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DESIGN OF PILOT PLANTS AND THE ISSUE OF SIMILITUDE WITH FULL- SCALE SYSTEMS IN WATER TREATMENT APPLICATIONS

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Design of Pilot Plants and the Issue of Similitude with Full-Scale Systems in Water Treatment Applications

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ABSTRACT

Satisfactory design and operation of pilot plants requires that there is process similitude (similarity) between the pilot-scale unit (model) and the full-scale process. The relationship between a pilot-plant and the full-scale system should be such that the pilot can be used to produce parameters useful for design, scale-up and prediction of performance for the full-scale unit. This report will highlight some of the design parameters critical to scale-up for: (a) adsorption systems (b) coagulation microfiltration systems and (c) coagulation settling and conventional filtration systems, which are the more common water treatment systems for arsenic removal.

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1.0 Introduction

In general, there are no fixed rules governing the sizing of pilot plants in terms of percentage of actual flow or ratio of sizing of pilot systems to that of a real life system. Satisfactory design and operation of pilot plants requires that there is process similitude (similarity) between the pilot-scale unit (model) and the full-scale process. Process similitude means that the relationship between a pilot-plant and the full-scale system should be such that the pilot can be used to produce parameters useful for design, scale-up and prediction of performance for the full-scale unit. The pilot units should be sized such that the critical dimensions have similitude with the full-scale plant. For example, if reactor height is critical to a process unit then, ideally, the height of the pilot should be as close as possible to the actual height of the real life unit. Another critical feature in designing a pilot is the similitude in the process components and process instrumentation (to the extent possible real-life components should be used).

Mechanistic models for predicting the performance of water treatment systems are few and usually are not reliable. The industry norm is to use a deterministic approach by using the results from pilot scale systems to design and predict the performance of full-scale systems. Process parameters that are commonly used to design full-scale systems include:

Loading (L_o) = (mass/time)/volume; $\text{kg/m}^3\text{-d}$

Hydraulic Retention Time (HRT) = reactor volume/flow rate; hours

Empty Bed Contact Time (EBCT) = reactor volume without media/flow rate; min

Flux ($f(x)$) = flow rate/membrane surface area; m/d

Service flow rate (SFR) = $1/\text{EBCT}$, flow rate/media volume including voids; min^{-1}

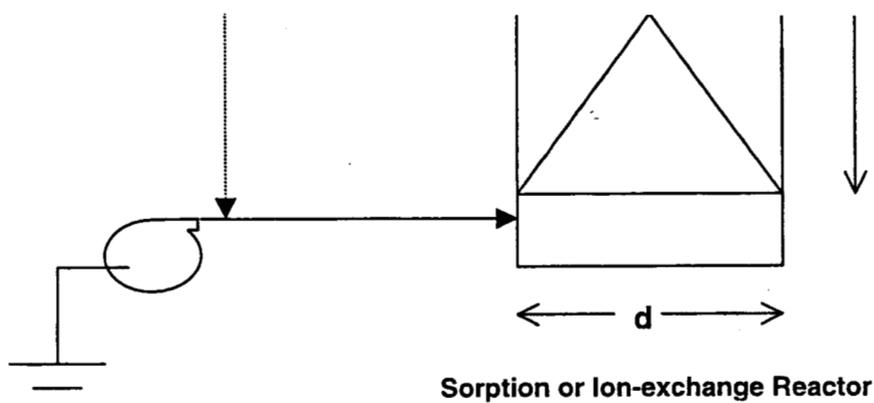
Surface Overflow Rate (SOR) = flow rate/clarifier surface area; m/d

These parameters are generally obtained or optimized deterministically by operating pilot plants. The optimized design parameters obtained from the pilot study are then used to design and predict the performance of the full-scale units they are designed to simulate. In the following discussion, examples will be used to illustrate the process parameters that can be obtained from pilot studies and subsequently used to design and predict the performance of full-scale systems. The examples given below are for illustration purposes only and the actual scenario may be much more complex. The three examples that will be used are: (1) Pilot reactor for the design of metal oxyhydroxide and ion-exchange reactors for sorption or co-precipitation of arsenic (2) Pilot reactor for the design of coagulation micro-filtration systems for arsenic removal and (3) Pilot reactor for the design coagulation –settling – conventional filtration in large-scale municipal systems for arsenic removal. The above-mentioned technologies are those of choice for removing arsenic from drinking water¹.

2.0 Metal Oxyhydroxide and Ion-exchange Reactors for Sorption of Arsenic

Adsorption is a mass transfer process in which a substance is transferred from the liquid phase to the surface of a solid, where it becomes bound by chemical or physical forces. In the case of oxyanions, such as arsenate and arsenite, adsorption occurs on the oxide water interface by forming a complex with surface sites that may be positively charged, such as a protonated surface hydroxyl group. Ion-exchange is a special case of adsorption where ionic species in aqueous solution are removed by exchange ions of a similar charge attached to a synthetic resin surface. Synthetic resins are made up of cross-linked polymer matrices possessing charged functional groups attached by covalent bonding.

