The future of environmental engineering: research concepts and conclusions

● To conclude this series of three articles on the future of environmental engineering, **REZA IRANPOUR, JUDY WILSON, BOB BIRK, YJ SHAW, MICHAEL STENSTROM, DAVID MILLER** and **MANOCHEHR VOSSOUGHI** look at some of the most promising technologies emerging from the research world and provide some overall conclusions.

The first two articles in this series of three illustrated the many opportunities that exist for research into new technologies for waste disposal and resource recovery. This concluding article presents several of the available options, including some that have already undergone substantial development but are not yet widely used, and new possibilities which have not been substantially developed or have not been attempted.

Several technologies which are not yet standard practice in wastewater treatment are nonetheless being increasingly widely applied, and it is likely that they will become standard practice in certain applications. One example is membrane filtration, one form of which - reverse osmosis - is already the most widely used desalination technique around the world.

Despite its success in this field, reverse osmosis requires very high pressures and therefore uses large amounts of energy. There are other applications in which the main aim is to remove particles much larger than salt ions, where a membrane filtration system with larger pores and lower pressures is preferable.

Depending on the pore size, these systems are variously classified as microfiltration, ultrafiltration or nanofiltration, with the boundaries between the different classes being somewhat arbitrary. The technology which has been most developed and most widely used is microfiltration, which has the largest pore size and requires the lowest pressures. The pores of microfiltration units are typically a few tenths of a micron to a few microns in diameter. This kind of unit can filter out nearly all particles contributing to turbidity, and those systems with submicron pore sizes also remove nearly all bacteria.

Although the microfiltration classification includes a range of pore sizes covering an order of magnitude or more, any particular membrane material is formed by chemical processes which control pore sizes within a very narrow range. Thus, for example, the material used in Memcor microfiltration units (*Memtec American Corporation, 1994*) has a nominal pore size of 0.2 microns, and the vast majority of the actual pores are between .195 and .205 microns. This means there is a relatively sharp boundary between the sizes of the particles that are passed and those that are removed by such a system, so if a system is designed with a pore size that will remove bacteria, then the designer can be confident that bacteria will indeed be removed unless the membrane is damaged (*Iranpour et al, 1998*)

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This kind of filtration unit can remove particles much more efficiently than conventional granular media filters such as sand beds, or multimedia filters with layers of other material such as anthracite coal or garnet. It is therefore expected that microfiltration will replace bed filters in water reclamation plants in the relatively near future (*Stenstrom, 1997*).

Microfiltration has also been used for water purification in some small systems. For example, families living at the pumping stations along the Colorado river aqueduct get water for all their household needs from small units that extract water from the aqueduct, microfilter it and chlorinate it (*Kostelecky et al, 1995*). It is possible that microfiltration will be used more widely for water purification in future, since it removes not only bacteria but also other organisms such as Cryptosporidium and Giardia, which sometimes survive conventional treatment in municipal water systems. It also removes all other organisms, apart from viruses, which are killed by chlorination or exposure to ultraviolet light. This means using microfiltration can provide protection not only against known pathogens but also against many potentially harmful but currently unknown bacteria (*Iranpour et al, 1998*).

Microfiltration is also likely to find applications in wastewater treatment plants, where serious problems with fouling and clogging of monitoring instruments can occur. Instruments that test for dissolved substances in wastewater are scarcely affected or even unaffected by filters which remove suspended or insoluble particles. In addition ultraviolet disinfection systems, which are discussed in more detail below, may suffer biofouling problems which can be alleviated if the water to be disinfected is first microfiltered *(Iranpour et al, 1999)*.

Since reclaimed wastewater must be disinfected, most systems use chlorination and dechlorination equipment. However, for safety reasons it is now more common to chlorinate with NaOCl and dechlorinate with $NaHSO_3$, instead of using Cl_2 and SO_2. However, chlorination produces traces of

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toxic or carcinogenic VOCs which are not removed by dechlorination. Furthermore, the combination of NaOCl and $NaHSO_3$ is more expensive than using Cl_2 and SO_2. Because of these problems other disinfection methods have been investigated, and it has been found that disinfection using ultraviolet radiation is the most cost effective alternative (*Loge, et al 1996, Darby, et al 1993, Iranpour et al, 1997, Blatchley et al, 1995*).

UV light is strongly absorbed by DNA at wavelengths of approximately 250 to 270nm, causing adjacent thymine bases to link with each other in a way that interferes with DNA replication. It is, then, very convenient that mercury vapour lamps' strongest emissions are in this range. Low pressure lamps emit primarily at the 253.7nm wavelength, while medium pressure mercury vapour lamps emit over a range of wavelengths, mainly in the 250 to 270nm band.

