# Air Cleaning Devices: Towards Design of Sustainable Buildings

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Université Concordia University
Building, Civil and Environmental Engineering

# *Acknowledgement*


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- Sponsors
  - Dectron Internationale
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  - Concordia University (Research Chair)


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# Introduction

- Sustainability, IAQ
- Substantial market
- Manufacturer’s claims on VOC removal
- Limited information data and measurement techniques
- Lack of standard methods for testing, etc.

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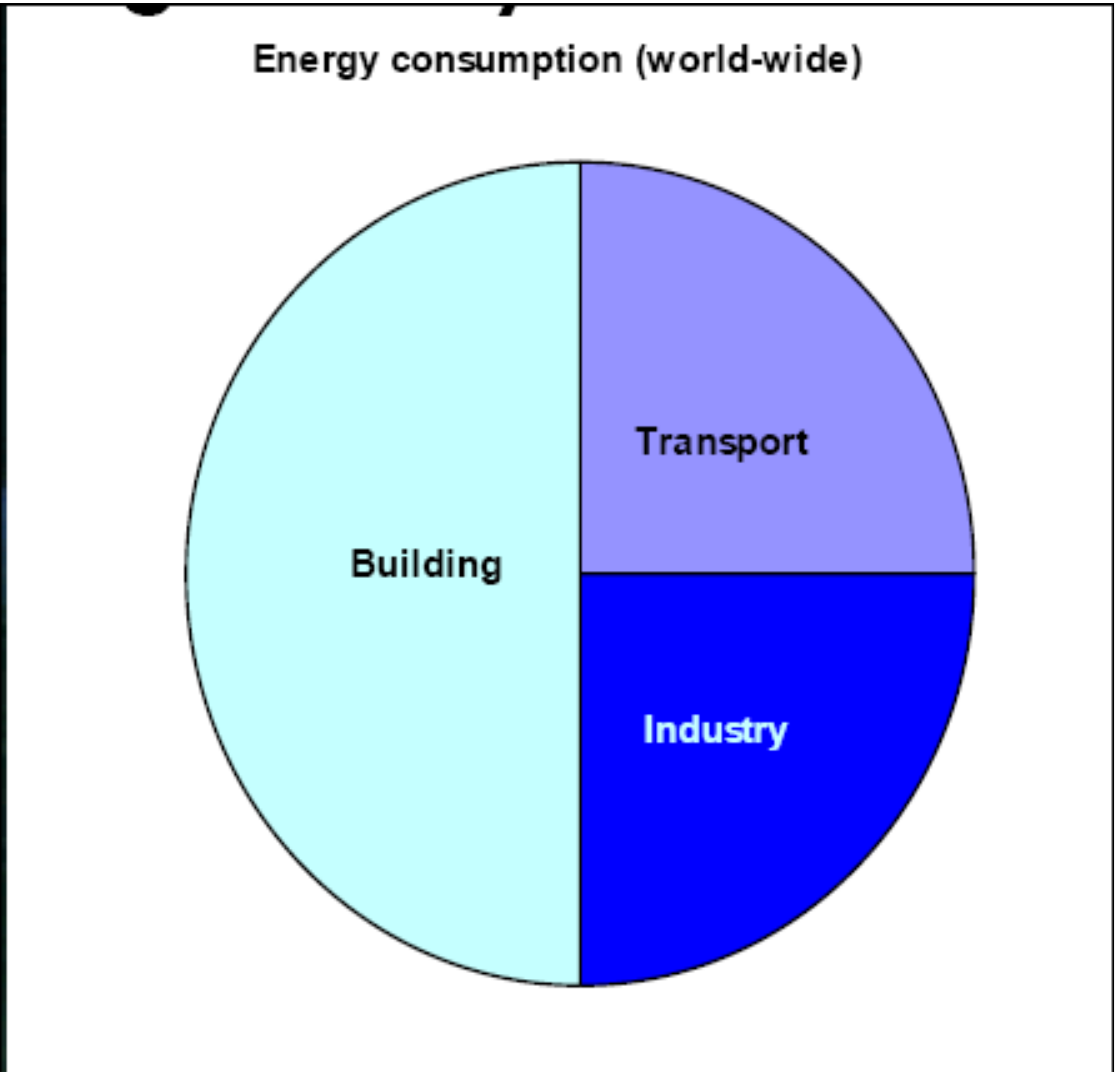


Source: website

# Air Cleaning Technologies

- Airborne Particles
  - Fibrous filters, electrostatic precipitators, etc.
- Microorganisms (Bioaerosols)
  - UV disinfection, HEPA filters, etc.
- Gases
  - Sorption filtration
  - Ultraviolet photocatalytic oxidation (UV-PCO)
  - Non-thermal plasma,
  - Etc.

# Ventilation Systems in Buildings

**Thermal Comfort**

ASHRAE Standard 55

**Indoor Air Quality**

ASHRAE Standard 62

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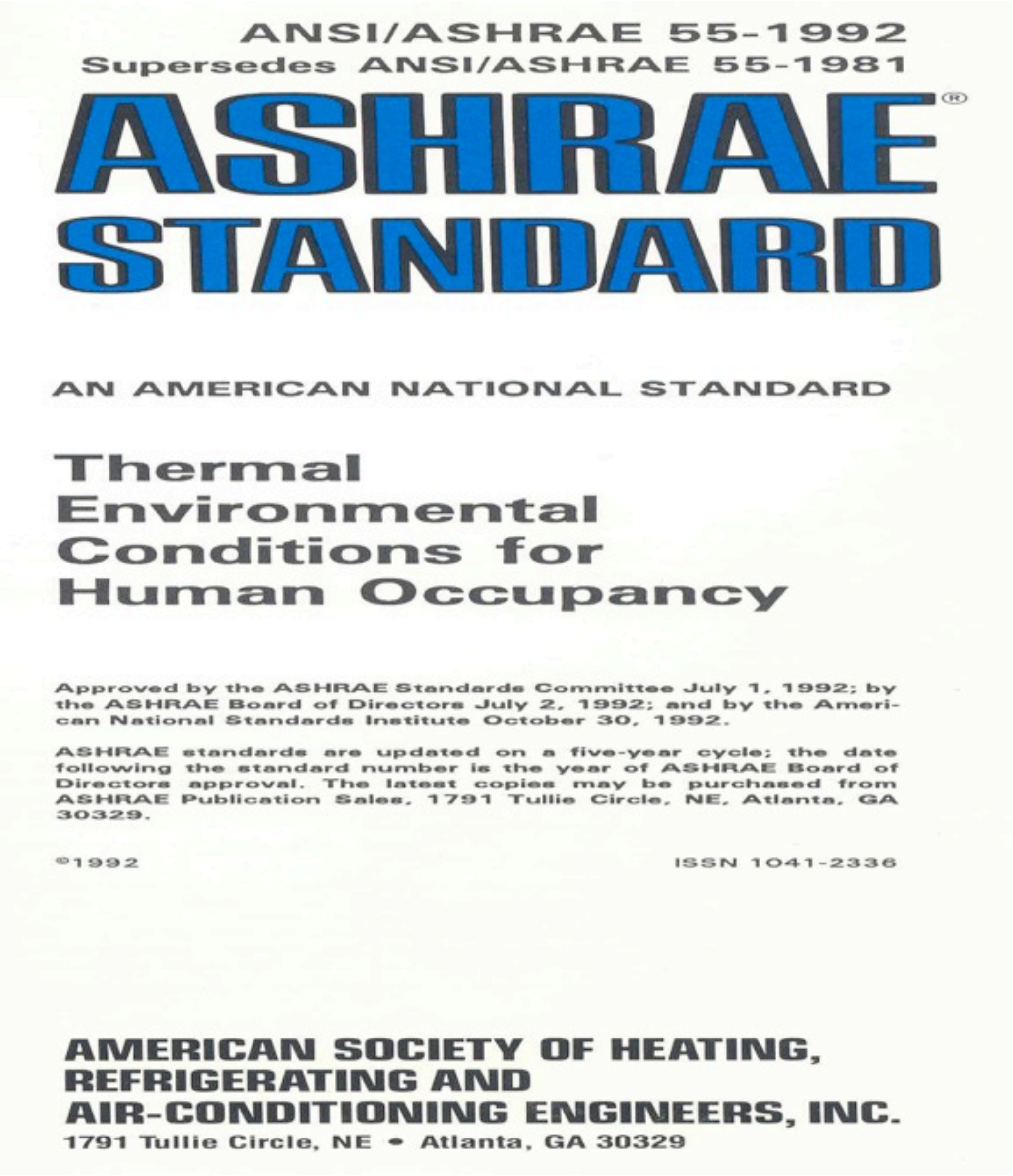
# Thermal Comfort


ANSI/ASHRAE 55-1992
Supersedes ANSI/ASHRAE 55-1981

ASHRAE® STANDARD

AN AMERICAN NATIONAL STANDARD

Thermal Environmental Conditions for Human Occupancy

Approved by the ASHRAE Standards Committee July 1, 1992; by the ASHRAE Board of Directors July 2, 1992; and by the American National Standards Institute October 30, 1992.

ASHRAE standards are updated on a five-year cycle; the date following the standard number is the year of ASHRAE Board of Directors approval. The latest copies may be purchased from ASHRAE Publication Sales, 1791 Tullie Circle, NE, Atlanta, GA 30329.

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# Global Thermal Comfort

- *Air Temperature*
- *Relative Humidity*
- *Air Velocity/Distribution*
- *Activity Level*
- *Clothing Thermal Resistance*

# ASHRAE Standard 62

ASHRAE 62-1999
(supersedes ANSI/ASHRAE 62-1989)
Includes ASHRAE Addenda Listed in Appendix I

**ASHRAE® STANDARD**

## Ventilation for Acceptable Indoor Air Quality

See Appendix I for approval dates by the ASHRAE Standards Committee and ASHRAE Board of Directors.

This standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. The change submittal form, instructions, and deadlines are given at the back of this standard and may be obtained in electronic form from ASHRAE's Internet Home Page, *http://www.ashrae.org*. The latest edition of an ASHRAE Standard may be purchased from ASHRAE Customer Service, 1791 Tullie Circle NE, Atlanta, GA 30329-2305. E-mail: *orders@ashrae.org*. Fax: 404-321-5478. Telephone: 404-636-8400 (worldwide) or toll free 1-800-527-4723 (for orders in the U.S. and Canada).



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# *Ventilation*

- *Von Pettenkofer (1858) suggested use of $CO_2$ as indicator of IAQ*
  - *1000 PPM  as a maximum level to overcome hindrance of odour from human effluents.*
  - *$\Delta CO_2$ = 500 PPM  (10 l/s)*

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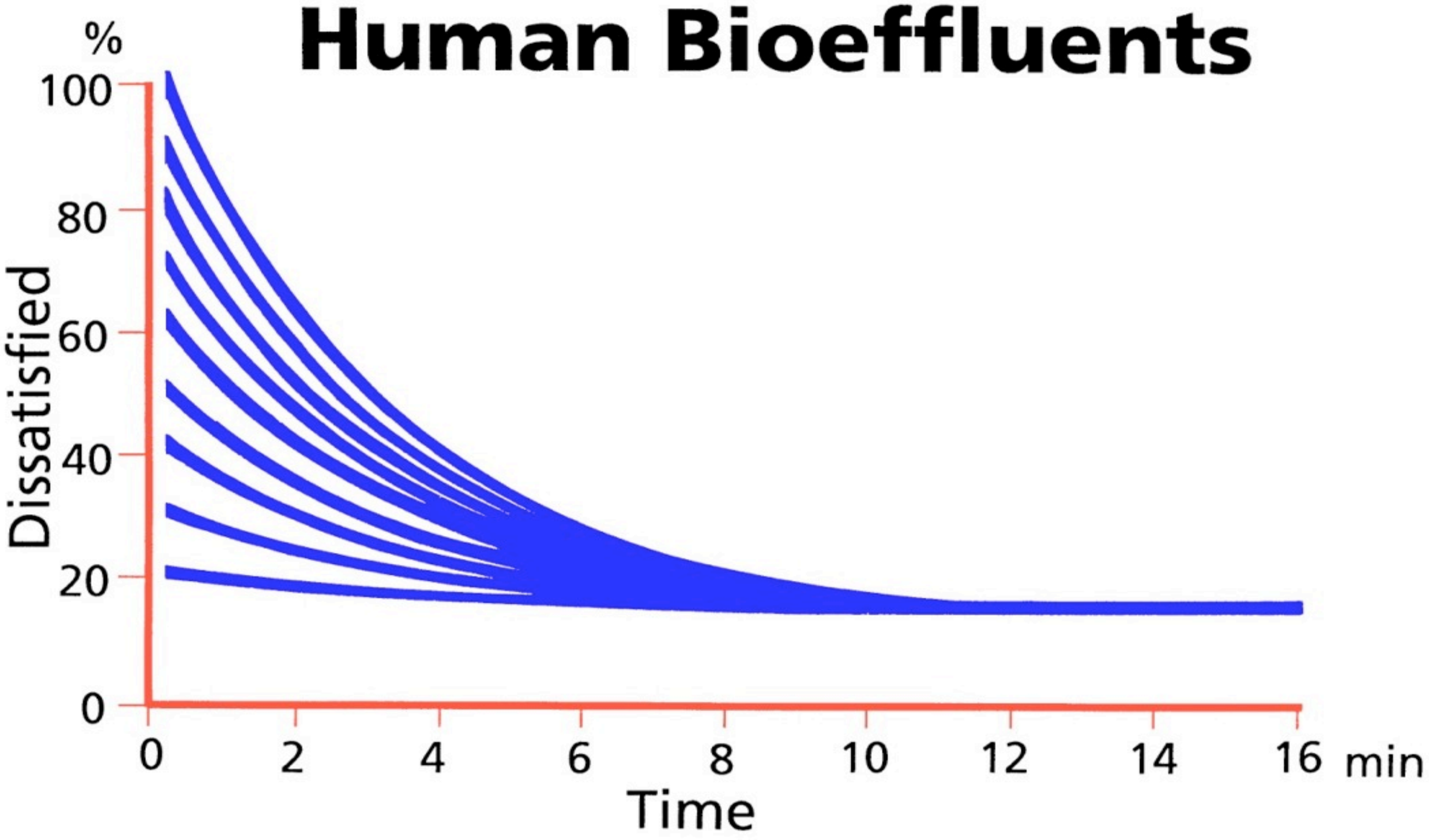
# IAQ & Adaptation

- Yaglou (1937)
  - –$CO_2$ limitation
  - –Occupants' adaptation
- Cain (1983)
  - –Occupants' adaptation
  - –No relation with ventilation rate

| Ventilation rate | % of odour acceptance | |
|---|---|---|
| $m^3/h$ | Visitors | Occupants |
| 9 | 68 | 96 |
| 18 | 75 | 96 |
| 27 | 79 | 92 |
| 36 | 81 | 95 |

# IAQ & Adaptation



# Carbon Dioxide Generation Rate

- According to ASHRAE standard 62, building occupants generate

| Activity | Liter/min | $Ft^3$/min |
| --- | --- | --- |
| Resting | 0.20 | 0.0071 |
| Sitting | 0.25 | 0.0088 |
| Light work | 0.38 | 0.0135 |
| Manual work | 0.50 | 0.0177 |

***0.0106 Ft3/min/person***.

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$$Q = \frac{\text{CFM}}{\text{Person}} = \frac{10600}{(C_i - C_0)_{ppm}}$$

*ASHRAE Standard 62-1999 states that $(C_i - C_0)$ should be higher than 700 ppm*

*Q = 15 CFM/person ~ 7.2 L/s/person*

| Ventilation Rate (l/s) | Basis | 1 lit/s = 2.11 CFM |
|---|---|---|
| > 0.3 | 2% $CO_2$, (respiration) | |
| >0.5 | 1% $CO_2$, (performance) | *NASA guideline* |
| > 1 | 0.5% $CO_2$, (TLV) | *US Navy guideline / OSHA Std.* |
| >3.5 | 0.15% $CO_2$, (body odor) | |
| 2.5 | ASHRAE Standard 62-1981 | |
| 3.5 | Swedish Building Code 1980 | |
| 4 | Nordic Building Regulation Committee 1981 | |
| 5-7 | Berglund et al (body odor) | |
| 8 | Fanger et al (body odor) | |
| 7.5 | ASHRAE Standard 62-1989 | *WHO guideline* |
| 5-10 | Swedish Building Code 1988 | |
| 10-30 | Swedish Allergy Committee 1989 | |
| 16-20 | Weber et al (Tobacco Smoke) | |
| 14-50 | Fanger et al (Total odor) | |

- How to evaluate and how to consider materials and equipment emission rate in order to determine the ventilation rate?

