BIOSORPTION: APPLICATION STRATEGIES

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ABSTRACT

Over the past 25 years, intensifying research into metal biosorption elucidated the principles of this effective metal-concentration phenomenon. Biosorption can be cost-effective particularly in environmental applications where low costs of the metal removal process are most desirable. Some efficient natural biosorbents have been identified that require little modification in their preparation. Engineering scale-up of the biosorption process seems fairly straightforward, based on experience from conventional sorption operations. While it seems that biosorption could hardly have any competition in many types of large-scale environmental metal removal applications, the process has not been applied as yet.

Several attempts for commercialization of the process so far have not been successful, due to mainly non-technical pitfalls involved in commercialization of technological innovations. As solid capitalization is required for innovative process ventures, partnership approach is perhaps advisable. However, the choice of partners appears critical.

While mining and ore processing companies appear to be excellent “clients” for innovative clean-up technologies, each is invariably concerned with mainly having only its own environmental problems successfully addressed. Pioneering and propagation of innovative environmental technologies is not necessarily an appealing venture for them. The “suppliers” of sorption and ion-exchange technologies, while closest to biosorption, is a handful of huge transnational companies with difficulties in operative decision making. Dynamic consulting companies are in an excellent position to acquire and push new process technologies into the marketplace. However, they are not known as capital-rich entities. All these aspects make a wide industrial application of a relatively little known biosorption process quite a challenge no matter how well its performance may look from the R&D angle.

Key words: Biosorption technology. Metal removal. Environmental enterprise. Metal recovery. Biosorbent materials. Acid mine drainage.

INTRODUCTION

Heavy metals (e.g. lead, copper, cadmium, zinc, chromium, etc.) are toxic even at low concentrations. As they are non-biodegradable, their threat is multiplied by their accumulation in the environment through the food chain. The detoxification of metal-bearing wastewater is a pressing environmental concern. All metal processing activities lose and/or discharge sometimes even large quantities of heavy metals. The development and implementation of cost-effective process for removal/recovery of metals is essential in order to improve the competitiveness of industrial processing operations and to minimize the environmental hazard of toxic metal-containing effluents.

The capacity of certain types of microbial and seaweed biomass to remove and concentrate heavy metals from solutions provides the basis for a cost-effective technology for detoxification of industrial effluents. New biosorbent materials can be extremely competitive and cost effective particularly in this application. Further work with biosorbents identified for their high metal uptake could best be directed to derivation of engineering process scale-up parameters for application in the clean-up of two most ubiquitous types of metal-contaminated industrial effluents: acid mine drainage (AMD) and electroplating effluents. The development and implementation of a cost-effective process for the removal and recovery of heavy metals is necessary on two fronts: first, to improve the competitiveness of mining (and electroplating) industries which constitute a major industrial sector of manufacturing economies; and second, to eliminate toxic metals from effluents as required by environmental regulations. Biosorption technology removes heavy metals from wastewater without creating hazardous sludges at costs much lower than conventionally used ion exchange systems. Regeneration of the biosorbent and concentration of the metal solution for eventual recovery further increase the cost effectiveness of the process.

High-sorbing biomass types have been discovered and their performance is now reasonably understood. Pilot sorption column tests should be carried out, based on earlier equilibrium metal uptake, to provide a basis for computerized process modeling of the biosorption system which is essential for effective optimization the metal removal process. Computer process simulations will then significantly reduce the scope of the necessary field tests. Development of the biosorption technology has reached the stage when it is ready for piloting with selected clients. Correspondingly, the technology is in the stage when pilot projects can be carried out to demonstrate the effectiveness of biosorbents as compared to synthetic resins for generally similar industrial applications. This line of activity should generate the necessary facts and application examples to convince and attract the technology venture equity partners, experienced consultants, biosorbent distributors and industrial clients for the process.

FEASIBILITY OF THE BIOSORPTION VENTURE

A brief outline of establishing an enterprise based on the biosorption technology will be discussed here. The feasibility of applying the biosorption process into wastewater purification would best be assessed based on a stage-wise approach. A considerable amount of research on biosorbent materials has developed a solid basis of knowledge and indicated their enormous potential. The highest priority at the early stage would be the preliminary and approximate assessment of the commercial potential and feasibility of application of the new technology based on the family of new biosorbent products. Correspondingly, the preliminary stage should consist of some basic studies:

A) Assessment of the competing technologies

The current costs and market share of the established conventional processes for metal removal/recovery from dilute solutions or wastewaters have to be summarized and assessed. Similarly for new unconventional and even new biosorbent-based processes which are approaching the stage of application in the field.

