A STUDY OF THE DYNAMIC BEHAVIOUR OF A PULSED COLUMN SOLVENT EXTRACTION PLANT

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Doctor of Philosophy

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May 1989

THESIS SUMMARY

The University of Aston in Birmingham

A Study of the Dynamic Behaviour of a Pulsed Column Solvent Extraction Plant

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Doctor of Philosophy
1988

A study has been made of the dynamic behaviour of a nuclear fuel reprocessing plant utilising pulsed solvent extraction columns.

A flowsheet is presented and the choice of an extraction device is discussed. The plant is described by a series of modules each module representing an item of equipment. Each module consists of a series of differential equations describing the dynamic behaviour of the equipment. The model is written in PMSP, a language developed for dynamic simulation models.

The differential equations are solved to predict plant behaviour with time. The dynamic response of the plant to a range of disturbances has been assessed. The interactions between pulsed columns have been demonstrated and illustrated. The importance of auxillary items of equipment to plant performance is demonstrated. Control of the reprocessing plant is considered and the effect of control parameters on performance assessed.

Keywords: Solvent Extraction
Pulsed Columns
Dynamic Behaviour
Control

ACKNOWLEDGEMENTS

I wish to thank Dr Clive Mumford for his guidance and advice in the preparation of this thesis. Also I would like to thank my husband for his patience whilst I have been writing up. Thanks are also due to Anita for tackling the typing. I also wish to thank Andy Hopkinson of AEE Winfrith for his advice and assistance during this work.

Finally, I wish to thank AEE Winfrith for providing the funds and facilities to make this work possible and who therefore own the copyright of the thesis.

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1 Introduction

Solvent extraction is a separation technique involving the contacting of two immiscible, or partially miscible, liquid solutions in which one or more components are selectively extracted from one phase into the other. The driving force for interphase mass transfer is a nonequilibrium distribution of the transferring species between the two phases. Many processes involve the contact of an aqueous phase with an organic phase, the aqueous phase after extraction being termed the raffinate and the solvent, the extract. One phase will be dispersed in the form of drops in the second continuous phase to provide a high interfacial area for mass transfer.

Solvent extraction has been used extensively in the nuclear industry for many years to reprocess spent reactor fuel (16) (37), (38). The PUREX process (30) is used to separate uranium and plutonium from the fission product waste. The process involves various steps in which the material is transferred between an aqueous nitric acid phase and an organic phase of tributyl phosphate (TBP) in an odourless kerosene (OK) diluent. The operation has traditionally been carried out in mixer-settler contactors to provide counter-current processes (86). With the need to improve performance and throughput the potential of pulse columns for use in the nuclear industry is being examined.

This present work involves the dynamic simulation of a spent fuel reprocessing plant including the pulse column contactors and ancilliary items. The interaction between two or more columns, and between a column and connected items has not been reported elsewhere but would be of some importance in any operating plant. Hence, although this work is specific to a pulse column plant reprocessing spent fast reactor fuel by the PUREX process, the analysis could be adapted to other applications provided data were available.

2 Nuclear Fuel Reprocessing

2.1 The Fuel Cycle

Uranium is the basis for the nuclear energy industry and the various stages in the uranium fuel cycle are illustrated in Figure 2.1. First generation reactors, like Magnox, use uranium metal as fuel. However, these have been superseded by thermal reactors, such as the Advanced Gas Cooled Reactor (AGR) and the Pressurised Water Reactor (PWR), using uranium oxide enriched to about 3% fissile U^{235} as fuel.

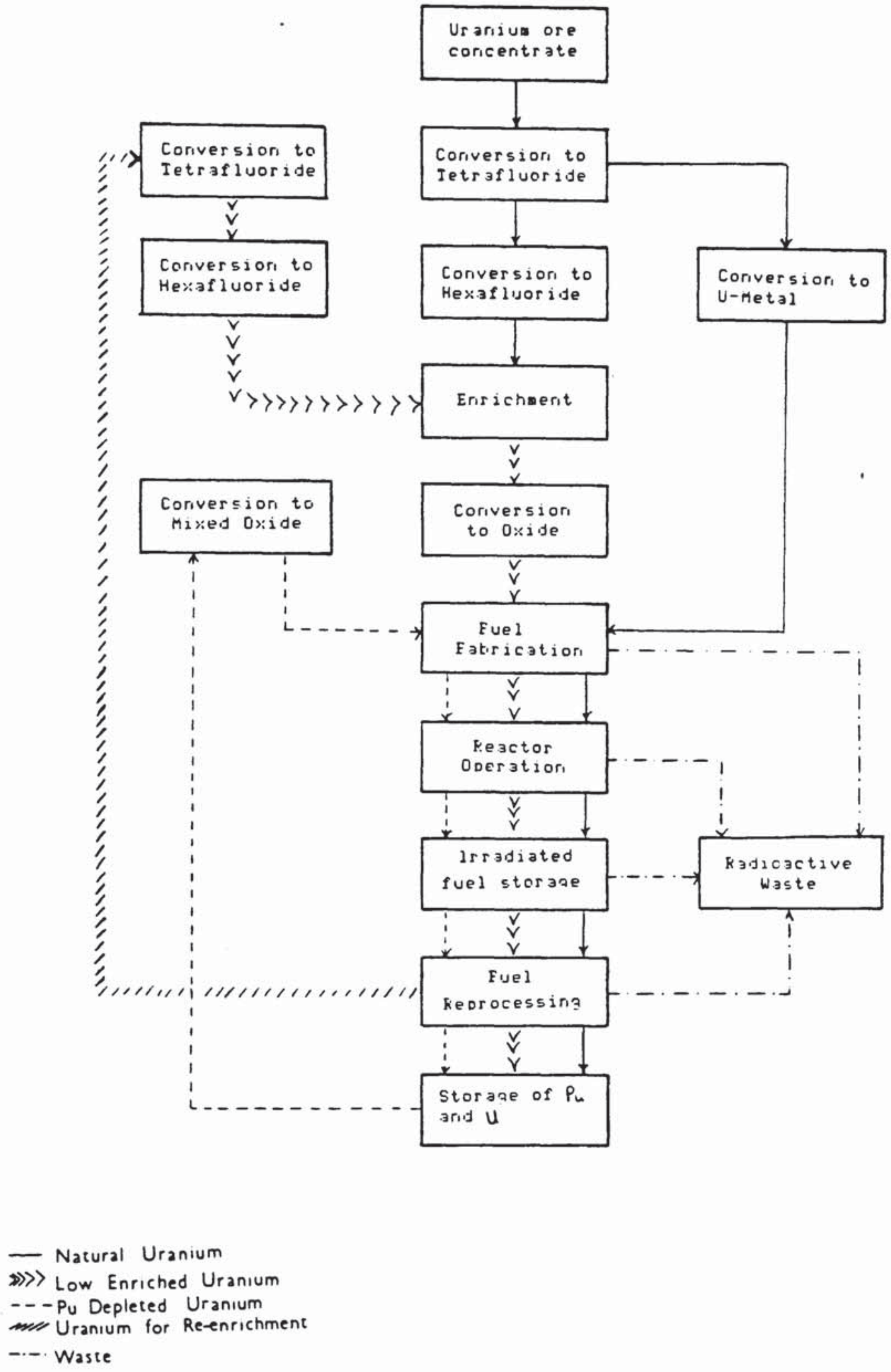


Figure 2.1 The Uranium Fuel Cycle

The core of these reactors consists of an array of fuel elements together with a moderator such as graphite or water, neutron absorbing control rods and neutron reflectors (34).

The moderator acts to slow down the high energy neutrons released by U^{235} fission to 'thermal' energy most efficient for splitting further fissile nuclei. Some neutrons will be absorbed by U^{238}, leading via Neptunium to Plutonium (Pu^{239}). Pu^{239} is itself fissile and will contribute to the reactor heat output and neutron flux. It may also absorb neutrons leading to Pu^{240} and higher isotopes of Plutonium and, by decay, other actinides such as Americium. Fission of the heavy nuclei produces fission products which are various isotopes, usually radioactive, of elements near the middle of the periodic table, for example Zirconium, Strontium, Ruthenium. Eventually the build-up of neutron absorbing fission products, physical degradation of the fuel and net consumption of fissile nuclei necessitates the removal of the fuel from the core before all the fissile material has reacted. Typically about 10% of fissile material reacts. The fuel can be stored indefinitely or reprocessed after a relatively short period of storage, typically 150 days, to allow fission product decay heat to dissipate, (137).

Currently, Fast Reactors, in which there is no moderator in the core and hence the neutrons are fast, are being developed for commercial use. These use a mix of uranium and plutonium oxides as fuel. The core is surrounded by a blanket of fertile depleted uranium, ie uranium with much of the fissile U^{235} removed, which will absorb some of the neutrons released in the core giving plutonium. Thus fast reactors can produce more fissile material than they consume. To recover this excess, in order to feed it back into the reactor as fuel, the spent fuel and blanket material must be reprocessed.

2.2 Reprocessing Chemistry

The composition of fuel fed to a reprocessing plant will vary widely. It depends on the composition of fuel fed to the reactor, specific power of the fuel, duration of irradiation and the cooling period between irradiation and reprocessing, (34, 137, 16). An additional complication in reprocessing fast fuels is the presence of the breeder assemblies in the feed. Typical fuel compositions from a light water reactor and a fast breeder reactor are summarised in Table 2.1. Reprocessing consists of three major stages:

(1) head end operations, in which the fuel is removed from its casing and chopped into short lengths ready for dissolution, (13, 120);

	Reactor	
	LMFBR	LWR
Coolant	Sodium	Water
Cladding material	Stainless steel	Zircaloy
Fuel rod diameter, cm	0.6–0.8	1.0–1.2
Reactor specific power, MW/Mg HM†		
Core	98	
Average, core and blankets	49.3	30
Burnup, MWd/MT		
Core	67,600	
Axial blanket	4,700	
Radial blanket	8,000	
Mixed core and blankets	37,000	33,000
Specific power of fuel cooled 150 days, kW/Mg HM		
Core	52	
Mixed core and blankets	28	20
Composition of mixed core and blanket cooled 150 days, w/o		
Uranium	85.6	95.4
Neptunium	0.025	0.075
Plutonium	10.3	0.90
Americium	0.035	0.014
Curium	0.0011	0.0047
Fission products	3.9	3.1
Specific activity of mixed core and blanket cooled 150 days, Ci/Mg HM		
Tritium	1,050	690
^{85}Kr	8,430	11,000
^{131}I	3.55	2.22
Strontium	162,500	174,000
Cesium	152,000	321,000
Ruthenium	1.21E6	0.50E6
Total	6.98E6	4.31E6

† Mg HM, megagrams (metric tons) heavy metal (uranium + plutonium) charged to reactor.

Table 2.1 Typical Fuel Compositions for a Fast and a Thermal Reactor

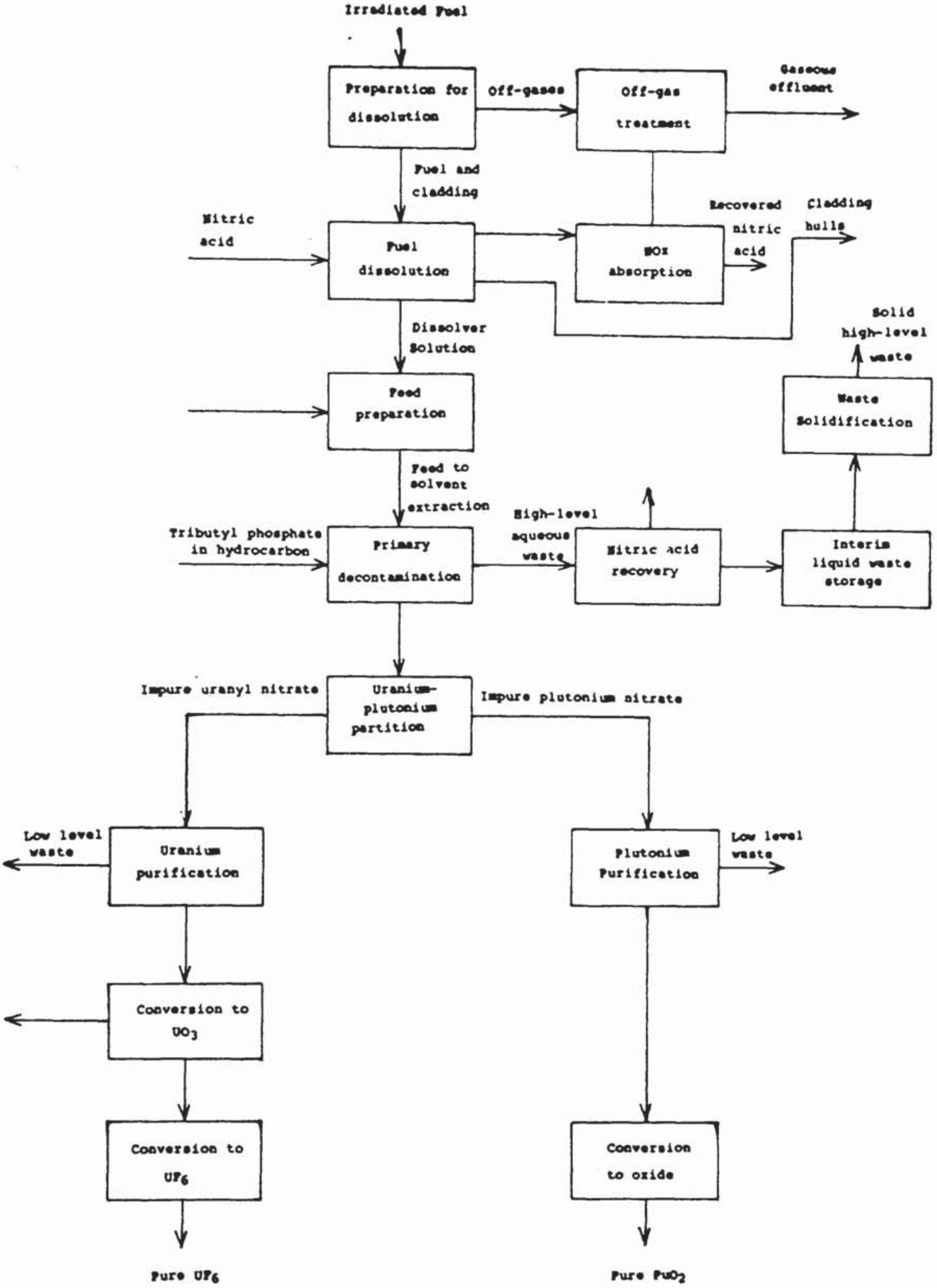


Figure 2.2 The Purex Process

(2) chemical separation, in which the fuel is dissolved, and uranium and plutonium are separated from fission products and from each other, (13, 71)

(3) product finishing, in which the uranium and plutonium are converted to the form most suitable for refabrication into fuel. Waste treatment facilities will also be provided.

A Purex-type process (30), (63) is used in all working fuel reprocessing plants for the separation stage. Figure 2.2 indicates schematically the principal steps in the full re-processing process for a plant handling stainless steel clad fuel. The process is described in detail by Benedict (16), Lo (76) and by Stoller and Richards (125). This work is primarily concerned with the reprocessing of fuels from fast reactors and the following summary therefore draws special attention to the particular problems of these fuels. Historically, other reprocessing routes such as the Butex Process (60, 98), the Redox Process (75), The Trigly process (24) and the Bismuth phosphate process (16) have been abandoned in favour of Purex for various reasons including improved recovery and improved waste handling.

The Purex process uses tri-butyl phosphate in a hydrocarbon diluent to extract uranyl nitrate and plutonium nitrate from a solution containing nitric acid.

The process was proposed in 1949 by Warf (136) who discovered that tetravalent cerium nitrate could be separated from the nitrates of trivalent rare earths by solvent extraction with TBP.

The fuel is dissolved in nitric acid. Allardice (3) states that Dounreay fast reactor fuel is 99.9% completely dissolved after 8 hours. PuO_2 dissolves more slowly than UO_2 and thus Fast Reactor fuel will dissolve slower than thermal reactor fuels due to the higher plutonium content. Precisely how slow the process is depends on the fuel fabrication methods and irradiation history. The following equations represent the reactions occurring,

$$3UO_2 + 8HNO_3 > 3UO_2(NO_3)_2 + 2NO + 4H_2O \qquad (2.1)$$

$$UO_2 + 4HNO_3 > UO_2(NO_3)_2 + 2NO_2 + 2H_2O \qquad (2.2)$$

Reaction 1 dominates with acid $\leq$ 10M
Reaction 2 dominates with acid $\geq$ 10M

Plutonium oxide is insoluble in nitric acid. Fast reactor fuel is a ceramic composite of plutonium and uranium oxides. Plutonium atoms replace uranium atoms within the uranium oxide crystal lattice which enables them to be taken into solution as follows,

$$UO_2.PuO_2 + 6HNO_3 > PuO_2(NO_3)_2 + 2NO_2 + 2H_2O + UO_2(NO_3)_2 \quad (2.3)$$

$$UO_2.PuO_2 + 8HNO_3 > Pu(NO_3)_4 + 4H_2O + U(NO_3)_4 \quad (2.4)$$

When dissolution is complete the solution and any fine suspended particles are drained from the remaining cladding fragments. The final solution is clarified by centrifugation (3), (38). Filtration has also been considered (63).

Three solvent extraction cycles are normally used in the Purex process (87). In Cycle 1 (primary codecontamination) uranium and plutonium are extracted into the organic phase leaving the bulk of the fission products behind. These reactions can be represented as follows,

$$UO_2(NO_3)_{2aq} + (2TBP)_{org} > (UO_2(NO_3)_2.2TBP)_{org} + 6H_2O \quad (2.5)$$

$$PuO_2(NO_3)_2 + 2TBP > Pu(NO_3)_4.2TBP \quad (2.6)$$

$$PuO_2(NO_3)_2 + 2TBP > PuO_2(NO_3)_2.2TBP \quad (2.7)$$

Both Pu^{6+} and Pu^{4+} are extractable with TBP but generally all the plutonium will be conditioned to give Pu^{4+}, the more extractable form. A scrub section using nitric acid will be necessary to suppress fission product carryover into the solvent. Depending on the uranium-plutonium partitioning agent used in Cycle 2, uranium and plutonium may be stripped back into the aqueous phase by dilute nitric acid. To meet product specifications a further extract/scrub stage may be necessary. The classic partitioning technique is to reduce plutonium to the relatively inextractable trivalent form whilst leaving uranium in the extractable hexavalent state.

The choice of reductant is discussed by Naylor (96) and in reference (16). Common reductants are ferrous sulphamate, hydroxylamine and uranous nitrate. The reactions with ferrous sulphamate and uranous nitrate are rapid whilst the reaction with hydroxylamine is slow. Ferrous sulphamate has the disadvantage that it adds non-volatiles to the waste streams and the quantities required for fast fuels would make waste treatment very difficult. Before re-extracting the plutonium it must be oxidised back to the tetravalent state; sodium nitrite is usually chosen for this purpose.

An alternative technique is to form inextractable complexes of plutonium, such as with sulphuric acid discussed by Naylor (96) and Mills (87). Careful control of the sulphate/nitrate ratio ensures that inextractable uranium sulphates are not formed.

Hydroxylamine and uranous nitrate could be used for fast fuels but the slow reaction kinetics call for long residence times and thus larger plant than would be necessary if ferrous sulphamate were used for the same feed rate. In addition, to maintain plutonium in the trivalent state a large excess, 35-40%, of hydroxylamine would be required.

Before passing to Cycle 3 the uranium will be transferred back to the aqueous phase. The plutonium stream may be scrubbed to remove uranium. In this cycle the uranium and plutonium product streams will be further purified to meet fuel fabrication plant limits.

2.3 Criticality Control

In nuclear fuel reprocessing plants a nuclear fission chain reaction, ie a 'criticality incident', must be avoided. Although unlikely to be energetic enough to cause mechanical damage, such a reaction would emit intense gamma and neutron radiation that could be hazardous to nearby plant personnel and release radioactive fission products, (I^{131}), outside the plant (16).

To prevent criticality a critical mass of fissile material must be prevented from accumulating in an

Fissile nuclide present.
Proportion of fertile nuclide (U^{238}, Pu^{240}) present diluting fissile nuclide.
Mass of fissile nuclide.
Geometry of vessel holding fissile material.
Volume of vessel holding fissile material.
Concentration of fissile material.
Nature and concentration of moderators.
Nature and concentration of reflectors surrounding fissile material. Nature and concentration of neutron absorbing poisons.
Homogeneity of fuel-moderator-poison mixture.
Interaction between regions containing fissile material.

Table 2.2 Factors Affecting Criticality Safety unacceptable configuration. The factors affecting criticality safety are summarised in Table 2.2.

Concentration limits, vessel size limits or vessel shape can each be used independently to control criticality. However since this could lead to inconveniently small batch or equipment size, two or more of the factors may be used together. The higher fraction of fissile material in fast reactor fuels make criticality control that much more restrictive. Furthermore, at low acidities and high temperatures plutonium forms a polymer that can deposit on equipment walls leading to accumulation of a critical mass. Combinations of temperature and acidity that must be avoided are demonstrated by Figure 2.3. The precise values are a function of the specific acid concerned.

2.4 Equipment Selection

The choice of equipment to be used in a reprocessing plant is restricted by the following factors,

(1) limitations on size and shape to give a plant that is by geometry safe from a criticality incident;
(2) the impossibility of, or severe difficulty in, maintaining equipment within the essential biological shielding, although improvements in robot design and control may mitigate this limitation

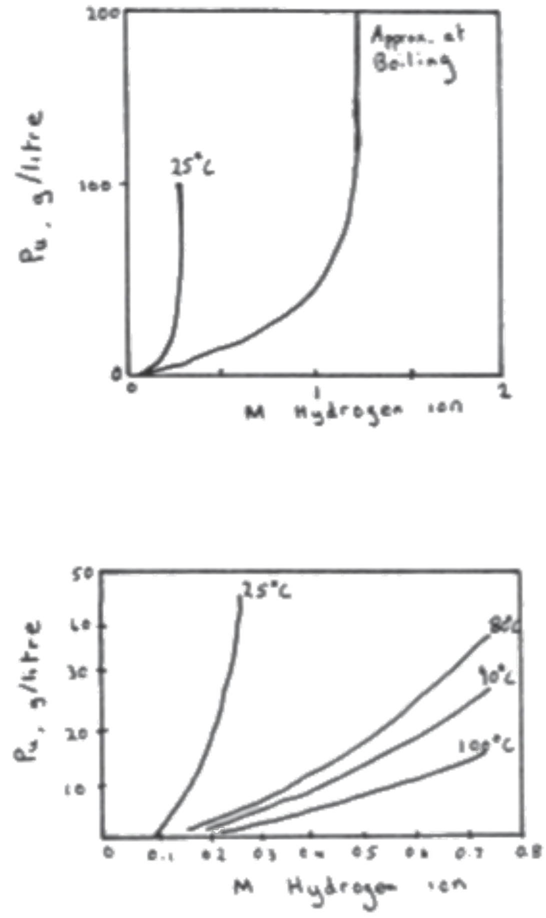


Figure 2.3 Plutonium Polymer Formation Limits

Figure 2.4 A Simple Box-type Mixer-Settler

The first reprocessing plant at Windscale employed conventional packed columns which, although of simple construction, suffered from inconvenient height and throughput limitations. There was also a possibility of channelling should the packing become orientated. As a result, in more modern plants the favoured contactor types have been mixer settlers (25) centrifugal contactors (8,100) and pulsed columns (25, 94, 109). The choice of contactor is discussed by Mills (86).

2.4.1 Mixer-settlers

Simple box-type mixer-settlers as described by Lowe (76) are used at Sellafield for reprocessing spent Magnox fuels. In this device shown in Figure 2.4, complexities such as interstage pumping are avoided; the interface is automatically located by a hydraulic balance through the various liquid-transfer ports. Methods of calculating interface position in both small and larger units have been described (80, 144). A turbine provides the necessary mixing. The impeller shaft passes through the concrete shield so that the motors are accessible for maintenance.

An alternative design (34) usedat Dounreay for reprocessing spent fuel from both the Dounreay Fast Reactor and the Prototype Fast Reactor is illustrated in Figure 2.5. Interstage flows are induced by the density difference between mixed and unmixed flows. No impeller is used; instead mixing is provided by alternately pressurising and depressurising the air lines into each mixer stage inducing pulsations of sufficient turbulence to form a dispersion of the requisite drop size distribution.

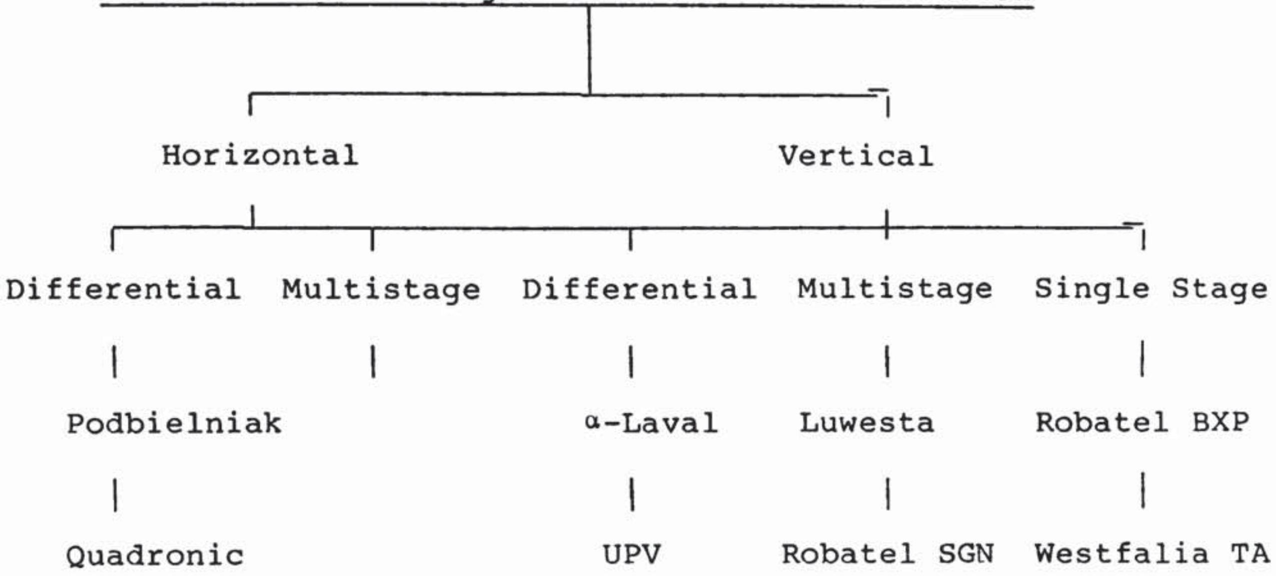
2.4.2 Centrifugal Contactors

Centrifugal contactors described by Hafez (76) can be classified as in Table 2.3. In differential contactors, typified by Figure 2.6, the light phase is introduced near the rim and the heavy phase near the shaft. Centrifugal force causes radial countercurrent flow of the heavy phase towards the rim which in turn causes the light phase to be displaced towards the shaft.

In stagewise extractors, Figure 2.7, both phases are introduced into a mixing compartment and flow out to a

Figure 2.5 The Air Pulsed Mixer Settler

Table 2.3: Centrifugal Contactor Classification



Notes

1. UPV - Unpressurised Vertical Contactor

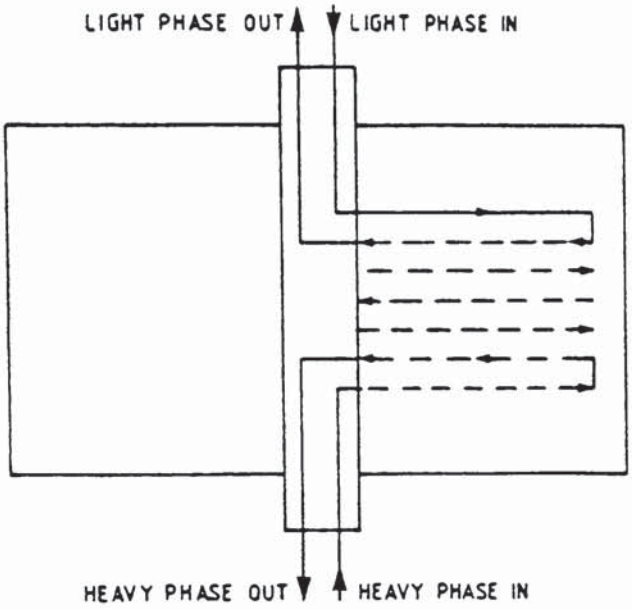


Figure 2.6 Operating Principle of a Differential Centrifugal Contactor

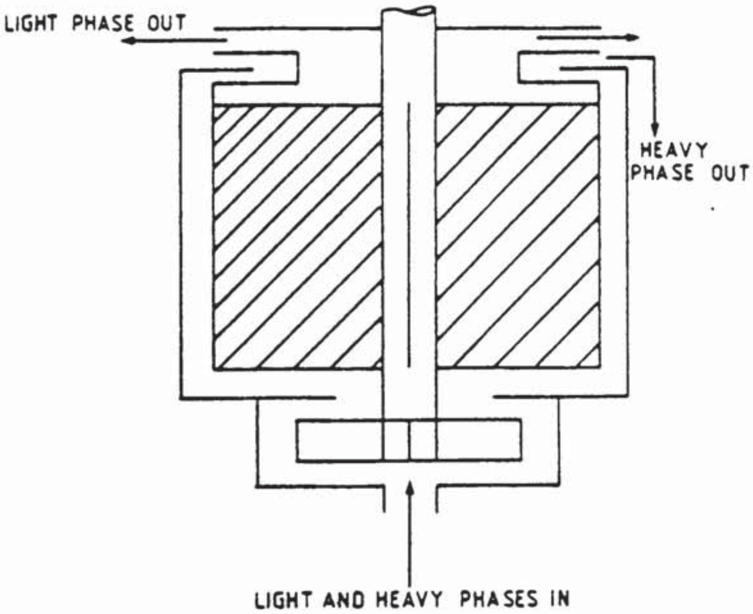


Figure 2.7 Operating Principle of a Staged Centrifugal Contactor

settling compartment under centrifugal force. Countercurrent flow is achieved internally in multistage designs or externally in cascades of single stage units.

2.4.3 Pulsed Columns

The pulsed plate column is a differential contactor in which mechanically energy is transmitted to the liquids by pulsing them up and down through the plates. This action provides a good dispersion of small drop size distribution with high interfacial area, promotes continuous phase turbulence, and also pumps the two phases through the column rendering downcomers unnecessary.

Pulsed packed columns have not been considered for use in nuclear fuel reprocessing, possibly because their efficiency could be affected by deposition of degradation products or interfacial scum over extended operating periods. There may also be a tendency for packing displacement, giving voidage variations, during extended pulsation.

The choice of contactor for any given reprocessing plant application is influenced by numerous factors. Table 2.4 lists these factors and indicates how well each contactor type is rated.

Table 2.4: Contactor Selection

Contactor Type	Short Residence Time	Mechanical Simplicity	Multi-stage Contact	Critically Safe Geometry for required throughput
Box-type (a) mixer-settler	X	✓	✓	X
Air pulsed(b) mixer-settler	X	✓	✓	X
Centrifugal Contactors	✓	X	✓	✓
Pulsed Plate Columns	✓	✓	✓	✓

Notes

x unsatisfactory

✓ acceptable

Short Residence Time < 5 hour

(a) This device could be made safe but an awkward geometry might result.

(b) This device is safe, but the throughput would be limited.

The relative weight given to each of the factors depends on the type of fuel to be reprocessed and the throughput.

Used Magnox fuel (uranium metal, not enriched) has a low plutonium content. In fact, up to U-Pu partition there are no criticality problems. Hence mixer-settler cascades are preferred because of their very stable operating characteristics. In addition fission product activity is lower for Magnox fuels and thus solvent degradation is not so severe; hence longer residence times are permissible (137).

Thermal reactor fuels (enriched uranium oxide) have a higher fission product activity when reprocessed than Magnox fuels. Therefore, mixer-settlers may not be desirable, particularly in Cycle 1 where the fission products are removed. Centrifugal contactors are mechanically complex and in spite of the very short residence times (typically 30s-240s) they offer, this weighs against them. Therefore pulsed columns may be selected.

For reprocessing fast reactor fuels, with their much higher plutonium content, criticality constraints place extremely severe limits on plant size. Therefore, other than for small scale plants such as those currently at Dounreay, mixer-settlers would require parallel stream processing. Centrifugal contactors are mechanically complex and possible maintenance problems must be taken into account. Pulsed plate columns are the only contactor which satisfies the throughput and mechanical simplicity conditions. Pulsed columns have been considered for other metal processing applications (52).

Other plant items face the same criticality and mechanical simplicity problems. Unless a pump can be mounted outside the shielding, fluid-transfer must be achieved by gravity or by means of mechanically-simple devices such as fluidic pumps (147), gas-lifts or Constant Volume Feeders (CVFs).

2.5 Flowsheet for Fast Reactor Fuel Reprocessing

The flowsheet described has been assumed for the purposes of this study, but as a result of the factors discussed here, will be typical of any fast fuel reprocessing plant. Figure 2.8 is a process flow diagram for the process.

In reprocessing fast reactor fuels their high fissile material content and the resultant equipment size constraints govern both the choice of uranium-plutonium partition agent and equipment. As ferrous sulfamate cannot be dissolved into sufficiently concentrated solutions it will not be used. Plant size/throughput considerations rule out uranous nitrate and hydroxylamine. Therefore the sulphate process has been selected as described by Mills (87) and Naylor (76).

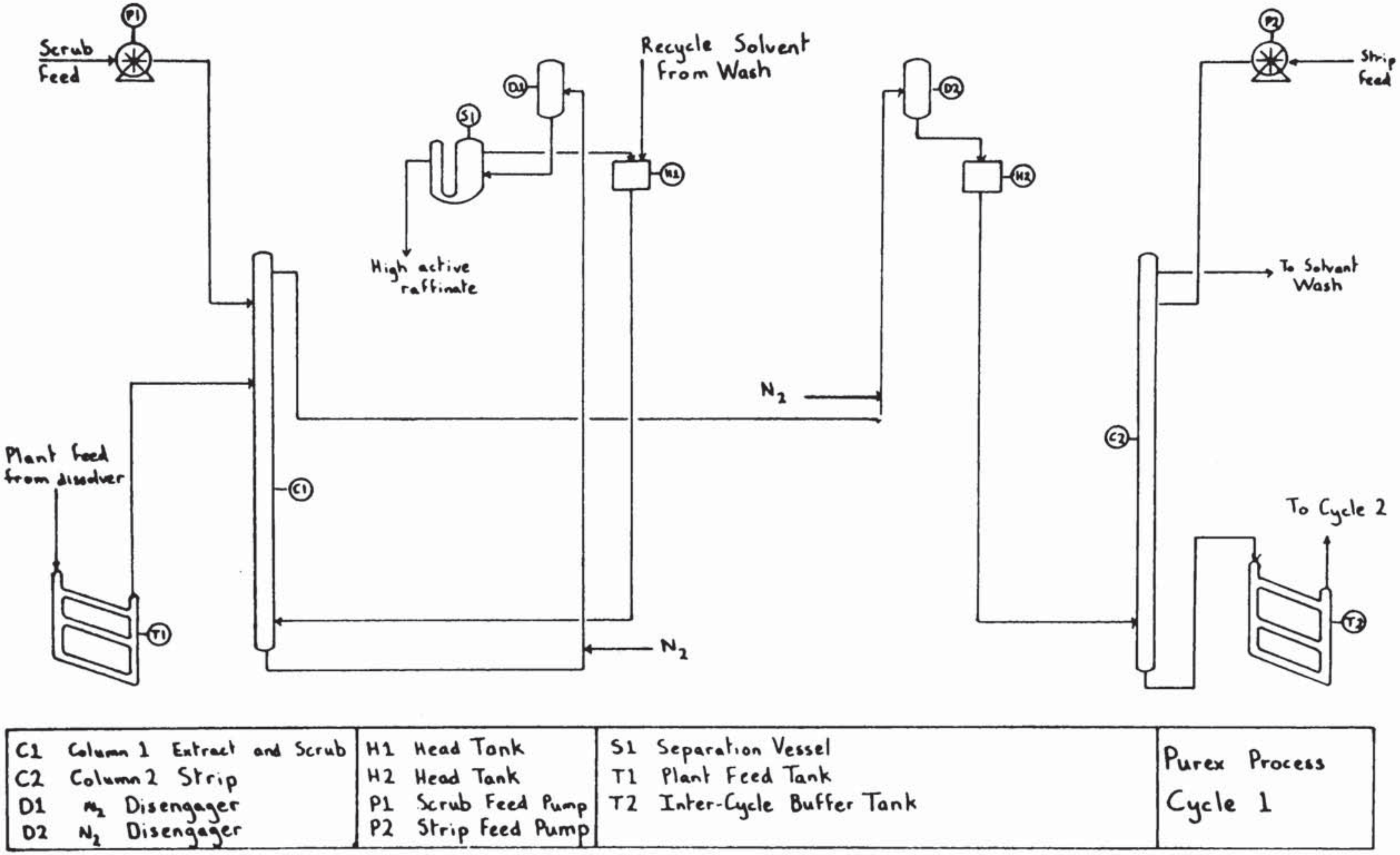
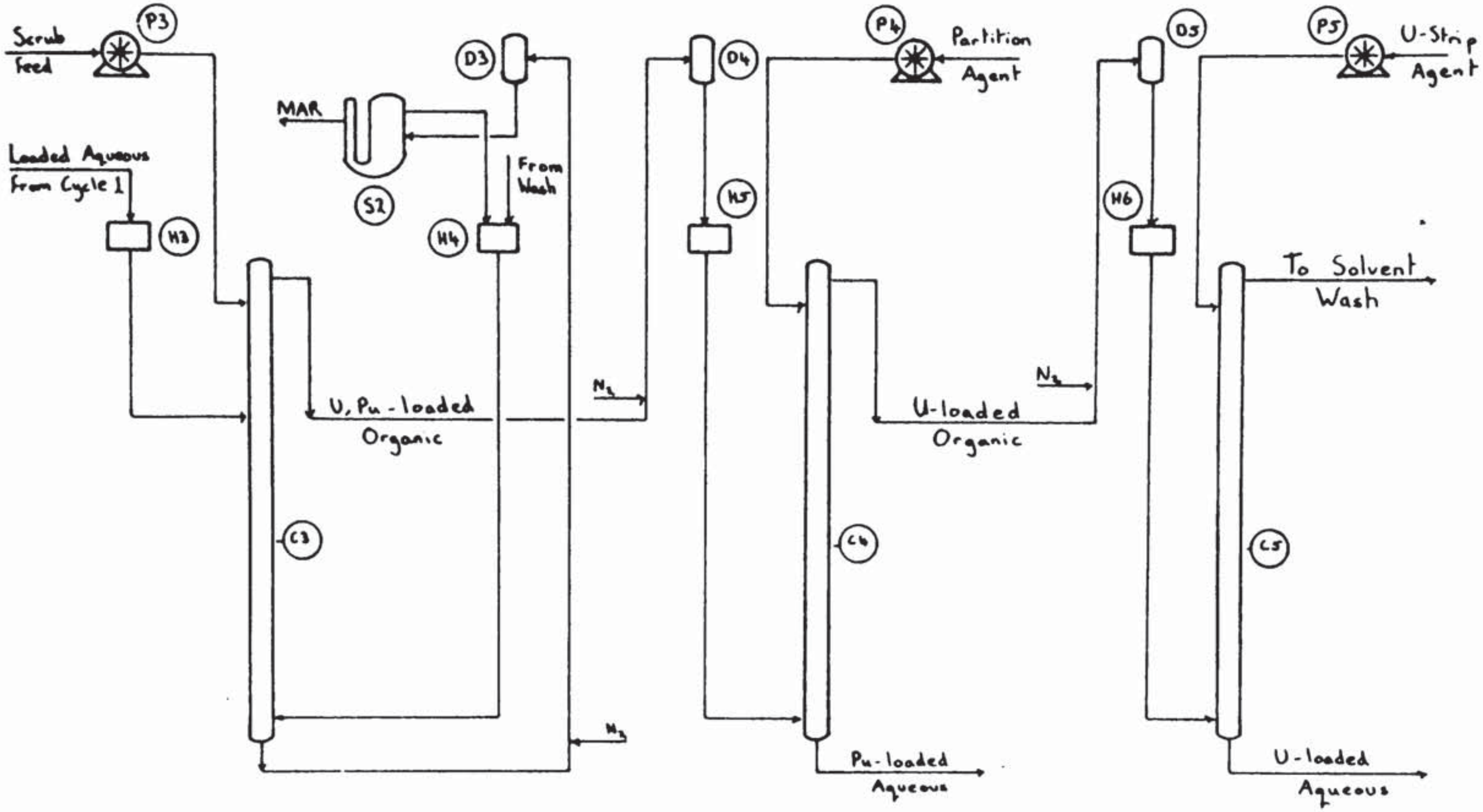


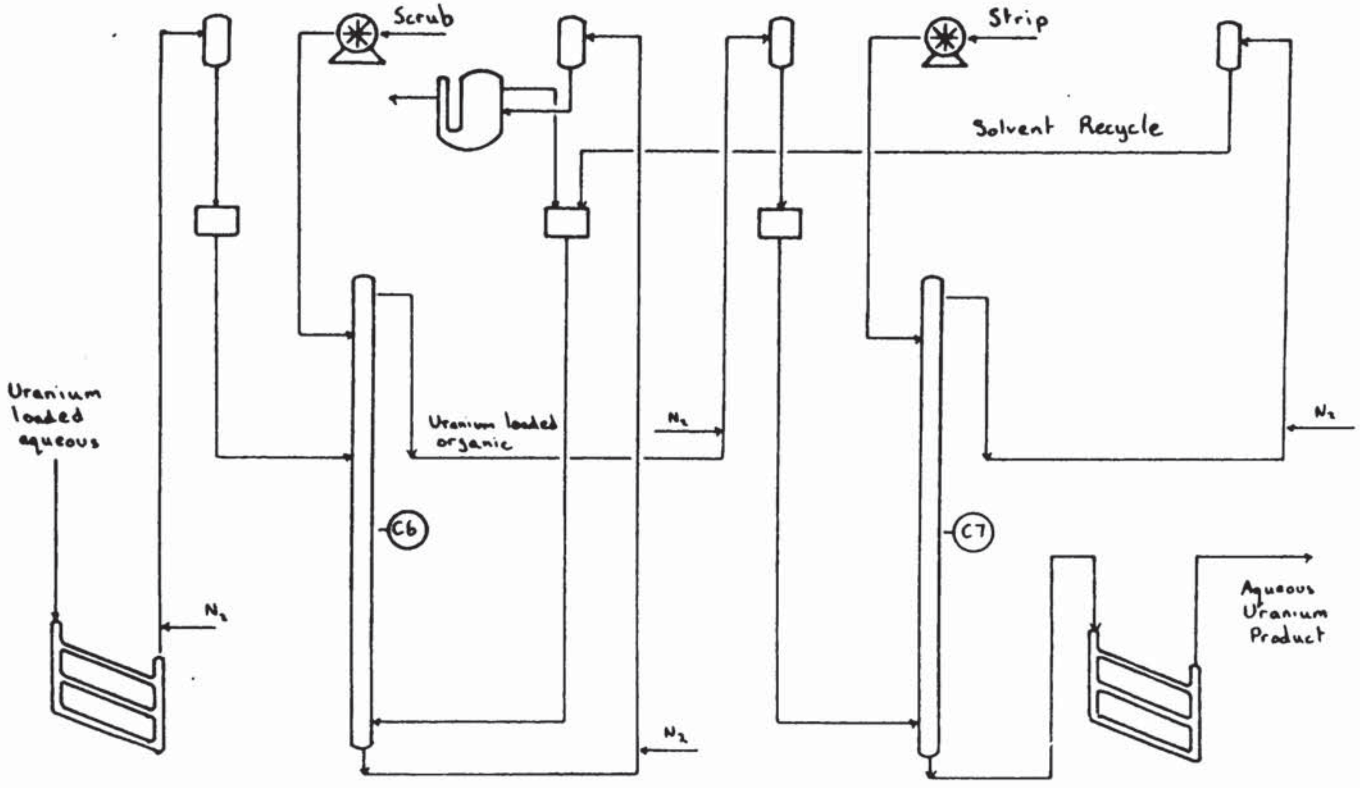
Figure 2.8a) Process Flow Diagram



C3	Column 3	Scrub/Extract	D5	Breakpot	P3	Pump
C4	Column 4	Partition	H3	Head tank	P4	Pump
C5	Column 5	U-Strip	H4	Head tank	P5	Pump
D3	Breakpot		H5	Head tank	S2	External Settler
D4	Breakpot		H6	Head tank		

Purex Process
Cycle 2

Figure 2.8 b)



C6 Column 6 Extract/Scrub
C7 Column 7 Strip

Purex Process
Cycle 3 - Uranium

Fig. 2.8 c)

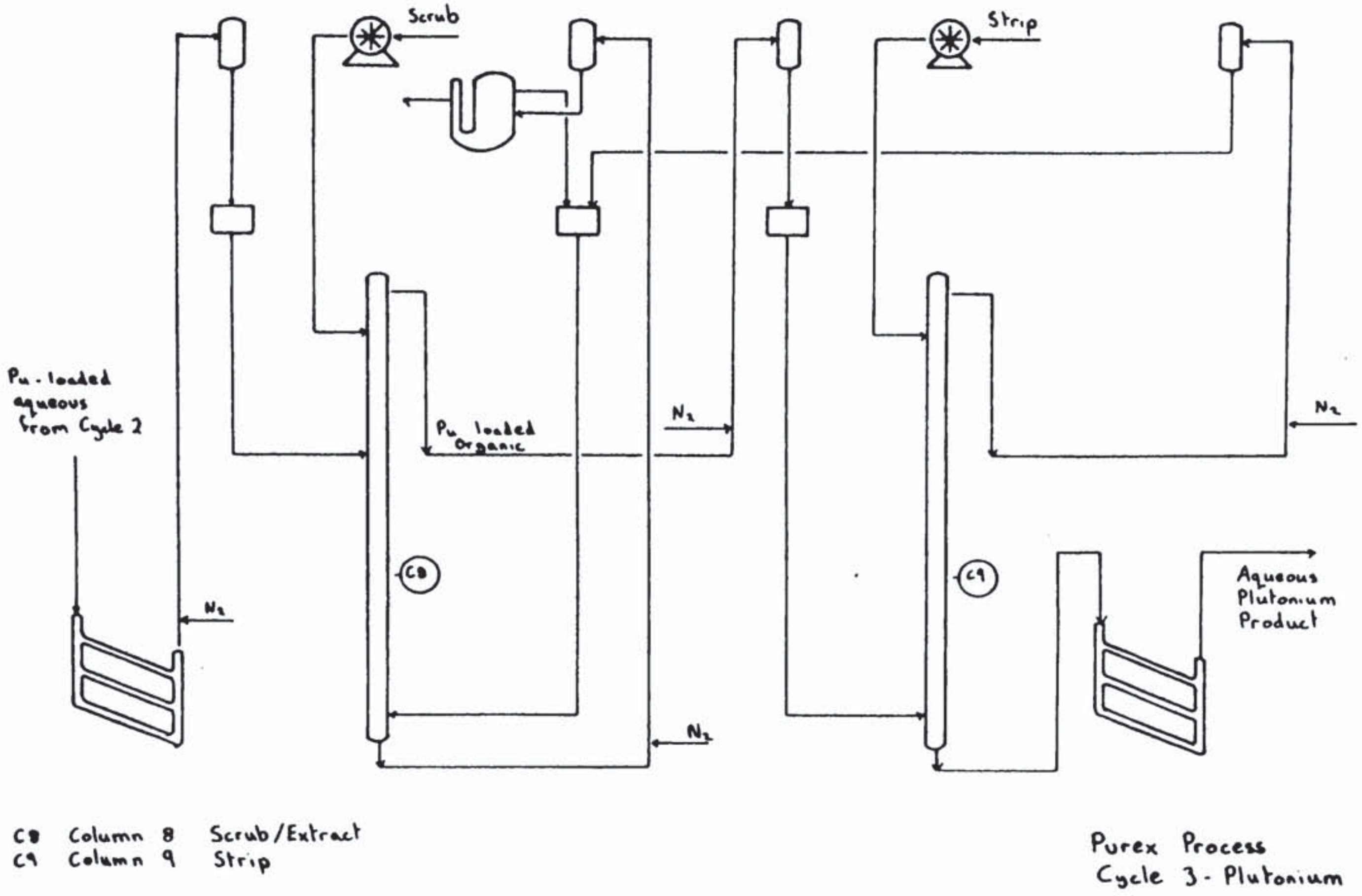

Scrub
Strip
Pu - loaded aqueous from Cycle 2
Pu loaded Organic
N2
N2
N2
N2
C8
C9
Aqueous Plutonium Product
C8 Column 8 Scrub/Extract
C9 Column 9 Strip
Purex Process
Cycle 3 - Plutonium

Fig. 2.8 d)

Engineering problems to do with mechanical complexity (and the need to use boron steel for criticality control) rule out mixer-settlers. Centrifugal contactors, although they have been used elsewhere, are mechanically complex and require regular maintenance. Pulsed columns have the necessary performance within the the criticality size limits and experience at Marcoule (25) and elsewhere has shown them to be reliable. Therefore they have been selected (50, 95).

The instrumentation used in a reprocessing plant must be able to withstand the severe conditions encountered. Sight glasses, any probe, contact, transducer or material of construction susceptible to radiation damage and any instrument probe likely to corrode, and to drop off and block pipes is obviously not suitable. In fact, ideally instruments would not intrude into vessels at all. Hence the attraction of ultrasonics for level measurement, interface detection and concentration measurement (7). These techniques make use of the fact that the velocity of ultrasound varies according to the fluid and solute concentration within a liquid.

Pneumercators measure interface position by detecting the small pressure difference across the interface caused by the different fluid densities. For solvent continuous columns with an interface at the base, the large static head and the varying pressure caused by the fluid pulsing make the pneumerator signal rather difficult to decipher. Phillips (103) claims that BNFL have solved the problem by developing a very accurate simulation of the air flow/liquid behaviour interaction. It is however more usual (25) to have a separate bottom settler and allow the interface to form there.

An air-lift pump will draw both aqueous and solvent phases from the bottom of the column and lift them to the settler, via an air disengager. From the settler the fluids will overflow and gravity feed to other vessels; the solvent will be recycled to the column.

2.5.1 A Description of a Typical Fast Reactor Fuel Reprocessing Plant

In a proposed fast reactor reprocessing plant (145) nine pulsed columns are used, arranged in three cycles. In Cycle I, column 1 will be a compound extract/scrub column in which the uranium and plutonium are extracted into the solvent phase leaving the bulk highly radioactive fission products behind in the aqueous stream. An acid scrub suppresses fission-product carryover. In column 2 uranium and plutonium are stripped back into the aqueous phase using sulphuric acid. The solvent is washed and recycled and the highly active fission product stream is sent to waste treatment. Entering Cycle II, column 3 is a further extract/scrub column providing further decontamination. In column 4 use of one of the previously discussed partition agents results in the uranium remaining with the solvent phase whilst the plutonium transfers to the aqueous phase. In column 5 the uranium is stripped back into the aqueous phase using sulphuric acid. The solvent is washed and recycled and the medium active aqueous waste stream is sent for treatment. In Cycle III-V column 6 is another compound extract/scrub column in which the uranium is further purified. In column 7 the uranium is stripped back into the aqueous phase. Similarly in Cycle III-Pu, column 8 is a compound extract/scrub and column 9 is a strip column.

The two aqueous streams are concentrated by evaporation and stored prior to further treatment (to convert the uranium and plutonium to oxides) or shipping.

3 The Pulsed Plate Column

The pulsed column was first described by Van Dijk (130), whose major claim in the patent application concerned the use of mechanically reciprocated plates to impart a reciprocating motion to the fluids. He also described a mode of operation in which the plates would be held stationary and the liquid contents of the column pulsed by some external means. A typical pulsed plate column is illustrated in Figure 3.1.

In a pulsed plate column, sieve or nozzle plates extend across the whole column diameter so that unlike in conventional sieve plate columns there are no downcomers or risers for continuous phase transport. Counter current flow under gravity is assisted by pulsing the liquids through the perforations either directly through a cam driven bellows or by air pulsing through a pulse limb as described by Thornton (127). In the nuclear industry the reciprocating plate column has not been pursued as an option because the moving parts could present maintenance problems on active plants, i.e. it would have no practical advantage over a rotary agitated column.

3.1 Column Behaviour

Sege and Woodfield (115) were amongst the earliest workers to investigate the characteristics of the pulsed plate column. Using equipment and liquids as summarised in Table 3.1 they investigated the effect of hole diameter, plate spacing and plate free area on column performance. From initial trial runs they identified a standard cartridge of stainless steel plates spaced 5 cm apart perforated with 3.18 mm holes to give 23% free area which offered a reasonable compromise between the conflicting considerations of volumetric throughput and extraction effectiveness. Essentially a high volumetric throughput requires a large flow area but this will result in reduced efficiency, with increased axial mixing. Plate configurations have also been investigated by Geier (49) with similar results.

Thornton (128) studied the effect of plate spacing, plate geometry and waveform on the flooding point of pulsed columns. In the latter case sinusoidal, saw-tooth and semi-square waveforms were selected. Not surprisingly it was found that drop size was primarily affected by the maximum rate of energy dissipation during the cycle.

Many authors including Sege and Woodfield (115) Schmidt (114), Rouyer (112) and Batey et al (14) have observed the existence of different flow regimes in pulsed columns as indicated in Figure 3.1. Mixer-settler type operation occurs at low throughput and pulse velocity; the dispersed phase droplets coalesce during quiescent periods of the

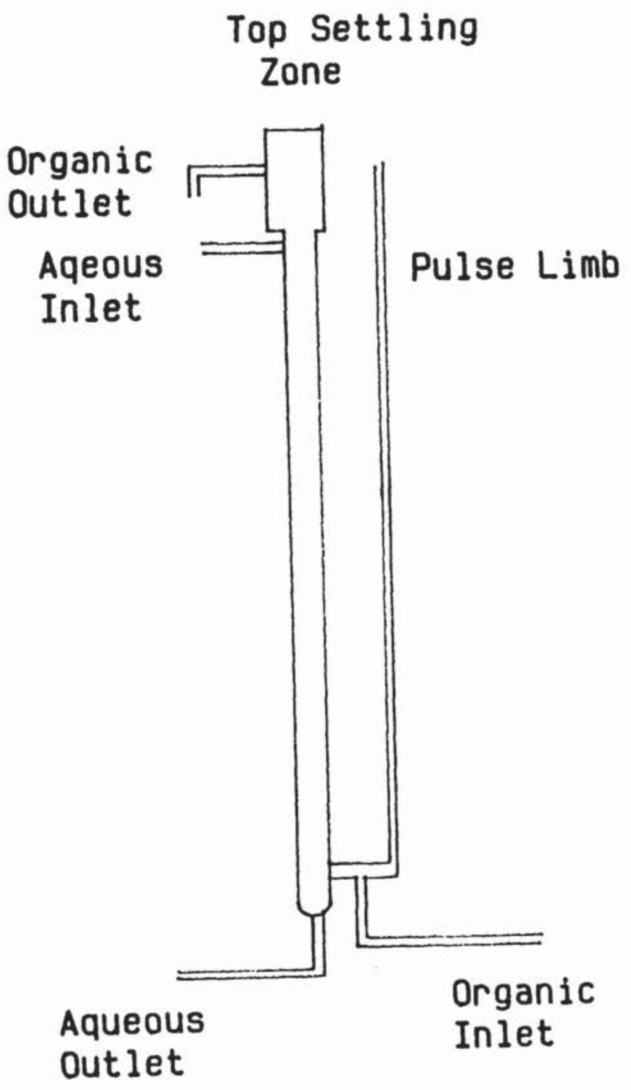


Figure 3.1 The Pulsed Column

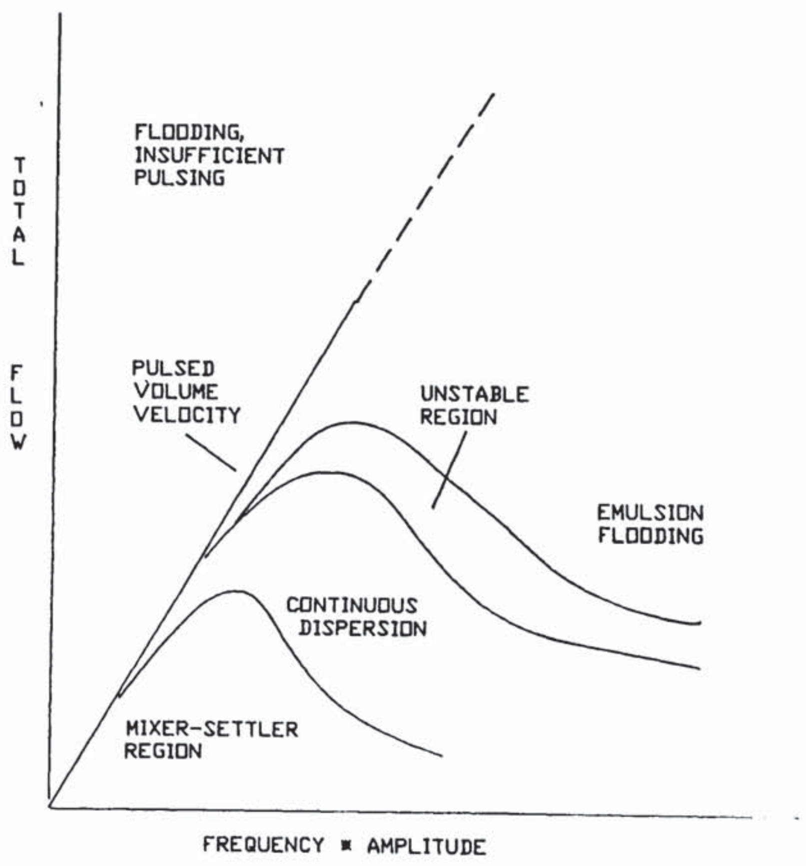


Figure 3.2 Pulsed Column Modes of Operation

TABLE 3.1

SYSTEMS AND COLUMN GEOMETRIES USED BY VARIOUS WORKERS

Reference	System	Column		Plates			Pulsing		Comments
		Height mm	Diameter mm	Hole Size mm	Free Area	Spacing mm	Frequency s^{-1}	Amplitude mm	
4	CCl_4 - H_2O	2000	50	2	0.20	50	Af = 2 - 8 cms^{-1}		Aqueous Continuous
5	CCl_4 - H_2O	1022	49	2.3	0.23	50	Af = 0.5 - 2.2 cms^{-1}		Surface active agent added. Aqueous Continuous
6	CCl_4 - H_2O	1022	49	2.3	0.23	50	Af = 0.5 - 2.2 cms^{-1}		Aqueous Continuous
9	Kerosene - H_2O	3000	150	14.3	0.61 Half Circle Segmental	27, 53	0.55 - 2.5	10 - 30	2 types of Plate with high E
10									
12, 13, 14	20%TBP/OK - 3N Nitric Acid	3000	72	3.175	0.23	50	Af = 1.27 - 2.6 cms^{-1}		Aqueous Continuous
15	n-hexane - water MIBK - water		50	3.18	0.23	56	0.3 - 3.3	0 - 75	Aqueous Continuous
20	kerosene/CCl_4 - water	1000	50	2	0.198	50	2 - 3	10 - 35	
29	20%/TBP/OK - water	1000 - 1200	6 - 50	3.18	0.24-0.28	50	0.33 - 3	5 - 50	Aqueous Continuous
36	40%TBP/OK - Uranyl nitrate - nitric acid	1000	40	2, 3	0.23	50	0.8 - 2.5	10 - 40	
39	CCl_4 - I_2 - H_2O	1022	48	2	0.18	50	1 - 3.66	9 - 34	
45	MIBK - water	1000	74	3.2	0.217	50	1, 1.5, 2.0	14	Aqueous Continuous
52	D2EHPA/5%TBP OK - C_OSO_4, $NiSO_4$	1190	101.6	2.38	0.148	76.2		5.1 - 19.1	Mixer-settler regime
56		2730	85	2 - 7	0.04-0.36		2 - 10	1 - 12	Vibrating Plate Column
64	30%TBP/OK - water	1000	50	3	0.2	40	1.2	1.6 - 7.1	Organic Continuous
68	Kerosene - H_2O CCl_4 - H_2O	4000	56	2	0.082	50	0.8 - 1.7	5 - 15	Aqueous Continuous
70	CCl_4 - I_2 - H_2O	1000	50	2	0.188	50	1 - 3.67	10 - 40	Aqueous Continuous

Reference	System	Column		Plates			Pulsing		Comments
		Height mm	Diameter mm	Hole Size mm	Free Area	Spacing mm	Frequency s^{-1}	Amplitude mm	
78	Toluene-acetone-water White Spirit-acetone-water		150,225, 300	3.18	0.25	50	2 - 4	6 - 15	Aqueous Continuous
83	Ferric nitrate in potassium thiocyanate soh	1500	50		0.23		0.3 - 3.0	0 - 125	Aqueous Continuous
88	Toluene - Water		76.2	4.76, 6.35	0.22,0.36	50,100	Af = 0.834 - 3.03 cms^{-1}		Aqueous Continuous
91	MIBK - Water	370,780, 860	32, 34	1.5, 3.0	0.095, 0.19	10 - 100	0.4 - 3.0	0 - 15	Aqueous Continuous
103	30% TBP/OK - Nitric Acid		150	4.5	0.23	50	Af = 1 - 4 cms^{-1}		Aqueous Continuous
112	30% TBP/OK - Nitric Acid 30% TBP/OK - Ethanol	4000	100-600	3 - 6	0.18-0.5	50 - 200	Af = 1.37 - 2.50 cms^{-1}		Wide Range of Operating Variables
115	TBP in various diluents - Nitric Acid	3000	75	1.5 - 4.76	0.1-0.4	50 - 100	Af = 0.8 - 2.96		Wide Range of Operating Conditions
116	Hexane, benzene, MIBK - water	2200	50	3.18	0.23	50	0.33 - 3.0	6.0 - 51	Aqueous Continuous
127	Toluene-acetone-water	1070	75	3.18	0.25	50	1 - 5	2 - 16	Aqueous Continuous
128	Toluene-water Butyl Acetate-water Ethyl Acetate-water MIBK-water Iso-Octane-water White Spirit-water	1070	75	3.18	0.13-0.62	50	1.5 - 3.5	6.35 - 22	Aqueous Continuous. Various Waveforms Used.

pulse cycle and the light and heavy phases separate into discrete layers in the inter-plate spacing. The hold-up is high at low pulse-frequencies and decreases with increasing frequency until a minimum is reached corresponding to the onset of the continuous dispersion mode of operation. Continuous dispersion type of behaviour is desirable for normal operation since it is associated with a high interfacial area, by generating a reasonably homogeneous dispersion, and a high degree of turbulence both of which promote mass transfer. A further increase in throughput and frequency leads to unstable operation characterised by the formation of large irregular blobs of dispersed phase and periodic inversions of continuous phase in short sections of the column. Schmidt (112) and Phillips (103) report the existence of high dispersed phase hold-up, sometimes in excess of 50%, without column flooding.

A loss of throughput with time has been reported by Coggan (29) and Schmidt (114) in columns operated continuously for prolonged periods. This was suggested to arise from a change in the wetting characteristics of the plates as some temporary improvement could be obtained by thorough cleaning of the columns. This is a phenomenon not generally reported in the literature, possibly because experimental rigs are used for short spells only and frequently cleaned, but it could cause operational difficulties on plant. For example, there is evidence that wetting of the internals of rotating disc contactors by the dispersed phase, due to an error in material selection or by displacement during operation or by a change in the contact angle due to solute concentration, will reduce both efficiency and volumetric throughput.

3.2 Column Hydrodynamics

3.2.1 Dispersed Phase Hold-up

Hold-up is defined as the volume fraction of dispersed phase present in the working section of the column. This parameter is of interest for,

(a) Calculation of the interfacial area available for mass transfer through the relationship:
Total interfacial area $A = a.V$ (3.1)
where 'a' is the specific interfacial area givenby;

$$a = \frac{6x}{d_{32}} \qquad (3.2)$$

(b) Estimation of the maximum volumetric flow, ie flooding;

(c) Estimation of the nuclear material inventory of a column.

Thornton (127) correlated hold-up with volumetric throughput using a characteristic velocity relationship of the form

$$\frac{Vc}{1-x} + \frac{Vd}{x} = \bar{V}_o \, (1-x) \tag{3.3}$$

Where $\bar{V}_o$, the characteristic velocity, is defined as the mean droplet velocity at zero continuous phase flow and very low dispersed phase flow. Thornton (127) points out that this approach is strictly only applicable where there is no droplet coalescence. The following expression is given for $\bar{V}_o$;

$$\frac{\bar{V}_o \; \mu_c}{\sigma} = 0.6 \left(\frac{\psi_f \mu_c^{5}}{\rho_c \; \sigma^4}\right)^{-0.24} \left(\frac{d_o \; \rho_c \; \gamma}{\mu_c^{2}}\right)^{0.9} \left(\frac{\mu_c^{4} \; g}{\Delta_\rho \; \sigma^3}\right)^{1.01} \left(\frac{\Delta\rho}{\rho_c}\right)^{1.80} \left(\frac{\mu_d}{\mu_c}\right)^{0.3} \tag{3.4}$$

This expression was obtained by dimensional analysis using hold-up data gathered from systems and column geometry as indicated in Table 3.1 and appears to fit the data to ±15%.

At the floodpoint both phase flow rates as functions of hold-up attain maxima. Therefore, rearranging equation (3.3) and differentiating with respect to x and equating $\frac{dVc}{dx}$ and $\frac{dVd}{dx}$ to zero yields the following expressions which may be used to estimate column throughput at flooding:

$$V_c = \bar{V}_o \ (1-2x_f) \ (1-x_f)^2 \qquad (3.5)$$

$$V_d = 2\bar{V}_o \ x_f^{\ 2} \ (1-x_f) \qquad (3.6)$$

and

$$x_f = \frac{(R^2 + 8R)^{0.5} - 3R}{4 \ (1-R)} \qquad (3.7)$$

where R is the flow ratio V_d/V_c at flooding.

Hussain et al (62) measured the characteristic velocity by injecting single droplets into pulsed and unpulsed columns. The following correlation was given:

$$\bar{V}_o/V_T = 1 - [d/(1+BS)d_o] - [fA/(1+0.78S) - (fA)^2/(1+2.6S) \qquad (3.8)$$

$$B = 0.275 + 0.365\ \varepsilon\ (\text{cm}^{-1}) \qquad (3.9)$$

(all linear dimensions are in centimetres). Over the range of conditions used in the tests, given in Table 3.1, the correlation is claimed to be accurate to ± 15%

Batey et al (14) used the characteristic velocity equation to correlate their data and also that of Vassallo (131, 132) and claim good agreement. The following two expressions are given for $\bar{V}_o$:

from Vasallo

$$\bar{V}_o = 0.0533 \exp - 43.4\ (fA) \qquad (3.10)$$

from Batey's data

$$\bar{V}_o = 0.146 \exp - 71.4\ (fA) \qquad (3.11)$$

The range of experimental conditions for which these expressions were derived are given in Table 3.1. All of the correlations and analyses using the characteristic velocity approach are only valid for the continuous dispersion mode of operation.

The effect of pulse frequency on column hold-up has been studied by Sehmel and Babb (116) for both the mixer-settler and continuous dispersion situations. The hold-up of the dispersed phase was found to pass through a minimum with increasing frequency; this was identified with a change in the mode of operation of the column from mixer-settler to continuous dispersion operation.

These authors showed that the transition frequency, f_t, corresponding to the minimum in the hold-up curve could be represented by an expression of the form:

$$f_t = 0.667\ (-3.373 + 388.3\ \mu_d\ \gamma\ \Delta\rho - \ln A) \qquad (3.12)$$

where the numerical constants were functions of the plate geometry and the material or construction. Furthermore, it was found that the holdup increased with the dispersed phase flowrate but that it was relatively insensitive to changes in the continuous phase flowrate. This finding has been confirmed by subsequent work (88).

Bell and Babb (15), using the same system as Sehmel and Babb (116), given in Table 3.1, gave the following parabolic form of expression which enables hold-up in both the mixer-settler and dispersion regimes to be calculated:

$$x = V_d \, (C_1 + (C_2 + C_3 \, V_c)(Af - C_4)^2) \qquad (3.13)$$

The values of the constants C_1 and C_2 are functions of physical properties and those of C_3 and C_4 are dependent on column geometry. These authors pointed out that the transition frequency predicted by equation 3.12 does not correspond to the required value of C_4 in their expression. Although no explanation was proffered there were small differences in the column geometries used. As the transition frequency phenomenon has been noted by many authors including (14, 15, 116) and it might be expected on physical grounds, it is surprising that Karpacheva et al (69) did not observe it at all.

Bell and Babb (15) used a shutter-plate technique to isolate sections of column and studied axial variations of hold-up. Whilst it was found that there were negligible axial variations under mixer-settler conditions, this was not so at high frequencies corresponding to continuous dispersion operation. In the latter case, axial variations could be significant for short columns consisting of twenty or less stages. Bell associated this effect with the appreciable column height required to establish a stable drop size distribution. By contrast, work by Rouyer et al (112), whilst confirming the end effect, indicated that axial variations could occur in columns up to 4 m in height. Ikeda (64), using an aqueous dispersed system, found some axial variation but no trend could be identified.

A number of empirical correlations are available (15, 71, 88, 90, 91) which represent hold-up as a function of the product (fA) and phase flowrates. Mishra and Dutt (88) examined the effect of plate geometry on hold-up and presented the following correlation:

$$x = 0.376 \; {\frac{(Af)^3}{S\beta}}^{0.27} \; V_d^{0.89} \; d_o^{-0.924} \tag{3.14}$$

Although the hole diameter in their series of experiments was only varied from 4.8 to 6.4mm, hold-up was reported to be strongly dependent on this parameter.

Miyauchi and Oya (91) developed a semi-empirical expression relating hold-up to design and operating variables. This is:

$$\text{for } K_1 < 0.0032, \; x = 493 \; K_1^{0.84} \; V_d^{0.67} \tag{3.15}$$

$$K_1 > 0.0032, \; x = 3.42 \times 10^6 \; K_1^{2.4} \; V_d^{0.67} \tag{3.16}$$

where $$K_1 = \left(\frac{Af}{(\beta S)^{0.33}}\right)\left(\frac{\mu_d^{\,2}}{\gamma \Delta\rho}\right)^{0.24} \qquad (3.17)$$

The derivation predicted that x should vary linearly with V_d but the best fit to the data was obtained using $V_d^{0.67}$. This deviation was ascribed to either erratic drop behaviour or significant drop coalescence at higher dispersed phase flowrates.

In an attempt to improve the equations developed by Miyauchi and Oya, Miao (90) correlated a large amount of experimental data using a polynomial regression based on a parabola. It proved impossible to develop a single expression which gave equally good results over the whole operating range of the column. Three separate expressions of the form:

$$x = P\,K_1^{\,m}\,V_d^{0.6667} \qquad (3.18)$$

were therefore proposed. The values of P and M depend upon the value of K_1 which is defined as in equation (3.17). It is however unlikely that any experimental data which might only be accurate to ±6% (14) would justify giving the values of the exponents and P to four decimal places.

The rate of energy dissipation per unit mass of mixed phase, E_1, was used by Kumar and Hartland (74) as a criterion to separate dispersion and 'emulsion' types of operation. These authors use the term 'emulsion' instead of the more common 'continuous dispersion' and 'dispersion' to mean that mode of column behaviour observed when the frequency of pulsation has been increased just enough to prevent mixer-settler operation. E is defined as follows:

$$E = \frac{(Af)^3}{\beta S} \; \frac{\rho_c}{\Delta\rho^{0.75} \; \sigma^{0.25} \; g^{1.25}} \tag{3.19}$$

As plate free area, plate spacing and hole diameter did not vary greatly over the 725 data points from the literature used in this study, these parameters were not included in Kumar and Hartland's expressions.

For $E < 0.05$

$$x = 6.91 \left(\frac{(Af)^3 \; \rho_c^{\,0.25}}{\beta S \; \sigma^{0.25} \; g^{1.25}} \right)^{0.31} \left(\frac{V_d^4 \; \rho_c}{g \; \sigma} \right)^{0.30} \left(1 + \frac{V_c}{V_d} \right)^{0.14} \left(\frac{\Delta\rho}{\rho_c} \right)^{-0.79} \left(\frac{\mu_d^{\,4} \; g}{\rho_c \; \sigma^3} \right)^{-0.01} \tag{3.20}$$

For E > 0.05

$$x = 3.73 \times 10^{-3} \left(\frac{(Af)^4 \rho_c}{g\ \sigma}\right)^{0.62} \left(\frac{V_d^{\,4} \rho_c}{g\ \sigma}\right)^{0.31}$$

$$\left(1 + \frac{V_c}{V_d}\right)^{0.45} \left(\frac{\Delta\rho}{\rho_c}\right)^{-2.20} \left(\frac{\mu_d^{\,4} g}{\rho_c\ \sigma^3}\right)^{-0.29} \qquad (3.21)$$

For the mixer-settler regime:

$$x = 3.91 \times 10^{-3} \left(\frac{A^2 \rho_c\ g}{\sigma}\right)^{-0.26} \left(\frac{f^4 \sigma}{\rho_c\ g^3}\right)^{-0.19}$$

$$\left(\frac{V_d^{\,4} \rho_c}{g\ \sigma}\right)^{0.28} \left(1 + \frac{V_c}{V_d}\right)^{0.19} \left(\frac{\Delta\rho}{\rho_c}\right)^{-0.81} \left(\frac{\mu_d^{\,4}\ g}{\rho_c\ \sigma^3}\right)^{-0.13} \qquad (3.22)$$

As A and f are split in equation (3.22) this suggests that energy dissipation is not the controlling factor for hold-up in mixer-settler type operation. Equations (3.20), (3.21) and (3.22) are rather cumbersome. Moreover column diameter does not appear in any of these expressions. Most workers have been limited to one column but Rouyer et al (112) using 100 mm, 300 mm and 600 mm columns found that column diameter had no effect on hold-up.

All the equations given above were derived from studies with mutually-saturated phases ie under conditions of non mass transfer. In the real situation therefore, effects due to varying solute concentration, ie differences in interfacial tension and in extreme cases phase flow rate, along the column will be superimposed upon them.

Khemangkorn et al (70) did study hold-up under conditions of mass transfer. The four expressions given for hold-up which were dependent on the direction of mass-transfer and the pulse velocity could all be written in the form:

$$x = P\ (Af^{1.24})^m\ V_d^{\ n} \qquad (3.23)$$

As there is no term in (3.23) to account for mass flux many of the comments made in the foregoing paragraph will still apply.

3.2.2 Droplet Size

A knowledge of droplet sizes and size distribution is important in the design of extraction columns since they affect the rate of drop rise (or fall), the interfacial area through equation (3.2), and the manner in which individual droplets partake in the mass transfer process ie whether they are stagnant, circulating or oscillating.

Numerous correlations relating drop size to operating conditions and physical properties are available in the literature (4, 5, 17, 68, 91, 131, 14, 71).

Asenov and co-workers (5,6) using the systems detailed in Table 3.1 (at the end of Section 3) investigated the effect of pulsation intensity and surfactant concentration on drop size. The results were presented as correlations of the following form:

$$\bar{d}_{32} = B \left(\frac{\sigma}{\Delta\rho \ g} \right)^{0.5} \left(\frac{(Af) \ \mu_c}{\sigma} \right)^{-0.5} N^{-0.1} \qquad (3.24)$$

The value of B is a function of surfactant concentration. The authors claim that the correlation is accurate, over the range of variables considered, to ± 20%. Equation 3.24 is suspect in that the value of B would also be specific to the surfactant used.

Based on the Kolmogoroff theory of the local structure of turbulent pulsation, Boyadzhiev and Spassov (20) present the following expression:

$$\bar{d}_{32} = (0.57 \pm 0.11) \left(\frac{\sigma}{\rho_L} \right)^{0.6} \varepsilon^{0.8} \left(\frac{d_o}{(2\ Af)^3} \right)^{0.4} \tag{3.25}$$

Comparison of predicted drop sizes and those measured using a system with details as given in Table 3.1 gave an accuracy of ± 20% for the correlation. The authors point out that the effects of mass transfer and the presence of surfactants had not been examined.

Kagan et al (68) used a correlation which had been adopted from one describing drop size in a Rotating Disc Contactor:

$$\bar{d}_{32} = 9.2 \times 10^{-3} \left(\frac{\sigma}{\rho_c\ g} \right)^{0.5} Re^{-0.1} \ Fr^{-0.1}\ N^{-0.11} \tag{3.26}$$

$$\text{where } Re = \frac{(Af)\ do\ \rho_c}{\mu_c} \tag{3.27}$$

$$\text{and } Fr = \frac{(Af)^2}{g\ d_o} \tag{3.28}$$

This correlation is claimed to be accurate to within ± 15%.

Using Kolmogoroff's concept of local isotropy together with Jealous and Johnson's analysis of the power dissipation in a pulsed column (67) Miyauchi and Oya (91) presented the following expression:

$$\bar{d}_{32} = 2.0 \times 10^{-5} \left((Af)/S^{0.33}\right)^{-1.2} \qquad (3.29)$$

As only one system was used, MIBK-water, and because plate geometry remained constant physical property and geometry parameters do not appear in the correlation.

Gondo and Matsuda (53) developed the following correlation specifically for pulsed columns:

$$\bar{d}_{32} = (B + 25.7V_d^{3.33})\ (d_o)^{0.7}\ (S)^{0.4}\ (Af)^{-0.313} \qquad (3.30)$$

This expression is surprisingly poor when compared to experimental data from Vassallo (131), with typically an error of ± 400%. This may, in part, be due to using the correlation well beyond its limit for dispersed phase flowrate.

It is clear from the foregoing that there is considerable confusion in this area. Drop size may be proportional to $(Af)^{-0.3}$ or proportional to $(Af)^{-1.2}$ a considerable difference.

As Vassallo (131) finds little evidence of varying drop size along the column it is difficult to explain why plate number should appear in several correlations.

Batey et al (14) present a much simpler expression:

$$\bar{d}_{32} = \overset{o}{d}_{32} + m(X) \tag{3.31}$$

$\overset{o}{d}_{32}$ is the droplet size as X → 0. The coefficient m is a function of (fA). As there are no terms in equation (3.31) to account for physical properties or plate geometry this expression would be specific to the experimental conditions for which it was derived. $\overset{o}{d}_{32}$ is measured experimentally.

Droplet coalescence and breakage rates in a pulsed column were modelled by Garg and Pratt (45) based on data gathered using a colorimetric technique (57). They found that the effect of polydispersivity on column performance was surprisingly small, suggesting that using the Sauter mean diameter in column design would give equally good results as including a drop size distribution. This is contrary to experience with Rotating Disc and conventional Sieve Plate Columns and an obvious explanation is that the applied pulsation induces local velocities which result in internal circulation or oscillation for even relatively small droplets.

3.3 Mass Transfer

In liquid-liquid extraction a solute is transferred from one liquid solvent to another across a phase boundary. Distribution data give information on concentration levels in the two phases at equilibrium but give no indication of the rate at which this equilibrium is established.

The simplest theory of mass transfer between two liquid phases across an interface was advanced by Whitman (140) as the Two Film Theory. The two postulates of this theory are:

1) that resistance to mass transfer lies in two stagnant films, one on each side of the interface;

2) that the phases are at equilibrium at the interface.

Mass transfer across the stagnant films is by the relatively slow process of molecular diffusion. Outside the films a uniform, bulk concentration exists as a result of eddy diffusion. The situation is illustrated in Figure 3.2.

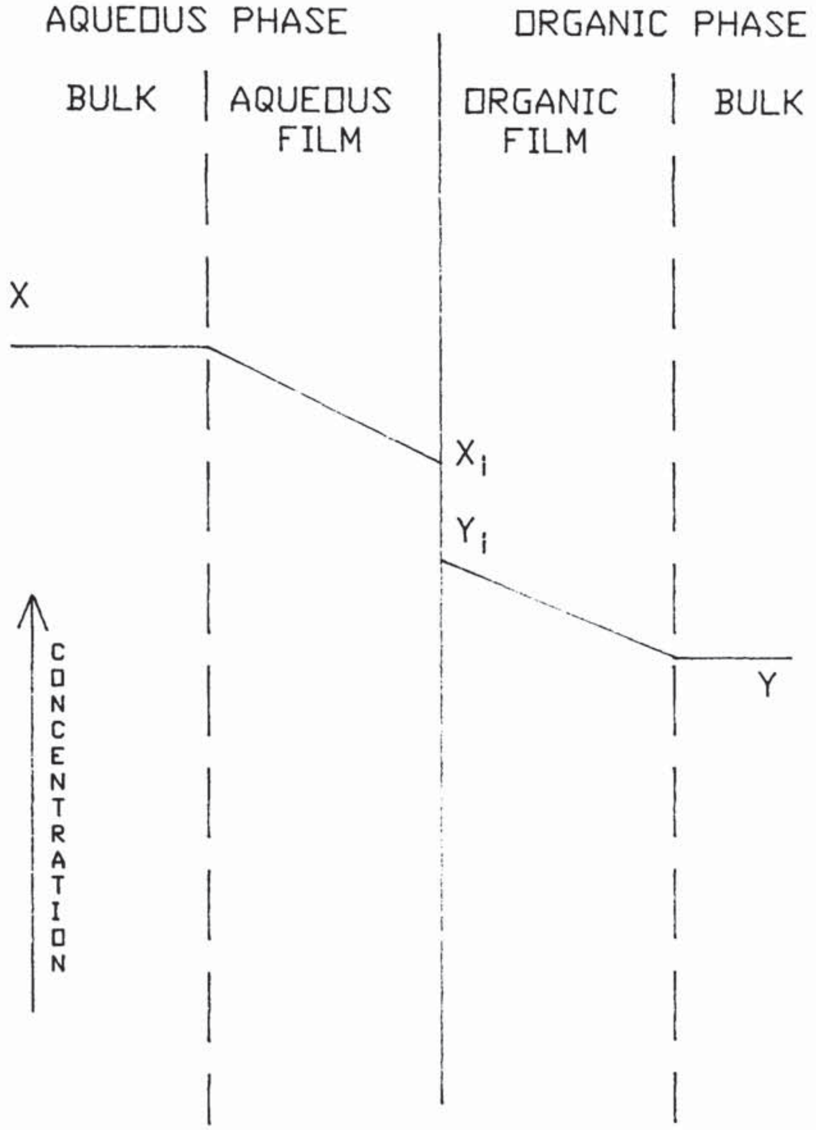


Figure 3.3 The Two Film Theory of Mass Transfer

The rate of mass transfer in each phase is proportional to both the interfacial area and the concentration driving force.

The rate of mass transfer $= k_x a\ (x - x_i) = k_y\ a\ (y_i - y)$ (3.32)

As concentrations at the interface cannot be measured the following form is used:

$$\begin{aligned}\text{Rate of mass transfer} &= K_{ox} a\ (x - x^*) \\ &= K_{oy} a\ (y^* - y)\end{aligned} \tag{3.33}$$

where

$$(y^* - y) = (y_i - y) + m\ (x - x_i) \tag{3.34}$$

Therefore

$$\frac{1}{K_{oy}} = \frac{1}{k_y} + \frac{m}{k_x} \tag{3.35}$$

and

$$\frac{1}{K_{ox}} = \frac{1}{mk_y} + \frac{1}{k_x} \tag{3.36}$$

3.3.1 Dispersed Phase Mass Transfer Coefficients

For droplets moving in a gravitational field there are three distinct regimes of mass transfer. At low drop Reynolds numbers, corresponding to small drops, liquid drops behave essentially as rigid spheres. As droplet size increases internal circulation begins. For large drops with high Reynolds numbers, $Re_d > 150$-200, the droplet oscillates between a prolate and oblate spheroidal form.

For rigid droplets mass transfer takes place relatively slowly by molecular diffusion. If there is no resistance to transfer in the continuous phase the extraction efficiency E is given by Newman (97) as:

$$E = 1 - \frac{6}{\pi^2} \sum_{n=1}^{n=\infty} \frac{1}{n^2} \exp - \frac{4n^2 \pi^2 Dt}{d^2} \qquad (3.37)$$

Comparison with the two film theory gives a mass transfer coefficient:

$$k_d = - \frac{d}{6t} \ln_e \frac{6}{\pi^2} \sum_{n=1}^{n=\infty} \frac{1}{n^2} \exp - \frac{4n^2 \pi^2 Dt}{d^2} \qquad (3.38)$$

$$\approx \frac{d}{6t} \ln_e 1 - \frac{2\pi \sqrt{Dt}}{\alpha} \qquad (3.39)$$

Where droplet circulation occurs, Re > 10, and there is negligible continuous phase resistance Kronig and Brink (73) found that

$$E_m = 1 - \frac{3}{8} \sum_{n=1}^{n=\infty} B_n^2 \exp - \frac{64\lambda\ Dt}{d^2} \qquad (3.40)$$

An appropriate solution is

$$k_d = \frac{d}{6t} \ln_e \frac{3}{8} \sum_{n=1}^{n=\infty} B_n{}^2 \exp - \frac{64\lambda_n Dt}{d^2} \qquad (3.41)$$

$$\approx 17.9 \frac{D}{d} \quad (t \rightarrow \infty \text{ from reference (23)}) \qquad (3.42)$$

Handlos and Baron (58), assuming negligible resistance in the continuous phase presented the following:

$$k_d = \frac{\lambda_1\ V}{768\ (1 + \mu_d/\mu_c)} \qquad (3.43)$$

where $\lambda = 2.88$ and V is the droplet velocity. When the continuous phase resistance is not negligible and the contact time is short Wellek and Skellend (139) gave correction factors for λ. Skellend and Wellek (119) presented the following empirical correlation for conditions where repeated coalescence and dispersion occur:

$$k_d = 31.4 \frac{D}{d} \left(\frac{4Dt}{d^2} \right)^{-0.34} \left(\frac{\mu d}{\sigma D} \right)^{-0.125} \left(\frac{dV^2 \rho_c}{\sigma} \right)^{0.37} \qquad (3.44)$$

Large oscillating drops may be completely mixed by vigorous oscillations and this gives rise to mass transfer coefficients up to 20 times those for stagnant drops. Determining a realistic value for 't' may in practice present some difficulty.

Rose and Kintner (111) assumed that complete mixing of the droplet occured at each oscillation. These authors took the age of a fluid element at the interface to be characterised by the time taken for one oscillation cycle and thereby calculated the dispersed phase mass transfer coefficient from Higbie's Penetration theory.

$$k_d = 0.45 \, (2\pi\omega D)^{\frac{1}{2}} \qquad (3.45)$$

where ω is the number of cycles per second.

An empirical correlation for oscillating drops was given by Skellend and Wellek (119):

$$k_d = 0.32\,\frac{D}{d}\left(\frac{4Dt}{d^2}\right)^{-0.14}\left(\frac{\rho_c\, dV}{\mu_c}\right)^{0.68}\left(\frac{\sigma^3\rho_c{}^2}{3\mu_c{}^4\Delta\rho}\right)^{0.1} \quad (3.46)$$

As this expression does not require knowledge of the droplet oscillation mode it may be useful for the analysis of pulsed column mass transfer.

3.3.2 Mass Transfer in the Continuous Phase

One of the major difficulties encountered in calculating the continuous phase mass transfer coefficient is the estimation of the drop wake contribution. As a drop passes through the continuous phase it drags a wake of liquid behind it causing a variation in concentration in the continuous phase around it. Frequent wake shedding as a result of droplet oscillation and agitation of the continuous phase promotes mass transfer by keeping the concentration driving force high around the droplet.

The correlation of Rowe, Claxton and Lewis (113) for rigid drops is:

$$Sh = 2.0 + 0.76\ Re^{0.5}\ Sc^{0.33} \qquad (3.47)$$

For circulating drops a number of equations have been proposed but their applicability is uncertain. A survey was presented by Godfrey (51).

