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AQUEOUS PROCESSING FOR ENVIRONMENTAL PROTECTION

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Environmental protection

Environmental Protection: Aqueous processing is already being embraced for environmental protection, because of numerous advantages. Moreover, it is highly likely that in the next few decades, aqueous processing will truly dominate the menu of possible technological approaches. Before discussing why aqueous processing offers such potential, and how much scope there is for aqueous processing for environmental protection, it is worth defining the term "environmental protection" in the context of this paper. In the broader sense, "environmental protection" includes regulatory policy, behavior modification, as well as technical activities. Only technical issues are discussed here. Ideally, this topic would be called "environmental engineering". However, this term has been appropriated for activities that react to problems, such as contaminated air and water. Clearly, the future will depend on proactive technologies that allow sustainable development and recycling of the earth's resources, with minimal impact to the overall system of the planet. "Green manufacturing" and "soft processing" are other terms used for this approach. It is here that aqueous processing has so much to offer.

Issues and Challenges: One of the greatest challenges in developing technologies for environmental protection is to adopt a rigorous systems approach, to allow the benefits and shortcomings of new processes to be compared quantitatively with those of existing processes. Much is unknown on the complex interplay between engineered processes and the natural environment, while the effects on organisms and ecosystems of long-term exposure to specific chemicals may only emerge after decades. Superimposed on this lack of information is the inherent difficulty in comparing dissimilar effects. Is it better to raise the level of trace metals in the groundwater below a leach residue storage pond, or to emit particulates into the air? When considering cleaning up contaminated sites, the environmental impact of generating energy, whether in internal combustion engines or in hydroelectric dams, is rarely considered. Yet for large scale projects, such as mines and mineral processing facilities, appreciable energy is needed. In the United States, contaminants are often taken from contaminated sites to a licensed management facility, specifically designed to contain the contaminant of concern. There are complex sociopolitical issues with the siting of such facilities, along with concerns over accidental release of the contaminant during transport. Finally, inadequacies are emerging in the cost/benefit analyses done when considering new technology for environmental protection. With current energy, commodity and land prices, there are many instances where by-product recovery from wastes, or recycling of complex scraps, appears less economic than discarding the waste or scrap. However, such analyses seldom consider *future* costs associated with waste disposal. Yet in the United States, companies and their successors are now being required to spend tens, sometimes hundreds of millions of dollars to remediate environmental damage caused by waste management practices that were perfectly legal when used decades ago. Had these future costs, and the associated legal costs, been anticipated when waste management practices were being developed, waste minimization, by-product recovery and recycling would have appeared more economic. This is particularly true when considering wastes that are classed as hazardous because of trace concentrations of metallic contaminants. Removing those contaminants and making them into useful products is unquestionably the soundest, and wisest strategy for the long term.

Potential and Limitations of Aqueous Processing: Given the current and future importance of environmental protection, there is clearly an urgent need for new or improved technologies for recycling, and waste treatment and minimization. There are undoubtedly many wastes for which physical separations and pyrometallurgical processes will be the most suitable. Nevertheless, aqueous processing offers enormous potential, that is relatively untapped at present. Some of this underutilization stems from the fact that hydrometallurgy is a relative newcomer to the arena of minerals/materials processing. In addition, however, the boundary conditions of the environmental protection problem are changing. Aqueous processing offers the potential of minimal air pollution and use of hazardous chemicals, modest energy utilization and unprecedented flexibility and suitability for local, small scale operation. Aqueous processing is suitable for both improving the environmental impact of existing minerals and materials production operations (environmentally protective aqueous processing) and for application well outside of the traditional materials processing arena (aqueous processing for environmental protection). However, it is essential to recognize the limitations of traditional hydrometallurgical processes. Many *do* cause air pollution, are energy intensive, and use hazardous materials. Traditional hydrometallurgical processes will, in general, require modification or replacement before they are optimal for environmental protection.

Modification of classical hydrometallurgical processes for environmental protection

Biomimetic approach: Not coincidently, our increasingly acute desire for environmental protection comes at a time where unbelievable advances in the life sciences are revealing the mechanisms involved in many biological processes. Fortunately, these advances provide insight and direction to our technological quest. Natural organisms and ecosystems are highly evolved for optimal function, adaptation to external circumstances and coexistence. There are some situations where biological processing methods are, indeed, highly attractive. In many others, however, biomimetic approaches promise huge advantages. This principle is explored below for a few cases; the reader will undoubtedly think of many more examples.

