Aalto University
School of Engineering

Comfortable and Healthy Indoor Climate

EEN-E4001

Lecture 5: Filtration

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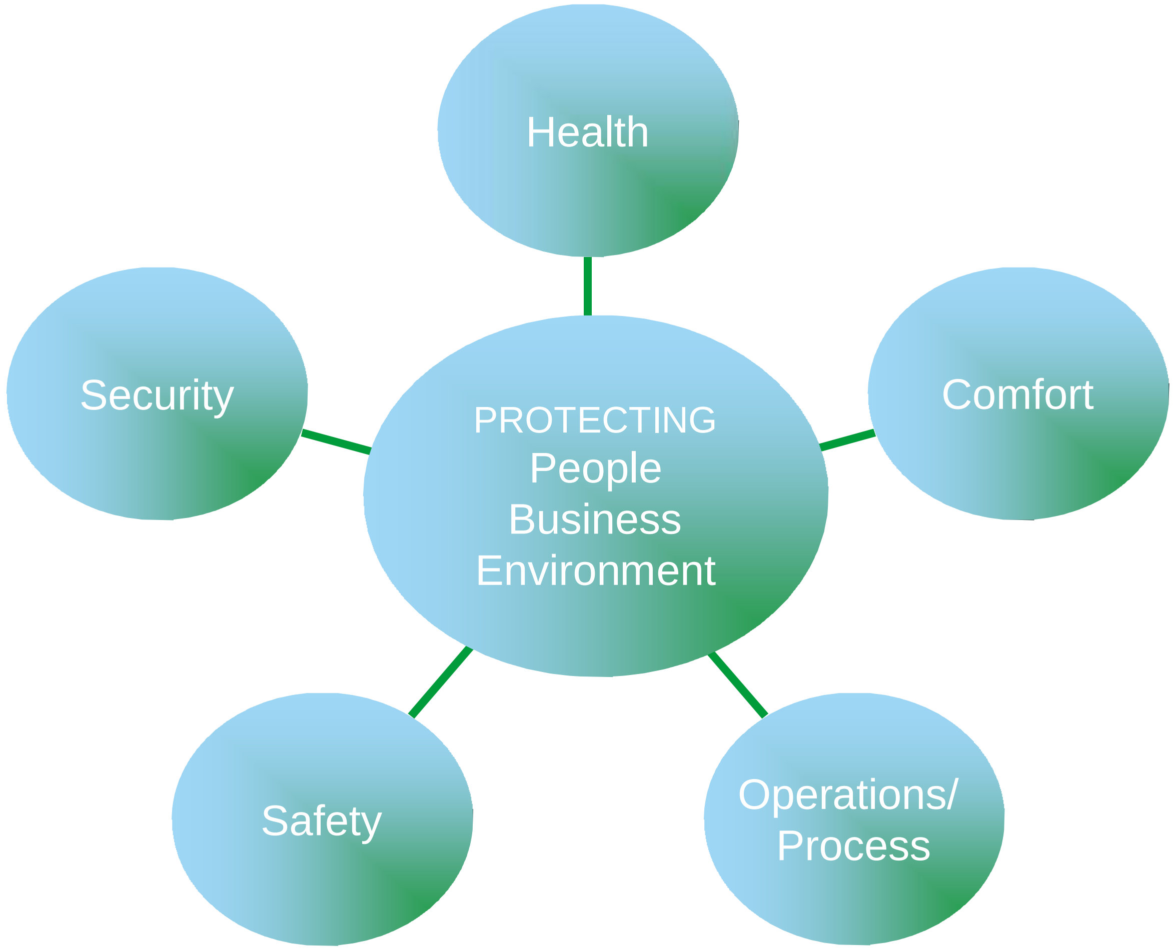
Learning outcome

- Importance of clean air
- Air cleaning technologies
- Efficiency of filters

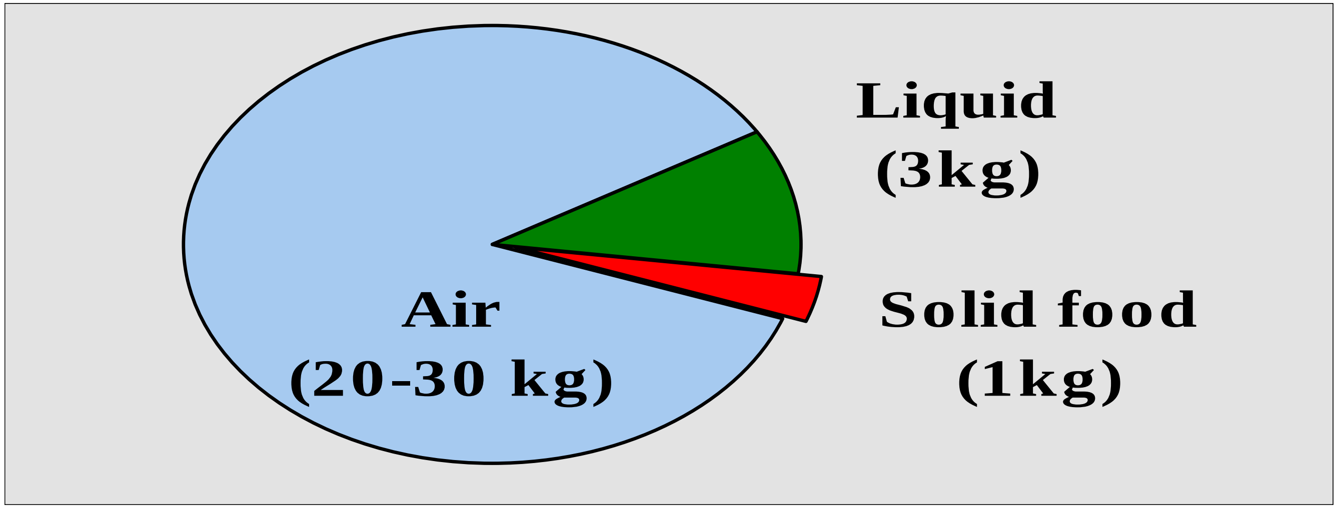
Short discussion

Why we need to filtrate ?

Clean Air Need Categories



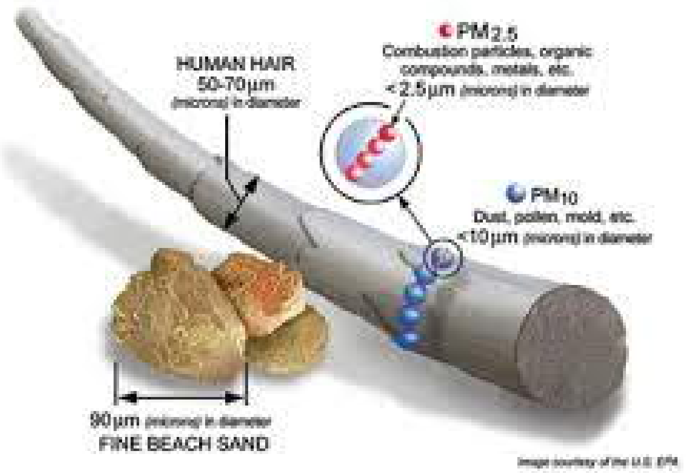
Human consumption of air, liquid and food over a 24-hour period.

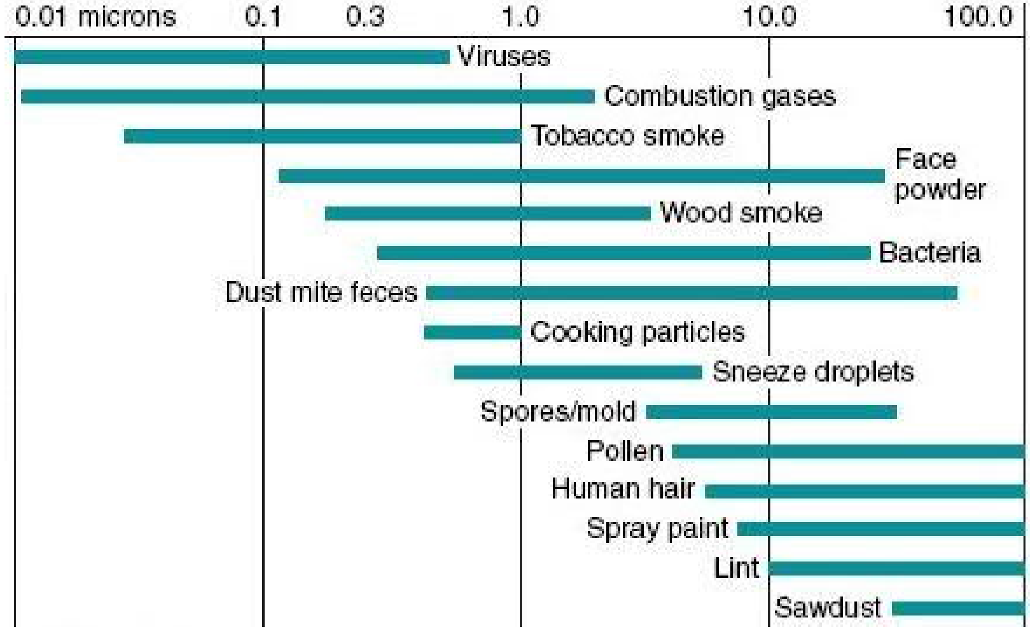


- We spend 90 percent of our time indoors and the vision should be that nobody gets sick because of the indoor air quality.
- The World Health Organization establishes in its document "*The right to healthy indoor air* (WHO 2000) that breathing healthy indoor air is a human right.

