SCALE-UP PROBLEMS

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ABSTRACT

The paper considers some of the problems of the scale-up of wastewater treatment processes; from bench-scale to pilot-scale, and from pilot-scale to full-scale. An attempt is made to put the question of scale-up problems into perspective by reference to the experience of the author and the work of others reported in the literature.

KEYWORDS

Scale-up; pilot plant; wastewater treatment; chemical treatment; physical treatment; biological treatment; research techniques.

INTRODUCTION

In considering scale-up, the question must be asked; 'Scale-up of what to what?' The theme of the State-of-the-art sessions is declared as being to focus on extending research results to practice. Thus, this paper should consider the problems related to the practical applications of research work. But at what stage of research does one move from the academic to the practical? The scientist considers a problem theoretically and tries to solve it in his laboratory using the smallest 'test-tube' scale and the cheapest equipment possible. If his work looks promising he is likely to build bench-scale pilot-plant equipment in order more realistically to simulate the full-scale situation. At this stage, and always assuming that his work has been successful, he will have published his findings - unless they are commercially sensitive. If the findings meet a need, then practical operators will take them and apply them. Usually this application will first be on a larger pilot-scale at a site where a suitable raw material is available in an adequate volume. Sometimes, modifications are made to an existing full-scale plant to allow it to be operated experimentally. This second stage of development may, or may not, involve the original researcher. Finally, the process may be accepted as being valid and may be widely introduced on full-scale. Even then, it will be modified in the light of experience as operational problems are identified and overcome.
Thus, the whole process of developing a theoretical concept to an operational technique is one of gradual and progressive 'scaling-up'. Scaling-up problems inevitably will be met at every stage and often may create greater difficulties than those related directly to the 'chemistry' of the process.

Another important area is laboratory and pilot plant tests used as a precursor to full-scale plant design. This is often necessary for many reasons. Summarising Eckenfelder, Goodman and Englande (1972), the needs may be stated to be; comparison of alternative treatment technologies, determination of planning parameters and coefficients, and observing possible operational problems. They conclude with the important statement that; "Flexibility should be paramount in design to account for model limitations and uncertainties". In a similar vein Purchas (1977) states; "Equipment scale-up has two meanings, the one obvious, the other equally important but less apparent. Explicit is the acquisition and extrapolation of data from small-scale, to permit the sizing of equipment for large-scale operations. Implicit in such an extrapolation is a selection process, so that the extrapolation is only carried out if the large-scale equipment is likely to be suitable for the proposed duty. In other words, a test programme aimed at the acquisition of data for equipment scale-up must simultaneously permit qualitative judgements to be made on the likely performance characteristics of specific types of equipment under the proposed operating conditions".

Each of these points is valid, but there is another. It is probably implicit in the foregoing, but should be emphasised. Thus, pilot plant work is very often initiated to allow full-scale costs to be assessed, adding an economic dimension to technical requirements.

Some workers in the wastewater field express the opinion that scale-up problems can be resolved theoretically. For example, Horvath (1979) states that; "Relationshiops between processes in different scaled systems are determined by the theory of similarity ..... [and] though a total similarity cannot be reached, by approximate modelling satisfactory results can be achieved". However, the difficulty of developing the theory is demonstrated by Horvath himself who, in the same paper, reports that the outcome of seventeen years of work "may serve as a basis in the modelling of such [wastewater treatment] systems".

A very great many papers have been written on the mathematical simulation of scaleup. Some are abstruse, some are theoretically valid but practically worthless, most offer a valuable contribution to the understanding of processes and their scale-up. There is no intention of underestimating the value and importance of this sort of approach, but often it is necessary for those applying processes in practice to take a more empirical stand - although the empiricism will probably have been based on the more solidly-founded scientific research of others.

This paper will try to put the question of scale-up problems into perspective by reference to the experience of the author, and some relevant work reported in the literature. It does not, and could not, purport to be a comprehensive review and commentary on every aspect of the subject. For clarity of presentation, discussion will be under three headings - chemical, physical and biological treatment. It is appreciated that such apparently clear-cut divisions do not necessarily apply in practice. It is hoped that this approach will be seen to be logical.

