Cornell Engineering
Civil and Environmental Engineering

CEE 4540

Sustainable municipal drinking water treatment

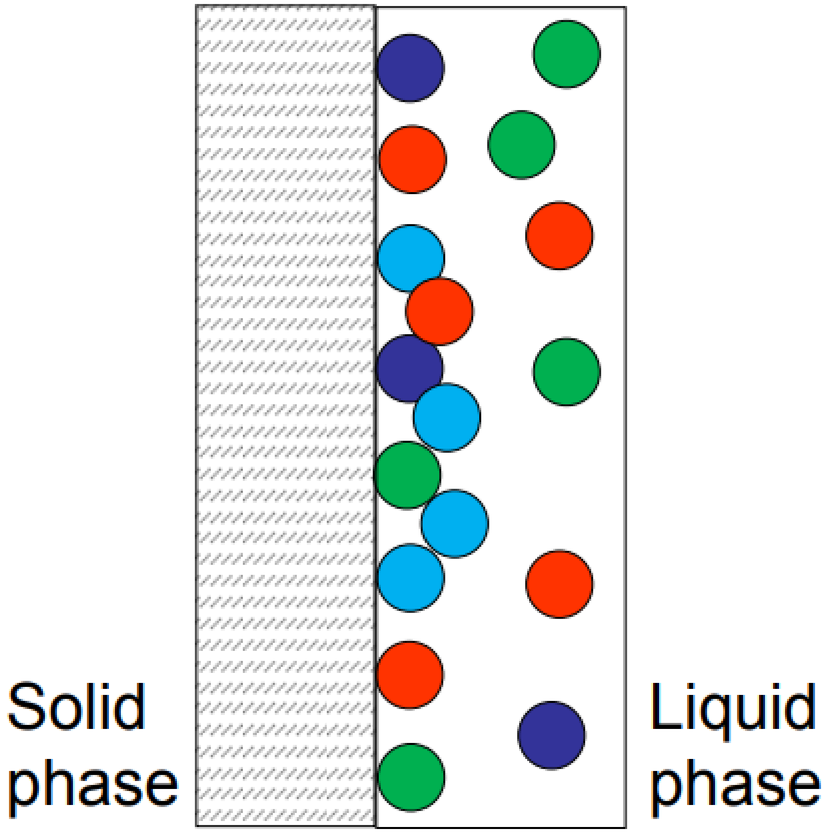
Topic: GAC

Instructor: YuJung Chang
YuJung.Chang@aecom.com

Class #24 11/26/2018 2:55 – 4:10pm

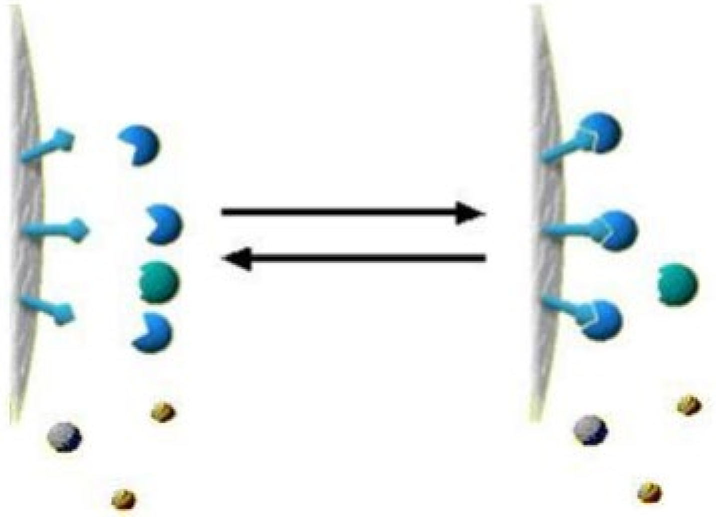
Basics of Adsorption

- Adsorption is a mass transfer process in which substances present in a liquid phase are adsorbed (attached to) and accumulated on a solid phase and thus removed from the liquid.

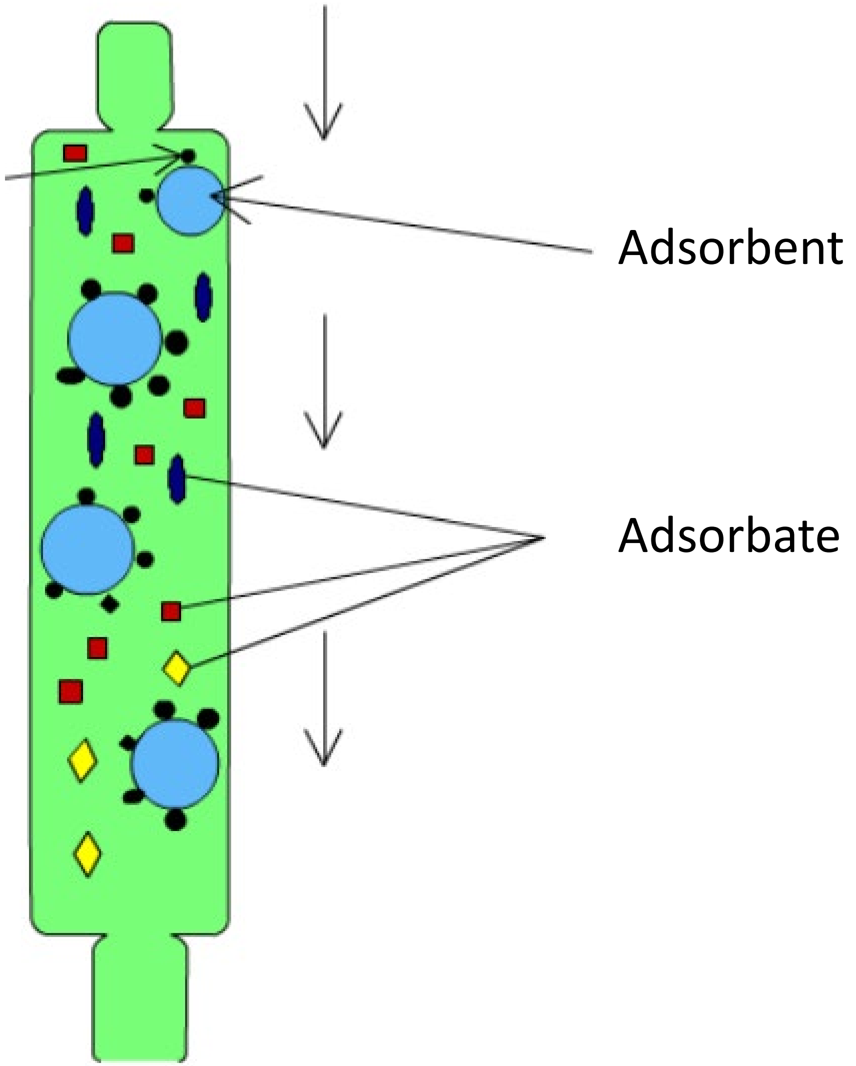


Mechanism of Adsorption

- Adsorption is one type of Van der Waal's force, which works on the molecular level to attract molecules to each other.
- Adsorbent: Material with affinity for adsorbate to attach to
- Adsorbate: Molecule that are adsorbed and accumulate on adsorbent
- Adsorption occurs due to
  - Hydrophobicity
  - Specific affinity



Adsorption Process



Reversible & Irreversible Adsorption

- Van der Waals interaction results in relatively weak, reversible adsorption
  - Adsorbed material could be desorbed if water chemistry change
  - Molecules that are already adsorbed could be displaced by other incoming adsorbates if the new adsorbates have stronger affinity to the adsorbent
- Some bindings between adsorbent and adsorbate are chemical and therefore very strong (2 – 20 kj/mol)
  - This type of binding may not be reversible

Applications for Adsorption

- Drinking Water
  - Taste & Odor
  - Halogenated organics & their precursors (NOM & disinfection byproducts)
  - Groundwater treatment for VOC or other organic contaminants
- Industrial Applications
  - Toxic organic compounds
  - Color removal
- Polishing of treated municipal wastewater (for reuse applications)

Adsorption Technologies

- Activated Carbon
- Ion Exchange Resin (IXR)
- Other Engineered Adsorbents for Specific Contaminants
  - Granular Ferric Hydroxide (GFH) for arsenic removal

Types of Activated Carbon

- Granular Activated Carbon (GAC)
  - GAC size: 0.5 – 1.0 mm
  - Surface Area: ~ 1,500 m2/gram

- Powdered Activated Carbon (PAC)
  - PAC size: 50 – 75 µm
  - Surface Area: ~ 2,500 m2/gram

Advantages of Activated Carbon

- AC has numerous internal pores
- Posses enormous surface area for adsorption
- Strong affinity to many organic contaminants
- Easy to implement and operate
- Economically feasible