Airborne Particulate Pollution

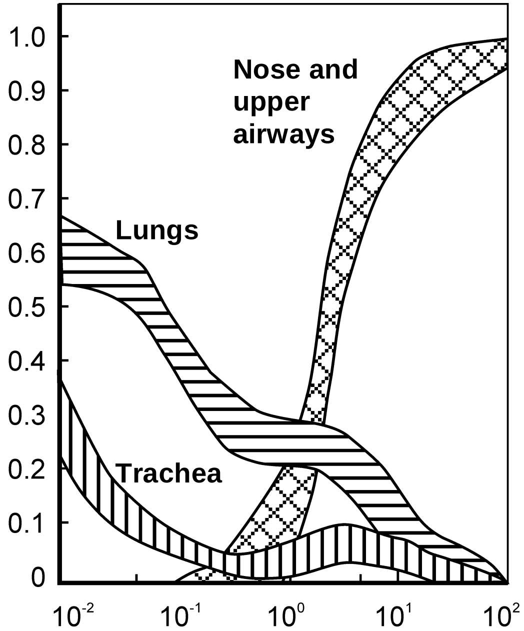
- Airborne particulate matter consists of both solid particles and liquid droplets of different sizes, compositions, and origins.
- They can range from small molecules less than 0.001 μm to pollens and spores ranging from 2 to 50 μm, and very large visible dust particles in the range of 100 μm and bigger.





Smallest particles will accumulate deep down in the lungs, coarse particles are removed from the air in the upper air ways

Fraction depositing in respiratory passage



Particle diameter, µm

Indoor air pollutants: the ventilation rate needed for dilution of the pollutants.

The dilution ventilation flow rate for a known emission rate and concentration level of a pollutant within the building can be calculated by equation

$$q_{v,\text{sup}} = \frac{G}{c_{ida} - c_{\text{sup}}}$$

Where

$q_{v,sup}$ = volume flow rate of supply air in m^3/s

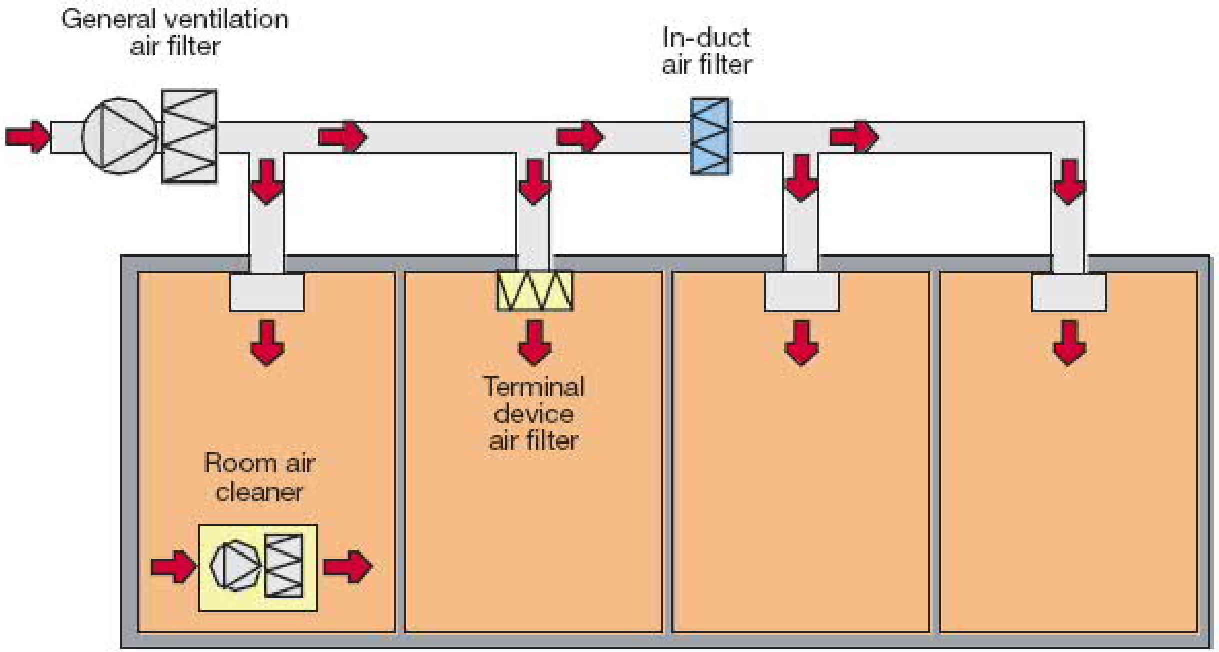
G = mass flow rate of emission in the room in mg/s

c_{ida} = allowed concentration in the room in mg/m^3

c_{sup} = concentration in the supply air in mg/m^3

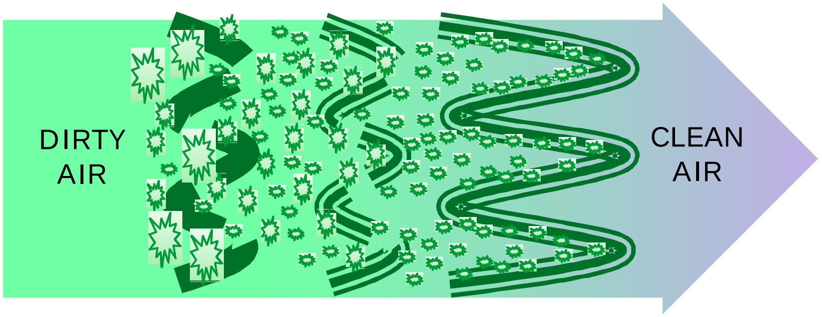
Where to Use Air Cleaning in Buildings?

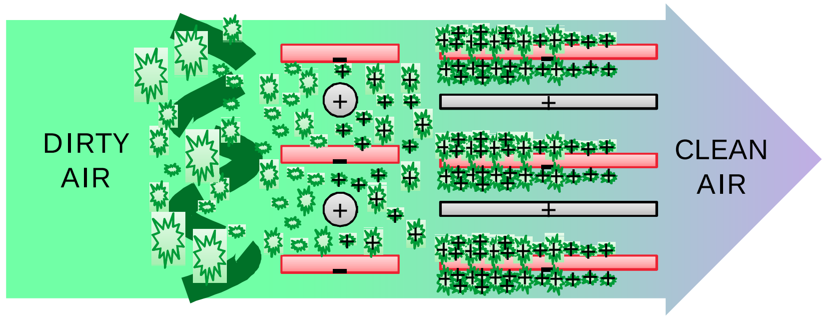
- Outdoor air intake/duct
  - *In-duct filters/devices*
- HVAC air recirculation duct
  - *In-duct filters/devices*
  - *Passive materials*
- In rooms
  - *Standalone air cleaners*
  - *Passive materials*



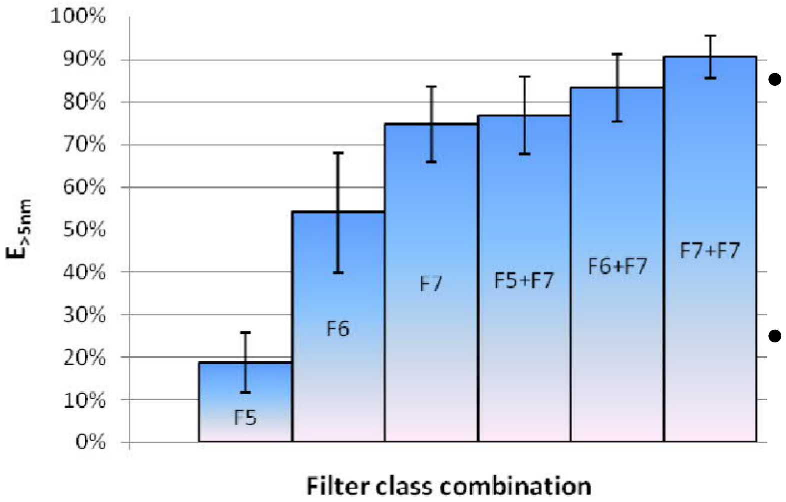
Particulate Filtration

- **Mechanical filters** removes the particulates from the air based on straining, interception, diffusion and inertial separation when the air passes through the filter media (glass fibre or cellulose based fabric).
- **Electrostatic precipitator (ESP)** is an air filtration device that removes fine particles, like dust and smoke, from air using electrical forces to move the particles out of the flowing gas stream and onto collector plates. The particles are given an electrical charge by forcing them to pass through a corona discharge. The electrical field that forces the charged particles to the walls comes from electrodes maintained at high voltage in the center of the flow lane.





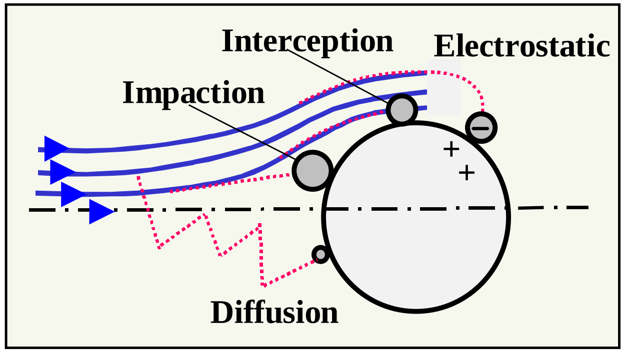
Air Filtration in Air Handling Unit



Source: http://www.energy-management.se/attachments/documents/35/removal_of_ultrafine_particles.pdf

- Air filtration is required for removing the impurities (e.g. particulates and gases) that may enter along with outdoor air thus improving the indoor air quality.
- Different filter for different purposes:
  - Bag filters with glass fibre media are the best performed air filters according to particle efficiency
  - Carbon filter is an effective gas filter, catching most of the diverse chemicals in the air.
- Installation of filters of class EU7 it should be possible to remove about 75% of the total number of ultra-fine particulates.

