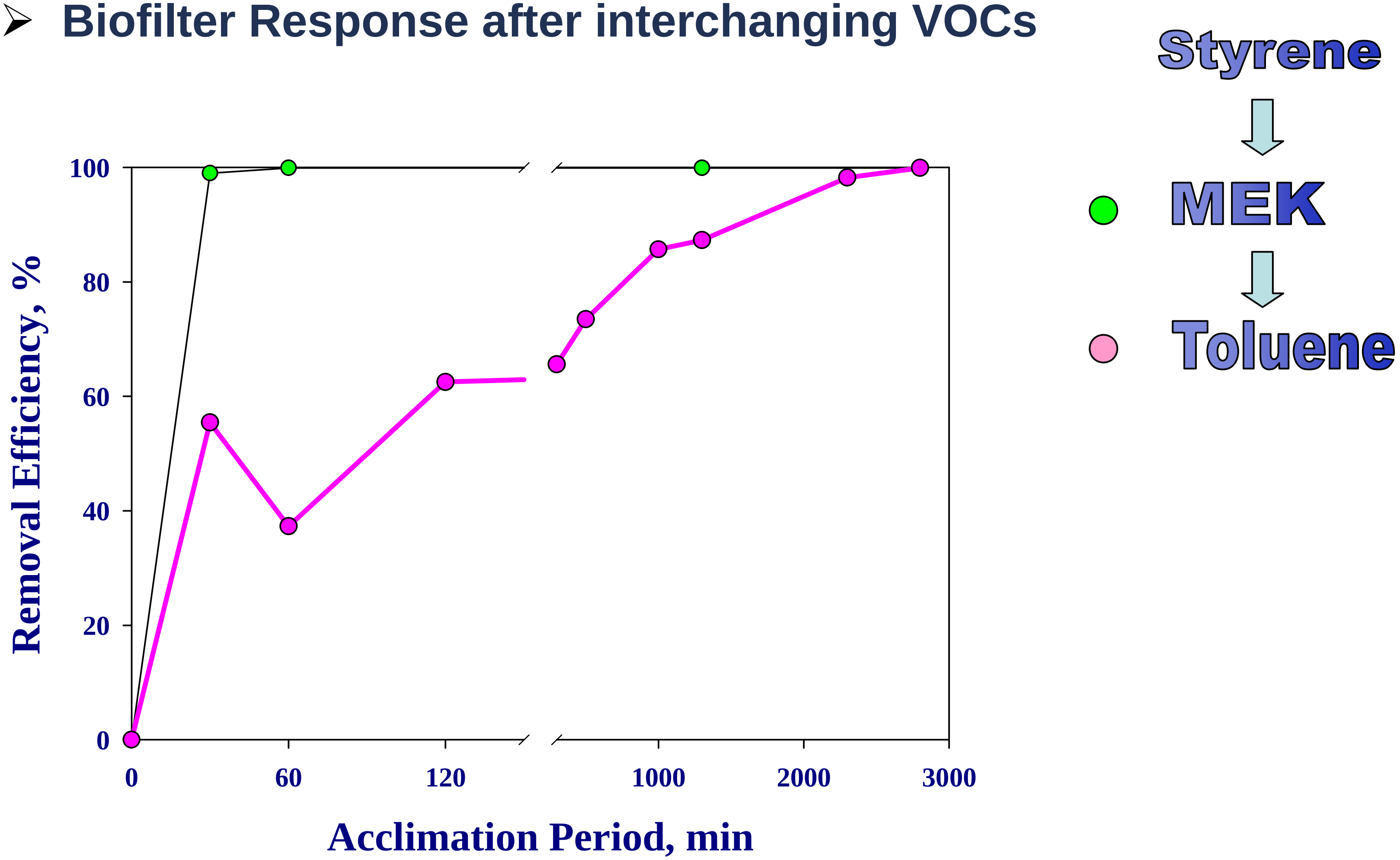
Results

- Biofilter Response after interchanging VOCs



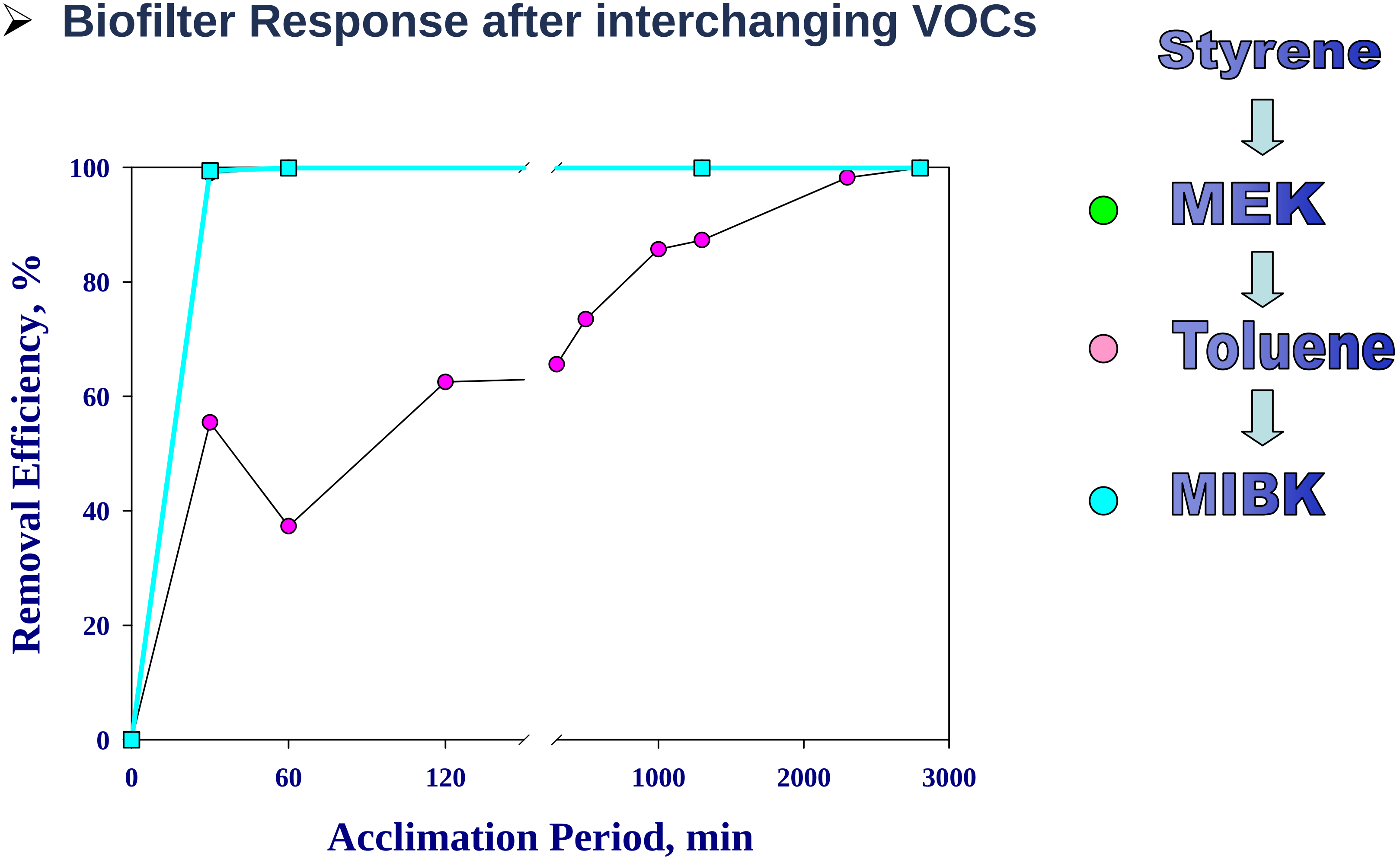
Results

- Biofilter Response after interchanging VOCs



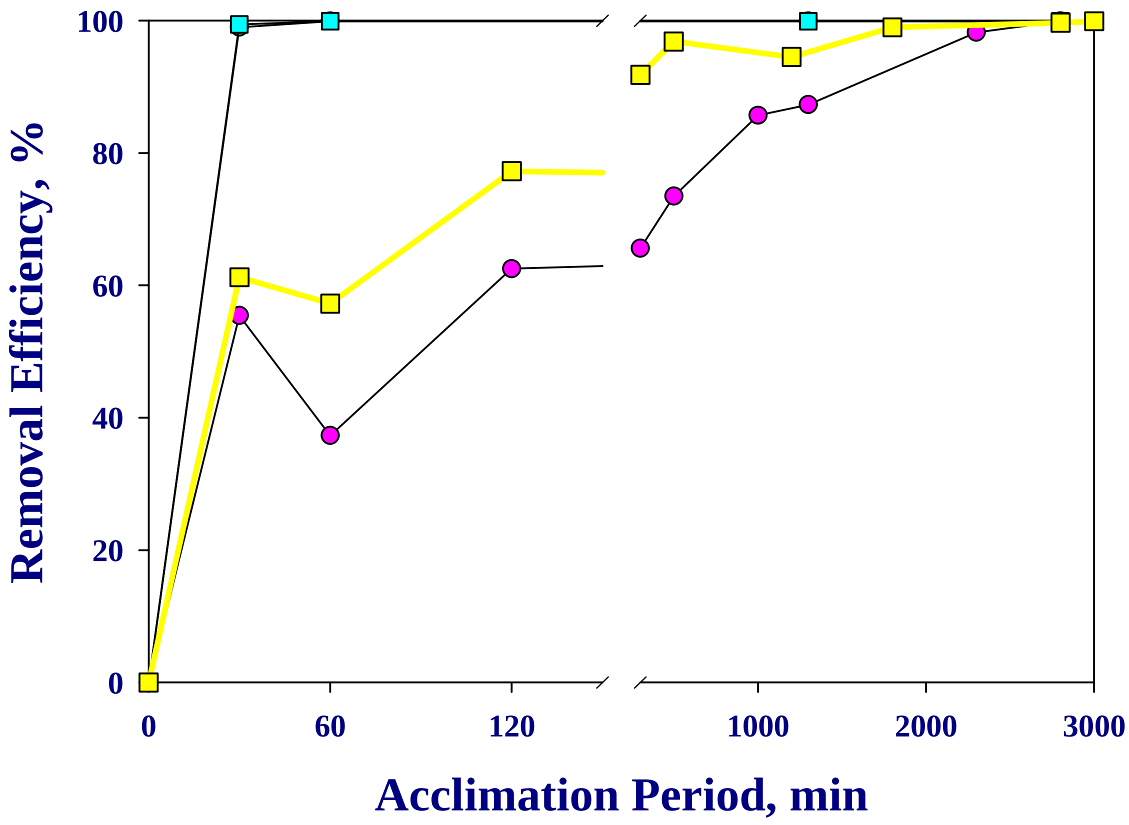
Results

- Biofilter Response after interchanging VOCs



Results

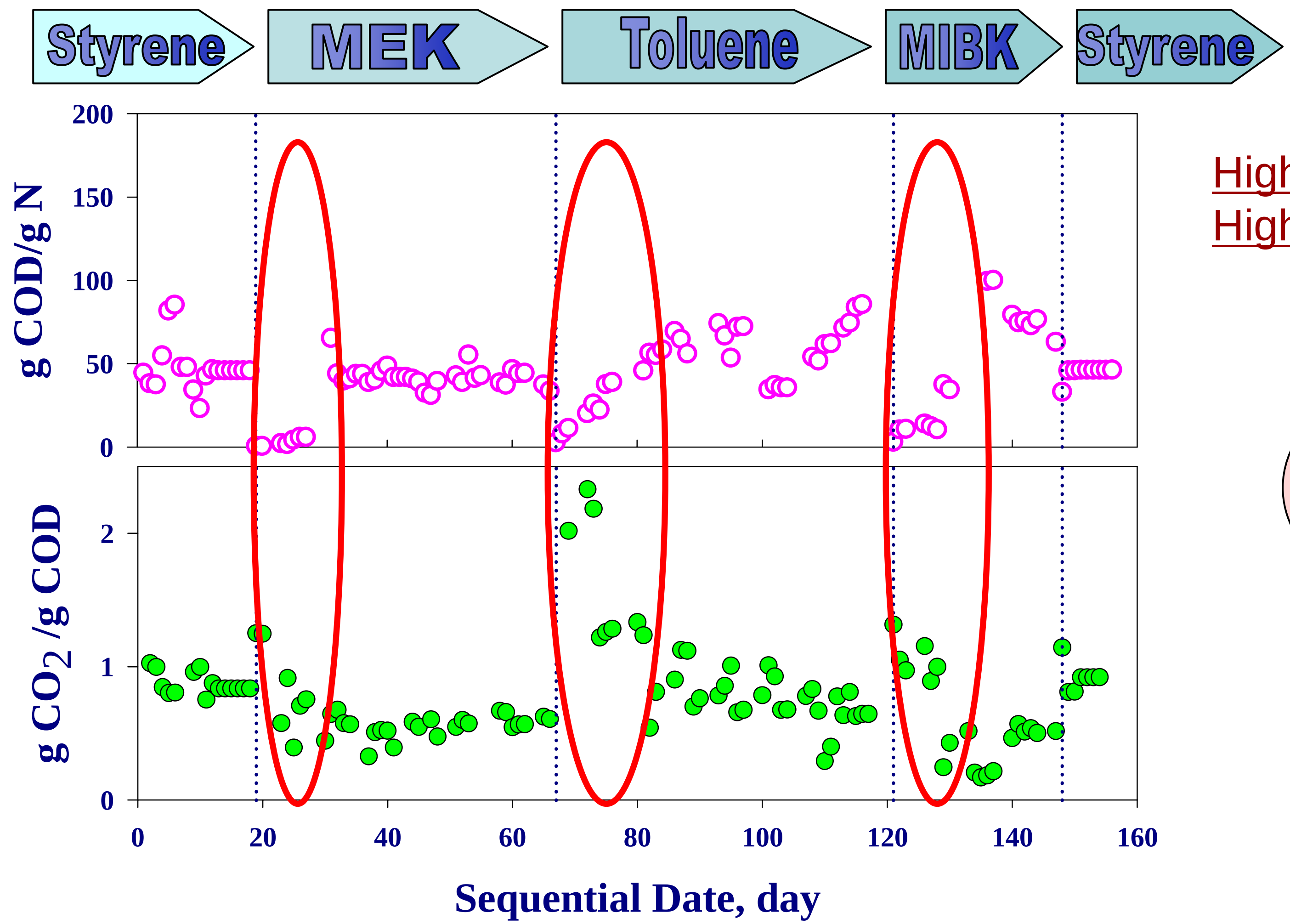
- Biofilter Response after interchanging VOCs



Styrene
⇓
MEK
⇓
Toluene
⇓
MIBK
⇓
Styrene

Results

➢ **Nitrogen Utilization and CO_2 Production**



High N utilization
High CO_2 /COD

Why?

Discussion

High N utilization
High CO_2 /COD

Possbile Reason

1. Need more proteins to make up the enzymes for utilizing new substrate

- More utilization of nitrogen

2. Facultative organisms: Denitrifying microorganisms

- Nitrogen utilization and CO_2 Production

Study of Microbial community structure & diversity

Summary of Phase II Study

