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- Figure 8.1-3** Powerful computer-based numerical methods are now easily available for solving the model equations
- Figure 8.1-4** Some basic models used for estimating the sorption column performance. Several will be discussed in more detail in this Chapter
- Figure 8.1-5** Experimental points and breakthrough curves generated by **IMPACT** simulation program for a column with Sargassum fed with an equimolar 3-metal mixture [7]
- Figure 8.2-1** While the ECM neglects all the mass transfer, eventually affecting the breakthrough curve shape, it is useful for multi-component mixtures: predicting the sorbate outlet sequences and concentration overshoots as well as the sorption column service time.
- Figure 8.2-2** Plateaus and Transitions considered in the column for the purpose of the ECM calculations
- Figure 8.2-3** Proportionate-pattern or gradual transition developing in the sorption column with time
- Figure 8.2-4** Constant-pattern or abrupt transition developing in the sorption column with time (EC Model)

- Figure 8.2-5** The ECM plot layout
- Figure 8.2-6** Algorithm for computer solution of equations (8.2-4,9,10)
- Figure 8.2-7** Example of Plateaus and Transitions in the ECM plot for column performance evaluation
- Figure 8.2-8** A typical column effluent concentration overshoot caused by competitive ion exchange
- Figure 8.2-9:** **A:** component with a (+) slope transition;  
**C:** component with a (-) slope transition
- Figure 8.2-10a** Compounds A and C on B-form biosorbent
- Figure 8.2-10b** Compounds A and B on C-form biosorbent
- Figure 8.2-10c** Compounds B and C on A-form biosorbent
- Figure 8.1-11a** Affinity of Fe<Cu and the concentration of Cu is much higher than that of Fe: Fe overshoots and breaks through earlier !
- Figure 8.2-11b** Affinity of Zn<Cu and the concentration of Cu is much higher than that of Zn: Zn overshoots earlier!
- Figure 8.2-11c** Affinity of Cd<Cu and Cd concentration is much lower than that of Cu: Cd overshoots earlier !
- Figure 8.2-11d** Affinity of Zn<Cu, and the Cd concentration is much higher than that of Zn: NO overshoot !
- Figure 8.2-12** Analysis of concentration overshoots for columns packed with B-sorbent fed with A and C (A=Cu; C=Ca).
- Figure 8.2-13a** A sorption column effluent concentration history predicted by the ECM
- Figure 8.2-13b** Experimental effluent concentration history. A Ca-biomass column treating a (Cu+Cd+Zn) metal mixture
- Figure 8.2-14** Comparison of Zn breakthrough from 4-component and 2-component sorption systems

**Table 8.2-1** Ion Exchange Equilibrium Constants for Metals with *Sargassum* Biomass

**Table 8.2-2** Evaluating a biosorption process to treat heavy metal pollution

- Figure 8.3-1** The powerful MTM requires the knowledge or estimate of the sorbate diffusion coefficient(s) and the equilibrium reaction parameters.
- Figure 8.3-2** Dimensionless ion exchange isotherm diagram
- Figure 8.3-3** Suitable equilibrium models need to be established (Chapter 6 or from the literature)
- Figure 8.3-4** The dimensionless groups used in the MTM
- Figure 8.3-5** Prediction of the Ca-biomass sorption column service time by the MTM model. Done for the Zn breakthrough in a (Cu+Cd+Zn) system
- Figure 8.3-6** Theoretically, N different mass transfer coefficients and 3(N-1) equations are necessary when N sorbates are considered
- Figure 8.3-7** The ECM procedure can assist in simplifying a multisorbate system into a binary system that can be handled by the MTM
- Figure 8.4-1** Response of the uranium column outlet concentration to the step function in the column inlet (switch to distilled water).  
(F = 175 ml/h,  $V_{bed}$ =280 ml, biosorbent = 22.64 g)
- Figure 8.4-2** Comparison of experimental uranium and Mass Transfer Model calculated breakthrough curves for protonated *Sargassum* biomass
- Figure 8.4-3** Residuals of experimental and the Mass Transfer Model calculated uranium breakthrough curve
- Figure 8.4-4** Process modeling ideally proceeds in a spiral to obtain good predictions of system performance. Process simulation can guide further experimentation.  
Model only needs to be as complex as necessary for its "reasonable" prediction capabilities

