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CONTROLLED UNSTEADY STATE PROCESSES AND TECHNOLOGIES – AN OVERVIEW

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ABSTRACT

The mass of contaminants present in domestic and industrial wastewaters, in leachates, groundwaters, and in soils naturally varies with either time or space. These natural and sometimes severe variations are coupled with the uncertainties associated with direct exposure to the environment. In the face of such an unsteady-state behavior, facilities used for the removal of contaminants are often designed with the potentially unrealistic expectation that they can be operated as steady-state systems. Variations in the mass flow rate of individual contaminants may be captured as the forcing function in models used to define them. In controlled unsteady-state systems the impact of the forcing function is intensified rather than minimized and integrated into the design by manipulating the rate functions that determine how, when, and where the constituents, including the contaminants, are created and destroyed in the system. Since system layout and operation have a strong impact on the rate functions, a question that arises regarding controlled unsteady-state systems in general and the periodic operation of such systems in particular is: Can a forcing function defined by the mass flow rate of natural but irregular variations in individual contaminants be modified in periodically operated, controlled unsteady-state systems in such a way that improved performance will result? Alternatively, can any system be operated in such a manner that the uncertainties associated with waste load variations are made unimportant? In this paper, descriptions are provided that show how periodically operated, controlled unsteady state systems such as the Sequencing Batch Reactor (SBR) impose a diverse array of operating conditions and selective pressures and thus become versatile tools for the enrichment of specific consortia and induction of desired metabolic pathways. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd

KEYWORDS

Batch technology, controlled unsteady state systems, forcing function, periodic processes, Sequencing Batch Reactor, Sequencing Batch Biofilm Reactor

CONCEPT

Contaminants present in domestic and industrial wastewaters, in leachates and groundwaters, and in soils, are characterized (with considerable redundancy and using virtually all possible combinations thereof) as either organic or inorganic, hazardous or nonhazardous, more or less dense in comparison to water, soluble or insoluble (sometimes as solids and other times as separate liquid phase emulsions) in water, volatile or nonvolatile, hydrophilic or hydrophobic, and biodegradable or nonbiodegradable. The mass of each contaminant naturally varies with either time (e.g., in a liquid stream, in part because of variations in the volumetric flow rate and, in part, because of how each is manufactured) or space (e.g., in a contaminated soil, in part because of how the soil was contaminated and later weathered and, in part, because of the heterogeneous nature of the soil's organic and mineral fractions). These natural and sometimes severe variations in the contaminants are coupled with the uncertainties associated with direct exposure to the environment.

In the face of such random change and potentially powerful unsteady-state behavior, facilities used for the removal of contaminants are often designed with the potentially unrealistic expectation that they can be operated as steady-state systems. The desire for steady-state operation is based on conventional wisdom that reasonably suggests that steady conditions are needed for effluent concentrations to be kept both constant and at permitted limits. Accordingly, engineers often design facilities that include components such as flow equalization tanks which dampen the impact of the system's unsteady character. Unfortunately, flow equalization is often not an effective method for equalizing variations in the mass flow rates. Such facilities, then, unwittingly become uncontrolled unsteady-state systems.

In truth, while the physical, chemical, and biological processes and operations in such uncontrolled unsteady-state systems often strain to meet steady-state demands, important but relatively simple effluent limits involving daily averages of surrogates such as biological oxygen demand and suspended solids are often met quite satisfactorily. Unfortunately, new limits for the removal of both nutrients and a multitude of specific hazardous compounds require the mitigation or elimination of uncertainties associated with natural variations in the contaminants and concomitant uncontrolled changes in biological catalyst. These new limits are not easily satisfied in uncontrolled unsteady state systems such as lagoons, trickling filters, or conventional, completely mixed, single tank activated sludge systems without selectors (Chudoba et al., 1973). Analysis by mathematical models that describe both controlled and uncontrolled unsteady-state processes and technologies provides insight into why controlled unsteady-state systems allow these new limits to be satisfied more readily.

Unsteady-state mass balances, an integral part of design models for wastewater treatment facilities (see, for example, Irvine and Ketchum, 1988), describe the unsteady behavior which results from natural variations in both the volumetric flow rate and the composition and concentration of the contaminants. Variations in the mass flow rate of individual contaminants are captured as the forcing function in the design model's differential equations. The forcing function describes the extent to which unsteady-state behavior should be expected in the system. In controlled unsteady-state systems the impact of the forcing function is intensified rather than minimized and integrated into the design by manipulating the rate functions that determine how, when, and where the constituents, including the contaminants, are created and destroyed in the system.