- **High removal performances were observed in the interchanging VOC-fed TBAB.**

- **TBAB easily acclimated to hydrophilic compounds (MEK & MIBK), while TBAB acclimations to hydrophobic compound (Toluene & Styrene) were delayed for more than 45 hrs.**

- **Right after interchanging feeding VOCs, TBAB has shown unusual performances (high nitrogen utilization & high CO_2/COD).**

Effect of Varying VOC Concentration

Phase III

Use of Integrated Systems

Load fluctuation

Solution = Buffer unit

Adsorption unit can be a buffer unit for a biofilter

Current application : Single bed of carbon filter

Consideration of current adsorption unit
High loading & Large fluctuation → Losing buffer capacity
Initial period of operation → No contaminant in effluent

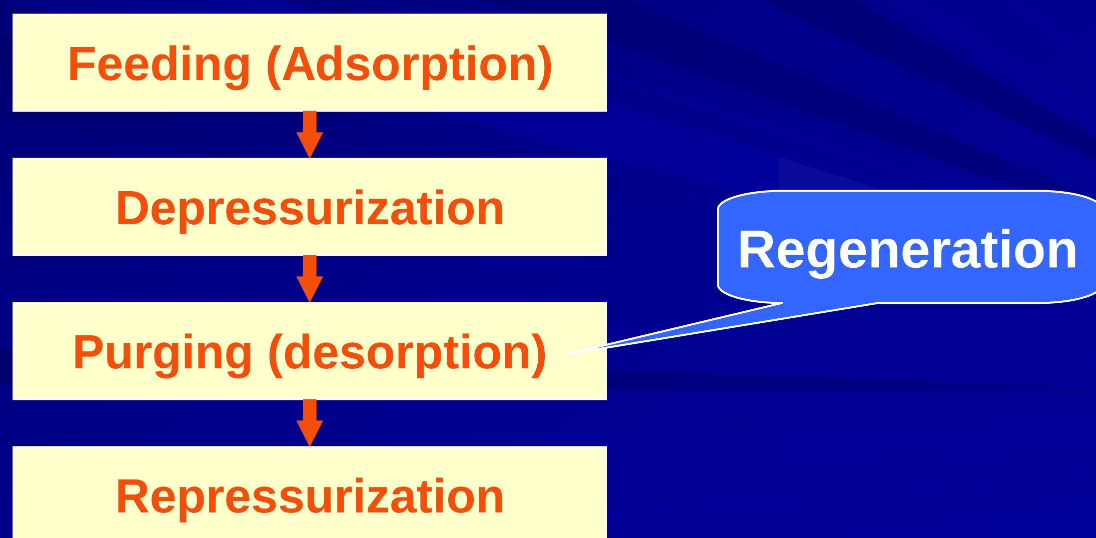
Theory of 2-Bed Adsorption

2-Bed Adsorption Unit

- Conceptually simple process to PSA
- PSA (Pressure Swing Adsorption) :