In general the empirical correlation of Garner, Foord and Tayeban (47) is recommended for larger, non-rigid drops:

$$Sh = -126 + 1.8\ Re^{0.5}\ Sc^{0.42} \qquad (3.48)$$

3.3.3 Interfacial Area

Knowledge of the hold-up in an extraction column will give the volume of dispersed phase per cubic working metre of column. As the mean droplet diameter can be predicted the drop volume can be estimated.

Number of drops per unit volume, $n_d = \frac{x}{V_d}$

Where V_d is the volume of a single drop

Thus;

Interfacial area per unit volume $A = n_d a_d$

3.3.4 Mean Concentration Driving Force

The concentration driving force depends on the shapes of the equilibrium and operating lines for a given application. Backmixing which is discussed in Section 3.5 reduces the available driving force as indicated in Figure 3.4. For multi-solute systems a further difficulty in estimating the mean concentration driving force is introduced if the equilibrium concentration of a particular solute is a function of the other solutes present.

3.3.5 Mass Transfer Performance of Pulsed Column

In most cases mass-transfer performance of pulsed columns has been reported in terms of overall mass transfer coefficients, or as height of transfer unit, without correction for axial mixing. As these are system specific the application of correlations to other systems, and to other scales of operation, can be of uncertain accuracy.

The apparent height of transfer unit sometimes exhibits a minimum value in the dispersion regime because at high pulse velocities increased axial mixing may be more important than decreasing drop size, increasing interfacial area and increasing mass-transfer coefficients

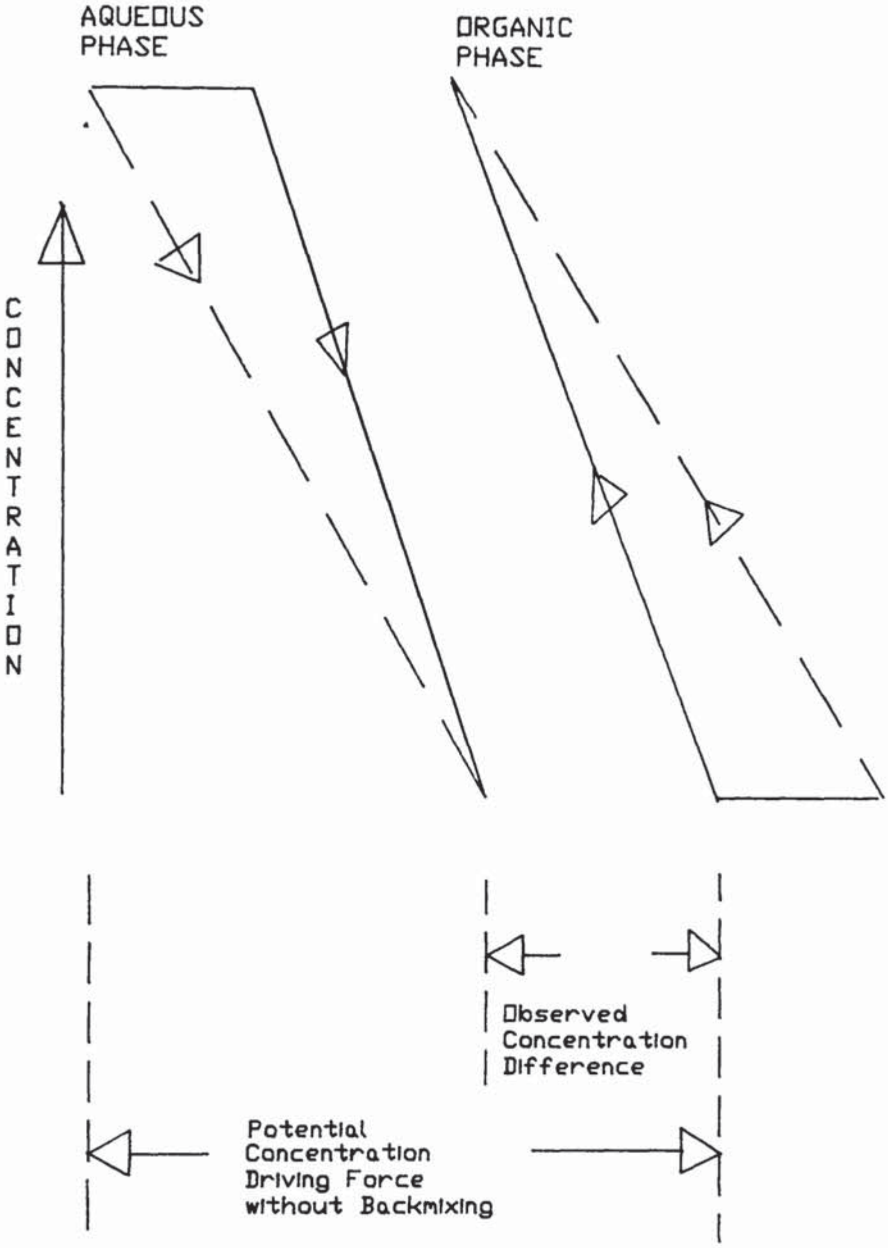


Figure 3.4 The Effect of Backmixing on Concentration Driving Force

(112, 115, 121, 128). Elenkov et al (39) however, claim that this effect is caused by a reduction in the overall mass-transfer coefficient at higher pulse velocities.

Smoot and Babb (121) correlated overall transfer units using MIBK - acetic acid - water with the organic phase dispersed and solute transfer from the dispersed to the continuous phase. The results were corrected for axial mixing:

$$H_{oc} = 504\, H_c \left(fA \frac{do\, \rho_d}{\mu_d}\right)^{-0.4} \left(\frac{V_c}{fA}\right)^{0.43} \left(\frac{V_c}{V_d}\right)^{0.56} \left(\frac{do}{H_c}\right)^{0.62} \tag{3.49}$$

Based on 285 experiments by various investigators Smoot et al (122) presented the following correlation:

$$H_{oc} = \frac{10.4\, V_c^{0.54}\, d_c^{0.32}\, H_c^{0.68}\, \sigma^{0.097}\, \Delta\rho^{1.04}}{D^{0.865}\, (fA/S)^{0.43}\, d_o^{0.43}\, \rho_d^{2.43}\, \mu_d^{3.27}\, V_d^{0.64}} \tag{3.50}$$

Equation 3.50 is valid only for the emulsion regime, and applies only to steel sieve plates and only to cases where the mass transfer direction is from the solvent dispersed to an aqueous continuous phase.

Thornton's (128) correlation for H_{oc} is:

$$H_{oc} = b\,(\mu_c{}^2/g\rho_c{}^2)^{0.33}\,(\mu_c g/\bar{V}_o{}^3\,(1-x)^3\,\rho_c)^{2m/3}.$$

$$.\ (\Delta\rho/\rho_c)^{(2/3)(m-1)}\,(V_d/V_c)^{0.50}$$

$$.\ (V_c{}^3\,\rho_c/g\,\mu_c\,x^3)^{0.33} \qquad (3.51)$$

For toluene-acetone-water and butyl acetate-acetone-water, m was 0.5 for mass transfer from continuous aqueous to organic dispersed. For the reverse direction m was 0.25. For the toluene systems b was approximately 3 x 10^3 (both directions) and 1.3 x 10^3 for the butyl acetate system.

Logsdail, in Lo (76) compared the values of H_{oc} predicted by various correlations with those obtained from single droplet correlations for the MIBK-acetic acid-water system. Considerable disparities were observed between the various correlations and the single drop models, typically up to 400%. Logsdail also examined the effect of increased pulse velocity upon the predicted values of H_{oc} and found a slight decrease with increased agitation.

Coggan (29) showed that increased agitation mainly affects interfacial area and has little effect on film mass-transfer coefficients.

No clear trend emerges for the effect of increased column diameter on mass transfer performance. Sege and Woodfield (115) found no scale-up effect between 75 mm and 200 mm columns but a fourfold increase of H_{oc} when the column diameter was increased from 75 mm to 600 mm. Logsdail and Thornton (78) found a 30% increase on increasing the diameter from 150 to 300 mm and suggested that $H_{oc} \alpha \exp (d_c/2)$ but this would lead to serious overestimation of the effect for columns much larger than 300 mm. Rouyer et al (112) reported that the variation in transfer unit height for diameters of 50 - 300 mm is not marked. The behaviour of different chemical systems and the effects of axial mixing may be sufficient to account for these varying observations. Values for H_{oc} will vary within a column if drop size or holdup vary and if the equilibrium line is curved.

Khemangkorn et al (70) studied the effect of mass-transfer direction on column performance for a single system but the results cannot be generalised.

From the foregoing discussion it is apparent that to design a column using published H_{oc} correlations could lead to a wildly erroneous final design. In these circumstances it would be preferable to use the fundamental equation describing mass transfer, equation 3.33, for design.

3.4 Backmixing

Backmixing is a deviation from ideal, piston flow. It adversely affects the extraction performance of a contactor by causing a reduction in the mass transfer driving force.

There are two mass transfer models which include backmixing. The stagewise model assumes that the contactor may be divided into a series of perfectly mixed cells whilst the diffusion model assumes the contactor to be truly continuous. These two models are described by Miyauchi and Vermeulen (92, 93) who also give some analytical solutions (93). Pratt (104, 105, 106) gives simplified solutions to the problem of designing backmixed contactors.

Mar and Babb (83) investigated backmixing in a 51 mm internal diameter pulsed column with the free area of the plates kept at 23%. Water was used as the continuous phase in all runs. Their results were correlated by means of the following expression:

$$\frac{E_c}{V_c d_o} = 0.0356 \left[\frac{\mu_c}{\rho_c V_c t}\right]^{1.45} \left[\frac{t}{d_o}\right]^{0.7} \left[\frac{s}{t}\right]^{0.68} \left[\frac{V_d \rho_c t}{\mu_c}\right]^{0.30} \left[\frac{\sigma \rho_c t}{\mu_c^{2}}\right]^{0.42} \left[\frac{f \rho_c t}{\mu_c}\right]^{0.36} \left[\frac{A}{t}\right]^{0.07} \quad (3.52)$$

From the small powers of 0.36 attached to frequency and of 0.07 attached to amplitude it appears that backmixing was almost independent of pulsing.

Smoot and Babb (121) studied longitudinal mixing in a 500 mm diameter pulsed perforated plate column and gave results as ratios of 'piston' to 'true' values of the HTU. They found that for water-acetic acid - MIBK the ratio was highly dependent on frequency and amplitude but for the water-acetone - 1, 1, 2 trichloroethane system it was virtually independent of frequency.

The authors suggest that this is because in the latter case the organic droplets fell rapidly through the column with little mixing.

Sehmel and Babb (116) showed that backmixing in the continuous phase is a function of dispersed phase holdup. The longitudinal dispersion coefficient passed through a maximum as the column transferred from the mixer-settler to the continuous dispersion mode of operation.

Miyauchi and Oya (91) correlated their data for both single and two-phase flow in 3.2 and 5.4 cm diameter columns in terms of the dispersion coefficient for the continuous phase as follows:

$$\frac{E_c}{AfxS} = \left[\frac{V_c}{afx}\right] \left[\frac{1}{2\beta - (1/n_p)}\right] + \frac{1}{\beta}$$

where β is the number of "perfectly mixed stages" per compartment given by

$$\beta = 0.57\, d_c^{0.667}\, S^{0.333} \left[\frac{\varepsilon}{d_h}\right] \qquad (3.54)$$

β generally has a value of between 1 and 2, that is there are 1 or 2 vortices formed betwen each pair of plates. However, for 'standard' geometry cartridges where $S = 5$ cm, $\varepsilon = 0.23$ and $d_h \approx 0.3$ cm then β is greater than 2 for $d_c > 4$ cm. Their data for dispersed phase backmixing was correlated in a similar manner. For the fixed plate spacing the data approached a line calculated from equation (3.53) as the pulse velocity Af increases suggesting that the dispersed phase approached an ideal backflow model with increasing pulse velocity.

Steiner et al (123) have recently presented models for the performance of columns based on actual drop behaviour.

The effect of column diameter on backmixing in pulsed plate columns has been noted by Sege and Woodfield (115). The HTU was found to pass through a minimum with increasing pulse intensity due to the competing effects of increased interfacial area and increased continuous phase backmixing. A combination of equations (3.53) and (3.54) indicate that backmixing should decrease as diameter increases which is not in agreement with the mass transfer data of Thornton (128), Logsdail and Thornton (78) and Sege and Woodfield (115). Garg and Pratt (46) using the data of Logsdail and Thornton (78) and Thornton (128) developed the following expression:

$$\alpha_c = d_c^{0.802} (Af)^{0.101} (0.170 + 0.302\ V_d/V_c) \qquad (3.55)$$

α_c and E_c can be related as shown by Miyauchi and Vermeulen (92) by:

$$\frac{1}{P_cB} = \frac{V_cL}{E_c} = \frac{1}{n_p} (\alpha_c + 1/2) \qquad (3.56)$$

It can be deduced from equation (3.55) that column diameter has a strong effect. The effect of pulse intensity is very weak as shown by the exponent of 0.101. In contrast the effect of the flow ratio is large. The authors explain these observations by quoting previous work which showed that continuous phase backmixing is largely caused by circulatory flow induced by the droplets dissipating their potential energy. Thus the relative flow rate of dispersed phase would be expected to influence the backmixing in a major way but the degree of dispersion would not. The authors suggest that the equation be used to generate relative rather than absolute values of α_c. It would be desirable to have an equation for backmixing coefficient that included system physical properties as well as the effect of diameter.

Balasubramanium (10) have studied backmixing in single phase flow. The dispersion coefficient was found to increase linearly with a^2f and to increase with either flowrate until a maximum was reached after which it fell. The authors suggested that this was due to a limiting eddy size.

4 Dynamic Simulation of a Pulsed Column

4.1 Previous Work

One of the earliest contributions to dynamic simulation of pulsed columns is that of Diliddo and Walsh (32). The model they developed applied only to mixer-settler operation of the column. Further, the method used to model mass-transfer rendered the model specific to the system, described in the previous Chapter, used by Sege and Woodfield (115). Variables such as drop size and holdup were not included nor was the model tested against experimental data.

Biery and Boylan (17) presented nine models of varying complexity to describe the behaviour of pulsed columns. Apart from the simplest model, in which it was assumed that the column could be represented as a series of equilibrium stages, mass transfer was modelled using:

$$N = (K_{oy}a)\ V\ (y^* - y) \qquad (4.1)$$

In all the models the flowrate of both the organic and aqueous phases was assumed to be independent of position in the column. Also, dispersed phase holdup was assumed to be independent of solute concentration and time. The $(K_{oy}a)$ term was assumed to be a function of column height but not of concentration or time. The models were all tested against experimental data and all but one were claimed to give reasonable agreement. The simpler models did not give as good a reproduction of the experimental data as did the more complicated models.

The dynamic behaviour of a pulsed plate extraction column was studied by Watjen and Hubbard (138). The theoretical differential model they developed was solved analytically using finite difference techniques and Laplace transforms. Flowrates of both phases, distribution coefficient and interfacial area per unit volume were all assumed to be constant. Mass transfer was dealt with by using a stage efficiency relationship. The resulting transfer functions were compared with experimental data collected using a 3/4" ID column with the system MIBK - acetic acid - water. The results highlighted the need for precise experimental techniques, such as continuous analysis of system response, and for more sophisticated models.

A stagewise model developed by Foster et al (43) predicting transient changes in hold-up was compared with experimental results for an MIBK - water system in a 2" column. The major assumptions were that phase flowrates remained constant throughout the column, that the dispersed phase droplets - assumed always to be organic - were all of the same size and that a slip velocity correlation could be used to relate hold-up to operating conditions. Reasonable agreement between model and experiment was claimed except for a lag following disturbances which was ascribed to slow droplet coalescence behaviour in the experimental system used.

A multi-solute stagewise model with backmixing was developed by Haas (46) to describe the behaviour of a compound extract-scrub column and a stripping column as might be used in a PUREX type process. Experimental data was collected for the TBP/OK - uranium - nitric acid system in two pulsed columns. A 2" diameter column was used for extract/scrub runs and a 3" column for stripping runs. Both columns were fitted with standard cartridges - that is stainless steel plates with 23% free surface area and 3.18 mm holes on a 2" pitch. Phase flowrates were allowed to vary with stage number, where a stage comprises that volume of liquid between the adjacent plates. Mass transfer was modelled using the fundamental equation 4.1. No indication is given of how hold-up, interfacial area or mass transfer coefficient are estimated for use in the model. Agreement between model and experiment for the uranium inventory of the column is good for extract and scrub columns, ± 2-20%, but poor for the stripping column runs. No explanation was offered for this phenomenon.

A similar model was originally presented by Wilkinson and Jones (142, 143) and solved by Ingham and Dunn (65). Work, done under contract to BNFL and UKAEA, and referred to in (40) describes an apparently similar model BRADSIM. No indication was given of how hold-up, drop size etc were calculated within the model.

The increasing complexity of models such as those presented by Haas and Ward over those described by Biery and Boylan and Foster et al has been made possible by increased computer power. Allowing further sophistication such as varying hold-up, drop size, and possibly the implicit solution of the two film mass transfer coefficients for each stage would require yet more power. Such models might be useful in design but could be far too slow to run in plant models or in real-time training simulators.

None of the models discussed above consider drop size distribution rather than $\bar{d}_{32}$. The pulsation within a pulsed column will subject droplets to constantly varying forces throughout the pulse cycle which may induce circulation or oscillation within droplets at lower Reynolds number than for other types of equipment. Garg and Pratt (45) showed that the effect of polydispersivity on pulsed columns performance was small.

Models of pulsed columns fall into two groups; the stagewise and differential models. These will be further discussed.

4.2 The Stagewise Model

The operation of a pulsed column is illustrated in Figure 4.1 using the stagewise model. The column is divided into N cells each containing a mixture of aqueous and organic phases. Each cell is assumed to be perfectly mixed. H is the fraction of the total cell volume occupied by the aqueous phase.

The dynamic mass balance for a component in a particular phase is given by:

This model is described in Chapter 6 of (76) and by Gonda and Matsuda (146).

$$\begin{bmatrix} \text{Rate of} \\ \text{Accumulation} \end{bmatrix} = \begin{bmatrix} \text{Rate of Flow} \\ \text{in} \end{bmatrix} - \begin{bmatrix} \text{Rate of Flow} \\ \text{Out} \end{bmatrix} \pm \begin{bmatrix} \text{Rate of Mass} \\ \text{Transfer} \end{bmatrix} \qquad (4.2)$$

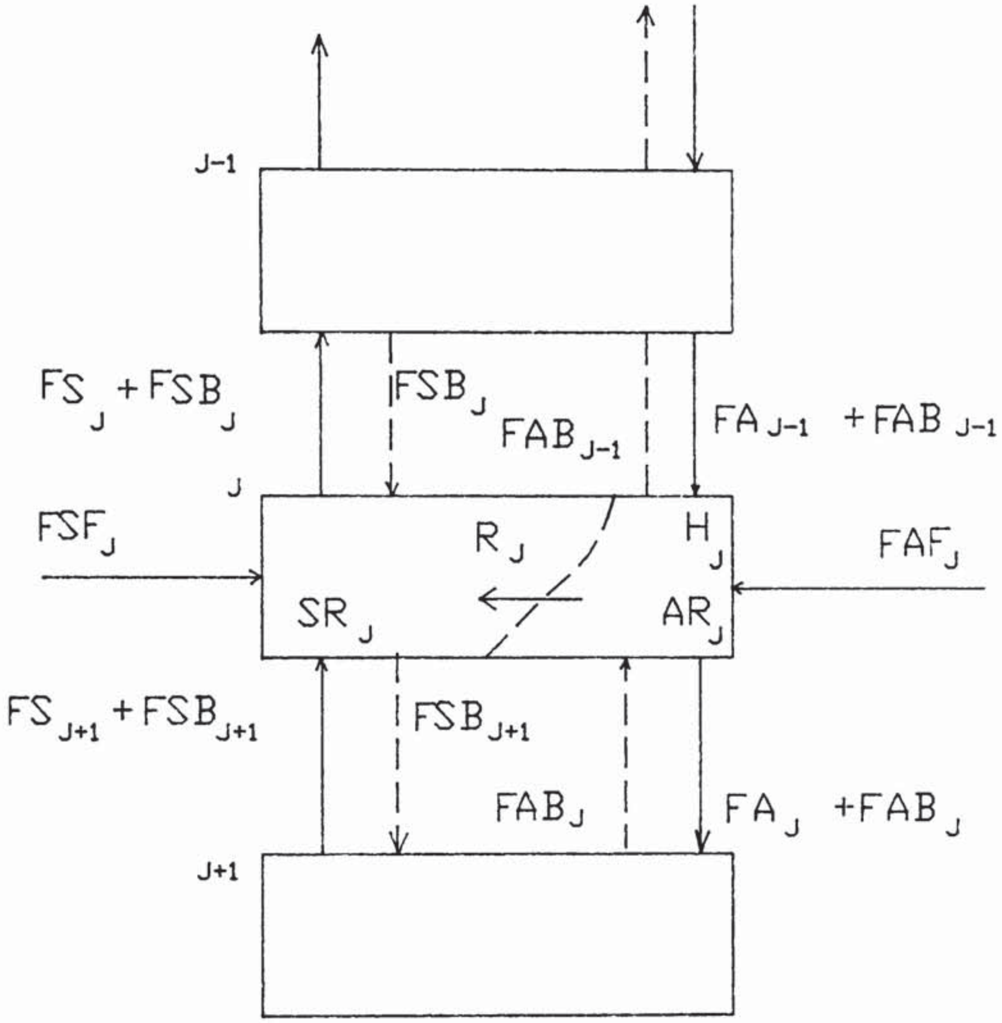


Figure 4.1 The Stagewise Model

$$\text{Rate of Accumulation} = \frac{d}{dt}(V_j\ H_j\ X_j^i) \tag{4.3}$$

Rate of Flow In = Bulk Flow In + Backflow + Feed Stream

$$= (FA_{j-1} + FAB_{j-1})X_{j-1}^i + FAB_jX_{j+1}^i + FAF_j\ C_j^i \tag{4.4}$$

Rate of Flow Out = Bulk Flow Out + Backflow

$$= (FA_j + FAB_j)X_j^i + FAB_{j-1}X_j^i \tag{4.5}$$

$$\text{Rate of Mass Transfer} = R_j^i \tag{4.6}$$

Substitution of equations 4.3 - 4.6 into equation 4.2 gives:

$$\frac{d}{dt}(V_jH_jX_j^i) = (FA_{j-1} + FAB_{j-1})X_{j-1}^i + FAB_j\ X_{j+1}^i + FAF_jC_j^i$$

$$- ((FA_j + FAB_j)X_j^i + FAB_{j-1}X_j^i) - R_j^i \tag{4.7}$$

Assuming constant cell volume, equation 4.7 can be rearranged to give:

$$\frac{d}{dt}(X_j^i) = \frac{1}{V_j H_j}\{(FA_{j-1} + FAB_{j-1})\ X_{j-1}^i + FAB_j X_{j+1}^i + FAF_j\ C_j^i$$

$$- ((FA_j + FAB_j)\ X_j^i + FAB_{j-1}\ X_j^i) - R_j^i\} - \frac{X_j^i}{H_j}\ \frac{dH_j}{dt} \qquad (4.8)$$

Similarly for the organic phase:

$$\frac{d}{dt}(Y_j^i) = \frac{1}{V_j(1 - H_j)}\{FS_{j+1} + FSB_{j+1}(Y_{j+1}^i + FSB_j\ Y_{j-1}^i +$$

$$FSF_j SC_j^i - ((FS_j + FSB_j)Y_j^i + FSB_{j+1}Y_j^i) + R_j^i\}$$

$$+ \frac{Y_j^i}{(1 - H_j)}\ \frac{dH_j}{dt} \qquad (4.9)$$

An overall mass balance on a cell would allow hydrodynamic factors to be taken into account.

Figure 4.2 is an outline flow diagram for a solution algorithm to such a model.

Clearly the model must also include a holdup correlation; a means of calculating the rate of mass transfer; a drop size correlation for the calculation of interfacial area; a parameter for axial mixing. As these factors have all been discussed in Chapter 3 they will not be re-examined in detail here.

4.3 The Diffusion Model

The diffusion model has been discussed by Miyauchi and Vermeulen (92, 93), Sleicher (120), and Gonda and Matsuda (146). The column is divided into N finite elements of thickness ΔZ which may be constant or vary along the column length. Consider such an element j as illustrated in Figure 4.3 for a time Δt for a component i in the organic phase.

a. The total change in the quantity of component i in the element j of volume AdZ during dt is:

$$n_1 = dZ \left\{(1-H_j)A(t+dt).Y_i(t+dt)-(1-H_j)A(t).\ Y_i(t)\right\} \quad (4.10)$$

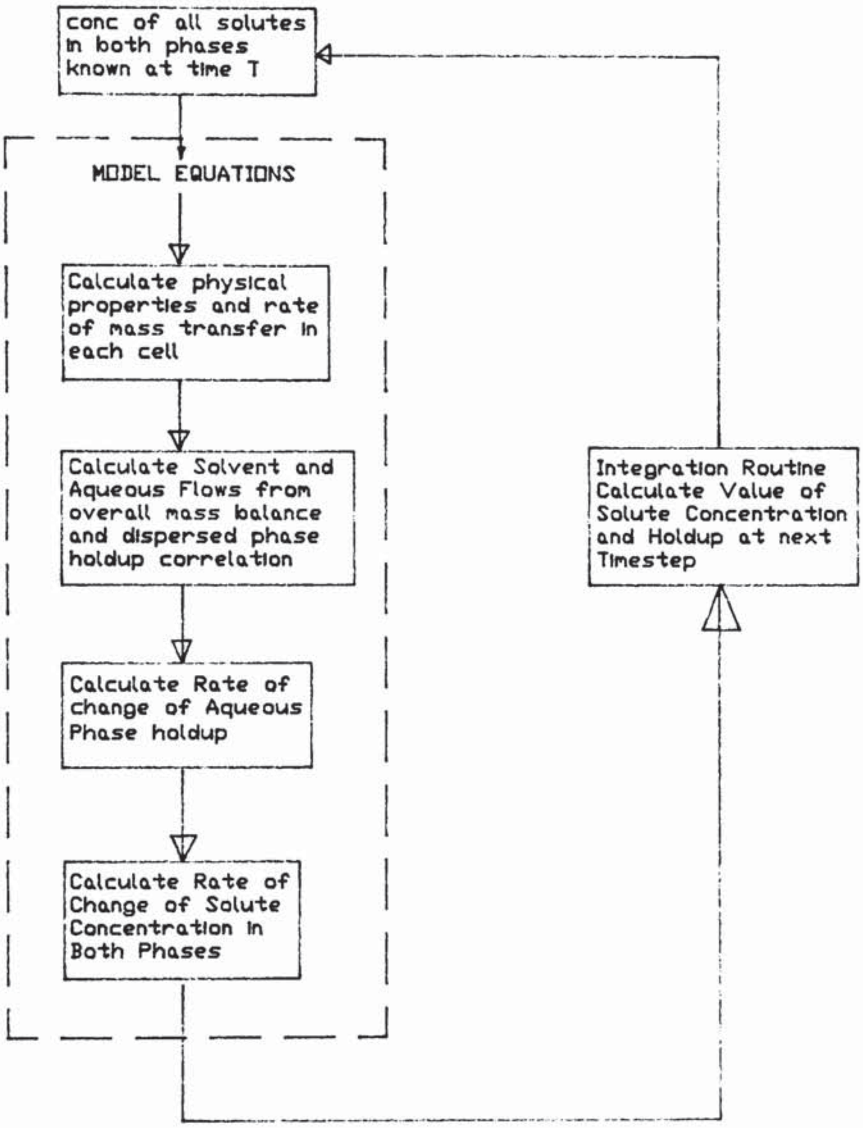
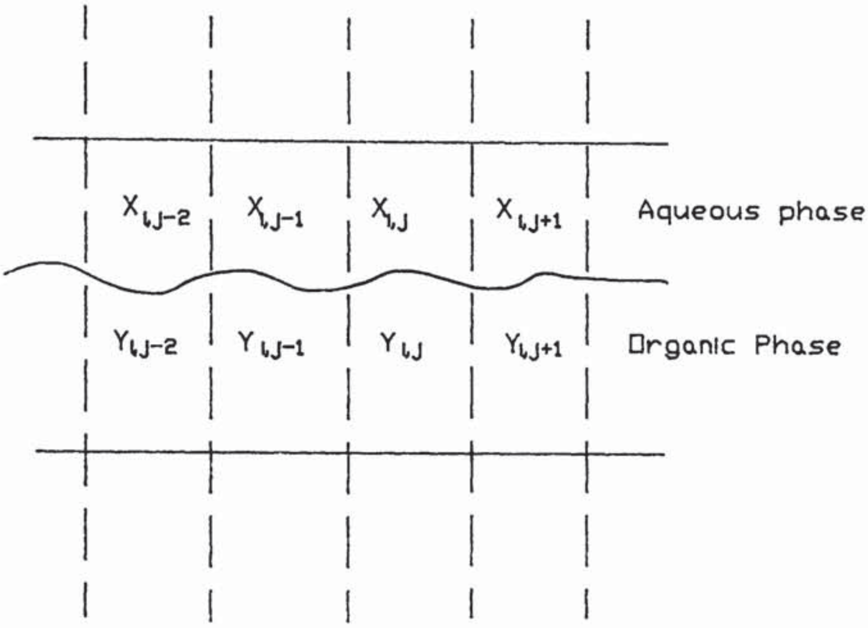


Figure 4.2 Flow Diagram of a Solution Algorithm for a Pulsed Column Model



Concentrations for each phase assumed to exist
at mid points

Figure 4.3 Differential Model Arrangement

b. The change due to bulk flow in time dt

$$n_2 = dt\{FS(Z).Y_i(Z) - FS(Z + dZ).\ Y_i(Z+dZ)\} \qquad (4.11)$$

c. Nett input by mass transfer from the aqueous phase:

$$n_3 = dt.\ K_{org}\ a\ (A.dz)\ (Y^* - Y_i) \qquad (4.12)$$

d. The input by axial mixing:

$$n_4 = dt\ (1 - H_j)\ A\ (Z + dZ)\ E_{org}\ (Z + dZ)\ \frac{dY_i}{dZ}\bigg|_{Z+dZ}$$

$$- (1 - H_j)\ A(Z)\ E_{org}\ (Z)\ \frac{dY_i}{dZ}\bigg|_{Z} \qquad (4.13)$$

$$\text{Now } n_1 = n_2 + n_3 + n_4 \qquad (4.14)$$

Then taking the limit as dt → 0 and dZ → 0

$$\frac{\partial}{\partial t}((1 - H_j)\ AY_i) = \frac{-\partial}{\partial Z}(FS\ Y_i) + \frac{\partial}{\partial Z}((1 - H_j)A)\ E_{org}\ \frac{\partial Y_i}{\partial Z}$$

$$+ (K_{org}\ aA)_i\ (Y_i^* - Y_i) \qquad (4.15)$$

Normally eddy diffusivities are based on total column cross-section area rather than phase flow areas. On this assumption equation 4.32 reduces to:

$$\frac{\partial Y_i}{\partial t} = - \frac{FS}{A} \frac{\partial Y_i}{\partial Z} + E_{org} \frac{\partial^2 Y_i}{\partial Z^2} + (K_{org} a)_i \, (Y_i^* - Y_i) \qquad (4.16)$$

Similarly for the aqueous phase:

$$\frac{\partial X_i}{\partial t} = \frac{FA}{A} \frac{\partial X_i}{\partial Z} + E_{aq} \frac{\partial^2 X_i}{\partial Z^2} - (K_{org} a)_i \, (Y_i^* - Y_i) \qquad (4.17)$$

Equations 4.16 and 4.17 can be reduced to ordinary differential equations by replacing the spatial derivative with finite difference approximations. Information concerning boundary conditions required for solution of the model can be obtained from several literature sources such as Sleicher (120), Miyauchi and Vermeulen (93) and Pratt and Baird (76).

Miyauchi and Vermeulen discuss the relationship between the two models and show that they become essentially identical if a large number of stages is assumed in the stagewise model.

4.4 Model Limitations

Several limitations are inherent in all the models discussed in the previous section. Firstly all use $\bar{d}_{32}$ rather than a drop size distribution model. As there is no clear indication in the literature about droplet size and local velocity distribution within a pulse column this may at the moment be a necessary assumption. Similarly there is no guidance about the boundaries between stagnant, circulating and oscillating droplet behaviour in a pulsed column.

Secondly, any drop size and holdup correlations used within these models are based on steady-state measurements. Their use in dynamic, unsteady state simulations is assumed to be valid but no work is available to verify this assumption.

Thirdly, no model makes any attempt to include the time-dependent reduction in maximum volumetric throughput observed by Schmidt (114). It has also been observed that in columns operated in the solvent continuous mode the dispersed phase forms irregular 'blobs' and streamers - a condition unlikely to be well modelled by dropsize/holdup correlations based on aqueous continuous operation.

Furthermore, pulsed columns are used primarily in nuclear fuel reprocessing applications (86), (30) and the organic phase used is tributyl phosphate diluted with odourless Kerosene. In time with this system a crud layer builds up at the interface. No model allows this effect to be included. This effect and the time-dependent, throughput reduction may of course be impossible to predict and therefore model but they represent important practical limitations. Finally, all mass transfer models are based on data collected at steady state. How valid it is to use these models for unsteady state simulations is uncertain.

5 Experimental Work

Two periods of experimental work were undertaken as part of this study. The first period was largely a familiarization exercise with pulsed columns. The second was intended to investigate dynamic effects of the gas lift/external settler combination.

5.1 The Dounreay Pulsed Column Rig

A small existing rig at Dounreay was used in the familiarization exercise. Data concerned with column dynamics was collected.

5.1.1 Equipment Description

Figure 5.1 illustrates equipment layout.

It consisted of a glass walled pulsed column 50 mm in diameter with a 1 m plated section. The standard cartridge used was made up of stainless steel nozzle plates perforated with 3.18 mm holes to give 23% free area. The plates were pitched at 50 mm. Pulsing was induced by a cam driven p.t.f.e. bellows.

The liquids used were nitric acid and 20% tributyl phosphate in odourless kerosene. Rotameters were used to measure flowrates.

5.1.2 Experimental Procedure

The phases were mutually saturated by passing them through the equipment. The same batches of each phase were used throughout.

The column was filled with continuous phase and its flowrate adjusted to the required value. Dispersed phase flow was then started up and the interface position stabilised by adjusting the aqueous flow leaving the column. Hold-up was measured by isolating the column and noting interface movement, i.e. the increase in the bulk dispersed phase volume.

For runs in which measurements were made of the change of hold-up with time after a disturbance was applied to the column the following procedure was adopted:

i) Start-up column feeds and establish a dispersion
ii) Stabilise interface position
iii) Isolate column and measure hold-up
iv) Restart feeds
v) Stabilise interface position
vi) Apply disturbance to column

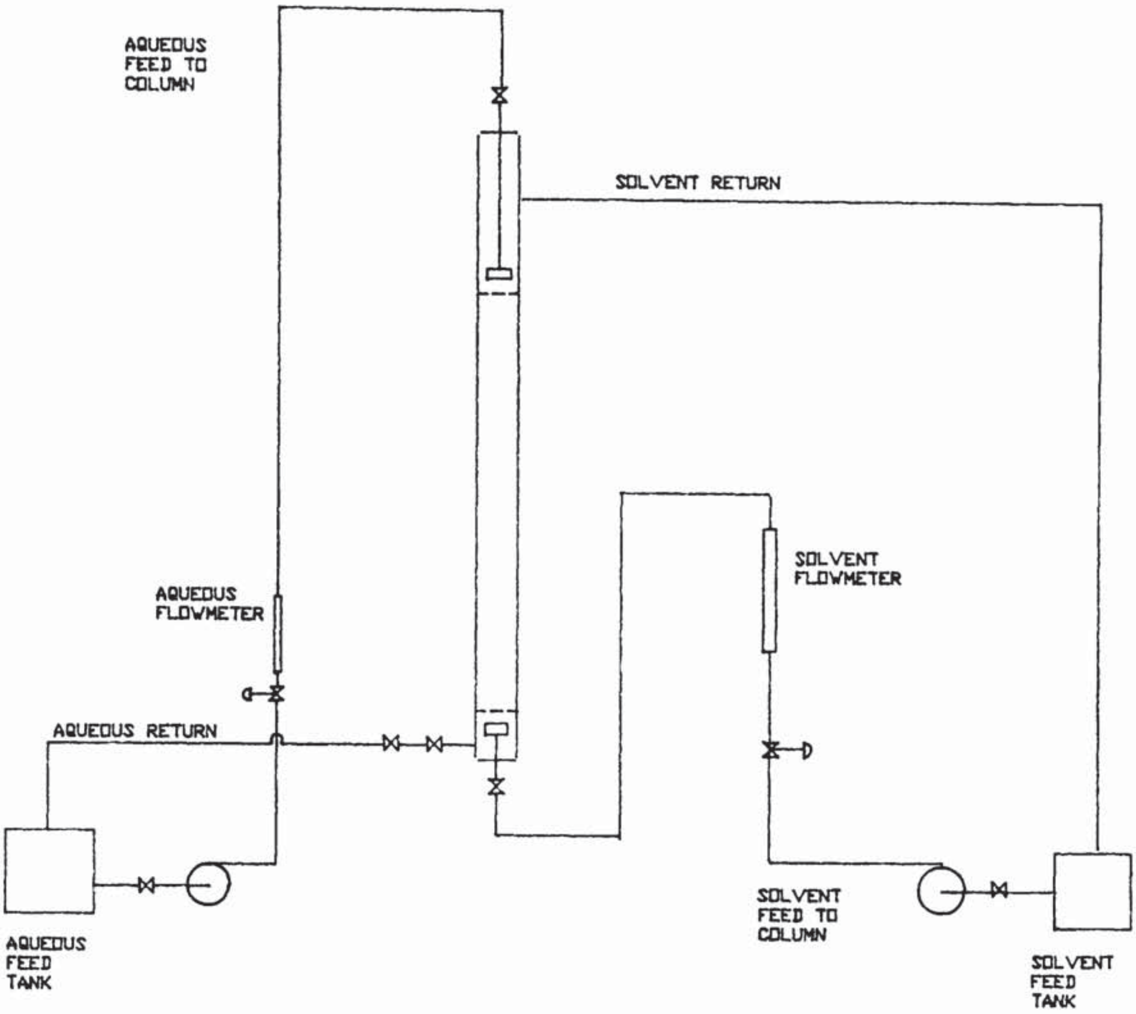


Figure 5.1 The Dounreay Pulsed Column Rig

vii) After desired time isolate column and measure interface position

viii) Repeat steps iv)-vii) until readings for maximum time interval obtained - either until no further changes observed or until it became impossible to hold interface stable.

All disturbances to the column were applied by making a step change in the solvent feed to the column. Altering the aqueous feed flowrate would have caused time-consuming delays in stabilising interface position.

Pulsing was applied at the requisite frequency and amplitude.

For runs where only the movement of the interface position was measured a simpler procedure was adopted:

i) Start-up column
ii) Stabilise interface position
iii) Isolate column and measure hold-up
iv) Restart feeds
v) Stabilise interface position
vi) Apply disturbance to column
vii) Measure interface position at set time intervals after disturbance

viii) Isolate column and measure hold-up at end of run

5.1.3 Results and Discussion

Results are given in Tables 5.1-5.7 and illustrated in Figures 5.2 to 5.8.

Since the data were limited by column availability, only very tentative conclusions can be drawn from these results. From Figures 5.2 to 5.9 it would appear that pulsed columns react very rapidly i.e. within seconds to applied disturbances, which will have important effects on control system design. Only in run 5.7 where the smallest disturbance was applied was any significant delay ~5 seconds observed between disturbance and column response.

The rig used had certain drawbacks which limited its usefulness in such work:

i) An oversized valve on the aqueous phase outlet line caused difficulties in controlling interface position.

ii) The rotameters had a highly non-linear response which made it difficult to apply small disturbances.

TABLE 5.1

Change of Interface Position;

No Intermediate Hold-up Readings Made

Acid continuous, F = 1.54 Hz, a = 5 mm, sinusoidal

TIME s	ACID FLOW mms^{-1}	SOLVENT FLOW mms^{-1}	INTERFACE MOVEMENT cm	HOLD-UP
0	4.15	2.39	0	0.041
5	4.15	4.09	0.4	
10	4.15	4.09	1.7	
15	4.15	4.09	2.7	
20	4.15	4.09	3.5	
25	4.15	4.09	4.4	
30	4.15	4.09	5.1	
35	4.15	4.09	6.0	
40	4.15	4.09	6.4	
45	4.15	4.09	6.7	
50	4.15	4.09	7.0	
55	4.15	4.09	7.3	
60	4.15	4.09	7.7	0.078

TABLE 5.2

Change of Interface Position with Time After Transient Applied

Acid continuous, F = 1.54 Hz, a = 5 mm, sinusoidal

TIME s	ACID FLOW mms^{-1}	SOLVENT FLOW mms^{-1}	INTERFACE MOVEMENT cm	HOLD-UP
0	4.15	2.39	0	0.041
10	4.15	4.09	1.9	
20	4.15	4.09	3.8	
30	4.15	4.09	5.4	
40	4.15	4.09	6.3	
50	4.15	4.09	6.8	
60	4.15	4.09	7.2	
70	4.15	4.09	7.6	
80	4.15	4.09	8.3	
90	4.15	4.09	9.3	
100	4.15	4.09	9.7	
110	4.15	4.09	9.9	
120	4.15	4.09	10.5	0.0875

TABLE 5.3

Hold-Up Changes and Interface Movement

Acid continuous, F = 1.54 Hz, a = 5 mm, sinusoidal

TIME	ACID FLOW	SOLVENT FLOW	INTERFACE MOVEMENT	HOLD-UP
s	mms^{-1}	mms^{-1}	cm	
0	5.87	2.39	0	0.038
15	5.87	4.10	4.0	0.059
30	5.87	4.10	5.0	0.067
60	5.87	4.10	6.0	0.079
90	5.87	4.10	8.0	0.079
120	5.87	4.10	12.0	0.079
150	5.87	4.10	11.0	0.079
Steady state at new Solvent Flow			0.079	

TABLE 5.4

Hold-up Changes and Interface Movements with Time After Disturbing the Column

Acid continuous, F = 1.91 Hz, a = 13.8 mm, sinusoidal

TIME s	ACID FLOW mms^{-1}	SOLVENT FLOW mms^{-1}	INTERFACE MOVEMENT cm	HOLD-UP
0	2.08	1.16	0	0.043
15	2.08	3.18	2.0	0.048
30	2.08	3.18	5.5	0.061
60	2.08	3.18	4.5	0.079
90	2.08	3.18	4.5	0.069
120	2.08	3.18	12.0	0.079
Stead state at		3.18		0.074

TABLE 5.5

Hold-up Changes and Interface Movement with Time After Disturbing the Column

Acid continous, F = 0.95 Hz, a = 13.8 mm, sinusoidal

TIME s	ACID FLOW mms^{-1}	SOLVENT FLOW mms^{-1}	INTERFACE MOVEMENT cm	HOLD-UP
0	2.16	2.09	0	0.042
15	2.16	2.47	1.5	0.045
30	2.16	2.47	1.0	0.51
45	2.16	2.47	2.0	0.053
60	2.16	2.47	2.0	0.054
90	2.16	2.47	2.5	0.055
120	2.16	2.47	2.0	0.055
Steady State at		2.47		0.043

TABLE 5.6

Hold-Up Changes and Interface Movement with Time After Column Disturbance

Acid continuous, F = 0.95 Hz, a = 13.8 mm, sinusoidal

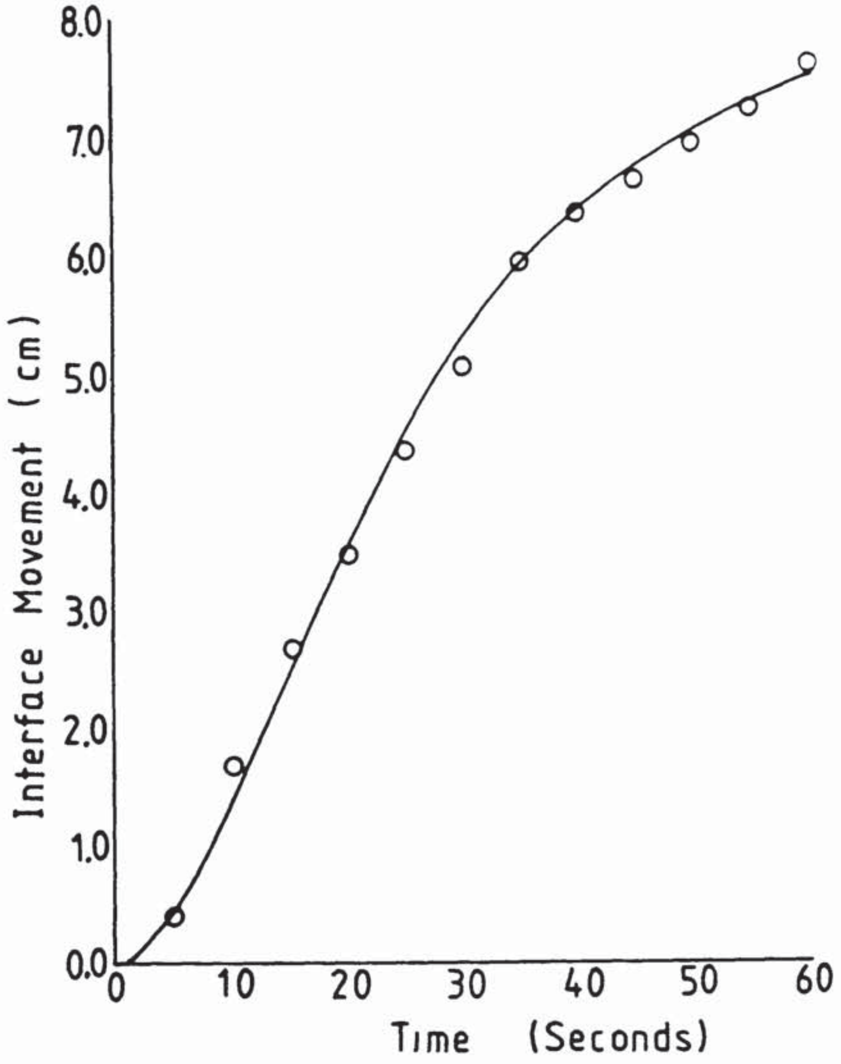
TIME s	ACID FLOW mms^{-1}	SOLVENT FLOW mms^{-1}	INTERFACE MOVEMENT cm	HOLD-UP
0	2.16	2.09	Not Measured During This Run	0.043
15	2.16	2.47		0.046
30	2.16	2.47		0.050
45	2.16	2.47		0.039
60	2.16	2.47		0.046
90	2.16	2.47		0.062

TABLE 5.7

Interface Movement and Hold-up Changes with Time After a Column Disturbance

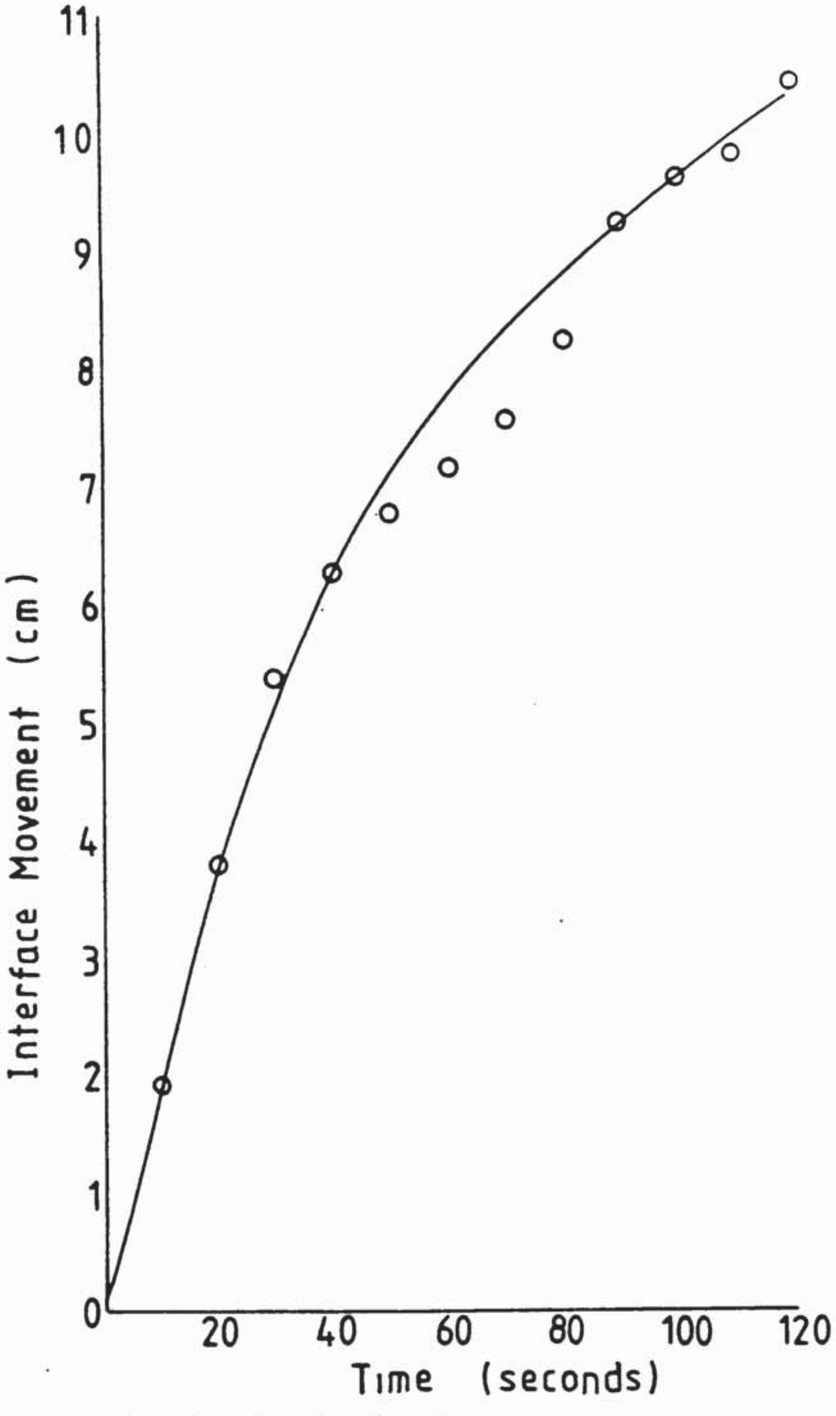
Acid continuous, F = 1.33 Hz, a = 13.8 mm, sinusoidal

TIME s	ACID FLOW mms^{-1}	SOLVENT FLOW mms^{-1}	INTERFACE MOVEMENT cm	HOLD-UP
0	2.16	2.09	0	0.088
15	2.16	2.47	0.5	0.098
30	2.16	2.47	4.5	0.103
45	2.16	2.47	2.5	0.099
60	2.16	2.47	2.0	0.112
Steady state at		2.47		0.121



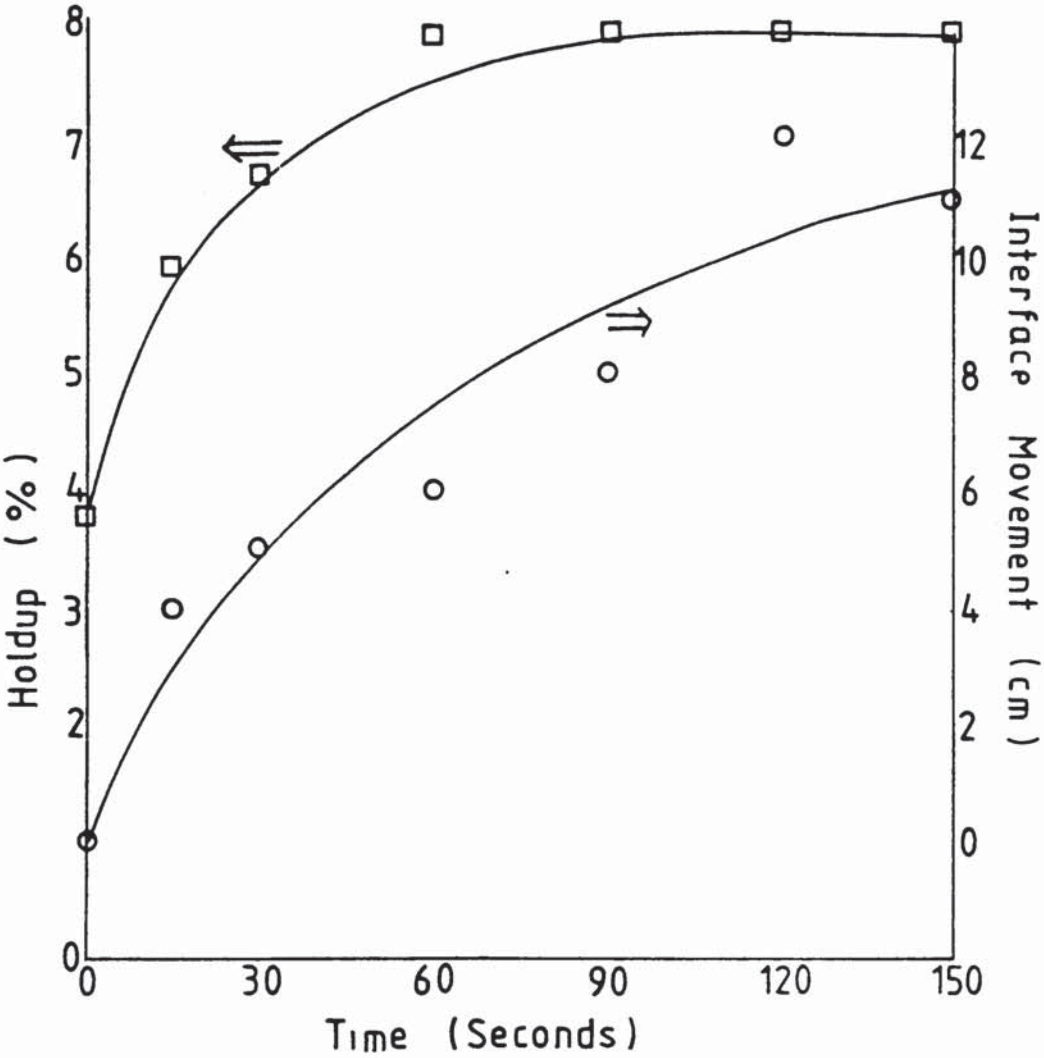
Run 1 Acid Continuous
$f = 1.54$ Hz
$a = 5.0$ mm
$u_c = 4.15$ mms^{-1}
$u = 2.39 - 4.09$ mms^{-1}

Figure 5.2 Interface Movement after Column Disturbance



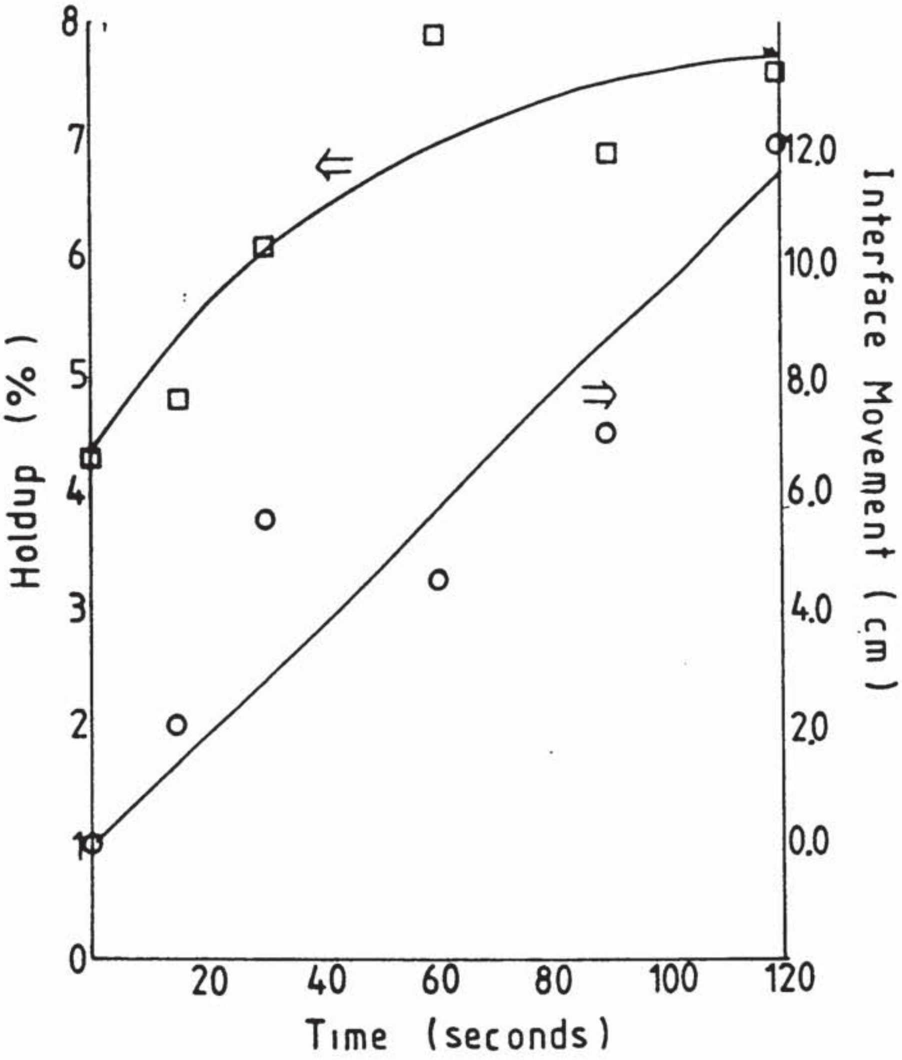
Run 2 Acid Continuous
$f = 1.54$ Hz $a = 5$mm
$u_c = 4.15$, $u_d = 2.39 - 4.09$ mms^{-1}

Figure 5.3 Interface Movement after a Column Disturbance



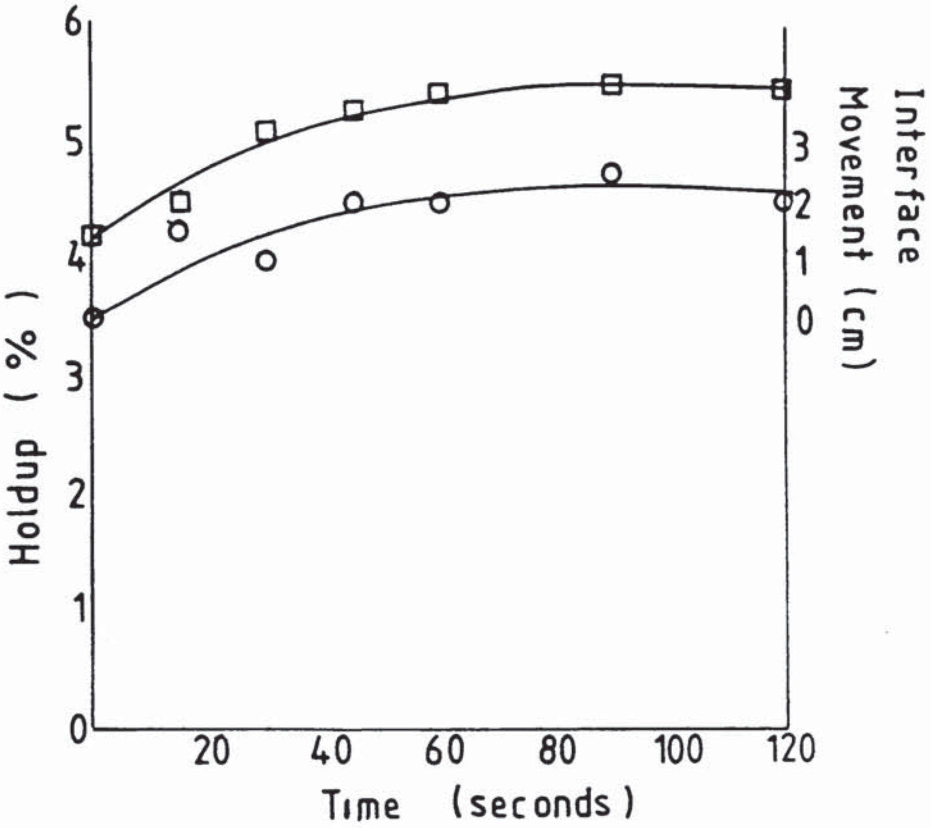
Run 3 Acid Continuous
$f = 1.54$ Hz
$a = 5$ mm
$u_c = 5.87 \, mms^{-1}$
$u_d = 2.39 \, mms^{-1}$ $4.1 mms^{-1}$

Figure 5.4 Holdup & Interface Movements following Column Disturbance



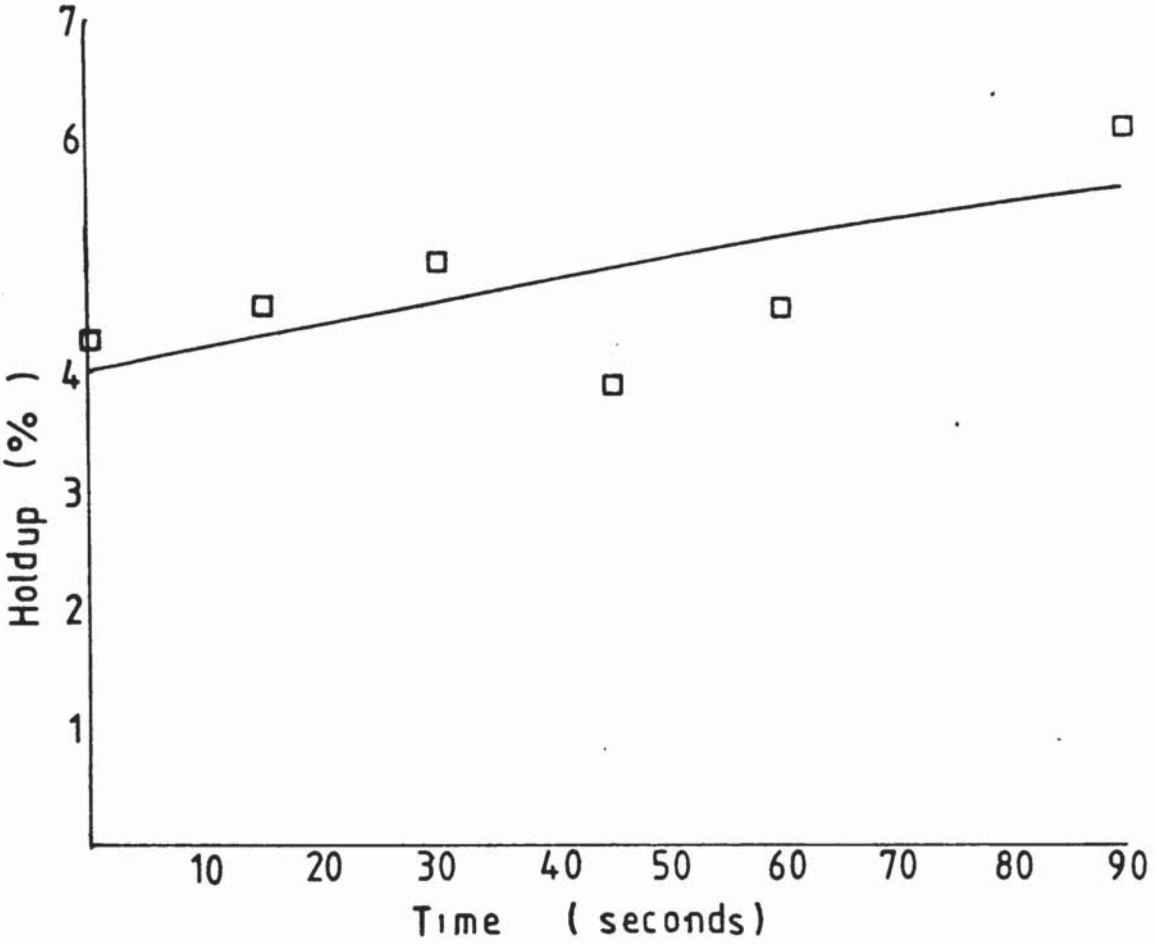
Run 4 Acid Continuous
f = 0.91 Hz
a = 13.8 mm
u_c = 2.08 mms^{-1}
u_d = 1.66–3.18 mms^{-1}

Figure 5.5 Holdup & Interface Response to Column Perturbation



Run 5 Acid Continuous
f 0 95 Hz
a 13 8 mm
u_c 2 16 mms^{-1}
u_d 2 09 2 47 mms^{-1}

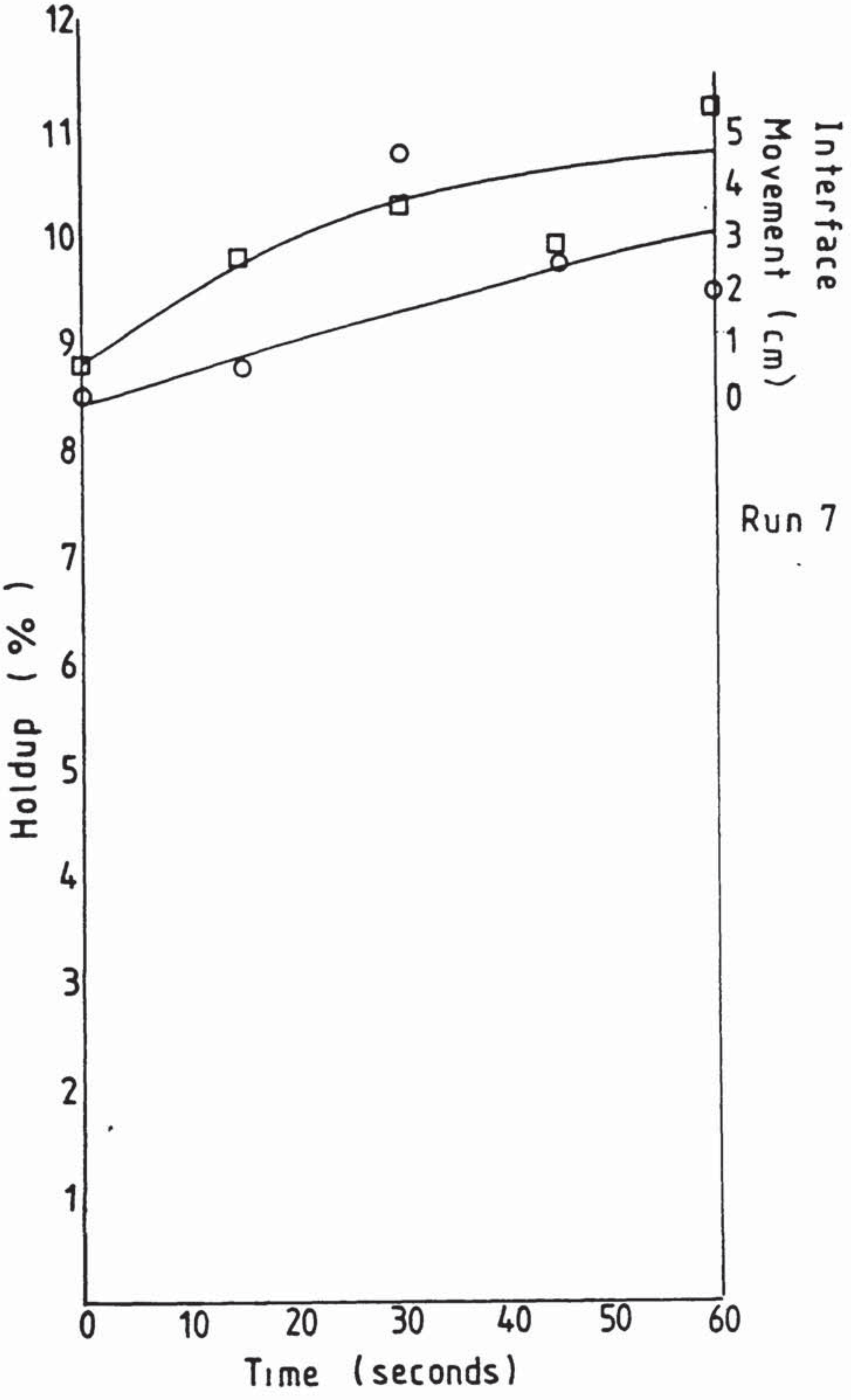
Fig 5.6 Interface & Holdup Response to Column Perturbation



Run 6

Figure 5.7 Holdup Changes following Column Perturbation

Fig. 5.8 Holdup Changes after a Column Perturbation



iii) There was a tendency for air locks to form in the drain lines.

iv) There was a tendency for the interface to suddenly shift position and become unstable in the absence of any disturbances. This became more important in long runs. This effect could have serious implications if it is typical of pulsed columns, though in large columns a change of 1.2 cm might not matter. It may have been caused by slight changes in pump delivery.

In the absence of a method to measure hold-up while the column was running a great deal of time was spent stabilising the interface position - typically 10-15 minutes each time. Therefore, to collect a set of 6 hold-up readings the interface had to be stabilised 7 times which could take two hours.

5.2 Investigation of Interface Detection Methods

The usual technique used to measure interface position in nuclear fuel reprocessing is the pneumercator tube. These instruments have certain drawbacks which limit their usefulness with pulsed columns:

i) The pulsation of the column contents causes the signal from the pneumercator to be noisier and difficult to process.

ii) In columns operated 'solvent continuous', when the interface is formed at the bottom of the column, the resultant large static head of liquid (possibly 14 m) over the pneumercator renders detection of the small pressure difference over the interface difficult.

Ideally, some other method of interface position measurement, free of these flaws, would need to be incorporated into a control scheme for use on production plant. Conversely on experimental rigs the usual technique for interface control appears to be semi-continuous human intervention. An investigation was therefore made into the possibilities of two instruments; an Endress and Hauser Silometer capacitance probe and a motion detection monitor.

5.2.1 Equipment Description

The capacitance meter works by measuring the capacitance of a liquid layer. Ionic liquids have a larger capacitance then non-ionic liquids and therefore give a stronger reading. Therefore they could be used to measure interface position.

The capacitance level meter consisted of the probe coupled to a calibration unit and an output dial. Technical details are given in Appendix F. Initial calibration tests were carried out using the probe in large measuring cylinders. It was also planned to test the probe on the pulsed column rig as indicated in Figure 5.9.

The motion detection monitor consisted of a video camera, a television as a monitor and a motion detector unit. The television screen had a 'target zone' 20 cm x 20 cm marked by a grid, 2 cm square, which is projected on to it by the motion detection unit. The user is able to adjust the size and position of this grid. Should the image of the interface, transmitted by the video camera to the screen, move outside the target zone this is picked up by the motion detection unit which sounds an alarm. The video camera was sited so that its field of view covered the likely zone of interface movement within the pulsed column. This was an experimental piece of equipment and no further details are available.

5.2.2 Experimental Procedure

The capacitance probe was initially calibrated using water. The probe was placed in an empty 2 litre measuring cylinder and the 'zero' calibration potentiometer adjusted

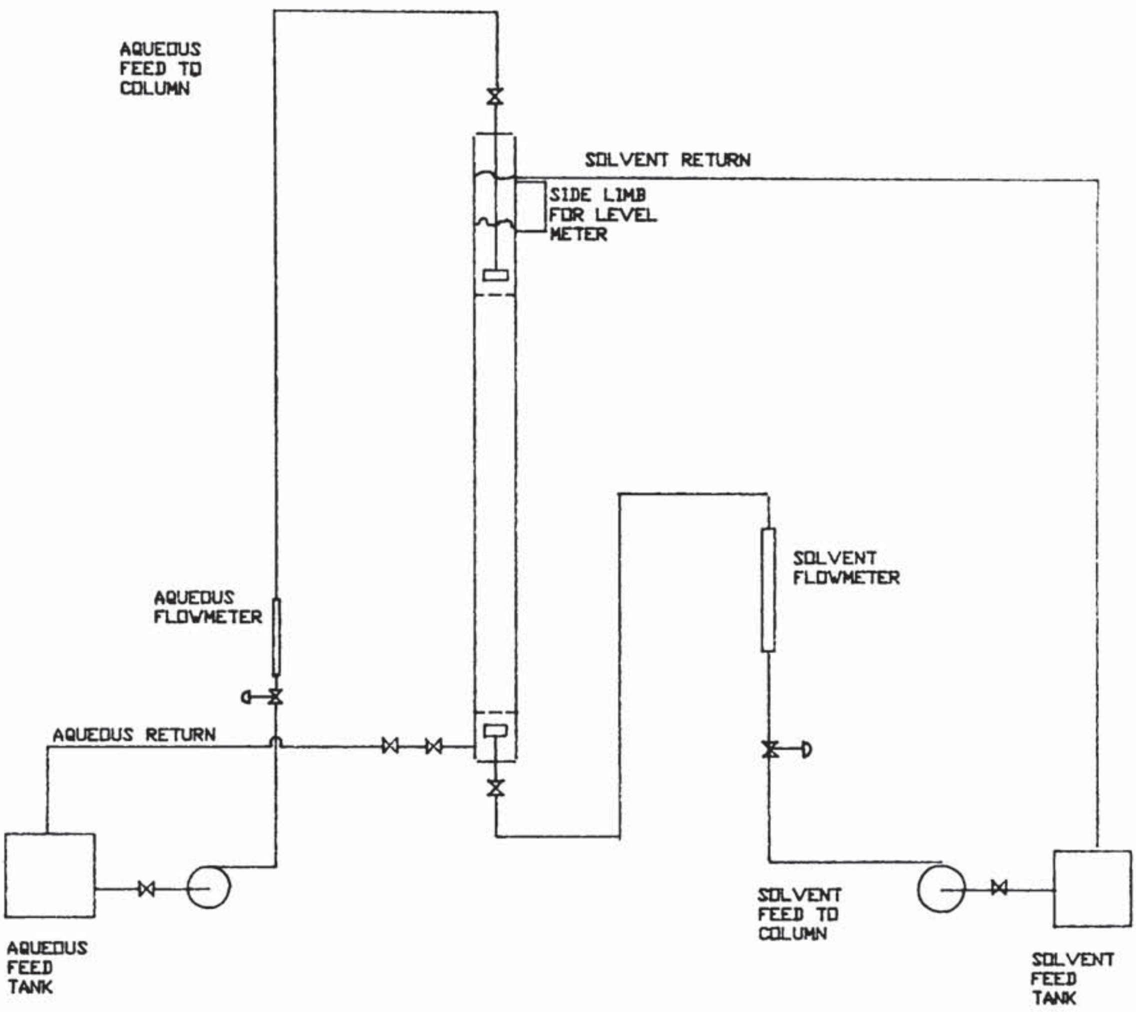


Figure 5.9 Sketch Showing the Position of the Interface Detection Probe

until a 0% scale reading was obtained. The cylinder was then filled and the 'full' calibration potentiometer adjusted until a 100% reading was obtained. The water level in the cylinder was varied and the response of the probe observed.

The procedure was subsequently repeated with nitric acid and then with solvent.

An interface was then introduced into the cylinder. With the interface in the lowest position of interest the probe was calibrated to give a 0% reading. For the highest interface position the calibration was adjusted to give a 100% reading. The interface position was changed and the instrument response observed.

For the trials involving the motion detection unit the column was started up as previously described. The target zone was adjusted to cover that part of the top settler in which interface movement was acceptable. The interface was then caused to move by adjusting the aqueous phase outlet from the column.

5.2.3 Results and Discussion

The capacitance probe worked very well in water and nitric acid being easy to calibrate and responding well, that is

10% less deflection for a 10% reduction in liquid level to level changes. In solvent it was impossible to attain full scale deflection even on the sensitive scale. Response to level changes was very erratic.

When an interface was present it proved impossible to achieve more than 5-10% scale deflection, which obviously would make accurate level measurement very difficult.

In the event it proved impracticable to test the probe in the column as the side-limb designed for the probe (see Figure 5.9) would have required the interface to be held very near the solvent exit weir. The connections were also extremely fragile and broke off very easily.

Initially the motion detection monitor performed very well even under normal laboratory lighting conditions which caused 'glare' on the glass wall of the column. The motion detector unit sounded the alarm reliably when the interface moved off target by a few millimetres. However in a second trial the unit failed to work even under improved lighting conditions. An electronic fault in the unit was suspected.

It was concluded that the capacitance probe used was not satisfactory for interface position measurement. An alternative design may prove more suitable. The motion detection monitor, although unsuitable for use on active plant, could be useful on experimental rigs although adequate lighting conditions would have to be provided.

5.3 Gas-Lift Pump Trials

As explained in Section 6.4, gas lift pumps are of interest in the nuclear fuel reprocessing industry because they offer a means of pumping liquids whilst not requiring any moving parts. The combination of gas-lift and external settler is new and thus of interest. The 'chugging' (slug flow) phenomenon reported by Parker (101) was also of interest because of the possible implications in active plant use. Further, no work has been reported on pumping two liquid phase mixtures with a gas lift which would be the normal operating condition on plant.

A series of gas-lift pump trials was therefore instituted.

5.3.1 Equipment Description

The equipment used in these trials is illustrated in Figure 5.10. It consisted of a column, 3 inches in diameter constructed from two 1 m sections of glass. The external settler was formed of a 1 m section of 6 inch diameter glass with a 1 inch side-limb. The breakpot was

6 inches in diameter. The upriser consisted of ¾ inch nominal bore polythene tubing. Overflow lines from the settler were ½ inch nominal bore polythene tubing. Flowrates were measured by directly calibrated rotameters. A standard nozzle plate 3/8" diameter holes pitched to give 23% free area made of brass formed the dispersed phase distributor.

The organic phase was 20% tributyl phosphate in odourless kerosene. Laboratory water was used as the aqueous phase.

Nitrogen was used from a cylinder through a pressure reducing valve. Nitrogen pressures are noted in the results.

5.3.2 Experimental Procedure

The first stage of the investigation was to calibrate the gas-lift using water only. For this purpose the column was filled with water and the settler filled to the level of the aqueous overflow. Nitrogen flow was initiated and the dispersed, aqueous, phase pump was switched on. Aqueous feed and exit flows were adjusted until a constant head in the column was obtained. The aqueous exit flowrate was adjusted by adjusting the nitrogen flow. Nitrogen and

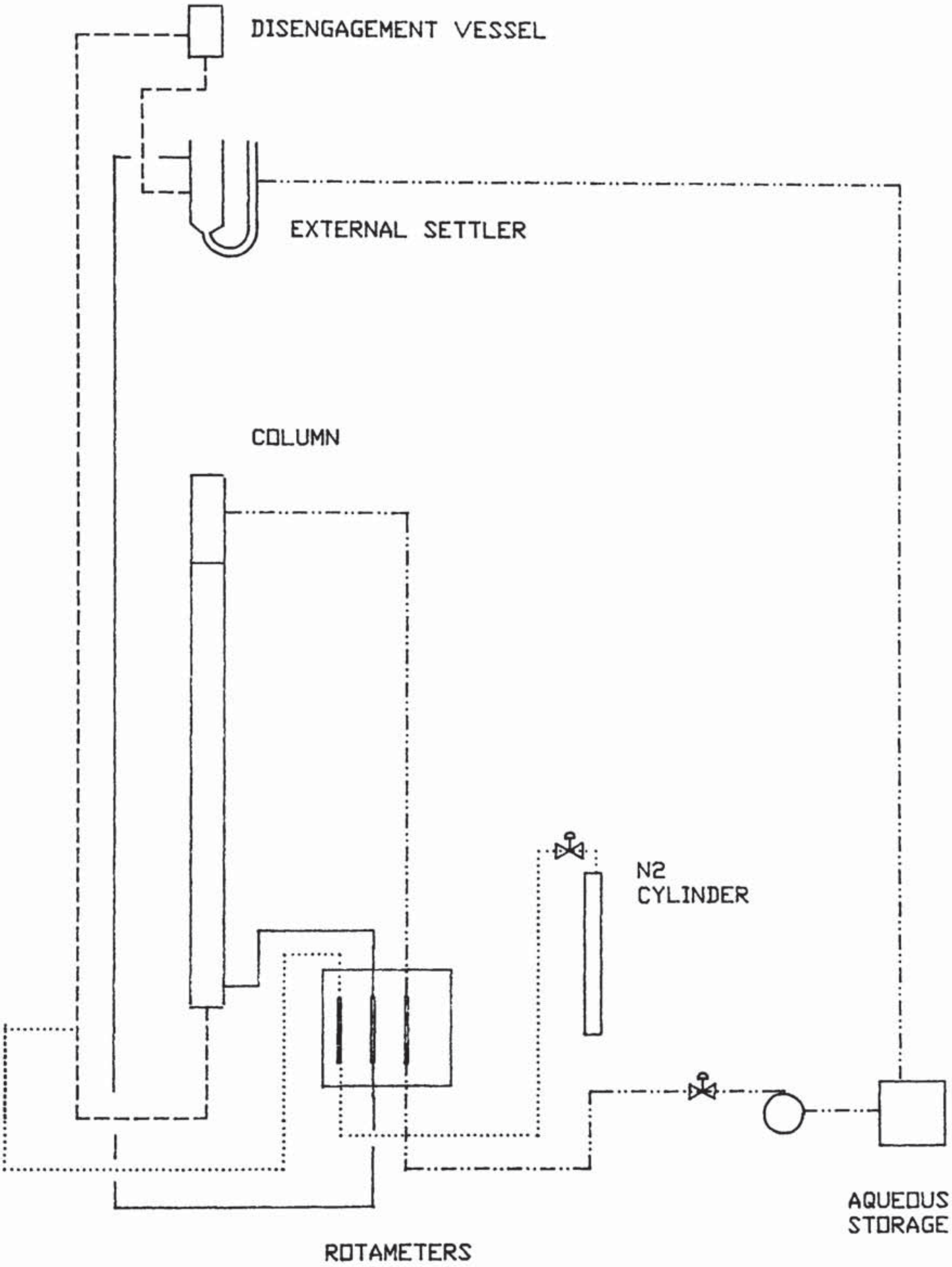


Figure 5.10 The Gas-Lift Rig

aqueous flowrates were noted. The procedure was repeated for a range of conditions.

For the two-phase runs the column was initially filled with organic phase. An aqueous plug was introduced to the settler followed by an organic phase plug. Dispersed phase, aqueous, flow was started. Nitrogen flow to the pump commenced. The continuous phase remained stagnant in the column.

Gas flow was increased until the interface formed at the base of the column was removed to the settler. Under this condition the gas lift pumped a two liquid phase mixture. Once steady state operation was achieved gas and liquid flowrates were noted.

5.3.3 Discussion

During operation it became apparent that the rig suffered from several design faults:

i) Difficulty in maintaining a constant head in the column caused by difficulty in balancing feeds to and take-offs from the column.

ii) A limit on the aqueous feed to the column caused by the high pressure drop over the distributor plate.

iii) Oscillation of the rotameter bob - attributed to the 'chugging' behaviour of the gas lift pump causing pressure surges throughout the equipment.

iv) When used with two liquid phases considerable difficulty was experienced in keeping the interface out of the column. The resultant adjustments to gas flow rate made stable operation difficult to achieve.

v) A low submergence ratio, ie 50% where submergence ratio is (liquid depth over gas injection point)/(delivery height above gas injection point).

vi) Leakage round joints.

Problem (iv) could have been circumvented by using a higher gas flow with a resultant large solvent recycle but this option was limited by the rotameter measuring the gas flow rate. Higher gas flows may have lessened the 'chugging' behaviour and thus reduced the rotameter bob oscillation which was observed. This 'slug' flow behaviour is common in two-phase flow and is not specific to gas-lift pumps. Also, having a pumped solvent return, rather than relying on a gravity fed return line, might have reduced the rotameter oscillation. However this would have lent a further complication to controlling the rig.

The external settler was too large for the pump capacity; changes in level in the settler were difficult to pick up quickly. Also, the settler took a long time, $\gg$10 minutes, to fill initially.

The results of this work are described in Chapter 7.

6 Modelling of Reprocessing Plant Equipment Items

The models describing various plant items are written in the simulation language PMSP, the Plant Modelling System Program. This FORTRAN-like language is described by Stirrup et al (124). A brief outline is given here.

6.1 A Summary of PMSP

The Plant Modelling System Program - PMSP - is a high-level language which enables dynamic systems to be simulated and analysed. PMSP is FORTRAN based and uses double precision arithmetic for accuracy.

6.1.1 Applications

PMSP can be applied to a range of design, commissioning and operation problems. For example it can speed up commissioning of automatic control schemes; it can predict the likely outcome of the plant dynamic response tests and it can provide the correlation between the performance of mathematical models and actual plant.

6.1.2 Features of PMSP

Construction of a PMSP model consists of the following stages:

1 Description of the process to be modelled by a series of ordinary differential and algebraic equations.

2 Conversion of these equations into PMSP source. The PMSP translator (language processor) automatically sorts the source code into the correct sequence, checks for faults (such as algebraic loops and undefined variables) and translates it into a FORTRAN subroutine which is compiled and executed with the selected numerical algorithms.

3 Debugging and testing the model.

PMSP offers many simply invoked functions which commonly occur in continuous processes e.g. time delay, dead spaces, function generators and lags. A choice of fixed and variable step length integration algorithms is offered. Variable step length methods offer savings in running times where a system is 'stiff' - that is, has widely differing time constants within it.

The MACRO facility rather like FORTRAN subprograms allows the same piece of code to be invoked as many times as required without the necessity to rewrite it each time.

Realistic models are non-linear and often incorporate empirical data. Use of the automatic lineariser provided within PMSP gives access to a range of design and analysis techniques. These include frequency response analysis, eigenvector analysis and control system design.

The features and use of PMSP have been described more fully by Stirrup (124).

6.2 Pulsed Columns

The pulsed column model employed consists of two parts: BRADSIM, as described in (40) was used to detail the phenomena encountered in the plated section of the column (40, 135), and either COLSM2 (for solvent - continuous columns) described below, or COLTES (for aqueous continuous columns) which provide an interface with models describing other plant items.

6.2.1 A Typical Model (40)

A typical model such as those described in (40) and (146) takes account of the hydrodynamic characteristics of the pulsed column. These have been discussed in Chapter 3 but briefly include drop size, dispersed phase holdup backmixing and mass transfer. The model is written as a system of dynamic mass balances describing the time variation of solute concentration and hold-up. The set of resultant ordinary differential equations is solved using one of the integration algorithms provided in PMSP. This type of model has been described in detail in Chapter 4.

Of particular interest is the method used to calculate the mass-transfer rate. The full model calculates a rate based on the Whitman two-film theory using individual film coefficients. These film coefficients are taken from correlations for single droplets and covering a limited range of systems published in the literature as described in Chapter 4 of this work.

Droplet behaviour is divided into three regimes: stagnant drops, circulating drops and oscillating drops, determined by the local Reynolds number. An obvious limitation is that the boundary between regimes is not clear and is based on single drop experiments. Within an agitated column the drops collide with each other, with the walls and with column internals inducing oscillations. In addition, in a pulsed column the droplets are subjected to constantly-varying forces and accelerations which would further increase the droplet tendency to circulate internally, and in the extreme, to oscillate. Also, the drops have to squeeze through holes which, up to recovery, would result in oscillations. Difficulties in correlating drop size with pulse conditions and fluid properties as described in Chapter 3 exacerbate the problem. Further difficulties arise in applying correlations based upon single-drop experiments to the behaviour in droplet swarms even when a weighted overall mass-transfer coefficient is used based on a droplet size population balance (117).

The two-film theory requires that the following equation be satisfied for the mass flux across the interface of solute i

$$M_i = K_a \, (X - X^*_i) = K_o \, (Y - Y^*_i) \qquad (6.1)$$

The solution must be found iteratively which slows program execution.

In the present work, using IBM 3081 and DEC Micro-Vax II, a much simplified technique therefore had to be adopted to give reasonable run time (1 : 10, CPU : REAL) for multi-column codes. Given the steady-state concentration profile and drop size the model is driven backwards to give a mass transfer coefficient which is then correlated with solute concentration in each phase. Then, given this 'look-up' function a Mass Transfer Coefficient can be deduced for each concentration difference along the column in dynamic runs. (59)

Each complication added to any model such as BRADSIM or PULCO adds to the solution time. A full model of a pulsed column would typically consist of several hundred differential equations. Large multi-column models such as have been developed become insoluble in real time even on very fast machines. For this work PULCO was not available and therefore the BRADSIM (40) model was used.

