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*Solid/liquid separation  
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**Citation:** WAKEMAN, R.J. and TARLETON, E.S., 1991. Solid/liquid separation equipment simulation & design – an expert systems approach. *Filtration & Separation*, 28 (4), pp. 268-274

**Additional Information:**

- This article was published in the journal, *Filtration & Separation* [© Elsevier] and the definitive version is available at: [http://dx.doi.org/10.1016/0015-1882\(91\)80118-O](http://dx.doi.org/10.1016/0015-1882(91)80118-O)

**Metadata Record:** <https://dspace.lboro.ac.uk/2134/5357>

**Version:** Accepted for publication

**Publisher:** © Elsevier

Please cite the published version.

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## SOLID/LIQUID SEPARATION EQUIPMENT SIMULATION & DESIGN – AN EXPERT SYSTEMS APPROACH

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### ABSTRACT

Published texts on solid/liquid separation technology have allowed a limited amount of knowledge to be available widely, but none put forward the rules of thumb in such a manner that they are readily assimilable by the non-expert. There are many unpublished techniques and approaches. The computer technologist might target solid/liquid separation as a technology ripe for the application of expert systems. It is argued here that expert systems on their own are inadequate in this subject area, but the most effective software utilises a well-chosen mix of algorithm, graphics, expert system, and interactive input from the engineer. In this paper some examples are given of both public and private knowledge and an example of the application of the combined approach to equipment selection demonstrates that efficient software can save time and enable decisions to be made rapidly. Equipment selection using the p<sup>C</sup>-SELECT software is demonstrated.

### INTRODUCTION

Artificial intelligence has achieved considerable success in the development of expert systems which can now be found in many areas of technical endeavour<sup>1-7</sup>. The area of expert systems uses techniques such as rapid prototyping (an iterative method consisting of concept development, knowledge acquisition and implementation, testing and analysis), backward and forward chaining and knowledge representation through production rules, semantic networks and frames to construct man-machine systems with specialised problem solving expertise. Figure 1 illustrates in a general sense the components of an expert system; the knowledge base contains the factual and empirical knowledge of experts in the subject, the inference mechanism simulates the problem-solving strategy of a human expert and the explanatory interface determines how the expert system interacts with the user.

Expertise comprises knowledge about a particular topic, understanding of the problems in the topic, and skill at solving some of these problems. Knowledge in this sense is usually of two sorts, *public* and *private*. Public knowledge includes published definitions, facts and theories of which textbooks are typically composed. But expertise in a technical area usually involves rather more than just this public knowledge; human experts generally possess private knowledge that has not found its way into the published literature. This private knowledge may consist of unpublished techniques or approaches, or it may take the form of *rules of thumb* that have come to be called *heuristics*. Heuristics enable the human expert to make *educated guesses* when formalised or algorithmic solutions are difficult or impossible to determine, to recognise promising approaches to problems and to deal in the best practicable way with errors or incomplete data. Elucidating and reproducing such knowledge is a central task in designing an expert system. An expert system, therefore, is simply a computer system that achieves high levels of performance in tasks for which human beings would require years of special education, training or experience.

The ideas that underlie an approach to intelligent problem solving are common to most technologies. These are the same ideas that motivate and explain the primacy of knowledge in an expert system development. The design of a tool for building an expert system for use in solid/liquid separation

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involves such considerations as generality and completeness of both the available data and the ultimate software, programming language features and database structures and the control mechanisms that shape and restrict the representation of procedural knowledge within the system. Probably the most important feature of any expert system devised, is its ultimate practical success, expressed through its ease of use (or user friendliness) and the reliability and quality of the advice which it dispenses. This is infinitely more important than any system evaluation in the technical sense as perceived by the computer scientist, which would refer to optimisation of the hardware/software combinations. The ability of the software to give advice or educate the user in a congenial fashion and in the user's own terms is paramount, so that any psychological barriers to computer use are avoided.

## EXPERT SYSTEMS IN SOLID/LIQUID SEPARATIONS TECHNOLOGY

Filtration and separation technology contains numerous heuristics, which can be evidenced by consulting industrial reference books such as *Solid/Liquid Separation Equipment Scale-up*<sup>8</sup> or *Guide de la Séparation Liquide-Solide*<sup>9</sup>. A majority of industrial process engineers need to possess wide ranging knowledge covering many unit operations and different types of plant, and rarely have the opportunity to gain in-depth specialist knowledge of filtration and separation technology. Consequently the large number of heuristics that have evolved in the technology must be confusing and probably presents to the non-expert a picture of a technology in disarray. This is compounded by published textbooks which are frequently remarkably similar to previous ones in their technical content, few of which show the practical insight into the technology which is needed for better process design. Furthermore, these generally convey the impression that developments in the understanding and formulation of more rational and reliable approaches to such factors as equipment selection and design have stagnated since about 1930. In reality it is true that heuristics abound and it is recognised that expert knowledge is needed to carry out many practical tasks such as the selection of a particular type of solid/liquid separation equipment for a specific duty, or the choice of an appropriate filter medium for a particular application, or the scale up and sizing of industrial equipment, or the prediction of the effects of changes in process conditions in the plant upstream of the separator, and so on. It is also the case that better design methods exist in published literature, but all too often there is the problem that book authors have not assimilated what is available and they may not have a good enough grasp of either fundamental or of heuristic knowledge to advance the technology through the written medium. The filtration and separation technologist needs to have at his/her fingertips an unusually large amount of both public and private knowledge.