Satisfactory disinfection of reclaimed wastewater has been achieved using both types of lamp arrays. Low pressure lamps are sensitive to the lamp temperature, and therefore to water temperature, and they are also subject to biofouling. But medium pressure lamps operate at such a high temperature that they work regardless of the water temperature, and since one medium pressure lamp produces as much light as hundreds of low pressure lamps, the irradiation sterilises all the organisms that come into contact with the UV unit (*Percy et al, 1994*). The costs of UV disinfection systems are comparable to those of NaOCl/$NaHSO_3$ systems, and the costs of high intensity medium pressure lamp systems are lower overall than those of low intensity lamps. Additionally, adequate UV irradiation is as effective as chlorination/dechlorination systems. For all these reasons, an increasing number of water reclamation plants are now using UV disinfection to make their water safe enough for beneficial reuse.

Since water reclamation is set to increase substantially in the future, it is likely that there will be an increasing number of UV disinfection systems in operation and that their capacities will increase. Because of the medium pressure lamp's much higher light output, these systems are much more compact than those using low pressure lamps. This means it will be possible to install these systems in plants with limited space. Since reclaimed wastewater will probably normally be sold to other agencies, water and wastewater agencies will be able to defray some of their costs by selling their reclaimed water.

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New possibilities

The systems discussed below are potential new techniques for reclaiming resources and removing or destroying the harmful components of a waste stream. The first two are applications of physical phenomena which cause indiscriminate breakdown of the materials to which they are applied. The next two are forms of controlled biodegradation. The last concerns a possible new source of energy which may become important to environmental engineers, although contributing to its development is likely to be outside the range of engineering laboratory research capabilities.

Plasma torch

A plasma torch is a device using an electric discharge to produce intense heat which breaks down wastes into very simple molecules, unlike incineration. In an incinerator, the lower combustion temperature means some of the complex molecules in wastes such as paper and plastics are not completely destroyed, but instead rearranged into toxic substances such as dioxins. The temperature in a plasma torch is so high that it breaks down all complex molecules.

The use of plasma torches for waste disposal arises from the earlier application of plasma torches for industrial processes such as applying refractory coatings to machine parts which are exposed to very high temperatures - for instance, parts of jet engines. As waste substances are ordinarily not refractory, they decompose instead of melting. Research is still continuing to develop larger units which would be suitable for municipal use - the present units are only large enough for pilot tests. One evident problem which needs to be answered in future is the amount of electricity needed to produce the arc. It may be possible to offset this by recovering some heat from the exhaust, and some units also produce methane.

Pyrolysis

Pyrolysis is a general term for decomposition and restructuring of organic materials under heat when oxidation is prevented or incomplete (*Blumer, 1976*). The world's coal and petroleum deposits are the result of pyrolytic reactions in organic sediments buried millions of years ago. Under the name of 'destructive distillation', pyrolysis has been used for centuries to produce tar and related substances used as sealants and to provide resistance to decomposition. More recently, efforts have been made to pyrolyse waste materials into petroleum-like substances which could be used for fuel, but this has not been widely applied because the energy content of the fuel used for the pyrolysis has been similar to the energy content of the pyrolytic 'oil', so there is little if any energy advantage. The only way to gain an energy advantage would be to use a source of heat that does not consume fuel, such as solar heat or geothermal heat.

Considering fossil fuels are formed by heat underground, and that the rate of pyrolytic reactions is highly sensitive to temperature - so at a high enough temperature reactions may occur in minutes or seconds, instead of millions of years - this raises the possibility that the heat in geothermal cones may be sufficient to cause a pyrolytic reaction over a period of days, weeks or months. If this were true, then it would become possible to use geothermal heat where the heat flow has previously proved insufficient to enable its use in steam generation for power plants, which has been one of the main applications in the past (*Duffield, A, 1994*). Moreover, under these conditions a long reaction time could be tolerated, whereas if the reaction were being carried out using conventional chemical plant equipment this would not be so. The possibility of prolonged processing is also a reason for tentatively preferring geothermal heat to solar, because it would take a large investment to build a collector and reaction unit large enough to treat useful quantities of organic material.