CHEMICAL TREATMENT

Chemical treatment is often particularly amenable to scaling-up; chemical reactions that work in the laboratory can usually be made to work on full-scale.
Acids and alkalis neutralise, flocculants flocculate and precipitants precipitate, regardless of scale, providing the conditions of reaction remain the same. The difficulty is in ensuring that they do. Even if the reaction can be made to work, it may not work as efficiently and effectively as it should. Another difficulty is the varying nature of the feedstock. It may be that a particular chemical reaction will work under controlled laboratory conditions with a wastewater of known and understood characteristics, but it is very much less easy to ensure reliable operation when wide variations in feed characteristics are experienced on full-scale.

Given that these difficulties are understood, it is a question of overcoming them by undertaking a prudent development programme. Essentially, this means ensuring that the process is applied in such a way that it experiences the variations in flow and wastewater characteristics that it will meet in practice - not always an easy task.

If the chemical process can be shown to work effectively on a particular wastewater then the transition to full-scale is really a question of developing equipment - chemical mixers, dosing plant and reaction tanks or vessels for example. It is probable that suitable mixing and dosing equipment will be commercially available; then the only problem is in proper selection. Reaction units may be more of a problem. An example of this may be given from the author's experience in the simple and well-understood area of pH control. An industrial biological treatment plant was not functioning well although it was underloaded and mechanically sound. The cause was established as being poor pH control. Pilot plant work had shown pH control to be necessary and effective. Full-scale design had offered an inadequate mixing zone and hunting led to variations in controlled pH that resulted in process inefficiency. A simple example of a common scaling-up error.

A common use of chemicals in wastewater treatment is as sludge conditioners, with polyelectrolytes playing an increasingly principal role. Laboratory tests have been developed to judge the effectiveness of chemicals in conditioning sludges - specific resistance to filtration and capillary suction time are commonly used. But these tests only give an indication of the effectiveness of conditioning. The only reliable way to judge full-scale effectiveness is on full-scale. Even intermediate stages, such as the leaf filter are less than completely reliable. However, it is possible to compromise to produce data that is 'good enough'. An empirical approach to filtration scale-up is well demonstrated by Dahlstrom and Silverblatt (1977). Discussing continuous vacuum and pressure filtration they present scale-up factors to relate bench-scale data to full-scale operation; factors for scale-up of rate of filtration, scale-up of actual filtration area, and scale-up of cake discharge. Multiplying bench-scale filtration rate by each of these factors gives the final design filtration rate. A simple approach that would undoubtedly be rejected by the purist, but typical of the pragmatic 'reasonable estimates' so often used by those who put theory into practice.

Some manufacturers feel the need to go to the considerable expense of maintaining mobile test units for on-site trials. An example of the need for full-scale trials is given by sludge dewatering trials carried out at Banbury (Sidwick, Butler and Ruscombe-King, 1975). At that time there had been much less experience in Britain of centrifuges than there is today and it was decided to carry out comparative trials using five different mobile machines. Tests were also carried out using a filter belt press. The results of the trials demonstrated the particular suitability of two of the centrifuges to the Banbury application and generated data that allowed sludge treatment facilities to be designed and costed with more precision than would otherwise have been the case.
PHYSICAL TREATMENT

Probably the greatest single area of difficulty in the field of physical treatment is that of sedimentation. And sedimentation in one form or another is one of the most widely used techniques in the field of water and wastewater treatment. There is considerable debate as to the most efficient design of sedimentation tanks. To try to resolve these differences much experimental work has been undertaken. However, a full-scale sedimentation tank cannot be replicated on smallscale. This problem was high-lighted during the development of the Sewage Treatment Optimisation Model (STOM) by the Water Research Centre and CIRIA (1981) in the UK. The author was a member of the Steering Group and its primary sedimentation Working Party. During the Group's deliberations it became evident that sufficient data did not exist to allow the development of a valid equation to model primary sedimentation tank performance. An equation was developed and, as was expected, the STOM primary sedimentation module does not always generate data that accords with practical experience. The module is being refined, but only as a result of using data generated from a test programme using full-scale and very large pilot-scale sedimentation tanks. It is likely that two of the main problems in scale-up, or even in the translation of results from one full-scale tank to another, are wind effects and weir loadings (Price and Clements, 1974).

