

# **DEVELOPMENT AND MODELLING OF A SEMI-BATCH FLOTATION APPARATUS**

**By**

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## ABSTRACT

When designing or optimizing flotation circuits in mineral processing plants, it is necessary to have accurate values of the flotation kinetics to ensure the correct mass pulls and material balances on the plant. Previous studies have shown that rate constants measured by single cell batch testing can cause a shift in the recovery—grade curve. The shift in the recovery—grade curve is the result of poor separation in conventional laboratory flotation devices.

This project involved the development and modelling of a flotation device that provides a better separation than a conventional batch flotation cell. The device is called a semi—batch flotation apparatus (SBFA) because it simulates the operations of a pilot plant in a laboratory environment. It also provides dynamic data which facilitates the evaluation of model parameters. The SBFA tested a synthetic ore made from limestone, talc and silica. The synthetic ore was used as it was economical and easy to analyze.

The results from the SBFA were compared to results obtained from conventional batch flotation tests; by using recovery—grade curves to assess the degree of separation achieved from both devices. The SBFA separated the limestone from the gangue (silica and talc) much better than the batch tests. For instance the final grade for a concentrate obtained from a single cell batch test was 20 % limestone while the final grade for a concentrate obtained from the SBFA was between 40 % and 70 % limestone. The improvements in separation can be attributed to the multistage design of the SBFA which has a pulp recycle between the stages.

A model has been developed for the SBFA. The model fitted the experimental data well with a correlation coefficient close to unity. The cumulative recoveries predicted from the SBFA model was compared to the actual cumulative recoveries, by using a global set of parameters ( $k_2$  and  $R_{MAX}$ ). The investigation showed that the model had problems in fitting the data for the early periods of the experiments because of the complex interaction between the stages in the SBFA.

## **PREFACE**

I, Nigel Valentino Ramlall declare that unless indicated, this thesis is my own work and that it has not been submitted for a degree at another University or Institution.

Nigel Valentino Ramlall

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## NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
$a$	Time delay for froth formation in cell one, SBFA	min
$A_c$	Cross sectional area of cell	$m^2$
$b$	Time delay for froth formation in cell one, SBFA	min
$P$	Exponential constant for equation 5 & 6	$mmin^{-i}$
$C$	Solids concentration for equation 2	$gm^{-3}$
$H$	Froth height	mm
$n$	Scaling parameter for equation 18	$m^{-1}$
$h$	Superficial gas/air velocity	$mmin^{-i}$
$k$	Flotation kinetic or rate	mm
$K$	Collection zone kinetic	$min^{-1}$
$L$	Perpendicular height between impeller and launder	m
$M$	Mass of valuable component for equation 11	g
$N$	Number of bubbles for equation 10	
$P$	Floatability for equation 9	
$P$	Density of recycle stream in SBFA	$gm$
$Q$	Air flow rate	$m^3-min$
	Recycle rate of stream in SBFA	$m^3min$
	Particle radius for equation 10	m
$r$	Correlation coefficient	
$R$	Percentage cumulative Recovery	
$R_h$	Bubble radius for equation 10	m
$R_f$	Percentage froth zone Recovery	
$Re$	Collection zone recovery	
$R_{MAX}$	Percentage maximum recovery	
$S_b$	Bubble surface area flux	mm
$SER$	Standard error of recovery	
$T$	Induction time for equation 10	mm
	Specific froth residence time	$mm\ mm$

$Xf_g^c$	Froth residence time	min
$\theta$	Reduced kinetics	—
$\langle p \rangle$	Fruitfulness froth factor for equation 10	—
$\nu$	Time correction for                      froth	min
$V$	Cell volume	m <sup>3</sup>
$x$	Mass fraction of valuables	—

## SUBSCRIPTS

1-CelloneofSBFA

2-CelltwoofSBFA

## INTRODUCTION

Flotation is an important mineral processing operation; almost 80 % of all low—grade ores are treated economically by flotation (Gutzeit 1968). Ernest Gayford (cited in Parekh, 1999) stated that,

*"The flotation process is undoubtedly the most important development in the recovery of minerals from ores that has taken place during the last century. No other process has effected such a great change in metallurgy in so short a time. Looked upon with suspicion by the old—time mill man, hampered by tedious and expensive patent litigation, it has nevertheless forged ahead until no one can foretell where it may lead us. "*

This project is concerned with the development and modelling of a laboratory flotation device called the semi—batch flotation apparatus (SBFA). The device is believed to separate material better than a conventional batch flotation device used in the laboratory. For instance single cell flotation devices do not separate valuable materials from gangue materials efficiently therefore the concentrate has to be re—flotated at least twice in order to obtain a separation close to that obtained in a pilot plant. The SBFA addressed this problem by using multiple stages with pulp recycles between the stages. The multistage design with pulp recycles gave a better separation than the single cell batch test. The SBFA can be extended to any number of stages; however a two stage design was investigated in this project.

### Conventional batch flotation tests

Flotation tests in a laboratory are normally conducted in a single batch flotation cell. A small mixture of diverse solids of a metalliferous ore can be treated in the batch cell so that it can be divided into its component parts. The more valuable component is collected as a concentrate of relatively small amount, while the remaining components are discharged as tailings.

It is for this reason that laboratory batch tests are considered the workhorse of flotation research and development, since studies can be done on reagent development, everyday plant performance, and plant optimization and design (Vera et al., 2002).

Aside from the solid, liquid and gaseous phase; flotation is complicated by many variables such as particle size, bubble size, air flow rate, impeller speed, etc that occur simultaneously. Therefore laboratory batch flotation tests cannot effect a complete separation of the valuable components from the gangue material.

The separation of an ore into its components can be best described by a recovery—grade curve. In the laboratory the recovery—grade curve for an ore can be generated by doing locked cycle batch tests, in which the concentrate is re—floated and the cleaner tailings recycled to the rougher flotation tests. These tests are time—consuming and subject to errors associated with manual removal of the froth by scraping.

Therefore the objective of this project was the development and modelling of a laboratory scale flotation device that can be used to separate an ore better than a conventional batch flotation test. The work covered in this thesis can be divided into three areas:

1. Batch flotation of a synthetic ore using conventional laboratory flotation techniques.
2. Development of a flotation device that incorporates the workings of a pilot plant but having the ease of operation familiar to a batch test.
3. Evaluation of the separation achieved in both the batch and SBFA tests.

The experiments done on the SBFA were duplicated to test for reproducibility. The kinetics and the final concentrate grade and recovery from the duplicate test did not vary considerably from the parent test.



## 2.0 LITERATURE SURVEY AND THEORY

This chapter provides a brief note on the theory governing froth flotation. The theory is divided into five sections:

1. Importance of froth flotation in mineral processing
2. Froth flotation
3. Flotation froth phase
4. Recovery—grade curves
5. Batch flotation models

### 2.1 Importance of froth flotation in mineral processing

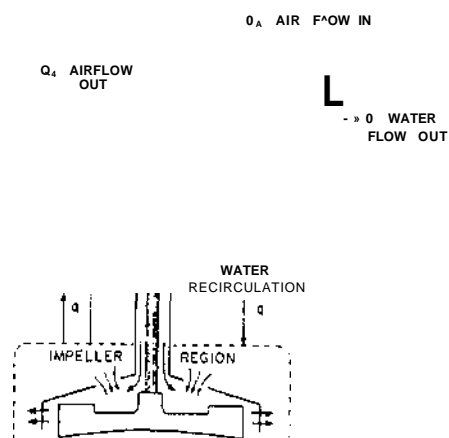
Crabtree (1968) stated that, "Probably no metallurgical process in the history of the mining industry has been responsible for such increased mineral production as flotation."

Flotation in the mining industry allows for the economic treatment of low—grade and complex ores bodies. Almost 80 % of all ore bodies are economically treated by flotation, (Gutzeit, 1968). Many of the ores treated by flotation are complex, finer grained and more refractory to treatment therefore further elaboration of the flotation process will demand a greater understanding of the fundamentals governing flotation. Many of the fundamentals governing flotation have been established by batch flotation tests carried out in a laboratory; see Figure 2—1 for a conventional batch flotation setup.

In order to assess the flotation process behavior, batch flotation tests are normally developed at laboratory scale. The results are then scaled up to plant operation based on empirical factors that are used to establish the proper operation strategy (Yianatos et al., 2006).

However conventional batch flotation tests are limited in the ability to separate the valuable components from gangue materials, since the total concentrate has to be re—floated at least twice in order to simulate the separation achieved in a flotation bank. In addition, froth effects are often ignored because the froth recovery ( $R_f$ ) is assumed to be 100 %; which is incorrect since inefficiencies in the froth zone can lead to inefficient separation of the valuable components.

Ferreira and Loveday (2000) stated that, "Probably the biggest stumbling block to the accurate modelling of flotation, is understanding what happens in the froth zone. It is known that the recycle of material from the froth zone back to the pulp can be as high as 90 %." Therefore the froth zone plays an important part in the separation.



**Figure 2—1.** A typical batch flotation cell used in laboratory tests (extracted from Harris, 1976).

## 2.2 Froth flotation

**2.2.1 Mechanics of froth flotation.** In order to effect the separation of valuable minerals from gangue material, the ore has to be crushed to a suitable size<sup>1</sup> and mixed with water and the reagent suite, for a defined period of time called the conditioning time. The reagent suite is a set of reagents that accentuate the differences in the behavior between the valuable minerals and the gangue materials. The reagent suite contains a collector, frother and regulator.

Collectors are generally organic compounds which render the valuable minerals water repellent, by reducing the stability of the hydrated layer separating the valuable mineral surface from the air bubble. The valuable mineral can then attach to the bubble to form a particle—bubble aggregate.

Frothers are water soluble chemicals that stabilize the particle—bubble aggregate by reducing the surface tension in the pulp zone. The stability of the particle—bubble aggregate depends on the efficiency of the frother i.e. the ability of the frother to reduce the surface tension.

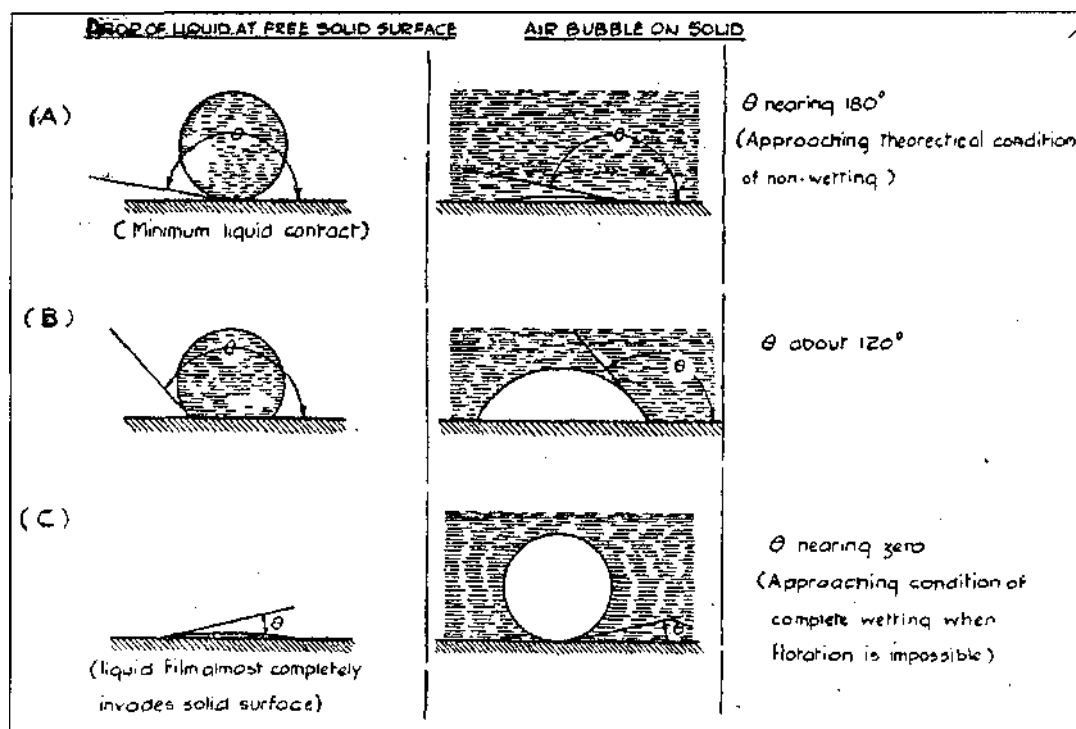
Regulators are reagents that alter the chemical nature of the mineral or gangue surface, so that the effect of the collector on the valuable minerals is enhanced while the collector effect on the gangue material is depressed. For example pH modifiers are used to create an environment suitable for collector adsorption onto the valuable mineral surface. Depressants, on the other hand, create an environment suitable for gangue material to reject the adsorption of the collector.

The combined effect of the reagent suite (collector, frother and regulator) creates a chemical environment suitable for particle—bubble aggregate formation and gangue rejection.

<sup>1</sup> A suitable size for optimal liberation of valuable minerals without crushing too fine (less than 10  $\mu\text{m}$ ) thereby forming slimes, or crushing too coarse thereby limiting the liberation of the valuable minerals.

After the pulp is conditioned with the reagent suite, the valuable minerals make contact with the air bubbles primarily in the turbulent zone of the impeller. The turbulent zone is a zone where shear forces disperse the air bubbles into smaller bubbles. The bubbles move rapidly relative to the pulp due to their high buoyancy.

The particles in the path of a bubble must cross the streamlines around the bubble and pierce the thin hydrated film between the particle and bubble in order to form a particle—bubble aggregate. Prevailing surface tension forces move the particles to an equilibrium position. Figure 2—2 shows an equilibrium contact angle on a flat surface.

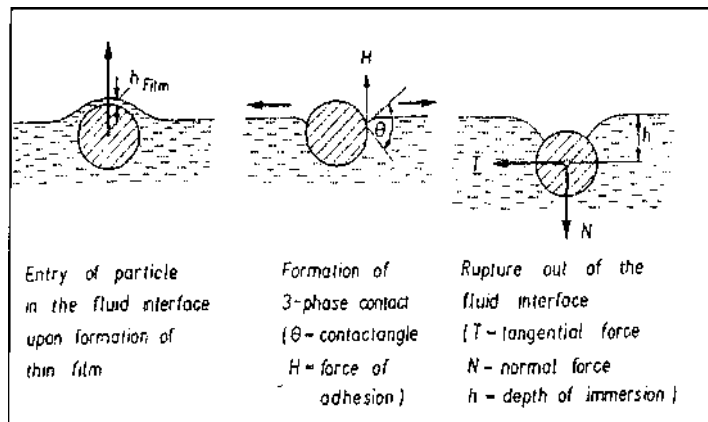


**Figure 2—2.** The importance of contact angle in forming a stable particle—bubble aggregate (extracted from Cullen and Lavers, 1936).

Large particles in the pulp have a greater probability of forming a particle—bubble aggregate but the large particle mass increases the probability of the particle detaching from the bubble surface. The detachment is due to a disruption in the forces acting on the particle—bubble aggregate.

Fine particles (less than 10  $\mu\text{m}$ ) have a lower probability of forming a particle—bubble aggregate due to the smaller particle mass which results in a lower particle momentum. The lower particle momentum makes it difficult for the fine particles to approach the air bubbles and pierce the hydrated film surrounding the bubble. Figure 2—3 shows the three processes involved in the formation of a particle—bubble aggregate.

Once the particle—bubble aggregates are formed, the bubble carries the attached particles into the froth zone. In the froth zone particles detach and reattach to the bubbles based on the particles hydrophobicity. In addition some entrained material may drain into the pulp zone. The mineralized froth is then collected in the frother launder.



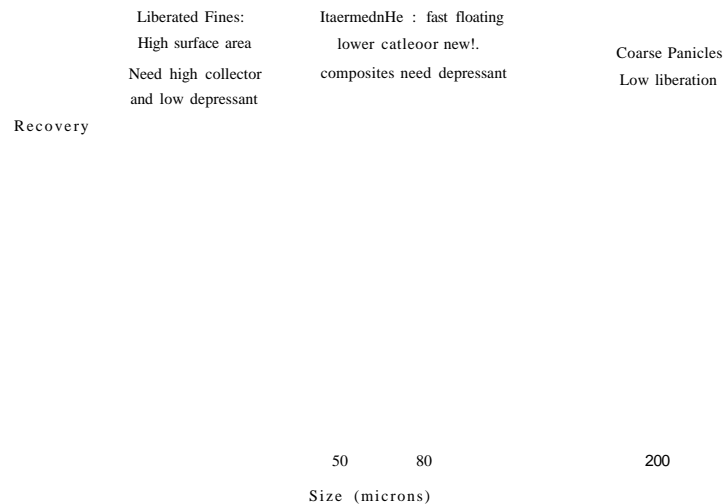
**Figure 2—3.** The three important processes involved in the attachment of a particle to a bubble (extracted from Schulze, 1977).

**2.2.2 Effect of particle size on flotation.** Flotation normally involves several mineral components with varying degrees of floatability, in a wide spectrum of particle sizes and degrees of mineral liberation. Particle size is an important variable in particle—bubble interaction, it influences the probability of particles colliding with bubbles; attachment of particles to bubbles and stabilization of the particle—bubble aggregate after attachment in the pulp zone.

The effect of particle size is encountered before the actual flotation process. Since the ore has to be crushed to a suitable size for optimal liberation of valuables without complicating events in the flotation process. For instance crushing the ore too fine can lead to the formation of slimes. In addition fine particles have large specific surface areas (surface area per unit mass) which leads to consumption of more reagents to form a suitable surface coating. In addition, fines have a smaller momentum (due to the particle mass) which results in the particles following the interstitial liquid between the bubbles and particle—bubble aggregates. Therefore fines tend to be recovered by entrainment rather than flotation.

Entrainment is a nonselective process by which fine particles are transported into the froth zone by the interstitial liquid; therefore fine particle recovery is related to water recovery. On the other hand, flotation is related to the recovery of the particle—bubble aggregates. Since fines are generally recovered by entrainment the rate of flotation of these particles tends to be lower for particle size classes greater than 10  $\mu\text{m}$ .

Large particles have a higher probability of crossing the bubble streamlines and contacting the bubble surface. However the particles have a large particle mass which decreases the buoyancy of the newly formed particle—bubble aggregate, therefore the particle may detach from the bubble surface. Figure 2—4 illustrates how particle size influences recovery. Generally coarse and fine particles are more difficult to recover than intermediate particle size classes.



**Figure 2—4.** The conventional view of how particle recovery depends on particle size (extracted from Pease et al, 2006).

In the froth zone, particle size plays a significant role in upgrading and preferential drainage of gangue into the pulp zone. Generally, upgrading is based on the particles varying hydrophobicity and size. Crawford and Ralston (1988) added that particle size together with contact angle leads to the concept of flotation domain, a region which determines whether a particle can float or not.

**2.2.3 Effect of impeller speed on air flow rate.** Gorain et al. (1999) stated that in a mechanical flotation cell the dispersion of the gas into fine bubbles can be expressed by:

- Bubble size
- Gas holdup
- Superficial gas velocity

The bubble size is an important variable since it determines the bubble carrying capacity i.e. how much mass the bubble can carry.

The gas flow rate and impeller speed are important for controlling the hydrodynamic conditions in a flotation cell. Kracht et al. (2005) stated that machine factors like gas flow, impeller speed and cell design do not affect the process performance in isolation but combined they create the hydrodynamic conditions governing flotation performance.

The superficial gas velocity ( $J$ ) is used to describe gas dispersion. Superficial gas velocity is a measure of the aeration ability of a cell and has a direct influence on the rate of flotation. Many flotation researchers accept that the superficial gas velocity can be estimated by the following equation:

$$A_c$$

Where  $Q$  is the volumetric gas flow rate and  $A_c$  is the cross sectional area of the flotation cell. Generally a high gas velocity reduces the stability of the pulp—froth interface and results in an increased entrainment of gangue in the froth zone.

Novett (cited in Gorain et al, 1995) noted that it is essential that the gas be completely dispersed in the pulp and not allowed to form comparatively large bubbles. When the impeller speed is increased there is a greater uniformity of the gas velocity at different locations which improves gas dispersion. Schubert and Bischofberger (1978) noted that turbulence is required for:

- Suspension of the particles in the pulp
- Feeding and dispersion of air
- Mixing the aerated pulp
- Reagent distribution and conditioning
- Rising of the particle—bubble aggregates and the removal of the froth

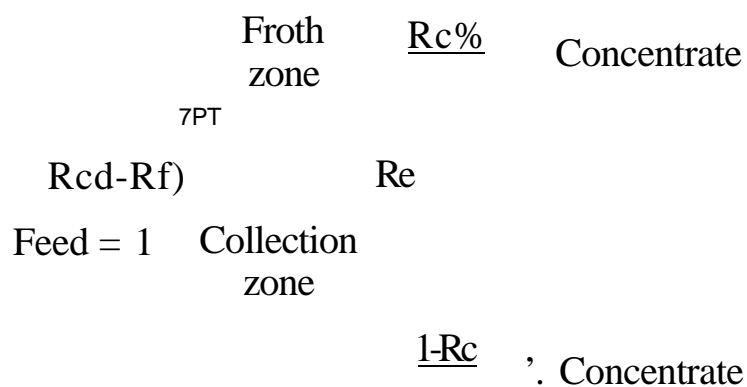


Superficial gas velocity and impeller speed are linked (Loveday, 2007) and for a given air velocity, the impeller has upper and lower limits which are characterized by particle sedimentation and surface turbulence respectively.

## 2.3 Flotation froth phase

**2.3.1 Froth recovery.** The flotation froth zone is important for accurate modelling of the flotation process. The recycle of material from the froth zone to the pulp zone can be as high as 90 %, Ferreira and Loveday (2000). In a conventional batch test the froth recovery ( $R_f$ ) is assumed to be 100 %. This assumption is misleading since it can lead to an incorrect estimation of flotation kinetics.

Harris and Rimmer (1966) were the first to account for the froth zone in modelling; they used a lumped parameter to account for the inefficiencies in the froth zone. Their results showed that the froth recovery ( $R_f$ ) reduced the overall rate constant as the froth residence time increased. Therefore the parameter  $R_f$  measures the froth performance i.e. the proportion of particle—bubble aggregates that are collected in the froth launder relative to those that enter the froth zone.



**Figure 2—5.** Interaction of the zones in a continuous flotation cell.

Figure 2—5 shows the relationship between the different flotation zones. A mathematical relationship can be established between the overall recovery and the recoveries in the froth and pulp (collection) zone, Figure 2—6 shows the relationship between the zones.

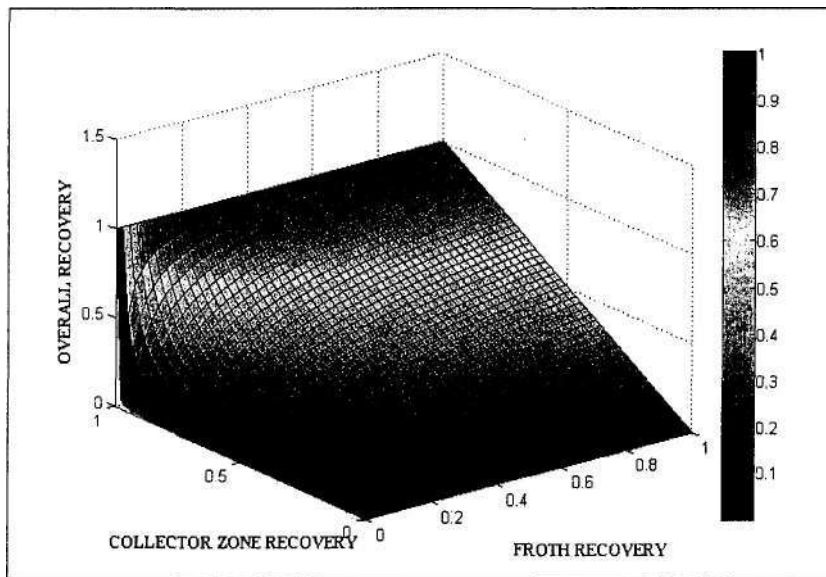


Figure 2—6. Importance of froth recovery on the overall recovery in a flotation cell. For instance, if there are inefficiencies in the froth phase (recoveries less than 100 %) then the overall recovery will be less than 100 % despite the collection zone having a recovery of 100 %.

There are two techniques that are used to measure  $R_f$  in the laboratory:

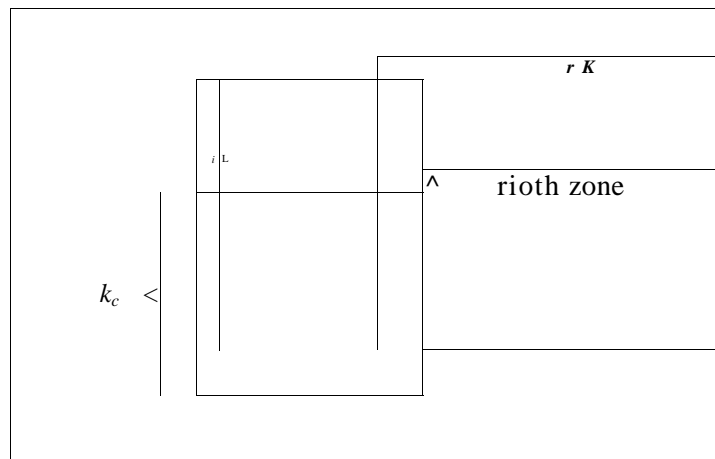
- The empirical relationship which relates the operating variable (froth height) to the metallurgical performance ( $k$ ) given by Vera et al. (1999).
- Direct measurement of the bubble loading which is the mass of the attached particles per unit volume of air bubbles below the pulp—froth interface given by Seaman et al. (2006).

The technique given by Vera is simple and inexpensive for estimating  $R_f$ . However there are two assumptions made when using this technique:

- Transfer of particles from the pulp to the pulp—froth interface depends only on events occurring in the pulp zone.
- Transfer of particles from the froth to the launder depends only on events occurring in the froth zone.

Vera showed that by varying the froth height ( $H$ ) in a batch flotation cell a set of  $k$  values can be obtained. The  $k$  values can then be extrapolated to a froth height of zero, to give the rate constant for the collection ( $k_c$ ). However the technique is dependent on cell design and impeller type. Figure 2—7 is an illustration of the technique given by Vera,  $R_f$  can be calculated by taking the ratio between  $k$  and  $k_c$ .

$$R_f = \frac{k}{k_c} \quad (2)$$



**Figure 2—7.** Illustration of the technique given by Vera for the determination of  $R_f$  in a batch cell.

Gorain et al. (1998) proposed a model that eliminated cell design and impeller type. The procedure for acquiring the data is similar to Vera's technique, however Gorain proposed an exponential model that related specific froth residence time ( $A_{fs}$ ) to  $k$ .  $X_{fs}$  is defined as:

$$h = \frac{L}{X_{fs}} \quad (0)$$

Where  $L$  is the perpendicular distance from the impeller to the froth launder.  $X_f$  is the froth residence time defined as:

$$h = \frac{H}{J_g} \quad (4)$$

$H$  is the froth height and  $J_g$  is the superficial gas velocity. The model proposed by Gorain is:

$$k = k_c e^{TM} \quad (5)$$

Equation 5 can be used to regress batch data to find the parameters  $k_c$  and  $TM$ , thereafter Equation 6 can be used to find  $R$ , for different values of  $A_{fs}$ . The parameter  $j\beta$  is related to the chemical and mechanical environment of the pulp zone.

**2.3.2 Entrainment.** Particle—bubble aggregates rising in the pulp stop near the pulp—froth interface. The particle—bubble aggregates accumulate at the interface and form layers of closely packed air bubbles and particle—bubble aggregates, which then rise in the froth zone.

However the bubbles burst at the surface and the water and particles disperse into the cavities between the bubbles and particle—bubble aggregates near the pulp—froth interface. The recovery of entrained particles with the interstitial water in the cavities is known as entrainment.

Entrainment begins near the pulp—froth interface and is closely related to conditions in the pulp such as solid concentration, particle size, gas flow rate and dispersion and bubble packing conditions at the pulp—froth interface (Zheng et al., 2006). Generally the degree of entrainment for a given particle size decreases with an increase in the froth residence time. The reason for this is that a deeper froth provides a longer froth residence time for the drainage of the entrained particles.

Increasing gas velocity increases the entrainment of a specific size fraction, generally less than 10  $\mu\text{m}$ . However increasing froth height and gas velocity provides conditions suitable for the drainage of coarse particles. The reason for this is that the particle—bubble aggregates in the froth zone tend to be loosely packed and therefore the coarse particles can drain through the cavities between the loosely packed particle—bubble aggregates.

In addition to froth residence time and superficial gas velocity, entrainment can also be accelerated by excessive froth flow which is related to high frother addition rates. Figures 2—8 and 2—9 show the different theories for particle entrainment and liquid recovery.

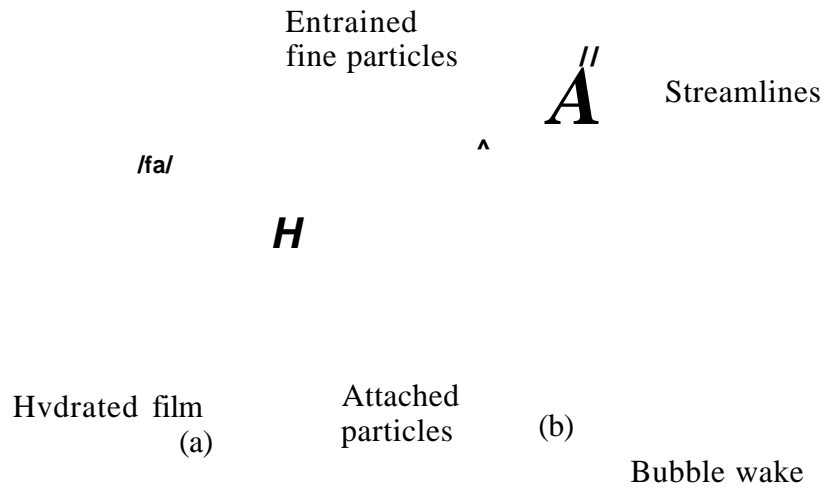


Figure 2—8. The two mechanisms by which particles are entrained, (a) The particles are carried in the thin hydrated film surrounding the bubble and (b) The particles are transported by the wake of an ascending bubble.

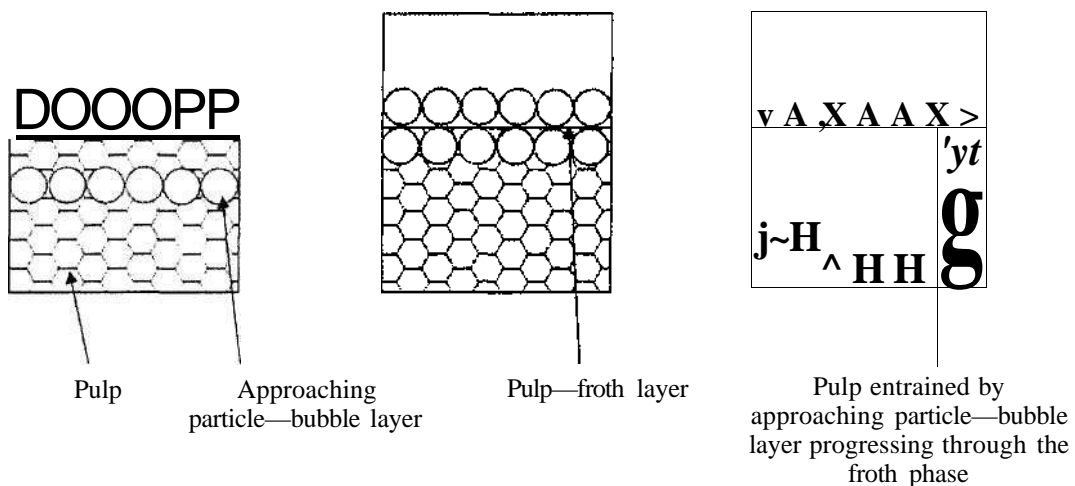


Figure 2—9. The bubble swarm theory proposed by Savassi et al. (1998). The theory infers that a layer of mineralized bubbles ascends through the froth zone with a portion of the pulp entrained in the voids between the mineralized bubbles.

2.3.3 Detachment and reattachment of particles in the froth zone. In order to understand the selectivity of particles in the froth zone one has to understand the sub—processes that affect the detachment and reattachment of particles in the froth zone. The sub—processes can be summarized as:

- Bubble coalescence
- Particle detachment
- Drainage of particles
- Particle reattachment

Bubble coalescence occurs in the upper regions of the froth; here the total available surface area of the bubbles is reduced. When bubbles coalesce the newly formed particle—bubble aggregate becomes more unstable. The unstable particle—bubble aggregate may eventually burst; resulting in the attached and entrained material dropping to the base of the froth zone.

High solids concentration in the pulp zone also influence bubble coalescence, since there is insufficient bubble surface area available for particle attachment hence particles compete for bubble space by displacing less hydrophobic particles. Particle detachment is determined by the varying degrees of hydrophobicity and particle size in the froth zone. Klassen and Mokrousov, (cited in Seaman et al, 2006) proposed six mechanisms of particle detachment, see Figure 2—10 for an illustration of these mechanisms. Seaman et al. (2006) proposed a seventh mechanism, which involves a particle—bubble aggregate striking a stationary or moving object. The particle—bubble aggregate then oscillates resulting in the particle detaching from the bubble surface.

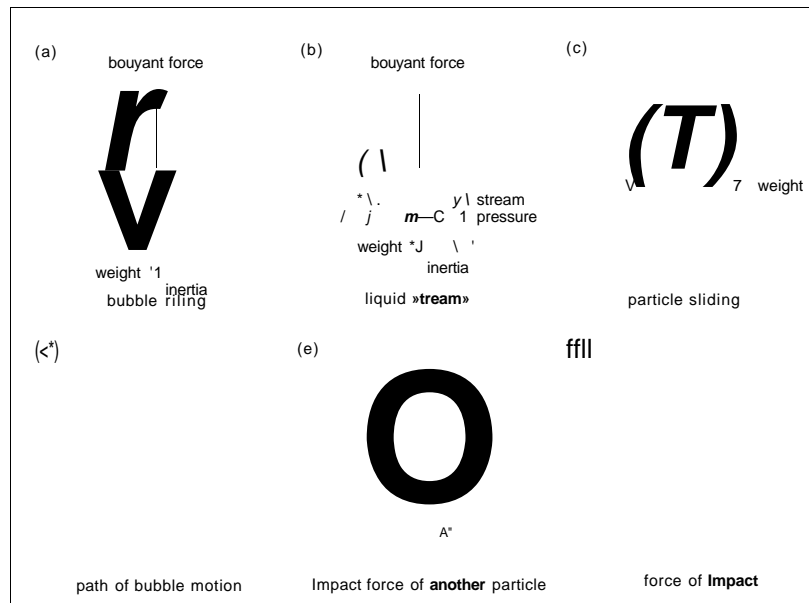


Figure 2—10. The six mechanisms of particle detachment (extracted from Klassen and Mokrousov, cited in Seaman et al., 2006). Forces tend to separate the mineral particles from the bubble: (a) during rise (acceleration or equilibrium) of a mineralized bubble surface; (b) under the action of liquid streamlines; (c) sliding of the particles along the bubble; (d) change in mineralized bubble motion; (e) impact or attrition of particles in the pulp against the mineralized bubble surface and (f) impact of a bubble with an obstacle (note that this is different from the seventh mechanism).

When particles detach in the froth zone some drain into the pulp. The drainage of previously attached particles into the pulp zone is selective with respect to particle size and density much like the entrainment mechanism.

The re—entry of particles into the pulp occurs because of the continuous drainage of liquid and bubble coalescence. Klassen and Mokrousov, (cited in Seaman et al. 2006) suggested that spraying the froth with water (froth irrigation) improves the grade because the irrigation system accelerates the drainage of liquid and entrained gangue material. In addition, increasing the froth residence time increases the drainage of material from the froth, which improves the grade.



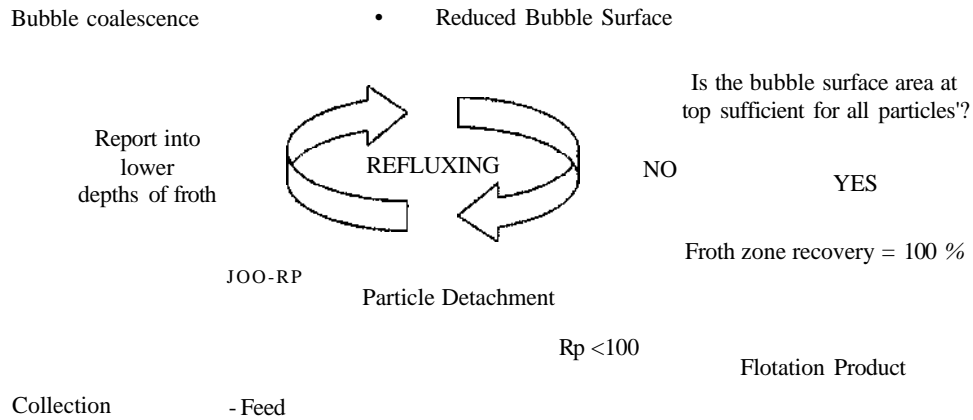


Figure 2—11. Illustration of the particle detachment process, (extracted from Honaker and Ozsever, 2003).

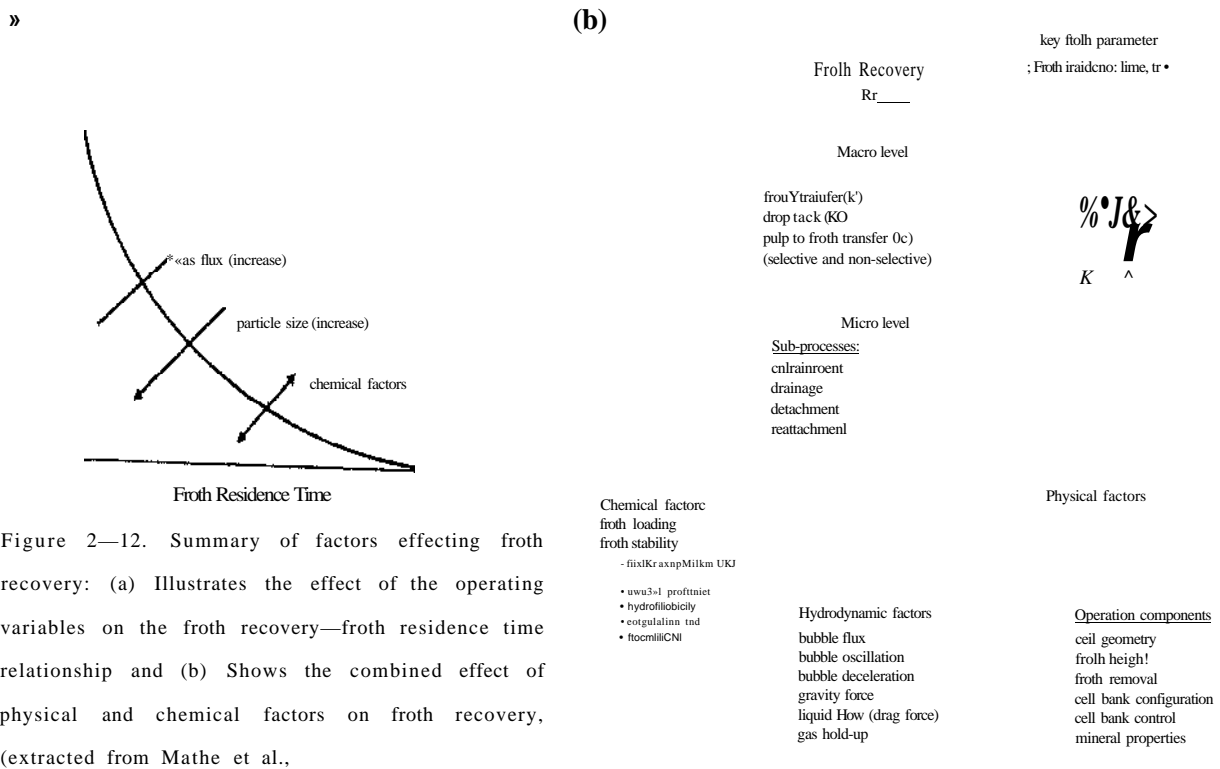


Figure 2—12. Summary of factors effecting froth recovery: (a) Illustrates the effect of the operating variables on the froth recovery—froth residence time relationship and (b) Shows the combined effect of physical and chemical factors on froth recovery, (extracted from Mathe et al.,

## 2.4 Recovery—grade curves

The effectiveness of separation is best described by a recovery—grade curve. The curve describes the purity (grade) of the valuable mineral in the cumulative concentrate and the recovery of the valuable mineral present in the original ore which is recovered in the concentrate.

Recovery—grade curves are affected by individual ore types and characteristics such as grade, texture, hardness, etc. In addition operating variables also have an effect on recovery—grade curves. Some operating variables that affect the recovery—grade curve include:

- Pulp density
- Size distribution
- Addition rates of reagent suite
- Pulp level
- Froth residence time
- Aeration rate
- Recycle between stages
- Cell size and design

High pulp densities (or high solid concentrations) are characterized by the presence of large amounts of gangue and composite particles which can be recovered in the concentrate thereby reducing the grade.

Particle size distribution is an important variable that affects grade. Fine particles are recovered in the concentrate by entrainment thereby reducing the grade.

High frother addition rates can lead to excessive froth flow and high water recovery which increases the amount of entrained gangue recovered and reduces the concentrate

grade. If insufficient collector is added then many of the valuables in the pulp may not be adequately coated which can lead to a reduced recovery of valuables.

Froth residence time is related to froth height. A shallow froth (lower froth residence time) is characterized by a higher recovery of valuables and a low grade. A deep froth (higher froth residence time) is characterized by a lower recovery of valuables and a high grade.

Superficial gas velocity influences the degree of entrainment and drainage in the froth zone.

Recycle between stages is important for optimizing separation of minerals. It is analogous to reflux in a distillation column. Loveday and Brouckaert (1995) demonstrated the effect of recycle on the sharpness of separation and the need to increase the size of the stage generating the recycle as the recycle rate is increased.

**2.5 Batch flotation models.** Loveday and Brouckaert (1995) stated that, "The ability of a model to reproduce the batch data is not a good enough criterion for ranking models because a typical flotation circuit contains at least three stages with circulating loads that can exceed the flow of floatable material in the flotation circuits."

In other words parameters obtained by regression to simple batch data (recovery —time sets) are insensitive to middling material since the fast floating material is dominant in these tests. In addition the regressed parameters seldom account for operating conditions like gas flow rate, froth recovery, etc. Therefore models that provide a physically meaningful description of the flotation process are a more reliable predictor of the flotation results than for example a regression curve fitted to experimental data but having no causal meaning, Szatkowski (1988).

Flotation studies in their simplest form (batch tests) involve many identifiable variables. Since knowledge of the interaction between variables is sparse, it is essential that an experimental design be formalized. In other words flotation models can never represent completely the actual process and it is therefore necessary to recognize the weakness of any model. There are three models that are used to describe the flotation process:

- Empirical models
- Probability models
- Kinetic models

Empirical models are developed from data obtained from online stream analysis equipment. The empirical models are usually system specific models that involve a trial and error feedback approach to optimize. Since the models are system specific it is not possible to estimate values outside the range of the model. Also it is difficult to present a coherent body of common findings or a suitable model form. However empirical models are less expensive on personnel and time.

Probability models allow for the recognition of individual compartments like the pulp and froth zones. The model accounts for particle—bubble collision, adhesion and froth stability in the form of probability models for each event. However the model parameters are difficult to evaluate and the probability of certain mechanisms are an approximation of doubtful events. The probability model reduces to the kinetic model under certain limiting conditions.

The kinetic model recognizes individual zones like the pulp and froth. The model is analogous to a chemical reaction taking place in a batch reactor. However a batch chemical reaction has only one mechanism while flotation has several mechanisms.

The general form of the batch flotation equation is:

$$\frac{dC}{dt} = -kC \quad (7)$$

Many authors like Fichera and Chudacek (1992) investigated the mechanism responsible for flotation and validated the notion that flotation is a first order process, therefore  $n$  is unity. In addition if the pulp volume is kept constant then Equation 7 can be rewritten in terms of mass. If the equation is integrated then Equation 7 can be rewritten in terms of cumulative mass recovered and time:

$$R = 1 - e^{-k_f t} \quad (8)$$

Equation 8 is one of many kinetic models. There are alternate models which are more complex and fit the experimental data better; however Equation 7 forms the basis for developing these alternate models. Table 2—1 shows some of the models developed from Equation 7.

**Table 2—1. Some common batch flotation models, source Bayat et al., 2004**

Model	Equation	Description
Classical model	$R = R_{MAX}(1 - e^{-\lambda t})$	<ul style="list-style-type: none"> <li>Model appears to predict the data best when recovery is low</li> <li>Gives added flexibility</li> </ul>
First order model with rectangular distribution of floatability	$R = R_{MAX} (1 - e^{-\lambda t})$	<ul style="list-style-type: none"> <li>Fit to data is reported to be the best</li> <li>The model forces the floatabilities to take a rectangular shape</li> </ul>
Second order model	$R = R_{MAX} (1 - e^{-\lambda t})^2$	<ul style="list-style-type: none"> <li>Two parameter expression describes the flotation of a monodisperse feed with particles having a constant floatability</li> </ul>
Second order model with rectangular distribution of floatability	$R = R_{MAX} (1 - e^{-\lambda t})^2$	<ul style="list-style-type: none"> <li>The assumed two order model has additional parameters therefore the model is more flexible</li> </ul>
Agar model	$R = R_{MAX} (1 - e^{-\lambda t})^2$	<ul style="list-style-type: none"> <li>The fit to data decreases as the <math>R_{MAX}</math> approaches 100 %</li> </ul>
Two rate constant model	$R = a_1(1 - e^{-k_1 t}) + a_2(1 - e^{-k_2 t})$ $a_0 = 1 - a_1 - a_2$	<ul style="list-style-type: none"> <li>Takes into account the time delay (<math>\nu</math>) in the formation of the froth zone</li> <li>Model identifies that there exist a fraction of the floatable material that floats fast and slow</li> </ul>

## SYMBOLS

$R_{MAX}$	— Maximum recovery
$k$	— Flotation kinetic/rate constant
$v$	— Time correction for froth formation
$a_0$	— Fraction of material that does not float
$a_1$	— Fraction of material that floats fast
$a_2$	— Fraction of material that floats slow

In the above models  $k$  describes the floatability of an ore.  $k$  is a function of a number of operating variables and ore characteristics. Yoon and Mao (cited in Parekh, 1999) showed that:

$$k \sim S_b P \quad (9)$$

Where  $S_b$  is the bubble surface area flux and  $P$  is the ore floatability. Sutherland (cited in Parekh, 1999) showed that  $A_i$  is a complex function of conditions in the froth and pulp zone:

$$k = 37 T_0 R_b r V N' \sec h \frac{3 V r}{L^4 \wedge J} \quad (10)$$

$(p$	—Fruitfulness froth factor
$R_b$	—Bubble radius
$r$	—Particle radius
$V$	—Cell volume
$N$	—Number of bubbles for equation
$T$	—Induction time

### 3.0 EXPERIMENTAL WORK- MINTEK RIG

This chapter details the work carried out on a rig provided by Mintek. Various experiments were performed to assess the performance of the rig. Two experimental configurations were investigated:

- Batch operation of the rig with one cell operational
- Batch operation of the rig with two cells operational

#### 3.1 Experimental apparatus and procedure

**3.1.1 Experimental apparatus.** The rig has six flotation cells arranged in a counter-current configuration. The counter—current arrangement allows for the transfer of froth up the bank of cells and pulp down the bank of cells, see Figure 3—1 for a schematic of the rig. The volume of each cell decreases up the bank.

The air was split from a common header into four of the six cells by using Saunders valves to control the air introduced into each cell air port. An impeller—sparger mechanism was used to disperse the air and suspend the solids in the pulp. A single three phase motor was used to drive the impellers in all six of the cells. A second three phase motor was used to drive the impellers in the launders. The launder impellers were used to break down the froth, to facilitate transfer to the next cell. The speed of the impellers (in the cells and launders) was controlled by frequency inverters having a range between 1-50 Hz.



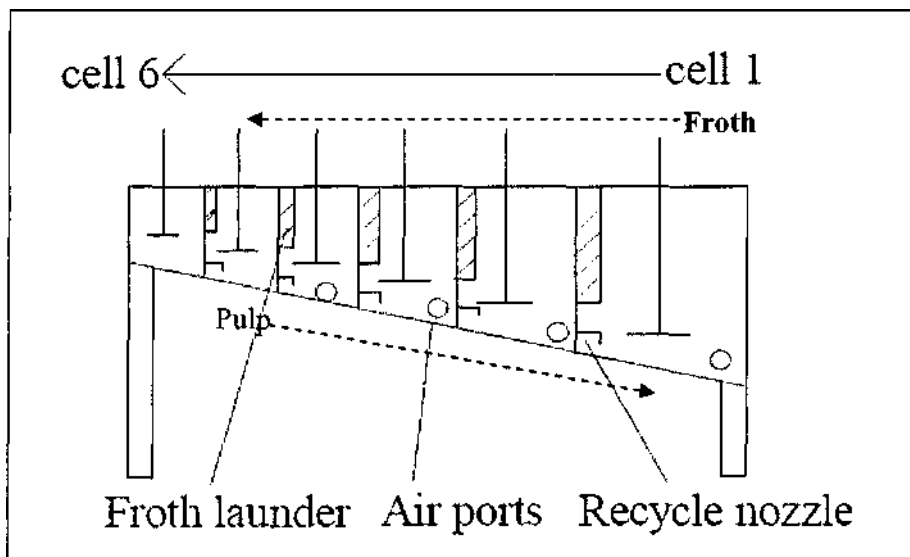


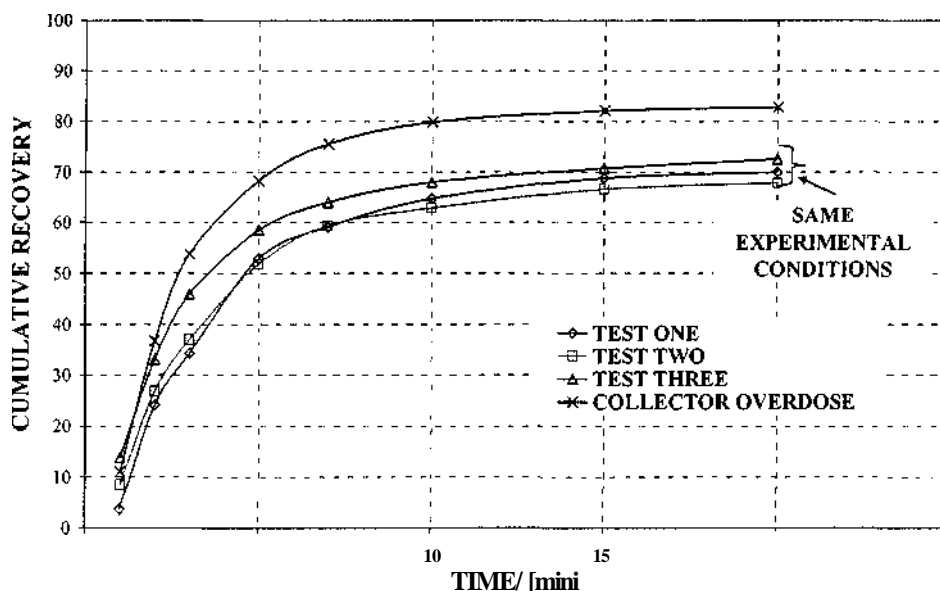
Figure 3—1. Schematic of the rig provide by Mintek.

**3.1.2 Experimental procedure.** A mixture of limestone, talc and silica was used in the experiments. The limestone simulated the valuable material, while the talc and silica simulated floatable and non—floatable gangue respectively. A detailed procedure for the operation of the rig is given in Chapter 8 Section 8.1.

## 3.2 Experimental work on rig

**3.2.1 Experiments.** Two experimental configurations were investigated. The first configuration was batch operation of the rig with only the largest cell operational and the second was batch operation of the rig with two cells operational. For the one cell configuration, tests were carried out at optimal collector dosages and high collector dosages— approximately 50 % more than the optimal dosage. The optimal collector dosage had been determined from batch tests done on a 3.4—litre Denver cell; as detailed in Section 4.2 of Chapter 4.

**3.2.2 Results and discussion.** Five experiments were carried on the rig, with only one cell operational. Figure 3—2 shows the cumulative recovery profiles for three experiments done at an optimal collector dosage of 0.234 g collector per 100 g of limestone and a high collector dosage of 0.351 g oleic acid per 100 g of limestone. The maximum recovery for the optimal collector dosage (at  $t = 20$  min) varied from 67.90 % to 72.58 %, while the maximum recovery for the high collector dosage was 82.83 %.



**Figure 3—2.** Recovery—time profiles for tests done at optimal collector dosage of 0.234 g of oleic acid per 100 g of limestone (test one, two and three) and 0.351 g of oleic acid per 100 g of limestone (collector overdose).

Generally limestone is coated easily with the collector and floated, giving recoveries greater than 90 %, as shown in batch experiments detailed in Chapter 4. It is believed that the low limestone recovery in the rig is the result of the impeller—sparger mechanism which provided poor hydrodynamic conditions i.e. poor dispersion of air and bubble generation. The low recovery can be attributed to dead zones or poor mixing conditions in the rig, therefore more collector was required to coat the particles to be floated. The latter (dead zones) were investigated by performing a test under dilute pulp conditions with limestone only, the results showed that approximately 70 % of the limestone was recovered while the remaining 30 % was found in the corners and underneath the sparger.

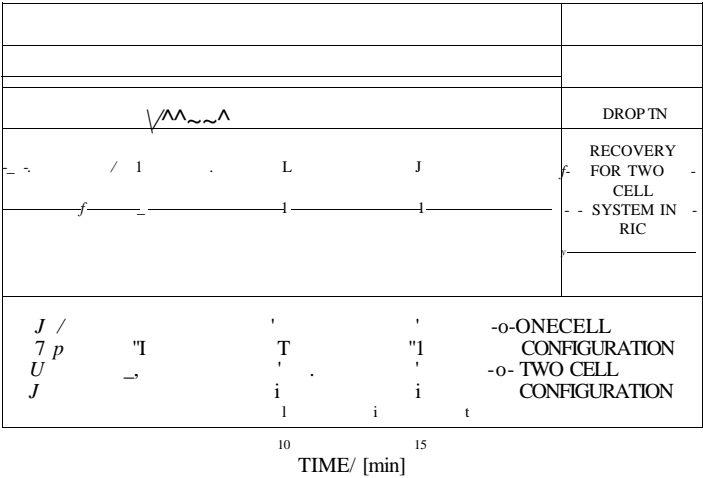
Figure 3-3 shows some of the limestone that settled beneath the impeller—sparger mechanism.

Possible dead zones in the rig design. The off centered impeller may have affected air dispersion and mixing.

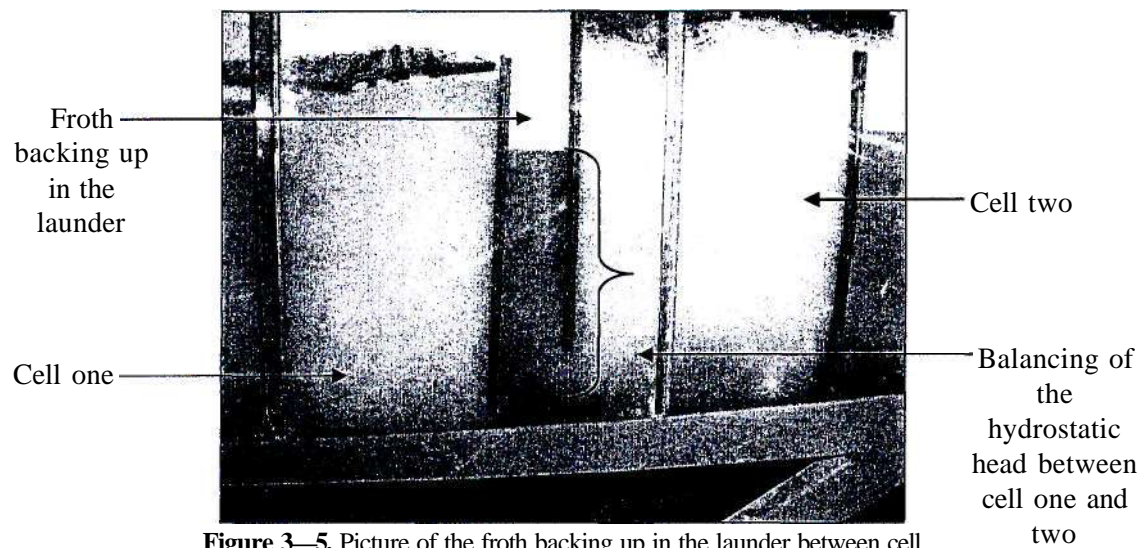


**Figure 3—3.** Picture of some of the limestone that had settled beneath the impeller—sparger mechanism.

The second system investigated was the two cell operation of the rig. Figure 3—4 shows a 42 % drop in the limestone recovery for a two cell configuration. This is due to the accumulation and sedimentation of froth in the launder. The launder impeller did little to break down into cell two. In addition the froth backed up in the launder due to the "balancing of the hydrostatic head" between cell one and two. Figure 3—5 shows a picture of the launder backing up with froth due to the "balancing of the hydrostatic head".



**Figure 3—4.** Recovery—time profiles for a 1 and 2 cell configuration of the rig.



**Figure 3—5.** Picture of the froth backing up in the launder between cell 1 and 2.

**3.2.3 Conclusions.** The rig has design flaws that made it difficult to float the synthetic mixture. These include the existence of dead zones, poor hydrodynamic conditions due to the impeller—sparger mechanism and the design of the froth launders. However the rig provided the ground work and methodology for the development of a new rig.

## 4.0 EXPERIMENTAL WORK- BATCH EXPERIMENTS

Single cell batch experiments were done with a Denver, Outokumpu and Wemco mechanism. The feed material used in most experiments was similar to the mixture used in the rig. The following variables were investigated in the batch tests:

1. Effect of the reagent suite on flotation
2. Effect of impeller speed and air flow rate on flotation
3. Effect of solid concentration on flotation
4. Effect of froth depth on flotation

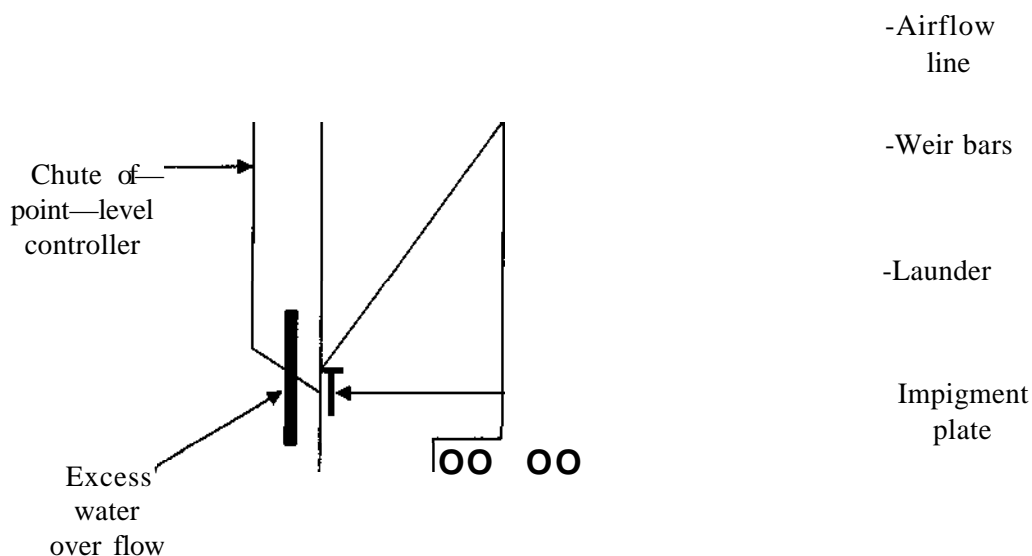
### 4.1 Experimental apparatus and procedure

**4.1.1 Experimental apparatus.** A 15—litre cell had been constructed and fitted with a Denver mechanism. A 56—litre cell with an Outokumpu mechanism was modified and a 3.4—litre cell was constructed and fitted with a Wemco mechanism. The 3.4—litre cell was also used with the Denver mechanism. Detailed drawings of the cells are provided in Chapter 5; however a few points on the design are noted here:

- A baffle was attached at an angle to the back of the flotation cell to assist in "steering" the froth into the launder, see Figure 4—1. The reason for using a baffle was to eliminate hand scraping of the froth. Hand scraping introduces operator error while natural gravitational transfer of the froth influences particle release and re—capture in the froth zone.
- The pulp level was controlled by a point—level controller, which is a simple chute attached to the cell, see Figure 4—1. The controller operated by using the difference in the hydrostatic head between the water level in the chute and the pulp level in the cell. The water in the chute was obtained from a hosepipe operated at a low flow rate.
- An impigment plate had been inserted near the point of contact between the chute and the cell to reduce solids entering the chute, see Figure 4—1.

Each cell had been fitted with weir bars, so that the froth height could be controlled, see Figure 4—1.

Lastly the air flow rate into each cell had been controlled with a gas rotameter.



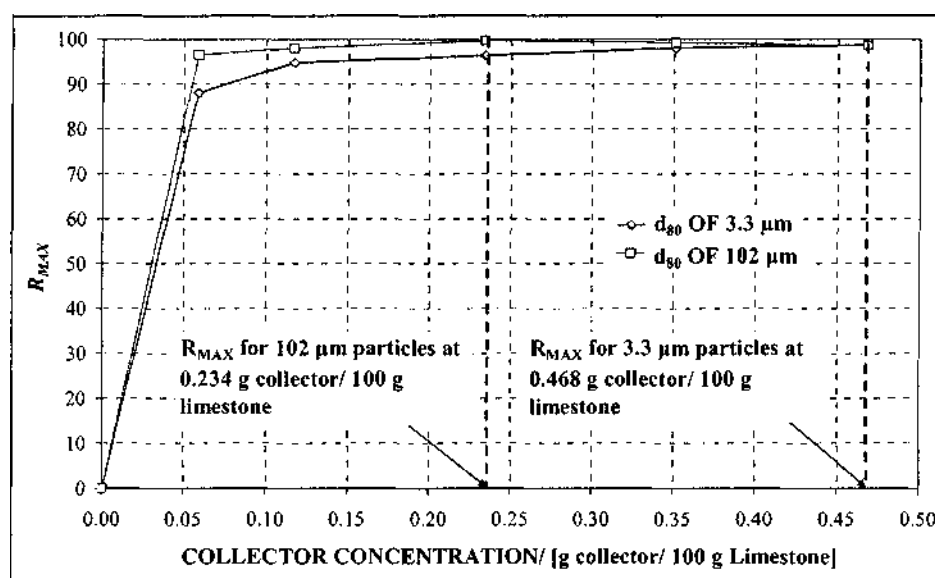
**Figure 4—1.** Schematic of the cell used in the batch flotation and SBFA tests.

**4.1.2 Experimental procedure.** Detailed procedures for the batch tests are provided in Chapter 8, Sections 8.2 to 8.5.

## 4.2 Effect of reagent suite on flotation

**4.2.1 Experiments.** The collector and frother concentration had been varied at constant operating conditions so that the optimal collector/frother concentration could be found. The tests were done in a 3.4—litre cell with a Denver mechanism. The collector was varied from 0 to 0.468 g collector per 100 g of limestone at a constant frother concentration of 25.00 mg per litre of water.

**4.2.2 Results and discussion.** The collector was added to a pulp having 10 % solids by mass of a synthetic mixture<sup>2</sup>. To investigate the effect of particle size on reagent dosage the collector concentration was varied for two sizes of limestone particles, with mean particle sizes of 102 and 3.3  $\mu\text{m}$ . Figure 4—2 shows the effect of particle size on reagent dosage. The fine particles consumed approximately 0.468 g of collector to achieve a maximum recovery of 98 % limestone while the 102  $\mu\text{m}$  particles consumed 0.234 g collector to achieve a maximum recovery of almost 100 %. This means that the fine particles consume twice the amount of collector used by the 102  $\mu\text{m}$  particles to achieve a maximum limestone recovery of almost 100 %. The fines consume more collector because the particles have a larger specific surface area.

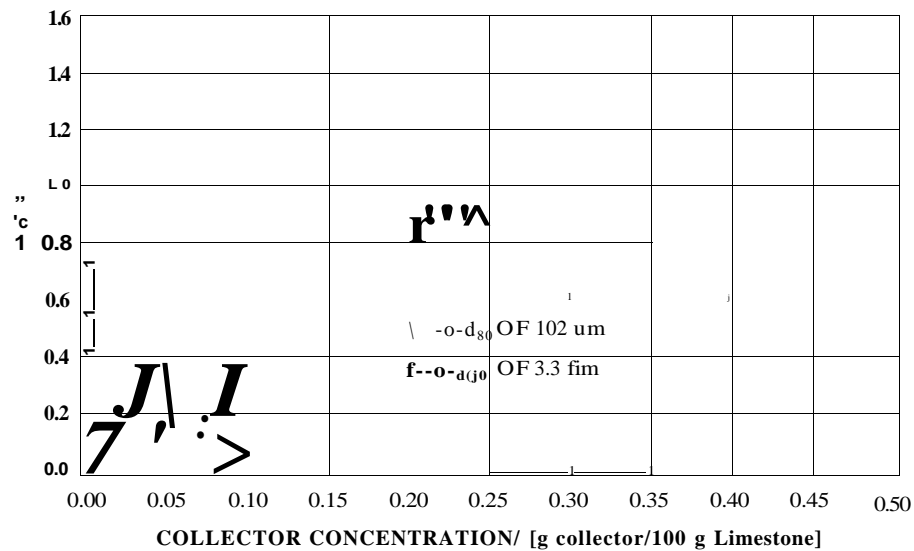


**Figure 4—2.** Effect of collector dosage for limestone particles with mean sizes of 102 and 3.3 ( $\mu\text{m}$ ).

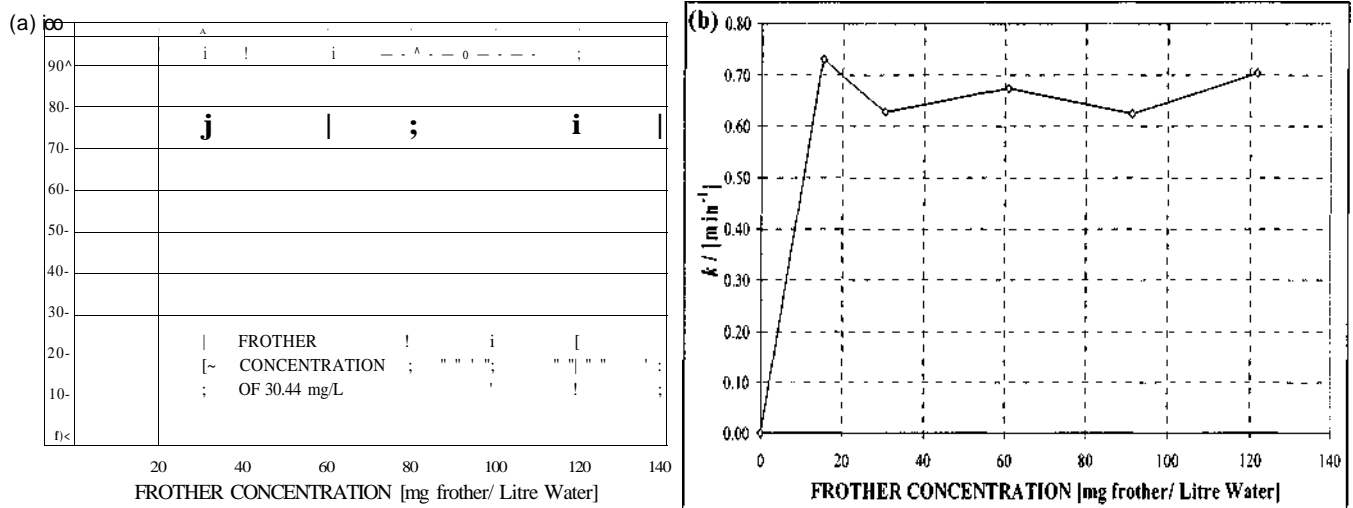
Figure 4—3 shows the variation of the flotation rate constants for different collector concentrations. The figure shows that the 3.3  $\mu\text{m}$  particles take longer to float than the 102  $\mu\text{m}$  particles. This observation is in keeping with the theory presented in section 2.2.2 of Chapter 2, which states that fine particles take longer to float because they can saturate bubble surfaces and are partially recovered by entrainment.