For cases when metal removal from contaminated industrial effluents is considered, the following process alternatives can be considered for a more detail evaluation and feasibility assessment:

- *Precipitation* by addition of appropriate chemicals, followed by conventional solid-liquid removal that could be by sedimentation, flotation, filtration, in extreme cases even by more expensive centrifugation. The metals are not that easy to recover from the resulting sludges that often eventually represent a serious disposal problem.
- *Reverse osmosis* is a membrane-based process that is very effective for removal of ionic species from solution. However, the membranes are relatively expensive both to procure and to operate. The use of elevated pressures makes this technique costly and sensitive to operating conditions. The resulting concentrated by-product solutions make eventual recovery of metals more feasible as the case also is for the ion exchange process.
- *Ion Exchange* is a process very similar to biosorption whereby the latter is known to actually function predominantly on the basis of ion exchange. Ion exchange, however, uses mainly hydrocarbon-derived polymeric resins. The hydrocarbon basis of synthetic ion exchange materials makes them dependent on the price of crude oil.
- *Bio-reduction* of metals and their mineralization (turning them into natural deposits) is an attractive low-rate but cost-effective option as the knowledge and control of microbial activities involved lately significantly advanced. Large volumes of metal-contaminated water can be economically purified.

B) Assessment of the market size

While it is known that the environmentally-based market for metal removal/detoxification of metal-containing (industrial) effluents is enormous, the actual figures to support this generally prevailing perception would be most convincing although not essential for launching the Company enterprise. The ion exchange market is as well established as this technology itself. The manufacture and supply of ion exchange hydrocarbon-derived polymer-based resins is concentrated in the hands of a very few transnational giant chemical companies. Rohm & Haas, Dow Chemicals, Bayer, and only a few more are the ones that have monopolized the ion exchange market. While ion exchange resins are commodity chemicals, it is worth mentioning that the exact figures of the sales volume and value are rather difficult to get from usual information sources. These figures appear to be a key to assessing the potential market for biosorbents. A quantitative review of the potential clientele for the biosorption metal-removal process needs to be carried out for different countries where applications of biosorption technology would be considered.

Comparison of costs between the conventional and the new technology establish the feasibility of biosorbent applications and their competitiveness in the market place. As the application of biosorbent technology proves cheaper and more competitive it is anticipated that new applications, otherwise perhaps not feasible, will significantly increase the size of the current market and the scope of potential clients for biosorption technology.

C) Assessment of costs of new biosorbents

At this point it is not known what would be the real production costs of new biosorbent materials processed into suitably applicable granules. Approximate costs of different types of raw biomass need to be ascertained, as well as the costs of processing the biomass into applicable biosorbent materials maintaining their high sorption efficiency. This stage will require travel and fact finding efforts necessary to reliably establish the exact costs and conditions under which waste industrial biomass can be obtained from the large-size industrial operators. Similarly for the price of ocean-based biomass of selected marine algae which has to be collected from high seas or offshore areas.

Estimation of the costs of preprocessing and drying the raw biomass to prevent its degradation will have to be carried out for selected representative types of biomass available in large quantities. Preliminary technical work needs to be carried out on the processing necessary for biomass formulation into a biosorbent product suitable for process uses. It is anticipated that different raw biomass materials (algae, fungi, bacteria) will require different and specific treatment for their optimal formulation into finished ready-to-use products. This part would entail specifically planned small-scale laboratory work and preliminary optimization of the procedures involved resulting in an efficient biosorbent material.

Ideally, all these preliminary assessments (A, B, C) should be carried out simultaneously as part of a better quantitative estimation of the venture feasibility. They could also be carried out simultaneously with the technically oriented pilot-plant efforts.

While it is not within the framework of this text to discuss the conventional metal-removal techniques in more detail, it would suffice to say that as the emission standards tighten the common ones are becoming progressively more inadequate or prohibitively costly for use of wastewater treatment. Better and effective metal-removal technologies are invariably more costly and often just not feasible for that purpose. The search is on for efficient and particularly cost-effective remedies. Biosorption promises to fulfill the requirements. Its overall performance and process application modes justify a comparison with the ion exchange technology. In the comparison of ion exchange and biosorption processes:

- The same equipment (i.e. pipes, columns, etc.) can be used with both (a given treatment installation can be interchangeably used with both types of sorbents).
- According to all estimates, biosorbents can be at least an order of magnitude cheaper (1/10).
- Only a shorter life cycle can be assumed for biosorbents.