6.2.2 COLSM2

The COLSM2 module describes the gross behaviour of a solvent-continuous column. The end sections are modelled and the rates of fluid entry and egress are calculated. COLSM2 provides an interface between BRADSIM and the rest of the cycle model.

An energy balance over the column and pulse limb is performed at each time step to determine the solvent flow-rate into the column. The nomenclature is indicated in Figure 6.1. From Coulson and Richardson (31) the energy balance equation for an incompressible fluid is:

$$\frac{\Delta u^2}{2} + g\ \Delta Z + \nu(P_2 - P_1) + W_s + F = 0 \qquad (6.2)$$

If no mechanical energy W_s is added, (6.2) can be rearranged to give:

$$\frac{U_2{}^2 - U_1{}^2}{2} = g\ (Z_1 - Z_2) + \nu(P_1 - P_2) - F \qquad (6.3)$$

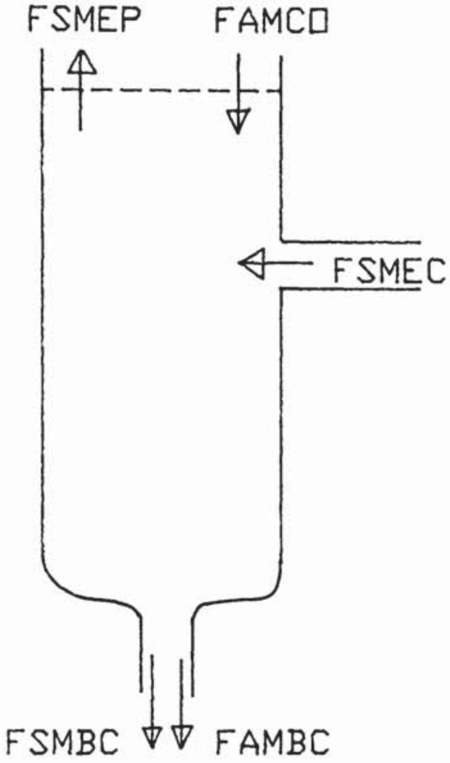


Figure 6.1 COLSM2 Nomenclature

Jenkins (66) gives the following expression for the frictional energy dissipation per unit mass per unit length as a fluid flows through a column with a perforated plate packing

$$F = \frac{n_p(1 - \varepsilon^2)}{\varepsilon^2 \; C_D{}^2} \; \frac{1}{2} \; U^2 \qquad (6.4)$$

Substituting 6.4 into 6.3 and rearranging gives

$$U_2 = \sqrt{2} \; \sqrt{[[\varepsilon^2 \; C_D{}^2(g\rho \; (Z_1 - Z_2) + (P_1 - P_2))]/ (\rho(\varepsilon^2 \; C_D{}^2 + n_p \; (1 - \varepsilon^2))]]} \qquad (6.5)$$

No allowance has been made for frictional losses between the two liquid phases nor for kinetic energy changes since the diameter difference between the main column and the pulse limb is not great for fast reactor fuel reprocessing plants.

The bottom section of the column, between the lowest plate and the exit pipe, Figure 6.1, must always be full of fluid. Therefore, assuming that aqueous drops cannot back track into the plated section, the flowrate of solvent entering the plated section is:

$$FS_{EP} = FS_{EC} + FA_{CO} - FA_{BC} - FS_{BC} \qquad (6.6)$$

FA_{BC} lags FA_{BP} by the time taken for the aqueous drops to pass from the bottom plate to the exit pipe. Their rate of descent is calculated using Hu and Kintner's (61) plot assuming a drop diameter of 3mm. Given the observed (114) extreme distortion of aqueous drops in solvent continuous columns this will clearly not be a good approximation. Poor dispersions of large, irregular 'blobs' and 'streamers' of aqueous phase are observed even under conditions of high turbulence when small regular drops might be expected. FS_{BC} is the difference between FT_{BC} and FA_{BC}. Clearly, if FS_{BC} is greater than FT_{BC} an interface will form at the bottom of the column and advance upwards until FT_{BC} is increased.

The fluid volume held in the top section of the column is not fixed. For the solvent flow out over the exit weir at the top of the column the following equation has been used (31)

$$FS_{TC} = \frac{2}{3} \; C_D L \sqrt{2g} \; d^{1.5} \qquad (6.7)$$

The solvent volume differential is:

$$\frac{d}{dt} (VS_{TC}) = FS_{CO} - FS_{TC} \qquad (6.8)$$

Where FS_{CO} is the solvent outflow from the plated section.

Assuming perfect mixing in the top sections the following concentration differentials are obtained:

$$\frac{d}{dt}(OU_{TC}) = FS_{CO}/VS_{TC} * (OU_{CO} - OU_{TC}) \qquad (6.9)$$

$$\frac{d}{dt}(OP_{TC}) = FS_{CO}/VS_{TC} * (OP_{CO} - OP_{TC}) \qquad (6.10)$$

$$\frac{d}{dt}(SX_{TC}) = FS_{CO}/VS_{TC} * (SX_{CO} - SX_{TC}) \qquad (6.11)$$

The differential equation describing the pulse limb is as follows:

$$\frac{d}{dt} VS_p = FS_{CVF} + FS_{DIV} + FS_{RCY} - FS_{EC} \qquad (6.12)$$

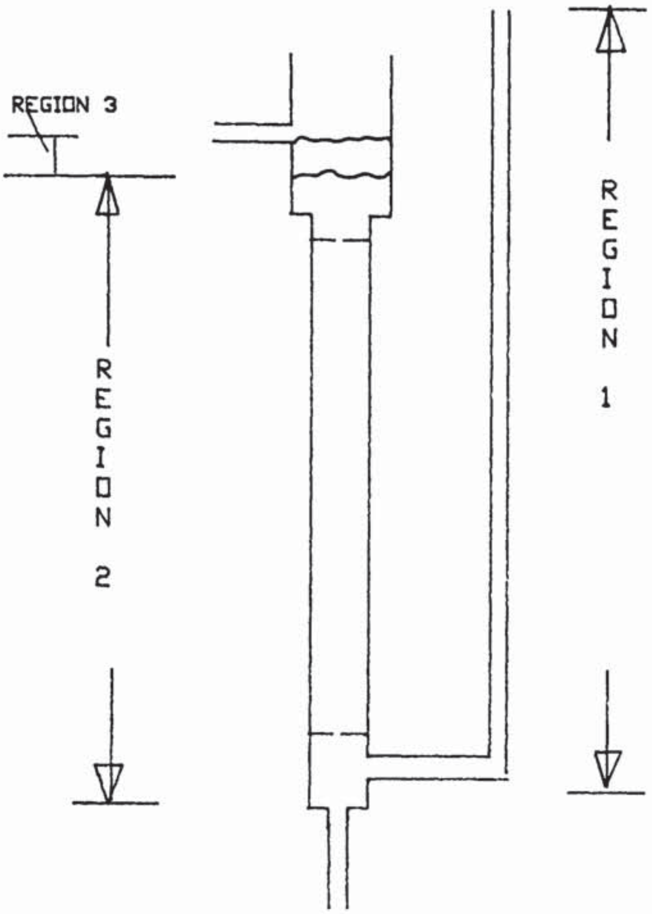
6.2.3 COLTES

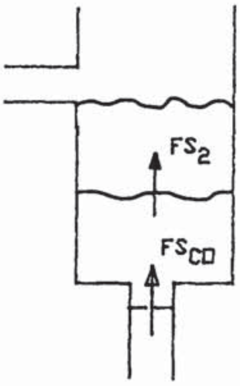
COLTES is similar to COLSM2 but describes aqueous continuous columns. The column is divided into three regions as indicated in Figure 6.2. The first of these is the pulse limb which is described by Equation 6.12.

Region 2 is the whole of the column up to the interface level. This is described by the following equation,

$$\frac{d}{dt} VA_2 = FA_{EC} + FS_{EC} - FA_{BC} - FA_{TC} - FS_2 \qquad (6.13)$$

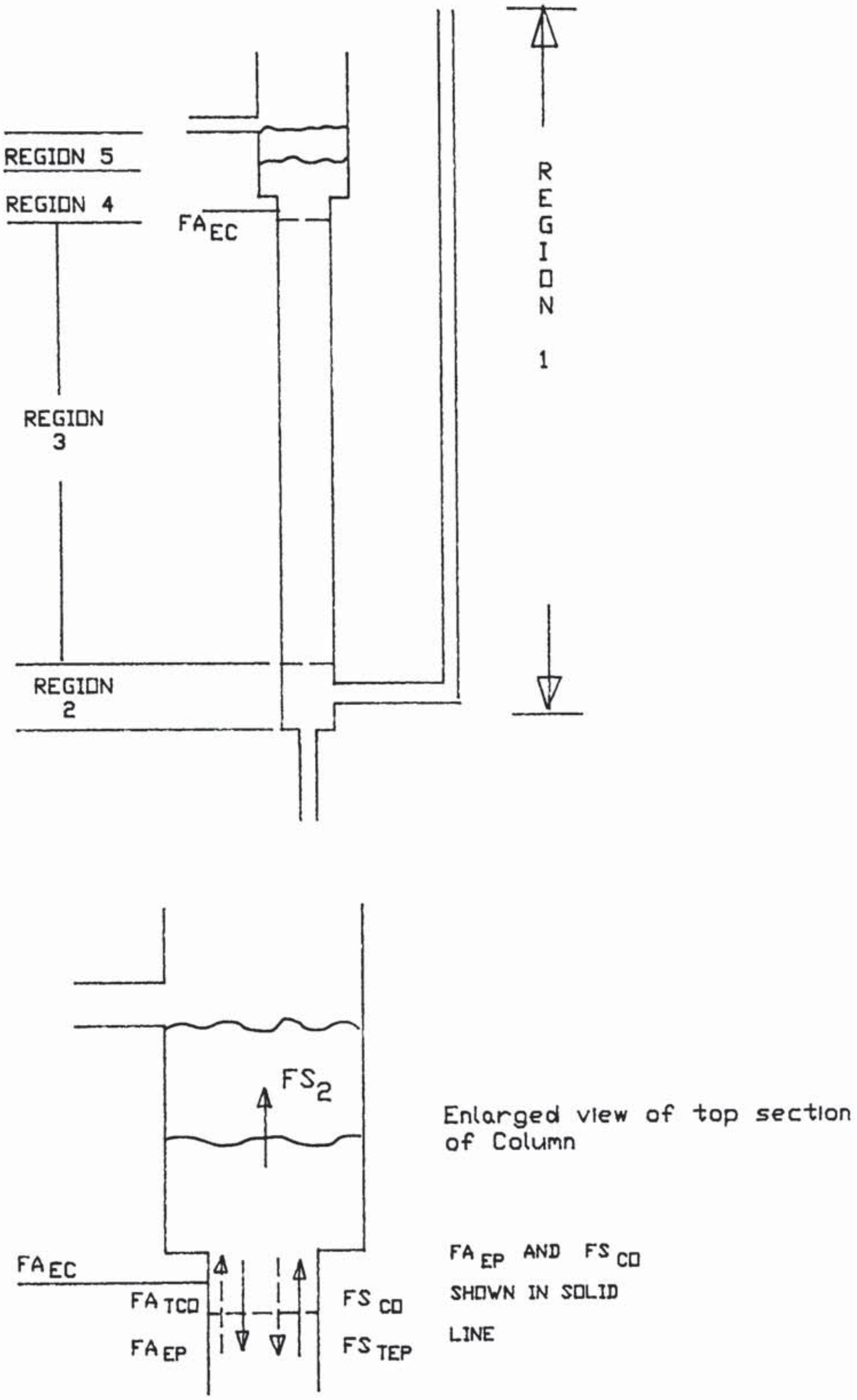
FS_2 is the solvent flow leaving region two and lags FS_{CO}





Enlarged view of top section of Column

Figure 6.2 The COLTES Model



Enlarged view of top section of Column

Figure 6.3 An Alternative COLTES Model

(solvent outflow) by the time taken for a solvent drop to travel from the top plate to the upper interface.

Region 3 is the solvent layer at the top of the column. The solvent outflow over the top weir is given by equation 6.7. Allowance has been made for the case in which the interface rises to the level of the top weir, when the aqueous phase will overflow.

An alternative would be to consider the column as five regions; the pulse limb; the bottom section below the lowest plate; the plated section; the aqueous continuous /solvent dispersed region between the top plate and the interface; the solvent layer above the interface. Figure 6.3 illustrates this. Two problems arise from this approach. Firstly, it introduces extra integrators and secondly in the determination of FA_{EP} unless it is assumed that no solvent can be sucked back into the column. Therefore, this model has not been used.

6.3 The Gas-Lift Pump

A Gas-Lift pump, is reliable and has a low maintenance requirement and is therefore ideal for use in nuclear fuel reprocessing plants where access after plant start-up is impossible unless robots are used.

The earliest theoretical approaches relied on an energy balance, equating the energy possessed by the compressed gas to the work done in raising the liquid. Shaw (117a) noted several such analyses. Assuming isothermal operation, for a pump with 100% efficiency, the volume of gas Vg at atmospheric pressure required to raise a volume V_L of liquid through a distance L is given by:

$$\frac{Vg}{V_L} = \rho_L gL \left[\rho_2 \ln (P_0/P_2)\right] \qquad (6.14)$$

where P_0 is the pressure at the gas introduction point and P_2 is the pressure at the pump outlet.

However, in the gaslift pump there are energy losses caused by slippage between the gas bubbles and surrounding liquid and between the liquid and the pump walls. The energy balance cannot therefore be applied without an efficiency term, which is usually only determinable after the pump as been constructed.

Nicklin (92) provided an analysis of the gas-lift pump based on a momentum balance. The pressure gradient was separated into the hydrostatic head term, predicted from the liquid and gas holdups evaluated using the two-phase drift-flux model, and frictional losses. This differential analysis is valid only at a single level in the pump since Nicklin assumed a constant gas superficial velocity whereas in fact it increases up the pump.

Todoroki et al (129) presented an analysis based on a momentum balance. Assuming a mean gas superficial velocity they obtained the following:

$$\frac{W_{10}^2}{2gL} = \frac{\sigma - \bar{f}_1}{C_1 \bar{f}_1^{\,-Z} + C_2 + C_3} \qquad (6.15)$$

where

$$\bar{f}_1 = \frac{w_{go}}{1.2\ (\bar{w}_{g0} + w_{10}) + 0.35\ \sqrt{gd}} \qquad (6.16)$$

Equation 6.16 is derived from Nicklin's (92) analysis.

Z is a constant dependent on pipe inclination and roughness. C_1, C_2, C_3 are coefficients relating to the frictional losses along the pump and at the entrance and exit. For solution of the gas-lift pump model it is necessary to know the liquid flow-rate that would result from a given gas flow, that is Equations 6.15 and 6.16 must be solved for W_{10}.

Figure 6.4 is a flow-diagram for a computer program for this purpose. Examination of Equations 6.15 and 6.16 reveals a possible problem. If $\bar{f}_1$ is larger than σ there is no real solution. This situation might arise where a low flow-rate is required in a pump with a low submergence ratio, typical of reprocessing operations.

Clark (27,28) has proposed a differential momentum balance. As acceleration effects due to gas expansion are small they are ignored. If the gas density in the upriser is also ignored this leads to the following:

$$- dP = \left[\rho_1 g \ (1 - \varepsilon) + F \right] dx \qquad (6.17)$$

where ε is the cross-sectional gas void fraction; and

F is the frictional loss per unit length.

Integrating 6.17 between the entrance condition ($x = 0$, $P = P_0$) and exit condition at the pump discharge ($x = x_2$, $P = P_2$) x_2 can be obtained explicitly and hence the pump lift can be evaluated.

The integration requires prediction of both the void fraction and frictional losses as a function of the gas and liquid flow-rates. Clark used the drift-flux model to predict gas void fraction:

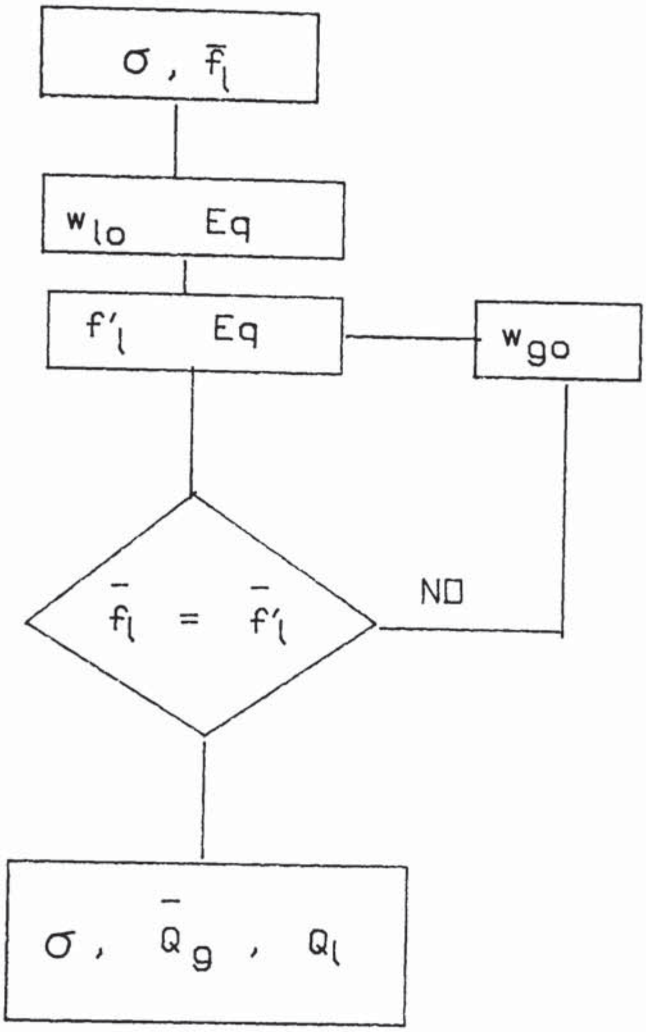


Figure 6.4 A Solution Algorithm for the Todoroki Analysis

$$W_g/\varepsilon = C_0\ (W_g + W_e) + V_v \tag{6.18}$$

where C_0 is a constant whose value depends on the flow regime and V_v is the drift velocity given by:

$$V_v = 0.35\ (gd)^{0.5} \tag{6.19}$$

The approach of Lockhart and Martinelli (77) was used by Clark to predict frictional losses as follows:

$$F = D\ \Phi_1^{\ 2} \tag{6.20}$$

Where D is the frictional loss per unit length if the liquid alone occupied the tube,

$$D = 4\rho_1\ fw_1^{\ 2}/2d \tag{6.21}$$

Orkizewski (100a) presented the following model to predict the two phase flow multipliers

$$\Phi_1^{\ 2} = 1/(1 - \varepsilon)^n \tag{6.22}$$

Expansion of this, truncating and combining with Equation 6.20 gives

$$F = D(1 + n\ \varepsilon) \qquad (6.23)$$

Combining 6.17 and 6.23 results in

$$- dp = \left[\rho_1 g\ (1 - \varepsilon) + D(1 + n\ \varepsilon)\ dx \right] \qquad (6.24)$$

For slug flow, which is commonly found in gas lifts, n takes the value of 1.5 (28). Equation 6.18 may then be substituted for the gas void fraction. Clearly, the gas void fraction will vary over the length of the lift. Let G be the mass flow of gas to the base of the pump then,

$$W_g = GP_a/A\rho_g \qquad (6.25)$$

Rearranging and integrating gives

$$\frac{P_2 - P_0}{(P_1 g + D)} - \frac{DnM - \rho_1 gM}{(\rho_1 g + D)^2 S} \log \frac{R + (\rho_1 g + D)\ SP_2}{R + (\rho_1 g + D)\ SP_0} + x_2 = 0 \qquad (6.26)$$

Where $R = \rho\lambda g\ M(C\ \ - 1) + DM(C\ \ + n)$

$$S = C_0 W_1 + V_v.$$

6.26 can be rearranged to give an explicit expression for x2, the lift of the pump. In this study x_2 is knownand w_1

is required for a given w_g. Since Equation 6.26 cannot be rearranged to give w_l explicitly it was therefore solved implicitly. A PMSP procedural routine (Appendix E) was written to do this using the bisection method.

Clark suggested that f, the friction factor for liquid flow be obtained from standard charts. This is not practical for a computer simulation; therefore f was calculated using the following expression recommended by HTFS (Heat Transfer and Fluid Flow Service):

$$\sqrt{\frac{1}{f}} = 7.2 \log (6.9/Re) + (\varepsilon/3.7d) \tag{6.27}$$

On an industrial plant air pressure/flow rate will be measured upstream of the injection point. Therefore G has been predicted from anticipated values assuming ideal behaviour.

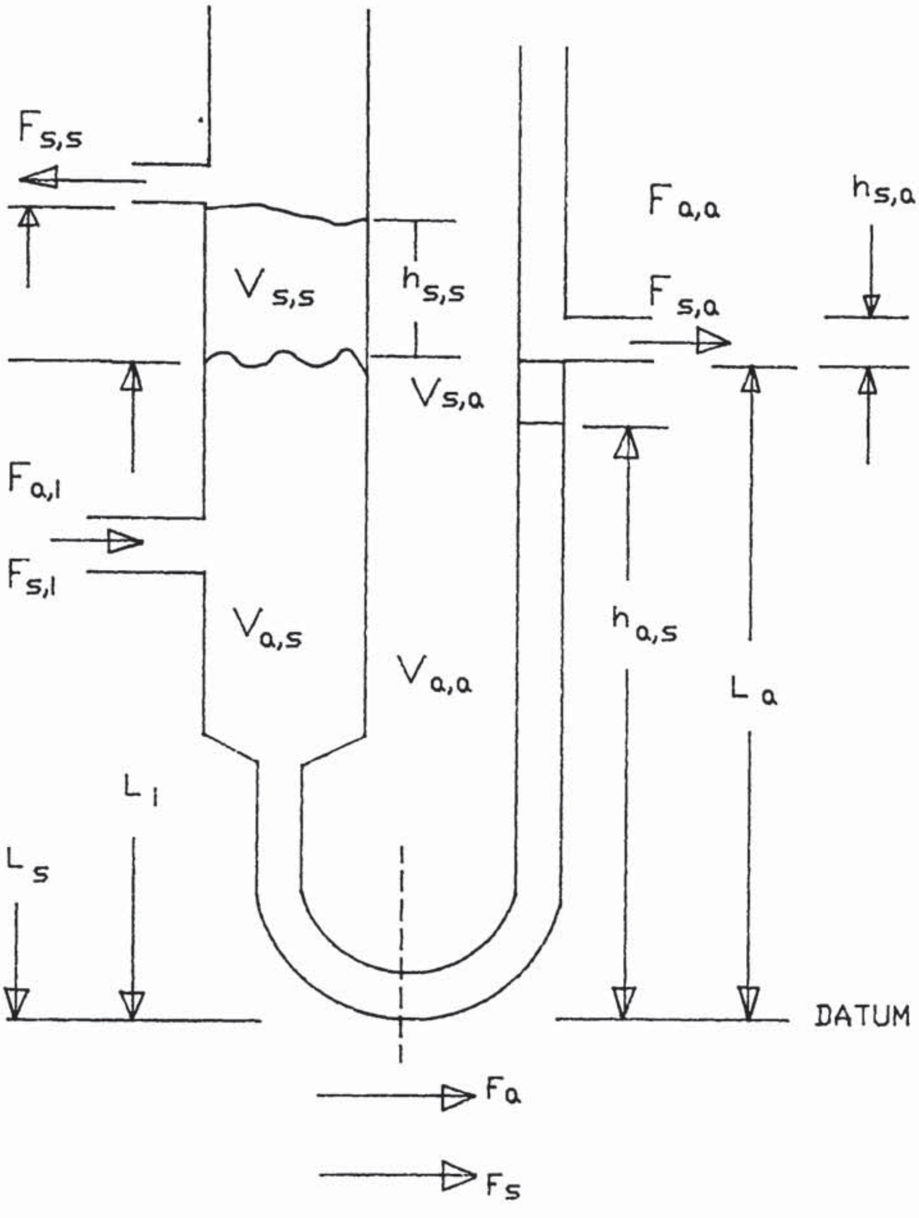
Alternative methods have been proposed to estimate two-phase frictional pressure drops; including those of Lockhart - Martinelli (77), Martinelli-Nelson (84), Baroczy (11), Chisholm and Sutherland (26) and Friedal (44). These models are described in detail in Appendix B.

6.4 The Gravity Settler

The gravity settler is illustrated in Figure 6.5. In nuclear fuel reprocessing plants, where access for maintenance after start-up is strictly-limited and often impossible, any instrument used must be reliable and preferably non-intrusive. If the bottom interface of a solvent-continuous column developed within the column it would be necessary to hold its position outside the plated section. Pneumercator tubes which rely on detecting the small pressure difference across an interface are the usual method used to measure interface position in reprocessing plants.

Practical problems arise when attempting to detect small pressure differences at the bottom of eg a 10 m tall column when subjected to pulsation. One possible solution is to remove the two-phase mixture from the bottom of the column to a separate vessel where an interface is allowed to form.

The differential equations describing the behaviour of this item are:



N.B.

$V_{s,a}$ usually 0.0

$F_{s,a}$ usually 0.0

Figure 6.5 The External Settler

$$\frac{d(V_{a,A})}{d\,t} = F_a - F_{a,a} \tag{6.28}$$

$$\frac{d(V_{a,S})}{dt} = F_{a,i} - F_a \tag{6.29}$$

$$\frac{d}{dt}\,(Vs,s) = F_{s,i} - F_{s,s} \tag{6.30}$$

$$\frac{d}{dt}\,(Vs,a) = F_s - F_{s,a} \tag{6.31}$$

The flows Fa,a, Fs,s, Fs,a over the circular cross-section exit weirs are given by equations of the form

$$F = \int_0^{D_T} 2\,C_D g^{\frac{1}{2}}\,h^{\frac{1}{2}}\,(r^2 - (r + h - D_T)^2)^{\frac{1}{2}}\,d\,h \tag{6.32}$$

using the notation illustrated in Figure 6.6.

Integrating numerically using a fourth-order Runge-Kutta method and fitting to an equation of the form

$$F = aD_T{}^b \tag{6.33}$$

yielded $a = 0.384$

$b = 2.02075$

Flows through the connecting link, Fa, Fs, are given by

$$F = A^{*}\, C_D^{*}\, \sqrt{(1/\rho} * \{(h_{a',s}\rho_a g + h_{s',s}\rho_s g) - (h_{a',a}\rho_a g + h_{s',a}\rho_s g)\} - E_f \qquad (6.34)$$

where E_f is the frictional energy dissipation

$$E_f = 2\, \frac{L}{d}\, f \; \frac{F}{A}^{2} \qquad (6.35)$$

6.34 and 6.35 must be solved implicitly.

The effects of the coalescence band on the behaviour of the device has been ignored, that is instantaneous coalescence is assumed. As other pieces of equipment are more critical to plant performance this assumption is acceptable given the normal order of coalescence times (30 s). If surfactant were present which hindered coalescence then it might be possible to fill the vessel with froth and the consequences of having, eg aqueous going into the solvent, could be very serious.

6.5 Inter-cycle Buffer Tanks

Buffer tanks provide feed liquid storage capacity, to even out temporary variations in concentration and to enable individual cycles to continue operating for several hours,

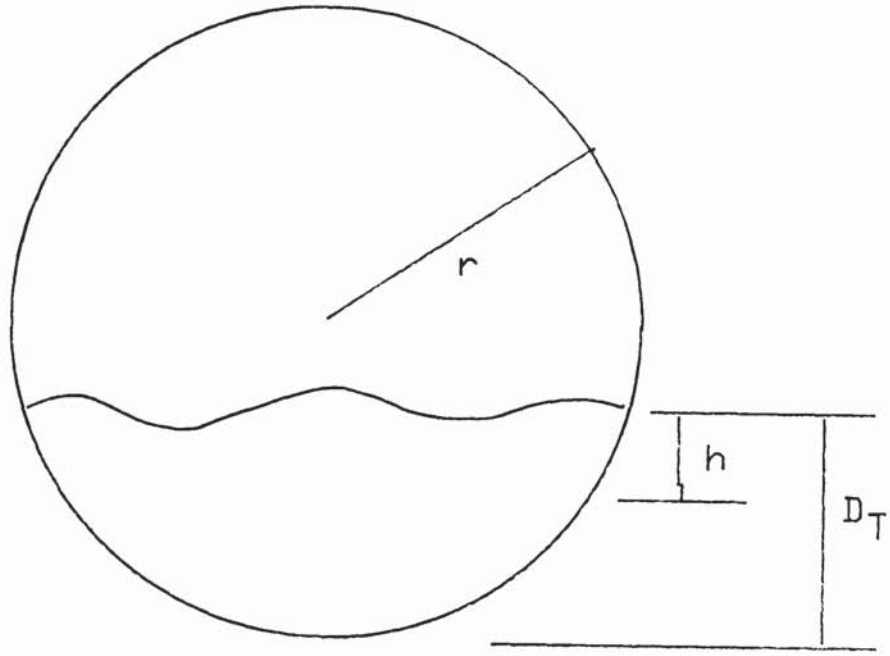


Figure 6.6 Weir Nomenclature

typically 6 if preceding, or following, cycles are temporarily shut down.

Figure 6.7 shows a typical tank. Each tank is well-mixed, due to the circulation provided by the fluidic pumps. Therefore perfect mixing has been assumed in the analysis. There are three flows into a tank, the product from the previous cycle (or for cycle I the dissolver product), a conditioning stream and a recycle stream. Designate these streams as F_1, F_2 and F_3.

$$F_T = F_1 + F_2 + F_c \tag{6.36}$$

$$\frac{dV}{dt} = F_T - F_O \tag{6.37}$$

Where F_O is the outlet flowrate provided by a fluidic pump. The fluidic pump has been represented by a 'dummy' characteristic. The concentration differentials for a component i have the form

$$\frac{dCi}{dt} = F_T/V[(F_1 \; C_{i,1} + F_2 \; C_{i,2} + F_3 \; C_{i,3})] \tag{6.38}$$

$C_{i,0}$, the outlet concentration of component i, is found by integrating $\frac{d}{dt}$ Ci through time to the point required.

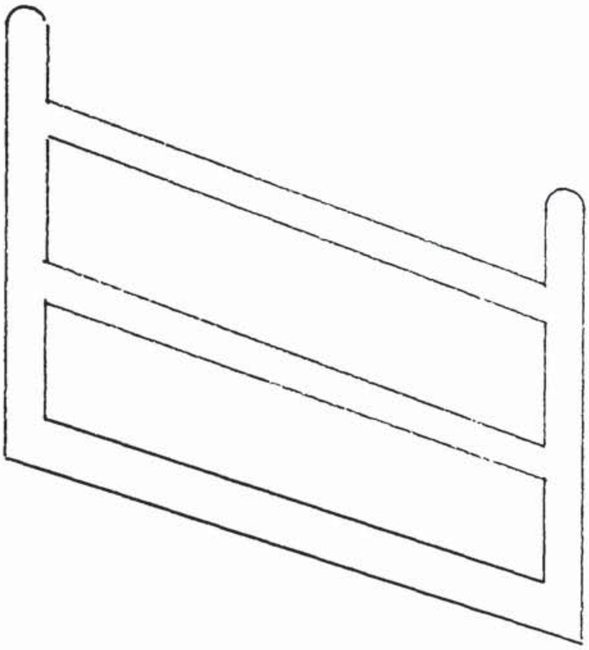


Figure 6.7 Sketch of a Typical Inter-Cycle Buffer Tank

6.6 The Proportional-Integral Controller

Columns operated in the aqueous-continuous mode eg as in Figure 6.2 have an interface formed at the top of the column. The position of this interface is dependent upon the flow of aqueous phase out of the bottom of the column. If this flow is smaller than the aqueous feed to the column then evidently the interface will rise towards the solvent off-take weir. Alternatively if the flow is too large the interface will move towards the plated section of the column. Clearly, the interface position, and hence the bottom flow from the column, must be controlled. This flow is induced by a gas-lift pump; hence the flow of gas to the pump will control the interface position. The piping layout around this system remains to be specified as do the gas-line valve characteristics and the position of the valve. If the valve is placed well away from the gas injection point a time lag and an additional pressure drop will be introduced to the system. Because of these unknowns and the large uncertainties in predicting two-phase flow behaviour, for example Butterworth (22) suggests that 50-60% errors occur in predicting frictional losses alone, the controller model cannot be very realistic. It was therefore decided to assume that the controller acted directly upon the gas flow-rate ignoring the effects of the valve and intervening pipe-work.

The equation describing the action of a proportional-integral controller is (81)

$$C = K_G e + \frac{K_G}{T_I} \int_o^t e \, dt + K_s \tag{6.39}$$

where e = error in the interface position

K_G = proportional gain

T_I = integral reset time

K_s = controller set-point

To avoid introducing unnecessary instabilities to the system K_G is set low (1.0D-05 M3/M/S) and T_I is set high (0.2 hours). If the open-loop response (no control action) is to be investigated K_G is set to zero and T_I increased to 5 hours. For 'bumpless' transfer from one reset time to another, hardware is usually implemented with the error divided by integral action time prior to integration.

It has been assumed that top interface position can be measured accurately.

6.7 The Constant Volume Feeder

A Constant Volume Feeder (CVF) illustrated in Figure 6.8 accurately delivers small flow rates typical of those found in a reprocessing plant, eg 100 litres/hour. It consists of a rotating wheel on which are mounted tubes open at one end. The wheel rotates in a trough containing liquid. The tubes pick up liquid whilst they are submerged and drain down through the hollow hub on the upward part of the rotation. The delivery rate from the CVF depends on tube size, speed of rotation and depth of fluid in the trough.

For the purposes of the model it has been assumed that the maximum fraction of tube submerged at any one time will be filled with liquid, that is, that fraction of the tube submerged as the open tube mouth surfaces on its upward surge, see Figure 6.9. A final design had not been decided upon and attempts to 'estimate' the fine detail of the performance of this item was not therefore attempted.

The fraction of the tube submerged is

$$F_T = V_O * \frac{\theta}{\alpha} \qquad (6.40)$$

where $\theta = \frac{180}{\Pi} * 2 \cos^{-1} (Z_L/R)$ (6.41)

V_O = total volume of tube

If there are n_t tubes/hub and the hub rotates at N

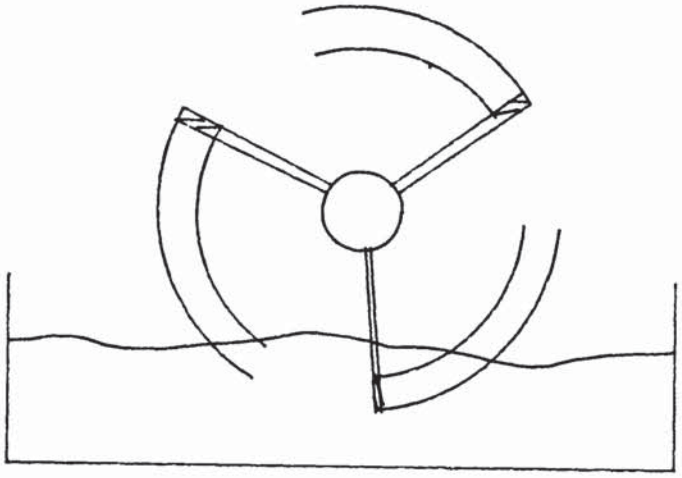


Figure 6.8 The Constant Volume Feeder (CVF)

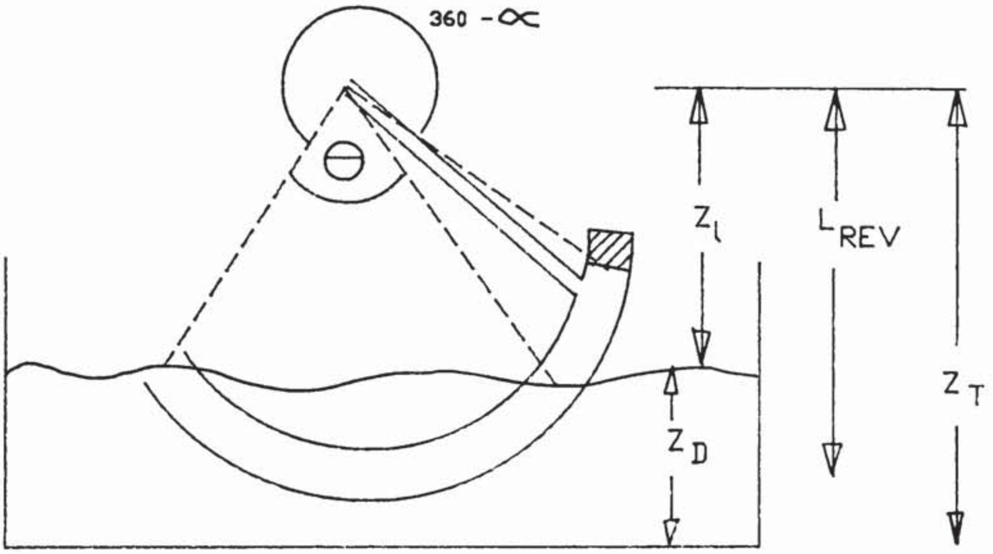


Figure 6.9 The Constant Volume Feeder

revolutions per second then the average fluid delivery rate is

$$F_o = V_o \frac{\theta}{\alpha} n_t N \tag{6.42}$$

During normal operation the trough is filled to the level of the overflow weir - more liquid is fed to the trough than is required, the excess overflowing. Should the feed to the trough be interrupted or reduced then the volume picked up by the tubes begins to immediately decrease. This is clearly undesirable where flow-rates are required to be metered accurately.

The flow-rate over the weir using a Francis equation for a full-width weir (148), is given by

$$F_W = 1.84\ L_a\ Z_w^{1.5} \tag{6.43}$$

The volume of liquid in the trough varies with time as

$$\frac{d}{dt} V_t = F_i - F_o - F_w \tag{6.44}$$

Dimensions of the device cannot be given.

6.8 The Combined Model

The models of individual plant items described in Chapter 6 were programmed as PMSP Macros. They were then combined to form models of individual cycles, or of the complete plant. The lags as fluid flows from one item to the next were included, as were the flow diverters, basically three way valves. These items are used during start-up and unusual operating conditions, for example running a section of the plant on total recycle. These were modelled as simple logic blocks; the value of the switch passed to the block determines the destination of the fluid entering the diverter.

Cycle III-U is illustrated in Figure 6.10. It comprised the following items:-

(i) A feed tank, filled with aqueous uranium product from Cycle II
(ii) A compound extract/scrub column
(iii) A strip column
(iv) Two constant volume feeders (CVF)
(v) Three gas lifts
(vi) Three gravity separators
(vii) A diverter
(viii) Two controllers
(ix) Inter connecting pipiework.

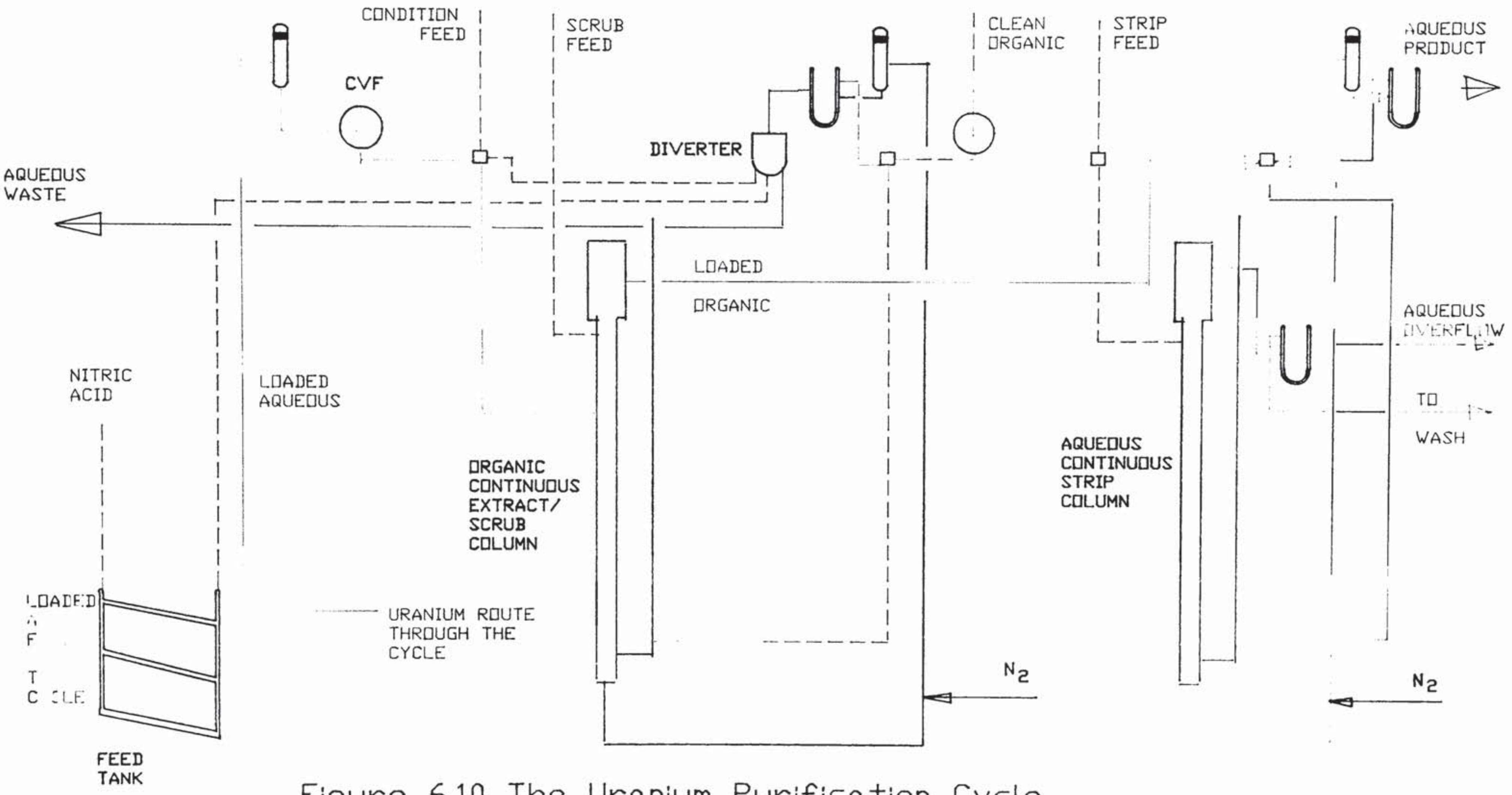


Figure 6.10 The Uranium Purification Cycle

The extract and scrub sections of compound columns are modelled separately. Cycle I, Cycle II and Cycle III - Pu each consist of a compound extract/scrub column and a strip column and are therefore very similar to Cycle III - U which will be used as an example.

An aqueous uranium product from Cycle II enters the Cycle III-U area. It is mixed with a conditioning stream of 22M acid and flows into the Cycle III-U feed tank. A fluidic pump feeds the loaded aqueous phase to the extract section of column 7 via a constant volume feeder (CVF). A nitric acid scrub enters the scrub section of column 7. A gas-lift pump pulls a two phase, solvent/aqueous, mixture from the bottom of column 7 and lifts it, via a breakpot, to a gravity settler. The aqueous stream from the settler flows to a three-way diverter which, in normal operation, directs the aqueous phase to the medium active liquor tank for waste treatment. During start-up or 'tickover' it can either divert the flow back to he tank or back to the column.

Clean solvent enters Cycle III-U from the stock tanks and is fed via a CVF to the pulse limb for column 7. The overflow from this CVF returns to the stock tanks. The solvent overflowing from the botton interface settler is recycled back to column 7 via the pulse limb. This solvent is clean, since it has not entered the plated section of the column.

Loaded solvent phase leaving column 7 flows by gravity to column 8 where it is contacted with a stripping agent. This stripping agent is introduced to the top of column 8 via a CVF. Loaded aqueous phase, together with some solvent is raised to a gravity separator by a gas lift pump. Aqueous phase overflow from the separator passes forward to the finishing plant; organic overflow returns to the column. Flow of nitrogen to the gas lift pump is governed by the PI controller which controls the position of the interface formed at the top of this aqueous continuous column. Organic overflows from the top of the column and passes, via a gravity separator to the solvent wash plant. This gravity separator is provided to cope with any PI controller malfunction and possible egress of loaded aqueous from the column to the solvent wash facility. Any aqueous phase flow from this separator is recycled to the column.

6.8.1 Bottom Interface Control

For columns operated in a solvent continuous mode, that is with an interface formed at the base of the column, the interface is assumed to be removed to an external settler via a gaslift pump. This will circumvent the problems described earlier in detecting an interface at the base of tall pulsed columns. The gas flow will be controlled through a flow-detection switch on the organic overflow line from the settler; if the organic flow falls below a certain level the gas flow is increased until the organic flow resumes at, or above, the preset level. Code has been included to mimic this behaviour and also to allow for an interface forming at the base of the column. The gas flow will be increased by a set amount at set time intervals e.g. 5% every 30 seconds until organic flow resumes.

Currently, no provision has been made within the model to reduce gas flow if solvent overflow from the separator becomes excessive - a situation which may arise if an aqueous 'plug' develops in the bottom of the column.

7 Analysis of Results

7.1 The Gas-Lift Model

Three methods for the prediction of gas-lift pump performance were assessed, viz the analyses of Clark (22,23), and Todoroki (108) which are specific to gas-lift pumps and Friedal's method (38) to predict two-phase frictional pressure drop. These three models were tested using data (82) and using experimental data gathered during the work described in Chapter 5.

7.1.1 Experimental Results

The results of the experimental work are tabulated in Appendix A. A range of rotameter readings, and hence flowrates of nitrogen and liquid, are quoted because the rotameter floats were observed to 'oscillate' at a frequency of about 0.5 - 1.0 Hz and did not settle at a particular level. This phenomenon was probably caused by pressure surges passing from the gas-lift upriser back through the connecting pipework to the rotameter. These pressure surges may have been caused by 'blowback' particularly at low flowrates or by the sudden mean density change in the upriser. Whilst this effect may also be experienced on plant it may be 'damped' by the pulse imposed on the column.

Figures 7.1-7.4 illustrate the relationship between gas and liquid flows.

The range of flowrates covered by the rotameter float 'oscillation' is given in Figure 7.1. In the remaining figures median flowrates are plotted. The results indicate that for the gas-lift configuration used in the experiments the liquid flow-rate delivered by the pump was very sensitive to changes in gas flow-rate. For example, a 10% increase in gas-flow rate increased the liquid flow-rate by 40%. Figure 7.4 shows the results when a two-liquid mixture was pumped. Comparison between Figures 7.1 and 7.4 shows that for a given liquid delivery rate the gas flow-rate required was higher for a two-liquid mix than for water alone. Where the mixture pumped was largely solvent, about 75% v/v, the gas-flow needed was approximately double that for a similar flow of water; a mainly water mixture required about 40% extra nitrogen.

7.1.2 Analysis by the Method of Clark (27, 28)

With Clark's analysis, the liquid delivery rate for a given pump configuration and gas flowrate must be obtained by iteration as discussed previously. For low gas-rates and low submergence ratios the required liquid flow for solution tends to zero which in turn causes an arithmetic failure.

In the event the predictions from this model did not match the experimental results, the model tending towards a zero liquid flow-rate which caused an arithmetic failure. A reason for this arithmetic difficulty becomes apparent when data from the literature are examined (82). The data are given in Appendix A. Figures 7.5-7.10 illustrate the data. Clearly, Clark's analysis consistently underpredicted performance. When very low gas-flows were used with low submergence ratios the predicted flow-rate was 10-20% of that observed. In most applications the combination of low gas flow with low submergence would not be encountered and therefore Clark's analysis would be acceptable. The variability of the predictions was not unexpected since two-phase flow is notoriously difficult to model and errors of 50-60% are common (146).

Table 7.1 lists the results of an series of simulations made to determine the effect of liquid density on performance. For an increase in density from 800 kg m^{-3} to 1200 kg m^{-3} no significant difference was observed.

The results of an experiment to determine the effect of the submergence ratio on performance are given in Table 7.2. Interestingly there appears to be a stronger dependancy on submergence where low gas rates are used than at higher gas-flows. Thus for a gas rate of 0.89 m^3/m^2s.

$$f_L \propto \sigma^{1.8} \qquad (7.1)$$

whereas for a gas rate of $5.49m^3/m^2s$

This means that, in practice for a reprocessing plant where σ is low, changes in nitrogen flow caused by a controller will cause relatively larger changes in liquid flow-rate. That is, liquid flow-rate will be very sensitive to nitrogen flow-rate and care would have to be exercised in determining controller settings.

$$f_L \propto \sigma^{0.88} \qquad (7.2)$$

7.1.3 <u>Analyses by Friedel's Model</u> (44)

Friedel presented a non-graphical method to predict the frictional pressure drop for a two phase mixture. For inclusion in a computer simulation a non-graphical method offers clear advantages over those of, for example, Baroczy (11). This was therefore included in a model to predict the total pressure drop for the flow of a two-phase mixture. Friedel's model does not output a liquid flow-rate for a given gas flow-rate but does give the total pressure drop along a pipe for a known two-phase mix. Friedel's approach has been discussed in Chapter 6. To determine the required liquid flowrate a trial and error method may be used or a graph can be plotted for a known gas rate to show outlet pressure as a function of liquid flow-rate. The solution is provided by the liquid rate that gives an outlet pressure equal to atmospheric pressure.

Friedel's approach proved incapable of reproducing the experimental results. Tables 7.1-7.5 include the results predicted by Friedel's method. This model underpredicts performance and gives consistently worse agreement than Clark's method.

7.1.4 The Todoroki Model

All attempts to use Todoroki's method (108) to predict data in reasonable agreement with the experimental results and literature data failed as the model tended towards a complex solution, as previously discussed in Chapter 6.

7.1.5 Discussion

None of the models tested were outstanding. However, Clark's and Friedel's models did converge on a real result unlike the model due to Todoroki et al. Friedel's model

Figure 7.1 Range of Rotameter Bob Oscillation

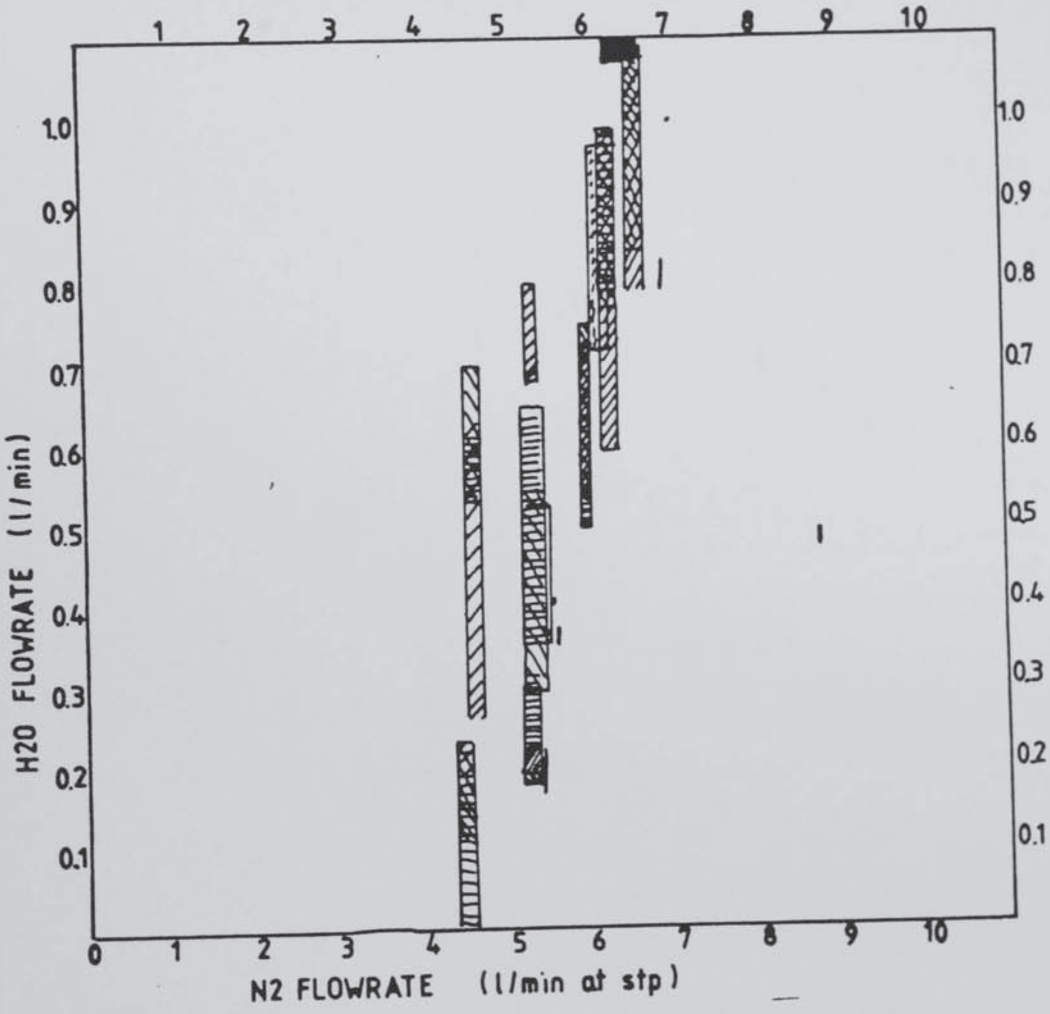


Figure 7.2 Gaslift Performance

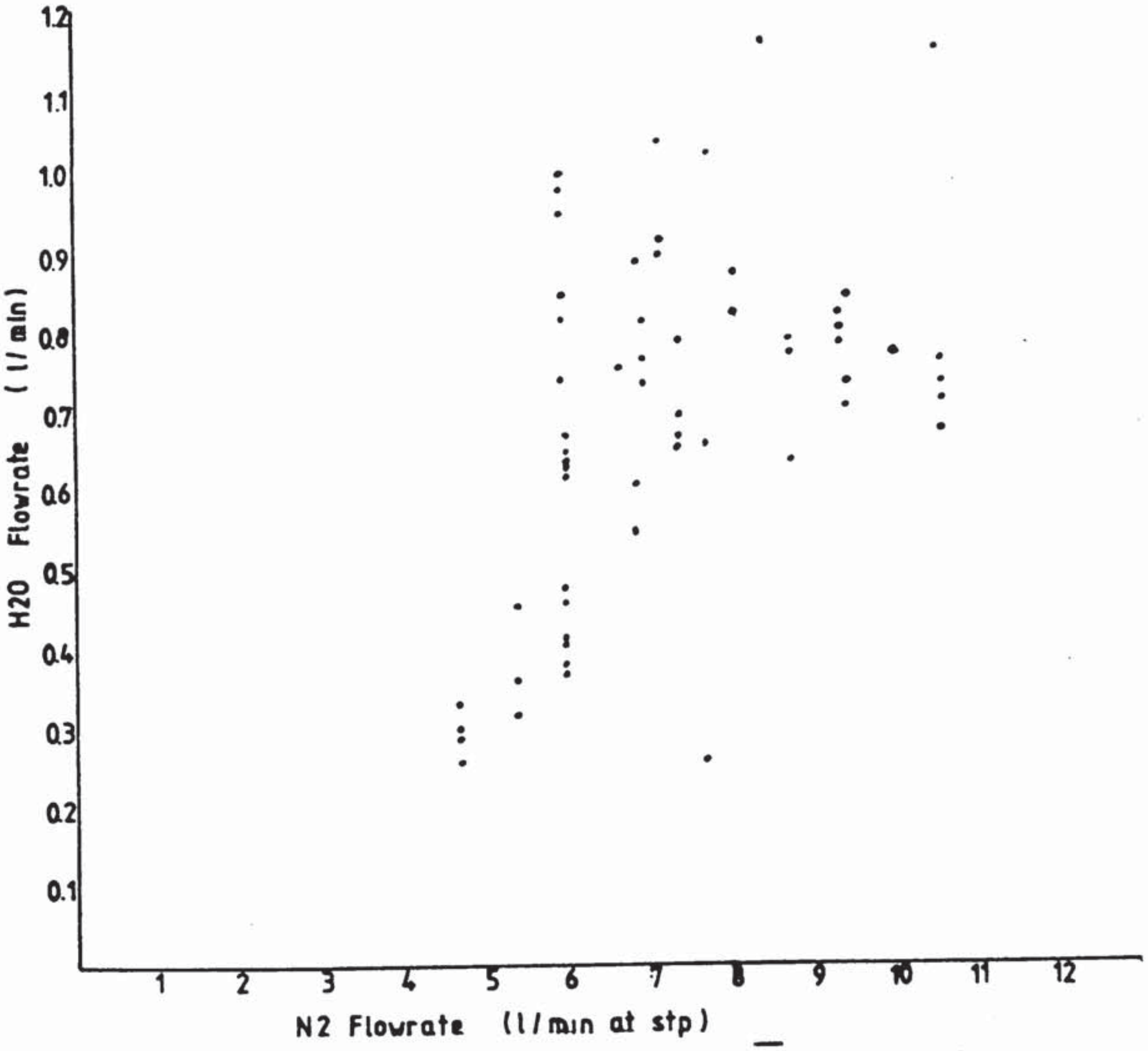


Figure 73 Gaslift Pump Performance

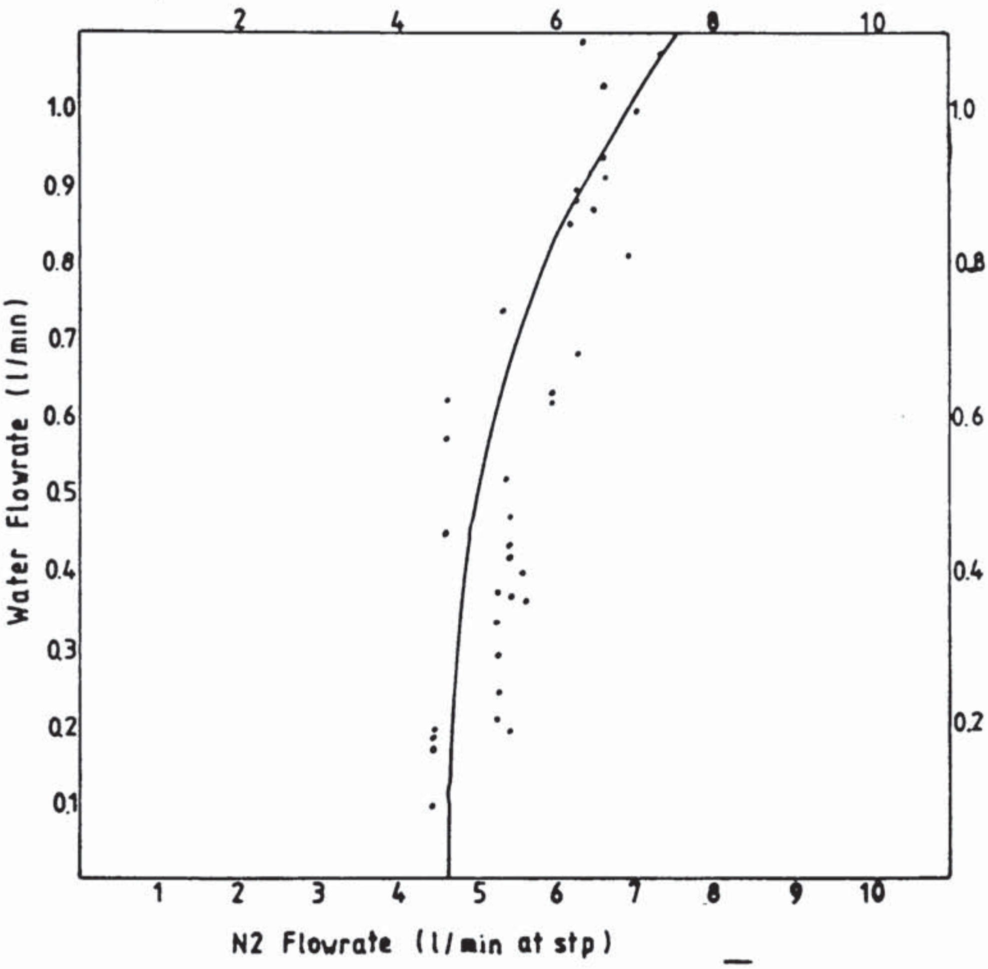


Figure 7.4 Gas Lift Pump Performance

for two phase mixtures

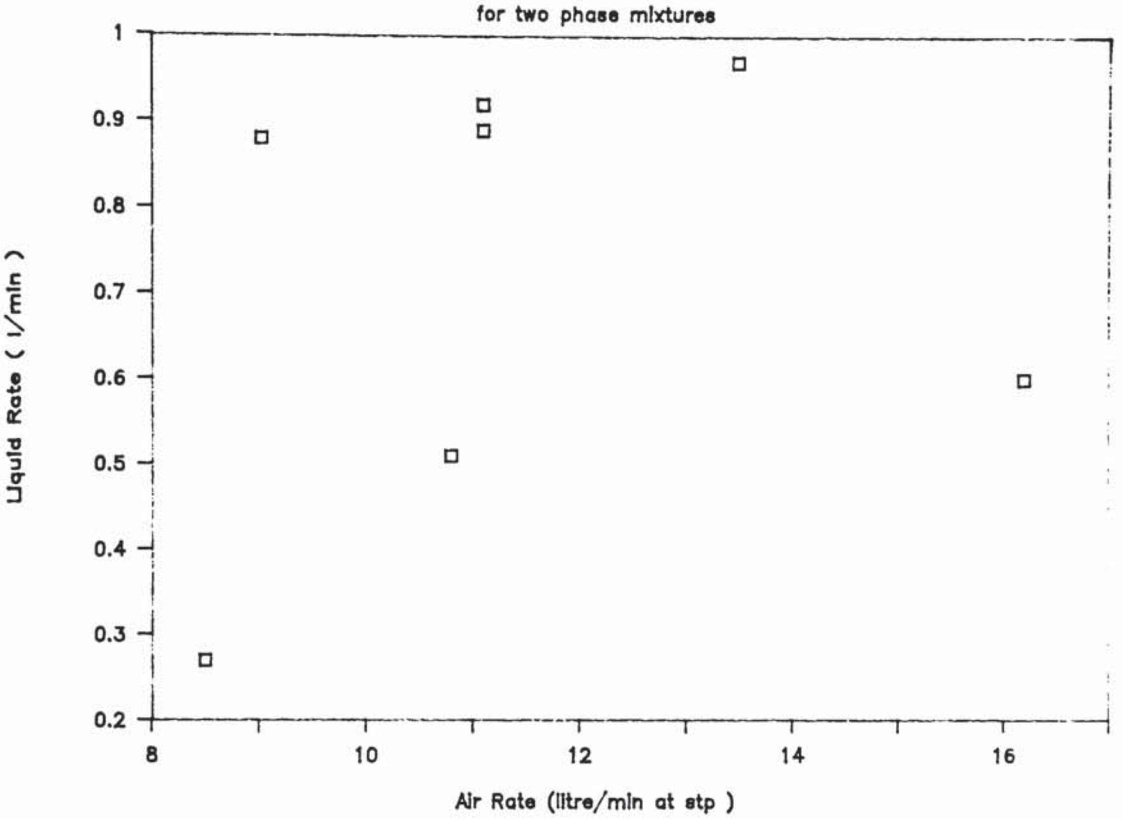


Figure 7.5 Gas Lift Pump Performance

Submergence = 56.3%

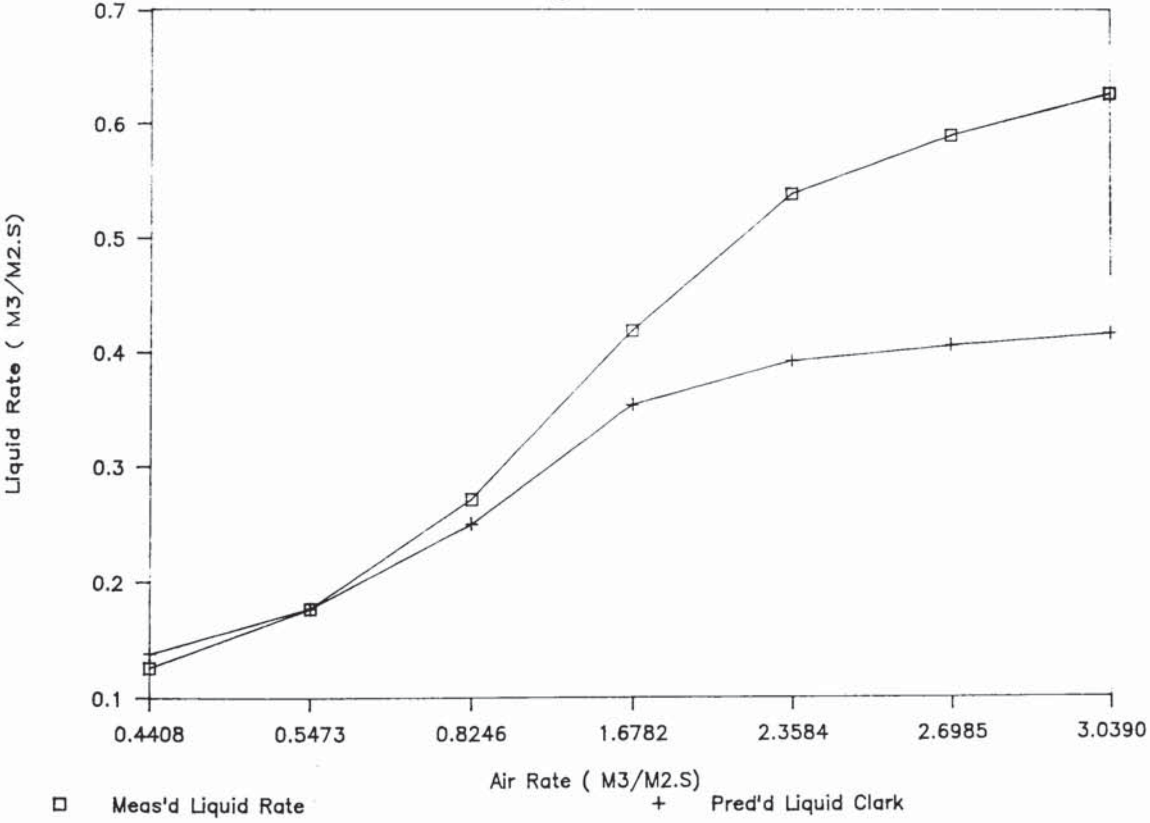


Figure 7.6 Gas–Lift Pump Performance

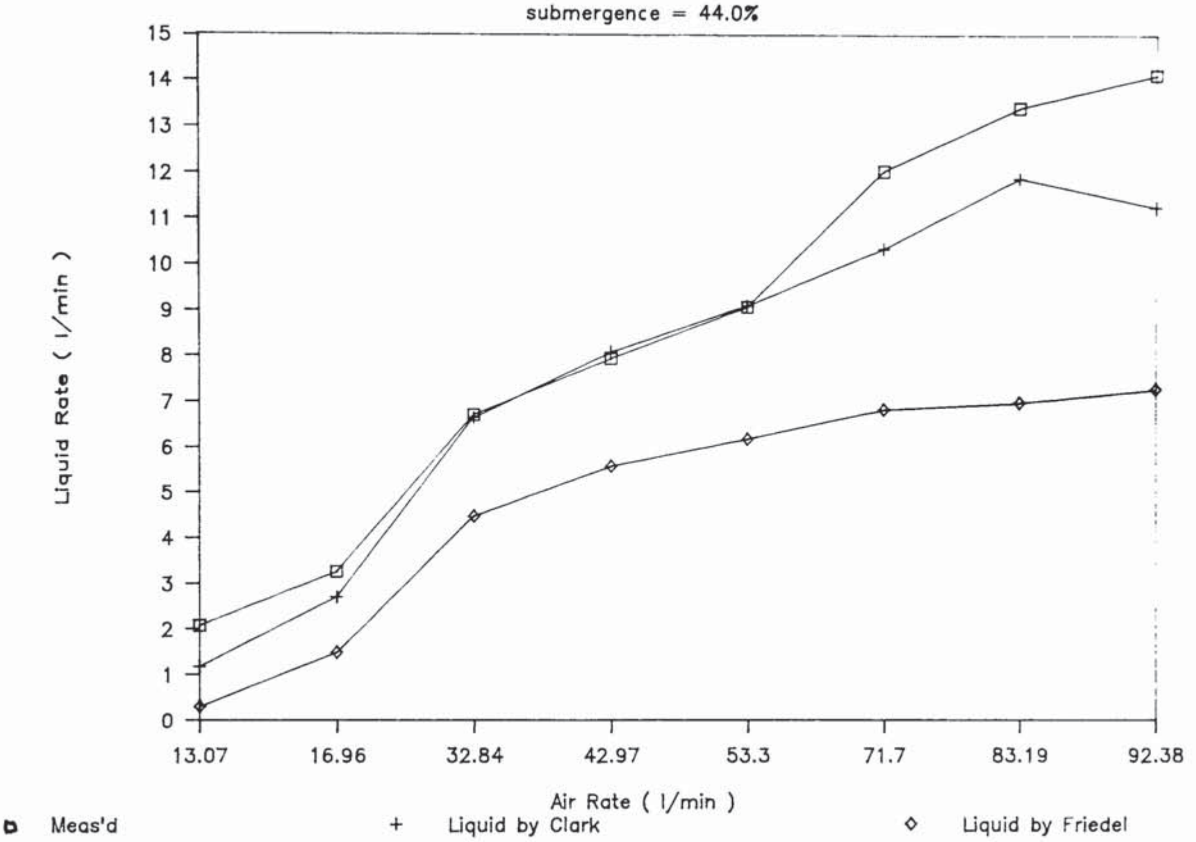


Figure 7.7 Gas Lift Pump Performance

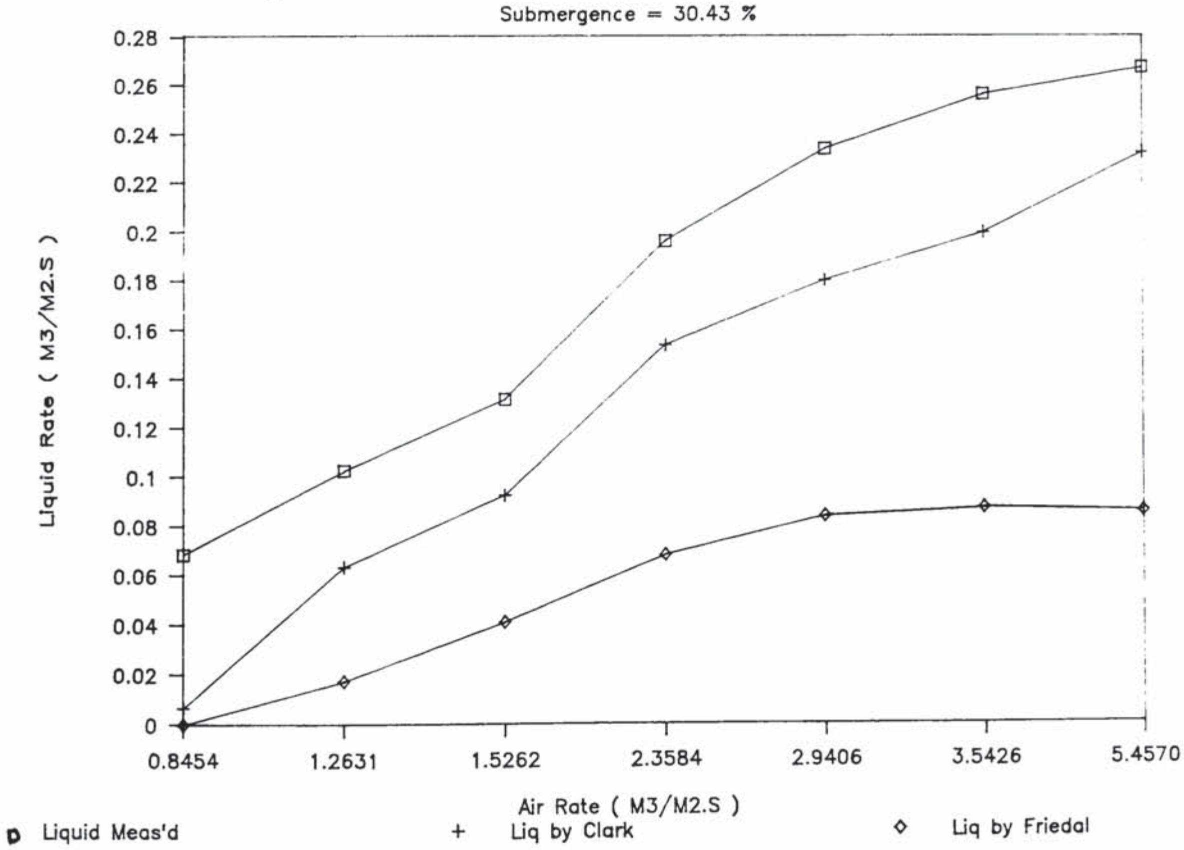


Figure 7.8 Gas Lift Pump Performance

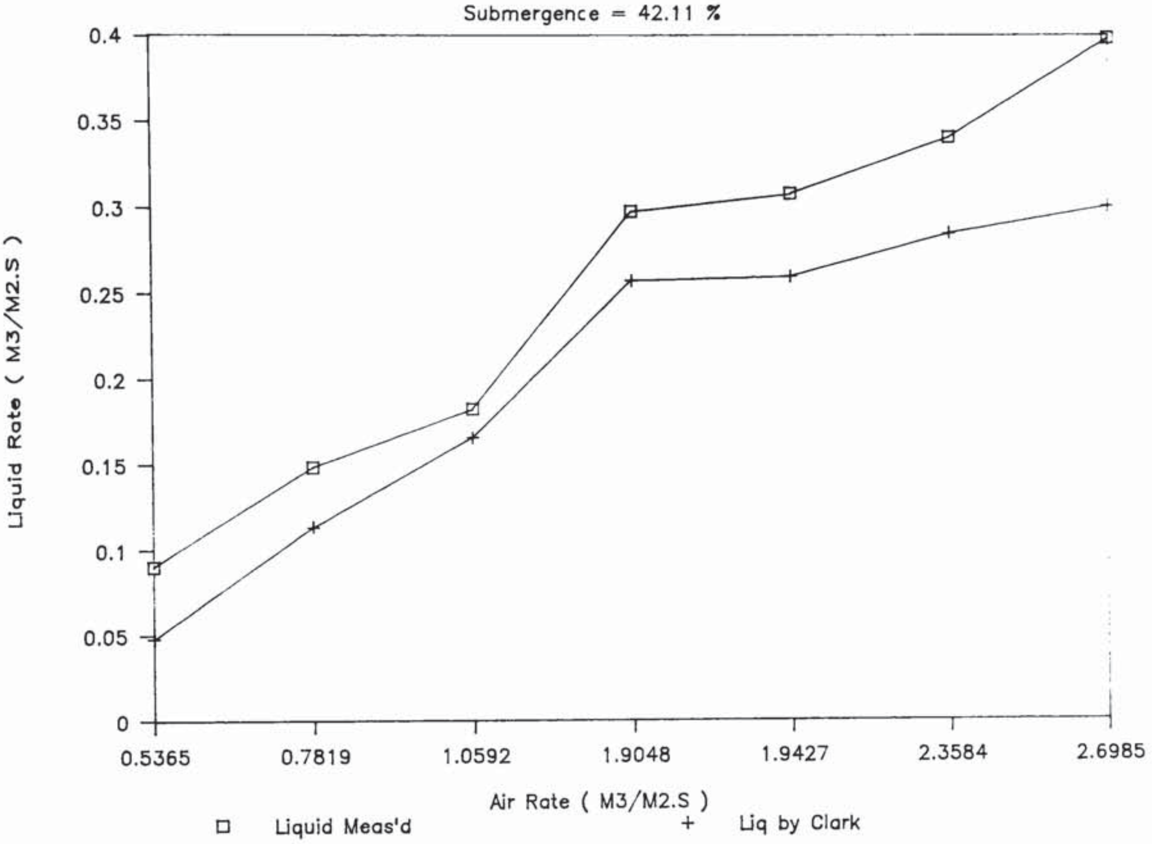


Figure 7.9 Gas Lift Pump Performance

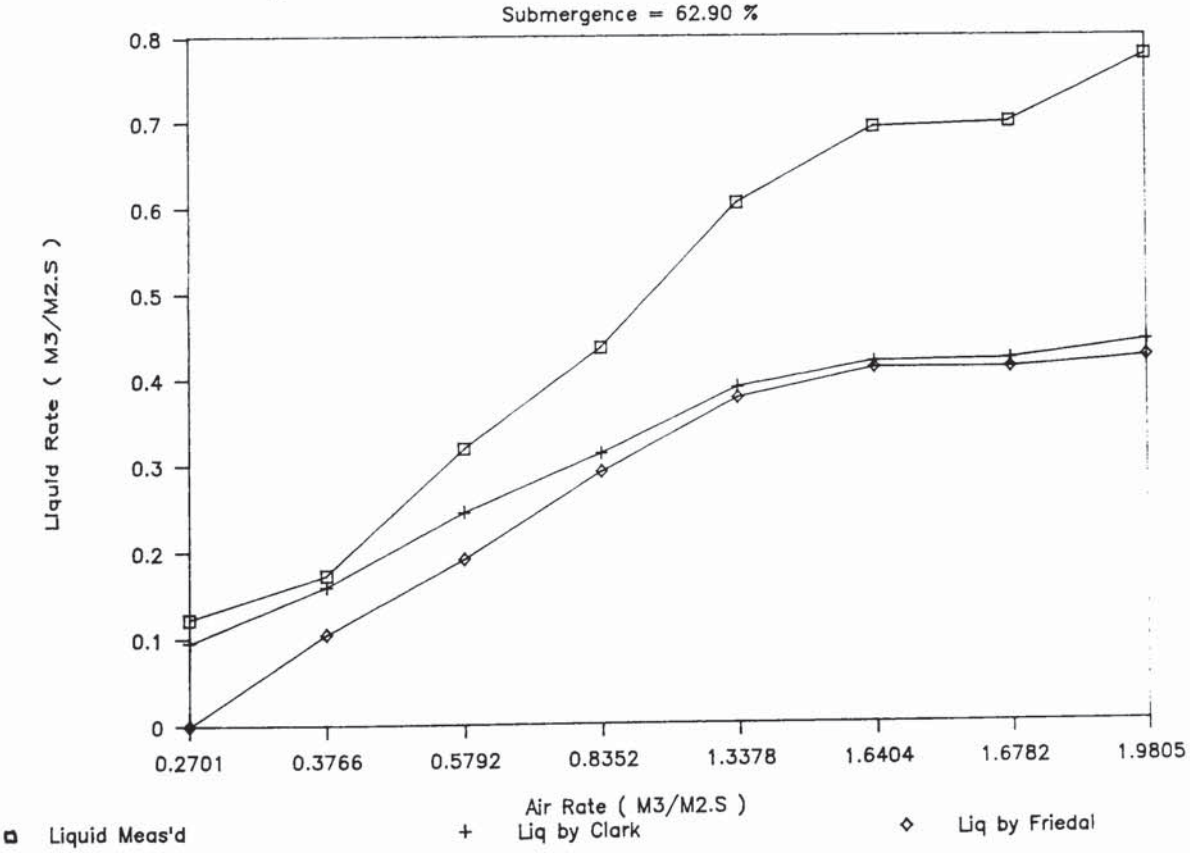
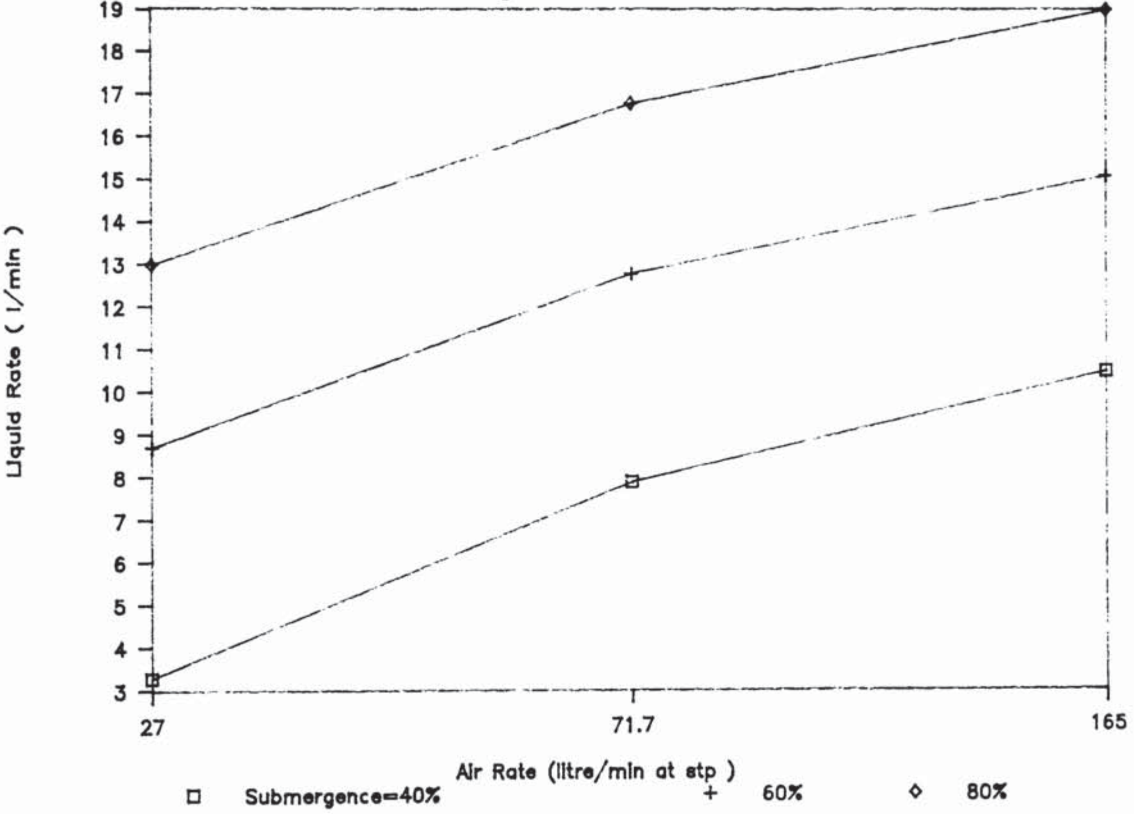


Figure 7.10 Effect of submergence ratio on gas-Lift Performance



was solved by integrating with respect to displacement along the upriser. To include this in a PMSP model integrated with respect to time would be impossible - the only solution would be to split the gas-lift into sections, calculate pressure drop in each section and sum them to give the total pressure drop in the gas-lift. The liquid flow-rate would then be adjusted and the calculations repeated until a liquid rate had been found which satisfied the

outlet pressure = atmospheric pressure

condition. Clearly this would be very time consuming. Therefore, since Clark's method was both simpler to incorporate into a whole plant model and gave the best agreement with available data, it was selected.

Fortunately, in view of the very poor performance of both models at very low flow-rates as an early design called for, the updated plant design calls for considerably higher throughputs than had originally been envisaged.

7.2 The Gravity Settler

The gravity settler model has been run independently of the other modules. Typical results are shown in Figure 7.11. Quite clearly, either the model or the equipment is

Table 7.1 The Effect of Liquid Density on Performance of a Gas-lift Pump

Submerged Ratio $\dot{\sigma}$ 62.9%

Air l/min stp	Liquid Density kg/m^3	Liquid Delivery l/min
27	800	7.6
27	1000	7.5
27	1200	7.4
166	800	14.0
166	1000	13.9
166	1200	13.9

Table 7.2 The Effect of Submergence Ratio on the Performance of a Gas-lift Pump

Liquid Density = 1000 kg/m^3

Submerged Ratio %	Air l/min stp	Liquid Delivery l/min
40	27	3.3
40	71.7	7.9
40	165	10.5
60	27	8.7
60	71.7	12.8
60	165	15.1
80	27	13.0
80	71.7	16.8
80	165	19.0

Table 7.3 The Relationship betwen Fluid Depth and Fluid Pick-up in a CVF

Fluid Depth cm	Fluid Pick Up cm^3
7.0	31.5
7.5	43.0
8.0	65.5
8.5	76.0
9.0	86.5

Tube Diameter = 25 mm

Radius of Revolution = 15 cm

Rate of Revolution = 5 RPM

Table 7.4 Interface Movement After a Disturbance - Predicted and Experimental Results

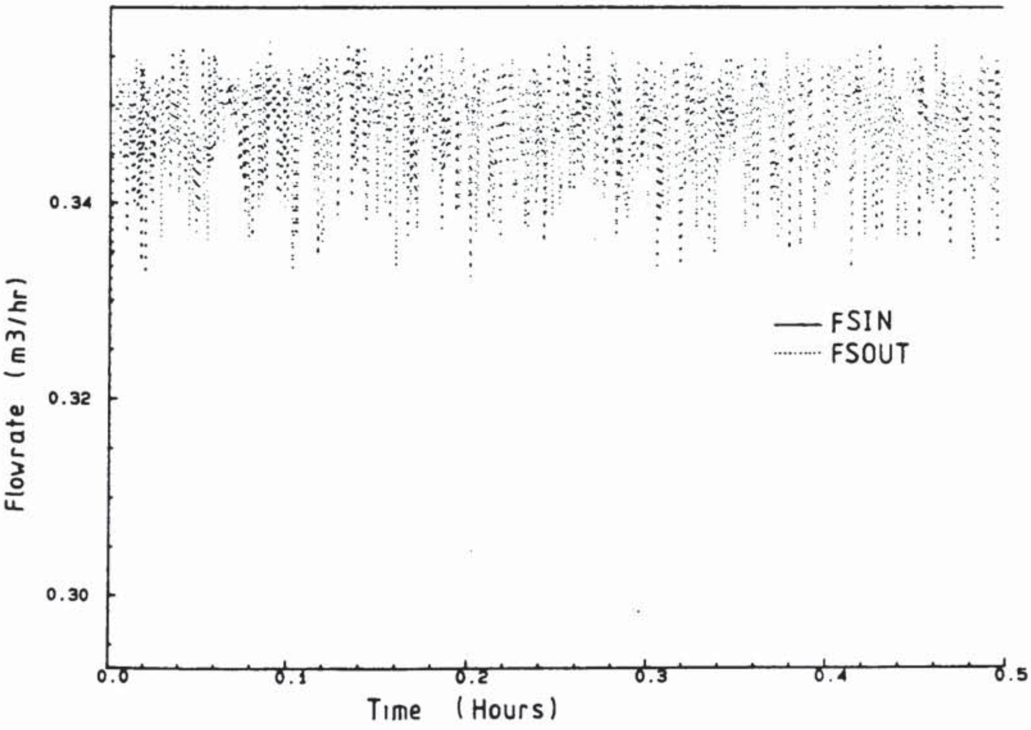
Time Elapsed Since Disturbance min	Interface Movement Model cm	Interface Movement Exptl 1 cm	Interface Movement Exptl 2 cm
0	0	0	0
0.25		1.5	0.5
0.50		1.0	4.5
0.60	1.0		
0.75		2.0	2.5
1.00		2.0	2.0
1.20	2.0		
1.50		2.5	
2.0		2.0	
2.4	4.0		
4.8	6.0		
6.0	8.0		

Model Dispersed Phase	0.865 mms^{-1} - 1.076 mms^{-1}
Exptl 1 Dispersed Phase	2.09 mms^{-1} - 2.47 mms^{-1}
Exptl 2 Dispersed Phase	2.09 mms^{-1} - 2.47 mms^{-1}

Table 7.5 Experimental Data

Initial Organic Flow mms^{-1}	Increased Organic Flow mms^{-1}	Change %	Interface Movement cm	Time Elased from Disturbance min
2.39	4.09	71.1	7.7	1.0
2.39	4.09	71.1	10.5	2.0
2.39	4.10	71.5	11.0	2.5
1.16	3.18	174.0	12.0	2.0
2.09	2.47	18.18	2.5	2.0
2.09	2.47	18.18	2.5	1.0

Figure 7.11 Undamped Behaviour of External Settler



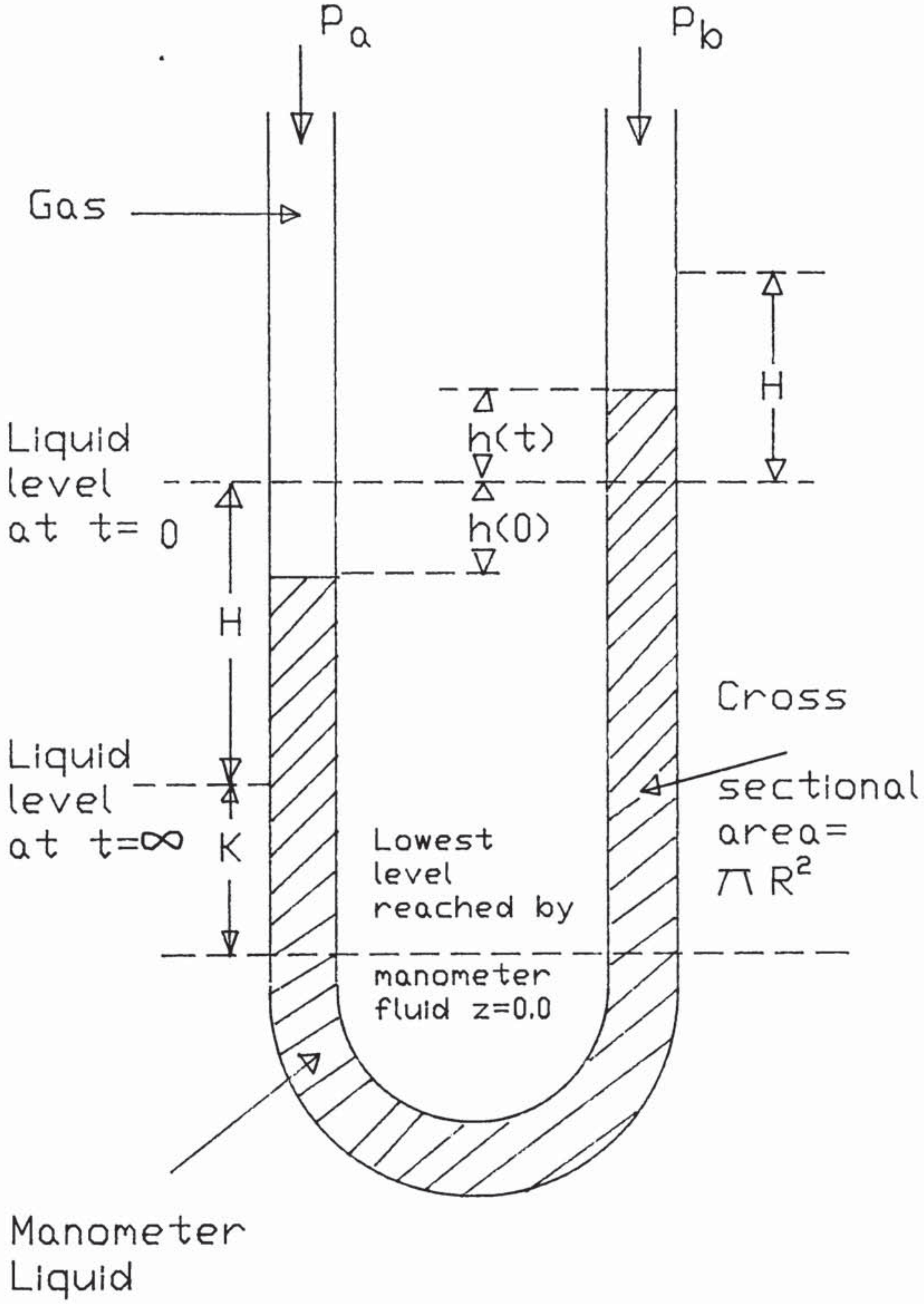


Figure 7.12 Nomenclature for Analysis of U-tube Oscillation

underdamped leading to prolonged oscillation. Treating the settler as a U-tube and making an energy balance over the system as in Bird, Stewart and Lightfoot (15) it was found that the settler was very underdamped or oscillatory. That is, following any disturbance the contents of the settler will continue to 'slosh' back and forwards for some time.