The difficulty with sedimentation tanks is important. A large proportion of experimental work involves sedimentation, whether the work be at bench or at larger pilot-scale. If the work is ultimately translated to full-scale, and if at fullscale the sedimentation tanks behave differently, then scale-up errors are likely to be introduced which can influence the efficiency of all the other treatment units.

Scale-up problems may also be created by peripheral factors such as pumping, mixing and aeration. For example, in the laboratory pumping is commonly achieved by airlifts or peristaltic pumps, mixing by magnetic stirrers, and aeration by porous diffusers. If these functions are undertaken on full-scale by, for example, highspeed centrifugal pumps, high-speed propeller mixers and direct-drive surface aerators different results may be demonstrated. Having said this, there are many physical treatment techniques that can be simulated accurately on small scale. An example of this is the work carried out at Wolverhampton (Joslin and Greene, 1970). This involved experimental sand filtration studies that were ultimately translated into a full-scale sand filtration plant that functioned almost exactly as had been predicted.

The thesis that experimental work must be designed with the end 'scaled-up' view in mind is supported by Bratby and Marais (1977) in the context of flotation. They state that dissolved air flotation experiments can be batch tests or undertaken on a continuous basis. They describe simple batch bench-scale tests, more sophisticated batch bench-scale tests, an unproven batch flotation column and a continuous test rig. They point out that the batch bench-scale equipment is valuable as a means of undertaking a preliminary 'culling', but that the continuous rig is necessary to simulate full-scale conditions. The problem with the continuous rig is that it is more complex and costly to construct and operate and must be mobile because of the need for relatively large volumes of feed. However, it is worth emphasising that the mobile rig flotation unit is only of 250mm dia and cost only £600 in the mid-seventies.

BIOLOGICAL TREATMENT

A vast range of experimental biological treatment has been carried out over the
years. As a result, considerable knowledge exists of the effectiveness of laboratory techniques and of larger pilot-scale units. However, problems remain and it would be less than prudent to claim an absolute understanding of full-scale effects on the basis of small-scale investigations. A very great deal can be achieved on a modest scale, but in reality design data acquired from studies using bench scale equipment (respirometers, pots, etc) is based on a combination of test results, process theory and experience with the extrapolation of test data to full-scale.

**Biological Filtration**

An interesting example of scale-up problems is given by the high-rate biological filter packed with ordered synthetic medium. When ICI were developing their Flocor medium they felt the need to determine its effectiveness on an experimental plant at Buckfastleigh - essentially a full-scale operational facility. This was a costly but sensible approach. Having demonstrated the validity of the process they were then faced with the need to study its effectiveness in the treatment of many different types of wastewater. To install pilot plants to generate the data needed to answer each enquiry would have been impracticable. So, the rolling-tube test was developed. No-one could suggest that this test directly parallels the high-rate filter, but it does simulate it and enables extrapolation of results with wastewaters whose behaviour on full-scale filters is known. However, if the characteristics of a wastewater are not known then pilot-scale filters must still be used. At one time very small filters were quite commonly used, but the experimental results were often not repeated on full-scale. One of the big problems was that as the cross-section of the filter reduced in area, the effect of the filter wall became progressively more significant; good distribution was also difficult to achieve. The author has used filters of 1m² cross section area with some success but would not do so for serious research. However, pilot plant scale can be reliable. A comparative pilot plant assessment of various natural and synthetic media was undertaken some years ago by Joslin and others (1971). The two full-scale plants resulting from it operate more-or-less as expected.

**Activated Sludge Treatment**

Conventional activated sludge processes are often scaled-up from quite small-scale units and even simple laboratory tests can generate data adequate for full-scale design providing the general waste characteristics are known. Much work has been carried out into scale-up effects. For example, Schmidtke and Horvath (1977) have demonstrated a relationship between surface-aerated reactors of approximately 5, 20, 113 and 6071 capacity. However, there remain areas of doubt. Stenstrom and Gilbert (1981) state that the scale-up of test equipment seems to affect dramatically the determination of alpha factors and that small scale laboratory equipment in general will not be representative of full-scale conditions. These authors also point to the difficulty of simulating the influence of changing oxygen transfer mechanisms in a rising bubble plume in a diffused air system.