PARTICULATE FILTRATION PRINCIPLES

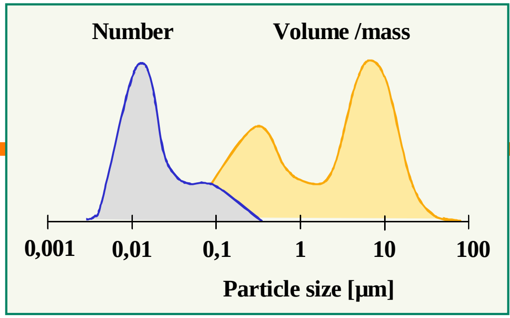


- **Inertial impaction-** The particle continues on its original path, collides against the fibre and remains attached to it.
- **Interception-** Smaller particles follow the stream lines around the fibres and are captured when the surface of the particle touches the surface of the fibre.
- **Diffusion-** Particles smaller than 1 µm are affected by the Brownian movements of air molecules and deviate randomly from the normal stream lines around the fibres. If the deviation is large enough, the particle will strike the fibre and become attached to it.

How to measure $PM_{2.5}$?

Singular spot or 24 h average measurements

Continuous measurement in BMS



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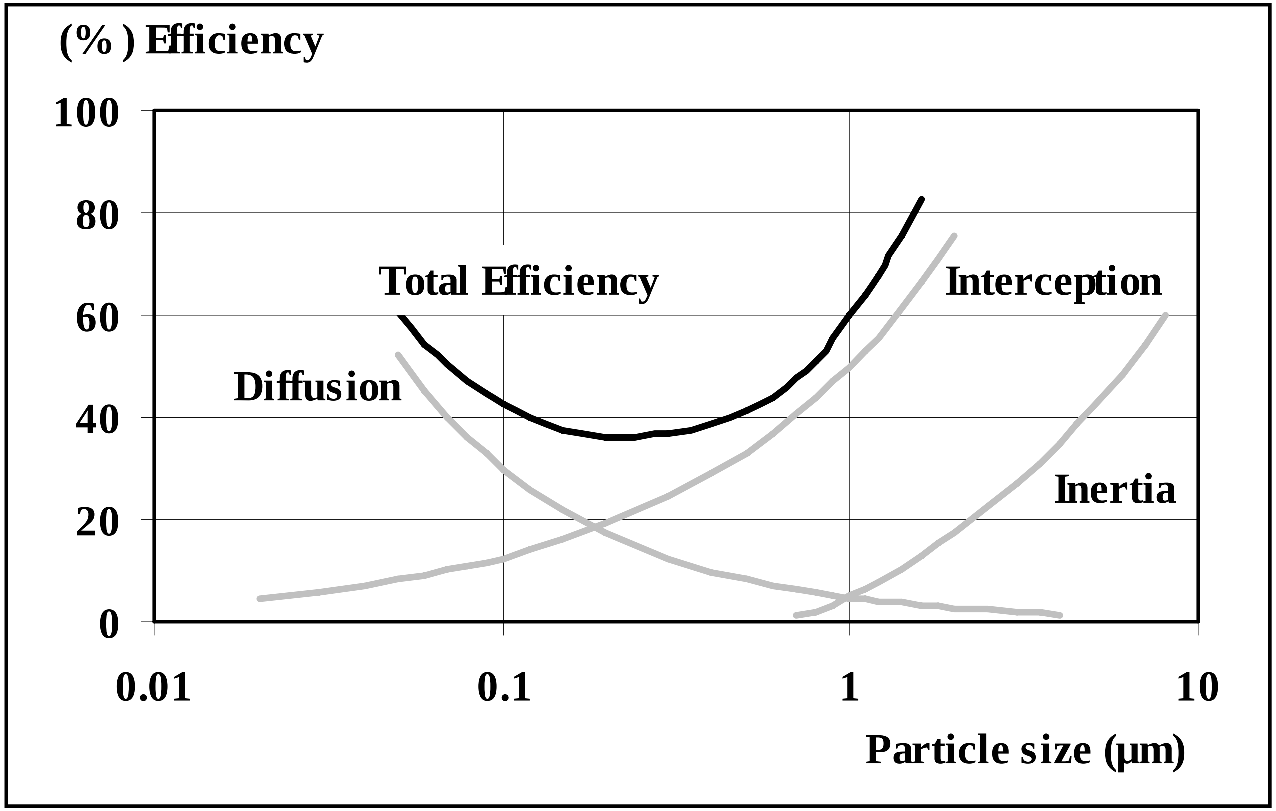
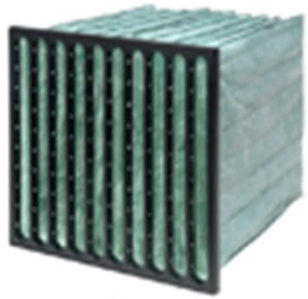


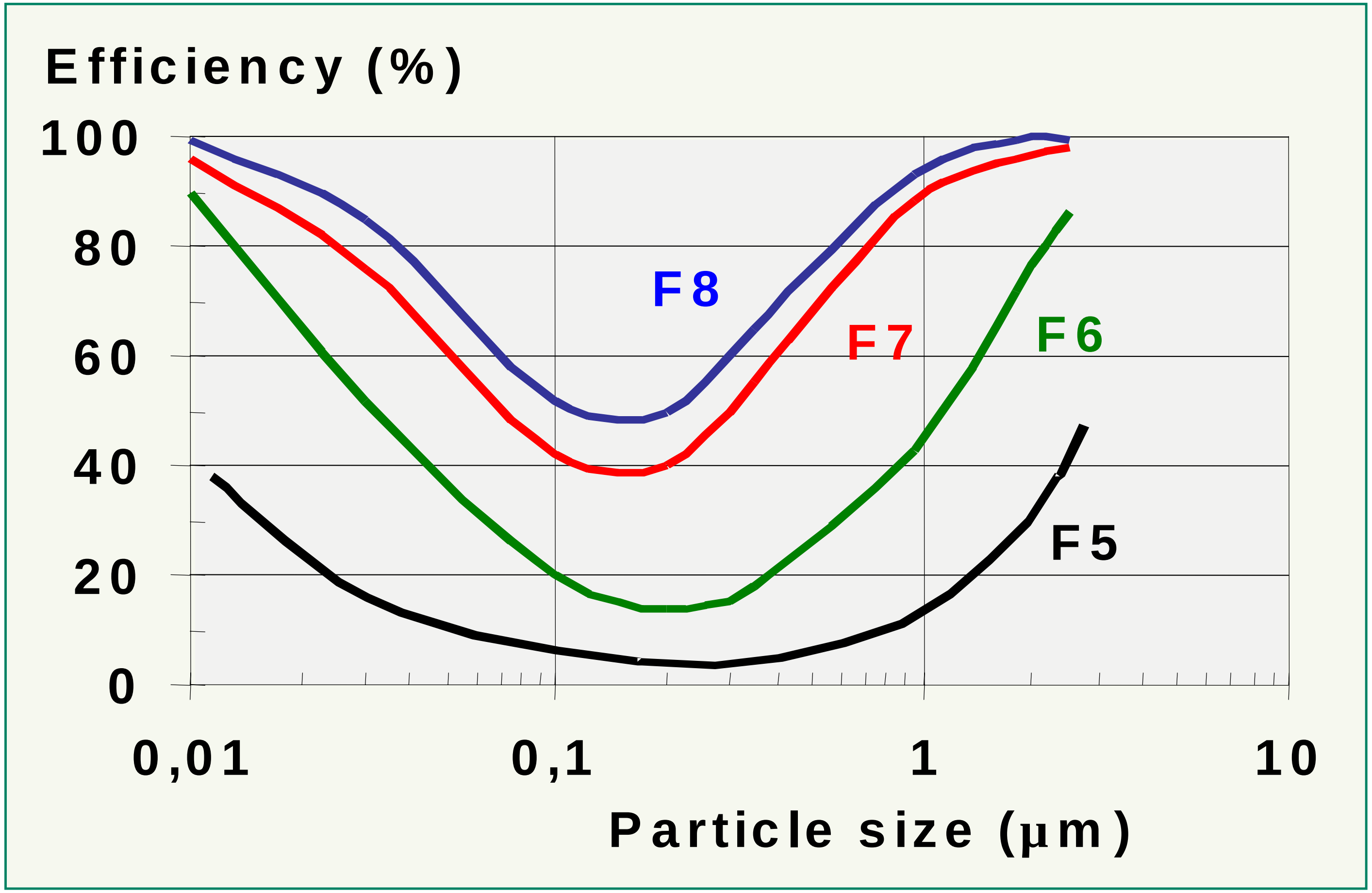
Air filter in air handling unit.

Mechanical Filters

- Filtration efficiency is depending on the density of the filter media and filters are classified either based on EU or MERV rating:
  - Coarse filters: EU 1-4 / MERV 1-8 (>95% of 10 µm)
  - Medium filters: EU 5-6 / MERV 9-12 (>95% of 5 µm)
  - Fine filters: EU 7-9 / MERV 13-15 (>95% of 0.4 µm)
  - HEPA filters: EU 10-14 / MERV 16-20 (99.99% of 0.4 µm)
- Filters are changed when the pressure loss becomes to the upper limit.
- Filtration efficiency of dirty filter is not reduced but the air flow rate may reduce without fan frequency control.
- Pressure loss of a filter depends on the filter type and either the filter is clean or dirty:
  - Pre-filter (EU 4 / MERV 8): 30 – 100 Pa;
  - Fine filter (EU 9 / MERV 15): 70 – 300 Pa;
  - HEPA filter (EU10 / MERV 16): 250 – 500 Pa.
- The depth of a filter varies depending on the model:
  - Panel filter 50-150 mm;
  - Compact V-bank 300 mm;
  - Bag filter 600 mm.