The analysis, using the nomenclature outlined in Figure 7.12 is presented in Appendix B.

In a large dynamic model composed of several modules the maximum time step for integration is determined by the largest derivative, that is the integrator which is changing most rapidly. As the settler's dynamic performance is not crucial to the performance of the plant as a whole it was considered wasteful of computer time to let it dominate the time step size. Two options to get around this problem would be:

i) to artificially increase the damping factor by increasing enormously the frictional drag in the system,

or

ii) to replace the full settler model by a simpler, non-oscillatory model.

The results of increasing the damping in the settler looks very much like a first order lag. As these are extremely simple to model in PMSP the full settler model has been replaced by a system of first order lags. Figure 7.11 illustrates the extreme oscillation in the undamped model and 7.13 illustrates the result of damping.

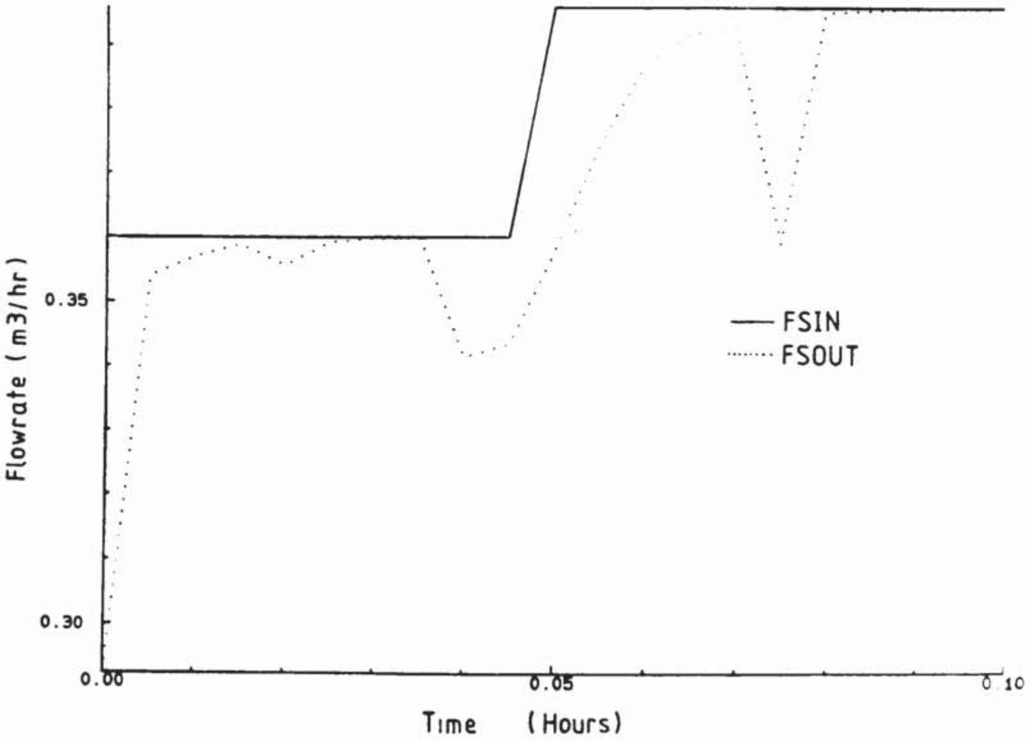
7.3 The Constant Volume Feeder

The model derived in Chapter 6 was written describing the fluid entry to a tube on a constant volume feeder. Of particular interest was the relationship between the depth of fluid in the constant volume feeder trough and the delivery rate from the device. The results for a hypothetical design are given in Table 7.3 and illustrated in Figure 7.14. From these it is obvious that the fluid delivery rate is critically dependant on the depth of liquid in the trough. An approximate relationship is:

$$F_L \propto d^{4.2} \qquad (7.3)$$

As it could lead to widely varying fluid discharge rates this would not be acceptable on plant. This design has

Figure 7.13 Damped Behaviour of External Settler



therefore been superseded by one where the delivery rate is less susceptible to fluctuations in liquid level. This has been reflected in the whole plant model and varying liquid depths in the trough have not been included. Delivery rate was assumed to be a function of tube size rotation rate only.

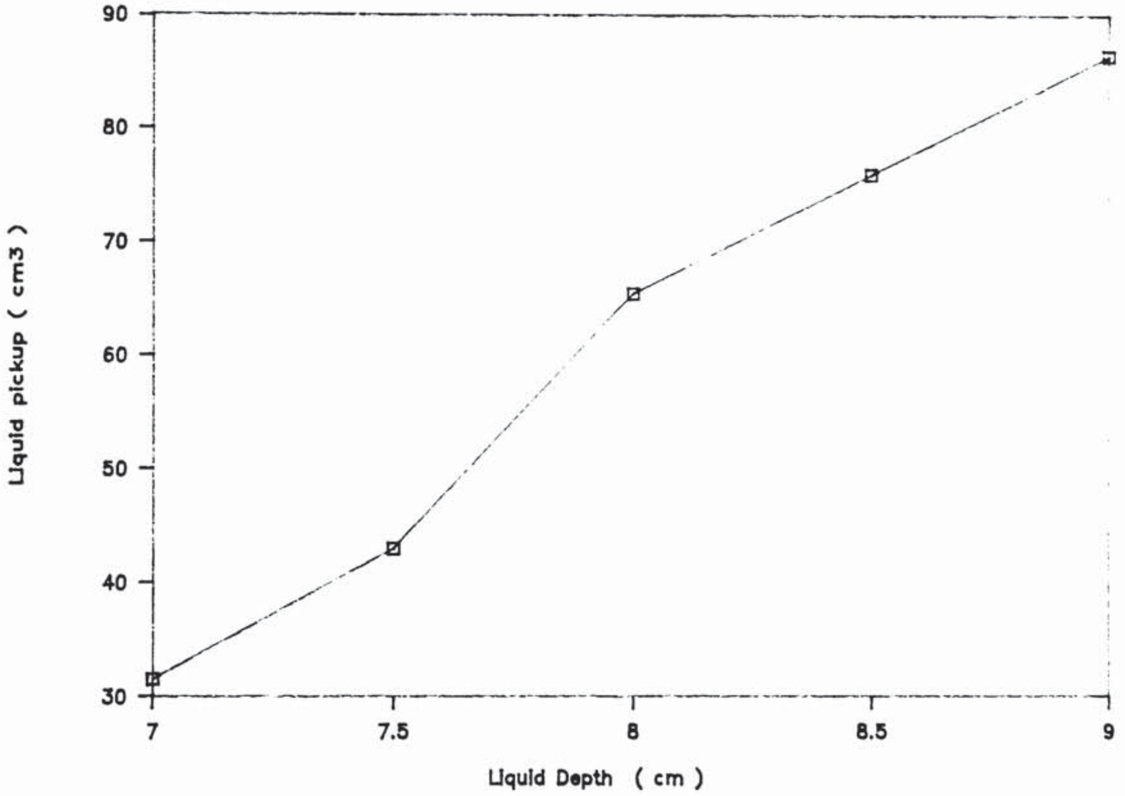
7.4 The Combined Model

7.4.1 General

The combined cycle model was intended to predict the response of a reprocessing plant cycle to disturbances - arising either by intent eg as a normal part of control or as the result of some unusual condition. For this purpose it was necessary to provide a steady-state solution to the model which would represent the plant at all normal, stable operating conditions. This solution would act as the starting point to which a disturbance could be applied. PMSP provides three routines to find steady-states for a model STEADY, SPARTAN and NEWTON. These are described by Stirrup et al (85, 124). A brief discussion of the steady-state finding algorithms is included as Appendix B.

Both methods STEADY and SPARTAN were tried with the combined model; but neither converged. NEWTON, was only

Figure 7.14 Liquid pickup in CVF



released very near the date on which this work was completed and could not therefore be assessed. From published information on the PMSP steady-state finders (82) it is clear that problems with steady-state finders are common in large models. Possible reasons for this failure are discussed later. The problem was circumvented by estimating a solution and allowing the model to run to a steady-state. The PMSP facility which enables the user to store values of integrators at the end of a run makes this process simple to implement. Several attempts can be made, each starting at the finishing point of the previous run.

Two other general problems were encountered. As previously discussed, Clark's analysis of the behaviour of a gas-lift pump predicts that, for the gas flowrates and equipment layout used, the pump output will be extremely sensitive to changes in gas flowrate. This, combined with the rapid response of the column models to applied disturbances leads to problems of stability in that the gas-lift over-reacts. This problem is closely allied to the control systems assumed to act on the gas feed rate.

The original PI control model which was assumed proved totally unsatisfactory, since it rapidly became out of phase with the system. The gas-rate was increased when it should have decreased and vice versa, the system oscillating about the set point. Increasing the integral action time and decreasing the controller gain resulted in a sluggish but effective control system.

Throughout this study it was assumed that the interface detector provides a reliable, accurate and non-noisy measurement. This is unlikely in practice given the difficulties in interface detection, discussed in Chapter 5, and the oscillation in interface position resulting from the pulsation applied to the column.

The effects of various disturbances were investigated and will be discussed. Notation, to aid in identification of various flows and levels etc is discussed in Appendix C.

7.4.2 The Effect of Varying Solvent Flows

The columns which operate with the aqueous phase continuous, typically the strip columns, receive as their solvent feed the overflow from preceding solvent continuous columns. Thus, there is no way of directly affecting solvent flow to these columns. Only their response to increased or decreased solvent feed to earlier columns may be observed.

7.4.2.1 Increase in Solvent Feed Rate

Figure 7.15 indicates the model response to a 10% increase in solvent feed, FSGFE, to column 7. As expected the solvent overflow, FS7TC, from column 7 rises rapidly to match. The difference between FSGFE and FS7TC is of course FSGBC, the solvent removed by the gas-lift. The solvent overflow from column 8 is more interesting and can be seen to oscillate. As the solvent feed to column 8 increases the interface in this column will begin to rise. In response the controller will increase the gas flow to compensate; it overreacts and the interface falls too far so the gas flow is now decreased. These oscillations gradually die down. The interface movement is plotted in Figure 7.15 (a). In Figure 7.16 the product concentrations from each of the two columns is plotted. As expected, the concentration of uranium in the overflow from column 7 falls as does the uranium concentration in the aqueous product from column 8 although this can be seen to be picking up gradually.

Figures 7.17, 7.18 and 7.19 illustrate the movement of uranium within the columns. As might be expected, the effect becomes noticeable most quickly at the point in column 7 where the loaded feed enters ie cell number G1. Generally the profiles retain a similar shape and merely 'shift' along the X-axis. The 'blip' in the outlet

Figure 7.15 Model Response to 10% Increase in FSGFE

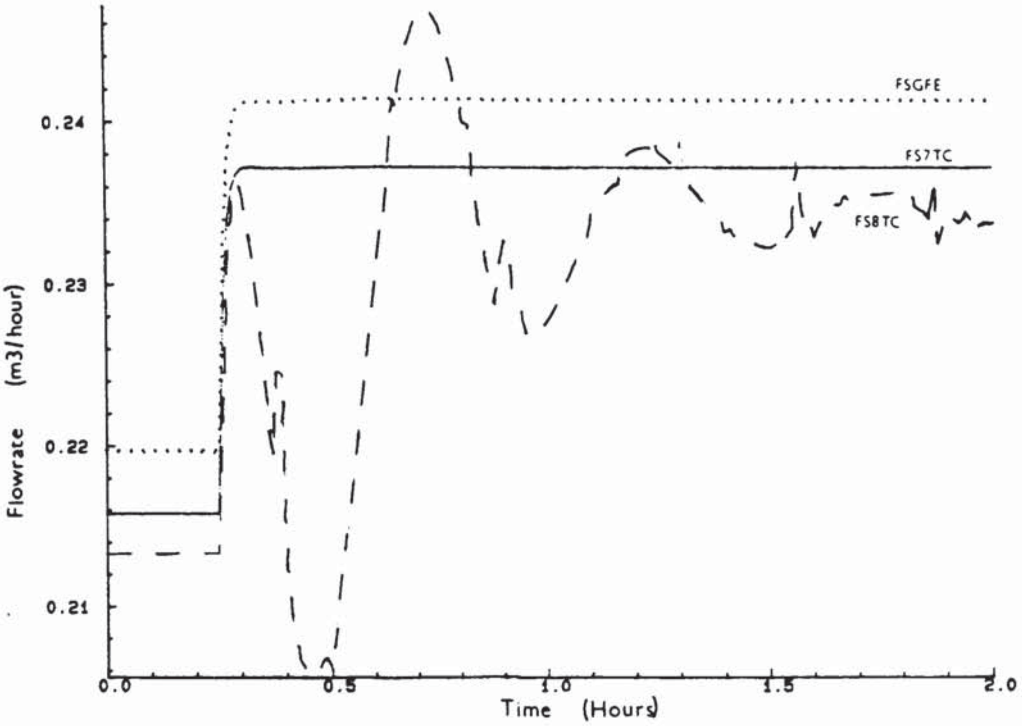


Figure 7.15a) Model Response to 10% Increase in FSGFE

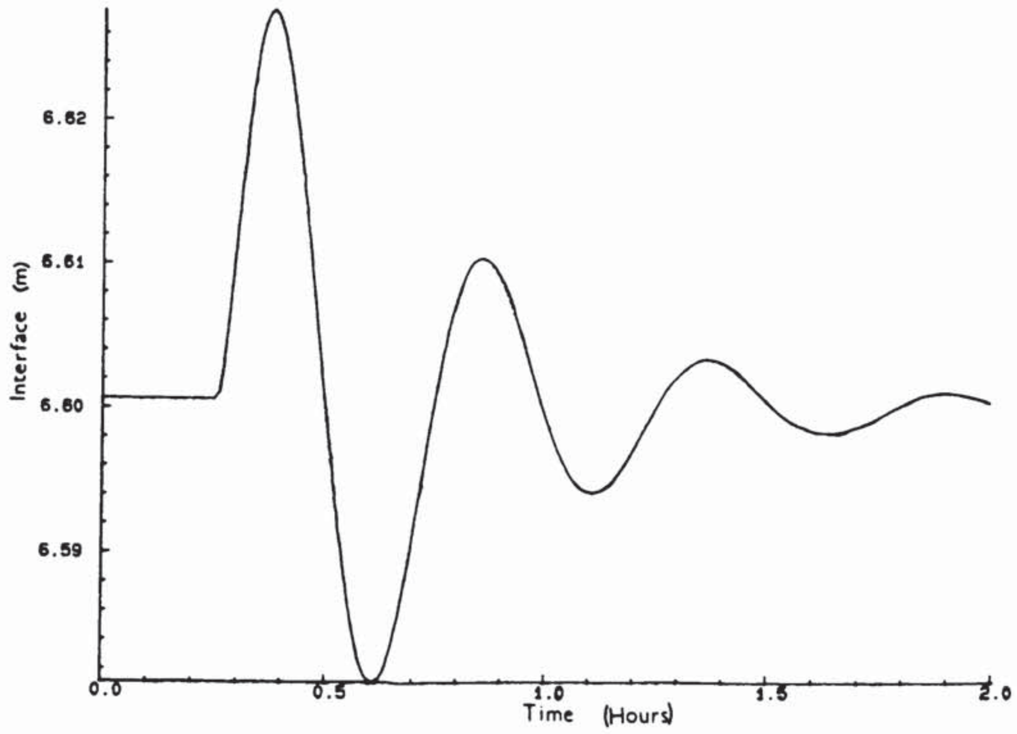


Figure 7.16 Model Response to 10% Increase in FSGFE

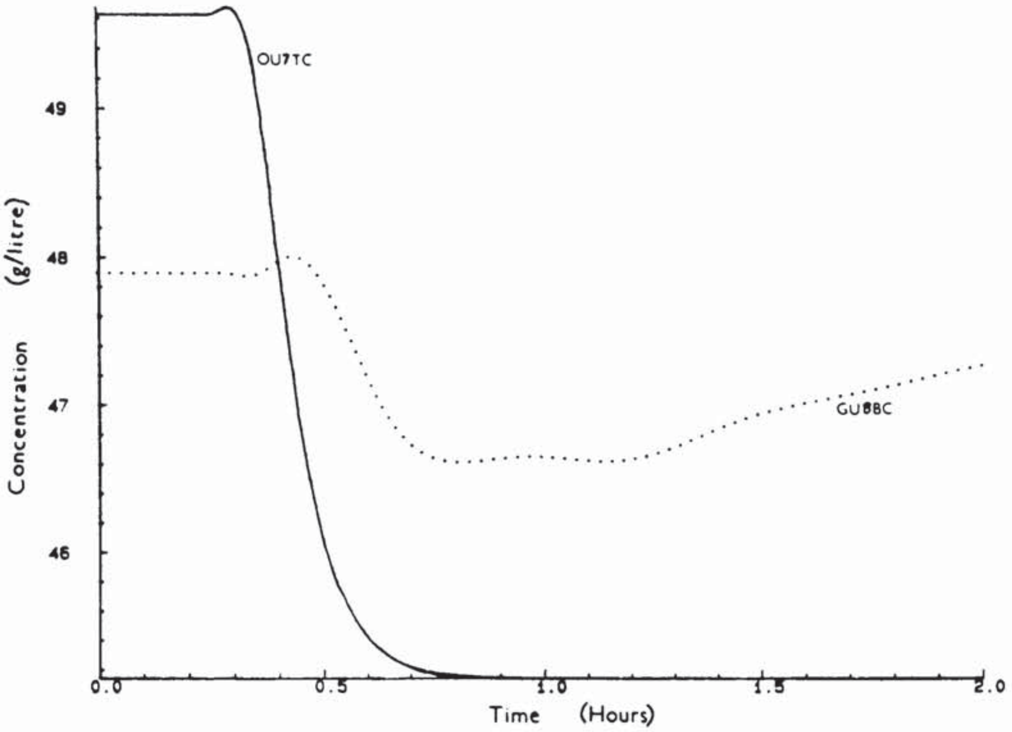
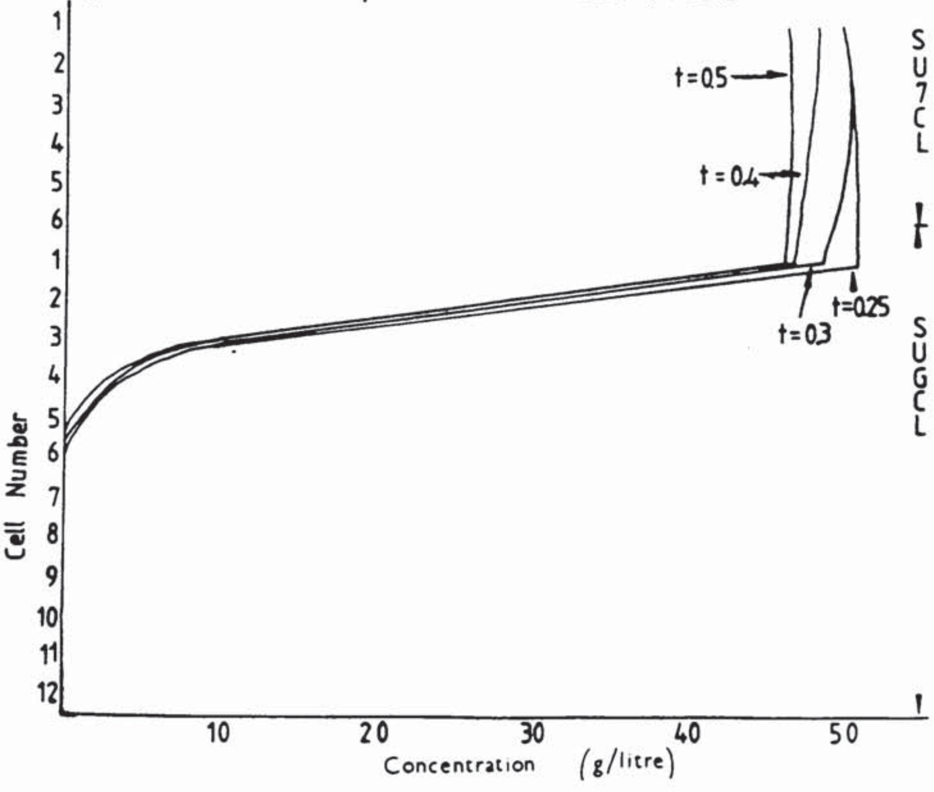


Figure 7.17 Predicted Response to 10% Increase in FSGFE



uranium concentrations shown in Figure 7.16 is not observed in these plots because the scale is too small. The numerical results given in Appendix D do however allow its progress to be followed. As the step change in solvent feed reaches the column, the column contents are pushed upwards so that briefly a higher than expected outlet concentration is observed. The scrub feed returns the column fairly rapidly (ie $<$ 15 minutes) to its usual profile. Column 8 also demonstrates this behaviour although there is some delay, caused by connecting equipment. This delay is slight ($\simeq$ 1 minute) as all connecting items operate under gravity flow, so that increased feed causes an instant increase in outflow.

Similar results are obtained when the increase in solvent feed is 25%. In this case however, as can be seen in Figure 7.26, the scrub feed requires approximately 25 minutes to restore the normal profile within the scrub section. In this case very sluggish control has been applied to maintain interface position in column 8, gain = IE-06, T_R = 5.0 hrs so that less oscillation is evident in the interface position, Figure 7.21 and FS8TC, Figure 7.20 Figure 7.23 indicates the effects on dispersed phase hold up in column 8 following this disturbance. The results are confusing but changes are first observed in the lower part of the column and work their way up the column; after an initial overshoot the column settles down in $\approx$ twenty minutes. Concentration profiles within column 8 are illustrated in Figures 7.24 and 7.25. In this case changes are gradual.

7.4.2.2 Decrease in Solvent Feed Rate

Figures 7.27 - 7.30 illustrate the model response to a 10% reduction in FSGFE. In this case the controller on column 8 appears to be too sensitive and may tend to instability as FS8TC in Figure 7.27 appears to be oscillating. This could of course be a function of the numerical algorithm. It may also be that if the print interval was reduced these oscillations would not be observed. The concentration profiles within the columns are illustrated in Figure 7.28 - 7.30. The columns gradually shift attaining a new steady state within 0.5 hrs for column 7 and 1 hr for column 8.

7.4.3 The Effect of Varying Aqueous Flows

Within the uranium purification cycle - Cycle III-U there are three aqueous feeds that may be varied.

(i) the loaded aqueous feed coming forward from Cycle II

(ii) the scrub feed to column 7, and

(iii) the strip feed to column 8.

Figure 7.18 Model Response to 10% Increase in FSGFE

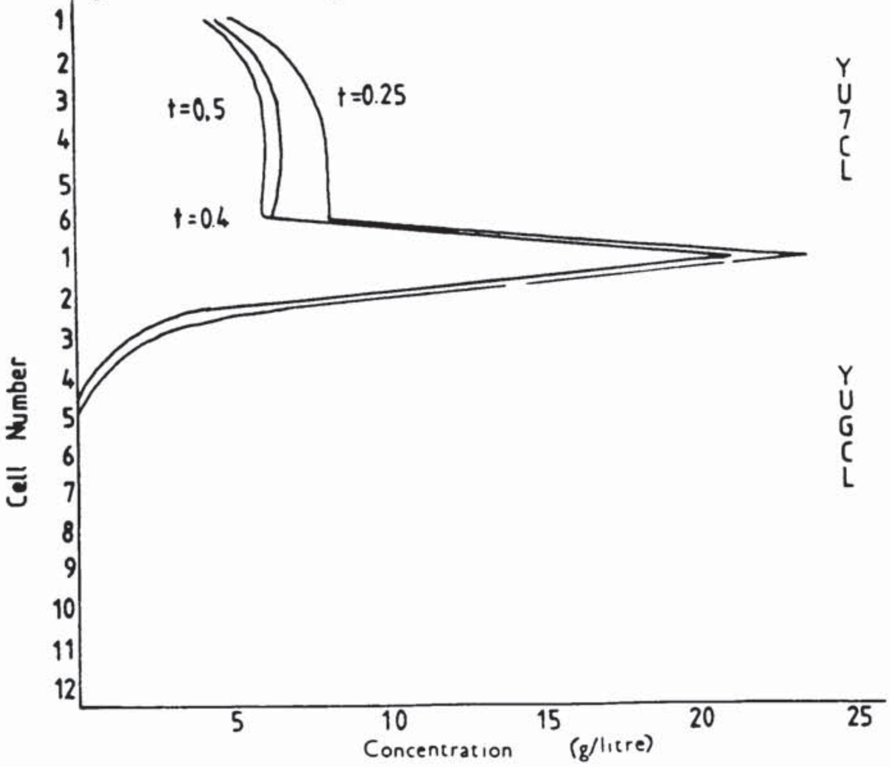


Figure 7.20 Model Response to 25% Increase in FSGFE

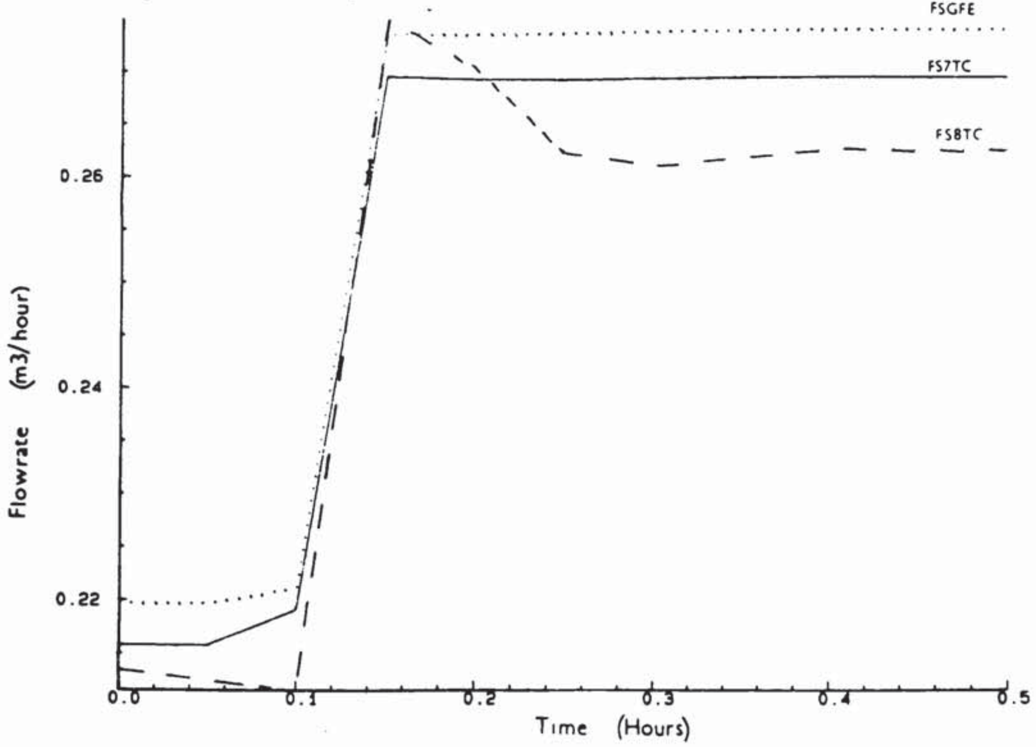
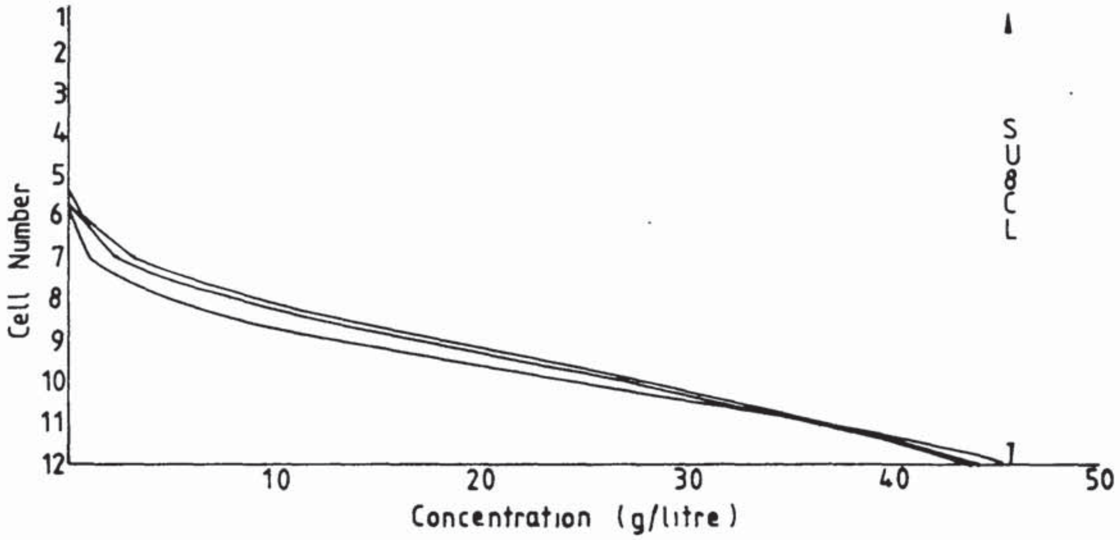


Figure 7.19 Response of Column 8 to a 10% Increase in FSGFE



In fact the scrub feed to column 7 was not varied since it is inherently small and therefore any changes would be small and difficult to follow.

7.4.3.1 Increase in Aqueous Feed Rate

The effects of increased loaded aqueous feed, FAGFE will be examined first. Figure 7.31 demonstrates that after an initial increase in solvent overflows from columns 7 and 8, as would be expected, these flows very soon fall back to their original levels. FS8TC is, of course, affected by the interface controller which causes the oscillations. Again the 'spikes' may be caused by the numerical instability. The outlet concentrations from the columns are shown in Figure 7.32. As discussed in section 7.4.2.1 the blip also appears here. Steady states are attained within 0.75 hours from column 7 and about 1.75 hours for column 8. Changes in column profile are illustrated in Figure 7.33 - 7.36, and support the timescales for column response given previously. In this case, holdup changes very little in either column ≈ 1%.

Increasing aqueous strip feed to column 8 has the effects indicated in Figure 7.37 - 7.40. Outlet aqueous concentration from column 8 falls, as would be expected. Changes in dispersed phase holdup were small.

Figure 7.21 Model Response to 25% Increase in FSGFE

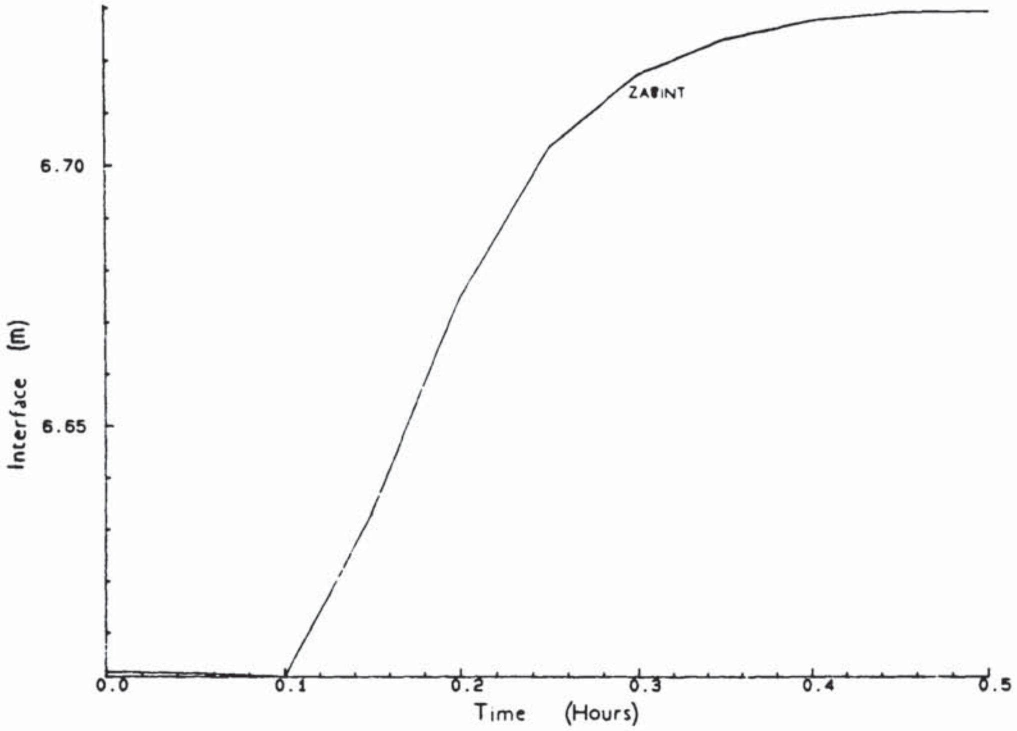


Figure 7.22 Response to 25% Increase in FSGFE

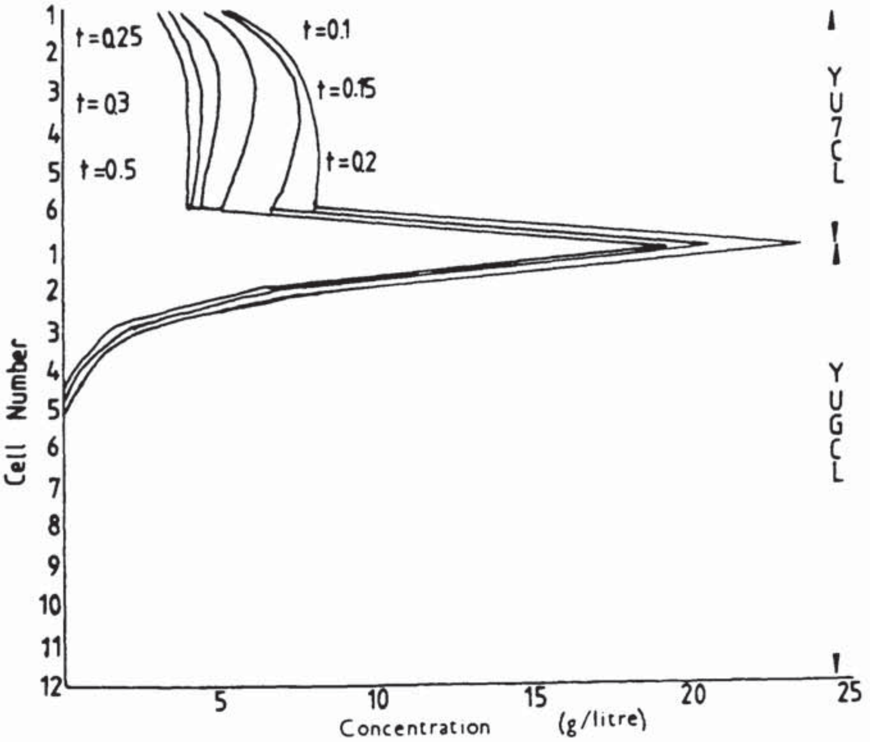


Figure 7.23 Response to 25% Increase in FSGFE

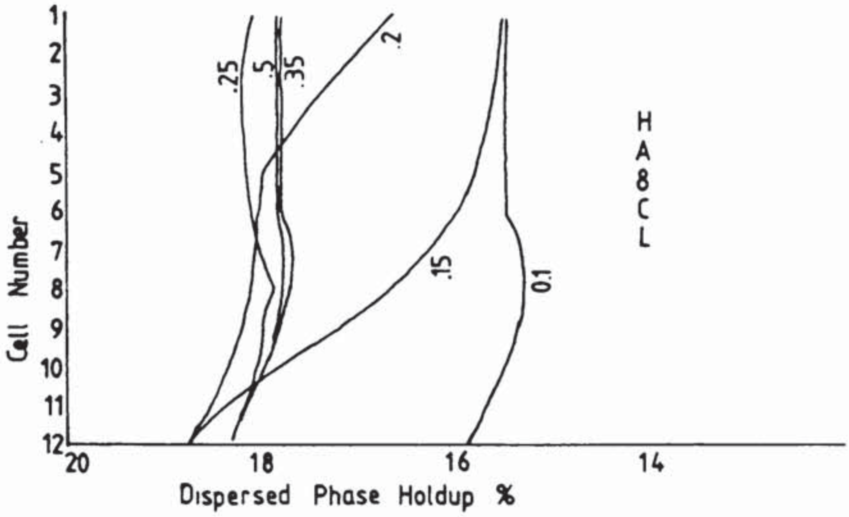
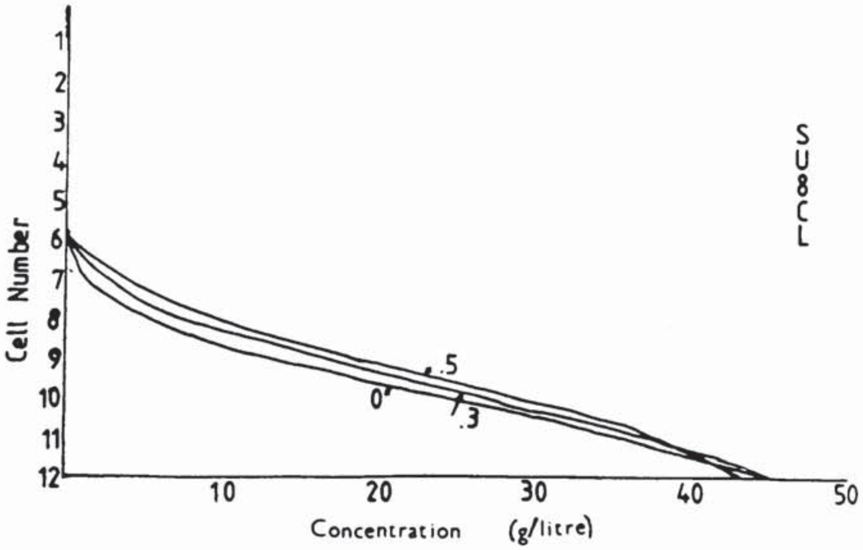


Figure 7.24 Response to 25% Increase in FSGFE



7.4.3.2 Decrease in Aqueous Feed Rate

As FAGFE is decreased by 10% the solvent overflows from columns 7 and 8 decrease but quickly recover. As would be expected the overflow from colummn 8 is subject to some oscillation as a result of the control applied to the interface position in column 8; this is shown in Figure 7.41. The outlet concentrations behave as indicated in Figure 7.42. The initial dip may be caused by a drop in the column contents as a feed was suddenly reduced. Column concentration profiles change as indicated in Figures 7.43 - 7.46. As discussed in the foregoing sections the effects of the disturbance are evident most rapidly at that part of the column where the decreased feed enters. The response of column 8 to a reduction in FA8FE are given in Figures 7.47 - 7.50. The outlet concentration of aqueous product from this column rises gradually as indicated in Figure 7.48. Column profiles changed gradually, with upto two hours being required for a new 'steady-state' to be reached.

7.4.4 The Effect of Control Parameters on Model Performance

Close control of the reprocessing plant is desirable. Other than feeds to the plant, there are few variables that can be changed readily: namely nitrogen rate to the gaslifts; steepness of the ramp on nitrogen rate in

Figure 7.25 Response to 25% Increase in FSGFE

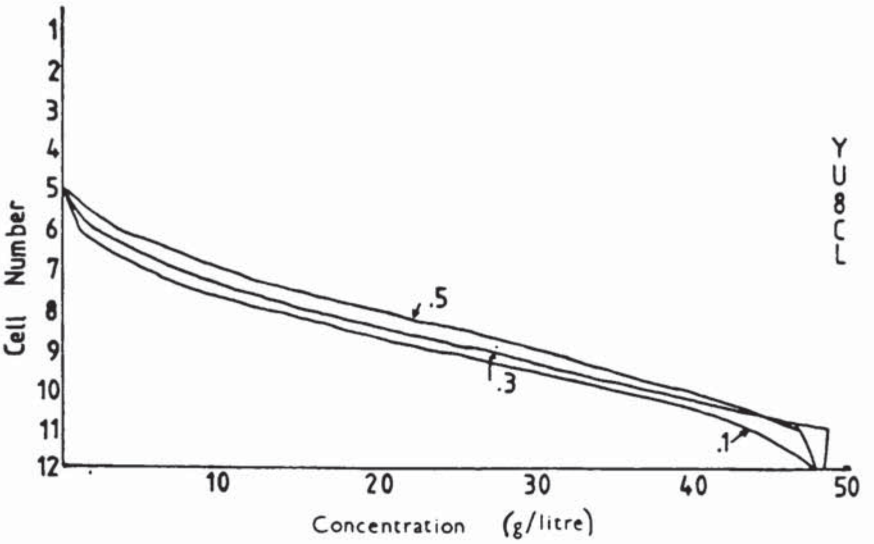


Figure 7.26 Response to 25% Increase in FSGFE

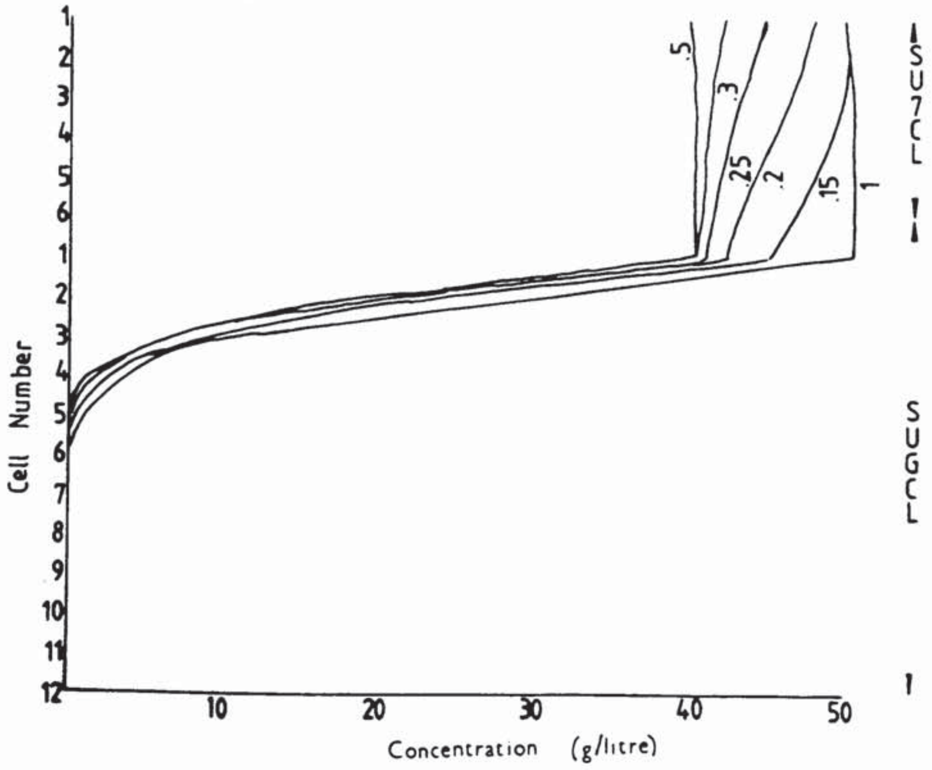


Figure 7.27 Model Response to 10% Reduction in FSGFE

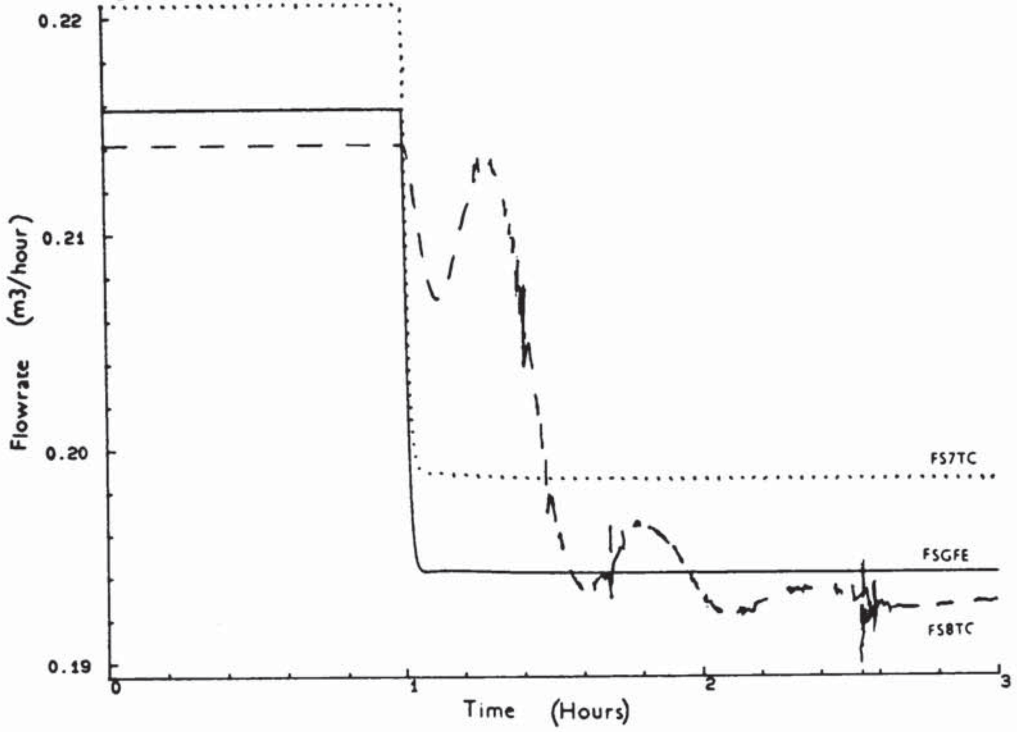


Figure 7.28 Effect of Decreasing FSGFE by 10%

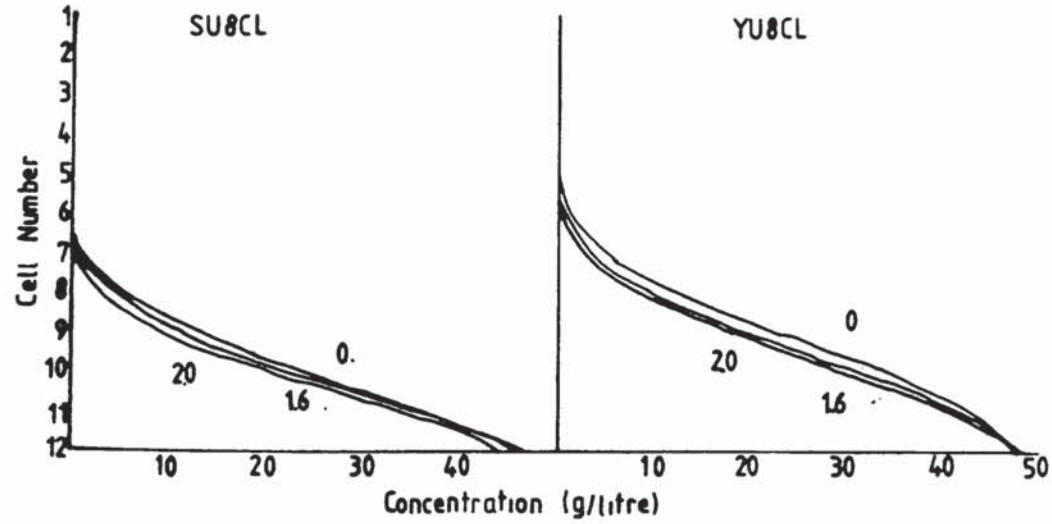


Figure 7.29 Response to 10% Reduction in FSGFE

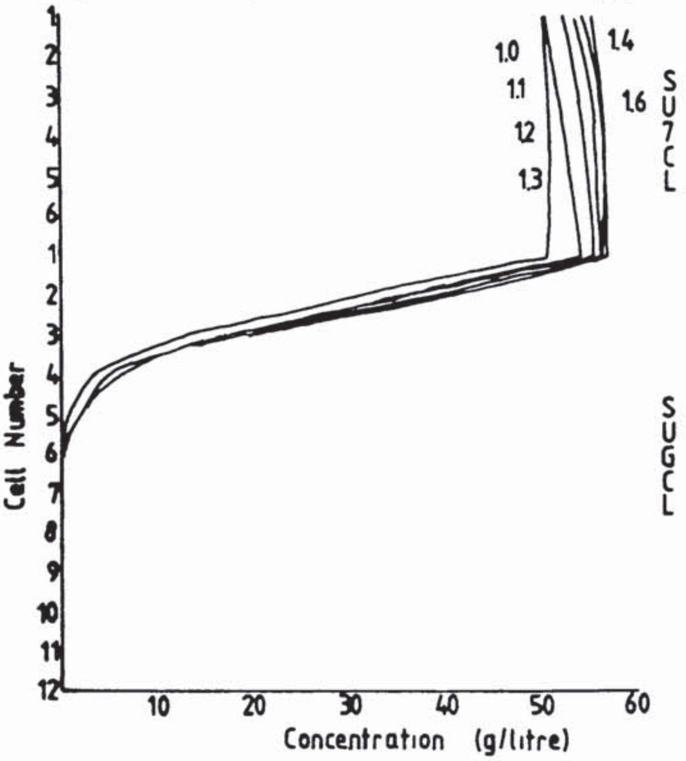
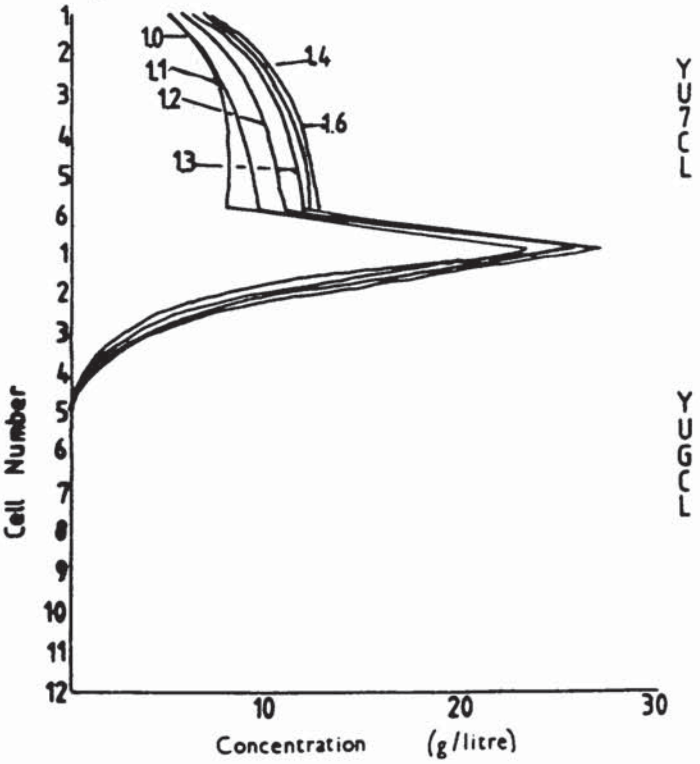


Figure 7.30 Effect of 10% Reduction in FSGFE



solvent continuous columns. Figures 7.51 and 7.52 illustrate the movement of an interface within a solvent continuous column when the nitrogen rate to the gas-lift is increasd by 2% every 30S. For this case, small, frequent increases are preferred to prevent the interface drifting into the plated section of the column and to avoid having an excessive gas rate. Since there will be no automatic reduction on this gas rate, operator intervention will be required.

For aqueous continuous columns the interface will form at the top of the column. In this case it is important that the control system is such as to avoid allowing the interface to leave the column.

Initially, it is useful to observe the results when disturbances are applied to a column with no control. Figure 7.53 and 7.54 therefore illustrate the effects of increasing FSGFE by 25% with no control on column 8. Comparison of these with Figures 7.55 and 7.56, in which are shown the results of applying a stepchange increase of 25% to FA8FE, reveals that the graphs are of different shapes. This is caused by intervening equipment ie the external settler and the solvent leg of column 8. It is clear that a considerable time will elapse ≈ 0.6 hours, before the interface leaves the column. This will

Figure 7.31 Model Response to 10% Increase in FAGFE

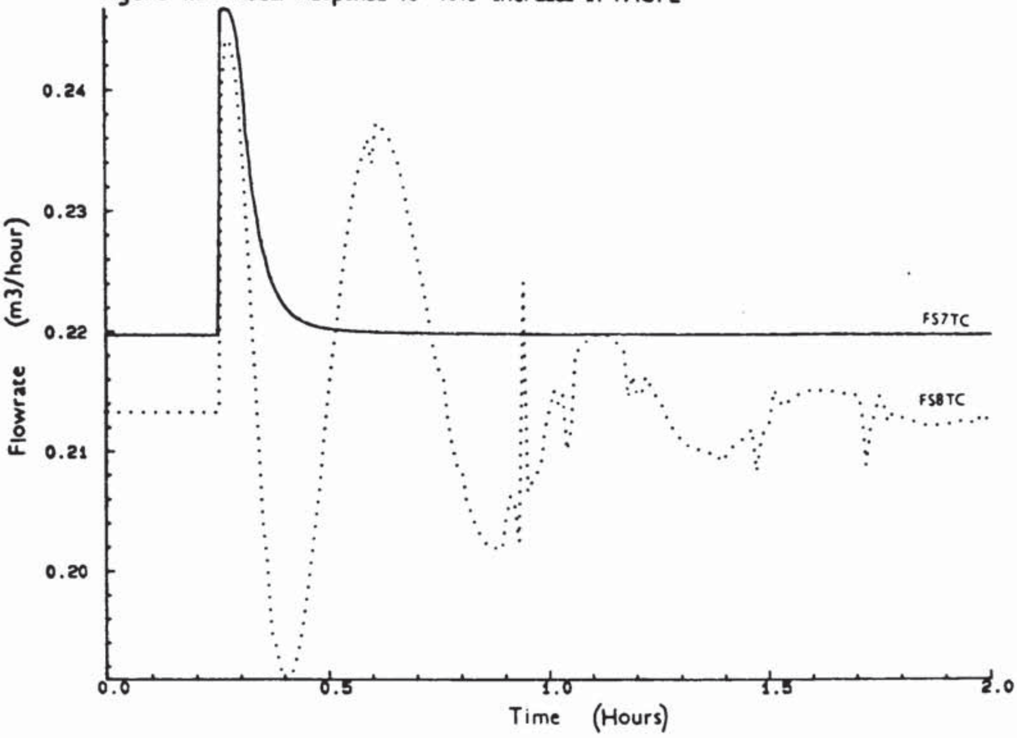


Figure 7.32 Model Response to 10% Increase in FAGFE

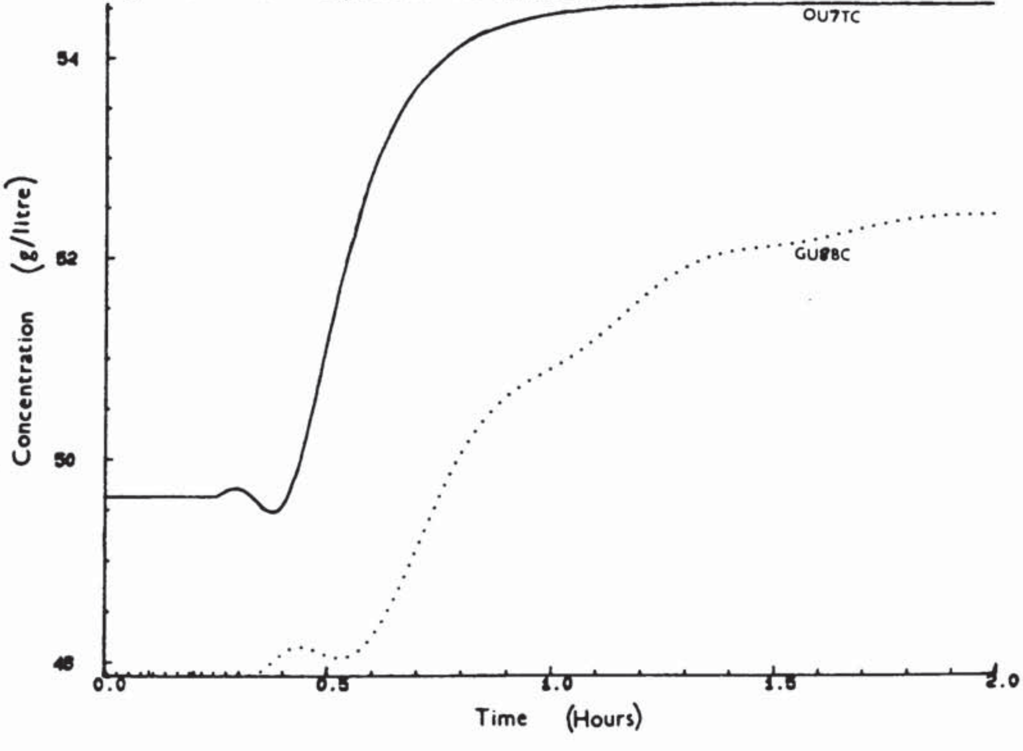


Figure 7.33 Response to 10% Increase in FAGFE

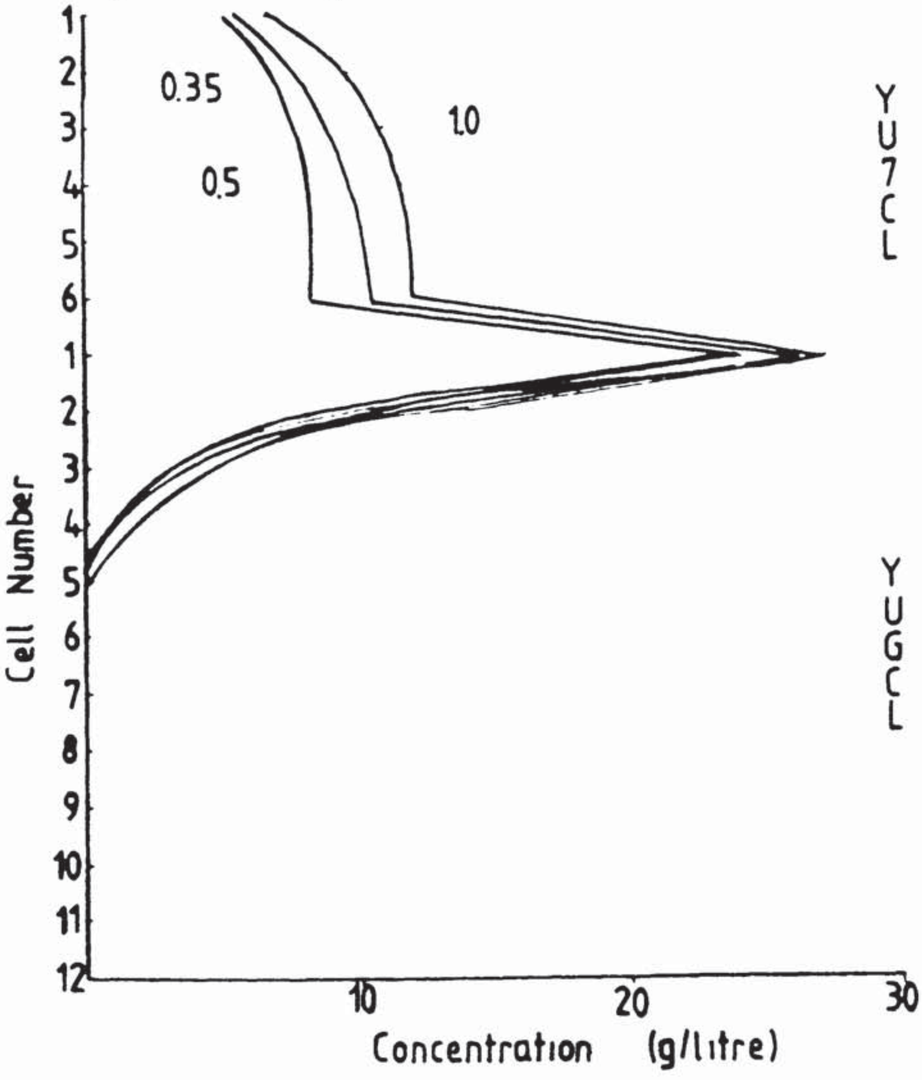


Figure 7.34 Effect of Increasing FAGFE by 10%

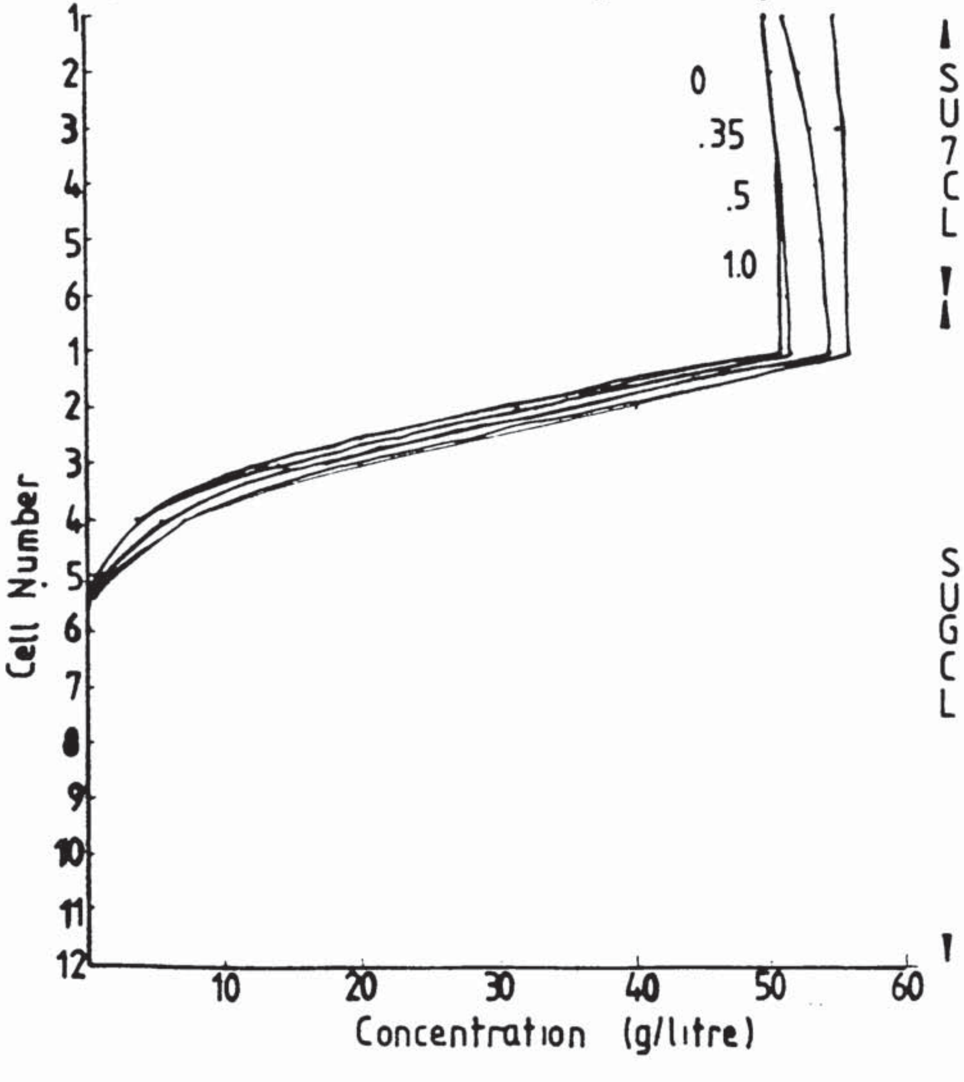


Figure 7.35 Variation in YU8CL with 10% Increase in FAGFE

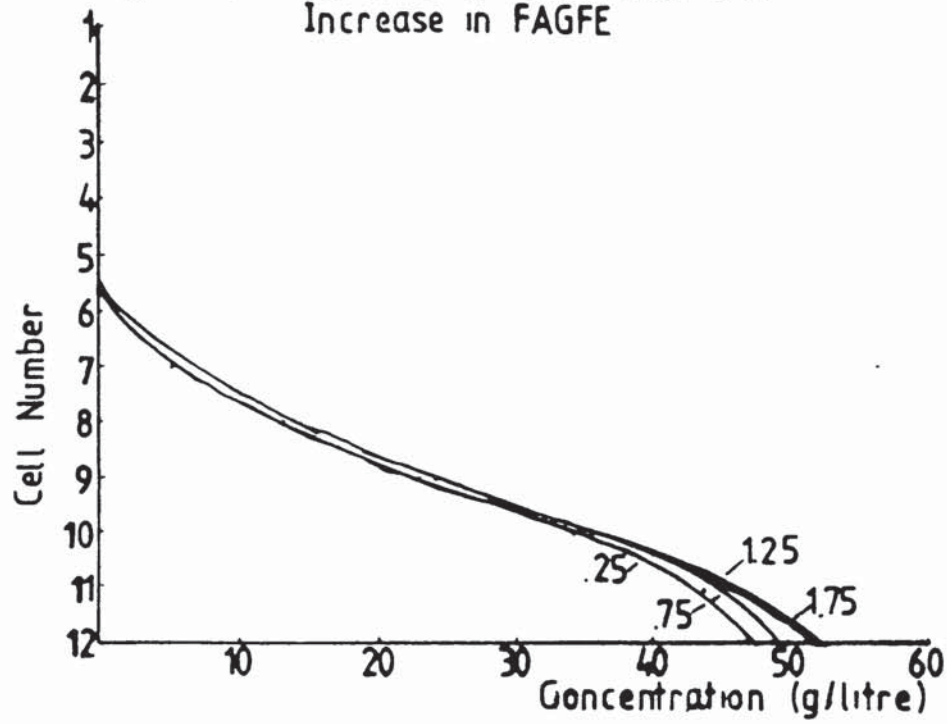


Figure 7.36 Response of SU8CL to 10% Increase in FAGFE

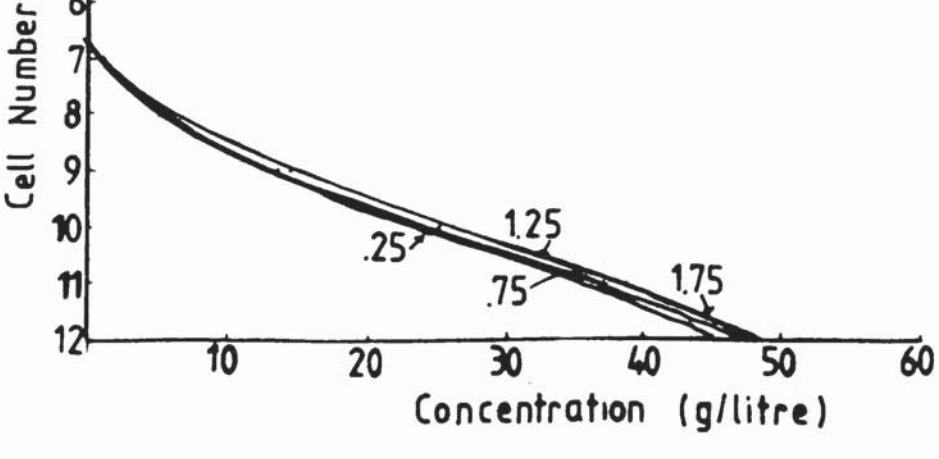


Fig. 7.37 Response to 25% Increase in FA8FE
YU8CL

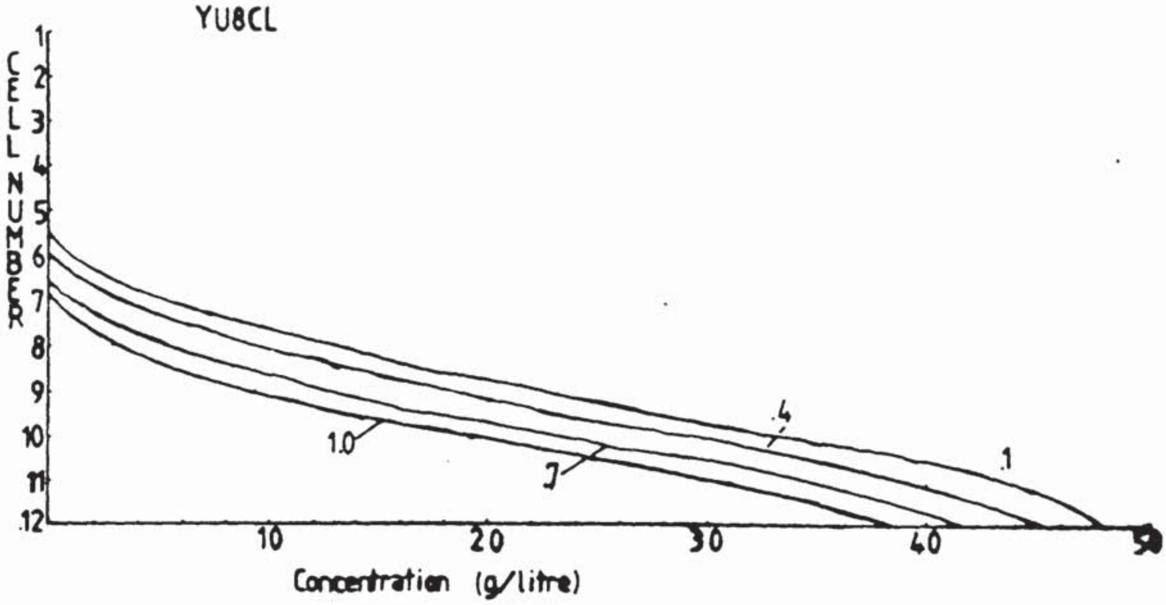


Fig. 7.38 Response to 25% Increase in FA8FE
SU8CL

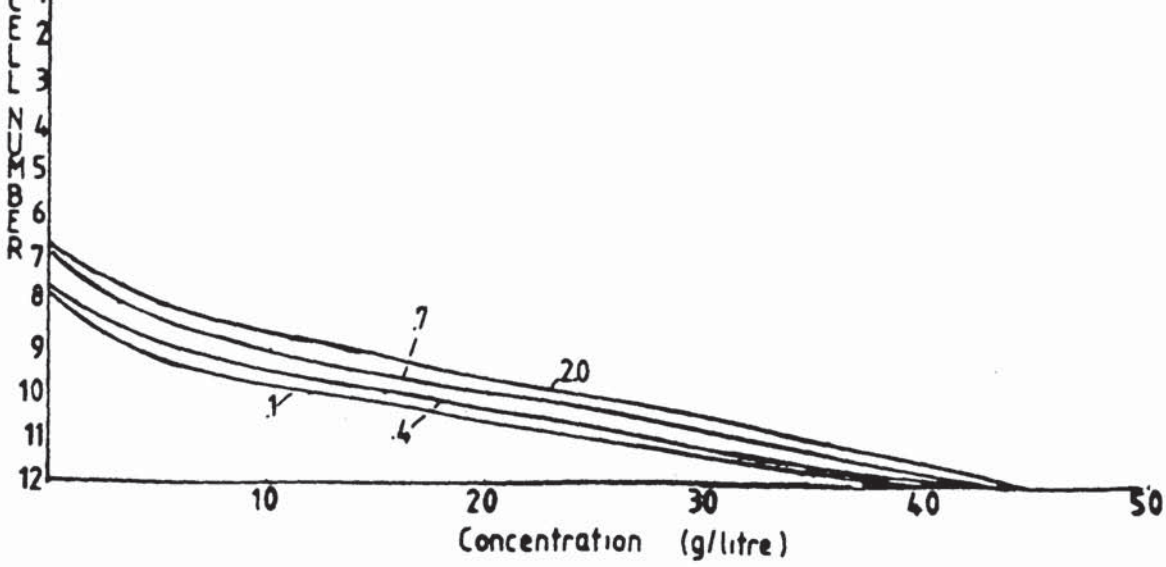


Figure 7.39 Changes in Product Concentration after a 25% Increase in Strip Feed to Column 8

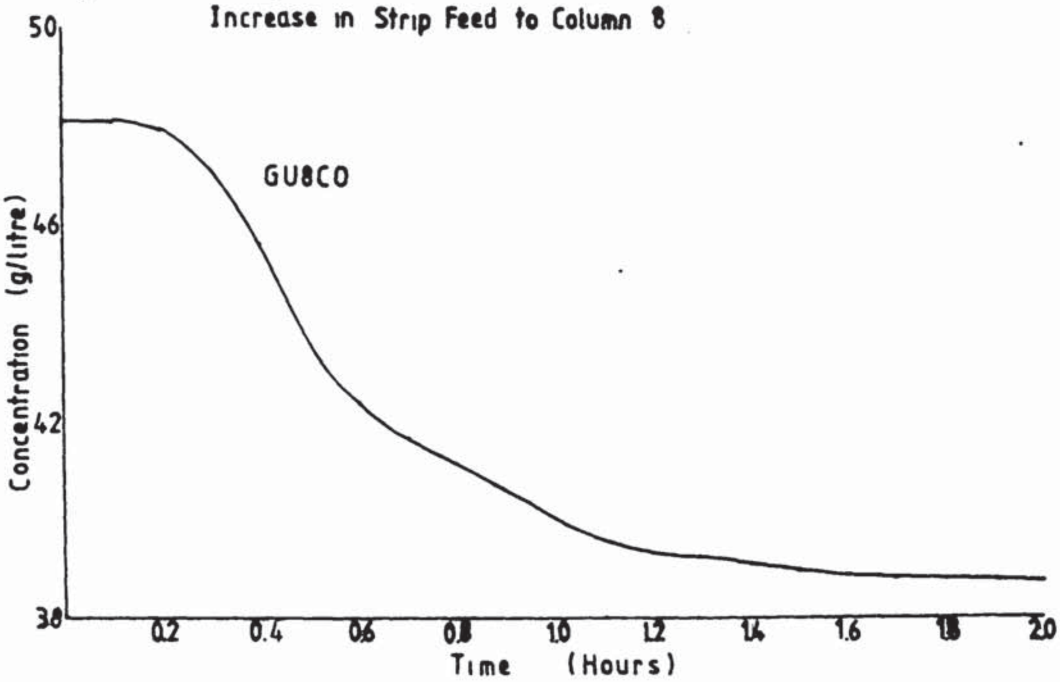


Figure 7.40 Interface Movement following a 25% Increase in Strip Feed to Column 8.

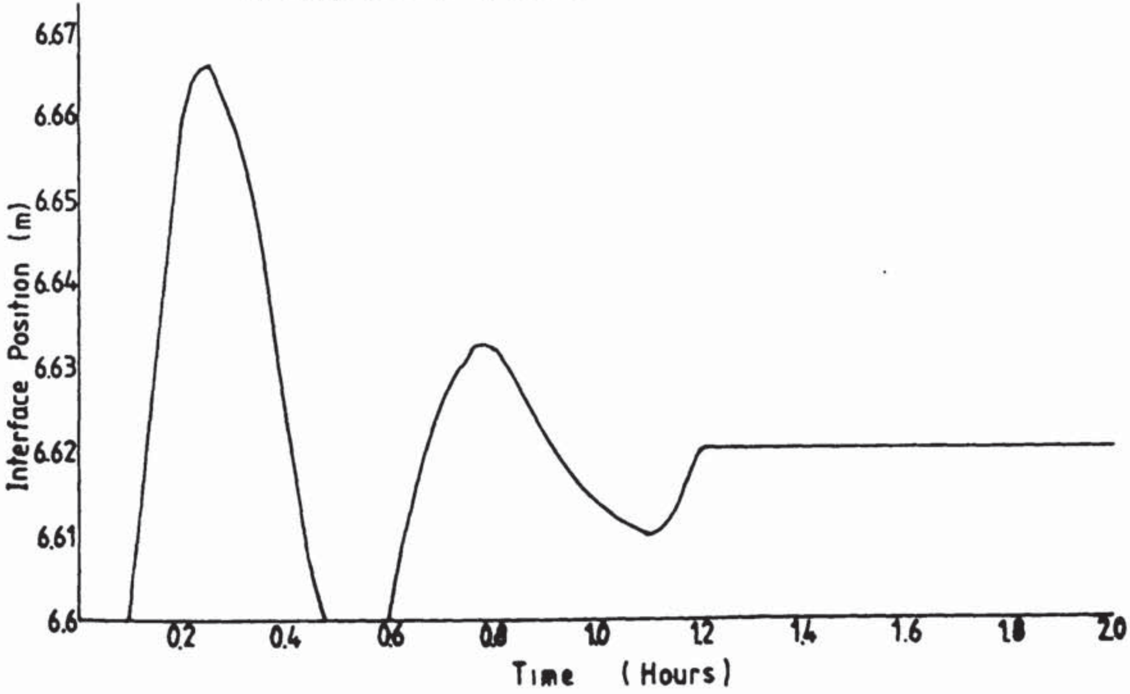


Figure 7.41 Model Response to 10% Reduction in FAGFE

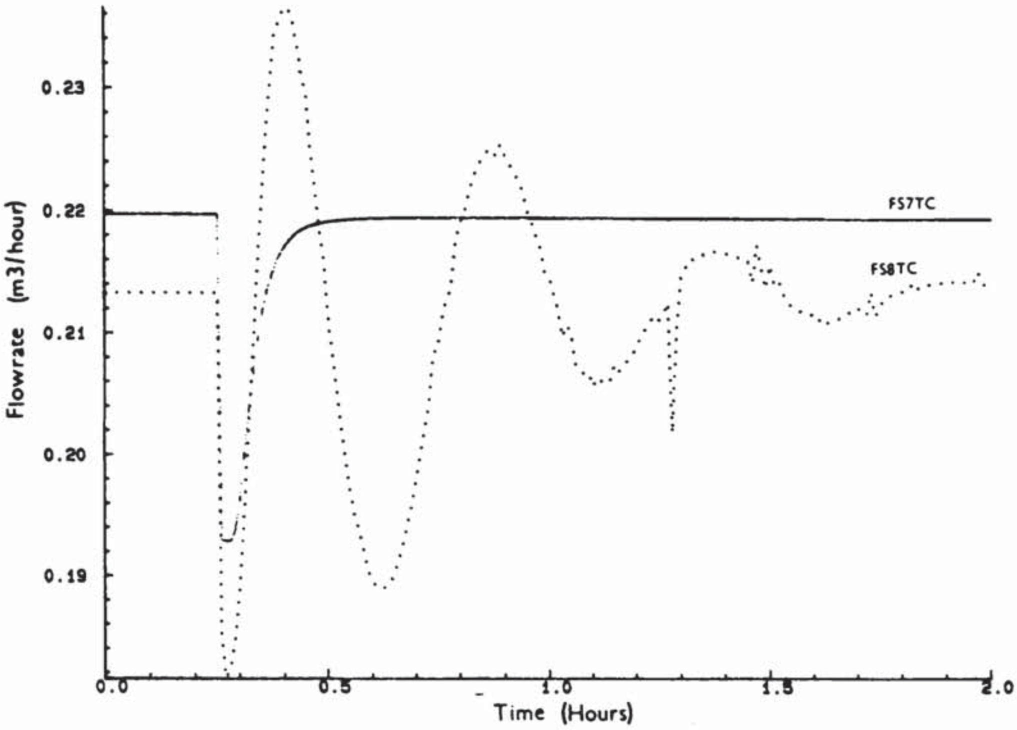


Figure 7.42 Model Response to 10% Reduction in FAGFE

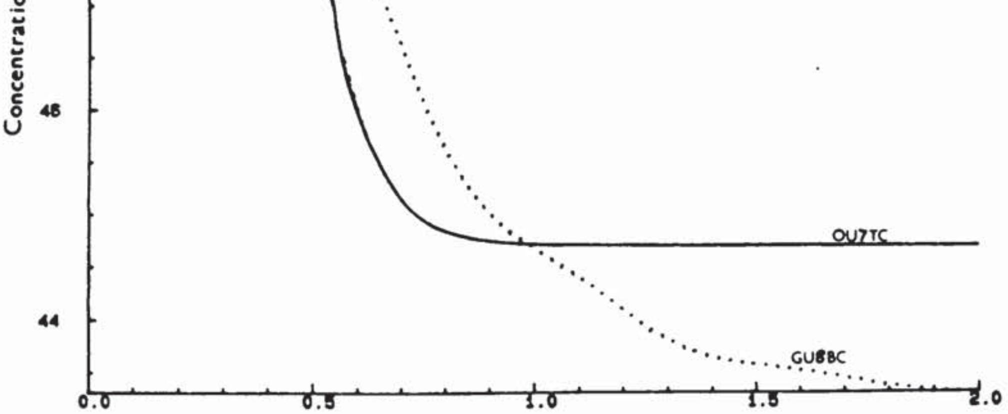


Figure 7.42a) Model Response to 10% Reduction in FAGFE

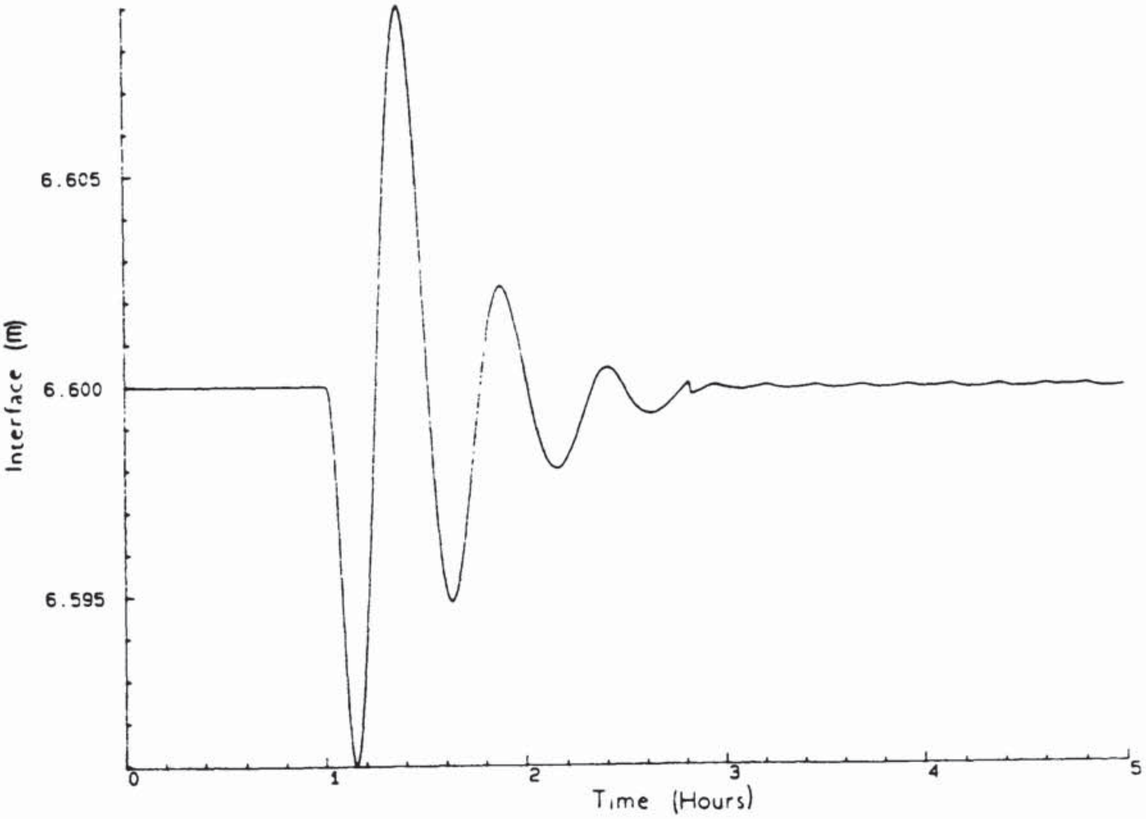


Fig. 7.43 Response to 10% Reduction in FAGFE

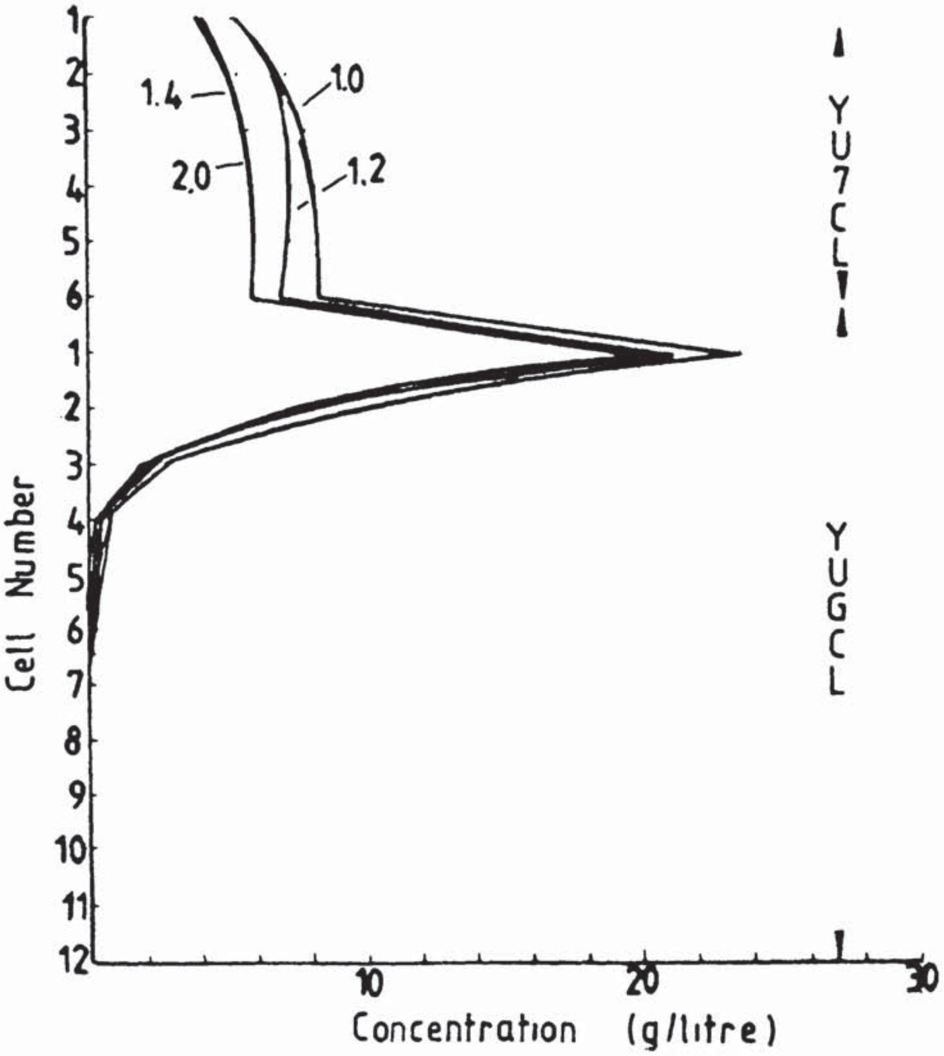


Fig. 7.44 Response to 10% Reduction in FAGFE

YU8CL

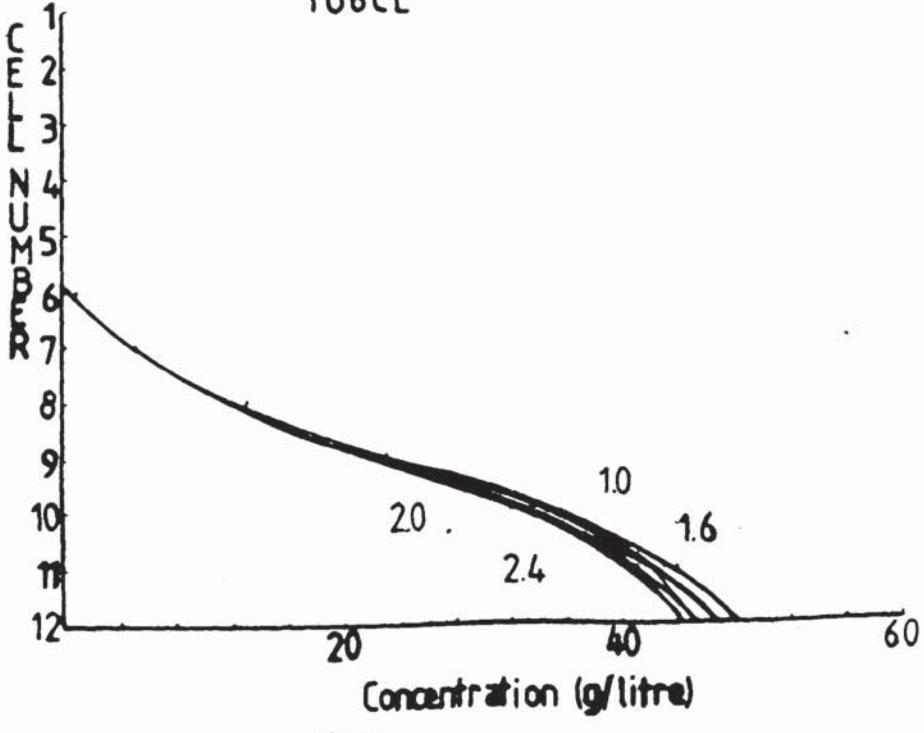


Fig. 7.45 Response to 10% Reduction in FAGFE
SU7CL - SU6CL

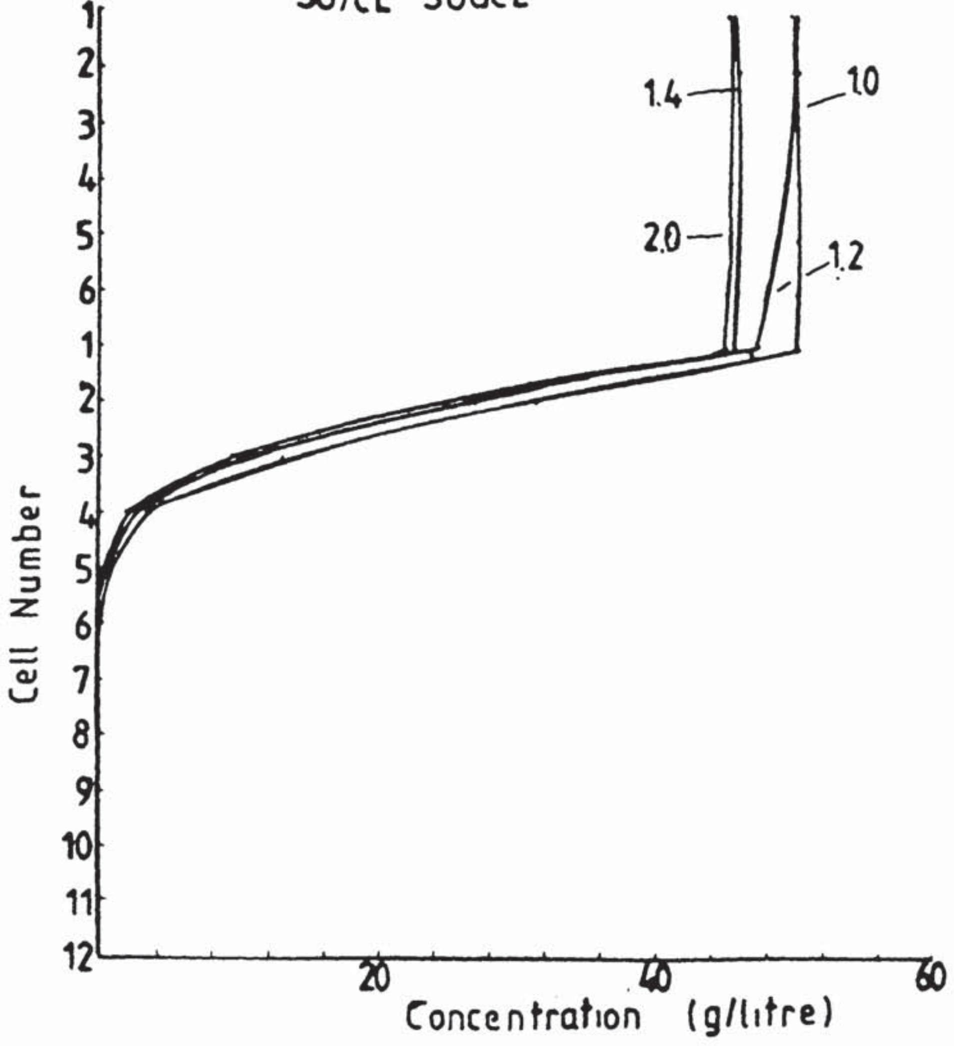
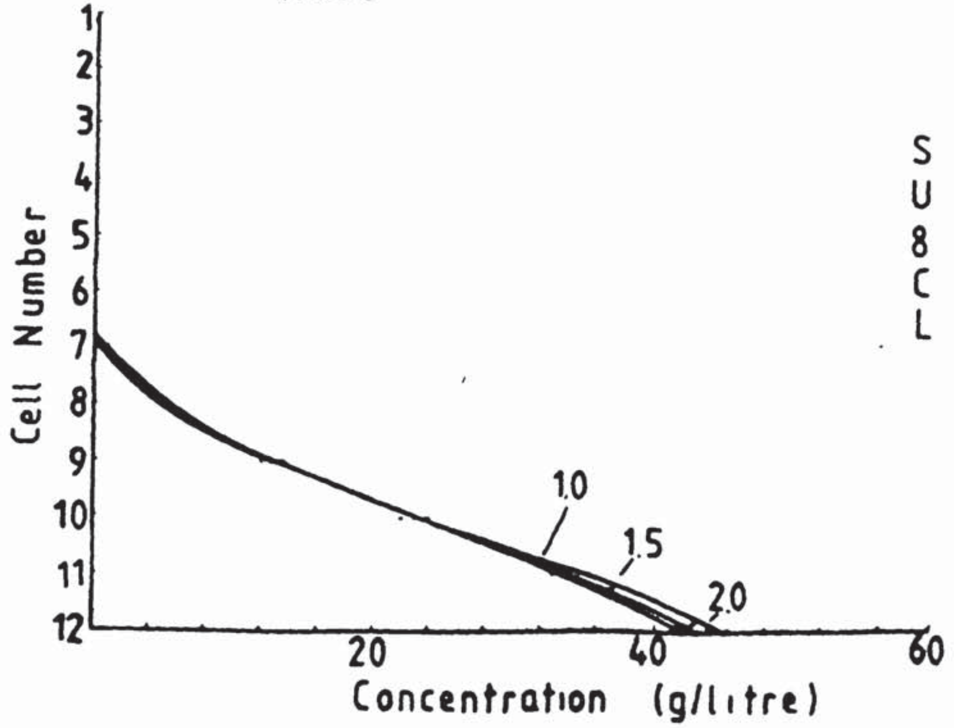


Fig 7.46 Response to 10% Reduction in FAGFE



obviously allow time for corrective action, provided, of course, that these trends are detected.