The experimental work carried out at Rye Meads in the UK by the Water Research Centre into nitrification/denitrification in the activated sludge process is a good example of scaling-up from small to large scale (Cooper and others, 1977; Cooper, Collinson and Green, 1977). The basic experimental work was carried out in a benchscale activated sludge plant with four 12.5l aeration compartments. This plant was operated successfully and the process was translated to full-scale by the conversion of part of the Rye Meads activated sludge plant. The full-scale aeration volume was 3796m³. Even with this huge transition, the process worked
much as had been predicted, albeit that further experimental work on both large and small-scale was needed to refine it.

The author has reported another translation from pilot-scale to full-scale (Sidwick, 1978). Pilot-plant studies with a pharmaceutical waste resulted in the eventual design of a full-scale plant incorporating oil separation, pH control, flocculation, air-stripping, primary sedimentation, biological filtration, activated sludge treatment, sand filtration, activated carbon treatment and reverse osmosis; with aerobic digestion of SAS, thickening and mechanical dewatering. Final effluent is recycled to the factory for process re-use. The pre-design investigations were extensive but their outcome emphasises the difficulty of scale-up. From the paper; "It soon became apparent that the [full-scale] treatment plant was not achieving the standard for which it was designed...... effluent quality was generally poor and operation was difficult". This was because the forecasts of wastewater strength extrapolated from basic data were wrong - the effect of some new processes was underestimated - and in-factory control was poor. Steps were taken to improve matters in-factory but still the treatment plant had to be extended to achieve a good effluent quality. No-one should assume that extensive pilot-plant studies will necessarily lead to the 'perfect' full-scale plant.

The oxygen activated sludge (OAS) process is now well established internationally. Experience with OAS demonstrates an interesting aspect of scale-up. Some years ago OAS treatment was considered as an option for extensions to the municipal treatment works at Palmersford in England. This was innovatory because there were then no OAS plants in the UK. To examine the suitability of the process extensive tests were carried out using a mobile pilot plant. As a result of the test programme, and the subsequent process design and costing, OAS was selected. The full-scale plant was commissioned in 1977. The then newly-created Wessex Water Authority, together with the Water Research Centre, decided to use the plant as an experimental facility. The results of the experimental programme are well-documented (WRC and WWA, 1978 to 1981). Although the original pilot-scale work was well planned and competently undertaken the full-scale plant operated much better than expected. Scale-up factors clearly applied that were not understood when the pilot-plant data was being interpreted. The development of OAS in Britain demonstrates that the need for experimental work diminishes with an increasing knowledge of the process. The author is involved with another OAS plant that is about to be commissioned and the process design stage has been reached with two others. In none of these cases was pilot plant work judged to be necessary in view of the Palmersford experience and experience elsewhere with the types of wastewater to be treated.

Turning to the deep shaft process, the author was associated with ICI in the design and installation of the first deep shaft plant in the UK. Some of this experience has been summarised elsewhere (Staples and Sidwick, 1978). The current status of the deep shaft process demonstrates a major scale-up problem. Thus, the original work on the process was based on a combination of full-scale work on one sewage, and laboratory 'fermentation' studies on many other wastewaters. But extrapolation from laboratory scale to full scale was speculative and full-scale design was difficult. The process design of the full-scale plant was therefore conservative. The process design of deep shaft plants probably remains conservative because of limited operational experience. Of course, the deep shaft-process is a special case because of the relatively high cost of a pilot plant.

Fluidised beds are something of an innovation. There is no doubt that both aerobic and anaerobic fluidised bed treatment will be practised increasingly in the future. A great deal of work has been carried out on the experimental application of fluidised bed treatment. But, so far as the author is aware, nobody would
Scale-up problems

be willing to present a definitive design of a treatment scheme without recourse to large-scale pilot plant work. Thus, we again have the situation where laboratory-scale work alone is inadequate; and where extrapolation is only possible when it can be based upon considerable experience of similar treatment problems. An example of scale-up work with fluidised beds has been given by Hancher, Taylor and Napier (1979). They report extensive laboratory studies on the operation of a fluidised bed bioreactor for denitrification and conclude that the scale-up of a 5cm dia. reactor to 10cm dia. does not affect operational efficiency. On this basis the authors declare their intention to build a 20cm dia. experimental plant. But this really does emphasise the difficulty. If so much work is necessary to scale-up from 5cm dia. to 10cm dia. and then to extrapolate to 20cm, how much more work should be undertaken to move on to full-scale?