Termites

Just as bacteria can be used to break down unwanted substances in the secondary treatment of wastewater, it may be possible to use termites to break down unwanted wood fibres, and substances made from wood fibres such as paper. Some 42% of all solid waste is paper, and there is an additional fraction composed of waste wood, such as wooden construction debris, and pallets used for storing or transporting cargo. This demonstrates that woody materials are a large fraction of the typical solid waste stream (*O'Leary, 1991*).

Paper recycling has been practised for a long time, but it has limitations. First, paper fibres can only be recycled a few times, and they are either used to make paper or cardboard of a lower quality than the material they were previously part of, or they are used in such small quantities that they do not perceptibly affect the quality of the material. At present, because of these limitations, the supply of recycled paper exceeds demand. Additionally, many types of waste wood are not suitable for processing into paper, so it would seem desirable to find another use for these woody materials rather than burning or burying them.

A controlled termite colony might be a desirable alternative, because the termite digestive process releases methane (*Zimmerman et al, 1982*) which could be collected and used for fuel, just as methane is collected from landfill sites. And the termites themselves might be a useful form of biomass - they could potentially be used as fertiliser, or as a source of protein for other organisms. This is highly speculative at the moment, for it is not currently known how many termites would be needed to consume a wood fibre waste stream of realistic size, which species would be the best, nor the culture conditions that would be needed for colony maintenance, methane collection and biomass harvesting. Nevertheless, considering the termite metabolism is a major means of achieving natural cellulose breakdown on the African continent, where earthworms are rare or absent in many areas, additional investigation of this possibility appears justified.

Accelerated degradation of VOCs

Recent experiments have demonstrated that bacterial cultures can be acclimatised to allow them to obtain their nutrition from VOCs which are normally toxic to them, and to human beings. The nature of the adaptation is not fully understood, but it has been observed in reliable experiments (*Naziruddin, et al, 1995*). This opens the possibility of using such bacteria to decompose VOCs that have previously been difficult to degrade safely.

This approach would differ from the related work in this field, in which the focus has been on identifying the particular strains of bacteria that degrade VOCs (*Pavlostathis, et al, 1997*). Forcing the evolution of a population of many strains of bacteria to achieve VOC degradation appears an easier and quicker approach. The previous experiments do, however, provided an outline for understanding what is happening, because they usually show that the bacteria which actually perform the degradation need other chemicals as nutrients or sources of energy. These would be provided by other strains of bacteria in the population using substances in the waste stream.

There are two possible applications which can be seen. One is to degrade the relatively high concentrations of these materials found in toxic waste sites or in disposal programmes for toxic materials such as military nerve gases. The other is to add aliquots of such cultures to wastewater as it enters primary or secondary treatment in an anoxic zone, if the bacteria are anaerobic, to degrade trace quantities of VOCs which could become health hazards to the public because of volatilisation in secondary treatment. Current tests of air emissions from aeration tanks indicate that some of these VOCs are emitted in quantities of several kilogrammes or even a few tonnes per year at large wastewater treatment plants (*Straub, 1995*). It is possible that acclimatised bacteria would enhance the degradation of these substances in a much more cost-effective way than alternative measures, such as enclosing aeration tanks and filtering the air.

A possible new source of energy

The research topics mentioned above involve studies which are closely enough related to previous waste disposal and resource recovery technologies that environmental engineers would be likely to investigate the possibilities themselves if the expected results seem sufficiently valuable. The following topic is outside the usual environmental engineering techniques, at least in its preliminary stages, but it may lead to developments that will soon find applications in certain areas of waste processing.

Readers may remember that in 1989 there was intense excitement when two chemists at the University of Utah, Stanley Pons and Martin Fleischmann, announced that they had found a way to cause a nuclear fusion reaction in pieces of palladium which had absorbed large amounts of deuterium from an electrolysis cell. They had been experimenting with these cells for several years, and they wanted to spend another year or more on the work, because they were still far from being able to produce large releases of heat reliably, or to show that it really was a nuclear reaction. Despite this, the University of Utah decided that their work should be announced so they would get credit for making an important discovery.

The result was intense criticism from scientists who said that such a reaction was impossible, and since the apparatus did not work reliably, nearly everyone has dismissed these claims as mistaken. Nevertheless, some scientists have continued to study this effect, which has been observed by a number of other researchers besides Pons and Fleischmann, and which had in fact first been observed 50 years or more before they began their work. Enough has now been learned about the reaction that theconditions under which it occurs and the reasons why the early experiments were not reliable are now partly understood. The nature of the reaction is still mysterious, because it appears to produce much more heat than any chemical reaction could, but it does not produce the energetic radiation commonly seen in nuclear reactions (*Goodstein, 1994*).