<sup>2</sup> The synthetic mixture composition is 5 % limestone, 5 % talc and 90 % silica by mass.

The simple model of  $R = iMAX (1 - e^{-kt})$  was regressed to the recovery—time data to obtain the rate constant  $k$ .



**Figure 4—3.** Variation in the flotation rate constant ( $k$ ) with collector concentration for 102 and 3.3 micrometer particles.



**Figure 4—4.** Variation of  $RMAX$  (a) and  $k$  (b) with frother concentration for 102 micrometer limestone particles.



Figures 4—4a and b show the variation in the maximum limestone recovery ( $R_{MAX}$ ) and  $k$  with frother concentration respectively.  $R_{MAX}$  and  $k$  show little variation with the frother concentration. This can be attributed to the ease at which the limestone particles form particle—bubble aggregates which are readily floated at any frother concentration.

**4.2.3 Conclusions.** The optimal collector concentration for the 3.3 and 102  $\mu$ m limestone particles was 0.468 and 0.234 g per 100 g of limestone respectively. The 3.3  $\mu$ m particles consumed more collector than the 102  $\mu$ m, in order to achieve a similar  $R_{MAX}$ . Variations in the frother concentration had little effect on  $R_{MAX}$  and  $k$  for the 102  $\mu$ m particles. The optimal frother concentration investigated was 30.44 mg frother per litre of water.

### 4.3 Effect of impeller speed and superficial air velocity on flotation

**4.3.1 Experiments.** The impeller speed was varied for five superficial air velocities. The impeller speeds investigated were 1090, 980, 870 and 763 rpm (impeller speeds were measured with a tachometer). The superficial air velocities investigated were 1.07, 0.85, 0.65, 0.56 and 0.36  $\text{m s}^{-1}$ . The tests were done in a 3.4—litre cell having a Denver mechanism. A pulp containing 10 % solids by mass was used. The experimental procedure is given in Chapter 8 Section 8.3.

**4.3.2 Results and discussion.** Figures 4—5a and b show the effect of the impeller speed and  $J_g$  on  $R_{MAX}$  and  $k$  respectively. Figure 4—5 shows that for a given superficial gas velocity an optimal impeller speed exists, which provides good cell hydrodynamics, bubble generation, air dispersion and mixing. The highest values of  $R_{MAX}$  for the superficial air velocities of 1.07, 0.85 and 0.36  $\text{m s}^{-1}$  were at impeller speeds of 980, 870 and 763 rpm respectively. At an air velocity of 1.07  $\text{m s}^{-1}$  the optimum impeller speed was 980 rpm. The drop in  $R_{MAX}$  for impeller speeds greater than 980 rpm can be attributed to an observed increase in turbulence near the pulp—froth interface which results in more material being recycled to the pulp. At low impeller speeds the value of  $R_{MAX}$  decreases due to poor bubble generation (i.e. bubbles with large diameters that

coalescence easily) and poor suspension of solids. The same explanation can also be applied to the other air velocity curves.

Figure 4—5b shows how  $k$  varies with the impeller speed for different superficial air velocities. The impeller speed and air velocity are operating variables that influence the hydrodynamics in a flotation cell, in particular the dispersion of bubbles to bubbles with diameters less than 2 mm, Gorain et al. (1995). Generally small bubbles are more buoyant than big bubbles because they are less dense. Therefore small bubbles carry the attached particles faster to the froth zone than big bubbles. However at low superficial air velocities the bubbles carry the limestone at a slower rate due to most of the bubbles being saturated with limestone. The saturated bubbles are more difficult to float due to the larger load that they have to carry, in other words a saturated bubble is less buoyant. At higher superficial air velocities and impeller speeds there are more bubbles available since small bubbles have a larger surface area per unit volume. Therefore most of the bubbles are only partially coated with limestone. A partially loaded bubble has higher buoyancy relative to the pulp therefore it floats faster. Hence from Figure 4—5b it follows that the higher the superficial air velocity ( $1.07 \text{ m/s}$ ) the higher the impeller speed (980 rpm) has to be, so that smaller air bubbles can be formed.

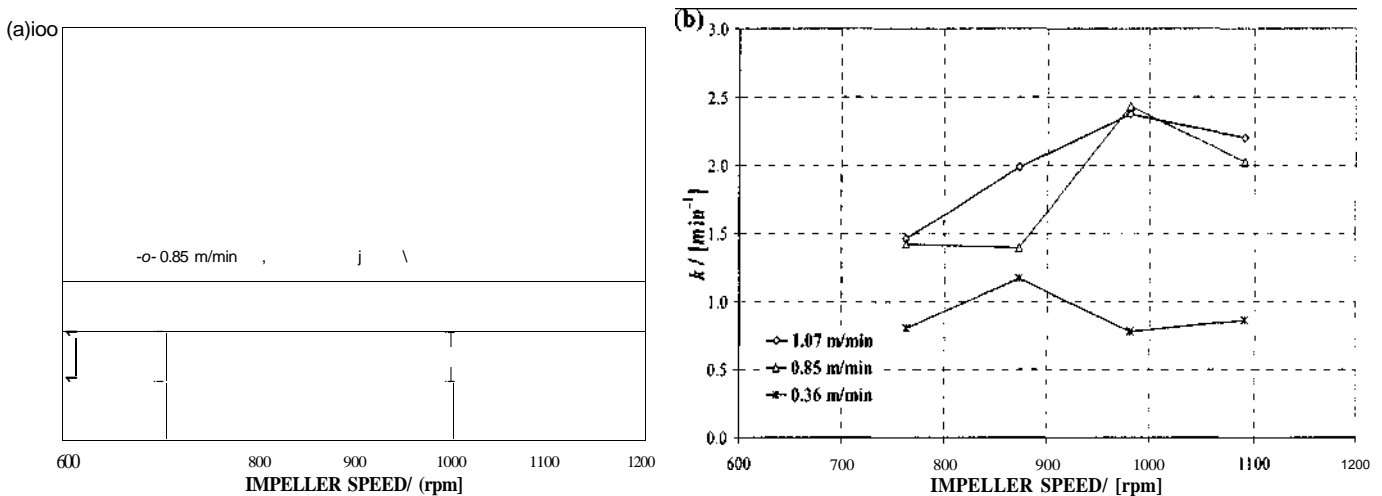
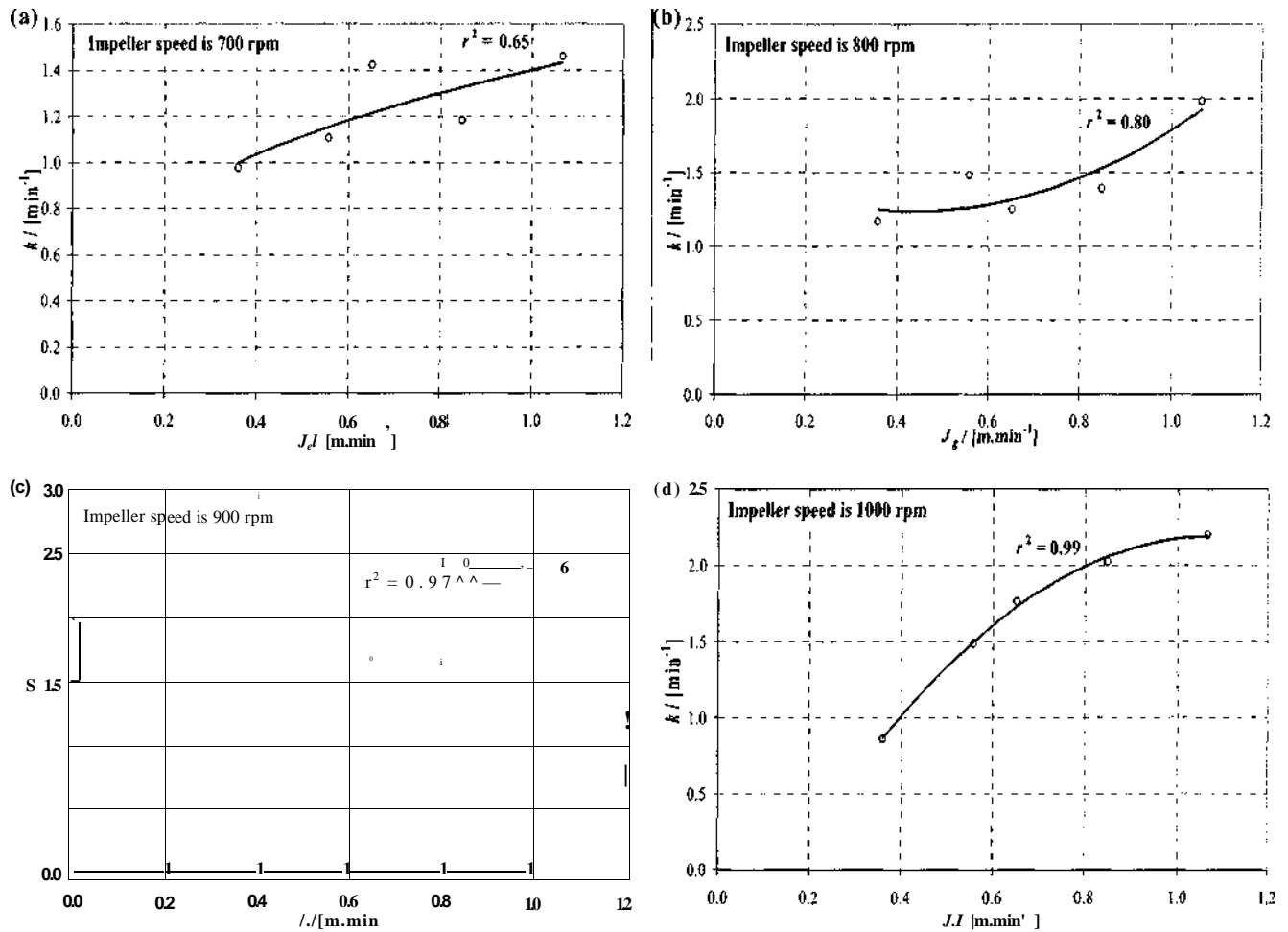


Figure 4—5. The influence of the operating variables impeller speed and  $J_g$  on RMAX (a) and  $k$  (b).

Many authors like Gorain (1998), Sutherland (cited in Parekh, 1999) and Yoon and Mao (cited in Parekh, 1999) proposed empirical correlations that scaled  $k$  by using operating and chemical quantities. In most of the empirical correlations,  $k$  was directly proportional to the superficial air velocity.

Figure 4—6 (a to d) shows the variation of  $k$  with air velocity for different impeller speeds. The data (from Figure 4—6 a to d) was regressed to a nonlinear second degree polynomial model and the correlation coefficient ( $r^2$ ) was used to investigate the relationship between  $k$  and air velocity. At low impeller speeds (Figure 4—6a, impeller speed is 700 rpm) the relationship was poor because the  $r^2$  value was low. The deviation may be attributed to poor mixing and air dispersion in the pulp zone at low impeller speeds. At high air velocities and impeller speeds (Figure 4—6d, impeller speed is 1000 rpm) there is better air dispersion and mixing in the pulp zone. Therefore Figure 4—6 a to d illustrates that as the impeller speed increases with increasing air velocity the relationship between the impeller speed and the air velocity improves. This is apparent from the correlation coefficient increasing from 0.65 at a low impeller speed (700 rpm) to almost unity for a high impeller speed (1000 rpm).



**Figure 4—6.** The relationship between  $k$  and  $J_g$  for different impeller speeds. The data for the different impeller speeds was regressed to a second degree polynomial.

**4.3.3 Conclusions.** The impeller speed and superficial air velocity was investigated. The investigation showed that the operating variables affected  $R_{MAX}$  and  $k$ . The rate constant  $k$  showed a strong relationship with the superficial air velocity at constant operating and chemical conditions. However the relationship was doubtful at low impeller speeds and high superficial velocities due to poor air dispersion in the cell.

## 4.4 Effect of solid concentration on flotation

**4.4.1 Experiments.** The solid concentration in the pulp was varied. The concentrations investigated were 5.00, 7.50, 10.00 and 15.00 % solids by mass in the pulp. The tests were done in a 15—litre cell with a Denver mechanism. The experimental procedure is given in Chapter 8 Section 8.4.

**4.4.2 Results and discussion.** Figures 4—7a and b show the effect of different solid concentrations on  $R_{MAX}$  and  $k$ .  $R_{MAX}$  remains relatively constant for different solid concentrations in the pulp. This can be attributed to the excellent floatability of limestone; which floats relatively easily when coated with sufficient collector.

Figure 4—7b shows that  $k$  decreased rapidly as the solid concentration changed from 5.00 to 7.50 %; thereafter  $k$  remained relatively constant when the solid concentration was varied from 10.00 to 15.00 %. The decrease in  $k$  with increasing solid concentration can be explained by the large amount of floatable material present in the feed material; i.e. limestone and talc. As the solid concentration increased, the amount of floatables increased and the bubbles have a greater probability of being saturated with the floatable particles. A saturated bubble is also heavier than a partially coated bubble obtained from a dilute pulp. The heavier bubble moves at a slow rate through the pulp zone. In the froth zone the saturated bubbles packed together to form a viscous froth, therefore the rate ( $k$ ) was low at a high solid concentration of 15 %.

However  $k$  remained relatively constant as the solid concentration increased from 10.00 to 15.00 %. It is believed that a critical saturation point had been reached in the pulp. At saturation, the rate of flotation remains constant and the effective rate decreases. However froth stability may increase resulting in increasing rate with solid concentration.

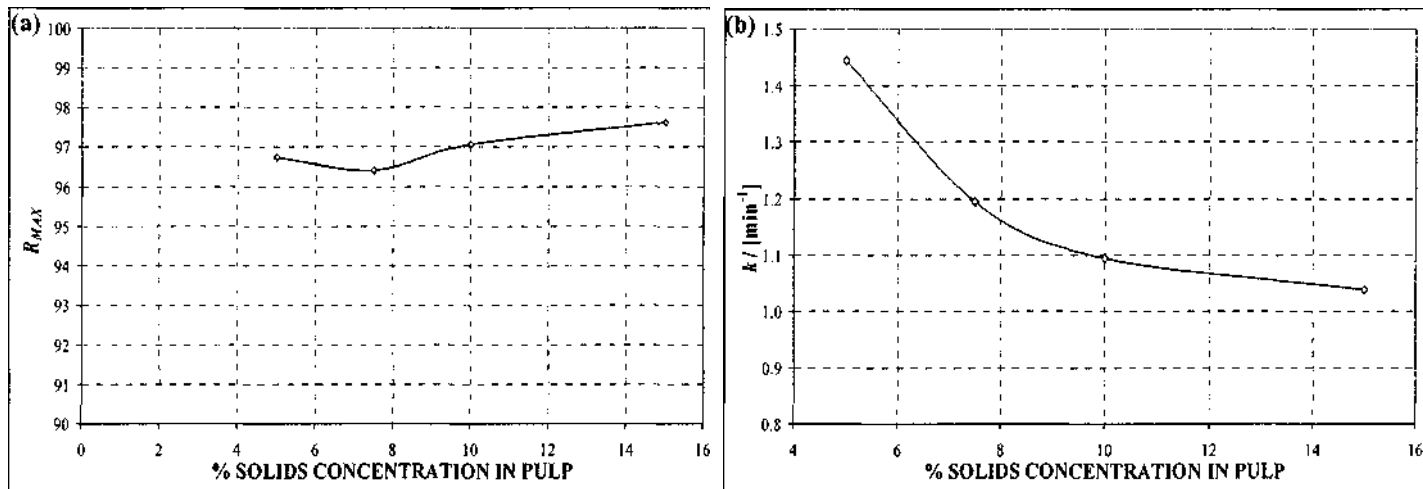


Figure 4—7. Effect of solid concentrations on  $R_{MAX}$  (a) and  $k$  (b) for a 15—litre Denver cell operating at an impeller speed of 1000 rpm and superficial air velocity of  $1.07 \text{ m-s}^{-1}$ .

Figure 4—8a and b shows the change in the cumulative concentrate grade with cumulative recovery (Figure 4—8a) and time, Figure 4—8b. At time  $t = 0.5 \text{ min}$  in figure 4—8a the grade is high for all solid concentrations. However the concentrate grade decreased with time due to the entrainment of gangue and the natural floatability of talc. In both Figures 4—8a and b, as the solid concentrations increased the concentrate grade decreased because of the presence of more floatable gangue and fines which are recovered by entrainment and flotation.

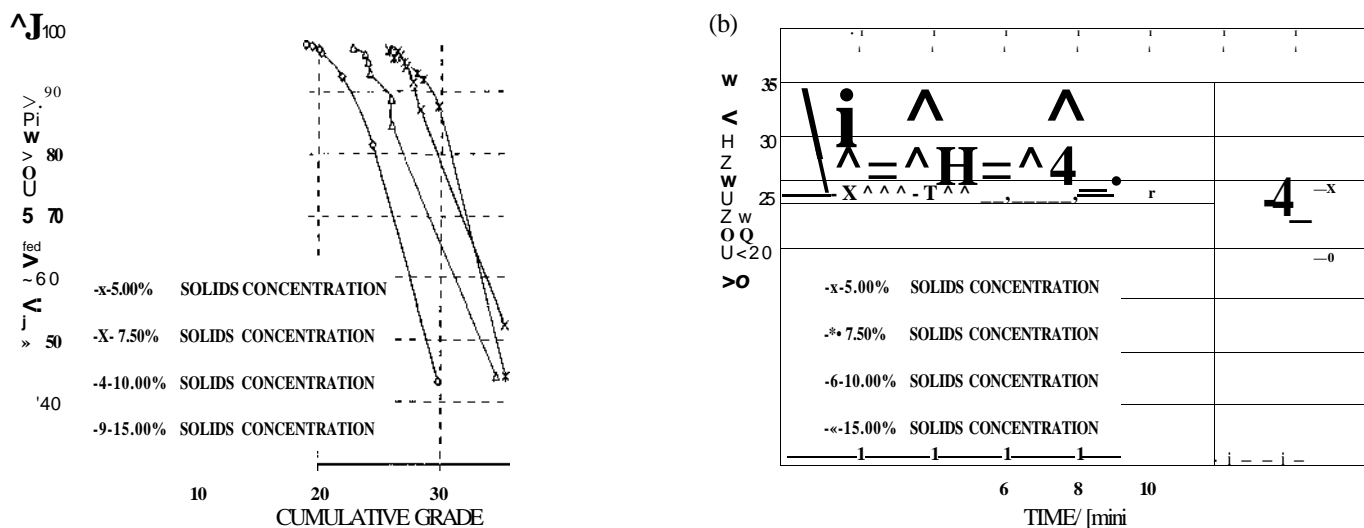


Figure 4—8. The influence of solid concentration on cumulative concentrate grade with cumulative recovery (a) and time (b) for a 15—litre Denver cell operating at an impeller speed of 1000 rpm and superficial air velocity of 1.07 nvs<sup>1</sup>.

Figure 4—9 shows the recovery by size for limestone. The recovery decreased for limestone particles having a mean particle size greater than 190  $\mu\text{m}$ . This can be attributed to the large mass associated with the large particles. The large mass results in the particles detaching from the bubble surface because the inertial and weight forces are greater than the buoyancy force, see Figure 2—10 in Chapter 2.

For the limestone particles between 49 and 190  $\mu\text{m}$  the recovery is above 90 %. The high recovery can be attributed to the formation of stable particle—bubble aggregates which are recovered in the concentrate.

For the limestone particles less than 49  $\mu\text{m}$  the recovery decreased gradually to 80—65 %. The fines are generally recovered by entrainment which is associated with the recovery of water. Generally the water recovery increased with solid concentration. This was evident for the solid concentration increasing from 7.50 to 10.00 %.

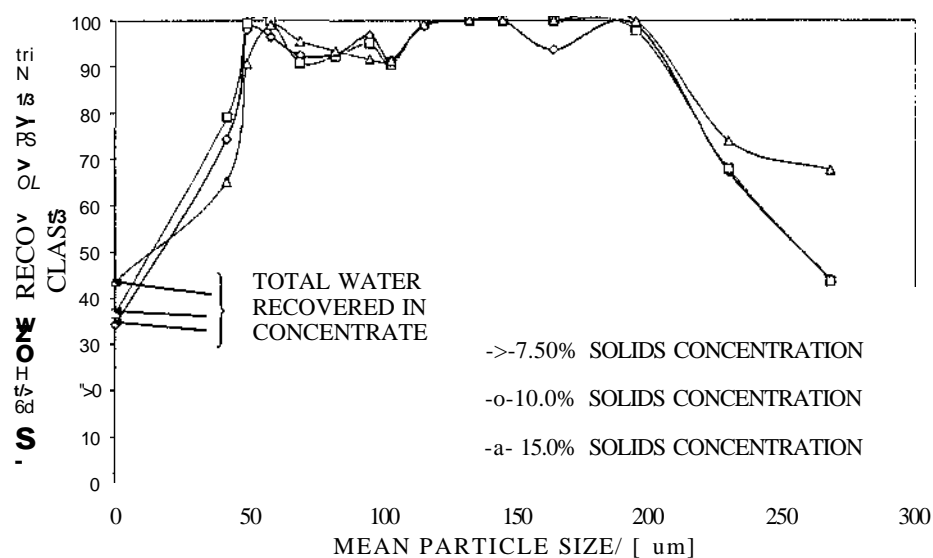


Figure 4—9. The recovery of limestone by particle size for batch test at different solid concentrations for a 15—litre Denver cell operating at an impeller speed of 1000 rpm and superficial air velocity of 1.07 nrs<sup>1</sup>.

Figure 4—10 shows the recovery by size for gangue, both silica and talc. The general trend observed from Figure 4—10 is that as the solid concentration increased the gangue recovery by size increased. This trend was due to the higher gangue content in the pulp as the solid concentration increased. In addition the recovery of the fine particles less than 49 um increased with water recovery.

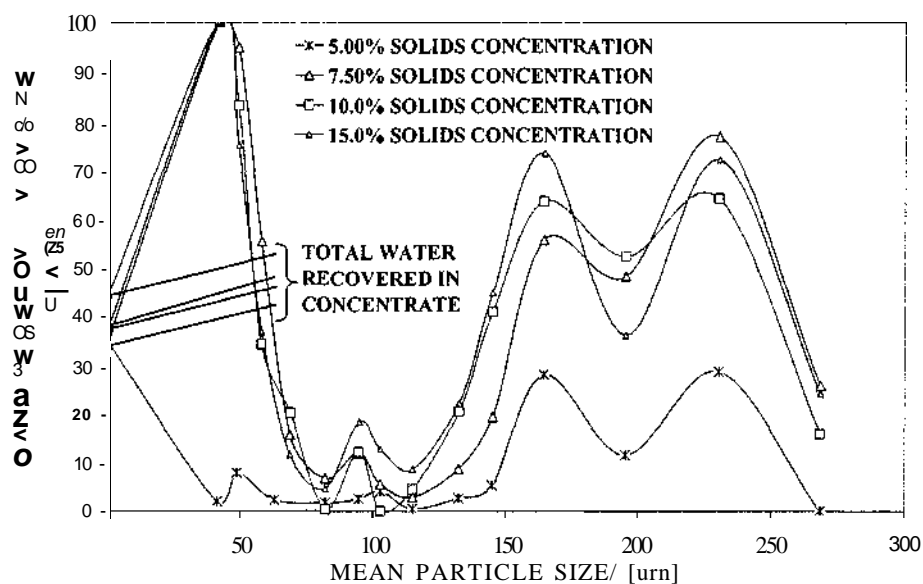
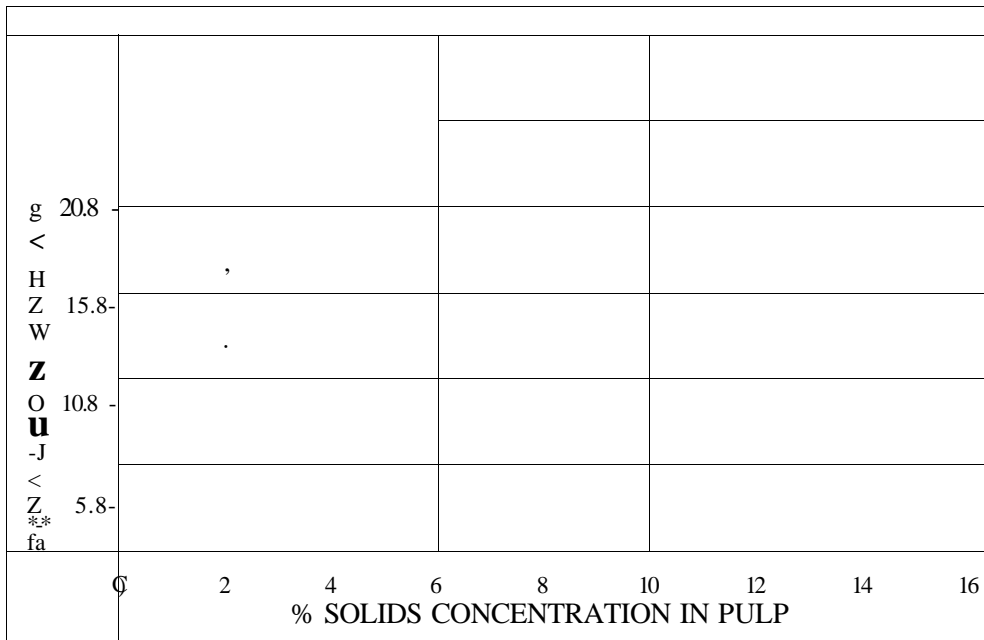


Figure 4—10. The recovery of gangue by particle size for batch test at different solid concentrations for a 15—litre Denver cell operating at an impeller speed of 1000 rpm and superficial air velocity of 1.07 nrs<sup>1</sup>.





**Figure 4—11.** The effect of solid concentration on the final grade for a batch test.

**4.4.3 Conclusions.** The solids concentration was varied in a 15—litre cell with a Denver mechanism. The results showed that  $k$  decreased as the solid concentration increased. However a critical bubble saturation point was reached at a solid concentration of 10 %, where  $k$  did not change significantly but grade reduced significantly when the solid concentration increased.

#### 4.5 Effect of froth height on flotation

**4.5.1 Experiments.** The froth height was varied in the 56, 15 and 3.4—litre cells. The froth height was varied so that froth recoveries ( $R_f$ ) could be linked to the froth height in these cells. The experimental procedure is given in Chapter 8 Section 8.5.

**4.5.2 Results and discussion.** The froth height was varied in a 56—litre cell with an Outokumpu mechanism, a 15—litre cell with a Denver mechanism and a 3.4 —litre cell with a Wemco mechanism. Sample calculations for the determination of  $R_f$  for different froth heights is given in Appendix I.III.

Two models were used to determine  $R_j$ , i.e. Vera's linear model and Gorain's exponential model. However the model proposed by Vera et al. (1999) depends on impeller type and cell design. Therefore the method proposed by Gorain et al. (1998) was used to determine  $R_j$  since the model was independent of impeller type and cell design. The variation in  $k$  for different froth heights is presented in Figure 4—12a to f; the linear plots show the regression of the data to the model proposed by Vera while the exponential plots show the regression of the data to the model proposed by Gorain.

For the 56—litre Outokumpu cell the collection zone rate ( $k_c$ ) is  $0.95 \text{ min}^{-1}$  for the model proposed by Gorain (Figure 4—12a) and  $0.93 \text{ min}^{-1}$  for model proposed by Vera (Figure 4—12b). Both the exponential and linear model fitted the experimental data well, since the correlation coefficient ( $r$ ) was close to unity, which indicates a good model fit to experimental data.

For the 15—litre Denver cell  $k_c$  is  $2.15 \text{ min}^{-1}$  (Figure 4—12c) and  $2.00 \text{ min}^{-1}$  (Figure 4—12d). The correlation coefficient  $r^2$  is 0.95 and 0.96 for Figure 4—12c and d respectively which indicates that the regression of the data to the models was good.

For the 3.4—litre Wemco cell  $k_c$  is  $2.88 \text{ min}^{-1}$  (Figure 4—12e) and  $2.80 \text{ min}^{-1}$  (Figure 4—12f). The correlation coefficient  $r$  is 0.96 and 0.97 for Figure 4—12e and f respectively which indicates that the regression of the data to the models was good.

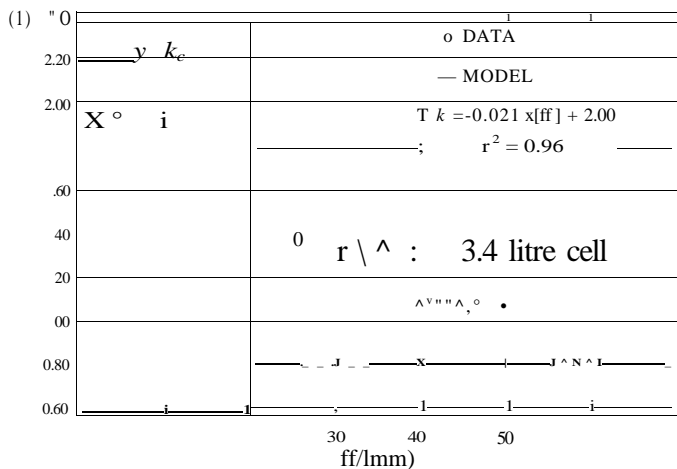
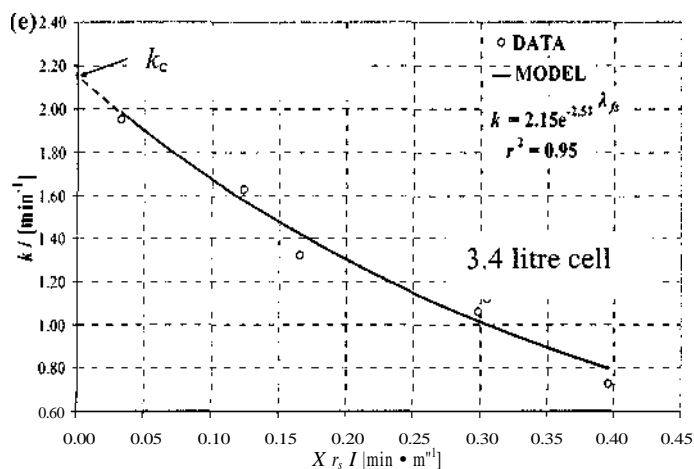
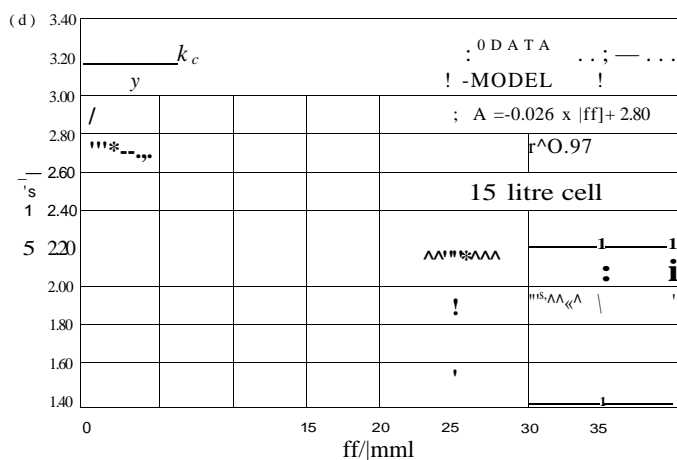
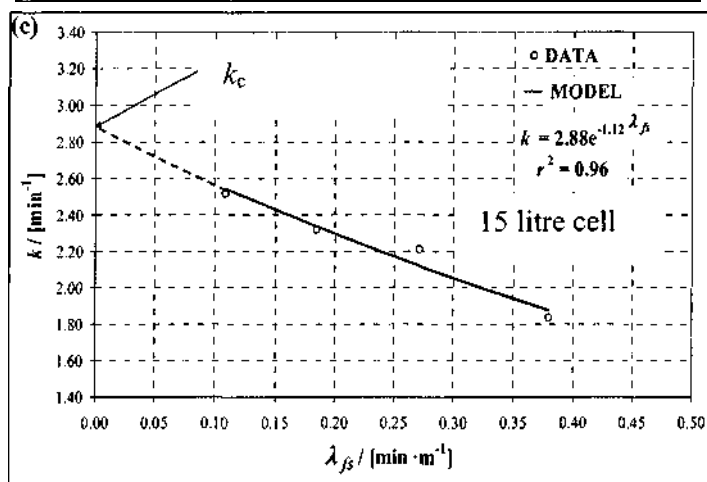
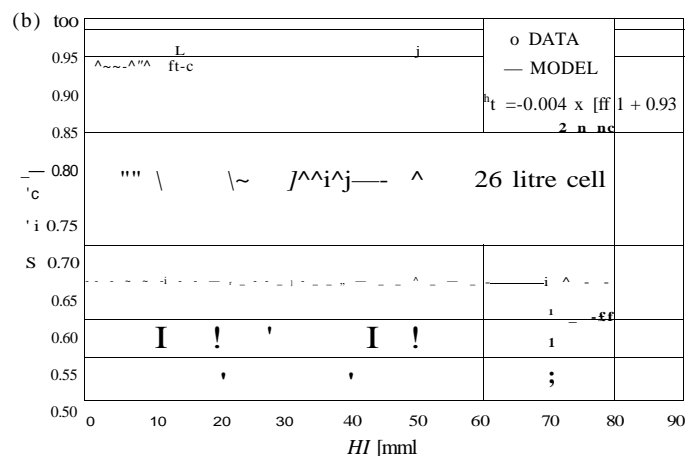
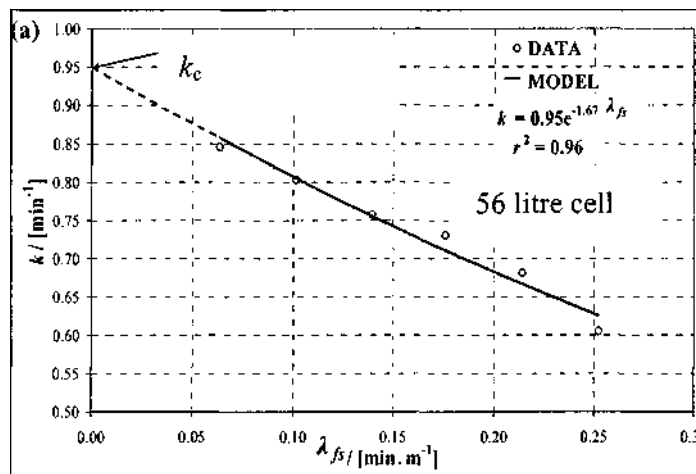


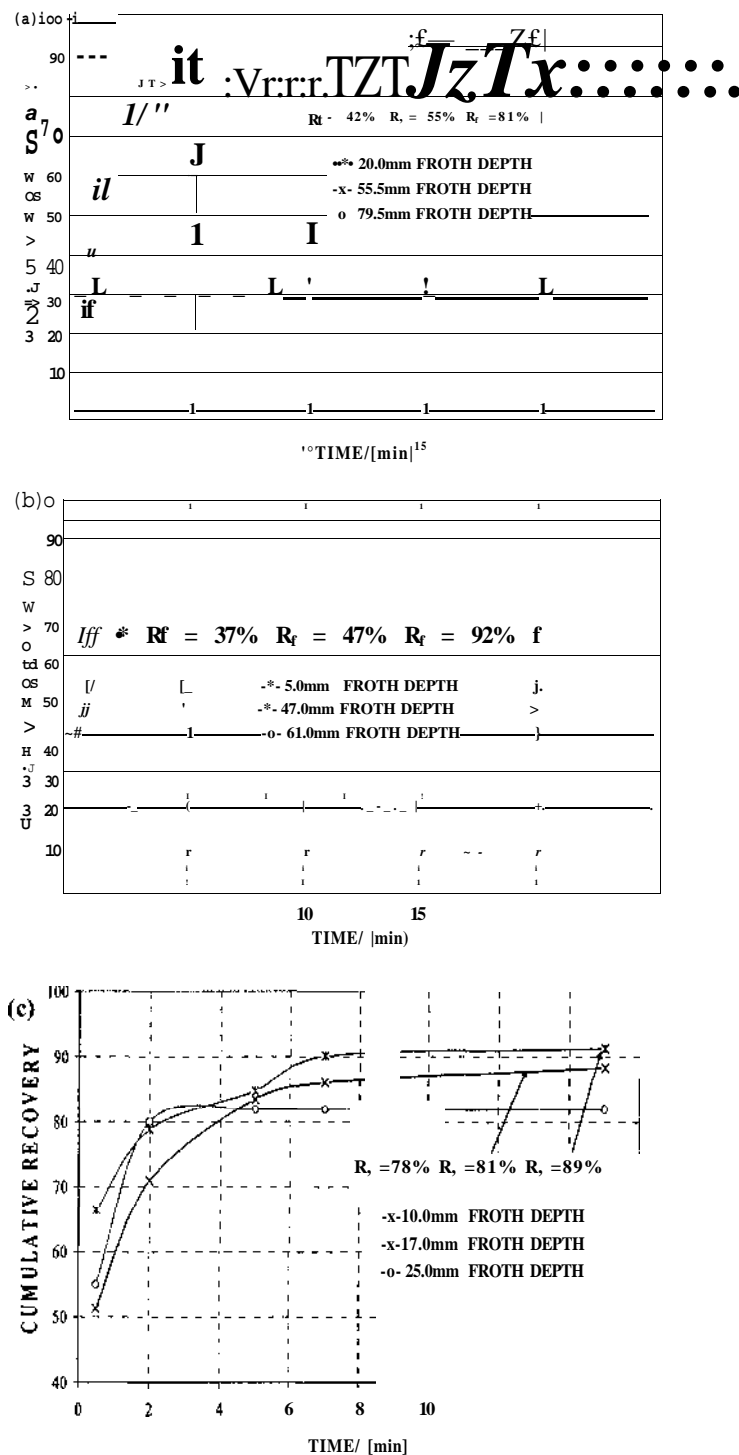
Figure 4—12. The regression of the data to the model proposed by Gorain (a, c and d) and Vera (b, c and f).  $R = \frac{k}{k_{\infty}}$  and  $A_{fs} = \frac{A_j - L}{L}$

Figure 4—12a, c and d can be used to compare  $k_c$ , since the model used to obtain  $k_c$  is independent of the impeller type and cell design. The general trend from Figure 4—12a, c, and d is that  $k_c$  increases as the cell volume decreases. The trend can be attributed to the larger energy per unit volume used in the smaller cells.

$Rf$  can be calculated from Equation 2 and 6, see Chapter 2.  $Rf$  calculated from Vera's model is slightly higher than the model proposed by Gorain. This may be attributed to Gorain's model being independent of impeller type and cell design. The value of  $Rf$  obtained from Gorain's model was applied to the SBFA, see Chapter 9 and Appendices I.IV and I.V.

From Table 4—1 the recovery of limestone was the largest at shallow froths heights but decreased as  $H$  increased. The reason for this is that as  $H$  increased, the froth residence time increased, therefore the fine limestone particles had a greater probability of draining into the pulp zone. In addition the bubbles may have coalesced and burst, which resulted in the bubble dropping the limestone into the lower regions of the froth or into the pulp zone. Therefore limestone recovery decreases as  $Rf$  increases, see Figure 4—13a, b and c.

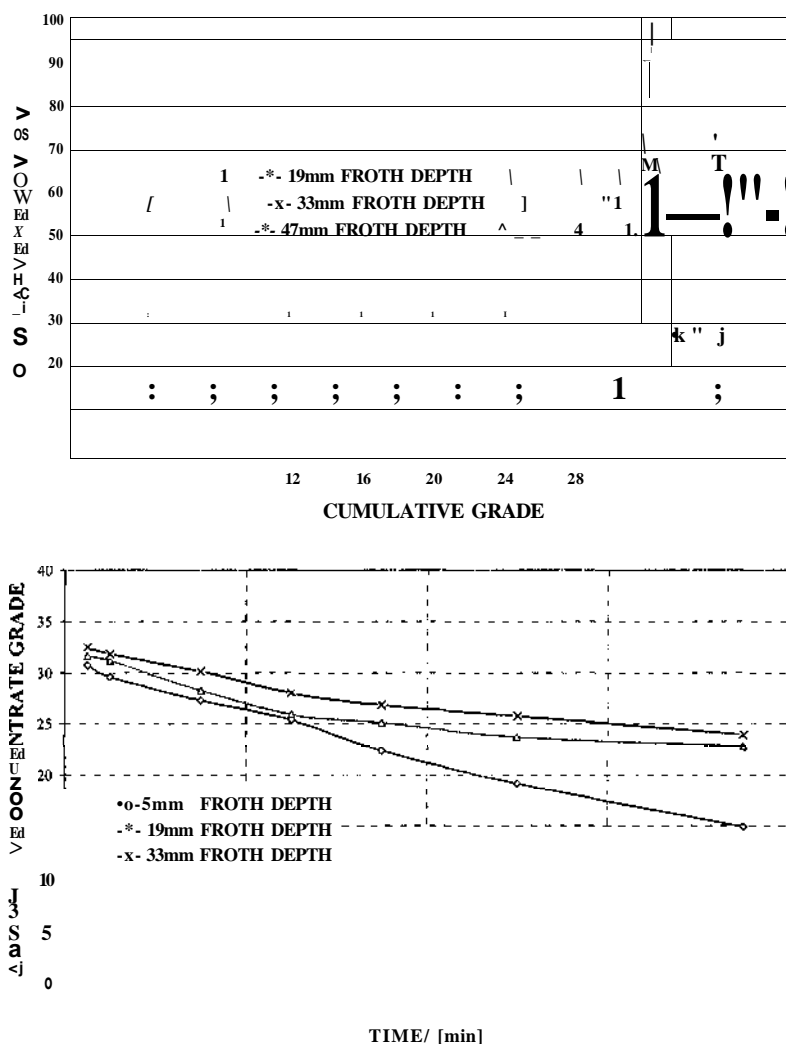
Figures 4—14a and b show the effect of froth height on the concentrate grade. The general trend observed was that as  $H$  increased, the grade of the concentrate improved. This can be attributed to the longer froth residence time which allows for the drainage of gangue.



**Figure 4—13.** Recovery—time profiles at different froth recoveries for an Outokumpu cell (a), Denver cell (b) and a Wemco cell (c).

Table 4—1: Summary of the froth recovery factors obtained from Vera's and Gorain's model for different froth heights in the Outokumpu, Denver and Wemco cell. The rate constants were obtained by regressing the batch recovery—time data to Agar's model

56—litre Outokumpu cell			
<i>HI</i> [mm]	<i>kl</i> [min <sup>-1</sup> ]	<i>Rfior</i> Gorain's model	<i>Rf</i> for Vera's model
20.00	0.85	90	90.94
32.00	0.80	84	86.34
44.00	0.76	79	81.47
55.50	0.73	75	78.61
67.50	0.68	70	73.24
79.50	0.61	66	65.07
15—litre Denver cell			
<i>HI</i> [mm]	<i>kl</i> [min <sup>-1</sup> ]	<i>Rfior</i> Gorain's model	<i>Rfior</i> Vera's model
5.00	1.95	93	98
19.00	1.63	77	82
25.50	1.32	70	66
46.00	1.06	53	53
47.00	1.12	52	56
61.00	0.72	73	36
3.4—litre Wemco cell			
<i>HI</i> [mm]	<i>kl</i> [min <sup>-1</sup> ]	<i>Rfior</i> Gorain's model	<i>Rfior</i> Vera's model
17	2.32	81	83
10	2.52	89	90
25	2.21	74	79
35	1.84	65	66

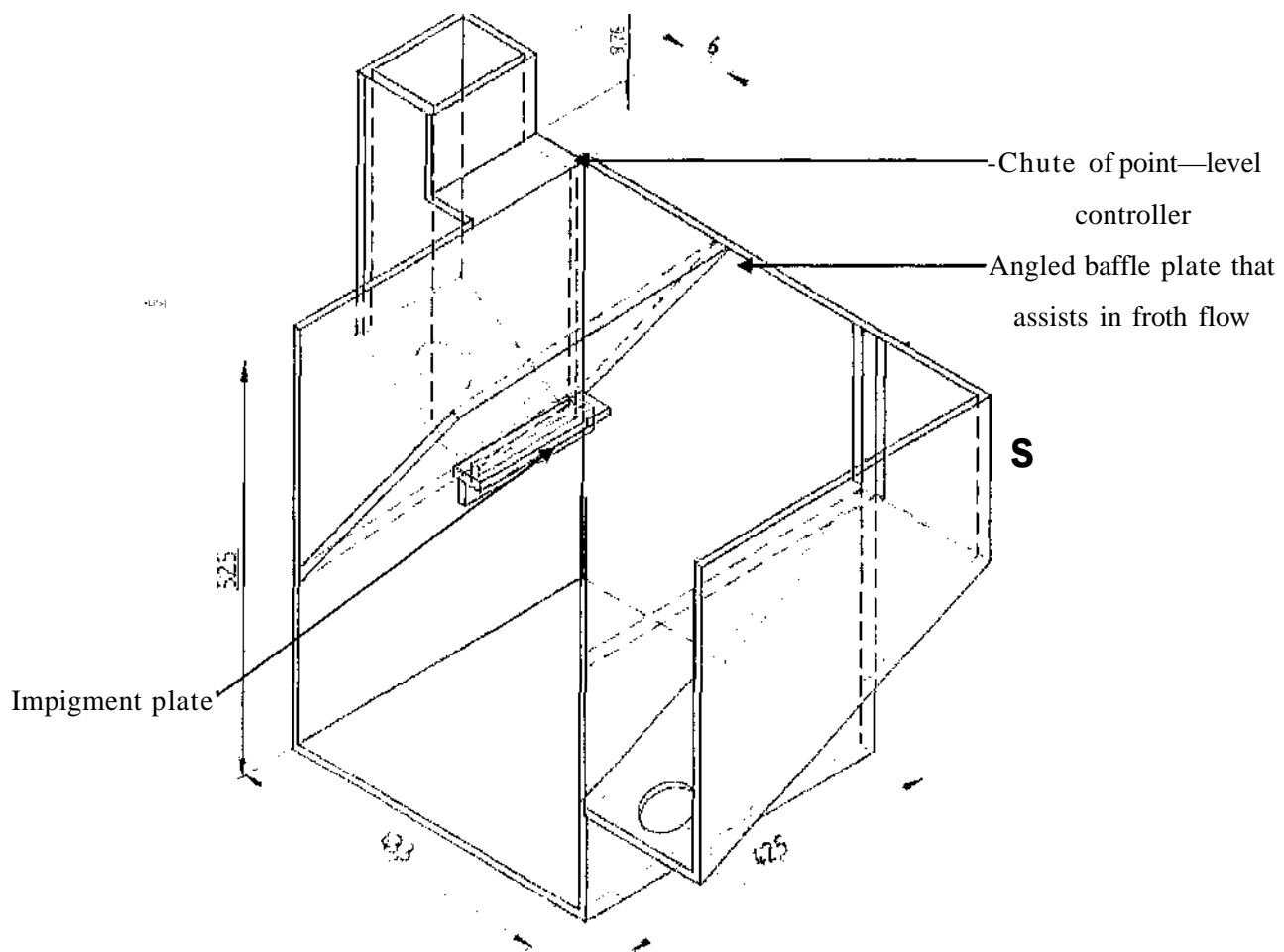


**Figure 4—14.** Recovery—grade curves (a) and grade—time curves (b) at different froth heights in the 15—litre Denver cell.

**4.5.3 Conclusions.** The froth height was varied in a 56—litre Outokumpu cell, 15—litre Denver cell and 3.4—litre Wemco cell. The linear model proposed by Vera and the exponential model proposed by Gorain was fitted to the experimental data and regressed to find the collection zone rate. Both models fitted the data well; however the model proposed by Gorain was used to calculate  $R_f$  for each cell used in the SBFA.

## 5.0 DESIGN OF BATCH CELLS

This chapter provides detailed drawings of the cells used for experiments. The cells were constructed and modified with perspex. The perspex was transparent, which was beneficial when it came to observing the flotation conditions within the cells. The cells were designed to function as a single batch flotation cell, and to fit together to form the SBFA.



**Figure 5—1.** Schematic of the modified cell fitted with the Outokumpu mechanism. Take note that all the dimensions are in centimeters and the diagram is not drawn to scale. The cell has a volume of 56 litres.



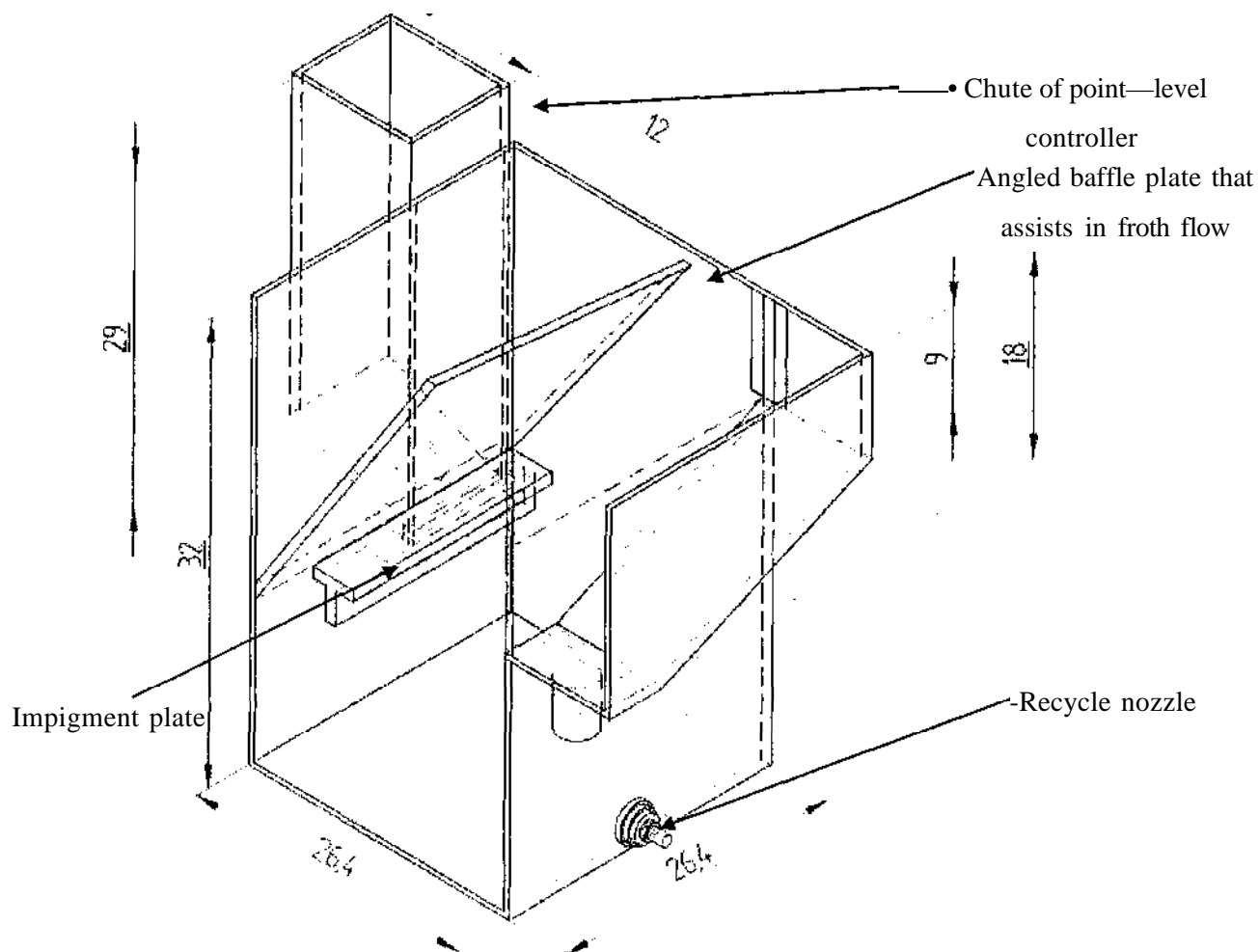
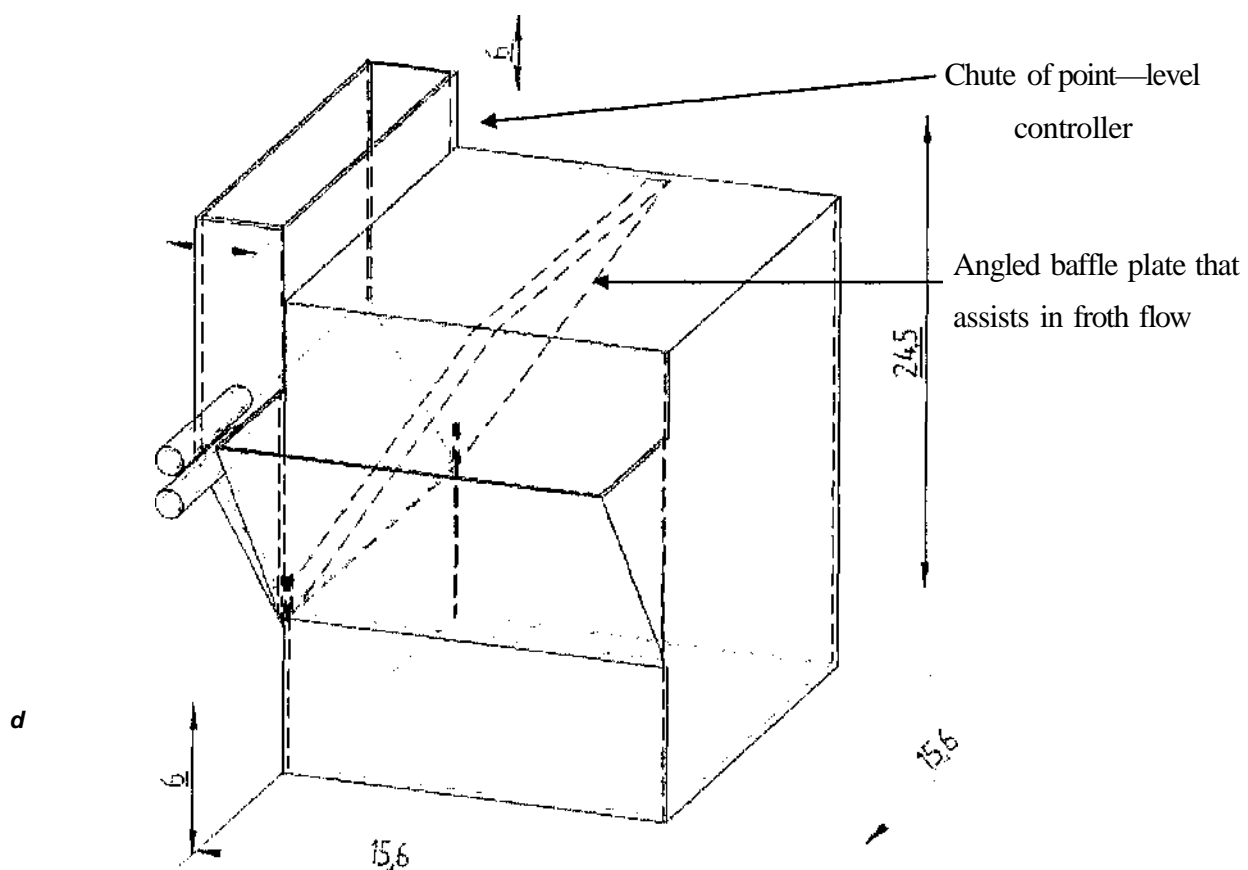


Figure 5—2. Schematic of the cell constructed and fitted with the Denver mechanism. Take note that all the dimensions are in centimeters and the diagram is not drawn to scale. The cell has a volume of 15 litres.



**Figure 5-3.** Schematic of the cell constructed and fitted with the Wemco or Denver mechanism. Take note all the dimensions are in centimeters and the diagram is not drawn to scale. The cell has a volume of 3.4 litres.

## 6.0 DESIGN OF SBFA

A detailed design of the SBFA is provided in this chapter. The SBFA had been constructed by joining the batch cells together— see Chapter 5.0 for cell schematics. The design methodology for the SBFA had been adopted from the Mintek rig which had pulp recycles and cells in series. However certain operating variables (like recycle rates, air flow rates, froth heights, etc) that had been left out from the rig design had been incorporated into the SBFA design.

The recycle between stages was one of the operating variables that had been measured and controlled in order to assess the effect on separation. A Lowara pump had been used to transport material between cell two and one, see Figure 6—1. The Lowara pump was a threaded centrifugal pump with an open impeller. The advantage of an open impeller pump is that it can handle liquids with suspended solids.

The recycle rate was measured with a liquid rotameter that had been recalibrated with a liquid carrying a suspension limestone, talc and silica. The calibration chart for the liquid carry a suspension was compared with the chart for a water system only and little difference was found.

The air flow rate was another operating variable that was measured and controlled in the SBFA. The air flow rate was measure with a gas rotameter calibrated for air at a temperature of 25°C.

The froth height was adjusted in each cell of the SBFA by using weir bars to increase the height of the froth zone.

The pulp level (i.e. volume) was controlled in each cell of the SBFA by a point—level controller. The point—level controller was operated by setting the chute level at the level the cell needed to operate at; a hose was then attached to the chute to provide water. The continuous supply of water in the chute maintained the cell pulp level, while the excess water was expelled through an outlet pipe attached in the chute.

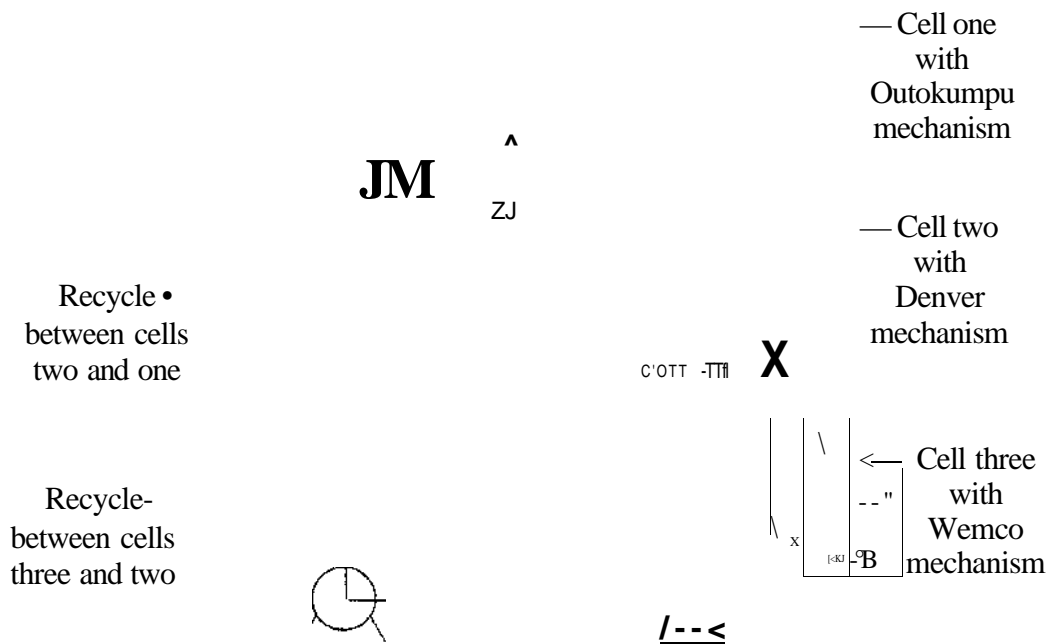


Figure 6—1. Schematic of the three cell SBFA.

Chapter 9 has a schematic of the two cell SBFA used, see Figure 9—1. The two cell SBFA was used because it was difficult to control the conditions in the last cell of the three cell SBFA. Therefore most of the test work was done on a SBFA with two cells i.e. the Wemco mechanism and cell was removed.

## 7.0 DEVELOPMENT OF THE SBFA MODEL

A detailed explanation of the SBFA model is given in this chapter. The model discussed in this chapter will be for a SBFA having two cells operational.

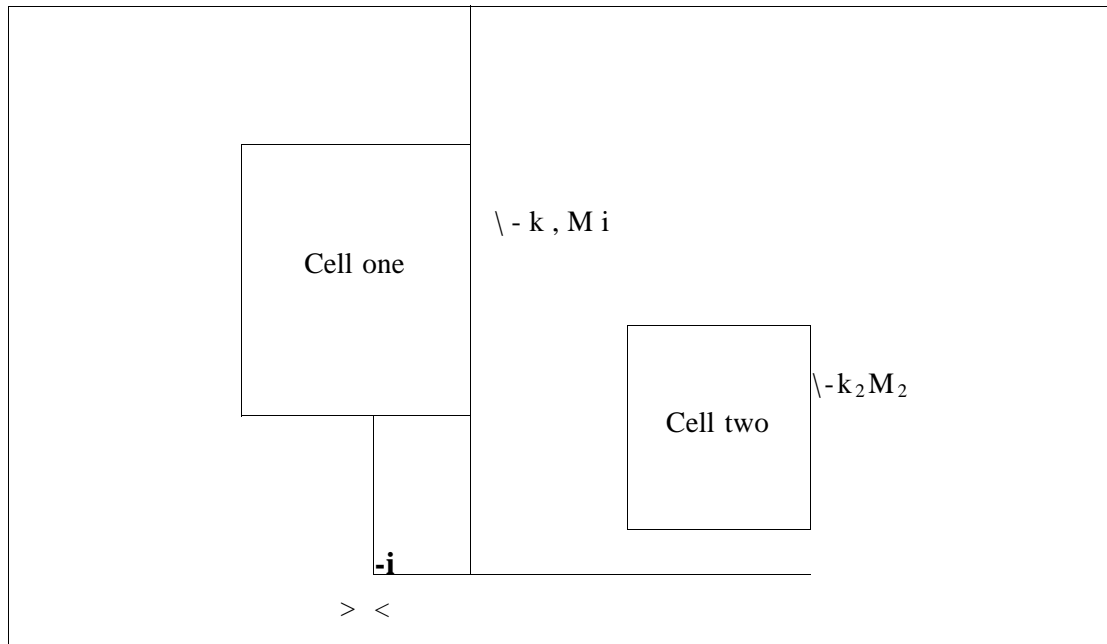


Figure 7—1. Block diagram of the SBFA.

The fundamental equation for a batch reactor (from Chapter 2, Section 2.5) was used to develop the model.

$$\frac{dC}{dt} = -kC^n \quad (7)$$

$n$  is unity, for the reason given in Chapter 2. If a constant pulp volume is maintained, then Equation 7 becomes

$$\frac{dM}{dt} = -kM$$

$$\frac{dM}{dt} = -kM \quad (11)$$

Equation 11 formed the basis for developing a model that will be used to describe the process taking place in Figure 7—1. The numerical subscripts 1 and 2 will be used in the model to refer to each cell. The flotation rate constant will be given as  $k$  and the recycle will be given as  $qp^*$ , where  $q$  is the volumetric flow rate;  $p$  is the recycle stream density and  $x$  is the mass fraction of the valuable material in the recycle stream.  $qpx$  refers to the mass flow rate of the valuable material recycled, which was assumed constant over the entire experiment by taking the average mass flow rate of the valuables over the entire experiment. The subscript 2—1 refers to the cell from which material is pumped from (cell 2) and discharged to— cell 1.