The question of anaerobic sludge digestion has been prominent in Britain of late. For many years it has been known that an acceptable degree of digestion could be achieved in the laboratory with retention periods as low as 8 or 9d; but few would accept that full-scale digesters should be designed to operate at less than, perhaps, 20d retention. It is now common practice to design for 15d retention; and 12d is becoming an increasingly acceptable concept. This change in thinking is mainly due to two factors - biodegradable synthetic detergents and improved mixing equipment. The latter is another 'scale-up problem'. Thus, good mixing was always possible in the laboratory, but even today full-scale mixing is less than totally effective. Were it possible to scale-up laboratory digesters directly, it would be possible to reduce digester size, and cost, by some 25-50%.

GENERAL

It would be wrong to discuss pilot-plant work without mentioning the UK Coleshill Project. This project was developed as part of the Advanced Wastewater Treatment Project of the NATO Committee on the Challenges of Modern Society. The plant has most recently been described and discussed by Banks and Butwell (1981). It was built between 1973 and 1978 primarily to examine the physico-chemical treatment of sewage. It employs the unusual, if not unique, concept of mobile treatment units that can be moved around the site to give different combinations of treatment processes. The original plant included facilities for flocculation, settlement, recarbonation, high-rate biological filtration, activated sludge treatment, sand filtration and activated carbon treatment. In 1979 the management of the plant was taken over by the WRC. Since then most of the work has been to take processes developed in the WRC laboratories and to operate them on a pseudo sewage works scale. In addition, development work is undertaken under contract to plant manufacturers. The original work demonstrated that PCT is generally uneconomic in the UK context. The outcome of subsequent studies is awaited, but the WRC are confident that the Coleshill plant offers them an invaluable tool for the scaling-up of processes developed on bench-scale.

Coleshill is, perhaps, the antithesis of the pilot plant concept. The facility offers the best of both worlds; a near-enough-full-scale plant with the experimental flexibility normally only offered at much smaller pilot scale. The interest of plant manufacturers in taking advantage of Coleshill to 'test-run' their equipment does, it may be thought, prove the point.

And one last example of the degree to which pilot-plant work can be taken. The author's firm designed and supervised the construction of a pilot sewage treatment plant in Hong Kong. The plant was commissioned in 1974 and operated experimentally from 1975 until 1977. The main works was designed to examine activated sludge treatment, high-rate biological filtration using natural medium and oxidation ponds and received the sewage from a population of 12,500. Thus, the units
were effectively full-sized although operational flexibility was considerable. In addition to the main stream activities smaller pilot units were used to examine high-rate biological filtration with synthetic media and OAS. The studies generated considerable basic data that has been valuable in the design of large new treatment works in Hong Kong. After the experimental period the plant continued to operate but in a non-experimental mode.

CONCLUSIONS

The author is aware that he might be accused of offering a paper that includes none of the complex mathematical scale-up formulae that are a part of the process designer's armament. So be it. He nails his standard to the 'State-of-the-art' concept; the erudite theory should rest with those presenting research papers.

So, to try to draw some conclusions on a wide-ranging topic;

- the researcher working at his bench to produce academic and theoretical explanations of why things happen can offer the key that will unlock the door of the more pragmatic,

- the bench-scale work of the researcher can often not be scaled-up with the reliability often implied,

- bench-scale plant usually needs to be developed into a reasonable pilot scale to simulate the full-scale; and then it doesn't always,

- in the final analysis nothing is as good as full-scale operation and, often, the interpretation of less-than-full-scale work is heavily influenced by full-scale operational experience,

- and, finally, the researcher generates the concepts that may, or may not, work in practice; the designer and the operator will see if they do and will learn much more about the mechanisms of the process thereby.

Scale-up problems can be considerable, but the blurred transition from bench-scale, to pilot-scale, to full-scale is inherent in the logical development of processes from academic aspiration to operational reality.

REFERENCES