These assumptions lead to considering the low cost of the biosorbent as the primary significant difference factor between the biosorption and ion exchange processes. For this reason, the study of the biomass sources and costs are particularly important and will allow a measurement of the economic performance of the process.

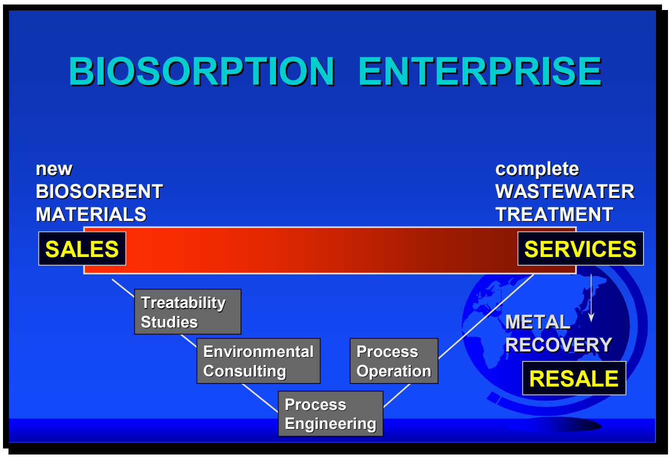

Figure 1
The enterprise based on biosorption can span a broad range or a selected specific part of it.

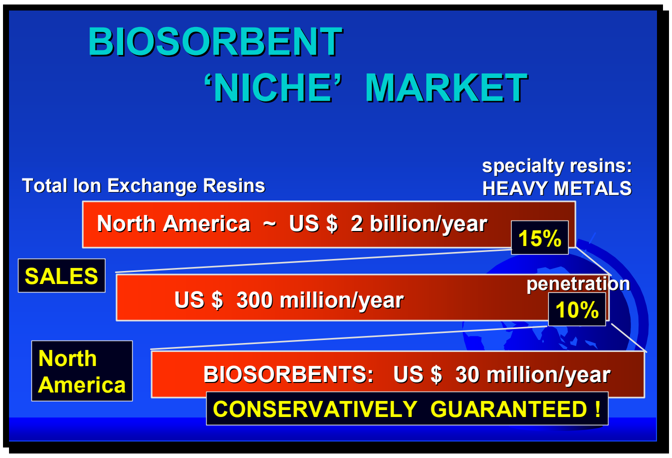

Figure 2
A conservative estimate for a biosorption enterprise niche market.

Obviously, it is no small feat to develop a business venture along these broad lines. This is perhaps why the commercialization of biosorption technology has been so relatively slow and painful for those few who attempted it. However, the potential is undoubtedly there. While the same equipment (i.e. piping, columns, etc.) can be used with both biosorption and ion exchange, a treatment installation can be interchangeably used with both sorbents.

It is perhaps worthwhile mentioning that some sources put current established ion exchange resin sales on the order of perhaps 2 billion US dollars per year in North America alone. While ion exchange resins are considered a commodity on the market, the actual sales figures are not reliably available. World-wide sales are perhaps approximately quadruple the figure for North America. However, only about 15% of the total ionex resin sales are for the specialty uses such as heavy metal removal. Considering that only 10% of that specialty-use volume could be 'penetrated' by (cheaper !) biosorbents, one is looking at the most conservatively estimated immediate and existing market for new biosorbent materials in the order of at least 30 million US dollars only in North America.

Huge markets already exist for cheap biosorbents. Electroplating and metal finishing operations, mining and ore processing operations, smelters, tanneries and printed circuit board manufacturers are a few of the industries in which metal bearing effluents pose a problem. All together, more than a thousand tons of heavy metal is released into Canadian waters by polluting industries in the area of Fabricated Metal Products Industry alone.

The potential application for biosorption appears to be enormous. While the high cost of the ion exchange process limits its application (as demonstrated by the huge amount of untreated effluents still released), the cost advantage of biosorption technology would guarantee a strong penetration of the large market of heavy metal polluting industries. It can easily be envisaged that cheaper biosorbents would open up new, particularly environmental, markets so far non-accessible to ion exchange resins because of their excessive costs which make them prohibitive for clean-up operation applications.

These considerations clearly demonstrate the economic feasibility and potential of the biosorption process for heavy metal removal/recovery purposes. It should be pointed out that there is a potential added benefit of metal-recovery as an *additional source of revenue* generated by a water treatment that *must* be carried out anyway (from a regulatory and environmental point of view). This cost reduction applies to "cheap" metal as well as "expensive" metal no matter what the economic indices may be.