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udefarver
Flügger

# *EXAMPLE*

- ***WOOD STAINS*: nonane, decane, undecane, dimethyloctane, dimethyl-nonane, trimethlylbenzene**
- ***POLYURETHANE*: nonane, decane, undecane, butanone, ethylbenzene, dimethylbenzene**
- ***LATEX PAINT*: 2-propanol, butanone, ethylbenzene, propylbenzene, 1,1-oxybisbutane, toluene**

# VOC

- ***BENZENE*** **(Source: paints, stains) respiratory tract irritation - long term exposure could increase the risk of cancer;**
- ***XYLENES*** **(Source: varnish and solvents) is a narcotic and irritant that can affect the heart, liver, kidney and nervous system;**
- ***TOLUENE*** **(Source: chipboard) is a narcotic and may cause anemia;**

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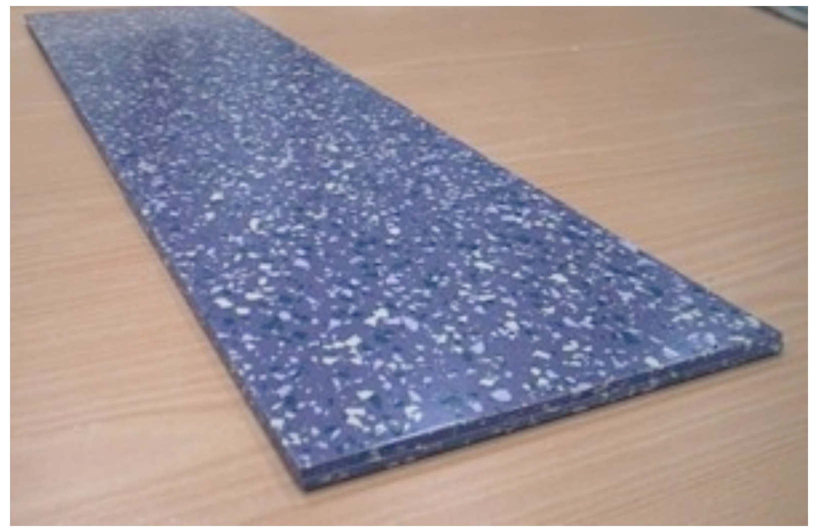
# Primary Sources

- *WOOD PRODUCTS*
- *FLOOR COVERINGS*
- *WALL COVERINGS*
- *CEILING MATERIALS*
- *INSULATION*
- *DUCT LINER*
- *FURNISHING*
- *PAINTS*
- *COATINGS*
- *ADHESIVES, CAULKS*
- *SEALANTS*
- *SOLVENTS, STAIN*
- *FLOOR WAX, TEXTILES*

- **OFFICE EQUIPMENTS, COPIERS, PRINTERS**



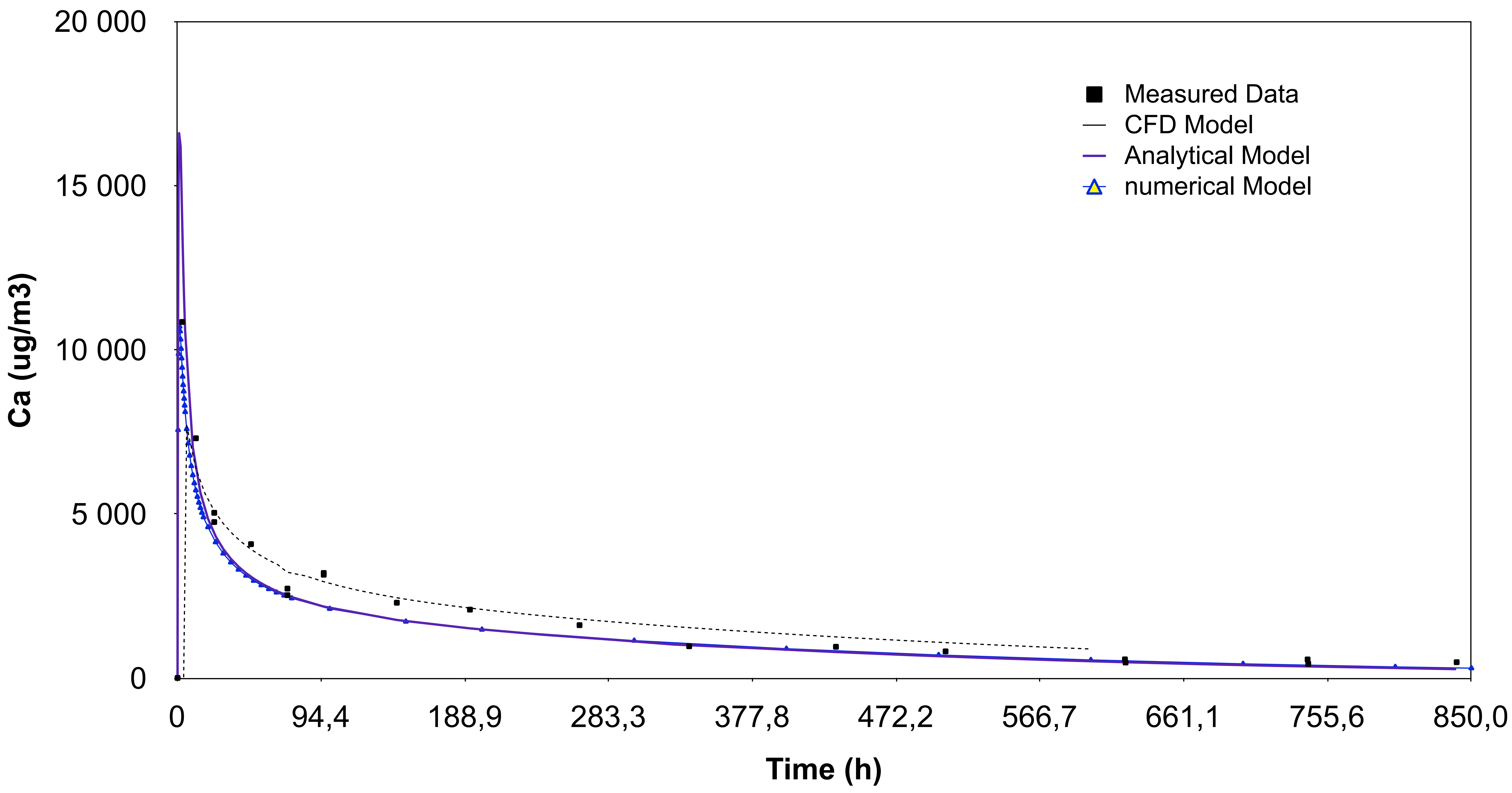

# *Primary Sources*

# *Source Characterization: Emission Rate*

***ASTM D 5116***

**0.5m×0.4m×0.25m**

# Emission Rate

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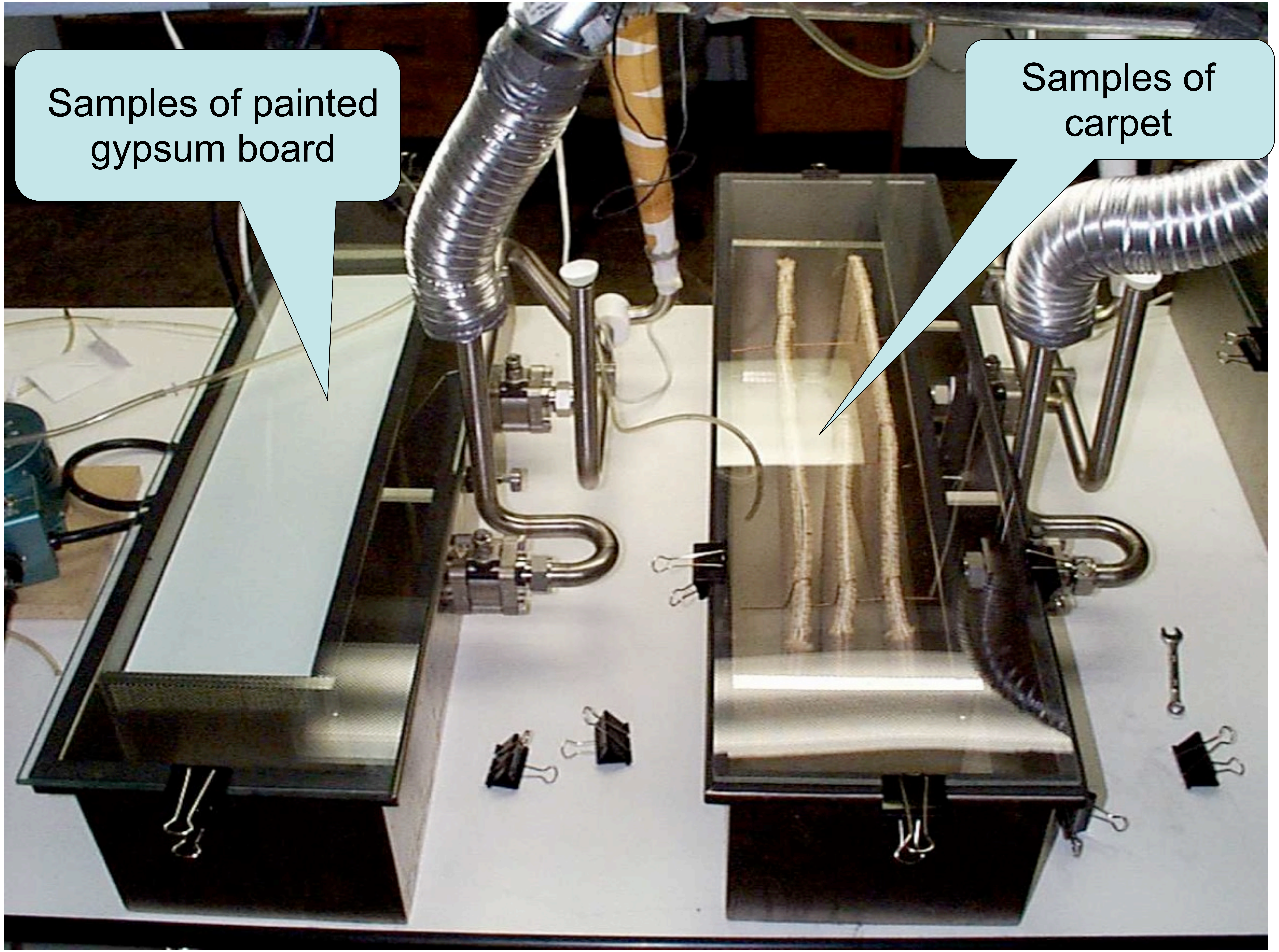


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# Experimental Set-up

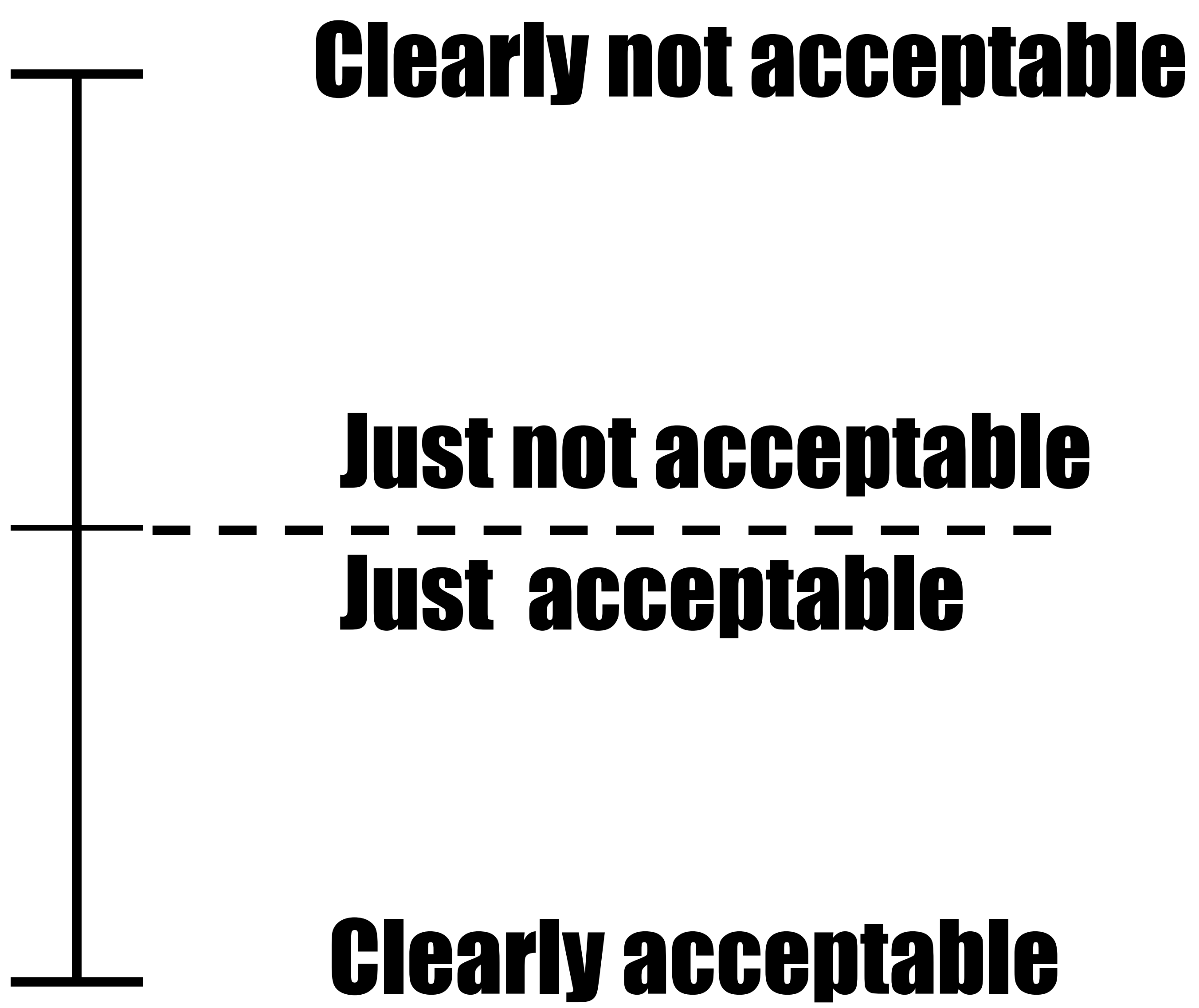
# Voting Sheet

**1. Acceptability rating**

During this test you are exposed to air which contains compounds usually found in office environments.

How acceptable is the air quality?

Please mark on the scale.




**2. Rating of odor intensity**

How intense is the odor in the air? Choose a number assuming the odor intensity in the laboratory is 10.

The odor intensity is: ____________

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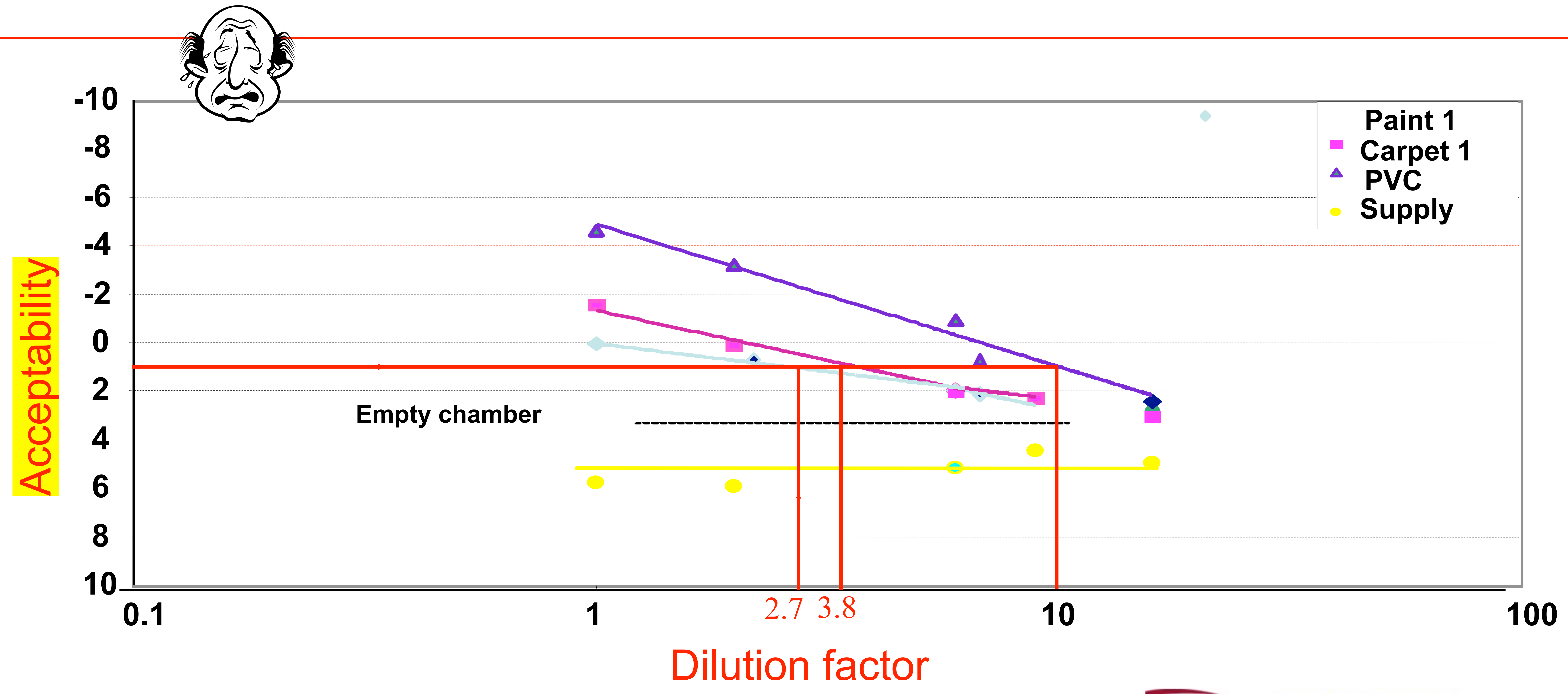
# Procedure

# Exposure-Response Relationship

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# Acceptability assessments for individual and combined materials with the required dilution needed to reach the acceptability of an empty chamber

| Materials | Paint | Carpet | PVC | PVC& Carpet | Paint & PVC | Paint & Carpet |
|---|---|---|---|---|---|---|
| Acceptability without dilution | -1.07 | -3 | -1.4 | -2.27 | -0.84 | -1.66 |
| Required dil. to match supply air acceptability (2) | 10.7 | 14.4 | 10.6 | 12.4 | 16.7 | 21.7 |

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# Conclusions

- The impact of increased ventilation on perceived air quality vary from one building material to another
- The relationship between acceptability and dilution factor is more flat for combined materials than for an individual material
- The ventilation rate needed to reach a certain acceptability level will be higher for combined materials than for an individual material
  - **Not sustainable**

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# One Cause and Effect - Heat Island

More heat and cooling load

Hotter outdoor temperatures

Increased use of cooling units

More energy consumption

Higher cooling costs

More air pollution

A blanket of ground-level ozone (smog)