Activated Carbon has Enormous Surface Area

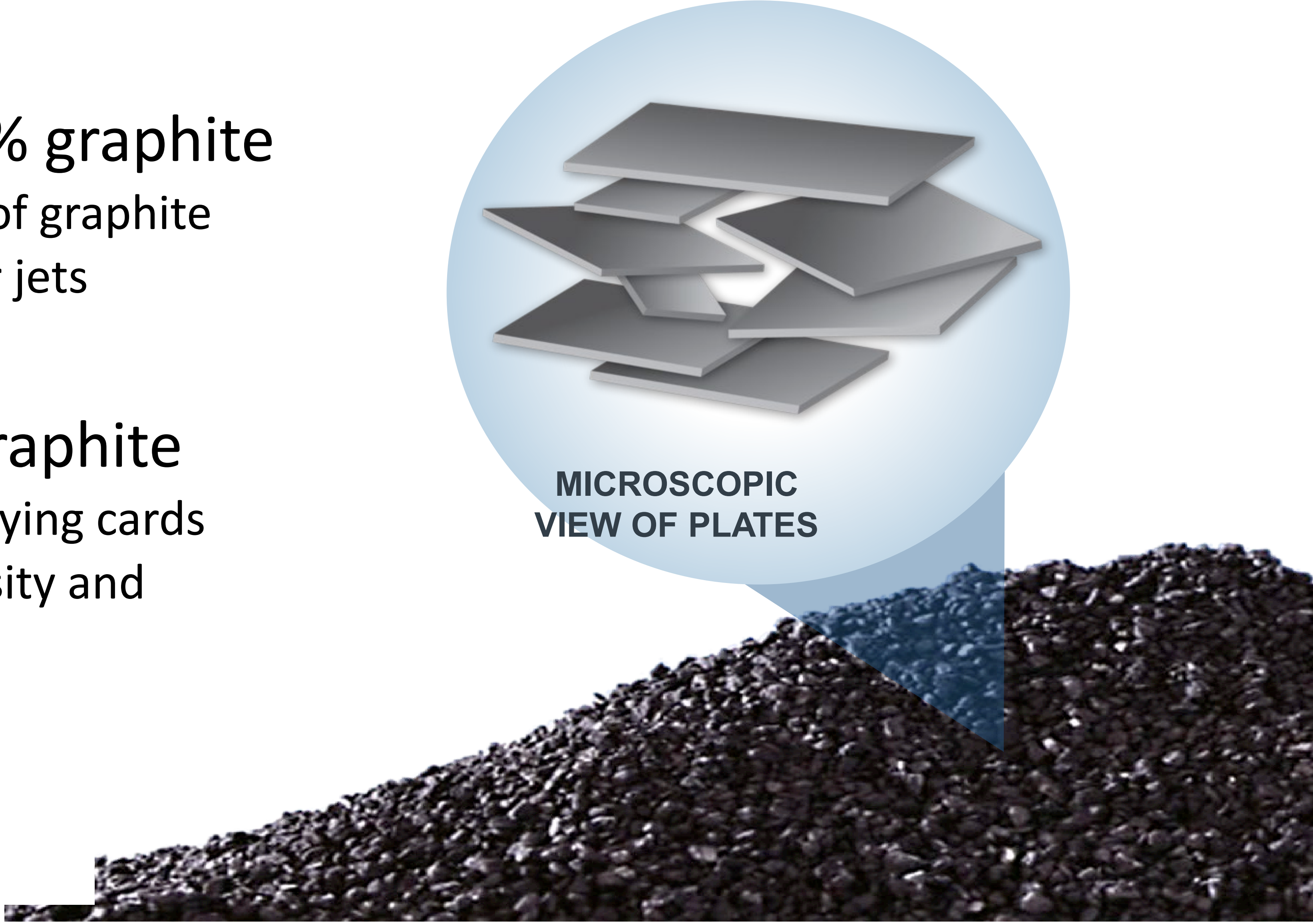
3 g of GAC

=

HUGE SURFACE AREA!

Activated Carbon Structure

- Activated Carbon is 99% graphite
  - Carbon is the base element of graphite
  - Used in pencil lead to fighter jets
- AC is a crude form of graphite
  - Like a deck of spread-out playing cards
  - Imperfections result in porosity and greater surface area



Material Used for Activated Carbon Production

Wood

Coconut Shell

Peat

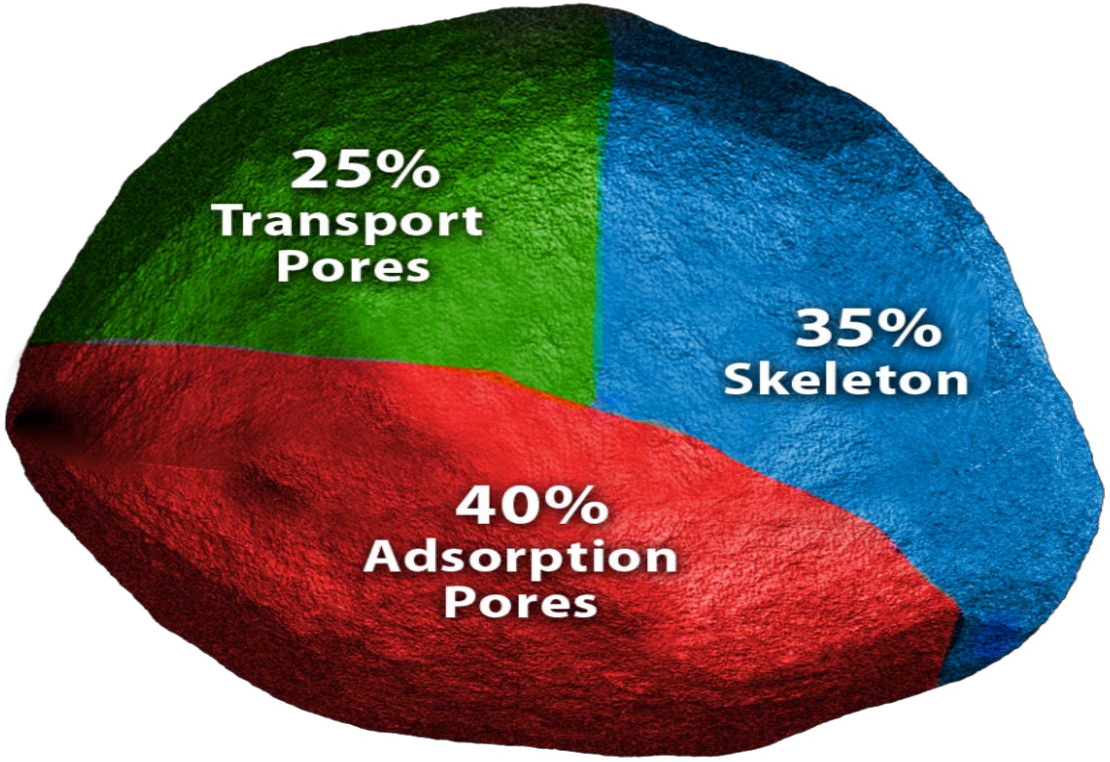
Coal

Preparation of Activated Carbon

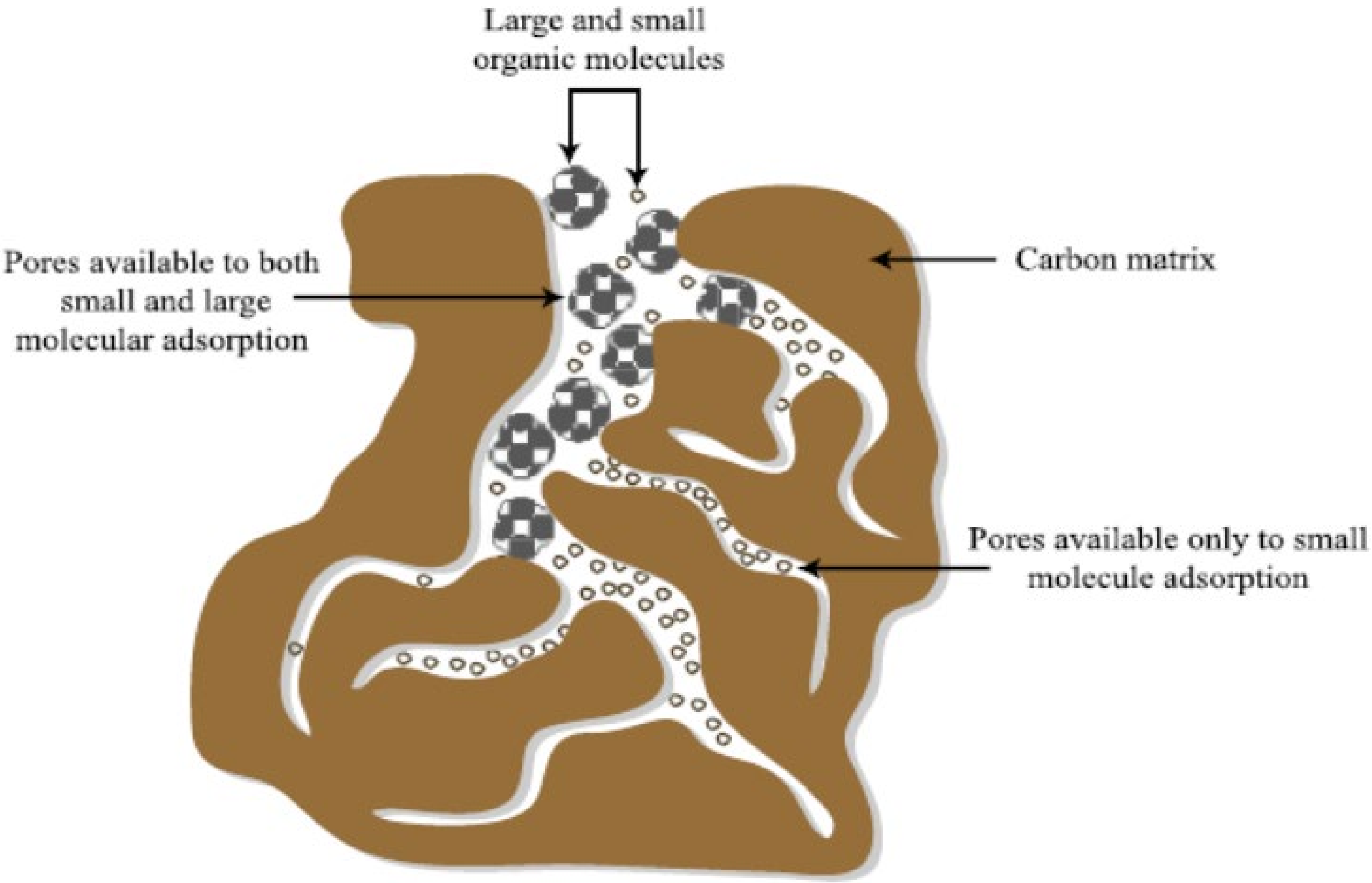
- Carbonization Step: Carbonaceous material (e.g., wood, coal, coconut shells, etc.) is heated in oxygen-starved environment to liberate carbon. At 600 ^{o}C volatile substances are driven off and carbon content (%) is increased
- Activation Step:
  - Carbonized material is exposed to steam or hot CO2 to cause pores and fissures to form.
  - At 1,000 ^{o}C and in an oxidizing atmosphere non-carbon impurities are burned, resulting a highly porous material with high surface area.
  - The nature of the surface and the porous structure are determined by the conditions of activation (temperature, time, air composition, etc.) and by the characteristics of the base material.