Techno-Economic Basis

The limits of ion exchange resins have, to a large degree, been reached and these products are considered a chemical commodity now. The growth rate of the ionex technology appears to have been a "flat" one already for quite some time. The price of ion exchange resins, that are hydrocarbon derivatives, is invariably linked to that of crude oil. Needless to say, crude oil is a finite resource and, in addition to that disadvantage, its price is also very much subject to the world trading stability.

The most compelling reasons for using biosorption technology, based on a renewable or waste raw materials, are that it is effective and inexpensive. That certainly guarantees the possibility of easily opening new markets. There is also an extremely high development potential associated with the new concept of biosorption. The main steps required prior to the actual launching of the biosorption technology venture could be identified as seen in Figure 3.

Identification of Potential Synergies and Partners

Relevant information has to be collected in order to develop and implement a strategy regarding potential synergies and partnership with players in suitable industrial sectors. Naturally, ion exchange manufacturers should watch the developing field of biosorption particularly closely as the new products could extend their own line. However, due mainly to their enormous size reflected in corporate decision-making, the cooperation of chemical multi-nationals controlling the ion exchange resin market is not easily forthcoming.

Figure 3
Technological, economic and organizational aspects need to be thoroughly developed.

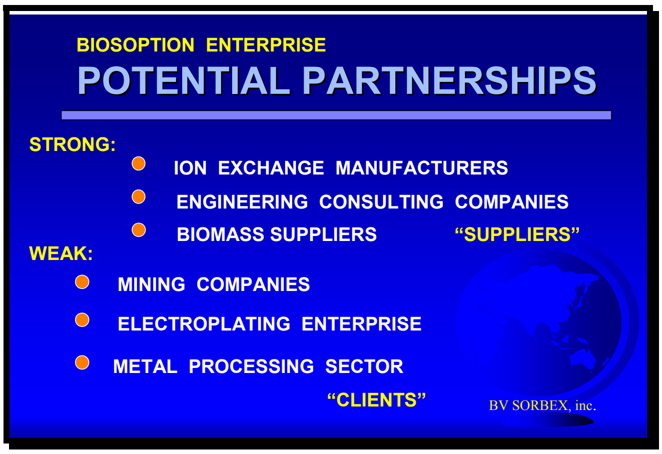

Figure 4
There are potential partners - and better ones …

Biosorption, as a direct competitor of ion exchange, is a tool that engineering *consulting companies* could use when designing wastewater treatment systems for their polluting clients. Biosorption would allow them to gain competitiveness by having a wider palette of remedial processes. Increased profits would stem from this kind of an enterprise not being restricted by how many times they 'sell' the process. Polluting customers would benefit from lower costs of buying the process. This goes quite contrary to the virtually 'possessive' nature of clients who are more often interested in having their problem solved - and in a proprietary manner.

The supply-side for suitable raw *biomass* represents a large new business opportunity and a good partnership chance.

The ease of operating a mobile biosorption pilot station is a very attractive feature that would facilitate testing of the process with various clients. While larger-scale pilot testing may be technically unnecessary, customers need to be reassured about the feasibility of deploying a 'new' system, all the more so as no previous record track for biosorption can be presented at this time.

Continuing and strong R&D work in the field of biosorption cannot be overestimated. Within this framework more effective engineering tools can also be developed for applying, scaling up and optimizing sorption processes in general.

FINANCIAL PROJECTIONS

Detailed financial projections with several alternatives for Company growth could be made as summarized here. A summary of these projections with some illustrative diagrams is presented in this section.

FINANCING 1: The Company will likely require two infusions of capital; a first one to assist the Company development for approximately 3 years. Following this period of Company's aggressive entry into the three facets of the environmental market (engineering, equipment, products) a positive cash flow could be expected.

FINANCING 2: The consolidation of Company's efforts and manufacturing facilities at this point (approximately 3 years after the financed start-up) will require another round of financing that will propel the enterprise into an unlimited growth phase.