Equation 12 and 13 can be used to describe the process taking place in each cell of the SBFA.

$$\frac{dM_1}{dt} = -k_1M_1 + qp^* \quad (12)$$

$$\frac{dM_2}{dt} = k_2M_2 - qpx_{2-1} \quad (13)$$

Equations 12 and 13 can be solved analytically.

$$\frac{dM_1}{dt} + W = qp^*$$

$$e^{kt} \int \frac{qp^*}{e^{kt}} dt + C$$

$$e^{k_2t} \int \frac{qp^* - k_2M_2}{e^{k_2t}} dt + C$$

$$e^{k_2t} \int \frac{qp^* - k_2M_2}{e^{k_2t}} dt + C$$

The constant of integration  $C$  can be determined at time  $t = a$ , which is the time it takes for the froth zone to form in cell 1.

$$C = e^{*10} M(0)$$

$$M_1(0) = [1 - e^{*10} M(0)] + e^{*10} M(0) \quad (14)$$

Equation 14 gives the mass of the valuables in cell one for time  $a$  to time  $t$ . At time  $a$  the mass in cell 1 is the same as the mass charge in, since no material has been transferred to cell 2. Equation 13 can be solved by using Equation 14.

$$\frac{dM_2}{dt} + k_2 M_2 = k_1 M_1 - qpx$$

$$\frac{dM_2}{dt} + k_2 M_2 = qpx e^{k_1 t - k_2 t} + k_1 M_1 e^{k_1 t - k_2 t}$$

Equation 15 gives the variation in mass in cell 2. From Equation 15 a recovery—time equation can be formulated for the two cell SBFA.

$$M_2(t) = \frac{\{k_1 M_1 e^{k_1 t} - qpx\}}{(k_2 - k_1)} e^{k_2 t} + \frac{qpx}{k_2 - k_1} e^{k_2 t} \quad (15)$$

$$R = R_0 - S^* e^{-(k_1 - k_2)t} - \frac{qpx}{k_2 - k_1} e^{k_2 t} \quad (16)$$

The parameters  $B$ , and  $y$  are:

$$B = \frac{[k_1 M_1 e^{k_1 a}] - [qpx]}{(k_2 - k_1) M(0)}$$

$$W = \frac{e^{k_2 t} M_2(t)}{M(0)}$$

A scale up equation had been developed. The equation relates the rate constant in cell 2 to the rate constant in cell 1 by using empirical parameters like the superficial air velocity — , the froth recovery  $\{R_f\}$  and a scaling parameter (n) that takes into account chemical and mechanical parameters that are difficult to evaluate. The empirical relationship is:

$$k_{2i} = k_{1i} \left( \frac{Q_{2i}}{Q_{1i}} \right)^n \left( \frac{R_{f2}}{R_{f1}} \right) \quad (17)$$

$i$  is the cell of interest for example the Denver, Outokumpu or Wemco cell.



## 8.0 EXPERIMENTAL PROCEDURE

The experiment procedure for each experiment performed is given in this chapter. A synthetic ore made from limestone, talc and silica was used in the experiments. The limestone simulated valuable material, while the talc and silica simulated floatable and non—floatable gangue respectively

### 8.1 Experimental procedure for rig

. The following procedure was used to operate the rig with only one cell operational:

1. Approximately 5.111 Kg of the synthetic ore\* was added to 46—litres of water in the first cell of the rig to form a pulp having 10 % solids.
2. Approximately 0.598 g of the collector, oleic acid was added to the pulp and conditioned for 10 minutes. Approximately 0.897 g of the collector was used in the experiment involving the addition of more collector.
3. Approximately 1.400 g of the frother, Senfroth 6040B was added to the conditioned pulp.
4. The impeller and air flow\* was switched on and the froth was allowed to form.
5. The concentrates was collected from the launder at times 1, 2, 3, 5, 7, 10, 15 and 20 minutes.
6. The concentrates were filtered under pressure and the cake formed was dried in an oven overnight.

\* The composition by mass for the synthetic ore/mixture is 5 % limestone, 5 % talc and 90 % silica.

\* The impeller speed was determined from scoping tests. The speed was set at frequency of 27 Hz. The speed was determined together with the air flow by trial and error using the criterion of a stable pulp—froth interface and the extent of bubble coalescence near the froth surface. In addition the apparatus had no equipment for measuring the air flow into each cell.

7. The dried cake was then analyzed for limestone, by acid dissolution with hydrochloric acid\*.

During the experiment water was added to the launder to wash the concentrates that may have attached to the launder walls.

Wash water with a froth concentration similar to the pulp was used to wash the impeller and walls of the cell. In addition, the wash water was used to maintain the pulp level in the cell.

The experimental procedure for the two cell configuration is similar to the one cell configuration; however the following points have to be noted:

1. The pulp was made and conditioned with 0.598 g of collector in the first cell of the rig only, similar to step one for a single cell configuration.
2. 1.400 g of frother was added to the pulp in the first cell and 0.650 g of frother was added to the water of the second cell.
3. The pulp recycle nozzle in cell two was opened so that material was recycled from cell two to cell one.
4. The air flow was turned on in cell one and the froth zone was allowed to form.
5. The air flow was turned on in cell two once the froth entered the launder.
6. The concentrates were collected from the second launder at times 1, 2, 3, 5, 7, 10, 15 and 20 minutes.

\* Hydrochloric acid was used to dissolve the limestone in the dried cake according to the chemical reaction:



The difference in the concentrate mass before and after acidification gives the amount of limestone present in the concentrate.

7. The concentrates were analyzed for limestone by the technique used in steps six to seven of Section 8.1 for a rig with one cell operational.

## 8.2 Experimental procedure for batch tests with the variable reagent concentration

For the investigation involving the effect of the reagent suite on flotation the following procedure was used:

1. Approximately 568.89 g of a synthetic mixture (with composition similar to that used in the rig) was added to the 3.4—litre cell with a Denver mechanism.
2. The superficial air velocity ( $1.070 \text{ m-s}^{-1}$ ), impeller speed (800 rpm) and pulp level (15 cm) was kept constant throughout each test, so that the influence of the operating variables on the tests were minimal<sup>f</sup>.
3. The optimal collector dosage was determined by fixing the frother concentration to a value obtained from similar experiments done by other students, which was 25.000 mg of frother per a litre of water.
4. The collector concentration set used was [0.000, 0.059, 0.117, 0.234 0.351 and 0.468] g collector per 100 g of limestone. The pulp in each experiment was conditioned for 10 minutes.
5. The air flow and impeller was turned on and the concentrates were collected at different timed interval.
6. The concentrates were analyzed for limestone by the technique used in steps six to seven of Section 8.1 for a rig with one cell operational.

<sup>f</sup> Although the operating variables were kept constant, this does not create similar flotation environments for every test. Since it is impossible to have the same feed particle size and the hydrodynamic conditions in every test, however attempts were made to keep as many variables constant so that the data could be analyzed with some confidence.

7. The optimal frother dosage was determined by fixing the collector concentration to the value which gave the best recovery of limestone from the collector tests, which was 0.234 g of collector per 100 g of limestone.
8. The frother concentration set used was [0.000, 15.22, 30.44, 60.87, 91.31 and 121.74] mg collector per a litre of water.

### 8.3 Experimental procedure for batch tests with the variables impeller speed and air flow rate

Once the optimal collector and frother concentrations were determined the next variable investigated was the effect of the impeller speed and the air flow rate on flotation. The following procedure was used:

1. Approximately 568.89 g of a synthetic mixture (with composition similar to that used in the rig) was added to the 3.4—litre cell with a Denver mechanism.
2. 0.067 g of collector was added to the pulp and conditioned for 10 minutes.
3. Thereafter 103.80 mg of frother was added to the conditioned pulp.
4. The impeller speed was varied for from 700 to 1000 rpm (in 100 rpm increments) along five air flow variations that gave superficial air velocities of: 1.07, 0.85, 0.65, 0.56 and 0.36  $\text{m s}^{-1}$
5. The concentrates were collected at different timed intervals.
6. The concentrates were analyzed for limestone by the technique used in steps six to seven of Section 8.1 for a rig with one cell operational.

## 8.4 Experimental procedure for batch tests with the variable pulp solid concentration

For the investigation involving the effect of solid concentration on flotation the following procedure was used:

1. A 15—litre cell was used with a Denver mechanism.
2. The pulp solid concentration was varied according to the following set [5.0, 7.5, 10.0 and 15] percent solids in the pulp by mass.
3. The collector was added according to the optimal concentration done in the 3.4—litre cell with the Denver mechanism, which was 0.234 g collector per 100 g of limestone. The pulp was condition for 10 minutes at an impeller speed of 1000 rpm.
4. Thereafter 451.72 mg of frother was used in all tests.
5. The air flow was set at a value that gave a superficial velocity of  $0.76 \text{ m}\cdot\text{s}^{-1}$ .
6. The concentrates were collected at different timed intervals.
7. The concentrates were analyzed for limestone by the technique used in steps six to seven of Section 8.1 for a rig with one cell operational.

## 8.5 Experimental procedure for batch tests with the variable froth height

For the investigation of froth height on flotation the following procedure was used:

1. A 15—litre cell was used with a Denver mechanism.
2. Approximately 781.05 g of a synthetic mixture (with composition similar to that used in the rig) was added to the cell.
3. The air flow, impeller speed and pulp level was kept constant, so that the influence of the operating variables on the tests was minimal.
4. 0.091 g of collector was added to the pulp and conditioned for 10 minutes.
5. 0.452 g of frother was added to the conditioned pulp.

6. The air flow was turned on and the concentrates were collected at different timed intervals.
7. The concentrates were analyzed for limestone by the technique used in steps six to seven of Section 8.1 for a rig with one cell operational.
8. The test was repeated for different froth heights by adding weir bars.
9. The test was also done in a 3.4 and 56—litre cells.

## 8.6 Experimental procedure for the SBFA

The following procedure was used in the operation of the SBFA with two cells:

1. The synthetic mixture was added to the first cell of the SBFA. The amount added depended on the solid concentration investigated— generally a pulp having 5 % solids was used.
2. 0.234 g of collector per a 100 g of limestone was added in the first cell only, and the pulp was conditioned for 10 minutes.
3. 30.44 mg of frother per a litre of water was added to the conditioned pulp of the first cell and the water of the second cell.
4. The froth depth and pulp level in both cells was set by using the weir bar and the point—level controller respectively.
5. The impeller in both cells was turned on.
6. The air flow to cell one was turned on and the time was recorded for the froth zone to form in cell one.
7. The air flow and the recycle rate in cell two was turned on once the froth formed in the cell one.
8. The time was recorded for the material to transfer to cell two and form a froth zone.
9. The concentrates and recycle samples were collected at different timed intervals.
10. The concentrates were analyzed for limestone by the technique used in steps six to seven of Section 8.1 for a rig with one cell operational.

## 8.7 Experimental procedure for the size analysis

The following procedure was used for size analysis of a sample:

1. A V2 set of sieves was used for the size analysis of the samples.
2. The sieve sizes were 250, 212, 180, 150, 140, 125, 106, 100, 90, 75, 63, 53, 45 and 38  $\mu\text{m}$ .
3. Approximately 50—90 g of material was sieved at an amplitude of 0.5 for a period of 15 minutes.
4. The material retained on each sieve was removed (with a sieve brush) and weight on an analytical balance accurate to four decimal points.
5. In the case of the sample being a mixture of limestone, talc and silica; steps one to four above was used to size the sample.
6. The sized samples were analyzed for limestone with hydrochloric acid according to steps six to seven of Section 8.1 for a rig with one cell operational.
7. The acidified samples were filtered and dried overnight.
8. The samples were then weight again.

## 9.0 EXPERIMENTAL WORK- SBFA

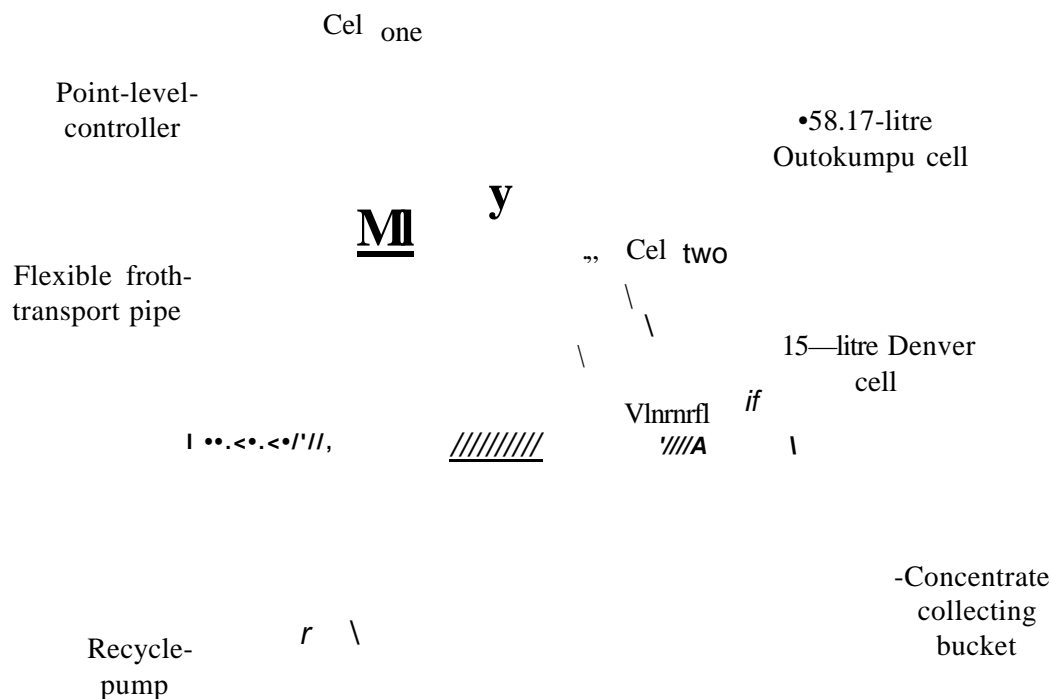
This chapter details the work done on the SBFA. Various experiments were performed to assess the performance of the SBFA. Initially experiments using a three cell configuration highlighted certain operating difficulties with the Wemco cell. It was therefore decided to limit this investigation to a two cell configuration. The following operating variables were investigated in the two cell configuration:

- Effect of recycle rate on flotation
- Effect of froth depth on flotation
- Effect of solid concentration on flotation

### 9.1 Experimental apparatus and procedure

**9.1.1 Experimental apparatus.** The SBFA was operated with two cells. The first cell was a 56—litre Outokumpu cell and the second cell was a 15—litre Denver cell. A flexible pipe was used to transport the froth generated in the first cell to the second cell. The flexible pipe was inserted near the Denver mechanism so that the concentrate could be dispersed more efficiently in the second cell. A pump was used to recycle the pulp from the second cell to the first cell. The recycle rate was monitored by a liquid rotameter and controlled by a Saunders valve. The air flow rate in each cell was set manually by a gas rotameter. The froth height was varied in each cell by adding and removing weir bars having different heights. The volume in each cell was controlled by a point—level controller. Figure 9—1 shows the experimental setup of the two cell SBFA. The design and construction of the rig is discussed in Chapter 5 and 6.





**Figure 9—1.** Schematic of the SBFA, with two flotation cells.

**9.1.2 Experimental procedure.** A mixture of limestone, talc and silica was used in the experiments. The limestone simulated valuable material, while the talc and silica simulated floatable and non—floatable gangue respectively. A detailed procedure for the operation of the SBFA is given in Chapter 8 Section 8.6.

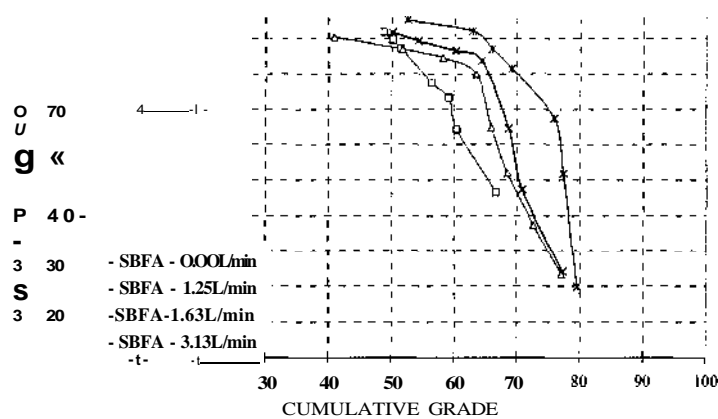
## 9.2 Effect of recycle rate on flotation

**9.2.1 Experiments.** The Effect of the rate of recycle on the separation of limestone from gangue was investigated by varying the recycle rate between cell two and one from 0.00 to 3.13 L-min<sup>-1</sup>.

**9.2.2 Results and discussion.** The froth heights in cells one and two were maintained at about 15 and 5 mm respectively. The recycle rate was varied according to the set, [0.00, 1.25, 1.63 and 3.13] L-min<sup>-1</sup>.

Figure 9—2 shows the cumulative limestone recovery versus grade for different recycle rates. The general trend indicates that as the recycle rate increased; the degree of separation improved because the curve shifted higher and to the right i.e. improved grade and recoveries. The recovery—grade curve shifted higher because as the recycle rate increased more material from cell two was recycled to cell one. The recycle stream was mainly composed of gangue material, therefore as the recycle rate was increased; more of the gangue material was recycled from cell two. Since more gangue material was recycled the grade of the concentrate improved because less gangue accumulated in cell two despite increased entrainment of gangue from cell one.

Figure 9—3a shows the variation of the concentrate grade with time. If the concentrate grades for the different recycle rates are compared at a time of  $t = 0.5$  min, then the data shows that as the recycle rate increased, the grade of the concentrate collected at  $t = 0.5$  min improved. The same improvement is evident for concentrate collection at other times. Figure 9—3b shows the cumulative percentage of the gangue recycled (relative to the mass of gangue in the feed) for the entire duration of the experiment. The figure shows that the amount of gangue recycled over the entire experiment increased as the recycle rate increased. The increase in the amount of gangue recycled, improves the concentrates grade.



**Figure 9—2.** Cumulative limestone recovery versus grade for different recycle rates

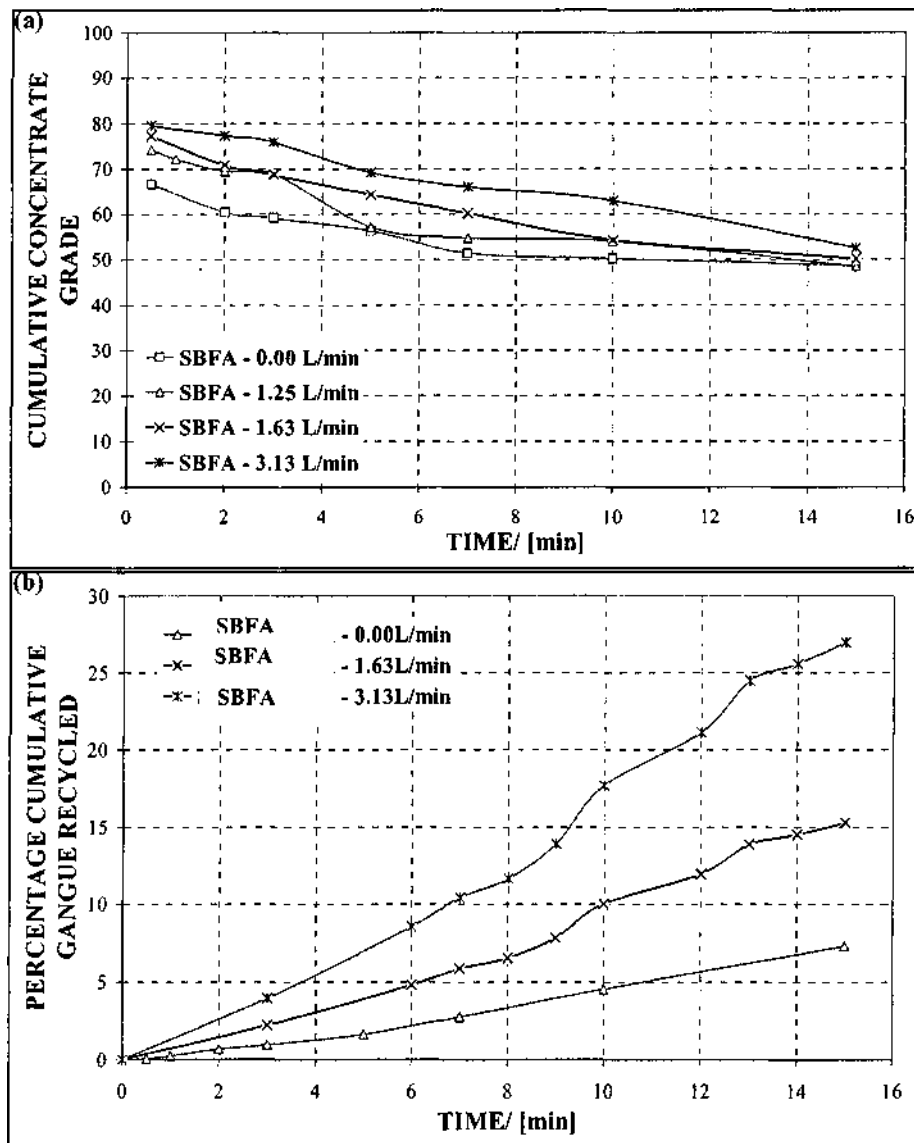


Figure 9—3. Variation in concentrate grade (a) and cumulative gangue recycled (b) with time.

**9.2.3 Conclusions.** The recycle rate was varied in the SBFA. The degree of separation improved as the recycle rate was increased, see Figure 9—2. The increase in recycle rate, also improved the cumulative grade of the concentrate since more gangue was removed from cell two of the SBFA before it could be recovered in the concentrate, see Figure 9-3 a.

### 9.3 Effect of froth depth on flotation

**9.3.1 Experiments.** The froth depth was varied in cells 1 and 2 of the SBFA. The froth depth was varied by adding and removing weir bars near the lip of the cell. A detailed experimental procedure is given in Chapter 8 section 8.6. Sample calculations and experimental data for the variation in froth height are given in Appendix II.VIII. The recycle rate had to be varied between 2.5 and 3.1 L-min<sup>-1</sup> to maintain the pulp level in cell two.

**9.3.2 Results and discussion.** Figure 9—4 shows the recovery—grade curve for different froth heights in cell one. The general trend observed in Figure 9—4 is that as the froth height in cell one increased, the degree of separation improved. This can be attributed to the large froth residence time associated with deeper froths. The large froth residence time allows sufficient time for the drainage of gangue material that can be entrained in the froth.

The superficial air velocity used in cell one was 1.17 m-min<sup>-1</sup>. This reasonably high superficial air velocity together with the high froth residence time provides an ideal condition for the drainage of gangue. Since the superficial air velocity creates a loose froth structure while the deep froth provides sufficient time for the gangue (both coarse and fine) to drain into the pulp.

Shallow froth depths are characterized by a shorter residence time and a lower grade. Therefore from Figure 9—5 at a concentrate collection time  $t_{\text{c}} = 0.5$  min, the grade of the concentrate improved as the froth depth was increased from a shallow depth of 5 mm to a deep depth of 29 mm.

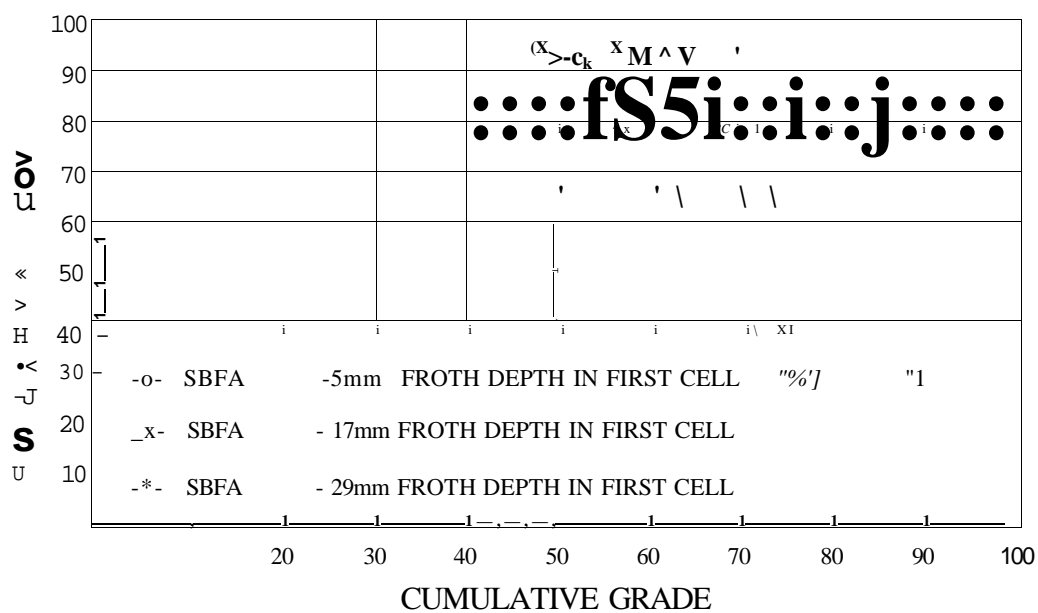


Figure 9—4. Recovery—grade curve for different froth heights in cell one of the SBFA, froth height in cell two was 5 mm.

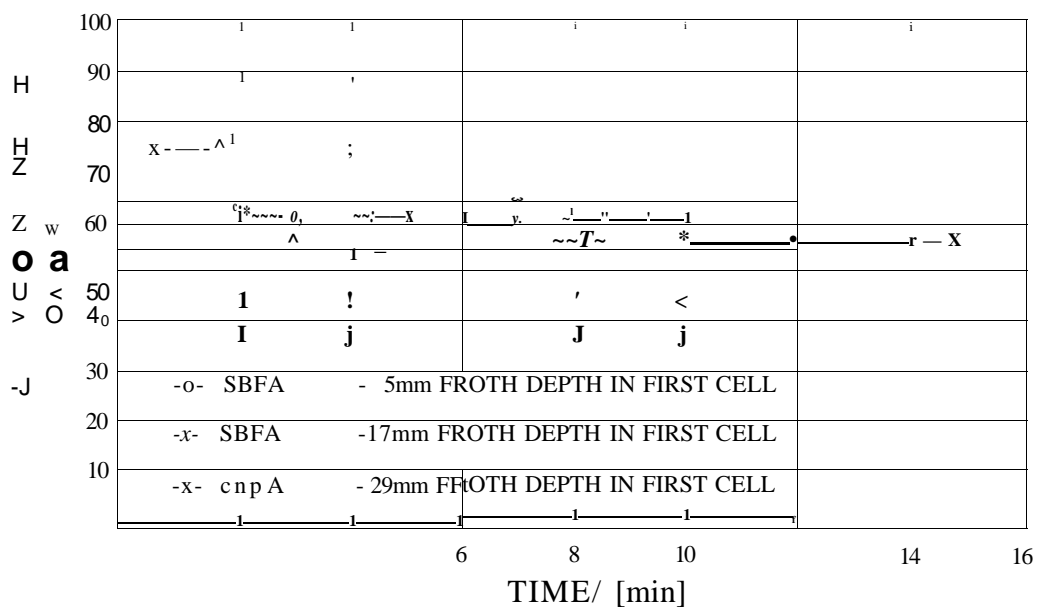
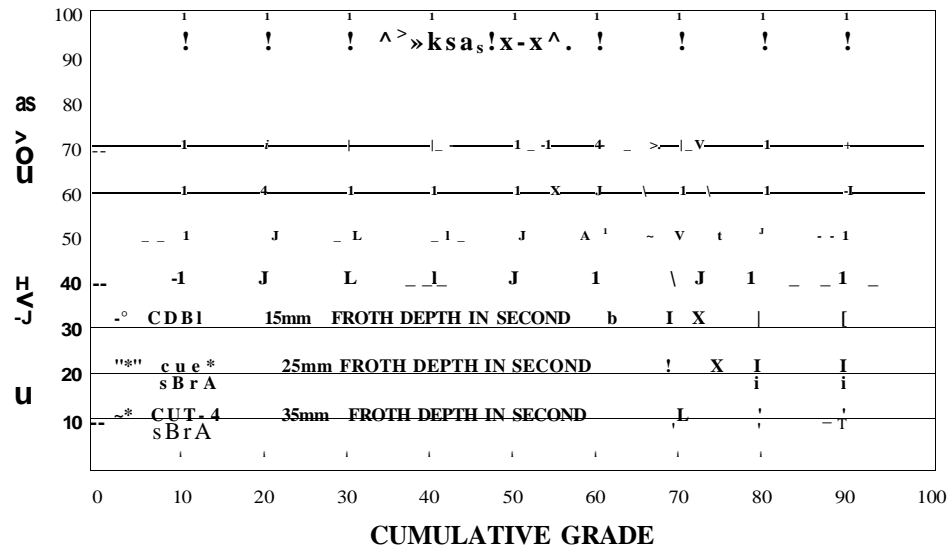
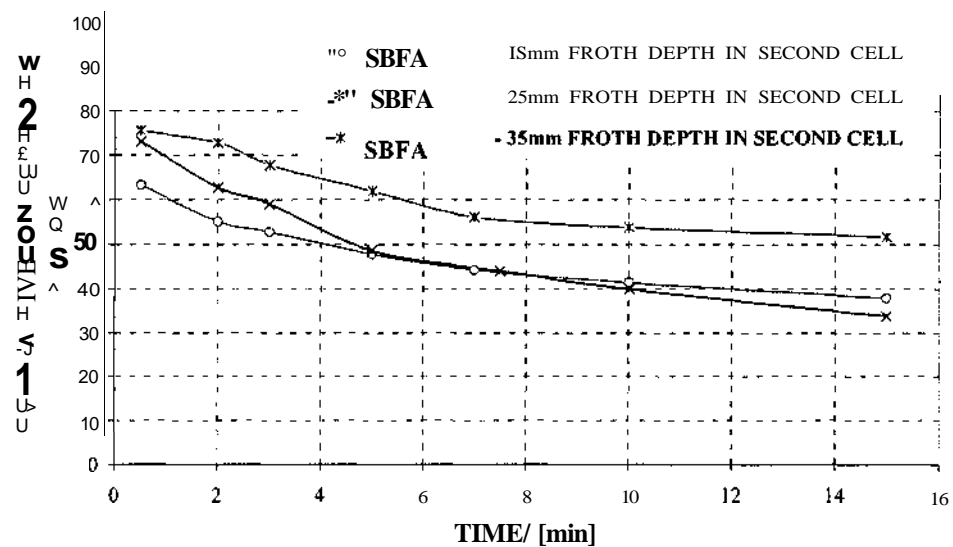


Figure 9—5. Variation in the concentrate grade with time for different froth heights in cell 1 of the SBFA, froth height in cell two was 5 mm.

Figure 9—6 and 9—7 show the effect of different froth heights (cell 2 of SBFA) on the concentrate grade. The trend for different froth heights in cell 2 is the same as the different froth heights in cell 1.



**Figure 9—6.** Recovery—grade curve for different froth heights in cell 2 of the SBFA, froth depth in cell one was 5 mm.



**Figure 9—7.** Variation in the concentrate grade with time for different froth heights in cell 2 of the SBFA, froth depth in cell one was 5 mm.

**9.3.3 Conclusions.** The froth height was varied in both cells of the SBFA. The degree of separation improved as the froth height was increased in both cells. The improvement in the concentrate grade was due to the improved drainage provided under the high froth residence time.

## 9.4 Effect of solid concentration on flotation

**9.4.1 Experiments.** The solid concentration was varied in the SBFA. A size analysis was done on the total concentrate for the different solid concentrations. A detailed experimental procedure is given in Chapter 8.4 and experimental data for the variations in the solid concentration are given in Appendix II.X. The recycle rate was maintained at  $2.5 \text{ L}\cdot\text{min}^{-1}$  and the froth depth in cell 1 and 2 was 10 and 7 mm respectively.

**9.4.2 Results and discussion.** Figure 5—8 shows the recovery—grade curve for initial different solid concentrations in cell 1. The general trend observed from Figure 5—8 is that as the solid concentration decreased; the degree of separation improved, since the recovery—grade curve shifted upwards indicating that the grade of the concentrate improved. At a dilute pulp density of 7.5 % solids there is less fine material and gangue material charged into the SBFA. Therefore the degree of entrainment is lower under dilute pulp conditions than at concentrated pulp conditions, like 15 % solids.

At a solid concentration of 15 % there is more limestone particles present. Therefore the bubbles will be saturated with the limestone particles and talc. Saturated bubbles are heavier than partially loaded bubbles. At the froth the saturated bubbles coalesce and burst dropping the limestone particles into the lower regions of the froth or the pulp zone, therefore there is a lower grade and recovery of limestone. From Figure 9—9 at a concentrate collection time of  $t = 0.5 \text{ min}$ , the grade of the concentrate improved as the solid concentration was decreased from 15 % to 7.5 % solids. This was due to less fine and floatable (talc) gangue being present at low solid concentrations.

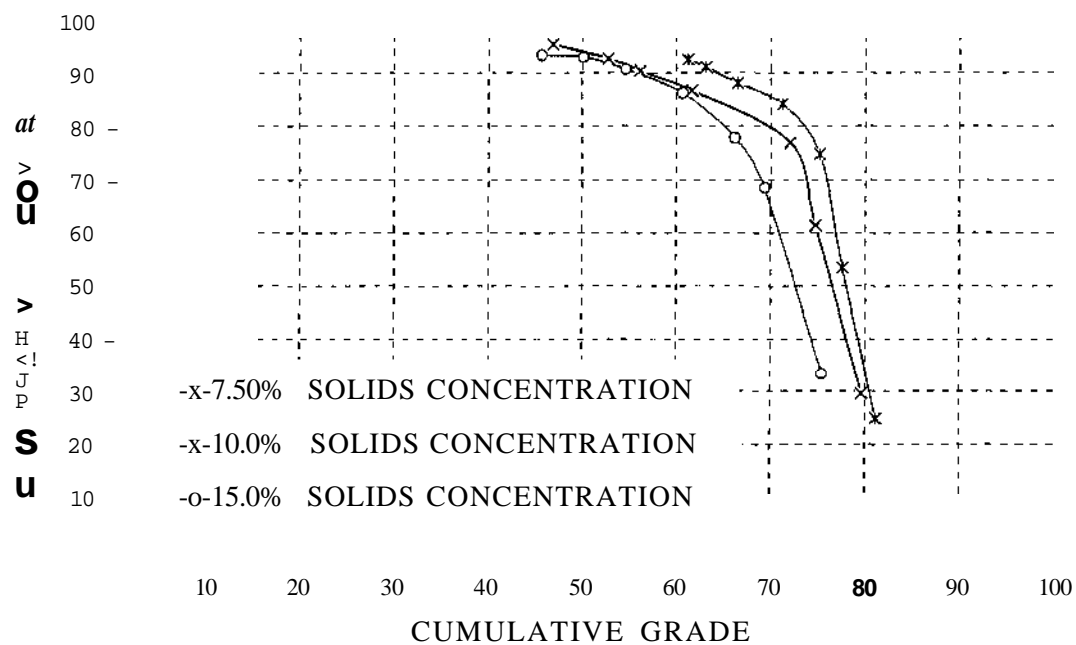


Figure 9—8. Recovery—grade curve for different solid concentrations.

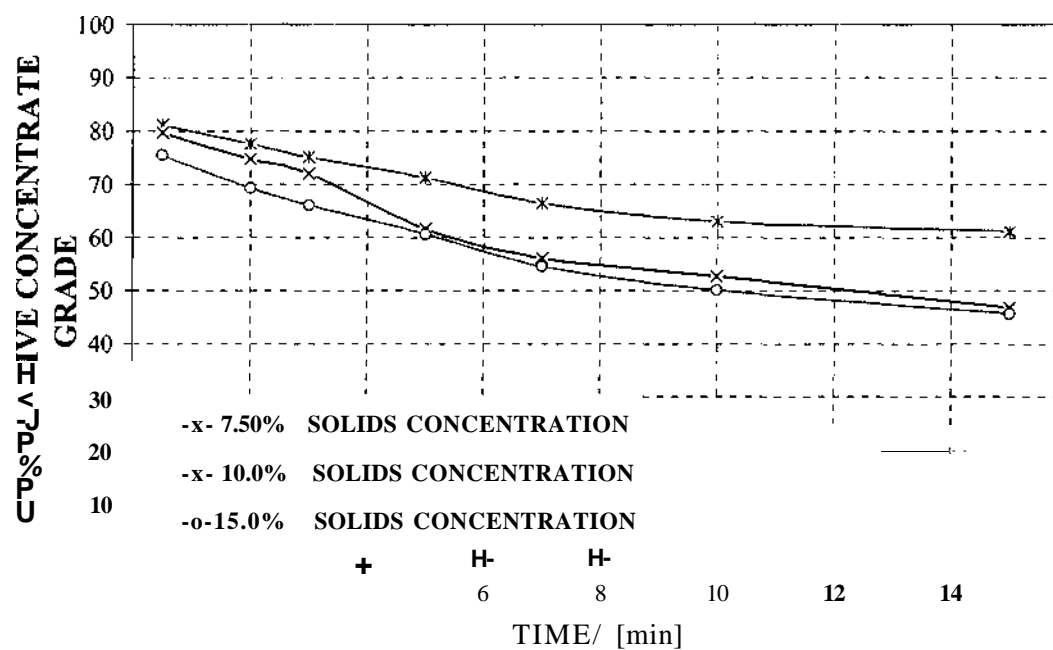


Figure 9—9. Variation in the concentrate grade with time for different solid concentrations.



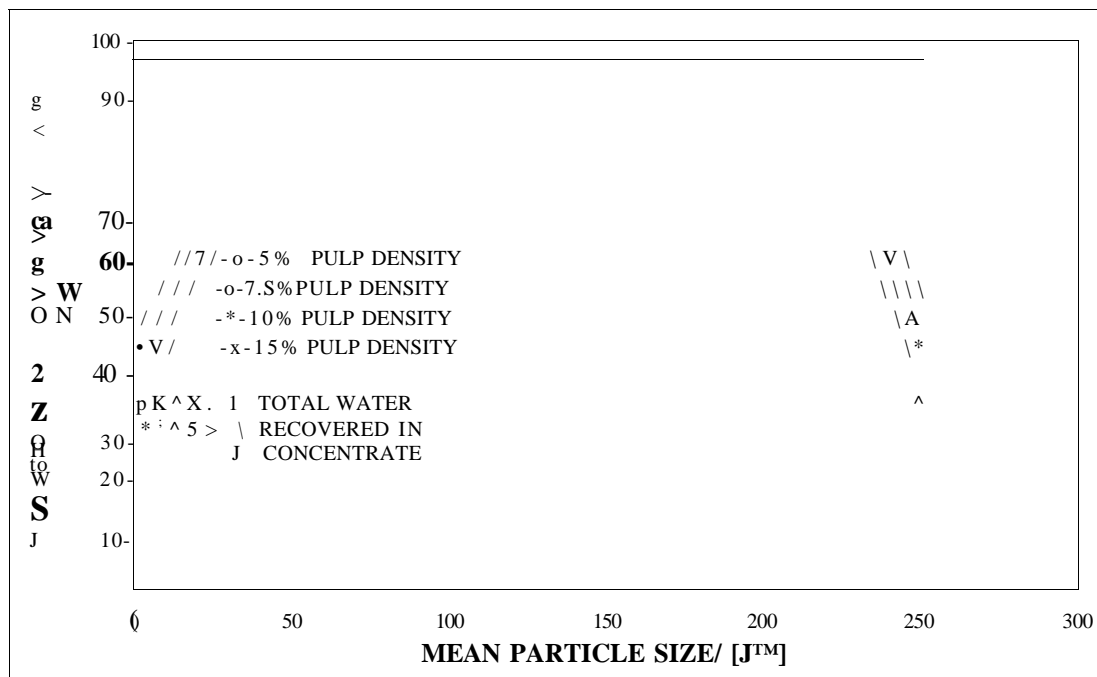


Figure 9—10. Recovery of limestone by particle size, in the SBFA at different pulp densities.

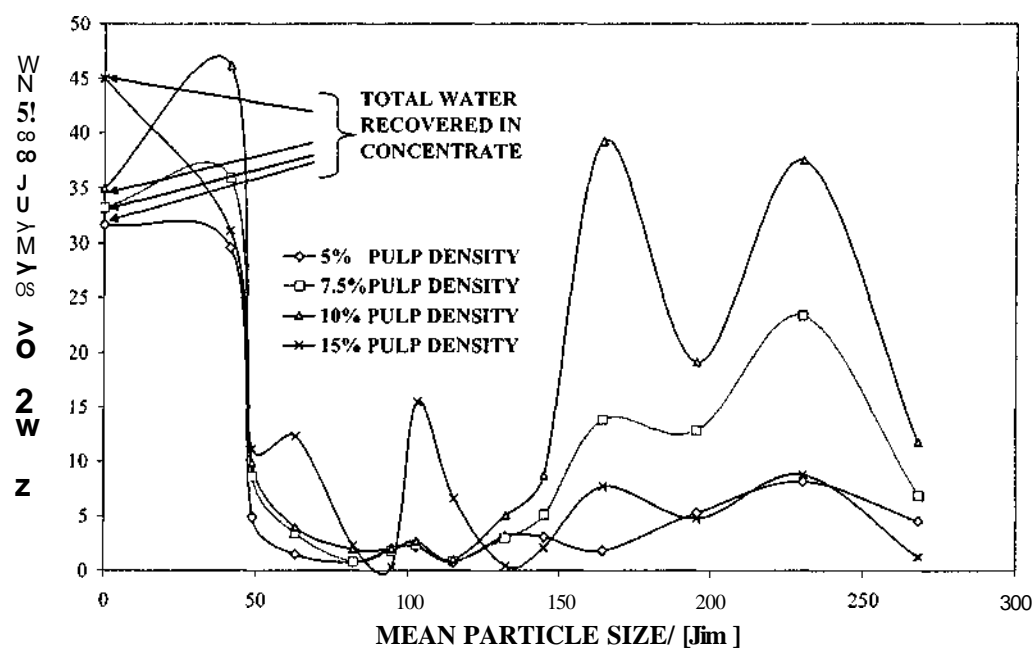
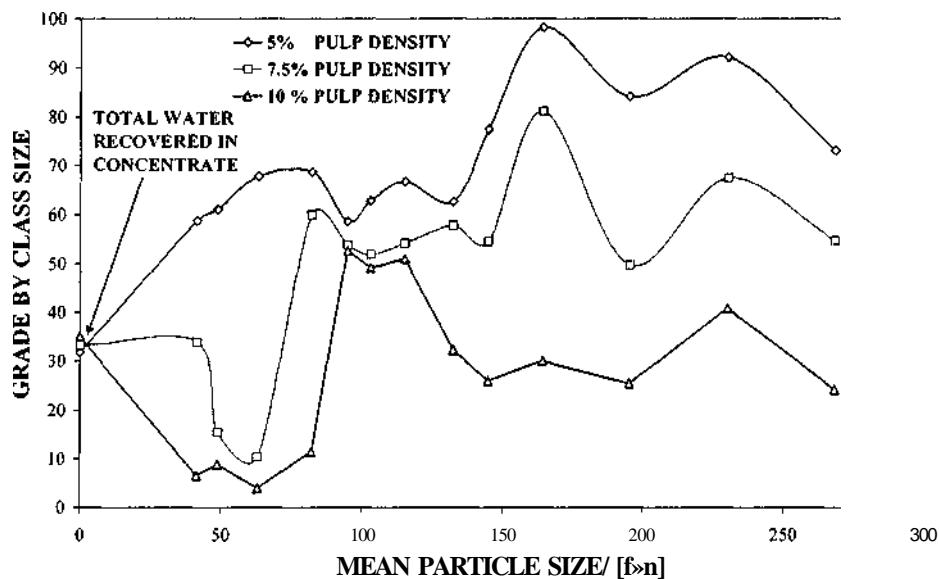


Figure 9—11. Recoveries of gangue by particle mean size, in the SBFA for different pulp densities.

The recoveries by mean particle size (Figure 9—10 and 9—11) profiles are similar to the profiles obtained from the Denver cell batch test (Figure 9—9) but there is a lower recovery of coarse particles. This could be due to the sedimentation of material in various parts of the SBFA.



**Figure 9—12.** Grade by particle size, in the SBFA.

Figure 9—12 shows that the SBFA reduces the recovery of fine particles by entrainment substantially. The grade for each size class decreased as the solid concentration was varied from a dilute pulp of 5 % to a concentrated pulp of 15 %. This can be attributed to the larger amount of gangue present as the solid concentration was increased.

**9.4.3 Conclusions.** The solid concentration was varied in the SBFA. The degree of separation improved as the solid concentration decreased. The improvement in the separation can be attributed to the lower fine gangue content at dilute pulp densities. The SBFA used dilute conditions in the second stage (initially having water only) resulting in a significant reduction of entrainment.

## **10.0 DISCUSSION**

This chapter provides an overview of the development, modelling and performance of the SBFA

### **10.1 Development of the SBFA**

Initially experiments were carried out using a flotation rig provided by Mintek. The results (see Chapter 3) showed that the rig had some design flaws which made it difficult to separate the valuable material (limestone) from the gangue material (talc and silica). The poor separation was caused by the impeller—sparger mechanism; dead zones and poor froth launder design. The impeller—sparger mechanism did not provide the proper hydrodynamic conditions for efficient air dispersion and mixing; and the presence of dead zones resulted in a portion of the limestone being excluded completely from the flotation process. In addition, the concentrate backed up in the froth launder and was not transported efficiently into the second cell of the rig, resulting in a reduced recovery of limestone.

The poor separation can also be attributed to the operating variables. For instance the operating variables like pulp recycles and air flow rates could not be measured and controlled hence the effect of these variables on the flotation process could not be assessed.

However credit must be given to Mintek for the concept of a semi—batch device with recycles. The SBFA was designed with the intention of being a portable flotation device that could be used to measure the floatability of a mineral in a stream of a flotation plant. Initially the SBFA was designed with three cells; however poor operating conditions in the third cell led to the development and testing of a two cell SBFA.

The two cell SBFA is analogous to a rougher—cleaner circuit in a flotation plant; it provides the operator with the benefits of a pilot plant (recycle, multiple cells, etc) and the ease of operation obtained from a conventional batch test<sup>3</sup>.

The recycle rate, air flow rate, froth height and pulp level was controlled and measured in each cell of the SBFA; see Chapter 5 for cell design. The concentrate generated in cell one entered cell two by gravity, while the pulp in cell two was recycled to cell one with an open impeller pump. The recycle rate was controlled and measured with a liquid rotameter.

## 10.2 Modelling of the SBFA

The SBFA was modeled using the equation for a batch reactor given in Chapter 2. Chapter 7 outlines the SBFA model development; the recovery—time equation for a two cell SBFA with recycle [7/9x]<sub>2]</sub> is given below.

$$R = R_{MAX} \frac{\{k_x e^{M(a)} - \{e^{[qpx]_2} - 1\} \}}{\{k_2 - k_x\} M^a} \left( \frac{V^*}{V} \right)^{k_2} e^{-h} \left( \frac{M J b}{M, (0)} \right)^{k_1 b} X e^{-k_2 t}$$

The equation has two parameters  $R_{MAX}$  and  $k_2$ . The constants  $a$  and  $b$  are the time delays for froth formation in cell one and two respectively.  $M$  is the mass in grams at time  $t$ . The flotation rate constant for each cell can be expressed by the empirical equation which was developed using conventional batch test on the different cells:

$$k_i = \frac{1}{t} \ln \left( \frac{M_i}{M_i(0)} \right) \quad (17)$$

Appendix I. IV shows the application of the empirical equation in determining the flotation rate constant for a batch test.

In this chapter the terra batch refers to laboratory test done in a single flotation cell.

<sup>1</sup>  $k_1$  is the flotation kinetic for cell one and  $k_2$  is the flotation kinetic for cell two.

Figure 10—1 shows the deviation of the flotation rate constants predicted from the empirical equation ( $k_{\text{Predicted}}$ ) and the experimentally determined rate constant ( $k_{\text{Experimental}}$ ) obtain from nonlinear regression of the recovery—time data for a batch test using the Agar model. The deviation of  $k_{\text{Predicted}}$  from  $k_{\text{Experimental}}$  is minimal because the correlation coefficient is close to unity.

The empirical equation can also be used to calculate the flotation rate constant in any one of the cells of the SBFA. This can be done by taking the ratio of the flotation rate constants as shown in the equation below. Therefore the recovery—time data obtained from the SBFA can be regressed to one flotation rate constant  $k_i$ , since the flotation rate constant for cell one ( $k_1$ ) can be calculated by the ratio of the empirical equations i.e.

$$R, \quad \frac{k_i}{k_1} = \frac{C_i}{C_1} \quad (19)$$

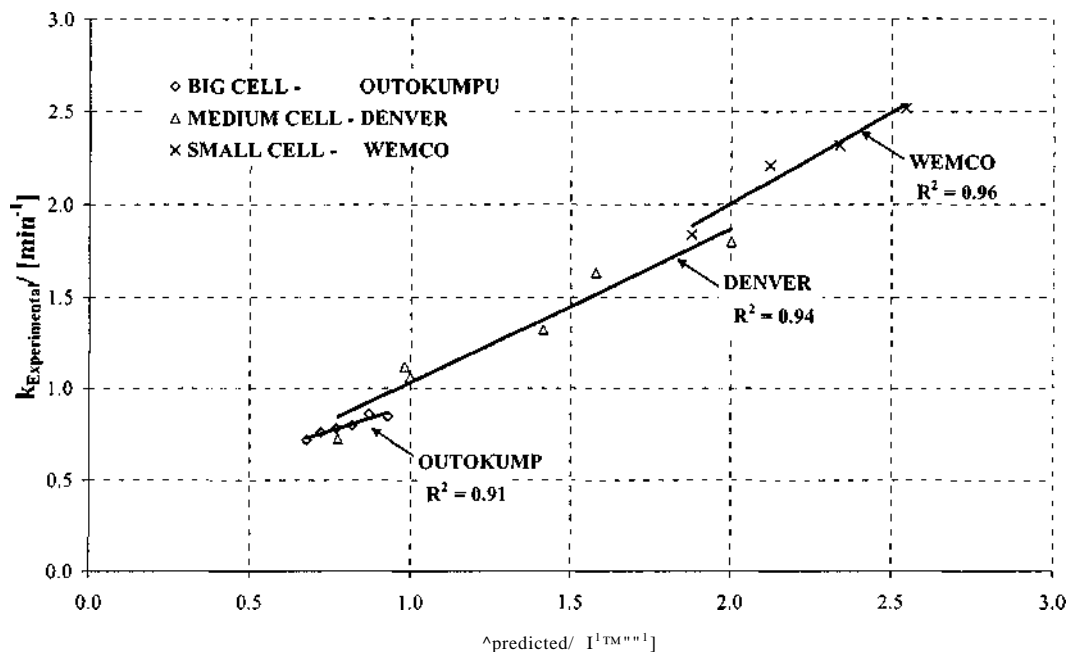


Figure 10—1. Deviation of Predicted from  $k_{\text{Experimental}}$

Imaizumi and Inoue (1963) and Loveday and Brouckaert (1995) investigated the performance of various flotation circuit designs by considering the shape of the fractional recovery curve as a function of the reduced flotation rate constant ( $\theta$ ). The fractional recovery versus  $\theta$  curve or the separation curve is analogous to the separation curve of a hydrocyclone which has an S—shape. However the flotation separation curve unlike the hydrocyclone curve is a theoretical curve. Therefore it is used to compare the performance of different flotation circuit arrangements and the effects of circulating loads.

Figure 10—2 shows the separation curve for different circulating loads. From Figure 10—2 the separation improves as the circulating load is increased. Imaizumi and Inoue (1963) showed that the improvement in separation can be determined by calculating the separation index (S.I) between the fractional recovery points  $R_{0.85}$  and  $R_{0.15}$ . Loveday and Brouckaert (1995) used a similar technique but related the separation index to the fractional recovery at 0.5. In both techniques, the closer S.I is to unity the better the separation.

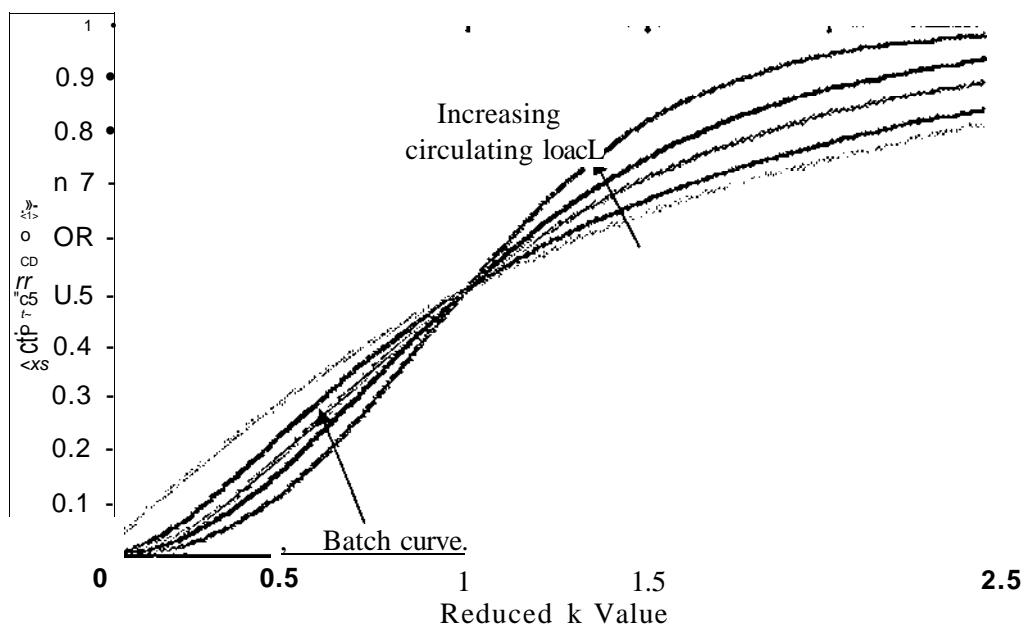
Figure 10—3 shows the theoretical separation curve for the SBFA and the batch test. The SBFA gives a better theoretical separation than the batch test. This can be proved by calculating the S.I for each curve and noting which S.I value is closer to unity. From Figure 10—3 the S.I value for the batch and SBFA theoretical separation curve is:

$$S.I_{\text{Batch}} = \frac{\frac{f_u}{V^{0.85}} - \frac{f_t}{R_{0.50}^{0.85}}}{\frac{f_u}{V^{0.15}} - \frac{f_t}{R_{0.50}^{0.15}}} = \frac{0.85 \times 1.90 - 0.50 \times 0.69}{0.50 \times 0.69 - 0.15 \times 0.16} = 0.33$$

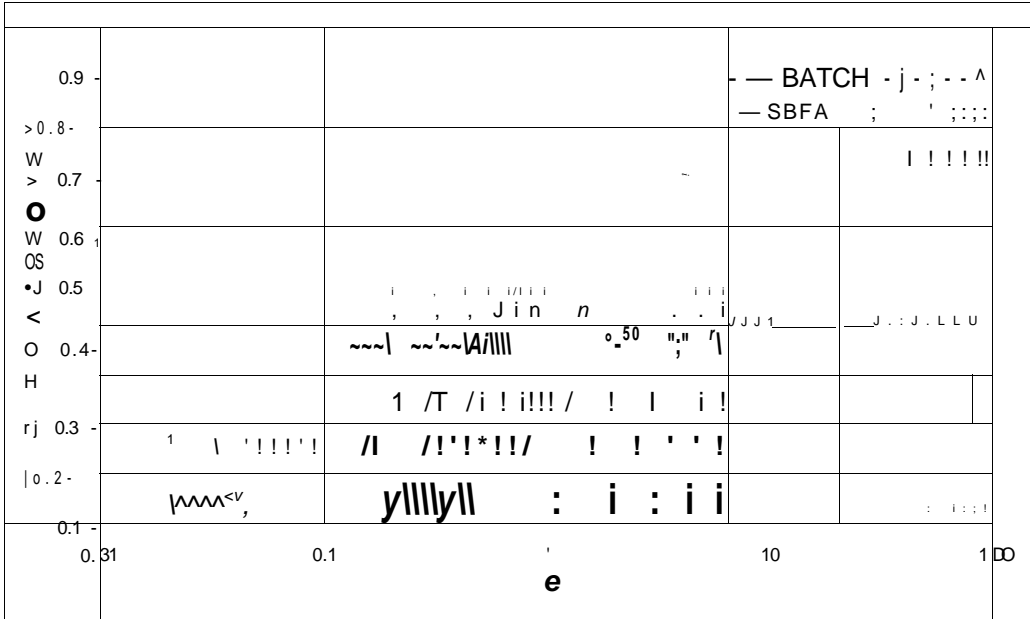
$$S.I_{\text{Simulator}} = \frac{\frac{f_u}{V^{0.85}} - \frac{f_t}{R_{0.50}^{0.85}}}{\frac{f_u}{V^{0.15}} - \frac{f_t}{R_{0.50}^{0.15}}} = \frac{0.85 \times 1.52 - 0.50 \times 0.70}{0.50 \times 0.70 - 0.15 \times 0.34} = 0.54$$

$$S.I_{\text{Batch}} < S.I_{\text{Simulator}} < (S.I_{\text{Perfect separation}} = 1)$$

Therefore the SBFA is theoretically much better at separating material than the single batch cell test. The improved separation for the SBFA can be attributed to the additional cell used in the SBFA and the circulating of material from cell 2 to cell 1.



**Figure 10—2.** Flotation separation curves for different circulation loads, (extracted Loveday and Brouckaert, 1995).



**Figure 10—3.** Flotation separation curves for the SBFA and batch.

### 10.3 Performance of the SBFA

Recovery—grade curves were used to compare the separation achieved in the SBFA and a batch test. The best recovery—grade curve for the batch tests was selected as a basis for comparing the SBFA performance. The best recovery—grade curve for the batch tests was at a froth height of 47 mm in a 15—litre cell having a Denver mechanism, see Figure 4—14a in Chapter 4. Figure 10—4 shows the recovery—grade curve for the SBFA at different recycle rates. It is evident from Figure 10—4 that the SBFA separates the limestone from gangue better than the batch for all recycle rates. This result is in keeping with the theoretical study performed on the SBFA and batch which showed that the SBFA separates better than the batch, see Section 10.2 above. It is also due to the dilute condition in the second cell.

In addition the separation of limestone from gangue improved as the recycle rate was increased. This can be attributed to the higher rate at which fine and mid—sized gangue was removed from cell two before it had a chance of being entrained in the concentrate thereby hindering separation. Froth height was maintained between 5 mm and 10 mm in both cells

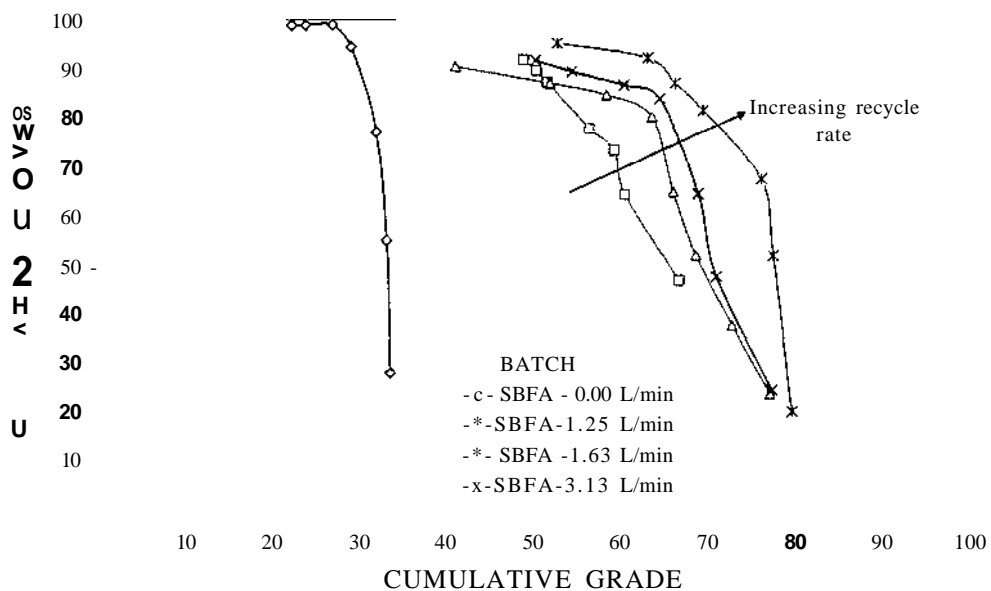


Figure 10—4. Recovery—grade curves for the batch and SBFA having different recycle rates.



Figure 10—5 shows the cumulative concentrate grade profiles for the different recycle rates. At time  $t = 0.5$  min the grade of the concentrate (for no recycle) obtained from the SBFA is almost 50 % better than the grade obtained from the batch. In addition the concentrates collected from the SBFA at  $t = 0.5$  min improved as the recycle rate was increased. Therefore recycling in the SBFA effects separation and the concentrate grade.

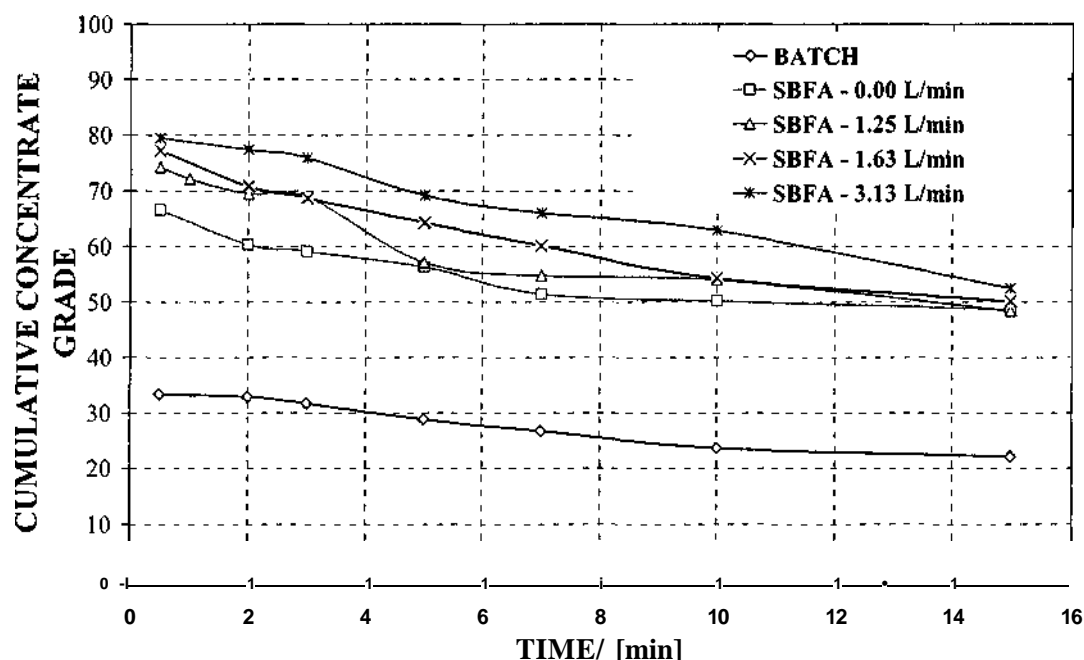
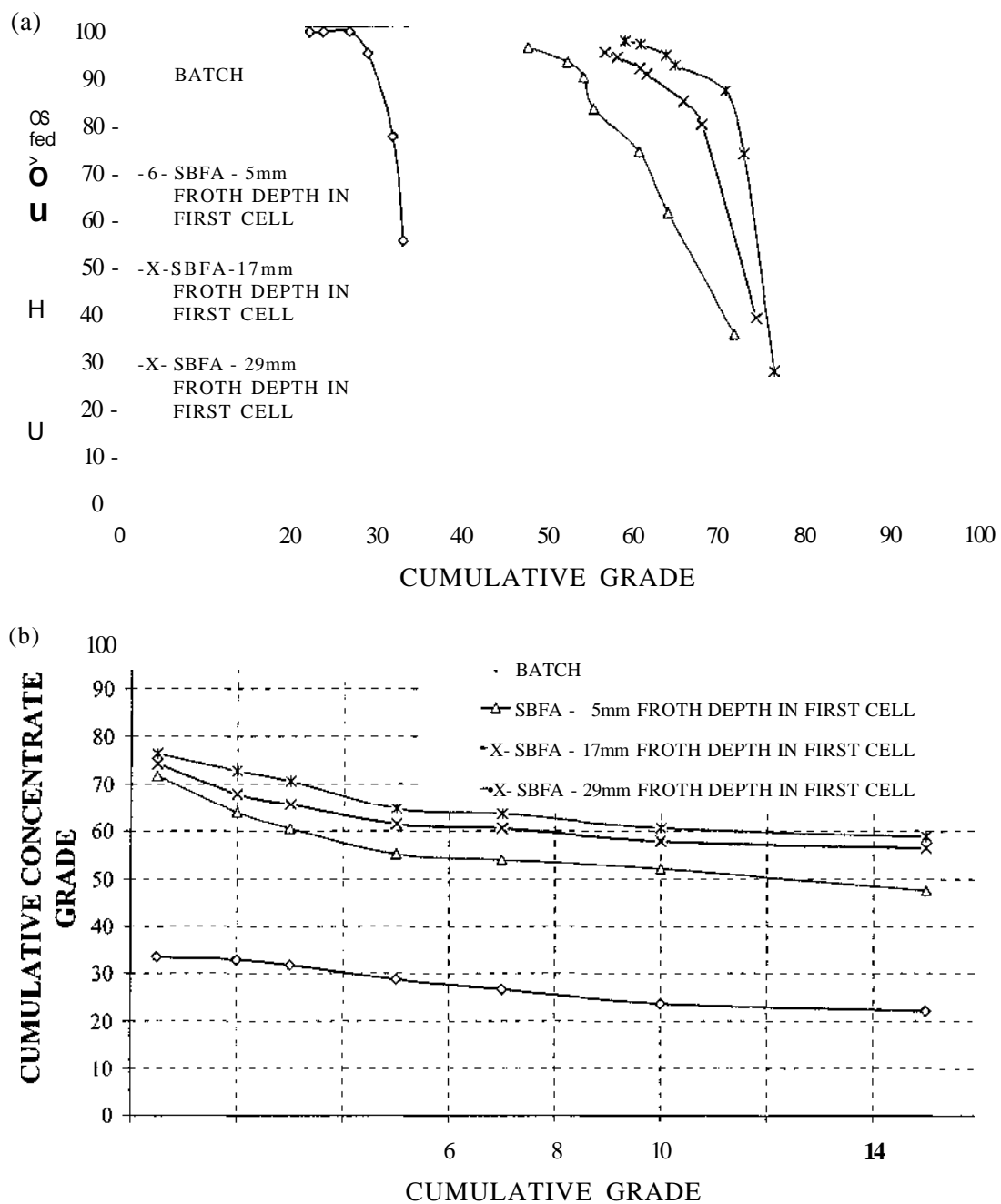


Figure 10—5. Cumulative concentrate grade profiles for the batch and SBFA having different recycle rates.

Figure 10—6a and 10—7a shows the recovery—grade curve for different froth heights in cell 1 and 2 respectively. The separation in the SBFA is better than the batch test for all froth heights. This can be attributed to multistage flotation of the concentrate and the recycle of the material from cell 2 to cell 1. In addition the separation in the SBFA improved as the froth height was increased in cell 1 and 2. The improvement was due to the higher froth residence time at higher froth heights, which allows for the drainage of more gangue from the froth thereby improving the grade.



**Figure 10—6.** Recovery—grade curves for the batch and SBFA having different froth heights in cell 1 (a) and cumulative concentrate grade profiles for the batch and SBFA having different froth heights in cell 1 (b). The froth depth in the batch test was 5 mm.