Since system layout and operation have a strong impact on the rate functions, a question that arises regarding controlled unsteady-state systems in general and the periodic operation of such systems in particular is: Can a forcing function defined by the mass flow rate of natural but irregular variations in individual contaminants be modified in periodically operated, controlled unsteady-state systems in such a way that improved performance will result? Alternatively, can any system be operated in such a manner that the uncertainties associated with waste load variations are made unimportant? The purpose of this issue of the Journal *Water Science and Technology*, (Wilderer et al., 1997) and this overview paper in particular is to demonstrate how and why periodically operated, controlled unsteady-state systems do, indeed, improve reactor performance. Descriptions are provided that show how periodically operated, controlled unsteady state systems such as the Sequencing Batch Reactor (SBR) impose a diverse array of operating conditions and selective pressures and thus become versatile tools for the enrichment of specific consortia and induction of desired metabolic pathways. By adding the system's own periodicity or forcing function, potentially negative impact of those forcing functions associated with variations in contaminant type, contaminant concentration, and other environmental uncertainties, can be mitigated.

CONTROLLED UNSTEADY STATE PROCESSES

Biological treatment of polluted materials such as those found in wastewater, landfill leachate or contaminated soils requires the presence and activity of a wide variety of microorganisms, and the execution of a vast number of metabolic processes as well. Moreover, the microorganisms being employed in biological treatment plants are known to differ greatly in growth rate and yield. Synergistic as well as antagonistic relationships exist between the various organisms. Aerobic, anoxic, and anaerobic conditions are needed to achieve various treatment goals. Fortunately, engineers involved in the development of the activated sludge treatment technology intuitively found means to handle biological systems exposed to varying conditions. Some have used controlled unsteady-state systems and others uncontrolled systems. Scientific explanations for the reasons why specific operation control methods were successful have, however, only been given recently. The evolution of the theory of sludge bulking control is an excellent example of how basic knowledge was used to raise the level of design and operating practice.

In Figure 1, a typical process schematic of a continuous flow activated sludge system, depicts one of many possible controlled unsteady-state systems that are in use today. In this representation, the aeration basin is designed as a three reactor cascade which produces the stepwise decrease of the substrate concentration. The microorganisms recirculating in the system are exposed to high and low substrate concentrations on a periodic, short-term basis.

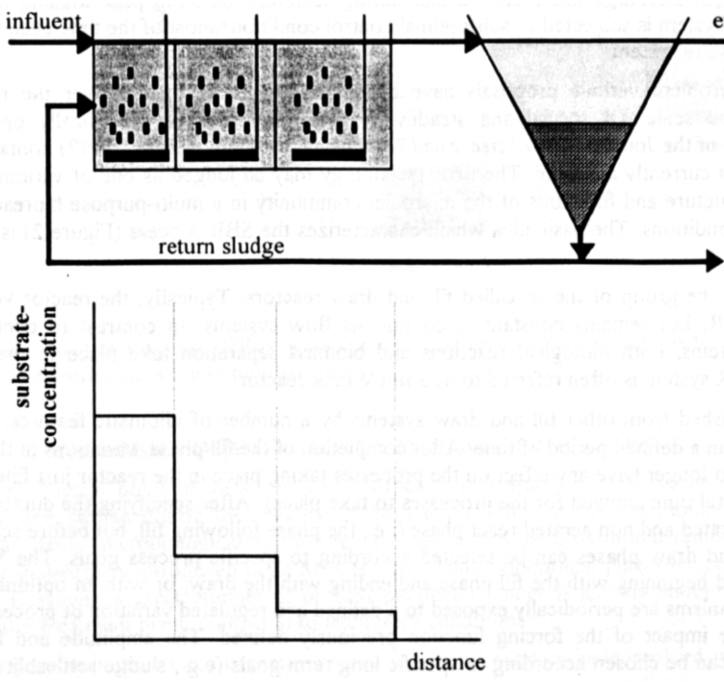

Figure 1. Process schematic of a continuous flow activated sludge system with the aeration basin designed as a reactor cascade (above), and the course of the substrate concentration developing with distance from the influent port of the cascade (below). It should be noticed that the micro-organisms recirulated in the system are frequently exposed to high and low substrate concentration

Accordingly, the growth rate in the first tank with the highest substrate concentration (the return sludge is directly blended with the raw wastewater in this tank) is notably greater than that in the last tank. Biomass, settled and recycled to the first tank, is subjected to repeated high growth rate and low growth rate environments (i.e., to alternating feast and famine conditions). Note that while normal variations in raw waste flow and concentration will force any real system into unsteady-state behavior, this is not a requirement for this controlled unsteady-state system. Even at steady-state the organisms are subjected to a repeated change in the growth rate environment, a necessary condition for a controlled unsteady-state system.