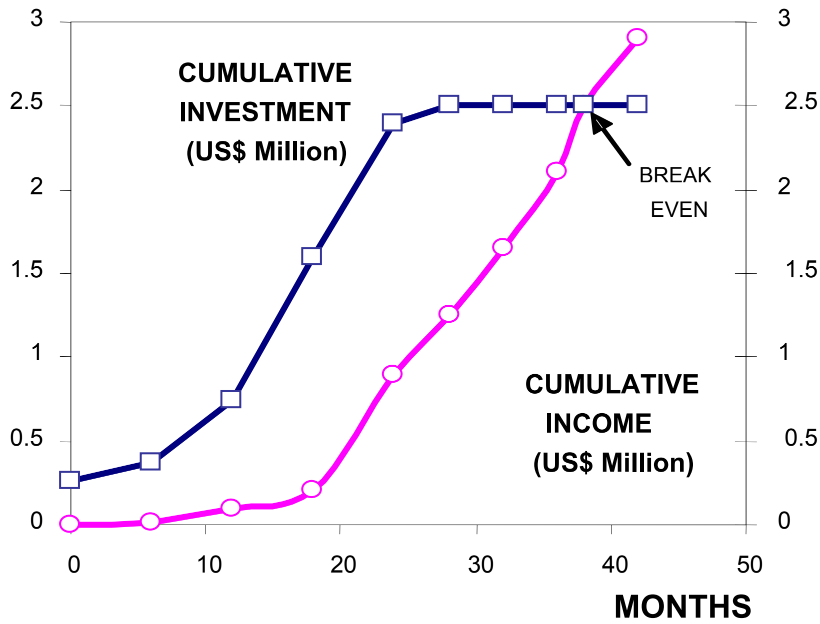

Figure 5. Income of the start-up Company during *Financing-1* phase follows the investment into the venture.

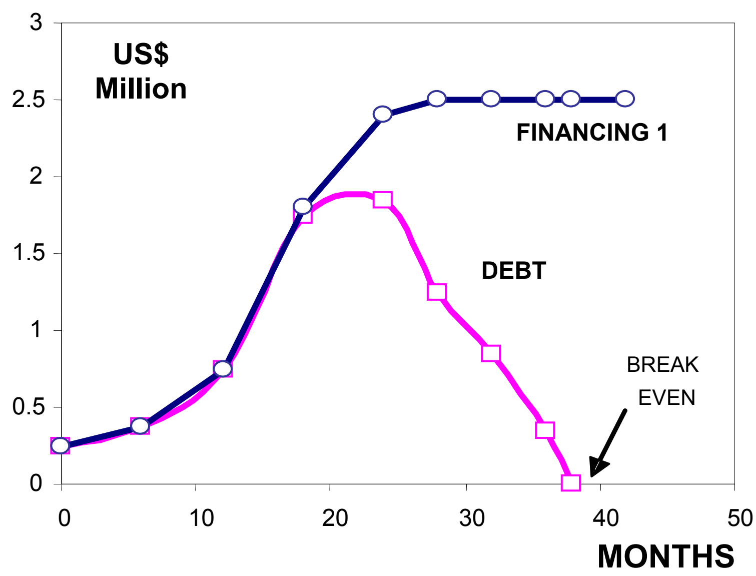

Figure 6. As the income is generated during *Financing-1* phase, the indebtedness of the start-up company diminishes.

RETURN ON INVESTMENT:

Revenues from early engineering services and later product and equipment sales are expected to bring the Company to the financial break even point in slightly more than 3 years. At that point the equity value of the well established enterprise is likely to represent a good value for the investment. Both biosorbents and sorption equipment are high-profit margin products, on average 85% and 63%, respectively. The Company's financial projections call for net profit in approximately two years following the second round of financing. At that point, the net profit after taxes is projected to be about 25%. The projected return on stockholder's equity (after-tax) in that period is estimated at 40%.

Figures 5 and 6 show an example of what could reasonably be expected during the venture *Financing-1* phase considering the cumulative investment of US$ 2.5 million. The growth of revenues appears with some delay (Figure 5), eventually bringing slowly down the company "indebtedness" (Figure 6).

In the following Figure 7 it is seen what the income of the start-up biosorption venture would likely consist of.

The income of a start-up Company based on new biosorption technology would involve 3 aspects:

- new family of biosorbent products,
- equipment that could even be of a standard nature (sorption columns and accessories) and
- engineering services centered around wastewater treatment consulting, process equipment installation and operation.

Revenue generated by these 3 areas would most probably start flowing in at a reverse sequence than listed above – the engineering and consulting services likely leading up the list of earnings (Figure 7).