Structure of Activated Carbon

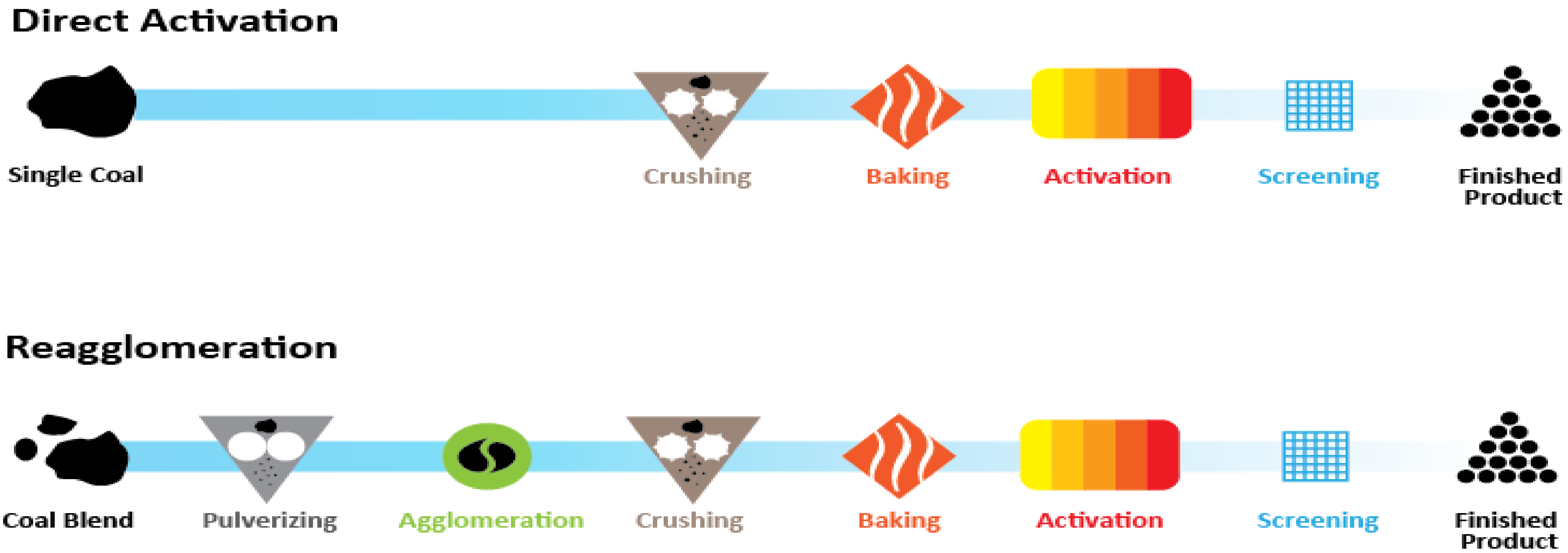
- **Adsorption Pore Structure**
  - Finest pores in structure
- **Transport Pore Structure**
  - Pores larger than the largest adsorption pores
  - Never adsorb
  - Diffusion pathways to transport adsorbates



Pore Structure of GAC: Macro, Meso, and Micro Pores

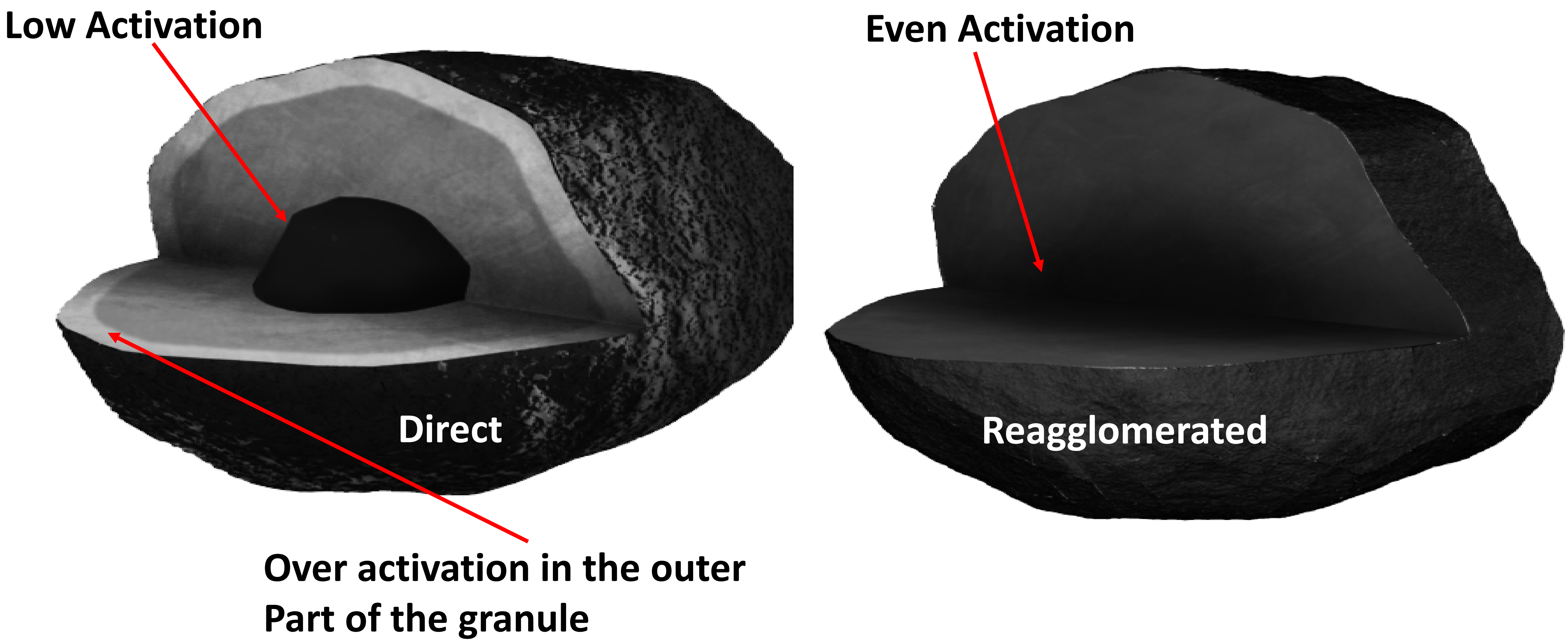


Manufacturing Processes: Direct Activation vs. Re-agglomeration



Granular Activated Carbon

Product differences: Re-agglomeration versus Direct Activation



Factors Affecting Activated Carbon Properties

- Starting materials (e.g., coal, wood, coconut shell)
- Number of pores and pore size distribution
- Internal surface area
- Surface chemistry (especially polarity)
- Apparent density
- Particle size (GAC or PAC)

Key Parameters

- Starting Material / Origin
  - Bituminous Coal, Wood, Coconut, Peat, Lignite, Sub-Bituminous
  - US Made or Imported
- Method of Manufacture
  - Reagglomerated vs. Direct Activated
- Density
  - Apparent Density (AD) is an indicator of pore structure
- Iodine Number
  - Indicates Surface Area
  - Doesn’t account for highly/minimally adsorbable compounds.
- Ash
  - Inorganic Material
  - Measures percent of non-adsorbable surface area
- Trace Capacity Number (TCN)
  - Indicates volume of high capacity pores
  - Indicates ability to adsorb trace pollutants
- Particle Size
  - Measures particle diameter by US Sieves
- Uniformity Coefficient
  - Ratio of size opening that will pass 60% of material divided by that opening that will pass 10% of same sample
- Abrasion Number or Hardness Number
  - Measure particle resistance to degradation of steel balls in an agitated sieve shaker pan
  - PAC with higher Abrasion Number could scratch and harm membrane surface

Example of GAC Characteristics

Activated Carbon		F 300	H 71	C25
Raw Material		Bituminous Coal	Lignite	Coconut Shell
Bed Density, ρ_F (kg/m^3)		500	380	500
Particle Density, ρ_P (kg/m^3)		868	685	778
Particle Radius (mm)		0.81	0.90	0.79
Surface Area BET (m^2/g)		875	670	930
Pore Volume (cm^3/g)				
Micro-	(radius < 1nm)	0.33	0.21	0.35
Meso-	(1nm < r < 25nm)	----	0.38	0.14
Macro-	(radius > 25nm)	----	0.58	0.16
Total		----	1.17	0.65