  → A technology for separation and purification for gas mixtures

  → 4 Steps for operational function



Theory of 2-Bed Adsorption

2-Bed Adsorption Unit

- Conceptually simple process to PSA
- Hypothetically, adsorption rate is equal to its desorption rate

  → Operational function is simplified to a 2-step

Feeding (Adsorption)

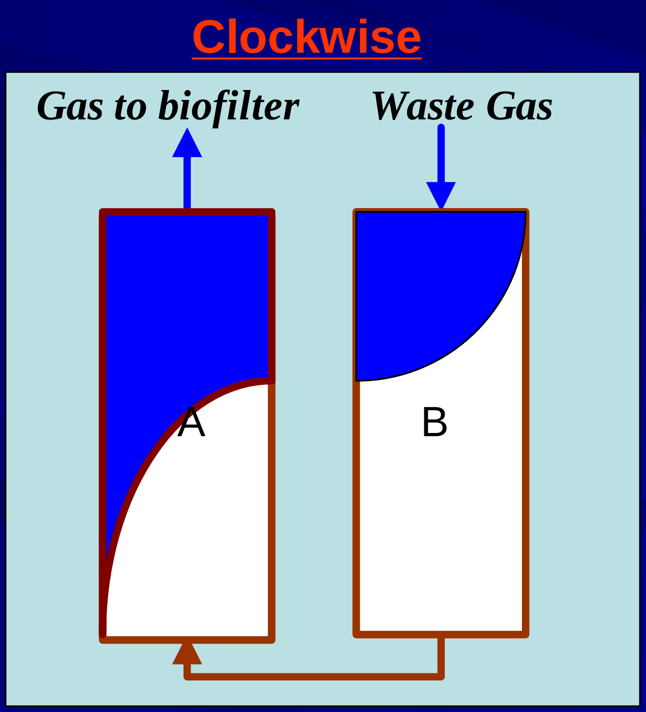
↓

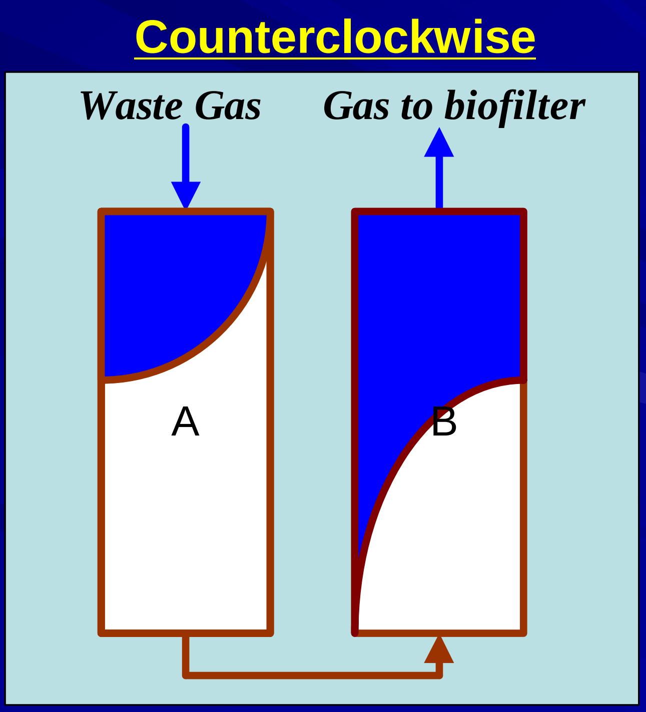
Purging (desorption) — Regeneration

Theory of 2-Bed Adsorption

2-Bed Adsorption Unit

- Cyclic operation : Shift of air flow direction
  → Each bed will not be fully saturated with adsorbate





Phase II: Adsorption Study

2-Bed Adsorption

- **Concept**

Will serve as

- Polishing unit during the initial acclimation period of the biofilter
- Buffer unit in load fluctuation
- Feeding source without any feeding phase during non-use periods

Objective

Main Objective

Evaluate Cyclic operation of 2-bed adsorption unit as load equalization
For air biofiltration system

Specfic Objective

- Mathematically simulate 2-bed adsorption unit performance
  to compare Cyclic operation vs. Non-cyclic operation

- Experimentally evaluate the performance of the integrated scheme of
  2-bed adsorption unit with air biofilter under transient loading of
  toluene (Integrated unit vs. control unit)

Phase II: Adsorption Study

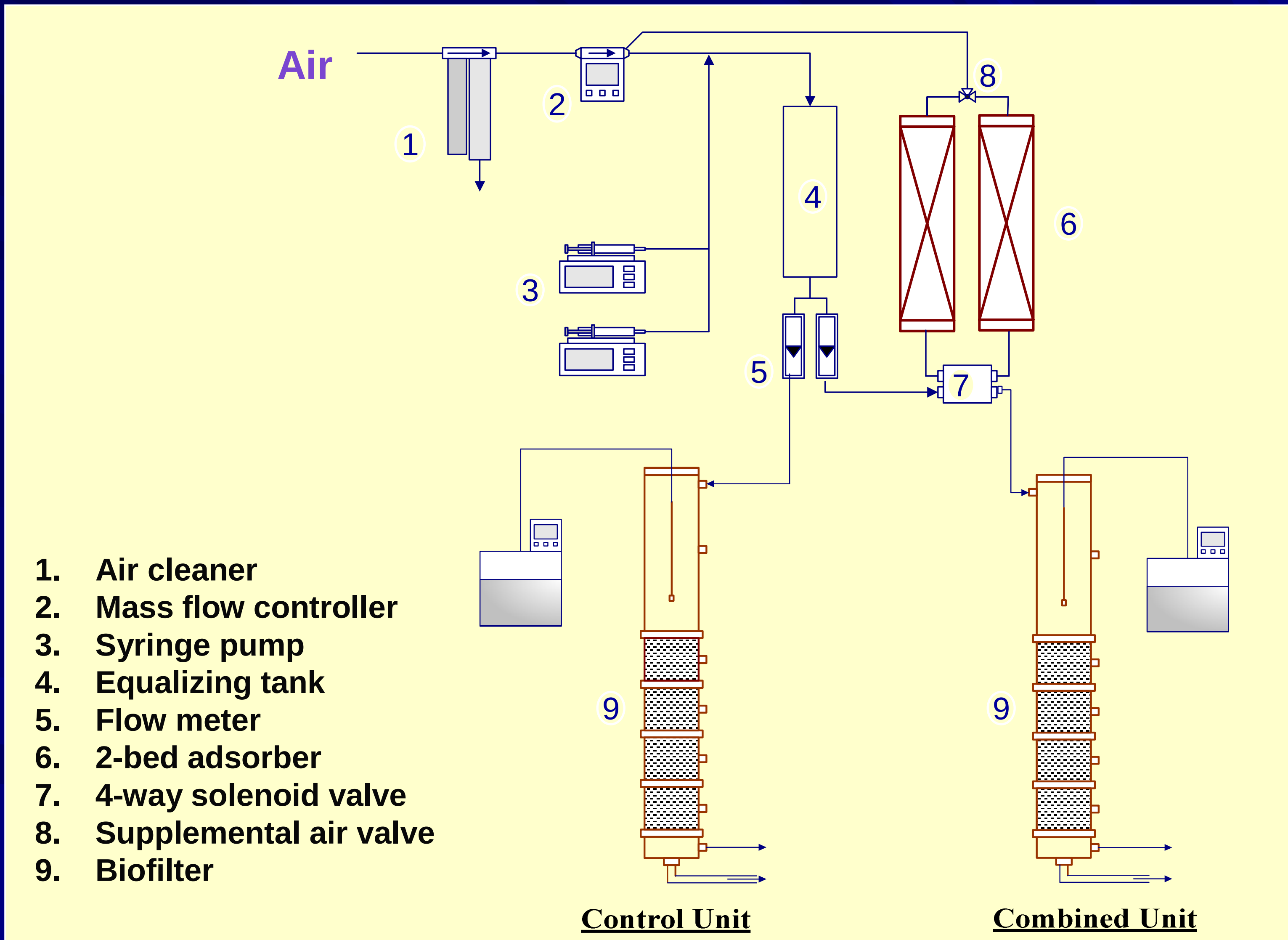
2-Bed Adsorption

- **Experimental Methods**

• 2 Beds
• Dimension : 2.5 cm (D) × 20 cm (L)
• Duration of one cycle : 8 hours
• EBRT: 5.6 sec (2.2 L/min)

• Adsorbate : Toluene
• Adsorbent : GAC (BPL 6 × 16)

Schematic Diagram of Experimental Setup



Results: Model Simulation

Model Simulation

- Model simulation of cyclic operation of 2-bed adsorption

- Model simulation of non-cyclic operation of 2-bed adsorption

Model Simulation

• Model simulation of cyclic operation of 2-bed adsorption

Mathematical model is formulated for a packed bed for simulation of the proposed cycle, which consists of overall and component material balances.