Efficiency vs. particle size for different Fine (F) filters.



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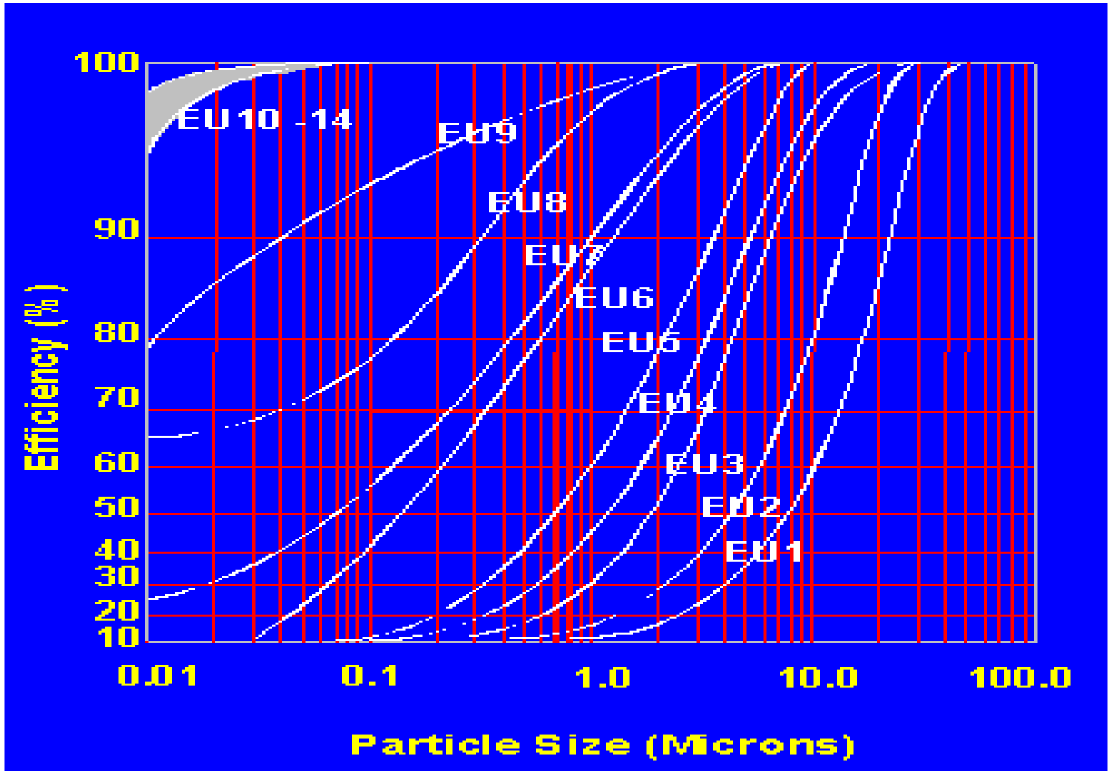
<u>OLD</u> EU Filter Classes (EN 779)



The coexistence period is expected to end in the middle of 2018.

Afterwards, EN 779:2012 will become obsolete.

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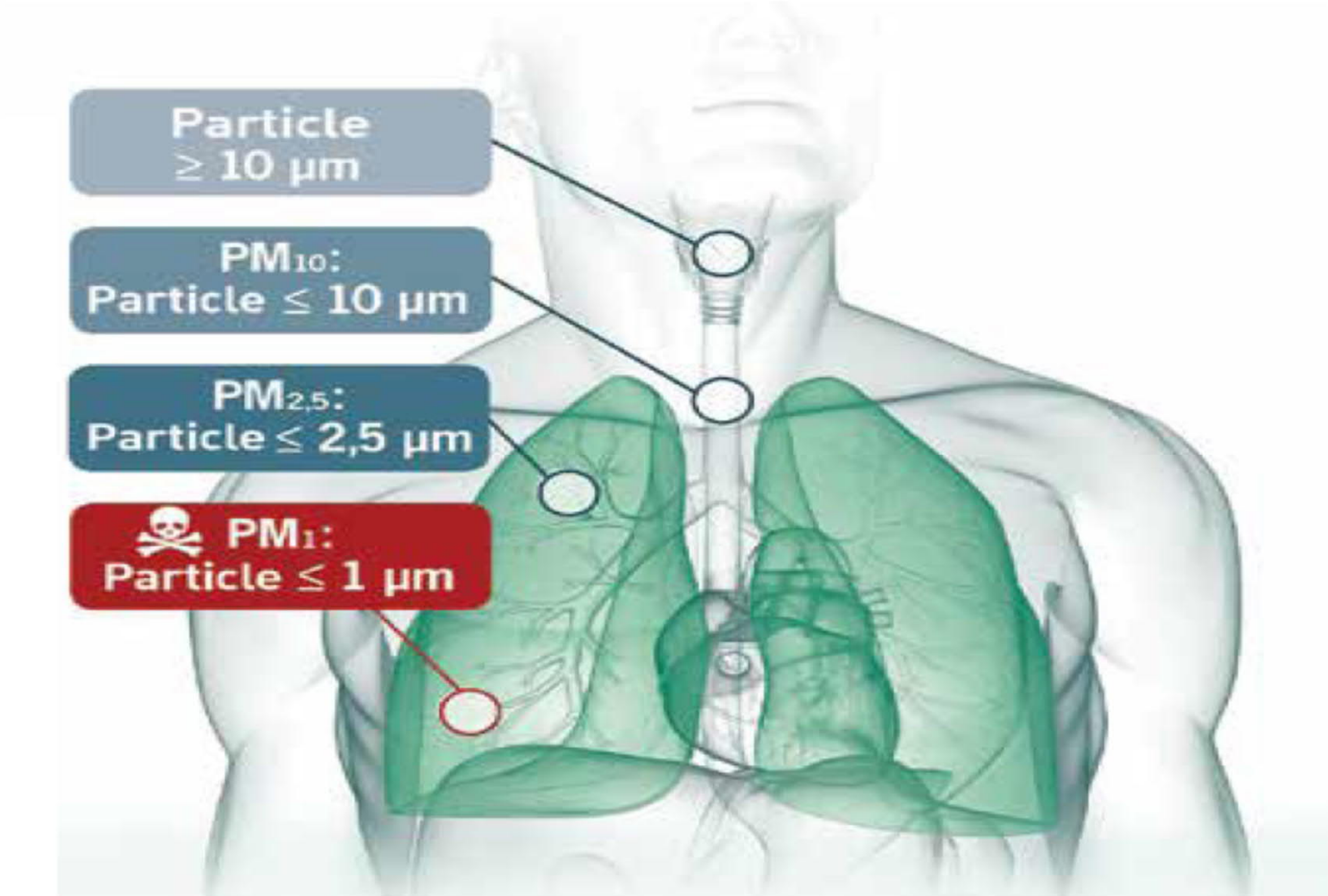
NEW EN ISO 16890

New classification introducing efficiency for various particle size ranges (ePM1, ePM2.5, ePM10)

PM10	PM2.5	PM1
Particles 10 µm in diameter or smaller can reach the respiratory ducts and potentially cause decreased lung function.	**Particles 2.5 µm** in diameter or smaller can penetrate the lungs and cause decreased lung function, skin and eye problems.	**Particles 1 µm** in diameter or smaller are most dangerous. They are tiny enough to enter the bloodstream and lead to cancer, cardiovascular diseases and dementia.

Particle size and Impact on Health



WHO Treshold values

The recommended annual mean limits to be observed when
selecting filter classes are the following:

- Annual mean for PM2.5 $<$ 10 µg/m3
- Annual mean for PM10 $<$ 20 µg/m3

At the time being, there are no recommendations for PM1 concentration.

Category	Description	Typical environment
ODA 1	**OUTDOOR AIR, WHICH MAY BE ONLY TEMPORARILY DUSTY** Applies where the World Health Organisation WHO (2005) guidelines are fulfilled (annual mean for PM2.5 ≤ 10 µg/m^3 and PM10 ≤ 20 µg/m^3).	
ODA 2	**OUTDOOR AIR WITH HIGH CONCENTRATIONS OF PARTICULATE MATTER** Applies where PM concentrations exceed the WHO guidelines by a factor of up to 1,5 (annual mean for PM2.5 ≤ 15 µg/m^3 and PM10 ≤ 30 µg/m^3).	
ODA 3	**OUTDOOR AIR WITH VERY HIGH CONCENTRATIONS OF PARTICULATE MATTER** Applies where PM concentrations exceed the WHO guidelines by a factor of greater than 1,5 (annual mean for PM2.5 > 15 µg/m^3 and PM10 > 30 µg/m^3).	

Supply air categories

SUP 1	refers to supply air with concentrations of particulate matter which fulfilled the WHO (2005) guidelines limit values multiplied by a factor x 0,25 (annual mean for PM2.5 ≤ 2.5 µg/m^3 and PM10 ≤ 5 µg/m^3).
SUP 2	refers to supply air with concentrations of particulate matter which fulfilled the WHO (2005) guidelines limit values multiplied by a factor x 0,5 (annual mean for PM2.5 ≤ 5 µg/m^3 and PM10 ≤ 10 µg/m^3).
SUP 3	refers to supply air with concentrations of particulate matter which fulfilled the WHO (2005) guidelines limit values multiplied by a factor x 0,75 (annual mean for PM2.5 ≤ 7.5 µg/m^3 and PM10 ≤ 15 µg/m^3).
SUP 4	refers to supply air with concentrations of particulate matter which fulfilled the WHO (2005) guidelines limit values (annual mean for PM2.5 ≤ 10 µg/m^3 and PM10 ≤ 20 µg/m^3).
SUP 5	refers to supply air with very high concentrations of particulate matter which fulfilled the WHO (2005) guidelines limit values multiplied by factor x 1,5 (annual mean for PM2.5 ≤ 15 µg/m^3 and PM10 ≤ 30 µg/m^3).