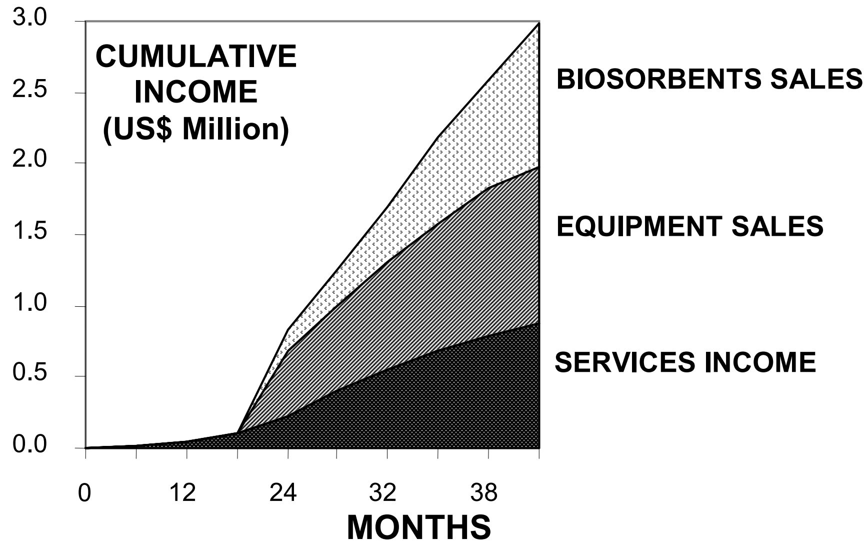

Figure 7. In the category of biosorption company income, water pollution control engineering services play an important and an early role.

BUSINESS BASIS: The financial projections have been based solely on sales in North America of the Company's marketable goods and service. Strategic business alliances should be forged to reinforce the Company's process engineering and marketing capabilities. Eventually, early entry to European markets as well as those of India, Japan, South America and China is possible, probably in that order of priority.

GOVERNMENT SUPPORT: Some unique government policies concerning particularly environmentally-oriented business ventures may enable unusual grant and financing schemes for new technology-based enterprises which offer 50-75% financing of new companies in the form of grants and additional schemes of generous loans, subsidies and tax breaks. Dynamic ventures qualifying for this unusual financial assistance can multiply any private investment by a factor of up to 2 to 4.

AMD - EXAMPLE OF A BIOSORPTION APPLICATION

Biosorption may be particularly well suited for AMD clean-up applications and is ready for demonstration tests. Extensive research and field work points at the biomass of seaweed *Sargassum* as the biosorbent of choice. To simulate the AMD liquid waste, the most usual heavy metals (Cu, Zn, Cd, Mn) adsorption was tested, in the presence of interfering elements (Al and Fe) at different pH values.

Treatment Outline

The treatment of AMD effluents vary, depending mainly on the Fe content.
In the worst case, four simple sequential stages may be required:

- STAGE 1: Adjustment to pH=5.0 and Fe precipitation
- STAGE 2: Fe removal by settling – some Cu and Zn will also be removed
- STAGE 3: **Biosorption** of residual Cu, Zn, etc.
- STAGE 4: pH adjustment

Due to the technological and the underlying process principles similarities between ion exchange and biosorption, heavy metals biosorption is most efficiently performed in fixed-bed continuous flow columns. Other choices of sorption system arrangements are mentioned in the following paragraphs. The pH adjustment(s) (Stage 1 and 4) would be carried out in stirred tanks with relatively short residence times of the fluid in the respective vessels.

STAGE 3:
The Fixed-Bed Biosorption of residual Cu, Zn, etc.

Biosorbent granules are tightly packed, however, allowing the metal-bearing stream to freely pass through the column (usually downward). Dissolved metals are gradually removed from the liquid phase which always meets fresher and fresher sorbent as it trickles down the bed. Effluent leaving the column contains extremely low residual metals in the range of 10-50 ppb, often undetectable. When the biosorbent in the column eventually becomes fully loaded and the effluent metal concentration at the exit starts gradually increasing, the column is shut down and the flow is diverted into a second stand-by fresh column (the break-through point). Saturated Column 1 is then appropriately processed (regenerated, washed) to prepare it for another run.

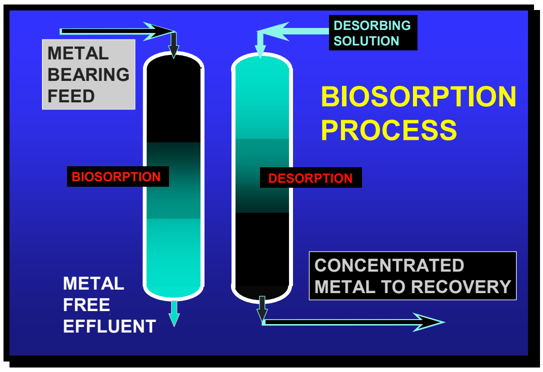

Figure 8
The fixed-bed sorption column system.