- Linear driving force model is incorporated into the model in order to include a mass transfer resistance with an adsorbent from a bulk gas phase.
- Freundlich isotherm equation is used for expression of isotherm capacity.

Assumption: (1) no pressure drop along a bed, (2) an isothermal operation, and (3) a plug flow through a bed with no dispersion.

• Model simulation of non-cyclic operation of 2-bed adsorption

Model Simulation

- Model simulation of cyclic operation of 2-bed adsorption

- Model simulation of non-cyclic operation of 2-bed adsorption

Plug flow homogeneous surface diffusion model (PFHSDM) which is embedded in an **Adsorption Design Software** (*AdDesignS*^{TM}) developed by Michigan Technological University is used.

The mechanisms incorporated in this model are:

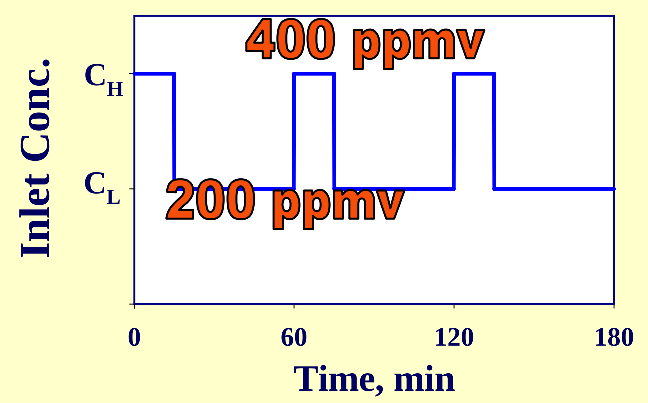
- Homogeneous surface diffusion
- Film transfer resistance at the adsorbent surface
- Advection dominates axial transport in bed.
- Local equilibrium Freundlich isotherm exists at the adsorbent surface.
- Freundlich isotherm equation is used for expression of isotherm capacity.

Model Simulation

- **Effluent Response in 2-bed Adsorption**

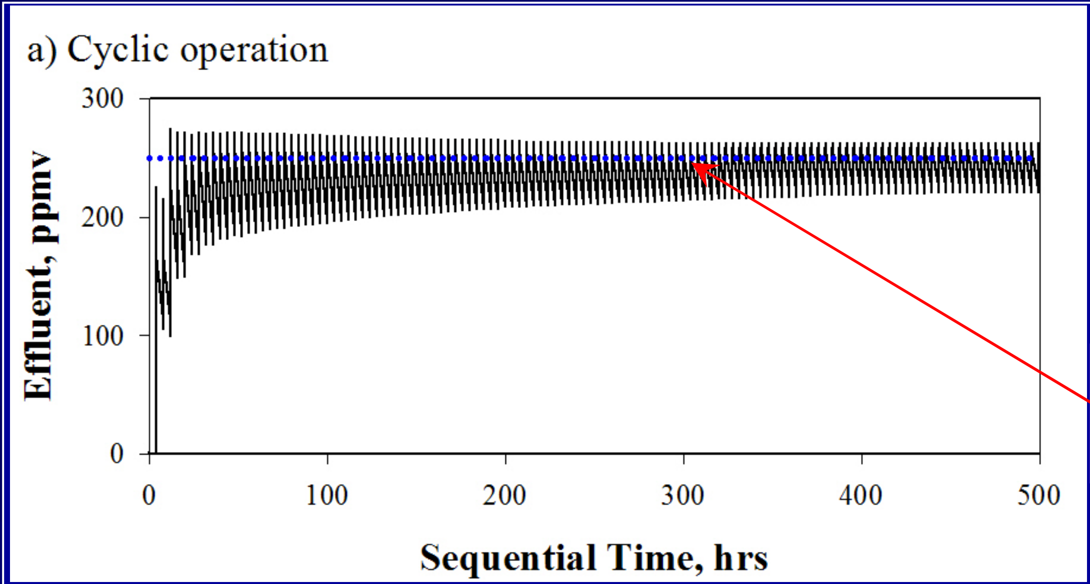
Transient Feeding Condition 1: Square wave change of inlet concentration

- Base = 200 ppmv
- Peak = 400 ppmv (15 mins / hour)



Model Simulation

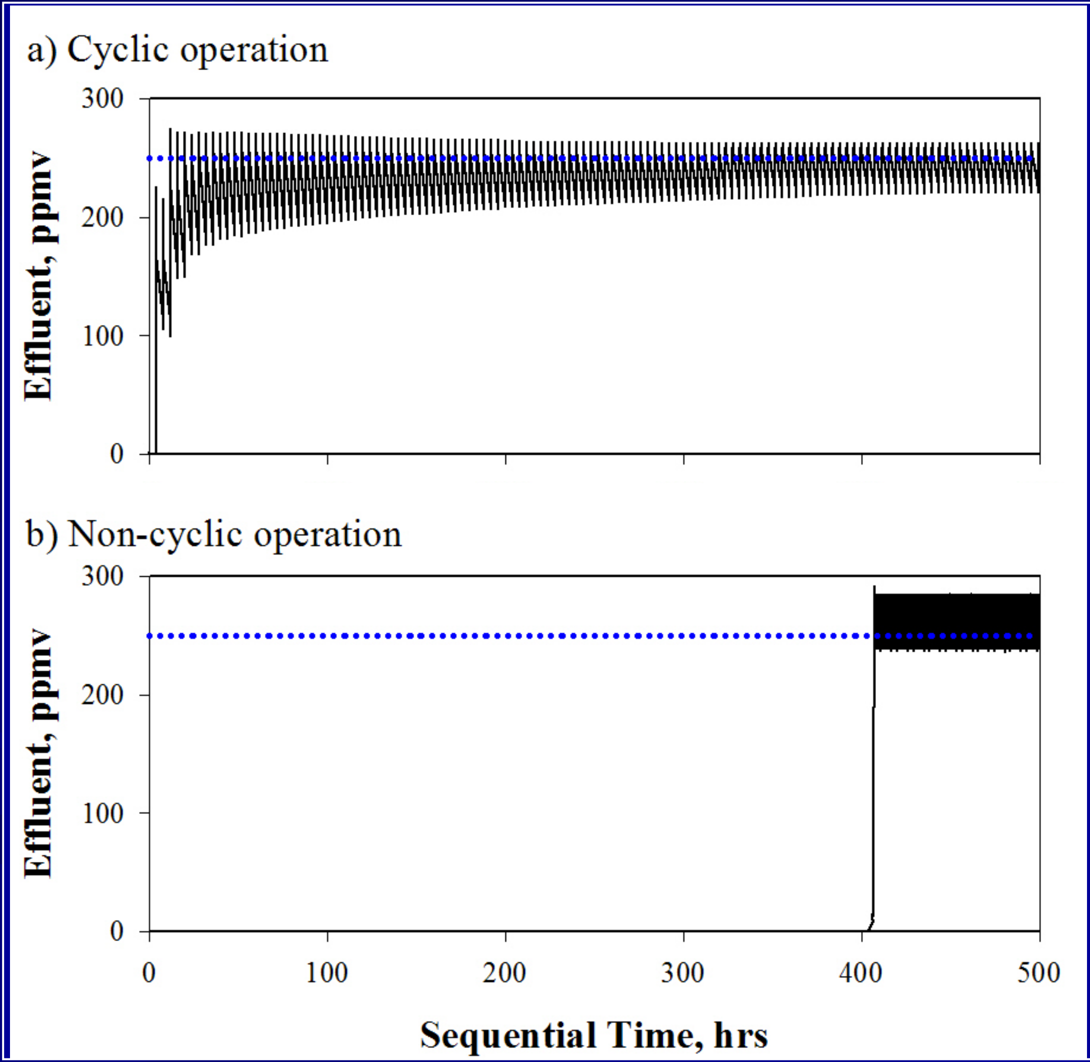
- **Effluent Responds in 2-bed Adsorption**