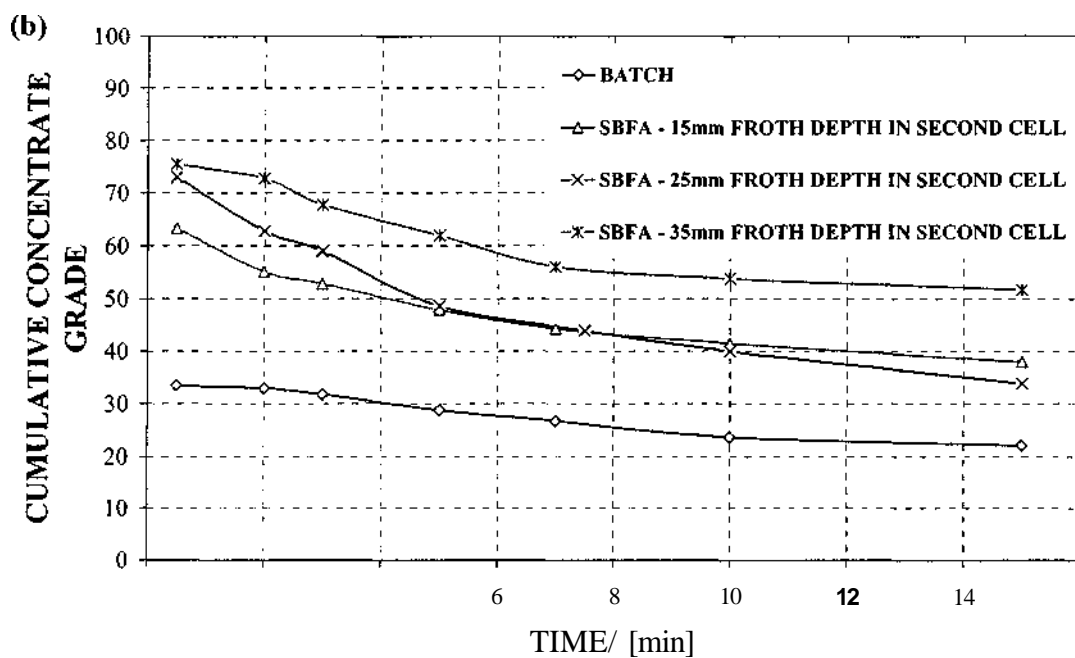
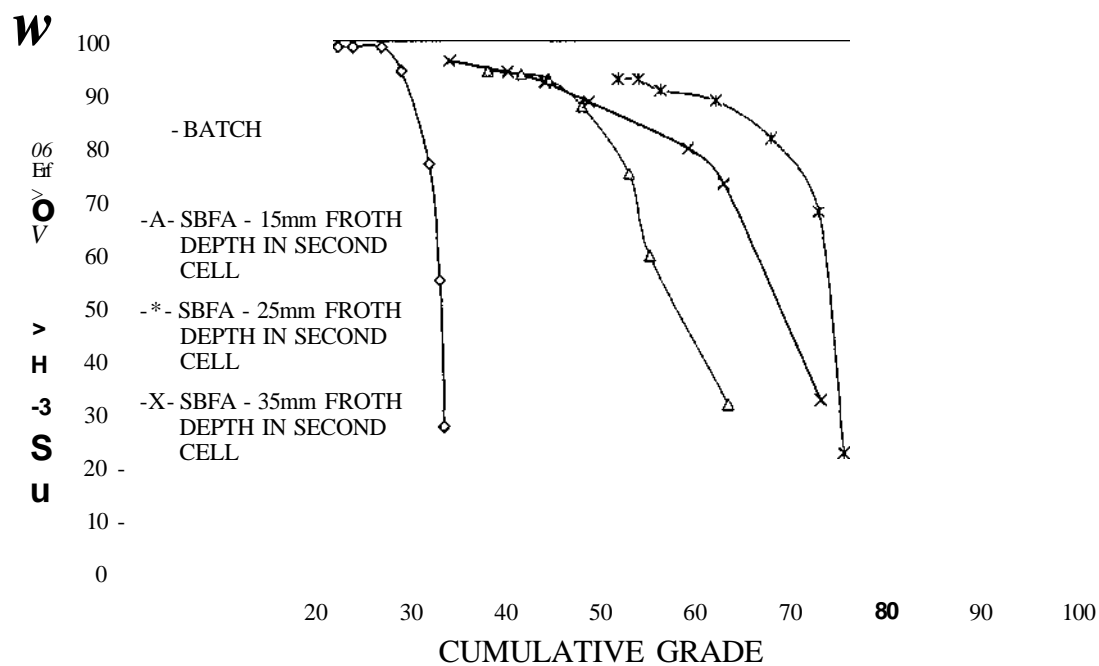


Figure 10—7. Recovery—grade curves for the batch and SBFA having different froth heights in cell 2 (a) and cumulative concentrate grade profiles for the batch and SBFA having different froth heights in cell 2 (b). The froth depth in the batch test was 5 mm.

Figure 10—6b and 10—7b shows the variation in the concentrates grade with time for different froth heights. For Figure 10—6b the cumulative concentrate grade improved as the froth height was increased. For Figure 10—7b the final cumulative concentrate grade (at  $t = 15$  min) for the froth heights of 15 and 25 mm in the SBFA did not improve significantly. This anomaly can be attributed to the higher recovery of gangue between time  $t = 5$  min and 15 min. The higher gangue recovery may have been caused by the point—level controller not maintaining the pulp level in cell two of the SBFA. Therefore some pulp may have been collected in the concentrate.

Figure 10—8 shows the recovery—grade curve for different solids concentration in the SBFA. The separation in the SBFA is better than the batch test for all solid concentrations. This can be attributed to multistage flotation of the concentrate and the recycle of the material from cell two to cell one. In addition the separation in the SBFA improved as the solid concentration was decreased. The improvement in separation can be attributed to the lower gangue content at lower solid concentration. Under dilute conditions (lower solid concentration) there is less entrainment because there is less fine gangue in the feed. However the fine gangue in the feed increased as the solid concentration increased, therefore entrainment was greater and separation was poorer.

Figure 10—9 shows the variation in the concentrates grade with time for different solids concentration. The cumulative concentrate grade improved as the solids concentration decreased. Even at under concentrated pulp conditions (15.0 % solids concentration) the SBFA gave a 50 % better grade for the final concentrate than the batch. The batch test was done with a solids concentration of 5 %.

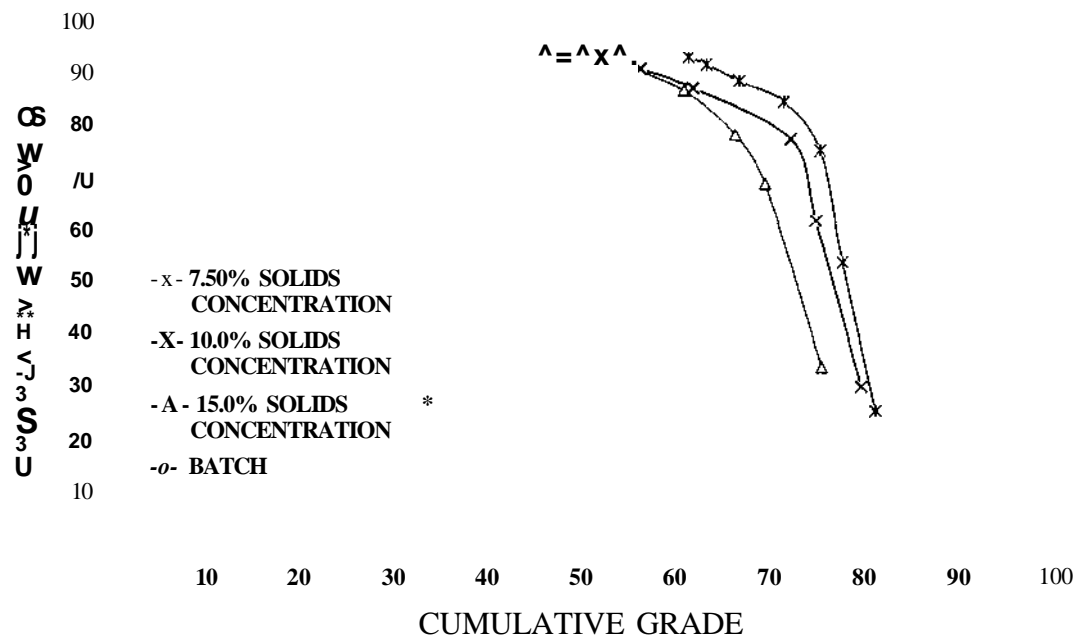


Figure 10—8. Recovery—grade curves for the batch and SBFA having different solids concentration.

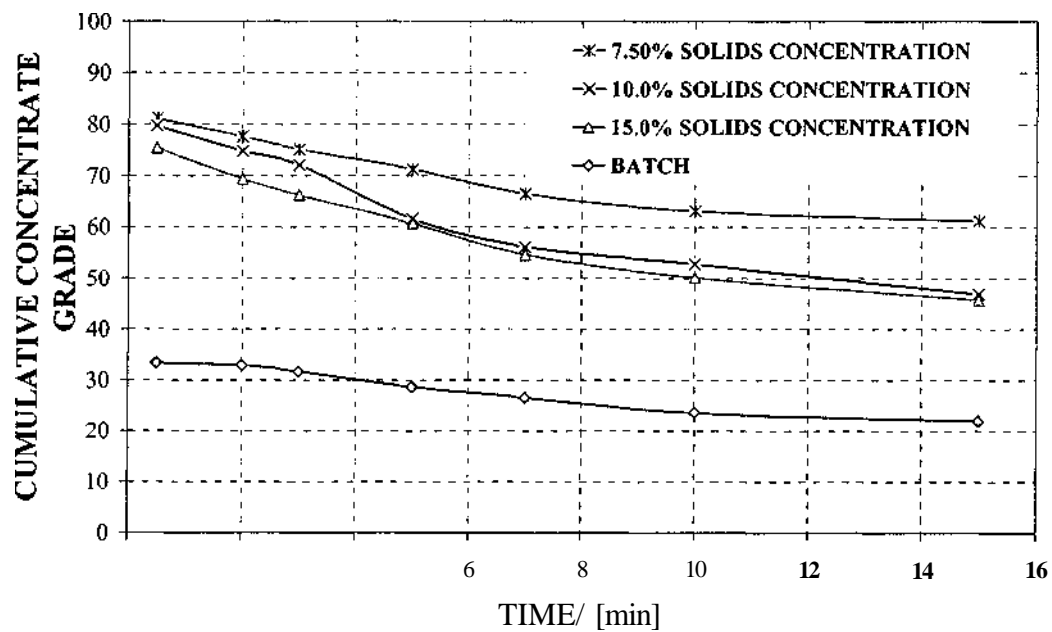


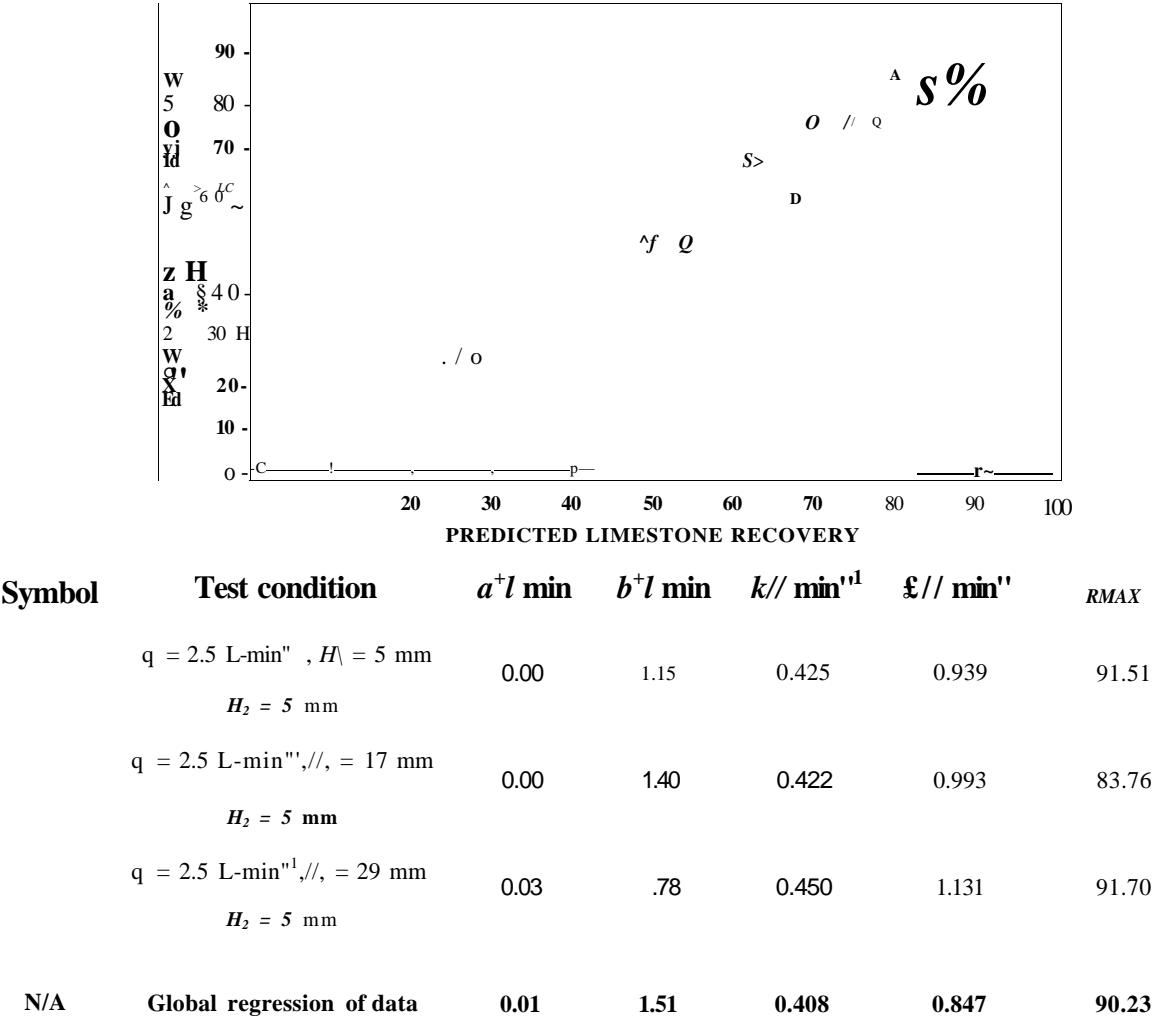
Figure 10—9. Cumulative concentrate grade profiles for the batch and SBFA having solids concentration.

#### 10.4 Evaluation of the progressive error from the SBFA model

In order to assess the accuracy of the model in predicting the data obtained from the SBFA, the data for each operating variable (flow rate and froth height) was regressed to obtain the global parameters  $A_j$  and  $R_{MAX}$ . In order words the cumulative limestone recoveries for each variation in the operating variables was regressed collectively. The collective regression of the recoveries gave a set of global parameters, namely  $\alpha_2$  and  $R_{MAX}$  which were used to calculate the cumulative limestone recoveries (predicted limestone recovery) at different variations in the operating variables. The predicted limestone recoveries were compared to the actual limestone recoveries, to assess the accuracy of the model in predicting the cumulative recovery over the experimental range.

Figure 10—10 compares the actual limestone recoveries and the recoveries predicted by the SBFA model. The experiment was conducted at different recycle rates. The figure shows that the SBFA model predicts the recoveries well for concentrates collected above 2 minutes. For concentrates collected between time 0.5 and 2 minutes there were deviations in the recoveries predicted from the SBFA model. This indicates that the model has problems in fitting the data for the initial period of the experiment. The problem can be attributed to the interaction between cells 1 and 2, the relationship between froth heights (in both cells of the SBFA) and the recycle rate. The interaction between the flotation cells provided a complex environment which included time delays for the froth formed in cell 1 and 2 of the SBFA. The delays were measured with a stop watch and accounted for in the SBFA model, however further work must be done on the SBFA model and the SBFA so that the interaction between the flotation cells is accurately accounted for.

The figures show deviations in the recoveries predicted by the model for the concentrates collected between time 0.5 and 2 minutes. This can be attributed to the interaction and the time delay for the froth formation in both cells of the SBFA. Each figure has a table that summarizes the experimental conditions and the regression data.

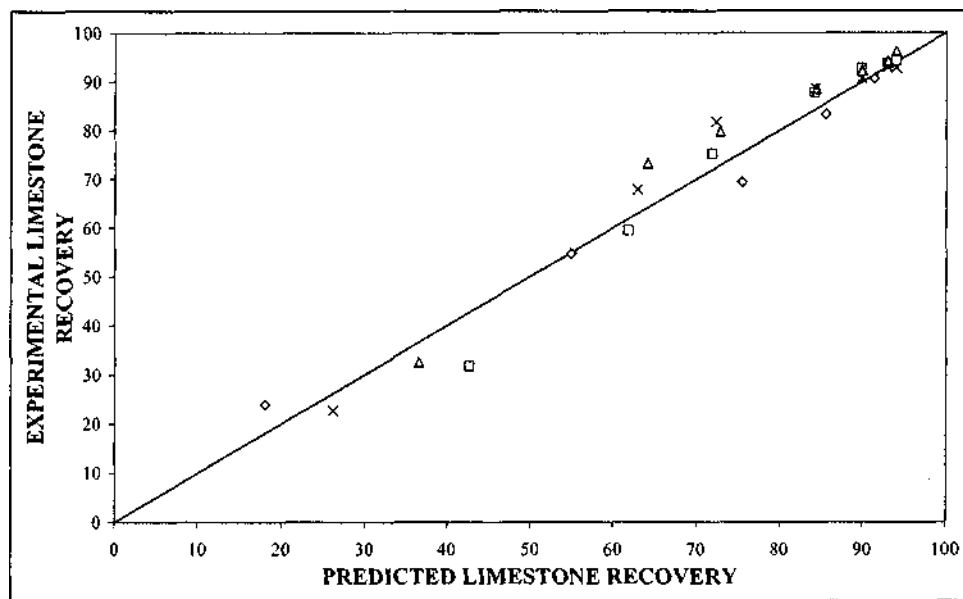


**Figure 10—11.** Comparison of the experimental and predicted recoveries for various froth heights in cell

Measured parameters

Parameter scaled by Equation 13

Regressed parameters



Symbol	Test condition	$a^+l \text{ min}$	$b^+l \text{ min}$	$\mathcal{E} // \text{ min}''$	$k_2^*l \text{ min}$	$R_{MAX}$
	$q = 2.50 \text{ L-min}, H_X = 5 \text{ mm}$ $H_2 = 5 \text{ mm}$	0.00	1.50	0.374	0.827	93.66
	$q = 2.50 \text{ L-min}''', H_f = 5 \text{ mm}$ $H_2 = 5 \text{ mm}$	0.00	.27	0.51	0.959	95.12
	$q = 2.50 \text{ L-min}''', //, = 5 \text{ mm}$ $//_2 = 25 \text{ mm}$	0.00	1.55	0.624	0.996	97.31
X	$q = 2.50 \text{ L-min}''', //, = 5 \text{ mm}$ $H_2 = 35 \text{ mm}$	0.00	1.59	0.749	.008	90.23
N/A	Global regression of data	0.00	1.51	0.428	0.889	94.16

**Figure 10—12.** Comparison of the experimental and predicted recoveries for various froth heights in cell 2.

Measured parameters

Parameter scaled by Equation 13

Regressed parameters



## 11.0 CONCLUSIONS AND RECOMMENDATIONS

### 11.1 Conclusions

- Initially experiments were carried out on a flotation rig provided by Mintek. However the rig had design flaws which made it difficult to operate.
- The poor operating conditions in the Mintek rig led to the development of a new rig, called the SBFA.
- The design of SBFA was based on some key principles used in the Mintek rig, i.e. multistage separation and pulp recycles.
- A two stage SBFA was developed, the first stage was a 56—litre cell fitted with an Outokumpu mechanism, while the second stage was a 15—litre cell fitted with a Denver mechanism.
- The SBFA was modeled by using the fundamental equation for a batch reactor as a basis for the model development.
- A theoretical analysis of the SBFA model and the batch model showed that the SBFA is theoretically better at separating than the batch.
- Experiments carried different recycle rates, froth heights and solid concentrations confirmed the theoretically analysis.
- The SBFA model fitted the experimental well because the correlation coefficient was close to unity.
- Use of the SBFA may allow a more valid estimation of recovery—grade data for industrial design as the SBFA allows a significantly better separation than batch tests.

## 11.2 Recommendations

- All the tests work was done using a synthetic ore which was a mixture of limestone, talc and silica. The reason for using the synthetic ore was because analysis of the material was simple and economic. However further work on the SBFA should be done using a real ore.
- It is recommended that the SBFA be fitted with accurate flow measurement devices and automated level controllers if any further work is to be undertaken.
- The empirical kinetic model used for scaling the rate constants was derived for simplicity. However a more sophisticated model which incorporates additional parameters such as air hold up, particle size etc can be used.
- The model developed for the SBFA was derived for a two stage SBFA. Any application of the model to more than two stages will require a more complex mathematical model.
- The scale up of parameters derived from the SBFA to pilot plants and production plants should be investigated, by testing suitable online pulp samples.

## REFERENCES

1. Agus, M. B. (2001). "Nonlinear regression analysis of data using a spreadsheet." [www.freepdfsearch.com](http://www.freepdfsearch.com), date accessed: March 2007, pp. 2.
2. Angadi, S. I., and Suresh, N. (2005). "A kinetic model for the prediction of water reporting to the froth products in batch flotation." *Trans IMM, Section C*, vol. 114, pp. 225-232.
3. Arbiter, N., Harris, C. C, and Yap, R. F. (1976). "The air flow number in flotation machine scale-up." *International Journal of Mineral Processing*, vol. 3, pp. 257-280.
4. Bayat, O., Ucurum, M., and Poole, C. (2004). "Effect of size distribution on flotation kinetics of Turkish sphalerite." *Institution of Mining and Metallurgy*, vol. 113, pp.55-59.
5. Brozek, M., and Mlynarczykowska, A. (2006). "Application of the stochastic model for analysis of flotation kinetics with coal as an example." *Physicochemical Problems of Mineral Processing*, vol. 40, pp. 31-44.
6. Cilek, E. C. (2004). "Estimation of flotation kinetic parameters by considering interactions of the operating variables." *Minerals Engineering*, vol. 17, pp. 81-85.
7. Crabtree, E. H. (1968). "Introduction to flotation." *Mineral engineering*, Vol. 50(no. 15), pp. 1-3.
8. Crawford, R., and Ralston, J. (1988). "The influence of particle size and contact angle in mineral flotation." *International Journal of Mineral Processing*, vol. 23, pp. 1-24.
9. Cullen, W., and Lavers, H. (1936). "Flotation as applied to the chemical industry." Chemical Society, Institute of Chemical Engineers, Burlington house, London, pp. 26-44.
10. Cutting, G. W. (1976). "Estimation of interlocking mass-balances on complex mineral beneficiation plants." *International Journal of Mineral Processing*, vol. 3, pp. 207-218.

11. Cutting, G. W., Watson, D., Whitehead, A., and Barber, S. P. (1981). "Froth structure in continuous flotation cells: Relation to the prediction of plant performance from laboratory data using process models." *International Journal of Mineral Processing*, vol. 7, pp. 347-369.
12. de Bruyn, P. L. (1968). "The chemical theory of flotation." *Mineral engineering*, Vol. 50(no. 15), pp. 5-14.
13. Duarte, A. C. P., and Grano, S. R. (2007). "Mechanism for the recovery of Silicate gangue minerals in the flotation of ultra fine sphalerite." *Minerals Engineering*, vol. 20, pp. 766-775.
14. Feng, D., and Aldrich, C. (1999). "Effect of particle size on flotation performance of complex sulphide ores." *Minerals Engineering*, vol. 12(no. 7), pp. 721-731.
15. Ferreira, J. P., and Loveday, B. K. (2000). "An improved model for simulation of flotation circuits." *Minerals Engineering*, vol. 13(no. 14-15), pp. 1441-1453.
16. Fichera, M. A., and Chudacek, M. W. (1992). "Batch cell flotation models-A review." *Minerals Engineering*, vol. 5(no. 1), pp. 41-55.
17. Frew, J. A. (1982). "Variation of flotation rate coefficients in zinc cleaning circuits" *International Journal of Mineral Processing*, vol. 9, pp. 173-189.
18. Frew, J. A., and Trahar, W. J. (1982). "Roughing and cleaning flotation behavior and the realistic simulation of complete plant performance." *International Journal of Mineral Processing*, vol. 9, pp. 101-120.
19. Gorain, B. K., Franzidis, J. P., and Manlapig, E. V. (1995). "Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell-Part 1: Effect on bubble size distribution." *Minerals Engineering*, vol. 8(no. 6), pp. 615-635.
20. Gorain, B. K., Franzidis, J. P., and Manlapig, E. V. (1995). "Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell-Part 2: Effect on gas holdup." *Minerals Engineering*, vol. 8(no.12), pp. 1557-1570.
21. Gorain, B. K., Franzidis, J. P., and Manlapig, E. V. (1996). "Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell-Part 3: Effect on superficial gas velocity." *Minerals Engineering*, vol. 9(no. 6), pp. 639-654.

22. Gorain, B. K., Franzidis, J. P., and Manlapig, E. V. (1997). "Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell-Part4: Effect of bubble surface area flux area flux on flotation performance." *Minerals Engineering*, vol. 10(no. 4), pp. 367-379.
23. Gorain, B. K., Franzidis, J. P., and Manlapig, E. V. (1999). "The empirical prediction of bubble surface area flux in mechanical flotation cells from cell design and operating data." *Minerals Engineering*, vol. 12(no. 3), pp. 309-322.
24. Gorain, B. K., Harris, M. C, Franzidis, J. P., and Manlapig, E. V. (1998). "The effect of froth residence time on the kinetics of flotation." *Minerals Engineering*, vol. 11 (no. 7), pp. 627-638.
25. Gorain, B. K., Napier-Munn, T. J., Franzidis, J. P., and Manlapig, E. V. (1998). "Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell-Part 5: Validation of  $k-St$  relationship and effect of froth depth." *Minerals Engineering*, vol. 11(no. 7), pp. 615-626.
26. Greaves, M., and Allan, B. W. (1974). "Steady-state and dynamic characteristics of flotation in a single cell." *Trans. Instn Chem. engrs*, vol. 52, pp. 136-148.
27. Gutzeit, G. (1968). "Details of industrial flotation." *Mineral engineering*, Vol. 50(no. 15), pp 25-30.
28. Gutzeit, G. (1968). "Laboratory procedures for flotation testing in chemical engineering problems." *Mineral engineering*, Vol. 50(no. 15), pp 31-37.
29. Hadler, K., Aktas, Z., and Cilliers, J. J. (2005). "The effects of frother and collector distribution on flotation performance." *Minerals Engineering*, vol. 18, pp. 171-177.
30. Hamilton, J. A., and Guy, P. J. (2001). "Pulp level control for flotation-options and a csiro laboratory perspective." *Minerals Engineering*, vol. 14(no. 1), pp. 77-86.
31. Harris, C. C. (1978). "Multiphase models of flotation machine behavior." *International Journal of Mineral Processing*, vol. 5, pp. 107-129.
32. Harris, C. C., and Cuadros-Paz, A. (1978). "Species interaction in flotation: A laboratory-scale semi-batch study." *International Journal of Mineral Processing*, vol. 5, pp. 267-283.

33. Harris, C. C, and Mensah-Biney, R. K. (1977). "Aeration characteristics of laboratory flotation machine impellers." *International Journal of Mineral Processing*, vol. 4, pp. 51-67.
34. Harris, M. C. (1976). "A recycle flow flotation machine model: Response of model to parameter changes." *International Journal of Mineral Processing*, vol. 3, pp. 9-25.
35. Harris, M. C, and Rimmer, H. W. (1966). "Study of a two-phase model of the flotation process." *Trans IMM, Section C*, pp. 153-162.
36. Heiskanen, K. (2000). "On the relationships between flotation rate and bubble surface area flux." *Minerals Engineering*, vol. 13(no. 2), pp. 141-149.
37. Hernainz, F., and Calero, M. (2001). "Froth flotation: Kinetic models based on chemical analogy." *Chemical Engineering and Processing*, vol. 40, pp. 269-275.
38. Hernandez-Aguilar, J. R., Rao, S. R., and Finch, J. A. (2005). "Testing the  $k-S_b$  relationship at the microscale." *Minerals Engineering*, vol. 18, pp. 591-598.
39. Honaker, R. Q., and Ozsever, A. V. (2003). "Evaluation of the selective detachment process in flotation froth." *Minerals Engineering*, vol. 16, pp. 975-982.
40. Imaizumi, T., and Inoue, T. (1963). "Kinetic consideration of froth flotation." *Proc, VI Int. Miner. Proc. Cong.*, pp. 255-271.
41. Kracht, W., Vallebuona, G., and Casali, A. (2005). "Rate constant modelling for batch flotation, as a function of gas dispersion properties." *Minerals Engineering*, vol. 18, pp. 1067-1076.
42. Lahtinen, M. (2004). "Is your plant economically optimized?" [www.freepdfsearch.com](http://www.freepdfsearch.com) , date accessed: March 2007, pp 1-4.
43. Loveday, B. K, and Brouckaert, C. J. (1995). "An analysis of flotation circuit design principles." *The Chemical Engineering Journal*, vol. 59, pp 15-21.
44. Loveday, B. K, and Hemphill, A. L. (2006). "Optimization of a multistage flotation plant using plant survey data." *Minerals Engineering*, vol. 19, pp. 627-632.
45. Loveday, B. K, (2007). Personal Communication

46. Mathe, Z. T, Harris, M. C, O'Connor, C. T., and Franzidis, J. P. (1998). "Review of froth modelling in steady state flotation systems." *Minerals Engineering*, vol. 11 (no. 5), pp. 397-421.
47. Melo, F., and Laskowski, J. S. (2006). "Fundamental properties of flotation frothers and their effect on flotation." *Minerals Engineering*, vol. 19, pp. 766-773.
48. Moys, M. H. (1978). "A study of a plug-flow model for flotation froth behavior." *International Journal of Mineral Processing*, vol. 5, pp. 21-38.
49. Napier-Munn, T. J. (1998). "Analyzing plant trials by comparing recovery-grade regression lines." *Minerals Engineering*, vol. 11 (no. 10), pp. 949-958.
50. Niemi, A. J. (1995). "Role of kinetics in modelling and control of flotation plants." *Powder Technology*, vol. 82, pp. 69-11.
51. Parekh, B. K. (1999). "Advances in flotation technology." Littleton Col: Society for mining, metallurgy and exploration, pp. 463.
52. Pease, J. D., D.C, C, and M.F, Y. (2006). "Designing flotation circuits for high fines recovery." *Minerals Engineering*, vol. 19, pp. 831-840.
53. Polat, M., and Chander, S. (2000). "First-order flotation kinetics models and methods for estimation of the true distribution of flotation rate constants." *International Journal of Mineral Processing*, vol. 58, pp. 145-166.
54. Ralston, J., Fornasiero, D., Grano, S., Duan, J., and Akroyd, T. (2007). "Reducing uncertainty in mineral flotation-flotation rate constant prediction for particles in an operating plant ore." *International Journal of Mineral Processing*, 84, pp. 89-98.
55. Savassi, O. N., Alexander, D. J., Franzidis, J. P., and Manlapig, E. V. (1998). "An empirical model for entrainment in industrial flotation plants." *Minerals Engineering*, vol. 11 (no. 3), pp. 243-256.
56. Schubert, H., and Bischofberger, C. (1978). "On the hydrodynamics of flotation machines." *International Journal of Mineral Processing*, vol. 5, pp. 131-142.
57. Schulze, H. J. (1977). "New theoretical and experimental investigations on stability of bubble/particle aggregates in flotation: A theory on the upper particle size of floatability." *International Journal of Mineral Processing*, vol. 4, pp. 241-259.

58. Schwarz, S., and Alexander, D. J. "JKSMFLOAT V6.F<sup>LUb</sup>: Improving flotation circuit performance by simulation." JKTech Pty Ltd, Brisbane, Australia
59. Schwarz, S., Alexander, D. J., Whiten, W. J., Franzidis, J. P., and Harris, M. C. "JKSimFloat V6: Improving Flotation circuit performance and understanding." JKtech Pty Ltd, Brisbane, Australia
60. Seaman, D. R., Manlapig, E. V., and Franzidis, J. P. (2006). "Selective transport of attached particles across the pulp-froth interface." *Minerals Engineering*, vol. 19, pp. 841-851.
61. Shi, F. N., and X.F, Z. (2003). "The rheology of flotation froths." *International Journal of Mineral Processing*, vol. 69, pp. 115-128.
62. Sripriya, R., Rao, P. V. T., and Choudhury, B. R. (2003). "Optimization of operating variables of fine coal flotation using a combination of modified flotation parameters and statistical techniques." *International Journal of Mineral Processing*, vol. 68, pp. 109-127.
63. Subrahmanyam, T. V., and Forssberg, K. S. E. (1988). "Froth stability, Particle entrainment and Drainage in flotation-A review." *International Journal of Mineral Processing*, vol. 23, pp. 33-53.
64. Sutherland, D. N. (1981). "A study on the optimization of the arrangement of flotation circuits." *International Journal of Mineral Processing*, vol. 7, pp. 319-346.
65. Szatkowski, M. (1988). "A model of flotation selectivity." *International Journal of Mineral Processing*, vol. 23, pp. 25-31.
66. Trahar, W. J. (1976). "The selective flotation of Galena from sphalerite with special reference to the effects of particle size." *International Journal of Mineral Processing*, vol. 3, pp. 151-166.
67. Trahar, W. J., and Warren, L. J. (1976). "The floatability of very fine particle-A review." *International Journal of Mineral Processing*, vol. 3, pp. 103-131.
68. Tsatouhas, G., Grano, S. R., and Vera, M. (2006). "Case studies on the performance and characterisation of the froth phase in industrial flotation circuits." *Minerals Engineering*, vol. 19, pp. 774-783.



69. Ucurum, M., and Bayat, O. (2006). "Effects of operating variables on modified flotation parameters in minerals separation." *Separation and Purification Technology*, pp. 1-9.
70. Valenta, M. M. (2007). "Balancing the reagent suite to optimize grade and recovery." *Minerals Engineering*, vol. 20, pp. 979-985.
71. Van der Westhuizen, A. P., and Deglon, D. A. (2007). "Evaluation of solids suspension in a pilot-scale mechanical flotation cell: The critical impeller speed." *Minerals Engineering*, vol. 20, pp. 233-240.
72. Vera, M. A., Franzidis, J. P., and Manlapig, E. V. (1999). "Simultaneous determination of collection zone rate constant and froth zone recovery in a mechanical flotation environment." *Minerals Engineering*, vol. 12(no. 10), pp. 1163-1176.
73. Vera, M. A., Mathe, Z. T., Franzidis, J. P., Harris, M. C., Manlapig, E. V., and O'Connor, C. T. (2002). "The modelling of froth zone recovery in batch and continuously operated laboratory flotation cells." *International Journal of Mineral Processing*, vol. 64, pp. 135-151.
74. Wills, B. A. (2003). *Mineral Processing Technology*, Butterworth-Heinemann.
75. Xiao, Z., and Vien, A. (2004). "Experimental designs for precise parameter estimation for non-linear models." *Minerals Engineering*, vol. 17, pp. 431-436.
76. Yianatos, J. B., Bergh, L. G., and Aguilera, J. (2003). "Flotation scale up: Use of separability curves." *Minerals Engineering*, vol. 16, pp. 347-352.
77. Yianatos, J. B., Bucarey, R., Larenas, J., Henriquez, F. D., and Torres, L. (2005). "Collection zone kinetic model for industrial flotation columns." *Minerals Engineering*, vol. 18, pp. 1373-1377.
78. Yianatos, J. B., and Henriquez, F. D. (2006). "Short-cut method for flotation rates modelling of industrial flotation banks." *Minerals Engineering*, vol. 19, pp. 1336-1340.
79. Yianatos, J. B., and Henriquez, F. D. (2007). "Boundary conditions for gas rate and bubble size at the pulp-froth interface in flotation equipment." *Minerals Engineering*, vol. 20, pp. 625-628.

80. Yianatos, J. B., Henriquez, F. H., and Oroz, A. G. (2006). "Characterization of large size flotation cells." *Minerals Engineering*, vol. 19, pp. 531-538.
81. Yuan, X. M., Palsson, B. I., and Forssberg, K. S. E. (1996). "Statistical interpretation of flotation kinetics for a complex sulphide ore." *Minerals Engineering*, vol. 9(no. 4), pp 429-442.
82. Zheng, X., Franzidis, J. P., and Johnson, N. W. (2006). "An evaluation of different models of water recovery in flotation." *Minerals Engineering*, vol. 19, pp. 871-882.
83. Zheng, X., Johnson, N. W., and Franzidis, J. P. (2006). "Modelling of entrainment in industrial flotation cells: Water recovery and degree of entrainment." *Minerals Engineering*, vol. 19, pp. 1191-1203.

## APPENDIX I: SAMPLE CALCULATIONS

This appendix details the calculations for the rig, batch and SBFA tests.

### I.I Sample calculation for the rig

The following data was obtained from operation of the rig at optimal collector concentration:

**Table I—1. Data acquired from the rig with one cell operational**

<b>Time/ [min]</b>	<b>Limestone in concentrate/ [g]</b>	<b>Cumulative limestone in concentrate/ [g]</b>	<b>Recovery</b>	<b>Cumulative Recovery</b>
1.00	9.56	9.56	3.74	3.74
2.00	52.11	61.67	20.39	24.13
3.00	26.02	87.69	10.18	34.31
5.00	47.55	135.24	18.61	52.92
7.00	16.10	151.34	6.30	59.22
10.00	14.31	165.64	5.60	64.82
15.00	10.36	176.00	4.05	68.87
20.00	2.90	178.90	1.13	70.00
<b>TAILINGS</b>	76.65	255.56	30.00	100.00
<b>Total</b>				
<b>limestone mass/ [g]</b>	255.56			

The concentrates were collected at the times given in Table I—1. The concentrates were then analyzed for limestone by acid dissolution to give the limestone content in the concentrate. For instance, the recovery for the 1 min concentrate can be calculated as follows:

$$\text{Recovery} = \frac{\text{mass at 1 min}}{\text{total mass of limestone}} \times 100 = \frac{9.56\text{g}}{255.56\text{g}} \times 100 = 3.74\%$$

The cumulative recovery for example, at time 10min was calculated as follows:

$$\text{Cumulative recovery} = \frac{\text{cumulative mass at 10min}}{\text{total mass of limestone}} \times 100 = \frac{165.64\text{g}}{255.56\text{g}} \times 100 = 64.82\%$$

The cumulative recovery was then plotted against time to give the cumulative recovery versus time profile, see Figure 3—2 in Chapter 3. The cumulative recovery—time data can also be regressed to a batch model to give the flotation rate constant and maximum recovery. The Agar model (from Table 2—1) was used to find the flotation rate constant.

The following procedure was used for nonlinear regression of the data:

1. The cumulative recovery—time data was entered into a spreadsheet; Microsoft Excel ® was used to setup and analyze the data.
2. The Agar model was entered into the spreadsheet, with initial estimates of the parameters  $R_{MAX}$ ,  $k$  and  $v$ , see Figure I—1.
3. The mean value of the cumulative recovery (cells C2 to C9) was calculated by the entering the formula: =AVERAGE (C2:C9) into cell B15, see Figure I—1.
4. The degree of freedoms ( $df$ ), which is defined as the number of data points minus the number of parameters in the model, was calculated by entering the formula: = COUNT(A2:A9) - COUNT(B11:B13) into cell B16, see Figure 1-1.

5. The standard error (SER) of the cumulative recovery was calculated by entering the formula:  $= \text{SQRT}(\text{SUM}((\text{B2:B9}-\text{C2:C9})^2)/\text{B16})$  into cell B17, however this formula had to be expressed as an array formula by pressing Ctrl, Shift and Enter on the keyboard together<sup>1</sup>, see Figure I—1.
6. The correlation coefficient  $r^2$  was calculated by entering the formula in array form into cell B18:  $= 1-\text{SUM}((\text{B2:B9}-\text{C2:C9})^2)/\text{SUM}((\text{B2:B9}-\text{B15})^2)$ , see Figure 1-1.
7. Once the spreadsheet was setup the solver function in Microsoft Excel® was used to find the parameters  $R_{\text{MAX}}$ ,  $k$  and  $v$ , see Figures 1-2,1-3 and 1-4 for the solver procedure.

Because this formula must be expressed as an array, excel denotes this by enclosing the function with a pair of curly bracket— { }.

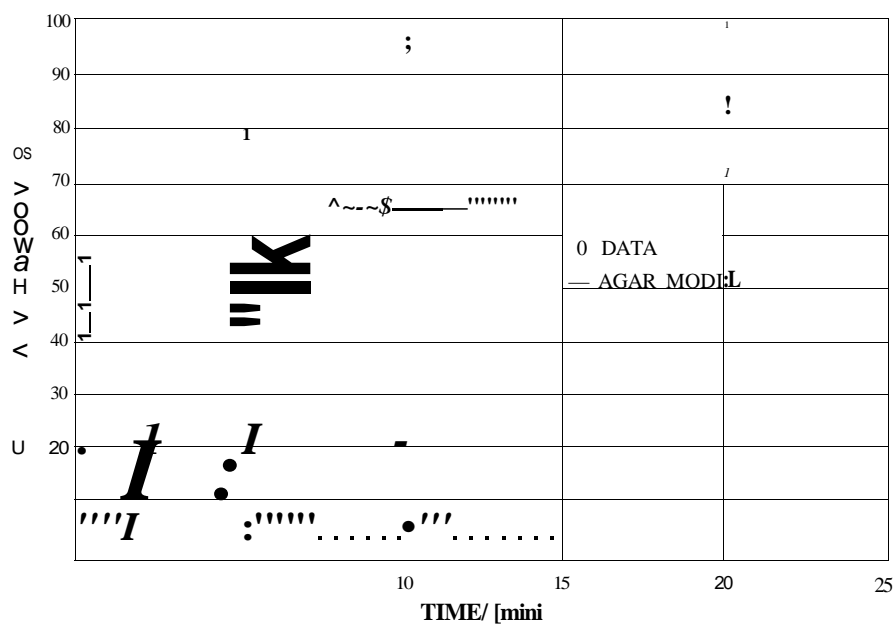
\Column	A	B	C	D
Row \ .				
1	Time/ [min]	Cumulative Recovery	Simulated Cumulative Recovery	Description
2	1.00	3.74	31.48	$C2 = B11X[1-\exp\{-B12x(A2+B13)\}]$
3	2.00	24.13	62.15	$C3 = B11X[1-\exp\{-B12x(A3+B13)\}]$
4	3.00	34.31	73.43	$C4 = B11x[1-\exp\{-B12x(A4+B13)\}]$
5	5.00	52.92	79.11	$C5 = B11x[1-\exp\{-B12x(A5+B13)\}]$
6	7.00	59.22	79.88	$C6 = B11X[1-\exp\{-B12x(A6+B13)\}]$
7	10.00	64.82	79.99	$C7 = B11X[1-\exp\{-B12x(A7+B13)\}]$
8	15.00	68.87	80.00	$C8 = B11X[1-\exp\{-B12x(A8+B13)\}]$
9	20.00	70.00	80.00	$C9 = B11X[1-\exp\{-B12x(A9+B13)\}]$
10				
11	"MAX	80.00		
12	$k$	1.00		
13	$V$	-0.50		
14				
15	Mean of C2-C9	47.25		
16	$df$	5.00		
17	$SE_{ERROR}$	32.60		
18	$r^2$	-0.31		

**Figure I—1.** Illustration of the data entering procedure into Microsoft Excel®.



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3		2	1.00	3.71	462				
4		3	2.00	21.13	22.38				
5		4	3.00	34.31	35.31				
6		5	5.00	52.92	51.60				
7		£	7.00	59.22	60.24				
8		7	10.00	64.82	66.23				
9		8	15.00	68.87	69.23				
10		9	20.00	70.00	69.65				
11		10							
12		11	RMAX	70.00					
13		12	k	0.32					
14		13	IO	0.78					
15		14							
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**Figure 1—4.** Illustration of data after using the solver function, take note that the correlation coefficient is 0.998 which indicates that the model fits the data well.



**Figure 1—5.** The cumulative recovery versus time profile for the test done on the rig.



**Table 1—2: Summary of model parameters after using solver**

$R_{mx}$	70.00
$k$	0.32
$v$	-0.78

### I.II Sample calculations for batch tests

The calculations for the batch tests involving the variables: reagent concentration, impeller speed, air flow rate and solid concentration are similar to the procedure for the rig with one cell operational, see Section I.I above.

### I.III Sample calculation for determination of $R_f$ in a batch cell

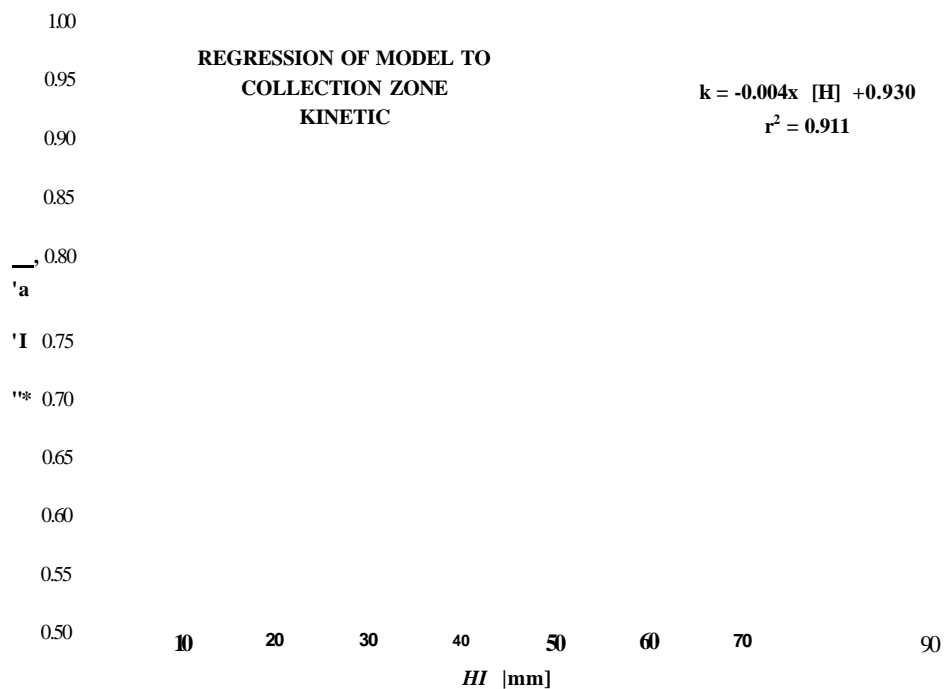
The froth height was varied in the cell and the data for each test had been regressed using the Agar model to find the flotation rate constant, see Section I.I above for the solving procedure. The flotation rates at each froth height was fitted to the models proposed by Vera et al (1999) and Gorain et al. (1999)- see Chapter 2, Section 2.3.1. The procedure for determining  $R_f$  is outlined below:

1. The procedure in Section I.I above was used to obtain the flotation rates for each test at different froth heights.
2. Once the flotation rates had been obtained the rates were plotted against froth height and regressed to a froth height of zero to obtain the collection zone rate, according to Vera et al. (1999).
3.  $R_f$  was then calculated by using Equation 2 in Chapter 2, Section 2.3.1.

**Table 1—3: Summary of the flotation rates for the various froth heights in the Outokumpu cell**

$kl$ [ $\text{min}^{-1}$ ]	$HI$ [mm]
0.85	20.00
0.80	32.00
0.76	44.00
0.73	55.50
0.68	67.50
0.61	79.50

The data in Table 1—3 was plotted and fitted with a linear model in Microsoft Excel®, see Figure 1—6 below.



**Figure 1—6** Extrapolation of the flotation rate to a froth height of zero.

From Figure 1—6 the collection zone rate is  $0.930 \text{ min}^{-1}$ , therefore  $R_f$  can be calculated from Equation 2, see Table 1—4.

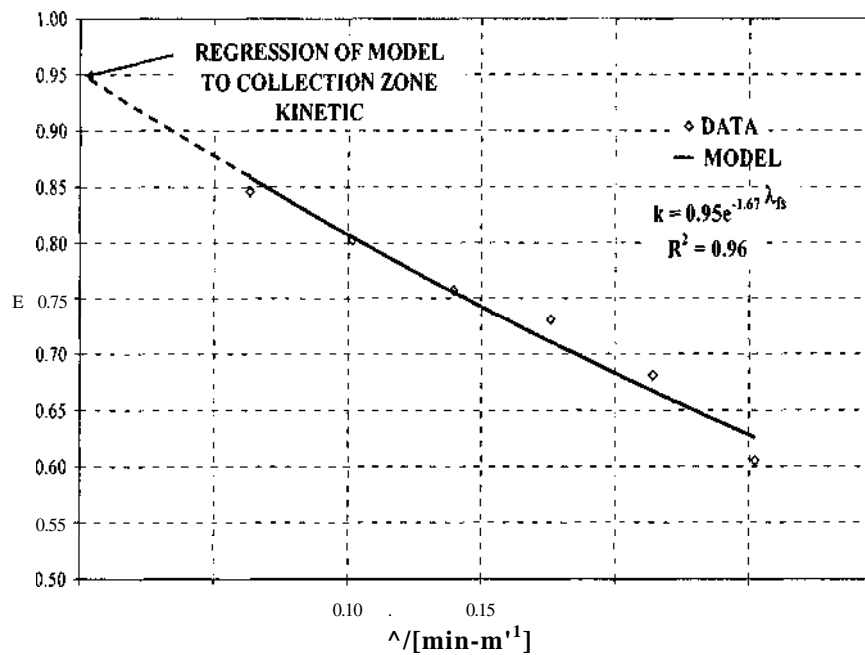
**Table 1—4: Summary of  $R_f$  for the various froth heights in the Outokumpu cell, according to Vera's model**

$HI$ [mm]	Percentage $R_f$
20.00	91
32.00	86
44.00	81
55.50	79
67.50	73
79.50	65

However the model given by Vera depends on impeller type and cell design therefore it is not suitable for scaling. The technique given by Gorain was used to calculate  $R_f$  at different froth heights. The froth residence time ( $t_g$ ) for each froth height had been determined by Equation 4, in Chapter 2, at a superficial velocity of  $1.17 \text{ m-s}^{-1}$ . The specific froth residence time ( $t_{fs}$ ) was calculated from Equation 3, in Chapter 2, at a perpendicular distance from impeller to launder ( $L$ ) of 27 cm. Table 1—5 summarizes the data required for the model proposed by Gorain.

**Table 1—5: Summary of data for the model proposed by Gorain**

$H$ [mm]	$kl$ [ $\text{min}^{-1}$ ]	$h_f J$ [min]	$X_{fs} l$ [ $\text{min-m}^{-1}$ ]
20.00	0.85	$1.71 \times 10^{-2}$	0.06
32.00	0.80	$2.74 \times 10^{-2}$	0.10
44.00	0.76	$3.77 \times 10^{-2}$	0.14
55.50	0.73	$4.75 \times 10^{-2}$	0.18
67.50	0.68	$5.78 \times 10^{-2}$	0.21
79.50	0.61	$6.81 \times 10^{-2}$	0.25



**Figure 1—7.** Regression of the flotation rate to the model proposed by Gorain.

The collection zone rate obtained from Gorain's model was  $0.950 \text{ min}^{-1}$ , which is almost the same as the rate obtained from Vera's model, which was  $0.930 \text{ min}^{-1}$ .  $R_f$  can be calculated from Equation 6 in Chapter 2, see Table 1—6 for a summary of  $R_f$  at various froth heights.

**Table 1—6: Summary of  $R_f$  for the various froth heights in the Outokumpu cell, according to Gorain's model**

$HI$ [mm]	$R_f$
20.00	85
32.00	80
44.00	75
55.50	71
67.50	66
79.50	62

#### I.IV Sample calculation for determination of $t_i$ for SBFA

A scale up equation had been developed; see Equation 12 in Chapter 10. The equation calculates the flotation rates by using empirical parameters like superficial air velocity

— , the froth recovery ( $R_f$ ) and a scaling parameter ( $n$ ) that takes into account  $v A J$

chemical and mechanical parameters that are difficult to evaluate. The superficial air velocity can be determined from the air flow rate and cell size, while  $R_f$  can be determined from the calculations done in Section I.III above.

The scaling parameter however was obtained by the following procedure:

1. Experiments were done at a constant superficial velocity.
2. The froth height was varied.
3. The flotation rate was obtained using the procedure given in Section I.I above.
4. The scaling parameter was obtained from Equation 17 with  $r$  being the subject of the formula, see Equation 18 below.

$$r = \frac{Q}{v A J} \quad (8)$$

For example for the first entry in Table 1—7 the scaling parameter is:

$$\lambda_{Wemco} = \frac{R_{V.Wemco}}{v A J_{Wemco}} \frac{(Q)}{(0.813)(0.555)} = 5.135m$$

The  $r$  values in Table 1—7 was averaged and taken as the scaling parameter for that cell and mechanism.

Table 1—7: Determination of  $n$  for the 3.4—litre cell with a Wemco mechanism

Experimental' $t_f$ [min"]	$R_f I$	$\frac{Q}{A}$ [m-min <sup>1</sup> ]	$n$ [m]	$t_{Predicted}'$ [min <sup>1</sup> ]
2.320	0.813	0.555	5.135	2.338
2.519	0.886	0.555	5.121	2.546
2.210	0.738	0.555	5.392	2.122
1.836	0.654	0.555	5.058	1.879

Scaling Parameter for Wemco cell

$$t_{Average}^f = M \quad 5.176$$

Table 1—8: Determination of  $n$  for the 15—litre cell with a Denver mechanism

Experimental' $t_f$ [min]	$R_f I$	$t_f$ [m-min <sup>1</sup> ]	$n$ [m]	$k_{Predicted}'$ [min <sup>1</sup> ]
1.799	0.919	0.756	2.591	2.002
1.631	0.725	0.756	2.977	1.579
1.323	0.649	0.756	2.696	1.415
1.060	0.459	0.756	3.057	1.000
1.119	0.451	0.756	3.283	0.983
0.724	0.356	0.756	2.693	0.775

Scaling Parameter for Denver cell

$$t_{Average}^f / [m] \quad 2.883$$

Table 1-9: Determination of  $n$  for the 56—litre cell with an Outokumpu mechanism

Experimental' $t_f$ [min"]	$R_f I$	$\frac{Q}{A}$ [m-min"]	$n$ [m]	$t_{Predicted}'$ [min"]
0.846	0.899	1.168	0.805	0.929
0.860	0.844	1.168	0.872	0.872
0.800	0.792	1.168	0.865	0.818
0.780	0.745	1.168	0.896	0.770
0.760	0.699	1.168	0.930	0.723
0.720	0.656	1.168	0.939	0.678

Scaling Parameter for Outokumpu cell

$$t_{Average}^f / M \quad 0.885$$

The flotation rate in any cell can also be related to the flotation rate of another cell. This was useful for the SBFA calculation procedure, in which only one cell flotation rate had

to be solved. Equation 19 demonstrates the procedure for relating a cell flotation rate to another.

$$k_{Denver} = k_{Wemco} \frac{A}{Q} \frac{T \backslash R}{T \backslash R_f}$$

J Denver

(13)

I.V Sample calculation for SBFA

The calculation procedure for the SBFA is similar to the procedure used in the rig calculation (except the model derived in Chapter 7 was used). Certain parameters had to be specified in advance in order to solve for the flotation rates and the maximum recovery.

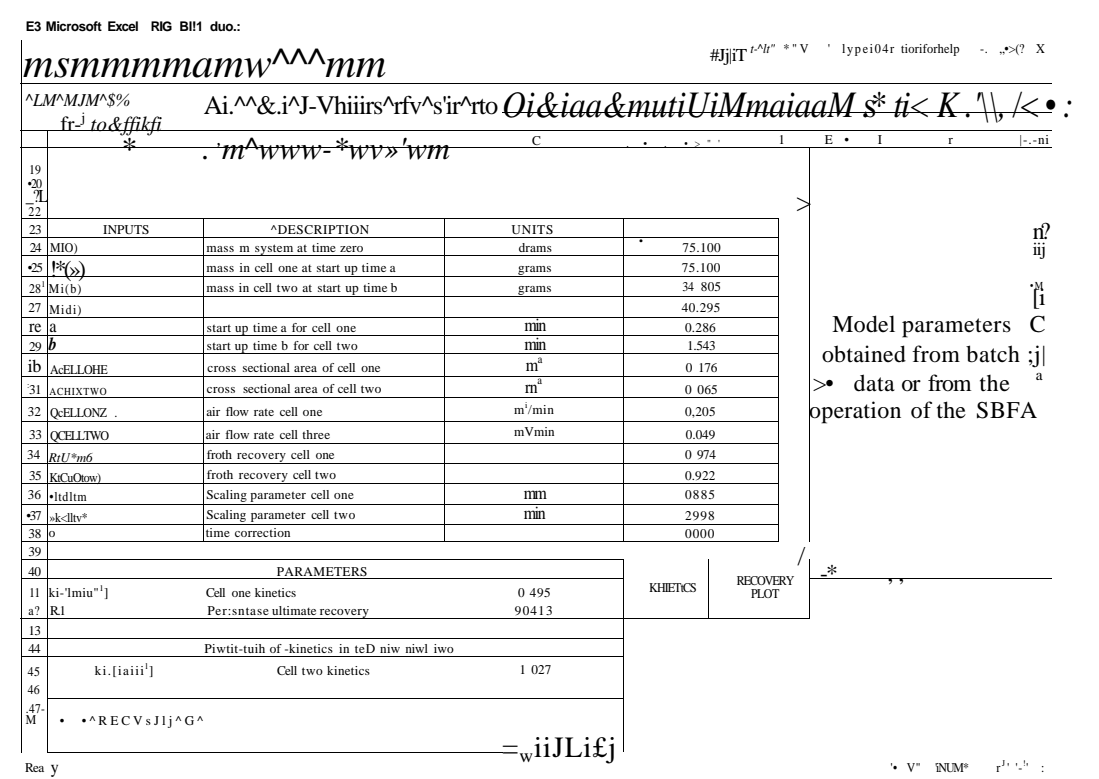


Figure 1—8. The spreadsheet that was created in Microsoft Excel® to solve the model for the SBFA. Macros were used to make the calculation procedure easier.

The correlation coefficient (similar to the Equation derived in Section I.I) was maximized by using the solver function. The solver parameters were the flotation rate in cell 2 and the maximum recovery. In addition the recycled rate  $[qpx]^\wedge$  was taken as the average rate of recycle of the valuable constituent (limestone) over the entire experiment.



APPENDIX II: SUMMARY OF DATA

This appendix is a summary of the test work done on the rig, batch cells and SBFA.

II.I Size analysis of the feed material

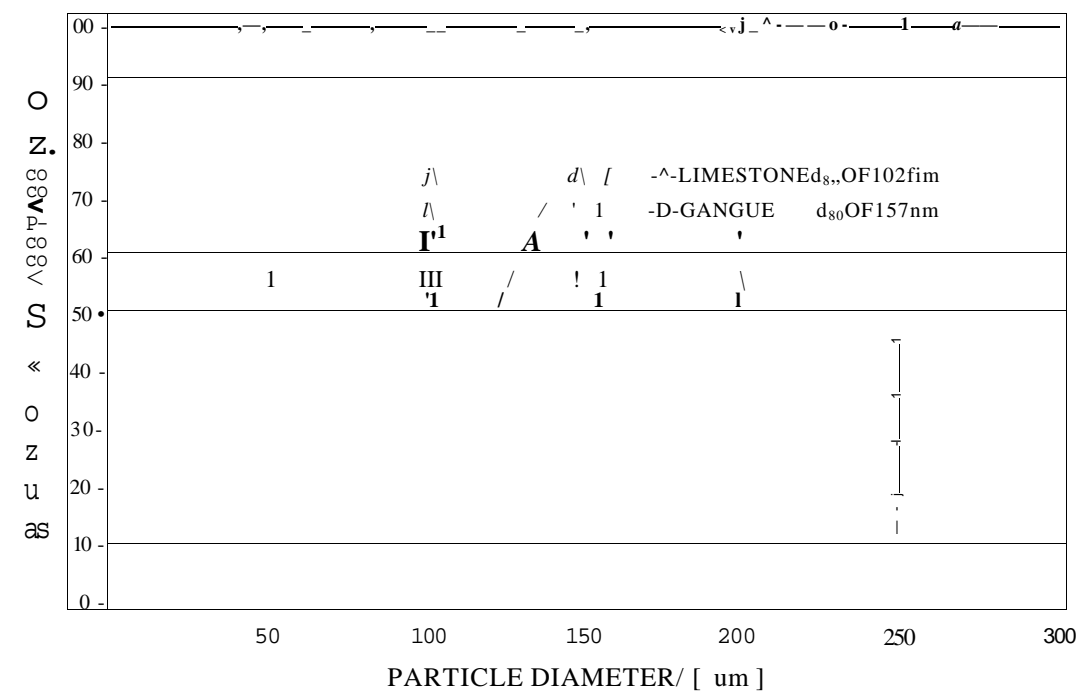
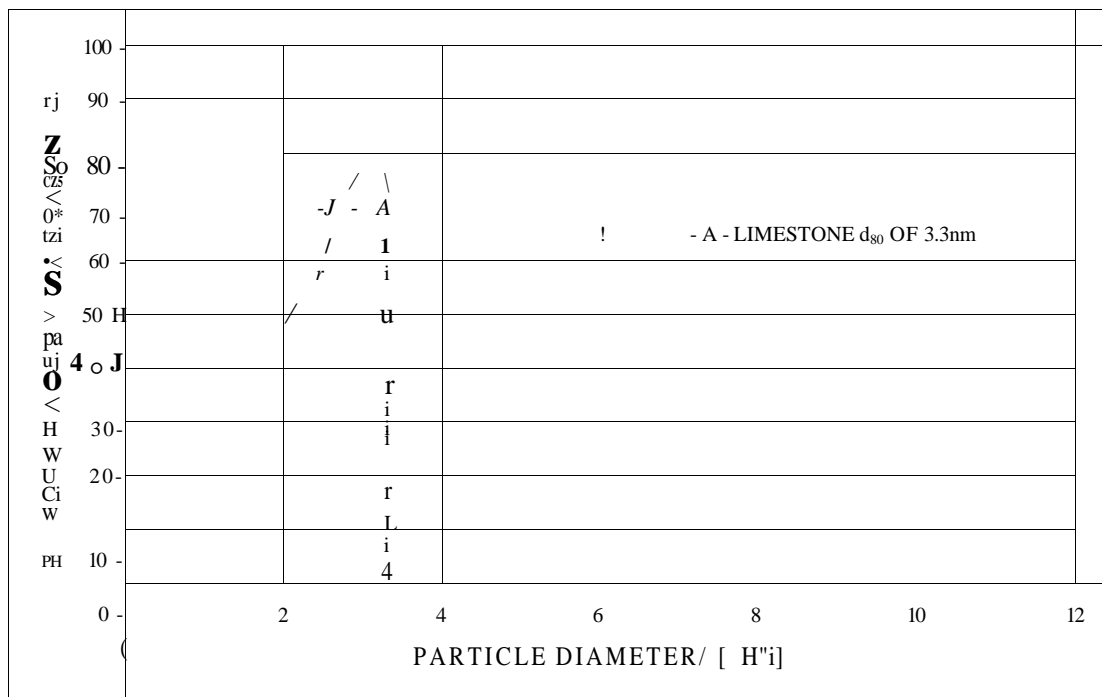


Figure II—1. Size analysis of the feed material used in the rig, batch tests and the SBFA.



**Figure II—2.** Size analysis of the fine limestone used in the reagent tests, the graph was reproduced from the manufacturer's data.