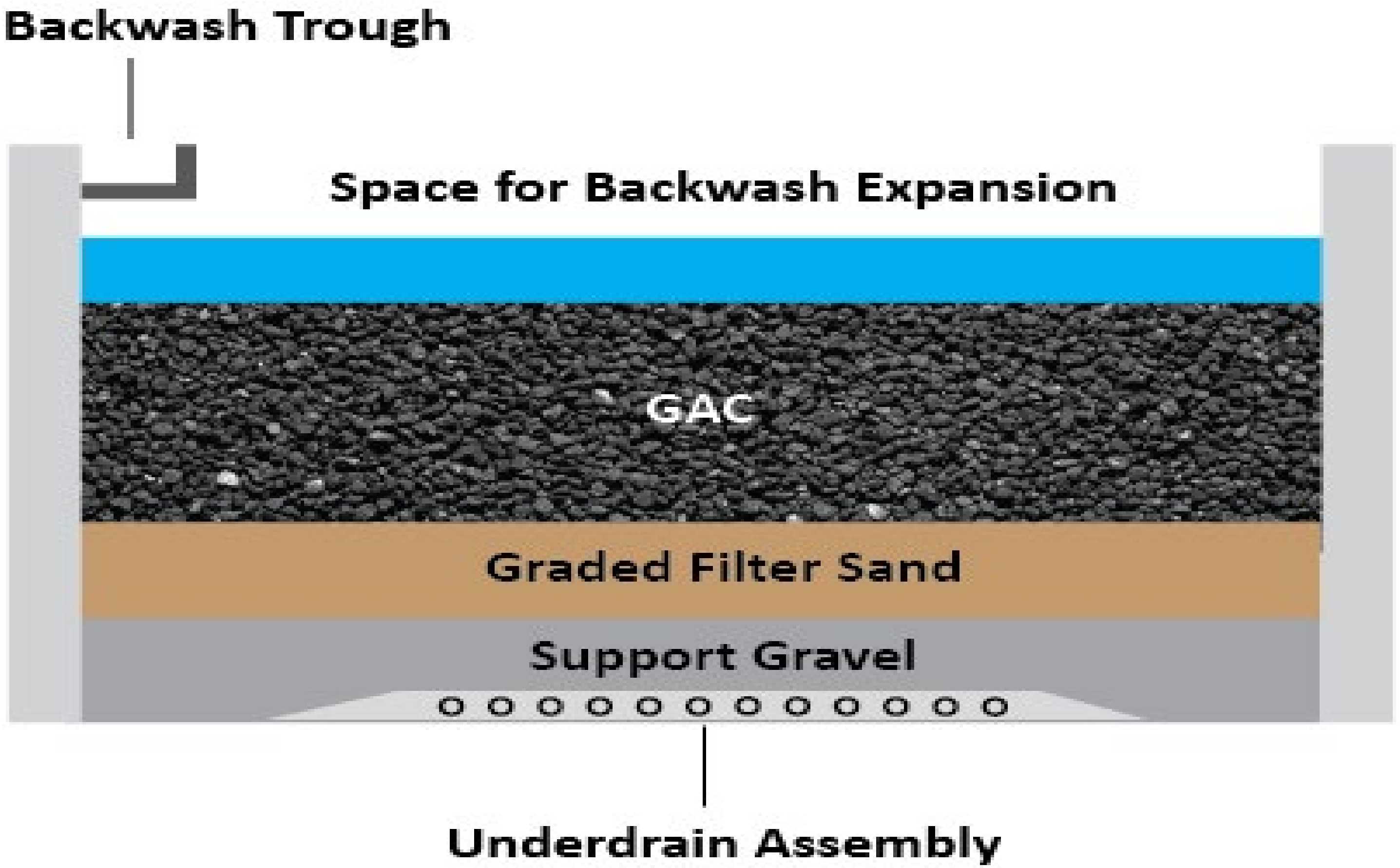
Where is Activated Carbon Used?

- **Surface Water**
  - TOC
  - DBPs and their precursors
  - Algal toxins
  - Taste and Odor
    - MIB/Geosmin
  - EDCs/PPCPs
  - Reuse

- **Groundwater**
  - TCE/PCE
  - PFAS
  - 1,2,3-TCP
  - DBCP
  - EDCs/PPCPs
  - Other VOCs
  - Reuse

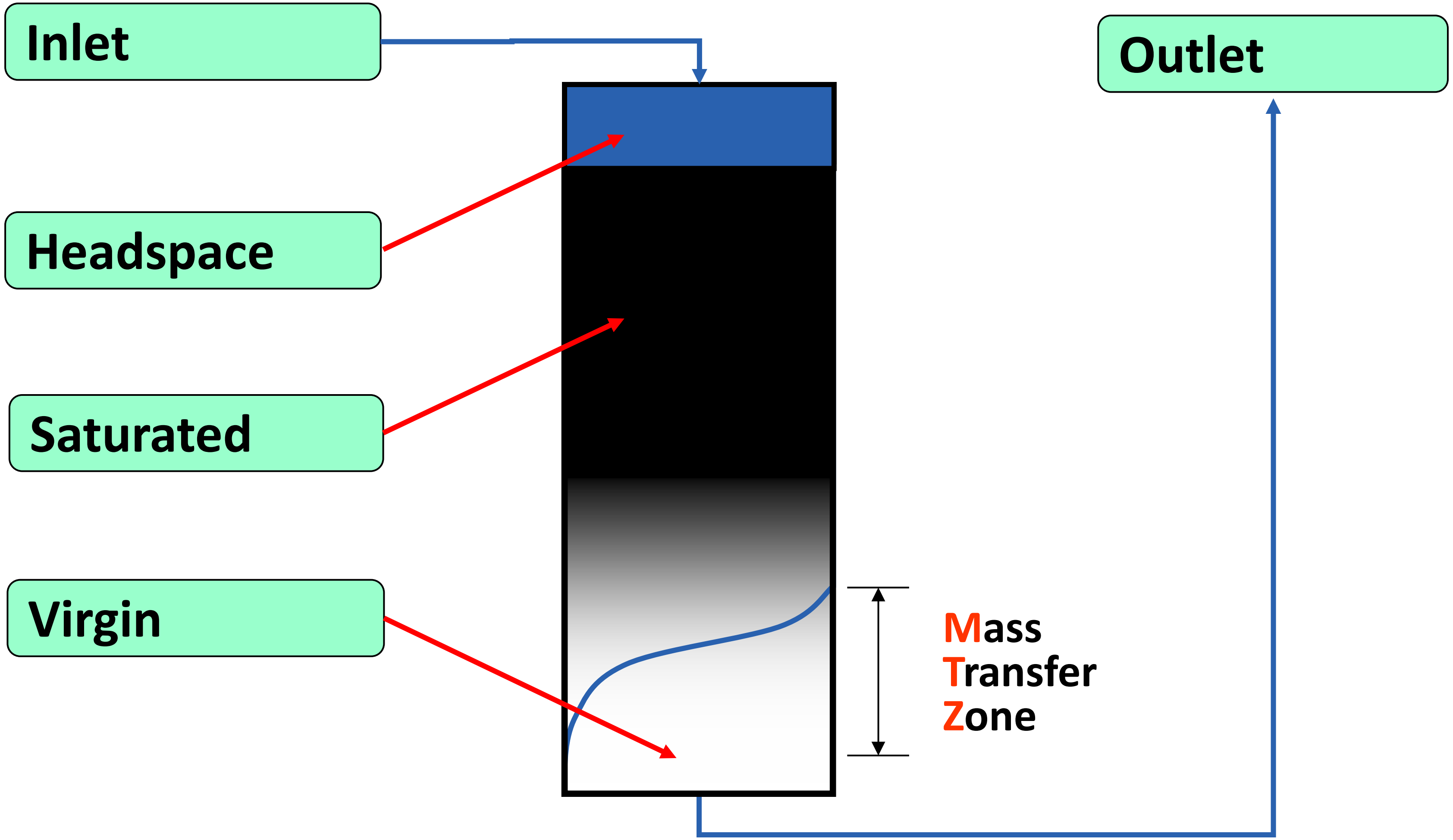
How is GAC Used?

- GAC is usually used as adsorbing filters or packed bed reactors
- GAC filters usually turn into biological filters