Solid/liquid separation technology, whether it be in the areas of selection or design, is best dealt with by software designed to run interactively, so that the engineer can input data and receive a result rapidly. The expert system can be used to ensure the correctness of input data as far as this is possible, and it can utilise interactive graphics facilities to show effects of changes in variables or to allow the engineer access to calculations to make value judgements where these are peripheral to the expert system. To be most effective the software must be a well-chosen mix of algorithm, expert system and input information from the engineer. The examples, chosen at random from solid/liquid separation technology, shown below illustrate how an expert systems approach could be adopted to provide the engineer with more reliable solutions to technical problems.

### The Effect of Pressure Difference in Filtration

It is a common assumption that an increase in pressure will improve the rate of filtration, the cake moisture content, or both.

#### *Public Knowledge*

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The above statement is public knowledge and is what all text books either infer or state explicitly; even in their discussions of compressible filtration. Sometimes additional qualitative descriptions can be found which try to convey what happens during filter cake formulation and growth. These generally follow the arguments:

- A large number of particles, normally of irregular shape, are forced together into a confined space on the surface of the filter medium
- The liquid which has transported the particles to the surface passes through the medium, leaving the particles on the medium as a cake or deposit
- In order to maintain an acceptable filtration rate it is essential that the solids do not form too tight a layer on the filter medium
- A preponderance of pore bridging must exist to ensure a permeable cake formation.

These qualitative statements may give the engineer a limited insight into some aspects of cake formation, but really are not informative about how detrimental effects can be avoided at higher filtration pressures. It is clear from these statements that to increase the filtration pressure is to encourage the formation of a tighter, less permeable cake, yet this is exactly what the engineer does not want to happen.

### *Private Knowledge*

The initial assumption is correct in so far as some improvement usually can be expected, however it is also true that when an increase is found it is never proportional to the increase in pressure. The pressure increase may even reduce the rate of filtration or have no effect whatsoever, but it will invariably increase the cost of operation. The expert will invoke heuristics into the assessment of the effects of increasing the filtration pressure and may consider several points including:

- The agglomerate or particle size distribution in the feed relative to the openness or pore sizes in the filter medium (if the particles are predominantly finer than the pore sizes it is likely that increasing the pressure will push the particles farther into the medium, thereby reducing its permeability and the filtration rate)
- The first layer of cake invariably determines the solids retention and so the expert will want to know how the pressure is applied (the filtration should be started with a low pressure differential which is gradually increased - an impressive initial filtration rate can rapidly deteriorate to a trickle or even stop altogether by increasing the pressure too rapidly or too much)
- The rate of pressure increase allowable is dependent on the solids concentration in the feed and the rate of build-up of cake thickness (a greater thickness of cake can usually withstand higher pressures without collapse or migration of the particles into the medium)
- At the end of the cake form part of the cycle a high pressure may be more beneficial. This technique is used in membrane presses for example.

The expert will weigh up and quantify the relative merits of such information and optimise the application of pressure.

### **Interpretation of Leaf Test Data**

The most common approach to filter sizing is by manipulation of data obtained from a leaf test or from small scale filtration equipment. The data is analysed to calculate a scale-up parameter, such as the filterability coefficient ( $F_K = A^2/K_1$ ) or the specific resistance of the filter cake ( $\alpha$ ).

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### Public Knowledge

The test is based on the simple equation used to describe the filtration process, which is

$$\frac{dV}{dt} = \frac{1}{K_1 V + K_2} \quad (1)$$

or for constant pressure filtration, the following integrated form can be used

$$\frac{t - t_i}{V - V_i} = \frac{K_1}{2}(V + V_i) + K_2 \quad (2)$$

where  $K_1 = \alpha c \mu / A^2 \Delta p$  and  $K_2 = \mu R / A \Delta p$ . That is, if either  $(dV/dt)^{-1}$  vs.  $V$  or  $(t - t_i)/(V - V_i)$  vs.  $(V + V_i)$  is plotted, a straight line should result, from which the scale-up parameter can be determined. The above procedures are documented in most textbooks and a typical plot of  $t/V$  vs.  $V$  is shown in Figure 2. (This implies that  $t_i = V_i = 0$ ).