Recommened efficiences for the different combinations of outdoor and supply air categories

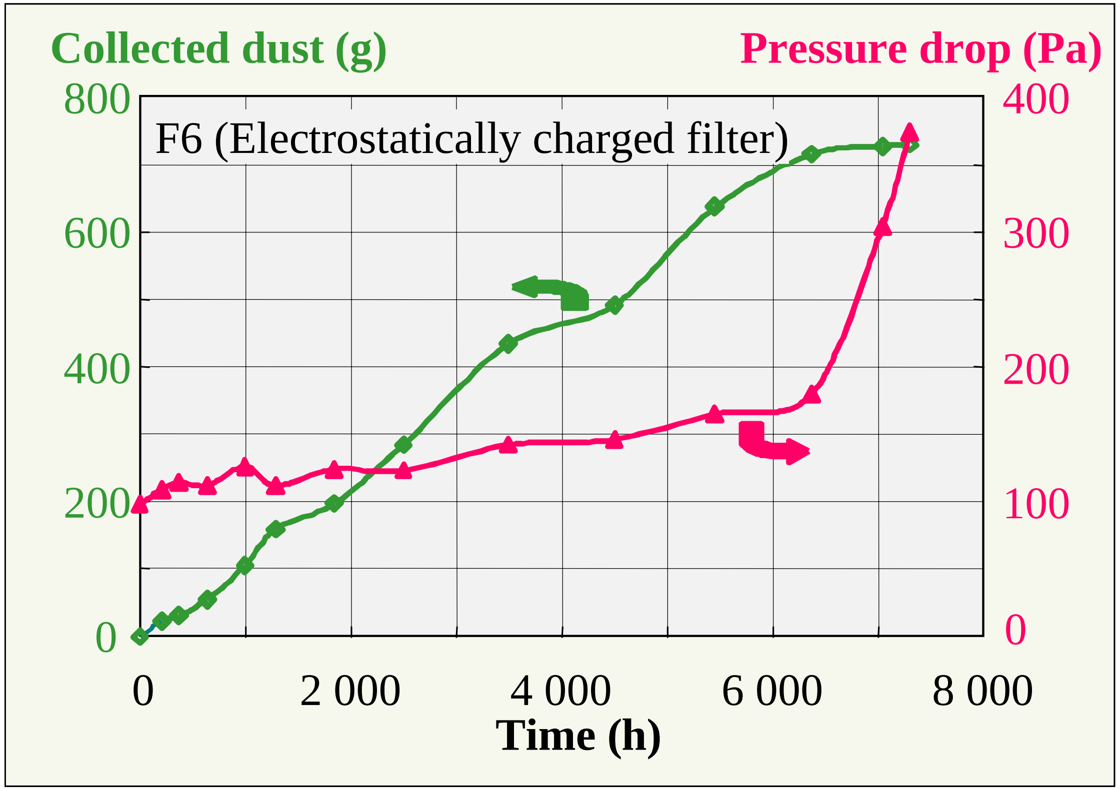
			SUPPLY AIR				
OUTDOOR AIR			SUP 1* PM2.5 ≤ 2.5 PM10 ≤ 5	SUP2* PM2.5 ≤ 5 PM10 ≤ 10	SUP3** PM2.5 ≤ 7.5 PM10 ≤ 15	SUP4 PM2.5 ≤ 10 PM10 ≤ 20	SUP5 PM2.5 ≤ 15 PM10 ≤ 30
Category	PM2.5	PM10	ePM_1	ePM_1	$ePM_{2.5}$	$ePM_{2.5}$	ePM_{10}
ODA 1	≤ 10	≤ 20	60%	50%	60%	60%	50%
ODA 2	≤ 15	≤ 30	80%	70%	70%	80%	60%
ODA 3	> 15	> 30	90%	80%	80%	90%	80%

CATEGORY	GENERAL VENTILATION		
SUP 1	-	-	
SUP 2	**Rooms for permanent occupation.** Example: Kindergardens, offices, hotels, residential buildings, meeting rooms, exhibition halls, conference halls, theaters, cinemas, concert halls.		
SUP 3	**Rooms with temporary occupation.** Examples: Storage, shopping centers, washing rooms, server rooms, copier rooms.		
SUP 4	**Rooms with short-term occupation.** Examples restrooms, storage rooms stairways.		
SUP 5	**Rooms without occupation.** Examples: Garbage room, data centers, underground car parks.		

CATEGORY	INDUSTRIAL VENTILATION	
SUP 1	**Applications with high hygienic demands.** Examples: Hospitals, pharmaceutics, electronic and optical industry, supply air to clean rooms.	
SUP 2	**Applications with medium hygienic demands.** Example: Food and beverage production.	
SUP 3	**Applications with basic hygienic demands.** Example: Food and beverages production with a basic hygienic demand.	
SUP 4	**Applications without hygienic demands.** Example: General production areas in the automotive industry.	
SUP 5	**Production areas of the heavy industry.** Examples: Steel mill, smelters, welding plants.	

Table 4. Industrial ventilation – indicative examples of application matched to corresponding SUP categories

Air flow resistance and collected dust as function of time for an F6 electrostatically charged filter loaded with outdoor air at 1 m³/s



LCC (Life Cycle Cost)

The life cycle cost ($\boldsymbol{LCC}_{\text{total}}$) can be defined as follows:

$$\boldsymbol{LCC}_{\text{total}} =$$

$$\boldsymbol{I}_{\text{Investment}} + \boldsymbol{LCC}_{\text{Energy}} + \boldsymbol{LCC}_{\text{Maintenance}} + \boldsymbol{LCC}_{\text{Disposal}}$$

Discounting costs with the present value method

Discounting costs with the present value method

$C_p / C_n = [1 + (i - p)]^{-n}$

where

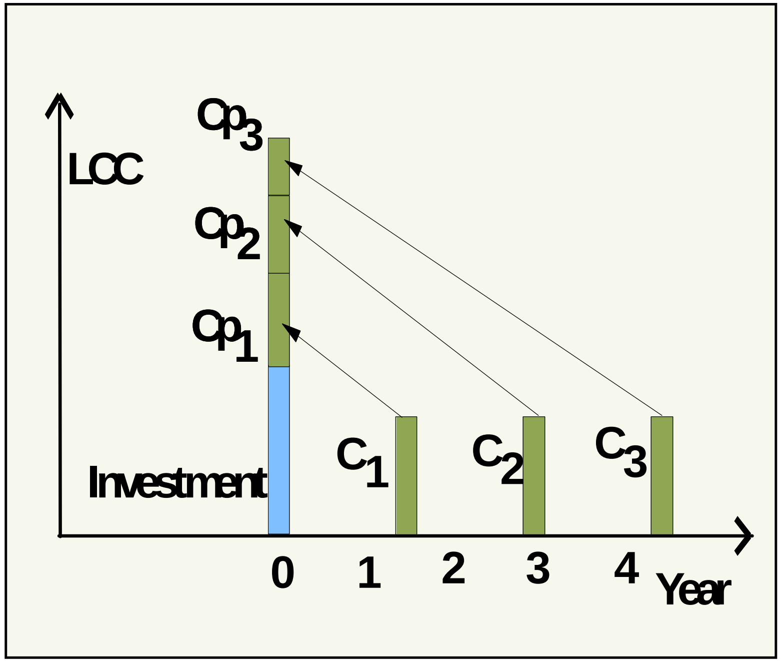
n = the number of years

p = the price increase

i = the interest rate (bank rate or any expected internal rate for investments within the company)

C_n = the cost paid after "n" years

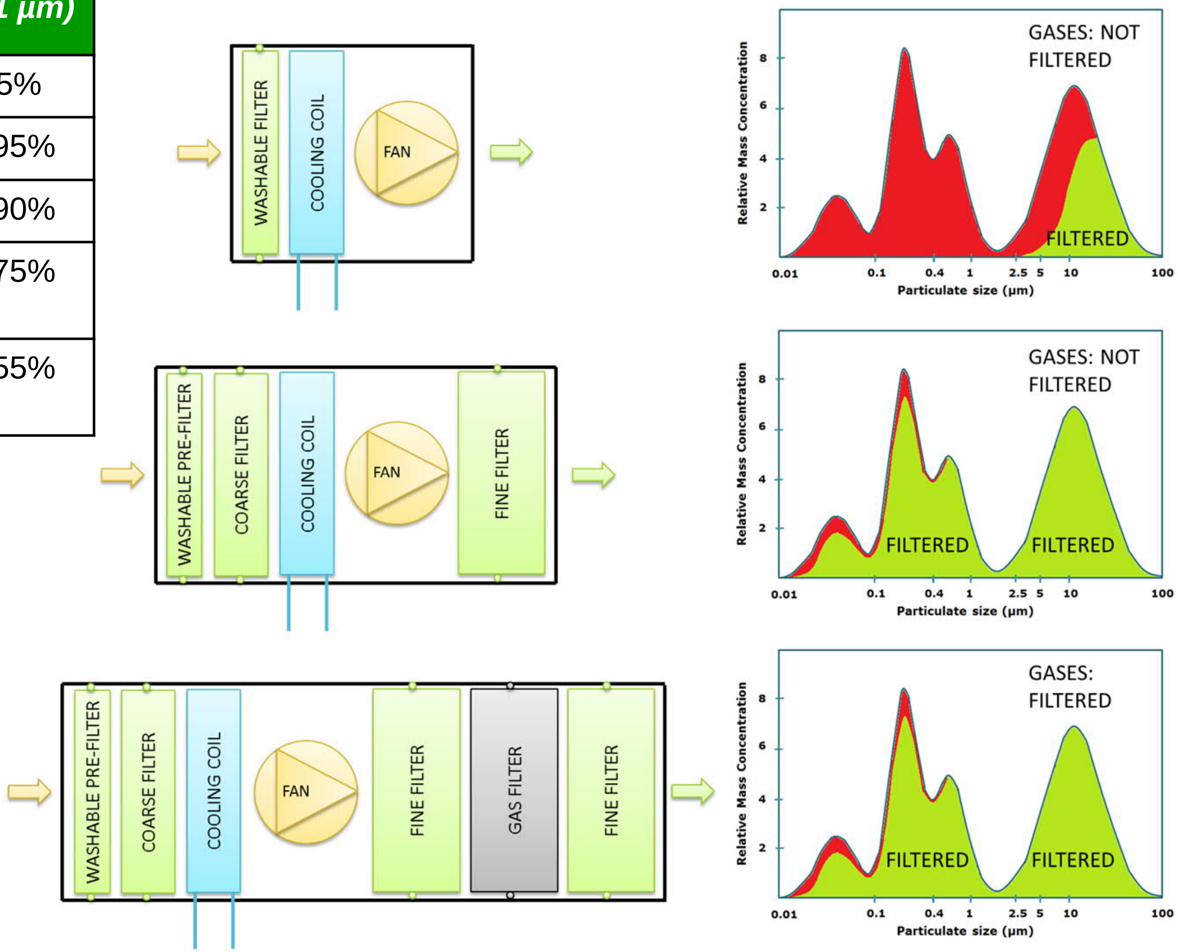
C_p = the present cost of a single cost element, C_n