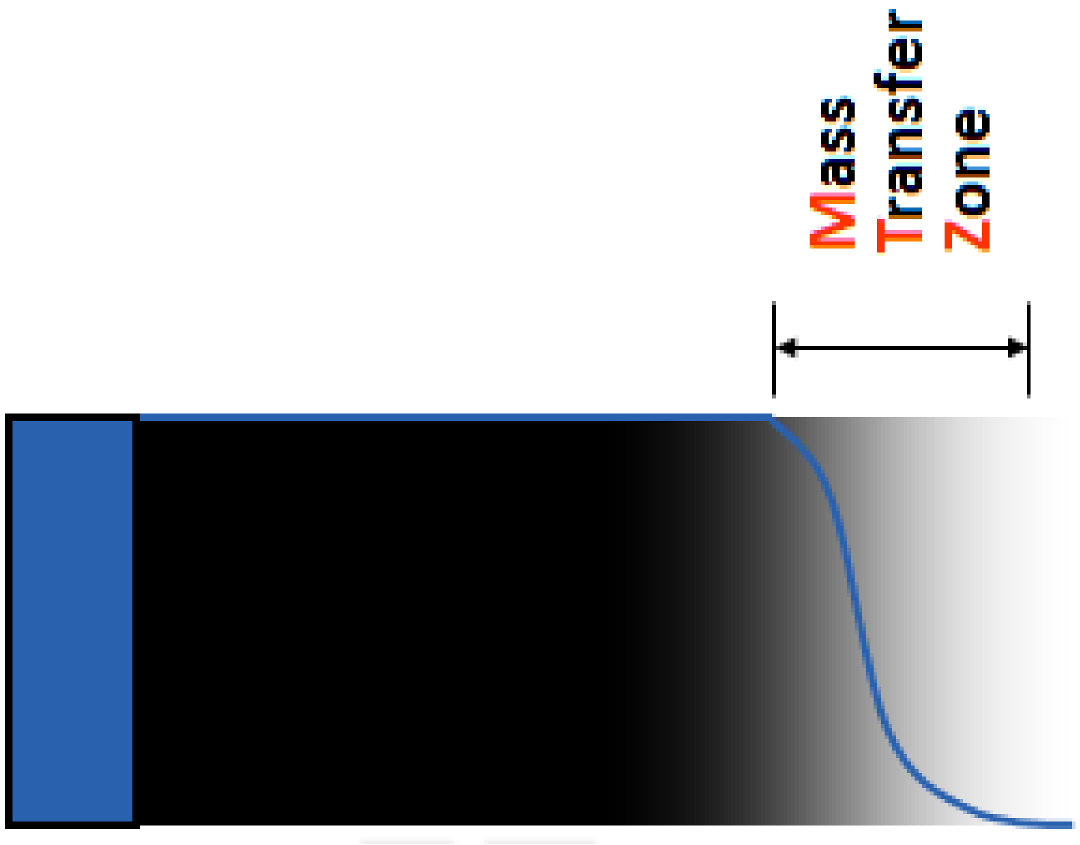


GAC Adsorption Vessels

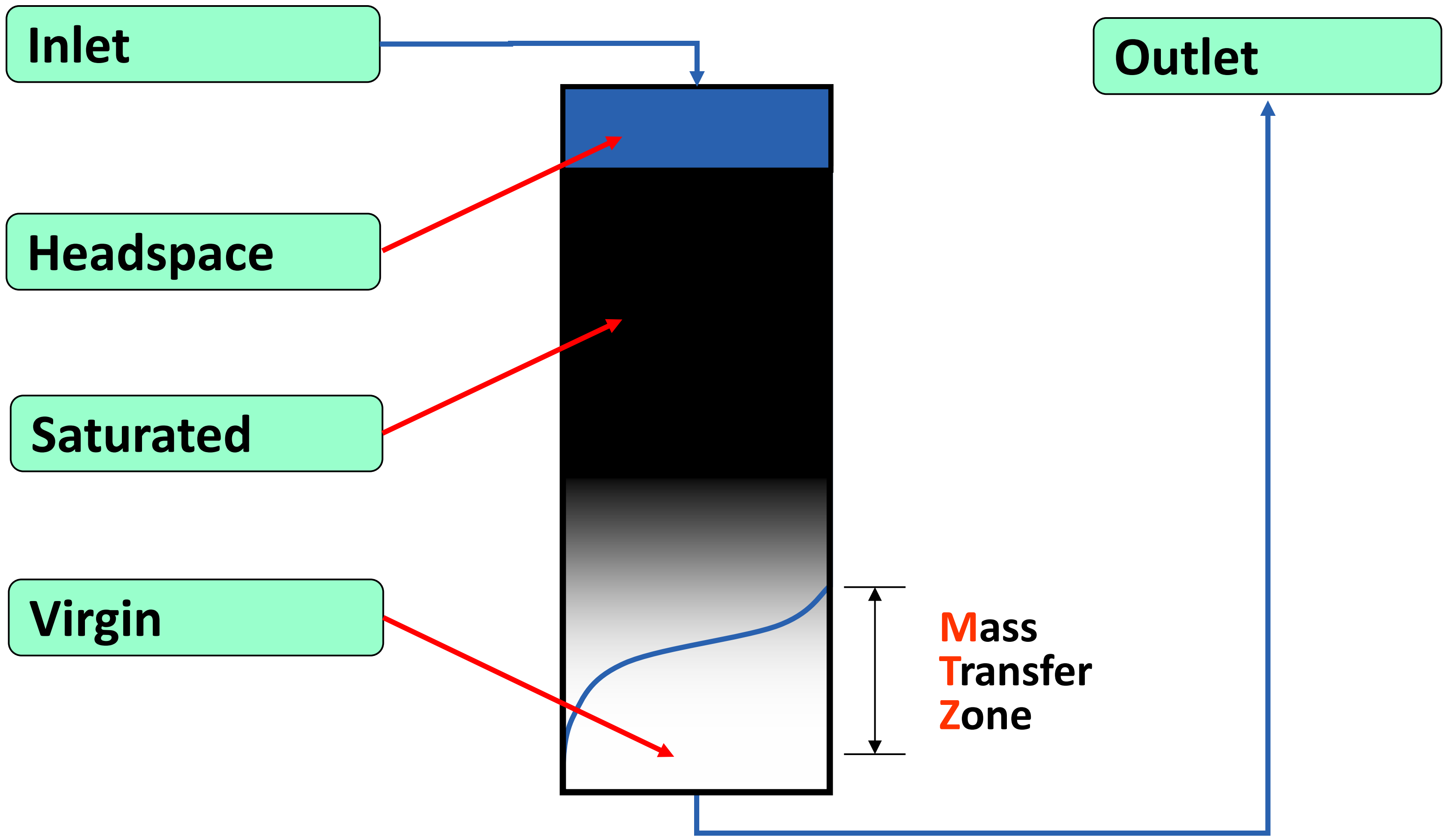
Down Flow Adsorption Breakthrough



A “Different Way” to Look at MTZ



Down Flow Adsorption Breakthrough

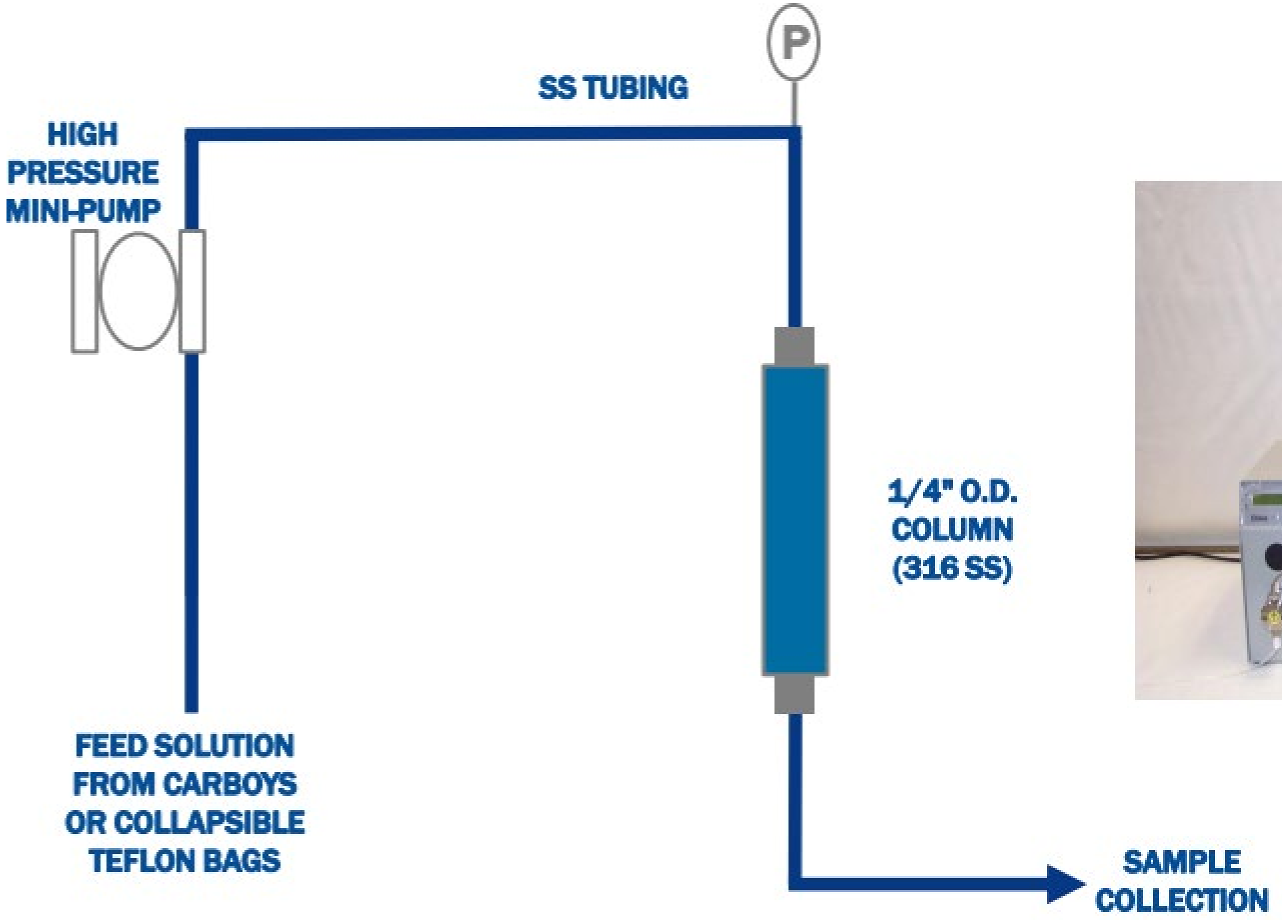


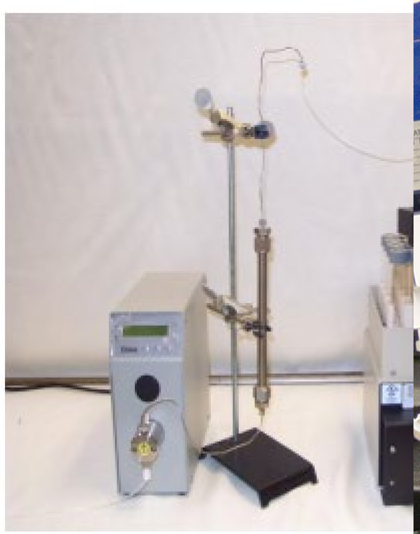
Design Considerations

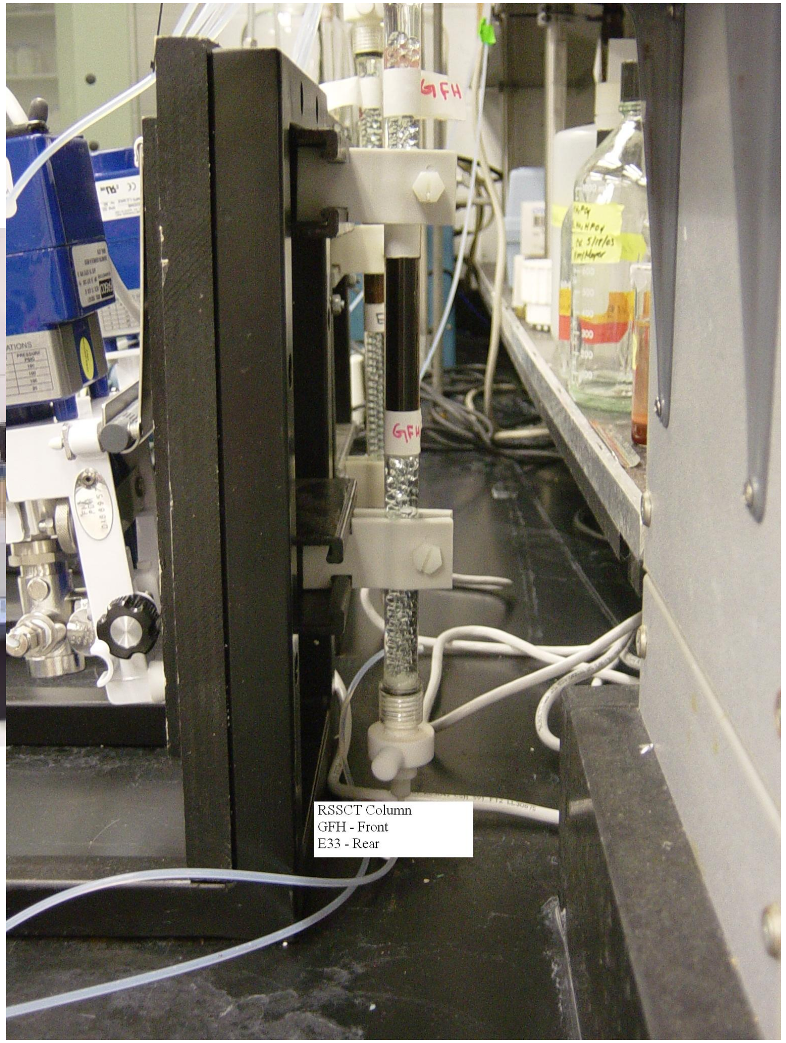
- Bench Scale Rapid Small Scale Colum Testing (RSSCT)
  - Days to breakthrough
  - Require good knowledge and hands-on skills to construct RSSCT columns and conduct testing procedure properly