Chudoba et al. (1973), Chiesa (1982), Chiesa and Irvine (1985), Chiesa et al. (1985), and various other researchers demonstrated experimentally that frequent shifting of activated sludges between feast and famine conditions is a very effective means to control excess growth of filamentous organisms. Frequent shifting of activated sludges between aerobic, anoxic, and anaerobic zones allows establishment of microbial communities capable of executing nitrification, denitrification, and enhanced biological phosphate uptake. Frequent shifts of certain process conditions and the resulting unsteady-state obviously has significant and very important long term effects. It appears that short-term unsteady-state conditions, if properly selected and controlled, are an effective tool to maintain long-term quasi-steady-state conditions; that is, control of structure and function of the activated sludge system upon which the performance of such systems depends to such a great extent.

In practice, the factors known to be effective in controlling the structure and function of microbial aggregates (e.g., activated sludges, biofilms) are difficult to maintain in continuous flow systems In such cases, the growth rate differentials needed to mitigate the impact of the forcing function"associated with the mass flow rate of the contaminants are not sufficiently strong. The frequency and amplitude of the changes needed to control variations in the rate functions can not be implemented because the reactor is designed for maximum influent loading so that discharge limits can be met during seldomly occurring peak loading periods. As a result, the biological system is subjected to sub-optimal control conditions most of the time even though it is a controlled unsteady-state system.

To overcome this problem various proposals have been made and investigated over the past years in laboratory and in full scale. Of special and steadily growing interest were periodically operated batch processes. This issue of the Journal *Water Science and Technology* (Wilderer et al., 1997) contains examples of batch technologies currently available. The SBR technology may be judged as one of various methods to gain control over structure and functions of the microbial community in a multi-purpose bioreactor exposed to varying influent conditions. The basic idea which characterizes the SBR process (Figure 2) is described in this paper.

The SBR belongs to the group of the so called fill and draw reactors. Typically, the reactor volume varies with time in the SBR, but remains constant in continuous flow systems. In contrast to continuous flow activated sludge systems, both biological reactions and biomass separation take place in the same tank. Accordingly, the SBR system is often referred to as a single tank reactor.

The SBR is distinguished from other fill and draw systems by a number of idiomatic features. The SBR is filled and drawn within a defined period of time. After completion of the fill phase, variations in the influent of the treatment plant no longer have any effect on the processes taking place in the reactor just filled (except to limit or extend the total time allowed for the processes to take place). After specifying the duration of the fill phase, time of the aerated and non aerated react phase (i.e., the phase following fill, but before settle), and the time for the settle and draw phases can be selected according to specific process goals. The SBR cycle is continuously repeated beginning with the fill phase and ending with the draw, or with an optional idle phase. By this the microorganisms are periodically exposed to a defined and regulated variation of process conditions that can mitigate the impact of the forcing function previously defined. The amplitude and frequency of system's periodicity can be chosen according to specific long term goals (e.g., sludge settleablity, size of the population of nitrifiers, denitrifiers, Bio-P-bacteria, etc.).

The activated sludge reactors developed by Ardern and Lockett (1914) were operated according to the principles of SBR technology. Systematic research on SBR technology began in 1971 (Irvine and Davis) more or less simultaneously to the development of other versions of batch processes (e.g., Goronszy, 1979). For various reasons, the acronym SBR became a synonym of a wide variety of batch processes. Unfortunately, process schematics and performance for various batch technologies are quite different than the SBR first described by Irvine and Davis (1971), and again by Irvine and Busch (1979) and Wilderer and Schroeder (1986). This issue of the Journal *Water Science and Technology* (Wilderer et al., 1997) will help getting a differentiated overview of the current state of batch technology.