Critical inlet Conc. (250 ppmv) to biofilter

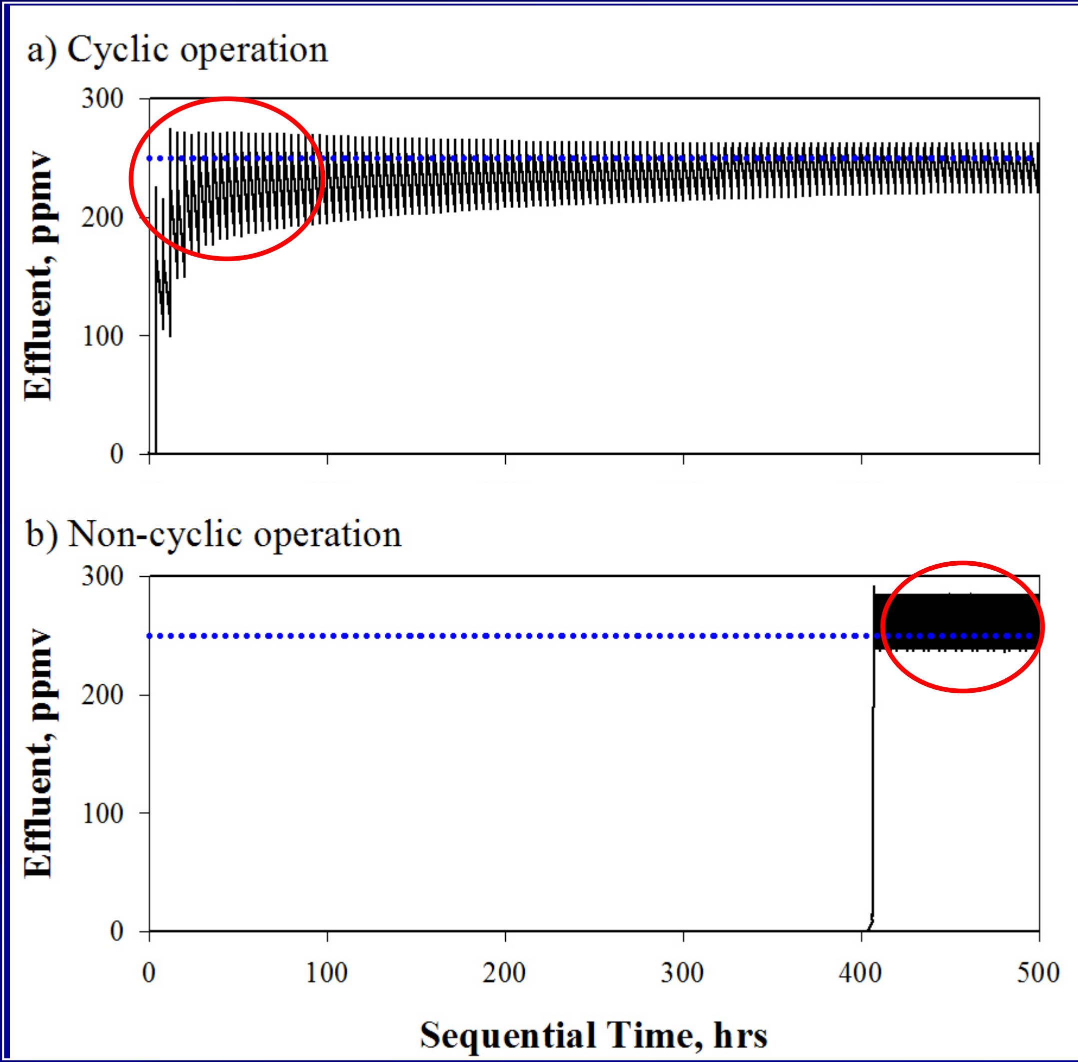
Model Simulation

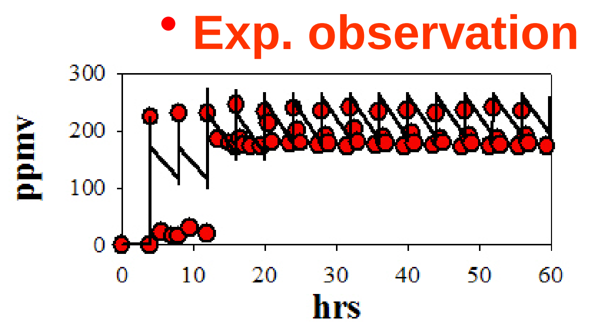
- **Effluent Responds in 2-bed Adsorption**