### Private Knowledge

It is rare for either the  $(dV/dt)^{-1}$  vs.  $V$  or the  $t/V$  vs.  $V$  plot of the experimental data to form a true straight line and yet the reasons for this and interpretations of the data are not elucidated in texts. Whichever plot is used for subsequent analysis non-linearities often occur at the start of data collection and towards the end of the test. The forms of these are shown on Figure 2 and are marked as A, B and C.

At the start of filtration the cake is very thin; most of the total pressure drop is over the filter medium and the values of  $K_1$  and  $K_2$  are not truly constant, hence leading to non-linearity A in Figure 2. As the cake becomes thicker a larger proportion of the total pressure is lost over the cake and cake properties start to dominate over medium properties. Since the medium resistance parameter  $R$  is determined by extrapolation of the linear part of the graph to the ordinate, erroneous, sometimes negative, values can be obtained. These are of little use in further analyses. Penetration and embedding of particles into the interstices of the medium cause its resistance to increase most noticeably at the start of deposition - this clearly points to the recommendation not to use excessive pressure at the start of filtration, as noted in the previous example.

For the cause of the non-linearities towards the end of the data the expert would look to the nature of the equipment on which the test was carried out. If the test was performed using a confined filter chamber volume, such as a frame in a plate-and-frame filter, a rapid increase of the slope of the curve may indicate that the filter chamber has filled and consequently the effective filter area has suddenly dropped to a very low value (the cross section of the pipework feeding the chamber). Such a condition gives rise to non-linearity B in Figure 2. Obviously this is not the case if a limited volume of suspension is being filtered on a leaf filter which has an unconfined volume for cake growth, when a more likely cause of the increase of the slope would be cake compression leading to a reduction of the filtration rate. Compression may arise as a result of the cake structure not being able to withstand the increasing cumulative fluid drag exerted on layers of particles closer to the filter medium as the cake thickness increases. Such data points to the possibility of there being a limiting cake thickness (associated with a particular operating pressure) beyond which a cake should not be formed. When compression is applied deliberately as a result of the *modus operandi* of the filter, as in a tube press

for example, the compressive behaviour is demonstrated by non-linearity C on Figure 2, which has more pronounced curvature than B in its earlier stages and approaches the vertical asymptotically.

When carrying out a test, it is most common to monitor the filtrate volume collected as a function of the filtration time and hence to utilise the  $t/V$  vs.  $V$  plot. The expert will recognise this as a cumulative plot which is less sensitive to small fluctuations in test conditions than the  $(dV/dt)^{-1}$  vs.  $V$  plot. The latter plot, therefore, has the disadvantage that it shows data scatter more readily than the  $t/V$  vs.  $V$  plot unless the filtrate rate (rather than the filtrate volume) has been monitored directly during the test. The data A-C plotted in Figure 2 are replotted as a reciprocal rate curve  $(dV/dt)^{-1}$  vs.  $V$  in Figure 3; one curve shows the full data and the other shows the data on an expanded scale up to point Y, which corresponds to Y on Figure 2. Figure 3 is typical in that it shows the deviation from linear behaviour more clearly than does the  $t/V$  vs.  $V$  plot.

These examples illustrate the difference between *public* and *private* knowledge in relation to two specific aspects of solid/liquid separation, and how the latter assists in providing more in-depth information and thereby enabling more effective analysis of a problem which may or may not be quantifiable at the outset. The expert widens rapidly the range of parameters taken into account and knows their inter-relationships. The first example also points to the obvious fact that careful analysis of the effect of pressure must be made at the design stages and assumptions in this area can be detrimental to the process operation. When troubleshooting an existing plant the original design test data may not be available or it is just as likely that changes are made to improve throughput or whatever without considering all the ramifications of the changes being introduced. Software based on an expert system interacting with input information from the engineer can facilitate more effective analysis and make information, previously available only to the *expert*, available to the non-expert in solid/liquid separation technology. It can not only remove the problems associated with equation solving, integrations or optimisation, but it can also put powerful reasoning and analysis at the disposal of the non-expert whilst also taking account of all known parameter interactions.

## EXPERT SYSTEMS IN SOLID/LIQUID SEPARATION EQUIPMENT SELECTION

There are so many examples of the use of heuristics in solid/liquid separation technology that it would be well beyond the scope of this paper to itemise and highlight but a few. The following illustrates how combined expert system, algorithmic and graphics approaches can work interactively with the engineer as an effective way to produce a solution to a specific problem – *the selection of equipment suitable for a particular solid/liquid separation duty*.