Health problems

Source: website

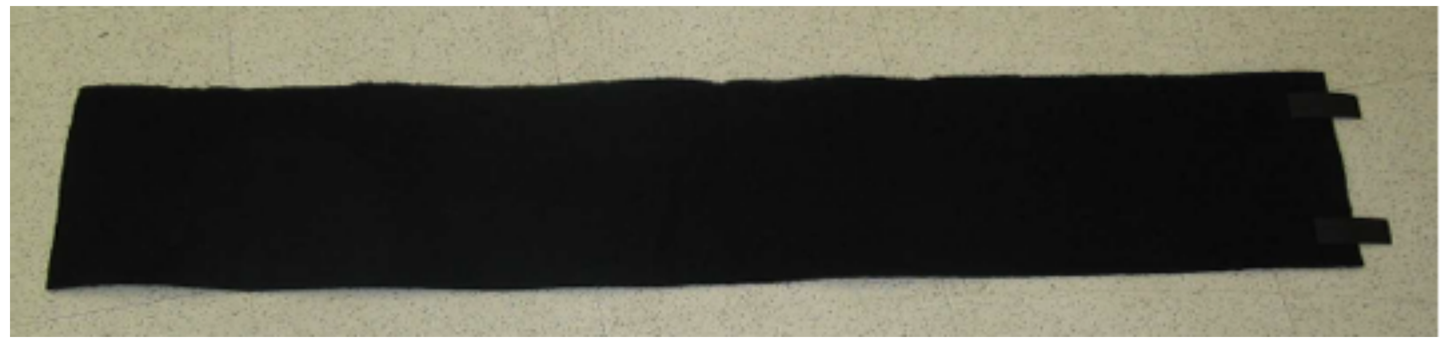
# *Unsustainable*

Source: website

- **How to improve the IAQ without increasing energy consumption?**

# Air Cleaners

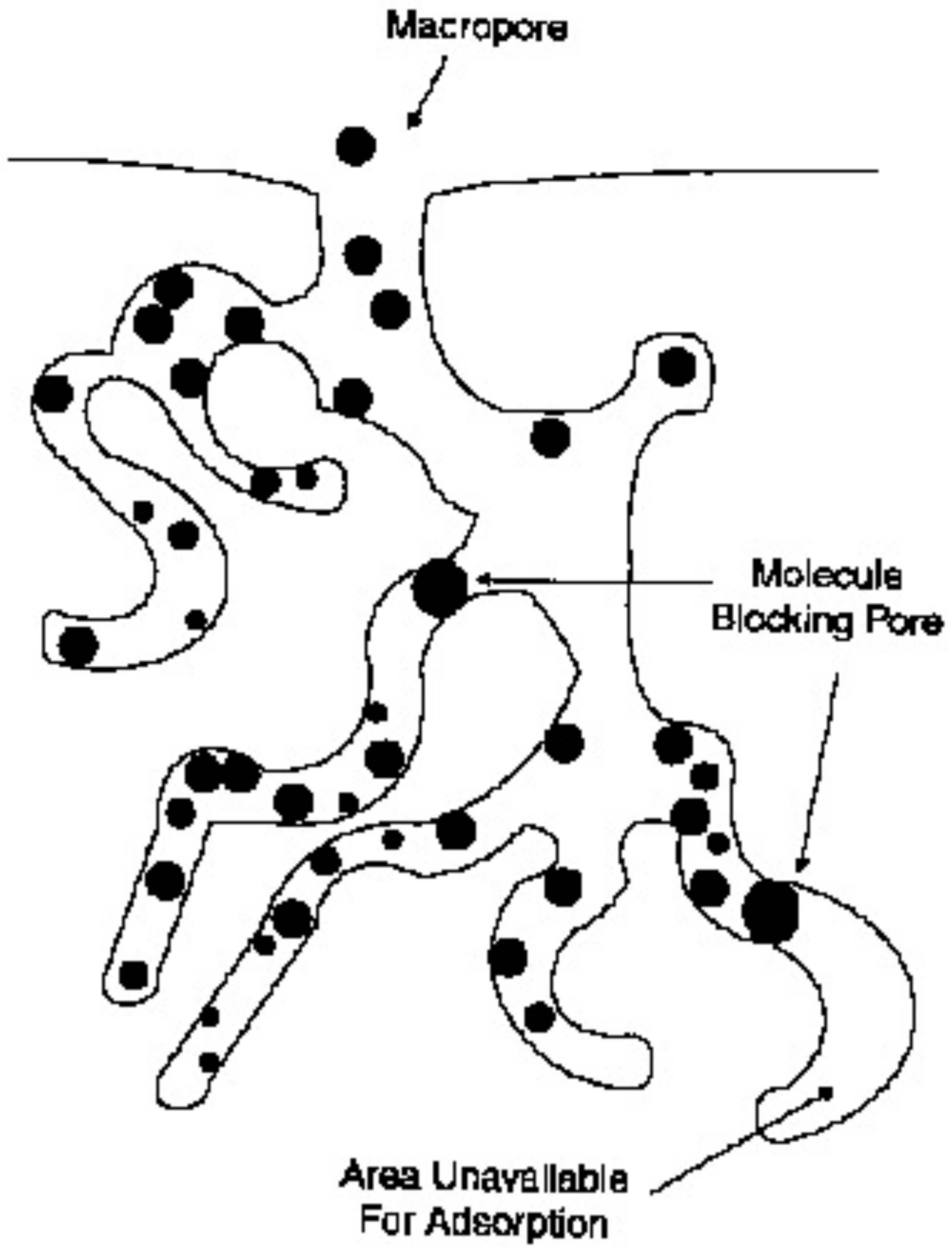
- Sorption filtration is the most widely used gaseous air cleaning mechanism in non-industrial buildings.
  - *Different sorbent materials*
    - *Activated carbon, Zeolite, etc.*
- Different product structures
  - Packed bed, pleated media, etc.



# Sorption Filtration

## *Steps in Contaminant Adsorption*

- *From bulk gas to the external surface of solid phase*
- *Diffusion through pore of solid and migration from external surface to internal pore surface*
- *Adsorption from gas phase to solid phase*




Hunter, P., S., T., Oyama, Control of Volatile Organic Compound Emissions, John Wiley & Sons, Inc., 2000, 45.

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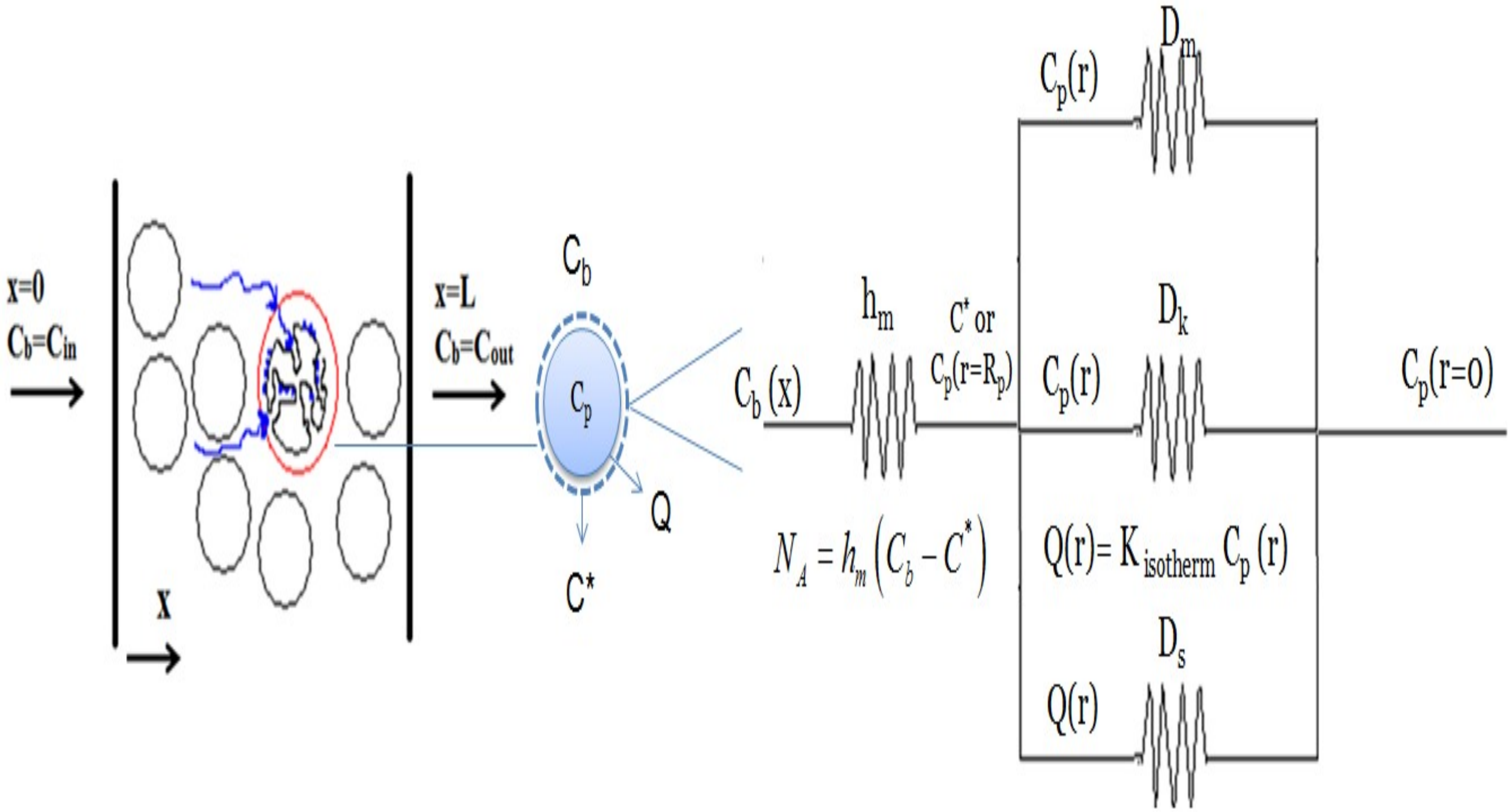
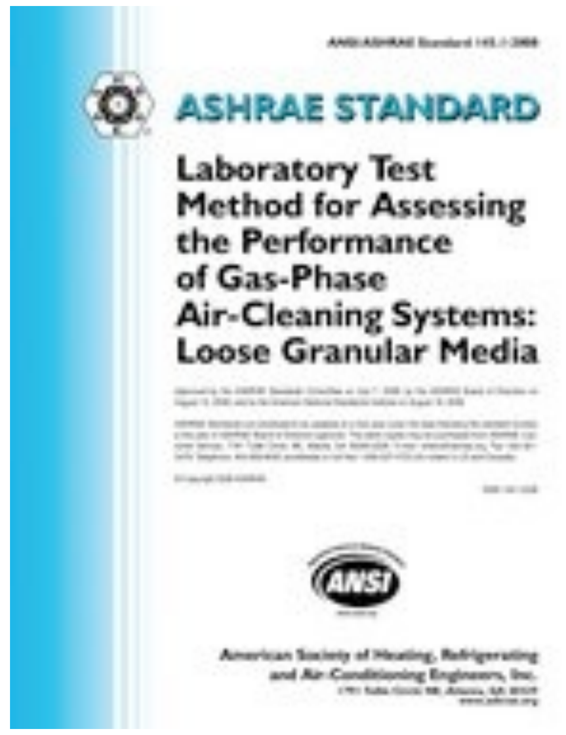
# Sorption Filtration



# Measurement Techniques/ Standards





**Loose Granular Media**

**ASHRAE Standard 145.1**

**Air Cleaning Devices**

**ASHRAE Standard 145.2**

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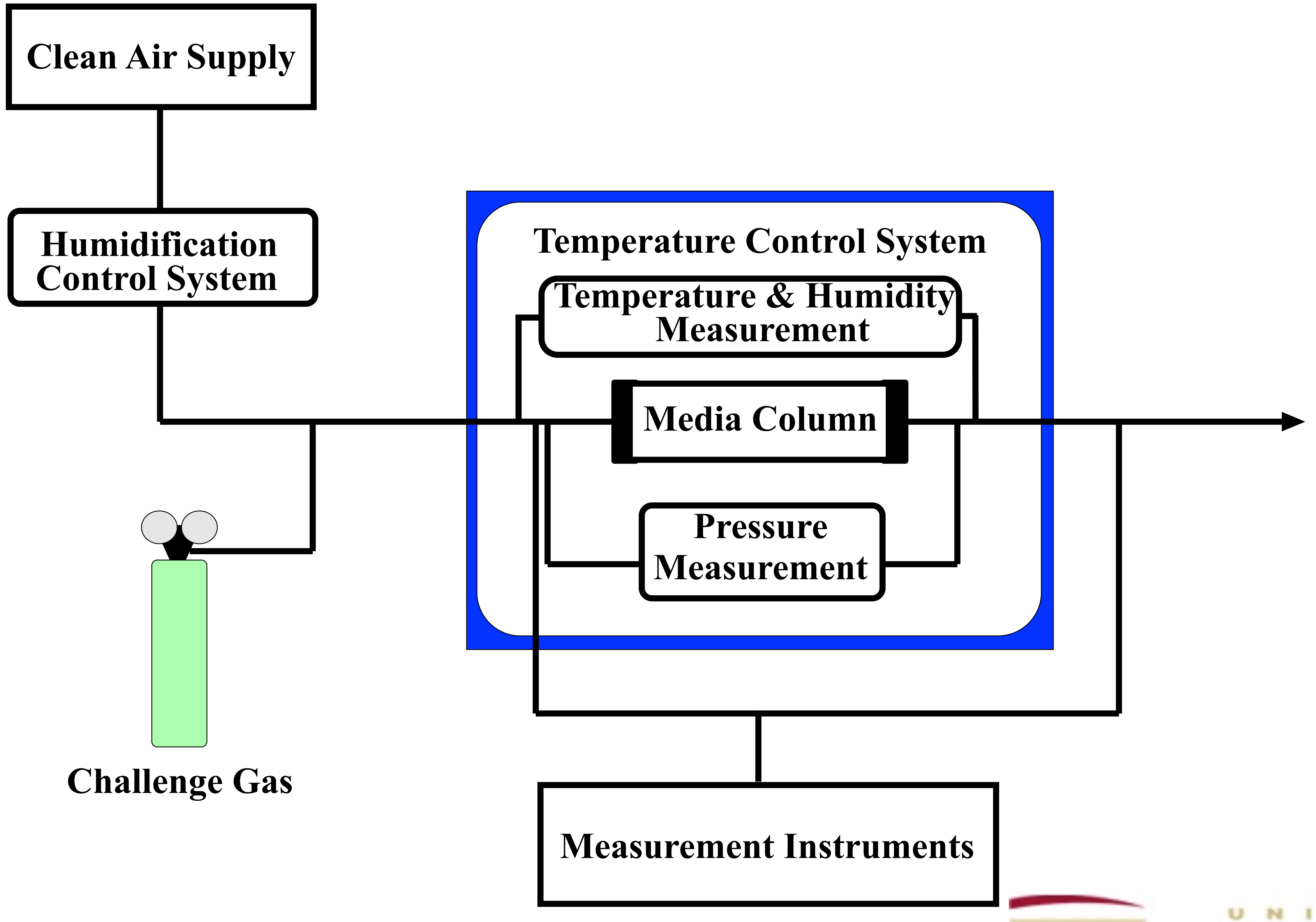
# *ASHRAE Standard 145.1*

## Laboratory Test Method for Assessing the Performance of Gas-Phase Air Cleaning Systems: Loose Granular Media

Source: ASHRAE Standard 145.1

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# *ASHRAE Standard 145.2*

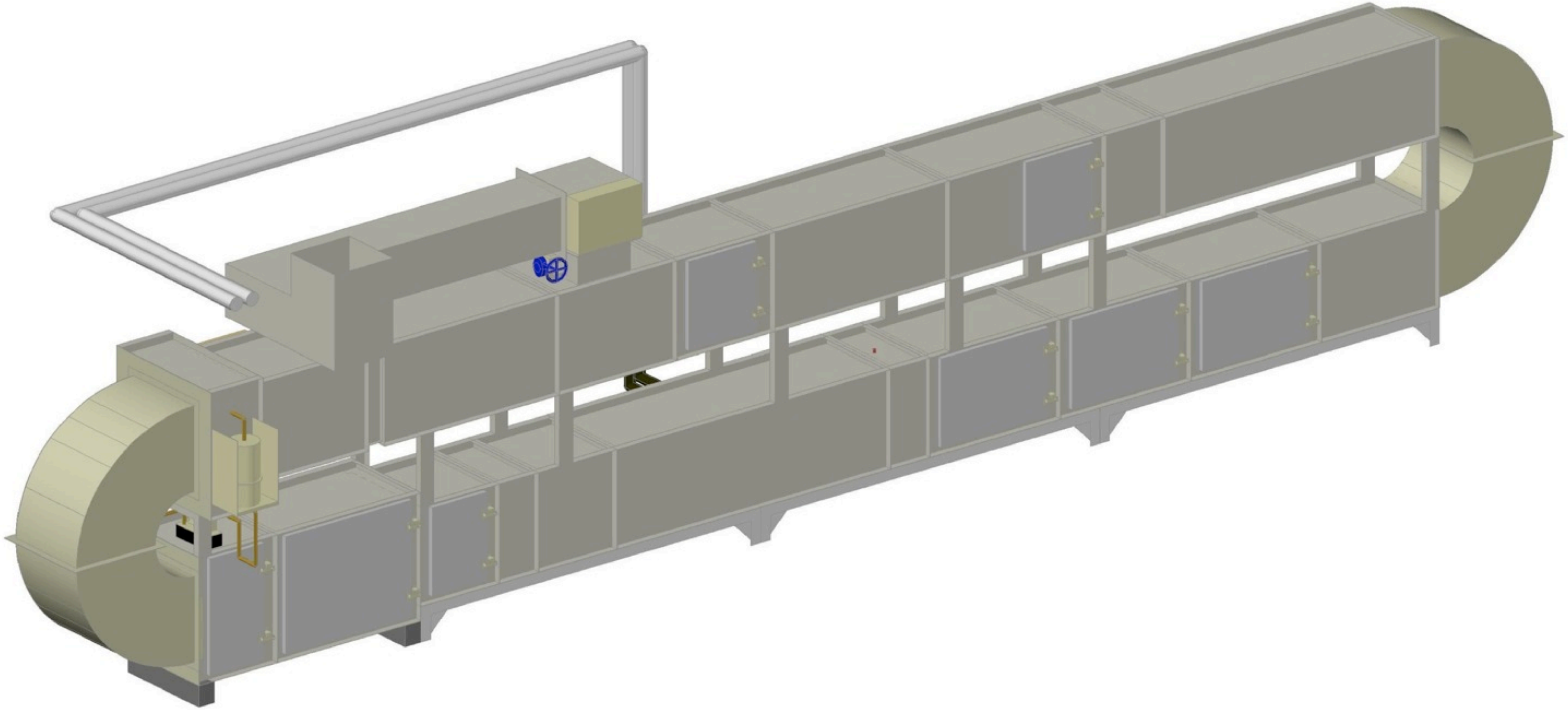
**Laboratory Test Method for Assessing the Performance of Gas-Phase Air Cleaning Systems: *Air Cleaning Devices***