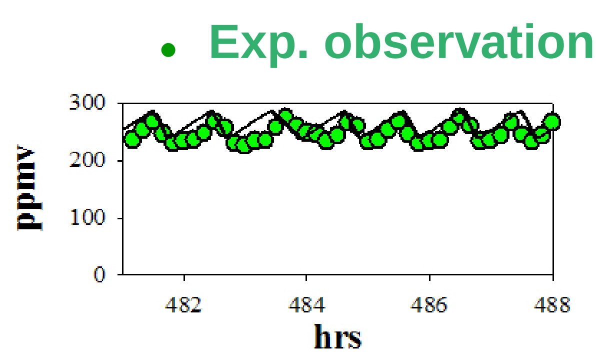


Model Simulation

- **Effluent Responds in 2-bed Adsorption**

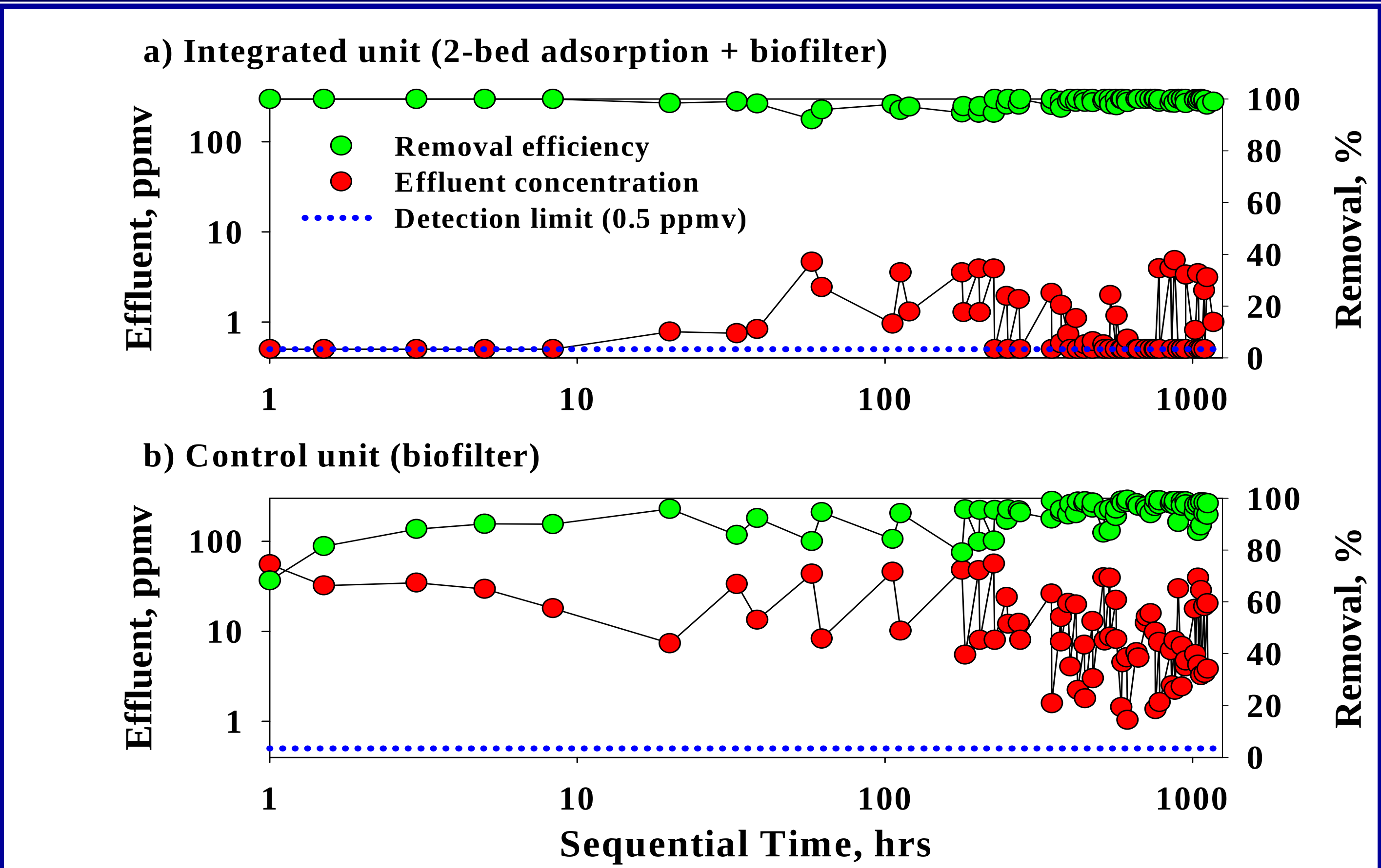






Results I: Feeding Condition 1

- Integrated unit vs. Control unit

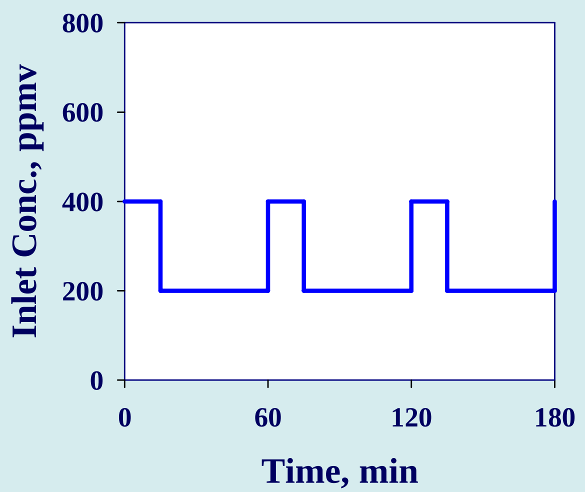


Integrated Treatment Scheme

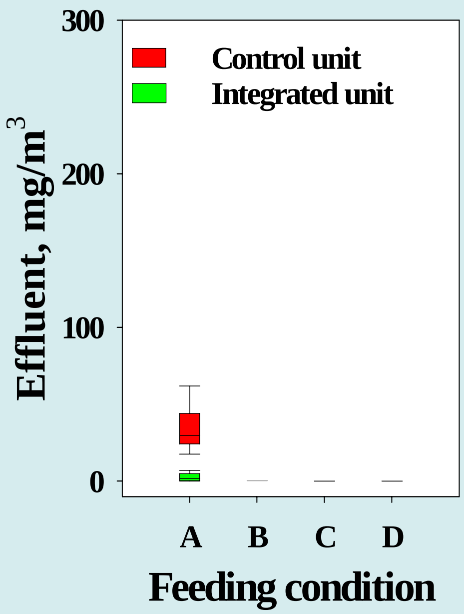
- **Results: Further Application**

Feeding Condition

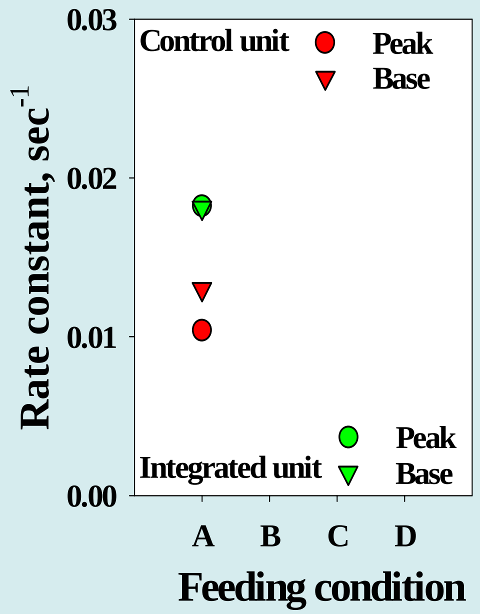
- **Type A** : 46.9 g/m³·hr



a)8-hr average effluent



b) Reaction rate constant

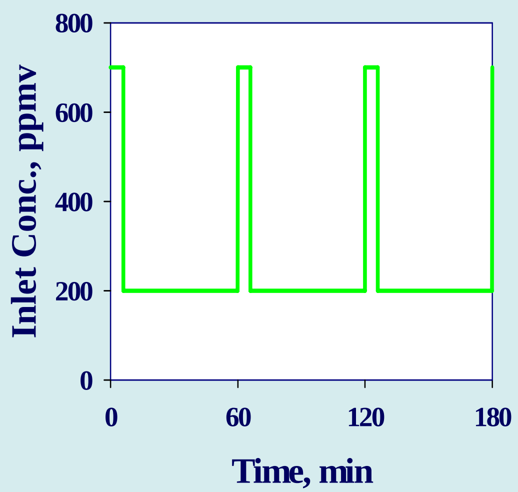


Integrated Treatment Scheme

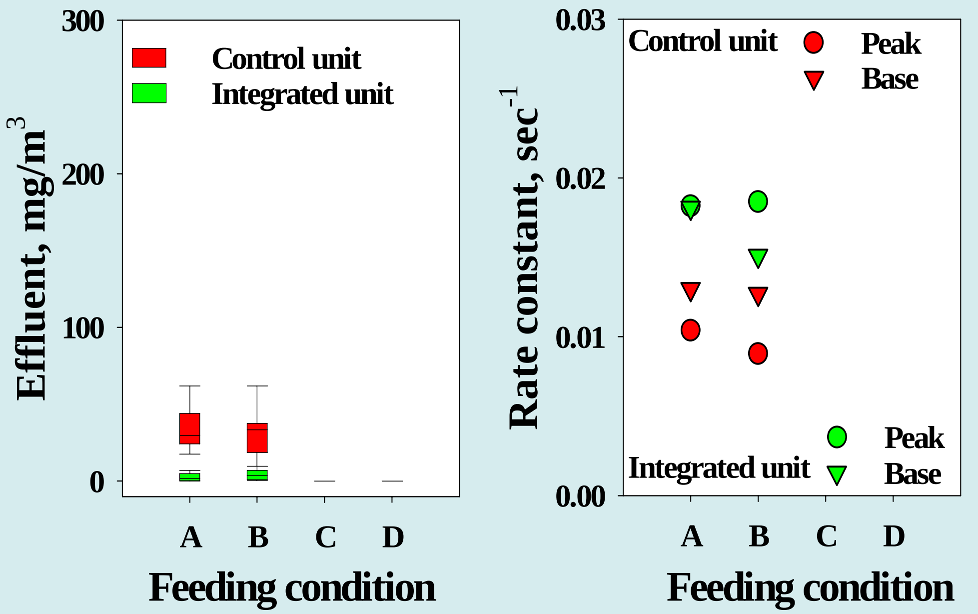
- **Results: Further Application**

Feeding Condition

- **Type B** : 46.9 $g/m^3 \cdot hr$ (High Peak)



a)8-hr average effluent **b) Reaction rate constant**

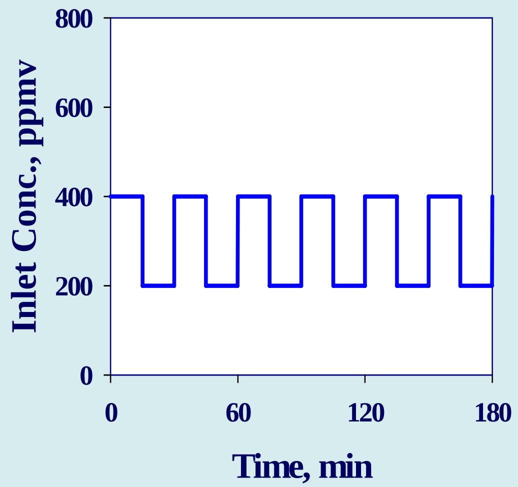


Integrated Treatment Scheme

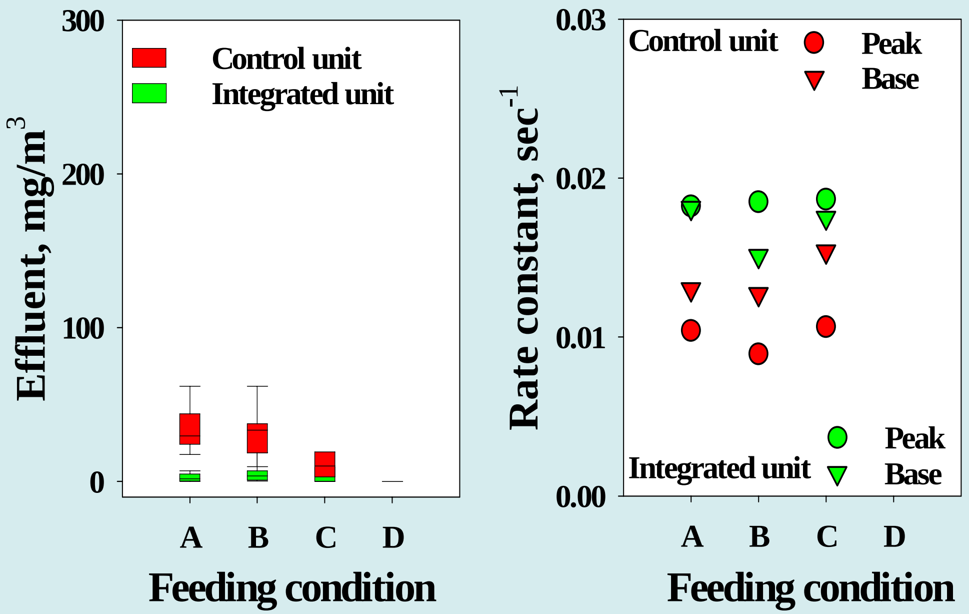
- **Results: Further Application**

Feeding Condition

- **Type C** : 56.3 $g/m^3 \cdot hr$
  (Frequent Peak)