There exist a number of charts which can serve as a guide to the initial approach to equipment selection, the better ones of which consider a variety of possible eventualities and indicate where decisions must be made. These charts generally have been devised by experts to be fairly comprehensive and are of value to the solid/liquid separation expert. They also illustrate the near-impossibility of combining comprehensiveness with useability when so much interacting information is presented in the written form. Purchas<sup>8</sup> introduced a general guide for the non-specialist, which is a valuable aid to one confronted with this confusing and complex area. The basis of this guide is adopted, suitability extended and adapted, for use in the software p<sup>C</sup>-SELECT<sup>10</sup> which incorporates features of the type discussed in this paper to produce an *expert system*.

The essential steps in solid/liquid separation selection were clearly identified and laid out by Purchas<sup>8</sup> and are shown in a simplified form in Figure 4. There are three principal sets of data which characterise the problem. The first set describes the requirements of the separation in the process environment, the second set concerns the data obtained from leaf and/or jar tests to characterise the

filtration and/or sedimentation behaviour of the slurry, and the third set constitutes a data bank which holds information about available solid/liquid separation equipment. Information associated with more than fifty general categories of equipment is held in the  $p^C$ -SELECT data bank. These data are analysed by  $p^C$ -SELECT using public knowledge, heuristics and decision making techniques such as *production rules*. The results from the analyses are data sheets which detail both experimental and calculated results from tests, and a list of recommended equipment which satisfies the process requirements and slurry characteristics. The list may be sorted and ranked according to various relative operational performance criteria or product quality demands. Any other screens displayed during the analysis also may be printed for inclusion in reports.

## EQUIPMENT SELECTION BY $p^C$ -SELECT

The following is a hypothetical problem illustrative of the type which the process engineer may face in the selection of solid/liquid separation equipment. *As part of the production cycle a plant needs to recover the solids constituent in a washed form at the rate of  $3 \text{ te h}^{-1}$  from an aqueous feed suspension carrying a solids mass fraction of 0.05%. The nature of the plant indicates that a continuous type operation will be required; identify a preliminary list of equipment which may be suitable for this separation. Leaf and jar test data have been measured.*

$p^C$ -SELECT allows entry into its rule based selection procedures at various levels, the level of entry being determined by the amount and type of information available. In terms of the amount and type of information available there are two important entry points, the first is the ability to enter for an initial list of equipment without any form of test data, but with a knowledge of the process. Here a list can be produced, but against each item in the list will be one or more warning messages indicating the need for additional data of a particular type. The second important entry point is after the analysis of leaf and/or jar test data, the results from which will enable a more reliable and shorter list to be drawn up than was possible at the previous entry level. Entry into the expert system with the low level of data specified above (excluding any test data) will lead to a long list of equipment which might be capable of achieving the separation (Figure 5). The list is divided into three parts. The top part is a summary of the information fed into the selection procedure. The second part is a list of the selected equipment (in order of an overall performance rating in this instance) that indicates for each item, through selection warnings, what further action should be taken to check the equipment suitability and what limitations the equipment may possess. The suitability of the equipment is also related to typical particle size ranges and feed concentrations. Although the latter information has been used in the selection, the values have been implied through the use of composite data and it is at this point the engineer can check the equipment information against values from the process. The third part of Figure 5 is the equipment listed together with relative performance criteria. These are based on a scale from 0 to 9, with larger numbers indicating better performance and showing whether the solid is generally discharged in cake (C) or slurry (S) form. The technical expert will recognise that some items in Figure 5 are not realistic alternatives. The selection warnings marked against each item in the list reflect this and clearly it would not be acceptable to rely on Figure 5 for anything other than *first impressions*.

Analysis of the leaf and jar test data, using  $p^C$ -SELECT, provides additional data which the selection procedure can utilise. The previous list of 20 items is reduced to the 7 listed in Figure 6, which also shows that inclusion of the additional data has removed most of the selection warnings. A full analysis using  $p^C$ -SELECT uses algorithm and graphics software with interactive input from the engineer to analyse test data followed by expert system software, again with engineer input. A selection and a report if desired, are completed within minutes and *what if?* queries are easily investigated.



It is not the purpose of the example to demonstrate all the facilities of p<sup>C</sup>-SELECT, but to illustrate the general method of approach to equipment selection using computers. It is interesting to note that avoidance of expert system tools has been recommended<sup>12</sup> in circumstances that arise in evaporation process design where the need for an interface between heuristic based selection and detailed calculation is similar to that required for solid/liquid separation equipment selection. The procedures outlined above enable the non-expert to come to rational decisions based on expert knowledge, without the need to consult an expert in the earlier stages of solving his problem. This is important in solid/liquid separation, as the expert is often a representative of an equipment manufacturing company whose job it is to sell a particular type of separator. Taking filters as an example; many types usually will be capable of carrying out a particular filtration, but probably only a few general types will be most suited to the task. It is wise to have an insight into which types these are, before consulting an expert.