The effects of increasing the gain in the PI controller are clearly shown in Figure 7.57 - 7.64. Interface movements are plotted in Figure 7.57 - 7.60. As gain is increased the controller takes action more quickly reducing the initial overshoot; consequently the oscillations die away more quickly. However, the valve controlling the gas flow rate is required to act more quickly and in fact when gain = 0.1 the valve slams shut and then reopens as shown in Figure 7.64. The controller model assumes that the valve is capable of immediate response and that it wil pass any flow required of it. In practice, of course valves have definite action times, generally a few seconds, 5-10 seconds possibly, and will have a maximum flow. At lower gain the gas rate varies less but the interface moves more. However in neither case does it approach the overflow weir. In all the above cases FA8FE was increased by 25%.

Altering the reset time, T_R, results in the effects indicated in Figures 7.65 and 7.66. In these, gain is set to 0.01 and a 10% step change increase is applied to FA8FE. As T_R is increased initial overshoot is reduced and cycle times reduce. Leaving T_R as 0.2 hours and reducing gain to 1.0E-04 causes the interface to gradually drift upwards, reaching the overflow after 0.4 hours. Clearly then, the model response is more acceptable with a

Figure 7.47 Interface Movement in Response to 10% Cut in FA8FE

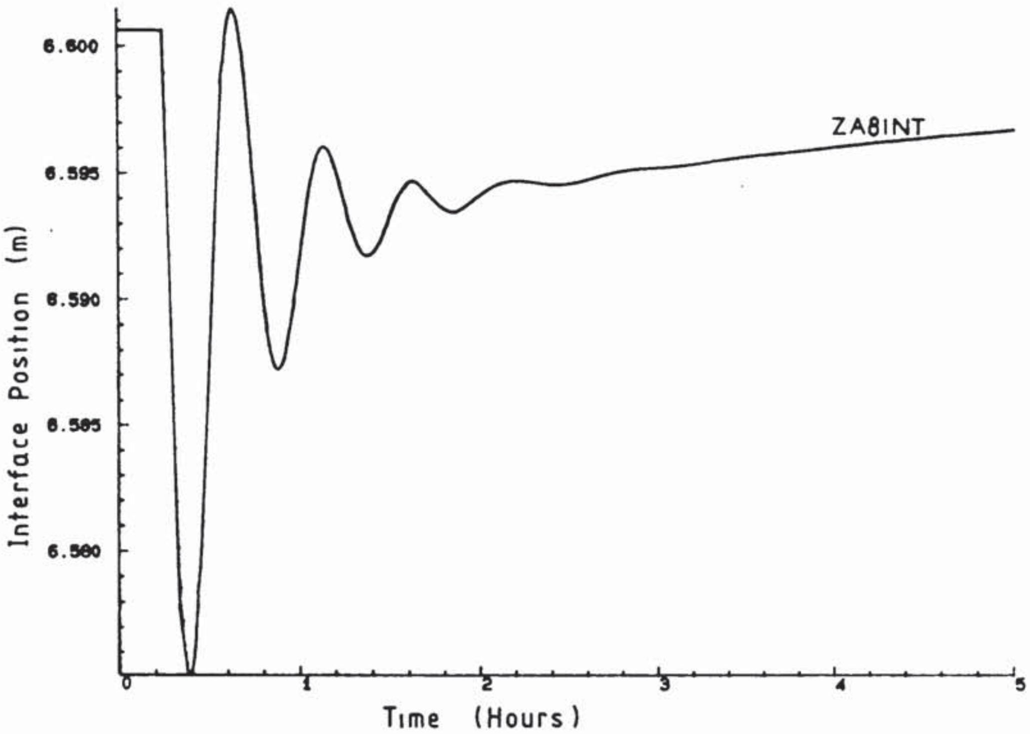


Figure 7.48 Product Concentration Changes in Response to a 10% Reduction in FA8FE

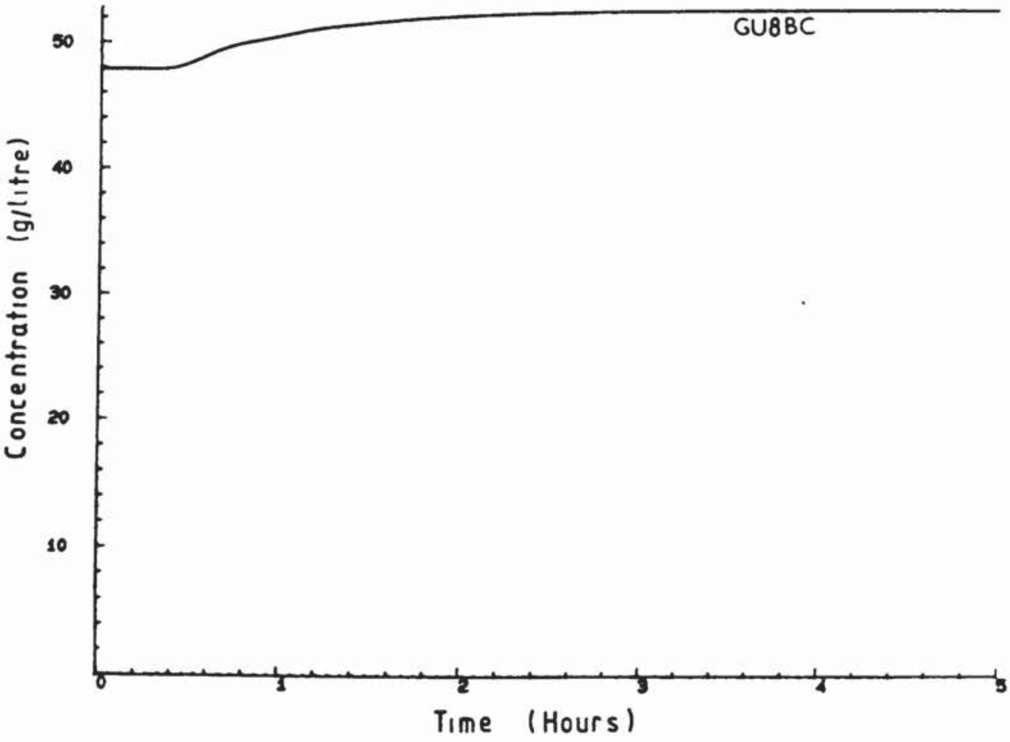


Fig. 7.49 Response to 10% Reduction in FA8FE

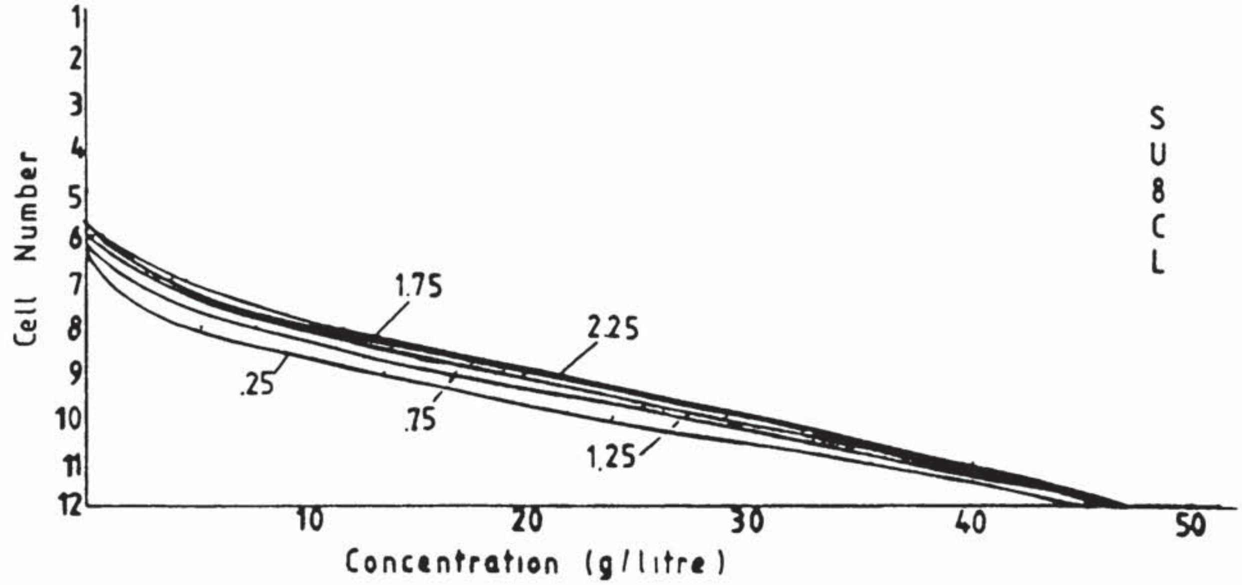


Figure 7.50 Response to 10% Reduction in FA8FE

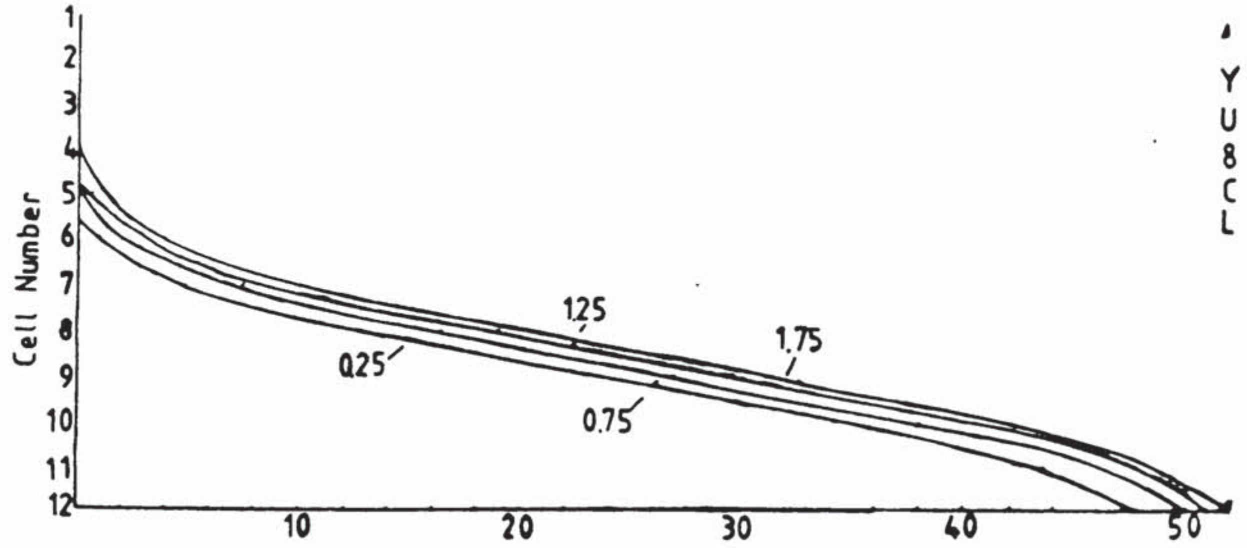


Figure 7.51 The Effect of gas Ramping on Lower Interface Position

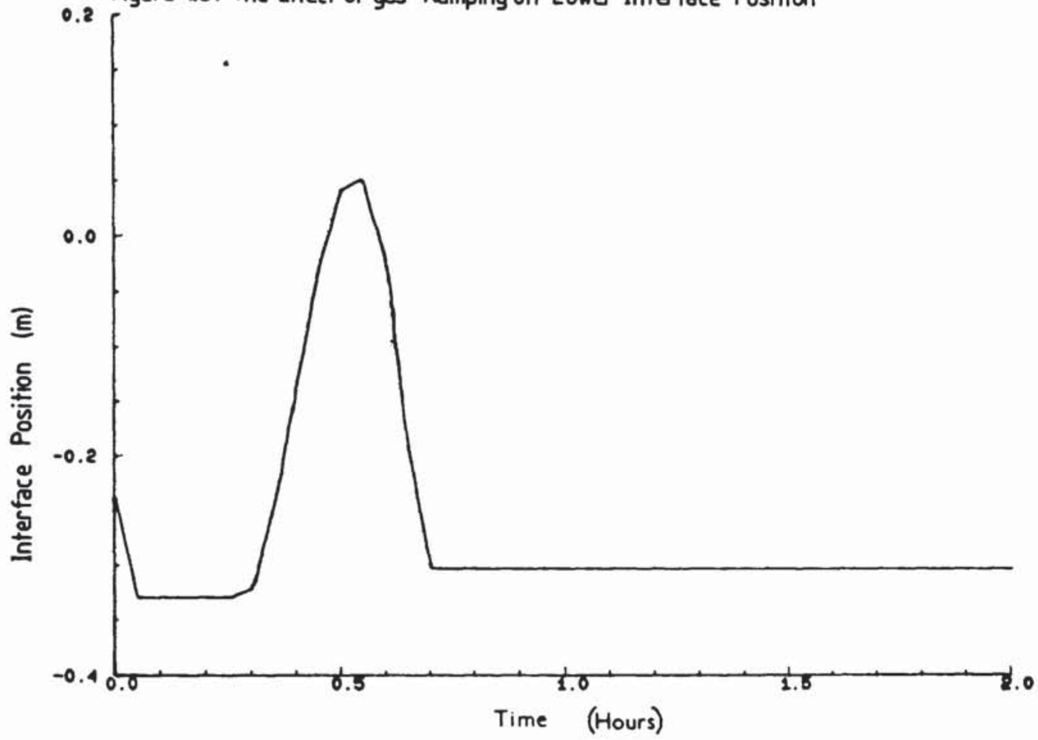
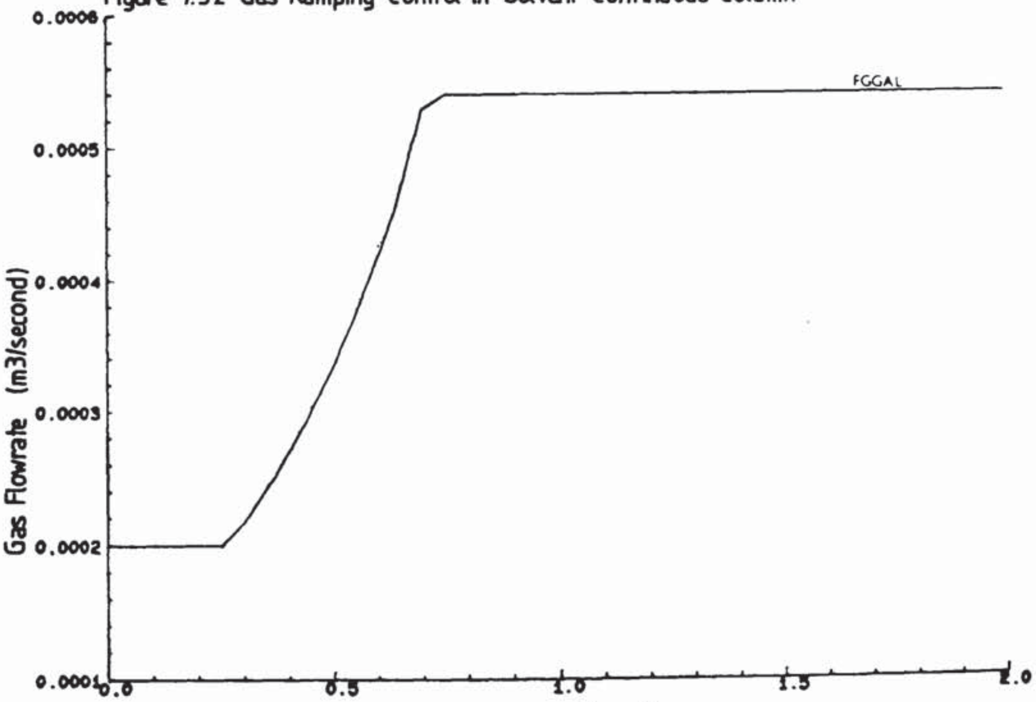


Figure 7.52 Gas Ramping Control in Solvent Continuous Column



moderate value of gain, say 1.0E-03 and a high reset time.

7.4.5 Model Response to Start-up Conditions

For the purpose of simulating the start up of Cycle III-U the following assumptions have been made:

(i) organic continuous columns are filled with organic phase;

(ii) aqueous continuous columns are filled to the required interface position with aqueous phase;

(iii) tanks are filled with feed of the required composition;

(iv) external settlers are filled to the aqueous overflow with aqueous phase.

The pulse limb of aqueous continuous columns is also assumed to be filled with organic phase.

The results are shown in Figure 7.67 - 7.67b and 7.68. As expected, flows from the columns commences immediately and soon attains steady state values. The outlet product concentration vary as shown in Figure 7.67a. Column 7 product concentration rises rapidly to attain steady state in about 0.6 hours. Column 8 lags behind, not settling out to a stable operation until 3.5 hrs have elapsed. The

Figure 7.53 Response to 25% Increase in FSGFE with no Control on Column 8

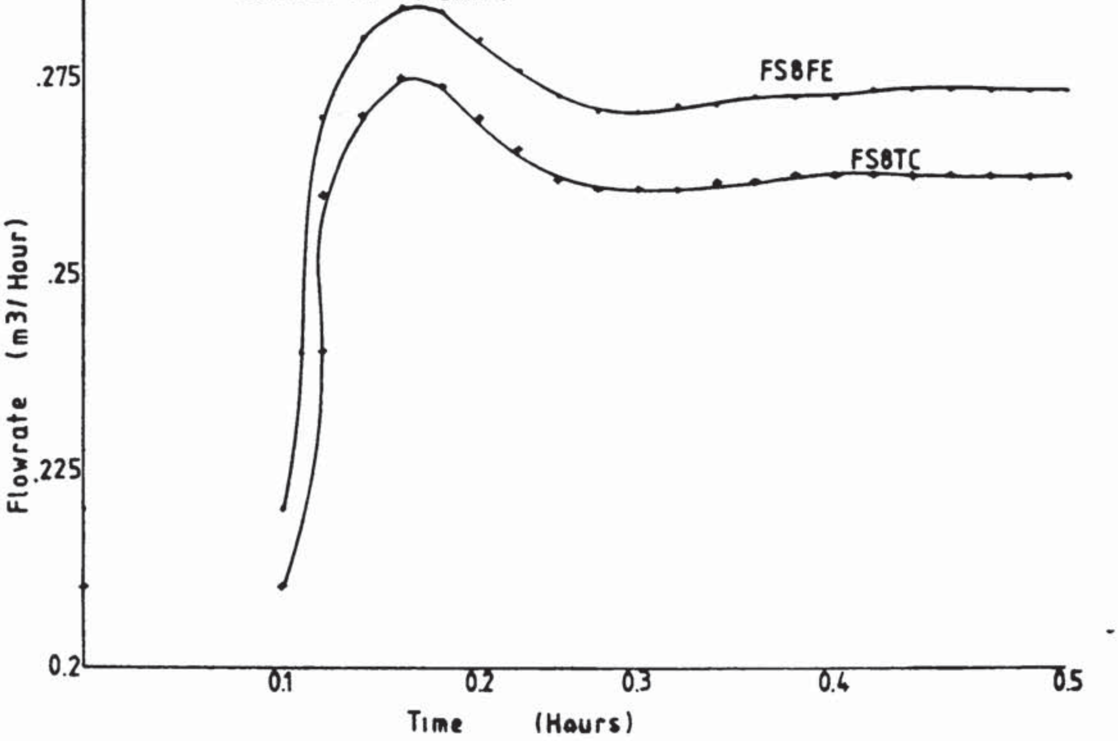


Figure 7.54 Uncontrolled Response of Interface Position to 25% Increase in FSGFE

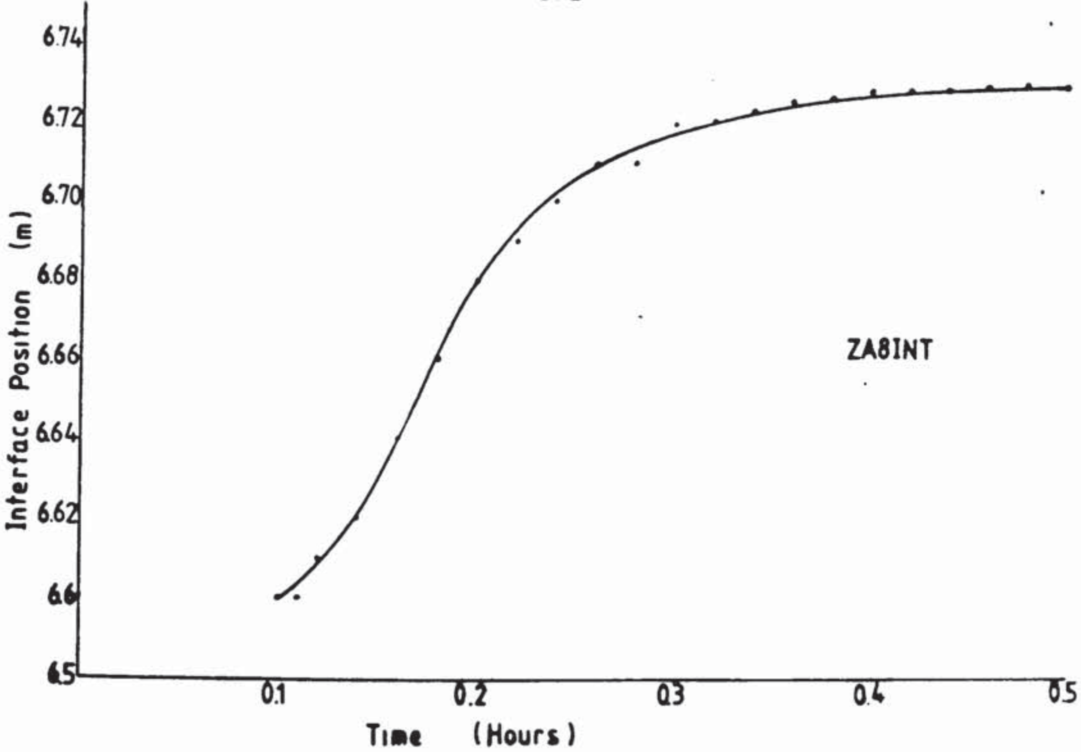


Figure 7.55 The Effect of Control Parameters on Model Performance

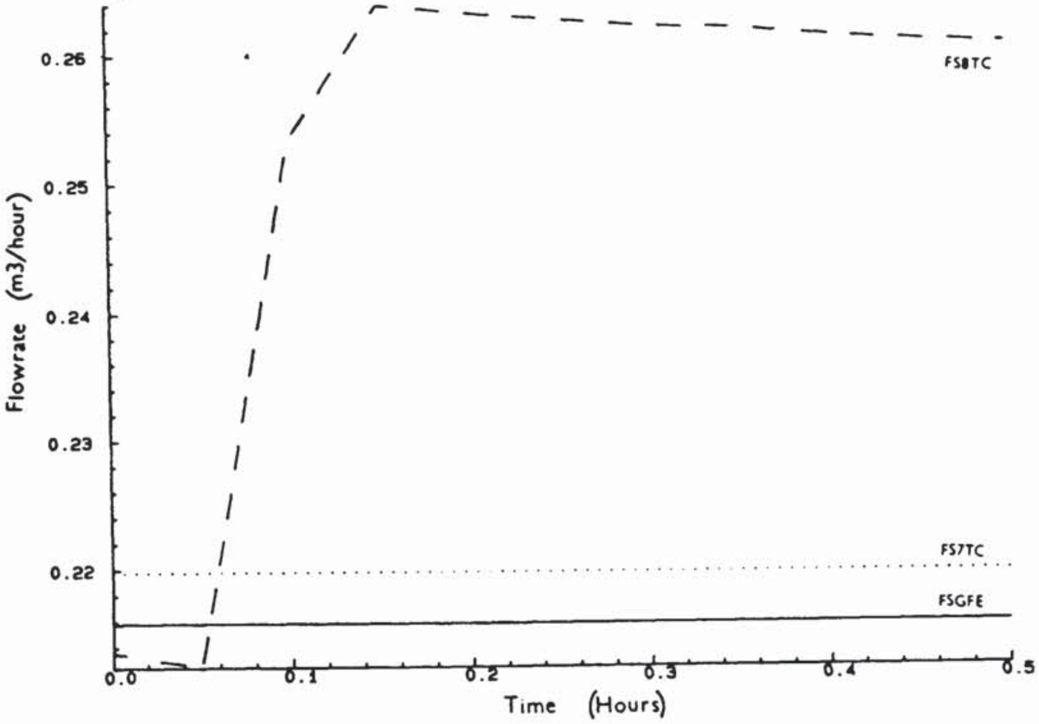


Figure 7.56 The Effect of Control Parameters on Model Performance

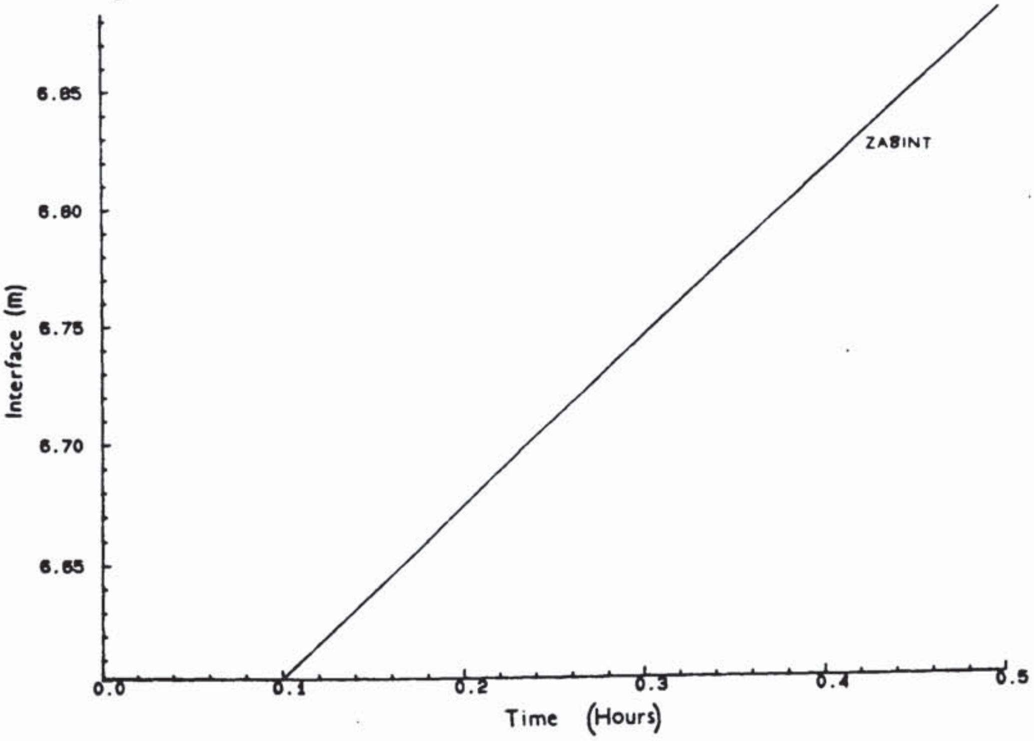


Figure 7.57 The Effect on Gain on Model Performance

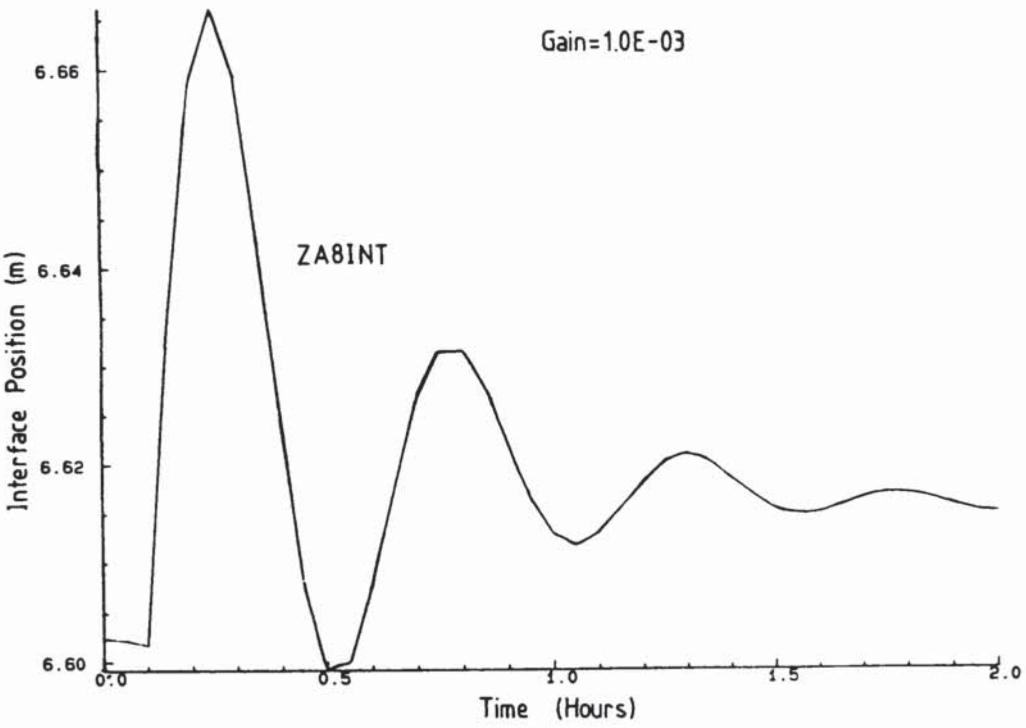


Figure 7.58 The Effect of Gain on Model Performance

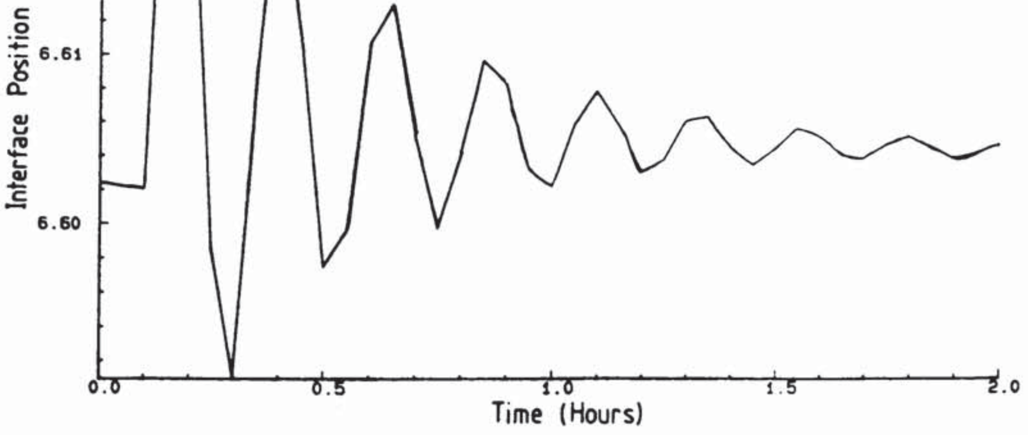


Figure 7.59 The Effect of Gain on Model Performance

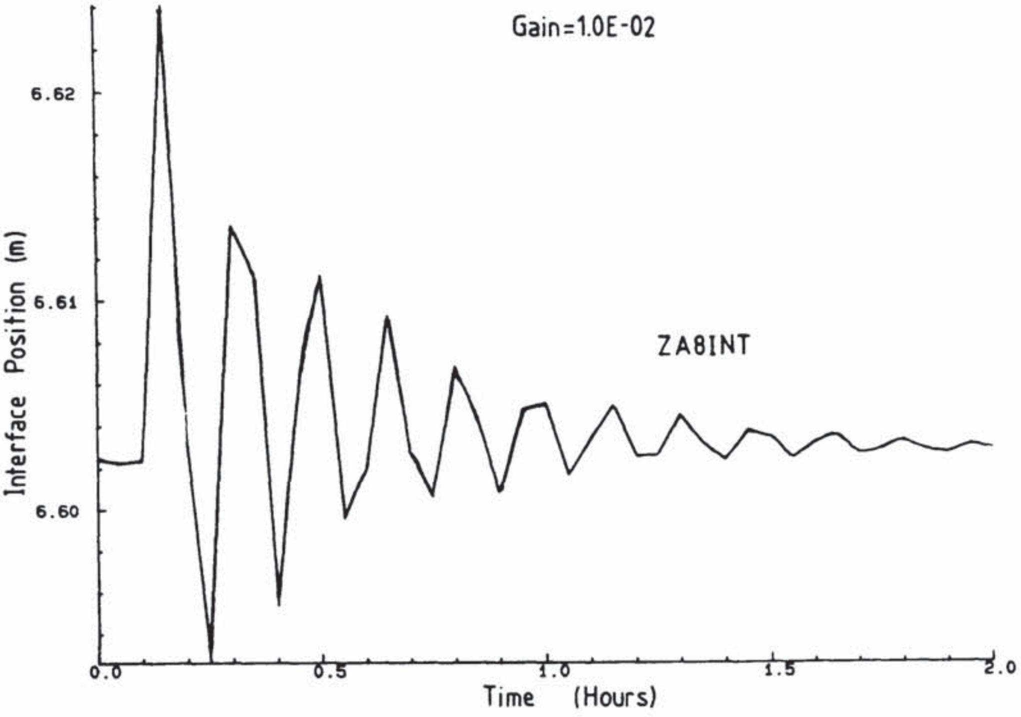


Figure 7.60 The Effect of Gain on Model Performance

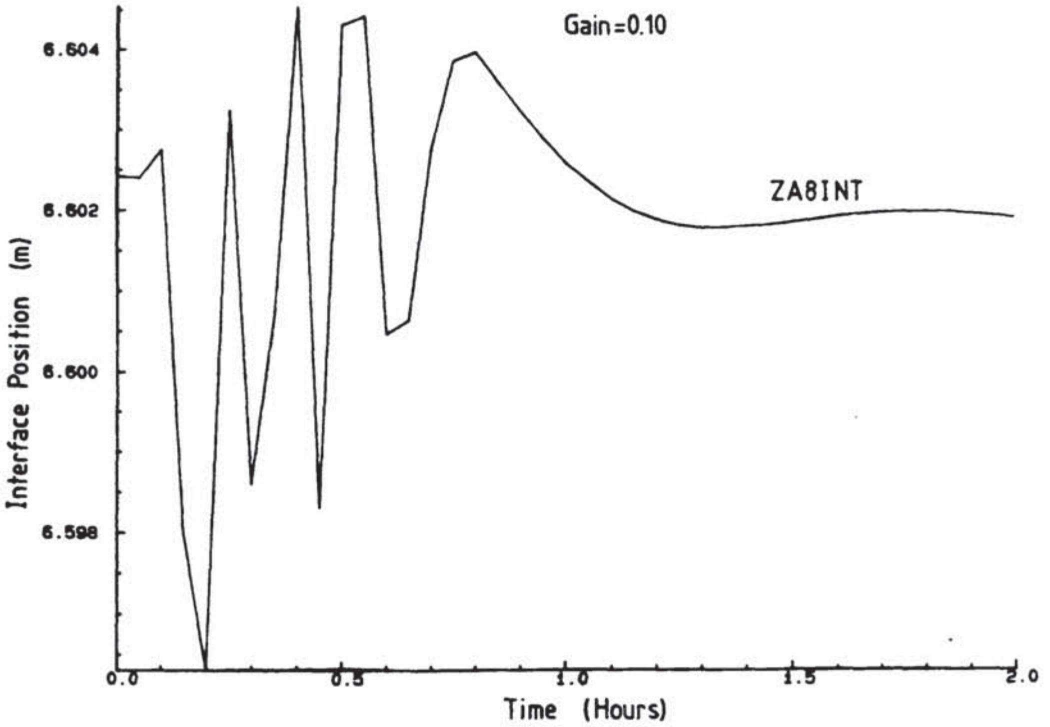


Figure 7.61 The Effect of Gain on Gas Feedrate to Gaslift Pump

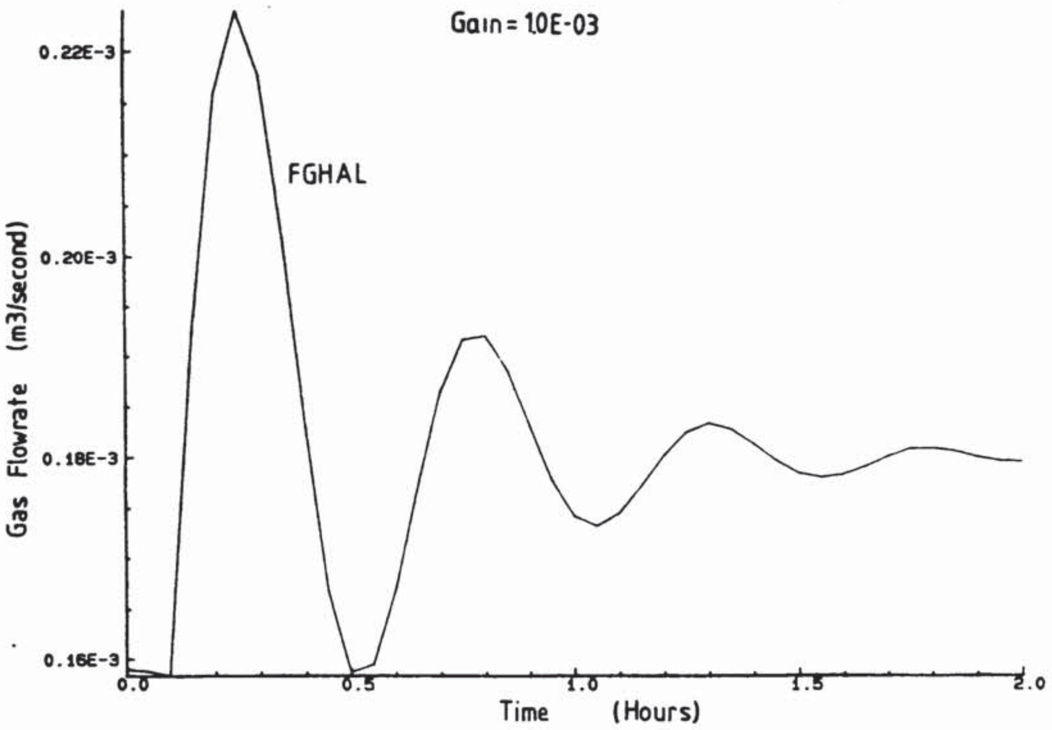


Figure 7.62 The Effect of Gain on Model Performance

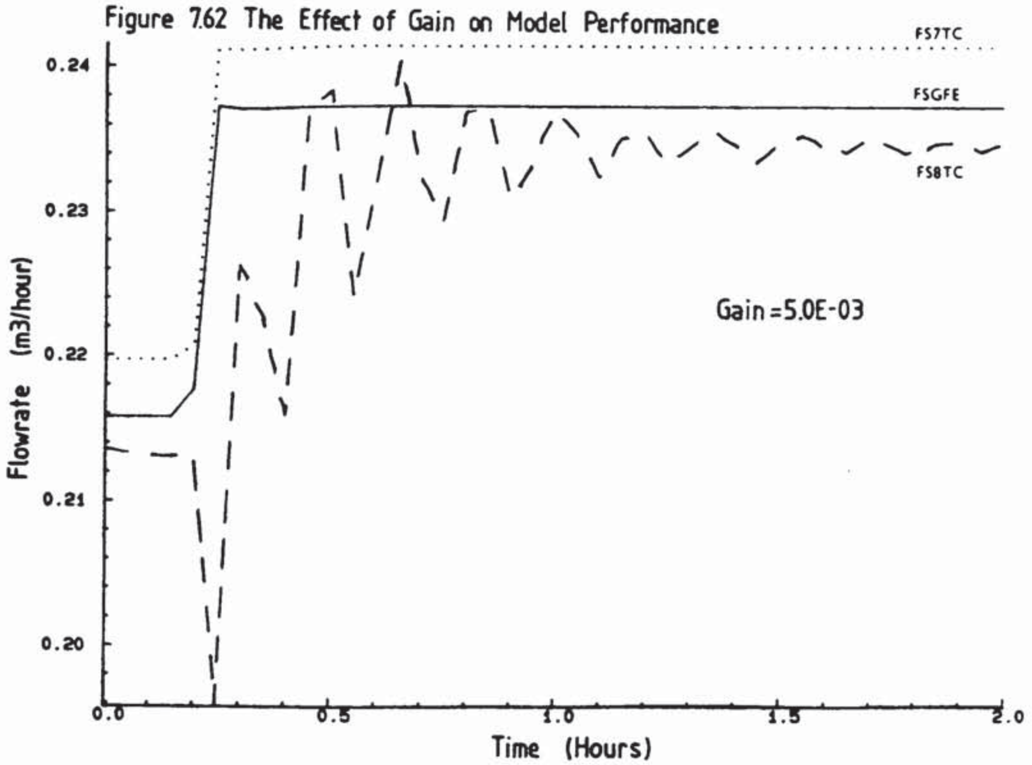


Figure 7.63 The Effect of Gain on Solvent Overflow Rate

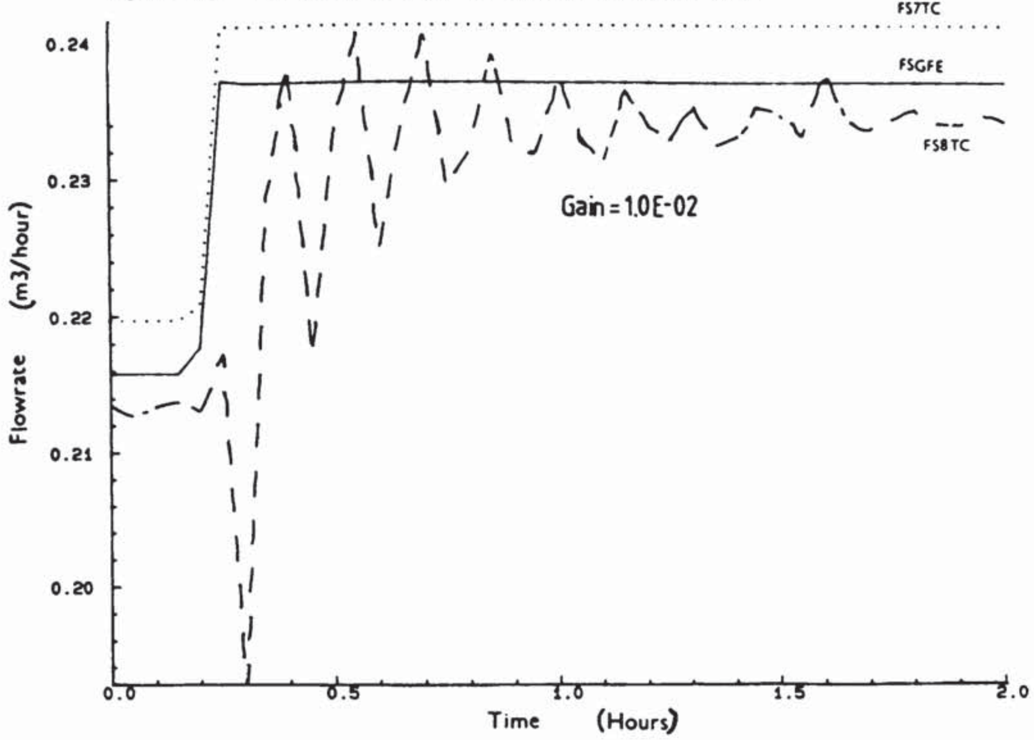


Figure 763a) Variation in Gas Feedrate in Response to a Perturbation

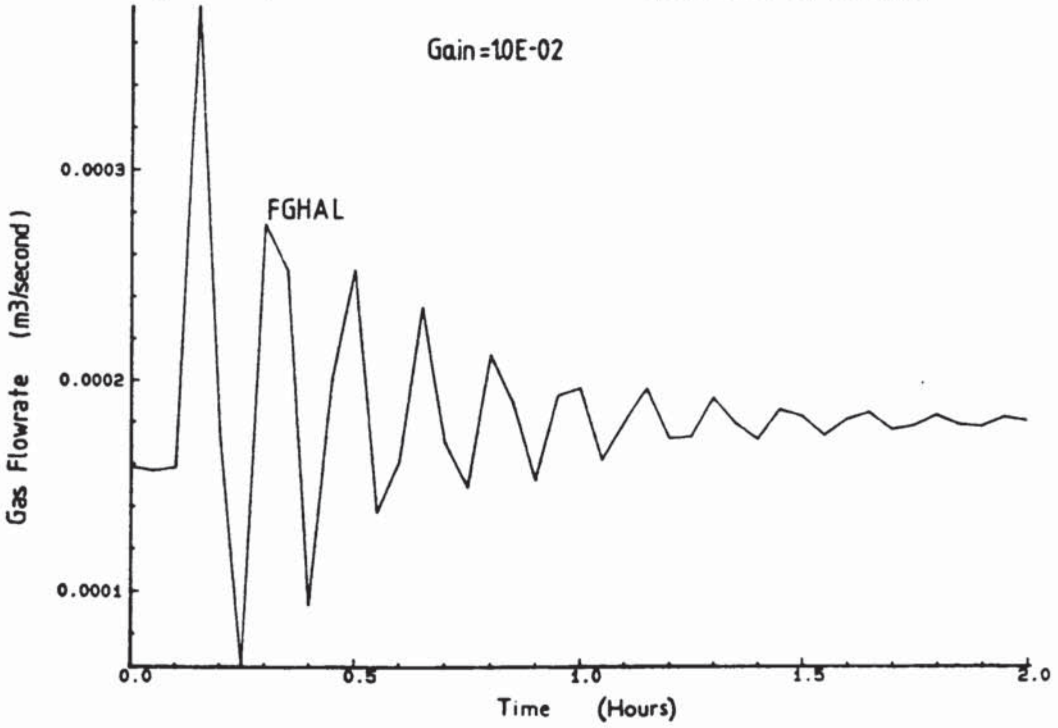


Figure 7.64 Gas Feedrate Variation after a Perturbation

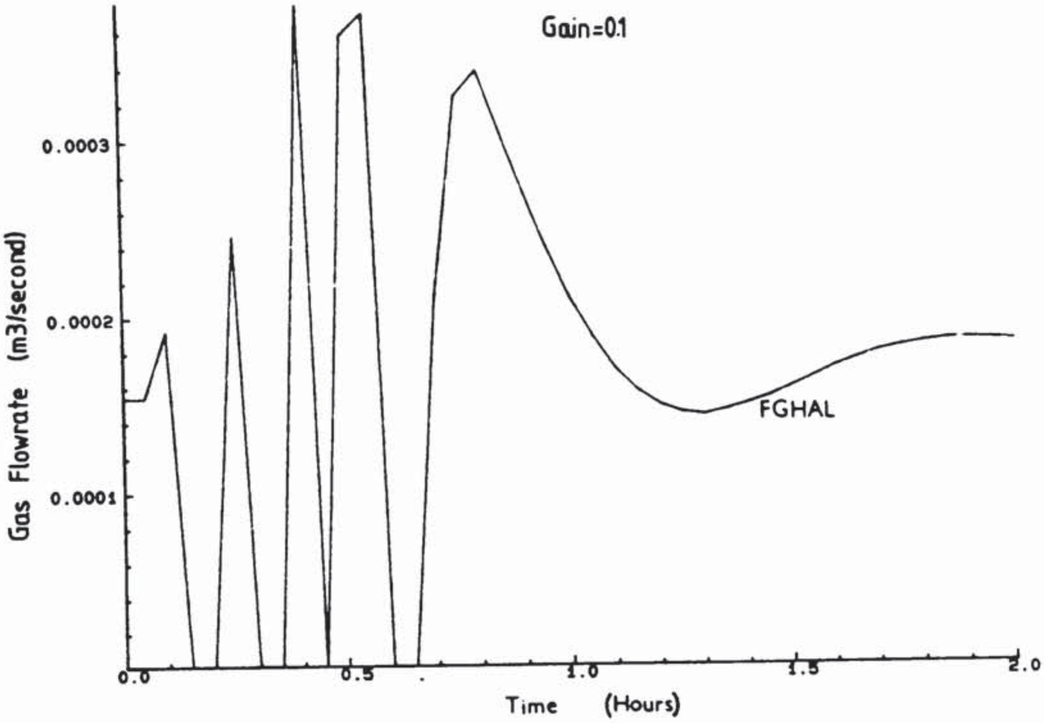
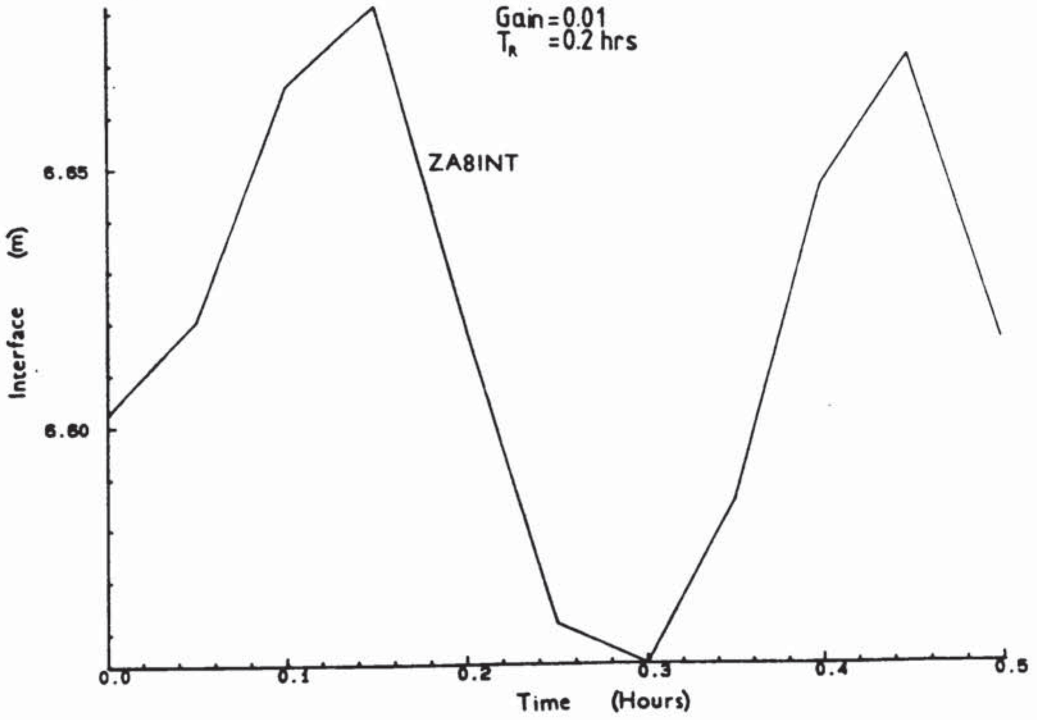


Figure 7.65 Effect of Reset Time on Model Performance



'overshoot' is interesting and suggests that the entire column behaves as a damped first order lag. Column 8 interface behaves as indicated in Figure 7.67. By initially filling the column to the desired interface level and then starting up the feeds it might be expected that the interface would rise and it does in fact leave the column briefly. As the uranium concentration will be very low <<< 1g/litre at this time the consequences are unlikely to be serious. The organic dispersed phase holdup will gradually build up and progress through the column as indicated in Figure 7.68.

7.4.6 Response to Loss of Acid Conditions

The acidity of the loaded aqueous feed to Cycle III-U is controlled by adjusting the flow of 22M nitric acid to the intercycle buffer tanks. As acidity and the 'salting out' effect of the nitrate ion affects the distribution coefficient of the transferring species, some effect would be expected as a result of losing this feed. The buffer tanks are large in comparison to the rest of the equipment, typically holding 10 hrs of feed, and they have been assumed to be perfectly-mixed since liquid will be recirculated round the tanks. Therefore any changes will be slow to make their effects felt.

For this reason a 20 hr simulation run was attempted. It crashed after 19 hrs. An unexpected phenomenon was observed

Figure 7.65a) Effect of T_R on N_2 Feedrate

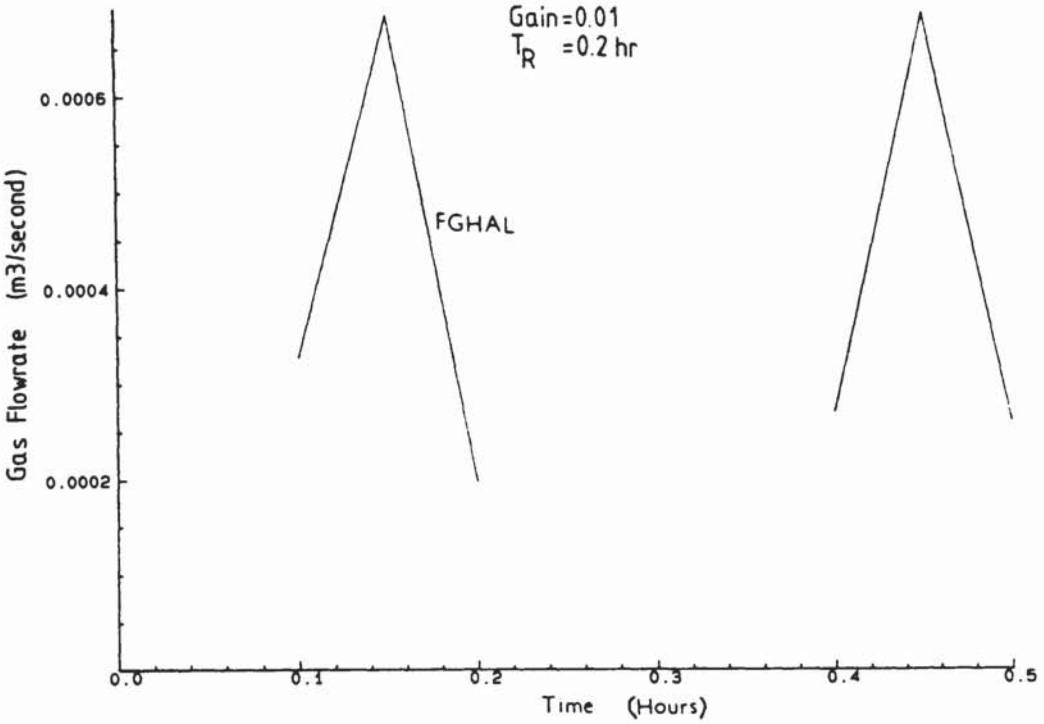


Figure 7.66 Effect of T_R on Model Response

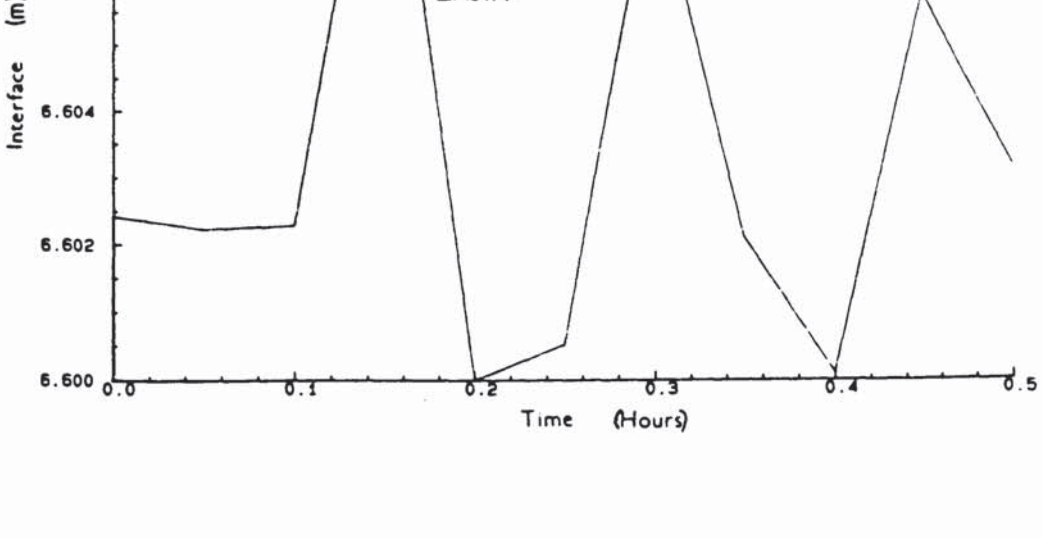


Figure 7.66 a) Effect of T_R on Model Performance

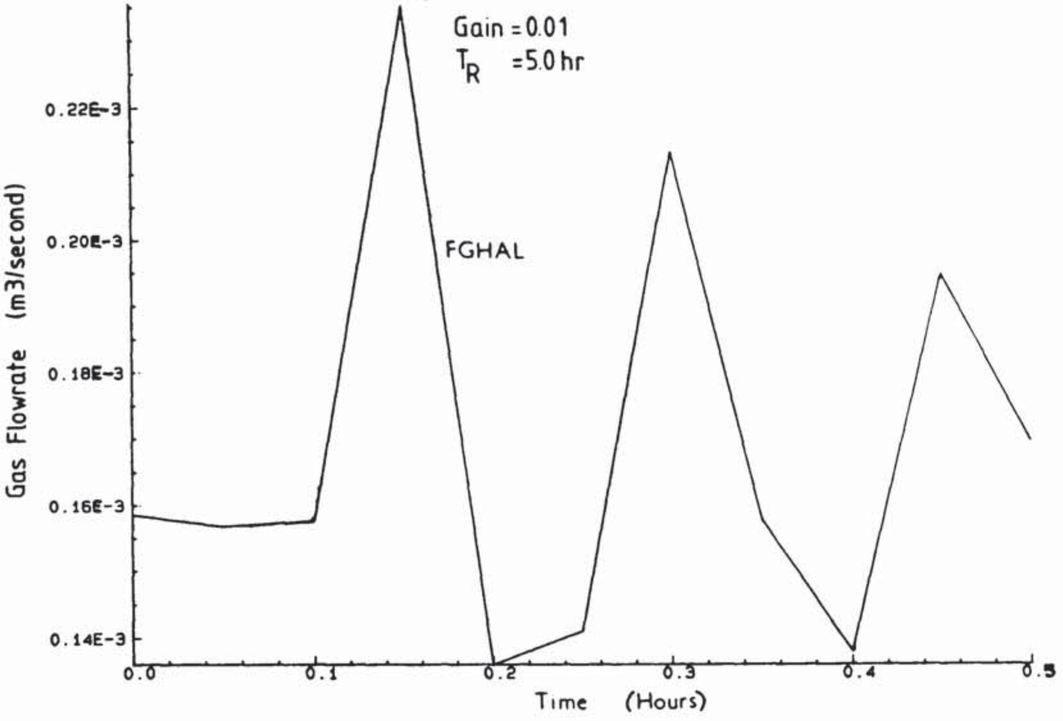


Figure 7.66 b) Effect of Control Parameters on Model Performance

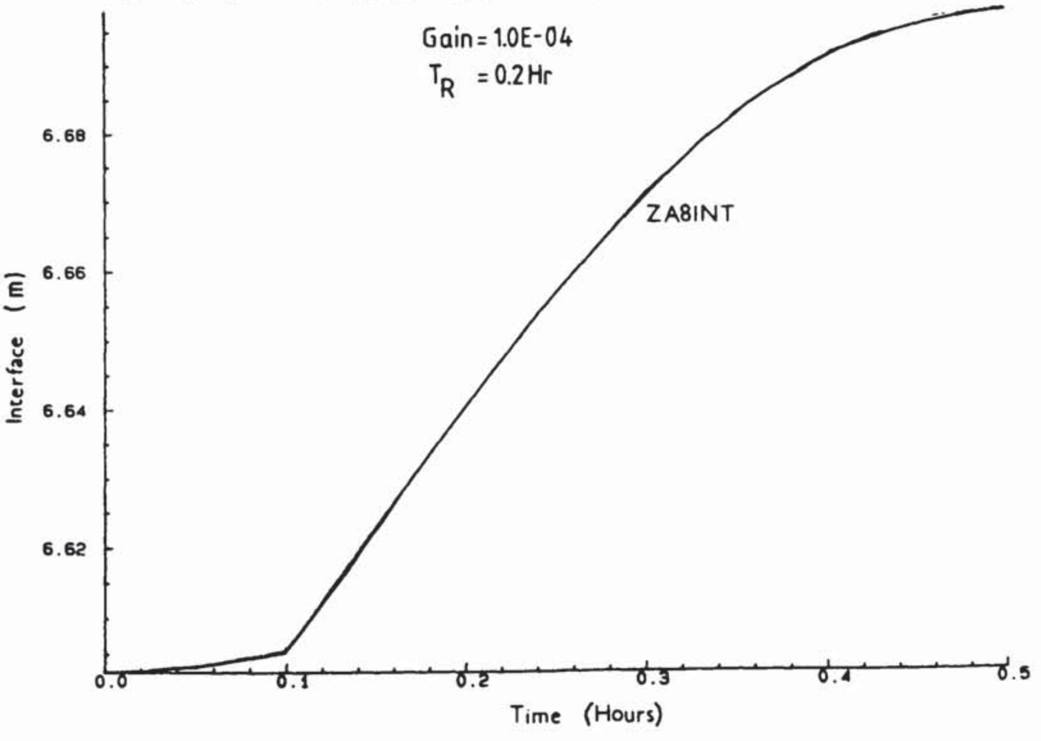


Figure 7.66 c) Effect of Control Parameters on Model Performance

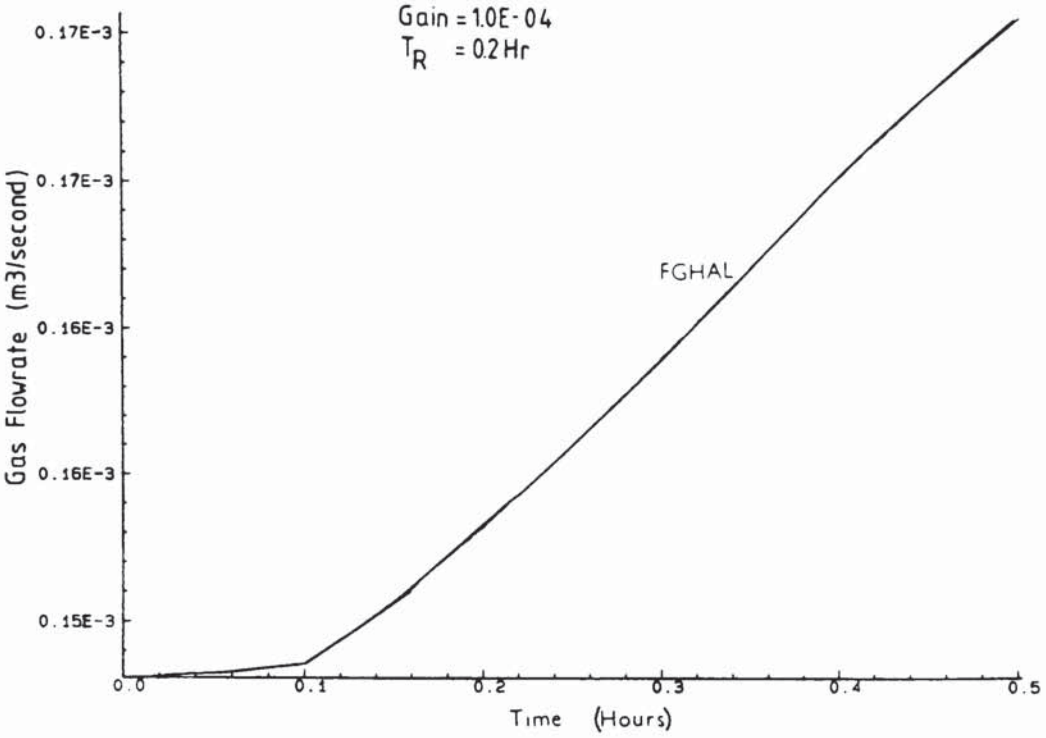
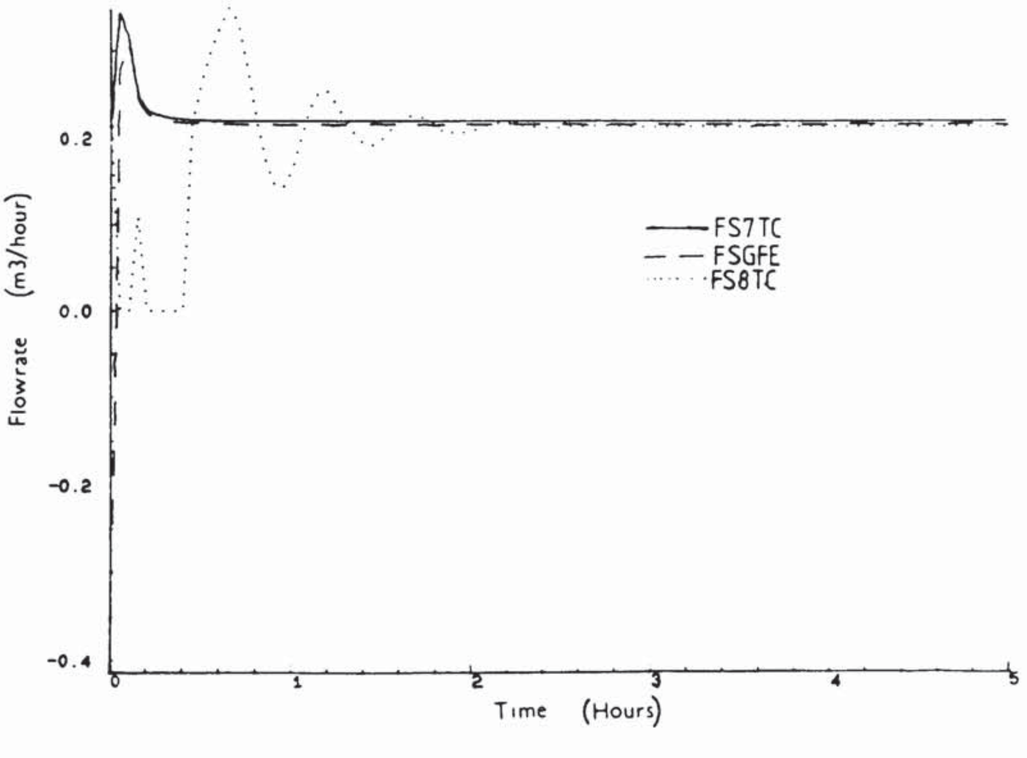


Figure 7.67 Predicted Behaviour at Startup — Solvent Flows



Flowrates became erratic, as shown in Figure 7.69. Outlet product concentrations, 'bottomed out' in Figure 7.69a and the feed concentration increased, as in Figure 7.69b. In addition an inordinate amount of CPU time was consumed, > over 30 hrs. The fault was eventually identified as an error in modelling the buffer tank. The actual flow of acid was cut off rather than replacing acid by say, water. As, in the simple model used, outlet flow from the tanks, and hence feed to Cycle III-U is considered independent of fluid level and condition eg density, in the tank. This is not so. As feed to the tank was slightly less than outlet flowrate the tank gradually emptied - with results as seen. This flow was corrected by modelling the fluidic pumps from the buffer tanks by means of a 'dummy' characteristic relating pump delivery to liquid level within the tasks. In this case as level in the tanks drop so does the feed to the cycle - feed concentration remains the same and therefore the effects will be much as discussed for the case of reduced aqueous feed. No attempt was made to write a more rigorous model of the fluidic pump because this would be unnecessary to model the behaviour of the plant and superfluous to this study.

7.4.7 Discussion of Results

The first deduction of this study is the relative insensitivity of dispersed phase holdup to changes in feed rate. The holdup changes, at the most, only 1-2% for a

Figure.7.67a Predicted Behaviour at Startup–Outlet Concentrations

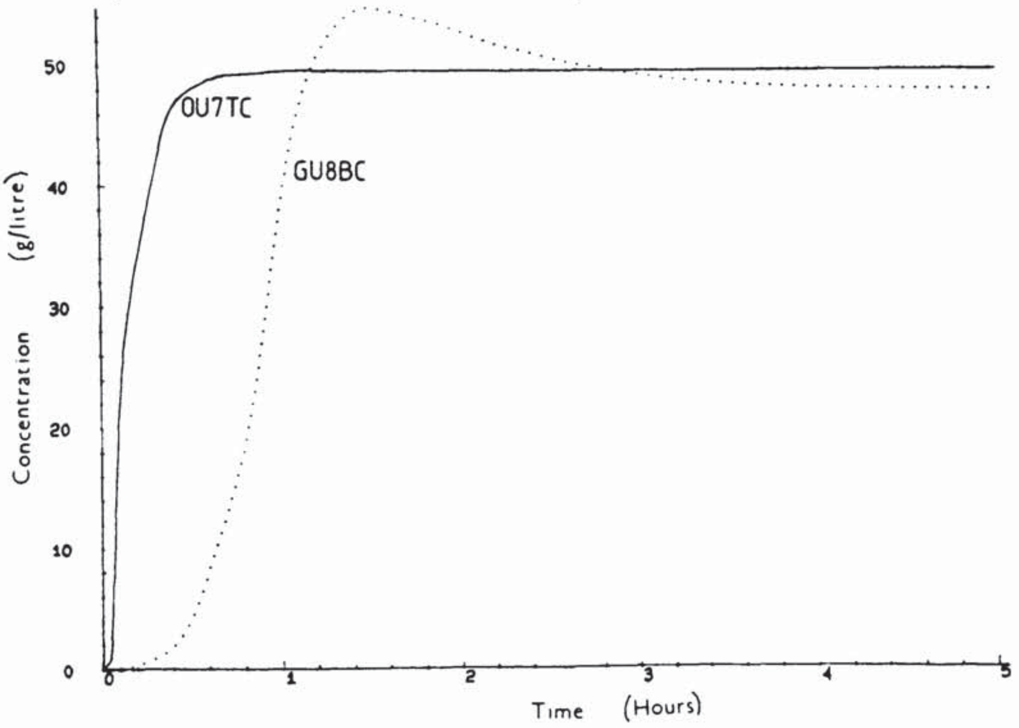
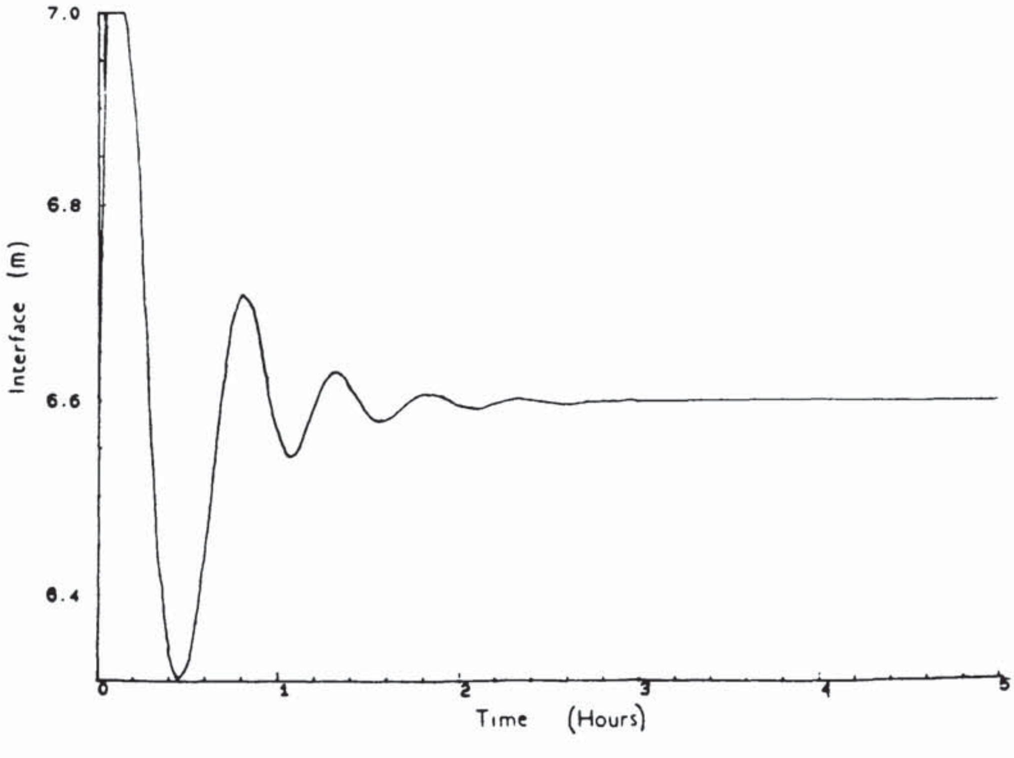


Figure 7.67b Predicted Behaviour at Startup-Interface Movement



25% increase in dispersed phase flowrate. This is in general agreement with Miao's (90) analysis which predicts that a 25% increase in dispersed phase flowrate will result in an increase in holdup by 16%. For the case where holdup was originally 10% the increase in dispersed phase flow would result in a hold up of 11.6%. In the absence of any proven method to measure hold up directly, although one technique has been suggested (66), it would appear unlikely that this parameter could be used to gauge the plant performance or in control applications.

Interface position might present a more realistic parameter on which to base some control loops. However, this depends upon the development of a reliable means of measuring it in the rigorous conditions of a reprocessing plant.

With regard to aqueous continuous columns, examination of previous figures reveals the interface position moves relatively little and does so relatively slowly. When no control is applied the interface does move. For example, typically for a 25% increase in continuous phase flowrate, 0.5 hrs will be required for the position of the interface to move 0.4 m, 1.33 cm min^{-1}. Unfortunately, no experimental data exist with which to compare these results.

Figure 7.68 Dispersed Phase Holdup after Startup

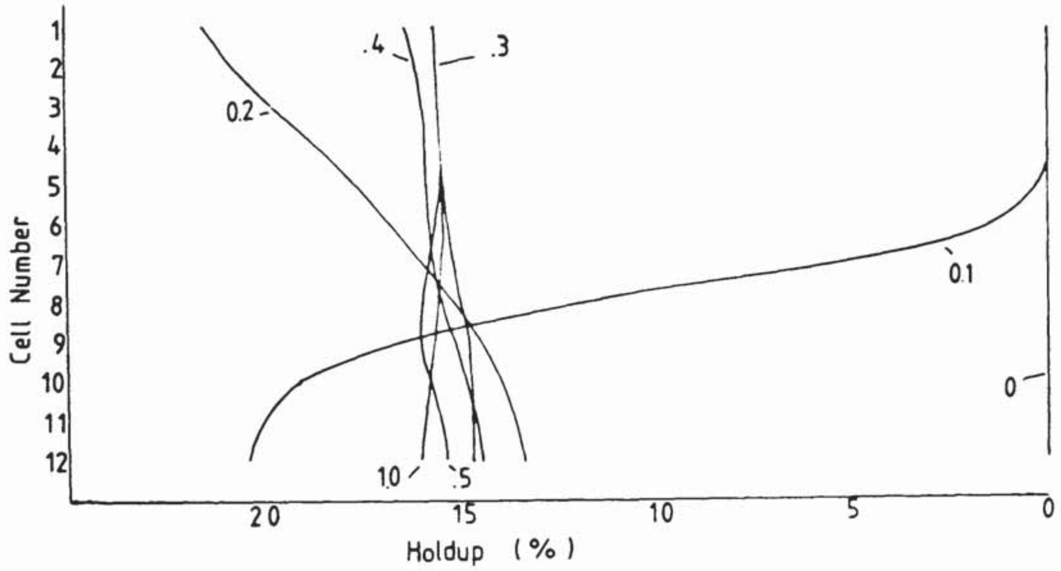


Figure 7.69 Response to Loss of Acid-Solvent Flows

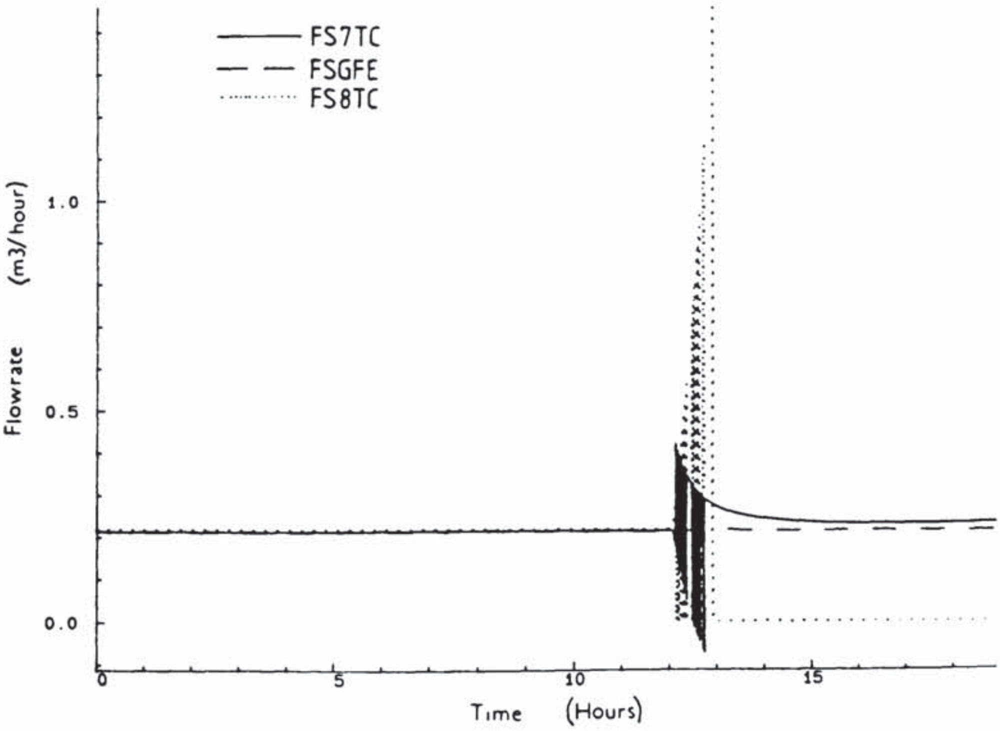


Figure 7.69a) Response to Loss of Acid Outlet Concentrations

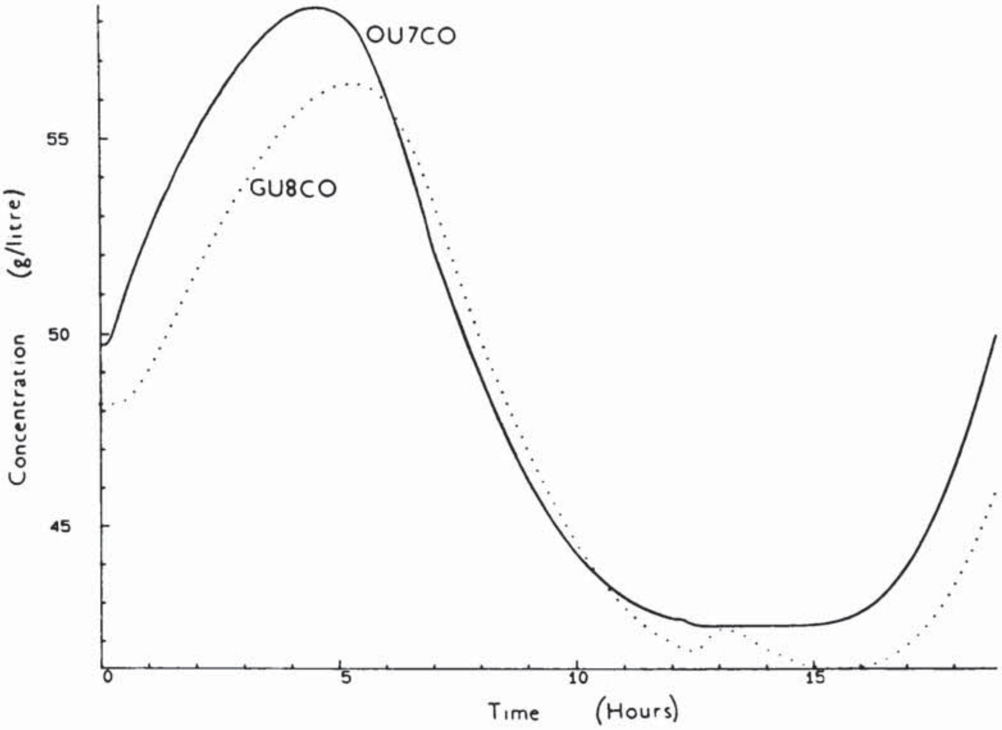
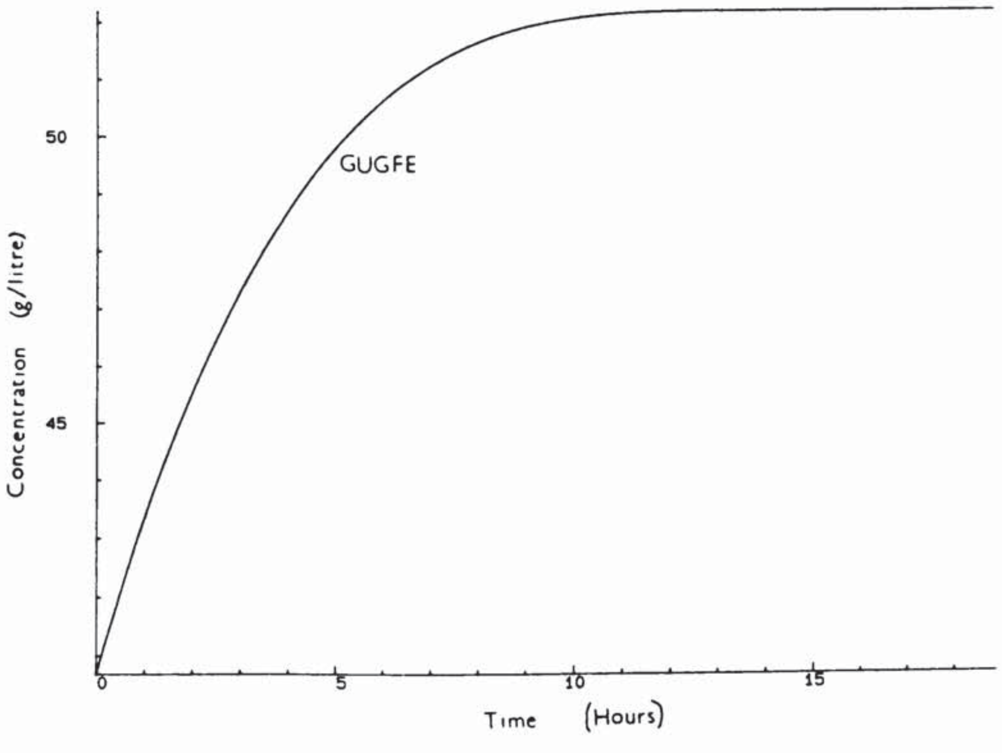


Figure 7.69b) Response to Loss of Acid-Cycle Feed Concentration



The dispersed phase feed rate to the acid continuous column in Cycle III-U can only be altered by disrupting the previous columns. Naturally, the effects of these disturbances take some time to feed through. For example Figure 7.53 and 7.54 demonstrate that in 0.4 hrs the interface moves 13 cm - 0.542 cm min^{-1}. Initially, the rate of movement is more than this ≈ 1.25 cm min^{-1}.