- Pilot Testing
  - Months to breakthrough
  - Hard to mimic actual plant operating condition
    - Flowrate varies depending on water demand
    - Synchronizing pilot flowrate requires additional planning and control instrumentation
    - Data interpretation could be a challenge
- GAC Adsorption Breakthrough Monitoring

Rapid Small Scale Column Test (RSSCT)

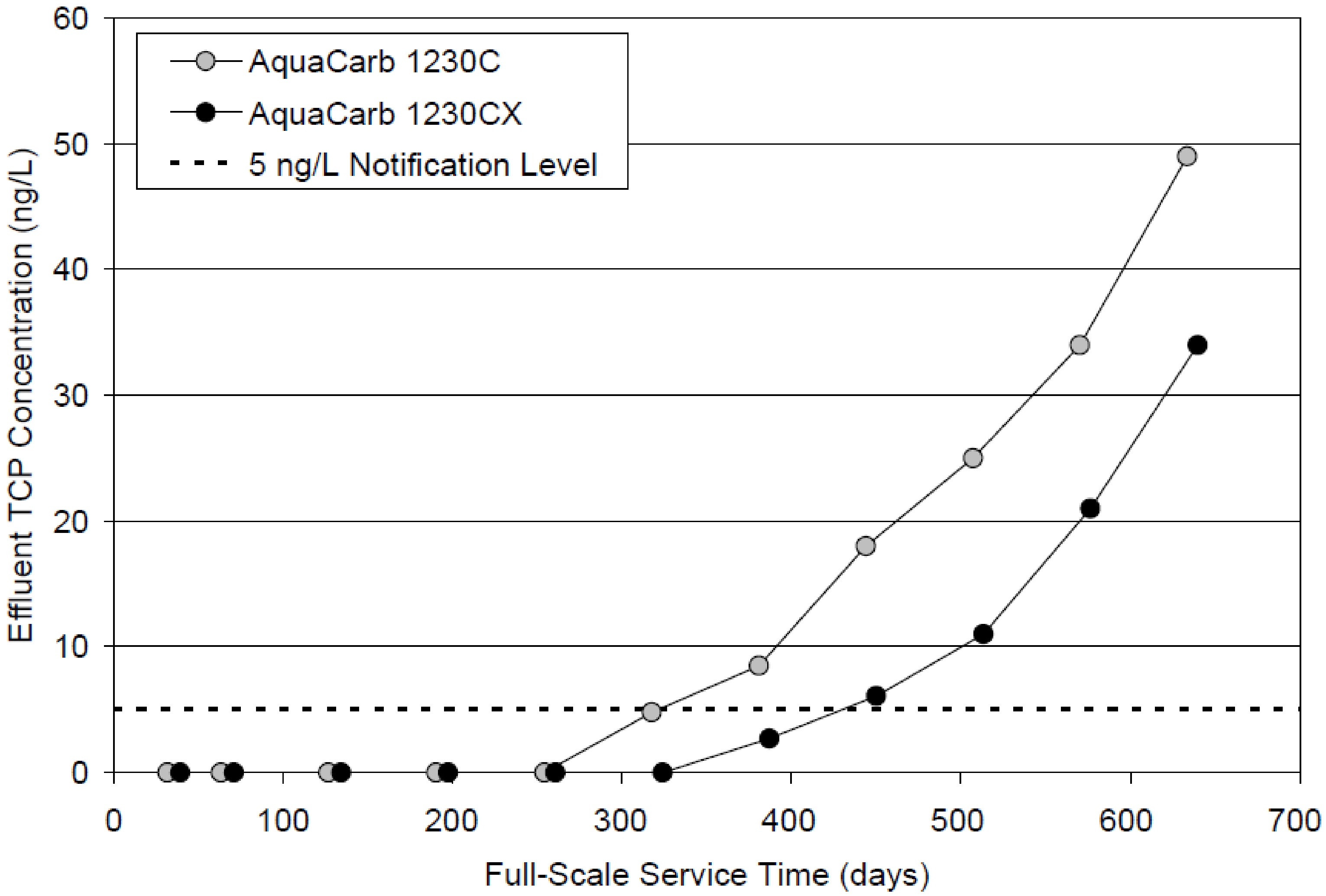
- Very tedious sample & mini-column preparation procedure







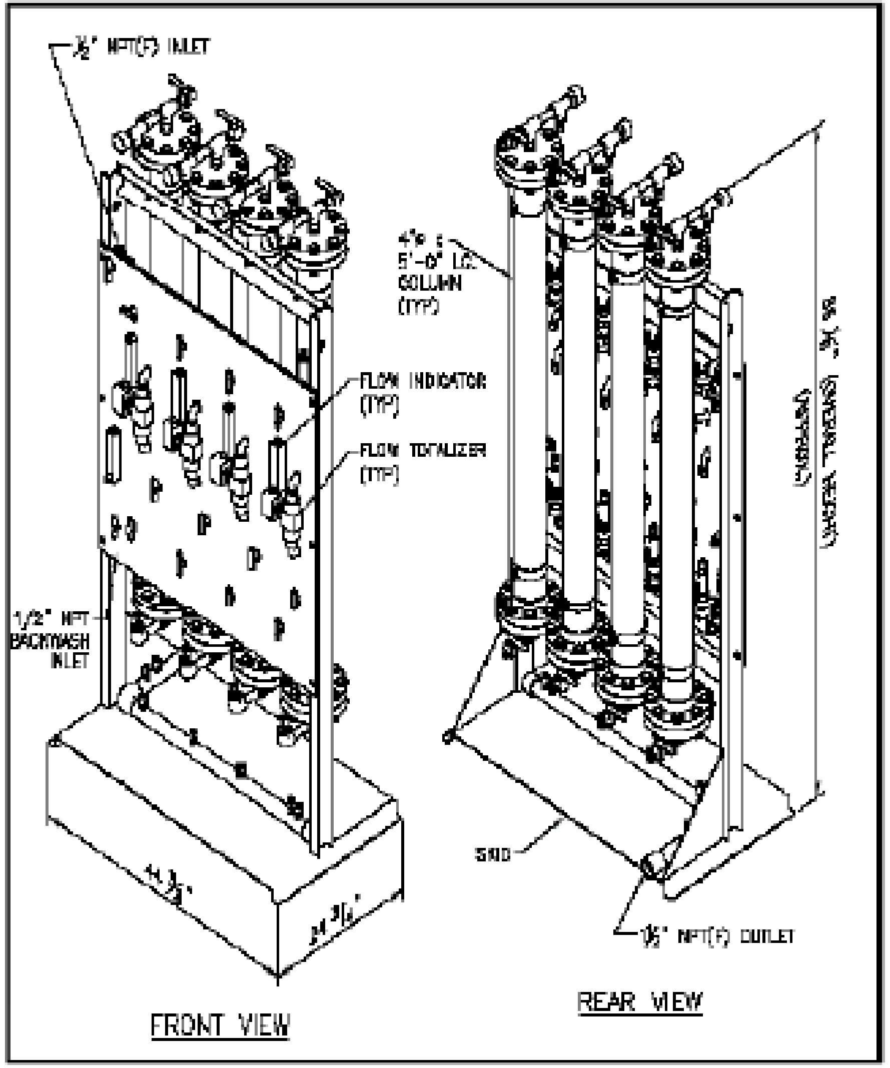
Example: 1,2,3 TCP Removal by GAC Pilot Testing