a)8-hr average effluent **b) Reaction rate constant**

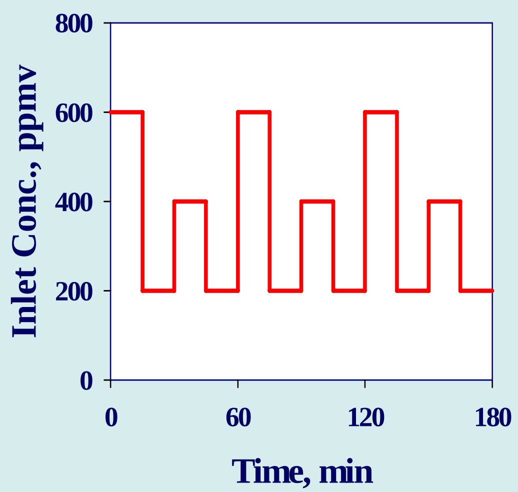


Integrated Treatment Scheme

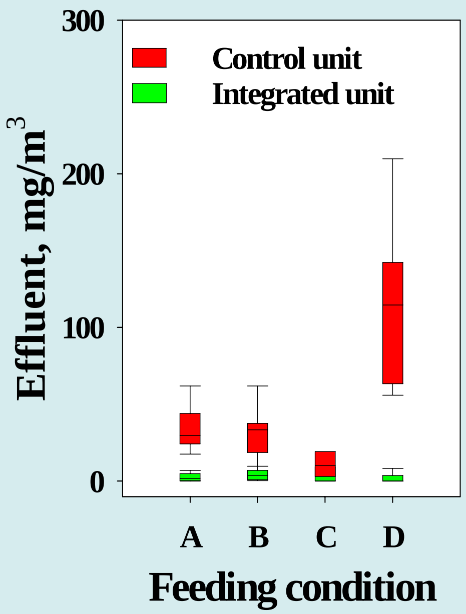
- **Results: Further Application**

Feeding Condition

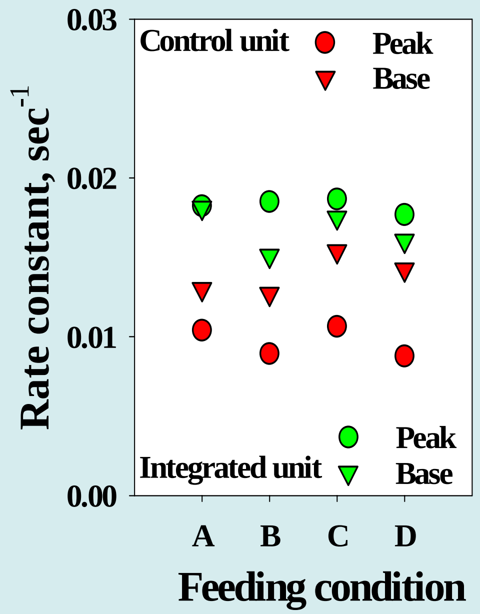
- **Type D** : 65.9 g/m³·hr
  (High & Frequent Peak)



a)8-hr average effluent

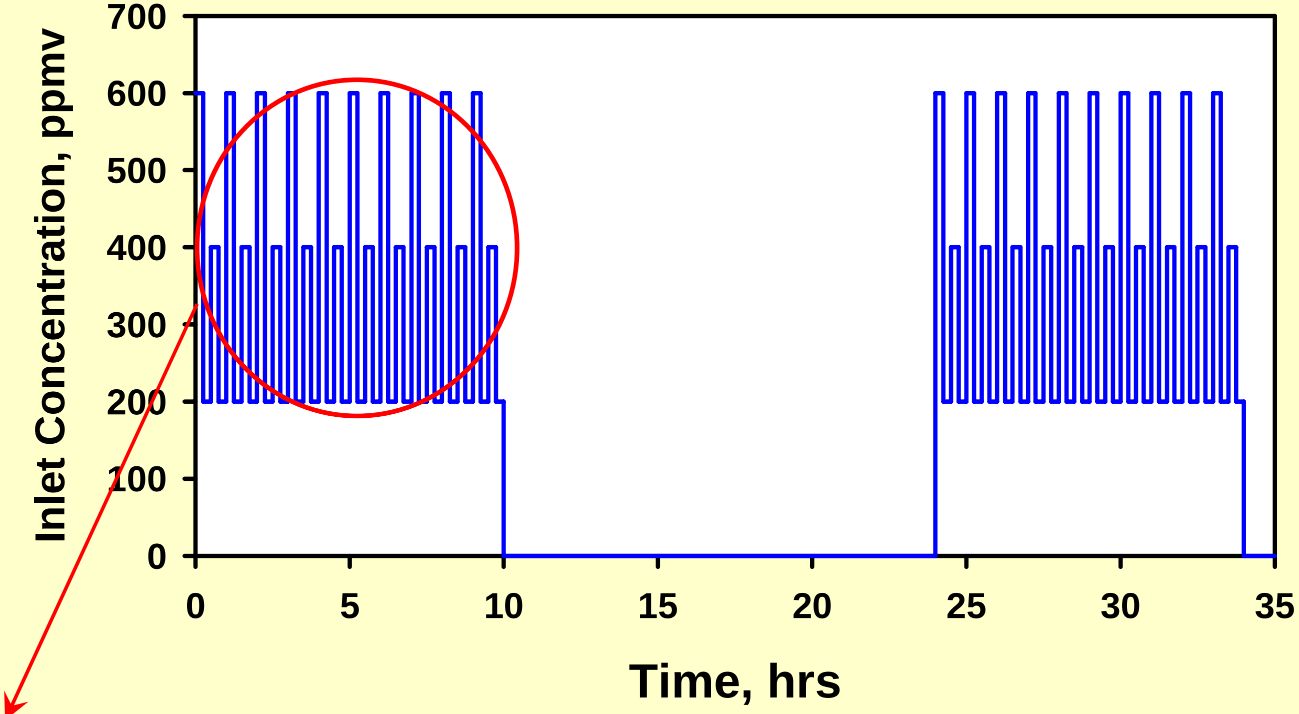


b) Reaction rate constant



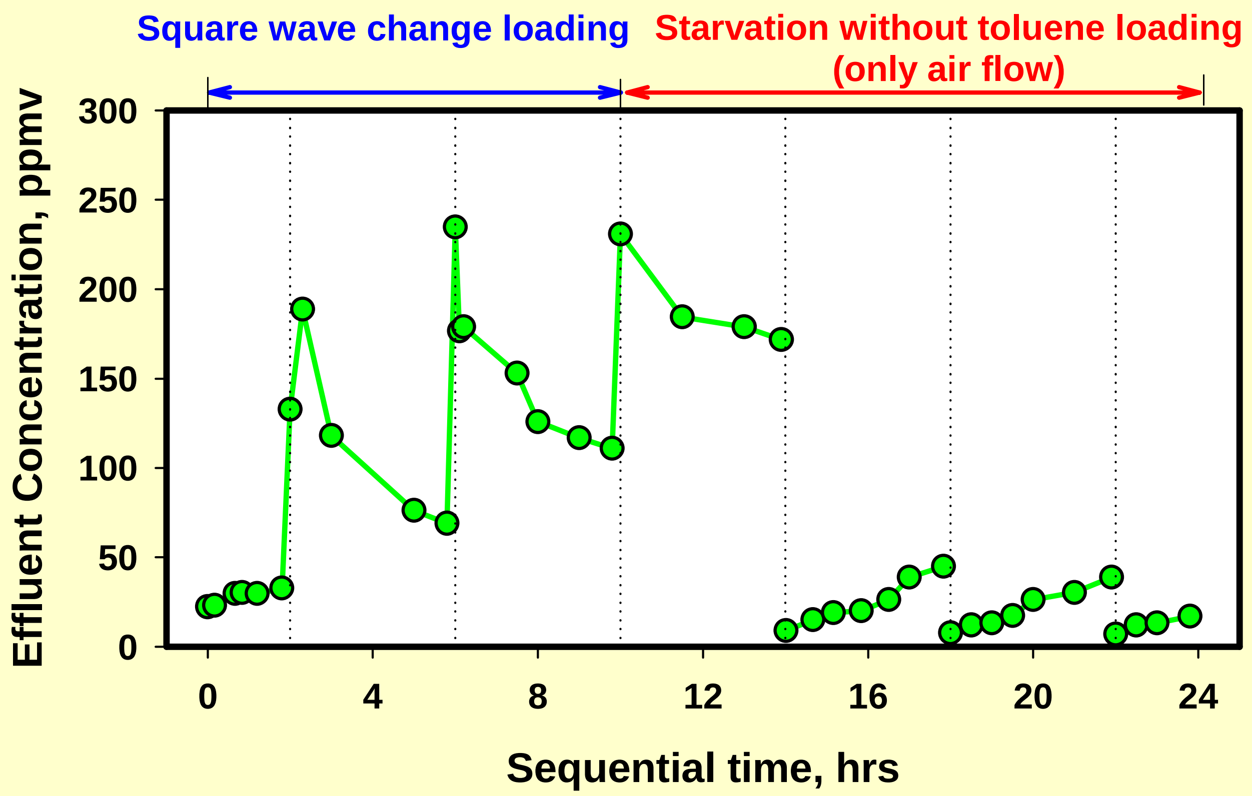
Results II: Feeding Condition 2

Transient feeding condition 2:
10 hrs square wave change + 14 hrs starvation without toluene loadings