–Full-scale test duct from ASHRAE *Standard 52.2*

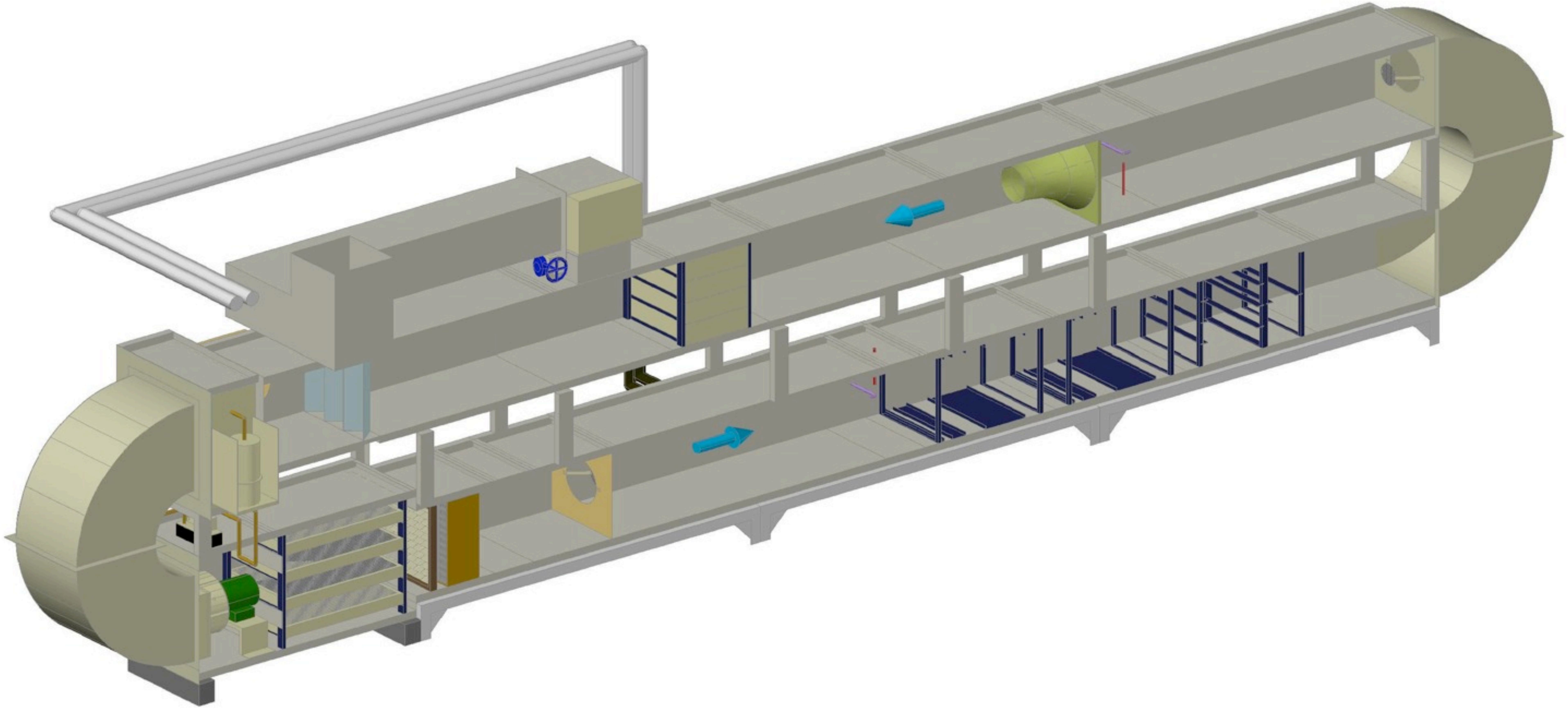
–Single compound at 100

# Experimental Set-up

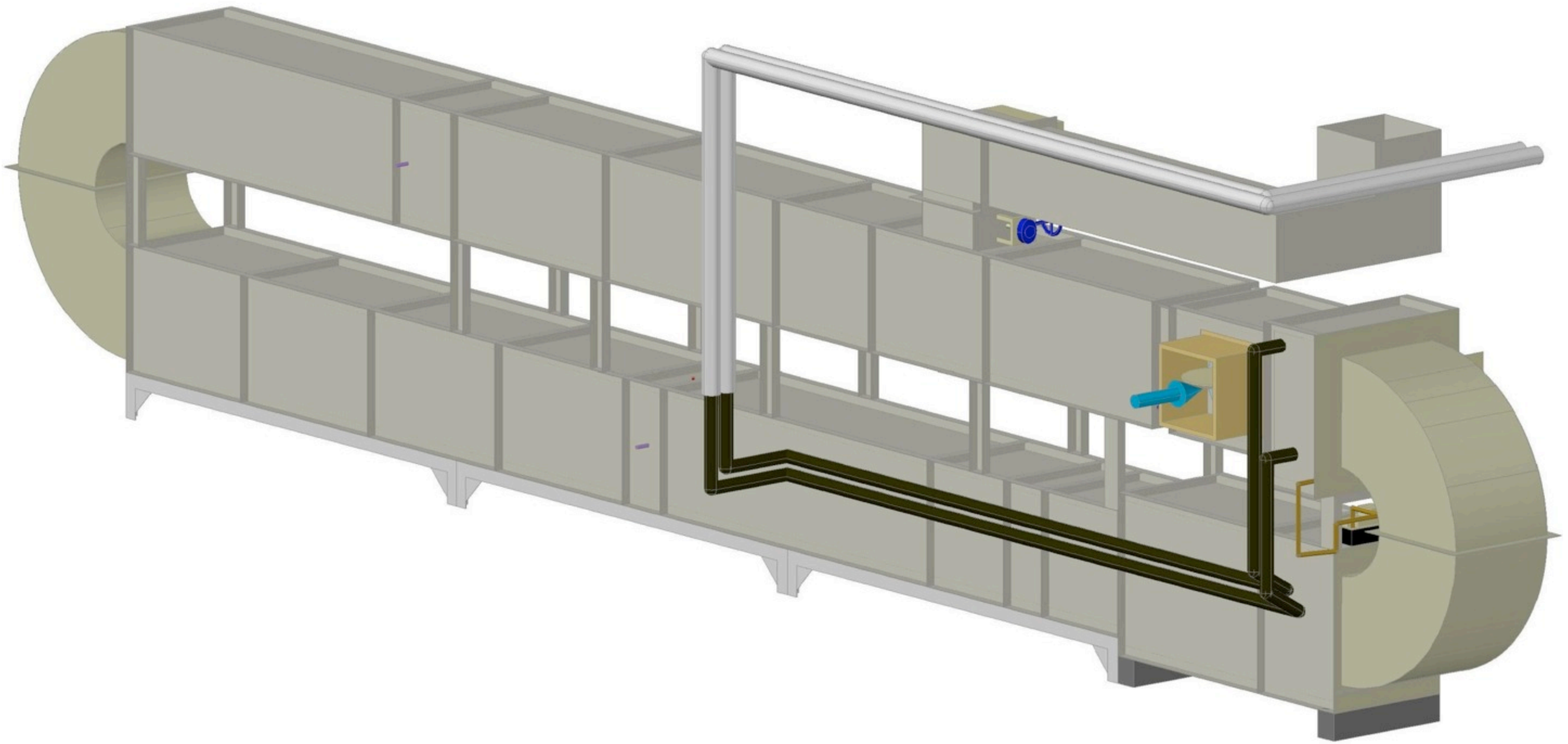
# Full-scale dynamic test set-up



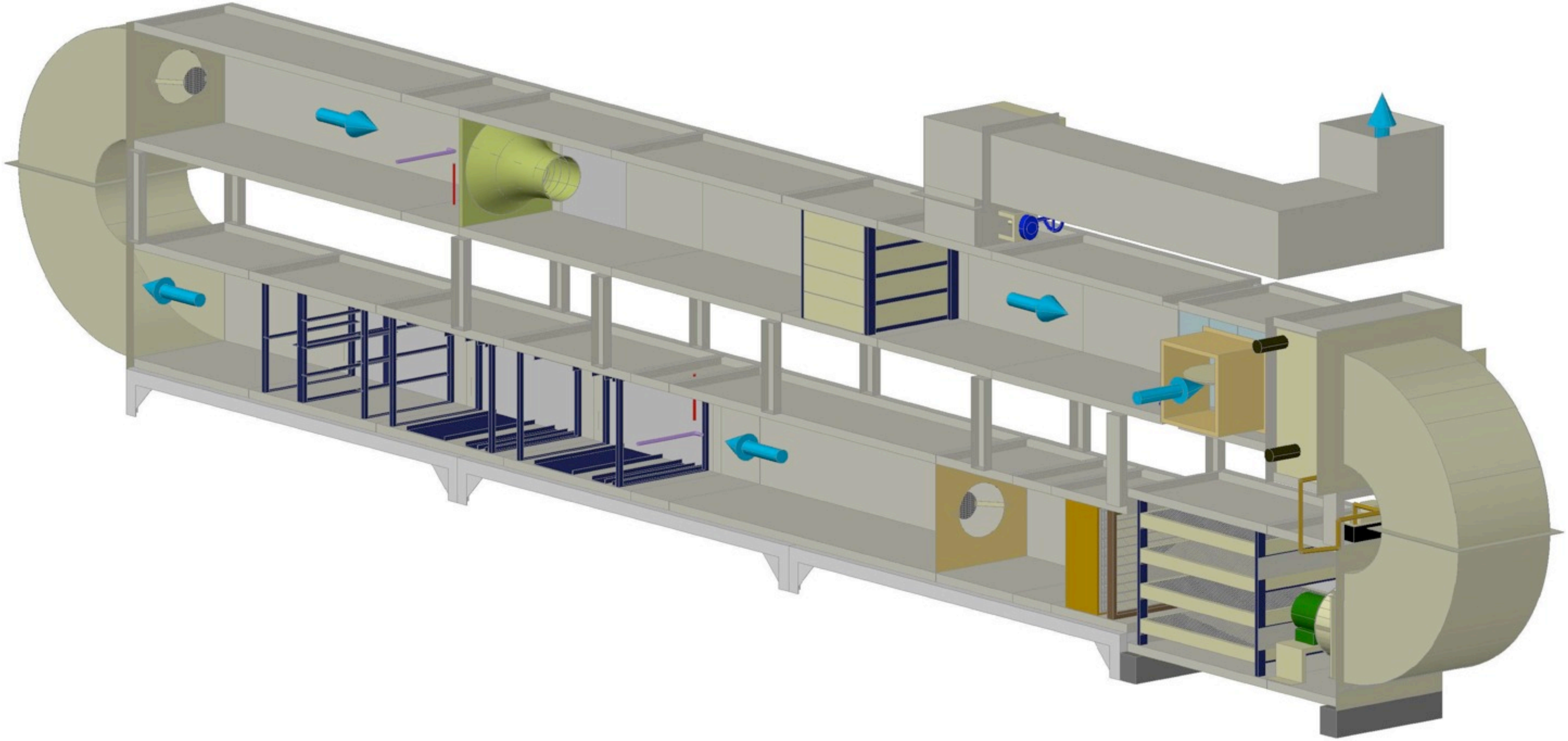
# Full-scale dynamic test set-up



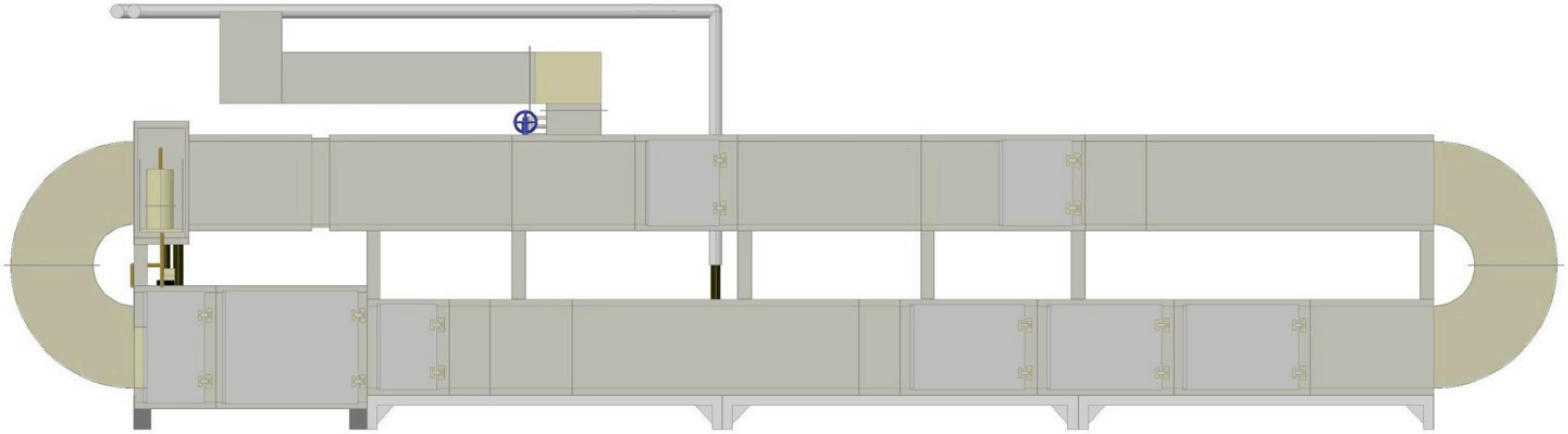
# Full-scale dynamic test set-up



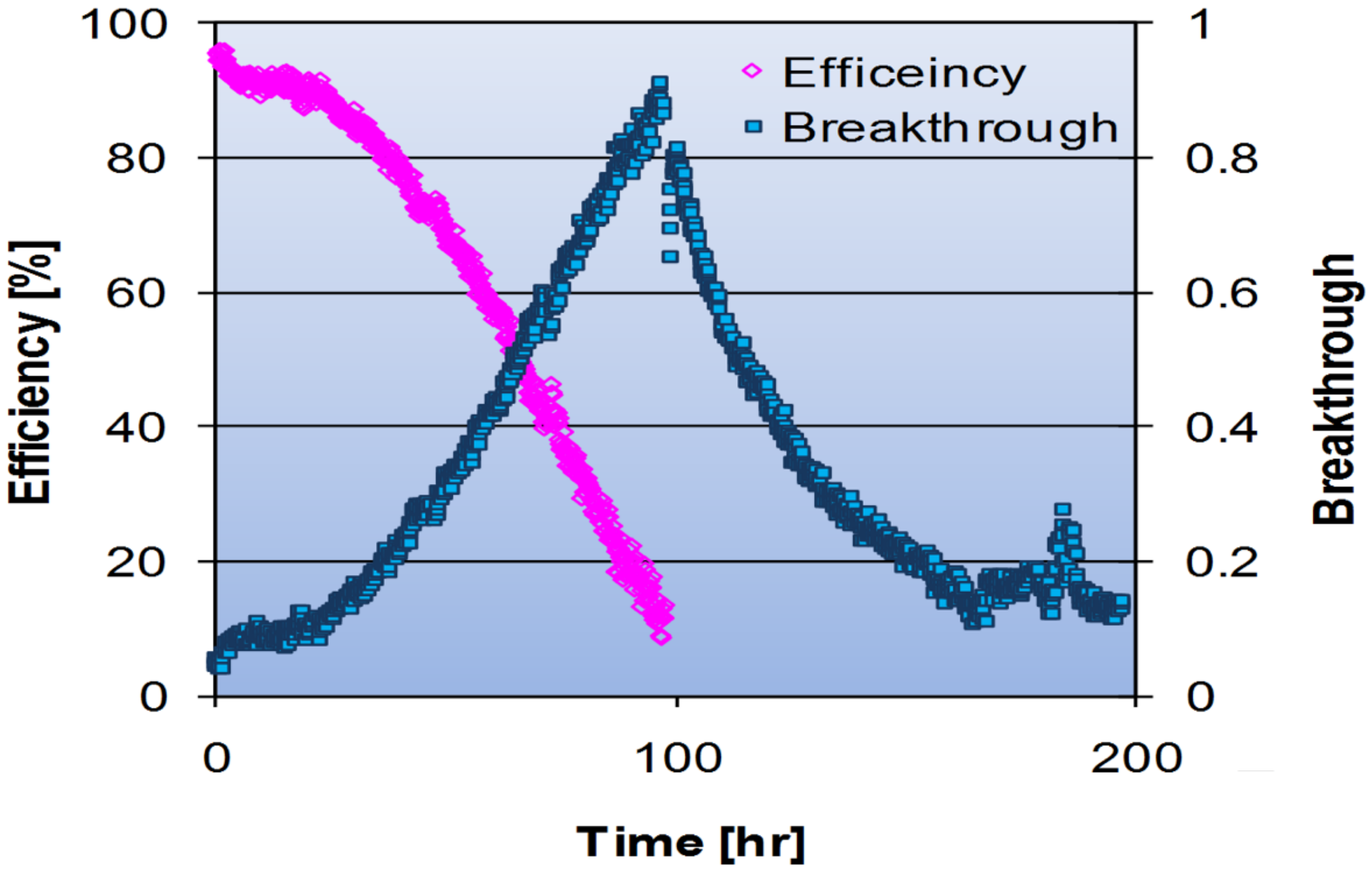
# Full-scale dynamic test set-up



# Full-scale dynamic test set-up



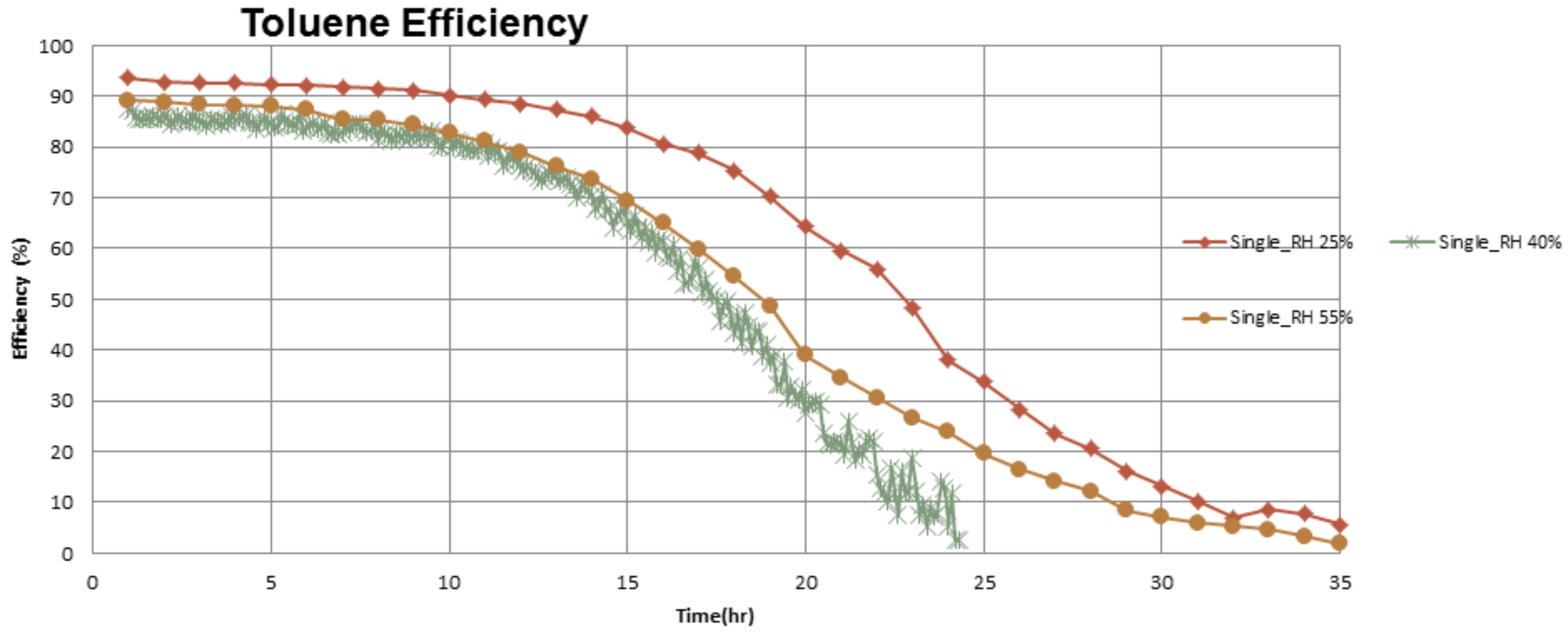