Software such as p<sup>C</sup>-SELECT enables the rapid analysis of data and exploration of alternatives, it puts the engineer in a position to ask more penetrating questions of whichever expert he or she may consult, and reduces expenditure on unwarranted pilot scale testwork. These advantages are gained without the need for extensive computer knowledge or high speed/capacity computers.

## CONCLUDING REMARKS

The widespread use of heuristics, the lack of standard approaches to most aspects of design and the limited information available to the design engineer in texts gives rise to several requirements in solid/liquid separation. There is a need to:

- Standardise small scale tests
- Rationalise the analysis of the data which come from the tests
- Formalise the approaches to process design and scale-up of equipment.

Manufacturers of different equipment types tend to use different heuristic approaches to equipment sizing, making it very difficult for a user engineer to check that the correct equipment is being specified for the separation and that the size of the equipment is appropriate. Computer software could be of considerable assistance not only in the areas identified above, but also in design and scale-up<sup>11</sup>. Design procedures and knowhow in many other branches of engineering, for example in heat transfer, are documented widely and simulation and model equations are freely available and well developed. This is not the case in solid/liquid separation where design codes and other useful information are effectively non-existent. Starting from the present overall position of the technology and the current state of design procedures it would be unrealistic to expect to formalise all aspects of design or scale-up, not least because of the wealth of *rule-of-thumb* knowledge which is not available to the technologist. The main problem is that this information is available to a limited number of technology experts, but to few others.

The use of an integrated software approach utilising a well-chosen mix of algorithm, graphics, expert system and input information from the engineer could overcome the problem that probably stems from deficiencies of communication between experts and non-experts, and between academics and industrialists. To bring all of the technology up to such a level that it is equally available to everyone that wishes to use it would be an enormous task, but perhaps it is a goal we should aim to achieve.

## NOMENCLATURE

A      filtration area (m<sup>2</sup>)

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$c$	solids concentration in the feed slurry, based on the filtrate volume and corrected for liquor retention by the cake ( $\text{kg m}^{-3}$ )
$F_K$	filterability coefficient ( $\text{m}^{10} \text{s}^{-1}$ )
$\Delta p$	pressure drop across the filter ( $\text{N m}^{-2}$ )
$R$	resistance of the filter medium ( $\text{m}^{-1}$ )
$t$	filtration time (s)
$t_i$	filtration time selected from which to start data analysis (s)
$V$	filtrate volume collected at time $t$ ( $\text{m}^3$ )
$V_i$	filtrate volume collected at time $t_i$ ( $\text{m}^3$ )
$\alpha$	specific resistance of the filter cake ( $\text{m kg}^{-1}$ )
$\mu$	viscosity of the liquid in the feed slurry ( $\text{Pa s}$ )

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## FIGURES AND TABLES

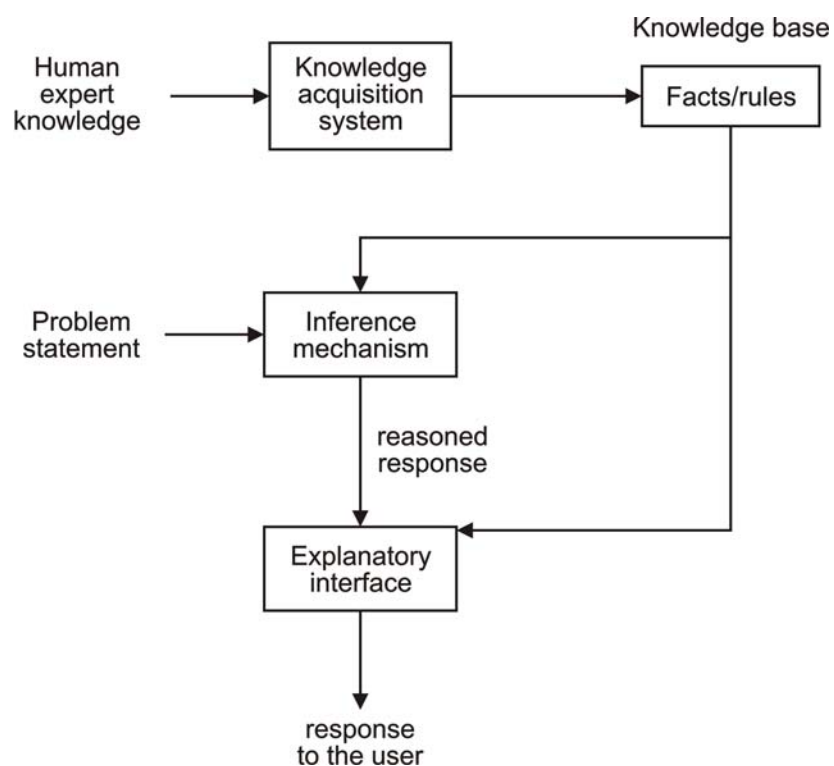


Figure 1: The basic elements of an expert system.