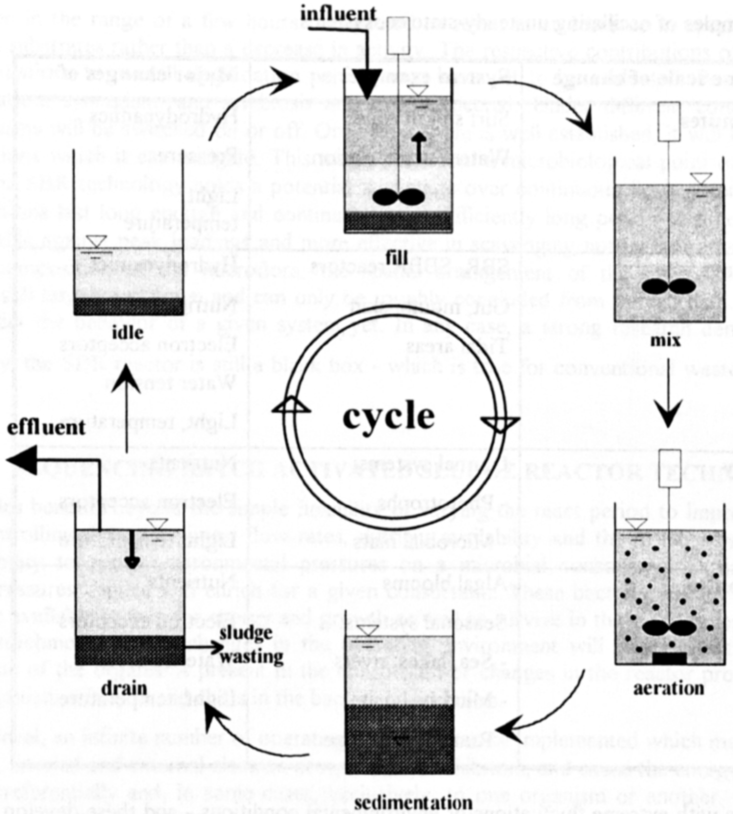

Figure 2. Schematic of a typical SBR process cycle with aerobic and anoxic phases to achieve nitrification and denitrification quasi-simultaneously.

MICROBIOLOGY OF UNSTEADY-STATE PROCESSES

From a microbiological point of view, the key characteristic features of SBR technology are the change between feast and famine during the reaction cycle and the different aerobic/anoxic/anaerobic conditions imposed. Considering microbiological approaches to achieve optimal growth and removal rates, suboptimal conditions are deliberately introduced in an SBR reactor. Thus, suboptimal performance should be expected, theoretically. However, a great number of process parameter values is already suboptimal in a continuous flow wastewater treatment plant, compared to laboratory conditions.

The interesting point is, that microorganisms living in natural habitats have evolved effective strategies to cope with suboptimal conditions during evolution. A selection of commonly oscillating parameters with which they have learned to cope include: i) Concentrations: electron donators (organics), electron acceptors (e.g., oxygen, nitrate, sulphate), including their ratios; phosphate, other salts, organic and inorganic particles; ii) Physico-chemical parameters: pH-value, redox potential; iii) Physical parameters: hydrodynamics, hydrostatic pressure, temperature, light; iv) Operational parameters: frequency (time scale) and amplitude (range) of changes. In nature, many systems work under oscillating conditions and perform very well (Table 1).

Naturally fluctuating systems, in which environmental parameters oscillate more or less regularly, work very well in terms of sustaining a rich, diverse and effective microbial population which can utilize even smallest amounts of nutrients and cope with changing conditions on various time levels. The duration of the switch-on and switch-off phases, however, differs profoundly. Some examples are given in Table 1. The time patterns can be extremely complex: Microbial mats in intertidal flats are exposed to short time, hourly, daily and

Table 1. Examples of oscillating unsteady-state ecosystems

Time scale of change	System examples	Major changes of
Minutes	Surf splash zone Waterline population	Hydrodynamics Pressure Light, temperature
Hours	SBR, SBBR reactors Gut, mouth, skin Tidal areas	Hydrodynamics Nutrients Electron acceptors Water tension Light, temperature
Day	Diurnal systems - Phototrophs - Microbial mats	Nutrients Electron acceptors Light, temperature
Months	Algal blooms Seasonal systems: - Sea, lakes, rivers - Microbial mats - Rumen, root zone	Nutrients Electron acceptors Water tension Light, temperature

seasonal changes with extreme fluctuations of environmental conditions - and these develop particularly well (Stal, 1994). A number of microbiological questions about the processes taking place in an SBR reactor still require further investigation. Some of these questions are elucidated on the background of the state of knowledge of microbial ecology:

How do the organisms interact (bacteria, fungi, algae, protozoa, metazoa) physiologically and genetically? The interactions between the different trophic levels are very complex and only scarcely investigated Positive interactions such as cooperation, synergism, and symbiosis are to be expected Under different conditions, different groups of organisms will be switched on or off. Once the system is well established, it is well probable that it will tolerate a certain range of oscillations which it can dampen. Predator-prey relationships will work as usual, i.e., self-regulating. Genetic exchange is expected to be facilitated, especially in biofilms

Which is the contribution of the free-living and the sessile population to overall degradation performance? It is quite likely that with high nutrient concentrations, free-living organisms will contribute much more to degradation, while under low nutrient conditions, biofilms and microbial aggregates will do most of the work

In biofilms: what is the impact on thickness, density, stability, morphology, architecture, production, and composition of extracellular polymer substances (EPS)? The most important influence will come from hydrodynamic conditions. It is likely that mechanically stable biofilms develop with a high proportion of filamentous organisms and dense EPS. The EPS production and composition will depend on the organisms present, on the growth phase, and on the C:N:P ratio. In many cases, nutrient depletion may lead to increased EPS formation, however, this is always at the expense of energy and carbon.

While knowledge of the composition of the overall population and of the microconsortia in biofilms under unsteady-state conditions is far from being understood, increased awareness has come through the use of in situ hybridization and confocal laser scanning microscopy. The interactions of the organisms are vast and complex. Not only bacteria but also fungi, protozoa, metazoa, and viral particles are involved - as well as abiotic matter such as clay, silt, humic substances, and organic debris. In general, the physiological answer to nutrient depletion in the range of a few hours is expected to result in an increase in uptake efficiency and range of utilized substrates rather than a decrease in activity. The respective contributions of free-living cells and biofilm populations to overall degradation performance have yet to be evaluated. Positive interactions such as cooperation, synergism, and symbiosis are to be expected. Under different conditions, different groups of organisms will be switched on or off. Once the system is well established, it will tolerate a certain range of oscillations which it can mitigate. This means that from a microbiological point of view, it can be explained that the SBR technology holds a potential advantage over continuous flow systems, provided the oscillating conditions last long enough and continue over a sufficiently long period of time. These systems may be more stable against peak loadings and more effective in scavenging nutrients in low concentrations. However, the composition of the microflora, the spatial arrangement of the microconsortia and their interactions are still largely unknown and can only be roughly concluded from overall data. It is simply not possible to predict the behavior of a given system yet. In any case, a strong research demand is obvious.

Microbiologically, the SBR reactor is still a black box - which is true for conventional wastewater treatment systems as well.

SEQUENCING BATCH ACTIVATED SLUDGE REACTOR TECHNOLOGY

The SBR provides benefits beyond the simple flexibility of varying the react period to improve contaminant removal. By controlling the cycle times, flow rates, nutrient availability and the availability of oxygen, the SBR has the ability to apply environmental pressures on a microbial consortium. During start-up, the environmental pressures applied will enrich for a given consortium. These bacteria will be those organisms which can utilize available carbon for energy and growth as well as survive in the environment created in the reactor. After enrichment, further changes in the operating environment will cause either changes in the physiological state of the organisms present in the consortium or changes in the reactor products as well as cause further organism selection and shifts in the bacterial population.

At the practical level, an infinite number of operating strategies can be implemented which manipulate growth rate differentials, internal and external electron acceptors, and inhibitors, and cause the energy or food source to be funneled preferentially and, in some cases, exclusively, to one organism or another. As a result, the periodicity imposed by the system's physical operation (i.e., the operating strategy or system's forcing function) can overwhelm or at least minimize the impact of variations in the rate of electron donor input to the system. In a very real sense, then, the designer can control the impact of an uncertain catalyst (i.e., the undefined mixed culture) and a randomly varying supply of raw materials (i.e., the raw waste constituents). This is a powerful notion because simple tricks such as minimizing energy supply during the fill phase (e.g., using either a non-mixed/non-aerated static fill or a mixed fill) can minimize much of the uncertainty that accompanies design.