# Results

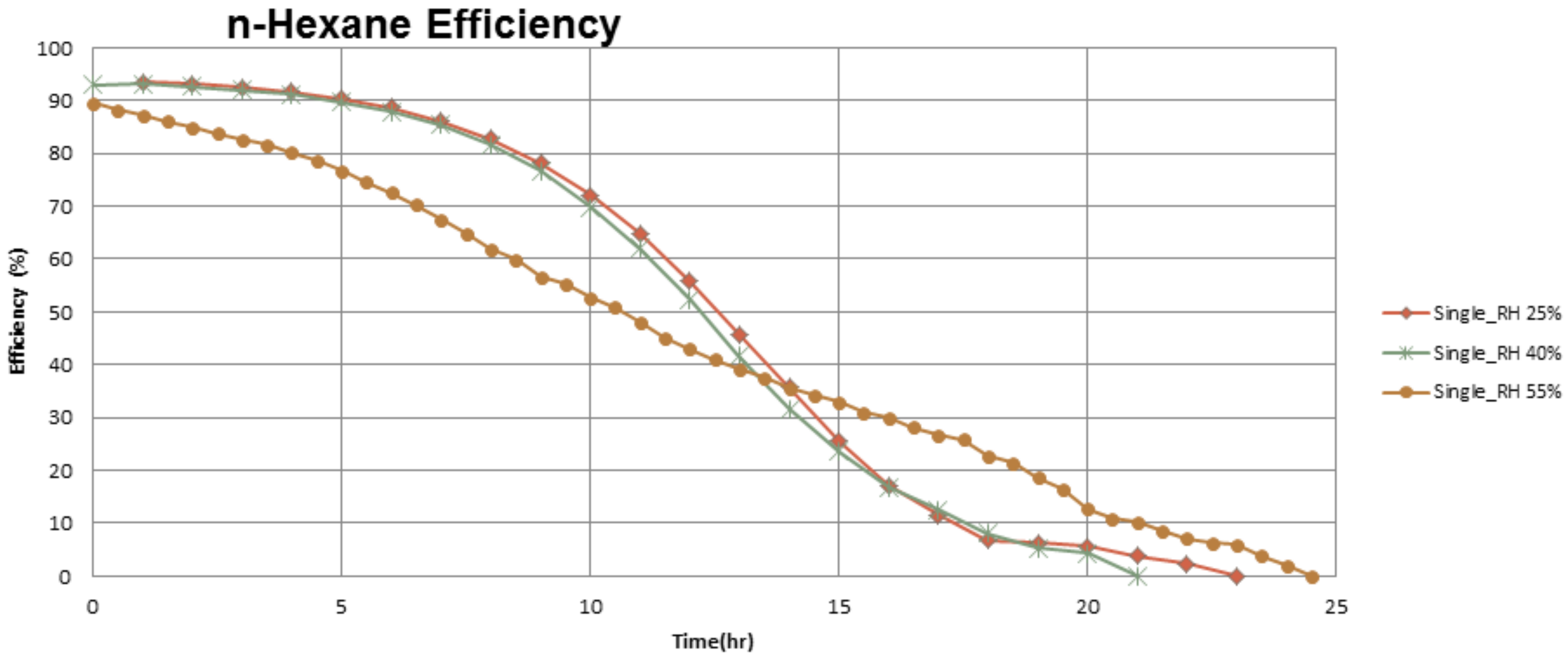


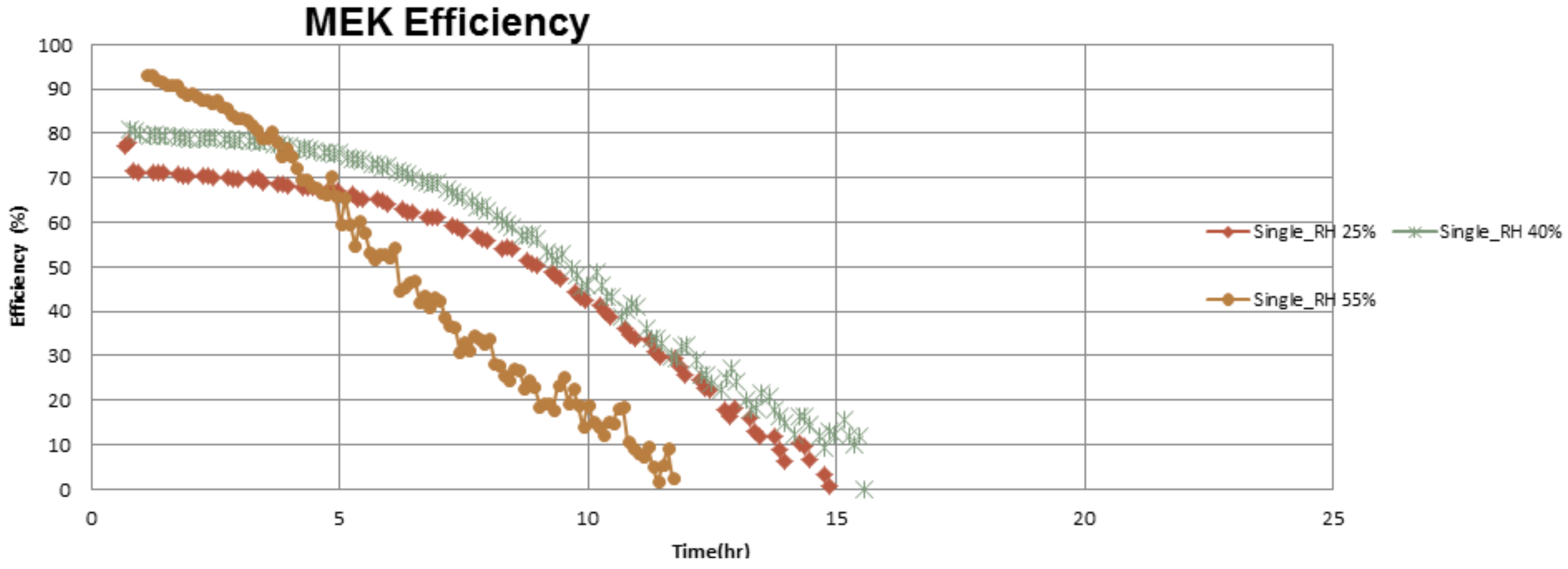

$$P = \frac{C_{down}}{C_{up}}$$

$$E = [1 - P] \times 100$$

# Effect of %RH

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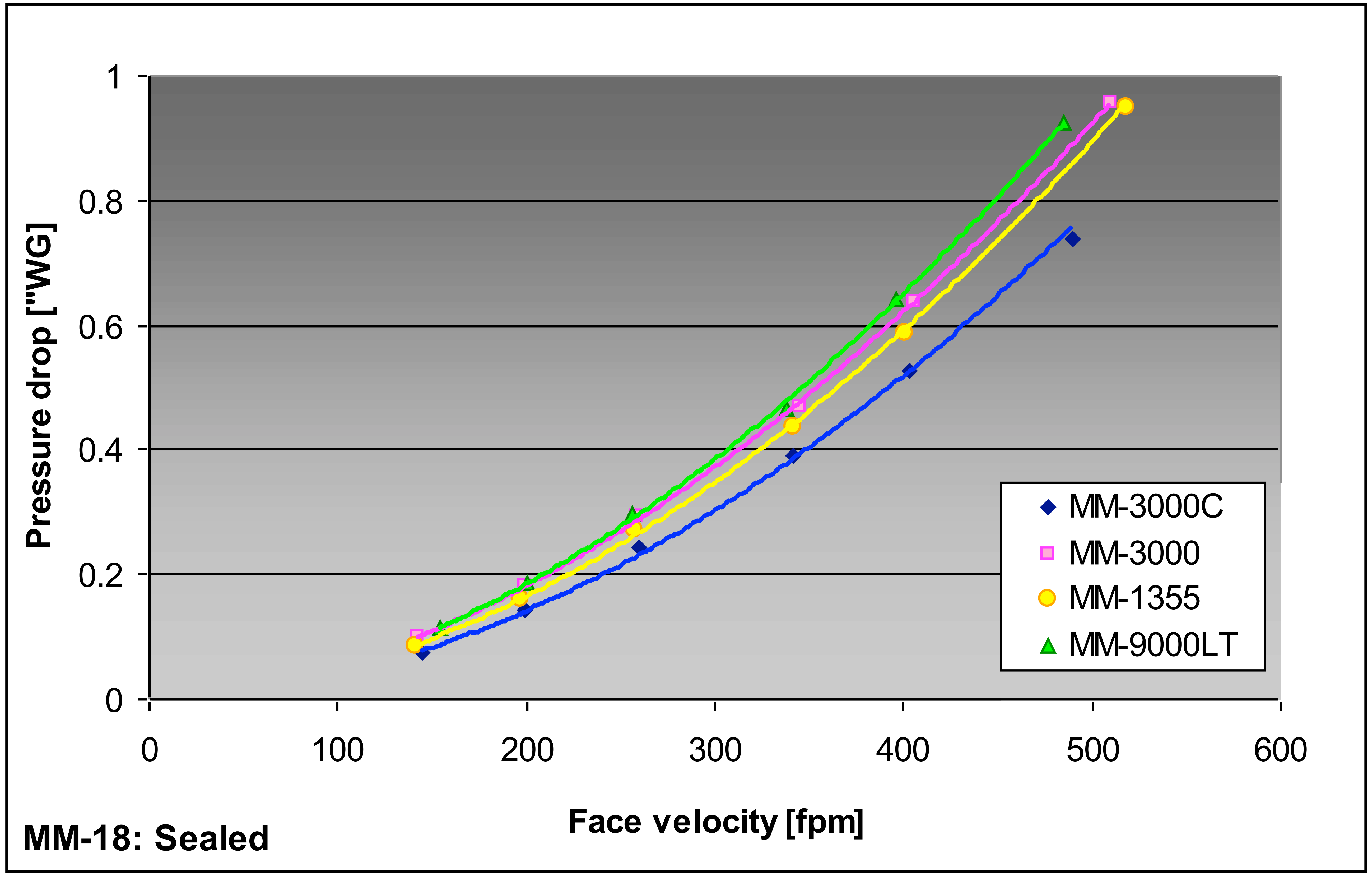
# V-shape Module

- Flow resistances (sealed)

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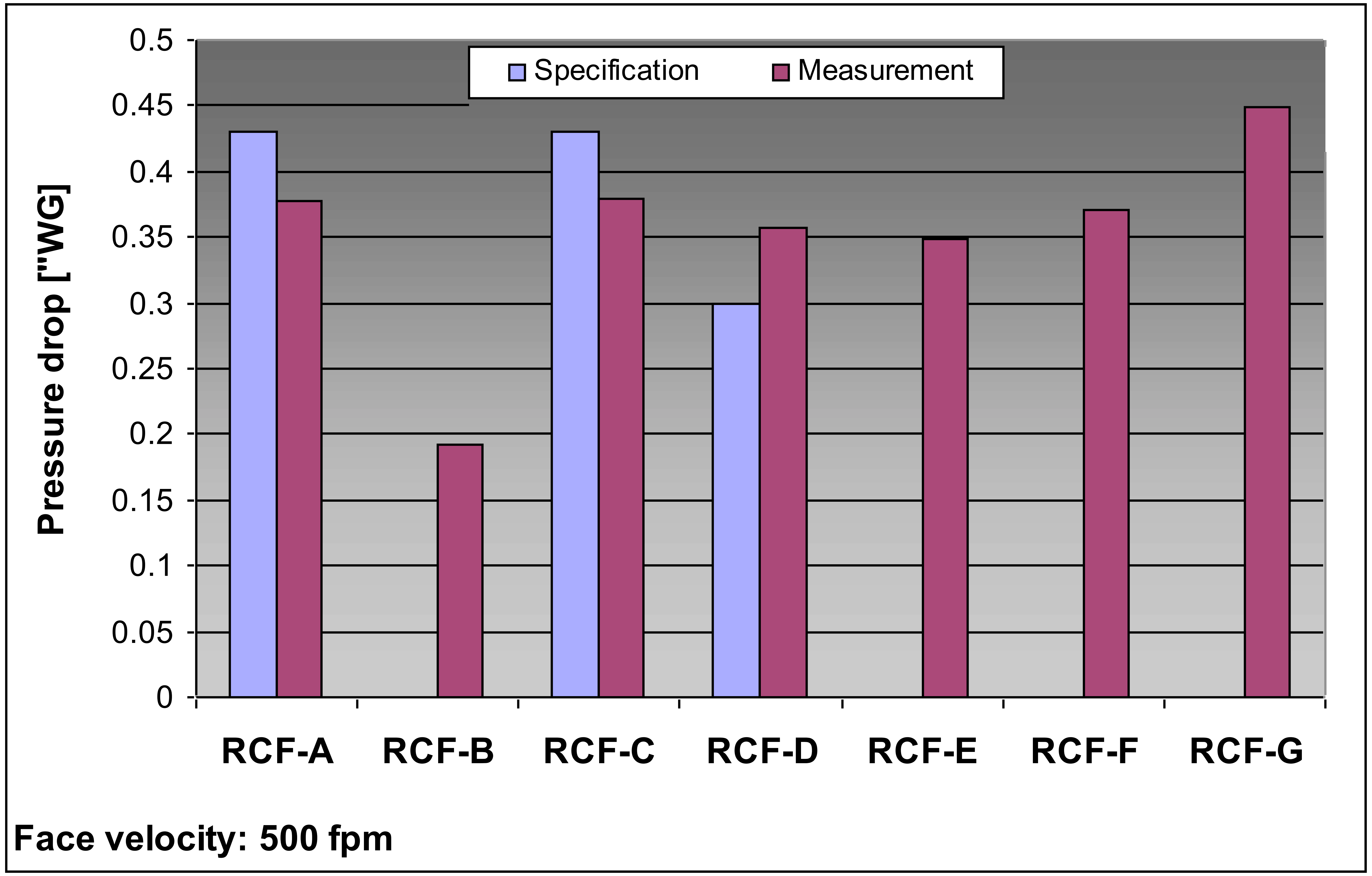
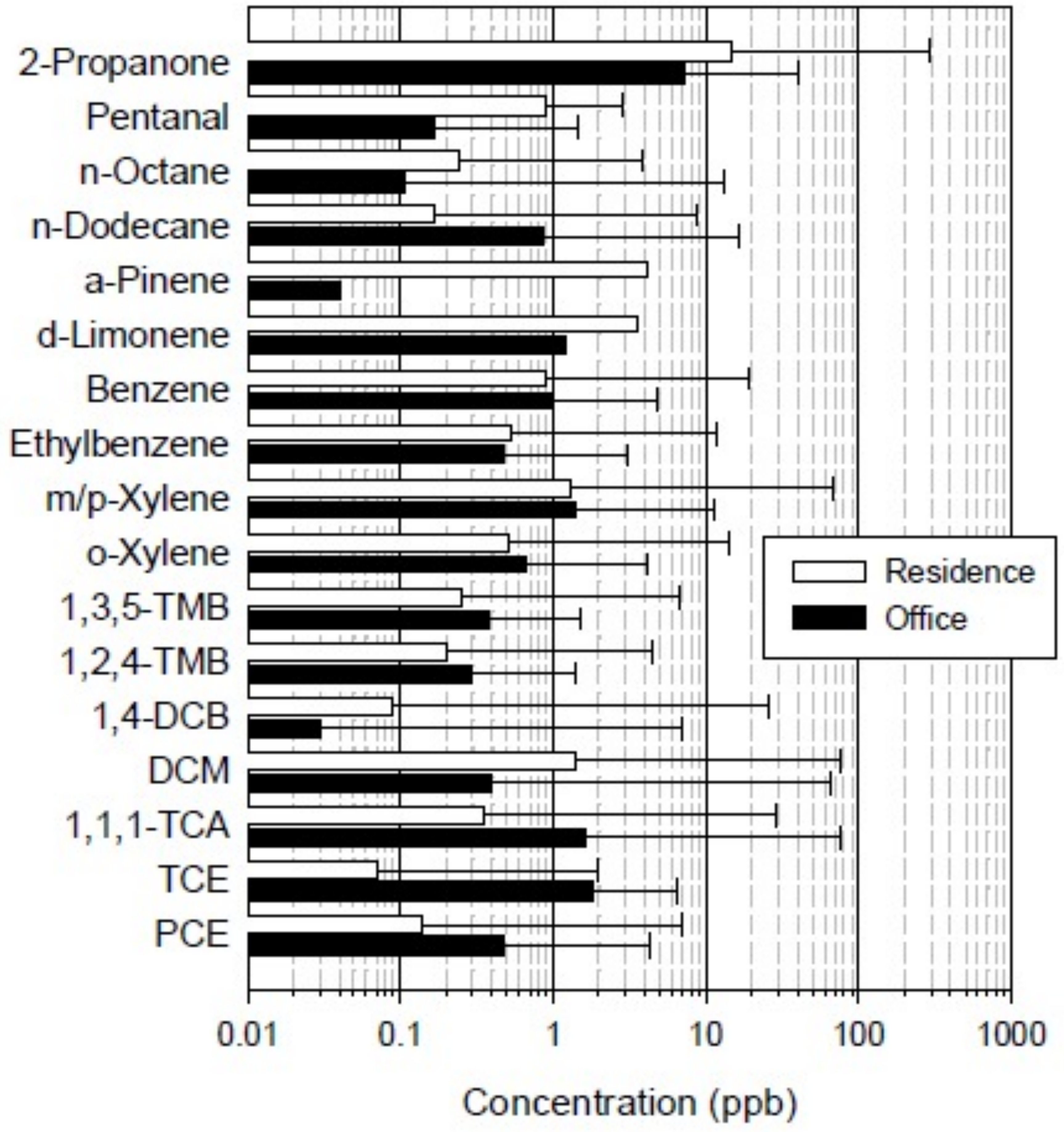
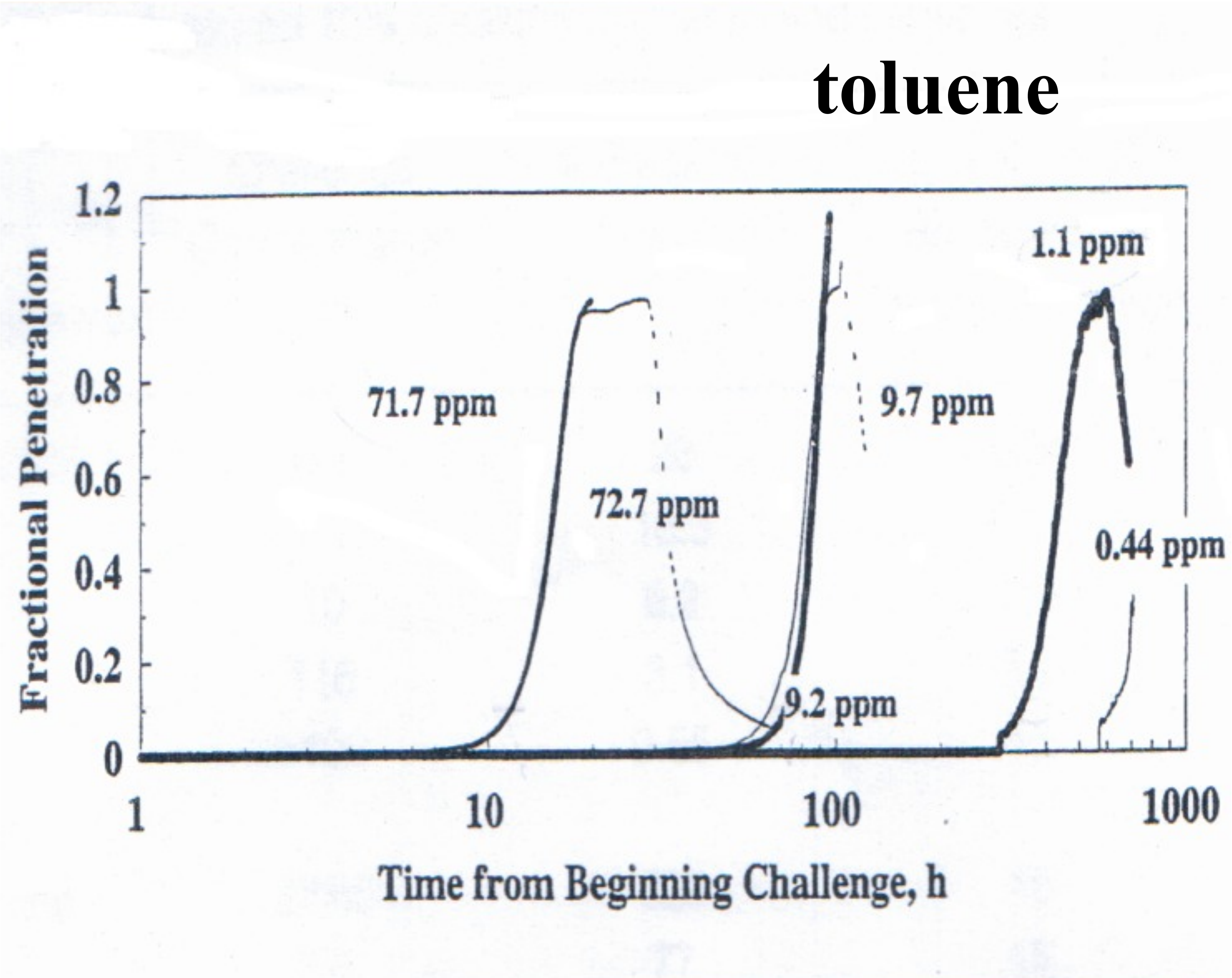
# Pleated Rigid Carbon Filters