The sorption column systems can be available in a variety of sizes in order to accommodate a wide spectrum of flow requirements and process performances. Cylindrical sorption columns do not typically exceed 1.5 m in diameter and 5 m in height. Virtually unlimited scale-up of the process is accomplished by using batteries of multiple columns that work in parallel and/or in series to optimize the performance of the process.

Advantages:
- Most effective configuration
- Continuous-flow operation
- Virtually unlimited scale-up
- No solid/liquid separation
- In situ regeneration and washing

Disadvantages:
- Cannot handle suspensions
- Requires column alternation
- Scales up by multiplying units
- Sensitive to pressure drop
- Complex valve and pipe systems

The Fluidized Bed Column Sorption System

Biosorbent granules are fluidized in the column bed by upward flowing liquid. The main advantage of this arrangement is that the feed stream does not need to be completely particle free.

Advantages:
- Allows handling of (dilute) suspensions
- Gravity-separation of particles possible
- No preliminary solid/liquid separation pretreatment is necessary

Disadvantages:
- Increased reactor volume
- Power requirement for fluidization
- Sorption particle attrition and loss
- Less effective and more complicated sorbent regeneration

The major disadvantage of the fluidized bed system is that it cannot utilize the biosorbent charge to its maximum potential because its contents is being mixed. This way the sorption driving force of the metal concentration gradient between the solid and liquid phases is always lower and it is more difficult to achieve a well polished effluent. Portions of used-up saturated biosorbent could be removed from the column bottom while fresh biosorbent is added at the top. Clear treated effluent flows out the top where it is in contact with the relatively most fresh biosorbent.
The fluidized bed is more expanded taking up 30-40% more volume. The fluid bed contactor typically consists of a 3 m high cylindrical column filled to slightly more than half with biosorbent which then expands upon fluidization. Even very high flows (200,000 L/d) can be conveniently handled by such systems which can be modularly combined in parallel.

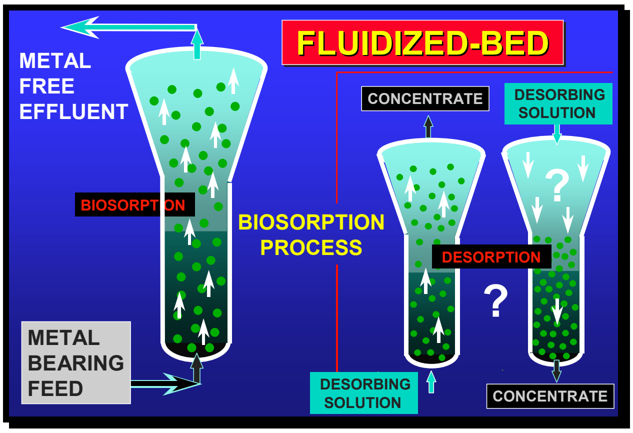

Figure 9. Fluidized-bed biosorption system does not utilize well the reactor volume.

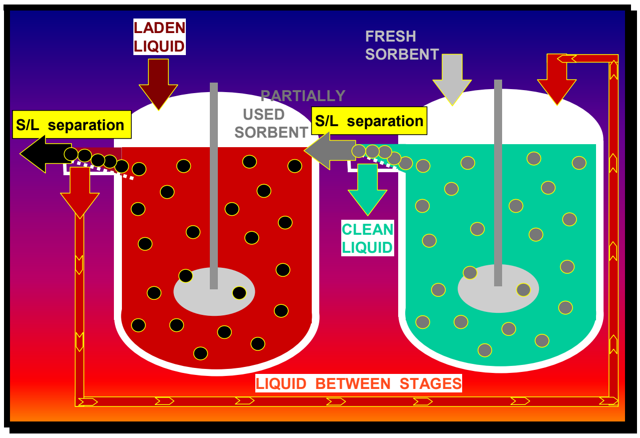

Figure 10. Counter-current sorption operation requires solid-liquid separation between stages.

The Completely Mixed Sorption System

In this type of a contact system the concentration gradient, important for effective sorption, is very diminished. In a one-stage system the concentration of the sorbate throughout the mixed contactor is the same as in its effluent. This type of a sorption system may be useful in the following cases:

- the effluent concentration is not of concern (metal recovery);
- the biosorbent is in a powder or granular form;
- there needs to be a solid/liquid separation step (e.g. a screen or filtration of the sorbent);
- several systems with intermittent solids concentration steps can be effectively operated in a counter-current series process arrangement.