**9 – BIOSORBENT MATERIAL PREPARATION**

- Figure 9-1** Granulation of the biosorbent is essential for its effective application in a sorption process
- Figure 9-2** Cheap biomass raw material comes from two major sources: as industry waste or an ocean-based natural and renewable resource
- Figure 9-3** Seaweeds represent plentiful and renewable biomass that could be collected and/or propagated
- Figure 9-4** Formulating a sorbent means striking a balance between the “micro” and “macro” considerations
- Figure 9-5** A sorbent particle has to be sturdy, rigid and easily penetrable by the sorbate compound
- Figure 9-6** We want to quantify and to be able to also manipulate the sorption particle properties
- Figure 9-7** Formulated and processed granules need to be tested and characterized
- Figure 9-8** Formulating a sorbent means striking a balance between the “micro” and “macro” considerations
- Figure 9-9** A number of types of chemical treatment aims at improving different aspects of biosorbents
- Figure 9-10** Active biosorbent material is “embedded” in a permeable substance making up the particle
- Figure 9-11** Permeability and durability of the encapsulating membrane may be a problem
- Figure 9-12** Both procedures reinforce the particle but may result in diminished sorption performance
- Figure 9-13** There are many crosslinking procedures – they invariably represent chemical interferences in the particle that must already be in existence
- Figure 9-14** FA crosslinking takes place in 2 stages
- Figure 9-15** UFA crosslinking with DMU does a different job and yields byproducts
- Figure 9-16** A generalized schematic flowchart of biomass processing into sorbent granules
- Figure 9-17** When biosorbent undergoes chemical treatment there are always chances that its performance may suffer
- Figure 9-18** Fluidization and agglomeration is involved in both granule-making processes that are highly empirical
- Figure 9-19** The sorption column breakthrough curve AND the pressure drop are the most important continuous-flow sorption process characteristics and operating parameters
- Figure 9-20** The optimum compromise has to be sought between the column mass transfer performance and its operating pressure drop
- Figure 9-21** Ideally, NO granulation would need to be done. Sargassum biosorbent has been such a case
- Figure 9-22** Performance of every sorption process depends directly on the preparation of the sorbent
- Figure 9-23** Formulation of biosorbent materials for application has to be carefully considered, optimized and the sorption performance examined after each treatment or procedure
- Figure 9-24** Opposite to the uptake (sorption), DESORPTION is an important study area leading to regeneration of the sorbent and to the eventual recovery of sorbate
- Figure 9-25** In equilibrium batch desorption studies, residual uptake of the sorbate (here at low pH) could distort the desorption results and conclusions
- Figure 9-26** A high-concentration peak of uranium exited the experimental column upon low-pH (pH 1.2) desorption wash
- Figure 9-27** Single-component desorption:  
 YELLOW: High and narrow elution peak is desirable for desorption particularly when the eluate is to be further processed (recovery !).  
 BLUE: Low, flat and trailing elution peak is a sign of desorption problems

- Figure 9-28** Multi-component operation:  
 YELLOW: Low-affinity compound **A** breaks through first as it is replaced in the column by **B** and **C**.  
 GREEN: Middle-affinity compound **B** also overshoots but less upon later breakthrough.  
 BLUE: High-affinity compound **C** eventually leaves the column in the normal breakthrough
- Figure 9-29** (repeated *Figure 2-21*) Concentration of the sorbate in the effluent eluate is important for its further recovery (or disposal)
- Figure 9-30** (repeated *Figure 2-22*) Biosorbent Solids to eluting Liquid ratio (S/L) is of importance to overall process effectiveness
- Figure 9-31** (repeated *Figure 2-23*) Complete sorbent regeneration may take two or more operations, usually "in situ" in the column
- Table 9-1** [9] Characteristics of pre-treated *Sargassum* biomass
- Table 9-2** [9] Behavior of modified *Sargassum* biomass during Zn biosorption
- Table 9-3** [9] Multicomponent Langmuir model parameters:  
 Equilibrium constants  $K$  (L/meq),  $K_{Zn}/K_M$  ratios and error function  $F_M$
- Table 9-4** [9] Multicomponent Langmuir model parameters:  
 Equilibrium constants  $K$  (L/meq),  $K_M/K_K$  ratios

## 10 – MONOCLONAL ANTIBODIES BIOSORPTION

- Figure 10-1** Example of a different type of biosorption: using monoclonal antibodies for bio-product recovery
- Figure 10-2** Highly selective and immobilized sorbent (mAb) retains only the desired type of sorbate (white) from a mixture of other molecules
- Figure 10-3** Antibodies are glycopeptides, this one is "IgG1"
- Figure 10-4** Chromatography is an operation based on a semi-continuous-flow sorption process
- Figure 10-5** Working with antibodies again represents a multi-faceted and interdisciplinary task
- Figure 10-6** Antibodies can be produced either *in vivo*, or *in vitro* by a laboratory technological process
- Figure 10-7** Techniques of eluting a loaded column can facilitate a difficult separation
- Figure 10-8** Affinity Chromatography – for purification of antibodies using immobilized protein (UPPER), or (LOWER) using immobilized antibodies to 'immunosorb' a protein
- Figure 10-9** Small columns used in laboratory immuno-affinity chromatography. Larger-scale operation is still in the future
- Table 10-1** Comparative mAb production scale
- Table 10-2** Commonly used affinity fusion systems
- Table 10-3** Summary of the mAbs work cited