- Flow resistances




# Limitations




VanOsdell 1996

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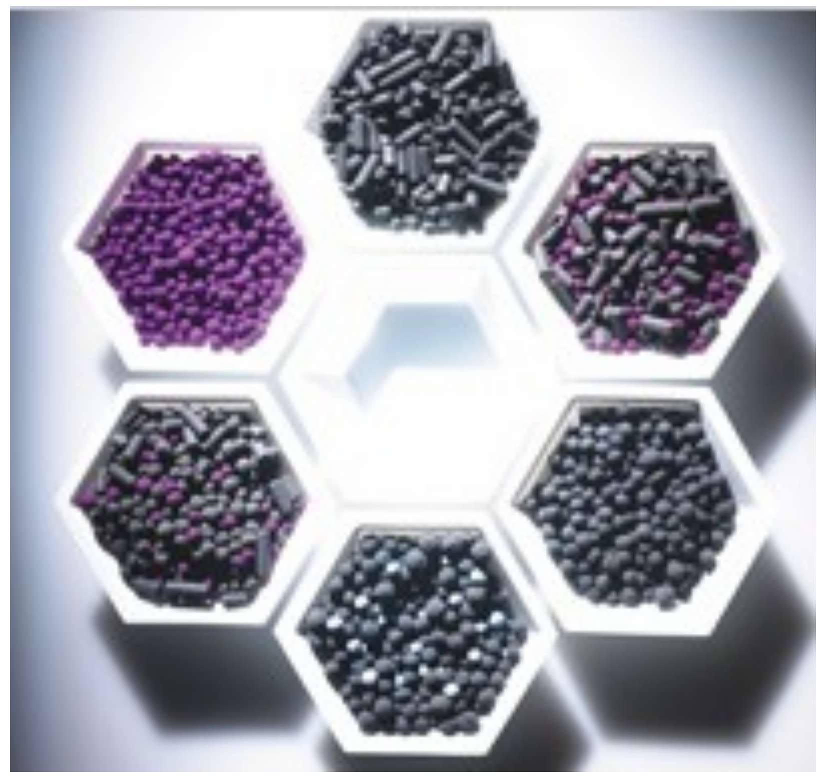
# Conclusions

- *AC could be a solution,*
- ASHRAE standards tests can be used to compare different filters,
- Needs to develop a procedure to predict the filter performance at low concentrations using existing standards
- Needs routine maintenance and cost *(pressure drop and regeneration)*

# Other Possible Techniques

## 1)Carbon filtration



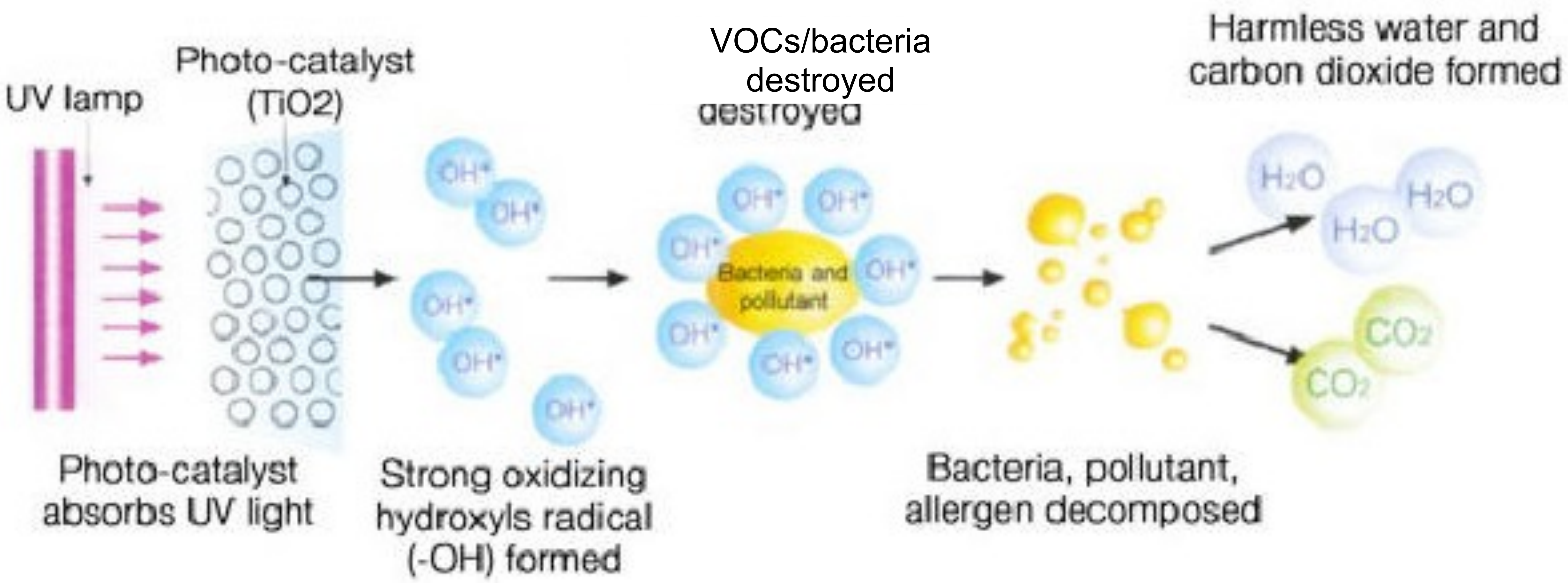
Advantages

- high capacity
- high efficiency

Disadvantages

- high pressure-drop
- high energy usage

## 2)PCO technology




- low pressure-drop
- low energy usage
- no post-treatment
- long life service
- Operation at room T and pressure

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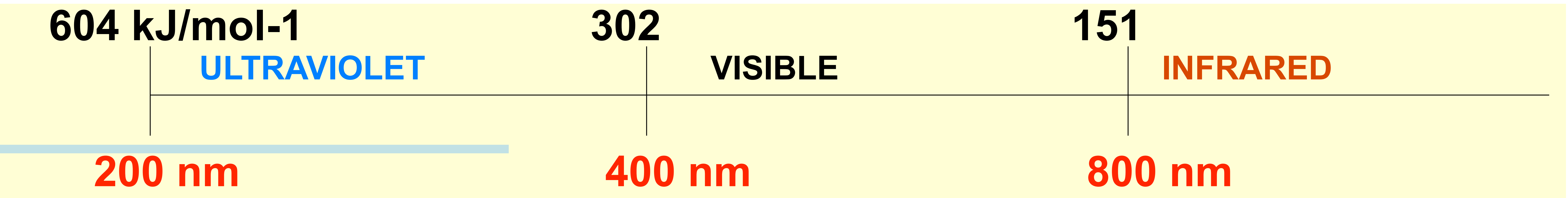
# UV-PCO Reactions

Chemical bond energies: 100 – 1000 kJ/mol

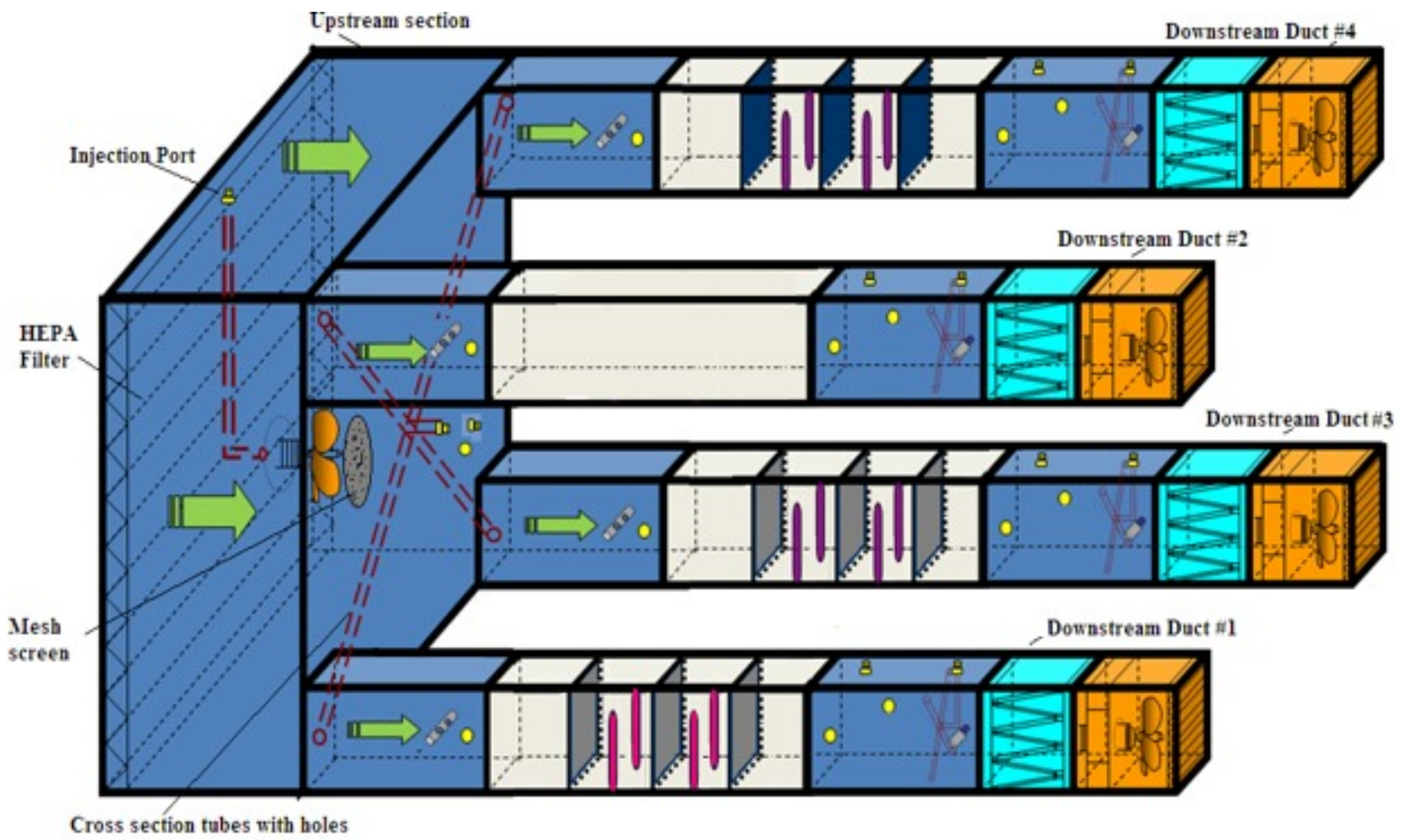
| Bond | E (kJ/mol) | λ (nm) |
|---|---|---|
| O-H | 465 | 257 |
| C-H | 415 | 288 |
| N-H | 390 | 307 |
| C-O | 360 | 332 |
| C-C | 348 | 344 |
| C-Cl | 339 | 353 |
| Br-Br | 193 | 620 |
| O-O | 146 | 820 |

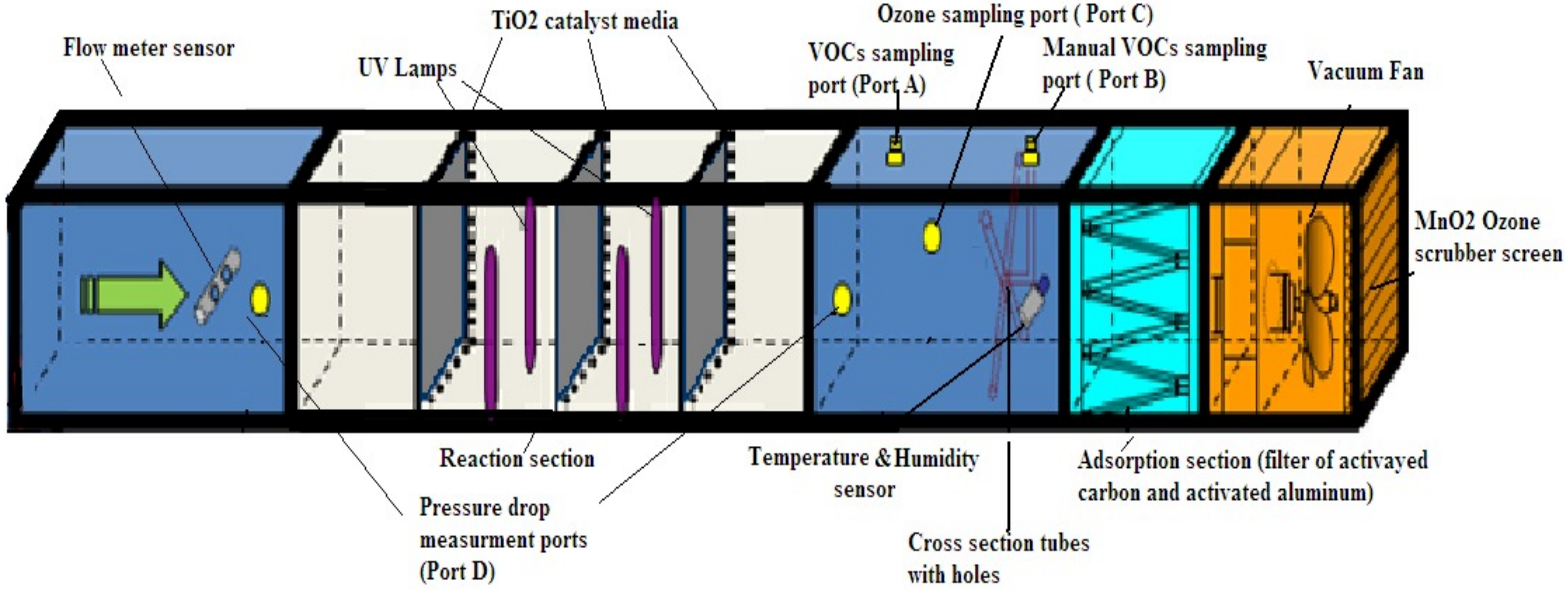



UV – and VIS region is expected to induce chemical reactions.

# UV-PCO


CIRCUL-AIRE


Upstream section
Downstream Duct #4
Injection Port
Downstream Duct #2
HEPA Filter
Downstream Duct #3
Mesh screen
Downstream Duct #1
Cross section tubes with holes


Flow meter sensor
UV Lamps
TiO2 catalyst media
VOCs sampling port (Port A)
Ozone sampling port ( Port C)
Manual VOCs sampling port ( Port B)
Vacuum Fan
MnO2 Ozone scrubber screen
Reaction section
Pressure drop measurment ports (Port D)
Temperature & Humidity sensor
Cross section tubes with holes
Adsorption section (filter of activayed carbon and activated aluminum)

# UV-Lamps and Catalyst substrates

## Catalyst:

Catalyst substrate A consists of $TiO_2$ coated on fiber glass and 105.7063 ± 1.6269 $m^2/g$ BET surface area.

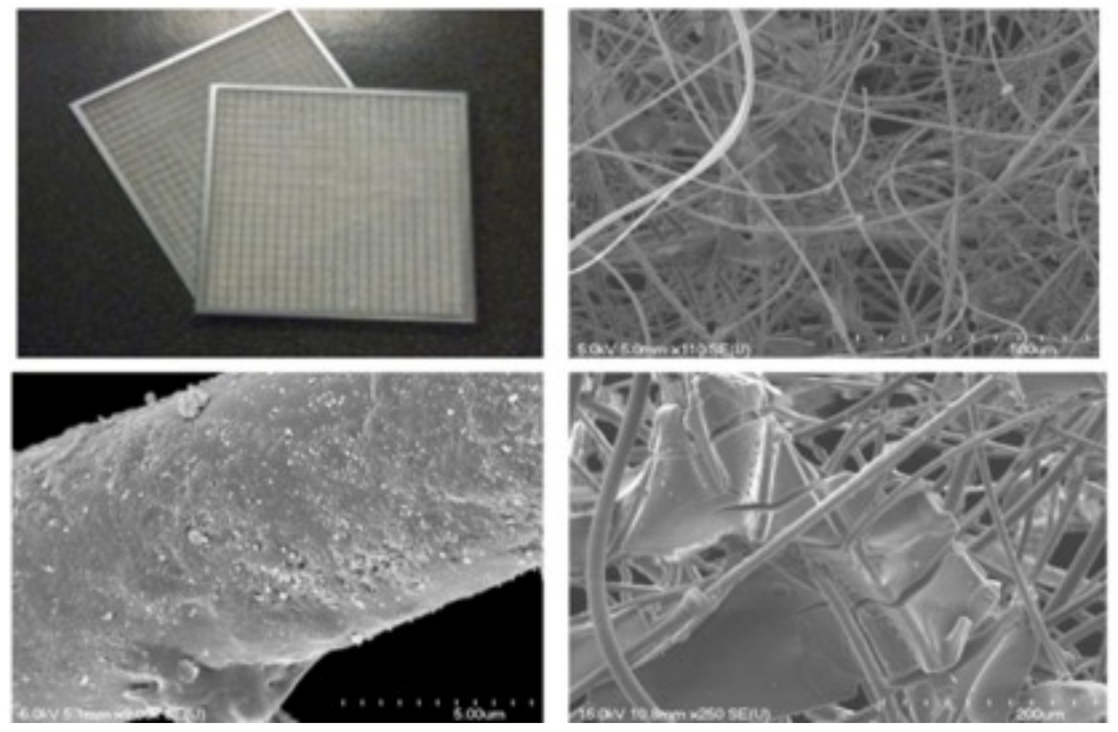
Catalyst substrate B consists of $TiO_2$ coated on activated carbon with 887.6638 ± 10.6871 $m^2/g$ BET surface area.