Adsorption processes commonly used in water treatment are adsorption onto activated alumina, ion-exchange, iron oxyhydroxides and manganese dioxide coated sand. The figure below summarizes the typical treatment set-up for sorption process for arsenic removal. The process entails the addition of an oxidizing agent and control of pH followed sorption onto metal oxihydroxides or ion-exchange resins. The overall process efficiency and optimum process design depends on the source water quality, intrinsic media properties, optimization of reactor design and operation parameters. The critical properties and parameters affecting system performance are listed below.



Critical reactor design parameters:

EBCT, minimum bed height (h), flow-through velocities or surface loading rate, bed height /bed diameter (d), water pressure head (x), etc.

Intrinsic media properties:

Sorption capacity, media grain size, bulk density, porosity, selectivity coefficient and separation factor, surface charge at operating pH, strength of sorption as defined by Toxicity Characteristics Leaching Procedure (TCLP), etc.

Critical operational parameters:

Flow rate, SFR, pH, free oxidant concentration, arsenic speciation, pre-filtration, etc.

Intrinsic water quality parameters affecting system performance:

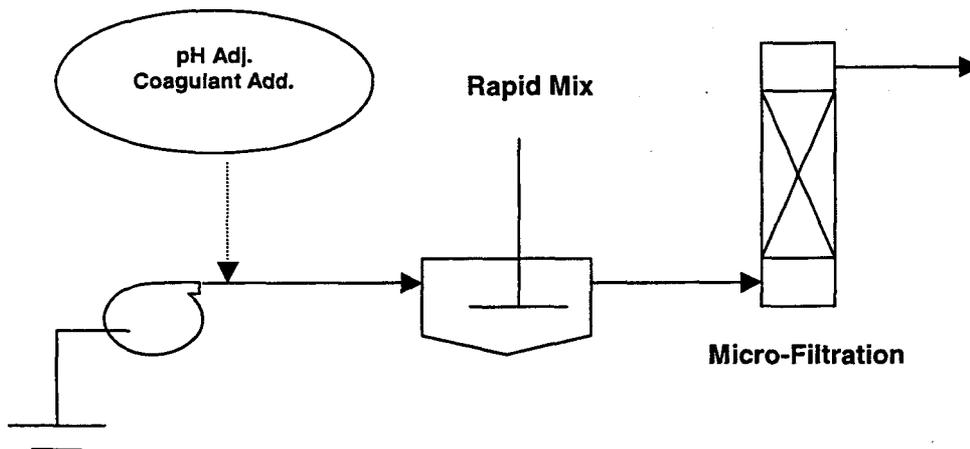
Competitive sorption and chromatographic peaking due to the presence of competing ions can cause fouling because of precipitation of insoluble salts, bio-fouling, etc.

Process Similitude:

Process similitude requires that the SFR and EBCT be the same for pilot and full-scale absorption column. This means that shallow beds operated at the same EBCT will not be equivalent to a deep bed operated at the same EBCT. This implies that the bed depth to height ratio is important and should be similar for the pilot to that of the full-scale unit. In the same token, it may be critical in the design of pilot and full-scale systems to maintain a minimum critical bed depth.

3.0 Coagulation Micro-filtration Systems for Arsenic Removal

Arsenic removal from water by coagulation entails the conversion of dissolved arsenic to insoluble products by the combined mechanisms of precipitation, co-precipitation and adsorption. The trivalent metal salts used for arsenic removal by coagulation are alum and ferric salts. The treatment train illustrated below for arsenic removal from groundwater using coagulation followed by microfiltration, requires a preoxidation step to convert all the arsenite to arsenate, pH adjustment for enhancement of coagulation, followed by coagulation to convert dissolved arsenic to insoluble products and settling/micro-filtration to remove the insoluble products of coagulation. The critical properties and parameters affecting system performance are listed below.



Critical design parameters:

Rapid mix: Rapid mix velocity gradient, rapid mix detention time, etc.

Micro-filtration: Micro-filtration flux rate, trans-membrane pressure, solids loading rate, etc.

Intrinsic membrane properties:

Material: Pore size, configuration (cross-flow vs dead-end), etc.

Critical operational parameters:

Rapid mix: pH, coagulant type and dosage, HRT, free oxidant concentration, etc.

Micro-filtration: operating pressure, flux, TMP, flow rate, backwash frequency, etc.

Intrinsic water quality parameters affecting system performance:

Source water quality (turbidity, total organic carbon, insoluble metal salts), arsenic speciation, effects of fouling due to precipitation of insoluble salts, bio-fouling, etc.