For a similar increase in dispersed phase flowrate the experimentally determined interface movement is of the order of 3 cm compared with 4 cm for the theoretical model and a similar time scale. On the hypothesis that interface movement is directly proportional to the increase in dispersed phase flowrate, this difference can be explained by the variation in the increase in dispersed phase flowrate, 18% c.f. 24%. This relationship holds for the remainder of the experimental data. A further complication is that the interface movement, and consequently the submergence ratio will affect the performance of the gas-lift pump. Even though the gas flow to the pump is unaltered the pump will become more efficient as the interface moves upwards, it will tend to remove more liquid and thus lower the interface.

Examination of concentration profiles within the columns reveals that, although there is a gradual change in response to disturbances there is no shift in position of any 'front' or 'spike' within the column. The detection of a concentration front might be reasonably straight forward using a BF_3 neutron detector. Detecting rapidly, and following, a gradual change in concentration is obviously more difficult and will present a challenge to instrument and controller designers.

In this respect it is highly unfortunate that the version of PMSP used in this study contained a programming flaw which made application of the PMSP frequency response and root finding algorithms impossible. Access to these features would have made a more stringent analysis of the control implications in this plant possible.

7.5 A Whole Plant Model

An attempt was made to run a whole plant model of a reprocessing plant. On the DEC MicroVAX II used for the bulk of this study this model ran in approximately 80 times real time. Unfortunately the machine crashed before any useful results were generated and it was clearly impractical and too expensive to repeat the exercise. The crash was caused by a power failure to the computer during a thunderstorm at which time approximately 40 hours of CPU time had been consumed for ≈ 0.5 hours of simulation.

8 Conclusions

Dynamic models, written in PMSP, have been created for all cycles of a plant to reprocess fast reactor fuel. The model of Cycle III-U has been used extensively to investigate the effects of disturbances on trains of pulsed columns. The results of this study support the, admittedly limited, deductions from experimental data that pulsed columns react very quickly to applied disturbances. The results confirm that changes such as interface position react immediately. Concentration effects require more time to become apparent - anything up to 15 minutes.

Plutonium mass transfer data were not available to be included in this study. This was unfortunate as models of U-Pu partitioning equipment may have yielded more interesting results as this is a vital part of the operation.

Mass transfer phenomena as discussed in Chapter 3 could not be modelled rigorously as this required inordinate computer CPU times - typically for one column, 3 times real time on a CRAY supercomputer or approximately 240 times real time on a MicroVAX II. This was clearly unacceptable for a multi-run study. In addition, there was no access to a CRAY for this study.

Control of the plant will present interesting challenges. Currently, a large amount of extra storage capacity is provided in reprocessing plants to cope with possible maloperations, for example:

(i) aqueous phase escaping into an organic line
(ii) loss of stripping agent
(iii) loss of conditioning agent causing off-specification product.

This extra capacity is very expensive to provide. Were it possible to prove that any perturbation could be detected and corrected the excess storage capacity would be unnecessary. This model could be used to design and test control strategies.

Instrumentation for use in the severe environment of the reprocessing plant must be robust, non-intrusive, reliable and, of course, be unaffected by radiation. It cannot contain any moving parts. Ultrasound techniques may, if they were available, present an answer, (7). Otherwise, devices such as flow-switches and pneumercators, with their attendent problems, must be used. This clearly limits control options and the chances of detecting maloperation quickly. If the only means of identifying maloperation is to take samples of final product and analyse them, relatively large volumes of out-of-specification material may have accumulated. The worst case would be to have all the equipment of a cycle filled with off-specification product. This might occur if a feed failure was not detected for some hours. It must be pointed out that samples must be analysed anyway for quality control and materials accountancy purposes.

The performance of trains of columns is affected by connecting equipment. These govern how rapidly disturbances propagate through the train. No previous studies of trains of columns have been reported and therefore this study represents the first analysis of interactions between columns.

In conclusion, the value of this study has been to create models capable of predicting the behaviour of trains of pulsed columns and to assess the impact on such trains of auxillary equipment. Control problems have been highlighted and solutions suggested. No other study has presented such a wideranging assessment of pulsed column response to perturbations in operating conditions.

9 Recommendations for Future Work

If possible, an experimental study should be made of the response of pulsed columns to applied disturbances. In particular, concentration profiles should be obtained. Standard methods to obtain concentration profiles will be adequate. As concentrations in both phases will be required separate samples of each should be obtained. As several profiles will be required to assess the impact of the disturbance, an automatic sampling system would be advantageous.

Plutonium mass transfer data must be included so that plutonium cycles may be studied.

In order to reduce computer times, some effort should be expended in investigating the possibility of replacing the full model with a simpler one - possibly a series of first and/or second order lags. The root finding and other control related options in PMSP should aid in this.

Instrumentation suitable for the reprocessing plant environment should be developed. An obvious technique for further development is ultrasound. If robots become sufficiently advanced to assist in maintenance, it may be possible to exploit other methods, for example load cells, piezoelectric techniques or intrusive techniques.

A more user-friendly front-end for models developed in this work should be written. An interactive 'dialogue' program could be written to obtain, from the user, starting values and required disturbances. Currently, a large input file has to be edited manually. A further refinement would be to provide a computer graphic 'mimic' to aid in visualising the process. These are available, for example the Ferranti PMS system.

In this work, the effect of single perturbations have been examined, in real life it is unlikely that a disturbance will be experienced in isolation. Therefore the effects of combined perturbations might be investigated. This would be easy to implement, facilities to mimic many perturbations have been included. The challenge arises in determining likely combinations. A further application would be to develop a 'fault-tree' to assist in identifying possible causes of observed plant maloperations, that is, an expert system to aid operators.

The signals received from plant instrumentation will be noisy and may be insufficiently reliable and accurate. The effect of this on control and subsequent plant behaviour should be investigated.

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Appendix A Experimental Results

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TABLE A1 RESULTS OF CALIBRATION RUNS IN EXPERIMENTAL WORK
GAS-LIFT PUMP TRIALS
DATE 2/8/85 TEMP = 17 C

N2 PRESSURE PSIG	N2 ROTAMETER READING 7K		N2 RATE L/MIN		N2 RATE AT STP L/MIN		MEAN N2 RATE AT ATP L/MIN	H2O READING 7S		WATER RATE L/MIN		MEAN H2O RATE L/MIN
15.00	9.00		4.60		8.75		8.75	12.80	13.20	0.47	0.49	0.48
14.00	17.20		7.80		14.33		14.33					
13.00	5.80		3.65		6.47		6.47	23.80	24.60	0.86	0.88	0.87
13.50	5.00		3.10		5.59		5.59	9.00	9.50	0.35	0.37	0.36
10.00	4.70		3.40		5.38		5.38	2.50	4.50	0.16	0.22	0.19
12.00	7.00		4.10		7.00		7.00	27.50		1.00		1.00
12.00	4.80		3.25		5.56		5.56	10.50	10.70	0.40	0.41	0.41
18.00	5.50		3.30		6.91		6.91	22.00	23.00	0.79	0.83	0.81
10.00	6.00	6.50	3.95	4.20	6.25	6.64	6.38	29.00	30.00	1.02	1.11	1.09
10.00	4.30	4.60	3.25	3.40	5.14	5.38	5.26	9.00	10.60	0.35	0.40	0.38
14.60	4.10	4.50	2.80	2.90	5.14	5.32	5.23	7.50	9.80	0.30	0.37	0.34
14.00	2.70	2.90	2.30	2.40	4.23	4.41	4.32					
14.00	3.30	3.50	2.50	2.60	4.59	4.77	4.68					
14.00	5.40	5.80	3.30	3.40	6.06	6.25	6.16	20.00	26.80	0.72	0.97	0.85
12.00	6.10	6.40	3.80	3.90	6.49	6.67	6.58	22.00	29.50	0.79	1.09	0.94
15.00	1.60	1.70	1.80	1.90	3.42	3.60	3.51					
15.00	3.40	3.60	2.50	2.60	4.75	4.94	4.85					
15.00	4.90	5.00	3.10	3.15	5.89	5.99	5.94	14.50	20.30	0.53	0.73	0.63
15.00	4.90	5.00	3.10	3.15	5.89	5.99	5.94	13.20	21.00	0.49	0.75	0.62
15.00	7.10	7.40	3.90	4.00	7.42	7.60	7.51					
8.00	7.30	7.80	4.50	4.70	6.54	6.83	6.69					
8.00	3.40	3.70	2.90	3.00	4.21	4.36	4.29					
8.00	5.20	5.40	3.60	3.70	5.23	0.37	5.30	18.80	22.20	0.68	0.80	0.74
8.00	3.80	4.10	3.00	3.10	4.35	4.51	4.43					
8.00	3.80	4.10	3.00	3.10	4.35	4.51	4.43	0.50	5.00	0.11	0.23	0.17
8.00	3.80	4.10	3.00	3.10	4.35	4.51	4.43	0.00	3.80	0.00	0.19	0.10
8.00	3.80	4.10	3.00	3.10	4.35	4.51	4.43	1.50	5.50	0.14	0.24	0.19
8.00	3.80	4.10	3.00	3.10	4.35	4.51	4.43	2.00	4.50	0.15	0.22	0.19
6.00	4.80	5.20	3.40	3.50	4.49	4.69	4.59	6.00	17.50	0.26	0.63	0.45
6.00	4.80	5.20	3.40	3.55	4.49	4.69	4.59	14.50	19.50	0.53	0.70	0.62
6.00	4.80	5.20	3.40	3.55	4.49	4.69	4.59	14.50	17.00	0.53	0.61	0.57
12.00	5.60	5.80	3.60	3.70	6.15	6.33	6.24	16.20	21.50	0.59	0.77	0.68
12.00	5.60	5.80	3.60	3.70	6.15	6.33	6.24	21.50	27.20	0.77	0.99	0.88
12.00	5.60	5.80	3.60	3.70	6.15	6.33	6.24	22.00	27.10	0.79	0.99	0.89
12.00	2.80	3.10	2.50	2.70	4.27	4.61	4.44					
12.00	4.40	4.60	3.10	3.20	5.30	5.47	5.39	9.40	13.10	0.36	0.48	0.42
12.00	4.40	4.60	3.10	3.20	5.30	5.47	5.39	11.00	14.20	0.41	0.52	0.47
12.00	4.40	4.60	3.10	3.20	5.30	5.47	5.39	9.36	13.70	0.37	0.50	0.44
15.00	2.50	2.80	2.20	2.30	4.75	4.37	4.56					
15.00	3.80	4.10	2.70	2.80	5.13	5.32	5.23	3.50	4.50	0.19	0.22	0.21
15.00	3.80	4.10	2.70	2.80	5.13	5.32	5.23	3.20	7.50	0.18	0.30	0.24
15.00	3.80	4.10	2.70	2.80	5.13	5.32	5.23	5.00	9.00	0.23	0.35	0.29
15.00	5.80	6.10	3.40	3.50	6.46	6.65	6.56	23.50	27.50	0.84	1.00	0.92
15.00	5.80	6.10	3.40	3.50	6.46	6.65	6.56	26.50	29.50	0.96	1.09	1.03
15.00	5.80	6.10	3.40	3.50	6.46	6.65	6.56					
10.00	4.50	4.80	3.30	3.45	5.22	5.45	5.34	13.50	15.00	0.48	0.54	0.52
10.00	4.50	4.80	3.30	3.45	5.22	5.45	5.34	12.80	14.50	0.47	0.53	0.50
10.00	4.50	4.80	3.30	3.45	5.22	5.45	5.34	10.00	18.30	0.38	0.65	0.52
10.00	4.50	4.80	3.30	3.45	5.22	5.45	5.34	7.00	12.00	0.29	0.44	0.37
10.00	5.90	6.70	3.90	4.10	6.17	6.48	6.33					

TABLE A2 RESULTS OF CALIBRATION RUNS IN EXPERIMENTAL WORK
GAS-LIFT PUMP TRIALS
DATE 6/8/85 TEMP = 17 C

N2 PRESSURE PSIG	N2 ROTAMETER READING 7K		N2 RATE L/MIN		N2 RATE AT STP L/MIN		MEAN N2 RATE AT ATP L/MIN	H20 READING 7S		WATER RATE L/MIN		MEAN H20 RATE L/MIN
15.00	6.50	6.70	3.70	3.80	7.04	7.23	7.10	23.00	28.00	0.82	1.02	0.92
10.00	4.10	4.30	3.20	3.30	5.06	5.20	5.13					
10.00	6.60	7.00	4.20	4.40	6.64	6.95	6.80	14.50	15.50	0.53	0.56	0.55
10.00	6.60	7.00	4.20	4.40	6.64	6.95	6.80	16.50	17.50	0.60	0.63	0.62
10.00	6.60	7.00	4.20	4.40	6.64	6.95	6.80	23.80	25.50	0.86	0.92	0.89
7.00	6.50	6.90	4.20	4.30	5.83	5.97	5.90	25.00	29.50	0.90	1.10	1.00
7.00	6.50	6.90	4.20	4.30	5.83	5.97	5.90	24.10	29.30	0.86	1.09	0.98
7.00	6.50	6.90	4.20	4.30	5.83	5.97	5.90	23.00	27.00	0.82	0.98	0.90
7.00	6.50	6.90	4.20	4.30	5.83	5.97	5.90	19.00	24.00	0.68	0.86	0.77
7.00	6.50	6.90	4.20	4.30	5.83	5.97	5.90	20.00	27.70	0.72	0.99	0.85
7.00	6.50	6.90	4.20	4.30	5.83	5.97	5.90	22.50	30.00	0.81	1.11	0.96
7.00	6.50	6.90	4.20	4.30	5.83	5.97	5.90	18.50	27.00	0.66	0.98	0.82
7.00	4.40	4.80	3.30	3.40	4.58	4.72	4.65	5.50	6.60	0.24	0.28	0.26
7.00	4.40	4.80	3.30	3.40	4.58	4.72	4.65	6.00	8.70	0.26	0.34	0.30
7.00	4.40	4.80	3.30	3.40	4.58	4.72	4.65	5.20	7.00	0.23	29.00	0.26
7.00	4.40	4.80	3.30	3.40	4.58	4.72	4.65	6.50	8.00	0.27	0.32	0.29
7.00	4.40	4.80	3.30	3.40	4.58	4.72	4.65	7.00	9.50	0.29	0.37	0.33
7.00	4.40	4.80	3.30	3.40	4.58	4.72	4.65	6.30	8.00	0.27	0.32	0.30
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	15.00	22.00	0.54	0.79	0.67
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	16.80	17.20	0.61	0.62	0.62
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	17.00	18.20	0.61	0.65	0.63
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	16.00	20.00	0.58	0.72	0.65
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	13.50	21.40	0.50	0.77	0.64
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	16.00	18.50	0.58	0.66	0.62
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	12.80	21.20	0.47	0.76	0.62
10.00	5.40	5.70	3.70	3.80	5.85	6.01	5.93	13.50	22.00	0.49	0.79	0.64
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	10.50	11.50	0.40	0.43	0.42
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	8.50	11.50	0.34	0.43	0.38
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	10.00	16.00	0.38	0.58	0.48
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	8.70	11.00	0.34	0.41	0.37
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	7.90	10.00	0.31	0.38	0.34
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	8.90	10.50	0.35	0.40	0.37
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	9.00	13.00	0.35	0.48	0.41
15.00	4.80	5.00	3.10	3.15	5.89	5.99	5.84	10.00	15.00	0.38	0.54	0.46
15.00	6.50	6.70	3.70	3.80	7.04	7.23	7.10	24.00	25.80	0.86	0.93	0.90
15.00	6.50	6.70	3.70	3.80	7.04	7.23	7.10	26.50	29.80	0.96	1.11	1.04
15.00	6.50	6.70	3.70	3.80	7.04	7.23	7.10	24.10	26.00	0.86	0.94	0.90

TABLE A3 RESULTS OF CALIBRATION RUNS IN EXPERIMENTAL WORK
GAS-LIFT PUMP TRIALS
DATE 7/8/85 TEMP = 17 C

N2 PRESSURE PSIG	N2 ROTAMETER READING 7K		N2 RATE L/MIN		N2 RATE AT STP L/MIN		MEAN N2 RATE AT ATP L/MIN	H20 READING 7S		WATER RATE L/MIN		MEAN H20 RATE L/MIN
10.50	8.50	9.50	5.00	5.40	8.06	8.71	8.40	14.00	17.00	1.06	1.28	1.17
10.50	7.50	8.30	4.60	4.90	7.42	7.90	7.70	12.00	14.50	0.96	1.10	1.03
10.50	11.00	11.40	6.10	6.30	9.84	10.16	10.00	9.30	10.50	0.74	0.82	0.78
15.00	7.20	7.60	3.90	4.10	7.42	7.86	7.64	0.40	2.20	0.22	0.30	0.26
15.00	7.20	7.60	3.90	4.10	7.42	7.86	7.64	6.50	9.50	0.56	0.76	0.66
8.00	11.50	12.20	6.30	6.60	9.15	9.59	9.37	9.50	11.00	0.76	0.86	0.81
8.00	11.50	12.20	6.30	6.60	9.15	9.59	9.37	9.50	10.50	0.76	0.81	0.79
8.00	11.50	12.20	6.30	6.60	9.15	9.59	9.37	10.00	11.20	0.78	0.87	0.83
9.00	11.00	11.50	6.10	6.30	9.25	9.56	9.40	8.00	9.50	0.66	0.76	0.71
9.00	11.00	11.50	6.10	6.30	9.25	9.56	9.40	8.00	10.50	0.66	0.81	0.74
9.00	11.00	11.50	6.10	6.30	9.25	9.56	9.40	10.00	12.00	0.78	0.92	0.85
10.00	6.80	7.10	4.30	4.40	6.80	6.96	6.88	8.50	10.00	0.70	0.78	0.74
10.00	6.80	7.10	4.30	4.40	6.80	6.96	6.88	9.50	10.00	0.76	0.78	0.77
10.00	6.80	7.10	4.30	4.40	6.80	6.96	6.88	9.50	10.00	0.76	0.78	0.77
10.00	6.80	7.10	4.30	4.40	6.80	6.96	6.88	9.70	10.00	0.77	0.86	0.82
15.00	11.50	11.80	5.50	5.60	10.46	10.65	10.55	22.00		1.65		1.65
15.00	11.50	11.80	5.50	5.60	10.46	10.65	10.55	19.00	21.00	1.42	1.58	1.50
15.00	11.50	11.80	5.50	5.60	10.46	10.65	10.55	15.00	16.00	1.12	1.20	1.16
15.00	11.50	11.80	5.50	5.60	10.46	10.65	10.55	8.50	10.00	0.70	0.78	0.74
15.00	11.50	11.80	5.50	5.60	10.46	10.65	10.55	7.00	9.80	0.60	0.79	0.68
15.00	11.50	11.80	5.50	5.60	10.46	10.65	10.55	8.00	9.50	0.67	0.76	0.72
15.00	11.50	11.80	5.50	5.60	10.46	10.65	10.55	7.00	9.40	0.60	0.75	0.77
7.00	7.80	8.10	4.70	4.80	6.53	6.67	6.60	7.80	10.80	0.66	0.85	0.76
7.00	8.80	9.50	5.10	5.40	7.08	7.50	7.30	7.30	8.50	0.62	0.69	0.66
7.00	8.80	9.50	5.10	5.40	7.08	7.50	7.30	8.00	9.00	0.67	0.72	0.70
7.00	8.80	9.50	5.10	5.40	7.08	7.50	7.30	7.50	8.50	0.64	0.70	0.67
7.00	8.80	9.50	5.10	5.40	7.08	7.50	7.30	9.50	10.50	0.76	0.82	0.79
5.00	12.00	13.00	6.70	7.10	8.43	8.93	8.68	7.00	8.00	0.60	0.67	0.64
5.00	19.20	20.00	10.20	10.60	12.83	13.34	13.00	9.00	10.60	0.72	0.83	0.78
5.00	19.20	20.00	10.20	10.60	12.83	13.34	13.00	9.00	11.00	0.72	0.85	0.79
7.50	19.10	19.10	9.70		13.76		13.76	20.00		1.45		1.45

TABLE A4 EXPERIMENTAL RESULTS ON PERFORMANCE OF A GAS-LIFT PUMP
DATE 8/8/85 TEMP 17 C

N2 PRESSURE PSIG	N2 ROTAMETER READING 7K SIZE		N2 RATE L/MIN		N2 RATE AT STP L/MIN		MEAN N2 RATE L/MIN	H2O ROTAMETER READING 10S SIZE		H2O RATE L/ MIN		MEAN H2O RATE L/MIN
11.00	4.60	4.80	3.20	3.30	5.26	5.43	5.35	1.50	3.00	0.28	0.36	0.32
11.00	4.60	4.80	3.20	3.30	5.26	5.43	5.35	3.00	5.50	0.36	0.50	0.43
11.00	4.60	4.80	3.20	3.30	5.26	5.43	5.35	2.00	4.00	0.30	0.42	0.36
11.00	8.70	9.50	4.75	5.00	7.81	8.23	8.02	10.00	11.50	0.80	0.85	0.83
11.00	8.70	9.50	4.75	5.00	7.81	8.23	8.02	11.50	12.00	0.85	0.92	0.88

TABLE A5 RESULTS OF GAS-LIFT TRIALS TWO LIQUID PHASES
DATE 8/8/85 TEMP 17 C

N2 PRESSURE PSIG	N2 ROTAMETER READING 7K SIZE		N2 RATE L/MIN		N2 RATE AT STP L/MIN		MEAN N2 RATE L/MIN	SOLVENT ROTAMETER READING SIZE 7S		SOLVENT FLOW L/ MIN		MEAN SOLVENT FLOW L/MIN	H2O ROTAMETER IN READING IN 10S SIZE	MEAN H2O RATE IN L/MIN	H2O ROTAMETER OUT READING OUT 10S SIZE		H2O FLOW RATE OUT L/MIN		MEAN H2O FLOW OUT L/MIN	TOTAL FLOW OUT L/MIN
8.00	4.30	4.50	3.25	3.35									1.30	0.26						
8.00	7.50	7.70	4.60	4.70									1.30	0.26						
8.00	10.30	10.60	5.80	5.90	8.40	8.60	8.50	TOO SMALL					1.30	0.26	1.00	1.80	0.24	0.30	0.27	0.27
8.00	13.70	14.30	7.30	7.60	10.60	11.04	10.80	TOO SMALL					1.30	0.26	7.50	8.50	0.32	0.70	0.51	0.51
8.50	21.20	21.80	10.80	11.10	16.00	16.40	16.20	3.50	5.50	0.18	0.24	0.21	3.50	0.38	3.00	4.00	0.36	0.42	0.39	0.60
DATE 9/8/85																				
8.00	13.00	14.00	5.00	7.45	7.26	10.80	9.03	0.00	5.00	0.07	0.22	0.15	9.00	0.73	8.50	9.50	0.70	0.76	0.73	0.88
10.00	12.50	13.50	6.80	7.20	10.75	11.40	11.10	0.00	8.00	0.07	0.31	0.19	9.00	0.73	8.50	9.50	0.70	0.76	0.73	0.92
10.00	12.50	13.50	6.80	7.20	10.75	11.40	11.10	0.00	6.00	0.07	0.25	0.16	9.00	0.73	8.50	9.50	0.70	0.76	0.73	0.89
10.00	16.00	17.00	8.30	8.80	13.10	13.90	13.50	5.00	6.00	0.22	0.25	0.24	9.00	0.73	8.50	9.50	0.70	0.76	0.73	0.97

TABLE A6 GAS-LIFT PUMP DATA

SUMERGENC %	AIR RATE MEASURED M3/M2.S	LIQUID RATE MEASURED M3/M2.S	LIQUID RATE PREDICTED CLARKS METHOD M3/M2.S	LIQUID RATE PREDICTED FRIEDALS METHOD M3/M2.S
56.30	0.4408	0.1263	0.1385	0.0000
56.30	0.5473	0.1773	0.1776	0.0000
56.30	0.8246	0.2717	0.2500	0.0000
56.30	1.6782	0.4187	0.3539	0.0000
56.30	2.3584	0.5388	0.3927	0.0000
56.30	2.6985	0.5901	0.4062	0.0000
56.30	3.0390	0.6269	0.4168	0.0000
44.00	0.4299	0.0687	0.0388	0.0099
44.00	0.5579	0.1079	0.0895	0.0493
44.00	1.0802	0.2214	0.2194	0.1480
44.00	1.4134	0.2618	0.2668	0.1842
44.00	1.7532	0.2990	0.3003	0.2039
44.00	2.3584	0.3967	0.3411	0.2253
44.00	2.7364	0.4421	0.3918	0.2303
44.00	3.0387	0.4658	0.3707	0.2401
30.43	0.8454	0.0687	0.0066	0.0000
30.43	1.2631	0.1026	0.0635	0.0174
30.43	1.5262	0.1316	0.0924	0.0411
30.43	2.3584	0.1964	0.1536	0.0681
30.43	2.9406	0.2339	0.1803	0.0839
30.43	3.5426	0.2562	0.1997	0.0872
30.43	5.4570	0.2671	0.2322	0.0855
42.11	0.5365	0.0905	0.0480	0.0000
42.11	0.7819	0.1490	0.1138	0.0000
42.11	1.0592	0.1829	0.1664	0.0000
42.11	1.9048	0.2980	0.2579	0.0000
42.11	1.9427	0.3082	0.2602	0.0000
42.11	2.3584	0.3411	0.2852	0.0000
42.11	2.6985	0.3987	0.3008	0.0000
62.90	0.2701	0.1233	0.0959	0.0000
62.90	0.3766	0.1730	0.1600	0.1053
62.90	0.5792	0.3187	0.2451	0.1908
62.90	0.8352	0.4362	0.3126	0.2911
62.90	1.3378	0.6046	0.3893	0.3766
62.90	1.6404	0.6934	0.4187	0.4112
62.90	1.6782	0.6993	0.4214	0.4112
62.90	1.9805	0.7776	0.4427	0.4243

Appendix B Numerical Methods

B1 PMSP Steady-State Finders (82)

A steady-state for a PMSP model is defined as that set of values for the integrators at which all the derivatives are zero or insignificantly small. This is equivalent to finding a zero for a set of algebraic equations where the equations define the derivative. The procedure used is to start with an initial guess for the integrator values and to iterate until a steady-state is found.

Let the vector $\underline{x}$ denote the array of integrators and the system of equations defining the derivatives be denoted by $\underline{f}$. The Jacobian matrix J is defined by:

$$J_{ij} = \partial f_i / \partial x_j \qquad \text{B1}$$

Newton's method lies at the heart of the PMSP steady-state algorithms. Each iteration starts from an initial approximation $\underline{x}^{(k)}$ and produces a new solution estiamte $\underline{x}^{(k+1)}$ by the formula:

$$\underline{x}^{(k+1)} = \underline{x}^{(k)} - (\underline{J}^{(k)})^{-1} \underline{f}^{(k)} \qquad \text{B2}$$

If $\underline{J}^{(k)}$ becomes singular the method fails.

This method works well provided that the initial estimate is near to the solution. Some non-linear equation solvers, the 'quasi-Newton methods', attempt to retain the local properties of Newton's method while being more reliable and less computationally demanding. The method due to Broyden (B1) is used by the algorithm STEADY.

Broyden's algorithm calculates a search direction $\underline{p}^{(k)}$ for each iteration as follows:

$$\underline{p}^{(k)} = - (B^{(k)})^{-1} \underline{f}^{(k)} \qquad \text{B3}$$

where $\underline{B}^{(k)}$ is an approximation to the Jacobian. This search direction is used to obtain a new solution estimate by:

$$\underline{x}^{(k+1)} = \underline{x}^{(k)} + t_k \underline{p}^{(k)} \qquad \text{B4}$$

where t_k is a scalar with a value between 0 and 1, chosen to minimise the value of $\underline{f}^{(k+1)}$.

Evaluating the system Jacobian is very expensive computationally. Therefore the matrix $\underline{B}^{(k)}$ is updated by:

$$\underline{B}^{(k+1)} = \underline{B}^{(k)} + (\underline{y}^{(k)} - t_k \underline{p}^{(k)}) \underline{p}^{(k)^T} / t_k \underline{p}^{(k)^T} \underline{p}^{(k)} \qquad \text{B5}$$

where $\underline{y}^{(k)} = \underline{f}^{(k+1)} - \underline{f}^{(k)}$ and $\underline{A}^T$ denotes the transpose of the matrix $\underline{A}$. $\underline{B}^{(k+1)}$ is an approximation to the Jacobian at $\underline{x}^{(k+1)}$.

Inverting large matrics is also very expensive. However, it is possible to avoid inverting $\underline{B}^{(k)}$ at every iteration by instead storing $\underline{H}^{(k)}$, the inverse of $B^{(k)}$ and updating this at each iteration .

Householder's modification (B2) applies the update B5 to $H^{(k)}$ instead of $B^{(k)}$ as follows:

$$\underline{H}^{(k+1)} = \underline{H}^{(k)} - (t_k\underline{P}^{(k)}+H^{(k)}\underline{y}^{(k)}).\ \underline{P}^{(k)}H^{(k)}/\underline{P}^{(k)}H^{(k)}\underline{y}^{(k)} \qquad \text{B6}$$

t_k is obtained by a Fibonacci search. If t_k is 1 as it very often will be as the algorithm converges all iterations result in full Newton steps so that the Fibonacci procedure is no longer required .

The full procedure used by STEADY is as follows. An initial guess for the steady-state solution is supplied by the user.

The initial Jacobian J is then calculated by a finite differencing method. This is used as the matrix $B^{(o)}$, and is inverted by Gaussian elimination to give $H^{(o)}$. Each iteration consists of the calculation of a search direction $\underline{P}^{(k)}$ by B3, the selection of t_k by the Fibonacci search and the calculation of a fresh estimate $H^{(k+1)}$ of the inverse of the system Jacobian.

The algorithm iterates until convergence is achieved. This is achieved in two stages. First, the residual error (the largest derivative) must be less than a threshold value. Once this achieved the error is expected to reduce with each iteration until rounding errors dominate when the limits of machine accuracy have been reached.

For large systems of equations, full matrix operations are very expensive. However most, large sets of equations are 'sparse': that is, each equation involves only a few of the variables, so that the Jacobian matrix contains many zeroes. By storing, and performing operations, only on these non-zero elements considerable economies can be made. This is the principle used by method SPARTAN.

This algorithm uses the same ideas as STEADY except in the storing and updating of the estimated Jacobian matrix. Since the inverse of a sparse matrix is not in general sparse, SPARTAN does not invert this matrix. Instead, the matrix is decomposed into triangular factors which can be used to solve equation B3. The original Jacobian matrix $B^{(o)}$ is decomposed into lower-triangular and upper-triangular factors L and U such that

$$B^{(o)} = L.U \qquad \text{B7}$$

These factors can be used to solve B3 without performing full matrix inversion.

As Broyden's update, B5, would not preserve the sparseness of the Jacobian estimate, another formula for the update is required. A method suggested by Schubert (B3) is used: the formula used is:

$$B^{(k+1)} = B^{(k)} + \sum_{i=1}^{n} \underline{e}_i \underline{e}_i^T (\underline{f}^{(k+1)} - (1-t_k)\underline{f}^{(k)}) \underline{p}_i^{(k)^T} / t_k \underline{p}_i^{(k)^T} \underline{p}_i^{(k)} \qquad \text{B8}$$

where $\underline{e}_i$ is column i of the unit matrix, and the vector $\underline{p}_i^{(k)}$ is obtained from the search direction $\underline{p}^{(k)}$ by setting to zero all the elements of $\underline{p}^{(k)}$ corresponding to zero elements in row i of the Jacobian estimate $B^{(k)}$. This update ensures that $B^{(k+1)}$ has the same sparsity structure as $B^{(k)}$. It also satisfies the equation

$$B^{(k+1)} (\underline{x}^{(k+1)} - \underline{x}^{(k)}) = \underline{f}^{(k+1)} - \underline{f}^{(k)} \qquad \text{B9}$$

which is characteristic of matrices produced by quasi-Newton updating formulae.

In all other respects, except scaling, SPARTAN uses the same procedure as STEADY.

B2 Scaling

The scaling procedure is critical to the success of the solution algorithms. The problem is as follows. When a system of equations is to be solved it is important that the residual errors for each equation should be in some sense comparable: otherwise considerable effort may be wasted on reducing one residual to an unnecessarily low level and failing to produce a balanced solution. The problem is particularly acute if the equations involved use widely disparate units.

When testing for convergence the PMSP algorithms monitor the derivative values divided by the corresponding integrator thus ensuring that a 'converged steady-state' is physically a steady-state, in which each variable is stationary.

SPARTAN uses a double scaling method which divides each of the rows and columns by different scaling factors. This formulates the problem so that each of the inputs in the initial guess, and each of the deriatives is normalised to unity. In theory the Jacobian will be well balanced.

The method used by STEADY is slightly different. The derivatives only are normalised by scaling factors which are a combination of the initial values of the integrators and their derivatives as follows

$$\underline{s} = (1-\mathrm{SSCALE}) \times f + \mathrm{SSCALE}\ \underline{x} \qquad \mathrm{B10}$$

where $\underline{s}$ is the vector of scaling factors and SSCALE is a weighting factor.

B3 Two-Phase Flow Models

Lockhart and Martinelli (77) were the first workers to introduce multipliers of the form

$$\frac{dP_F}{dZ} = \phi_L^2 \text{ or } G \tag{B11}$$

where dP_f/dz is the two-phase frictional pressure gradient and $(dP_f/dz)_L$ and $(dP_f/dz)_G$ are the frictional pressure gradients for the liquid or gas respectively if they are flowing alone in the same tube. The multipliers $\phi^2{}_L$ and ϕ $\phi^2{}_G$ are simply factors defined by Equation 6.28 and are determined empirically.

The squares on the multipliers are arbitrary (ie it was dictated by the graph paper Lockhart and Martinelli had available). As an independent variable with which to correlate the multipliers Lockhart and Martinelli defined the parameter X:

$$X^2 = \frac{dP_F}{dZ}_L \Big/ \frac{dP_F}{dZ}_G \tag{B12}$$

Taking a Blasius-type friction factor relationship, X may be evaluated in terms of the quality x and physical properties. For example, for turbulent flow in smooth tubes

$$f = C_1/Re^{0.2} \tag{B13}$$

which, for the liquid flowing alone in the tube yields

$$F_L = C_1 {\frac{\mu_L}{(1 - x)\ GD}}^{0.2} \tag{B14}$$

where G is the total mass velocity in the tube kg/m²s.

Therefore

$$- {\frac{dP_F}{dz}}_L = \frac{4f_L}{D} \frac{(1-x)^2\ G^2}{2\rho_L} = \frac{2\mu_L^{0.2}\ (1-x)^{1.8}\ G^{1.8}}{D^{1.2}\ \rho_L} \tag{B15}$$

Similarly, for the gas phase flowing alone

$$- {\frac{dp_F}{dZ}}_G = \frac{2\mu_G^{0.2}\ x^{1.8}\ G^{1.8}}{D^{1.8}\ \rho_G} \tag{B16}$$

Dividing B15 by B16 gives

$$X^2 = {\frac{1-x}{x}}^{1.8} \frac{\rho_G}{\rho_L} {\frac{\mu_L}{\mu_G}}^{0.2} \tag{B17}$$

Lockhart and Martinelli presented graphs of Φ_L or Φ_G against X. These are reproduced by Butterworth and Hewitt (22). These graphs were based on air-oil and air-water data at ambient temperatures and pressures.

Martinelli and Nelson (84) extended the Lockhart-Martinelli correlation to apply to steam-water data from atmospheric pressure to the critical pressure. They noted that, at the critical pressure Φ^{2}_{LO} becomes unity and hence

$$\Phi^{2}_{L} = \left(\frac{1}{1 - x}\right)^{2-n} \qquad \text{(B18)}$$

at these conditions. Also, at the critical pressure

$$X^{2} = \left(\frac{1 - x}{x}\right)^{2-n} \qquad \text{(B19)}$$

Eliminating x gives

$$\Phi^{2}_{L} = 1 + (1/X)^{2/(2-n)}{}^{2-n} \qquad \text{(B20)}$$

Martinelli and Nelson took the Lockhart-Martinelli curve to predict atmospheric steam-water data and inserted curves between this curve and the critical pressure curve in order to fit steam-water pressure-drop data at intermediate pressures.

Baroczy (11) correlated the two-phase multipliers using

$$\Lambda = \left(\frac{\rho_G}{\rho_L}\right) \left(\frac{\mu_L}{\mu_G}\right)^{0.2} \qquad \text{(B21)}$$

The two-phase flow multipliers were presented as a function of Λ and quality x for various mass velocities.

Chisholm and Sutherland (26) were able to transform Baroczy's correlation and present it in a much simpler form. They generalised the parameter Λ as

$$\Gamma^2 = \frac{dp_F}{dz}_{GO} \bigg/ \frac{dp_F}{dZ}_{LO} \qquad (B22)$$

The derivation of this model is described by Butterworth and Hewitt (22).

Friedal's correlation is the most recent and was obtained by optimising an equation for Φ^2_{LO} using a large bank of two-phase flow data and does not involve any graphs. The equation is

$$\Phi^2_{LO} = A_1 + A_2 \qquad (B23)$$

Where

$$A_1 = (1 - x)^2 + x^2 \quad \frac{P_L \; f_{GO}}{P_g \; f_{LO}}$$

$$A_2 = \frac{3.24 \; x^{0.78} \; (1-x)^{0.224} \left(\frac{\rho_L}{\rho_G}\right)^{0.91} \left(\frac{\mu_G}{\mu_L}\right)^{0.19} \left(1 - \frac{\mu_G}{\mu_L}\right)^{0.7}}{F_r^{\;0.045} \; W_e^{\;0.035}} \qquad (B24)$$

f_{GO} = single phase Fanning friction factor assuming the total mass flux has the gas-phase physical properties

f_{LO} = single phase Fanning friction factor assuming the total mass flux has the liquid-phase physical properties

F_r is a two-phase Froude number defined by

$$F_r = \frac{\dot{m}^2}{\rho_H^2\, dg} \tag{B25}$$

W_e is a two-phase Weber number defined by

$$W_e = \frac{\dot{m}^2\, d}{\rho_H\, \sigma} \tag{B26}$$

Where σ = surface tension

Returning to the two phase momentum balance

$$-\frac{dp}{dz} = -\,\Phi^2{}_{LO}\quad\frac{dp_F}{dz} \qquad\qquad \frac{)^2}{\rho_L}$$

$$+\; g\sin\theta\;(\varepsilon\rho_G + (1-\varepsilon)\rho_L \tag{B27}$$

If the accelerational term is neglected as being relatively small (22), and the small gravitational term for the gas phase is also ignored, Equation B25 reduces to,

$$-\frac{dp}{dz} = -\phi^2_{LO}\left.\frac{dp_F}{dz}\right._{LO} + g\,(1-\varepsilon)\rho_L \qquad \text{(B28)}$$

Substituting for ϕ^2_{LO} and $\frac{dP_F}{dz}$ gives an integral that must be solved numerically to give the total pressure drop along a tube for a given gas and liquid flow. It cannot be solved analytically for the liquid flow-rate corresponding to a given gas-flow in a pump of known dimensions. Therefore to predict gas-lift performance it is integrated over the length of the pump for a given W_L and W_G to give the total pressure drop along the tube. The value of W_L is adjusted until the predicted pressure drop matches the available head.

B4 An Analysis of the External Settler

$$\frac{d}{dt}(K_{tot} + \Phi_{tot}) = -\Delta\left[(\tfrac{1}{2}(\bar{V}^3/\bar{V}) + \Phi + P/\rho)w\right] - W - E_v \qquad \text{(B.28)}$$

where W = the work done by the system on the surroundings

E_v = frictional energy loss per unit mass

w = rate of liquid entry or exit to the system.

No liquid enters or leaves the system so that

$$w_1 = w_2 = 0$$

The energy balance equation 7.1 reduces to

$$\frac{d}{dt}\,(K_{tot} + \Phi_{tot}) = -W - E_v \qquad (B.29)$$

Assuming a parabolic velocity profile

$$v\,(r,_1 t) = 2 \quad v \quad \left[1 - (r/R)^2\right] \qquad (B.30)$$

v is a function of time and is assumed to be positive when liquid flows from left to right.

The rate of change of kinetic energy is given by:

$$\frac{d}{dt}\,(K_{tot}) = \frac{d}{dt} \int_o^L \int_o^K \tfrac{1}{2}\,\rho v^2 . \quad 2\Pi r dr dl \qquad (B.31)$$

$$= \Pi \rho L R^2 \frac{d}{dt} \int_o^1 v^2 \,\frac{r}{R}\; d\frac{r}{R}$$

$$= 4\Pi \rho L R^2 \int_o^1 (1 - \xi^2)\; \xi \; d\; \xi \; \frac{d}{dt} \; v^{\;2} \qquad (B.32)$$

$$= \frac{4}{3}\,\rho\; LS \quad v \; \frac{d}{dt} \; v \qquad (B.33)$$

The rate of change of potential energy is given by

$$\frac{d}{dt}\Phi_{tot} = \frac{d}{dt}\int_0^L \int_0^R \rho g\ z\ 2\Pi r dr dl \qquad (B.34)$$

$$= \frac{d}{dt}\begin{bmatrix}\text{integral over portion}\\ \text{below Z = 0 which}\\ \text{is constant}\end{bmatrix} + \rho g S\int_0^{k+H-h} ZdZ$$

$$+ \rho g S\int_0^{K+H+h} ZdZ \qquad (B.35)$$

$$= 2\rho g\ Sh\ \frac{dh}{dt}$$

$$= 2\rho g\ Sh\ \ v \qquad (B.36)$$

The net work done by the system on the surroundings is

$$-W = (P_a - P_b)\ S\ \ v \qquad (B.37)$$

the friction loss per unit mass of liquid is

$$E_v = -\int_0^L \int_0^R (\tau\colon \nabla v)\ 2\Pi r dr dl \qquad (B.38)$$

$$= 2\Pi L\mu \int_0^R \left(\frac{dv_Z}{dt}\right)^2 rdr$$

$$= 8 \Pi L \mu \; v^{\;2} \int_{o}^{1} (-2\;\xi)^2 \;\xi\; d\xi$$

$$= 8 \Pi L \mu \; v^{\;2}$$

$$= 8 L S \mu \; v^{\;2} / R^2 \qquad \text{(B.39)}$$

Substituting back into the energy balance, and noting that v = dh/dt, gives

$$d^2h/dt^2 + (6\mu/R^2\rho)\; dh/dt + 2(3g/4L)h$$

$$= 3/4\; ((p_a - p_b)/\rho L) \qquad \text{(B.40)}$$

at $t = 0$, $h = 0$, $dh/dt = 0$

Let $k = 2h - (p_a - p_b)/\rho g$

Substituting K into equation 7.12 converts it into a homogeneous differential equation of the following form:

$$d^2K/dt^2 + (6\mu/R^2\rho)\; dk/dt + (3g/2L)k = 0 \qquad \text{(B.41)}$$

This is a second order differential equation with a possible solution $k = e^{mt}$

where

$$m \pm = \tfrac{1}{2}\; [-(6\mu/R^2\rho) \pm \surd((6\mu/R^2\rho)^2 - (6g/L))]$$

$$(B.42)$$

There are two solutions

$$k = C_+ e^{m_+ t} + C_- e^{m_- t} \qquad m_+ \neq m_- \qquad (B.43)$$

$$k = C_1 e^{mt} + C_2 t e^{mt} \qquad m_+ = m_- = m \qquad (B.44)$$

(a) If $(6\mu/R^2\rho)^2 \quad (6g/L)$ the system is overdamped

(b) If $(6\mu/R^2\rho)^2 \quad (6g/L)$ the system is underdamped

(c) If $(6\mu/R^2\rho)^2 = (6g/L)$ the system is critically damped

The tube radius for critical damping is thus

$$R_{cr} = (6\mu^2 L/g\rho^2)^{\frac{1}{4}} \qquad (B.45)$$

References

B1 BROYDEN, C. G., 'A class of methods for solving non-linear simulataneous equations' Maths. Comp <u>19</u> (1965) 577-593.

B2 HOUSEHOLDER, A. S., 'Principles of Numerical Analysis' McGraw-Hill 1953.

B3 SCHUBERT, L. K., 'Modification of a quasi-Newton method for non-linear equations with a sparse Jacobian' Maths. Comp. <u>25</u> (1970) 27-30.

Appendix C Nomenclature

Chapter 3

A	Eqn 3.1 Area		m^2
A	Amplitude		m
B	$0.275 + 0.365\ \varepsilon$		m^2/s
D	Diffusivity		m^2/s
E	Eddy Diffusivity		m/s
H	Height of Transfer Unit		m
K	Overall mass transfer coefficient		m/s
L	Length of Column		m
N	Plate Number		
Pe	Peclet Number	$v d / D_{AB}$	
R	Flow Ratio at Flooding		
S	Plate Spacing		m
Sc	Schmidt Number	$\mu / \rho D_{AB}$	
Sh	Sherwood Number	$k d / D_{AB}$	
V	Eqn 3.1 Volume of Dispersed Phase		m^3
V	Velocity		m/s
a	Specific area		m^2/m^3
d	Diameter		m
d_c	Column diameter		m

f	Frequency	$1/s$
g	Gravitational acceleration	m/s^2
k	Mass transfer coefficient	m/s
n_p	number of stages	
t	time	s
v	droplet volume	m^3
x	organic phase concentration	kg/m^3
x	dispersed phase holdup (fractional)	
y	aqueous phase concentration	kg/m^3
α	backmixing ratio	
β	Plate Parameter $\varepsilon^2/(1 - \varepsilon)(1 - \varepsilon^2)$	
ε	Plate Fractional Free Area	
μ	Viscosity	Ns/m^2
σ	Interfacial Tension	N/M
ρ	Density	kg/m^3
ψ	Energy Dissipation/Unit Mass	J/kg

Subscripts

c	continuous phase
d	dispersed phase or drop
o	orifice
x	organic phase
y	aqueous phase
i	conditions at interface

Chapter 4

A	Area	m^2
C	Feed Concenttration	$kmole/m^3$
E	Backmixing Coefficient	m^2/s
FA	Flowrate of Aqueous Phase	m^3/s
FAB	Backmixing Flow of Aqueous	m^3/s
FAF	Aqueous Feed Rate	m^3/s
FS	Flowrate of Organic Phase	m^3/s
FSB	Backmixing Organic Flow	m^3/s
FSF	Organic Feed Rate	m^3/s
H	Hold-up	

K	Mass transfer coefficient	m/s
M	Rate of mass transfer	kg/s
R	Rate of mass transfer	kmole/s
V	Volume	m^3
W	Molecular weight	kg/kmole
X	Aqueous phase concentration	$kmole/m^3$
Y	Organic phase concentration	$kmole/m^3$
a	Specific area	m^2/m^3
a	Aqueous phase density coefficient	kg/kmole
b	Organic phase density coefficient	kg/kmole

Superscripts

i	relating to component i
f	feed condition

Subscripts

a	aqueous phase
j	relating to cell j
o	organic phase

Chapter 6

C_D	Coefficient of Discharge	
F	Flow Rate	m^3/s

F	Frictional Energy Dissipation/Unit Mass	J/kg
FA	Aqueous Flow Rate	m^3/s
FS	Organic Flowrate	m^3/s
K	Controller Gain	
L	Length of Weir	m
OU	Organic phase Uranium Concentration	$kmole/m^3$
OP	Organic phase Plutonium Concentration	$kmole/m^3$
P	Pressure	N/m^2
T_I	Integral Action Time	s
U	Velocity	m/s
VA	Aqueous Volume	m^3
VS	Organic Volume	m^3
W_s	Mechanical energy input	J/kg
d	Diameter	m
f	Friction factor	
g	Gravitational acceleration	m/s^2

h	Fluid head	m
n_p	Number of plates per metre	1/m
w	Mass flow rate	kg/s
x	Vapour quality	
ε	Fractional free area	
ε	Pipe roughness	
ν	Specific volume	m^3/Kg
ρ	Density	kg/m^3

Subscripts

BC	Base of column
CO	Outlet of plated section
CVF	Constant volume feeder
DIV	Diverter
EC	Entrance to column
EP	Entrance to plated section
H	Homogeneous property
RCY	Recycle stream
TC	Top of Column
g	Property assuming all fluid flow in gas
go	property if gas alone flowed
i	inlet condition
l	property if liquid alone flowed
lo	property assuming all fluid flow is liquid
o	outlet condition

p	Pulse limb
s	Organic phase
t	Trough of CVF
w	Property at a weir

Chapter 7

FAGFE	Loaded aqueous feed to Cycle III-U	m^3/hr
FA8FE	Aqueous strip feed to Column 8	m^3/hr
FSGBC	Organic phase flow from base of Column 7	m^3/hr
FSGFE	Organic phase feed to extract section of Column 7	m^3/hr
FS7TC	Organic phase flow from top of Column 7	m^3/hr
FS8TC	Organic phase flow from top of Column 8	m^3/hr
HA8CL	Aqueous holdup in Column 8	%
SUGCL	Organic phase uranium concentration in extraction section of Column 7	g/litre
SU7CL	Organic phase uranium concentration in scrub section of Column 7	g/litre

SU8CL	Organic phase uranium concentration in Column 8	g/litre
YUGCL	Aqueous phase concentration in uranium in extract section of Column 7	g/litre
YU7CL	Aqueous phase concentration of uranium in scrub section of Column 7	g/litre
YU8CL	Aqueous phase uranium concentration in Column 8	g/litre

Appendix D - Computer Simulation Results

TABLE D1.1 COLUMN RESPONSE TO 10% INCREASE IN FSGFE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME			SUGCL												SU7CL			
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
HOURS					G/LITRE													
0.00	50.599	31.428	13.121	3.715	0.837	0.178	0.038	0.008	0.001				49.628	50.235	50.463	50.554	50.587	50.596
0.05																		
0.10																		
0.15																		
0.20																		
0.25																		
0.30	48.516	28.993	11.656	3.225	0.722	0.154	0.033	0.007	0.001				49.668	50.194	50.304	50.163	49.794	49.214
0.35	47.222	27.265	10.505	2.814	0.621	0.132	0.028	0.006	0.001				49.168	49.383	49.137	48.685	48.159	47.655
0.40	46.546	26.363	9.910	2.600	0.568	0.120	0.026	0.005					47.978	48.047	47.776	47.417	47.074	46.781
0.45	46.188	25.892	9.606	2.493	0.541	0.114	0.024	0.004					46.841	46.991	46.855	46.657	46.470	46.312
0.50	45.998	25.645	9.448	2.438	0.527	0.110	0.023	0.004					46.086	46.345	46.329	46.241	46.146	46.065
0.55	45.896	25.514	9.365	2.409	0.519	0.108	0.022	0.004					45.563	45.989	46.043	46.017	45.974	45.932
0.60	45.841	25.444	9.321	2.394	0.516	0.108	0.022	0.004					45.415	45.796	45.891	45.898	45.881	45.860
0.65	45.813	25.407	9.322	2.385	0.514	0.107	0.022	0.004					45.289	45.694	45.808	45.834	45.832	45.823
0.70	45.798	25.387	9.286	2.381	0.513	0.107	0.022	0.004					45.222	45.639	45.765	45.800	45.805	45.803
0.80	45.784	25.371	9.275	2.378	0.512	0.107	0.022	0.004					45.165	45.594	45.729	45.772	45.784	45.786
0.90	45.782	25.366	9.272	2.377	0.512	0.107	0.022	0.004					45.151	45.579	45.720	45.765	45.779	45.782
1.00	45.779	25.364	9.272	2.376	0.511	0.107	0.022	0.004					45.146	45.577	45.717	45.763	45.777	45.779

TABLE D1.2 COLUMN RESPONSE TO 10% INCREASE IN FSGFE
GAIN = 1.0E-03
RESET = 5.0 HOURS

TIME			YU7CL								YUGCL							
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
HOURS			G/LITRE									G/LITRE						
0.00	4.998	6.908	7.659	7.958	8.076	8.124	23.400	9.758	2.763	0.623	0.133	0.029	0.006	0.001				
0.10	4.998	6.908	7.659	7.959	8.076	8.124	23.400	9.758	2.763	0.623	0.133	0.029	0.006	0.001				
0.20	4.998	6.908	7.659	7.959	8.076	8.124	23.400	9.758	2.763	0.623	0.133	0.029	0.006	0.001				
0.30	5.011	6.902	7.610	7.819	7.772	7.560	22.263	8.829	2.418	0.539	0.115	0.025	0.005	0.001				
0.40	4.572	6.091	6.509	6.535	6.437	6.316	21.168	7.909	2.066	0.449	0.095	0.020	0.004					
0.50	4.109	5.449	5.866	5.971	5.977	5.955	20.876	7.675	1.978	0.428	0.090	0.020	0.004					
0.60	3.955	5.252	5.679	5.814	5.851	5.857	20.795	7.610	1.954	0.422	0.090	0.019	0.004					
0.70	3.911	5.197	5.627	5.770	5.816	5.830	20.772	7.592	1.947	0.420	0.090	0.019	0.004					
0.80	3.898	5.181	5.613	5.758	5.806	5.822	20.765	7.586	1.945	0.419	0.088	0.019	0.004					
0.90	3.895	5.177	5.608	5.754	5.803	5.820	20.763	7.585	1.945	0.419	0.088	0.019	0.004					
1.00	3.894	5.176	5.607	5.753	5.803	5.820	20.763	7.585	1.945	0.419	0.088	0.019	0.004					
			HA7CL								HAGCL							
			%								%							
0.00	4.080	4.080	4.080	4.080	4.080	4.080	19.730	19.330	18.980	18.820	18.780	18.770	18.770	18.760	18.760	18.740	18.710	18.670
0.10	4.080	4.080	4.080	4.080	4.080	4.080	19.730	19.330	18.980	18.820	18.780	18.770	18.770	18.760	18.760	18.740	18.710	18.670
0.20	4.080	4.080	4.080	4.080	4.080	4.080	19.730	19.330	18.980	18.820	18.780	18.770	18.770	18.760	18.760	18.740	18.710	18.670
0.30	4.080	4.080	4.080	4.080	4.080	4.080	19.680	19.280	18.960	18.820	18.790	18.790	18.770	18.770	18.760	18.740	18.710	18.670
0.40	4.070	4.070	4.070	4.070	4.070	4.070	19.640	19.230	18.930	18.810	18.780	18.770	18.770	18.760	18.750	18.740	18.710	18.660
0.50	4.070	4.070	4.070	4.070	4.070	4.070	19.630	19.220	18.920	18.810	18.780	18.770	18.770	18.760	18.750	18.740	18.710	18.660
0.60	4.060	4.060	4.060	4.060	4.060	4.060	19.630	19.210	18.920	18.800	18.770	18.770	18.770	18.760	18.750	18.740	18.710	18.660
0.70	4.060	4.060	4.060	4.060	4.060	4.060	19.630	19.210	18.910	18.800	18.770	18.770	18.770	18.760	18.750	18.740	18.710	18.660
0.80	4.060	4.060	4.060	4.060	4.060	4.060	19.630	19.210										
0.90	4.060	4.060	4.060	4.060	4.060	4.060	19.630	19.210										
1.00	4.06	4.06	4.06	4.06	4.06	4.06	19.63	19.21										

TABLED1.3 COLUMN RESPONSE TO 10% INCREASE IN FSGFE

GAIN = 1.0E-03

RESET TIME = 5.0 HOURS

TIME HOURS	1	2	3	4	5	YUBCL 6 G/LITRE	7	8	9	10	11	12
0.00				0.008	0.107	1.050	5.025	12.865	22.893	34.182	43.606	47.893
0.10				0.008	0.107	1.050	5.025	12.865	22.893	34.182	43.606	47.893
0.20				0.008	0.107	1.050	5.025	12.865	22.893	34.182	43.606	47.893
0.30				0.008	0.108	1.060	5.054	12.914	22.963	34.272	43.633	47.886
0.40				0.010	0.124	1.176	5.363	13.343	23.418	34.679	43.897	47.974
0.50				0.011	0.139	1.278	5.625	13.695	23.785	34.948	43.992	47.824
0.60				0.011	0.156	1.302	5.657	13.684	23.676	34.693	43.621	47.195
0.70				0.012	0.155	1.393	5.934	14.110	24.138	35.060	43.727	46.742
0.80				0.105	0.187	1.622	6.559	15.022	25.173	35.978	44.268	46.619
0.90				0.018	0.231	1.901	7.220	15.881	26.094	36.735	44.711	46.646
1.00				0.022	0.269	2.104	7.633	16.343	26.520	37.014	44.837	46.657
1.10				0.024	0.294	2.226	7.864	16.582	26.704	37.095	44.846	46.631
1.20				0.026	0.318	2.351	8.119	16.883	26.992	37.314	44.975	46.638
1.30				0.029	0.349	2.511	8.453	17.295	27.422	37.678	45.222	46.724
1.40				0.032	0.384	2.673	8.770	17.670	27.815	38.001	45.446	46.846
1.50				0.035	0.413	2.795	8.988	17.910	28.046	38.175	45.567	46.953
1.60				0.037	0.433	2.878	9.131	18.060	28.177	38.268	45.634	47.024
1.70				0.038	0.451	2.953	9.265	18.208	28.317	38.378	45.713	47.079
0.80				0.040	0.470	3.035	9.416	18.385	28.498	38.530	45.822	47.145
1.90				0.042	0.491	3.119	9.570	18.563	28.679	38.682	45.934	47.217
2.00				0.044	0.509	3.190	9.690	18.696	28.810	38.787	46.013	47.283

TABLE D1.4 COLUMN RESPONSE TO 10% INCREASE IN FSGFE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME					SUBCL							
	1	2	3	4	5	6	7	8	9	10	11	12
HOURS					G/LITRE							
0.00												
0.10												
0.20					0.009	0.112	1.096	5.239	13.402	23.826	35.533	45.275
0.30					0.010	0.119	1.150	5.398	13.652	24.121	35.821	45.387
0.40					0.011	0.136	1.262	5.661	13.968	24.412	35.983	45.372
0.50			0.001	0.001	0.012	0.150	1.358	5.906	14.265	24.626	35.959	44.979
0.60			0.001	0.001	0.012	0.150	1.353	5.852	14.105	24.312	35.452	44.318
0.70			0.001	0.001	0.014	0.164	1.451	6.085	14.427	24.581	35.510	44.028
0.80			0.001	0.001	0.017	0.202	1.706	6.742	15.245	25.380	36.007	44.023
0.90	0.001	0.001	0.001	0.001	0.021	0.249	1.983	7.357	15.965	26.030	36.362	44.004
1.00	0.001	0.001	0.001	0.001	0.024	0.282	2.148	1.700	16.270	26.225	36.381	43.880
1.10	0.001	0.001	0.001	0.001	0.027	0.300	2.237	7.816	16.375	26.249	36.314	43.766
1.20	0.002	0.002	0.002	0.002	0.028	0.323	2.343	8.015	16.579	26.416	36.395	43.760
1.30	0.002	0.002	0.002	0.002	0.032	0.355	2.495	8.312	16.090	26.725	36.600	43.832
1.40	0.003	0.003	0.003	0.003	0.035	0.388	2.645	8.589	17.210	26.996	36.766	43.873
1.50	0.003	0.003	0.003	0.003	0.037	0.413	2.747	8.762	17.380	17.130	36.828	43.878
1.60	0.003	0.003	0.003	0.003	0.039	0.429	2.811	8.863	17.470	27.189	36.845	43.871
1.70	0.003	0.003	0.003	0.003	0.041	0.340	2.872	8.966	17.571	27.272	36.892	43.887
1.80	0.003	0.003	0.003	0.003	0.043	0.463	2.947	9.095	17.707	27.396	36.973	43.918
1.90	0.003	0.003	0.003	0.004	0.045	0.482	3.024	9.227	17.848	27.522	37.057	43.950
2.00	0.003	0.003	0.004	0.004	0.046	0.498	3.084	9.326	17.946	27.606	37.104	43.966

TABLE D1.5 COLUMN RESPONSE TO 105 INCREASE IN FSGFE

GAIN = 1.0E-03

RESET TIME = 5.0 HOURS

TIME						HABCL						
	1	2	3	4	5	6	7	8	9	10	11	12
HOURS						%						
0.00	84.510	84.510	84.510	84.510	84.520	84.540	84.630	84.690	84.630	84.520	84.310	84.120
0.10	84.510	84.510	84.510	84.510	84.520	84.540	84.630	84.690	84.630	84.520	84.310	84.120
0.20	84.510	84.510	84.510	84.510	84.520	84.540	84.630	84.690	84.630	84.520	84.310	84.120
0.30	84.510	84.500	84.490	84.460	84.410	84.350	84.310	84.200	83.940	83.630	83.620	82.970
0.40	83.470	83.420	83.390	83.380	83.380	83.420	83.520	83.600	83.560	83.450	83.520	83.090
0.50	83.500	83.510	83.520	83.520	83.530	83.570	83.650	83.710	83.640	83.510	83.300	83.110
0.60	83.510	83.520	83.510	83.510	83.510	83.540	83.640	83.690	83.620	83.510	83.300	83.120
0.70	83.510	83.510	83.510	83.510	83.520	83.600	83.650	83.700	83.630	83.520	83.310	83.140
0.80	83.510	83.510	83.510	83.510	83.520	83.600	83.700	83.700	83.620	83.500	83.310	83.140
0.90	83.510	83.500	83.500	83.500	83.510	83.560	83.660	83.690	83.610	83.480	83.300	83.140
1.00	83.500	83.500	83.500	83.500	83.500	83.560	83.660	83.680	83.610	83.480	83.300	83.140

TABLE D2.1 COLUMN RESPONSE TO 25% INCREASE IN FSGFE
GAIN = 1.0E-06
RESET TIME = 5.0 HOURS

TIME			YU7CL									YUGCL						
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
HOURS			G/LITRE									G/LITRE						
0.00	4.997	6.905	7.656	7.955	8.074	8.121	23.398	9.756	2.762	0.623	0.133	0.029	0.006	0.001				
0.05	4.997	6.905	7.656	7.955	8.074	8.121	23.398	9.756	2.762	0.623	0.133	0.029	0.006	0.001				
0.10	4.997	6.905	7.656	7.955	8.074	8.121	23.398	9.756	2.762	0.623	0.133	0.029	0.006	0.001				
0.15	4.922	6.852	7.447	7.458	7.121	6.567	20.536	7.532	1.961	0.430	0.092	0.020	0.004	0.001				
0.20	4.544	5.896	6.058	5.788	5.404	5.043	19.144	6.497	1.594	0.339	0.071	0.015	0.003					
0.25	3.774	4.765	4.875	4.739	4.565	4.415	18.587	6.107	1.462	0.307	0.064	0.014	0.003					
0.30	3.283	4.149	4.313	4.288	4.228	4.170	18.363	5.954	1.411	0.295	0.061	0.013	0.003					
0.35	3.053	3.879	4.080	4.107	4.093	4.073	18.271	5.892	1.391	0.290	0.060	0.013	0.003					
0.40	2.956	3.768	3.984	4.034	4.039	4.033	18.232	5.866	1.382	0.288	0.060	0.013	0.003					
0.45	2.915	3.722	3.945	4.003	4.016	4.016	18.215	5.855	1.380	0.287	0.060	0.013	0.003					
0.50	2.898	3.703	3.928	3.990	4.006	4.009	18.207	5.850	1.377	0.286	0.060	0.013	0.003					
			SU7CL									SUGCL						
0.00	49.621	50.228	50.458	50.347	50.581	50.593	50.595	31.422	13.116	3.712	0.835	0.177	0.037	0.007				
0.05	49.621	50.228	50.458	50.347	50.581	50.593	50.595	31.422	13.116	3.712	0.835	0.177	0.037	0.007				
0.10	49.621	50.228	50.458	50.347	50.581	50.593	50.595	31.422	13.116	3.712	0.835	0.177	0.037	0.007				
0.15	49.666	50.001	49.813	49.118	48.088	46.636	45.091	25.283	9.564	2.551	0.564	0.120	0.025	0.004				
0.20	47.790	47.295	46.315	45.156	44.020	43.035	42.257	21.923	7.576	1.888	0.405	0.085	0.017	0.003				
0.25	44.462	43.895	43.135	42.419	41.829	41.374	41.038	20.540	6.801	1.638	0.345	0.072	0.015	0.003				
0.30	42.014	41.795	41.441	41.117	40.862	40.669	40.531	19.981	6.500	1.544	0.322	0.067	0.014	0.002				
0.35	40.750	40.800	40.686	40.560	40.455	40.377	40.320	19.752	6.380	1.507	0.314	0.064	0.013	0.002				
0.40	40.189	40.370	40.367	40.327	40.286	40.253	40.229	19.656	6.330	1.491	0.310	0.064	0.013	0.002				
0.45	39.948	40.189	40.232	40.227	40.212	40.198	40.189	19.614	6.308	1.485	0.308	0.063	0.013	0.002				
0.50	39.846	40.110	40.174	40.184	40.181	40.175	40.170	19.595	6.298	1.482	0.308	0.063	0.013	0.002				
			HA7CL %									HAGCL %						
0.00	4.080	4.080	4.080	4.080	4.080	4.080	19.720	19.370	18.980	18.820	18.780	18.770	18.760	18.760	18.750	18.740	18.710	18.660
0.05	4.080	4.080	4.080	4.080	4.080	4.080	19.720	19.370	18.980	18.820	18.780	18.770	18.760	18.760	18.750	18.740	18.710	18.660
0.10	4.080	4.080	4.080	4.080	4.080	4.080	19.720	19.370	18.980	18.820	18.780	18.770	18.760	18.760	18.750	18.740	18.710	18.660
0.15	4.080	4.080	4.080	4.080	4.080	4.080	19.620	19.220	18.930	18.820	18.790	18.790	18.780	18.780	18.760	18.750	18.720	18.660
0.20	4.070	4.070	4.070	4.060	4.060	4.050	19.560	19.150	18.890	18.800	18.780	18.780	18.770	18.770	18.760	18.740	18.710	18.660
0.25	4.060	4.060	4.050	4.050	4.060	4.060	19.530	19.120	18.880	18.800	18.780	18.770	18.770	18.760	18.750	18.730	18.710	18.660
0.30	4.050	4.050	4.050	4.050	4.050	4.050	19.520	19.110	18.870	18.790	18.780	18.770	18.770	18.760	18.750	18.730	18.700	18.660
0.35	4.040	4.040	4.040	4.040	4.040	4.040	19.520	19.110	18.870	18.790	18.780	18.770	18.770	18.760	18.750	18.730	18.700	18.660
0.40	4.040	4.040	4.040	4.040	4.040	4.040	19.510	19.110	18.860	18.780	18.770	18.770	18.760	18.760	18.750	18.730	18.700	18.660
0.45	4.040	4.040	4.040	4.040	4.040	4.040	19.510	19.100	18.860	18.790	18.770	18.770	18.760	18.760	18.750	18.730	18.700	18.660
0.50	4.040	4.040	4.040	4.040	4.040	4.040	19.510	19.100	18.860	18.790	18.770	18.770	18.760	18.760	18.750	18.730	18.700	18.660

TABLE D2.2 COLUMN RESPONSE TO 25% INCREASE IN FSGFE
GAIN = 1.0E-06
RESET TIME = 5.0 HOURS

TIME HOURS	1	2	3	4	5	6	7	8	9	10	11	12
						YUBCL G/LITRE						
0.00				0.009	0.120	1.155	5.311	13.262	23.304	34.536	43.863	48.088
0.05				0.009	0.120	1.155	5.311	13.262	23.304	34.536	43.863	48.088
0.10				0.009	0.120	1.155	5.311	13.262	23.304	34.536	43.863	48.088
0.15				0.009	0.123	1.172	5.363	13.353	23.448	34.719	43.880	48.036
0.20				0.011	0.146	1.320	5.698	13.746	23.812	34.993	44.006	48.045
0.25				0.015	0.184	1.578	6.412	14.826	25.077	36.226	44.920	48.368
0.30				0.020	0.240	1.943	7.352	16.159	26.632	37.616	45.841	48.514
0.35				0.026	0.312	2.350	8.260	17.311	27.882	38.587	46.343	48.305
0.40				0.034	0.399	2.773	9.097	18.290	28.848	39.239	46.569	47.878
0.45				0.044	0.500	3.207	9.885	19.168	29.657	39.741	46.677	47.369
0.50				0.055	0.614	3.640	10.617	19.955	30.351	40.147	46.725	46.860
0.00						SUBCL						
0.05												
0.10					0.010	0.125	1.191	5.488	13.718	24.107	35.714	45.327
0.15					0.012	0.145	1.339	5.892	14.315	24.799	36.359	45.563
0.20			0.001	0.001	0.015	0.171	0.472	6.126	14.522	24.938	36.374	45.506
0.25	0.001	0.001	0.001	0.001	0.018	0.209	0.728	6.789	15.427	25.910	37.043	45.566
0.30	0.002	0.002	0.002	0.002	0.024	0.279	2.147	7.760	16.655	27.134	37.742	45.389
0.35	0.002	0.002	0.002	0.003	0.033	0.364	2.568	8.622	17.615	27.929	37.968	44.892
0.40	0.003	0.003	0.003	0.003	0.042	0.458	2.969	9.329	18.312	28.391	37.928	44.304
0.45	0.003	0.004	0.004	0.004	0.053	0.560	3.357	9.950	18.879	28.719	37.835	43.775
0.50	0.004	0.005	0.005	0.005	0.066	0.671	3.735	10.508	19.364	28.986	37.746	43.335
						HABCL %						
0.00	84.510	84.510	84.510	84.510	84.520	84.550	84.630	84.690	84.630	84.520	84.310	84.130
0.05	84.510	84.510	84.510	84.510	84.520	84.550	84.630	84.690	84.630	84.520	84.310	84.130
0.10	84.510	84.510	84.510	84.510	84.520	84.550	84.630	84.690	84.630	84.520	84.310	84.130
0.15	84.500	84.480	84.430	84.350	84.200	83.970	83.690	83.290	82.730	82.170	81.610	81.230
0.20	83.350	83.000	82.650	82.330	82.070	81.920	81.900	81.890	81.790	81.660	81.450	81.290
0.25	81.870	81.790	81.750	81.750	81.770	81.850	82.000	82.100	82.070	81.990	81.810	81.680
0.30	81.880	81.930	81.970	82.010	82.060	82.150	82.280	82.330	82.260	82.120	81.910	81.760
0.35	82.110	82.120	82.140	82.140	82.150	82.210	82.310	82.320	82.220	82.070	81.860	81.730
0.40	82.130	82.120	82.110	82.110	82.110	82.170	82.270	82.260	81.170	82.030	81.840	81.730
0.45	82.080	82.080	82.070	82.070	82.080	81.160	82.260	82.250	82.160	82.020	81.850	81.740
0.50	82.060	82.060	82.060	82.060	82.080	82.160	82.260	82.240	82.150	82.020	81.850	81.740

TABLE D3.1 COLUMN RESPONSE TO 10% CUT IN FSGFE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME	YU7CL						YUGCL											
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
HOURS	G/LITRE						G/LITRE											
0.00	4.998	6.908	7.659	7.958	8.077	8.124	23.400	9.758	2.763	0.623	0.133	0.029	0.006	0.001				
1.00	4.998	6.908	7.659	7.958	8.077	8.124	23.400	9.758	2.763	0.623	0.133	0.029	0.006	0.001				
1.05	4.982	6.903	7.686	8.056	8.329	8.663	24.612	10.826	3.178	0.725	0.155	0.033	0.007	0.001				
1.10	5.051	7.096	8.060	8.657	9.152	9.627	25.492	11.751	3.594	0.838	0.180	0.039	0.008	0.002				
1.20	5.631	8.128	9.394	10.139	10.642	11.020	26.446	12.852	4.132	0.992	0.215	0.047	0.010	0.002				
1.30	6.156	8.946	10.335	11.068	11.510	11.800	26.963	13.447	4.439	1.084	0.236	0.051	0.011	0.003				
1.40	6.447	9.400	10.840	11.584	11.994	12.238	27.237	13.783	4.617	1.138	0.249	0.054	0.012	0.003				
1.50	6.604	9.645	11.124	11.873	12.268	12.488	27.391	13.975	4.721	1.169	0.257	0.056	0.012	0.003				
1.60	6.691	9.784	11.285	12.037	12.424	12.631	27.479	14.086	4.782	1.188	0.261	0.057	0.013	0.003				
1.70	6.740	9.863	11.378	12.132	12.515	12.713	27.532	14.150	4.817	1.199	0.264	0.057	0.013	0.003				
1.80	6.769	9.909	11.431	12.186	12.567	12.761	27.560	14.187	4.838	1.205	0.265	0.058	0.013	0.003				
	SU7CL						SUGCL											
0.00																		
1.00	49.628	50.235	50.463	50.554	50.587	50.596	50.599	31.428	13.121	3.715	0.837	0.178	0.038	0.008	0.001			
1.05	49.568	50.242	50.561	50.834	51.237	51.865	52.674	34.027	14.786	4.291	0.974	0.207	0.044	0.009	0.002			
1.10	49.842	50.775	51.434	52.074	52.743	53.395	53.976	36.123	16.484	4.983	1.153	0.244	0.053	0.011	0.002			
1.20	51.800	52.984	53.731	54.274	54.699	55.042	55.321	38.456	18.595	5.942	1.420	0.307	0.066	0.014	0.003			
1.30	53.360	54.419	55.004	55.373	55.633	55.830	55.982	39.641	19.742	6.497	1.581	0.344	0.074	0.016	0.003			
1.40	54.159	55.145	55.647	55.937	56.120	56.247	56.340	40.291	20.387	6.820	1.677	0.366	0.079	0.017	0.003			
1.50	54.576	55.528	55.992	56.242	56.387	56.477	56.540	40.655	20.755	7.008	1.734	0.379	0.082	0.017	0.003			
1.60	54.802	55.737	56.185	56.413	56.537	56.608	56.651	40.862	20.968	7.117	1.767	0.387	0.084	0.018	0.003			
1.70	54.930	55.856	56.292	56.508	56.623	56.682	56.715	40.984	21.091	7.181	1.786	0.392	0.085	0.108	0.003			
1.80	55.001	55.923	56.354	56.565	56.673	56.725	56.753	41.053	21.162	7.218	1.797	0.394	0.085	0.018	0.003			

TABLE 3.2 COLUMN RESPONSE TO 10% REDUCTION IN FSGFE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME						SUBCL						
	1	2	3	4	5	6	7	8	9	10	11	12
HOURS						G/LITRE						
0.00					0.009	0.112	1.096	5.239	13.402	23.826	35.533	45.275
1.00					0.009	0.112	1.096	5.239	13.402	23.826	35.533	45.275
1.05					0.008	0.106	1.042	5.075	13.137	23.505	35.212	45.146
1.10					0.008	0.097	0.990	4.969	13.043	23.453	35.217	45.163
1.15					0.007	0.092	0.946	4.831	12.834	23.227	35.041	45.113
1.20					0.007	0.087	0.897	4.676	12.599	22.987	34.872	45.132
1.30					0.006	0.083	0.875	4.635	12.600	23.104	35.176	45.622
1.40					0.006	0.080	0.845	4.549	12.512	23.096	35.357	46.067
1.50					0.005	0.070	0.717	4.104	11.804	22.363	34.865	46.160
1.60					0.004	0.051	0.571	3.565	10.919	21.448	34.210	46.155
1.70					0.003	0.042	0.483	3.232	10.389	20.971	33.967	46.298
2.00					0.002	0.033	0.394	2.878	9.852	20.579	33.922	46.691
						YUBCL						
0.00				0.008			5.025	12.866	22.893	34.182	43.606	47.895
1.00				0.008	0.107	1.050	5.025	12.866	22.893	34.182	43.606	47.895
1.05				0.008	0.106	1.042	4.997	12.817	22.822	34.086	43.573	47.898
1.10				0.007	0.098	0.996	4.884	12.678	22.696	33.991	43.542	47.900
1.15				0.007	0.093	0.943	4.718	12.416	22.395	33.694	43.314	47.793
1.20				0.006	0.087	0.894	4.565	12.173	22.111	33.418	43.121	47.717
1.30				0.006	0.082	0.853	4.474	12.092	22.086	33.503	43.309	48.014
1.40				0.006	0.077	0.816	4.347	11.892	21.893	33.400	43.356	48.423
1.50				0.005	0.042	0.708	3.937	11.150	20.985	32.508	42.778	48.471
1.60				0.004	0.052	0.573	3.422	10.229	19.869	31.404	42.040	48.285
1.70				0.003	0.042	0.475	3.053	9.601	19.166	30.783	41.698	48.257
2.00				0.002	0.030	0.361	2.598	8.815	18.344	30.167	41.455	48.504

TABLE D3.3 COLUMN RESPONSE TO 10% REDUCTION IN FSGFE

GAIN = 1.0E-03

RESET TIME = 5.0 HOURS

TIME	HA7CL %						HA6CL %											
HOURS	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
0.00	4.080	4.080	4.080	4.080	4.080	4.080	19.730	19.330	18.980	18.820	18.780	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.00	4.080	4.080	4.080	4.080	4.080	4.080	19.730	19.330	19.040	18.820	18.780	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.10	4.080	4.080	4.080	4.080	4.080	4.080	19.790	19.420	19.080	18.840	18.780	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.20	4.090	4.090	4.090	4.090	4.090	4.090	19.820	19.470	19.100	18.860	18.790	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.30	4.100	4.100	4.100	4.100	4.100	4.100	19.840	19.500	19.120	18.870	18.790	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.40	4.100	4.100	4.100	4.100	4.100	4.100	19.840	19.510	19.120	18.870	18.790	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.50	4.110	4.110	4.110	4.110	4.110	4.110	19.850	19.520	19.130	18.880	18.790	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.60	4.110	4.110	4.110	4.110	4.110	4.110	19.850	19.520	19.130	18.880	18.800	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.70	4.110	4.110	4.110	4.110	4.110	4.110	19.850	19.530	19.130	18.880	18.800	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.80	4.110	4.110	4.110	4.110	4.110	4.110	19.850	19.530	19.130	18.880	18.800	18.780	18.770	18.770	18.760	18.740	18.720	18.670
1.90	4.110	4.110	4.110	4.110	4.110	4.110	19.850	19.530	19.130	18.880	18.800	18.780	18.770	18.770	18.760	18.740	18.720	18.670
2.00	4.110	4.110	4.110	4.110	4.110	4.110	19.850	19.530	19.130	18.880	18.800	18.780	18.770	18.770	18.760	18.740	18.720	18.670

	HA8CL %									
0.00	84.510	84.510	84.510	84.510	84.520	84.540	84.630	84.520	84.310	84.120
1.00	84.510	84.510	84.510	84.510	85.440	84.540	84.630	84.520	84.310	84.120
1.10	84.900	85.030	85.170	85.310	85.610	85.580	85.750	85.740	85.550	85.350
1.20	85.670	85.660	85.650	85.630	85.540	85.610	85.670	85.560	85.360	85.160
1.30	85.540	85.550	85.540	85.540	85.550	85.570	85.570	85.570	85.650	85.170
1.40	85.550	85.550	85.550	85.550	85.550	85.570	85.630	85.550	85.350	85.150
1.50	85.540	85.540	85.540	85.540	85.550	85.560	85.630	85.560	85.360	85.140
1.60	85.550	85.550	85.550	85.550	85.560	85.570	85.630	85.580	85.370	85.140
1.70	85.560	85.560	85.560	85.560	85.560	85.570	85.630	85.590	85.380	85.130
1.80	85.560	85.560	85.560	85.560	85.560	85.570	85.630	85.580	85.370	85.130
1.90	85.560	85.560	85.560	85.560	85.560	85.570	85.630	85.580	85.370	85.120
2.00	85.560	85.560	85.560	85.560	85.560	85.570	86.620	85.580	85.370	85.120

TABLE4.1 COLUMN RESPONSE TO 10% INCREASE IN FAGFE

GAIN = 1.0E-03

RESET TIME = 5.0 HOURS

TIME			YU7CL									YUGCL						
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
HOURS			G/LITRE									G/LITRE						
0.00	4.998	6.908	7.659	7.958	8.077	8.124	23.400	9.758	2.763	0.623	0.133	0.029	0.006	0.001				
0.25	4.998	6.908	7.659	7.958	8.077	8.124	23.400	9.758	2.763	0.623	0.133	0.029	0.006	0.001				
0.30	5.019	6.918	7.646	7.906	7.965	7.936	23.448	9.827	2.825	0.649	0.141	0.031	0.007	0.002				
0.35	4.975	6.838	7.543	7.821	7.973	8.135	24.112	10.394	3.043	0.703	0.152	0.033	0.007	0.002				
0.40	4.971	6.897	7.730	8.186	8.537	8.881	24.990	11.276	3.422	0.804	0.175	0.038	0.009	0.002				
0.50	5.442	7.764	8.895	9.543	9.983	10.321	26.178	12.540	4.023	0.976	0.215	0.047	0.011	0.002				
0.60	5.979	8.607	9.865	10.525	10.911	11.164	26.737	13.193	4.358	1.076	0.238	0.053	0.012	0.003				
0.80	6.438	9.291	10.663	11.318	11.649	11.826	27.156	13.696	4.625	1.158	0.258	0.057	0.013	0.003				
1.00	6.555	9.497	10.871	11.527	11.845	12.002	27.263	13.831	4.698	1.181	0.263	0.058	0.013	0.003				
			SU7CL									SUGCL						
0.00	49.628	50.235	50.463	50.554	50.587	50.596	50.599	31.428	13.121	3.715	0.837	0.178	0.038	0.008	0.001			
0.25	29.628	50.235	50.463	50.554	50.587	50.596	50.599	31.428	13.121	3.715	0.837	0.178	0.038	0.008	0.002			
0.30	49.702	50.237	50.406	50.406	50.311	50.173	50.078	31.004	13.020	3.742	0.857	0.185	0.040	0.009	0.002			
0.35	49.533	50.040	50.208	50.306	50.475	50.796	51.287	32.423	13.889	4.043	0.931	0.201	0.044	0.009	0.002			
0.40	49.542	50.261	50.720	51.163	51.656	52.193	52.738	34.498	15.418	4.636	1.083	0.235	0.051	0.011	0.002			
0.50	51.191	52.234	52.898	53.402	53.814	54.162	54.452	37.273	17.777	5.669	1.368	0.299	0.065	0.014	0.003			
0.60	52.846	53.800	54.326	54.661	54.902	55.085	55.233	38.618	19.029	6.267	1.543	0.341	0.075	0.016	0.003			
0.80	54.128	54.961	55.359	55.563	55.678	55.749	55.794	39.613	19.997	6.749	1.688	0.375	0.082	0.018	0.003			
1.00	54.440	55.247	55.613	55.790	55.875	55.918	55.940	39.872	20.255	6.881	1.728	0.385	0.084	0.018	0.003			
			HA7CL									HAGCL						
0.00	4.080	4.080	4.080	4.080	4.080	4.080	19.730	19.330	18.980	18.820	18.780	18.770	18.770	18.760	18.740	18.710	18.670	
0.25	4.080	4.080	4.080	4.080	4.080	4.080	19.730	19.330	18.980	18.820	18.780	18.770	18.770	18.760	18.740	18.710	18.670	
0.30	4.080	4.080	4.080	4.080	4.080	4.080	20.880	20.470	20.110	19.950	19.900	19.890	19.890	19.870	19.860	19.820	19.770	
0.35	4.080	4.080	4.080	4.080	4.080	4.080	20.910	20.500	20.120	19.940	19.900	19.890	19.890	19.870	19.860	19.820	19.770	
0.40	4.080	4.080	4.080	4.080	4.080	4.080	20.940	20.550	20.150	19.950	19.900	19.890	19.890	19.870	19.860	19.820	19.770	
0.50	4.090	4.090	4.090	4.090	4.090	4.090	20.980	20.610	20.200	19.970	19.900	19.890	19.890	19.870	19.860	19.830	19.780	
0.60	4.100	4.100	4.100	4.100	4.100	4.100	21.000	20.640	20.220	19.990	19.910	19.890	19.890	19.870	19.860	19.830	19.780	
0.80	4.100	4.100	4.100	4.100	4.100	4.100	21.010	20.660	20.250	20.000	19.910	19.890	19.890	19.870	19.860	19.830	19.790	
1.00	4.100	4.100	4.100	4.100	4.100	4.100	21.020	20.660	20.250	20.000	19.910	19.890	19.890	19.870	19.860	19.830	19.780	