A substantial increase of the initial substrate concentration is required to favor growth of floc forming organisms over filamentous organisms. Figure 3 was developed from SBR systems supplied with readily biodegradable substrates. As can be seen from this figure, filamentous organisms are discouraged in systems that have high growth rates (i.e., at elevated substrate concentrations) and prolonged starvation periods. As a general principle, organism selection depends upon a number of factors including the magnitude of the maximum growth rate achieved and the total time during which that rate was maintained, the magnitude and extent of starvation, and the frequency with which such feast and famine conditions occur. It should be noted the magnitude of the maximum growth needed to provide the desired selection depends upon the nutritive quality of the substrate supplied. As a result, the appropriate elevated substrate concentration needed could be appreciably different.

The treatment plant operator may choose from the following three strategies in order to develop high growth rate or feast conditions:

- introduce the wastewater into the SBR over a relatively short period of time (dump fill strategy),
- eliminate or reduce aeration and mixing during the fill phase (static fill strategy),
- increase the volumetric exchange ratio.

Strategies that are exactly opposite to those noted above may have to be implemented to avoid substrate inhibition for industrial wastewaters which contain high substrate levels. Indeed, anaerobically operated SBRs

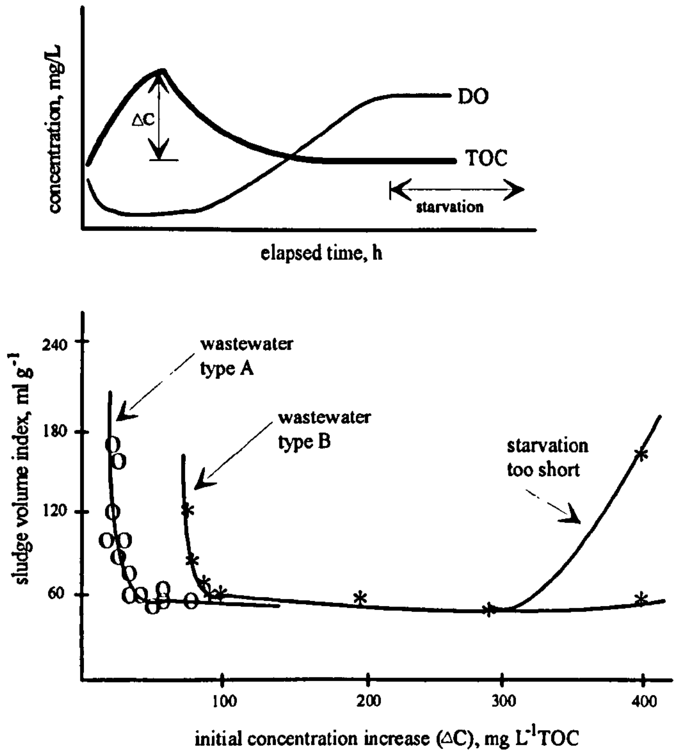

Figure 3. Effect of the increase of the initial substrate concentration (during the fill phase), and of the duration of the final starvation phase, on sludge settleablity, expressed in terms of Sludge Volume Index (SVI). It should be noticed that the required initial concentration increase (ΔC) and the required duration of the final starvation time depends greatly on the composition of the wastewater (Chiesa, 1982; Wilderer and Schroeder, 1986)

treating phenolic wastes and producing methane, developed granular-like sludge with excellent settling characteristics, when an extended rather than a short fill phase was employed (Ketchum and Earley, 1988). In aerobically-based SBRs, the magnitude and extent of starvation has an impact on the relative abundance of floc formers, and on the ability of these organisms to sythesize EPS needed to maintain flocs integrity EPS production including production of exo-enzymes is favored at the commencement of starvation Sludge settleability deteriorates, when the reaction time is too short, and the time for starvation is insufficient (Wilderer and Schroeder, 1986; Franta et al., 1994).

NOVEL APPLICATIONS

The concept of enforcing short term unsteady state conditions in order to control biological systems on the long run is applicable to activated sludge as well as to biofilm and soil slurry systems. It is applicable to aerobic and anaerobic treatment of wastewater. Over the past years, a wide variety of innovative batch treatment technologies have been described in literature. Common basis of these novel approaches is controlled application of sequences of process conditions. Common goal is control of the composition and activity of microbial communities.