Since it is still so poorly understood, it has not yet been used to produce useful quantities of energy, although unlike the existing experiments with controlled nuclear fusion, which use large magnets or laser systems, successful experiments have produced more energy at temperatures below the boiling point of water than was supplied to the electrolysis cell (*Patterson, 1994*). This has now been accomplished with an increasing range of cell and cathode configurations (*Patterson, 1997; Patterson and Cravens, 1997*). A plausible explanation has also been formulated to explain how deuterons could approach each other closely enough to fuse (*Violante and De Ninno, et al, 1995, 1996*). Furthermore, a way has been found to greatly improve the reliability of the reaction in another type of cell by baking palladium samples at a relatively high temperature in compressed deuterium gas before they are used in electrolysis cells (*De Ninno, et al, 1996; De Marco et al, 1996*).

It appears, therefore, that enough has been learned to enable these cells to be developed into a useful technology for producing heat at temperatures around the boiling point of water in the next few years. This energy could be extremely cheap, because the cost of deuterium is very low compared to its energy content and, although palladium is expensive, only a small amount is needed. It may also be possible to use less expensive metals. However, it would probably be difficult to turn off the heat once the reaction is started, because the reaction appears to be self-sustaining until the deuterium absorbed in the metal has been depleted. This means the first uses are likely to be in applications where heat at modest temperatures is needed for long periods. Several aspects of sludge processing in many wastewater treatment plants are obvious examples of such applications (*Metcalf and Eddy, 1995*). Using these cells as heat sources would be another example of the point made earlier about using low temperature heat so that methane can be used elsewhere at higher temperatures.

Environmental engineering organisations and waste disposal agencies might therefore be early users of this technology if the results of current chemical and physical research are sufficiently successful. Moreover, this development would open up new opportunities for waste disposal and resource recovery, although this would mean that additional areas of environmental engineering research would be needed.

Eventually, the temperature at which the energy is produced is likely to rise, as the reaction is understood better, and then it would become useful for many more applications. A major new source of energy would bring many economic changes, and one can expect that these would include changes in the types of waste produced. Among other things, if it replaced much of the current fossil fuel consumption, CO_2 production would be reduced, which could reduce or reverse the present global warming trends. Although there are still many uncertainties about whether this research will produce a useful energy source, these results are a reminder that a situation that has changed little for a long time may not be static forever. There is an enormous future for environmental engineering research.

Conclusions

Many of the changes which can be predicted for environmental engineering in future imply that professionals in the field will have to make an even greater effort than they do now to keep up with new knowledge and changing practices. They will also have to be familiar with a wider range of disciplines, and many will have to deal with colleagues or collaborators from a wider range of fields. In many cases, resource recovery will involve more than merely designing an additional sewer or treatment plant. Finding markets for reclaimed materials and convincing the public to separate recyclable materials are two of the non technological aspects of resource recovery. Changing economic conditions, such as efforts to privatise municipal utilities, will also complicate efforts to make plans in future.

Under these conditions, the best way to apply technological knowledge to these changes is to investigate new technologies which can be used either to enable more reclamation of useful materials or for removal or rendering harmless the contaminants that make wastes undesirable. A number of examples of such possible areas of future research have been listed, but many others are certainly possible.

It is also certain that computers will play an increasing role in environmental engineering and resource recovery. Not only will they be used for established applications, such as design, modelling, and plant control, but environmental engineering organisations will follow other offices in becoming increasingly dependent on networked information systems. New forms of data display and support for design and construction continue to be introduced.

Energy use and recovery are important concerns both when looking at the efficiency of waste processing systems and for their global effects on the environment. The overall pattern of energy use has changed only modestly in the past several decades, and the most obvious way for environmental engineers to contribute to the energy supply is by increased recovery of methane and perhaps other fuels from biomass. However, there are new technologies that may eventually change the energy economy more radically, and it appears that the requirements of waste processing might be suited to early applications of these technologies.

It is also clear that the world population must eventually stop growing, or it will eventually outweigh the benefits of all innovations and improvements in resource recovery. However, since the effects of most improvements in waste processing are local, the world population is a less important consideration than the local population where a particular resource recovery system is operating or to be established. The distribution of waste processing and resource recovery systems in the world is extremely uneven. There are many places where even the most basic waste processing systems have not been introduced. The world's many needs for improvements in waste processing and resource recovery will provide a vast and increasing range of opportunities as well as challenges for environmental engineers.●

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