## 11.11 Summary of the rig data

Table II—1. Summary of the Agar model parameters for the rig

Test number	$kl$ [min <sup>-1</sup> ]	$R_{MAXI}$ [—]	$\nu l$ [min]
Test one	0.33	70.00	0.83
Test two	0.34	67.90	0.60
Test three	0.38	72.58	0.44
Overdose	0.32	81.01	0.47
Overdose two	0.43	82.83	0.67

II.III Summary of batch data for the variables impeller speed and air flow rate

**Table II—2. Summary of the data for the tests done at an impeller speed of 1090.51 rpm and different superficial air velocities in a 3.4—litre Denver cell**

Superficial Air Velocity [m/min]	1.07	0.85	0.65	0.56	0.36
Time/ [min]	Recovery	Recovery	Recovery	Recovery	Recovery
0.50	69.03	68.73	55.37	50.44	26.37
1.00	90.08	89.08	79.09	73.95	44.23
3.00	99.23	97.58	96.27	93.51	73.83
5.00	99.31	97.64	96.85	94.43	80.05
10.00	99.31	97.64	96.87	94.47	81.68
12.00	99.31	97.64	96.87	94.47	81.70

**Table II—3. Summary of the data for the tests done at an impeller speed of 981.46 rpm and different superficial air velocities in a 3.4—litre Denver cell**

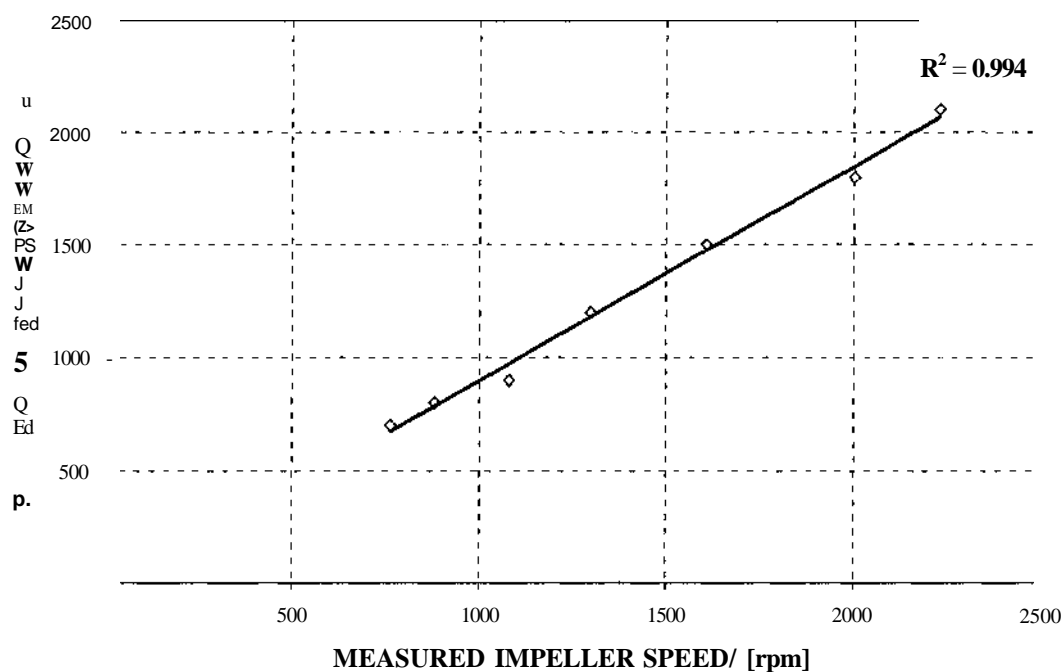
Superficial Air Velocity [m/min]	1.07	0.85	0.65	0.56	0.36
Time/ [min]	Recovery	Recovery	Recovery	Recovery	Recovery
0.50	67.75	63.29	58.90	52.35	32.06
1.00	78.55	75.67	76.87	70.01	49.06
3.00	91.64	91.20	93.49	91.03	80.12
5.00	94.34	92.99	95.80	93.62	81.62
10.00	95.77	93.77	96.93	95.17	86.69
12.00	96.19	94.38	97.27	95.48	87.98

Table II—4. Summary of the data for the tests done at an impeller speed of 872.41 rpm and different superficial air velocities in a 3.4—litre Denver cell

Superficial Air Velocity [m/min]	Time/ [min]	1.07	0.85	0.65	0.56	0.36
		Recovery	Recovery	Recovery	Recovery	Recovery
	0.50	61.28	49.63	44.67	51.59	43.34
	1.00	83.97	74.35	68.54	76.14	67.48
	3.00	97.07	97.37	93.73	97.28	94.91
	5.00	97.32	98.79	95.79	98.36	97.55
	10.00	97.32	98.88	95.97	98.42	97.83
	12.00	97.32	98.88	95.97	98.42	97.83

Table II—5. Summary of the data for the tests done at an impeller speed of 763.36 rpm and different superficial air velocities in a 3.4—litre Denver cell

Superficial Air Velocity [m/min]	Time/ [min]	1.07	0.85	0.65	0.56	0.36
		Recovery	Recovery	Recovery	Recovery	Recovery
	0.50	49.72	43.43	49.72	41.07	37.89
	1.00	73.68	67.44	74.11	64.66	61.12
	3.00	94.74	94.37	96.23	93.04	92.75
	5.00	95.88	96.89	97.51	96.13	97.23
	10.00	95.94	97.15	97.59	96.50	97.96
	12.00	95.94	97.15	97.59	96.50	97.96



**Figure II—3** Comparison of the impeller speed displayed on the Denver cell and the speed measured by a tachometer.

## II.IV Summary of batch data for the variable solid concentration

Table II—6. Summary of size analysis data for the concentrate obtained from  
15—litre Denver cell with a pulp having 7.50 % solids by mass

Percentage solid concentration in pulp	7.50			
Total mass of concentrate/ [g]	273.70			
Mean particle diameter/ [urn]	Concentrate limestone mass/ [g]	Concentrate gangue mass/ [g]	Tailings limestone mass/ [g]	Tailings gangue mass/ [g]
268.33	0.002	0.919	0.003	2.659
230.22	0.135	3.399	0.066	1.026
195.35	0.179	16.114	0.002	17.205
164.32	0.004	3.764	0.000	2.990
144.91	3.393	6.874	0.000	28.600
132.29	4.050	9.372	0.000	98.035
115.11	2.310	4.200	0.027	142.371
102.96	19.234	3.578	1.842	61.401
94.87	26.091	24.388	0.875	178.132
82.16	11.743	13.554	0.928	189.000
68.74	10.680	27.726	0.882	149.974
57.78	0.216	42.754	0.008	34.371
48.84	0.137	30.411	0.003	1.644
41.35	0.389	7.155	0.134	0.000
0.000	0.000	0.000	0.000	0.000

Table II—7. Summary of size analysis data for the concentrate obtained from a  
15—litre Denver cell with a pulp having 10.00 % solids by mass

Percentage solids concentration in pulp	10.00			
Total mass of concentrate/ [g]	334.90			
Mean particle diameter/ [urn]	Concentrate limestone mass/ [g]	Concentrate gangue mass/ [g]	Tailings limestone mass/ [g]	Tailings gangue mass/ [g]
268.33	0.003	0.699	0.004	3.718
230.22	0.195	2.564	0.093	1.434
195.35	0.115	26.462	0.003	24.055
164.32	0.192	7.292	0.000	4.180
144.91	0.018	27.598	0.000	39.987
132.29	10.427	35.082	0.000	137.068
115.11	4.234	9.378	0.038	199.058
102.96	23.982	0.020	2.575	85.848
94.87	23.488	34.571	1.223	249.057
82.16	15.170	0.810	1.297	264.250
68.74	11.983	52.887	1.233	209.688
57.78	8.804	24.916	0.011	48.057
48.84	0.688	11.322	0.004	2.299
41.35	0.710	1.289	0.188	0.000
0.000	0.000	0.000	0.000	0.000

Table II—8. Summary of size analysis data for the concentrate obtained from a  
15—litre Denver cell with a pulp having 15.00 % solids by mass

Percentage solids	15.00			
concentration in pulp				
Total mass of concentrate/	581.40			
[g]				
Particle diameter/ [µm]	Concentrate limestone mass/ [g]	Concentrate gangue mass/ [g]	Tailings limestone mass/ [g]	Tailings gangue mass/ [g]
268.33	0.013	1.806	0.006	5.713
230.22	0.401	5.696	0.142	2.204
195.35	3.154	20.908	0.004	36.965
164.32	7.604	17.677	0.001	6.424
144.91	9.261	49.933	0.000	61.447
132.29	19.128	59.712	0.001	210.632
115.11	6.967	28.898	0.058	305.890
102.96	40.810	19.337	3.958	131.922
94.87	20.327	85.913	1.879	382.724
82.16	27.938	19.378	1.993	406.071
68.74	40.068	42.376	1.894	322.226
57.78	1.779	42.928	0.017	73.849
48.84	0.062	10.593	0.006	3.533
41.35	0.539	0.000	0.289	0.000
0.000	0.000	0.000	0.000	0.000



## II.V Summary of batch data for the variable froth height

Table II—9. Summary of the data for  $H$  of 20.00 mm in the 56—litre Outokumpu cell

Froth depth/ [mm]	20.00	
$\ast/ [\text{min}^{-1}]$	0.85	
$\nu l [\text{min}]$	-0.26	
$R_{MAX}$	94.38	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.43	10.59	12.35
1.00	46.93	43.72
2.00	74.30	72.64
3.00	79.41	85.05
7.00	89.60	94.06
8.00	89.85	94.24
10.00	93.22	94.35
15.00	94.23	94.38
20.00	94.38	94.38

Table II—10. Summary of the data for  $H$  of 32.00 mm in the 56—litre Outokumpu cell

Froth depth/ [mm]	32.00	
$kl [\text{min}^{-1}]$	0.80	
$\nu l [\text{min}]$	-0.14	
$R_{MAX}$	95.09	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	22.58	24.07
1.00	49.29	47.56
2.00	75.99	73.80
5.00	82.61	93.18
7.00	87.47	94.71
10.00	89.59	95.06
15.00	94.31	95.09
20.00	95.09	95.09

Table 11—11. Summary of the data for  $H$  of 44.00 mm in the 56—litre Outokumpu cell

Froth depth/ [mm]	44.00	
$kl$ [ $\text{min}^{-1}$ ]	0.76	
$\nu l$ [min]	0.00	
$R_{MAX}$	92.26	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	27.57	29.09
1.00	53.50	49.01
2.00	70.71	71.99
3.00	81.78	82.75
5.00	85.16	90.17
7.00	87.71	91.80
10.00	89.83	92.21
15.00	91.43	92.25
20.00	92.26	92.26

Table 11—12. Summary of the data for  $H$  of 55.50 mm in the 56 —litre Outokumpu cell

Froth depth/ [mm]	55.50	
$kl$ [ $\text{min}^{-1}$ ]	0.73	
$\nu l$ [min]	0.00	
$R_{MAX}$	92.69	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	25.63	28.38
1.00	54.37	48.07
2.00	70.42	71.21
3.00	80.37	82.35
5.00	84.23	90.29
7.00	86.18	92.13
10.00	89.52	92.62
15.00	91.60	92.69
20.00	92.69	92.69

Table II—13. Summary of the data for  $H$  of 67.50 mm in the 56—litre Outokumpu cell

Froth depth/ [mm]	67.50	
$kl$ [min <sup>-1</sup> ]	0.68	
$v_l$ [min]	0.00	
$R_{MAX}$	90.67	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	24.42	26.17
1.00	47.03	44.79
2.00	71.48	67.45
3.00	73.15	78.92
5.00	86.47	87.66
7.07	87.90	89.94
10.00	89.27	90.57
15.00	90.24	90.67
20.00	90.67	90.67

Table II—14. Summary of the data for  $H$  of 79.50 mm in the 56—litre Outokumpu cell

Froth depth/ [mm]	79.50	
$kl$ [min <sup>-1</sup> ]	0.61	
$v_l$ [min]	0.00	
$R_{MAX}$	89.43	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	26.78	23.35
1.00	47.00	40.61
2.00	59.64	62.77
3.00	72.35	74.88
7.08	76.84	88.20
8.00	81.57	88.73
10.00	85.32	89.22
15.00	87.68	89.42
20.00	89.43	89.43

**Table II—15. Summary of the data for  $H$  of 5.00 mm in the 15—litre Denver cell**

Froth depth/ [mm]	5.00	
$kl$ [ $\text{min}^{-1}$ ]	1.95	
$vl$ [min]	0.00	
$R_{MAX}$	95.47	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	63.42	59.49
1.00	77.94	81.91
2.00	89.60	93.54
3.00	93.25	95.19
5.00	94.64	95.46
7.00	95.07	95.47
10.00	95.17	95.47
15.00	95.47	95.47

**Table 11—16. Summary of the data for  $H$  of 19.00 mm in the 15—litre Denver cell**

Froth depth/ [mm]	19.00	
$kl$ [ $\text{min}^{-1}$ ]	1.63	
$vl$ [min]	-0.01	
$R_{MAX}$	95.76	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	52.44	53.00
1.00	78.69	76.84
2.00	89.50	92.06
3.00	93.21	95.04
5.00	95.53	95.73
7.00	95.61	95.76
10.00	95.76	95.76
15.00	95.76	95.76

Table 11—17. Summary of the data for  $H$  of 25.50 mm in the 15—litre Denver cell

Froth depth/ [mm]	25.50	
$kl$ [ $\text{min}^{-1}$ ]	1.32	
$vl$ [min]	0.00	
$R_{MAX}$	97.04	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	52.07	46.95
1.00	70.38	71.18
2.00	84.28	90.15
3.00	90.35	95.20
7.00	95.08	97.03
10.00	96.42	97.04
15.00	96.83	97.04
20.00	97.04	97.04

Table 11—18. Summary of the data for  $H$  of 46.00 mm in the 15—litre Denver cell

Froth depth/ [mm]	46.00	
$kl$ [ $\text{min}^{-1}$ ]	1.06	
$vl$ [min]	0.00	
$R_{MAX}$	94.66	
Time/ [min]	Percentage cumulative recovery	Simulated cumulative recovery
0.50	39.12	37.60
1.00	64.68	60.26
2.00	78.44	82.16
3.00	83.37	90.12
5.00	90.76	94.06
7.00	93.74	94.58
10.00	94.56	94.66
15.17	94.66	94.66

Table 11—19. Summary of the data for  $H$  of 47.00 mm in the 15—litre Denver cell

<b>Froth depth/ [mm]</b>	47.00	
<b><math>kl</math> [<math>\text{min}^{-1}</math>]</b>	1.12	
<b><math>\nu l</math> [min]</b>	0.00	
<b><math>R_{MAX}</math></b>	92.58	
<b>Time/ [min]</b>	<b>Percentage cumulative recovery</b>	<b>Simulated cumulative recovery</b>
0.50	39.25	39.68
1.00	64.35	62.35
2.00	81.71	82.71
3.00	86.45	89.36
7.00	88.42	92.54
10.00	89.81	92.58
15.00	90.83	92.58
20.00	92.58	92.58

Table 11—20. Summary of the data for  $H$  of 61.00 mm in the 15—litre Denver cell

<b>Froth depth/ [mm]</b>	61.00	
<b><math>kl</math> [<math>\text{min}^{-1}</math>]</b>	0.72	
<b><math>\nu l</math> [min]</b>	0.00	
<b><math>R_{MAX}</math></b>	86.51	
<b>Time/ [min]</b>	<b>Percentage cumulative recovery</b>	<b>Simulated cumulative recovery</b>
0.50	28.79	26.28
1.00	50.60	44.58
2.00	64.84	66.19
3.00	71.44	76.66
5.00	74.36	84.19
10.00	78.56	86.44
15.00	82.61	86.51
20.00	86.51	86.51

Table 11—21. Summary of the data for  $H$  of 10.00 mm in the 3.4—litre Wemco cell

<b>Froth depth/ [mm]</b>	10.00	
<b><math>kl</math> [min<sup>1</sup>]</b>	2.52	
<b><math>\nu l</math> [min]</b>	0.00	
<b><math>R_{MAX}</math></b>	91.21	
<b>Time/ [min]</b>	<b>Percentage cumulative recovery</b>	<b>Simulated cumulative recovery</b>
0.50	66.40	65.32
2.00	78.88	90.62
5.00	84.82	91.21
7.00	90.10	91.21
15.00	91.21	91.21

able 11—22. Summary of the data for  $H$  of 17.00 mm in the 3.4—litre Wemco c<

<b>Froth depth/ [mm]</b>	17.00	
<b><math>kl</math> [min<sup>1</sup>]</b>	2.32	
<b><math>\nu l</math> [min]</b>	0.00	
<b><math>R_{MAX}</math></b>	92.97	
<b>Time/ [min]</b>	<b>Percentage cumulative recovery</b>	<b>Simulated cumulative recovery</b>
0.50	67.01	66.04
2.00	82.38	92.32
5.00	87.39	92.97
7.00	91.66	92.97
15.00	92.97	92.97

able 11—23. Summary of the data for  $H$  of 25.00 mm in the 3.4—litre Wemco ce

<b>Froth depth/ [mm]</b>	25.00	
<b><math>kl</math> [min<sup>1</sup>]</b>	2.21	
<b><math>\nu l</math> [min]</b>	0.00	
<b><math>R_{MAX}</math></b>	81.96	
<b>Time/ [min]</b>	<b>Percentage cumulative recovery</b>	<b>Simulated cumulative recovery</b>
0.50	54.95	54.82
2.00	80.12	80.98
5.00	81.96	81.96
7.00	81.96	81.96
15.00	81.96	81.96

Table 11—24. Summary of the data for  $H$  of 35.00 mm in the 3.4—litre Wemco cell

<b>Froth depth/ [mm]</b>	35.00	
<b><math>kl</math> [min<sup>1</sup>]</b>	1.84	
<b><math>\nu l</math> [min]</b>	0.00	
<b><math>R_{MAX}</math></b>	93.90	
<b>Time/ [min]</b>	<b>Percentage cumulative recovery</b>	<b>Simulated cumulative recovery</b>
0.50	55.41	54.29
2.00	87.27	90.93
5.00	90.10	93.88
7.00	90.18	93.90
15.00	93.90	93.90



.VI Summary of cumulative recovery—grade data for 15—litre Denver cell

Table 11—25. Summary of cumulative recovery—grade data for  $H$  of 5.00 mm

Froth Height/ [mm]		5.00	
Time/ [min]	Cumulative	Time/ [min]	Cumulative
	concentrate		concentrate
	Grade/ <b>H</b>		Grade/ <b>H</b>
0.50	30.77	0.50	30.77
1.00	29.63	1.00	29.63
3.00	27.32	3.00	27.32
5.00	25.39	5.00	25.39
7.00	22.38	7.00	22.38
10.00	19.19	10.00	19.19
15.00	14.92	15.00	14.92

Table II—26. Summary of cumulative recovery—grade data for  $H$  of 19.00 mm

Froth Height/ [mm]		19.00	
Time/ [min]	Cumulative	Time/ [min]	Cumulative
	concentrate		concentrate
	Grade/ [-]		Grade/ [-]
0.50	31.70	0.50	31.70
1.00	31.21	1.00	31.21
3.00	28.31	3.00	28.31
5.00	25.94	5.00	25.94
7.00	25.12	7.00	25.12
10.00	23.70	10.00	23.70
15.00	22.83	15.00	22.83

Table 11—27. Summary of cumulative recovery—grade data for  $H$  of 33.00 mm

Froth Height/ [mm]		33.00	
Time/ [min]	Cumulative	Time/ [min]	Cumulative
	concentrate		concentrate
	Grade/ [-]		Grade/ [-]
0.50	32.52	0.50	32.52
1.00	31.86	1.00	31.86
3.00	30.17	3.00	30.17
5.00	28.04	5.00	28.04
7.00	26.86	7.00	26.86
10.00	25.78	10.00	25.78
15.00	23.94	15.00	23.94

Table 11—28. Summary of cumulative recovery—grade data for  $H$  of 47.00 mm

Froth Height/ [mm]		47.00	
Time/ [min]	Cumulative	Time/ [min]	Cumulative
	concentrate		concentrate
	Grade/ <b>H</b>		Grade/ [-]
0.50	33.45	0.50	33.45
1.00	32.92	1.00	32.92
3.00	31.74	3.00	31.74
5.00	28.78	5.00	28.78
7.00	26.68	7.00	26.68
10.00	23.65	10.00	23.65
15.00	22.08	15.00	22.08

## II.VII Summary of data for SBFA with the variable recycle rate

**Table 11—29. Summary of the SBFA model input parameters for a recycle rate of 0.00 L-min<sup>-1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	54.500
M <sub>1</sub> (a)	Limestone in cell one at time a	grams	54.500
M <sub>1</sub> (b)	Limestone in cell one at time b	grams	22.845
M <sub>2</sub> (b)	Limestone in cell two at time b	grams	31.655
a	Startup time a, related to first cell in SBFA	min	0.000
b	Startup time a, related to second in SBFA	min	1.315
R <sub>f,1</sub>	Froth recovery for cell one	—	0.974
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
in	Flotation rate scaling parameter related to cell one		0.885
"H2	Flotation rate scaling parameter related to cell two		2.998

**Table 11—30. Summary of data for a recycle rate of 0.00 L'min<sup>-1</sup> in the SBFA**

<b>Time/ [min]</b>	<b>Mass Before Acid Dissolution/ [g]</b>	<b>Mass After Acid Dissolution/ [g]</b>	<b>Mass Limestone/ [g]</b>	<b>Cumulative concentrate Grade/ [-]</b>	<b>Cumulative Limestone Recovery/ <b>H</b></b>	<b>Simulated Limestone Recovery/ <b>H</b></b>
0.50	38.10	12.70	25.40	66.67	46.61	47.22
2.00	19.80	10.20	9.60	60.45	64.22	61.29
3.00	9.50	4.60	4.90	59.20	73.21	69.97
5.00	7.70	5.30	2.40	56.32	77.61	81.48
7.00	17.30	12.10	5.20	51.41	87.16	87.13
10.00	4.90	3.60	1.30	50.15	89.54	90.41
15.00	5.40	4.20	1.20	48.69	91.74	91.59
<b>Tailings</b>	2574.00	2569.00	4.50	—	—	—

**Table 11—31. Summary of model parameters for a recycle rate of 0.00 L'min<sup>-1</sup>, after  
using solver**

<b>Parameter</b>	<b>Units</b>	<b>Model estimate</b>
<i>RMAX</i>	-	91.768
<i>ki</i>	min <sup>-1</sup>	0.413
<i>k<sub>2</sub></i>	min <sup>-1</sup>	0.857
<i>V</i>	Min	-0.125
SER	-	2.650
<i>r</i> <sup>2</sup>	-	0.978
Residual	-	0.004



**Table II—32. Summary of the SBFA model input parameters for a recycle rate of  
1.25 L\*min<sup>-1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	75.100
M <sub>1</sub> (a)	Limestone in cell one at time a	grams	75.100
M <sub>1</sub> (b)	Limestone in cell one at time <b>b</b>	grams	34.805
M <sub>2</sub> (b)	Limestone in cell two at time <b>b</b>	grams	40.295
a	Startup time a, related to first cell in SBFA	min	0.286
<b>b</b>	Startup time a, related to second in SBFA	min	1.543
R <sub>f,1</sub>	Froth recovery for cell one	—	0.974
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
n <sub>1</sub>	Flotation kinetic scaling parameter related to cell one		0.885
112	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—33. Summary of data for a recycle rate of 1.25 L-min<sup>-1</sup> in the SBFA

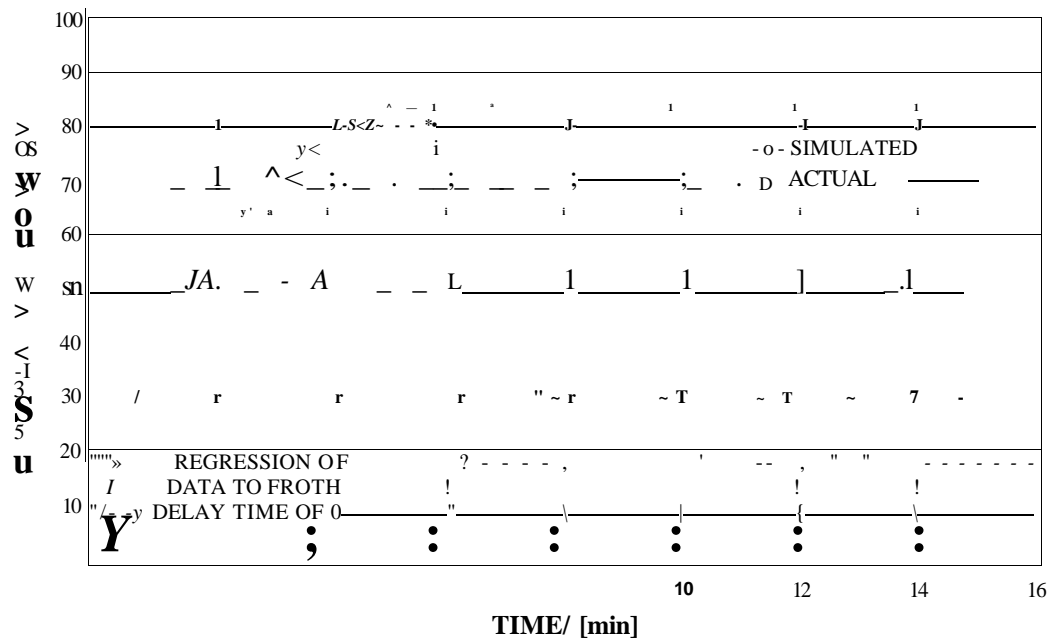
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass imestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ [-]	Simulated Limestone Recovery/ [-]
0.50	22.70	5.20	17.50	77.09	23.30	24.19
1.00	15.80	5.30	10.50	72.73	37.28	37.00
2.00	18.40	7.40	11.00	68.54	51.93	56.44
3.00	16.90	7.20	9.70	65.99	64.85	69.20
5.00	20.90	9.50	11.40	63.46	80.03	82.36
7.00	14.40	11.00	3.40	58.20	84.55	87.40
10.00	17.20	15.40	1.80	51.70	86.95	89.73
15.00	39.70	37.10	2.60	40.90	90.41	90.36
<b>Tailings</b>	2637.00	2629.00	7.20	—	—	—

Table 11—34. Summary of model parameters for a recycle rate of 1.25 L-min<sup>-1</sup>, after using solver

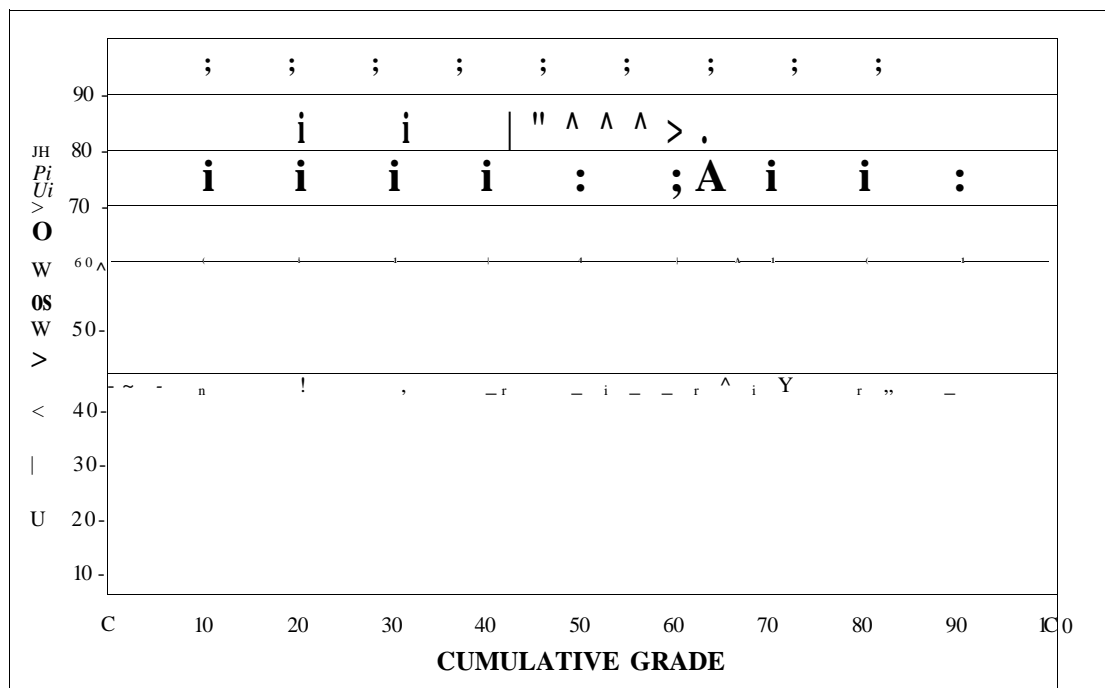
Parameter	Units	Model estimate
$R/AAX$	—	90.413
$*_1$	min <sup>-1</sup>	0.495
$h$	min <sup>-1</sup>	1.027
$v$	Min	0.000
SER	—	3.198
$?$	—	0.986
Residual	—	0.006

Table 11—35. Summary of cumulative gangue recycled, for a recycle rate of 1.25 L-min<sup>-1</sup>

Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	0.94	0.94	0.03
1.00	5.65	6.59	0.24
2.00	12.55	19.14	0.70
3.00	7.53	26.66	0.98
5.00	18.85	45.51	1.67
7.00	30.17	75.68	2.78
10.00	49.10	124.77	4.58
15.00	75.57	200.34	7.35

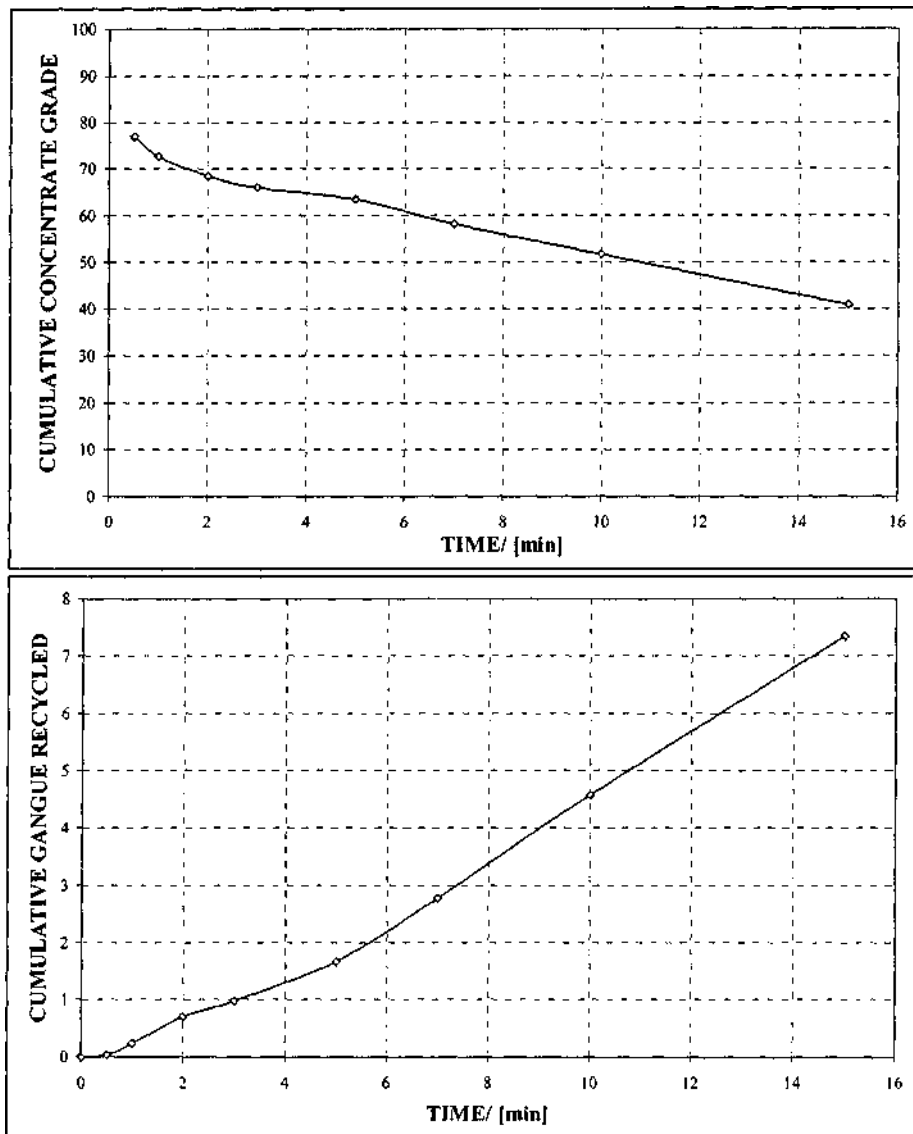


**Figure II—6.** Cumulative recovery—time profile for SBFA at a recycle rate of 1.25 L·min<sup>-1</sup> .



**Figure II—7.** Cumulative recovery—grade curve for SBFA at a recycle rate of 1.25 L·min<sup>-1</sup>





**Figure II—8.** Variation in the cumulative concentrate grade with the recycle of gangue at a rate of 1.25 L-min<sup>-1</sup>.

**Table 11—36. Summary of the SBFA model input parameters for a duplicate test with a recycle rate of 1.25 L'min"<sup>1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	74.900
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	74.900
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time <b>b</b>	grams	32.829
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time <b>b</b>	grams	42.071
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.308
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.974
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min" <sup>1</sup>	0.205
<b>Q<sub>2</sub></b>	SBFA rate in cell two	m <sup>3</sup> • min" <sup>1</sup>	0.049
<b>"<sub>1</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>"<sub>H2</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—37. Summary of data for a duplicate test with a recycle rate of 1.25 L-min<sup>-1</sup> in the SBFA

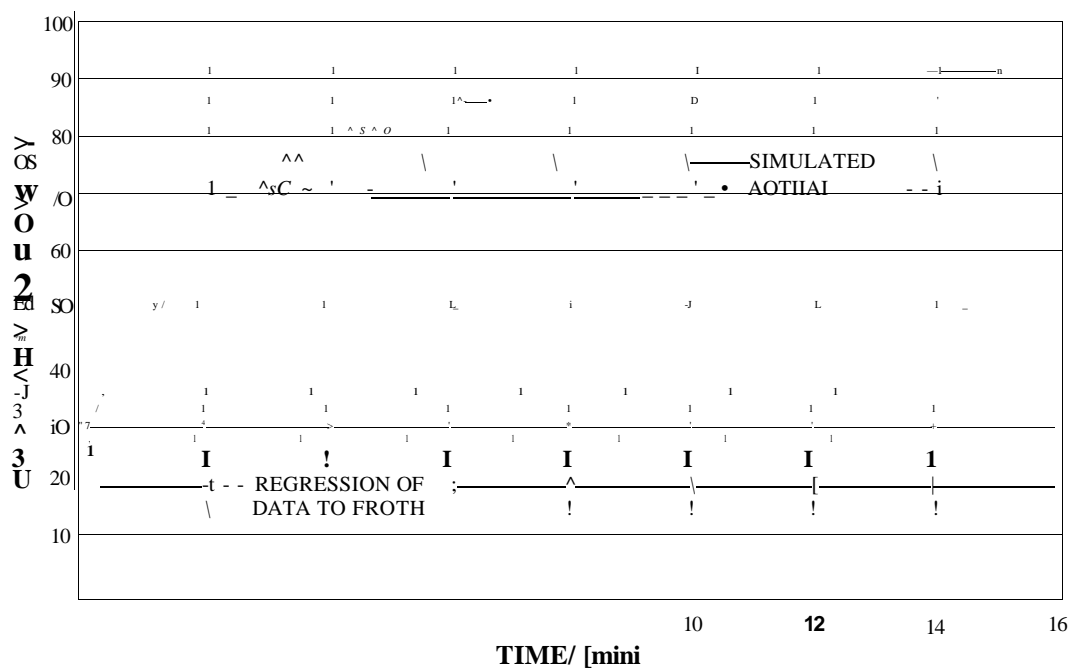
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass imestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ [-]
0.50	38.60	9.90	28.70	74.35	38.32	24.19
1.00	9.70	3.50	6.20	72.26	46.60	37.00
2.00	18.30	6.90	11.40	69.52	61.82	56.44
3.00	7.80	2.80	5.00	68.95	68.49	69.20
5.00	31.80	22.40	9.40	57.16	81.04	82.36
7.00	8.90	6.60	2.30	54.74	84.11	87.40
10.00	4.60	3.00	1.60	53.97	86.25	89.73
15.00	21.80	17.80	4.00	48.48	91.59	90.36
<b>Tailings</b>	2484.00	2477.00	6.30	—	—	—

Table 11—38. Summary of model parameters for a duplicate test with a recycle rate of 1.25 L-min<sup>-1</sup>, after using solver

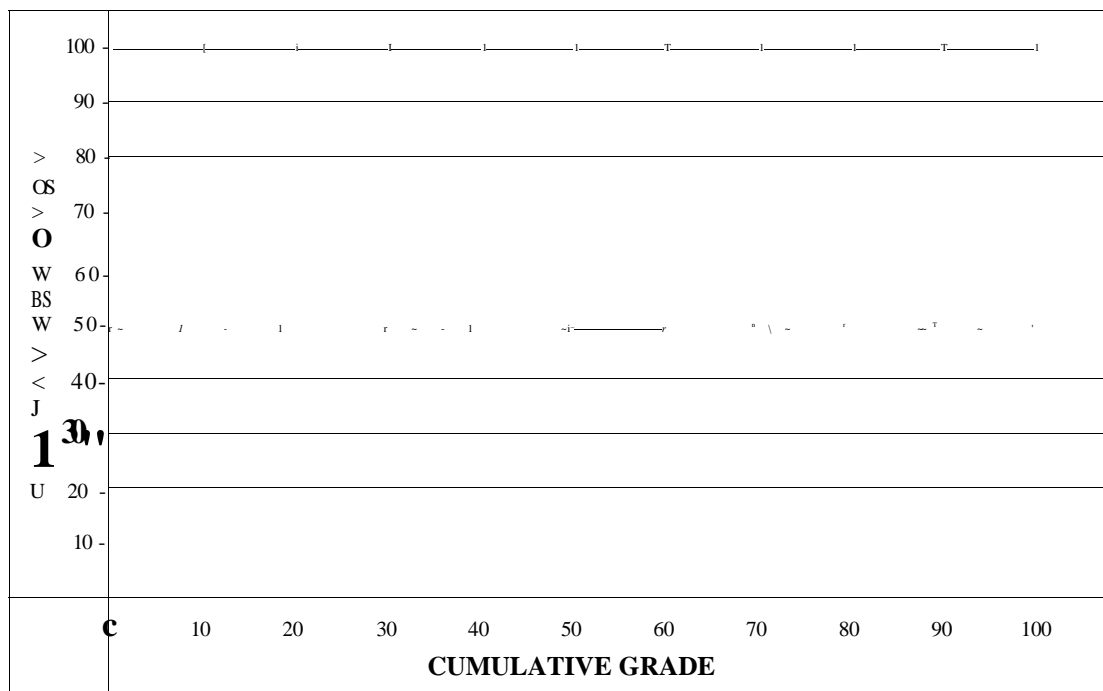
Parameter	Units	Model estimate
<sup>-</sup> MAX	—	91.589
<b>h</b>	min <sup>-1</sup>	0.441
<i>k</i> <sub>2</sub>	min <sup>-1</sup>	0.915
<i>v</i>	<b>Min</b>	0.000
SER	—	2.622
<i>r</i> <sup>2</sup>	—	0.985
Residual	—	0.004

Table II—39. Summary of cumulative gangue recycled for a duplicate recycle rate of 1.25 L-min<sup>-1</sup>

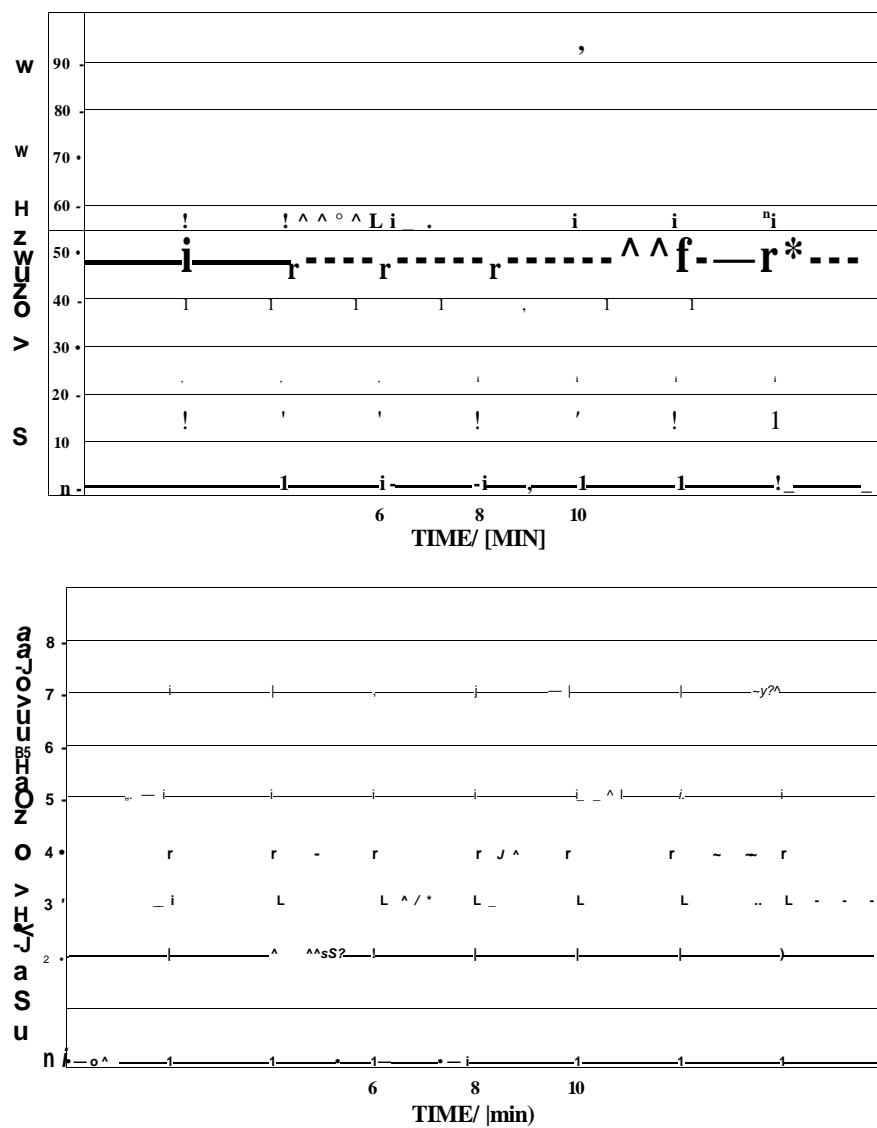
	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	1.25	1.25	0.05
1.00	6.27	7.53	0.30
2.00	13.81	21.34	0.84
3.00	11.29	32.62	1.28
5.00	20.10	52.73	2.07
7.00	25.14	77.87	3.05
10.00	37.77	115.63	4.54
15.00	75.57	191.20	7.50



**Figure II—9.** Cumulative recovery—time profile for SBFA at a duplicate test, with a recycle rate of 1.25 L-min<sup>-1</sup>.



**Figure 11—10.** Cumulative recovery—grade curve for SBFA at a duplicate test, with a recycle rate of 1.25 L-min<sup>-1</sup>.



**Figure II—11.** Variation in the cumulative concentrate grade with the recycle of gangue for a duplicate test at a recycle rate of  $1.25 \text{ Lmin}^{-1}$ .

**Table II—40. Summary of the SBFA model input parameters for a recycle rate of 1.63 L-min<sup>-1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	86.150
M <sub>1</sub> (a)	Limestone in cell one at time a	grams	86.150
M <sub>1</sub> (b)	Limestone in cell one at time b	grams	41.160
M <sub>2</sub> (b)	Limestone in cell two at time b	grams	44.990
a	Startup time a, related to first cell in SBFA	min	0.040
b	Startup time a, related to second in SBFA	min	1.315
R <sub>f,1</sub>	Froth recovery for cell one	—	0.974
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	l <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	l <sup>3</sup> • min <sup>-1</sup>	0.049
n <sub>1</sub>	Flotation kinetic scaling parameter related SBFA		0.885
112	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—41. Summary of data for a recycle rate of 1.63 L·min<sup>-1</sup> in the SBFA

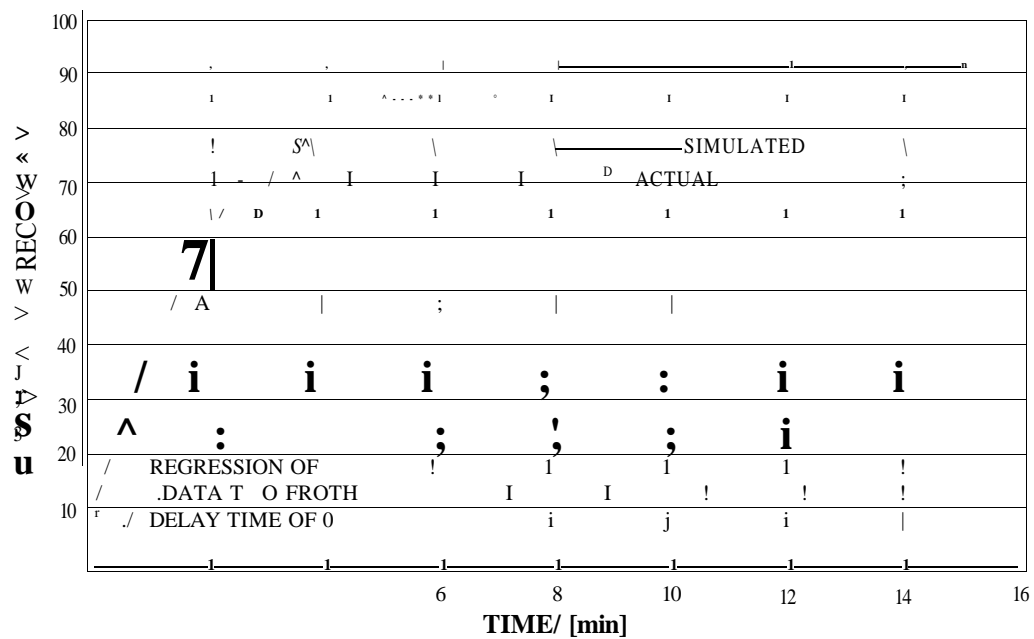
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ <b>H</b>
0.50	26.90	6.10	20.80	77.32	24.14	25.94
2.00	30.75	10.70	20.05	70.86	47.42	60.59
3.00	23.10	8.40	14.70	68.79	64.48	72.90
5.00	31.40	14.80	16.60	64.33	83.75	84.85
7.00	11.70	9.30	2.40	60.19	86.54	89.19
10.00	18.00	15.60	2.40	54.25	89.32	91.11
15.00	15.80	13.80	2.00	50.08	91.64	91.60
<b>Tailings</b>	2473.00	2465.00	7.20	—	—	—

Table 11-42. Summary of model parameters for a recycle rate of 1.63 L·min<sup>-1</sup>, after using solver

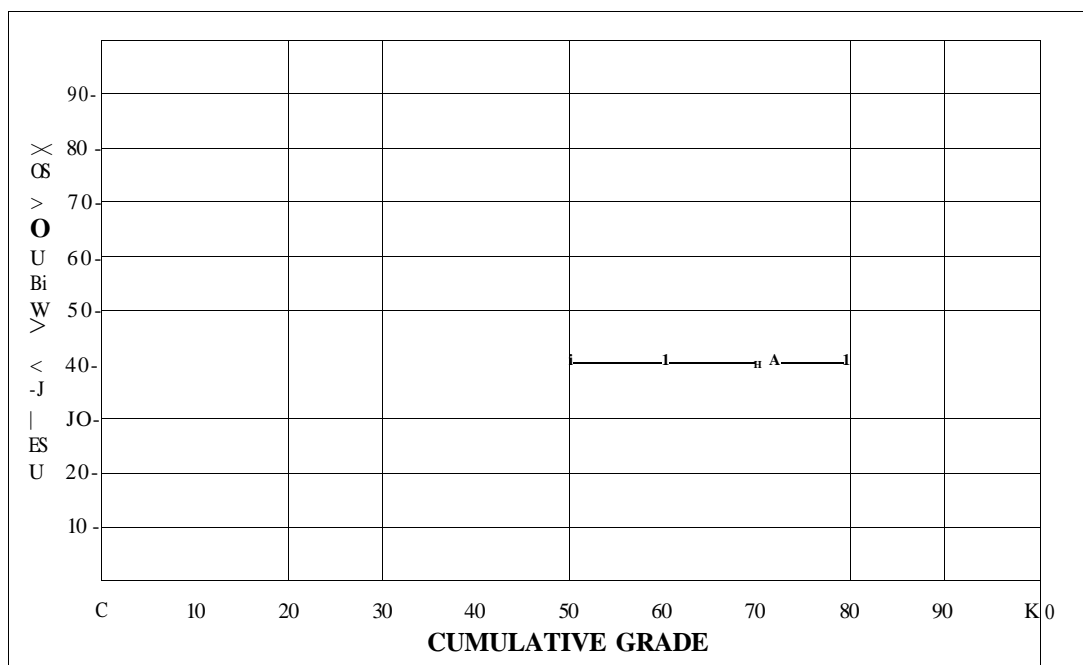
Parameter	Units	Model estimate
<sup>^</sup> MAX	—	91.642
* <sub>1</sub>	min <sup>-1</sup>	0.510
<i>k</i> <sub>2</sub>	min <sup>-1</sup>	1.057
<i>v</i>	Min	0.000
<b>SER</b>	—	7.197
<i>r</i> <sup>2</sup>	—	0.936
Residual	—	0.021

Table 11—43. Summary of cumulative gangue recycled for a recycle rate of 1.63 L·min<sup>-1</sup>

Time/ [min]	Mass Recycled/ [g]	Cumulative Ma Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	48.80	48.80	1.92
6.00	34.23	83.03	3.26
7.00	12.72	95.74	3.76
8.00	14.68	110.42	4.34
9.00	24.48	134.90	5.30
10.00	16.31	151.21	5.94
12.00	45.74	196.94	7.74
13.00	29.41	226.35	8.90
14.00	32.73	259.08	10.19
15.00	49.12	308.20	12.12

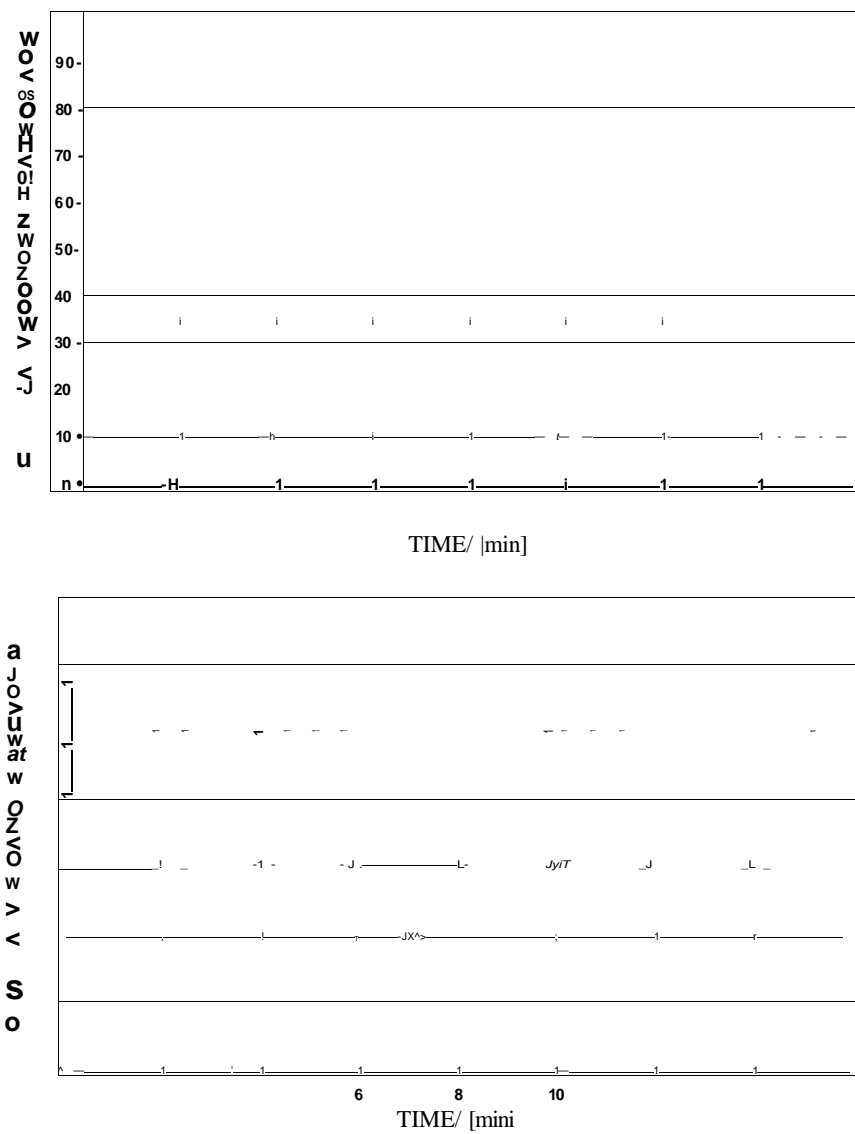


**Figure 11—12** Cumulative recovery—time profile for SBFA, with a recycle rate of 1.63 L·min<sup>-1</sup>



**Figure VI—13.** Cumulative recovery—grade curve for SBFA at a duplicate test, with a recycle rate of 1.63 L·min<sup>-1</sup>.





**Figure 11—14.** Variation in the cumulative concentrate grade with the recycle of gangue for a recycle rate of 1.63 L/min<sup>3</sup>.

**Table II—44. Summary of the SBFA model input parameters for a duplicate test with a recycle rate of 1.63 Irmin"**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	72.900
M <sub>i</sub> (a)	Limestone in cell one at time a	grams	72.900
M <sub>i</sub> (b)	Limestone in cell one at time b	grams	32.916
M <sub>2</sub> (b)	Limestone in cell two at time b	grams	39.984
a	Startup time a, related to first cell in SBFA	min	0.000
b	Startup time a, related to second in SBFA	min	1.218
R <sub>f,i</sub>	Froth recovery for cell one	—	0.974
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
A <sub>i</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>i</sub>	Air flow rate in cell one	$\frac{\text{m}^3}{\text{s}} \cdot \text{mm}^{-1}$	0.205
Q <sub>2</sub>	Air flow rate in cell two	$\frac{\text{m}^3}{\text{s}} \cdot \text{min}^{-1}$	0.049
	Flotation kinetic scaling parameter related to cell one		0.885
" 2	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—45. Summary of data for a duplicate test with a recycle rate of 1.63 Lmin<sup>-1</sup> in the SBFA

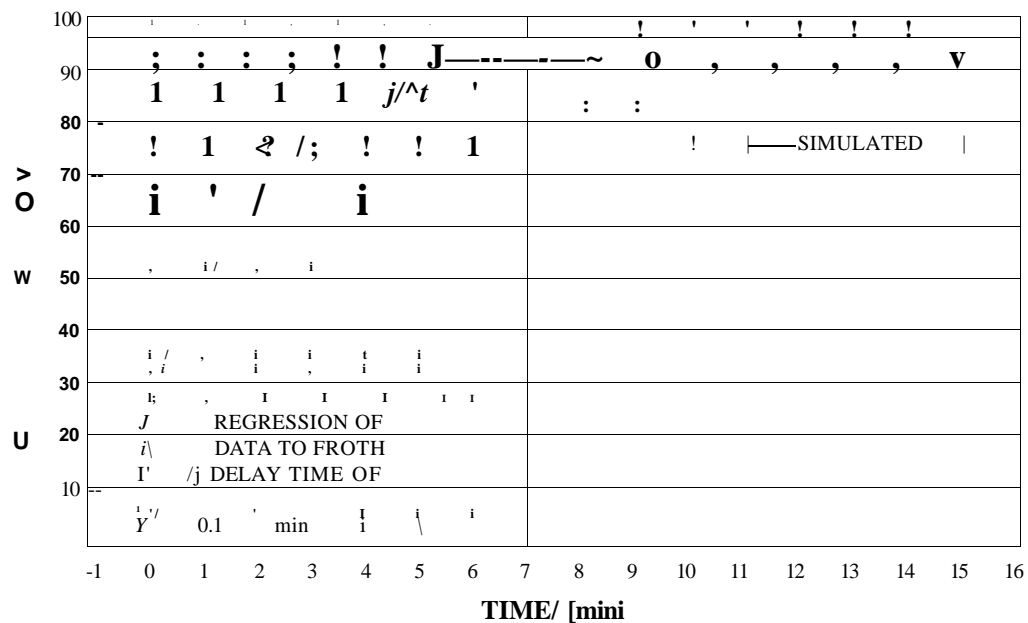
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ [-]	Simulated Limestone Recovery/ [-1]
0.50	38.00	9.30	28.70	75.53	39.37	39.47
2.00	48.30	22.10	26.20	63.62	75.31	65.90
3.00	11.00	6.90	4.10	60.64	80.93	77.13
5.00	21.70	17.40	4.30	53.19	86.83	89.08
7.00	8.40	6.20	2.20	51.41	89.85	93.75
10.00	29.00	26.10	2.90	43.73	93.83	95.93
15.00	19.00	18.10	0.90	39.51	95.06	96.52
Tailings	2363.00	2359.00	3.60	—	—	—

Table 11—46. Summary of model parameters for a duplicate test with a recycle rate of 1.63 L-min<sup>-1</sup>, after using solver

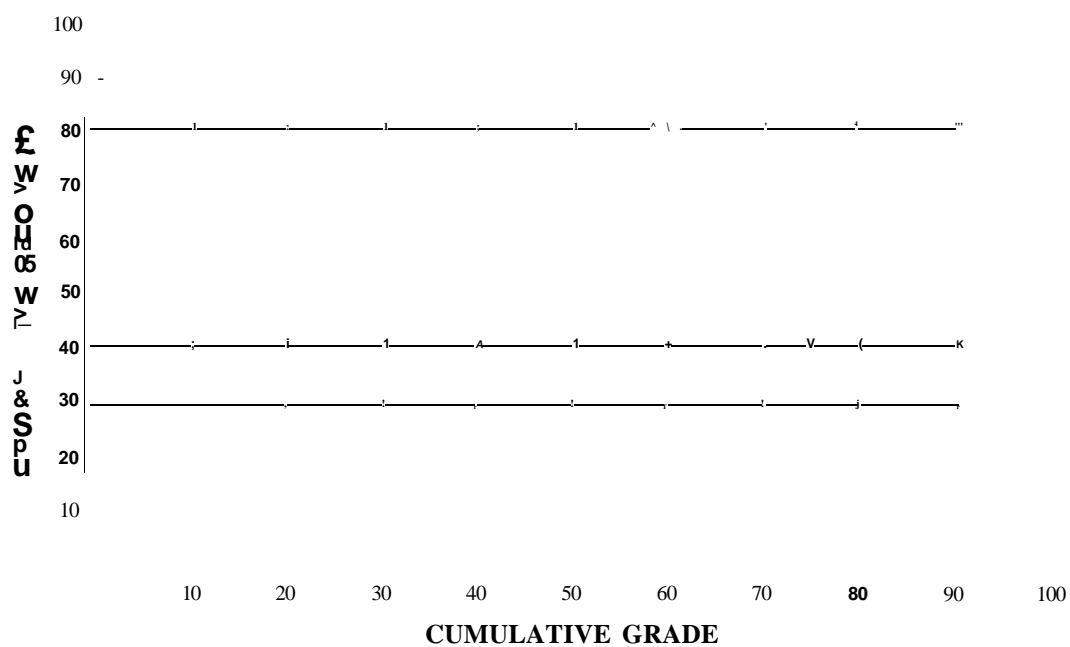
Parameter	Units	Model estimate
-KMAX	—	96.580
*1	min <sup>-1</sup>	0.493
$k_2$	min <sup>-1</sup>	1.023
$v$	Min	-0.100
SER	—	5.097
$r^2$	—	0.942
Residual	—	0.013

Table 11—47. Summary of cumulative gangue recycled for a duplicate recycle rate of 1.63 L-min<sup>-1</sup>

Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	55.16	55.16	2.24
6.00	63.99	119.15	4.83
7.00	25.92	145.07	5.88
8.00	16.72	161.79	6.56
9.00	31.79	193.58	7.85
10.00	53.77	247.35	10.03
12.00	47.44	294.80	11.96
13.00	47.26	342.06	13.88
14.00	15.61	357.67	14.51
15.00	19.27	376.94	15.29



**Figure 11—15.** Cumulative recovery—time profile for SBFA at a duplicate test, with a recycle rate of 1.63 L-min<sup>-1</sup>.



**Figure II- 16.** Cumulative recovery—grade curve for SBFA at a duplicate test, with a recycle rate of 1.63 L-min<sup>-1</sup>.

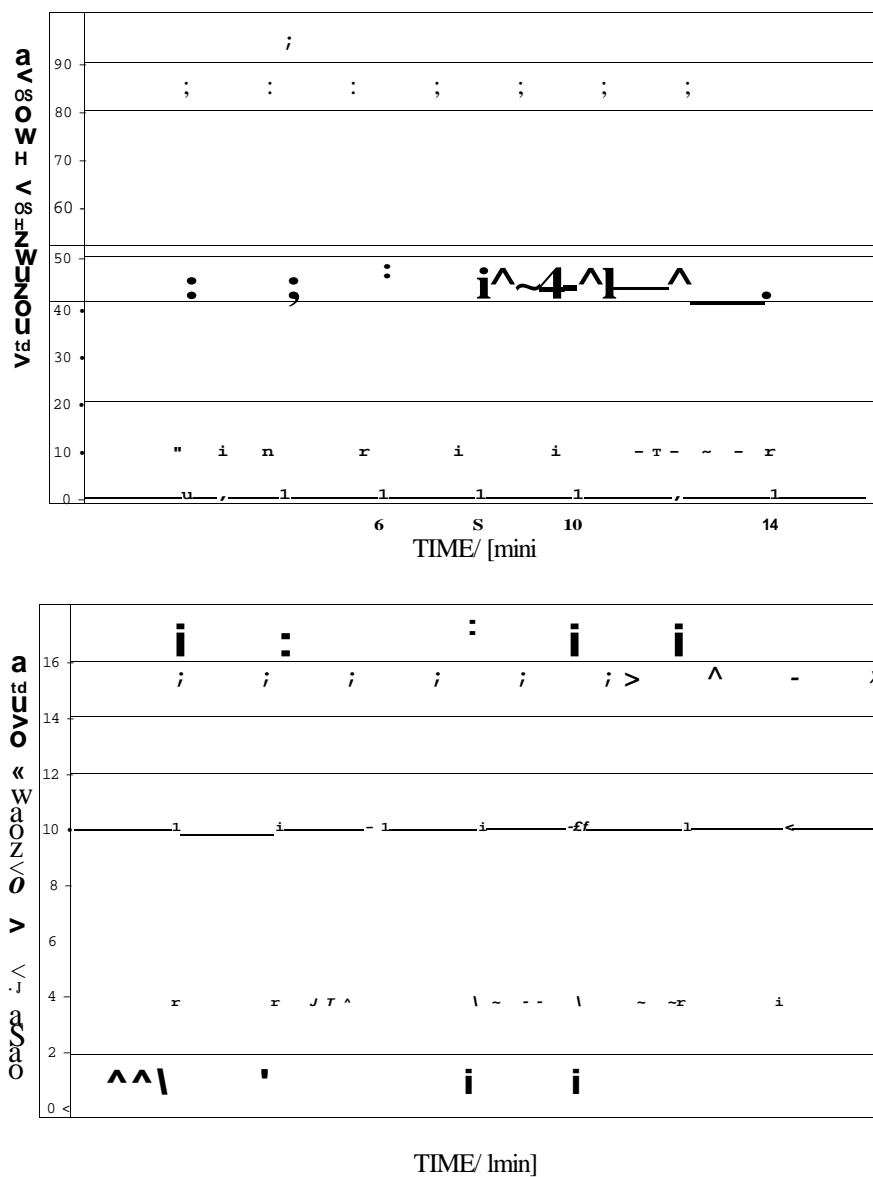


Figure 11—17. Variation in the cumulative concentrate grade with the recycle of gangue for a duplicate test at a recycle rate of 1.63 Lmin<sup>-1</sup>.