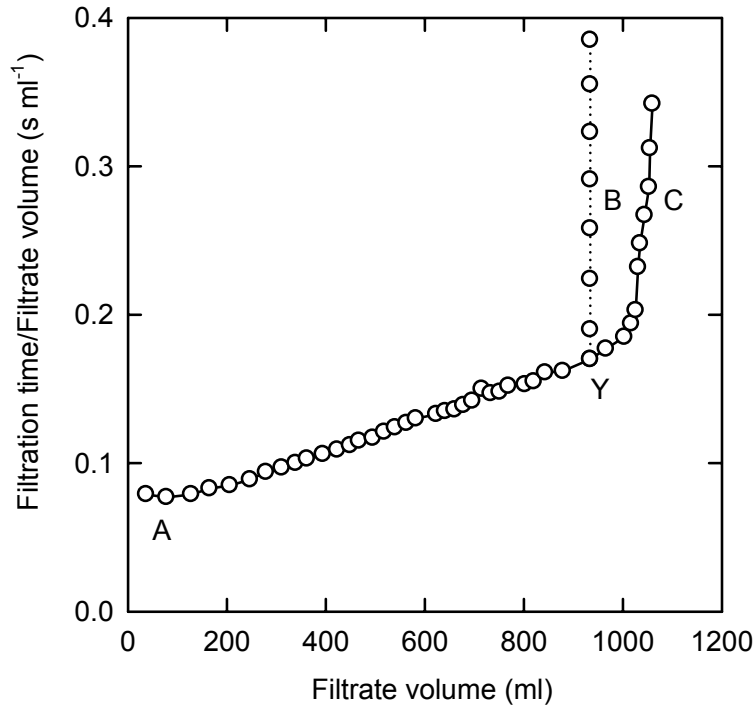


Figure 2: Plot of filtration test data in the form  $t/V$  vs.  $V$ .

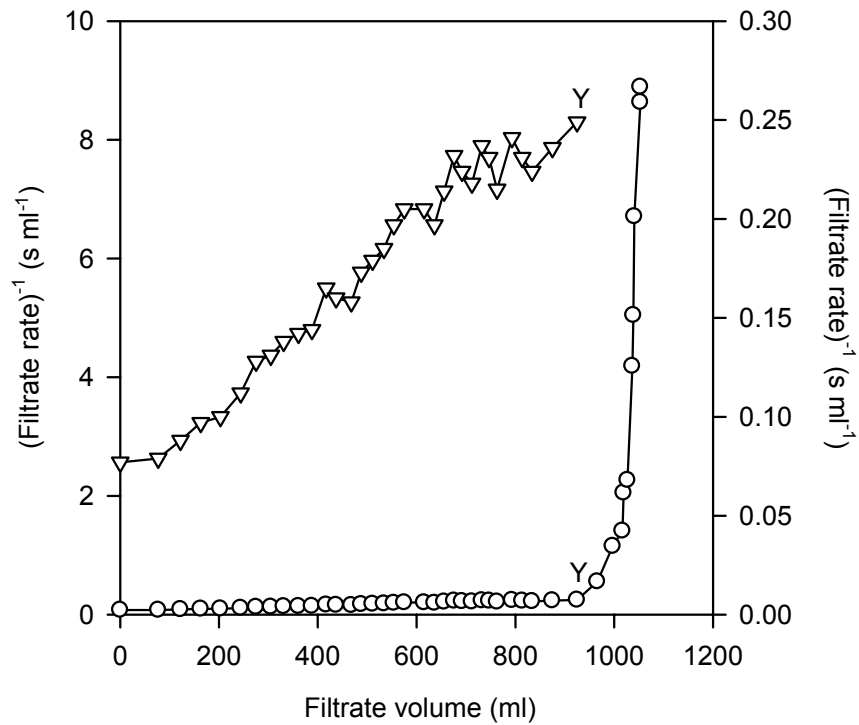


Figure 3: The data in Figure 2 replotted as a reciprocal rate plot.