Sequencing batch operation of a biofilm reactor was proposed by Wilderer (1992), and further investigated by Gonzales et al. (1990) in order to achieve enhanced biological phosphate removal in fixed bed reactors Kaballo et al. (1994) compared response of continuous flow and Sequencing Batch Biofilm (SBBR) reactors to peak loading. Break through events could be successfully avoided by temporary prolongation of the duration of the react phase.

Jaar et al. (1991), Kolb (1995) and Chozick and Irvine (1991) packed the reactor with granular activated carbon. By means of adsorption processes during the FILL phase the concentration of critical pollutants (e.g., volatile organics, inhibitory organic substances) could be decreased in the bulk liquid. During the REACT phase biodegradation and desorption became the dominant processes. The wastewater was effectively treated, and the activated carbon biologically regenerated.

The SBR has also been shown to be a cost effective and energy efficient means of removing hazardous organic compounds found in industrial wastes (Irvine and Ketchum, 1988), soils (Irvine et al., 1993a,b; Irvine and Cassidy, 1995), and leachates from landfills (Irvine et al., 1984; Herzbrun et al., 1985).

SUMMARY

In practice, most of the SBR plants consist of two or more identically operated tanks that provide for the time sequencing of operations such as equalization, biological conversions, sedimentation and clarification during a complete reactor cycle. Some periodic systems (e.g., those treating slurried soils) employ mixing and/or aeration to keep the microorganisms and other solids (e.g., soil) in suspension while the reactor is filling. Mixing and/or aeration are normally turned off to allow for clarification during a quiescent settle period in suspended growth systems (e.g., activated sludge). In this case a clear supernatant is withdrawn from the reactor and an active culture remains in the reactor for the beginning of the next cycle. A settle period is not necessary for a fixed film system and is often inappropriate for many slurry reactor systems because the resuspension of settled slurries may be difficult. In way of contrast, periodically operated in situ bioremediation systems utilize the ground as the reactor and involve the periodic addition of the amendments These batch oriented periodically operated systems maximize overall contaminant removal by allowing for a wide range of aerobic, anoxic, and anaerobic reactions to take place.

The direction of energy flow (i.e., the food source), so critical in the selection and enrichment of the final microbial consortium, must be determined experimentally. The data from such studies, then, can be interpreted and used to construct structured bacterial models that distinguish the physiological state of one member of the microbial consortium from another. Such factors as the impact of RNA content on both maximum growth rate and survival during starvation can be integrated into stoichiometric and kinetic models which would then better define how the system's forcing function can be used to mitigate the forcing functions defined by the variations in the mass flow rates of individual contaminants. These descriptions can then, for example, be used to explain how the same average specific growth rate and corresponding average solids residence time (SRT) can result in a wide range of settling rates simply by using growth rate differentials to shift the (net) supply of electron donors to either the filaments or to the floc formers and predicting net yield. The microbiological, biochemical, and mathematical challenges offered by a periodically operated, controlled unsteady-state system and the potentials of such systems to control a mixed culture system are impressively large.

REFERENCES

Ardern, E. and Lockett, W.T. (1914): Experiments on the Oxidation of Sewage without the Aid of Filters. *J.Soc.Chem.Ind.* **33**, 523-534

Chiesa, S.C. (1982): *Control and Growth of Filamentous Organisms in Activated Sludge Systems.* Ph.D. Dissertation, University of Notre Dame, Indiana, USA

Chiesa, S.C., Irvine, R.L., and Manning, J.F. Jr., (1985): Feast/Famine Growth Environments and Activated Sludge Population Selection. *Biotechn. and Bioeng.*, **27**, 562-568

Chiesa, S.C. and Irvine, R.L. (1985): Growth and Control of Filamentous Microbes in Activated Sludge: An Integrated Hypothesis, *Wat. Res.*, **19**, 471-479

Chozick, R. and Irvine, R. L. (1991): Preliminary Studies on the Granular Activated Carbon - Sequencing Batch Biofilm Reactor, *Env. Prog.*, **10**, 282-289

Chudoba, J., Grau, P. and Ottova, V. (1973): Control of Activated Sludge Filamentous Bulking II: Selection of Microorganisms by Means of a Selector. *Wat. Res.* **7**, 1384-1406

Franta, J., Wilderer, P.A., Miksch, K. and Sykora, V. (1994): Effects of Operation Conditions on Advanced COD Removal in Activated Sludge Systems. *Wat.Sci.Tech.* **29**(7), 189-192