TABLE05.1 RESPONSE TO 10% REDUCTION IN FAGFE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME	YU7CL						YUGCL											
HOURS	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
							G/LITRE											
0.00	5.024	6.950	7.710	8.013	8.134	8.182	23.401	9.744	2.751	0.619	0.132	0.029	0.006	0.001				
1.00	5.024	6.950	7.710	8.013	8.134	8.182	23.401	9.744	2.751	0.619	0.132	0.029	0.004					
1.20	4.894	6.631	7.150	7.177	7.014	6.792	21.077	7.823	2.010	0.430	0.090	0.019	0.003					
1.40	3.988	5.289	5.697	5.807	5.820	5.805	20.229	7.162	1.773	0.372	0.077	0.016	0.003					
1.60	3.832	5.089	5.509	5.648	5.693	5.706	20.144	7.098	1.751	0.367	0.076	0.016	0.003					
1.80	3.816	5.069	5.490	5.632	5.680	5.696	20.135	7.091	1.749	0.366	0.076	0.016	0.003					
2.00	3.814	5.067	5.488	5.630	5.678	5.694	20.134	7.090	1.748	0.366	0.075	0.016	0.003					
	SU7CL						SUGCL											
0.00	49.721	50.330	50.563	50.653	50.687	50.699	50.701	31.497	13.131	3.707	0.834	0.178	0.038	0.008	0.001			
1.00	49.721	50.330	50.563	50.653	50.687	50.699	50.701	31.497	13.131	3.707	0.834	0.178	0.038	0.008				
1.20	49.209	49.442	49.197	48.745	48.221	47.699	47.229	26.934	10.109	2.621	0.564	0.118	0.025	0.005				
1.40	45.558	45.882	45.903	45.841	45.767	45.700	45.644	24.881	8.826	2.187	0.459	0.094	0.020	0.003				
1.60	44.856	45.306	45.444	45.482	45.489	45.487	45.482	24.767	8.701	2.146	0.449	0.092	0.019	0.003				
1.80	44.782	45.246	45.396	45.446	45.460	45.465	45.465	24.654	8.689	2.142	0.448	0.092	0.019	0.003				
2.00	44.775	45.239	45.391	45.441	45.458	45.460	45.463	24.652	8.687	2.141	0.448	0.092	0.019	0.003				
	HA7CL						HAGCL											
0.00	4.080	4.080	4.080	4.080	4.080	4.080	19.840	19.440	19.080	18.920	18.880	18.870	18.860	18.860	18.800	18.830	18.810	18.760
1.00	4.080	4.080	4.080	4.080	4.080	4.080	19.840	19.440	19.080	18.920	18.880	18.870	18.860	18.860	18.850	18.830	18.810	18.760
1.20	4.080	4.080	4.080	4.080	4.070	4.070	18.550	18.160	17.860	17.740	17.720	17.710	17.710	17.700	17.690	17.680	17.650	17.610
1.40	4.060	4.060	4.060	4.060	4.060	4.060	18.520	18.120	17.840	17.730	17.710	17.710	17.700	17.700	17.690	17.680	17.650	17.610
1.60	4.060	4.060	4.060	4.060	4.060	4.060	18.510	18.110	17.830	17.720	17.710	17.710	17.700	17.700	17.690	17.670	17.650	17.610
1.80	4.060	4.060	4.060	4.060	4.060	4.060	18.510	18.110	17.830	17.730	17.710	17.710	17.700	17.700	17.690	17.670	17.650	17.610
2.00	4.060	4.060	4.060	4.060	4.060	4.060	18.510	18.110	17.830	17.730	17.710	17.710	17.700	17.700	17.690	17.670	17.650	17.610

TABLE 5.2 RESPONSE TO 10% REDUCTION IN FAGFE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME HOURS	1	2	3	4	5	6	7	8	9	10	11	12
						SUBCL G/LITRE						
0.00					0.010	0.123	1.177	5.459	13.696	24.112	35.750	45.391
1.00					0.010	0.123	1.177	5.459	13.696	24.112	35.750	45.391
1.20					0.009	0.114	1.114	5.291	13.465	23.867	35.550	45.306
1.40					0.009	0.114	1.114	5.294	13.472	23.869	35.495	45.108
1.60					0.008	0.101	1.004	4.939	12.884	23.115	34.603	44.173
1.80					0.007	0.093	0.932	4.725	12.547	22.680	34.017	43.376
2.00					0.007	0.090	0.907	4.641	12.390	22.433	33.622	42.807
2.20					0.007	0.084	0.853	4.465	12.099	22.073	33.208	42.388
2.40					0.006	0.080	0.826	4.384	11.978	21.932	33.044	42.197
						YUBCL						
0.00				0.009	0.118	1.133	5.258	13.201	23.260	34.527	43.890	48.176
1.00				0.009	0.118	1.133	5.258	13.201	23.260	34.527	43.890	48.176
1.20				0.008	0.111	1.082	5.117	12.996	23.030	34.303	43.742	48.107
1.40				0.008	0.109	1.069	5.089	12.968	23.010	34.286	43.692	47.947
1.60				0.007	0.099	0.983	4.794	12.456	22.337	33.475	42.859	46.936
1.80				0.007	0.090	0.908	4.582	12.148	21.965	33.001	42.235	45.827
2.00				0.006	0.087	0.883	4.507	12.026	21.793	32.723	41.793	45.030
2.20				0.006	0.082	0.834	4.349	11.763	21.458	32.309	41.322	44.399
2.40				0.006	0.078	0.805	4.262	11.634	21.309	32.132	41.100	44.035
						HABCL						
0.00	84.470	84.470	84.470	84.470	84.480	84.500	84.590	84.650	84.590	84.480	84.270	84.080
1.00	84.470	84.470	84.470	84.470	84.480	84.500	84.590	84.650	84.590	84.480	84.270	84.080
1.20	84.840	84.840	84.840	84.840	84.840	84.850	84.930	84.970	84.900	84.780	84.570	84.360
1.40	84.650	84.650	84.650	84.650	84.650	84.650	84.730	84.780	84.720	84.610	84.400	84.210
1.60	84.550	84.550	84.550	84.550	84.550	84.570	84.650	84.710	84.660	84.550	84.350	84.160
1.80	84.510	84.510	84.510	84.510	84.510	84.530	84.610	84.680	84.630	84.520	84.330	84.140
2.00	84.490	84.490	84.490	84.490	84.490	84.510	84.590	84.660	84.620	84.510	84.330	84.130
2.20	84.480	84.480	84.480	84.480	84.480	84.500	84.580	84.660	84.610	84.510	84.320	84.120
2.40	84.480	84.480	84.480	84.480	84.480	84.500	84.580	84.650	84.610	84.510	84.320	84.120

TABLE D6.1 RESPONSE TO 25% INCREASE IN FABFE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME					HABCL							
	1	2	3	4	5	6	7	8	9	10	11	12
HOURS					%							
0.00	84.510	84.510	84.510	84.510	84.520	84.550	84.630	84.690	84.690	84.520	84.310	84.130
0.10	84.510	84.510	84.510	84.510	84.520	84.550	84.630	84.690	84.690	84.520	84.310	84.130
0.15	84.510	84.510	84.510	84.520	84.530	84.560	84.650	84.720	84.720	84.550	84.350	84.160
0.20	84.530	84.540	84.540	84.550	84.550	84.580	84.660	84.720	84.720	84.540	84.340	84.140
0.30	84.530	84.530	84.520	84.520	84.520	84.560	84.620	84.680	84.680	84.520	84.310	84.100
0.40	84.510	84.500	84.500	84.500	84.500	84.520	84.590	84.660	84.660	84.530	84.330	84.070
0.50	84.510	84.510	84.510	84.510	84.510	84.530	84.580	84.660	84.660	84.560	84.370	84.080
					SUBCL							
0.00					0.010	0.120	1.191	5.489	13.719	24.107	35.714	45.327
0.10					0.010	0.120	1.191	5.489	13.719	24.107	35.714	45.327
0.15					0.009	0.123	1.175	5.445	13.659	24.045	35.666	45.308
0.20					0.009	0.112	1.141	5.345	13.510	23.881	35.529	45.241
0.30					0.007	0.092	0.913	4.626	12.386	22.611	34.417	44.715
0.40					0.004	0.051	0.547	3.337	10.215	20.163	32.213	43.704
0.50					0.001	0.025	0.289	2.188	8.019	17.643	29.836	42.512
0.60					0.001	0.015	0.179	1.575	6.644	16.063	28.417	41.859
0.70						0.011	0.138	1.305	6.027	15.399	27.929	41.702
2.00						0.004	0.050	0.571	3.754	12.142	24.835	40.663
					YUBCL							
0.00				0.009	0.121	1.156	5.311	13.262	23.305	34.536	43.863	48.088
0.10				0.009	0.121	1.156	5.311	13.262	23.305	34.536	43.863	48.088
0.15				0.009	0.119	1.142	5.271	13.200	23.235	34.467	43.813	48.062
0.20				0.090	0.115	1.111	5.171	13.034	23.032	34.258	43.644	47.969
0.30				0.007	0.094	0.923	4.524	11.909	21.626	32.763	43.431	47.255
0.40				0.004	0.058	0.595	3.337	9.768	18.915	29.824	40.036	45.627
0.50				0.002	0.029	0.326	2.210	7.544	16.055	26.654	37.406	43.728
0.60				0.001	0.016	0.189	1.522	6.039	14.124	24.547	35.688	42.366
0.70					0.011	0.131	1.187	5.261	13.510	23.574	34.946	41.686
2.00					0.003	0.039	0.442	2.906	9.402	19.263	31.152	38.746

TABLE 6.2 RESPONSE TO 25 % REDUCTION IN FA8FE
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME	GU8CO	FS8TC	ZA8INT
0.00	48.090	0.254	6.602
0.10	48.090	0.254	6.602
0.15	48.060	0.256	6.636
0.20	47.970	0.235	6.659
0.25	47.720	0.213	6.643
0.30	47.250	0.195	6.624
0.35	46.540	1.860	6.607
0.40	45.630	0.187	6.599
0.45	44.650	0.195	6.600
0.50	43.730	0.209	6.608
0.55	42.950	0.220	6.618
0.60	42.370	0.227	6.627
0.65	41.970	0.227	6.632
0.70	41.690	0.224	6.632
0.75	41.450	0.217	6.628
0.80	41.220	0.210	6.622
0.85	40.940	0.206	6.617
0.90	40.630	0.205	6.613
0.95	40.300	0.207	6.610
1.00	40.000	0.210	6.620
1.10	39.560	0.219	6.620
0.12	39.360	0.217	6.620
1.30	39.260	0.213	6.620
1.40	39.140	0.210	6.620
1.50	38.980	0.212	6.620
1.60	38.870	0.214	6.620
1.70	38.830	0.214	6.620
1.80	38.810	0.213	6.620
1.90	38.780	0.212	6.620
2.00	38.750	0.213	6.620

TABLED7.1 RESPONSE TO 10% CUT IN FABFE

GAIN = 1.0E-03

RESET TIME = 5.0 HOURS

TIME HOURS	1	2	3	4	5	6	7	8	9	10	11	12
						HABCL %						
0.00	84.510	84.510	84.510	84.510	84.510	84.540	84.630	84.690	84.630	84.520	84.310	84.120
0.25						84.540	84.630	84.690	84.630		84.310	84.120
0.50						84.550	84.640	84.700	84.630		84.320	84.140
0.75						84.570	84.660	84.690	84.610	84.490	84.300	84.160
1.00	84.520	84.520	84.520	84.520	84.520	84.580	84.680	84.690	84.610	84.490	84.310	84.170
1.25	84.510	84.510	84.510	84.510	84.510	84.600	84.690	84.680	84.600	84.480	84.300	84.180
						SUBCL	G/LITRE					
0.00				0.002	0.009	0.112	1.096	5.239	13.402	23.826	35.533	45.275
0.25				0.002	0.009	0.112	1.096	5.239	13.402	23.826	35.533	45.275
0.50				0.002	0.011	0.140	1.319	5.901	14.392	24.933	36.466	45.720
0.75				0.002	0.022	0.258	2.088	7.736	16.697	27.230	38.092	46.381
1.00				0.002	0.031	0.358	2.582	8.676	17.680	28.070	38.580	46.555
1.25				0.003	0.044	0.491	3.153	9.688	18.755	29.036	39.187	46.793
1.50				0.004	0.055	0.593	3.523	10.268	19.320	29.498	39.451	46.888
1.75				0.005	0.066	0.696	3.873	10.801	19.852	29.950	39.727	46.995
2.00				0.006	0.075	0.775	4.120	11.155	20.191	30.226	39.886	47.055
2.50				0.007	0.090	0.898	4.484	11.659	20.673	30.616	40.115	47.143
						YUBCL	G/LITRE					
0.00				0.008	0.107	1.050	5.025	12.866	22.893	34.182	43.606	47.895
0.25				0.008	0.107	1.050	5.025	12.866	22.893	34.182	43.606	47.895
0.50				0.009	0.128	1.228	5.617	13.860	24.121	35.460	44.618	48.450
0.75				0.018	0.235	1.967	7.491	16.418	27.015	38.092	46.593	49.832
1.00				0.027	0.340	2.528	8.642	17.768	28.362	39.175	47.412	50.554
1.25				0.040	0.477	3.146	9.807	19.127	29.762	40.339	48.290	51.230
1.50				0.050	0.589	3.578	10.533	19.919	30.521	40.941	48.750	51.627
1.75				0.068	0.702	3.975	11.174	20.623	31.209	41.500	49.173	51.965
2.00				0.076	0.790	4.265	11.618	21.095	31.652	41.852	49.442	52.189
2.50				0.087	0.929	4.691	12.246	21.757	32.275	42.350	49.821	52.496

TABLE D8 HOLDUP IN COLUMN 8 AFTER STARTUP
GAIN = 1.0E-03
RESET TIME = 5.0 HOURS

TIME HOURS					HABCL %							
	1	2	3	4	5	6	7	8	9	10	11	12
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.10	0.999	0.999	0.999	0.999	0.998	0.986	0.943	0.881	0.834	0.809	0.799	0.796
0.20	0.785	0.792	0.802	0.812	0.823	0.832	0.841	0.849	0.856	0.861	0.865	0.866
0.30	0.843	0.844	0.844	0.844	0.845	0.847	0.849	0.850	0.852	0.853	0.853	0.853
0.40	0.836	0.839	0.841	0.841	0.841	0.841	0.842	0.845	0.848	0.851	0.854	0.856
0.50	0.844	0.844	0.845	0.845	0.844	0.843	0.841	0.840	0.841	0.842	0.844	0.846
0.60	0.843	0.844	0.844	0.845	0.846	0.845	0.844	0.842	0.841	0.841	0.841	0.843
0.70	0.845	0.845	0.846	0.847	0.847	0.846	0.845	0.844	0.842	0.841	0.840	0.842
1.00	0.844	0.844	0.845	0.846	0.846	0.846	0.845	0.844	0.843	0.842	0.841	0.840

```
TABLE99.1 EFFECT OF CONTROL PARAMETERS
    GAIN = .1
    RESET TIME = 5.0 HOURS

TIME      ZABINT   FGHAL
    0.00   6.6024 1.54E-04
    0.05   6.6024 1.54E-04
    0.10   6.6027 1.92E-04
    0.15   6.5980 0.00E+00
    0.20   6.5963 0.00E+00
    0.25   6.6032 2.47E+00
    0.30   6.5986 0.00E+00
    0.35   6.6007 0.00E+00
    0.40   6.6045 3.77E+00
    0.45   6.5983 0.00E+00
    0.50   6.6043 3.60E+00
    0.55   6.6044 3.72E+00
    0.60   6.6005 0.00E+00
    0.65   6.6006 0.00E+00
    0.70   6.6027 2.13E+00
    0.75   6.6039 3.26E+00
    0.80   6.6040 3.41E+00
    0.85   6.6036 3.06E+00
    0.90   6.6032 2.72E+00
    0.95   6.6029 2.41E+00
    1.00   6.6023 2.13E+00
    1.05   6.6021 1.90E+00
    1.10   6.6020 1.72E+00
    1.15   6.6019 1.59E+00
    1.20   6.6018 1.51E+00
    1.25   6.6018 1.46E+00
    1.30   6.6018 1.45E+00
    1.35   6.6018 1.47E+00
    1.40   6.6018 1.51E+00
    1.45   6.6018 1.55E+00
    1.50   6.6019 1.61E+00
    1.55   6.6019 1.66E+00
    1.60   6.6019 1.72E+00
    1.65   6.6020 1.77E+00
    1.70   6.6020 1.81E+00
    1.75   6.6020 1.83E+00
    1.80   6.6020 1.85E+00
    1.85   6.6020 1.87E+00
    1.90   6.6020 1.87E+00
    1.95   6.6019 1.87E+00
    2.00   6.6019 1.86E+00
```

```
TABLE D9.2 EFFECT OF CONTROL PARAMETERS
    GAIN = 0.01
    RESET TIME = 5.0 HOURS

TIME      ZAGINT   FGHAL

    0.00   6.6024 1.59E+00
    0.05   6.6022 1.56E+00
    0.10   6.6024 1.58E+00
    0.15   6.6241 3.78E+00
    0.20   6.6035 1.73E+00
    0.25   6.5926 6.40E+00
    0.30
    0.35
    0.40
    0.45
    0.50
    0.55
    0.60
    0.65
    0.70
    0.75
    0.80
    0.85
    0.90
    0.95
    1.00
    1.05
    1.10
    1.15
    1.20
    1.25
    1.30
    1.35
    1.40
    1.45
    1.50
    1.55
    1.60
    1.65
    1.70
    1.75
    1.80
    1.85
    1.90
    1.95
    2.00
```

TABLE D10 LOSS OF ACID CONDITIONS

GAIN = 0.001
RESET TIME = 5.0 HOURS

TIME HOURS	FAGBC M3/HOUR	FSGBC
0.00	0.293	0.395
0.25	0.292	0.398
0.50	0.292	0.403
0.75	0.292	0.409
1.00	0.292	0.416
1.25	0.292	0.421
1.50	0.292	0.427
1.75	0.292	0.432
2.00	0.292	0.437
2.25	0.292	0.442
2.50	0.292	0.447
2.75	0.292	0.451
3.00	0.292	0.455
3.25	0.292	0.458
3.50	0.292	0.462
3.75	0.293	0.466
4.00	0.293	0.469
4.25	0.293	0.471
4.50	0.292	0.475
4.75	0.292	0.477
5.00	0.292	0.480
6.00	0.292	0.489
7.00	0.293	0.502
8.00	0.293	0.507
9.00	0.294	0.507
10.00	0.294	0.507
11.00	0.294	0.507
12.00	0.294	0.507
13.00	0.294	0.434
14.00	0.294	0.422
15.00	0.293	0.419
16.00	0.294	0.418
17.00	0.294	0.418
18.00	0.293	0.417

Appendix-E Program Listings

```
MACRO ZSMTC, ZSMP, FSMTC, FSMEC, FSMEP, FAMBC, FSMBC, OPMTC, ...
      OUMTC, SXMTC, VSMTC, VSM2, VAMBC, ZAMBC, FAM2 =          ...
      COLSM2 (ASMEC, ASMTC, DAMBC, DSMBC, DAMTC, DSMTC, FAMEC,...
      FSMCVF, FSMRCY, FTMBC, LPLCL, NPLCL, PBMPL, PBMTC,       ...
      VPMZ, VSM2Z, VSMTCZ, ZSMOW, ZTPLTE, FSMDIV, ZDATUM, ...
      ZPMBTM, CIRCS, FAMCO, FSMCO, OPMCO, OUMCO, SXMCO, ...
      OUMTCZ, OPMTCZ, SXMTCZ, VSMCOL, VAMBCZ, ASMCOL, ZCMBTM)
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$$   LIST OF VARIABLES
$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$       HEAD = HEAD DIFFERENCE BETWEEN COLUMN AND PULSE LIMB
$       ZSMP = LEVEL ABOVE DATUM OF SOLVENT IN PULSE LIMB
$       ZSMTC = LEVEL ABOVE DATUM OF SOLVENT IN COLUMN
$       GEE    = GRAVITATIONAL ACCELERATION
$       DSMTC   = DENSITY OF SOLVENT IN TOP OF COLUMN
$       PBMPL   = PRESSURE OF AIR IN PULSE LIMB
$       PBMTC   = PRESSURE OF AIR ABOVE COLUMN
$       VC      = VELOCITY
$       EPSLN2  =
$       CDS2    = SQUARE OF DISCHARGE COEFFICIENT
$       DSMBC   = DENSITY OF SOLVENT AT BOTTOM OF COLUMN
$       NPLCL   = NO OF PLATES/UNIT LENGTH OF COLUMN
$       LPLCL   = PLATED LENGTH OF COLUMN
$       FSMEC   = VOLUMETRIC FLOWRATE OF SOLVENT INTO COLUMN
$       ASMEC   = XSA OF SOLVENT ENTRY LINE TO COLUMN
$       FSMTC   = FLOW OF SOLVENT FROM TOP OF COLUMN
$       FSMEC   = FLOW OF SOLVENT ENTERING COLUMN
$       FSMEP   = FLOW OF SOLVENT ENTERING PLATED PORTION OF COLUMN
$       FAMBC   = FLOW OF AQ FROM BOTTOM OF COLUMN
$       FSMBC   = FLOW OF SOLVENT FROM BOTTOM OF COLUMN
$       OPMTC   = CONC OF PLUT IN ORGANIC LEAVING TOP OF COLUMN
$       OUMTC   = CONC OF URANIUM IN ORG LEAVING TOP OF COLUMN
$       SXMTC   = NITRIC ACID IN ORG PHASE AT TOP OF COLUMN
$       VSMTC   = VOL OF ORG PHASE AT TOP OF COLUMN
$       VSM2    = TOTAL VOLUME FLUID IN COLUMN
$       VAMBC   = VOL OF AQ AT BOTTOM OF COLUMN
$       ZAMBC   = HEIGHT ABOVE DATUM OF INTERFACE AT BASE OF COLUMN
$       FAM2    = DELAYED VARIABLE
$       ASMTC   = XSA TOP SEC OF COLUMN
$       DAMBC   = DENSITY OF AQ AT BOTTOM OF COLUMN
$       DSMBC   = DENSITY OF SOLVENT AT BASE OF COLUMN
$       DAMTC   = DENSITY OF AQ PHASE AT TOP OF COLUMN
$       DSMTC   = DENSITY OF ORG AT TOP OF COLUMN
$       FAMEC   = FLOW OF AQ ENTERING COLUMN
$       FSMCVF  = FLOW OF SOLVENT FROM CVF
$       FSMRCY  = FLOW OF ORG FROM THE FLOW DIVERTER

$       FTMBC   = TOTAL FLOW FROM BASE OF COLUMN
$       VPMZ    = VOLUME OF ORG IN PULSE LIMB AT TIME 0
$       VSM2Z   = TOTAL FLUID VOLUME IN COL AT TIME 0
$       VSMTCZ  = TOTAL ORG VOLUME IN TOP OF COL AT TIME 0
$       ZSMOW   = LEVEL OF ORG OVERFLOW WEIR
$       ZTPLTE  = LEVEL OF TOP PLATE
$       FSMDIV  = FLOW OF ORG FROM DIVERTER
$       ZDATUM  = LEVEL OF DATUM
$       ZPMBTM  = LEVEL OF BASER OF PULSE LIMB
$       CIRCS   = CIRCUMFERENCE OF SOLVENT WEIR
$       FAMCO   = AQ FLOW FROM PLATED SECTION OF COLUMN FROM BRADSIM
```

```
$       FSMCO   = ORG FLOW FROM PLATED SECTION OF COLUMN FROM BRADSIM
$       OPMCO   = ORG CONC OF PLUT FROM BRADSIM
$       OUMCO   = ORG CONC OF U FROM BRADSIM
$       SXMCO   = ORG NITRIC FROM BRADSIM
$       OUMTCZ  = ORG U CONC AT T=0
$       OPMTCZ  = ORG PLUT CONC AT T=0
$       SXMTCZ  = ORG NITRIC ACID AT T=0
$       VSMCOL  = VOL OF LIQUID TO FILL COLUMN TO OVERFLOW
$       VAMBCZ  = VOL AQ AT BASE OF COL AT T= 0
$       ASMCOL  = XSA OF MAIN PART OF COL
$       ZCMBTM  = LEVEL OF BASE OF COLUMN

$
$
$     CALCULATE HEAD DIFFERENCE BETWEEN COLUMN AND PULSE LIMB
$
      HEAD = ( ZSMP - ZSMTC ) * GEE * DSMTC + ( PBMPL - PBMTC )
      AHEAD = ABS ( HEAD )
$
$     CALCULATE ABSOLUTE VELOCITY OF FLUID ENTRY TO COLUMN
$     IGNORE ACCELERATIONAL EFFECTS SO THAT VC CAN BE OBTANED
$     EXPLICITLY
$
      VC = DSQRT ( 2.0D0 * AHEAD * EPSLN2 * CDS2 / ...
                ( NPLCL * ( 1 - EPSLN2 ) * DSMBC * LPLCL ) )
$
$     VOLUMETRIC FLOWRATE OF SOLVENT INTO COLUMN = AREA * VELOCITY
$
      FSMEC = ASMEC * VC * 3600.0D0
$
$     CHECK FOR DIRECTION OF FLOW
$
PROCEDURE X = PETROL ( HEAD )
      IF ( HEAD .GT. 0.0D0 ) THEN
$
$         FLOW INTO COLUMN
$
          X = 1.0D0
      ELSE IF ( HEAD .LT. 0.0D0 ) THEN
$
$        FLOW OUT OF COLUMN
$
         X = 0.0D0
      ENDIF
ENDPRO
$
$     CALCULATE THE BEHAVIOUR OF THE BOTTOM SECTION OF THE COLUMN
$     SET AQ OUT = DELAYED AQ OUT FROM PLATED SECTION
$     IF FAMBC > FTMBC THEN COLUMN STARTS TO FILL WITH AQ
$
PROCEDURE FAM2 = LORNA ( FAMCO )
          FAM2 = DELAY ( 5, 0.001, FAMCO )
ENDPRO
PROCEDURE FAMBC = BOTTOM ( FAM2, FTMBC, VAMBC )
        IF ( FTMBC .GE. FAM2 .AND. VAMBC .LE. 0.0D0 ) THEN
$
$                OKAY NORMAL OPERATION NO AQ BUILDUP ALL AQ UP AIRLIFT
$
            FAMBC = FAM2
```

```
        ELSE

$
$              GASLIFT NOT PULLING ENOUGH COLUMN FILLING WITH AQ
$

             FAMBC = FTMBC

        ENDIF
ENDPRO
PROCEDURE FSMBC = BOTTOM ( FAM2, FTMBC, VAMBC, FAMBC )

          IF ( FTMBC .GE. FAM2 .AND. VAMBC .LE. 0.0D0 ) THEN
$
$           OKAY NORMAL OPERATION NO AQ BUILUP
$
               FSMBC = FTMBC - FAMBC

          ELSE

$
$           GASLIFT NOT PULLING ENOUGH COLUMN FILLING WITH AQ
$

               FSMBC = 0.0D0

          ENDIF
ENDPRO
PROCEDURE VAMBCD = DERIVS ( FAMBC, VAMBC, FTMBC, FAM2 )

          IF ( FTMBC .GE. FAM2 .AND. VAMBC .LE. 0.0D0 ) THEN
$
$              OKAY NORMAL OPERATION NO AQ BUILDUP
$
               VAMBCD = 0.0D0

          ELSE

$
$             GASLIFT NOT PULLING ENOUGH COLUMN FILLING WITH AQ OR AQ
$             PRESENT AT BOTTOM OF COLUMN
$

               VAMBCD = FAM2 - FAMBC

          ENDIF
ENDPRO

$
$         CALCULATE THE SOLVENT ENTRY TO THE PLATED SECTION.ASSUME THAT COLUMN
$         BELOW BOTTOM PLATE MUST STAY FULL
$

          FSMEP = FSMEC * X + FAMCO - FAMBC - FSMBC

$
$         CALCULATE FLOW OUT OVER THE SOLVENT WEIR
$
PROCEDURE FSMTC = WEIRS ( ZSMOW, ZSMTC, CIRCS, CDS )
             D = ZSMTC - ZSMOW
```

```
          FSMTC = 0.0D0
          IF ( D .GT. 0.0D0 ) THEN

                FS = CDS * CIRCS * DSQRT ( 2.0 * GEE ) * 2.0D0/3.0D0...
                      * D ** 1.5D0 * 3600.0D0
          ELSE

                FS = 0.0D0

          ENDIF
          FSMTC = FS
ENDPRO
$
$           DEFINE COLUMN DERIVATIVES
$

           VSMD = FSMCO - FSMTC
           VSPD = FSMCVF - FSMEC * X + FSMRCY + FSMDIV
         OUMTCD = FSMCO / VSMTC * ( OUMCO - OUMTC )
         OPMTCD = FSMCO / VSMTC * ( OPMCO - OPMTC )
         SXMTCD = FSMCO / VSMTC * ( SXMCO - SXMTC )
$
$        THIS DERIVATIVE ONLY USED IF ASSUME VOLUME CONSERVED
$        OR TO CHECK THAT ZSMTC>ZTPLTE
$
          VSM2D = FAMEC + FSMEC - FSMBC - FAMBC - FSMTC
$
$         CALL INTEGRATION ALGORITHMS
$
           VSM2 = INTGRL ( VSM2Z , VSM2D  )
           VSMP = INTGRL ( VPMZ  , VSPD   )
          OUMTC = INTGRL ( OUMTCZ, OUMTCD )
          OPMTC = INTGRL ( OPMTCZ, OPMTCD )
          SXMTC = INTGRL ( SXMTCZ, SXMTCD )
          VSMTC = INTGRL ( VSMTCZ, VSMD   )
          VAMBC = INTGRL ( VAMBCZ, VAMBCD )
$
$         CALCULATE HEADS
$
          HSP   = VSMP / ASMEC
          HAMBC = VAMBC / ASMCOL
$
$         CALCULATE LEVELS AT TOP OF VARIOUS LAYERS
$
          ZSMP  = ZPMBTM + HSP
          ZAMBC = ZCMBTM + HAMBC
PROCEDURE ZSMTC = TOPS ( VSM2, ZTPLTE, VSMTC, ASMTC, VSMCOL, ASMCOL )

         IF ( VSM2 .GT. VSMCOL ) THEN

$
$          OKAY
$
              ZSMTC = ( VSM2 - VSMCOL ) / ASMTC + ZTPLTE

         ELSE

$
$             COLUMN RUNNING ONLY PARTIALLY FULL
$
```

```
              ZSMTC = VSM2 / ASMCOL + ZCMBTM

         ENDIF
ENDPRO
ENDMAC
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$$$        MACRO TO PREDICT AIRLIFT PERFORMANCE USING N.N. CLARKS THEORY
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$        FAA     = FLOW OF LIQUID DELIVERED BY GASLIFT PER HOUR
$        ZGIN    = LEVEL OF GAS INJECTION POINT
$        GFF     = MASS FLOW OF GAS TO PUMP
$        Z3      = LEVEL OF LIQUID ABOVE GAS INJECTION
$        ZD      = DELIVERY LEVEL OF PUMP
$        AG1     = XSA OF MAIN PUMP RISER
$        DFS     = DENSITY OF LIQID IN SUBMERGENCE LIMB
$        DFL     = DENSITY OF FLUID PUMPED
$        DIAM    = DIAMEETER OF PUMP RISER
$        PCOL    = PRESSURE ABOVE SUBMERGENCE LIMB
$        PDEL    = PRESSURE ABOVE DELIVERY LIMB
$        VISC    = VISCOSITY OF LIQUID BEING PUMPED
$        ROUGH   = ROUGHNESS OF PIPE
$        KCLARK  = CONSTANT DEPENDENT ON FLOW REGIME IN PUMP
$        CNVIMA  == CONVERGENCE TOLERANCE
$        PGMIN   = GAS PRESSURE MEASURED BEFORE INJECTION

MACRO FAA = CLARK ( ZGIN, GFF, Z3, ZD, AG1, DFS, DFL, DIAM, PCOL,...
                    PDEL, VISC, ROUGH, KCLARK, CNVIMA, PGMIN )
PROCEDURAL

         P0 = PCOL + GEE * DFS * (Z3 - ZGIN )
         P6 = PDEL + GEE *DFL * (ZD - ZGIN )
         WG = FGG / AG1
         WL = WG / 5.0D0
         ZL = ZD - ZGIN

         IF ( FGG .LE. 6.0D-05 ) THEN

              $CHECK FOR LOW GAS FLOW GIVING ZERO LIQUID FLOW

              FAA = 0.0D0

         ELSE IF ( P0 .LE. 0.25D0 * P6 ) THEN

              $ CHECK FOR TOO LOW SUBMERGENCE GIVING ZERO LIQUID FLOW

              FAA = 0.0D0

         ELSE

              $ GET START CONDITION FOR ITERATION

              Y2 = CHEMSA ( DFL, WL, WG, DIAM, P0, PDEL, VISC, ROUGH,...
                            KCLARK, FGG, AG1, PGMIN )

              $ CALC ERROR BETWEEN PREDICTED AND REQUIRED LIFT

              R = Y2 - ZL

              IF ( R .GT. 0.0D0 ) THEN

                  $ OVERPREDICTING LIFT SO USE THIS WL AS LOW POINT FOR SEARCH
                  $ INCREASE LIQUID RATE TILL Y2<ZL FOR SECOND SEARCH BOUND
```

```
              WL1 = WL
                Z = WL / 10.0D0

                 DO 10 , I = 1 , 100

                  WL = WL + Z

                  Y2 = CHEMSA ( DFL, WL, WG, DIAM, PO, PDEL, VISC, ROUGH,...
            .            KCLARK, FGG, AG1, PGMIN )

                  R = Y2 - ZL

                      IF ( R .LE. 0.0D0 ) THEN

                         $ UNDERPREDICTING LIFT SO USE THIS WL AS THE HIGH
                         $ START POINT

                         WL2 = WL
                         GOTO 55

                      END IF

10              CONTINUE

           ELSE IF ( R .LT. 0.0D0 ) THEN

                 $ UNDER PREDICTING SO USE THIS WL AS UPPER BOUND FOR SEARCH

                 WL2 = WL

                   Z = WL / 25.0D0

                 DO 20 J = 1,24

                     $ DECREASE WL TILL Y2)ZL AND SO FIND LOWER SEARCH BOUND

                     WL = WL - Z

                     $ IF WL GOES VERY SMALL PROBLEMS CAN ARISE IN CHEMSA
                     $ CALCULATING THE FRICTION FACTOR ( DIVIDE BY ZERO )

                     Y2 = CHEMSA ( DFL, WL, WG, DIAM, PO, PDEL, VISC,...
                                   ROUGH, KCLARK, FGG, AG1, PGMIN )

                      R = Y2 - ZL

                      IF ( R .GT. 0.0D0 ) THEN

                           $ LOWER BOUND FOUND

                           WL1 = WL

                           GOTO 55

                      END IF
20           CONTINUE

        ENDIF

55   CONTINUE
```

```
$         IF UPPER BOUND ON WL IS TOO SMALL ( FROM KNOWLEDGE OF
$         DESIRED FLOWRATES AND COMMON SENSE ABORT EXECUTION

      IF ( WL2 .LE. 1.0D-03  ) THEN

           FAA = 0.0D0

      ELSE

           CONV = ZL/10000.0D0

           DO 30 , N = 1, 500

$              IF ( N .EQ. 100 ) THEN
$
$              WRITE ( 6, 100 )
$
$              ENDIF
$

$               USE HALVING THE INTERVAL TECHNIQUE TO HOME IN ON SOLUTION

                WL3 = ( WL1 + WL2 ) / 2.0D0
                 Y2 = CHEMSA ( DFL, WL3, WG, DIAM, PO, PDEL, VISC, ...
                             ROUGH, KCLARK, FGG, AG1, PGMIN )

                  R = Y2 - ZL

               TEST = ABS ( R / ZL )

               IF ( TEST .GT. CONV ) THEN

                   IF ( R .GT. 0.0D0 ) THEN
                     WL1 = WL3

                   ELSE

                     WL2 = WL3

                   END IF

              ELSE IF ( TEST .LE. CONV ) THEN

                   WL = WL3

                   GOTO 65

              END IF

   30      CONTINUE

   65   CONTINUE

        FAAS = WL * AG1
        FAA  = FAAS * 3600.0D0

     ENDIF

     ENDIF___

$100  FORMAT ( 1X, 'CONVERGENCE NOT FOUND ')
ENDMAC
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$4$$$$$$$$$$$$$$$$$$$
$$$
$$$        MACRO TO PREDICT THE LIFT OF AN AIRLIFT PUMP
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

MACRO Y2 = CHEMSA ( DA1, WL, WG, DIAM, PO, PDEL, VISC, ROUGH,  ...
                    KCLARK, FGG, AG1, PGMIN )

PROCEDURAL

$
$       CHECK FOR VERY LOW FLOWS. IF SO SET Y2 ARTIFICIALLY LOW TO DRIVE
$            WL UP
%

        IF ( WL .LE. 1.0D-20 ) THEN

           Y2 = 2.0D0

        ELSE

$
$          REYNOLDS NUMBER
$

           RE = DIAM * DA1 * WL / VISC

$
$            FRICTION FACTOR AS IF LIQUID FLOWED ALONE
$

           FF = ( 1.0D0 / (3.60D0 * DLOG10 ( 6.9 / RE + (ROUGH / 3.7 ...
                 * DIAM ) ) ** 1.11 ) ) ) ** 2.0D0 * 2.0D0

$
$           FLUID PRESSURE DROP GETTING TO GAS INJECTION POINT
$
           F  = 25.0D0 * WL *WL * DA1

$
$          CORRECTED PRESSURE TO USE IN CALCS
$

           P1 = PO - F

$
$          DRIFT VELOCITY
$

           VV = 0.35 * DSQRT ( GEE * DIAM )

$
$          GAS DENSITY AT INLET POINT ASSUMING PERFECT GAS AT 25 CENTIGRADE
$          GAS ASSUMED TO BE NITRIGEN
$              ___
```

```
          DG = ( 28.0D-03 / 22.4D-03 ) * ( P1 / 1.0D+05 ) * ...
               ( 273.0D0 / 298.0D0 )

$
$         GAS DENSITY AT MEASURE POINT ASSUMING PERFECT GAS AT 25 CENTIGRADE
$         GAS ASSUMED TO BE NITROGEN
$

          DGM = ( 28.0D-03 / 22.4D-03 ) * ( PGMIN / 1.0D+05 ) * ...
                ( 273.0D0 / 298.0D0 )
$
$         MASSFLOW OF GAS INTO PUMP
$

          G   = WG * DGM * AG1
$
$         DENSITY OF GAS AT OUTLET PRESSURE AND TEMPERATURE
$
          DG1 = ( 28.0D-03 /22.4D-03 ) * ( 273.0D0 / 298.0D0 ) * ...
                ( PDEL / 1.0D-05 )
$
$         CONVENIENCE VARIABLE
$
          M   = G * PDEL / ( AG1 * DG1 )
$
$         FRICTIONAL PRESSURE DROP IF LIQUID FLOWED ALONE
$

          DELTAP = 4.0D0 * DA1 * FF * WL * WL / ( 2.0D0 * DIAM )
$
$         CONVENIENCE VARIABLE
$
          W   = DA1 * GEE + DELTAP
          R   = DA1 * GEE * M * 0.2 + DELTAP * M * 2.7
          S   = 1.2 * WL + VV
          X   = ( PDEL - P1 ) / W
          Y   = ( KCLARK * DELTAP * M - DA1 * GEE * M ) / ( W ** 2.0D0 * S )
          Z   = ( R + W * S * PDEL ) / ( R + W * S * P1 )
$
$         DELIVERY HEIGHT OF PUMP
$
          Y2  = Y * DLOG ( Z ) - X

        ENDIF

  ENDMAC
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$4$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$4$$$$$$$
$$$
$$$    SIMULATION PROGRAM OF BOTTOM INTEFACE SEPARATION DEVICE
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$44$$$$$$$$$$$$$$$$$$$
$$$
$$$    ALL FLOWS VOLUMETRIC UNLESS STATED OTHERWISE
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$       FSWS    = ORG FLOW OVER ORG WEIR
$       FAWA    = AQ FLOW OVER AQ WEIR
$       FSWA    = ORG FLOW OVER AQ WEIR
$       HS1     = HEAD OF ORG ON ORG SIDE OF PUMP
$       HS2     = HEAD OF ORG ON AQ SIDE OF PUMP
$       HA1     = HEAD OF AQ ON ORG SIDE OF PUMM
$       HA2     = HEAD OF AQ ON AQ SIDE OF PUMP
$       VA1     = VOL OF AQ ON ORG SIDE OF PUMP
$       VA2     = VOL OF AQ ON AQ SIDE OF PUMP
$       VS1     = VOL OF ORG ON ORG SIDE OF PUMP
$       VS2     = VOL OF ORG ON AQ SIDE F PUMP
$       VA1D    = DERIV OF VA1
$       VA2D    = DERIV OF VA2
$       VS1D    = DERIV OF VS1
$       VS2D    = DERIV OF VS2
$       FAW3    = FLOW OF AQ THROUGH CONNECTING LEG
$       FSW3    = FLOW OF ORG THROUGH CONNECTING LEG
$       DELTZ1  = DELTAP CAUSING FLOW IN CORRECT DIRECTION
$       DELTZ2  = DELTAP CAUSING FLOW IN WRONG DIRECTION
$       CDWA    = DISCHARE COEFFICIENT OF AQ WEIR
$       CDWS    = DISCHARGE COEFF OF ORG WEIR
$       CDO     = DISCHARGE COEFF OF CONNENTING LEG
$       LA      = LEVEL OF AQ WEIR
$       LS      = LEVEL OF ORG WEIR
$       AA      = XSA OF AQ SIDE
$       AS      = XSA OF ORG SIDE
$       FSIN    = FLOW OF ORG TO SETTLER
$       FAIN    = FLOW OF AQ TO SETTLER
$       DA1     = AQ PHASE DENSITY
$       DS1     = ORG PHASE DENSITY
$       VAMCON  = VISCOSITY
$       DEPS1   = DEPTH OF ORG OVER WEIR
$       DEPS2   = DEPTH OF ORG OVER AQ WEIR
$       HA1     = HEAD OF AQ ON ORG SIDE OF DEVICE
$       HA2     = HEAD OF AQ ON AQ SIDE
$       HS1     = HEAD OF ORG ON ORG SIDE
$       HS2     = HEAD OF ORG ON AQ SIDE
$       SPEED1  = VELOCITY OF AQ THRU CONNECTING LINK
$       SPEED2  = VELOCITY OF ORG THRU CONNECTING LINK WHEN INTERFACE
$                 HAS SHIFTED TO WRONG SIDE
$

MACRO FSWS, FAWA, FSWA, HS1, HS2, HA1, HA2, VA1, VA2, VS1, VS2, ...
      VA1D, VA2D, VS1D, VS2D, FAW3, FSW3, DELTZ1, DELTZ2        ...
      = SETTLE ( CDWA, CDWS, CDO, LA, LS, AA, AS, VA1Z, VA2Z,   ...
                 VS1Z, VS2Z, FSIN, FAIN, DA1, DS1, VAMCON )

$
$       SIDE 1 IS THE SOLVENT SIDE OF THE SETTLER
```

```
$
$       CALCULATE FLOW AREA THRU LEG RADIUS = 12.5MM
$

        A0 = PI * 12.5D-03 ** 2.0D0

$
$       PROCEDURE TO CALCULATE THE FLOWS AT VARIOUS PARTS OF THE SETTLER
$

PROCEDURE FAWA, FSWS, FSWA, FSW3, FAW3, = LEG ( HA1, HA2, HS1, HS2, ...
                                             DA1, DS1, A0, CD0,  ...
                                             LA, LS, VAMCON )

         FAWA = 0.0D0
         FSWS = 0.0D0
         FSWA = 0.0D0
         FAW3 = 0.0D0
         FSW3 = 0.0D0

         IF ( HA1 .GT. 0.0D0 ) THEN

$
$             INTERFACE ON THE CORRECT SIDE OF THE SETTLER
$

              FSW3   = 0.0D0
              SPEED1 = IMPL ( 1.0D-03 , 1.0D-05, FOFY )
$              RE     = 25.0D-03 * SPEED1 * DA1 / VAMCON
$              FF     = 0.0396 / ( RE ** 0.25D0 )
              FF     = 0.015
              DELTZ1 = ( HA1 * DA1 + HS1 * DS1 ) - ( HA2 * DA1 ) - ...
                       ( 4.0D0 * FF * ( 5.0D0 / 25.0D-03 ) * SPEED1 ** 2.0D0 )
              ADELZ1 = DABS ( DELTZ1 )
              FOFY   = DSQRT ( 2.0D0 * GEE * ADELZ1 / DA1 )


             IF ( DELTZ1 .GE. 0.0D0 ) THEN

$                 CHECK FOR FLOW DIRECTION
$
$

                 FAW3 = SPEED1 * A0 * CD0 * 3600.0D0

             ELSE

                 FAW3 = ( -1.0D0 ) * SPEED1 * A0 * CD0 * 3600.0D0

             ENDIF

             DEPS1 = ( HS1 + HA1 ) - LS

             IF ( DEPS1 .GT. 0.0D0 ) THEN

                 FSWS = 0.384 * DEPS1 ** 2.0275 * 3600.0D0

             ELSE

                 FSWS = 0.0D0

             END IF
```

```
             IF ( HS2 .GT. 0.0D0 ) THEN

                   DEPS2 = HA2 + HS2 - LA

                   IF ( DEPS2 .GT. 0.0D0 ) THEN

                        FSWA = 0.384 * DEPS2 ** 2.0275 * 3600.0D0

                   ELSE

                        FSWA = 0.0D0

                   END IF

             ELSE IF ( HS2 .LE. 0.0D0 ) THEN

                   DEPA2 = HA2 - LA

                   IF ( DEPA2 .GT. 0.0D0 ) THEN

                        FAWA = 0.384 * DEPA2 ** 2.0275 * 3600.0D0

                   ELSE

                        FAWA = 0.0D0

                   END IF

             END IF

         ELSE IF ( HA1 .LE. 0.0D0 ) THEN

$
$            INTERFACE SHIFTED TO WRONG SIDE OF SETTLER
$

             SPEED2 = IMPL ( 1.0D-03, 1.0D-05, FOFV )

$            RE = 25.0D-03 * SPEED2 * DS1 / VAMCON
$            FF = 0.0396 / ( RE ** 0.25D0 )
             FF = 0.015
         DELTZ2 = HS1 * DS1 - ( HA2 * DA1 + HS2 * DS1 ) - ...
                  ( 4.0D0 * FF * ( 5.0D0 / 25D-03 ) * SPEED2 ** 2.0D0

         ADELZ2 = DABS ( DELTZ2 )
           FOFV = DSQRT ( 2.0D0 * GEE * ADELZ12 / DS1 )

            IF ( DELTZ2 .GT. 0.0D0 ) THEN

                 FSW3 = SPEED2 * A0 * CD0 * 3600.0D0

            ELSE

                 FSW3 = ( -1.0D0 ) * SPEED2 * A0 * CD0 * 3600.0D0

            END IF

            DEPS2 = HA2 + HS2 - LA
```

```
            IF ( DEPS2 .GT. 0.0D0 ) THEN

                 FSWA = 0.384 * DEPS2 ** 2.0275 * 3600.0D0

            ELSE

                 FSWA = 0.0D0

            END IF

            DEPS1 = HS1 - LS

            IF ( DEPS1 .GT. 0.0D0 ) THEN

                 FSWS = 0.384 * DEPS1 ** 2.0275 * 3600.0D0

            ELSE

                 FSWS = 0.0D0

            END IF

       END IF

ENDPRO

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$44$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$$$       DEFINE DERIVATIVE
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

         VA1D = FAIN - FAW3
         VA2D = FAW3 - FAWA
         VS1D = FSIN - FSWS - FSW3
         VS2D = FSW3 - FSWA

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$
$$$$$         CALL INTEGRATION ALGORITHMS
$$$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

          VA1 = INTGRL ( VA1Z , VA1D )
          VA2 = INTGRL ( VA2Z , VA2D )
          VS1 = INTGRL ( VS1Z , VS1D )
          VS2 = INTGRL ( VS2Z , VS2D )

$
$         CALCULATE DEPTHS OF VARIOUS LAYERS
$
          HA1 = VA1 / AS
          HA2 = VA2 / AA
          HS1 = VS1 / AS
          HS2 = VS2 / AA

ENDMAC
```

```
MACRO ZSMTC, ZIM, ZSMP, VAM2D, VSM3D, VSMPD, VAM2, VSM3, VSMP, ...
      FSMTC, FAMTC, FSMEC, FSMEP, FAMEP, OUMTC, OPMTC, SXMTC   ...
      = COLTES ( ASMEC, ASMTC, FAMEC, FSMCVF, FSMRCY, FAMBC,   ...
                 LPLCL, NPLCL, PBMPL, PBMTC, VAM2Z, VSM3Z,     ...
                 VSMPZ, LSM, FSMDIV, ZDATUM, ZPMBTM, CIRCS,    ...
                 FSMCO, FAMCO, ZTPLTE, CDS, OUMCO, OPMCO,      ...
                 JMMCL, DAMCL, DSMCL, HAMCL, FAMEPZ, VAMCOL,   ...
                 FSM2Z, OUMTCZ, OPMTCZ, SXMTCZ, SXMCO, AAMCOL )

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$$$       VARIABLES
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$       AAMCOL  = XSA PLATED PART OF COLUMN
$       ASMEC   = XSA PULSE LIMB OPENING INTO COLUMN
$       ASMTC   = XSA TOP SECTION OF COLUMN
$       CDS     = DISCHARGE COEFFICIENT
$       DAMCL   = AQ DENSITY ARRAY
$       DSMCL   = ORGANIC DENSITY ARRAY
$       FAMBC   = FLOW OF AQ FROM BOTTOM OF COLUMN
$       FAMEC   = TOTAL AQ FEED TO COLUMN
$       FAMEP   = FLOW OF AQ ENTERING PLATED PART OF COLUMN
$       FAMTC   = FLOW OF AQ FROM TOP OF CLUMN
$       FSMCVF  = ORG FLOW FROM CVF
$       FSMDIV  = ORG FLOW FROM DIVERTOR
$       FSMRCY  = ORG FLOW FROM RECYCLE
$       FSMTC   = ORG FLOW OVER TOP WEIR
$       FSMEC   = FLOW OF ORG ENTERING COLUMN
$       FSMEP   = FLOW OF ORG ENTERING PLATED SECTION OF COLUMN
$       HAMCL   = AQ HOLDUP ARRAY
$       JMMCL   = COUNTER FOR NUMBER OF CELLS
$       LSM     = LEVEL OF ORG WEIR
$       LPLCL   = PLATED LENGTH OF COLUMN
$       NPLCL   = NO OF PLATES PER UNIT LENGTH
$       LSMOW   = LEVEL ABOVE DATUM OF TOP WEIR
$       OPMCO   = ORG CONC OF PU AT BRADSIM OUTLET
$       OUMCO   = ORG CONC OF U AT BRADSIM OUTLET
$       OPMTC   = ORG CONC OF PU AT TOP COLUMN EXIT
$       OUMTC   = ORG CONC OF U AT TOP COLUMN EXIT
$       PBMPL   = AIR PRESSURE OVER PULSE LIMB
$       PBMTC   = AIR PRESSURE OVER TOP OF COLUMN
$       VSM3    = VOL OF ORG IN TOP SECTION
$       VAM2    = VOL OF AQ IN COLUMN
$       PAMCL   = STATIC PRESSURE IN CELL
$       PAMCOL  = STATIC HEAD IN COLUMN
$       PSMTOP  = STAIC HEAD OF ORG LAYER IN TOP OF COLUMN
$       PAMTOP  = STATIC HEAD OF AQ LAYER IN TOP OF COLUMN
$       PSMPUL  = STATIC HEAD OF ORG IN PULS LIMB
$       ZIM     = LEVEL ABOVE DATUM OF INTERFACE
$       ZSMTC   = LEVEL OF ORG IN TOP OF COLUMN
$       ZSMP    = LEVEL OF ORG IN PULSE LIMB
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      FIXED I

$
$     CALCULATE LENGTH OF CELL
```

```
$
      LAMCL = LPLCL / JMMCL

$
$     PROCEDURE TO CALCULATE THE HYDROSTATIC PRESSURE BETWEEN THE
$     COLUMN AND PULSE LIMB USING THE INDIVIDUAL CELL VALUES OF
$     DENSITY AND HOLDUP
$
      PROCEDURE PAMCOL , PS,TOP , PAMTOP , PSMPUL = DENSP ( JMMCL , LAMCL,...
                DAMCL , HAMCL , DSMCL , ZIM , ZSMP , ZSMTC , ZTPLTE )

              PAMCOL = 0.0D0

              DO 10 , I = 1 , JMMCL

                    PAMCL = HAMCL (I) * LAMCL * GEE * DAMCL(I)
                    PAMCOL = PAMCOL + PAMCL

   10         CONTINUE

              PSMTOP = ( ZSMTC - ZIM ) * GEE * DSMCL(1)
              PAMTOP = ( ZIM - ZTPLTE ) * GEE * DAMCL(1)
              PSMPUL = ( ZSMP - ZPMBTM ) * GEE * DSMCL(JMMCL)

       ENDPRO

$
$      CALCULATE  HEAD DIFFERENCE BETWEEN COLUMN AND PULSE LIMB
$

       HEAD = PSMPUL - PAMCOL - PSMTOP -PAMTOP + ( PBMPL - PBMTC )
       AHEAD = ABS ( HEAD )

$
$      DYNAMIC RUN SO USE NORMAL METHOD
$      CALCULATE FRICTIONAL PRESSURE DROP OF FLUID AS IT FLOWS THROUGH
$      THE PLATE ORIFICES USING MID RANGE VALUE OF AQUEOUS DENSITY
$

        VC = DSQRT ( 2.0D0 * AHEAD * EPSLN2 * CDS2 / ( NPLCL * ( ...
              1 - EPSLN2 ) * DAMCL ( JMMCL ) * LPLCL ) )

$
$       VOLUMETRIC FLOWRATE OF SOLVENT INTO COLUMN
$

        FSMEC = ASMEC * VC * 3600.0D0

$
$       CHECK FOR DIRECTION OF FLOW
$
        PROCEDURE X = PETROL ( HEAD )

             X = 1.0D0

             IF ( HEAD .GT. 0.0D0 ) THEN

$
$                  NORMAL FLOW INTO COLUMN
$
                   X = 1.0D0
```

```
            ELSE IF ( HEAD .LT. 0.0D0 ) THEN

$
$               FLOW OUT OF COLUMN
$
                X + ( 0.0D0 )

            END IF

        ENDPRO

$
$       SET UP LAGS FOR ASSORTED THINGS TO TRAVERSE PIPES ETC
$

        FSM2 = REALPL ( FSM2Z , 1.0D-01 , FSMCO )
        OUM3 = REALPL ( OUMTCZ , 1.0D-01 , OUMCO )
        OPM3 = REALPL ( OPMTCZ , 1.0D-01 , OPMCO )

$
$       DOES FAMEP FOLLOW FAMBC AS I HAVE HERE ASSUMED ? PROBABLY MUCH
$       MORE COMPLEX
$

        FAMEP = REALPL ( FAMEPZ , 1.0D-01 , FAMBC )
        SXM3  = REALPL ( SXMTCZ , 1.0D-01 , SXMCO )

$
$       CALCULATE FLOW OUT OVER THE SOLVENT EXIT WEIR
$
        PROCEDURE FSMTC , FAMTC = WEIRS ( LSM , ZSMTC , CIRCS , CDS , ZIM )

            IF ( ZIM .LE. LSM ) THEN

                $
                $  NORMAL SITUATION INTERFACE BELOW OFFTAKE PIPE
                $

                 DS = ZSMTC - LSM

                IF ( DS .GT. 0.0D0 ) THEN

                    FSMTC = CDS * CIRCS * DSQRT ( 2.0D0 * GEE ) *  ...
                            2.0D0 / 3.0D0 * DS ** 1.5D0 * 3600.0D0

                    FAMTC = 0.0D0

                ELSE

                    $
                    $  SOLVENT NOT UP TO WEIR - NO FLOW
                    $

                    FSMTC = 0.0D0
                    FAMTC = 0.0D0

                END IF

            ELSE
```

```
                $
                $  INTERFACE ABOVE OFFTAKE.ZSMTC USED INSTEAD OF ZIM TO
                $  ALLOW FOR A GREATER PRESSURE HEAD
                $

                DA = ZSMTC - LSM
                $DS = ZSMTC -ZIM

                FAMTC = CDS * CIRCS * DSQRT ( 2.0D0 * GEE ) * ...
                        2.0D0 / 3.0D0 * DA ** 1.5D0 * 3600.0D0
                FSMTC = 0.0D0

            END IF

        ENDPRO

$
$       SET SOLVENT INTO PLATES EQUAL TO SOLVENT ENTERING COLUMN BUT
$
        FSMEP = FSMEC * X

$
$       DEFINE COLUMN DERIVATIVES
$

        VAM2D = FAMEC + FSMEC - FSM2 - FAMBC - FAMTC
        VSM3D = FSM2 - FSMTC

        VAM2  = INTGRL ( VAM2Z , VAM2D )

        VSM3  = INTGRL ( VSM3Z , VSM3D )

        VSMPD = FSMCVF - FSMEC * X + FSMRCY + FSMDIV

        VSMP  = INTGRL ( VSMPZ , VSMPD )

       OUMTCD = FSMCO / VSM3 * ( OUM3 - OUMTC )
       OPMTCD = FSMCO / VSM3 * ( OPM3 - OPMTC )
       SXMTCD = FSMCO / VSM3 * ( SXM3 - SXMTC )

$
$      CALL INTEGRATION ALGORITHMS
$

       OUMTC  = INTGRL ( OUMTCZ , OUMTCD )
       OPMTC  = INTGRL ( OPMTCZ , OPMTCD )
       SXMTC  = INTGRL ( SXMTCZ , SXMTCD )

$
$      CALCULATE HEADS
$

       HSMP   = VSMP / ASMEC

$
$      CALCULATE LEVELS AT TOP OF VARIOUS LAYERS
$
       ZSMP = ZPMBTM + HSMP
```

```
      PROCEDURE ZIM , ZSMTC = TOPS ( VAM2 , VAMCOL , ASMTC , AAMCOL ,...
                                     ZTPLTE , VSM3 )

             IF ( VAM2 .GT. VAMCOL ) THEN

                 $
                 $  OKAY INTERFACE ABOVE TOP PLATE
                 $ .

                 ZIM = ( VAM2 - VAMCOL ) / ASMTC + ZTPLTE
                 ZSMTC = ZIM + VSM3 / ASMTC

             ELSE

                 $
                 $  INTERFACE DROPPED INTO PLATES
                 $

                 ZIM = VAM2 / AAMCOL + ZDATUM
                 ZSMTC = ZIM + VSM3 / AAMCOL

             END IF

         ENDPRO

ENDMAC
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$$$          MACRO CVFNEW TO SIMULATE THE BEHAVIOUR OF A NEW STYLE CVF
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$$                        VARIABLES
$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$       VT      = VOL OF LIQUID IN TROUGH
$       ZD      = DEPTH OF FLUID IN TROUGH
$       FMO     = VOLUMETRIC DELIVERY RATE FROM DEVICE
$       FMW     = VOLUMETRIC FLOW OVER WEIR
$       QMO     = CONC OF COMPONENT IN OUTLET STREAM
$       QMW     = CONC OF COMPONENT IN WEIR STREAM
$       FMI     = VOLUMETRIC IN FLOW OF LIQUID
$       QMI     = CONC OF COMPONENT IN INLET STREAM
$       ALPHA   = ANGLE IN DEGREES SUBTENDED BY CVF ARM AT CENTRE OF ROTATION
$       LRREV   = RADIUS OF REVOLUTION OF DEVICE
$       LRPPE   = RADIUS OF PIPE MOUTH
$       NREV    = NUMBER OF REVOLUTIONS PER SECOND
$       NTUBES  = NUMBER OF TUBES PER HUB
$       ZT      = TOTAL DISTANCE FROM HUB CENTRE TO BASE OF TROUGH
$       LA      = DIMENSION OF TROUGH
$       LB      = DIMENSION OF TROUGH
$       LW      = LEVEL ABOVE BASE OF TROUGH OF WEIR
$

MACRO  VT , ZD , FMO , FMW , QMO , QMW =                                       ...
       CVFNEW ( FMI , QMI , ALPHA , LRREV , LRPPE , NREV , NTUBES , ZT ,     ...
                LA , LB , LW , VTZ , QTZ )

        AT = LA * LB           $  CALCULATE XSA FEED TROUGH

        ZD = VT / AT           $ CALCULATE DEPTH OF FLUID IN TROUGH

        ZL = ZT - ZD           $ CALCULATE CLEARANCE BETWEEN FLUID SURFACE
                               $ AND CENTRE OF ROTATION

 PROCEDURE FMO , THETA , VO = DEPTH ( ZL , LRREV , ALPHA , NREV , NTUBES )

 $    PROCEDURE CHECKS TO SEE IF THERE IS ENOUGH FLUID IN THE TROUGH TO
 $     GIVE ANY OUTFLOW

       IF ( ZL .GE. LRREV ) THEN

          FMO = 0.0D0

       ELSE

          THRADS = 2.0D0 * DACOS ( ZL / LRREV )   $ CALC SUBMERGENCE ANGLE

          THETA1 = 180.0D0 * THRADS / PI          $ CONVERT ANGLE TO DEGREES

          IF ( THETA1 .GT. ALPHA ) THEN

            THETA = ALPHA

          ELSE
```

```
            THETA = THETA1

         END IF

         VO = ALPHA / 360.0D0 * PI ** 2.0D0 * LRREV * 2.0 * ( LRPPE  ...
              / 2.0D0 ) ** 2.0D0            $ TOTALLY FULL VOLUME OF TUBE

         FMO = ( THETA / ALPHA * VO * NREV * NTUBES ) * 3600.0D0
                $ CALCULATE AVERAGE FLUID DELIVERY M3/HOUR

      END IF

ENDPRO

PROCEDURE FMW = WEIR ( LW , ZD )

$
$      THIS PROCEDURE CALCULATES THE FLOW OVER THE WEIR
$

      IF ( ZD .GT. LW ) THEN

          ZW  = ZD - LW
          FMW = 1.84 * LA * ZW ** 1.5 * 3600.0D0

      ELSE

          FMW = 0.0D0

      END IF

 ENDPRO

          VTD = FMI - FMO - FMW
           VT = INTGRL ( VTZ , VTD )
          QTD = FMI / VT * ( QMI - QT )
           QT = INTGRL ( QTZ , QTD )

          QMW = QT

 ENDMAC
```

4

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$$$     MACRO BUFTNK FOR THE BUFFER TANKS
$$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$$                            VARIABLES
$$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$       VTM     = VOLUME OF LIQUID IN TANK
$       GUMMO   = U CONC IN OUTLET
$       GPMMO   = PU CONC IN OUTLET
$       YZMMO   = SULPHURIC ACID MOLARITY
$       YXMMO   = NITRIC ACID MOLARITY
$       FMMO    = VOLUMETRIC OUTFLOW
$       FMMI1   = INLET FLOWS 1
$       FMMI2   = INLET FLOW 2
$       FMMI3   = INLET FLOW 3
$$

MACRO VTM , GUMMO , GPMMO , YZMMO , YXMMO = BUFTNK ( GUMMI1 , GPMMI1 , ...
      YZMMI1 , YXMMI1 , FMMI1 , FMMO , VTZ , GUMMZ , GPMMZ , YZMMZ , ...
      YXMMZ , GUMMI2 , GPMMI2 , YZMMI2 , YXMMI2 , FMMI2 , FMMI3 , GUMMI3 , ...
      GPMMI3 , YZMMI3 , YXMMI3 )

$
$       CALCULATE TOTAL FLOW IN AND MEAN CONCENTRATIONS ENTERING
$

        FMMI  = FMMI1 + FMMI2 + FMMI3
        GUMMI = ( FMMI1 * GUMMI1 + FMMI2 * GUMMI2 + FMMI3 * GUMMI3 ) / FMMI
        GPMMI = ( FMMI1 * GPMMI1 + FMMI2 * GPMMI2 + FMMI3 * GPMMI3 ) / FMMI
        YZMMI = ( FMMI1 * YZMMI1 + FMMI2 * YZMMI2 + FMMI3 * YZMMI3 ) / FMMI
        YXMMI = ( FMMI1 * YXMMI1 + FMMI2 * YXMMI2 + FMMI3 * YXMMI3 ) / FMMI

$
$       DEFINE DERIVATIVES
$

        VTD   = FMMI - FMMO
        GUMMD = FMMI / VTM * ( GUMMI - GUMMO )
        GPMMD = FMMI / VTM * ( GPMMI - GPMMO )
        YZMMD = FMMI / VTM * ( YZMMI - YZMMO )
        YXMMD = FMMI / VTM * ( YXMMD - YXMMO )

$
$       INTEGRATE
$

        VTM   = INTGRL ( VTZ   , VTD   )
        GUMMO = INTGRL ( GUMMZ , GUMMD )
        GPMMO = INTGRL ( GPMMZ , GPMMD )
        YZMMO = INTGRL ( YZMMZ , YZMMD )
        YXMMO = INTRGL ( YXMMZ , YXMMD )

ENDMAC
```

```
MACRO CJMOUT , ERROR , ERRINT = PICONT ( SIGNAL , SETPNT , GAIN , RESET , ...
                                         CJMSET , CJVECT , ERRZ )

$    CJMOUT = OUTPUT
$       ERROR = ERROR IN SIGNAL
$       ERRINT = INTEGRAL OF ERROR
$       SIGNAL = SIGNAL
$       SETPNT = SET POINT OF CONTROLLER
$       GAIN   = PROPORTIONAL GAIN
$       RESET  = INTEGRAL ACTION TIME
$       CJMSET = START POINT OF OUTPUT SIGNAL
$       CJVECT = SENSE OF CONTROL ACTION

PROCEDURAL
$
$       MACRO FOR PI CONTROLLER
$
        ERROR  = SETPNT - SIGNAL
        ERRINT = INTGRL ( ERRZ , ERROR )
        CJM1   = ( GAIN * ERROR + GAIN /RESET * ERRINT ) * CJVECT + ...
                 CJMSET

$
$       THIS BIT SPECIFIC FOR GASLIFT TO STOP CLARK TRYING TO SOLVE FOR
$       RIDICULOUSLY SMALL GAS-FLOWS .NB - I SHOULD PUT A CHECK IN CLARK TOO ?
$

        IF ( CJM1 .LE. 1.0D-06 ) THEN

           CJMOUT = 1.0D-06

        ELSE

           CJMOUT = CJM1

        ENDIF

ENDMACRO
```

```
LLLLLLLLLL    11111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111    LLLLLLLLLL
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LLLLLLLLLL    11111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111    LLLLLLLLLL


                                           III   L      L       SSSS  L      EEEEE  Y   Y
                                            I    L      L      S      L      E      Y   Y
                                            I    L      L      S      L      E       Y Y
                                            I    L      L       SSS   L      EEEE     Y
                                            I    L      L          S  L      E        Y
                                            I    L      L          S  L      E        Y
                                           III   LLLLL  LLLLL  SSSS   LLLLL  EEEEE    Y


                                 CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE      11
                                 CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE      11
                               CC          YY      YY  CC          LL          EE            1111
                               CC          YY      YY  CC          LL          EE            1111
                               CC            YY  YY    CC          LL          EE              11
                               CC            YY  YY    CC          LL          EE              11
                               CC              YY      CC          LL          EEEEEEEE        11
                               CC              YY      CC          LL          EEEEEEEE        11
                               CC              YY      CC          LL          EE              11
                               CC              YY      CC          LL          EE              11
                               CC              YY      CC          LL          EE              11
                               CC              YY      CC          LL          EE              11
                                 CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE   111111
                                 CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE   111111


                                           PPPPPPPP    MM      MM    SSSSSSSS      ;;;;    44    44
                                           PPPPPPPP    MM      MM    SSSSSSSS      ;;;;    44    44
                                           PP      PP  MMMM  MMMM  SS              ;;;;    44    44
                                           PP      PP  MMMM  MMMM  SS              ;;;;    44    44
                                           PP      PP  MM  MM  MM  SS                      44    44
                                           PP      PP  MM  MM  MM  SS                      44    44
                                           PPPPPPPP    MM      MM    SSSSSS        ;;;;    4444444444
                                           PPPPPPPP    MM      MM    SSSSSS        ;;;;    4444444444
                                           PP          MM      MM          SS      ;;;;          44
                                           PP          MM      MM          SS      ;;;;          44
                                   ....    PP          MM      MM          SS        ;;          44
                                   ....    PP          MM      MM          SS        ;;          44
                                   ....    PP          MM      MM  SSSSSSSS        ;;            44
                                   ....    PP          MM      MM  SSSSSSSS        ;;            44


FILE _DU90:[ILLSLEY.PMSP]CYCLE1.PMS;4 (12313,14,0), LAST REVISED ON 30-JUL-1987 09:15, IS A 35 BLOCK SEQUENTIAL FILE OWNED BY UIC
[DYNAMICS,ILLSLEY].  THE RECORDS ARE VARIABLE LENGTH WITH IMPLIED (CR) CARRIAGE CONTROL.  THE LONGEST RECORD IS 72 BYTES.

JOB CYCLE1 (27) QUEUED TO SYS$PRINT ON 30-JUL-1987 14:43 BY USER ILLSLEY, UIC [DYNAMICS,ILLSLEY], UNDER ACCOUNT    AT PRIORITY 100,
STARTED ON PRINTER _LPA0: ON 30-JUL-1987 14:43 FROM QUEUE SYS$PRINT.