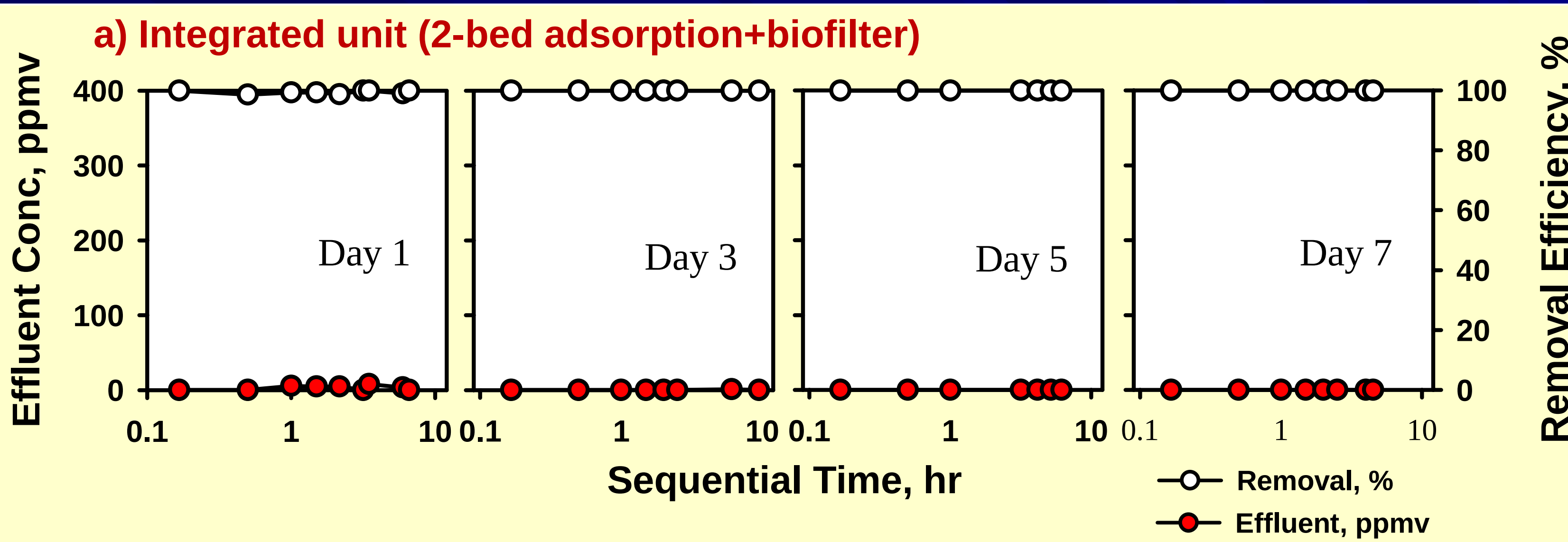


600ppmv (15min) → 200ppmv (15min) → 400ppmv(15min) → 200ppmv(15min) / 1 Hr

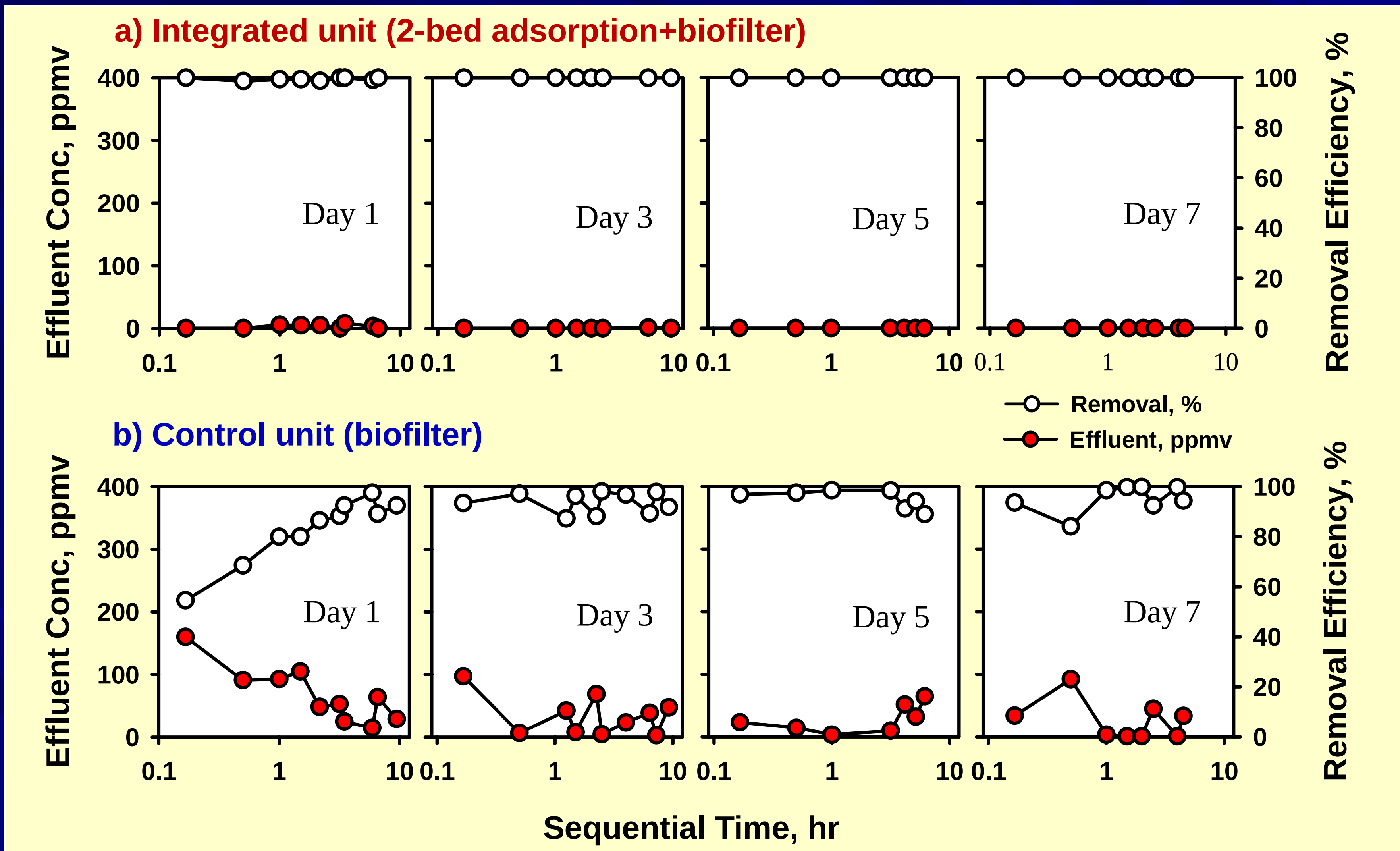
Desorption profiles of 2-bed adsoprion unit



Overall Removal Performance (with backwashing as biomass control)



Overall Removal Performance (with backwashing as biomass control)



Integrated Treatment Scheme

- **Results: Further Application**

Reactor volume of a single biofilter to achieve the same treatment goal as in the integrated system

Feeding Condition	Type A	Type B	Type C	Type D
Peak concentration ($C_{i,p}$), ppmv	400	700	400	600
(g/m^3)	(1.53)	(2.68)	(1.53)	(2.30)
Biofilter bed volume required (V), m^3 **	0.00435	0.00761	0.00435	0.00653
V / $V_{integrated}$ **	1.5	2.6	1.5	2.2

* Volume of the integrated unit = 0.00293 m^3

Integrated Treatment Scheme

Summary

The net effect of the 2-bed adsorption was VOC concentration stabilization that makes it amenable for effective stable biodegradation

1. The 2-step cycle in the adsorption unit successfully performed particular functions as
   - A polishing unit to abate the initial acclimation for the biofilter;
   - A buffering unit to mitigate the biofilter performance;
   - A feeding source for the biofilter without any feeding phase
2. Details of the reactor volume suggest that capital expense can be minimized by achieving a careful design and operation of the integrated treatment scheme.

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