**Table 11—48. Summary of the SBFA model input parameters for a recycle rate of 2.50 L·min<sup>-1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	85.600
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	85.600
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	38.156
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	47.444
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.694
<b>b</b>	Startup time a, related to second in SBFA	min	1.852
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.974
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
<b>T<sub>11</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>T<sub>12</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—49. Summary of data for a recycle rate of 2.50 L-min<sup>-1</sup> in the SBFA

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/	Simulated Limestone Recovery/ H
0.50	26.10	6.00	20.10	77.01	23.48	24.25
2.00	36.10	9.00	27.10	75.88	55.14	53.26
3.00	18.40	8.10	10.30	71.34	67.17	67.18
5.00	24.10	13.60	10.50	64.95	79.44	82.32
7.00	18.50	15.80	2.70	57.39	82.59	88.19
10.00	27.90	24.00	3.90	49.37	87.15	90.85
15.00	16.20	12.40	3.80	46.86	91.59	91.53
<b>Tailings</b>	2554.00	2546.00	7.20	—	—	—

Table II-50. Summary of model parameters for a recycle rate of 2.50 L<sup>min</sup><sup>-1</sup>, after using solver

Parameter	Units	Model estimate
<i>RMAX</i>	—	91.589
<i>*1</i>	min <sup>-1</sup>	0.510
<i>h</i>	min <sup>-1</sup>	1.057
<i>v</i>	min	0.000
SER	—	3.390
<i>r</i> <sup>2</sup>	—	0.983
Residual	—	0.006

Table 11—51. Summary of cumulative gangue recycled for a recycle rate of 2.50 L-min<sup>-1</sup>

Time/ [min]	Mass Recycled/ [g]	Cumulative Ma Recycled/ [g]	to total gangue added
0.00	0.00	0.00	0.00
3.00	83.64	83.64	3.17
6.00	96.86	180.50	6.85
7.00	39.13	219.63	8.34
8.00	25.38	245.01	9.30
9.00	47.82	292.83	11.11
10.00	79.84	372.68	14.14
12.00	71.71	444.39	16.87
13.00	70.45	514.83	19.54
14.00	23.71	538.54	20.44
15.00	29.21	567.75	21.55

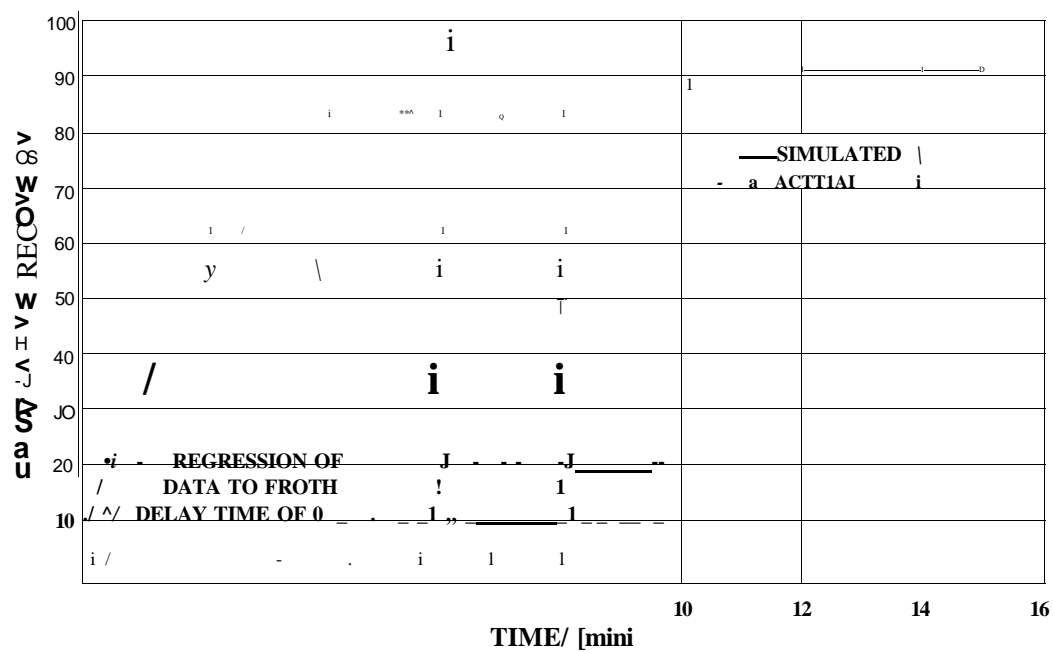


Figure 11—18. Cumulative recovery—time profile for SBFA, with a recycle rate of 2.50 L·min<sup>-1</sup>

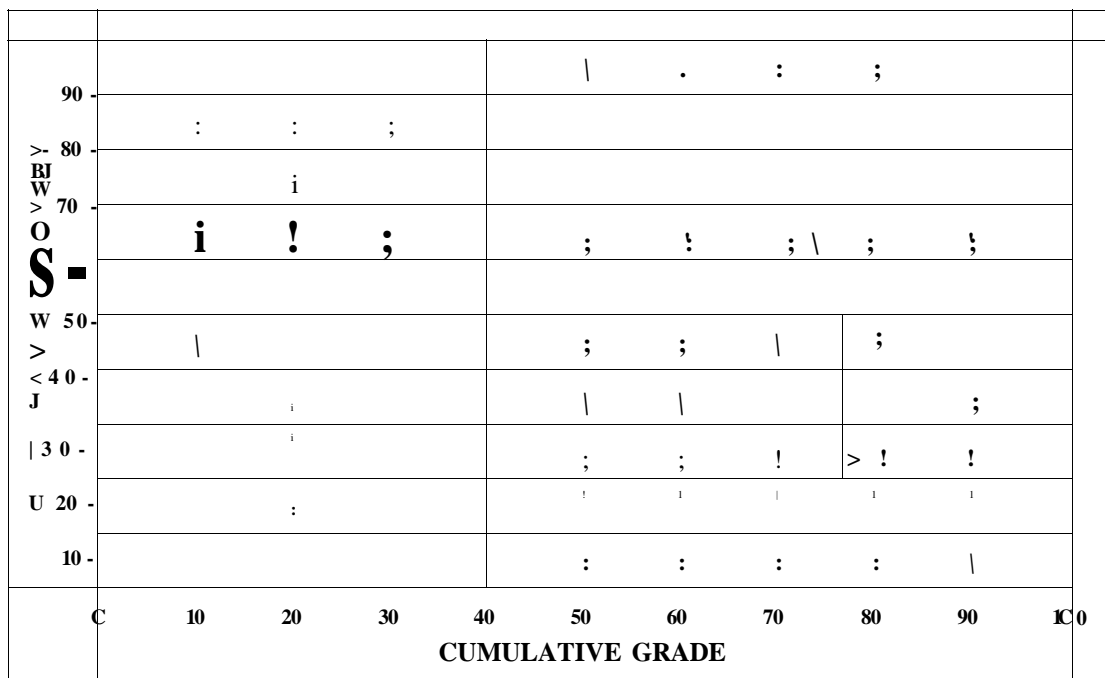
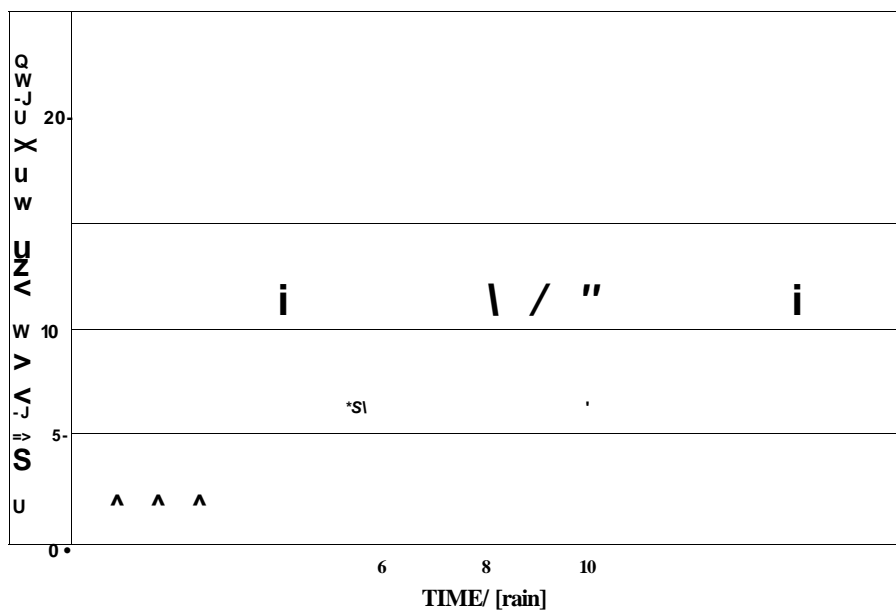
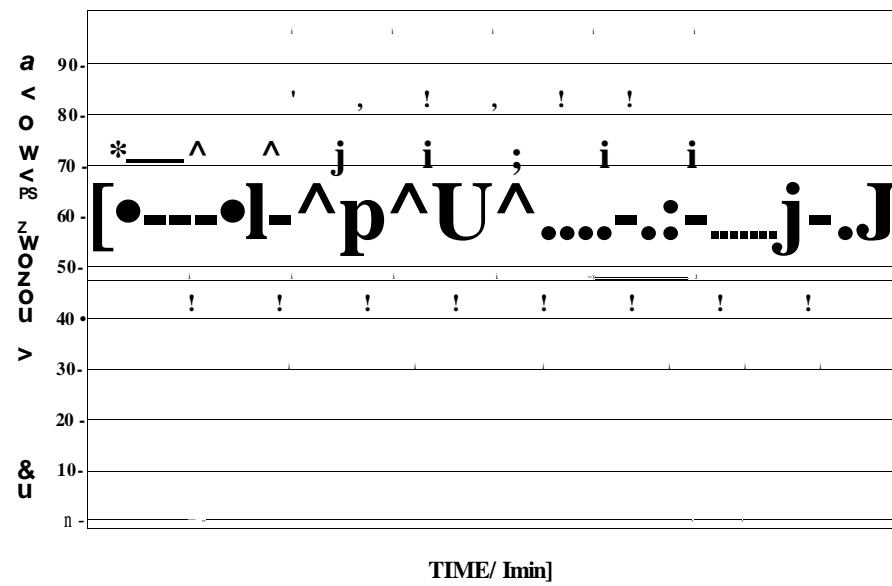


Figure II—19. Cumulative recovery—grade curve for SBFA at a duplicate test, with a recycle rate of 2.50 L·min<sup>-1</sup>





**Figure 11—20.** Variation in the cumulative concentrate grade with the recycle of gangue for a recycle rate of 2.50 L-min<sup>-1</sup>.

**Table 11—52. Summary of the SBFA model input parameters for a duplicate test with a recycle rate of 2.50 L-min<sup>-1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	74.300
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	74.300
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	31.477
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	42.823
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.609
<b>b</b>	Startup time a, related to second in SBFA	min	1.847
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.974
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
<b>n<sub>1</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>n<sub>2</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—53. Summary of data for a duplicate test with a recycle rate of 2.50 L-min<sup>-1</sup> in the SBFA

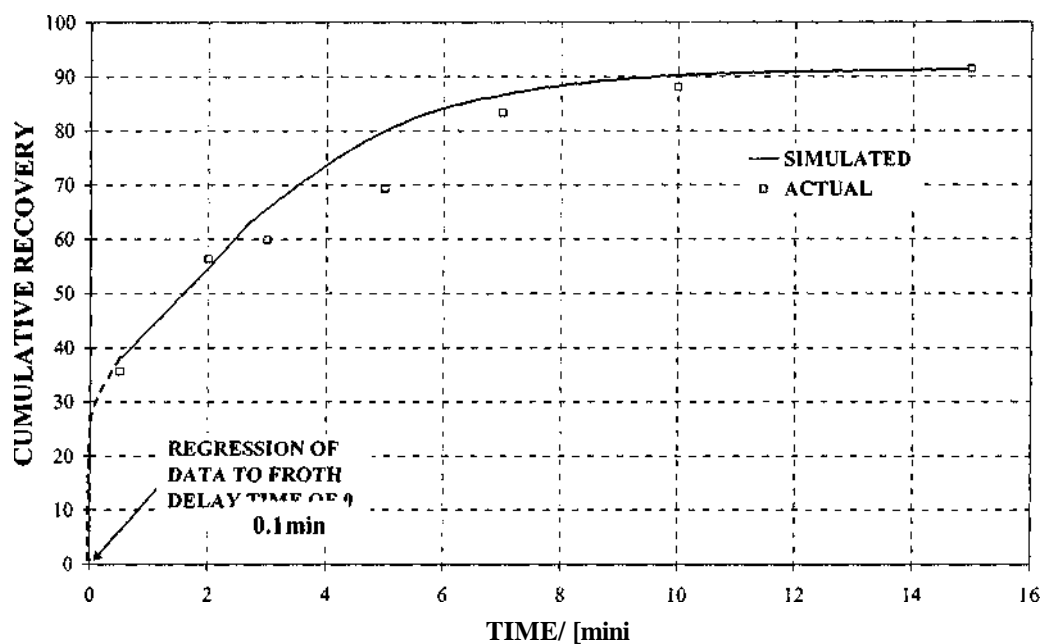
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ H	Simulated Limestone Recovery/ [-1
0.50	43.40	16.90	26.50	61.06	35.67	37.87
2.00	36.10	20.70	15.40	52.70	56.39	54.62
3.00	5.60	3.00	2.60	52.29	59.89	65.71
5.00	13.90	6.90	7.00	52.02	69.31	80.03
7.00	21.60	11.10	10.50	51.41	83.45	86.66
10.00	11.40	7.90	3.50	49.62	88.16	90.23
15.00	16.20	13.70	2.50	45.88	91.52	91.38
Tailings	2317.00	2310.00	6.30	—	—	—

Table H-54. Summary of model parameters for a duplicate test with a recycle rate of 2.50 L-min<sup>-1</sup>, after using solver

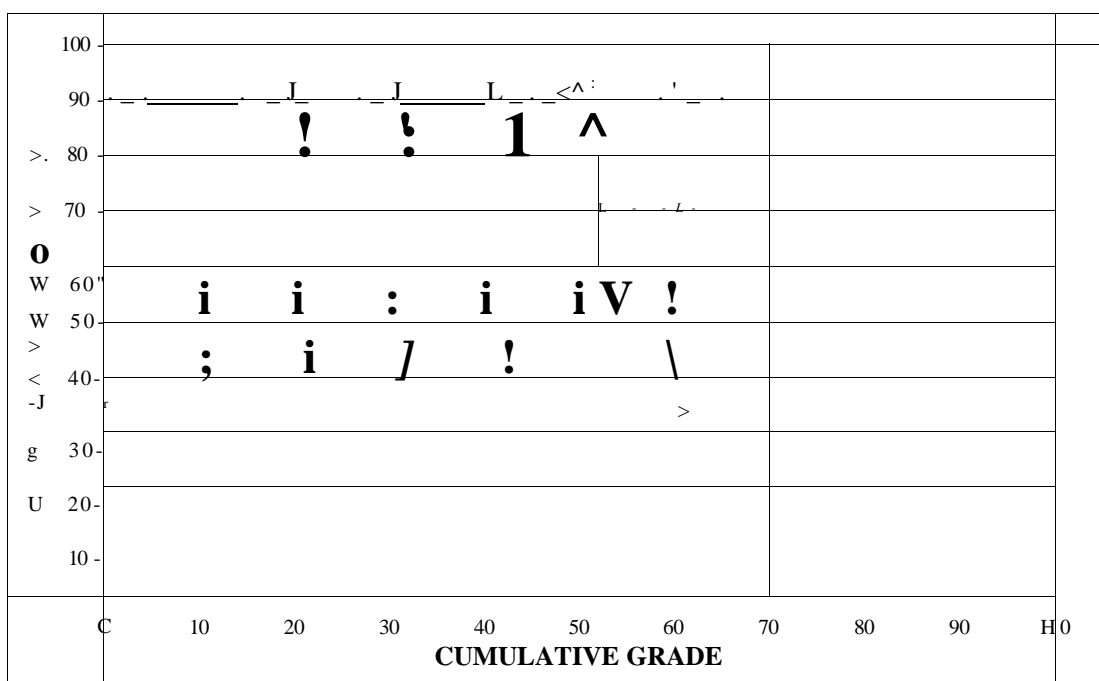
Parameter	Units	Model estimate
-RMAX	—	91.521
*1	min <sup>-1</sup>	0.445
<i>h</i>	min <sup>-1</sup>	0.924
<i>v</i>	min	0.000
SER	—	5.852
<i>r</i> <sup>2</sup>	—	0.930
Residual	—	0.017

Table 11-55. Summary of cumulative gangue recycled for a duplicate recycle rate of 2.50 L-min<sup>-1</sup>

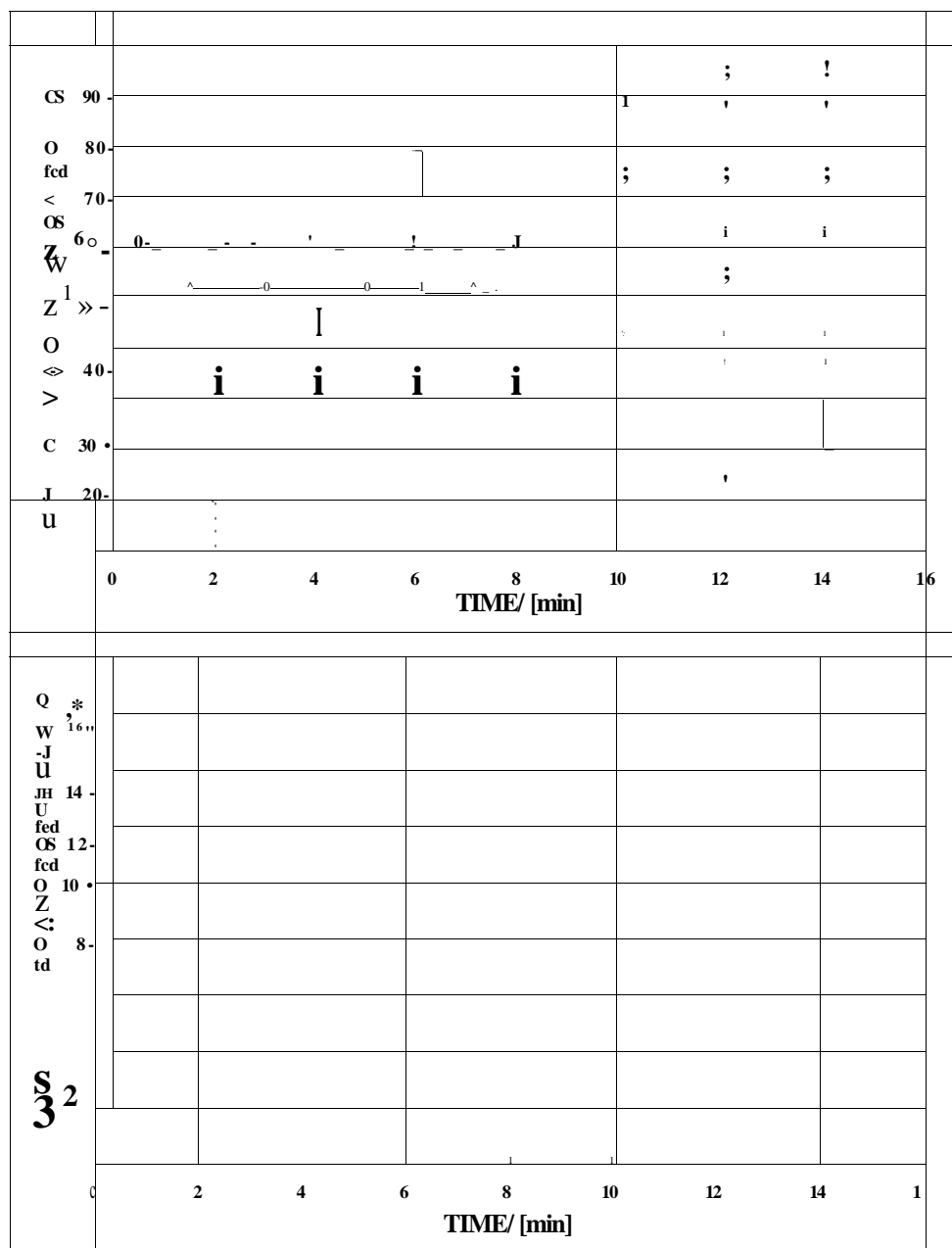
Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	65.27	65.27	2.73
6.00	75.13	140.40	5.87
7.00	32.65	173.05	7.24
8.00	21.82	194.87	8.15
9.00	26.76	221.63	9.27
10.00	25.07	246.70	10.32
12.00	52.68	299.38	12.53
13.00	27.66	327.04	13.68
14.00	26.40	353.44	14.79
15.00	27.55	380.99	15.94



**Figure II—21.** Cumulative recovery—time profile for SBFA at a duplicate test, with a recycle rate of 2.50 L·min<sup>-1</sup>.



**Figure 11—22.** Cumulative recovery—grade curve for SBFA at a duplicate test, with a recycle rate of 2.50 L·min<sup>-1</sup>.



**Figure 11—23.** Variation in the cumulative concentrate grade with the recycle of gangue for a duplicate test at a recycle rate of 2.50 L·min<sup>-1</sup>.

**Table 11—56. Summary of the SBFA model input parameters for a recycle rate of 3.13 L-min<sup>-1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	70.200
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	70.200
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	33.898
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	36.302
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.315
R <sub>f,1</sub>	Froth recovery for cell one	—	0.974
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
<b>T<sub>11</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>T<sub>12</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—57. Summary of data for a recycle rate of 3.13 L-min<sup>-1</sup> in the SBFA

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/	Simulated Limestone Recovery/ <b>1-1</b>
0.50	24.10	6.80	17.30	71.78	24.64	25.44
2.00	31.80	11.80	20.00	66.73	53.13	61.58
3.00	21.10	7.40	13.70	66.23	72.65	74.23
5.00	14.30	6.20	8.10	64.73	84.19	86.50
7.33	19.50	15.70	3.80	56.77	89.60	91.39
10.00	6.80	5.30	1.50	54.76	91.74	93.01
15.00	6.40	5.10	1.30	52.98	93.59	93.54
Tailings	2584.00	2579.00	4.50	—	—	—

Table 11—58. Summary of model parameters for a recycle rate of 3.13 L<sup>min</sup><sup>-1</sup>, after using solver

Parameter	Units	Model estimate
<i>RMAX</i>	—	93.590
<b><i>h</i></b>	min <sup>-1</sup>	0.502
<i>k<sub>2</sub></i>	min <sup>-1</sup>	1.041
<i>v</i>	min	0.000
SER	—	4.113
<i>r</i> <sup>2</sup>	—	0.978
Residual	—	0.008

Table 11—59. Summary of cumulative gangue recycled for a recycle rate of 3.13 L-min<sup>-1</sup>

Time/ [min]	Mass Recycled/ [g]	Cumulative Ma Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	104.82	104.82	3.98
6.00	121.38	226.20	8.58
7.00	49.03	275.24	10.44
8.00	31.81	307.04	11.64
9.00	59.92	366.97	13.91
10.00	100.06	467.02	17.71
12.00	89.87	556.89	21.12
13.00	88.28	645.17	24.46
14.00	29.71	674.89	25.59
15.00	36.60	711.49	26.98

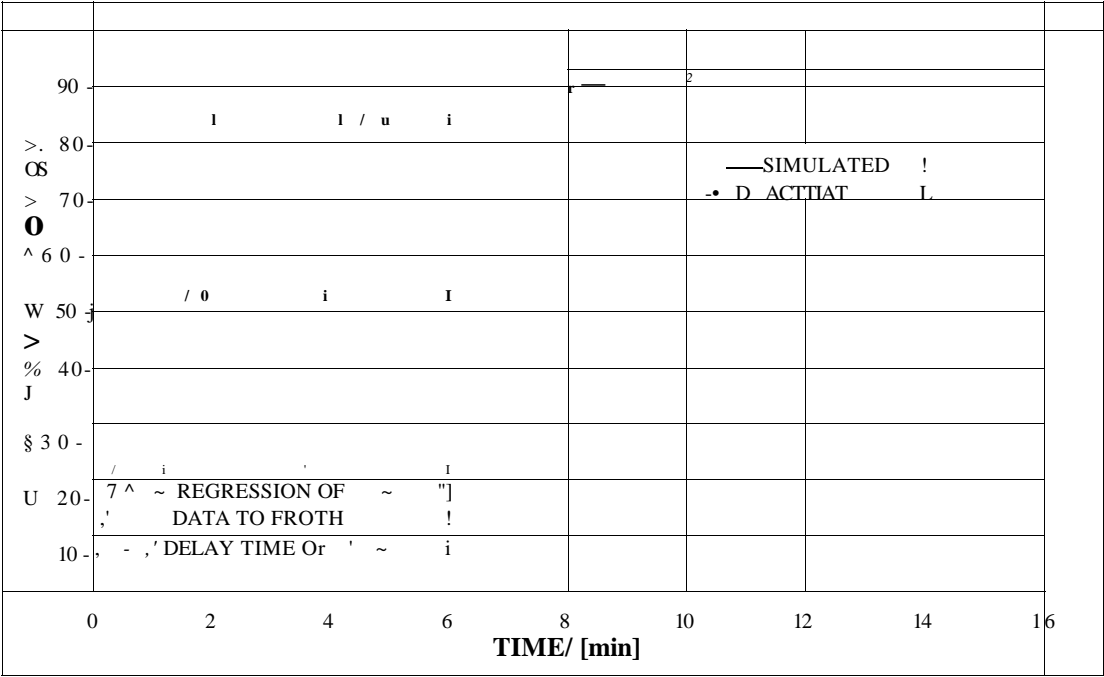


Figure II—24. Cumulative recovery—time profile for SBFA, with a recycle rate of 3.13 Lmin" .

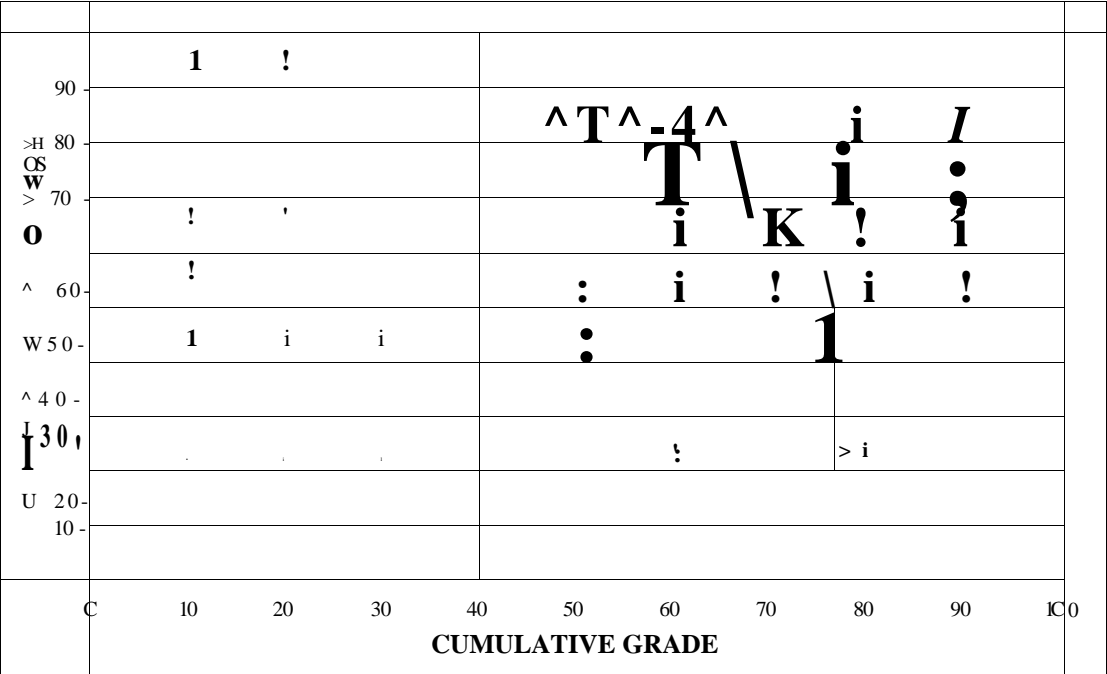
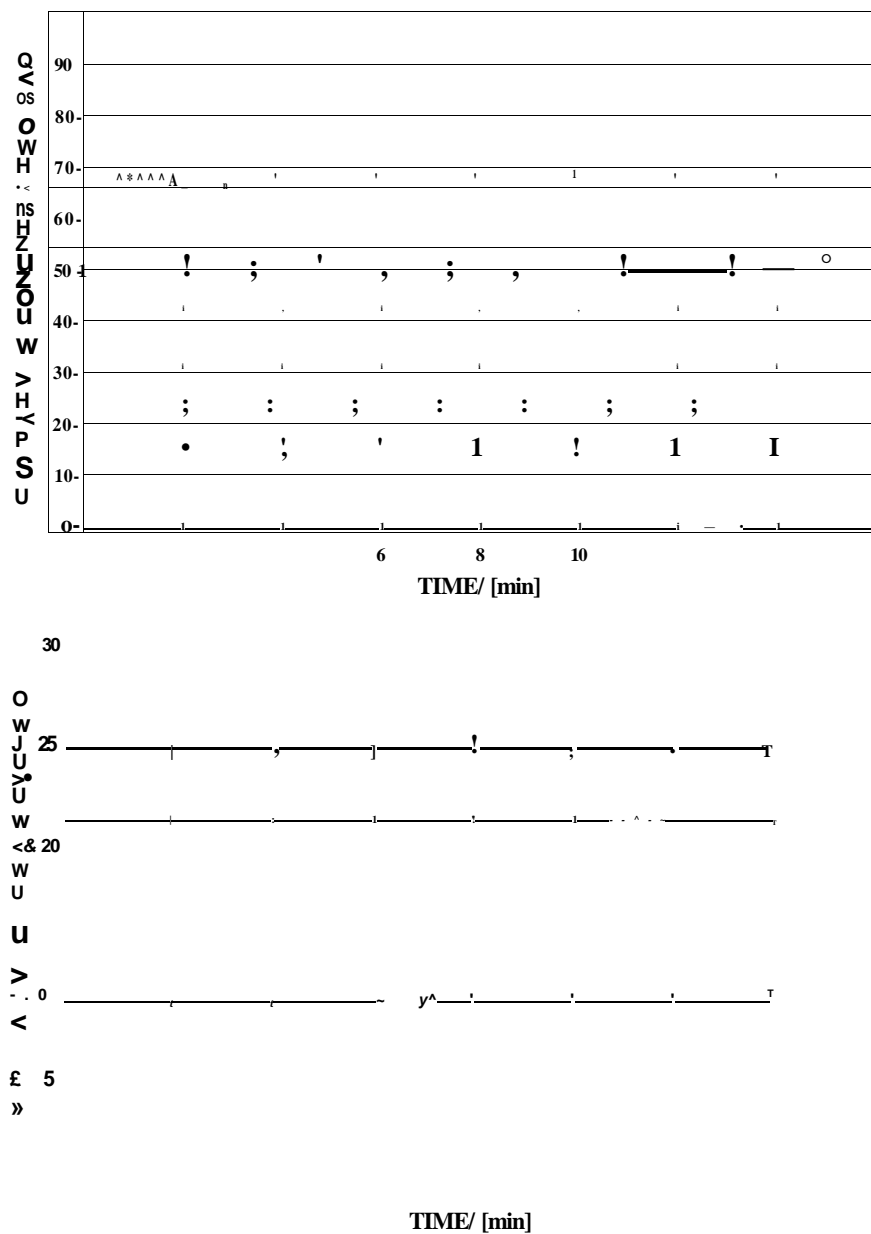


Figure 11—25. Cumulative recovery—grade curve for SBFA at a duplicate test, with a recycle rate of 3.13 L-min"





**Figurell—26.** Variation in the cumulative concentrate grade with the recycle of gangue for a recycle rate of 3.13 L-min"

**Table 11—60. Summary of the SBFA model input parameters for a duplicate test with a recycle rate of 3.13 L-min<sup>-1</sup>**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	94.300
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	94.300
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	49.479
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	44.821
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.757
<b>b</b>	Startup time a, related to second in SBFA	min	1.973
Rf,1	Froth recovery for cell one	—	0.974
Rf,2	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
n <sub>1</sub>	Flotation kinetic scaling parameter related to cell one		0.885
n <sub>2</sub>	Flotation kinetic scaling parameter related to cell two		2.998

Table II—61. Summary of data for a duplicate test with a recycle rate of 3.13 L-min<sup>-1</sup> in the SBFA

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ [-1]	Simulated Limestone Recovery/ [-1]
0.50	23.50	4.80	18.70	79.57	19.83	19.82
2.00	39.70	9.50	30.20	77.37	51.86	45.83
3.00	20.50	5.80	14.70	75.99	67.44	63.98
5.00	27.20	14.00	13.20	69.25	81.44	84.47
7.00	13.30	8.00	5.30	66.10	87.06	91.84
10.00	13.70	9.00	4.70	62.94	92.05	94.66
15.00	33.00	30.00	3.00	52.55	95.23	95.20
<b>Tailings</b>	2573.00	2568.00	4.50	—	—	—

Table 11—62. Summary of model parameters for a duplicate test with a recycle rate of 3.13 L-min<sup>-1</sup>, after using solver

Parameter	Units	Model estimate
<i>R</i> <sub>MAX</sub>	—	95.228
*1	min <sup>-1</sup>	0.612
<i>k</i> <sub>2</sub>	min <sup>-1</sup>	0.966
<i>V</i>	min	0.000
SER	—	4.176
<i>r</i> <sup>2</sup>	—	0.981
Residual	—	0.009

Table 11-63. Summary of cumulative gangue recycled for a duplicate recycle rate of 3.13 L-min<sup>-1</sup>

Time/ [min]	Mass Recycled/ [gl]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	32.64	32.64	1.23
6.00	77.95	110.58	4.17
7.00	50.20	160.79	6.07
8.00	31.62	192.41	7.26
9.00	26.48	218.88	8.26
10.00	60.09	278.97	10.53
12.00	92.93	371.90	14.04
13.00	58.92	430.82	16.26
14.00	36.13	466.95	17.63
15.00	79.45	546.40	20.63

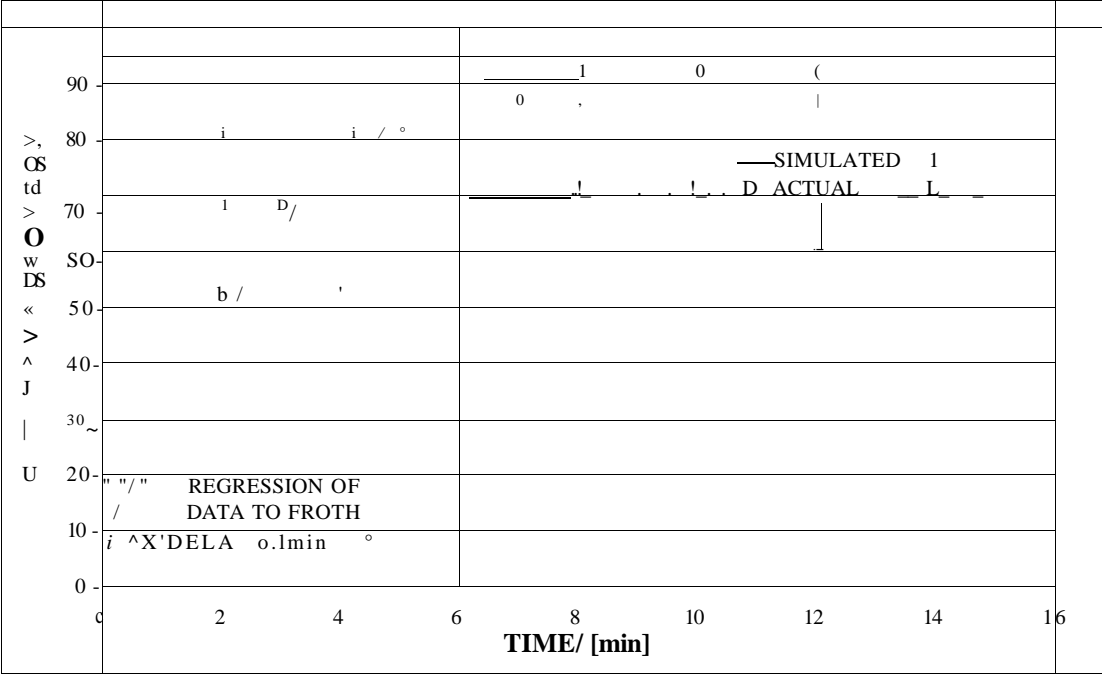


Figure 27—27. Cumulative recovery—time profile for SBFA at a duplicate test, with a recycle rate of 3.13 L-min"

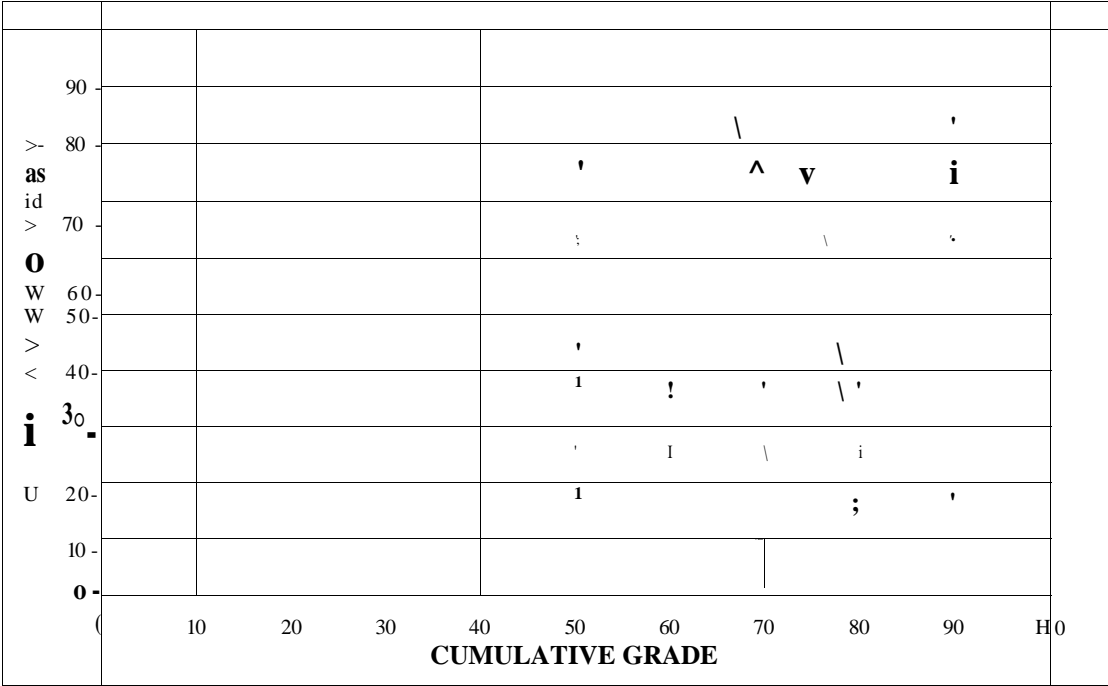
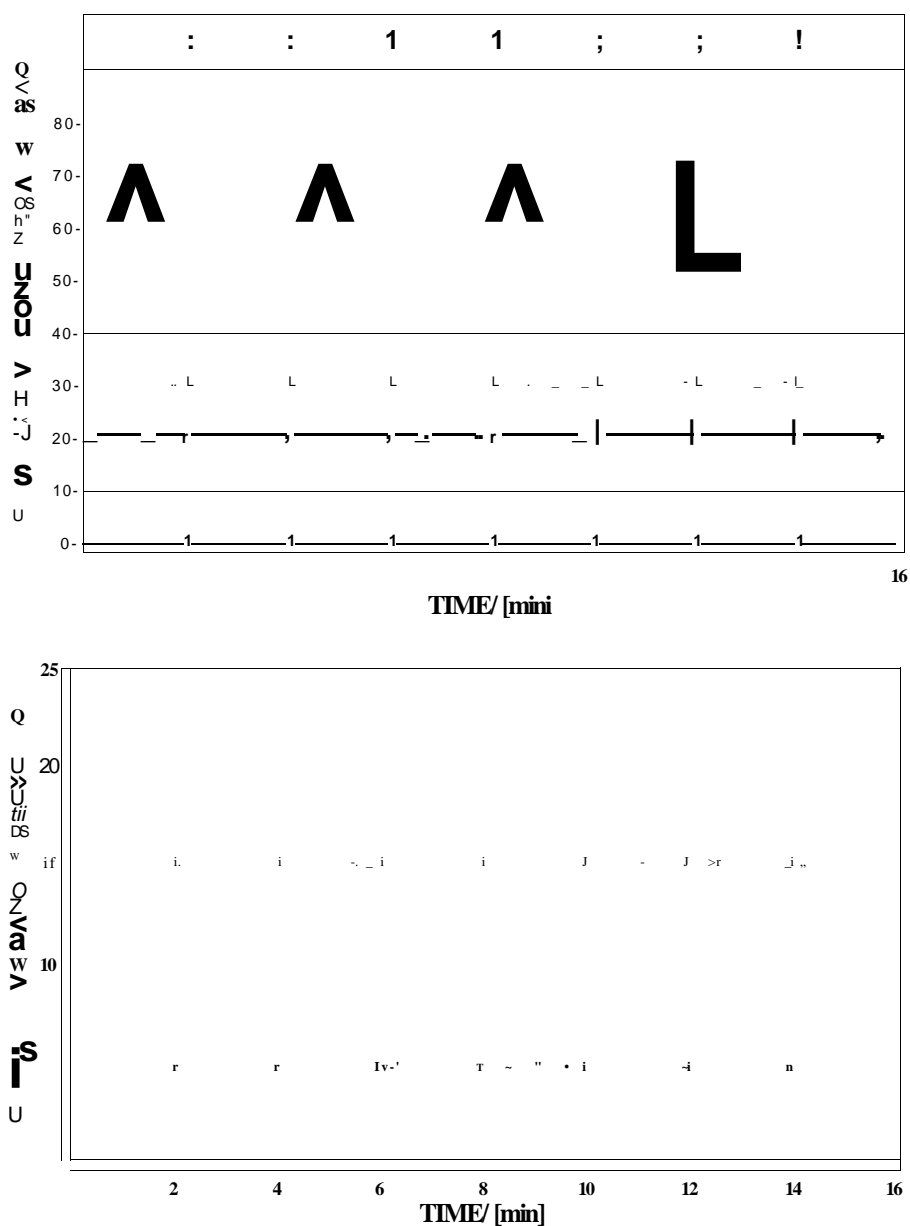


Figure 28—28. Cumulative recovery—grade curve for SBFA at a duplicate test, with a recycle rate of 3.13 L-min"



**Figure II—29.** Variation in the cumulative concentrate grade with the recycle of gangue for a duplicate test at a recycle rate of 3.13 L·min<sup>-1</sup>.

II.VIII Summary of data for SBFA with the variable froth height for cell One

**Table 11—64. Summary of the SBFA model input parameters for  $H$  of 17.00 mm in cell one of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	81.200
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	81.200
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	35.522
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	45.678
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.389
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.914
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
<b>ill</b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>"H<sub>2</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—65. Summary of data for *H* of 17.00 mm in cell one of the SBFA

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ <b>H</b>
0.50	42.10	10.80	31.30	74.35	38.55	38.80
2.00	52.70	19.60	33.10	67.93	79.31	65.52
3.00	9.10	5.20	3.90	65.74	84.11	76.84
5.00	14.90	10.20	4.70	61.45	89.90	89.73
7.00	3.30	2.30	1.00	60.61	91.13	95.49
10.00	8.90	7.00	1.90	57.94	93.47	98.69
15.00	4.80	4.00	0.80	56.48	94.46	99.84
<b>Tailings</b>	2631.00	2626.00	4.50	—	—	—

Table 11—66. Summary of model parameters for *H* of 17.00 mm in cell one of the SBFA

Parameter	Units	Model estimate
<sup>^</sup> MAX	—	100.000
<b><i>h</i></b>	min <sup>-1</sup>	0.414
<b><i>h</i></b>	min <sup>-1</sup>	0.916
<b><i>v</i></b>	min	0.000
SER	—	7.977
<b>?</b>	—	0.864
Residual	—	0.032

Table II—67. Summary of cumulative gangue recycled for *H* of 17.00 mm in cell one of the SBFA

Time/ [min]	Mass Recycled/ [g]	Cumulative Ma Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	18.70	18.70	0.70
2.00	81.45	100.15	3.73
3.00	39.10	139.25	5.19
5.00	39.00	178.25	6.64
7.00	171.20	349.45	13.01
10.00	119.40	468.85	17.46
15.00	100.00	568.85	21.19





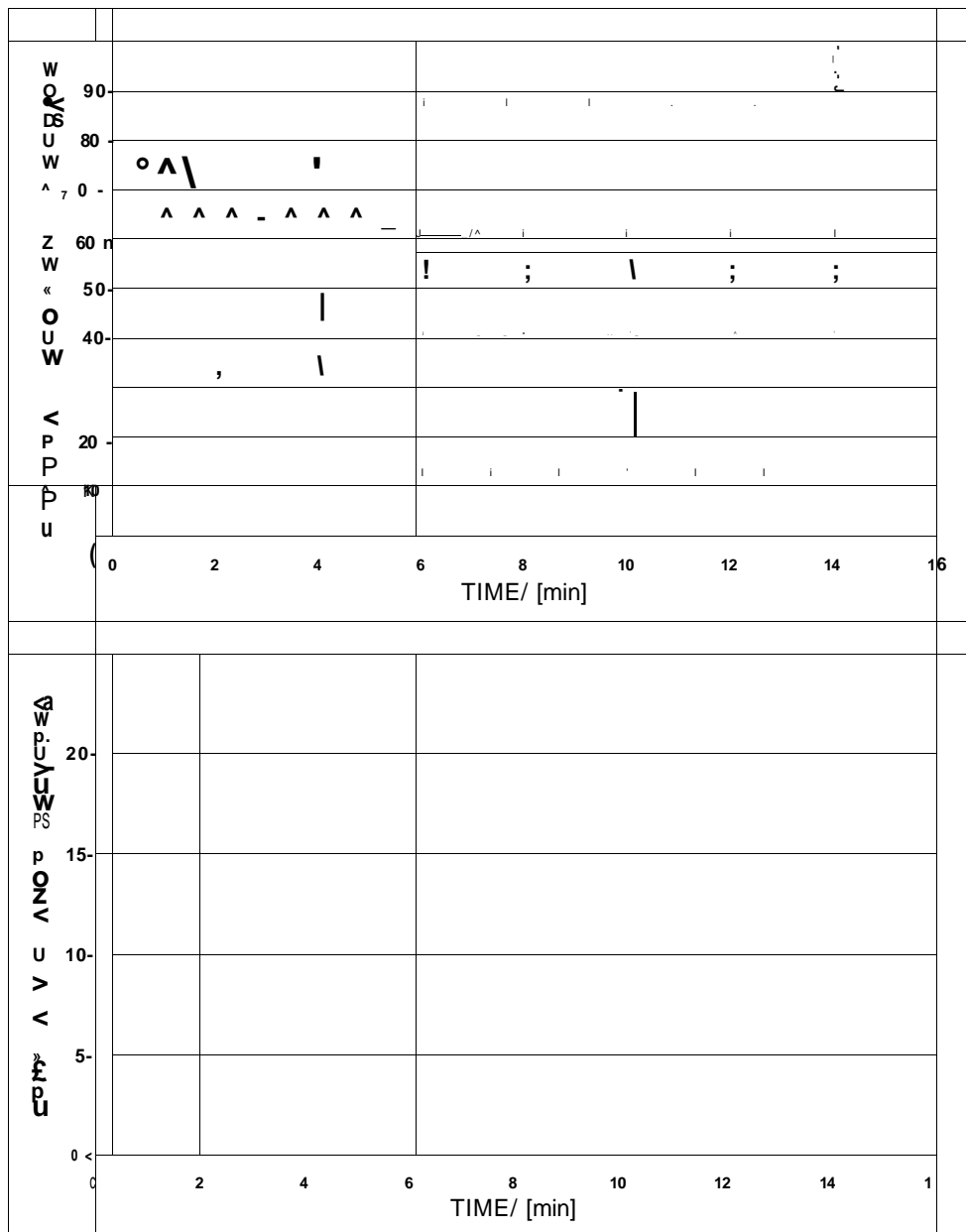


Figure 11—32 Variation in the cumulative concentrate grade at //of 17.00 mm in cell one of the SBFA.

**Table 11—68. Summary of the SBFA model input parameters for a duplicate test at *H* of 17.00 mm in cell one of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	74.200
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	74.200
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	28.600
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	45.600
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.146
R <sub>f,1</sub>	Froth recovery for cell one	—	0.914
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.17.6
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
n <sub>1</sub>	Flotation kinetic scaling parameter related to cell one		0.885
T <sub>12</sub>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—69. Summary of data for a duplicate test at  $H$  of 17.00 mm in cell one of the SBFA

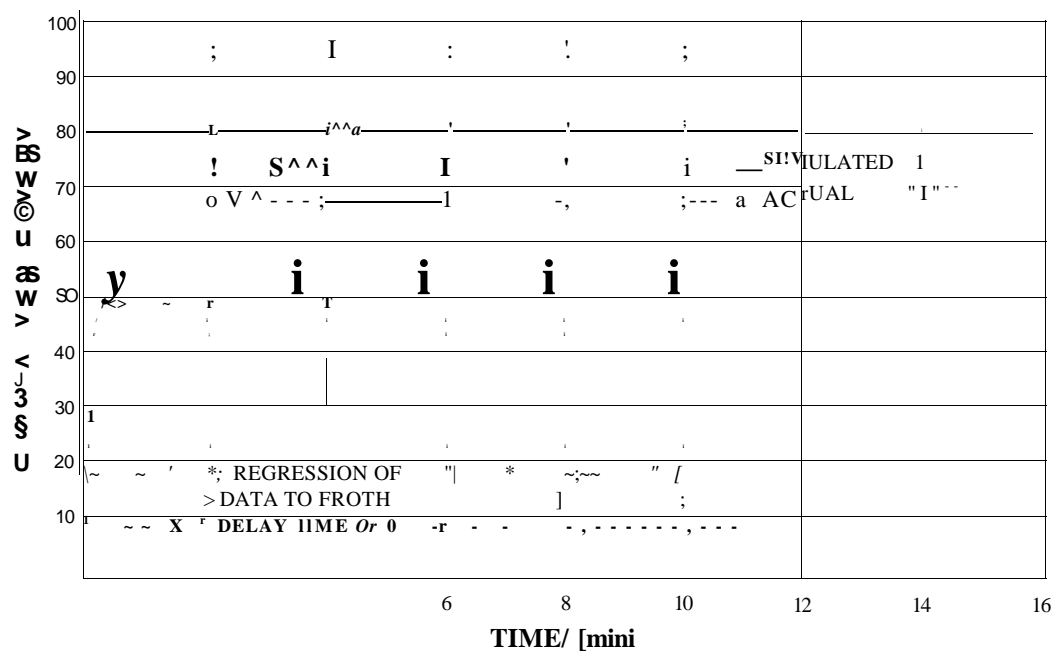
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ [-]	Simulated Limestone Recovery/ <b>H</b>
0.50	50.40	13.30	37.10	73.61	50.00	50.89
2.00	26.60	13.70	12.90	64.94	67.39	64.21
3.00	19.70	14.50	5.20	57.08	74.39	72.34
5.00	13.10	9.00	4.10	54.01	79.92	82.78
7.00	16.70	13.20	3.50	49.64	84.64	87.69
10.00	21.20	18.70	2.50	44.21	88.01	90.43
15.00	38.80	36.20	2.60	36.41	91.51	91.38
<b>Tailings</b>	2265.00	2258.00	6.30	—	—	—

Table 11—70. Summary of model parameters for a duplicate test at  $H$  of 17.00 mm in cell one of the SBFA

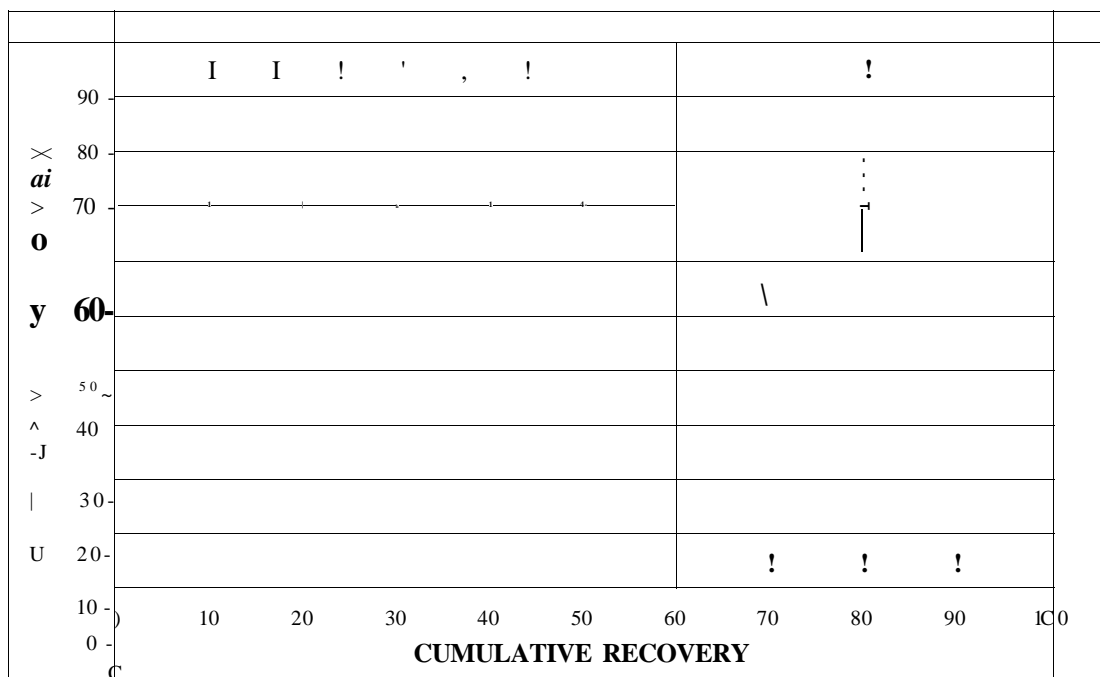
Parameter	Units	Model estimate
$\wedge_{MAX}$	—	91.509
<b><math>h</math></b>	<b>min<sup>"1</sup></b>	0.425
$k_2$	<b>min<sup>"</sup></b>	0.939
$v$	<b>min</b>	0.000
SER	—	2.775
$r^2$	—	0.970
Residual	—	0.024

Table 11—71. Summary of cumulative gangue recycled for a duplicate test at  $H$  of 17.00 mm in cell one of the SBFA

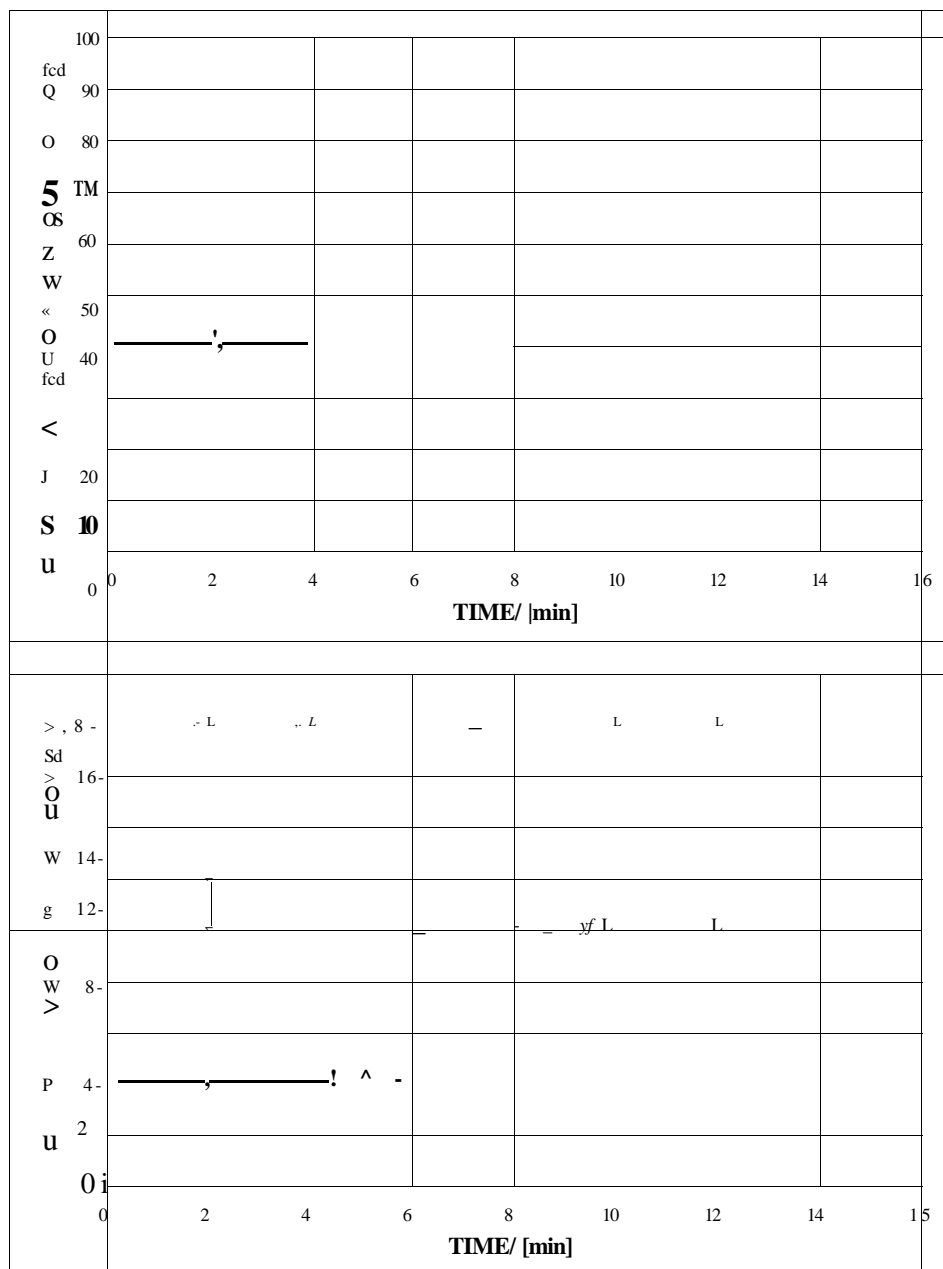
Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	39.03	39.03	1.64
7.00	123.62	162.65	6.84
8.00	25.44	188.09	7.91
9.00	32.38	220.48	9.28
13.00	167.88	388.36	16.34
15.00	44.54	432.89	18.21



**Figure 11—33.** Cumulative recovery—time profile for a duplicate test at  $H$  of 17.00 mm in cell one of the SBFA.



**Figure 11—34.** Cumulative recovery—grade curve for a duplicate test at  $H$  of 17.00 mm in cell one of the SBFA.



**Figure 11—35.** Variation in the cumulative concentrate grade for a duplicate test at  $H$  of 17.00 mm in cell one of the SBFA.

**Table 11—72. Summary of the SBFA model input parameters for  $H$  of 29.00 mm in cell one of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	86.900
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	86.900
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	39.379
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	47.521
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.500
Rf <sub>1</sub>	Froth recovery for cell one	—	0.858
Rf <sub>2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
<b>*11</b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>*12</b>	Flotation kinetic scaling parameter related to cell two		2.998

**Table II—73. Summary of data for *H* of 29.00 mm in cell one of the SBFA**

<b>Time/ [min]</b>	<b>Mass Before Acid Dissolution/ [g]</b>	<b>Mass After Acid Dissolution/ [g]</b>	<b>Mass Limestone/ [g]</b>	<b>Cumulative concentrate Grade/ [-]</b>	<b>Cumulative Limestone Recovery/ <b>H</b></b>	<b>Simulated Limestone Recovery/ [-1]</b>
0.50	31.00	7.30	23.70	76.45	27.27	26.85
2.00	56.30	16.40	39.90	72.85	73.19	63.92
3.00	18.90	7.50	11.40	70.62	86.31	76.74
5.00	16.90	12.20	4.70	64.74	91.72	89.96
7.00	5.10	3.20	1.90	63.65	93.90	95.56
10.00	9.60	7.60	2.00	60.67	96.20	98.68
15.00	5.40	4.80	0.60	58.80	96.89	99.82
<b>Tailings</b>	2055.00	2052.00	2.70	—	—	—

**Table 11—74. Summary of model parameters for *H* of 29.00 mm in cell one of the SBFA**

<b>Parameter</b>	<b>Units</b>	<b>Model estimate</b>
•KMAX	—	100.000
<i>kx</i>	min <sup>-1</sup>	0.402
<b><i>h</i></b>	min"	0.948
<i>v</i>	min	0.000
SER	—	6.296
<i>r</i> <sup>2</sup>	—	0.947
Residual	—	0.020

**Table 11—75. Summary of cumulative gangue recycled for *H* of 29.00 mm in cell one of the SBFA**

<b>Time/ [min]</b>	<b>Mass Recycled/ [g]</b>	<b>Cumulative Mass Recycled/</b>	<b>Percentage Recycled, relative to total gangue added</b>
0.00	0.00	0.00	0.00
0.50	9.94	9.94	0.47
2.00	54.31	64.24	3.04
3.00	70.11	134.36	6.36
5.00	93.80	228.15	10.81
7.00	28.23	256.39	12.15
10.00	240.06	496.45	23.52
15.00	40.34	536.79	25.43

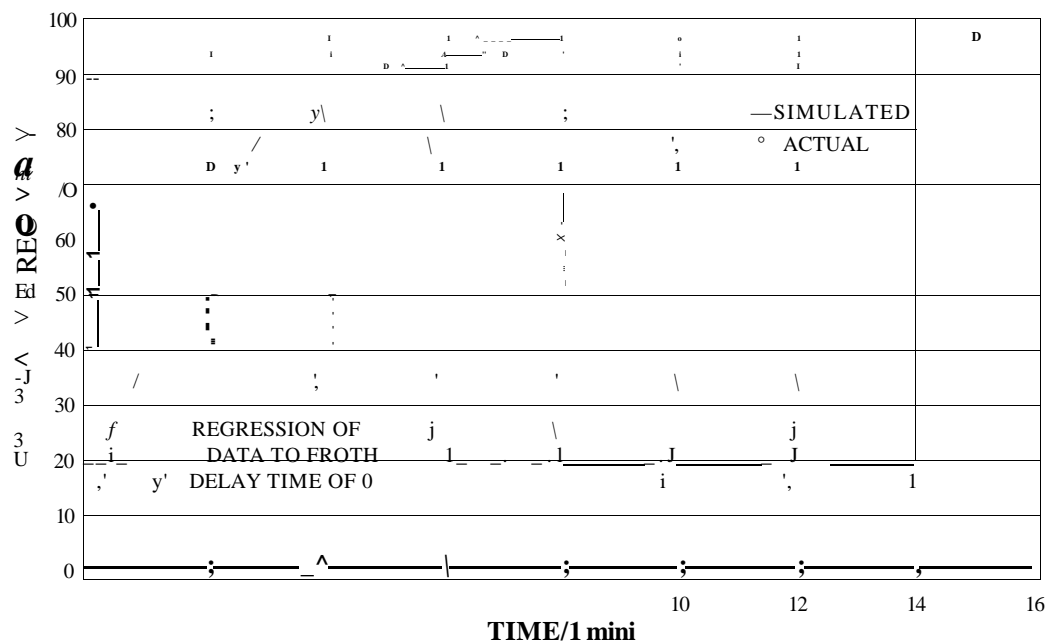


Figure 11—36. Cumulative recovery—time profile at  $H$  of 29.00mm in cell one of the SBFA.

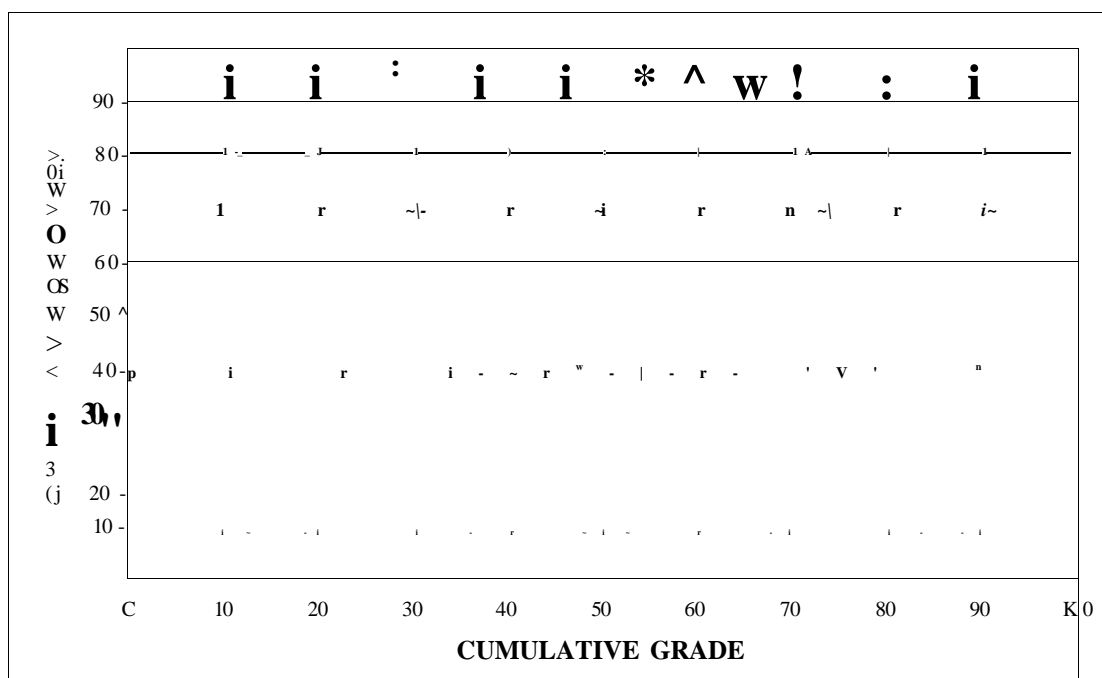


Figure 11—37. Cumulative recovery—grade curve for at  $H$  of 29.00 mm in cell one of the SBFA.



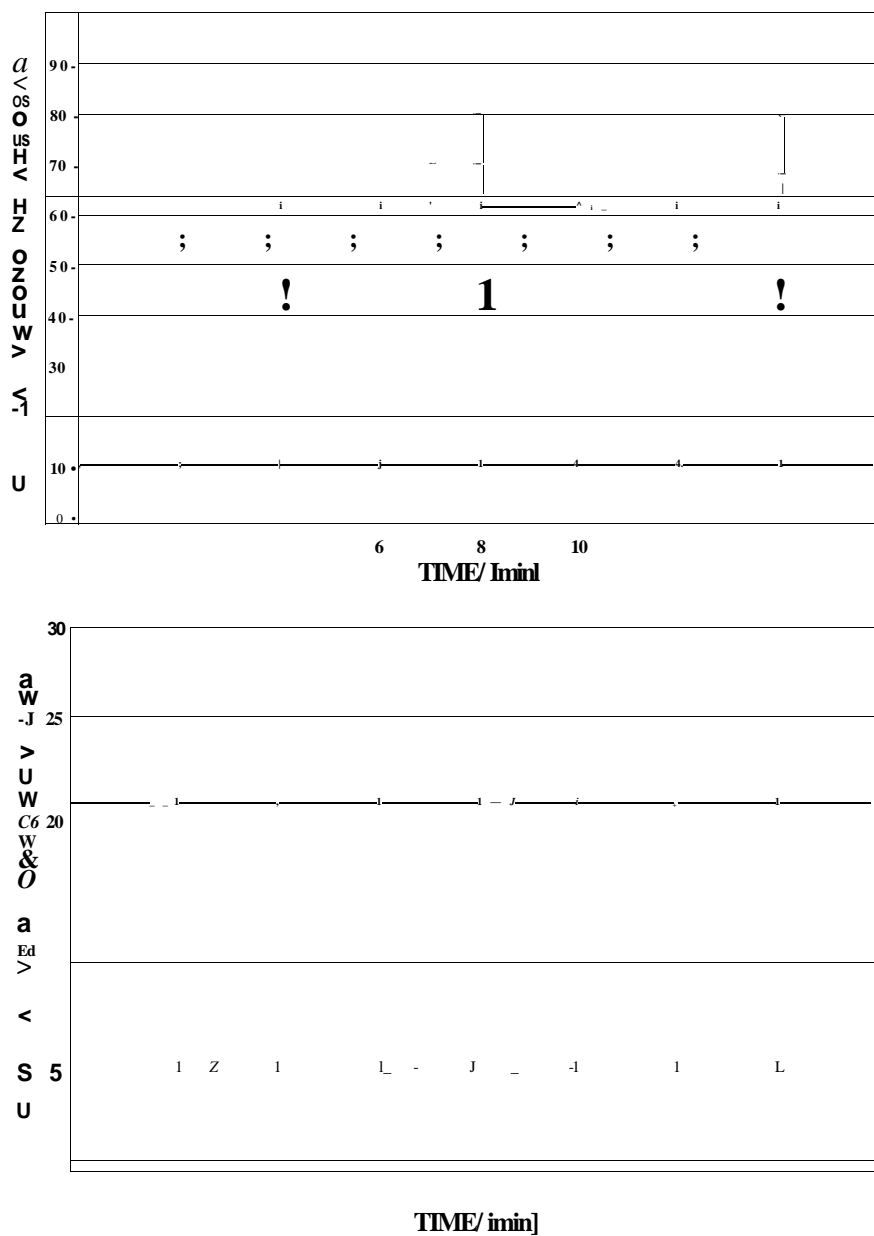


Figure 11—38 Variation in the cumulative concentrate grade at//of 29.00 mm in cell one of the SBFA.