Pilot Testing System

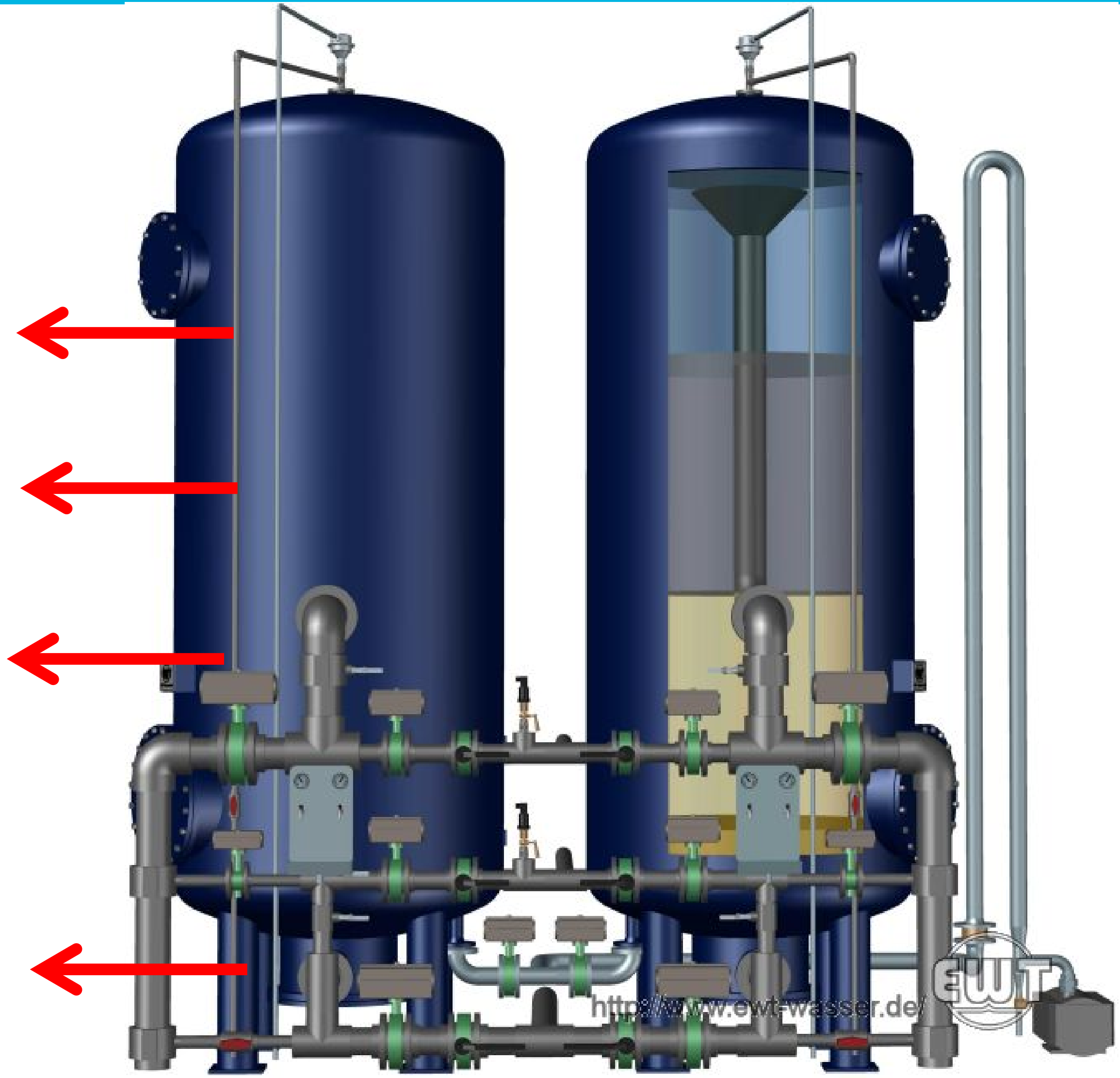
– Considerations

- Incorporates
  - fluctuations in influent
  - flow rate
  - pH
  - bio activity
  - temperature
  - TSS
  - physical filtration
- Backwashable



GAC Performance Monitoring

- Monitor breakthrough at 4 locations to track MTZ migration
- Predict bed-life remaining
- Prepare for GAC media change-out
  - Procuring new GAC
  - Arrange shipping, storage, and labor
  - Acquire permit for discharge initial GAC backwash wastewater



Typical GAC System Design

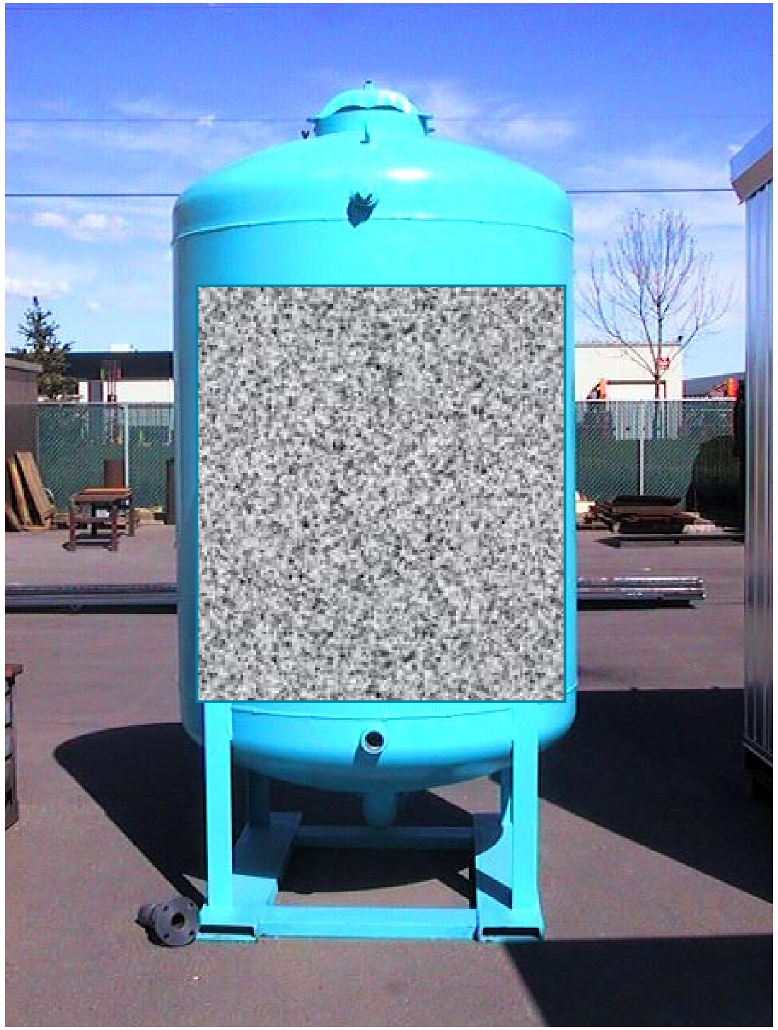
- Loading rate at 1.5 – 3.5 L/s-m^2
- Lead-Lag Operation
- Empty Bed Contact Time (EBCT): 10 – 15 min (prefer 15 min)
  - Ensure adequate reaction time for adsorption to take place (allow time for solutes to migrate further into the micro pores and be adsorbed
  - Need to balance performance with costs
- PAC is usually dosed in with coagulants in conventional WTP
  - Particles containing PAC are much heavier and tend to settle much faster
  - There will be carried over PAC and will be captured by downstream filtration process (impact of membranes?)

Empty Bed Contact Time (EBCT)

- **Empty Bed Contact Time** (EBCT) A measure of the **time** during which a water to be treated is in **contact** with the treatment medium in a **contact** vessel, assuming that all liquid passes through the vessel at the same velocity.
- EBCT is equal to the volume of the **empty bed** divided by the flow rate.