Leaching/solubilization: Most commercial hydrometallurgical processes were designed using the principle that faster is better, even at a significant equipment and operating cost. Autoclaves increased in prevalence, often using concentrated acids or bases, with attendant costs and equipment failures. The last twenty or so years have challenged this principle. Heap leaching now provides such outstanding performance for such modest capital and operating costs that it has revolutionized the gold and hydrometallurgical copper industries. For gold, biological pretreatment of sulfidic ores with chemoautotrophs offers many advantages over roasting or autoclaving. However, significant environmental pitfalls have emerged when toxic or aggressive lixiviants such as cyanide or sulfuric acid are used in heap leaching. Biological agents offer significant promise for replacing aggressive lixiviants. Whereas chemoautotrophic microorganisms have been used widely, far less attention has been paid to heterotrophs. Certainly the former are cheaper to use, since their metabolic substrate is the mineral to be oxidized, whereas heterotrophs require an organic substrate. But heterotrophs promise significant potential in a far wider range of applications than those for which chemoautotrophs are effective. Fermentation technology has long used these microorganisms to synthesize bulk chemicals such as organic acids. The metabolic pathways are well understood, along with how to modify these. Genetic engineering offers further possibilities, for example, allowing agricultural wastes or sewage to be used as substrates, or allowing the synthesis of unusual species. Much work is still needed, to devise new flowsheets and reactors that prevent poisoning of microorganisms, and allow appropriate solid/liquid separations. However, the incentive for this work is the promise of low-cost, environmentally acceptable lixiviants with unprecedented specificity for targeted species. Such reagents are also likely to gain broad acceptance in other industrial sectors, such as general degreasing and cleaning in the electronics industry, where they could replace solvents with known environmental problems.

Solution purification and separations: The single most important advantage of aqueous processing routes for environmental protection is the flexibility to separate different solutes from solutions, almost at will. Solvent extraction has been the workhorse for such separations, but the intrinsic solubility of solvent extraction reagents in aqueous solutions is likely to become increasingly problematic. Instead, as many of the engineering issues associated with ion exchange resins are resolved, these are likely to be used increasingly for both mineral and metal production, and environmental remediation applications. Many biological processes are now gaining acceptance for environmental remediation. Numerous organic materials, such as chitin, lignite, and rice straw have been found effective for removing metal contaminants from solutions, albeit with somewhat low and uncontrollable selectivities. Many microorganisms can remove metal ions from their environment with some degree of selectivity; reactive trenches containing sulfate-reducing bacteria are now being installed for polishing when remediating metal-contaminated sites. Wetlands are being used increasingly for environmental remediation. Looking to the future, there is significant promise if advanced separation methods such as supported liquid membranes are stabilized using films analogous to lipid bilayers or other semi-permeable biomimetic structures.

Product recovery, and crystallization and precipitation: In conventional hydrometallurgical processes, metals are recovered either by electroplating, or reductive precipitation, while other processes (such as the Bayer process) precipitate a metal-bearing compound. Developments continue with electrolysis, to reduce overvoltages, change the anode reactions, and improve mass transport to allow deposition from dilute solutions. All of these have environmental and economic benefits. Precipitation processes are increasingly being scrutinized to minimize environmental impacts. “Clean” oxidants and reducing agents (notably hydrogen peroxide and hydrogen, respectively) are being increasingly valued for their absence of extraneous, contaminating species. In addition, there are numerous technological and economic advantages, of which environmental acceptability is just one, in the increased use of aqueous processing for producing solid materials. Electro- and electroless-deposition of copper is being adopted widely in semiconductor manufacturing. Increased use of copper is likely to eventually improve our ability to recycle electronic scrap, although the diffusion barrier layers needed with copper metallization will complicate recycling. In the more distant future, microbially produced organic compounds are likely to be used in nanotechnology, for selective dissolution of nanostructured templates, as surfactants to modify the size and morphology of nanocrystals, and as the building blocks of biodegradable polymeric materials. Some bacteria themselves can abstract metal ions from solutions and create nanosized precipitates, while viruses are being explored as templates for the precipitation of nanoparticles.

Conclusions

This is an exciting and rewarding time to be working in the area of aqueous processing. Far from being a mature, “sunset” field, where most of the developments have been made, there is enormous potential to modify and expand the field to improve the environmental acceptability of mineral and material processing, to produce “advanced” materials in an environmentally sustainable way, and to remediate existing environmental problems. Many challenges will have to be overcome, but the rewards more than justify the effort that will be needed to achieve these goals.