LLLLLLLLLL    11111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111    LLLLLLLLLL
LLLLLLLLLL    111111111111111111111111  DIGITAL EQUIPMENT CORPORATION - VAX/VMS VERSION V4.5  111111111111111111111111    LLLLLLLLLL
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```

```
INITIAL
£
£      COLUMN GEOMETRY CALCULATIONS XSA OF COLUMN TOP SETTLER AND PULSE
£
       AM1TC  = PI/4.0D0 * LM1TC  ** 2.0D0
       AM1COL = PI/4.0D0 * LM1DIA ** 2.0D0
       AM2TC  = PI/4.0D0 * LM2TC  ** 2.0D0
       AM2COL = PI/4.0D0 * LM2DIA ** 2.0D0
       AM1PU  = PI/4.0D0 * DIA1PU ** 2.0D0
       AM2PU  = PI/4.0D0 * DIA2PU ** 2.0D0
       AM1AL  = PI/4.0D0 * LM1AL ** 2.0D0
       AM2AL  = PI/4.0D0 * LM2AL ** 2.0D0
£
£      VOLUME OF COLUMN TO LEVEL OF TOP PLATE
£
       VA2COL = ( ZP2TOP - ZC2BTM ) * AM2COL
       VS1COL = ( ZP1TOP - ZC1BTM ) * AM1COL

       LM1CRC = PI * LM1EXT
       LM2CRC = PI * LM2EXT

       EPSLN2 = EPSLON * EPSLON
       CDS2   = CDS * CDS
NOSORT
£
£      CALCULATE INITIAL VOLUMES FROM LEVELS IF REQUIRED
£

IF ( INITAL .GE. 0.5D0 ) THEN

       VS1TCZ = AM1TC * ( ZS1TCZ - ZP1TOP )
       VS1PZ  = AM1PU * ( ZS1PUZ - ZP1BTM )
       VA22Z  = ( ZA2INZ - ZP2TOP ) * AM2TC + VA2COL
       VS23Z  = AM2TC * ( ZS2TCZ - ZA2INZ )
       VS2PZ  = AM2PU * ( ZS2PUZ - ZP2BTM )

ENDIF

      UPDTE = 0.0D0
£   SET VALUES FOR  IDMP,ICDMP
      IDMP = CIDMP + 0.1
      ICDMP = CICDMP + 0.1
£  SET CONVERGENGE FACTOR FOR USE IN SULPHATE.
      IF ( ( STEADY .GT. 0.5 ) .OR. ( ALINE .GT.0.5 ) ) THEN
        CONV = CONVS
      ELSE
        CONV = CONVD
      ENDIF
SORT
£   CALCULATE CONSTANT FACTOR IN MIAOS CORRELATION FROM PLATE FREE AREA
      FRSQ1 = XMUFRE * XMUFRE
      KMUSI1 = FRSQ1 / ( 1.0D0 - XMUFRE ) / ( 1.0D0 - FRSQ1 )
£   COLUMN GEOMETRY CALCULATIONS , X-SECTIONAL AREA AND CELL VOL.
      AM1XS = 7.853981634D-1 * ( LM1DIA ** 2 )          ££££   PI / 4
      AMAXS = AM1XS
      VMACL = AMAXS * LMALEN / NMACL
      VM1CL = AM1XS * LM1LEN / NM1CL
£  CONSTANT FACTORS FOR INTERFACIAL AREA CALCULATION.
      AA1IFF = 6.0D0 * VM1CL / LA1DIA
```

```
      AAAIFF = 6.0D0 * VMACL / LAADIA
£   COLUMN GEOMETRY CALCULATIONS , X-SECTIONAL AREA AND CELL VOL.
      AM2XS = 7.853981634D-1 * ( LM2DIA ** 2 )        ££££   PI / 4
      VM2CL = AM2XS * LM2LEN / NM2CL
£  CONSTANT FACTOR IN INTERFACIAL AREA CALCULATION.
      AS2IFF = 6.0D0 * VM2CL / LS2DIA
DYNAMIC
        FAAFE = BFAAFE + BFAAFE * STEP(TFAAFE) * SFAAFE
       FSACVF = BFSACV + BFSACV * STEP(TFSACV) * SFSACV
        FA2FE = BFA2FE + BFA2FE * STEP(TFA2FE) * SFA2FE
 NOSORT
      UPDTE = UPDTE + 1.0D0
 SORT
£
£       SOLVENT FLOWS FROM COLUMN 1 TO COLUMN 10
£
       SX2FE = SX1TC
       OU2FE = OU1TC
       OP2FE = OP1TC
£
£       COLUMN 1 MACRO SOLVENT CONTINUOUS
£
£  CALL TO MACRO MACAG4 FOR COLUMN 1E.
     FAACL , HAACLD , YXACLD , YUACLD , YPACLD , ...
     FSACL , SXACLD , SUACLD , SPACLD , ...
     FAACO , YXACO , GUACO , GPACO , FSACO , SXACO , ...
     OUACO , OPACO , DAACL ,DSACL , YZACLD , YZACO = ...
     MACAG4 ( FAATTE , YXAMIE , GUAMIE , GPAMIE , HAACL , YXACL , ...
               YUACL , YPACL , XA1BM , 0.0D0 , FA1BE , 0.0D0 , ...
               0.0D0 , 0.0D0 , 0.0D0 , FSAFE , SXAFE , ...
               OUAFE , OPAFE , SXACL , SUACL , SPACL , XOAINS , ...
               XS1BM , 1.0D0 , 0.0D0 , SX1BE , OU1BE , ...
               OP1BE , OS1BE , NMACL , 30 , AAAIFF , IQ1EQ , ...
               AB1PL , BB1PL , VMACL , AMAXS , TQACL , ...
               HAACLZ , YUACLZ , YPACLZ , YXACLZ , ...
               SUACLZ , SPACLZ , SXACLZ , YZAMIE , ...
               YZACL , 0.0D0 , YZACLZ , RQ1SLC , QAIDEN )
£    CONNECT SCRUB AND EXTRACT PARTS OF COLUMN 1.
£    SOLVENT FROM EXTRACT TO SCRUB,INCLUDING COMPENSATING FOR BACKFLOW
      FSABE = XS1BM * FSACO
      FS1FE = FSACO + FSABE
      SX1FE = SXACO
      OU1FE = OUACO
      OP1FE = OPACO
£    CALCULATE AQUEOUS BACK FLOW ACROSS JOIN
      FA1BE = XA1BM * FA1CO
      FA1GRO = FA1CO + FA1BE
£    AQUEOUS FROM SCRUB TO EXTRACT , AND MIX WITH LOADED FEED.
      FAATTE = FA1GRO + FAAFE
      YXAMIE = ( FA1GRO * YX1CO + FAAFE * YXAFE ) / FAATTE
      GUAMIE = ( FA1GRO * GU1CO + FAAFE * GUAFE ) / FAATTE
      GPAMIE = ( FA1GRO * GP1CO + FAAFE * GPAFE ) / FAATTE
      YZAMIE = ( FA1GRO * YZ1CO + FAAFE * YZAFE ) / FAATTE
£    PROCEDURES FOR COPYING CONCENTRATIONS IN BACK FLOWS.
PROCEDURE YXABE , GUABE , GPABE , DAABE , YZABE = ...
          CONCP1( YXACL , YUACL , YPACL , DAACL ,YZACL )
      YXABE = YXACL(1)
      GUABE = YUACL(1) * MUUAW
      GPABE = YPACL(1) * MPUAW
      DAABE = DAACL(1)
```

```
      YZABE = YZACL(1)
ENDPRO
PROCEDURE SX1BE , OU1BE , OP1BE , DS1BE = ...
          CONCP2( SX1CL , SU1CL , SP1CL , DS1CL )
      JJ = NM1CL + 0.1D0
      SX1BE = SX1CL(JJ)
      OU1BE = SU1CL(JJ) * MUUAW
      OP1BE = SP1CL(JJ) * MPUAW
      DS1BE = DS1CL(JJ)
ENDPRO

£ CALL TO MACRO MACAQ4 FOR COLUMN 1S.
      FA1CL , HA1CLD , YX1CLD , YU1CLD , YP1CLD , ...
      FS1CL , SX1CLD , SU1CLD , SP1CLD , ...
      FA1CO , YX1CO , GU1CO , GP1CO , FS1CO , SX1CO , ...
      OU1CO , OP1CO , DA1CL ,DS1CL , YZ1CLD , YZ1CO = ...
      MACAQ4 ( FA1FE , YX1FE , GU1FE , GP1FE , HA1CL , YX1CL , ...
               YU1CL , YP1CL , XA1BM , 1.0D0 , 0.0D0 , YXABE , ...
               GUABE , GPABE , DAABE , FS1FE , SX1FE , ...
               OU1FE , OP1FE , SX1CL , SU1CL , SP1CL , XOAINS , ...
               XS1BM , 0.0D0 , FSABE , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , NM1CL , 9 , AA1AFF , IQ1EQ , ...
               AB1PL , BB1PL , VM1CL , AM1XS , TQ1CL , ...
               HA1CLZ , YU1CLZ , YP1CLZ , YX1CLZ , ...
               SU1CLZ , SP1CLZ , SX1CLZ , YZ1FE , ...
               YZ1CL , YZABE , YZ1CLZ , RQ1SLC , Q1IDEN )

        FA1FE = FA1FE + FAAFE + FAARCY
£
£  CALL COLUMN MACRO COLSM2
£
   ZS1TC, ZS1PU, FS1TC, FS1EC, FSAFE, FAABC, FSABC, OP1TC,OU1TC,...
   SX1TC, VS1TC, VS12, VA1BC, ZA1BC, FA12 =                       ...
   COLSM2 ( AM1PU, AM1TC, DAACL(30), DSACL(30),DA1CL(1),DS1CL(1),...
            FA1EC, FSACVF, FSARCY, FTABC, LPLC1, NPLC1,           ...
            PB1TP, PB1TC, VS1PZ, VS1TCZ, ZS1wIR, ZP1TOP,          ...
            FSADIV, ZC1BTM, ZP1BTM, LM1CRC, FAACO,FS1CO, OP1CO, ...
            OU1CC, SX1CO, OU1TCZ, OP1TCZ, SX1TCZ, VS1COL, VA1BCZ,...
            AS1COL, ZC1BTM )
£
£    CALL SETTLER MACRO
£
      FAASEP, FSASEP = SVSIM ( FAABC, FSABC )

      FSARCY = DELAY ( 5, 0.1D0, FSASEP )

£
£    DESTINATION OF AQ OVERFLOW DEPENDS ON DIVERTER SETTING
£
PROCEDURE FAARCY, FAAMAL, FAATNK = DIVERT ( ICADIV, FAASEP )

            FAARCY = 0.0D0
            FAAMAL = 0.0D0
            FAATNK = 0.0D0

        IF ( ICADIV .GT. 0.5D0 .AND. ICADIV .LE. 1.5D0 ) THEN
£
£           NORMAL OPERATION AQ TO MALS RECEIPT TANK
£
```

```
          FAAMAL = FAASEP
          FAARCY = 0.0D0
          FAATNK = 0.0D0

      ELSE IF ( ICADIV .GT. 1.5D0 .AND. ICADIV .LE. 2.5D0 ) THEN
£
£         AQUEOUS STREAM RECYCLED TO FEED TANK
£
          FAATNK = DELAY ( 5, 5.0D-03, FAASEP )
          FAARCY = 0.0D0
          FAAMAL = 0.0D0

      ELSE
£
£         AG OVERFLOW RECYCLED TO COLUMN
£
          FAARCY = DELAY ( 5, 5.0D-03, FAASEP )
          FAATNK = 0.0D0
          FAAMAL = 0.0D0

      ENDIF
ENDPRO
£
£   PROCEDURE TO CALCULATE GAS SETTING TO A GAS.LIFT TO ALLOW FOR
£   FSASEP FAILING
£
PROCEDURE FGAAL = CHECK ( FGASET,FSASEP, TSASTP, FSASTP, FSACUT )

    IF ( FSASEP .GE. FSACUT ) THEN
£
£     OKAY
£
      FGAAL = FGASET
      IAFLAG = 0.0D0

    ELSE IF ( FSARCY .LT. FSACUT .AND. TIME .GE. (IAFLAG + ...
              TSASTP )) THEN
£
£     SOLVENT OVERFLOW FAILED STEP UP GAS FLOW BY 2%
£     SET IAFLAG=TIME TO PREVENT MULTIPLE INCREASES
£

      FGAAL = FGASET * ( 1 + FSASTP )
      FGASET = FGAAL
      IAFLAG = TIME

£
£   THIS BIT IS JUST TO COVER THE SITUATION THAT ARISES AT TIME=0.0
£   WHEN TIME = 0.0,IAFLAG=DELT AND FSASEP=0.0D0 WHICH CAUSES A
£   CRASH IN CLARK
£
    ELSE

        FGAAL = FGASET

    ENDIF

ENDPRO
£
£  CALL GASLIFT MACRO
```

```
£
    FTABCT= CLARK (ZGAIN, FGAAL,ZS1TC, ZG1DEL, AM1AL, DSACL(30),...
                   DAACL(30), LM1AL, PB1TC, PP1DEL, VAMCON, ROUGH, ...
                   KCLARK, CNVIMA, PG1IN )


    FTABC = DELAY ( 5, 2.0D-03, FTABCT )

£
£  CALL TO MACRO MACS04 FOR COLUMN 2
£
     FA2CL , HA2CLD , YX2CLD , YU2CLD , YP2CLD , ...
     FS2CL , SX2CLD , SU2CLD , SP2CLD , ...
     FA2CO , YX2CO , GU2CO , GP2CO , FS2CO , ...
     SX2CO , OU2CO , OP2CO , DA2CL , DS2CL, YZ2CLD, YZ2CO    = ...
     MACS04 ( FA2FE , YX2FE , GU2FE , GP2FE , HA2CL , YX2CL , ...
              YU2CL , YP2CL , XA2PM , 0.0D0 , 0.0D0 , 0.0D0 , ...
              0.0D0 , 0.0D0 , 0.0D0 , FS2FE , SX2FE , ...
              OU2FE , OP2FE , SX2CL , SU2CL , SP2CL , XC2INS , ...
              XS2BM , 0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , ...
              0.0D0 , 0.0D0 , NM2CL , 6 , AS2IFF , IQ2EQ , ...
              AB2PL , BB2PL , VM2CL , AM2XS , TQ2CL , HA2CLZ , ...
              YU2CLZ , YP2CLZ , YX2CLZ , SU2CLZ , SP2CLZ , ...
              SX2CLZ ,YZ2FE, YZ2CL, 0.0D0, YZ2CLZ ,...
              RU2FUN , RP2FUN , RX2FAC , Q2IDEN )

 £
 £      COLUMN 2 MACRO AQUEOUS CONTINUOUS, DYNAMIC VERSION
 £
        ZS2TC, ZA2INT, ZS2PU, VA22D, VS23D, VS2PD, VA22, VS23,  ...
        VS2P, FS2TC, FA2TC, FS2EC, FS2FE, FA2FE, OU2TC, OP2TC,   ...
        SX2TC ...
         = COLTES ( AM2PU, AM2TC,                                ...
        FA2FE, FS1TC, FS2RCY, FT2BC, LPLC2, NPLC2,PB2TP,         ...
        PB2TC, VA22Z, VS23Z, VS2PZ, ZS2WIR, FS2DIV, ZC2BTM,      ...
        ZP2BTM, LM2CRC, FS2CO, FA2CO, ZP2TOP, CDS, OU2CO, OP2CO,...
        6, DA2CL, DS2CL, HA2CL, FA2EPZ, VA2COL, FS22Z, OU2TCZ, ...
        OP2TCZ, SX2TCZ, SX2CO, AM2XS )

 £
 £      PI CONTROLLER USED INCORRECTLY
 £
         FG2AL, ERROR2, ERINT2 = PICONT ( ZA2INT, ZA2SET, GAIN2, ...
                                   RESTI2, FG2SET, CJ2SEN, ERR2Z )
          FT2BCT = CLARK ( ZG2IN, FG2AL, ZS2TC, ZG2DEL, AM2AL, ...
                   DA2CL(6), DA2CL(6), LM2AL, PB2TC, PB2DEL, ...
                   VAMCON, ROUGH, KCLARK, CNVIMA, PG2IN )

     FT2BC = DELAY(5,2.0D-03,FT2BCT)

     FA2BC = FT2BC
     FS2BC = 0.0D0

     FA2TC = 0.0D0
     FS2DIV = 0.0D0
     FS2RCY = 0.0D0

 SPACE METHOD=50000
 SPACE PRINT = 150
 SPACE PLOT = 100
```

```
TITLE CYCLE 3 DYNAMIC RUN FIRST ATTEMPT
METHOD WARP2
ABSERR YP1CL(1)=1.0D-6
SPACE HOLD = 20
TIMER PRDEL=0.010D0,FINTIM =0.5000D0,DELT = 0.01,OUTDEL=0.0005
TERMINAL
      IF ( IDMP .GT. 0 ) THEN
        CALL DUMPI ( IDMP )
      ENDIF
      IF ( ICDMP .GT. 0 ) THEN
        CALL DUMPIC ( ICDMP )
      ENDIF
      UPDTE = 0.0D0
£ CONSTANTS IN SLATER CORRELATION AS MODIFIED BY AH 28/08/85.
£ VALUES TO MATCH DESIGN SS.
      STORAGE RQ1SLC(7)
   TABLE RQ1SLC(1-7) = 1.1040 , 0.7416 , 0.02874 , ...
                       0.0 , 0.0 , 0.02874 , ...
                       0.093297
£   OVERWRITE RQ7SLC(1-3) FOR REVISED COEFFS.
   TABLE RQ1SLC(1-3) = 0.75000 , 0.74160 , 0.02000
£££££££££££££££££££££
PRINT UPDTE,OU1CO ,OP1CO ,GUACO ,GPACO ,YZACO
PRINT OP1TC, OU1TC, SX1TC

PRINT  ZS1TC, ZS1PU, FS1TC, FS1FE, FAABC, FSABC, FSARCY, FAASEP,...
FSASEP, FTABC, FSACVF,                                           ...
       FSAFE
PRINT SX2CO, YX2CO,OU2CO,GU2CO
PRINT ZS2TC, ZS2PU, FS2TC, ZA2INT, FS2FE,  ...
      FTABC ,FGAAL
PLOT FS1TC, FS2TC
PLOT ZA2INT
PLOT GP2CO,OP2CO,GP1CO,OP1CO
END
STOP
ENDJOB
```

```
MMMMMMMMMM     22222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222     MMMMMMMMMM
MMMMMMMMMM     2222222222222222222222222 DIGITAL EQUIPMENT CORPORATION - VAX/VMS VERSION V4.5 2222222222222222222222222     MMMMMMMMMM
MMMMMMMMMM     22222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222     MMMMMMMMMM

                                            III   L      L       SSSS  L      EEEEE  Y   Y
                                             I    L      L      S      L      E      Y   Y
                                             I    L      L      S      L      E       Y Y
                                             I    L      L       SSS   L      EEEE     Y
                                             I    L      L          S  L      E        Y
                                             I    L      L          S  L      E        Y
                                            III   LLLLL  LLLLL  SSSS   LLLLL  EEEEE    Y

                                  CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE    222222
                                  CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE    222222
                                CC          YY      YY  CC          LL          EE          22      22
                                CC          YY      YY  CC          LL          EE          22      22
                                CC            YY  YY    CC          LL          EE                  22
                                CC            YY  YY    CC          LL          EE                  22
                                CC              YY      CC          LL          EEEEEEEE          22
                                CC              YY      CC          LL          EEEEEEEE          22
                                CC              YY      CC          LL          EE              22
                                CC              YY      CC          LL          EE              22
                                CC              YY      CC          LL          EE            22
                                CC              YY      CC          LL          EE            22
                                  CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE  2222222222
                                  CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE  2222222222

                                      PPPPPPPP    MM      MM    SSSSSSSS      ;;;;        11        222222
                                      PPPPPPPP    MM      MM    SSSSSSSS      ;;;;        11        222222
                                      PP      PP  MMMM  MMMM  SS              ;;;;      1111      22      22
                                      PP      PP  MMMM  MMMM  SS              ;;;;      1111      22      22
                                      PP      PP  MM  MM  MM  SS                          11              22
                                      PP      PP  MM  MM  MM  SS                          11              22
                                      PPPPPPPP    MM      MM    SSSSSS        ;;;;        11            22
                                      PPPPPPPP    MM      MM    SSSSSS        ;;;;        11            22
                                      PP          MM      MM          SS      ;;;;        11          22
                                      PP          MM      MM          SS      ;;;;        11          22
                              ....    PP          MM      MM          SS        ;;        11        22
                              ....    PP          MM      MM          SS        ;;        11        22
                              ....    PP          MM      MM  SSSSSSSS        ;;        111111    2222222222
                              ....    PP          MM      MM  SSSSSSSS        ;;        111111    2222222222


FILE _DUB0:[ILLSLEY.PMSP]CYCLE2.PMS;12 (1624,14,0), LAST REVISED ON 30-JUL-1987 14:41, IS A 46 BLOCK SEQUENTIAL FILE OWNED BY UIC
[DYNAMICS,ILLSLEY].  THE RECORDS ARE VARIABLE LENGTH WITH IMPLIED (CR) CARRIAGE CONTROL.  THE LONGEST RECORD IS 72 BYTES.

JOB CYCLE2 (26) QUEUED TO SYS$PRINT ON 30-JUL-1987 14:43 BY USER ILLSLEY, UIC [DYNAMICS,ILLSLEY], UNDER ACCOUNT   AT PRIORITY 100,
STARTED ON PRINTER _LPA0: ON 30-JUL-1987 14:44 FROM QUEUE SYS$PRINT.

MMMMMMMMMM     22222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222     MMMMMMMMMM
MMMMMMMMMM     2222222222222222222222222 DIGITAL EQUIPMENT CORPORATION - VAX/VMS VERSION V4.5 2222222222222222222222222     MMMMMMMMMM
MMMMMMMMMM     22222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222     MMMMMMMMMM
```

```
INITIAL
£
£       COLUMN GEOMETRY CALCULATIONS XSA OF COLUMN TOP SETTLER AND PULSE
£
        AM3TC  = PI/4.0D0 * DIA3TC ** 2.0D0
        AM3COL = PI/4.0D0 * LM3DIA ** 2.0D0
        AM3PU  = PI/4.0D0 * DIA3PU ** 2.0D0
        AM3AL  = PI/4.0D0 * DIA3AL ** 2.0D0
        AM4TC  = PI/4.0D0 * DIA4TC ** 2.0D0
        AM4COL = PI/4.0D0 * LM4DIA ** 2.0D0
        AM4PU  = PI/4.0D0 * DIA4PU ** 2.0D0
        AM4AL  = PI/4.0D0 * DIA4AL ** 2.0D0
        AM5TC  = PI/4.0D0 * DIA5TC ** 2.0D0
        AM5COL = PI/4.0D0 * LM5DIA ** 2.0D0
        AM5PU  = PI/4.0D0 * DIA5PU ** 2.0D0
        AM5AL  = PI/4.0D0 * DIA5AL ** 2.0D0
        AM6TC  = PI/4.0D0 * DIA6TC ** 2.0D0
        AM6COL = PI/4.0D0 * LM6DIA ** 2.0D0
        AM6PU  = PI/4.0D0 * DIA6PU ** 2.0D0
        AM6AL  = PI/4.0D0 * DIA6AL ** 2.0D0
£
£        CALCULATE VOLUMES OF FLUID HELD IN AQ CONTINUOUS COLUMNS
£        TO LEVEL OF TOP PLATE
£
        VA4COL = ( ZP4TOP - ZC4BTM ) * AM4COL
        VA5COL = ( ZP5TOP - ZC5BTM ) * AM5COL
        VA6COL = ( ZP6TOP - ZC6BTM ) * AM6COL
        VS3COL = ( ZP3TOP - ZC3BTM ) * AM3COL
NOSORT
£
£       CALCULATE INITIAL VOLUMES FROM LEVELS IF REQUIRED
£
  IF ( INITAL .GE. 0.5D0 ) THEN

        VS3TCZ = AM3TC * ( ZS3TCZ - ZP3TOP )
        VS3PZ  = AM3PU * ( ZS3PUZ - ZP3BTM )
        VA42Z  = ( ZA4INZ - ZP4TOP ) * AM4TC + VA4COL
        VS43Z  = AM4TC * ( ZS4TCZ - ZA4INZ )
        VS4PZ  = AM4PU * ( ZS4PUZ - ZP4BTM )

        VA52Z = ( ZA5INZ - ZP5TOP ) * AM5TC + VA5COL
        VS53Z  = AM5TC * ( ZS5TCZ - ZA5INZ )
        VS5PZ  = AM5PU * ( ZS5PUZ - ZP5BTM )

        VA62Z  = ( ZA6INZ - ZP6TOP ) * AM6TC + VA6COL
        VS63Z  = AM6TC * ( ZS6TCZ - ZA6INZ )
        VS6PZ  = AM6PU * ( ZS6PUZ - ZP6BTM )
        VA33CZ = AM3COL * ( ZA33CZ - ZC3BTM )
        VS32Z  = VS3COL + ( ZS3TCZ - ZP3TOP ) * AM3TC

      ENDIF

        EPSLN2 = EPSLON * EPSLON
        CDS2   = CDS * CDS
SORT
£   CALCULATE CONSTANT FACTOR IN MIAOS CORRELATION FROM PLATE FREE AREA
      FRSQ1 = XMUFRE * XMUFRE
       KMUSI1 = FRSQ1 / ( 1.0D0 - XMUFRE ) / ( 1.0D0 - FRSQ1 )
£
£       CALCULATE CIRCUMFERENCE OF SOLVENT OFFTAKE LINES
```

```
£
       LM3CRC = PI * DM3EXT
       LM4CRC = PI * DM4EXT
       LM5CRC = PI * DM5EXT
       LM6CRC = PI * DM6EXT

NOSORT
      UPDTE = 0.0D0
£   SET VALUES FOR  IDMP,ICDMP
      IDMP = CIDMP + 0.1
      ICDMP = CICDMP + 0.1
£  SET CONVERGENGE FACTOR FOR USE IN SULPHATE.
      IF ( ( STEADY .GT. 0.5 ) .OR. ( ALINE .GT.0.5 ) ) THEN
        CONV = CONVS
      ELSE
        CONV = CONVD
      ENDIF
SORT
£
£   CALCULATE CONSTANT FACTOR IN MIAOS CORRELATION FROM PLATE FREE AREA
£
      FRSQ1 = XMUFRE * XMUFRE
      KMUSI1 = FRSQ1 / ( 1.0D0 - XMUFRE ) / ( 1.0D0 - FRSQ1 )
£
£   COLUMN GEOMETRY CALCULATIONS , X-SECTIONAL AREA AND CELL VOL.
£
      AM3XS = 7.853981634D-1 * ( LM3DIA ** 2 )        ££££   PI / 4
      AMCXS = AM3XS
      VMCCL = AMCXS * LMCLEN / NMCCL
      VM3CL = AM3XS * LM3LEN / NM3CL
      AM4XS = 7.853981634D-1 * ( LM4DIA ** 2 )        ££££   PI / 4
      AM5XS = 7.853981634D-1 * ( LM5DIA ** 2 )        ££££   PI / 4
      VM4CL = AM4XS * LM4LEN / NM4CL
      VM5CL = AM5XS * LM5LEN / NM5CL
      AM6XS = 7.853981634D-1 * ( LM6DIA ** 2 )        ££££   PI / 4
      VM6CL = AM6XS * LM6LEN / NM6CL
£
£  CONSTANT FACTORS FOR INTERFACIAL AREA CALCULATION.
£
      AA3IFF = 6.0D0 * VM3CL / LA3DIA
      AACIFF = 6.0D0 * VMCCL / LACDIA
      AA4IFF = 6.0D0 * VM4CL / LA4DIA
      AA5IFF = 6.0D0 * VM5CL / LA5DIA
      AA6IFF = 6.0D0 * VM6CL / LA6DIA
DYNAMIC
NOSORT
      UPDTE = UPDTE + 1.0D0
SORT

£
£     ORGANIC FLOWS FROM COLUMN 3 DIRECT TO COLUMN 4
£
      OU4FE = OU3CO
      OP4FE = OP4CO
      SX4FE = SX3CO

     FS4RCY = FS3TC
     FS6RCY = FS4TC
£
£     AQUEOUS FLOWS FROM COL 4 TO COL 5
```

```
£
      FA5FE1 = FA4BC
       YX5FE = YX4CO
       GU5FE = GU4CO
       GP5FE = GP4CO
£
£      ORGANIC FLOWS FROM COL 4 TO COL6
£
       OU6FE = OU4CO
       OP6FE = OP4CO
       SX6FE = SX4FE
       GU3BC = GUCCO
       GP3BC = GPCCO
       YX3BC = YXCCO
       YZ3BC = YZCCO

       GU2BCD = GU2CO
       GP2BCD = GP2CO
       FA2BCD = FA2BC
       YZ2BCD = YZ2CO
       YX2BCD = YX2CO
£
£       FEED TANK TO CYCLE2 IS FILLED FROM AG COLUMN 2
£
 VA3TNK, GUCFE, GPCFE, YZCFE, YXCFE = BUFTNK ( GU2BCD, GP2BCD, ...
         YZ2BCD, YX2BCD, FA2BCD, FACFE, VTNK3Z, GUTN3Z, GPTN3Z,  ...
         YZTN3Z, YXTN3Z, GUCCON, GPCCON, YZCCON, YXCCON,FACCON, ...
         FACTNK, GU3BC, GP3BC, YZ3BC, YX3BC )

         FACFE = BFACF1 + BFACF1 * STEP(TFACF1) * SFACF1
£
£      CALL MACAG4 FOR COLUMN 3E
£
       FACCL, HACCLD, YXCCLD, YUCCLD, YPCCLD, FSCCL, SXCCLD,...
       SUCCLD, SPCCLD, FACCO, YXCCO, GUCCO, GPCCO, FSCCO,    ...
       SXCCO, OUCCO, OPCCO, DACCL, DSCCL, YZCCLD, YZCCO =    ...
MACAQ4( FACTTE, YXCMIE, GUCMIE, GPCMIE, HACCL, YXCCL,        ...
         YUCCL, YPCCL, XA3BM, 0.0D0, FA3BE,0.0D0,0.0D0 ,     ...
         0.0D0, 0.0D0, FSCFE, SXCFE, OUCFE, OPCFE, SXCCL,    ...
         SUCCL, SPCCL, XOCINS, XS3BM, 0.0D0,0.0D0 , SX3BE,   ...
         OU3BE, OP3BE, DS3BE, NMCCL, 22, AACIFF, IG3EQ, AB3PL,  ...
         BB3PL, VMCCL, AMCXS, TQCCL, HACCLZ, YUCCLZ, YPCCLZ,...
         YXCCLZ, SUCCLZ, SPCCLZ, SXCCLZ,      ...
         YZCMIE, YZCCL, 0.0D0, YZCCLZ, RQ3SLC, QCIDEN )
£
£       CONNECT SCRUB AND EXTRACT PARTS OF COLUMN 3
£       SOLVENT FLOWS
£
        FSCBE = XS3BM * FSCCO
        FS3FE = FSCCO + FSCBE
        SX3FE = SXCCO
        OU3FE = OUCCO
        OP3FE = OPCCO
£
£       AQUEOUS BACKFLOW ACROSS JCIN
£
        FA3BE = XA3BM * FA3CO
        FA3GRO = FA3CO + FA3BE
£
£       AQUEOUS FLOWS FROM SCRUB TO EXTRACT SECTIONS OF COLUMN,
```

```
£       MIXING WITH LOADED FEED
£
        FACTTE = FA3GRO + FACFE
        YXCMIE = ( FA3GRO * YX3CO + FACFE * YXCFE ) / FACTTE
        GUCMIE = ( FA3GRO * GU3CO + FACFE * GUCFE ) / FACTTE
        GPCMIE = ( FA3GRO * GP3CO + FACFE * GPCFE ) / FACTTE
        YZCMIE = ( FA3GRO * YZ3CO + FACFE * YZCFE ) / FACTTE
£
£       COPY CONCENTRATIONS TO BACKFLOWS
£
PROCEDURE YXCBE, GUCBE, GPCBE, GACBE, YZCBE, DACBE = ...
           CONCP1 ( YXCCL, YUCCL, YPCCL, DACCL, YZCCL )
         YXCBE = YXCCL(1)
         GUCBE = YUCCL(1) * MUUAW
         GPCBE = YPCCL(1) * MPJAW
         DACBE = DACCL(1)
         YZCBE = YZCCL(1)
ENDPRO
PROCEDURE SX3BE, OU3BE, OP3BE, DS3BE = ...
           CONCP2 ( SX3CL, SU3CL, SP3CL, DS3CL )
        JJ = NM3CL + 0.1D0
        SX3BE = SX3CL(JJ)
        OU3BE = SU3CL(JJ) * MUUAW
        OP3BE = SP3CL(JJ) * MPUAW
        DS3BE = DS3CL(JJ)
ENDPRO
£
£ MACAQ4 FOR COLUMN 3S
£
      FA3CL, HA3CLD, YX3CLD, YU3CLD, YP3CLD, FS3CL, SX3CLD,...
      SU3CLD, SP3CLD, FA3CO, YX3CO, GU3CO, GP3CO, FS3CO,    ...
      SX3CO, OU3CO, OP3CO, DA3CL, DS3CL, YZ3CLD, YZ3CO =    ...
MACAQ4( FA3FE, YX3FE, GU3FE, GP3FE, HA3CL, YX3CL,           ...
         YU3CL, YP3CL, XA3BM, 1.0D0,0.0D0,YXCBE, GUCBE ,    ...
         GPCBE, DACBE, FS3FE, SX3FE, OU3FE, OP3FE, SX3CL,   ...
         SU3CL, SP3CL, XOCINS, XS3BM,0.0D0,FSCBE, 0.0D0,  ...
         0.0D0, 0.0D0, 0.0D0, NM3CL, 7,AA3IFF, IQ3EQ, AB3PL,  ...
         BB3PL, VM3CL, AM3XS, TQ3CL, HA3CLZ, YU3CLZ, YP3CLZ,...
         YX3CLZ, SU3CLZ, SP3CLZ, SX3CLZ,     ...
         YZ3FE, YZ3CL, YZCBE ,YZ3CLZ, RO3SLC, G3IDEN )
£
£       CALL MACRO COLSM2 FOR COLUMN 3
£       FA3EC ALL AQ ENTERING COLUMN
£


      FA3EC = FA3FE + FACFE + FACRCY

      ZS3TC, ZS3PU, FS3TC, FS3EC, FSCFE, FA3BC, FS3BC , ...
      OP3TC, OU3TC, SX3TC, VS3TC, VS32, VA3BC, ZA3BC, FA32 = ...
      COLSM2 ( AM3PU, AM3TC, DACCL(22), DSCCL(22), DA3CL(1),...
               DS3CL(1), FA3EC, FS3CVF, FS3RCY, FT3BC, LM3LEN,...
               NPLC3, PB3PL, PB3TC, VS3PZ, VS32Z, VS3TCZ, ZS3WIR, ...
               ZP3TOP, FS3DIV, ZC3BTM, ZP3BTM, LM3CRC, FACCO,...
               FS3CO, OP3CO, OU3CO, SX3CO, OU3TCZ, OP3TCZ, SX3TCZ,...
               VS3COL, VA3BCZ, AM3COL, ZC3BTM )
£
£     CALL MACRO CLARK FOR  AIRLIFT
£
      FT3BCT = CLARK ( ZG3INJ, FGCAL, ZS3TC, ZS3DEL, AM3AL, ...
                    DSCCL(10),DACCL(22), DIA3AL, PB3TC, PB3DEL,...
```

```
                     VAMCON, ROUGH, KCLARK, CNVIMA, PG3IN )
£
£      USE DELAY TO BREAK ALGEBRAIC LOOP OF ZS3TC AND FT3BCT
£
       FT3BC = REALPL ( 0.0D0, 2.0D-01, FT3BCT )
£
£      CALL SIMPLE SETTLER MACRO
£
       FACSEP, FSCSEP = SVSIM ( FA3BC, FS3BC )
       FS3RCY = DELAY ( 5, 3.0D-03, FSCSEP )
£
£      DIVERTER ON COLUMN 3
£
PROCEDURE FACRCY, FACMAL, FACTNK = DIVRT3 ( ICCDIV, FACSEP )

       FACRCY = 0.0D0
       FACMAL = 0.0D0
       FACTNK = 0.0D0

       IF ( ICCDIV .GT. 0.5D0 .AND. ICCDIV .LE. 1.5D0 ) THEN

             £ NORMAL, AQ TO MALS

             FACMAL = FACSEP
             FACRCY = 0.0D0
             FACTNK = 0.0D0

       ELSE IF ( ICCDIV .GT. 1.5D0 .AND. ICCDIV .LE. 2.5D0 ) THEN

             £ AQ BACK TO FEEDTANK

             FACTNK = DELAY ( 5, 5.0D-03, FACSEP )
             FACRCY = 0.0D0
             FACMAL = 0.0D0

       ELSE

             £ AQ BACK TO COLUMN

             FACRCY = DELAY ( 5, 5.0D-03, FACSEP )
             FACTNK = 0.0D0
             FACMAL = 0.0D0

       ENDIF
ENDPRO
£
£      PROCEDURE TO SET GAS RATE FOR COL 3
£
PROCEDURE FGCAL = CHECK3 ( FGCSET , FSCSEP, TSCSTP, ...
                           FSCSTP, FSCCUT )

       IF ( FSCSEP .GE. FSCCUT ) THEN

             FGCAL = FGCSET
             ICFLAG = 0.0D0

       ELSE IF ( FSCRCY .LT. FSCCUT .AND. TIME .GE. ( ICFLAG + ...
                   TSCSTP )) THEN

             FGCAL = FGCSET * ( 1.0D0 + FSCSTP )
```

```
            FGCSET = FGCAL
            ICFLAG = TIME

      ELSE

            FGCAL = FGCSET

      ENDIF

ENDPRO

£
£     MACSO4 FOR COLUMN 4
£
      FA4CL , HA4CLD , YX4CLD , YU4CLD , YP4CLD , ...
      FS4CL , SX4CLD , SU4CLD , SP4CLD , ...
      FA4CO , YX4CO , GU4CO , GP4CO , FS4CO , SX4CO , ...
      OU4CO , OP4CO , DA4CL ,DS4CL , YZ4CLD , YZ4CO = ...
      MACSO4 ( FA4FE , YX4FE , GL4FE , GP4FE , HA4CL , YX4CL , ...
               YU4CL , YP4CL , XA4BM , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , 0.0D0 , FS4TFE , SX4TFE , OU4TFE , ...
               OP4TFE , SX4CL , SU4CL , SP4CL , XO4INS , XS4BM , ...
               0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , NM4CL , 5 , AS4IFF , IQ4EQ , ...
               AB4PL , BB4PL , VM4CL , AM4XS , TQ4CL , HA4CLZ , ...
               YU4CLZ , YP4CLZ , YX4CLZ , SU4CLZ , SP4CLZ , SX4CLZ , ..
               YZ4FE , YZ4CL , 0.0D0 , YZ4CLZ , ...
               RU4FUN , RP4FUN , RX4FAC , Q4IDEN )
£
£     COMBINE LOADED FEED FROM CYCLE1 WITH THE SOLVENT FLOW FROM COL 5
£
      FS4TFE = FS4FE + FS5CO
      OU4TFE = ( OU4FE * FS4FE + OU5CO * FS5CO ) / FS4TFE
      OP4TFE = ( OP4FE * FS4FE + OP5CO * FS5CO ) / FS4TFE
      SX4TFE = ( SX4FE * FS4FE + SX5CO * FS5CO ) / FS4TFE
£
£     CALL MACSO4 FOR COLUMN 5
£
      FA5CL , HA5CLD , YX5CLD , YU5CLD , YP5CLD , ...
      FS5CL , SX5CLD , SU5CLD , SP5CLD , ...
      FA5CO , YX5CO , GU5CO , GP5CO , FS5CO , SX5CO , ...
      OU5CO , OP5CO , DA5CL ,DS5CL , YZ5CLD , YZ5CO = ...
      MACSO4 ( FA5FE , YX5FE , GU5FE , GP5FE , HA5CL , YX5CL , ...
               YU5CL , YP5CL , XA5BM , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , 0.0D0 , FS5FE , SX5FE , OU5FE , ...
               OP5FE , SX5CL , SU5CL , SP5CL , XO5INS , XS5BM , ...
               0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , NM5CL , 5 , AS5IFF , IQ5EQ , ...
               AB5PL , BB5PL , VM5CL , AM5XS , TQ5CL , HA5CLZ , ...
               YU5CLZ , YP5CLZ , YX5CLZ , SU5CLZ , SP5CLZ , SX5CLZ , ...
               YZ4CO , YZ5CL , 0.0D0 , YZ5CLZ , ...
               RU5FUN , RP5FUN , RX5FAC , Q5IDEN )

£
£     CALL COLTES MACRO FOR COLUMN 4
£
      ZS4TC, ZA4INT, ZS4P, VA42D, VS43D, VS4PD, VA42, VS43,...
      VS4P, FS4TC, FA4TC, FS4EC, FS4FE, FA4FE, OU4TC, OP4TC,...
                                                            ...
      SX4TC =
      COLTES ( AM4PU, AM4TC, FA4FE1, FS4CVF, FS4RCY, FA4BC, ...
```

```
                LM4LEN, NPLC4, PB4PL, PB4TC, VA42Z, VS43Z,     ...
                VS4PZ, ZS4WIR, FS4DIV, ZC4BTM, ZP4BTM, LM4CRC,...
                FS4CO, FA4CO, ZP4TCP, CDS, OU4CO, OP4CO, 5 , ...
                DA4CL, DS4CL, HA4CL, FA4EPZ, VA4COL, FS42Z, ...
                OU4TCZ, OP4TCZ, SX4TCZ, SX4CO, AM4XS )
£
£     CALL IDEALIZED PI CONTROLLER FOR N2 FLOWRATE
£
      FG4AL, ERROR4, ERINT4 = PICONT ( ZA4INT, ZA4SET, GAIN4, ...
                              RESTI4, FG4SET, CJ4SEN, ERR4Z )
£
£     CALL MACRO CLARK FOR  AIRLIFT
£
      FT4BCT = CLARK ( ZG4INJ, FG4AL, ZS4TC, ZS4DEL, AM4AL, ...
                     DS4CL(3),DA4CL(5), DIA4AL, PB4TC,PB4DEL,...
                        VAMCON, RCUGH, KCLARK, CNVIMA, PG4IN )
£
£     USE DELAY TO BREAK ALGEBRAIC LOOP OF ZS3TC AND FT3BCT
£
      FA4BC = REALPL ( 0.0D0, 2.0D-01, FT4BCT )
£
£     CALL COLTES MACRO FOR COLUMN 5
£
      ZS5TC, ZA5INT, ZS5P, VA52D, VS53D, VS5PD, VA52, VS53,...
      VS5P, FS5TC, FA5TC, FS5EC, FS5FE, FA5FE, OU5TC, OP5TC,...
      SX5TC                                              = ...
      COLTES ( AM5PU, AM5TC, FA5FE1, FS5CVF, FS5RCY, FA5BC, ...
                LM5LEN, NPLC5, PB5PL, PB5TC, VA52Z, VS53Z,     ...
                VS5PZ, ZS5WIR, FS5DIV, ZC5BTM, ZP5BTM, LM5CRC,...
                FS5CO, FA5CO, ZP5TOP, CDS, OU5CO, OP5CO, 5 , ...
                DA5CL, DS5CL, HA5CL, FA5EPZ, VA5COL, FS52Z,    ...
                OU5TCZ, OP5TCZ, SX5TCZ, SX5CO, AM5XS )
£
£     CALL IDEALIZED PI CONTROLLER FOR N2 FLOWRATE
£
      FG5AL, ERROR5, ERINT5 = PICONT ( ZA5INT, ZA5SET, GAIN5, ...
                              RESTI5, FG5SET,CJ5SEN, ERR5Z )
£
£     CALL MACRO CLARK FOR  AIRLIFT
£
      FT5BCT = CLARK ( ZG5INJ, FG5AL, ZS5TC, ZS5DEL, AM5AL,...
                        DS5CL(3),DA5CL(5),  DIA5AL, PB5TC,PB5DEL,...
                        VAMCON, RCUGH, KCLARK, CNVIMA, PG5IN )
£
£     USE DELAY TO BREAK ALGEBRAIC LOOP OF ZS3TC AND FT3BCT
£
      FA5BC = REALPL ( 0.0D0, 2.0D-01, FT5BCT )
£
£     CALL MACS04 FOR COLUMN 6
£
      FA6CL , HA6CLD , YX6CLD , YU6CLD , YP6CLD , ...
      FS6CL , SX6CLD , SU6CLD , SP6CLD , ...
      FA6CO , YX6CO , GU6CO , GP6CO , FS6CO , SX6CO , ...
      OU6CO , OP6CO , DA6CL ,DS6CL , YZ6CLD , YZ6CO = ...
      MACS04 ( FA6FE , YX6FE , GL6FE , GP6FE , HA6CL , YX6CL , ...
               YU6CL , YP6CL , XA6BM , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , 0.0D0 , FS6FE , SX6FE , OU6FE , ...
               OP6FE , SX6CL , SU6CL , SP6CL , XO6INS , XS6BM , ...
               0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , NM6CL , 5 , AS6IFF , IQ6EQ , ...
```

```
              AB6PL , BB6PL , VM6CL , AM6XS , TQ6CL , HA6CLZ , ...
              YU6CLZ , YP6CLZ , YX6CLZ , SU6CLZ , SP6CLZ , SX6CLZ , ...
              YZ6FE , YZ6CL , 0.0D0 , YZ6CLZ , ...
              RU6FUN , RP6FUN , RX6FAC , Q6IDEN )
£
£     CALL COLTES MACRO FOR COLUMN 6
£
      ZS6TC, ZA6INT, ZS6P, VA62D, VS63D, VS6PD, VA62, VS63,...
      VS6P, FS6TC, FA6TC, FS6EC, FS6FE, FA6FE , OU6TC, OP6TC,...
      SX6TC = ...
      COLTES ( AM6PU, AM6TC, FA6FE1,FS6CVF, FS6RCY, FA6BC, ...
              LM6LEN, NPLC6, PB6PL, PB6TC, VA62Z, VS63Z,   ...
              VS6PZ, ZS6WIR, FS6DIV, ZC6BTM, ZP6BTM, LM6CRC,...
              FS6CO, FA6CO, ZP6TOP, CDS, OU6CO, OP6CO, 6 , ...
              DA6CL, DS6CL, HA6CL, FA6EPZ, VA6COL, FS62Z,...
              OU6TCZ, OP6TCZ, SX6TCZ, SX6CO, AM6XS )
£
£     CALL IDEALIZED PI CONTROLLER FOR N2 FLOWRATE
£
      FG6AL,ERROR6, ERINT6 = PICCNT ( ZA6INT, ZA6SET, GAIN6, ...
                             RESTI6, FG6SET,CJ6SEN, ERR6Z )
£
£     CALL MACRO CLARK FOR  AIRLIFT
£
      FT6BCT = CLARK ( ZG6INJ, FG6AL, ZS6TC, ZS6DEL, AM6AL, ...
                       DS6CL(3),DA6CL(5), DIA6AL, PB6TC, PB6DEL,...
                       VAMCON, ROUGH, KCLARK, CNVIMA, PG6IN )
£
£     USE DELAY TO BREAK ALGEBRAIC LOOP OF ZS6TC AND FT6BCT
£
      FA6BC = REALPL ( 0.0D0, 2.0D-01, FT6BCT )
£
£     SETTLER FOR TOP FLOWS FROM COL6 AQ TO CYCLE3 U ORG TO STOCK
£
      FA6OVR, FS6STK = SVSIM ( FA6TC, FS6TC )
SPACE METHOD 80000
SPACE PRINT 200
SPACE PLOT 200
TITLE CYCLE23 DYNAMIC RUN FIRST ATTEMPT
METHOD WARP2
SPACE HOLD = 20
TIMER PRDEL=0.10D0,FINTIM =1.000D0,DELT = 0.001,OUTDEL=0.05
TERMINAL
      IF ( IDMP .GT. 0 ) THEN
        CALL DUMPI ( IDMP )
      ENDIF
      IF ( ICDMP .GT. 0 ) THEN
        CALL DUMPIC ( ICDMP )
      ENDIF
      UPDTE = 0.0D0
£ CONSTANTS IN SLATER CORRELATION AS MODIFIED BY AH 23/08/85.
£ VALUES TO MATCH DESIGN SS.
      STORAGE RQ7SLC(7)
£     STORAGE YP7CLZ(6)
   TABLE RQ7SLC(1-7) = 1.1040 , 0.7416 , 0.02874 , ...
                       0.0 , 0.0 , 0.02874 , ...
                       0.093297
£   OVERWRITE RQ7SLC(1-3) FOR REVISED COEFFS.
   TABLE RQ7SLC(1-3) = 0.75000 , 0.74160 , 0.02000
   TABLE YZ7CLZ(1-6) = 6*1.0D-08
```

```
   TABLE YP7CLZ(1-6) = 6*1.0D-12
  TABLE YPGCLZ(1-12)=12*1.0D-12
  TABLE SPGCLZ(1-12)=12*1.0D-12
  TABLE SP7CLZ(1-6) =6*1.0D-12
   TABLE YP8CLZ(1-12) = 12 * 1.0D-6
   TABLE SP8CLZ(1-12) = 12 * 1.0D-6
££££££££££££££££££££££££
  PRINT UPDTE,OU7CO ,OP7CO ,GUGCO ,GPGCO ,YZGCO
PRINT  ZS7TC, ZS7PU, FS7TC, FS7FE, FAG3C, FSGEC, FSGPCY, FAGSEP,...
FSGSEP, FTG3C, FSGCVF,                                             ...
         FSGFE
  PRINT SX8CO, YX8CO,OU8CO,GU8CO
PRINT ZS8TC, ZS8P, FS8TC, ZA8INT, FS8FE, FS8EC, FSHRCY, ...
        FTH8C ,FGHAL
PRINT HA8CL
PLOT FS7TC, FS8TC, FSGFE
PLOT ZA8INT
PLOT GU8CO,OU8CO,GU7CO,OU7CO
PLOT FTH8C
£ CONSTANTS IN SLATER CORRELATION AS MODIFIED BY AH 28/08/85.
£ VALUES TO MATCH DESIGN SS.
       STORAGE RQ3SLC(7)
    TABLE RQ3SLC(1-7) = 1.1040 , 0.7416 , 0.02874 , ...
                        0.0 , 0.0 , 0.02874 , ...
                        0.093297
£   OVERWRITE RQ7SLC(1-3) FOR REVISED COEFFS.
    TABLE RQ3SLC(1-3) = 0.75000 , 0.74160 , 0.02000
££££££££££££££££££££££££
PRINT OU3CO ,OP3CO ,GUCCO ,GPCCO ,YZCCO
££££££££££££££££££££££££
PRINT OU6CO ,OP6CO ,GU6CO ,GP6CO ,...
      YZ6CO
PRINT OP4CO, OP5CO, OU4CO, OU5CO, GU4CO, GU5CO, GP4CO, GP5CO
PRINT FG4AL,FG5AL,FG6AL,ZA4INT,ZA5INT,ZA6INT
PLOT  FG4AL,FG5AL,FG6AL,ZA4INT,ZA5INT,ZA6INT
PLOT GU3CO,OU3CO,GUCCO,GP3CO,OP3CO,GPCCO
PLOT OP4CO, OP5CO, OU4CO, OU5CO, GU4CO, GU5CO, GP4CO, GP5CO
PLOT GU6CO,OU6CO,GP6CO,OP6CO
END
STOP
ENDJOB
```

```
KKKKKKKKK     00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000    KKKKKKKK
KKKKKKKKK     000000000000000000000000  DIGITAL EQUIPMENT CORPORATION - VAX/VMS VERSION V4.5  000000000000000000000000    KKKKKKKK
KKKKKKKKK     00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000    KKKKKKKK

                                           III   L      L       SSSS  L      EEEEE  Y   Y
                                             I    L      L      S      L      E      Y   Y
                                             I    L      L      S      L      E       Y Y
                                             I    L      L       SSS   L      EEEE     Y
                                             I    L      L          S  L      E        Y
                                             I    L      L          S  L      E        Y
                                           III   LLLLL  LLLLL  SSSS   LLLLL  EEEEE    Y

                           CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE    333333    UU      UU
                           CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE    333333    UU      UU
                         CC          YY      YY  CC          LL          EE          33      33  UU      UU
                         CC          YY      YY  CC          LL          EE          33      33  UU      UU
                         CC            YY  YY    CC          LL          EE                  33  UU      UU
                         CC            YY  YY    CC          LL          EE                  33  UU      UU
                         CC              YY      CC          LL          EEEEEEEE          33    UU      UU
                         CC              YY      CC          LL          EEEEEEEE          33    UU      UU
                         CC              YY      CC          LL          EE                  33  UU      UU
                         CC              YY      CC          LL          EE                  33  UU      UU
                         CC              YY      CC          LL          EE          33      33  UU      UU
                         CC              YY      CC          LL          EE          33      33  UU      UU
                           CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE    333333    UUUUUUUUUU
                           CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE    333333    UUUUUUUUUU

                                     PPPPPPPP    MM      MM    SSSSSSSS      ;;;;      222222    77777777
                                     PPPPPPPP    MM      MM    SSSSSSSS      ;;;;      222222    77777777
                                     PP      PP  MMMM  MMMM  SS              ;;;;    22      22          77
                                     PP      PP  MMMM  MMMM  SS              ;;;;    22      22          77
                                     PP      PP  MM  MM  MM  SS                              22          77
                                     PP      PP  MM  MM  MM  SS                              22          77
                                     PPPPPPPP    MM      MM    SSSSSS        ;;;;          22          77
                                     PPPPPPPP    MM      MM    SSSSSS        ;;;;          22          77
                                     PP          MM      MM          SS      ;;;;        22          77
                                     PP          MM      MM          SS      ;;;;        22          77
                             ....    PP          MM      MM          SS        ;;      22          77
                             ....    PP          MM      MM          SS        ;;      22          77
                             ....    PP          MM      MM  SSSSSSSS        ;;      2222222222  77
                             ....    PP          MM      MM  SSSSSSSS        ;;      2222222222  77

FILE _DUA0:[ILLSLEY.PMSP]CYCLE3U.PMS;27 (7955,37,0), LAST REVISED ON 30-JUL-1987 14:38, IS A 48 BLOCK SEQUENTIAL FILE OWNED BY UIC
[DYNAMICS,ILLSLEY].  THE RECORDS ARE VARIABLE LENGTH WITH IMPLIED (CR) CARRIAGE CONTROL.  THE LONGEST RECORD IS 72 BYTES.

JOB CYCLE3U (25) QUEUED TO SYS$PRINT ON 30-JUL-1987 14:42 BY USER ILLSLEY, UIC [DYNAMICS,ILLSLEY], UNDER ACCOUNT   AT PRIORITY 100,
STARTED ON PRINTER _LPA0: ON 30-JUL-1987 14:42 FROM QUEUE SYS$PRINT.

KKKKKKKKK     00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000    KKKKKKKKK
KKKKKKKKK     000000000000000000000000  DIGITAL EQUIPMENT CORPORATION - VAX/VMS VERSION V4.5  000000000000000000000000    KKKKKKKKK
KKKKKKKKK     00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000    KKKKKKKKK
```

```
INITIAL
£
£       COLUMN GEOMETRY CALCULATIONS XSA OF COLUMN TOP SETTLER AND PULSE
£       XSA AG SIDE OF G SEPARATOR
£
        AAGSEP = PI/4.0D0 * DAGSEP ** 2.0
£
£       XSA ORG SIDE OF G SETTLER
£
        ASGSEP = PI/4.0D0 * DSGSEP ** 2.0
£
£       SAME FOR H SETTLER
£
        AAHSEP = PI/4.0D0 * DAHSEP ** 2.0D0
        ASHSEP = PI/4.0D0 * DSHSEP ** 2.0D0
£
£       SAME FOR 8 SETTLER
£
        AA8SEP = PI/4.0D0 * DA8SEP ** 2.0D0
        AS8SEP = PI/4.0D0 * DS8SEP ** 2.0D0
£
£       XSA TOP SECTION OF COL 7
£
        AS7TC  = PI/4.0D0 * DIA7TC ** 2.0D0
£
£       XSA MAIN SECTION COL 7
£
        AS7COL = PI/4.0D0 * DIAM7  ** 2.0D0
£
£       SAME FOR COL 8
£
        AS8TC  = PI/4.0D0 * DIA8TC ** 2.0D0
        AA8COL = PI/4.0D0 * DIAM8  ** 2.0D0
£
£       XSA PULSE LIMB TO COL 7
£
        AS7PU  = PI/4.0D0 * DIA7PU ** 2.0D0
£
£       SAME FOR COL 8
£
        AS8PU  = PI/4.0D0 * DIA8PU ** 2.0D0
£
£       XSA AIRLIFT
£
        AG7AL  = PI/4.0D0 * DIA7AL ** 2.0D0
        AG8AL  = PI/4.0D0 * DIA8AL ** 2.0D0

£
£        CALCULATE VOLUMES OF FLUID HELD IN ALL CONTINUOUS COLUMNS
£        TO LEVEL OF TOP PLATE
£
        VA8COL = ( ZP8TOP - ZC8BTM ) * AA8COL
        VS7COL = ( ZP7TOP - ZC7BTM ) * AS7COL
NOSORT
       UPDTE = 0.0D0
£   SET VALUES FOR  IDMP,ICDMP
      IDMP = CIDMP + 0.1
      ICDMP = CICDMP + 0.1
£  SET CONVERGENGE FACTOR FOR USE IN SULPHATE.
```

```
      IF ( ( STEADY .GT. 0.5 ) .OR. ( ALINE .GT.0.5 ) ) THEN
        CONV = CONVS
      ELSE
        CONV = CONVD
      ENDIF
£
£       CALCULATE INITIAL VOLUMES OF FLUIDS IN COLUMNS
£
     IF ( INITAL .GE. 0.5D0 ) THEN
£
£       INITIAL AQ VOL IN G SETTLER ON SOLVENT SIDE
£
        VAGSSZ = ASGSEP * LAGSSZ
£
£       INITIAL AG VOL IN G SETTLER ON AQ SIDE
£
        VAGSAZ = AAGSEP * LAGSAZ
£
£       INIT VOL OF ORG IN ORG SIDE OF G STTLER
£
        VSGSSZ = ASGSEP * LSGSSZ
£
£       INIT VOL OF ORG ON AQ SIDE OF G SETTLER
£
        VSGSAZ = AAGSEP * LSGSAZ
£
£       SAME FOR H SETTLER
£
        VAHSSZ = ASHSEP * LAHSSZ
        VAHSAZ = AAHSEP * LAHSAZ
        VSHSSZ = ASHSEP * LSHSSZ
        VSHSAZ = AAHSEP * LSHSAZ
£
£       SAME FOR 8 SETTLER
£
        VA8SSZ = AS8SEP * LA8SSZ
        VA8SAZ = AA8SEP * LA8SAZ
        VS8SSZ = AS8SEP * LS8SSZ
        VS8SAZ = AA8SEP * LS8SAZ
£       TOTAL VOL SOLV IN COL AT T=0.0

        VS72Z  = VS7COL + ( ZS7TCZ - ZP7TOP ) * AS7TC
£       VOL SOLV IN TOP SECTION
        VS7TCZ = ( ZS7TCZ - ZP7TOP ) * AS7TC
£       VOL SOLV IN PULSER
        VS7PZ  = AS7PU * ( ZS7PUZ - ZP7BTM )
£       VOL AG AND SOLV IN TOP SECTION
        VA83Z  = ( ZA8INZ - ZP8TOP ) * AS8TC


        VS83Z  = AS8TC * ( ZS8TCZ - ZA8INZ )
        VS8PZ  = AS8PU * ( ZS8PUZ - ZP8BTM )
        VA82Z  = VA8COL + VA83Z
        VSGCVZ = LACVFG * LBCVFG * LSGCVZ
        VA7BCZ = AS7COL * ( ZA7BCZ - ZC7BTM )
       ENDIF
        EPSLN2 = EPSLON * EPSLON
        CDS2   = CDS * CDS
£
£    SET UP START VALUE FOR IGFLAG ( MAKE SURE IT IS MUCH LESS THAN TIME
```

```
£    THIS IS FOR THE RAMP ON THE GAS FEED TO COLUMN 7
          IGFLAG = 0.0D0 - ( 10 * DELT )
NOSORT
SORT
£   CALCULATE CONSTANT FACTOR IN MIAOS CORRELATION FROM PLATE FREE AREA
      FRSQ1 = XMUFRE * XMUFRE
      KMUSI1 = FRSQ1 / ( 1.0D0 - XMUFRE ) / ( 1.0D0 - FRSQ1 )
£
£      CALCULATE CIRCUMFERENCE OF SOLVENT OFFTAKE PIPES
£
       LS7CRC = PI * DS7EXT
       LS8CRC = PI * DS8EXT

       EPSLN2 = EPSLON * EPSLON
       CDS2   = CDS * CDS
SORT
£
£   CALCULATE CONSTANT FACTOR IN MIAOS CORRELATION FROM PLATE FREE AREA
£
      FRSQ1 = XMUFRE * XMUFRE
      KMUSI1 = FRSQ1 / ( 1.0D0 - XMUFRE ) / ( 1.0D0 - FRSQ1 )
£
£   COLUMN GEOMETRY CALCULATIONS , X-SECTIONAL AREA AND CELL VOL.
£
      AM7XS = 7.853981634D-1 * ( LM7DIA ** 2 )        ££££   PI / 4
      AMGXS = AM7XS
      VMGCL = AMGXS * LMGLEN / NMGCL
      VM7CL = AM7XS * LM7LEN / NM7CL
      AM8XS = 7.853981634D-1 * ( LM8DIA ** 2 )       ££££   PI / 4
      VM8CL = AM8XS * LM8LEN / NM8CL
£
£  CONSTANT FACTORS FOR INTERFACIAL AREA CALCULATION.
£
      AA7IFF = 6.0D0 * VM7CL / LA7DIA
      AAGIFF = 6.0D0 * VMGCL / LAGDIA
      AS8IFF = 6.0D0 * VM8CL / LS8DIA

       EPSLN2 = EPSLON * EPSLON
       CDS2   = CDS * CDS
       FSGFDI = FSGFDE
DYNAMIC
NOSORT
      UPDTE = UPDTE + 1.0D0
SORT

£ CYCLE3-U ALONE SO PUT IN FEEDS FROM CYCLE2

          GU6BCD = GU6C0
          GP6BCD = GP6C0
          FA6BCD = FA6BC
          YZ6BCD = YZ6C0
          YX6BCD = YX6C0

£
£       SET UP STEP DISTURBANCES ON FEEDS
£

      FAGFE = BFAGF1 + BFAGF1 * STEP(TFAGF1) * SFAGF1
     FSGCVF = BFSGCV + BFSGCV * STEP(TFSGCV) * SFSGCV
     FA8FE1 = BFA8F1 + BFA8F1 * STEP(TFA8F1) * SFA8F1
```

```
£
£      LINK COLUMNS 7 AND 8 VIA THE SOLVENT FLOWS
       FS8RCY = FS7TC
       OU8FE = OU7TC
       OP8FE = OP7TC
       SX8FE = SX7TC

        GU7BC  = GUGCO
        GP7BC  = GPGCO
        YX7BC  = YXGCO
        YZ7BC  = YZGCO
£
£       USE DUMMY CHARACTERISTIC OF FLUIDIC PUMP TO CALC FAGFE
£       I KNOW NOTHING ABOUT THE FLUIDIC PUMP SO NO MODEL IS INCLUDED
£       BUT THIS IS PROBABLY REQUIRED AS THE LEVEL IN THE FEED TANK WILL
£       AFFECT PUMP PERFORMANCE IN CONCERT WITH THE VARIATION IN GAS FLOW
£       BUT PMSP DOES NOT ALLOW 3-D INTERPOLATION
£       15/5/87 HASHED OUT - CAUSING VERY SLOW RUNNING. JUST LEAVE ALARMS
£        FAGFEP = SPLINE ( FLPMPG, VA7TNK )
£       27/5/87 EVERYTHING HASHED STILL RUNNING SO SLOW
£       30/7/87 PUT BACK IN AS NOT CAUSE OF SLOW RUNNING ( I HOPE !)
£       BE WARNED - NOT TESTED !!!!!!!!!!!!!

PROCEDURE LOWGAL, HIHGAL = PUMP1 (VA7TNK, LOWGLE, HIHGLE )

        LOWGAL = 0.000
        HIHGAL = 0.000

        IF ( VA7TNK .LE. LOWGLE ) THEN

            £ TRIGGER THE LOW LEVEL ALARM AND ASSUME PUMP
            £ WILL NO LONGER WORK

            LOWGAL = 1.000
            HIHGAL = 0.000
            FAGFE  = 0.000

        ELSE IF ( VA7TNK .GT. LOWGLE .AND. VA7TNK .LT. HIHGLE ) THEN

            £ NORMAL OPERATION ALL ALARMS OFF

            LOWGAL = 0.000
            HIHGAL = 0.000
            FAGFE = FAGFEP

        ELSE

            £ TRIGGER HIGH ALARM
            £ SET PUMP OUTPUT TO MAXIMUM

            LOWGAL = 0.000
            HIHGAL = 1.000
            FAGFE  = FAGFEM £ FAGFEM = MAX OUTPUT OF PUMP

        ENDIF

ENDPRO

£
£       FEED TANK TO CYCLE3 URANIUM IS FILLED FROM AG COLUMN 6
```

```
£      CODE RE-INSERTED 30/7/87 - NOT TESTED !!!!!!!!!!

  VA7TNK, GUGFE, GPGFE, YZGFE, YXGFE = BUFTNK ( GU6BCD, GP6BCD, ...
        YZ6BCD, YX6BCD, FA6BCD, FAGFE, VTNK7Z, GUTN7Z, GPTN7Z,  ...
        YZTN7Z, YXTN7Z, GUGCON, GPGCON, YZGCON, YXGCON, FAGCON,...
        FAGTNK, GU7BC, GP7BC, YZ7BC, YX7BC )

£
£        COLUMN 7 MACRO SOLVENT CONTINUOUS

£  CALL TO MACRO MACAQ4 FOR COLUMN 7E.
     FAGCL , HAGCLD , YXGCLD , YUGCLD , YPGCLD , ...
     FSGCL , SXGCLD , SUGCLD , SPGGLD , ...
     FAGCO , YXGCO , GUGCO , GPGCO , FSGCO , SXGCO , ...
     OUGCO , OPGCO , DAGCL ,DSGCL , YZGCLD , YZGCO = ...
     MACAQ4 ( FAGTTE , YXGMIE , GUGMIE , GPGMIE , HAGCL , YXGCL , ...
              YUGCL , YPGCL , XA7BM , 0.0D0 , FA7BE , 0.0D0 , ...
              0.0D0 , 0.0D0 , 0.0D0 , FSGFE , SXGFE , ...
              OUGFE , OPGFE , SXGCL , SUGCL , SPGCL , XOGINS , ...
              XS7BM , 1.0D0 , 0.0D0 , SX7BE , OU7BE , ...
              OP7BE , DS7BE , NMGCL , 12 , AAGIFF , IQ7EQ , ...
              AB7PL , BB7PL , VMGCL , AMGXS , TQGCL , ...
              HAGCLZ , YUGCLZ , YPGCLZ , YXGCLZ , ...
              SUGCLZ , SPGCLZ , SXGCLZ , YZGMIE , ...
              YZGCL , 0.0D0 , YZGCLZ , RQ7SLC , QGIDEN )
£    CONNECT SCRUB AND EXTRACT PARTS OF COLUMN 7.
£    SOLVENT FROM EXTRACT TO SCRUB,INCLUDING COMPENSATING FOR BACKFLOW
      FSGBE = XS7BM * FSGCO
      FS7FE = FSGCO + FSGBE
      SX7FE = SXGCO
      OU7FE = OUGCO
      OP7FE = OPGCO
£    CALCULATE AGUEOUS BACK FLOW ACROSS JOIN
      FA7BE = XA7BM * FA7CO
      FA7GRO = FA7CO + FA7BE
£    AQUEOUS FROM SCRUB TO EXTRACT , AND MIX WITH LOADED FEED.
      FAGTTE = FA7GRO + FAGFE
      YXGMIE = ( FA7GRO * YX7CO + FAGFE * YXGFE ) / FAGTTE
      GUGMIE = ( FA7GRO * GU7CO + FAGFE * GUGFE ) / FAGTTE
      GPGMIE = ( FA7GRO * GP7CO + FAGFE * GPGFE ) / FAGTTE
      YZGMIE = ( FA7GRO * YZ7CO + FAGFE * YZGFE ) / FAGTTE
£
£    PROCEDURES FOR COPYING CONCENTRATIONS IN BACK FLOWS.
£
PROCEDURE YXGBE , GUGBE , GPGBE , DAGBE , YZGBE = ...
          CONCP1( YXGCL , YUGCL , YPGCL , DAGCL ,YZGCL )
      YXGBE = YXGCL(1)
      GUGBE = YUGCL(1) * MUUAW
      GPGBE = YPGCL(1) * MPUAW
      DAGBE = DAGCL(1)
      YZGBE = YZGCL(1)
ENDPRO
PROCEDURE SX7BE , OU7BE , OP7BE , DS7BE = ...
          CONCP2( SX7CL , SU7CL , SP7CL , DS7CL )
      JJ = NM7CL + 0.1D0
      SX7BE = SX7CL(JJ)
      OU7BE = SU7CL(JJ) * MUUAW
      OP7BE = SP7CL(JJ) * MPUAW
      DS7BE = DS7CL(JJ)
ENDPRO
```

```
£  CALL TO MACRO MACAQ4 FOR COLUMN 7S.
      FA7CL , HA7CLD , YXM7CD , YU7CLD , YP7CLD , ...
      FS7CL , SX7CLD , SU7CLD , SP7CLD , ...
      FA7CO , YX7CO , GU7CO , GP7CO , FS7CO , SX7CO , ...
      OU7CO , OP7CO , DA7CL ,DS7CL , YZ7CLD , YZ7CO = ...
      MACAQ4 ( FA7FE , YX7FE , GU7FE , GP7FE , HA7CL , YX7CL , ...
               YU7CL , YP7CL , XA7BM , 1.0D0 , 0.0D0 , YXGBE , ...
               GUGBE , GPGBE , DAGBE , FS7FE , SX7FE , ...
               OU7FE , OP7FE , SX7CL , SU7CL , SP7CL , XOGINS , ...
               XS7BM , 0.0D0 , FSGBE , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , NM7CL , 6 , AA7IFF , IQ7EQ , ...
               AB7PL , BB7PL , VM7CL , AM7XS , TQ7CL , ...
               HA7CLZ , YU7CLZ , YP7CLZ , YX7CLZ , ...
               SU7CLZ , SP7CLZ , SX7CLZ , YZ7FE , ...
               YZ7CL , YZGBE , YZ7CLZ , RQ7SLC , Q7IDEN )
£
£  CALL COLUMN MACRO COLSM2
£
£  TOTAL AQ ENTERING COLUMN 7 MUST BE USED
£
   FA7EC = FA7FE + FAGFE + FAGRCY

   ZS7TC, ZS7PU, FS7TC, FS7EC, FSGFE, FAGBC, FSGBC, OP7TC, OU7TC,...
   SX7TC, VS7TC, VS72, VA7BC, ZA7BC, FA72 =                         ...
   COLSM2 ( AS7PU, AS7TC, DAGCL(12), DSGCL(12),DA7CL(1),DS7CL(1),...
            FA7EC, FSGCVF, FSGRCY, FTGPC, LPLC7, NPLC7,          ...
            PB7TP, PB7TC, VS7PZ, VS72Z, VS7TCZ, ZS7WIR, ZP7TCP,...
            FSGDIV, ZC7BTM, ZP7BTM, LS7CRC, FAGCO,FS7CO, OP7CO, ...
            OU7CO, SX7CO, OU7TCZ, OP7TCZ, SX7TCZ, VS7COL, VA7BCZ,...
            AS7CCL, ZC7BTM )
£
£    CALL SETTLER MACRO
£
     FAGSEP, FSGSEP = SVSIM ( FAGBC, FSGBC )
£
£    SOLVENT OVERFLOWING THE SETTLER IS RECYCLED TO COLUMN 7
£
     FSGRCY = DELAY ( 5, 3.0D-03, FSGSEP )
£
£    DESTINATION OF AQ OVERFLOW DEPENDS ON DIVERTER SETTING
£
PROCEDURE FAGRCY, FAGMAL, FAGTNK = DIVERT ( ICGDIV, FAGSEP )

          FAGRCY = 0.0D0
          FAGMAL = 0.0D0
          FAGTNK = 0.0D0

      IF ( ICGDIV .GT. 0.5D0 .AND. ICGDIV .LE. 1.5D0 ) THEN
£
£          NORMAL OPERATION AQ TO MALS RECEIPT TANK
£

           FAGMAL = FAGSEP
           FAGRCY = 0.0D0
           FAGTNK = 0.0D0

       ELSE IF ( ICGDIV .GT. 1.5D0 .AND. ICGDIV .LE. 2.5D0 ) THEN
£
£          AQUEOUS STREAM RECYCLED TO FEED TANK
£
```

```
            FAGTNK = DELAY ( 5, 5.0D-03, FAGSEP )
            FAGRCY = 0.0D0
            FAGMAL = 0.0D0

        ELSE
£
£           AQ OVERFLOW RECYCLED TO COLUMN
£
            FAGRCY = DELAY ( 5, 5.0D-03, FAGSEP )
            FAGTNK = 0.0D0
            FAGMAL = 0.0D0

        ENDIF
ENDPRO
£
£   PROCEDURE TO CALCULATE GAS SETTING TO G GAS.LIFT TO ALLOW FOR
£   FSGSEP FAILING
£
PROCEDURE FGGAL = CHECK ( FGGSET,FSGSEP, TSGSTP, FSGSTP, FSGCUT )

    IF ( FSGSEP .GE. FSGCUT ) THEN
£
£     OKAY
£
      FGGAL = FGGSET
      IGFLAG = 0.0D0

    ELSE IF ( FSGRCY .LT. FSGCUT .AND. TIME .GE. (IGFLAG + ...
              TSGSTP )) THEN
£
£     SOLVENT OVERFLOW FAILED STEP UP GAS FLOW BY 2%
£     SET IGFLAG=TIME TO PREVENT MULTIPLE INCREASES
£

      FGGAL = FGGSET * ( 1 + FSGSTP )
      FGGSET = FGGAL
      IGFLAG = TIME

£
£   THIS BIT IS JUST TO COVER THE SITUATION THAT ARISES AT TIME=0.0
£   WHEN TIME = 0.0,IGFLAG=DELT AND FSGSEP=0.0D0 WHICH CAUSES A
£   CRASH IN CLARK
£
    ELSE

        FGGAL = FGGSET

    ENDIF

ENDPRO
£
£  CALL GASLIFT MACRO
£
     FTGBCT= CLARK ( ZG7IN, FGGAL,ZS7TC, ZGGDEL, AG7AL,DSGCL(12),...
              DAGCL(12),DIA7AL, PB7TC, PBGDEL, VAMCON, ROUGH, ...
              KCLARK, CNVIMA,PG7IN )
£
£    SHORT DELAY USED TO BREAK ALGEBRAIC LOOP FTGBC AND ZS7TC
£
     FTGBC = REALPL ( 0.0D0, 2.0D-01, FTGBCT )
```

```
£
£  CALL TO MACRO MACSO3 FOR COLUMN 8.
£
      FA8CL , HA8CLD , YX8CLD , YU8CLD , YP8CLD , ...
      FS8CL , SX8CLD , SU8CLD , SP8CLD , ...
      FA8CO , YX8CO , GU8CO , GP8CO , FS8CO , ...
      SX8CO , OU8CO , OP8CO , DA8CL , DS8CL = ...
      MACSO3 ( FA8FE , YX8FE , GU8FE , GP8FE , HA8CL , YX8CL , ...
               YU8CL , YP8CL , XA8BM , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , 0.0D0 , FS8FE , SX8FE , ...
               OU8FE , OP8FE , SX8CL , SU8CL , SP8CL , XO8INS , ...
               XS8BM , 0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , NM8CL , 12 , AS8IFF , IQ8EQ , ...
               AB8PL , BB8PL , VM8CL , AM8XS , TQ8CL , HA8CLZ , ...
               YU8CLZ , YP8CLZ , YX8CLZ , SU8CLZ , SP8CLZ , ...
               SX8CLZ , RU8FUN , RP8FUN , RX8FAC , G8IDEN )

£
£        COLUMN 8 MACRO AQUEOUS CONTINUOUS, DYNAMIC VERSION
£
         ZS8TC, ZA8INT, ZS8PU, VA82D, VS83D, VS8PD, VA82, VS83,  ...
         VS8P, FS8TC, FA8TC, FS8EC, FS8FE, FA8FE, OU8TC, OP8TC,...
         SX8TC    ...
          = COLTES ( AS8PU, AS8TC,                                 ...
         FA8FE1, FS8RCY, FSHRCY, FTH8C, LPLC8, NPLC8,PE8TP,          ...
         PB8TC, VA82Z, VS83Z, VS8PZ, ZS8WIR, FSHDIV, ZC8BTM,       ...
         ZP8BTM, LS8CRC, FS8CO, FA8CO, ZP8TOP, CDS, OU8CO, OP8CO,...
         12, DA8CL, DS8CL, HA8CL, FA8EPZ, VA8COL, FS82Z ,...
         OU8TCZ, OP8TCZ, SX8TCZ, SX8CO, AM8XS )
£
£        PI CONTROLLER USED ASSUMED IDEAL
£
          FGHAL,ERROR,ERRINT = PICONT ( ZA8INT, ZI8SET, GAIN8, ...
                               RESTIM, FGHSET , CJ8SEN, ERR8Z )
£
£         GAS-LIFT MACRO
£
           FTH8CT = CLARK ( ZG8IN, FGHAL, ZS8TC, ZGHDEL, AG8AL, ...
                    DA8CL(12), DA8CL(12), DIA8AL, PB8TC, PGHDEL,...
                    VAMCON, ROUGH, KCLARK, CNVIMA, PG8IN )

       FTH8C = REALPL( 0.0D0, 0.2D0, FTH8CT)

£
£     ASSUME NO SOLVENT CAN GET OUT OF THE BOTTOM OF THE COLUMN
£     SHOULD ALLOW FOR THE COLUMN FILLING WITH SOLVENT THOUGH
£
      FAHBC = FTH8C
      FSH8C = 0.0D0
£
£     SETTLER TOP FLOWS FROM COL 8 AQ IS PRODUCT, SOLV TO WASH
£
£      FA8PRD, FS8WSH = SVSIM ( FA8TC, FS8TC )
      FSHDIV = 0.0D0
      FSHRCY = 0.0D0
ALGEBRAIC VA82, FA8FEP, ZA8INT, ZS7TC, ZS8TC, ZS7PU, ZS8PU, FTH8CT,...
FTH8C,FTG8C,FGGAL,VS72
SPACE METHOD 80000
SPACE PRINT = 200
SPACE PLOT = 200
```

```
TITLE CYCLE30
METHOD RECT
ABSERR YUGCL(1)=1.0D-6
SPACE HOLD = 40
TIMER PRDEL=1.0D0,FINTIM =10.00D0,DELT=0.0001,OUTDEL=0.05,DELMIN=...
      1.0D-06,CFUFIN=10000.0D0
HOLDLIST DYNAM (YP8CL(1-12),SP8CL(1-12),YZ7CL(1-6),YPGCL(1-12),...
                SPGCL(1-12),YP7CL(1-6),SP7CL(1-6),SUGCL(1-12),...
                YUGCL(1-12),SXGCL(1-12),YZGCL(1-12),SU8CL(1-12),...
                YU8CL(1-12),SX8CL(1-12))
TERMINAL
      IF ( IDMP .GT. 0 ) THEN
        CALL DUMPI ( IDMP )
      ENDIF
      IF ( ICDMP .GT. 0 ) THEN
        CALL DUMPIC ( ICDMP )
      ENDIF
      UPDTE = 0.0D0
£ CONSTANTS IN SLATER CORRELATION AS MODIFIED BY AH 28/08/85.
£ VALUES TO MATCH DESIGN SS.
£££££££££££££££££££££££

£ CONSTANTS IN SLATER CORRELATION AS MODIFIED BY AH 28/08/85.
£ VALUES TO MATCH DESIGN SS.
      STORAGE RQ7SLC(7)
£     STORAGE YP7CLZ(6)
   TABLE RQ7SLC(1-7) = 1.1040 , 0.7416 , 0.02874 , ...
                       0.0 , 0.0 , 0.02874 , ...
                       0.093297
£   OVERWRITE RQ7SLC(1-3) FOR REVISED COEFFS.
   TABLE RQ7SLC(1-3) = 0.75000 , 0.74160 , 0.02000
 £  TABLE YZ7CLZ(1-6) = 6*1.0D-08
 £  TABLE YP7CLZ(1-6) = 6*1.0D-12
 £ TABLE YPGCLZ(1-12)=12*1.0D-12
 £ TABLE SPGCLZ(1-12)=12*1.0D-12
£  TABLE SP7CLZ(1-6) =6*1.0D-12
£   TABLE YP8CLZ(1-12) = 12 * 1.0D-6
£   TABLE SP8CLZ(1-12) = 12 * 1.0D-6
£££££££££££££££££££££££
  PRINT UPDTE,OU7CO ,CP7CO ,GUGCO ,GPGCO ,YZGCO
PRINT  ZS7TC, ZS7PU, FS7TC, FS7FE, FAGBC, FSGBC, FSGRCY, FAGSEP,...
FSGSEP, FTGBC, FSGCVF,                                          ...
        FSGFE,GUGFE,YXGFE,YZGFE
  PRINT SX8CO, YX8CO,OU8CO,GU8CO,ERROR,ERRINT,FGGAL
PRINT ZS8TC, ZS8PU, FS8TC, ZABINT, FS8FE, FS8EC, FSHRCY, ...
       FTHBC ,FGHAL, ZA7BC, FA8TC,HAGCL,SUGCL,YUGCL,HA7CL,SU7CL,YU7CL
PRINT  HA8CL,SU8CL, YU8CL,VA7TNK, LOWGAL,HIHGAL
PLOT FS7TC, FS8TC, FSGFE,GUGFE,ZS8TC,FS8EC,FS8FE
PLOT ZABINT,ERROR,ERRINT,FGHAL,VA7TNK
PLOT GU8CO,OU8CO,GU7CO,OU7CO
PLOT FTHBC,FGGAL,FAGBC,FSGBC,ZA7EC, FA8TC,ZS8PU
      UPDTE = 0.0D0
END
STOP
ENDJOB
```

```
NNNNNNNNNN    333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    NNNNNNNN
NNNNNNNNNN    3333333333333333333333333  DIGITAL EQUIPMENT CORPORATION - VAX/VMS VERSION V4.5   33333333333333333333333    NNNNNNNN
NNNNNNNNNN    333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    NNNNNNNN

                                            III  L     L      SSSS L     EEEEE Y   Y
                                              I   L     L     S     L     E     Y   Y
                                              I   L     L     S     L     E      Y Y
                                              I   L     L      SSS  L     EEEE    Y
                                              I   L     L         S L     E       Y
                                              I   L     L         S L     E       Y
                                            III  LLLLL LLLLL SSSS  LLLLL EEEEE   Y

                      CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE    333333    PPPPPPPP    UU      UU
                      CCCCCCCC  YY      YY    CCCCCCCC  LL          EEEEEEEEEE    333333    PPPPPPPP    UU      UU
                    CC          YY      YY  CC          LL          EE          33      33  PP      PP  UU      UU
                    CC          YY      YY  CC          LL          EE          33      33  PP      PP  UU      UU
                    CC            YY  YY    CC          LL          EE                  33  PP      PP  UU      UU
                    CC            YY  YY    CC          LL          EE                  33  PP      PP  UU      UU
                    CC              YY      CC          LL          EEEEEEEE          33    PPPPPPPP    UU      UU
                    CC              YY      CC          LL          EEEEEEEE          33    PPPPPPPP    UU      UU
                    CC              YY      CC          LL          EE                  33  PP          UU      UU
                    CC              YY      CC          LL          EE                  33  PP          UU      UU
                    CC              YY      CC          LL          EE          33      33  PP          UU      UU
                    CC              YY      CC          LL          EE          33      33  PP          UU      UU
                      CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE    333333    PP          UUUUUUUUUU
                      CCCCCCCC      YY        CCCCCCCC  LLLLLLLLLL  EEEEEEEEEE    333333    PP          UUUUUUUUUU

                                            PPPPPPPP    MM      MM    SSSSSSSS    ;;;;        222222
                                            PPPPPPPP    MM      MM    SSSSSSSS    ;;;;        222222
                                            PP      PP  MMMM  MMMM  SS            ;;;;      22      22
                                            PP      PP  MMMM  MMMM  SS            ;;;;      22      22
                                            PP      PP  MM  MM  MM  SS                              22
                                            PP      PP  MM  MM  MM  SS                              22
                                            PPPPPPPP    MM      MM    SSSSSS      ;;;;            22
                                            PPPPPPPP    MM      MM    SSSSSS      ;;;;            22
                                            PP          MM      MM          SS    ;;;;          22
                                            PP          MM      MM          SS    ;;;;          22
                                    ....    PP          MM      MM          SS      ;;        22
                                    ....    PP          MM      MM          SS      ;;        22
                                    ....    PP          MM      MM  SSSSSSSS      ;;        2222222222
                                    ....    PP          MM      MM  SSSSSSSS      ;;        2222222222


FILE _DUB0:[ILLSLEY.PMSP]CYCLE3PU.PMS;2 (4561,2,0), LAST REVISED ON 30-JUL-1987 14:43, IS A 39 BLOCK SEQUENTIAL FILE OWNED BY UIC
[DYNAMICS,ILLSLEY].  THE RECORDS ARE VARIABLE LENGTH WITH IMPLIED (CR) CARRIAGE CONTROL.  THE LONGEST RECORD IS 72 BYTES.

JOB CYCLE3PU (23) QUEUED TO SYS$PRINT ON 30-JUL-1987 14:44 BY USER ILLSLEY, UIC [DYNAMICS,ILLSLEY], UNDER ACCOUNT    AT PRIORITY
100, STARTED ON PRINTER _LPA0: ON 30-JUL-1987 14:45 FROM QUEUE SYS$PRINT.

NNNNNNNNNN    333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    NNNNNNNNNN
NNNNNNNNNN    3333333333333333333333333  DIGITAL EQUIPMENT CORPORATION - VAX/VMS VERSION V4.5   33333333333333333333333    NNNNNNNNNN
NNNNNNNNNN    333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    NNNNNNNNNN
```

```
INITIAL
£
£       COLUMN GEOMETRY CALCULATIONS XSA OF COLUMN TOP SETTLER AND PULSE
£
        AM9TC  = PI/4.0D0 * LM9TC   ** 2.0D0
        AM9COL = PI/4.0D0 * LM9DIA ** 2.0D0
        AMOTC  = PI/4.0D0 * LMOTC   ** 2.0D0
        AMOCOL = PI/4.0D0 * LMODIA ** 2.0D0
        AM9PU  = PI/4.0D0 * DIA9PU ** 2.0D0
        AMOPU  = PI/4.0D0 * DIAOPU ** 2.0D0
        AM9AL  = PI/4.0D0 * LM9AL   ** 2.0D0
        AMOAL  = PI/4.0D0 * LMOAL   ** 2.0D0
        VAOCOL = ( ZPOTOP - ZCOBTM ) * AMOCOL
        VS9COL = ( ZP9TOP - ZC9BTM ) * AM9COL
£       CIRCUMFERENCE OF SOLVENT OFTAKES
        LM9CRC = PI * LM9EXT
        LMOCRC = PI * LMOEXT
        EPSLN2 = EPSLON * EPSLON
        CDS2   = CDS * CDS
£       TIMER FLAG FOR GASLIFT CONTROL ON COL 9
        I9FLAG = 0.0D0 - ( 10.0 * DELT )
NOSORT

IF ( INITAL .GE. 0.5D0 ) THEN

        VS92Z =  VS9COL + ( ZS9TCZ - ZP9TOP ) * AM9TC
        VS9TCZ = AM9TC * ( ZS9TCZ - ZP9TOP )
        VS9PZ  = AM9PU * ( ZS9PUZ - ZP9BTM )
        VAO2Z  = ( ZAOINZ - ZPOTOP ) * AMOTC + VAOCOL
        VSO3Z  = AMOTC * ( ZSOTCZ - ZAOINZ )
        VSOPZ  = AMOPU * ( ZSOPUZ - ZPOBTM )

ENDIF
       UPDTE = 0.0D0
£    SET VALUES FOR  IDMP,ICDMP
       IDMP = CIDMP + 0.1
       ICDMP = CICDMP + 0.1
£  SET CONVERGENGE FACTOR FOR USE IN SULPHATE.
       IF ( ( STEADY .GT. 0.5 ) .OR. ( ALINE .GT.0.5 ) ) THEN
         CONV = CONVS
       ELSE
         CONV = CONVD
       ENDIF
SORT
£   CALCULATE CONSTANT FACTOR IN MIAOS CORRELATION FROM PLATE FREE AREA
       FRSQ1 = XMUFRE * XMUFRE
       KMUSI1 = FRSQ1 / ( 1.0D0 - XMUFRE ) / ( 1.0D0 - FRSQ1 )
NOSORT
       UPDTE = 0.0D0
£    SET VALUES FOR  IDMP,ICDMP
       IDMP = CIDMP + 0.1
       ICDMP = CICDMP + 0.1
£  SET CONVERGENGE FACTOR FOR USE IN SULPHATE.
       IF ( ( STEADY .GT. 0.5 ) .OR. ( ALINE .GT.0.5 ) ) THEN
         CONV = CONVS
       ELSE
         CONV = CONVD
       ENDIF
SORT
```

```
£
£   CALCULATE CONSTANT FACTOR IN MIAOS CORRELATION FROM PLATE FREE AREA
£
      FRSQ1 = XMUFRE * XMUFRE
      KMUSI1 = FRSQ1 / ( 1.0D0 - XMUFRE ) / ( 1.0D0 - FRSQ1 )
       EPSLN2 = EPSLON * EPSLON
       CDS2   = CDS * CDS
£   COLUMN GEOMETRY CALCULATIONS , X-SECTIONAL AREA AND CELL VOL.
      AM9XS = 7.853981634D-1 * ( LM9DIA ** 2 )         ££££   PI / 4
      AMIXS = AM9XS
      VMICL = AMIXS * LMILEN / NMICL
      VM9CL = AM9XS * LM9LEN / NM9CL
£  CONSTANT FACTORS FOR INTERFACIAL AREA CALCULATION.
      AA9IFF = 6.0D0 * VM9CL / LA9DIA
      AAIIFF = 6.0D0 * VMICL / LAIDIA
£   COLUMN GEOMETRY CALCULATIONS , X-SECTIONAL AREA AND CELL VOL.
      AMOXS = 7.853981634D-1 * ( LMODIA ** 2 )         ££££   PI / 4
      VMOCL = AMOXS * LMOLEN / NMOCL
£  CONSTANT FACTOR IN INTERFACIAL AREA CALCULATION.
      ASOIFF = 6.0D0 * VMOCL / LSODIA
DYNAMIC
NOSORT
      UPDTE = UPDTE + 1.0D0
SORT

       GU5BCD = GU5CO
       GP5BCD = GP5CO
       FA5BCD = FA5BC
       YZ5BCD = YZ5CO
       YX5BCD = YX5CO
£
£      FEED TANK TO CYCLE3 PLUTONIUM IS FILLED FROM AQ COLUMN 5
£
 VA9TNK, GUIFE, GPIFE, YZIFE, YXIFE = BUFTNK ( GU5BCD, GP5BCD, ...
        YZ5BCD, YX5BCD, FA5BCD, FAIFE, VTNK9Z, GUTN9Z, GPTN9Z,  ...
        YZTN9Z, YXTN9Z, GUICON, GPICON, YZICON, YXICON, FAICON,...
        FAITNK, GU9BC, GP9BC, YZ9BC, YX9BC )
£       STEP DISTURBANCES ON VARIOS FEEDS
        FAIFE = BFAIFE + BFAIFE * STEP(TFAIFE) * SFAIFE
       FSICVF = BFSICV + BFSICV * STEP(TFSICV) * SFSICV
        FAOFE = BFAOFE + BFAOFE * STEP(TFAOFE) * SFAOFE

£
£       SOLVENT FLOWS FROM COLUMN 9 TO COLUMN 10
£
       SXOFE = SX9TC
       OUOFE = OU9TC
       OPOFE = OP9TC
       FSORCY = FS9TC
£
£       COLUMN 9 MACRO SOLVENT CONTINUOUS
£
£  CALL TO MACRO MACAQ4 FOR COLUMN 9E.
     FAICL , HAICLD , YXICLD , YUICLD , YPICLD , ...
     FSICL , SXICLD , SUICLD , SPIGLD , ...
     FAICO , YXICO , GUICO , GPICO , FSICO , SXICO , ...
     OUICO , OPICO , DAICL ,DSICL , YZICLD , YZICO = ...
     MACAQ4 ( FAITTE , YXIMIE , GUIMIE , GPIMIE , HAICL , YXICL , ...
              YUICL , YPICL , XA9BM , 0.0D0 , FA9BE , 0.0D0 , ...
              0.0D0 , 0.0D0 , 0.0D0 , FSIFE , SXIFE , ...
```

```
               OUIFE , OPIFE , SXICL , SUICL , SPICL , XOIINS , ...
               XS9BM , 1.0D0 , 0.0D0 , SX9BE , OU9BE , ...
               OP9BE , DS9BE , NMICL , 16 , AAIIFF , IQ9EQ , ...
               AB9PL , BB9PL , VMICL , AMIXS , TQICL , ...
               HAICLZ , YUICLZ , YPICLZ , YXICLZ , ...
               SUICLZ , SPICLZ , SXICLZ , YZIMIE , ...
               YZICL , 0.0D0 , YZICLZ , RG9SLC , QIIDEN )
£    CONNECT SCRUB AND EXTRACT PARTS OF COLUMN 9.
£    SOLVENT FROM EXTRACT TO SCRUB,INCLUDING COMPENSATING FOR BACKFLOW
      FSIBE = XS9BM * FSICO
      FS9FE = FSICO + FSIBE
      SX9FE = SXICO
      OU9FE = OUICO
      OP9FE = OPICO
£    CALCULATE AQUEOUS BACK FLOW ACROSS JOIN
      FA9BE = XA9BM * FA9CO
      FA9GRO = FA9CO + FA9BE
£    AQUEOUS FROM SCRUB TO EXTRACT , AND MIX WITH LOADED FEED.
      FAITTE = FA9GRO + FAIFE
      YXIMIE = ( FA9GRO * YX9CO + FAIFE * YXIFE ) / FAITTE
      GUIMIE = ( FA9GRO * GU9CO + FAIFE * GUIFE ) / FAITTE
      GPIMIE = ( FA9GRO * GP9CO + FAIFE * GPIFE ) / FAITTE
      YZIMIE = ( FA9GRO * YZ9CO + FAIFE * YZIFE ) / FAITTE
£    PROCEDURES FOR COPYING CONCENTRATIONS IN BACK FLOWS.
PROCEDURE YXIBE , GUIBE , GPIBE , DAIBE , YZIBE = ...
          CONCP1( YXICL , YUICL , YPICL , DAICL ,YZICL )
      YXIBE = YXICL(1)
      GUIBE = YUICL(1) * MUUAW
      GPIBE = YPICL(1) * MPUAW
      DAIBE = DAICL(1)
      YZIBE = YZICL(1)
ENDPRO
PROCEDURE SX9BE , OU9BE , OP9BE , DS9BE = ...
          CONCP2( SX9CL , SU9CL , SP9CL , DS9CL )
      JJ = NM9CL + 0.1D0
      SX9BE = SX9CL(JJ)
      OU9BE = SU9CL(JJ) * MUUAW
      OP9BE = SP9CL(JJ) * MPUAW
      DS9BE = DS9CL(JJ)
ENDPRO

£  CALL TO MACRO MACAQ4 FOR COLUMN 9S.
      FA9CL , HA9CLD , YX9CLD , YU9CLD , YP9CLD , ...
      FS9CL , SX9CLD , SU9CLD , SP9CLD , ...
      FA9CO , YX9CO , GU9CO , GP9CO , FS9CO , SX9CO , ...
      OU9CO , OP9CO , DA9CL ,DS9CL , YZ9CLD , YZ9CO = ...
      MACAQ4 ( FA9FE , YX9FE , GU9FE , GP9FE , HA9CL , YX9CL , ...
               YU9CL , YP9CL , XA9BM , 1.0D0 , 0.0D0 , YXIBE , ...
               GUIBE , GPIBE , DAIBE , FS9FE , SX9FE , ...
               OU9FE , OP9FE , SX9CL , SU9CL , SP9CL , XOIINS , ...
               XS9BM , 0.0D0 , FSIBE , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , NM9CL , 4 , AA9IFF , IQ9EQ , ...
               AB9PL , BB9PL , VM9CL , AM9XS , TQ9CL , ...
               HA9CLZ , YU9CLZ , YP9CLZ , YX9CLZ , ...
               SU9CLZ , SP9CLZ , SX9CLZ , YZ9FE , ...
               YZ9CL , YZIBE , YZ9CLZ , RQ9SLC , Q9IDEN )
£
£  CALL COLUMN MACRO COLSM2
£
   FA9EC = FA9FE + FAIFE + FAIRCY
```

```
   ZS9TC, ZS9PU, FS9TC, FS9EC, FSIFE, FAIBC, FSIBC, CP9TC,OU9TC,...
   SX9TC, VS9TC, VS92, VA9BC, ZA9BC, FA92 =                        ...
   COLSM2 ( AM9PU, AM9TC, DAICL(20), DSICL(20),DA9CL(1),DS9CL(1),...
             FA9EC, FSICVF, FSIRCY, FTIBC, LPLC9, NPLC9,          ...
             PB9TP, PB9TC, VS9PZ, VS92Z, VS9TCZ, ZS9WIR, ZP9TOP,...
             FSIDIV, ZC9BTM, ZP9BTM, LM9CRC, FAICO,FS9CO, OP9CO, ...
             OU9CO, SX9CO, OU9TCZ, OP9TCZ, SX9TCZ, VS9COL, VA9BCZ, ...
             AS9CCL, ZC9BTM )
£
£    CALL SETTLER MACRO
£
     FAISEP, FSISEP = SVSIM ( FAIBC, FSIBC )

     FSIRCY = DELAY ( 5, 8.0D-03, FSISEP )
£
£    DESTINATION OF AQ OVERFLOW DEPENDS ON DIVERTER SETTING
£
PROCEDURE FAIRCY, FAIMAL, FAITNK = DIVERT ( ICIDIV, FAISEP )

          FAIRCY = 0.0D0
          FAIMAL = 0.0D0
          FAITNK = 0.0D0

       IF ( ICIDIV .GT. 0.5D0 .AND. ICIDIV .LE. 1.5D0 ) THEN
£
£           NORMAL OPERATION AQ TO MALS RECEIPT TANK
£

            FAIMAL = FAISEP
            FAIRCY = 0.0D0
            FAITNK = 0.0D0

        ELSE IF ( ICIDIV .GT. 1.5D0 .AND. ICIDIV .LE. 2.5D0 ) THEN
£
£           AQUEOUS STREAM RECYCLED TO FEED TANK
£
            FAITNK = DELAY ( 5, 5.0D-03, FAISEP )
            FAIRCY = 0.0D0
            FAIMAL = 0.0D0

        ELSE
£
£           AQ OVERFLOW RECYCLED TO COLUMN
£
            FAIRCY = DELAY ( 5, 5.0D-03, FAISEP )
            FAITNK = 0.0D0
            FAIMAL = 0.0D0

        ENDIF
ENDPRO
£
£   PROCEDURE TO CALCULATE GAS SETTING TO I GAS.LIFT TO ALLOW FOR
£   FSISEP FAILING
£
PROCEDURE FGIAL = CHECK ( FGISET,FSISEP, TSISTP, FSISTP, FSICUT )

    IF ( FSISEP .GE. FSICUT ) THEN
£
£      OKAY
£
```

```
      FGIAL = FGISET
      IIFLAG = 0.0D0

    ELSE IF ( FSIRCY .LT. FSICUT .AND. TIME .GE. (IIFLAG + ...
              TSISTP )) THEN
£
£     SOLVENT OVERFLOW FAILED STEP UP GAS FLOW BY 2%
£     SET IIFLAG=TIME TO PREVENT MULTIPLE INCREASES
£

      FGIAL  = FGISET * ( 1 + FSISTP )
      FGISET = FGIAL
      IIFLAG = TIME

£
£   THIS BIT IS JUST TO COVER THE SITUATION THAT ARISES AT TIME=0.0
£   WHEN TIME = 0.0,IIFLAG=DELT AND FSISEP=0.0D0 WHICH CAUSES A
£   CRASH IN CLARK
£
    ELSE

        FGIAL = FGISET

    ENDIF

ENDPRO
£
£  CALL GASLIFT MACRO
£
     FTIBCT= CLARK (ZG9IN, FGIAL,ZS9TC, ZG9DEL, AM9AL, DSICL(20),
             DAICL(20),LM9AL, PB9TC, PB9DEL, VAMCON, ROUGH, KCLARK, ...
             CNVIMA, PG9IN )
     FTIBC = DELAY ( 5, 2.0D-01, FTIBCT )

£
£  CALL TO MACRO MACSO3 FOR COLUMN 10
£
      FAOCL , HAOCLD , YXOCLD , YUOCLD , YPOCLD , ...
      FSOCL , SXOCLD , SUOCLD , SPOCLD , ...
      FAOCO , YXOCO , GUOCO , GPOCO , FSOCO , ...
      SXOCO , OUOCO , OPOCO , DAOCL , DSOCL = ...
      MACSO3 ( FAOFE , YXOFE , GUOFE , GPOFE , HAOCL , YXOCL , ...
               YUOCL , YPOCL , XAOBM , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , 0.0D0 , FSOFE , SXOFE , ...
               OUOFE , OPOFE , SXOCL , SUOCL , SPOCL , XOOINS , ...
               XSOBM , 0.0D0 , 0.0D0 , 0.0D0 , 0.0D0 , ...
               0.0D0 , 0.0D0 , NMOCL , 11 , ASOIFF , IQOEQ , ...
               ABCPL , B9OPL , VMOCL , AMOXS , TGOCL , HAOCLZ , ...
               YUOCLZ , YPOCLZ , YXOCLZ , SUOCLZ , SPOCLZ , ...
               SXOCLZ , RUOFUN , RPOFUN , RXOFAC , QOIDEN )

£
£       COLUMN 10 MACRO AQUEOUS CONTINUOUS
£
        ZSOTC, ZAOINT, ZSOPU, VAO2D, VSO3D, VSOPD, VAO2, VSO3,  ...
        VSOP, FSOTC, FAOTC, FSOEC, FSOFE, FAOFE, OUOTC, OPOTC, ...
         SXOTC                                                 ...
         = COLTES ( AMOPU, AMOTC,                               ...
        FAOFE, FSORCY, FSIRCY, FTOBC, LPLCO, NPLCO,PBOTP,        ...
        PBOTC, VAO2Z, VSO3Z, VSOPZ, ZSOWIR, FSODIV, ZCOBTM,     ...
```

```
        ZPOBTM, LMOCRC, FSOCO, FAOCO, ZPOTOP, CDS, OUOCO, OPCCO,...
        11, DAOCL, DSOCL, HAOCL, FAOEPZ, VAOCOL, FSO2Z , OUOTCZ,...
        OPOTCZ, SXOTCZ, SXOCO, AMOXS )

£
£       PI CONTROLLER USED INCORRECTLY
£
         FGOAL, ERRORO, EROINT = PICONT ( ZAOINT, ZAOSET, GAINO, ...
                RESTIO, FGOSET, CJOSEN, ERROZ )
          FTOBCT = CLARK ( ZGOIN, FGOAL, ZSOTC, ZGODEL, AMOAL, ...
                 DAOCL(11), DAOCL(11), LMOAL, PBOTC, PBODEL,...
                 VAMCON, ROUGH, KCLARK, CNVIMA, PGOIN )


      FTOBC = DELAY(5,2.0D-01,FTOBCT)

£
£     SETTLER ON BOTTOM OUTFLOW FROM COL 10,AQ TO PRODUCT WASH
£
      FAOPRD, FSORCY = SVSIM ( FAOBC, FSOBC )
£
£     SETTLER ON TOP OUTFLOW FROM COL10 SOLVENT TO WASH , AQ RETURNED
£
      FAORTN, FSOWSH = SVSIM ( FAOTC, FSOTC )
      FAOBC = FTOBC
      FSOBC = 0.0D0

      FSODIV = 0.0D0

 SPACE METHOD=50000
 SPACE PRINT = 150
 SPACE PLOT = 100
TITLE EORP DYNAMIC RUN FIRST ATTEMPT
METHOD WARP2
ABSERR YP9CL(1)=1.0D-6
SPACE HOLD = 20
TIMER PRDEL=0.010D0,FINTIM =0.5000D0,DELT = 0.01,OUTDEL=0.01
TERMINAL
      IF ( IDMP .GT. 0 ) THEN
        CALL DUMPI ( IDMP )
      ENDIF
      IF ( ICDMP .GT. 0 ) THEN
        CALL DUMPIC ( ICDMP )
      ENDIF
      UPDTE = 0.0D0
£ CONSTANTS IN SLATER CORRELATION AS MODIFIED BY AH 28/08/85.
£ VALUES TO MATCH DESIGN SS.
      STORAGE RQ9SLC(7)
   TABLE RQ9SLC(1-7) = 1.1040 , 0.7416 , 0.02874 , ...
                       0.0 , 0.0 , 0.02874 , ...
                       0.093297
£  OVERWRITE RQ7SLC(1-3) FOR REVISED COEFFS.
   TABLE RQ9SLC(1-3) = 0.75000 , 0.74160 , 0.02000
£££££££££££££££££££££££££

£ CONSTANTS IN SLATER CORRELATION AS MODIFIED BY AH 28/08/85.
£ VALUES TO MATCH DESIGN SS.
£££££££££££££££££££££££££
£ VALUES TO MATCH DESIGN SS.
£££££££££££££££££££££££££
```

```
PRINT UPDTE,OU9CO ,OP9CO ,GUICO ,GPICO ,YZICO
PRINT OP9TC, OU9TC, SX9TC
PRINT  ZS9TC, ZS9PU, FS9TC, FS9FE, FAIBC, FSIBC, FSIRCY, FAISEP,...
FSISEP, FTIBC, FSICVF,                                            ...
       FSIFE
PRINT SX0CO, YX0CO,OU0CO,GU0CO
PRINT ZS0TC, ZS0PU, FS0TC, ZA0INT, FS0FE,  ...
      FTIBC ,FSIAL
END
STOP
ENDJOB
```

APPENDIX F

TECHNICAL DATA