**Table 11—76. Summary of the SBFA model input parameters for a duplicate test at  $H$  of 29.00 mm in cell one of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	94.200
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	94.200
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	42.007
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	52.193
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.400
R <sub>f,1</sub>	Froth recovery for cell one	—	0.858
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
T <sub>11</sub>	Flotation kinetic scaling parameter related to cell one		0.885
T <sub>12</sub>	Flotation kinetic scaling parameter related to cell two		2.998

Table II—77. Summary of data for a duplicate test at  $H$  of 29.00mm in cell one of the SBFA

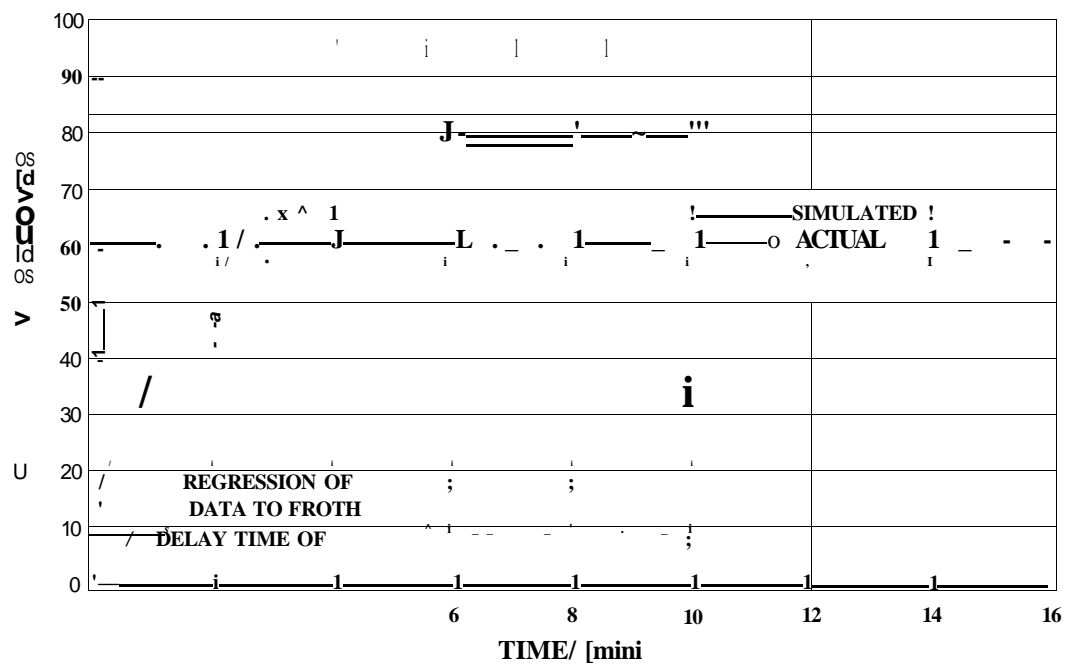
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ <b>H</b>
0.50	32.00	8.30	23.70	74.06	25.16	26.10
2.00	35.40	14.70	20.70	65.88	47.13	55.46
3.00	16.80	6.30	10.50	65.20	58.28	65.69
5.00	26.50	10.60	15.90	63.96	75.16	76.17
7.50	10.20	6.30	3.90	61.79	79.30	80.52
10.00	7.60	5.30	2.30	59.92	81.74	82.85
15.00	9.30	7.40	1.90	57.26	83.76	83.65
<b>Tailings</b>	2363.00	2346.00	15.30	—	—	—

Table II—78. Summary of model parameters for a duplicate test at  $H$  of 29.00 mm in cell one of the SBFA

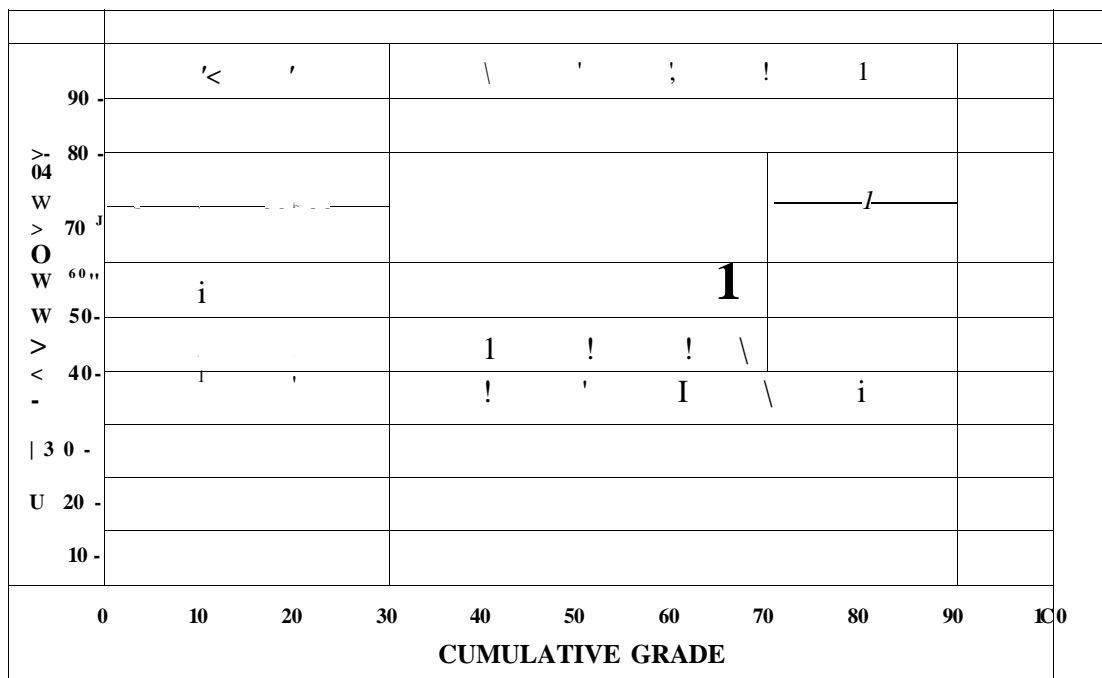
Parameter	Units	Model estimate
-KMAX	—	83.758
*1	min <sup>"1</sup>	0.422
<b><i>h</i></b>	min <sup>"1</sup>	0.993
<i>v</i>	min	0.000
SER	—	5.076
<i>r</i> <sup>2</sup>	—	0.957
Residual	—	0.038

Table 11—79. Summary of cumulative gangue recycled for a duplicate test at  $H$  of 29.00 mm in cell one of the SBFA

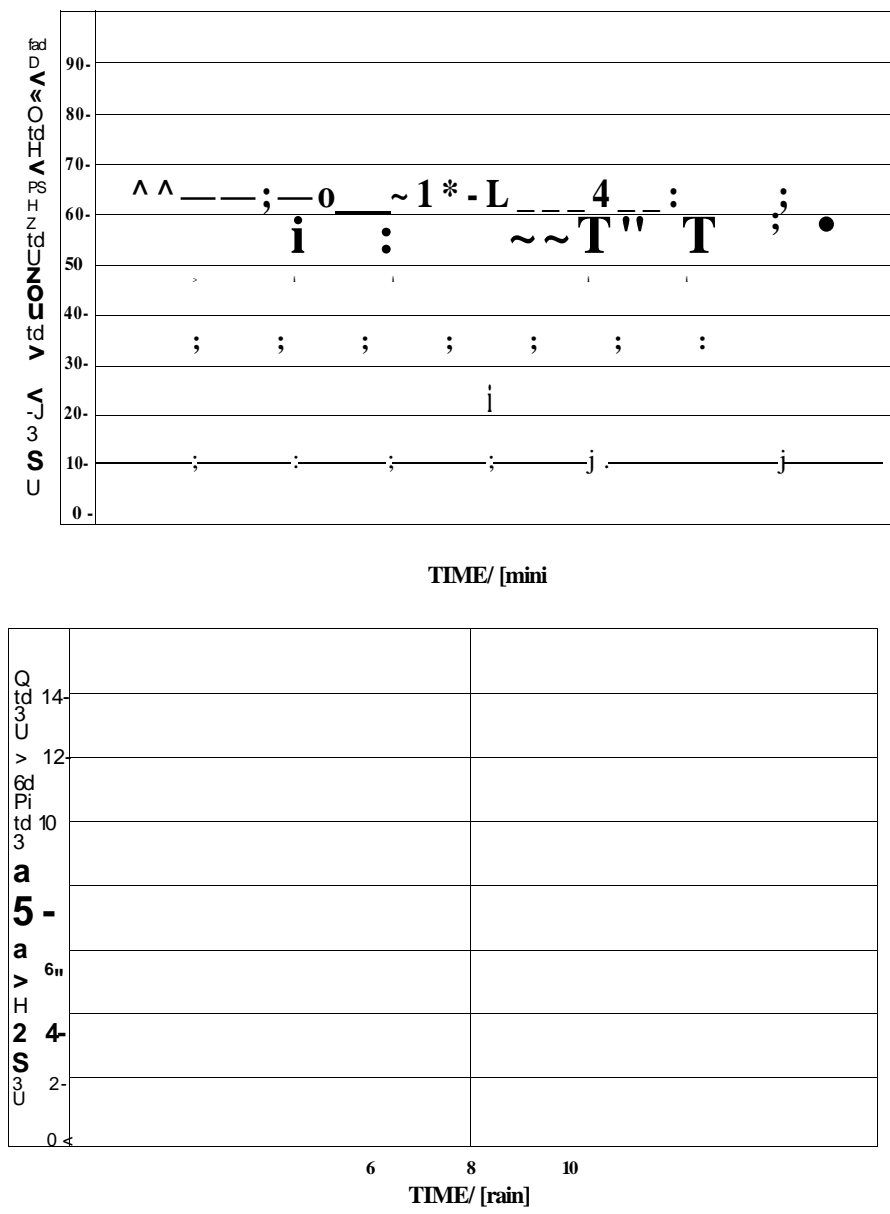
Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	29.70	29.70	1.23
7.00	94.23	123.93	5.15
8.00	19.38	143.31	5.96
9.00	24.69	168.00	6.99
13.00	128.10	296.10	12.31
15.00	33.92	330.02	13.72



**Figure 11—39.** Cumulative recovery—time profile for a duplicate test at  $H$  of 29.00 mm in cell one of the SBFA.



**Figure 11—40.** Cumulative recovery—grade curve for a duplicate test at  $H$  of 29.00 mm in cell one of the SBFA.



**Figure 11—41.** Variation in the cumulative concentrate grade for a duplicate test at *H* of 29.00 mm in cell one of the SBF A.

**Table 11—80. Summary of the SBFA model input parameters for  $H$  of 41.00 mm in cell one of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	95.200
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	95.200
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	38.336
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	56.864
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.557
<b>b</b>	Startup time a, related to second in SBFA	min	1.777
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.805
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
	Flotation kinetic scaling parameter related to cell one		0.885
112	Flotation kinetic scaling parameter related to cell two		2.998

**Table II—81. Summary of data for  $H$  of 41.00 mm in cell one of the SBFA**

<b>Time/ [min]</b>	<b>Mass Before Acid Dissolution/ [g]</b>	<b>Mass After Acid Dissolution/ [g]</b>	<b>Mass Limestone/ [g]</b>	<b>Cumulative concentrate Grade/ [-]</b>	<b>Cumulative Limestone Recovery/ <b>H</b></b>	<b>Simulated Limestone Recovery/ <b>H</b></b>
0.50	32.00	8.30	23.70	74.06	24.89	24.64
2.00	35.40	14.70	20.70	65.88	46.64	53.25
3.00	17.80	6.30	11.50	65.20	58.72	63.97
5.00	26.50	10.60	15.90	63.96	75.42	75.41
7.50	10.20	6.30	3.90	61.79	79.52	80.28
10.00	7.60	5.30	2.30	59.92	81.93	82.90
15.00	9.30	7.40	1.90	57.26	83.93	83.80
<b>Tailings</b>	2363.00	2346.00	15.30	—	—	—

**Table 11—82. Summary of model parameters for  $H$  of 41.00mm in cell one of the SBFA**

<b>Parameter</b>	<b>Units</b>	<b>Model estimate</b>
$\bullet K_{MAX}$	—	83.929
$k_x$	min <sup>-1</sup>	0.423
$k_2$	min"	1.061
$v$	min	0.000
SER	—	3.819
$\frac{2}{r}$	—	0.976
Residual	—	0.044

**Table 11—83. Summary of cumulative gangue recycled for  $H$  of 41.00mm in cell one of the SBFA**

<b>Time/ [min]</b>	<b>Mass Recycled/ lg]</b>	<b>Cumulative Mass Recycled/ [g]</b>	<b>Percentage Recycled, relative to total gangue added</b>
0.00	0.00	0.00	0.00
3.00	39.03	39.03	1.62
7.00	123.62	162.65	6.76
8.00	25.44	188.09	7.82
9.00	32.38	220.48	9.17
13.00	167.88	388.36	16.15
15.00	44.54	432.89	18.00

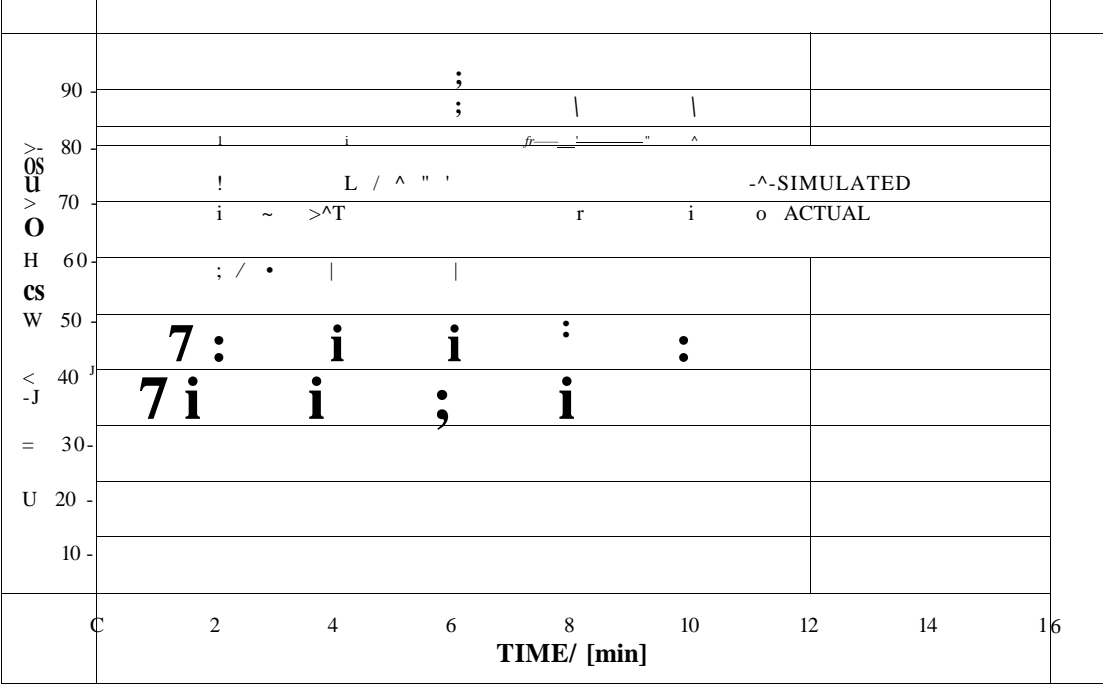


Figure 11-42. Cumulative recovery—time profile at//of 41.00mm in cell one of the SBFA.

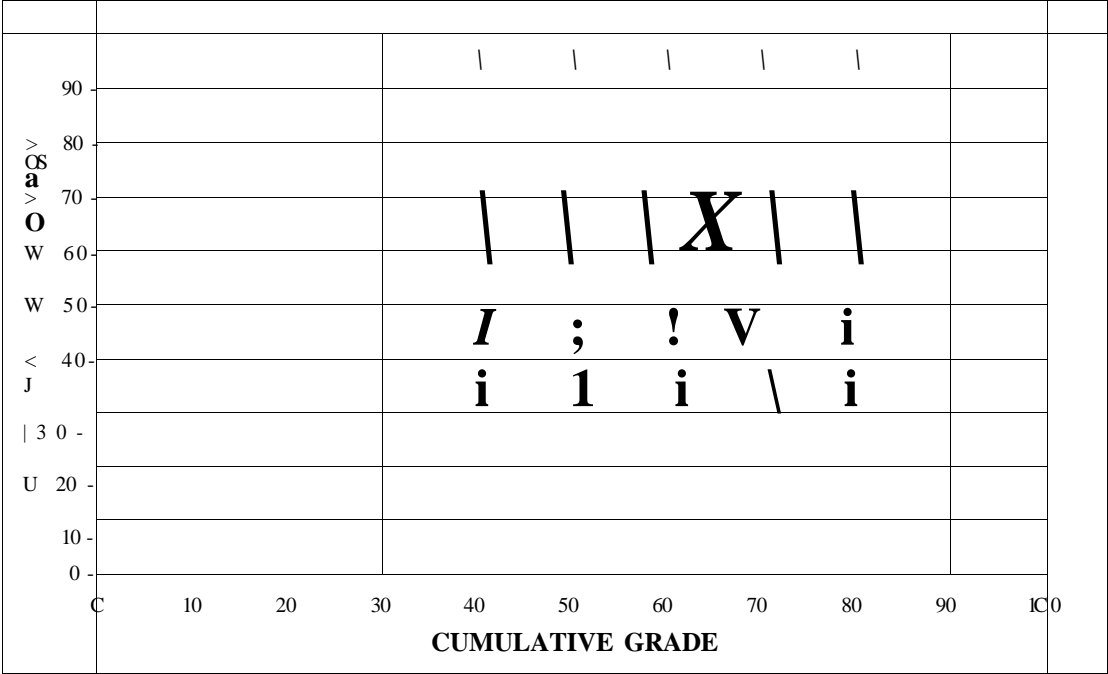


Figure 11-43. Cumulative recovery—grade curve at//of 41.00mm in cell one of the SBFA.



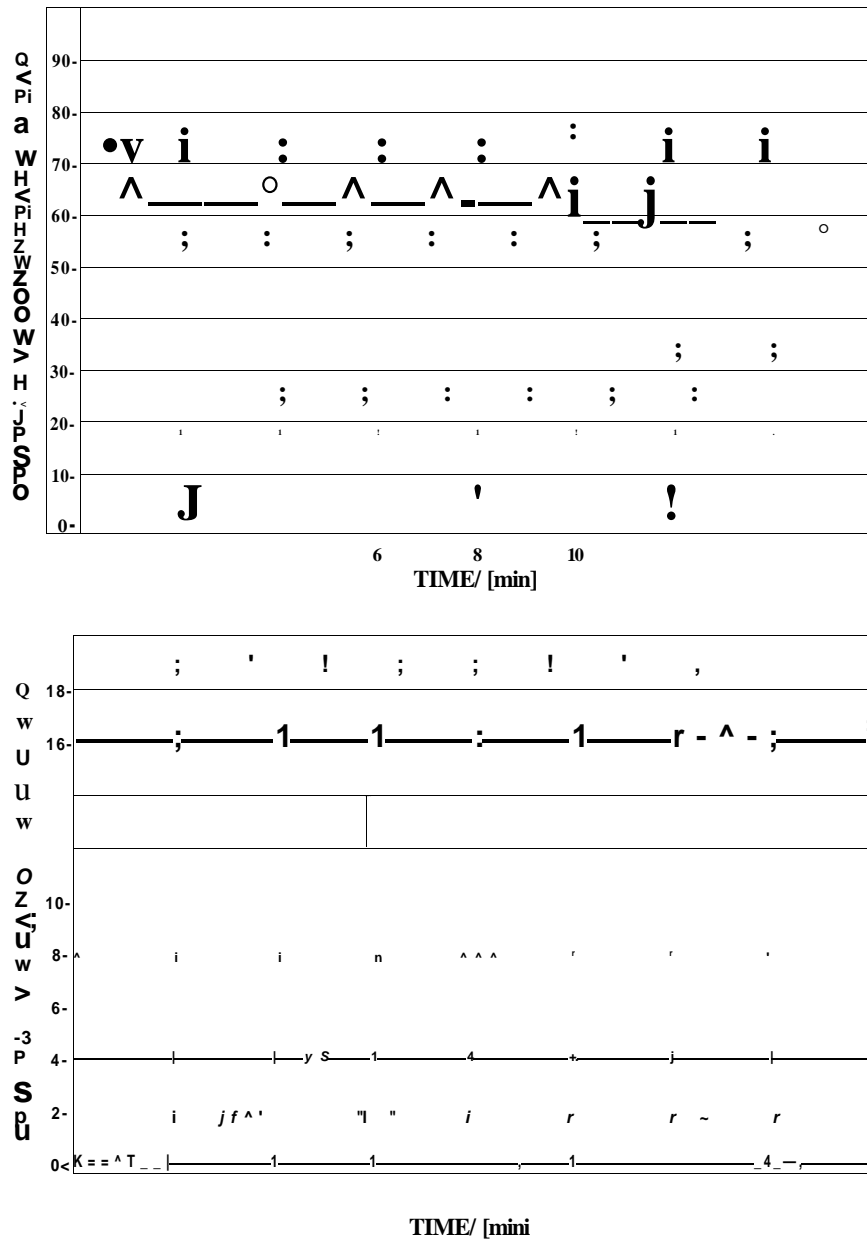


Figure 11—44. Variation in the cumulative concentrate grade *atH* of 41,00mm in cell one of the SBFA,

**Table 11—84. Summary of data for a duplicate test at  $H$  of 41.00 mm in cell one of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	77.600
M <sub>1</sub> (a)	Limestone in cell one at time a	grams	77.600
M <sub>1</sub> (b)	Limestone in cell one at time b	grams	34.347
M <sub>2</sub> (b)	Limestone in cell two at time b	grams	43.253
a	Startup time a, related to first cell in SBFA	min	0.000
b	Startup time a, related to second in SBFA	min	1.298
R <sub>f1</sub>	Froth recovery for cell one	—	0.805
R <sub>f2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
T <sub>11</sub>	Flotation kinetic scaling parameter related to cell one		0.885
112	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—85. Summary of data for a duplicate test at  $H$  of 41.00 mm in cell one of the SBFA

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ <b>H</b>
0.50	22.50	5.50	17.00	75.56	21.91	21.72
2.00	47.30	13.50	33.80	72.78	65.46	63.09
3.00	20.50	10.10	10.40	67.77	78.87	74.71
5.00	16.90	11.70	5.20	61.94	85.57	85.18
7.33	13.80	12.30	1.50	56.12	87.50	89.45
10.00	8.20	6.60	1.60	53.79	89.56	91.03
15.00	5.30	5.30	0.00	51.67	89.56	91.63
<b>Tailings</b>	2548.00	2539.00	8.10	—	—	—

Table II—86. Summary of model parameters for a duplicate test at  $H$  of 41.00 mm in cell one of the SBFA

Parameter	Units	Model estimate
$\lambda_{\text{MAX}}$	—	91.697
$kx$	min <sup>-1</sup>	0.450
$ki$	min <sup>-1</sup>	1.131
$v$	min	-0.227
SER	—	2.580
$r^2$	—	0.991
Residual	—	0.003

Table 11—87. Summary of cumulative gangue recycled for a duplicate test at  $H$  of 41.00 mm in cell one of the SBFA

Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	2.19	2.19	0.08
2.00	46.27	48.46	1.86
3.00	14.20	62.66	2.41
5.00	23.46	86.12	3.31
7.33	20.81	106.94	4.11
10.00	35.45	142.39	5.47
15.00	10.09	152.48	5.86

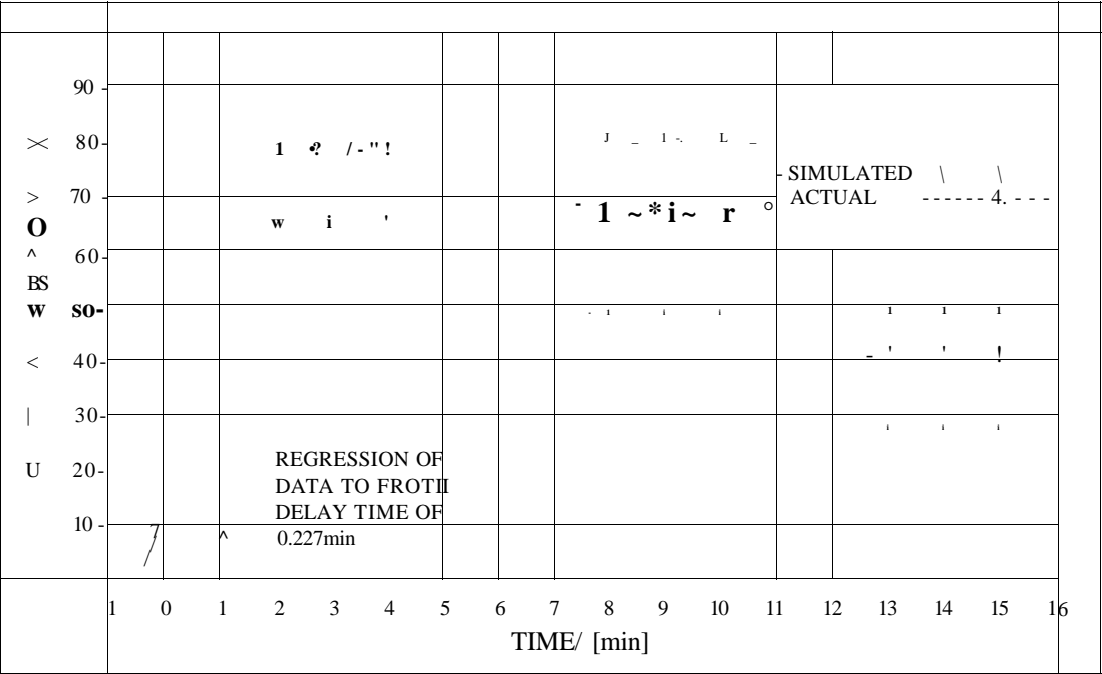


Figure 11-45. Cumulative recovery—time profile for a duplicate test at  $H$  of 41.00mm in cell one of the SBFA.

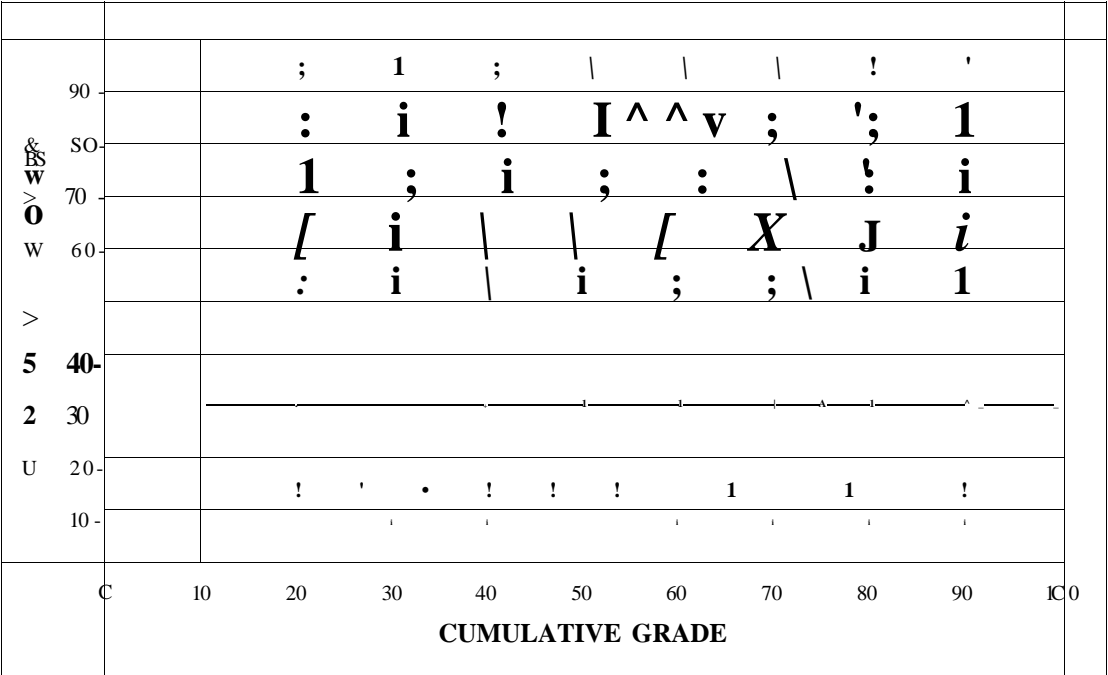
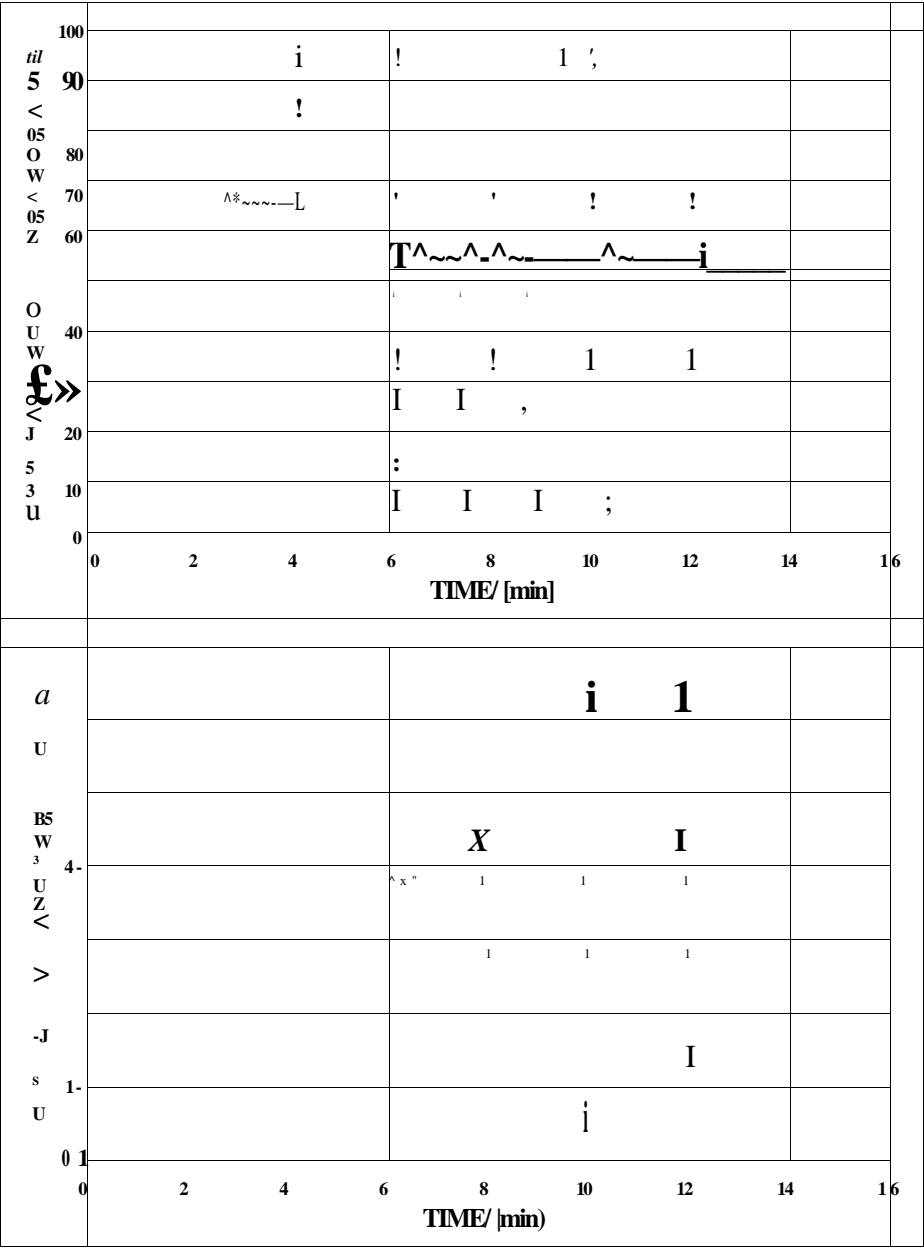


Figure 11-46. Cumulative recovery—grade curve for a duplicate test at  $H$  of 41.00mm in cell one of the SBFA.



**Figure 11—47.** Variation in the cumulative concentrate grade for a duplicate test at  $H$  of 41.00mm in cell one of the SBF A.

II.IX Summary of data for SBFA with the variable froth height for cell two

**Table 11—88. Summary of the SBFA model input parameters for  $H$  of 5.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	80.600
<b>M,(a)</b>	Limestone in cell one at time a	grams	80.600
<b>M,(b)</b>	Limestone in cell one at time b	grams	35.516
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	45.084
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.022
<b>b</b>	Startup time a, related to second in SBFA	min	1.339
Rf,i	Froth recovery for cell one	—	0.914
Rf,2	Froth recovery for cell two	—	0.922
A,	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Qi	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
Til	Flotation kinetic scaling parameter related to cell one		0.885
112	Flotation kinetic scaling parameter related to cell two		2.998

Table 11-89. Summary of data for  $H$  of 5.00 mm in cell two of the SBFA

Time/ [min]	Mass Before Acid Dissolution/ lg]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ [-1
0.50	39.40	11.10	28.30	71.83	35.11	36.24
2.00	37.20	16.50	20.70	63.97	60.79	63.63
3.00	21.50	11.10	10.40	60.55	73.70	74.72
5.00	22.50	15.30	7.20	55.22	82.63	86.81
7.33	12.50	7.20	5.30	54.02	89.21	92.40
10.00	9.80	7.20	2.60	52.13	92.43	94.57
15.00	19.00	16.50	2.50	47.56	95.53	95.43
<b>Tailings</b>	2564.00	2560.00	3.60	—	—	—

Table 11—90. Summary of model parameters at  $H$  of 5.00 mm in cell two of the SBFA

Parameter	Units	Model estimate
•RMAX	—	95.533
$kx$	min <sup>-1</sup>	0.441
$k_2$	min <sup>-1</sup>	0.975
$V$	min	0.000
SER	—	2.917
$r^I$	—	0.985
Residual	—	0.004

Table 11—91. Summary of cumulative gangue recycled at  $H$  of 5.00 mm in cell one of the SBFA

Time/ [min]	Mass Recycled/ lg]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	7.58	7.58	0.29
2.00	58.72	66.30	2.51
3.00	45.59	111.88	4.23
5.00	131.22	243.11	9.19
7.33	176.89	420.00	15.88
10.00	120.26	540.26	20.43
15.00	16.16	556.42	21.04

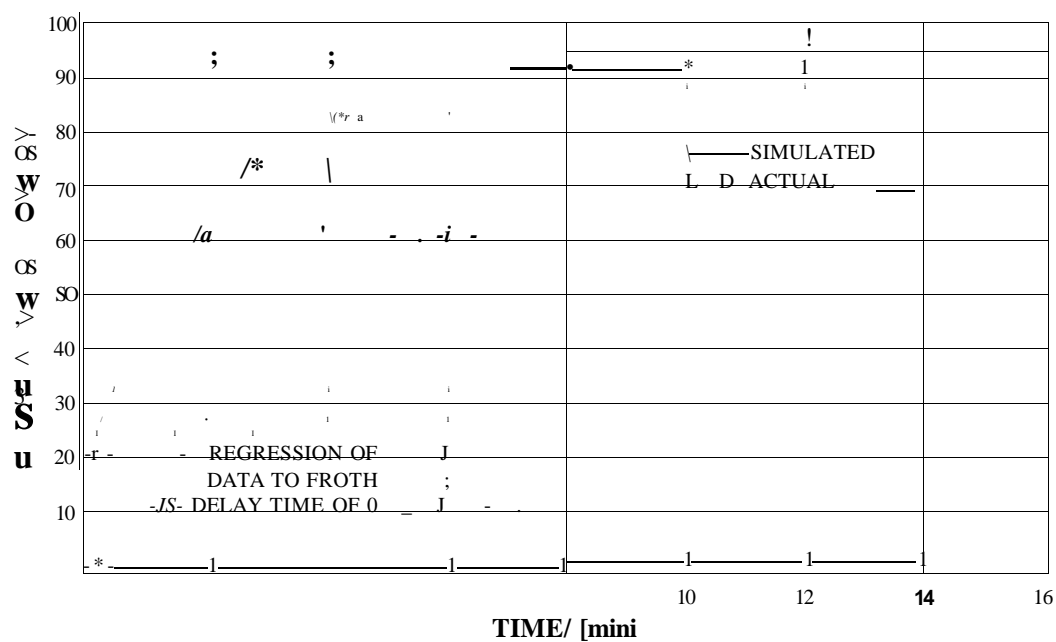


Figure 11—48. Cumulative recovery—time profile at  $H$  of 5.00 mm in cell two of the SBFA.

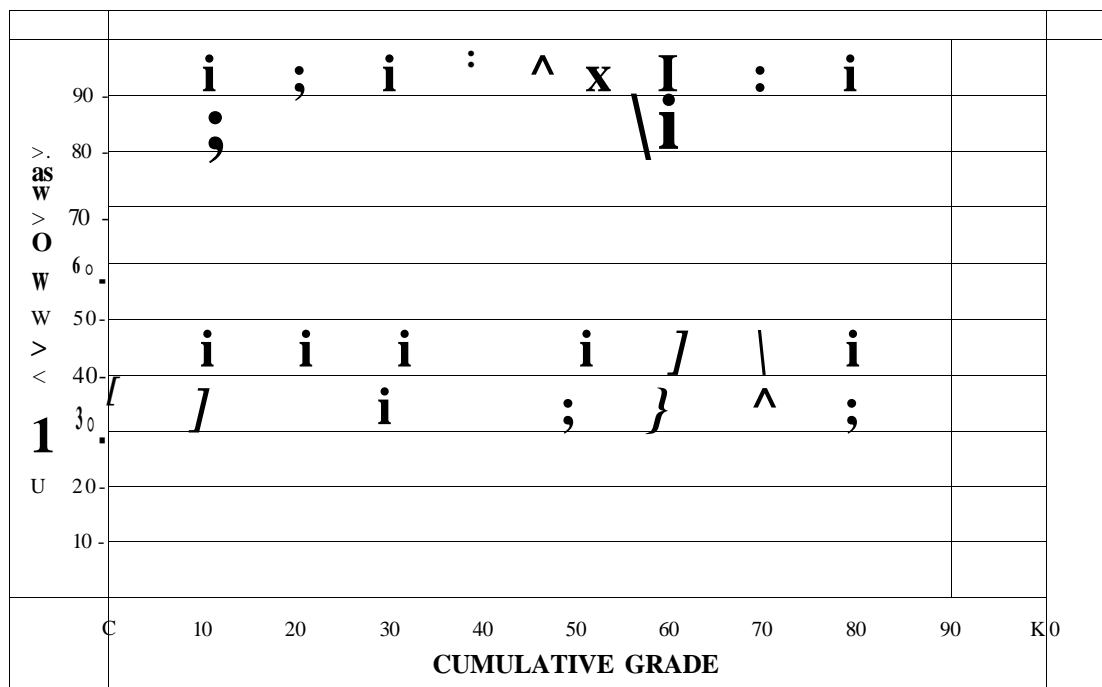
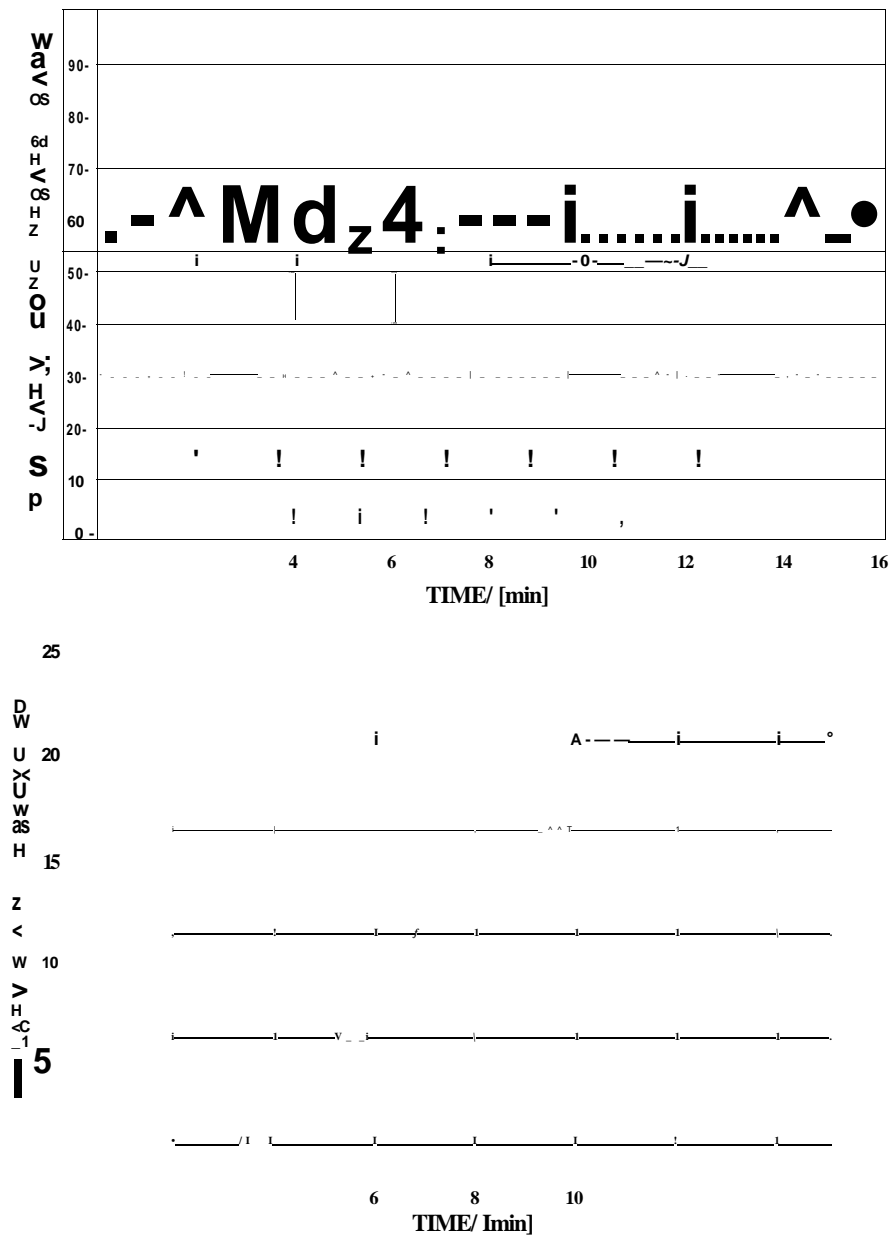


Figure II—49. Cumulative recovery—grade curve at  $H$  of 5.00 mm in cell one of the SBFA.





**Figure 11—50.** Variation in the cumulative concentrate grade at//of 5.00 mm in cell two of the SBFA.

**Table II—92. Summary of the SBFA model input parameters for a duplicate test at *H* of 5.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	85.200
M <sub>1</sub> (a)	Limestone in cell one at time a	grams	85.200
M <sub>1</sub> (b)	Limestone in cell one at time b	grams	35.969
M <sub>2</sub> (b)	Limestone in cell two at time b	grams	49.231
a	Startup time a, related to first cell in SBFA	min	1.184
b	Startup time a, related to second in SBFA	min	2.651
R <sub>f,1</sub>	Froth recovery for cell one	—	0.914
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	i <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	L <sup>3</sup> • min <sup>-1</sup>	0.049
T <sub>11</sub>	Flotation kinetic scaling parameter related to cell one		0.885
T <sub>12</sub>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—93. Summary of data for a duplicate test at  $H$  of 5.00 mm in cell two of the SBFA

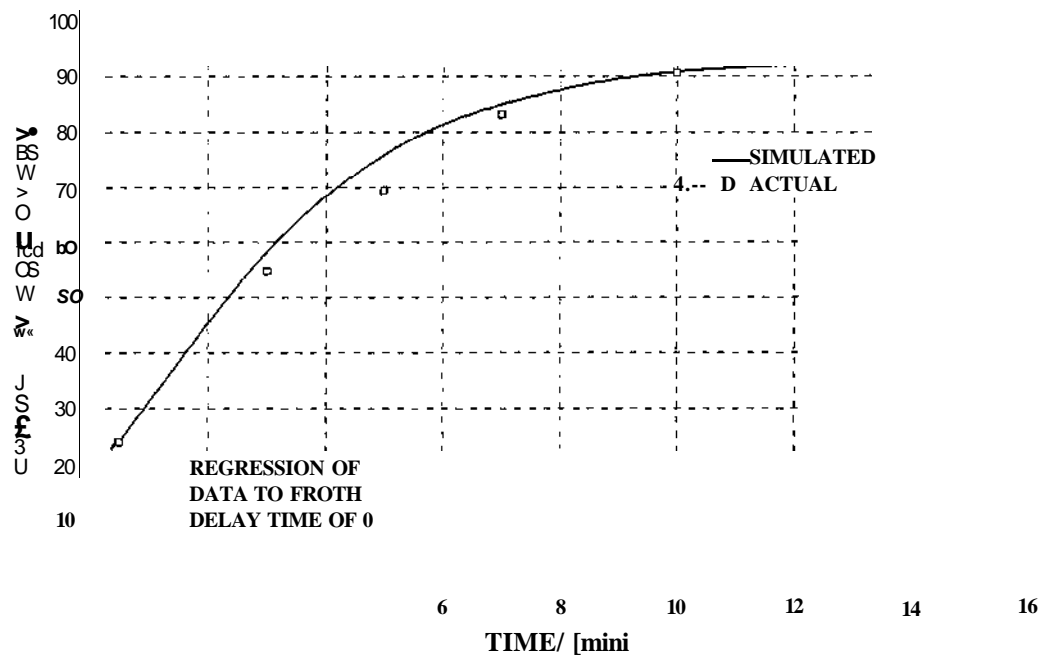
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ <b>H</b>
0.50	26.00	5.60	<b>20.40</b>	78.46	23.94	24.25
3.00	39.90	13.70	<b>26.20</b>	70.71	54.69	58.30
5.00	19.00	6.50	<b>12.50</b>	69.61	69.37	75.83
7.50	36.30	24.50	<b>11.80</b>	58.50	83.22	85.01
10.00	21.60	15.30	6.30	54.06	90.61	90.81
15.00	35.00	32.40	2.60	44.88	93.66	93.22
<b>Tailings</b>	2426.00	2420.00	5.40	—	—	—

Table 11—94. Summary of model parameters for a duplicate test at  $H$  of 5.00 mm in cell two of the SBFA

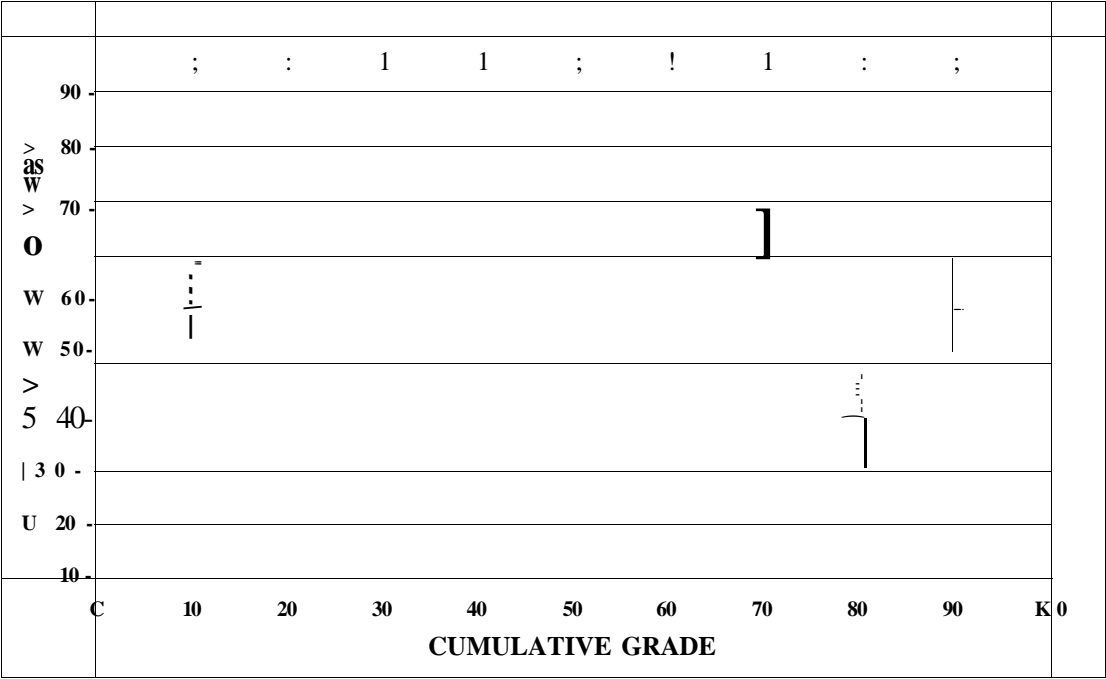
Parameter	Units	Model estimate
-KMAX	—	93.662
$k $	min <sup>-1</sup>	0.374
$h$	min <sup>-1</sup>	0.827
$v$	min	0.000
SER	—	3.819
$r^2$	—	0.983
<b>Residual</b>	—	0.006

Table II—95. Summary of cumulative gangue recycled for a duplicate test at  $H$  of 5.00 mm in cell two of the SBFA

Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	47.32	47.32	1.88
7.00	163.15	210.46	8.36
8.00	35.85	246.31	9.78
9.00	57.74	304.05	12.08
13.00	134.55	438.60	17.42
15.00	75.09	513.69	20.40



**Figure 11—51.** Cumulative recovery—time profile for a duplicate test at  $H$  of 5.00 mm in cell two of the SBFA.



**Figure 11—52.** Cumulative recovery—grade curve for a duplicate test at  $H$  of 5.00 mm in cell two of the SBFA.

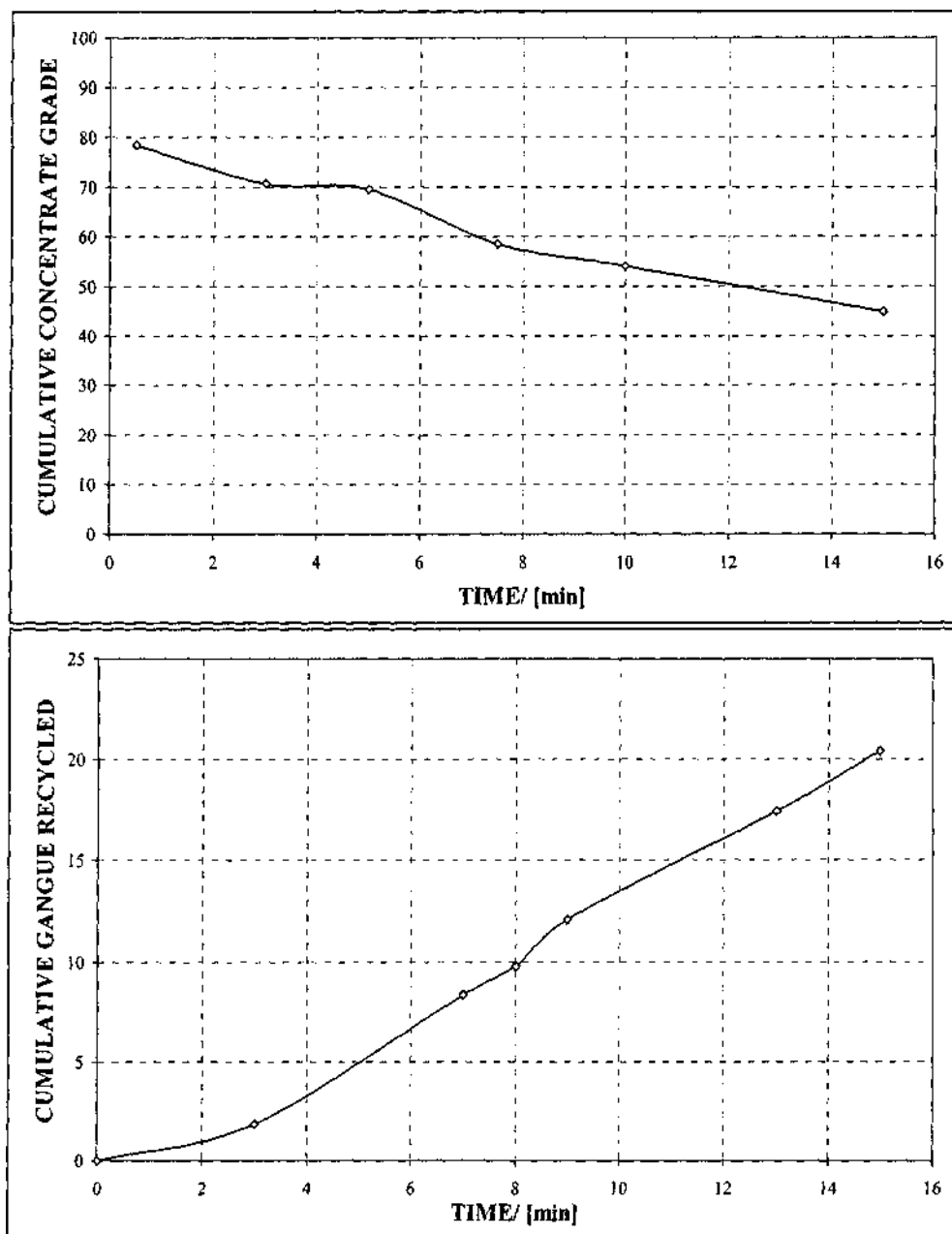


Figure 11—53. Variation in the cumulative concentrate grade for a duplicate test at  $H$  of 5.00 mm in cell two of the SBF A.

**Table 11—96. Summary of the SBFA model input parameters for  $H$  of 15.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	92.200
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	92.200
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	44.053
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	48.147
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.272
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.914
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.783
<b>A<sub>1</sub></b>	Cross sectional area of cell one	<b>m<sup>2</sup></b>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	<b>m<sup>2</sup></b>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m • min <sup>-1</sup>	0.049
<b>ill</b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>τ<sub>12</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table II-97. Summary of data for  $H$  of 15.00mm in cell two of the SBFA

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ <b>H</b>
0.50	40.80	10.10	30.70	75.25	33.30	34.54
2.00	50.10	21.20	28.90	65.57	64.64	61.65
3.00	12.40	5.90	6.50	63.99	71.69	73.83
5.00	22.70	13.40	9.30	59.84	81.78	87.00
7.50	28.00	18.40	9.60	55.19	92.19	92.13
10.00	26.50	24.30	2.20	48.31	94.58	94.47
15.00	44.70	44.20	0.50	38.94	95.12	95.07
<b>Tailings</b>	2526.00	2521.00	4.50	—	—	—

Table II—98. Summary of model parameters at  $H$  of 15.00 mm in cell two of the SBFA

Parameter	Units	Model estimate
$R_{MAX}$	—	95.119
$k \backslash$	min <sup>-1</sup>	0.511
<b><math>h</math></b>	min <sup>-1</sup>	0.959
$v$	min	0.000
SER	—	2.913
<b>?</b>	—	0.986
Residual	—	0.004

Table II—99. Summary of cumulative gangue recycled at  $H$  of 15.00 mm in cell one of the SBFA

Time/ [min]	Mass Recycled/ lg]	Cumulative Mass Recycled/	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
3.00	37.09	37.09	1.40
7.00	117.51	154.60	5.82
8.00	24.18	178.78	6.72
9.00	30.79	209.57	7.88
13.00	159.62	369.18	13.89
15.00	42.33	411.51	15.48

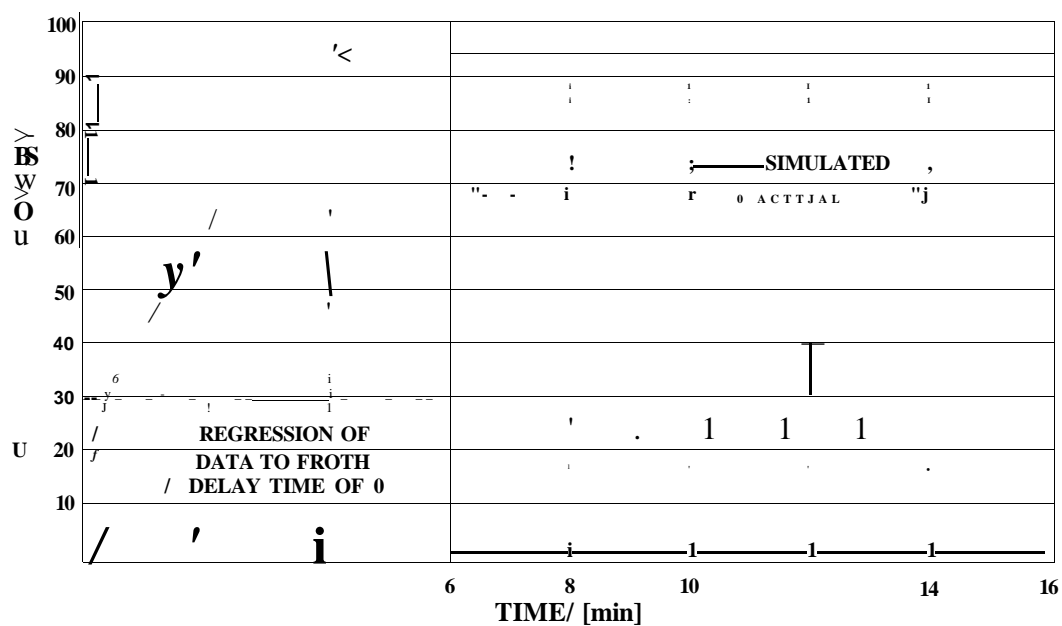


Figure 11—54. Cumulative recovery—time profile at //of 15.00 mm in cell two of the SBFA.

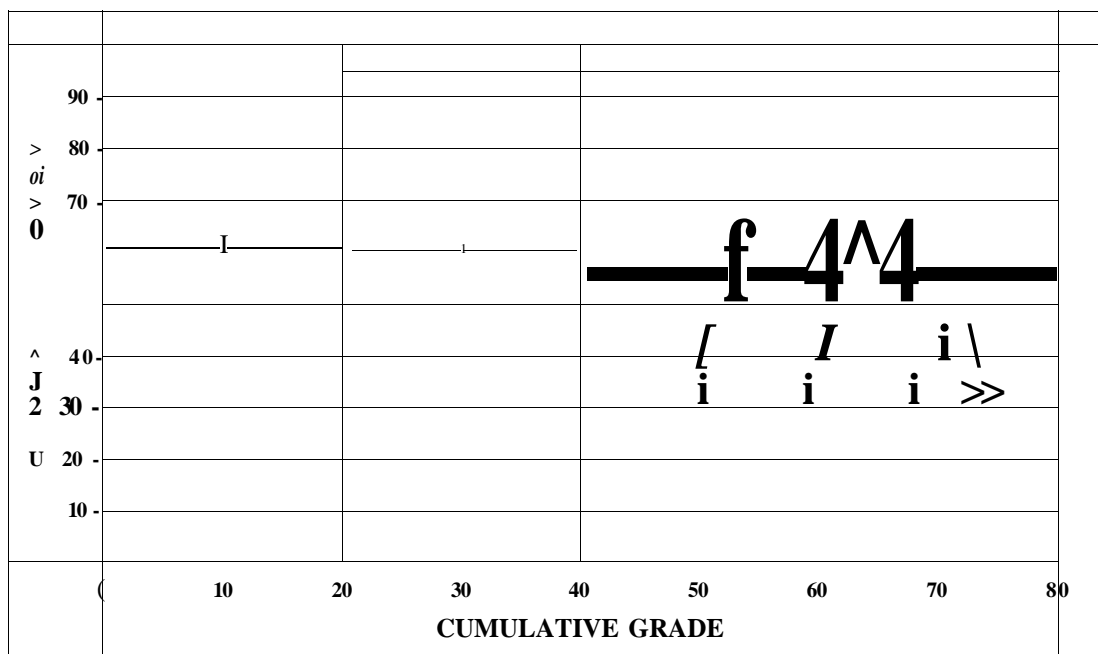
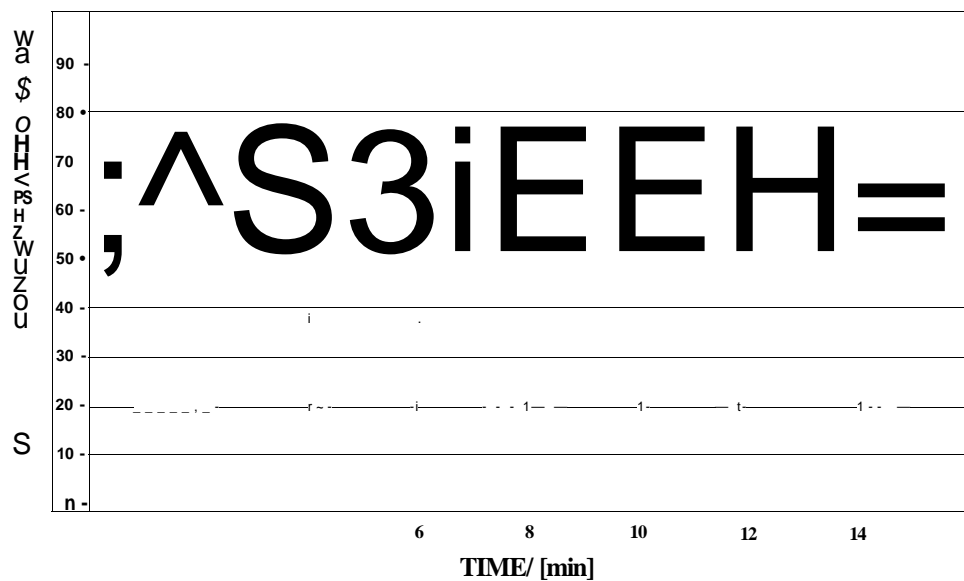


Figure 11—55. Cumulative recovery—grade curve at //of 15.00 mm in cell one of the SBFA.





**Figure 11—56.** Variation in the cumulative concentrate grade at  $H$  of 5.00 mm in cell two of the SBF A.

**Table 11—100. Summary of the SBFA model input parameters for a duplicate test at  $H$  of 15.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	63.600
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	63.600
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	30.961
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	32.639
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.022
<b>b</b>	Startup time a, related to second in SBFA	min	1.339
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.914
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.783
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
<b>k<sub>1</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>k<sub>2</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table II—101. Summary of data for a duplicate test at  $H$  of 15.00 mm in cell two of the SBFA

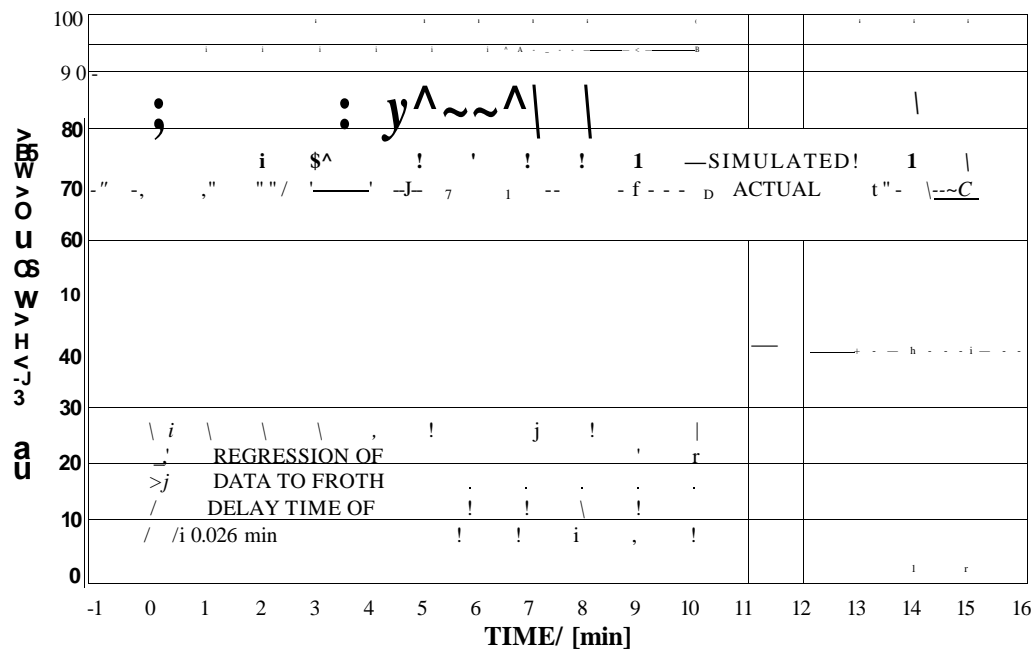
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ <b>H</b>	Simulated Limestone Recovery/ <b>I-I</b>
0.50	31.90	11.70	20.20	63.32	31.76	31.34
2.00	36.70	19.10	17.60	55.10	59.43	60.59
3.00	21.90	11.90	10.00	52.82	75.16	73.32
5.00	26.10	18.10	8.00	47.86	87.74	86.96
7.00	16.70	13.50	3.20	44.26	92.77	92.27
10.00	10.50	9.90	0.60	41.45	93.71	94.71
15.00	14.50	14.10	0.40	37.90	94.34	95.35
<b>Tailings</b>	2532.00	2528.00	3.60	—	—	—

Table 11-102. Summary of model parameters for a duplicate test at  $H$  of 15.00 mm in cell two of the SBFA

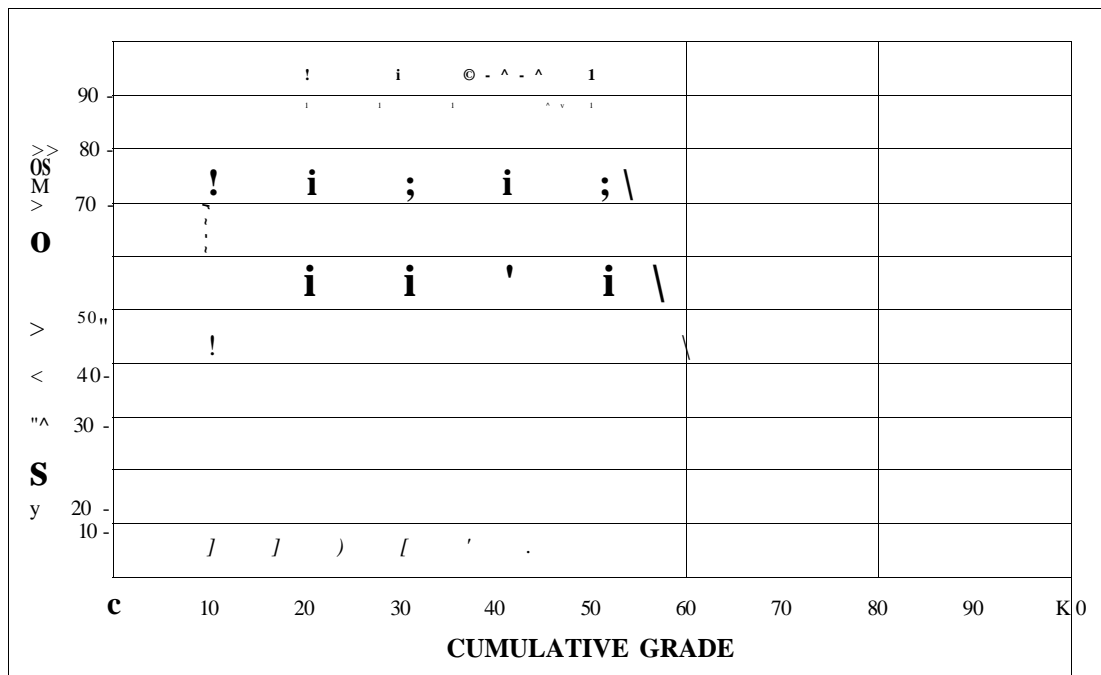
Parameter	Units	Model estimate
$R_{MAX}$	—	95.404
$h$	min <sup>-1</sup>	0.506
$h$	min <sup>-1</sup>	0.951
$v$	min	-0.026
SER	—	1.246
$^2$	—	0.998
Residual	—	0.001

Table 11—103. Summary of cumulative gangue recycled for a duplicate test at  $H$  of 15.00 mm in cell two of the SBFA

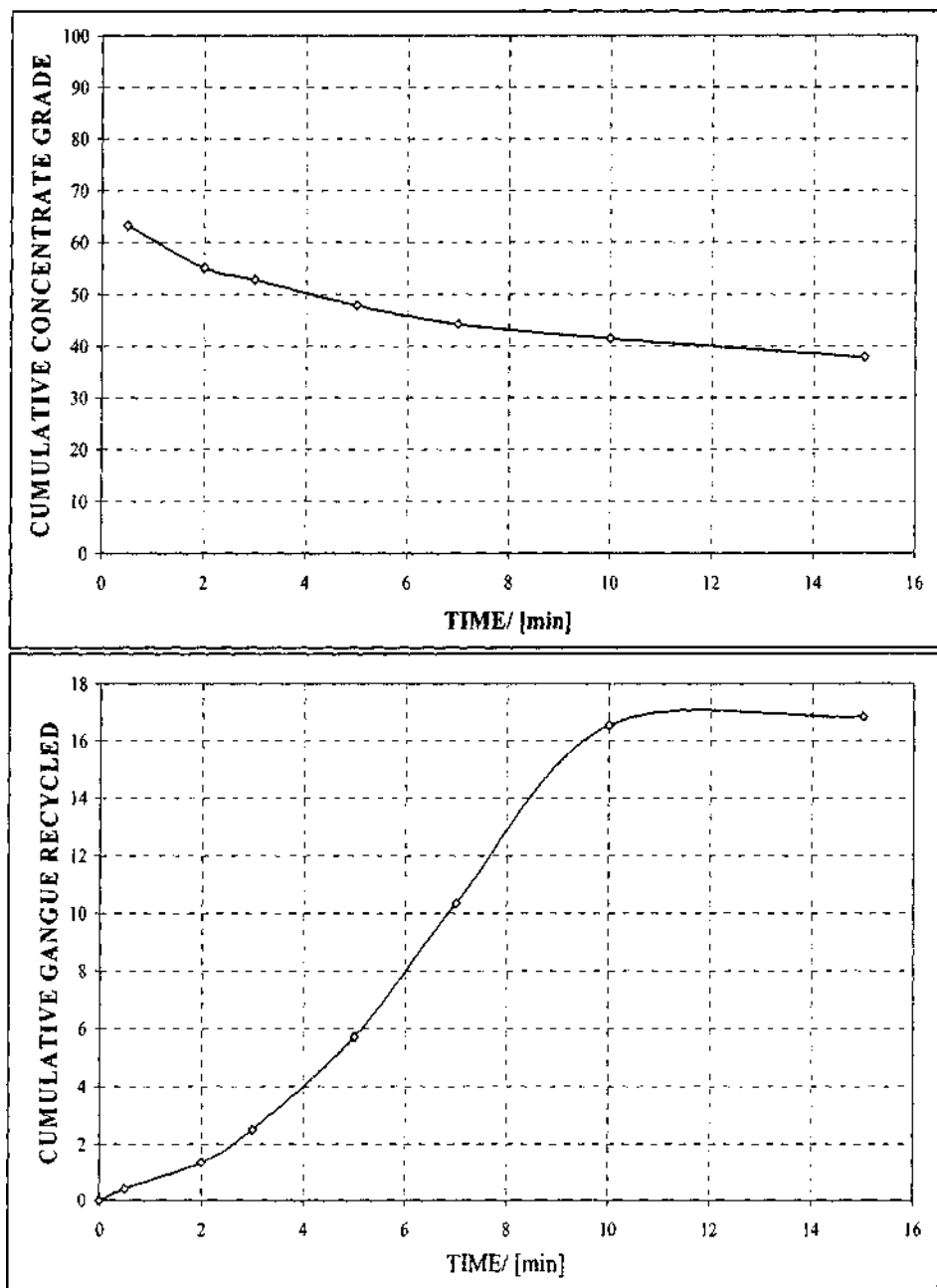
Time/ [min]	Mass Recycled/ [g]	Cumulative M Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	10.91	10.91	0.42
2.00	24.45	35.36	1.35
3.00	30.42	65.78	2.50
5.00	84.51	150.29	5.72
7.00	121.21	271.50	10.34
10.00	162.87	434.37	16.54
15.00	8.07	442.44	16.85



**Figure 11—57.** Cumulative recovery—time profile for a duplicate test at // of 15.00 mm in cell two of the SBFA.



**Figure II—58.** Cumulative recovery—grade curve for a duplicate test at  $H$  of 15.00 mm in cell two of the SBFA.



**Figure II—59.** Variation in the cumulative concentrate grade for a duplicate test at  $H$  of 15.00 mm in cell two of the SBFA.