## UV-Lamps:

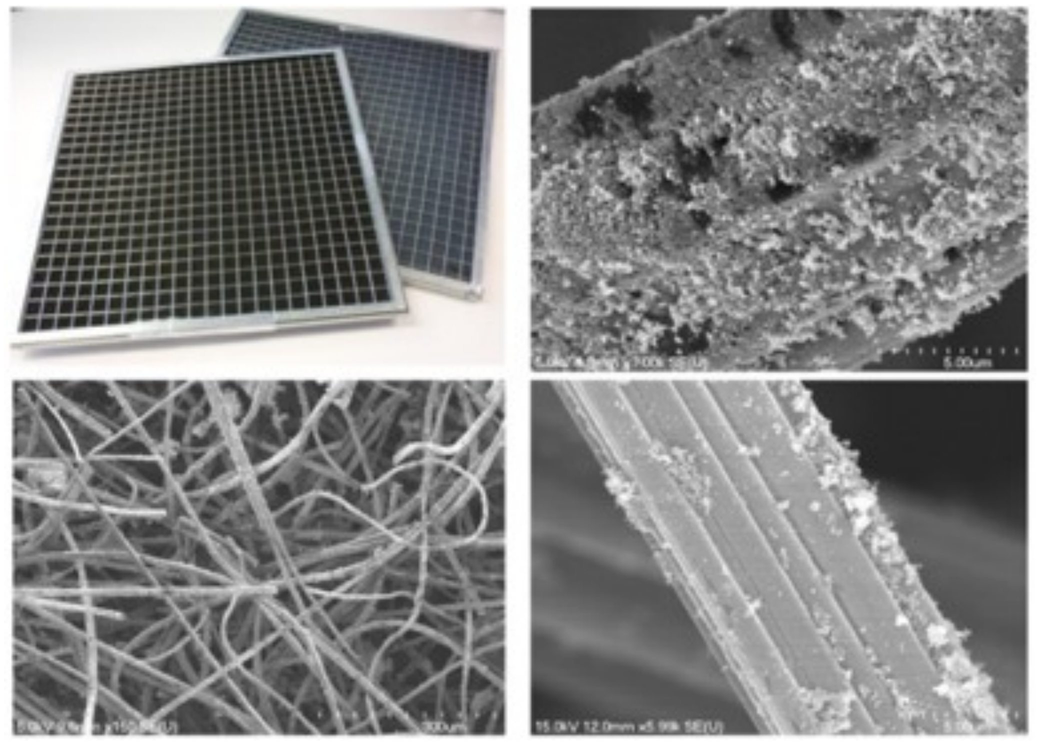
**VUV** lamps with 254nm+185nm wavelength irradiation;

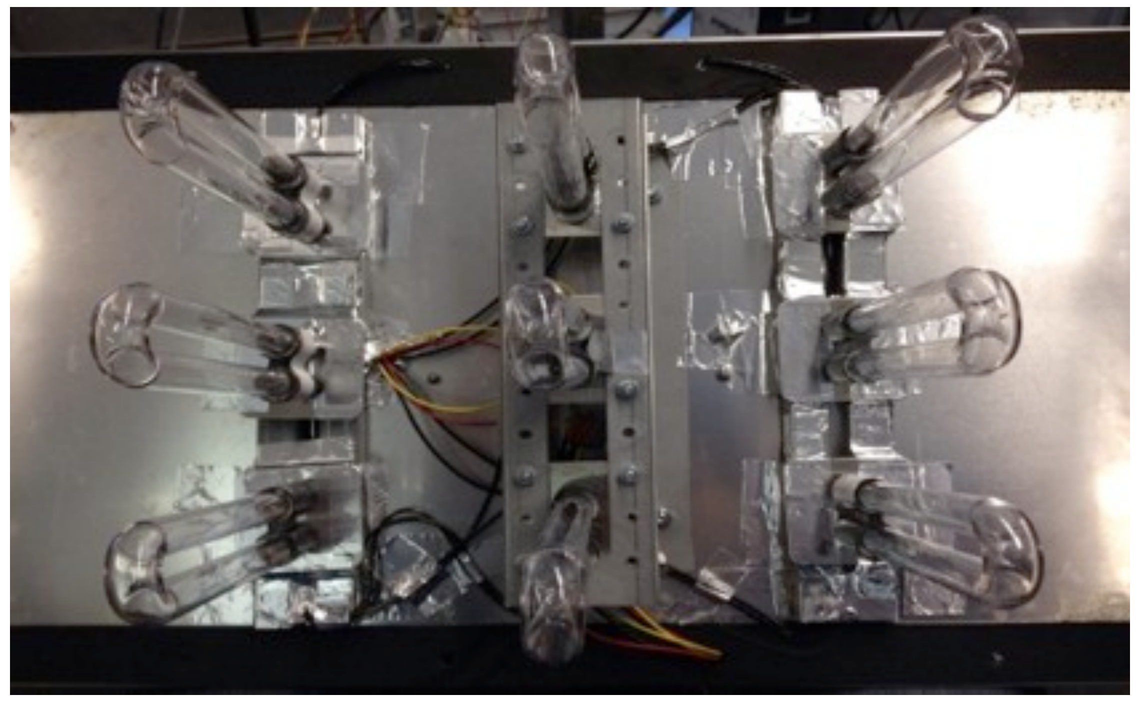
**UVC** lamps with 254nm wavelength irradiation

Catalyst A



Catalyst B



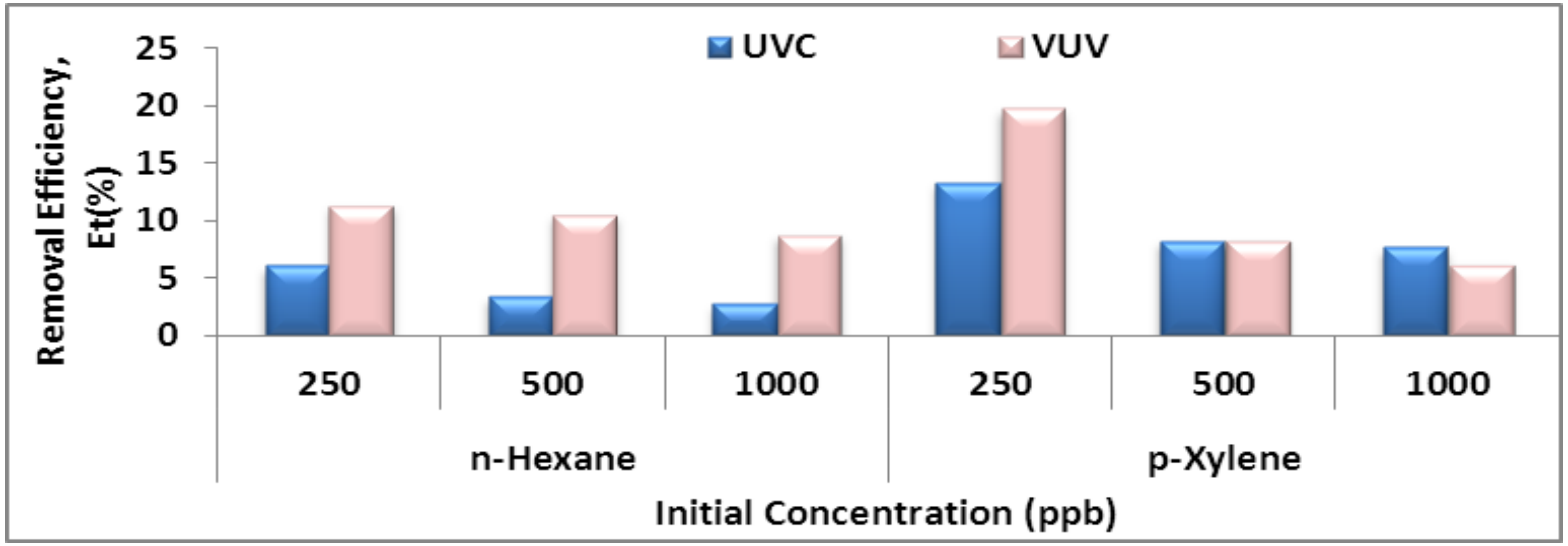


# *Effect of UV-Lamps*

- A

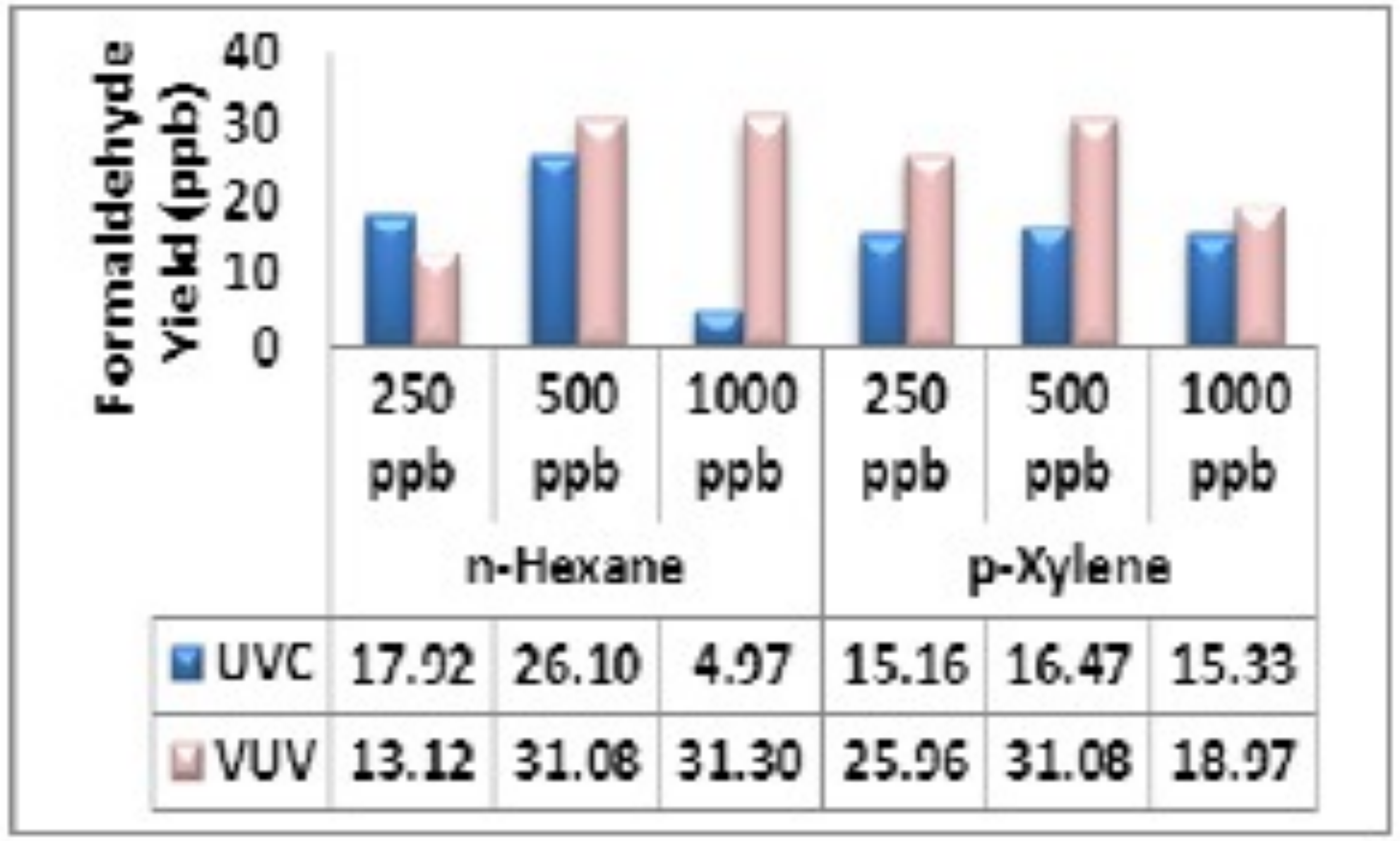
In order to present and discuss the experimental results the following two definitions were given:

1. Single pass removal efficiency, Et (%): $E_t = ((C_{up,t} - C_{down,t})/C_{up,t}) \times 100\%$
2. By-products yield, Ga (by-product) (ppb): $G_{a(by\text{-}product)} = C_{up(by\text{-}product)} - C_{down(by\text{-}product)}$

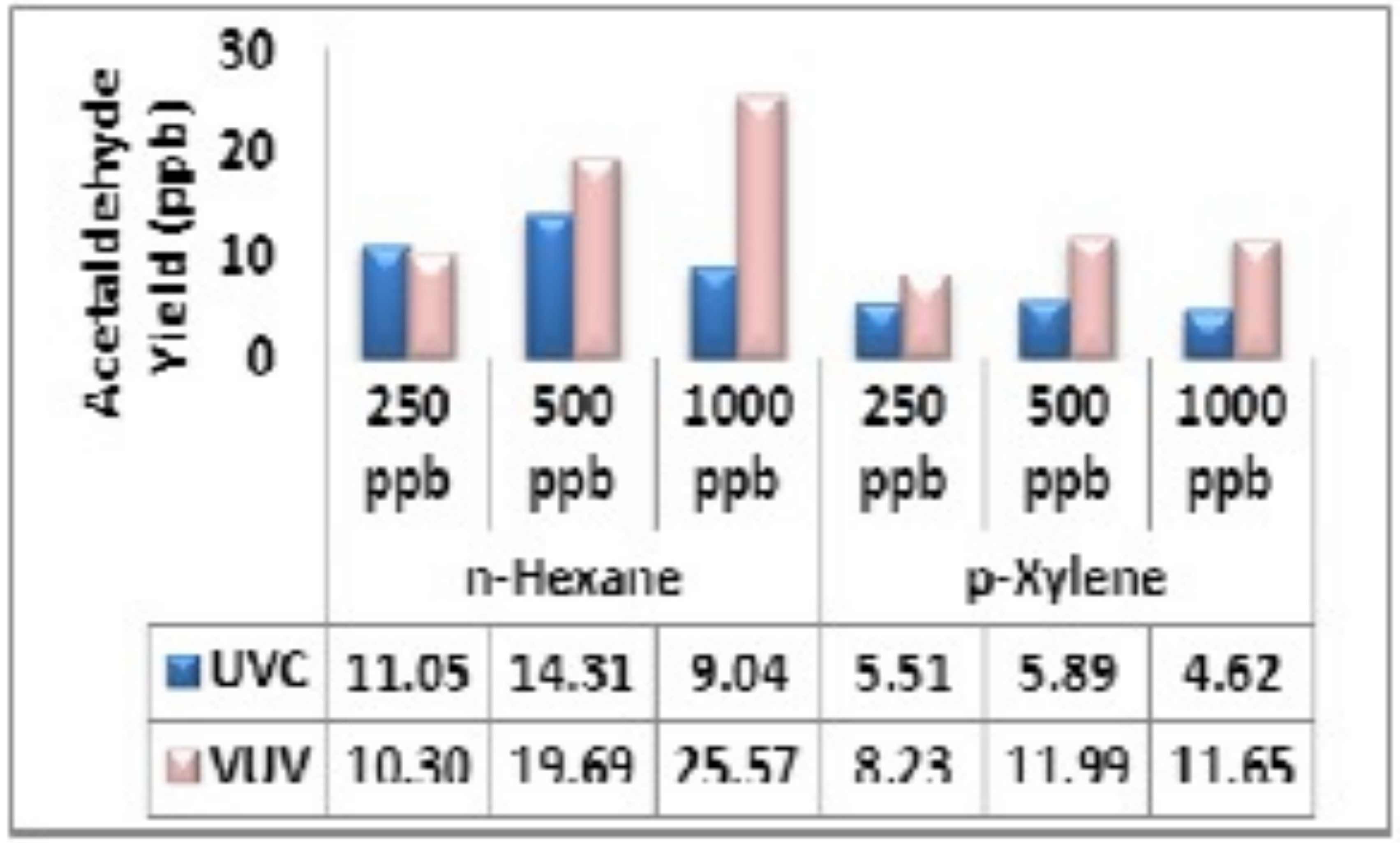



Removal efficiency versus the initial concentration of target compounds in the presence of VUV and UVC lamps.