  EBCT = V $(m^3)/(m^3/min)$, or
  EBCT = V (gal)/(gal/min)

- V (entire bed volume) includes the volume of media and void space in the bed

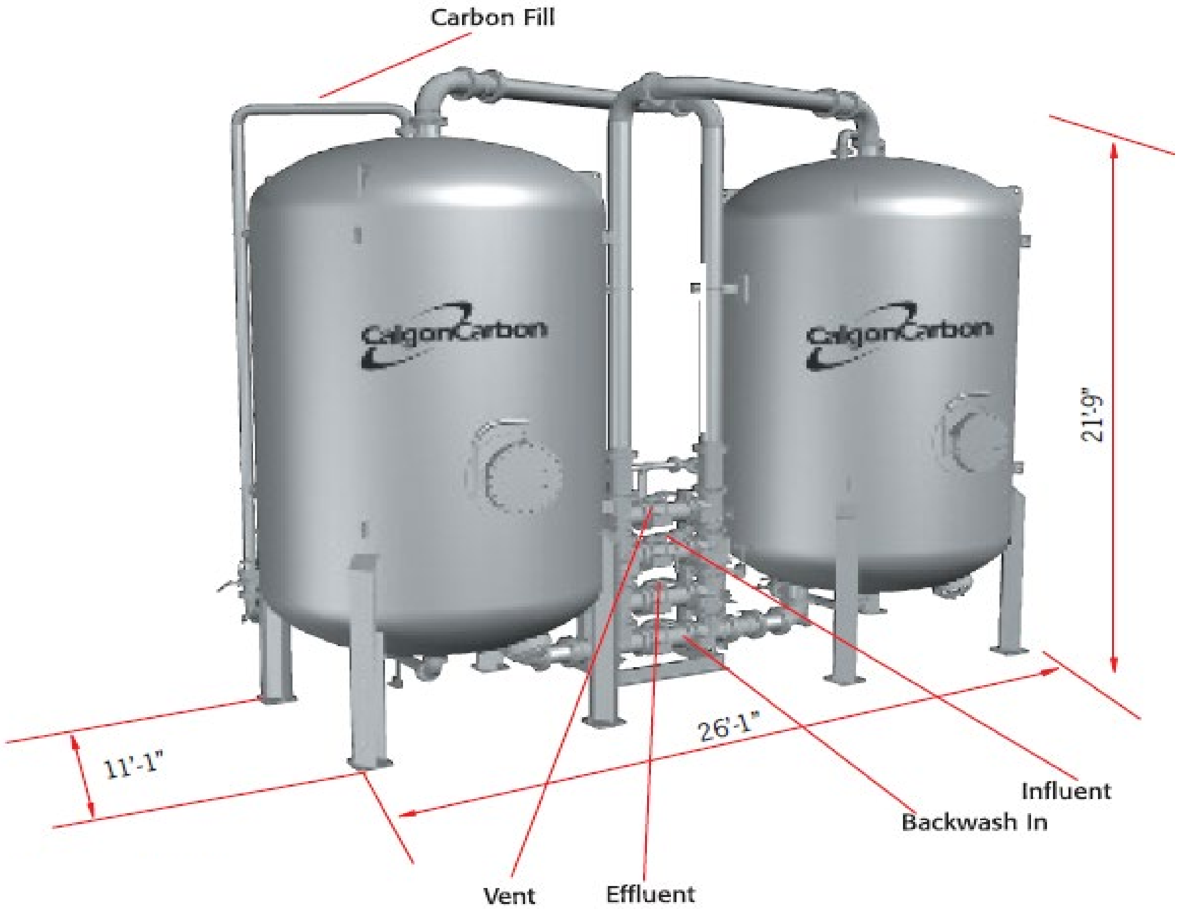


Example of Equipment Selection– Calgon Model 10

- Flow rates

  100 to 1000 GPM (in series)

  200 to 1400 GPM (in parallel)

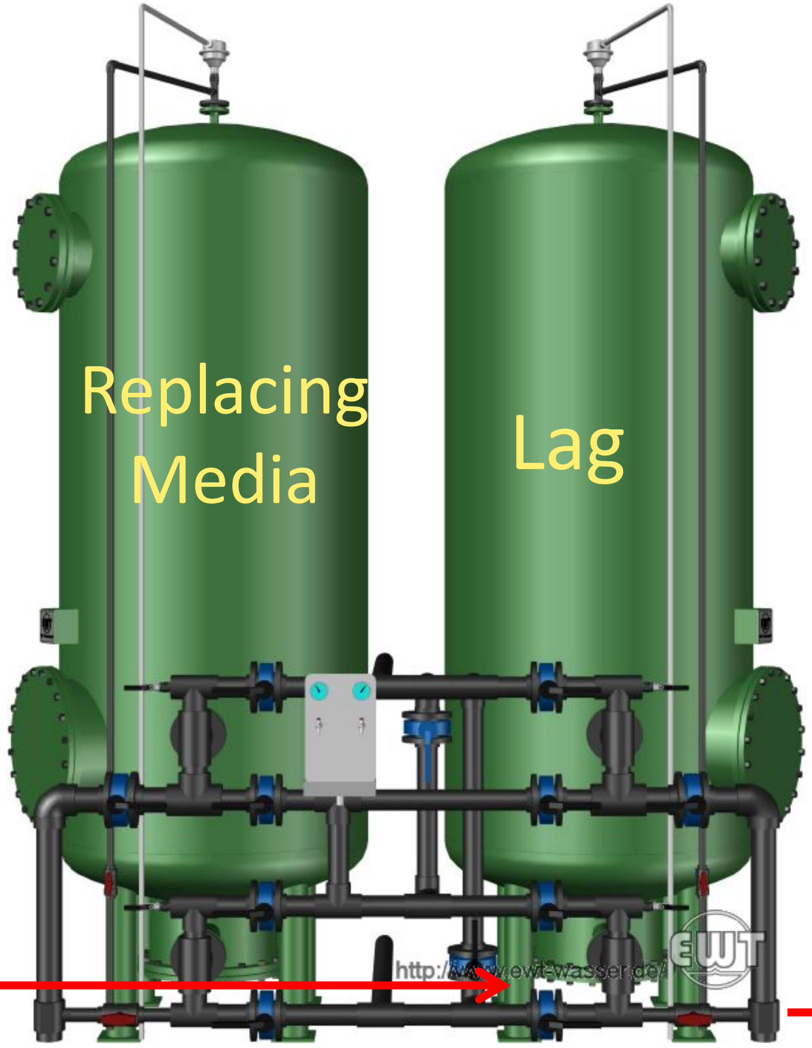


Operation Mode: One-through vs. Lead-Lag

- One-Through GAC Operation
  - Raw water passes through the GAC vessels just once
  - Pros: Simple plant configuration and easy operation
  - Cons: adsorption capacity of GAC is only partially utilized
    - The portion towards the bottom of the vessels) still posses adsorption capacity remaining

GAC Lead-Lag Operation: Normal Operation

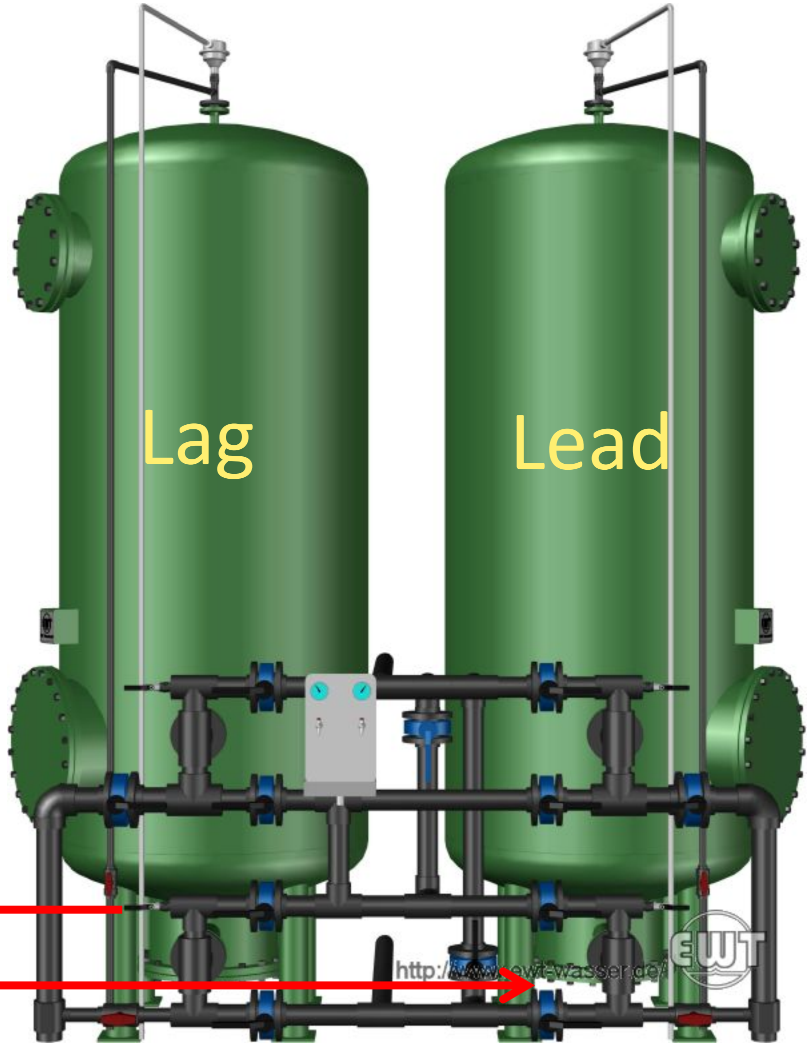
GAC Lead-Lag Operation: Media Replacement



Feed

Finished Water

GAC Lead-Lag Operation: Reverse Lead-Lag



Finished Water

Feed

Pros & Cons for Lead-Lag Operations

- GAC capacity could be fully utilized (lower GAC costs)
- Requires more complicated piping/valving
- Requires more operator training (with better signs and instructions posted)
- Lead-lag GAC vessel design is considered the default option in new installations

GAC System Design Considerations: Selecting the Right GAC

- Not all GAC are created the same
  - Coal based vs. Coconut Shell based
  - Adsorption Isotherm only tells you the equilibrium concentration, not the useful life of GAC
  - Pilot Testing is recommended (3 – 6 months)
  - Adsorption Capacity for specific compounds varies and it could vary from batch to batch
- Use Performance Based Criteria for selecting the right GAC, rather than just based on costs
- Consider the need for on-site backwashing GAC prior to first use
  - How to get rid of the backwash wastewater that might contain arsenic, heavy metals, particulates, etc.
- Consider water production at WTP varies from season to season; how to maintain adequate EBCT for GAC

A Few Words for IXR

- The principal & design concept is very similar to GAC
- The major deviations are:
  - Select different types of IXR for specific ion removal
  - IXR can be regenerated onsite (vs. GAC needs to be reactivated off-site)
  - IXR regeneration brine needs to be disposed properly (usually discharge to sewer line)
  - IXR could remove trace radionuclides (such as uranium) unintentionally, which could turn the entire media bed into hazardous material)