Gonzales-Martinez, S. and P.A. Wilderer (1990): Phosphate Removal in a Biofilm Reactor. *Wat.Sci.Tech.*, **23**(7-9), 1405-1416

Goronszy, M.S. (1979): Intermittent Operation of the Extended Aeration Process for Small Systems *J. Water Pollut. Contr. Fed.*, **51**, 274-287

Herzbrun, P.A., Irvine, R.L., and Malinowski , K.C. (1985). Biological Treatment of Hazardous Wastes in the SBR. *J. Water Pollut. Contr. Fed.*, **57**, 1163-1167

Irvine, R.L. and Davis, W.B. (1971): Use of Sequencing Batch Reactors for Waste Treatment - CPC International, Corpus Christi, Texas. *Proc. of the 26th Ann. Purdue Indust. Waste Conf.*, **26**, 450-462.

Irvine, R.L. and Busch, A.W. (1979): Sequencing Batch Biological Reactors - An Overview. *J. Water Pollut. Contr. Fed.*, **51**, 235-243.

Irvine, R.L., Sojka, S.A., and Colaruotolo, J.F. (1984): Enhanced Biological Treatment of Leachates for Industrial Landfills. *Haz. Waste*, **1**, 123-135

Irvine, R.L. and Ketchum, L.H. Jr., (1988): Sequencing Batch Reactors for Biological Wastewater Treatment. *Crit. Revs. in Env. Contr.*, CRC Press, Inc., **18**, 255-294

Irvine, R.L., Earley, J.P., Kehrberger, G.J., and Delaney, B.T. (1993a): Bioremediation of Soils Contaminated with Bis-(2-ethylhexyl) Phthalate (BEHP) in a Soil Slurry-Sequencing Batch Reactor. *Env. Prog.*, **12**, 39-44

Irvine, R.L., Yocum , P.S., Earley, J.P., and Chozick, R. (1993b): Periodic Processes for In Situ and On-Site Bioremediation of Leachates and Soils. *Wat.Sci.Tech.*, **27** (7-8), 97-104

Irvine, R.L. and Cassidy, D.P. (1995): Periodically Operated Bioreactors for the Treatment of Soils and Leachates. In: *Biological Unit Processes for the Treatment of Soils and Leachates* (Hinchee, R.B et al., eds). Battelle Press, Columbus, OH, 289-298

Jaar, M. A. (1991), *Biologische Regeneration schadstoffbeladener Aktivkohle am Beispiel der Modellsubstanzen 3-Chlorbenzoesaure und Thioglykols%oure*, Dissertation, Hamb. Berichte zur Siedlungswasserwirtschaft, TU Hamburg-Harburg, 9

Ketchum, Jr., L.H. and Earley, J.P. (1988): Anaerobic Sequencing Batch Reactor Treatment of Coal Conversion Wastewaters. In: *Anaerobic Treatment of Industrial Wastewaters* (Torpy, M.F. ed) Noyes Data Corp., Park Ridge, NJ, 90

Kaballo, H.-P., Rehbein, V., Zhao, Y. und Wilderer, P.A. (1994). Das Sequencing-Batch-Biofilm-Reactor (SBBR)-Verfahren. *awt Abwassertechnik Abfalltechnik und Recycling*, **2**/94, 49-54

Kolb, F.R. and Wilderer, P.A. (1995): Activated Carbon Membrane Biofilm Reactor for the Degradation of Volatile Organic Pollutants. *Wat.Sci.Tech.* **31** (1), 205-213

Stal, L.J. (1994): Microbial Mats in Costal Environments. In: *Microbial Mats*, Stal, L.J. and Caumette, P. (Eds). NATO ASI Der. 35, Sringer, Berlin, 21-32

Wilderer, P.A. (1992). Sequencing batch biofilm reactor technology. In: *Harnessing Biotechnology for the 21st Century*, Ladisch, M.R. and Bose, A. (Eds.). American Chemical Society, 475-479

Wilderer, P.A. and Schroeder, E.D. (1986): *Anwendung des Sequencing Batch Reactor (SBR)-Verfahrens zur biologischen Abwasserreinigung*. Hamb. Berichte zur Siedlungswasserwirtschaft, TU Hamburg-Harburg, 4

Wilderer, P.A., Irvine, R.L. and Doellerer, J. (eds). (1997): *Sequencing Batch Reactor Technology - Batch Application of Periodic Processes. Wat. Sci. Tech.* **35** (1)