Examples of Air Filtration Solutions

EU	*Efficiency (0.4 µm)*	*ASHRAE*	*Efficiency (0.3-1 µm)*
F9	>95%	MERV 15	>95%
F8	90-95%	MERV 14	90-95%
F7	80-90%	MERV 13	80-90%
M6	60-80%	MERV 11-12	60-75%
M5	40-60%	MERV 9-10	40-55%

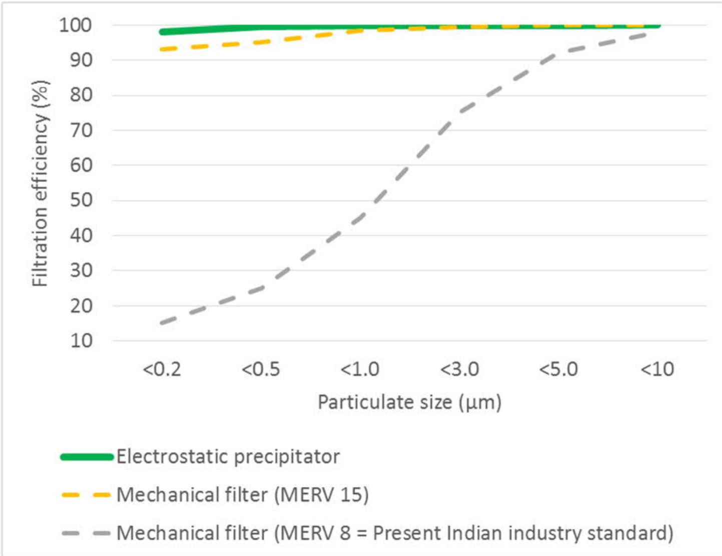
F9 / MERV 15 Fine filter



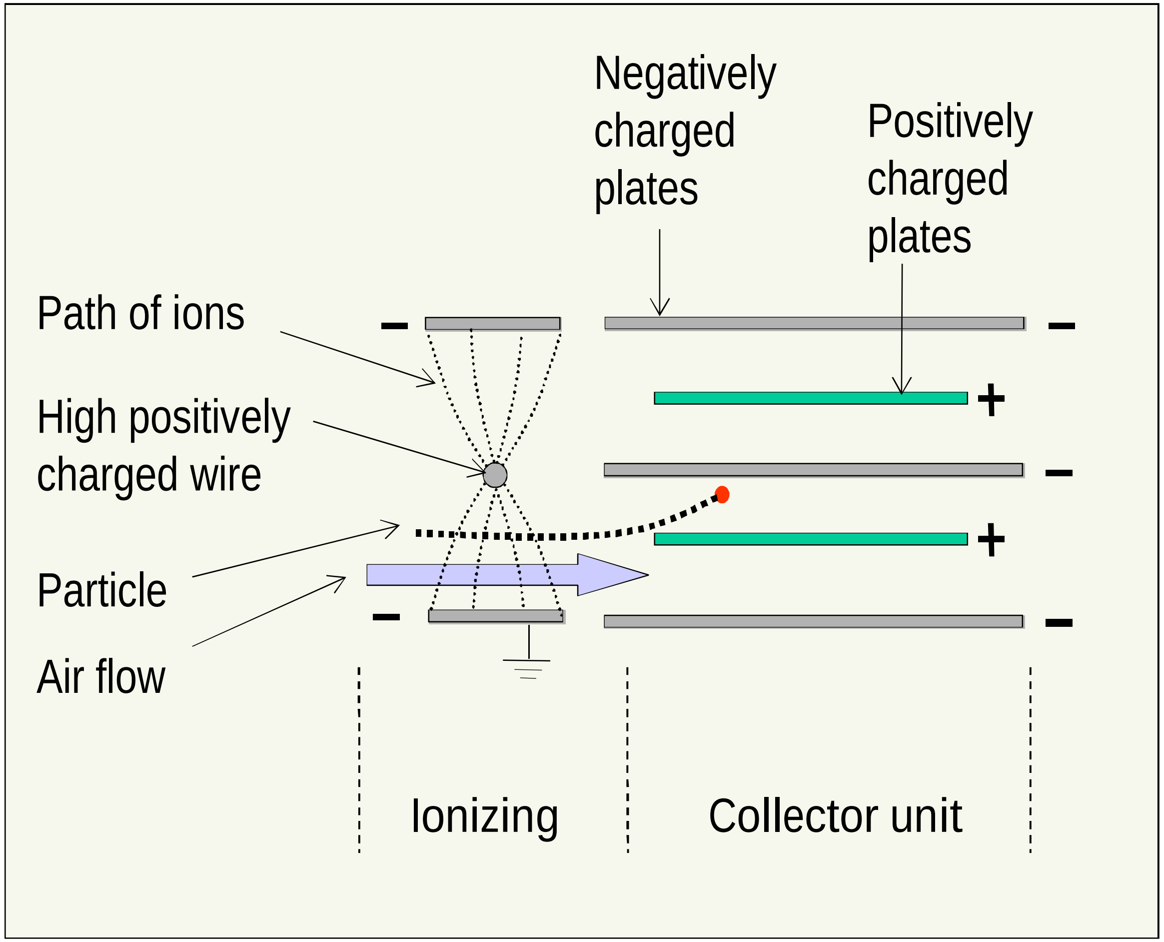
Reality of Filtration

Electrostatic Precipitator

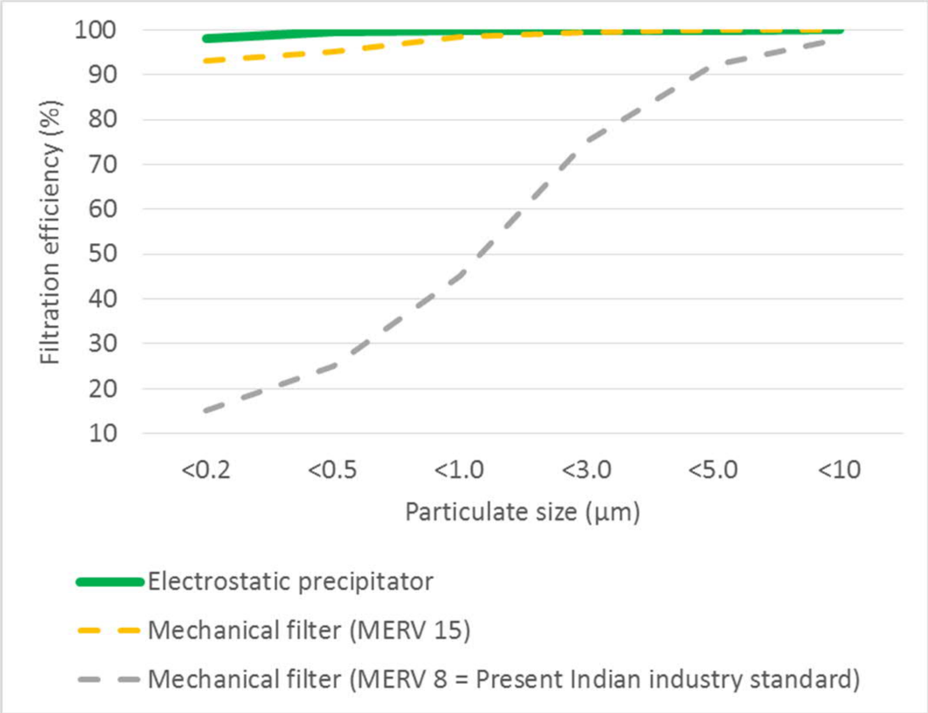
- Removes particulates, droplets and microbiological contamination (e.g. viruses and bacteria) that are electronically charged in corona discharge and collected into the collector plates.
- Pressure loss of the ESP-unit is 5-30 Pa and stays nearly constant either the filter is clean or dirty.
- Collector plates are regularly washed to avoid short circuit between the plates.



Working principle of electronic air cleaners.