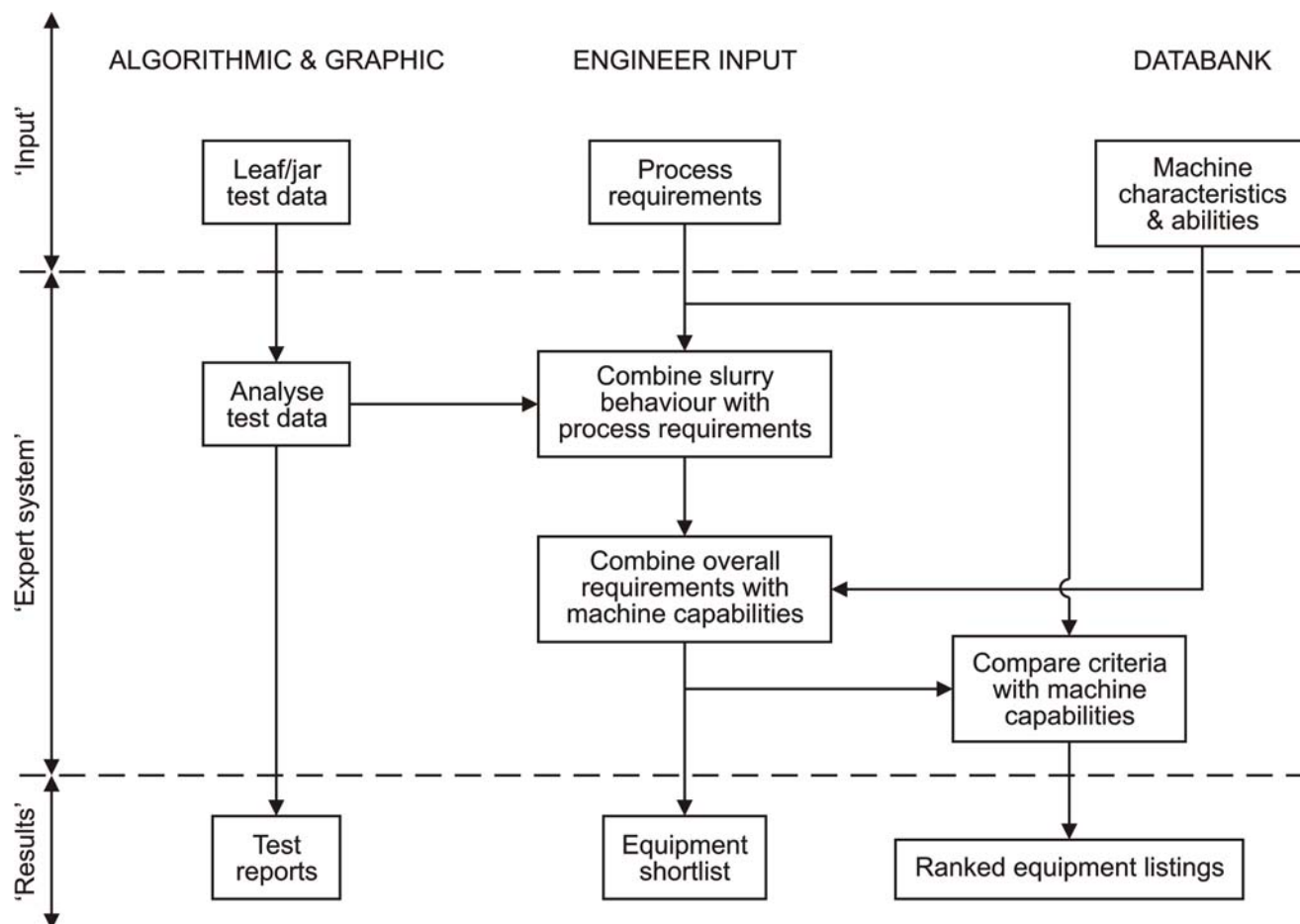


Figure 4: The steps involved in the selection of separation equipment.

## Solid/Liquid Separation Equipment Simulation &amp; Design, PC-SELECT

## DATA SHEET FOR EQUIPMENT SELECTION

## Specifications

Duty            Scale:- medium (10 m<sup>3</sup>/hr)  
                   Operation:- continuous  
                   Objective:- washed solids recovery

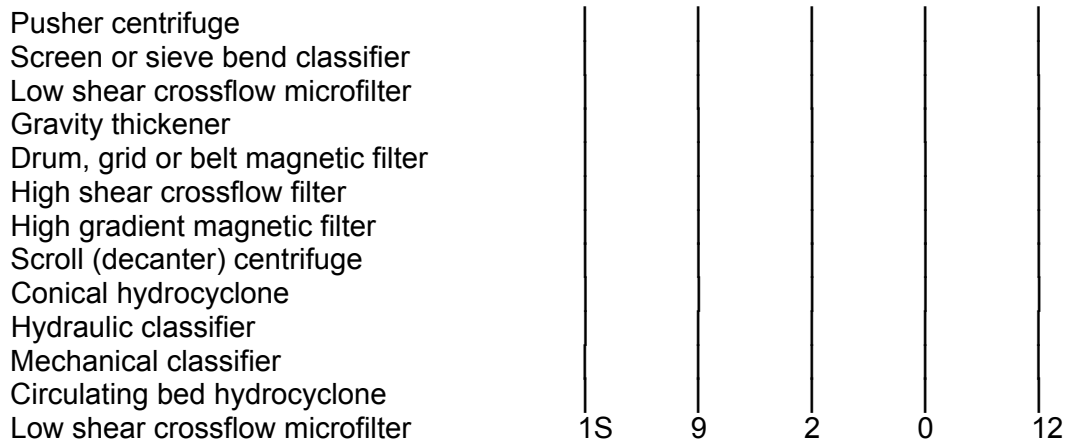
Settling        Rate:- not specified  
                   Overflow clarity:- not specified  
                   Sludge proportion:- not specified