The mixing in the sorption contactors is either mechanical or pneumatic. The sorption suspension has to be relatively dilute to allow mixing. Correspondingly, the volumes of contactor vessels are large. Mixed bed contactors are often utilized in series in order to handle the large volumes of inflow and to assure effluent standards. The number of stages and the residence time of the solution in each contactor is determined for the desired optimum performance of the system.

Different flow schemes of CSTRs (Continuous Stirred Tank Reactor) then may be utilized. Counter-current contact between the sorbate-laden liquid and the solid sorbent is more efficient. Fresh ‘hungry’ sorbent is fed where it meets the leanest liquid at the exit. Then the gradually more saturated sorbent proceeds through the stages of the process contacting richer and richer liquid. The sorbent leaves the process at the point of the most sorbate-rich liquid inlet. That way the sorbent leaves saturated at the highest sorbate concentration. In order to achieve the counter-currency of the operation (Figure 10) there has to be a solid-liquid separation between the stages which separates the solid sorbent stream flowing in one direction from the liquid which flows in the opposite direction (e.g. granular activated carbon in the ‘carbon-in-pulp’ extraction of gold from ore suspensions). While this type of operation requires suitable granulation of the solid sorbent, it allows working with slurry (pulp) instead of clear liquid.

The performance of a serial counter-current operating sorption scheme actually approaches that of the fixed-bed column as the number of its stages approaches infinity. While the completely mixed CSTR is on one extreme of the scale, the theoretical plug-flow reactor (fixed-bed plug-flow column) represents the other extreme, theoretically with no mixing whatsoever. Fluidized bed reactors are partially mixed and on the theoretical scale would be placed somewhere between the CSTR and the plug-flow fixed-bed column. These are all textbook considerations taught as reaction engineering fundamentals.

Effluent Quality

All metals targeted for removal/recovery (Cu, Zn. Cd, Mn) including Fe can be removed from the AMD effluent. Unlike some synthetic ion exchange resins, *Sargassum* biomass is rather insensitive to the alkaline and alkaline earth metals (K, Na, Mg and Ca) in waste water. Consequently, the concentration levels of these metals in the treated effluent will be only slightly lower than their respective concentrations in the original AMD.

Metal Concentrate Stream

The targeted metals, from the given effluent, can be removed and may be concentrated for the metals of interest. Due to the different affinities of the targeted metals toward the biomass, each metal can be singled out and concentrated. The degree of metal separation and concentration depends on the respective selectivity of the metal toward the biomass, on the elution technique employed, and the concentration of the elutant. Table 1 below displays the concentration factor, i.e., the factors by which the metal concentration is raised with respect to the concentration of incoming wastewater, for metals of interest.

Table 1. EXAMPLE: **Concentration of Metals by Biosorption** (*Sargassum* biosorbent) [1]
(Based on laboratory results: 1M HCl as elutant, 10 minute batch contact, no demage to biomass)

Metal (AMD)	**Concentration In** (mg/L)	**Elutant Concentrate** (mg/L)	**Concentration Factor**	**Resulting Effluent** (mg/L)
Cu	172	31,774	185	<0.05
Zn	549	35,899	65	<0.1
Cd	382	56,205	147	<0.05
Fe	2346	50,056	21	<0.5

CONCLUSION

As public awareness of the environmental impact of industrial activities increases, consequently placing greater pressure on governments and businesses to reduce pollution, more stringent environmental regulations are being enacted and enforced around the world. The increasing demand for more effective remedial technologies results in a huge window of opportunity for biosorption whose competitive advantage warrants its future success.

The initial information gathered in preliminary economic feasibility studies, leads to three main conclusions regarding the application of biosorption technology:

- viewed as a water treatment process (its currently considered primary function), biosorption allows significant cost savings in comparison with existing competing technology, i.e. ion exchange, its closest rival.
- in terms of its technical performance, operational qualities and chemical properties, the technology can be more effective in many cases than its closest rival, ion exchange. Moreover, there are indications that it also has low sensitivity to environmental and impurity factors, which make this technology widely usable.
- additional cost reduction results from the possible recovery of heavy metals. Costs savings are obviously reinforced by a higher market value of recovered metal and lower costs of biomass. The process is even economically viable for the recovery of metals as a stand-alone activity for more “expensive” metals (market price>$15/kg).

Finally, there is also the added benefit that the existing wastewater treatment facilities using ion exchange can be easily converted to the biosorption process with a good payback from savings produced by operating with an equally effective process using a more inexpensive sorbent material.

The enormous potential of application for biosorption and its strong economic and technical advantages open considerable market opportunities that can actually be quantified through a responsible market analysis.

ACKNOWLEDGEMENT

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