Process Similitude

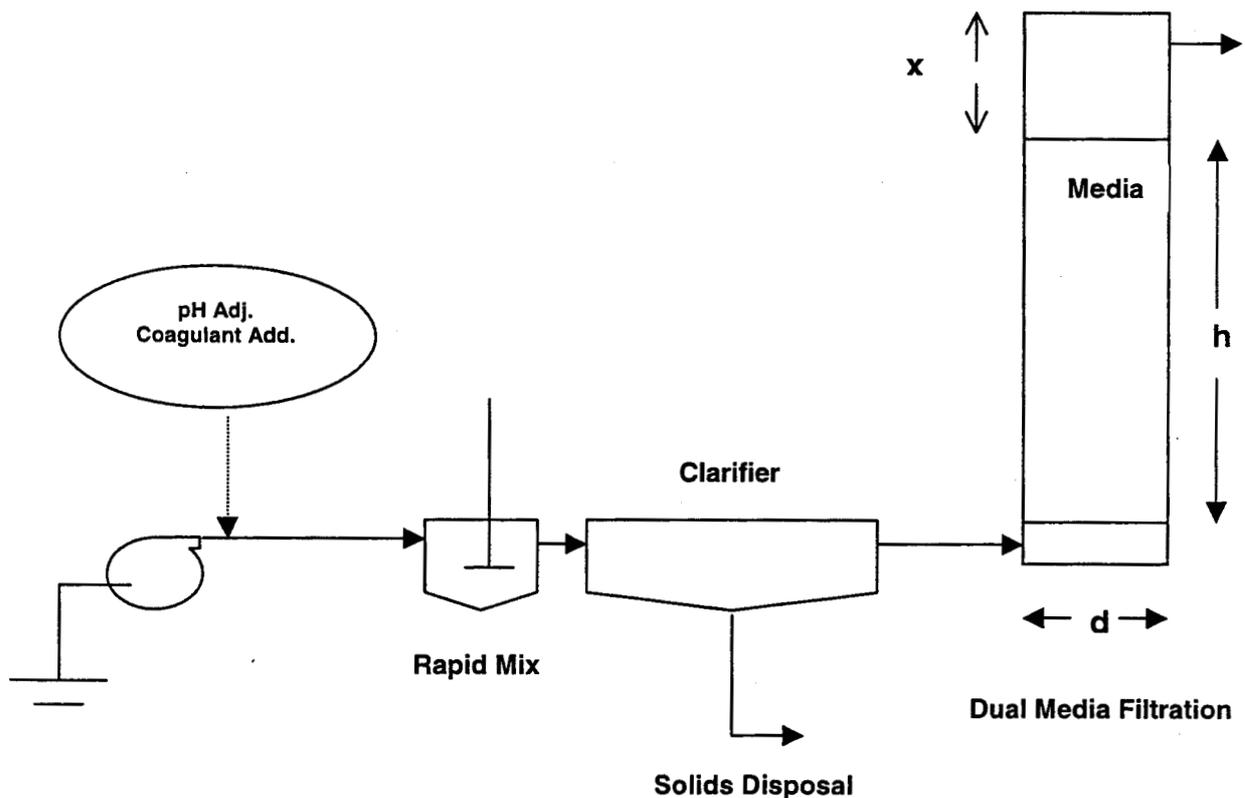
The process most susceptible to inadequate similitude is the membrane reactor.

For process similitude, the pilot membrane must have the same L_0 and $f(x)$ relationships inside and outside the membrane segment and the same HRT.

Therefore, the membrane assemblies should have the same $f(x)$ as the intended full-scale process. The pilot system should be operated to the design TMP and washed using equivalent methods.

4.0 Coagulation –Settling – Conventional Filtration Large Scale Municipal Systems for Arsenic Removal

The treatment train illustrated below for arsenic removal from water using coagulation followed by dual media (sand and anthracite) filtration, requires a preoxidation step to convert all the arsenite to arsenate; pH adjustment for enhancement of coagulation, followed by coagulation to convert dissolved arsenic to insoluble products; and settling/dual media filtration to remove the insoluble products of coagulation. The critical properties and parameters affecting system performance are listed below.



Critical reactor design parameters:

Rapid Mix: Rapid mix velocity gradient, rapid mix detention time.

Clarifier: height (h), diameter (d), surface area, HRT, SOR, geometry, etc.

Dual Media Filter: Hydraulic loading rate, solids loading rate, minimum bed height (h), bed height /bed diameter (d), available pressure head (x).

Intrinsic filter media properties:

Filter media type, grain size, etc.

Critical operational parameters:

Rapid mix: pH, coagulant type and dosage, HRT, free oxidant concentration, etc.

Clarifier: HRT, SOR, solids wasting rate, etc.

Dual Media Filter: Flow rate, pressure drop across media, backwash frequency, backwash flow rate, extent of bed expansion during fluidization, etc.

Intrinsic water quality parameters affecting system performance:

Source water quality and arsenic speciation.

Process Similitude:

The processes most subject to inadequate similitude are the clarifier and the dual-media filter. For process similitude, the depth of the pilot clarifier should be the same as the depth of the full-scale clarifier. The unit should be operated at HRT and Lo rates which are equivalent to those anticipated for the full-scale system.

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¹ Joseph D. Chwirka, Bruce M. Thomson, and John M. Stomp III.
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