Filtration      Cake growth rate:- not specified

Selected equipment description	Selection warnings	Particle size (µm)	Feed conc. (% v/v)
Horizontal belt, pan or table filter	2,3	20-80,000	3-40
Bottom fed drum filter, knife dis.	2,3	1-200	3-30
Bottom fed drum filter, roll dis.	2,3	1-50	3-30
Bottom fed drum filter, string dis.	2,3	1-70	3-30
Continuous pressure filter	2,3	1-100	0.01-30
Variable volume filter	1h,2,3	1-200	0.1-25
Top fed drum filter			
Pusher centrifuge			
Screen or sieve bend classifier			
Low shear crossflow microfilter			
Gravity thickener			
Drum, grid or belt magnetic filter			
High shear crossflow filter			
High gradient magnetic filter			
Scroll (decanter) centrifuge			
Conical hydrocyclone			
Hydraulic classifier			
Mechanical classifier			
Circulating bed hydrocyclone			
Low shear crossflow microfilter	1h,2,3	0.001-0.05	<10

Selected equipment description	F3: index	F4: index	F5: index	F6: index	F7: index
Horizontal belt, pan or table filter	7C	7	9	8	31
Bottom fed drum filter, knife dis.	6C	7	7	8	28
Bottom fed drum filter, roll dis.	6C	7	7	8	28
Bottom fed drum filter, string dis.	6C	7	7	8	28
Continuous pressure filter	6C	7	6	7	26
Variable volume filter	8C	7	4	7	26
Top fed drum filter					

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F3 index:- Solid product dryness

F4 index:- Liquid product clarity

F5 index:- Washing performance

F6 index:- Crystal breakage

F7 index:- Overall performance

Equipment listed in order of overall performance rating

Figure 5: Equipment selection with a *low level* of data.

## Solid/Liquid Separation Equipment Simulation &amp; Design, PC-SELECT

## DATA SHEET FOR EQUIPMENT SELECTION

## Specifications

Duty	Scale:- medium (10 m <sup>3</sup> /hr) Operation:- continuous Objective:- washed solids recovery
Settling	Rate:- low (less 0.1 cm/s) Overflow clarity:- good Sludge proportion:- high (greater than 20% vol)
Filtration	Cake growth rate:- medium (0.02 – 1 cm/min)

Selected equipment description	Selection warnings	Particle size (µm)	Feed conc. (% v/v)
Horizontal belt, pan or table filter	none	20-80,000	3-40
Bottom fed drum filter, knife dis.	none	1-200	3-30
Bottom fed drum filter, roll dis.	none	1-50	3-30
Bottom fed drum filter, string dis.	none	1-70	3-30
Continuous pressure filter	none	1-100	0.01-30
Variable volume filter	1h	1-200	0.1-25
Scroll (decanter) centrifuge	1hA	1-5000	4-40

Selected equipment description	F3: index	F4: index	F5: index	F6: index	F7: index
Horizontal belt, pan or table filter	7C	7	9	8	31
Bottom fed drum filter, knife dis.	6C	7	7	8	28
Bottom fed drum filter, roll dis.	6C	7	7	8	28
Bottom fed drum filter, string dis.	6C	7	7	8	28
Continuous pressure filter	6C	7	6	7	26
Variable volume filter	8C	7	4	7	26
Scroll (decanter) centrifuge	4C	4	3	3	14

F3 index:- Solid product dryness

F4 index:- Liquid product clarity

F5 index:- Washing performance

F6 index:- Crystal breakage

F7 index:- Overall performance

Equipment listed in order of overall performance rating

Figure 6: Equipment selection with a *high level* of data.

**Cite paper as:** Wakeman R.J. and Tarleton E.S., 1991, Solid/liquid separation equipment simulation & design – an expert systems approach, *Filtration and Separation*, **28**(4), 268-274. Also presented at Expert Systems for Filtration and Separation Conference, 1991, The Filtration Society, Harwell, UK. Paper awarded Filtration Society Gold Medal, 1993.