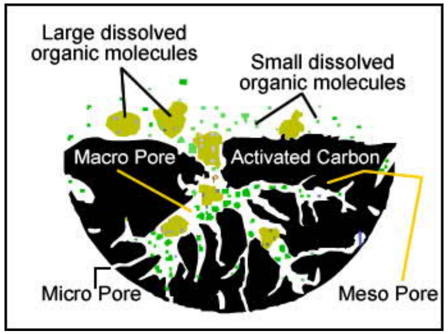
Technical Comparison

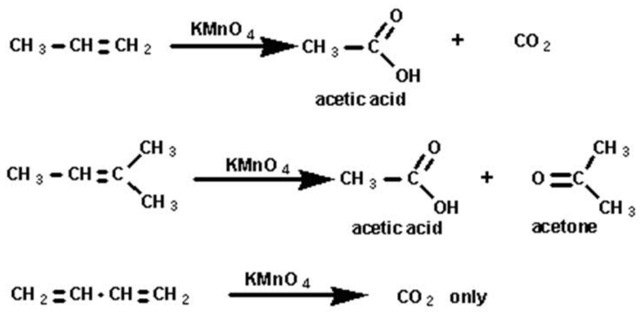


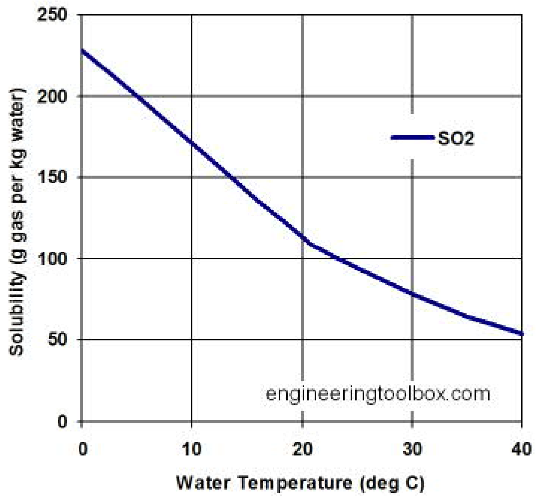
- Pre-filter (MER 8 / EU 4): 30 – 100 Pa;
- Coarse filter (MERV 9 / EU 5): 70 – 300 Pa;
- Fine filter (MERV 15 / EU 9): 70 – 300 Pa;
- HEPA filter: 250 – 500 Pa;
- Electrostatic precipitator: 5 – 30 Pa.

Gas Filtration

- **Chemical filters** can both adsorb (active carbon or zeolite) and oxidise (Potassium Permanganate $KMnO_4$) the gases.
- Packed-bed / packed-tower **wet scrubbers** dissolve the scrubbing liquid soluble inorganic gases and VOCs by reaction with a sorbent or reagent slurry, or absorption into liquid solvent.







Chemical Filtration

- All VOCs can be adsorbed to the active carbon or zeolite based filter and stored in the media.
- Inorganic gases are both adsorbed and oxidised (killed) in filters having potassium permanganate ($KMnO_4$) with the active carbon or zeolite.
- Gas removal efficiency is dependent on the quality and amount of adsorbing material and the time gas is in contact with the material (face velocity).
- Chemical filters are not recommended when the air has high concentrations (continuously in ppm level) of gases.
- Before the filter reaches the break-through point, it needs to be changed.
- Fine particulate filter is recommended after the active carbon filter.
- Chemical filter can be either honeycomb filter or granular loose-fill filter (V-modules / tubes)

Removal of Bio-aerosols (viruses, bacteria, fungi, mould, etc.)

- They are so small, some less than 0.03 microns, that most air purifiers cannot capture them effectively.
- Can be removed from air using various technologies like:
  - HEPA-filters;
  - Electrostatic-precipitators;
  - UV-lights (Ultraviolet Germicidal Irradiation (UVGI));
  - Negative-ion-generators;
  - Ozone-generators (according EPA, can be a threat to public health);
  - Cold plasma, Photo-hydro-ionization etc.

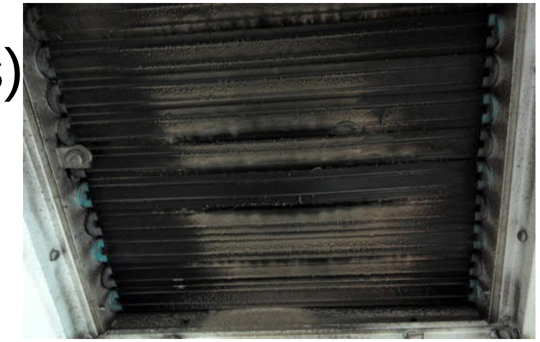
COLLECT (HEPA-filters; Electrostatic-precipitators)

KILL (UV-lights; Negative-ion-generators; Ozone-generators; Cold plasma, Photo-hydro-ionization etc.)

- These are not typically used in central ventilation system but locally in the areas where bio-aerosols are creating health problems or sensitive people occupies.
- There is no standardized test methods and filtration efficiency is very much depending on the application, equipment and air velocity.

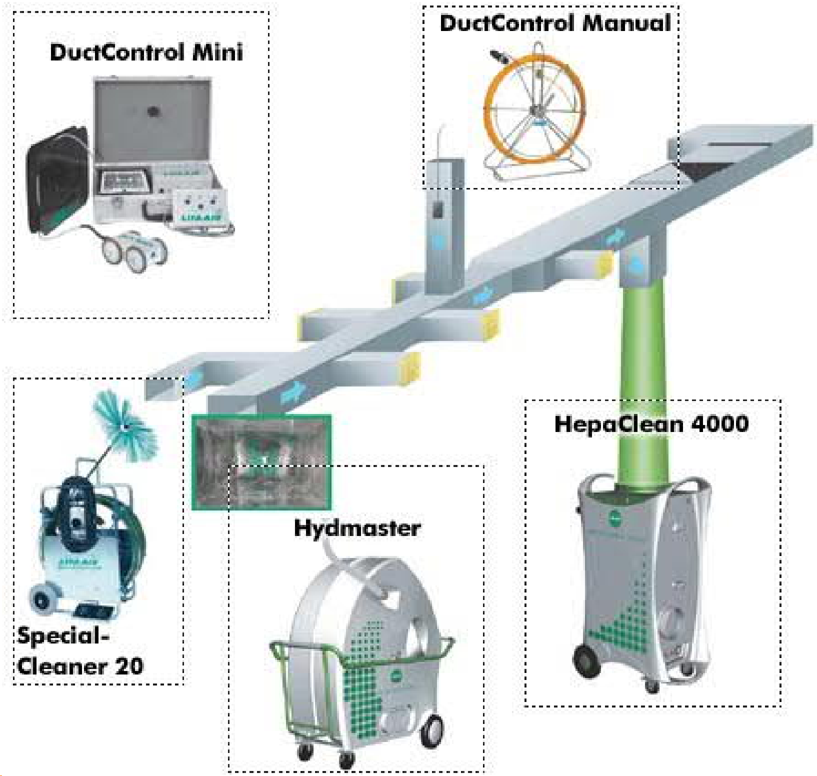
Cleanliness of Ventilation System

- Ducts and components needs to be cleaned regularly (once in every 1-3 years)
- AHU rooms are part of ventilation system and needs to be kept clean from outside objects, standing water etc.
- Cleaning methods:
  - Dry cleaning methods:
    - mechanical brushing
    - compressed air
    - hand vacuuming
  - Wet cleaning methods:
    - hand washing
    - steam washing
    - mechanical power washing
    - use of detergents



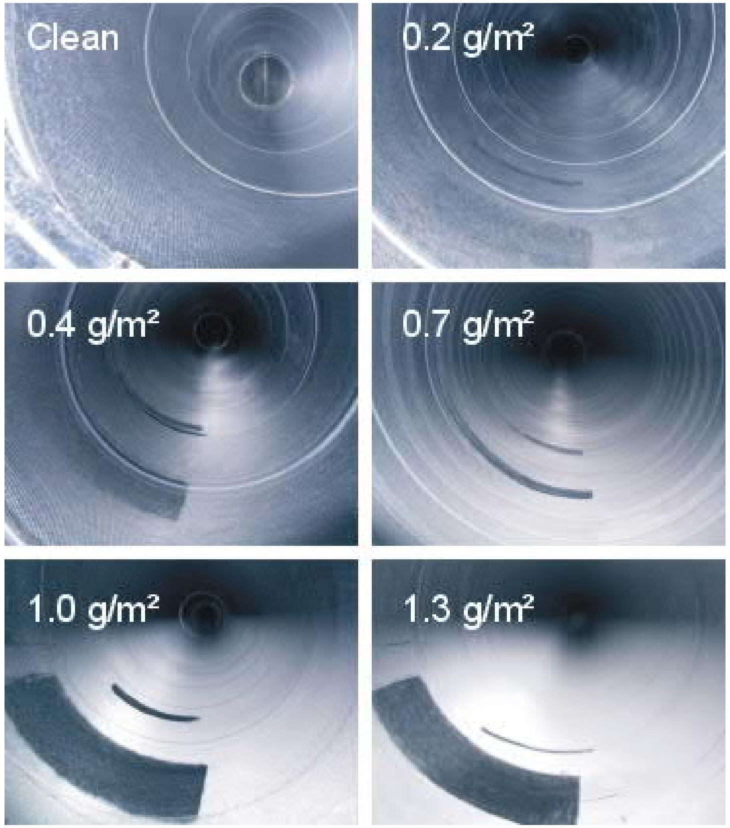
Duct Cleaning

- Brushing – with automatic brushing systems.
- Vacuum unit - to keep the ductwork in negative pressure and collect the dust.
- Quality check - by making a video of cleaned duct.