# Effect of UV-Lamps

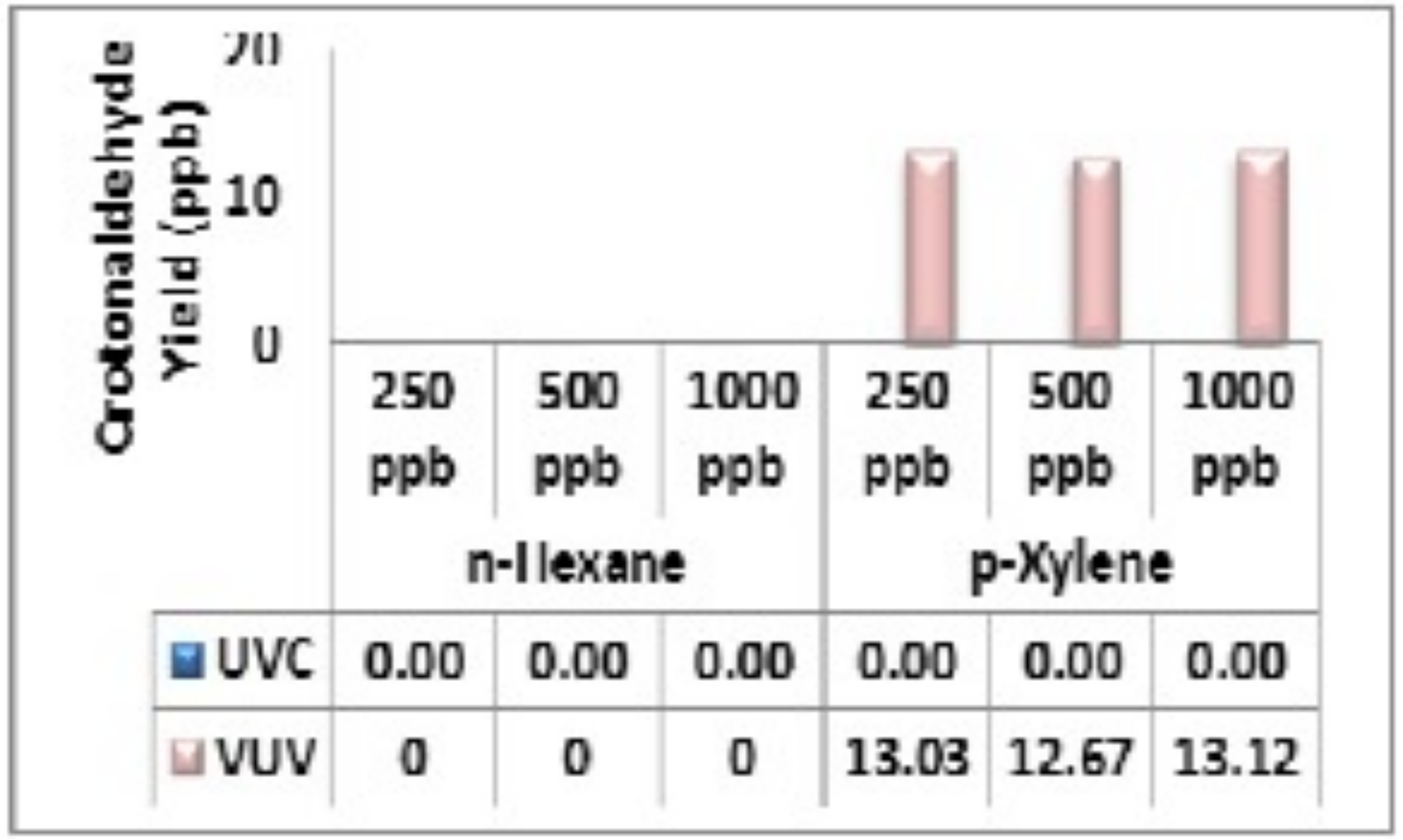



| | n-Hexane 250 ppb | n-Hexane 500 ppb | n-Hexane 1000 ppb | p-Xylene 250 ppb | p-Xylene 500 ppb | p-Xylene 1000 ppb |
|---|---|---|---|---|---|---|
| UVC | 17.92 | 26.10 | 4.97 | 15.16 | 16.47 | 15.33 |
| VUV | 13.12 | 31.08 | 31.30 | 25.96 | 31.08 | 18.97 |



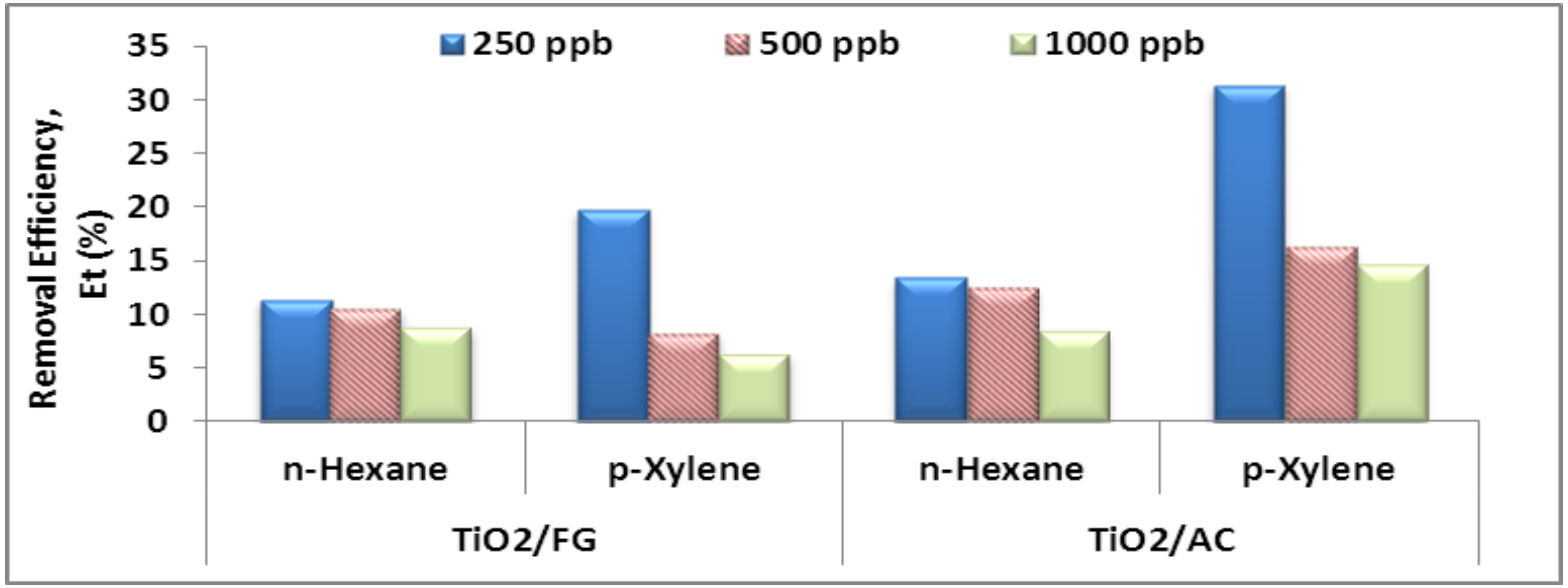

| | n-Hexane 250 ppb | n-Hexane 500 ppb | n-Hexane 1000 ppb | p-Xylene 250 ppb | p-Xylene 500 ppb | p-Xylene 1000 ppb |
|---|---|---|---|---|---|---|
| UVC | 11.05 | 14.31 | 9.04 | 5.51 | 5.89 | 4.62 |
| VUV | 10.30 | 19.69 | 25.57 | 8.23 | 11.99 | 11.65 |

By-products yield versus the initial concentration of target compounds in the presence of VUV and UVC lamps.



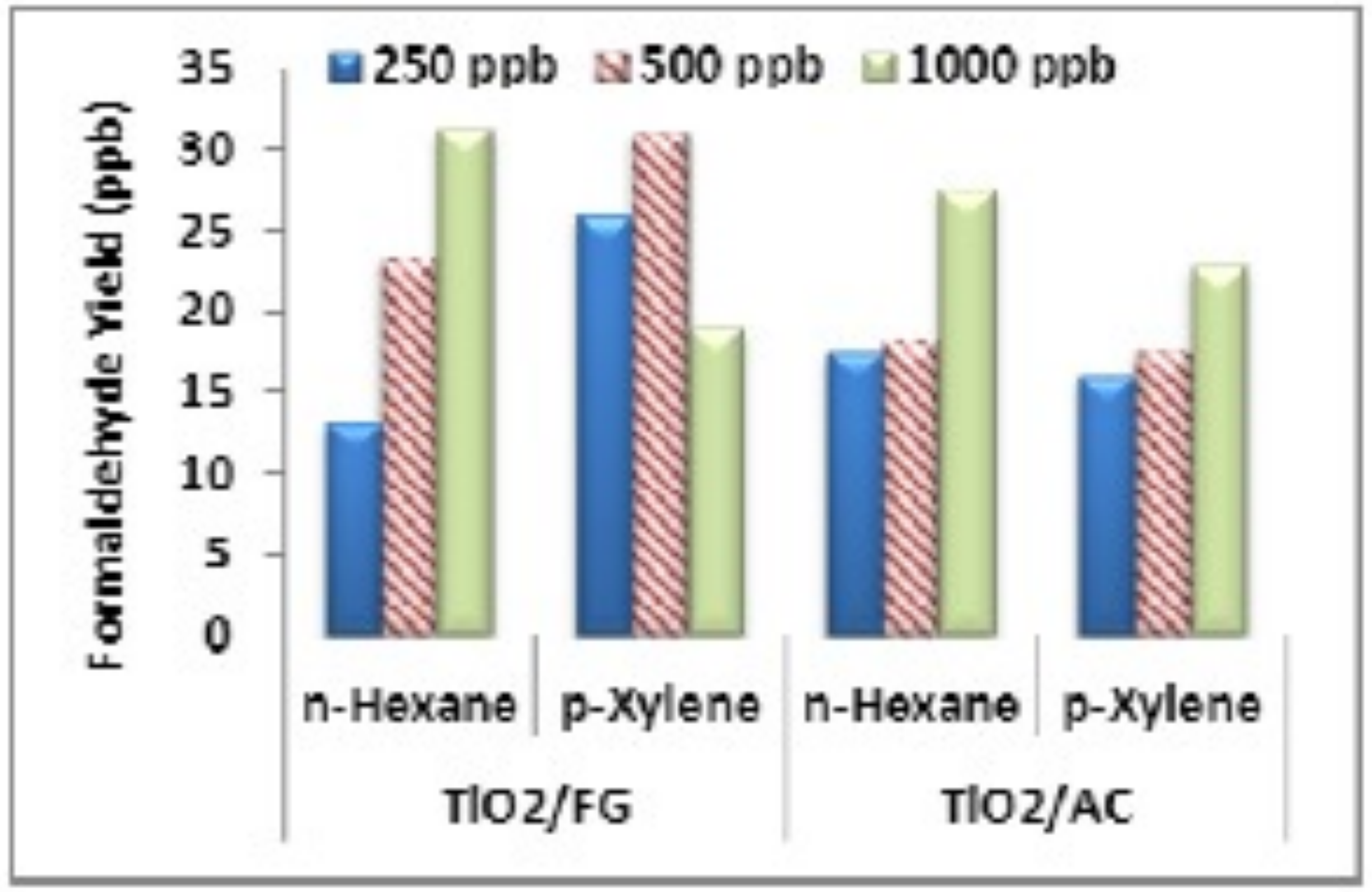

| | n-Hexane 250 ppb | n-Hexane 500 ppb | n-Hexane 1000 ppb | p-Xylene 250 ppb | p-Xylene 500 ppb | p-Xylene 1000 ppb |
|---|---|---|---|---|---|---|
| UVC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| VUV | 0 | 0 | 0 | 13.03 | 12.67 | 13.12 |

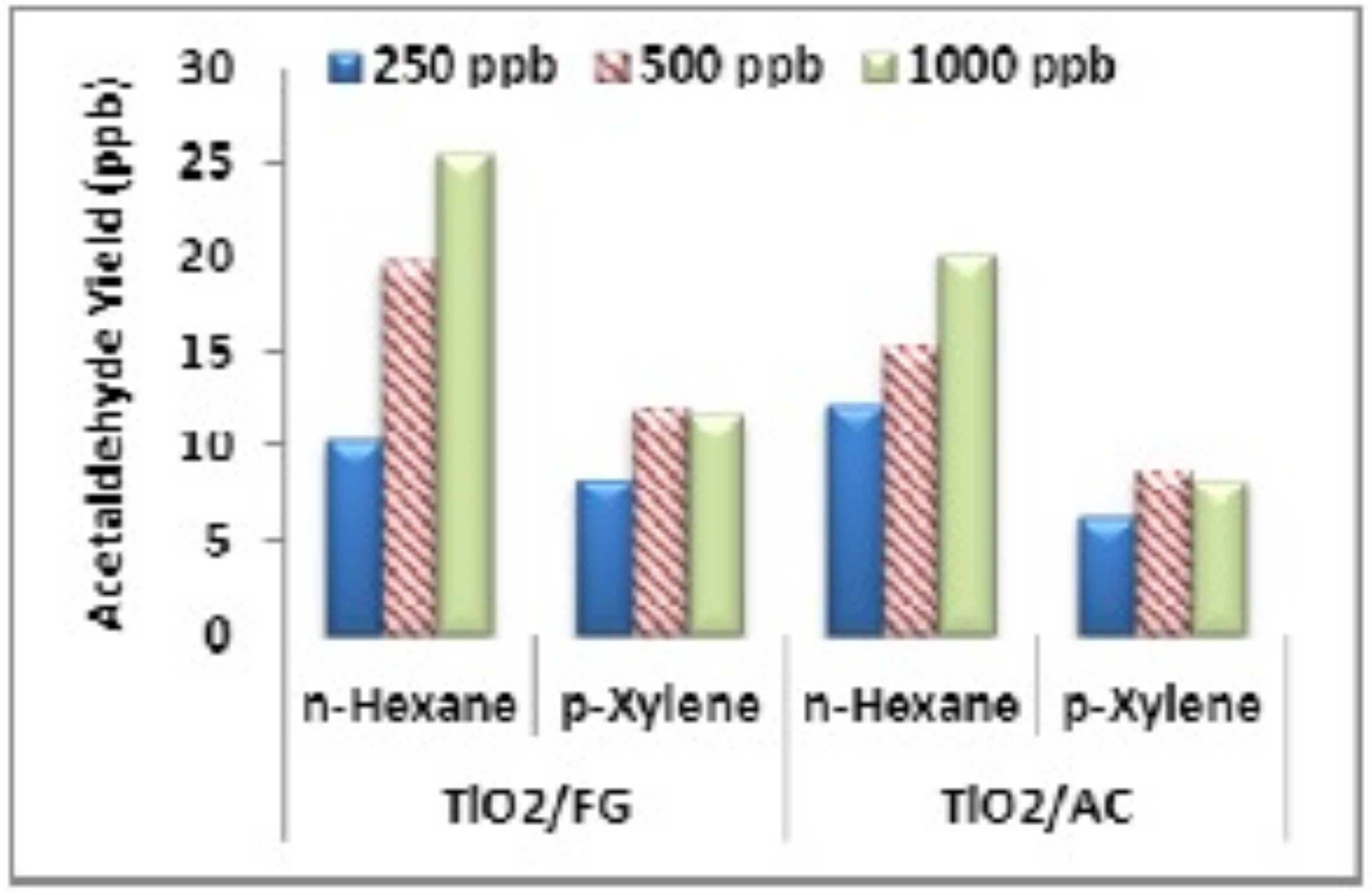
# Effect of Catalyst Substrate



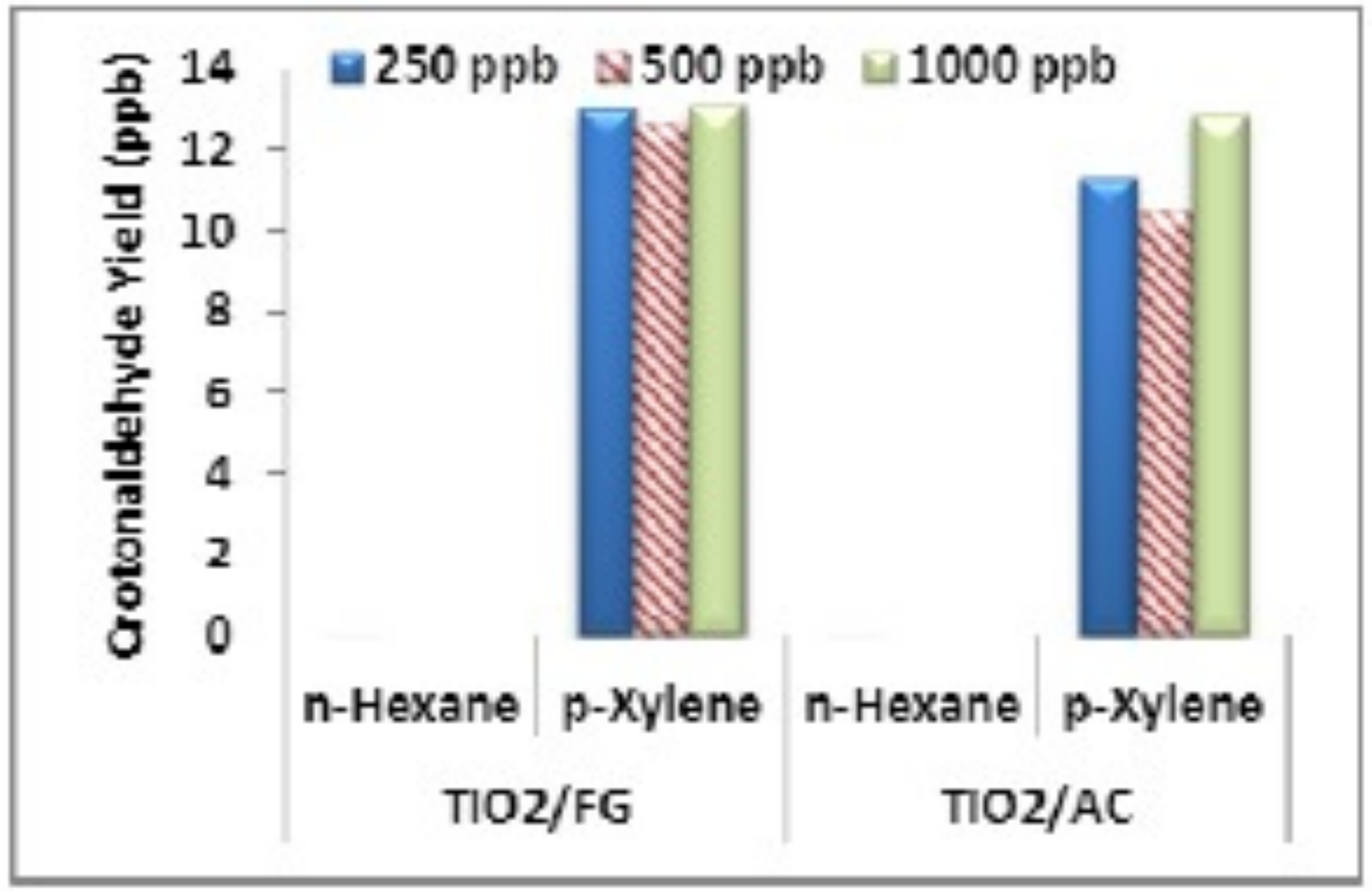

Removal efficiency versus the initial concentration of target compounds in the presence of VUV over $TiO_2$/AC and $TiO_2$/FG

# Effect of Catalyst Substrate




By-products yield versus the initial concentration of target compounds in the presence of VUV over $TiO_2$/AC and $TiO_2$/FG

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# Preliminary Conclusion

- Experimental results demonstrated that VUV lamps outperformed UVC lamps for degradation of model compounds. However, higher amount of by-products were formed in the case of VUV lamps, and crotonaldehyde was only generated in the presence of VUV lamps for both p-xylene and n-hexane.

- The yield of by-products in UV-PCO of n-hexane was greater than p-xylene in the presence of both VUV and UVC lamps. This demonstrates that more partial oxidation and side reactions happen in n-hexane oxidation compared to the p-xylene.

- Comparison of the performance of catalyst substrates, TiO2 /FG and TiO2 /AC, showed that TiO2 /AC has better properties for degradation of target compounds. This is the case especially for UV-PCO of p-xylene where even lower amount of by-products were formed over this catalyst substrate.

# Summary and Conclusion

- Sorption filtration is still the most effective off-the-shelf commercial technology,
- UV-PCO is a promising technology if designed properly,
- However, products tested did not show significant removal effectiveness and generated by-products;
  - Develop the appropriate substrate,
  - Develop a methodology to optimize the design
- Further work is needed to develop rating system for product evaluation.