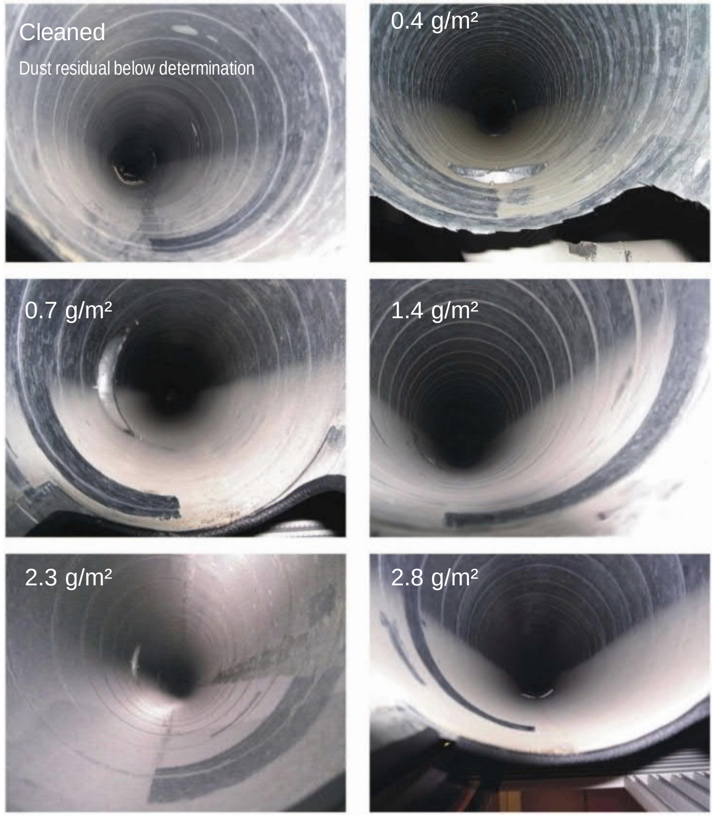


Cleanliness Scale

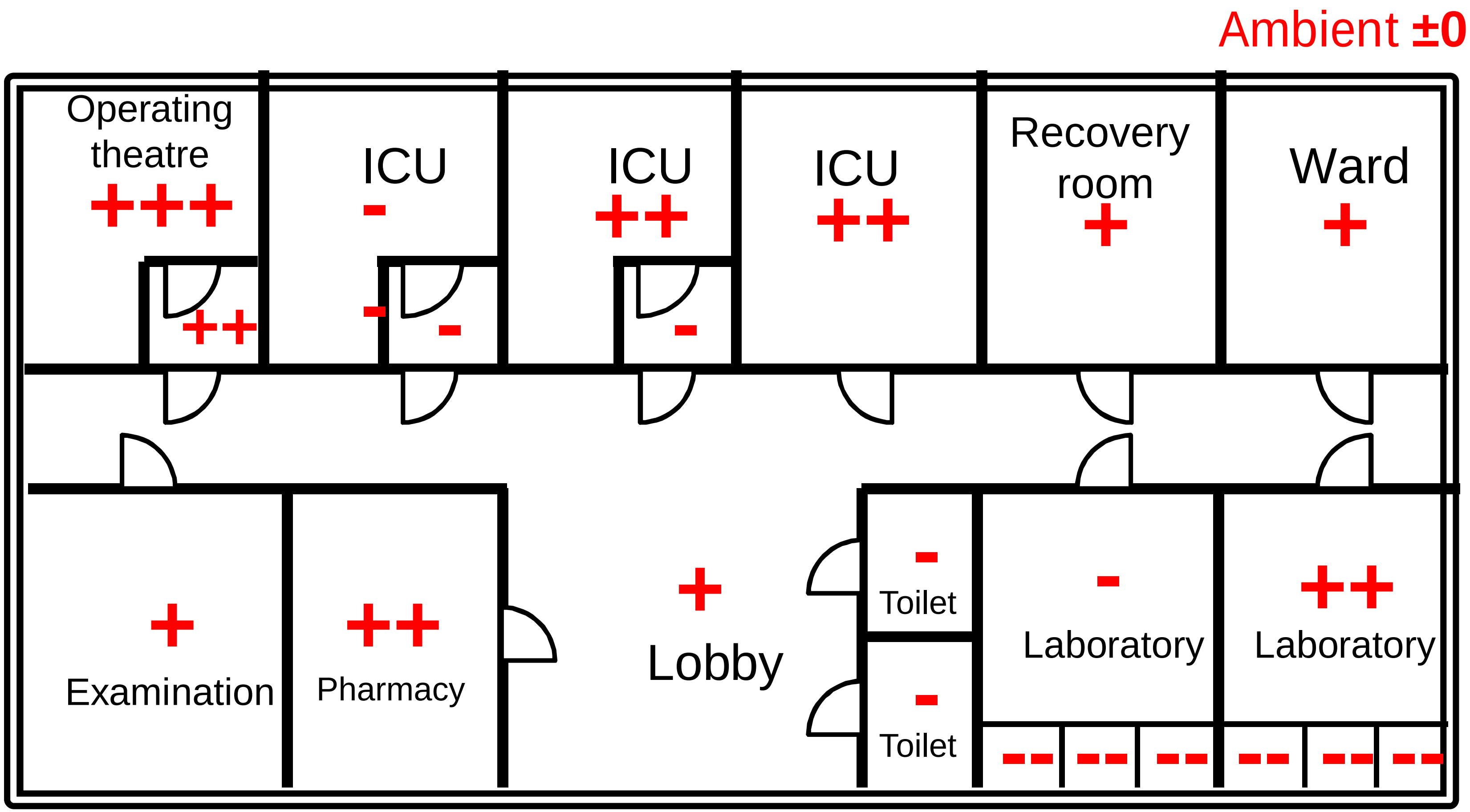
Scale for new



Scale for existing



Hospital Applications:
Pressurization of Spaces



Critical: air flow balancing and control, pressure measurement

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Portable Air Cleaner / Room Air Purifier

- Portable air cleaners generally contain a fan to circulate the air and use one or more of the air-cleaning technologies:
  - Mechanical air filters
  - Electronic air cleaners
  - Gas-phase air filters
  - UVGI / <PCO cleaners (UV-lamp).
- Many portable air cleaners have moderate to large air delivery rates for small particles.
- Most of the portable air cleaners do not have high enough air delivery rates to remove large particles such as pollen.
- Ozone generators are not always safe and effective in controlling indoor air pollutants. Ozone is a potent lung irritant.
- Use of air cleaners increases energy use.

Source: *Residential Air Cleaners, US Environmental Protection Agency EPA, 2009*

Summary of Air Cleaning Technologies Used in Portable Air Cleaners

AIR-CLEANING TECHNOLOGIES		POLLUTANTS ADDRESSED	LIMITATIONS
Filtration	Air filters	Particles	Ineffective in removing larger particles because most settle quickly from the air and never reach the filters.
	Gas-phase filters	Gases	Used much less frequently in homes than particle air filters. The lifetime for removing pollutants may be short.
Other Air Cleaners	UVGI	Biologicals	Bacterial and mold spores tend to be resistant to UV radiation and require more light, longer exposures to UV light, or both to be killed.
	PCO	Gases	Application for homes is limited because currently available catalysts are ineffective in destroying gaseous pollutants in indoor air.
	Ozone generators	Particles, gases, biologicals	Sold as air cleaners, they are not always safe and effective in removing pollutants. By design they produce ozone, a lung irritant.

Source: *Residential Air Cleaners, US Environmental Protection Agency EPA, 2009*

Room Air Purifiers

- Nearly every model is developed to solve IAQ problems in European and North American buildings:
  - Fungal and bacteria growth in moisture damaged buildings;
  - Much lower PM level indoors than outdoors;
- Recommended for occupants who has reduced lung capacity, allergy or asthma.
- Therefore room air purifiers are developed to remove or kill microbiological contamination.

1. HEPA filter to remove particulates and microbiological contamination

   No proper coarse particulate filtration to protect HEPA filter =>

   Life time of HEPA is only 6-12 weeks => High filtration cost

2. Different technologies to sterilize air:
   - UV-light
   - Gold plasma
   - Photo-hydro-ionization

3. Deodorization of air:
   - Oxidation
   - Ionizer unit
   - Ozoniser unit

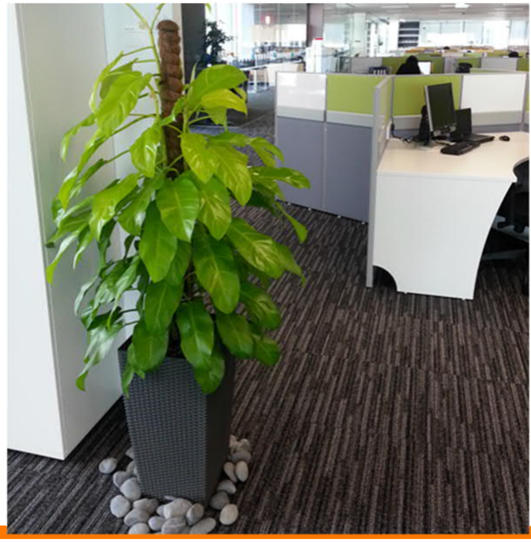
Plants to Purify Air: 2-3 plants / person

Produces O_2 during day and removes CO_2

Produces O_2 during night and removes CO_2

Produces O_2 during day, removes VOC and CO_2

Different Technical Solutions



Plants Requires Maintenance

- Be sure that your plants get light.
  - Identify how much natural light is available and needed.
- Water them as needed and watch out pots and soil.
  - Plants need water, but not too much nor too little.
  - Clean and nutritious soil is important for plant's health.
  - Standing water and humid soil can become contaminated with bacteria, fungi and mould as well increase the indoor air humidity unnecessarily.
- Watch out for plant pests.
  - Sometimes plants attract pests
- Wipe leafs from dust regularly.
  - Dust in leaf surface reduces the oxygen production.

Thank you

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