**Table 11—104. Summary of the SBFA model input parameters for *H* of 25.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	71.700
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	71.700
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	39.261
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	32.439
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.272
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.914
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.666
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	$\frac{\text{m}^3}{\text{m} \cdot \text{min}} \cdot \text{mm}^{-1}$	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	$\frac{\text{m}^3}{\text{m}^3 \cdot \text{min}} \cdot \text{min}^{-1}$	0.049
<b>n<sub>1</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>T<sub>12</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—105. Summary of data for  $H$  of 25.00 mm in cell two of the SBFA

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/	Simulated Limestone Recovery/ I-]
0.50	31.90	8.60	23.30	73.04	32.50	32.83
2.00	51.70	22.50	29.20	62.80	73.22	62.80
3.00	13.30	8.60	4.70	59.03	79.78	76.76
5.00	33.80	27.50	6.30	48.58	88.56	90.72
7.50	19.70	17.10	2.60	43.95	92.19	95.32
10.00	18.50	17.10	1.40	39.96	94.14	97.00
15.00	35.30	33.80	1.50	33.79	96.23	97.30
<b>Tailings</b>	2550.00	2547.00	2.70	—	—	—

Table II-106. Summary of model parameters at  $H$  of 25.00 mm in cell two of the SBFA

Parameter	Units	Model estimate
-KMAX	—	97.312
$h$	min"	0.624
$k_2$	min" <sup>1</sup>	0.996
$V$	min	-0.219
SER	—	5.322
$r^2$	—	0.953
Residual	—	0.014

Table 11—107. Summary of cumulative gangue recycled at  $H$  of 25.00 mm in cell one of the SBFA

Time/ [min]	Mass Recycled/ [g]	Cumulative Ma Recycled/ [g]	to total gangue added
0.00	0.00	0.00	0.00
3.00	27.82	27.82	1.04
6.00	123.82	151.64	5.65
7.00	44.45	196.09	7.31
8.00	35.56	231.65	8.64
9.00	55.52	287.17	10.71
10.00	34.65	321.82	12.00
11.00	25.00	346.81	12.93
12.00	35.67	382.48	14.26
13.00	41.16	423.65	15.79
14.00	41.39	465.04	17.34
15.00	38.62	503.66	18.78

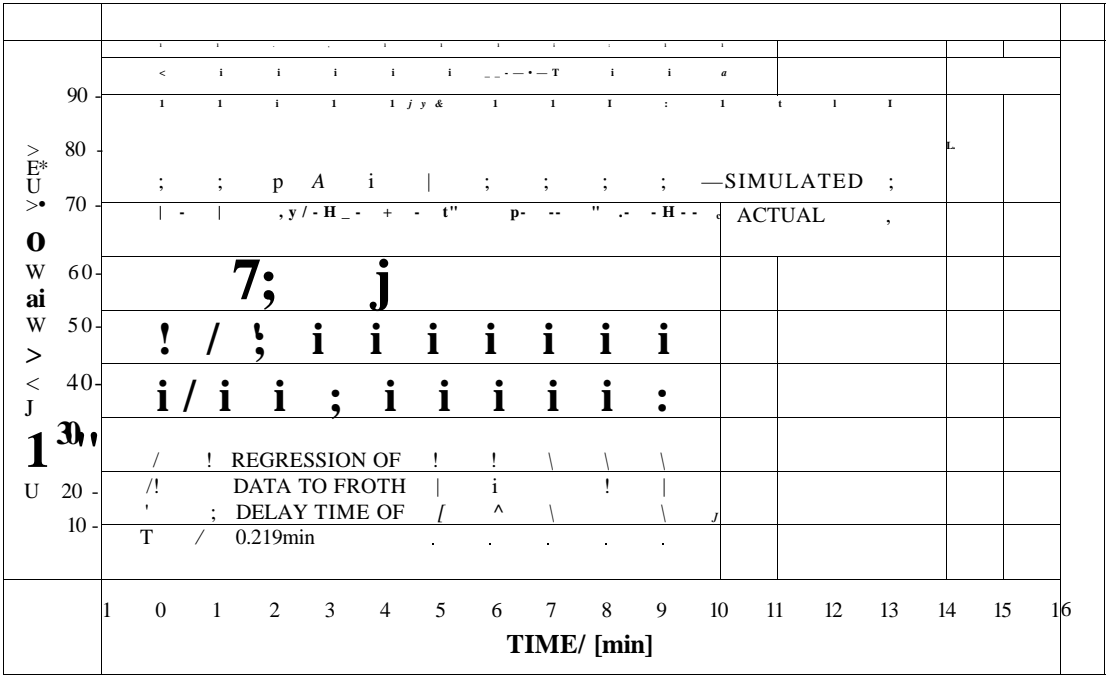


Figure 11—60. Cumulative recovery—time profile at  $H$  of 25.00 mm in cell two of the SBFA.

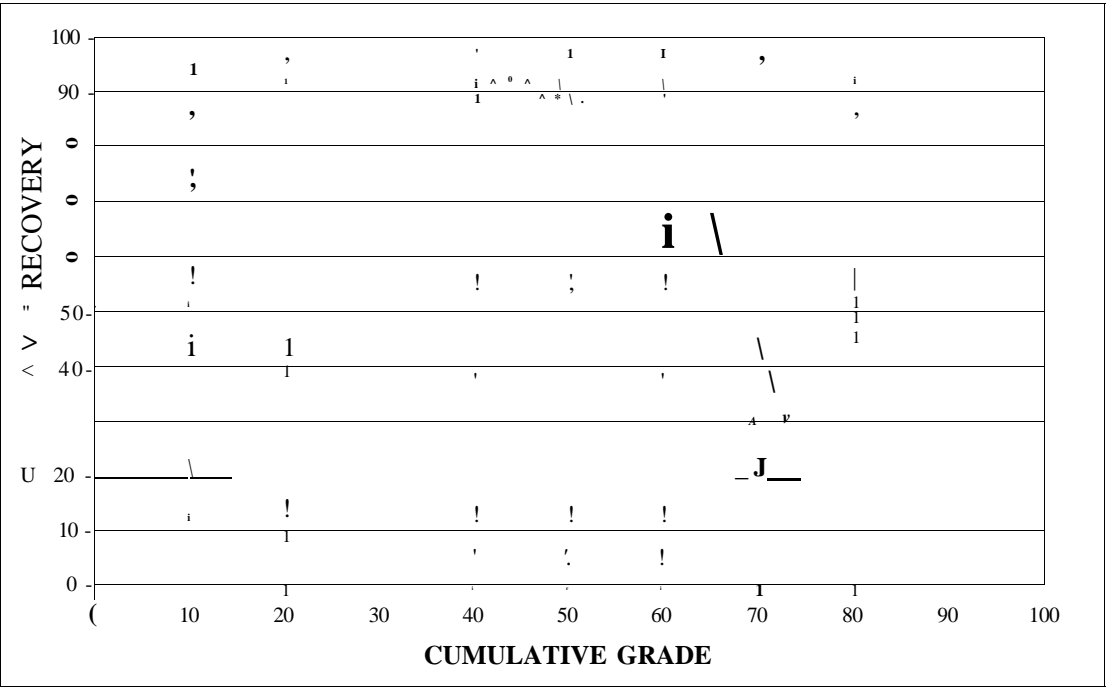


Figure 11—61. Cumulative recovery—grade curve at  $H$  of 25.00mm in cell one of the SBFA.



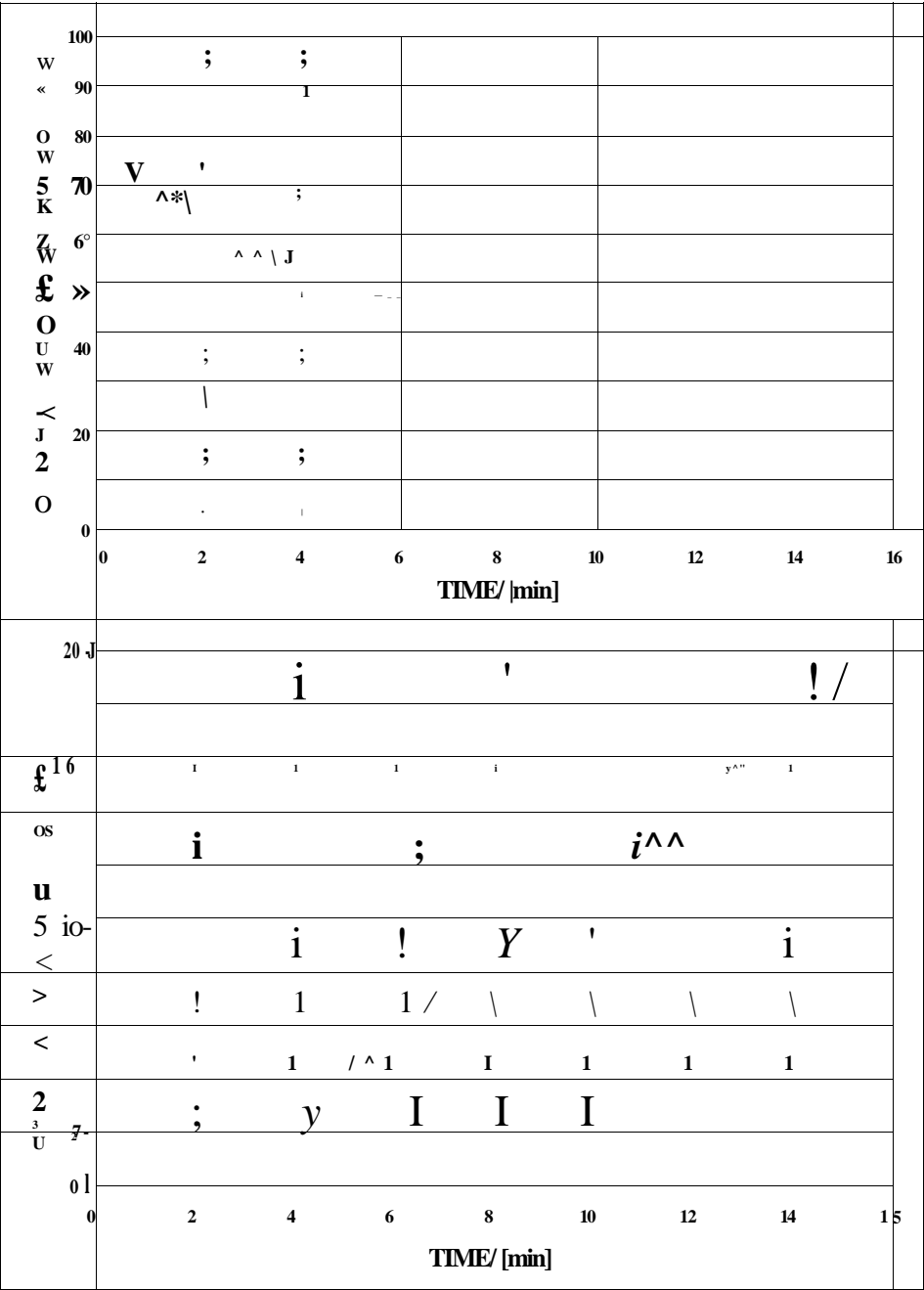


Figure 11—62 Cumulative recovery—grade curve at // of 25.00 mm in cell one of the SBFA.

**Table II—108. Summary of the SBFA model input parameters for a duplicate test at  $H$  of 25.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	76.300
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	76.300
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	43.376
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	32.924
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.405
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.914
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.666
<b>A<sub>1</sub></b>	Cross sectional area of cell one	<b>m<sup>2</sup></b>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	<b>m<sup>2</sup></b>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	<b>m<sup>3</sup> • min<sup>-1</sup></b>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	<b>m<sup>3</sup> • min<sup>-1</sup></b>	0.049
<b>T<sub>11</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>T<sub>12</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

**Table II—109. Summary of data for a duplicate test at  $H$  of 25.00 mm in cell two of the SBFA**

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/	Simulated Limestone Recovery/ <b>H</b>
0.50	12.10	3.20	8.90	73.55	11.66	11.69
2.00	49.10	14.10	35.00	71.73	57.54	54.68
3.00	20.30	9.40	10.90	67.24	71.82	71.08
5.00	27.60	16.00	11.60	60.86	87.02	86.65
7.33	6.90	5.20	1.70	58.71	89.25	92.19
10.00	18.80	17.10	1.70	51.78	91.48	93.71
15.00	12.30	10.30	2.00	48.81	94.10	94.08
<b>Tailings</b>	2441.00	2436.00	4.50	—	—	—

**Table 11-110. Summary of model parameters for a duplicate test at  $H$  of 25.00 mm in cell two of the SBFA**

Parameter	Units	Model estimate
$R_{MAX}$ .	—	94.102
$h$	min"	0.598
$ki$	min <sup>-1</sup>	0.956
$V$	min	0.000
SER	—	2.117
$r^2$	—	0.996
Residual	—	0.002

**Table 11—111. Summary of cumulative gangue recycled for a duplicate test at  $H$  of 25.00 mm in cell two of the SBFA**

Time/ [min]	Mass Recycled/ lg]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	4.09	4.09	0.16
2.00	23.20	27.29	1.09
3.00	25.72	53.02	2.11
5.00	74.69	127.71	5.09
7.33	114.58	242.28	9.65
10.00	266.29	508.57	20.25
15.00	63.65	572.23	22.79

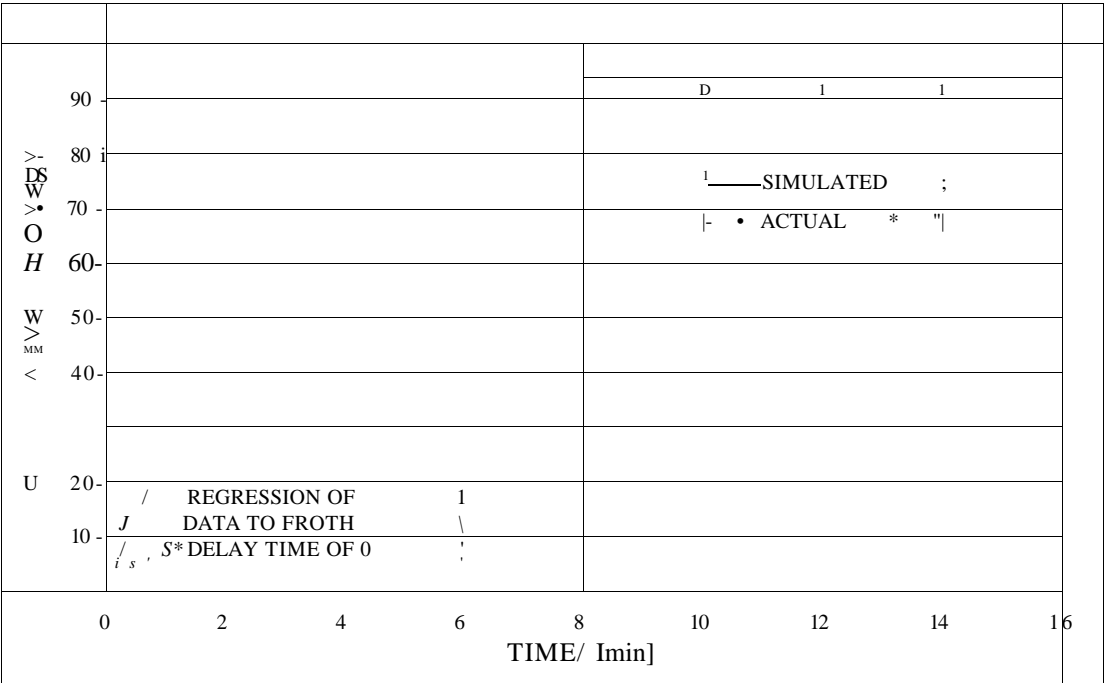


Figure 11—63. Cumulative recovery—time profile for a duplicate test at  $H$  of 25.00 mm in cell two of the SBFA.

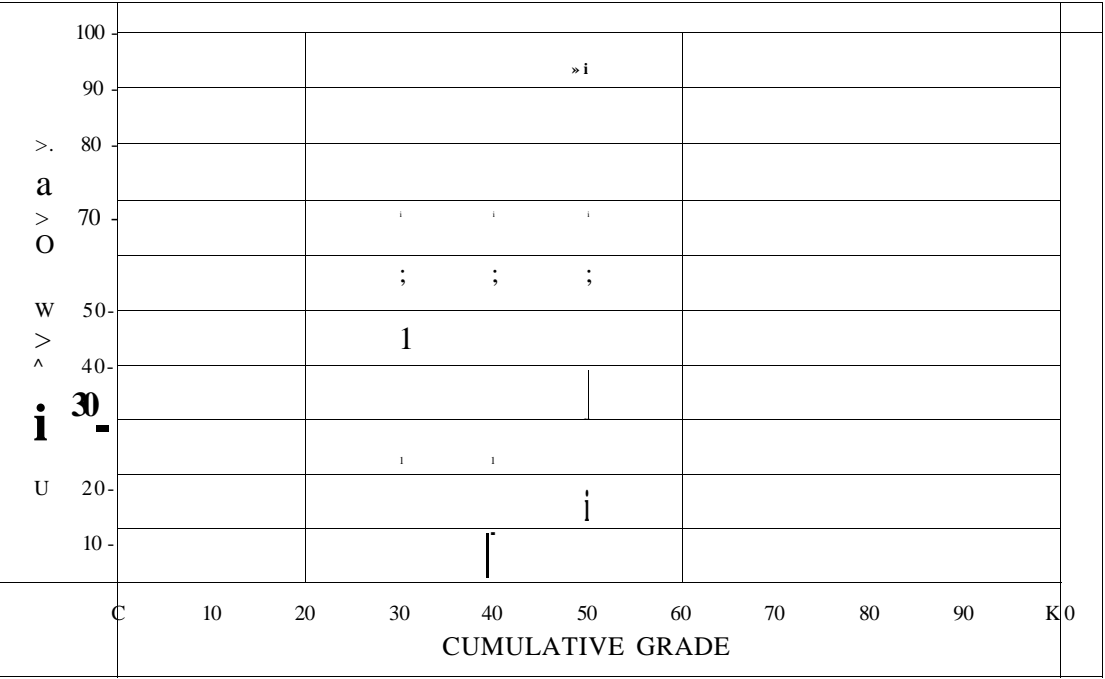
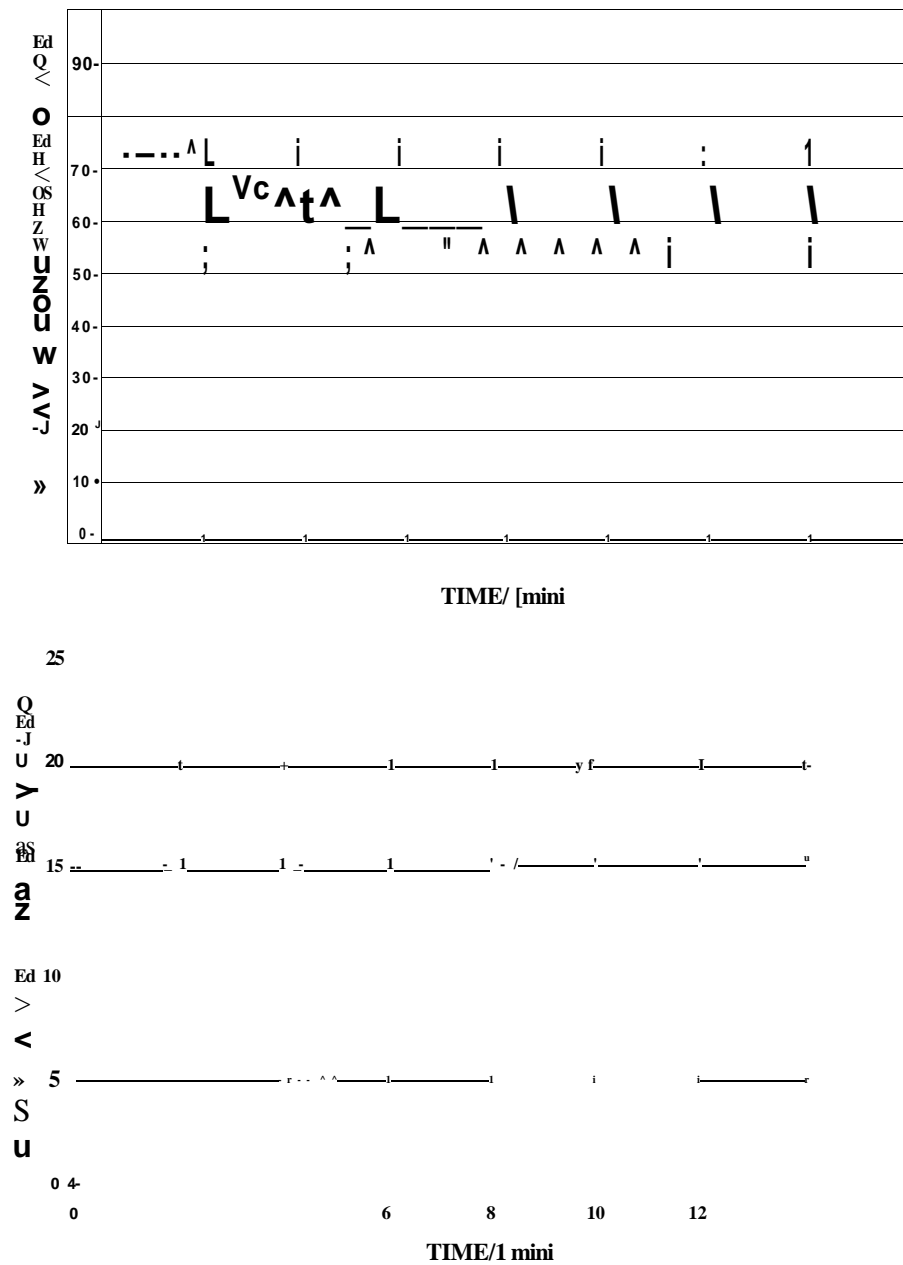


Figure 11—64. Cumulative recovery—grade curve for a duplicate test at  $H$  of 25.00 mm in cell two of the SBFA.



**Figure 11—65.** Variation in the cumulative concentrate grade for a duplicate test at  $H$  of 25.00 mm in cell two of the SBF A.

**Table 11—112. Summary of the SBFA model input parameters for  $H$  of 35.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	73.700
M <sub>1</sub> (a)	Limestone in cell one at time a	grams	73.700
M <sub>1</sub> (b)	Limestone in cell one at time b	grams	45.278
M <sub>2</sub> (b)	Limestone in cell two at time b	grams	28.422
a	Startup time a, related to first cell in SBFA	min	0.000
b	Startup time a, related to second in SBFA	min	1.272
R <sub>f,1</sub>	Froth recovery for cell one	—	0.914
R <sub>f,2</sub>	Froth recovery for cell two	—	0.566
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	l <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	l <sup>3</sup> • min <sup>-1</sup>	0.049
T <sub>11</sub>	Flotation kinetic scaling parameter related to cell one		0.885
T <sub>22</sub>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11-113. Summary of data for  $H$  of 35.00 mm in cell two of the SBFA

Time/ [min]	Mass Before Acid Dissolution/ lg]	Mass After Acid Dissolution/ [g]	Mass Limestone/ lg]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/	Simulated Limestone Recovery/ <b>H</b>
0.50	26.40	6.30	20.10	76.14	27.27	28.10
2.00	42.60	17.00	25.60	66.23	62.01	57.75
3.00	12.50	5.90	6.60	64.17	70.96	72.09
5.00	29.20	19.80	9.40	55.74	83.72	85.32
7.00	19.70	17.30	2.40	49.16	86.97	89.02
10.00	24.50	23.40	1.10	42.09	88.47	90.09
15.00	15.90	14.60	1.30	38.93	90.23	90.23
<b>Tailings</b>	2451.00	2443.00	7.20	—	—	—

Table 11-114. Summary of model parameters at  $H$  of 35.00 mm in cell two of the SBFA

Parameter	Units	Model estimate
$R_{MAX}$	—	90.231
$*1$	$\text{min}''^1$	0.749
$k_2$	$\text{min}''$	1.008
$V$	$\text{min}$	-0.174
<b>SER</b>	—	2.427
$r_{\sim}^i$	—	0.991
Residual	—	0.003

Table 11—115. Summary of cumulative gangue recycled at  $H$  of 35.00 mm in cell one of the SBFA

Time/ [min]	Mass Recycled/ lg]	Cumulative Ma Recycled/ [g]	to total gangue added
0.00	0.00	0.00	0.00
3.00	27.82	27.82	1.09
6.00	123.82	151.64	5.95
7.00	44.45	196.09	7.70
8.00	35.56	231.65	9.09
9.00	55.52	287.17	11.27
10.00	34.65	321.82	12.63
11.00	25.00	346.81	13.61
12.00	35.67	382.48	15.02
13.00	41.16	423.65	16.63
14.00	41.39	465.04	18.26
15.00	38.62	503.66	19.77

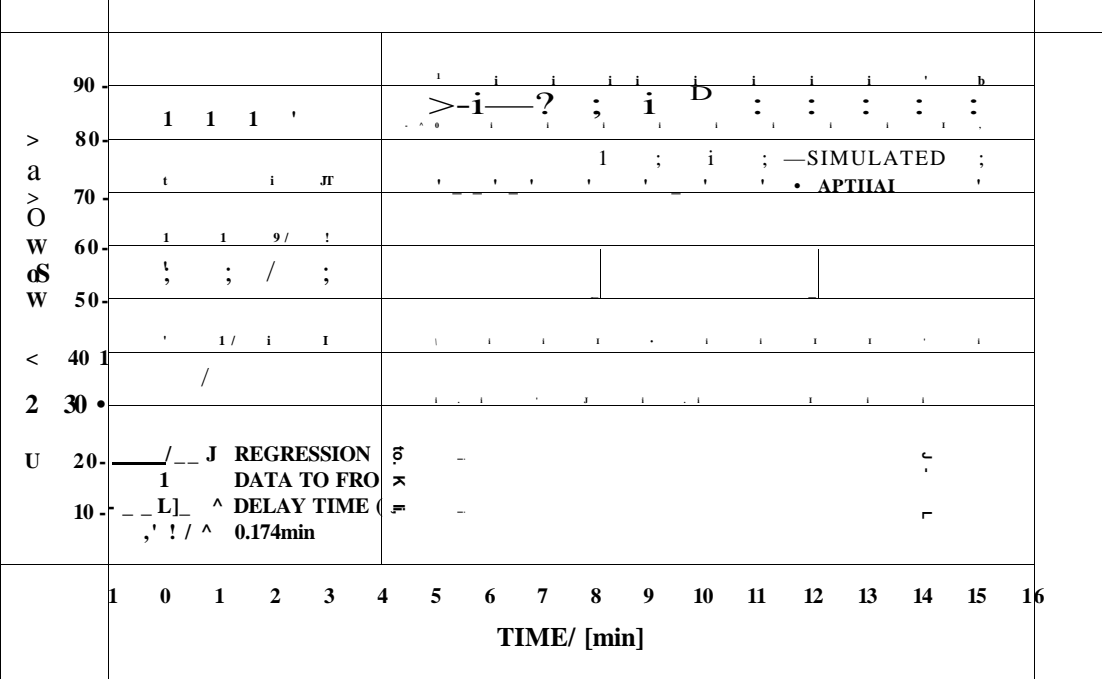


Figure 11-66. Cumulative recovery—time profile at // of 35.00 mm in cell two of the SBFA.

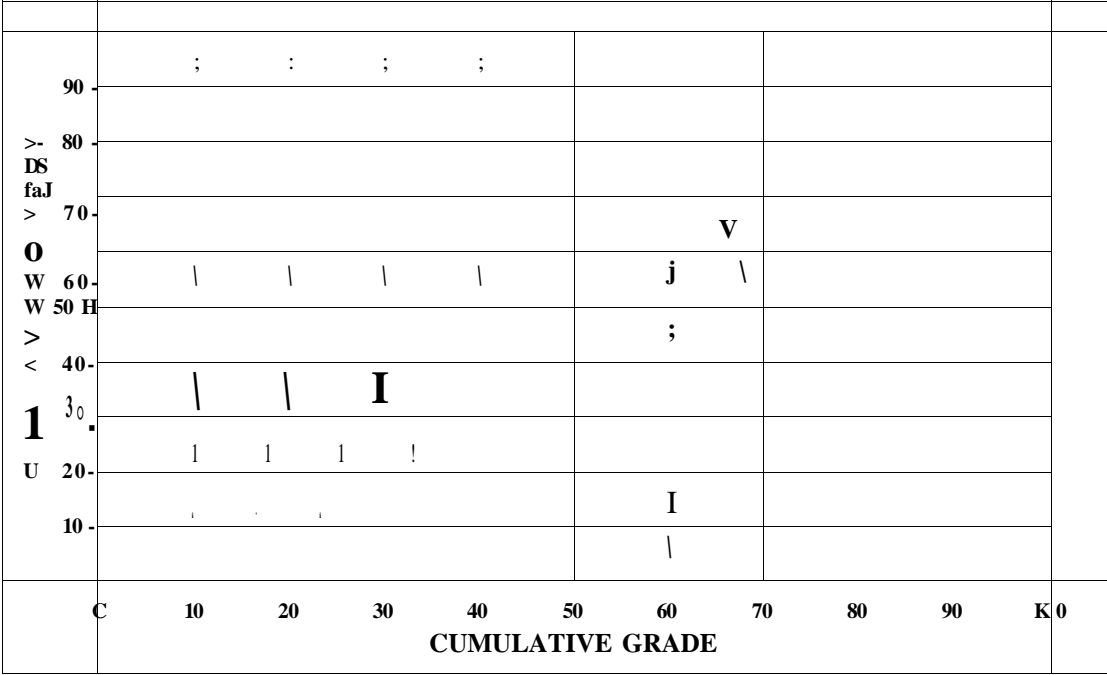
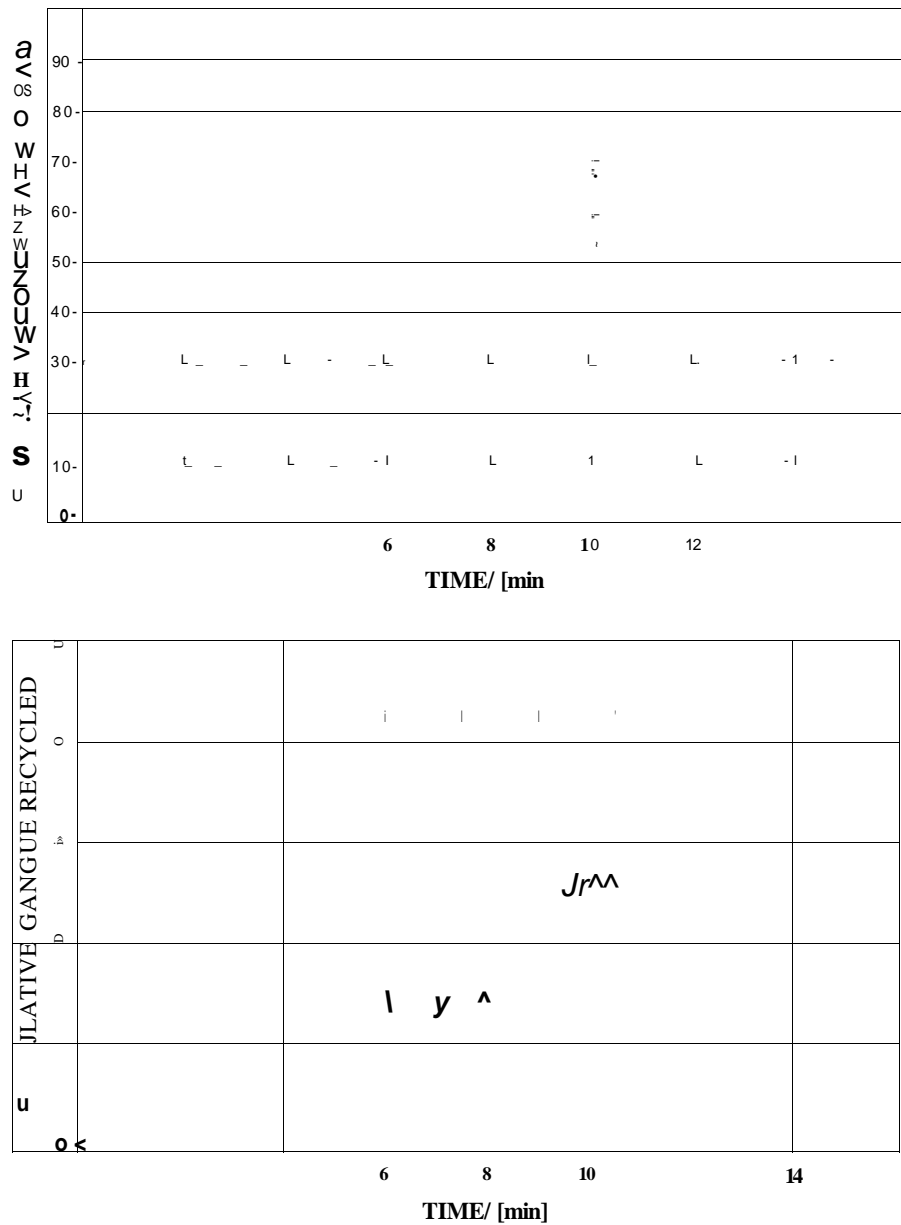


Figure 11-67. Cumulative recovery—grade curve at // of 35.00 mm in cell one of the SBFA.





**Figure 11—68.** Variation in the cumulative concentrate grade at//of 35.00 mm in cell two of the SBFA.

**Table 11—116. Summary of the SBFA model input parameters for a duplicate test at  
H of 35.00 mm in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	74.900
<b>M,(a)</b>	Limestone in cell one at time a	grams	74.900
<b>M,(b)</b>	Limestone in cell one at time b	grams	46.466
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	28.434
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.303
Rf,i	Froth recovery for cell one	—	0.914
Rf,2	Froth recovery for cell two	—	0.566
A <sub>i</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>i</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
Til	Flotation kinetic scaling parameter related to cell one		0.885
H2	Flotation kinetic scaling parameter related to cell two		2.998

**Table II—117. Summary of data for a duplicate test at  $H$  of 35.00 mm in cell two of the SBFA**

Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ [-]	Simulated Limestone Recovery/ <b>H</b>
0.50	22.50	5.50	17.00	75.56	22.70	22.17
2.00	47.30	13.50	33.80	72.78	67.82	59.20
3.00	20.50	10.10	10.40	67.77	81.71	75.46
5.00	16.90	11.70	5.20	61.94	88.65	90.16
7.00	13.80	12.30	1.50	56.12	90.65	94.24
10.00	8.20	6.60	1.60	53.79	92.79	95.44
15.00	5.30	5.30	0.00	51.67	92.79	95.59
<b>Tailings</b>	2548.00	2542.00	5.40	—	—	—

**Table 11—118. Summary of model parameters for a duplicate test at  $H$  of 35.00 mm in cell two of the SBFA**

Parameter	Units	Model estimate
#MAX	—	95.590
$h$	min"	0.743
$k_2$	min"	1.000
$v$	min	-0.140
SER	—	5.360
$r^I$	—	0.963
Residual	—	0.014

**Table II—119. Summary of cumulative gangue recycled for a duplicate test at  $H$  of 35.00 mm in cell two of the SBFA**

Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
0.50	1.75	1.75	0.07
2.00	37.02	38.77	1.49
3.00	53.25	92.03	3.53
5.00	82.37	174.39	6.69
7.00	82.47	256.86	9.85
10.00	169.62	426.48	16.36
15.00	15.85	442.33	16.97

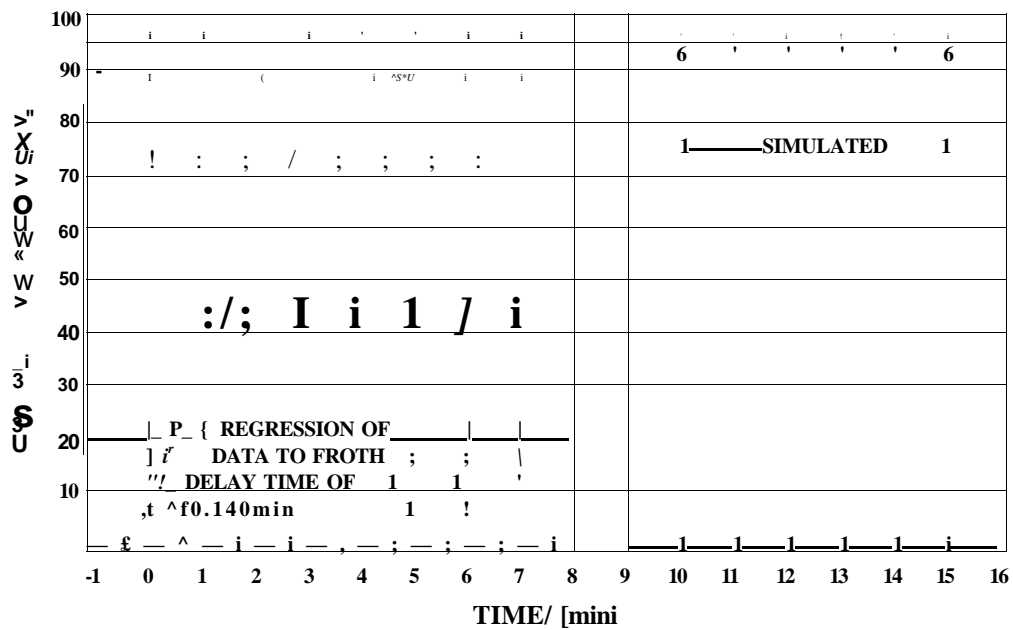


Figure 11—69. Cumulative recovery—time profile for a duplicate test at  $H$  of 35.00 mm in cell two of the SBFA.

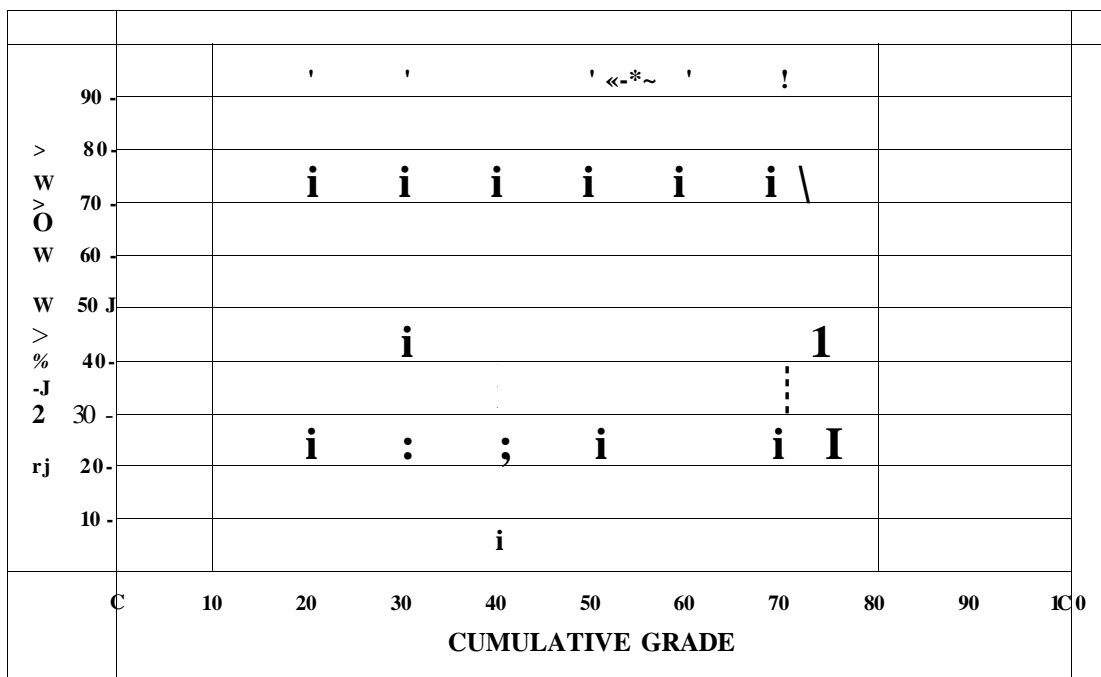
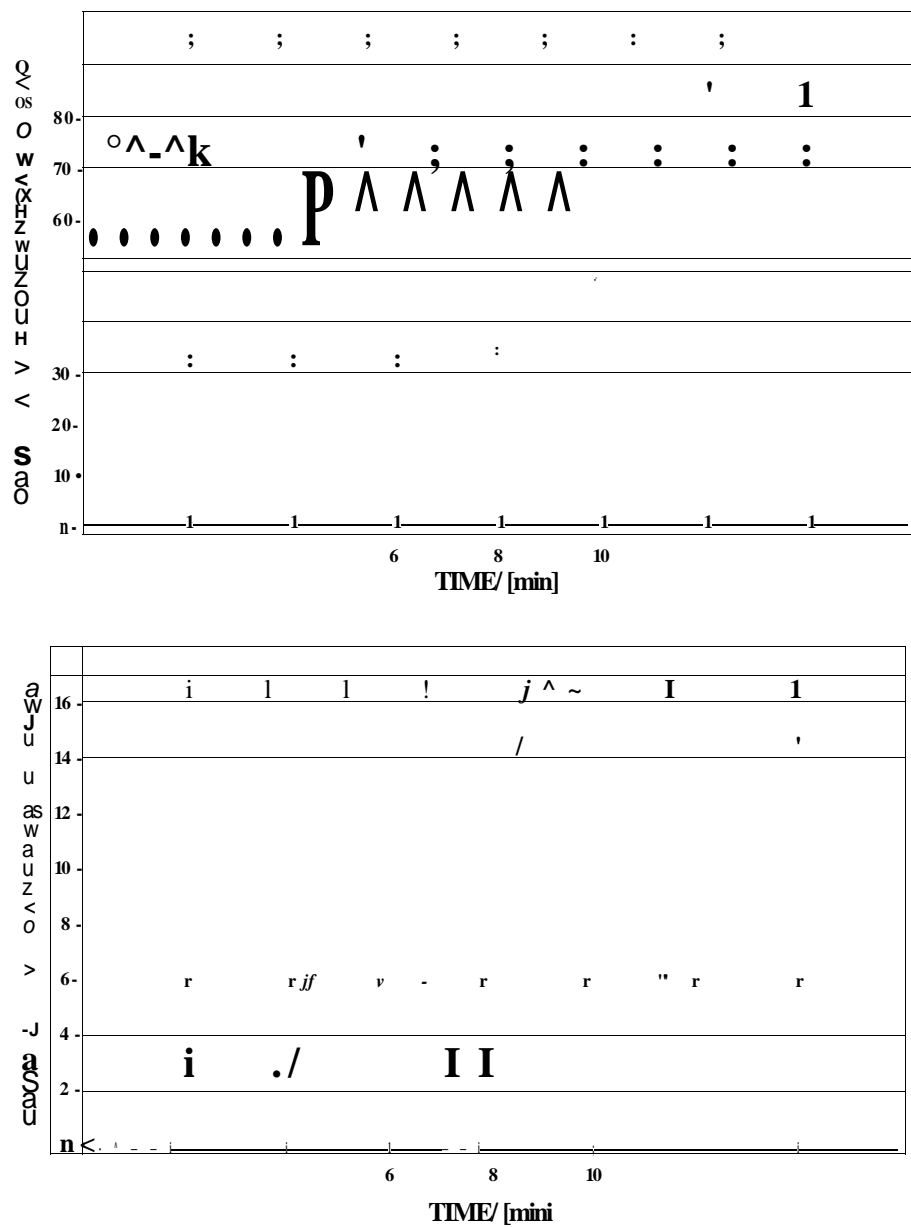


Figure 11—70. Cumulative recovery—grade curve for a duplicate test at  $H$  of 5.00 mm in cell two of the SBFA.



**Figure 11—71.** Variation in the cumulative concentrate grade for a duplicate test at  $H$  of 35.00 mm in cell two of the SBF A.

## II.X Summary of data for SBFA with the variable solid concentration

**Table II—120. Summary of the SBFA model input parameters for a solid concentration of 7.50 % in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	134.980
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	134.980
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	66.304
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	68.676
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.243
<b>R<sub>f,1</sub></b>	Froth recovery for cell one	—	0.974
<b>R<sub>f,2</sub></b>	Froth recovery for cell two	—	0.922
<b>A<sub>1</sub></b>	Cross sectional area of cell one	m <sup>2</sup>	0.176
<b>A<sub>2</sub></b>	Cross sectional area of cell two	m <sup>2</sup>	0.065
<b>Q<sub>1</sub></b>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
<b>Q<sub>2</sub></b>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
<b>k<sub>1</sub></b>	Flotation kinetic scaling parameter related to cell one		0.885
<b>k<sub>2</sub></b>	Flotation kinetic scaling parameter related to cell two		2.998

Table 11—121. Summary of data for a duplicate test at a solid concentration of 7.50 % in cell two of the SBFA

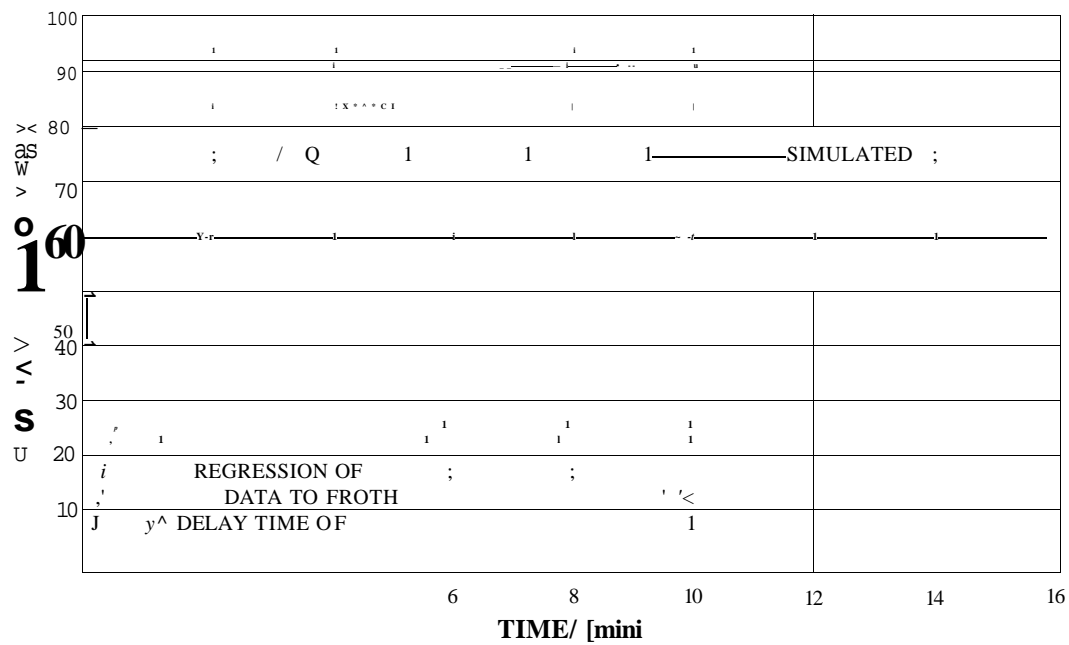
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ [g]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ [-]	Simulated Limestone Recovery/ H
0.50	41.40	7.80	33.60	81.16	24.89	23.10
2.00	51.50	13.00	38.50	77.61	53.42	62.79
3.00	41.30	12.50	28.80	75.19	74.75	75.44
5.00	25.00	12.40	12.60	71.29	84.09	86.82
7.00	19.40	14.10	5.30	66.52	88.01	90.61
10.00	16.30	12.10	4.20	63.11	91.12	92.16
15.00	9.20	7.30	1.90	61.20	92.53	92.51
<b>Tailings</b>	3659.90	3648.70	10.08	—	—	—

Table 11—122. Summary of model parameters for a solid concentration of 7.50 % in cell two of the SBFA

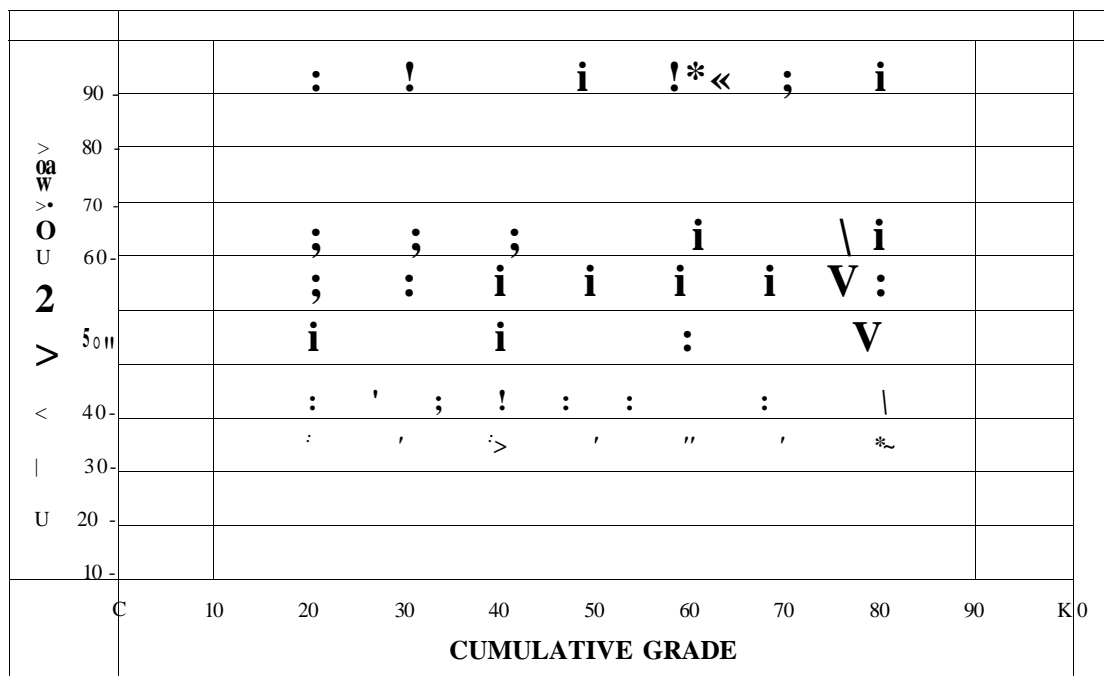
Parameter	Units	Model estimate
<i>RMAX</i>	—	92.532
<i>*1</i>	min <sup>-1</sup>	0.543
<i>h</i>	min <sup>-1</sup>	1.128
<i>v</i>	min	0.000
SER	—	4.625
<i>r</i> <sup>2</sup>	—	0.972
Residual	—	0.011

Table 11—123. Summary of cumulative gangue recycled for a solid concentration of 7.50 % in cell two of the SBFA

Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, Relative To Total Gangue Added
0.00	0.00	0.00	0.00
2.00	28.45	28.45	0.76
3.00	22.59	51.04	1.37
5.00	41.49	92.53	2.48
7.00	38.64	131.17	3.52
10.00	184.71	315.87	8.47
15.00	262.12	577.99	15.50

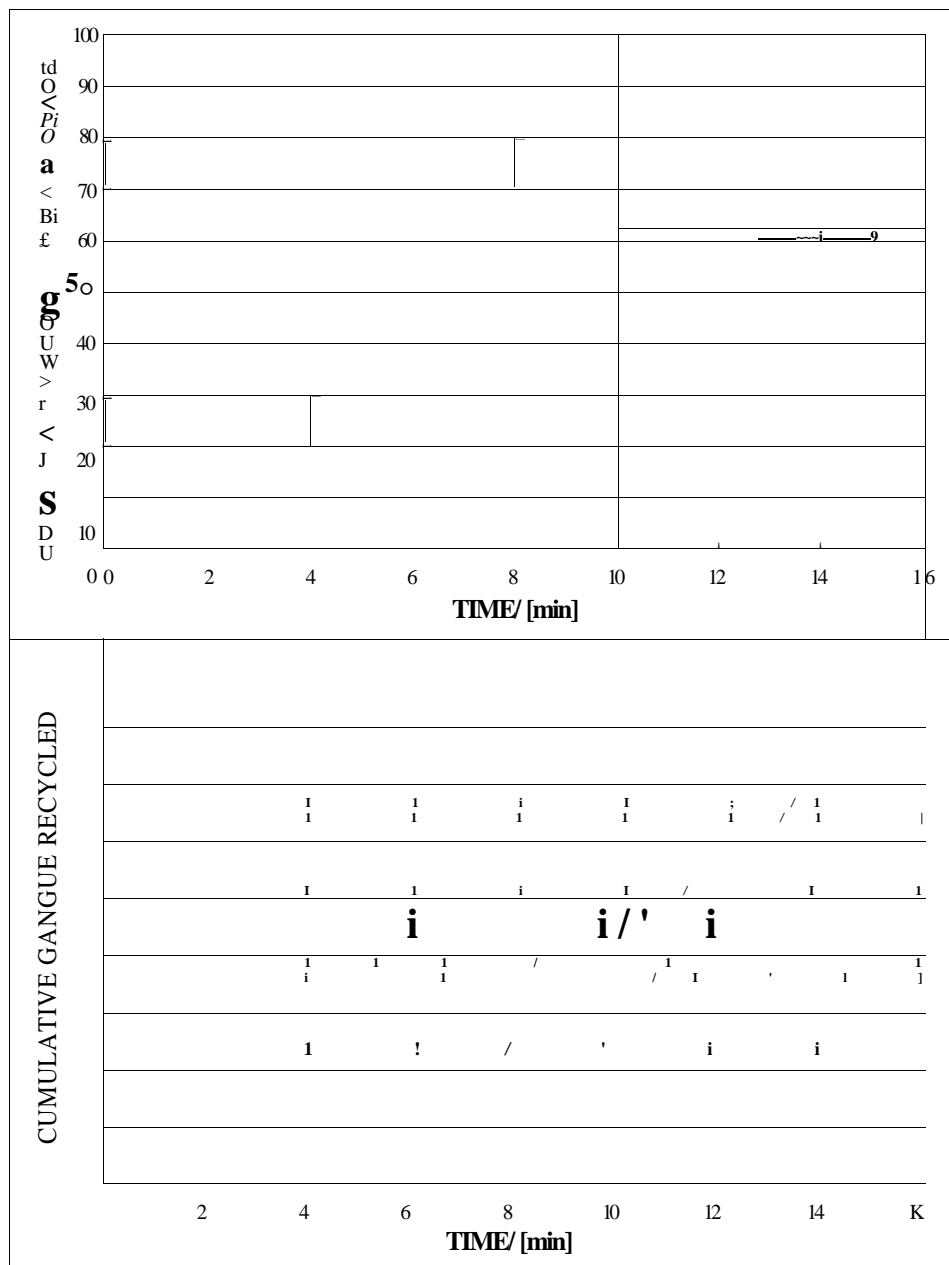


**Figure 11-72.** Cumulative recovery—time profile for a solid concentration of 7.50 % in cell two of the SBFA.



**Figure II-73.** Cumulative recovery—grade curve for a solid concentration of 7.50 % in cell two of the SBFA.





**Figure 11—74.** Variation in the cumulative concentrate grade for a solid concentration of 7.50 % in cell two of the SBFA.

**Table II—124. Summary of the SBFA model input parameters for a solid concentration of 10.00 % in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
M(0)	Total mass limestone charged into SBFA	grams	156.600
M <sub>1</sub> (a)	Limestone in cell one at time a	grams	156.600
M <sub>1</sub> (b)	Limestone in cell one at time b	grams	74.855
M <sub>2</sub> (b)	Limestone in cell two at time b	grams	81.745
a	Startup time a, related to first cell in SBFA	min	0.000
b	Startup time a, related to second in SBFA	min	1.232
R <sub>f,1</sub>	Froth recovery for cell one	—	0.974
R <sub>f,2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	t <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	l <sup>3</sup> • min <sup>-1</sup>	0.049
n <sub>1</sub>	Flotation kinetic scaling parameter related to cell one		0.885
H <sub>2</sub>	Flotation kinetic scaling parameter related to cell two		2.998

Table II—125. Summary of data for a duplicate test at a solid concentration of 10.00  
% in cell two of the SBFA

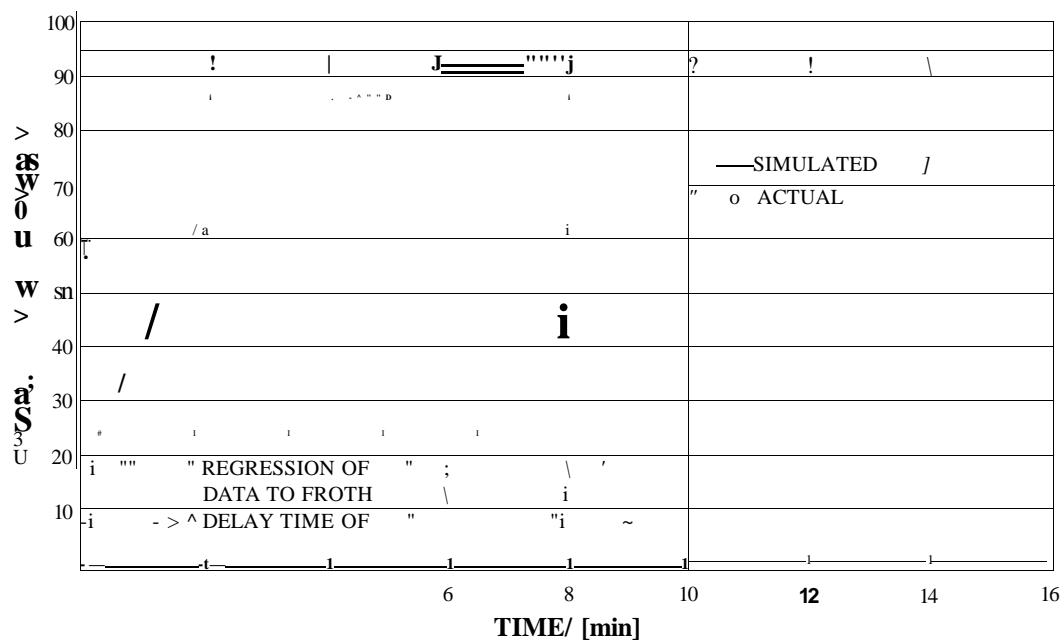
Time/ [min]	Mass Before Acid Dissolution/ [g]	Mass After Acid Dissolution/ [g]	Mass Limestone/ lg]	Cumulative concentrate Grade/ [-]	Cumulative Limestone Recovery/ H	Simulated Limestone Recovery/ H
0.50	58.10	11.80	46.30	79.69	29.57	28.85
2.00	70.40	20.60	49.80	74.79	61.37	64.83
3.00	38.70	14.30	24.40	72.07	76.95	77.29
5.00	52.90	37.70	15.20	61.65	86.65	89.07
7.00	31.90	26.10	5.80	56.15	90.36	93.20
10.00	22.90	19.30	3.60	52.78	92.66	94.95
15.00	43.90	39.60	4.30	46.86	95.40	95.37
<b>Tailings</b>	5250.00	5242.00	7.20	—	—	—

Table 11—126. Summary of model parameters for a solid concentration of 7.50 % in  
cell two of the SBFA

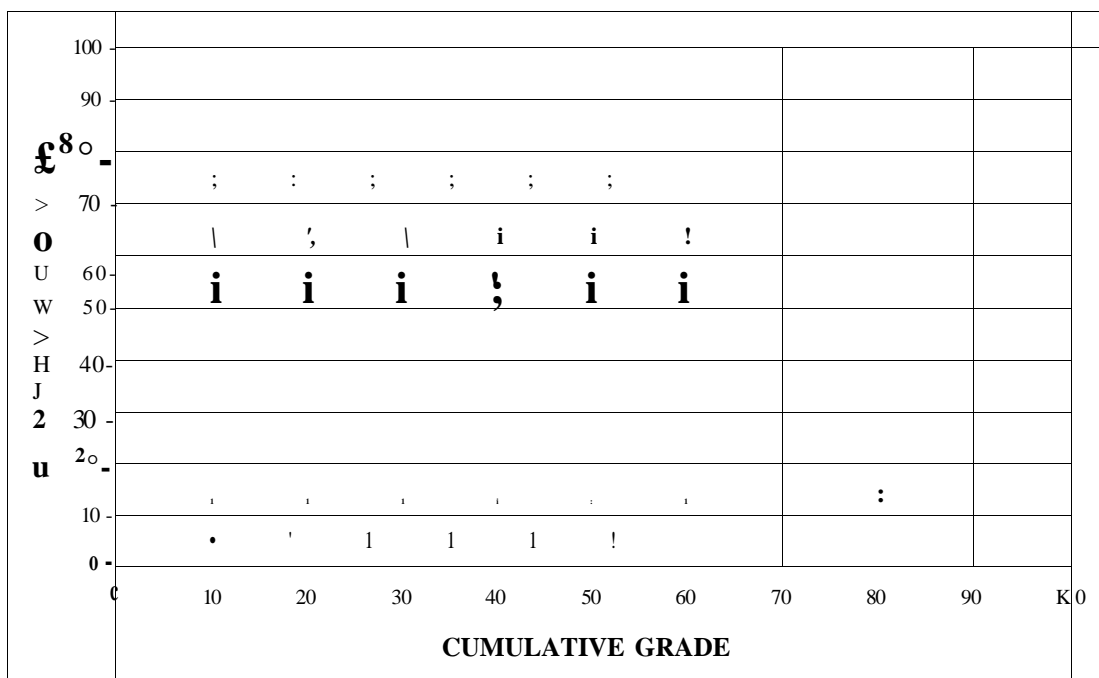
Parameter	Units	Model estimate
-KMAX	—	94.402
<b><i>h</i></b>	<b>min<sup>-1</sup></b>	0.528
<b><i>k</i><sub>2</sub></b>	<b>min<sup>-1</sup></b>	1.095
<b><i>v</i></b>	<b>min</b>	0.000
SER	—	2.521
<b>?</b>	—	0.990
Residual	—	0.003

Table 11—127. Summary of cumulative gangue recycled for a solid concentration of  
10.00 % in cell two of the SBFA

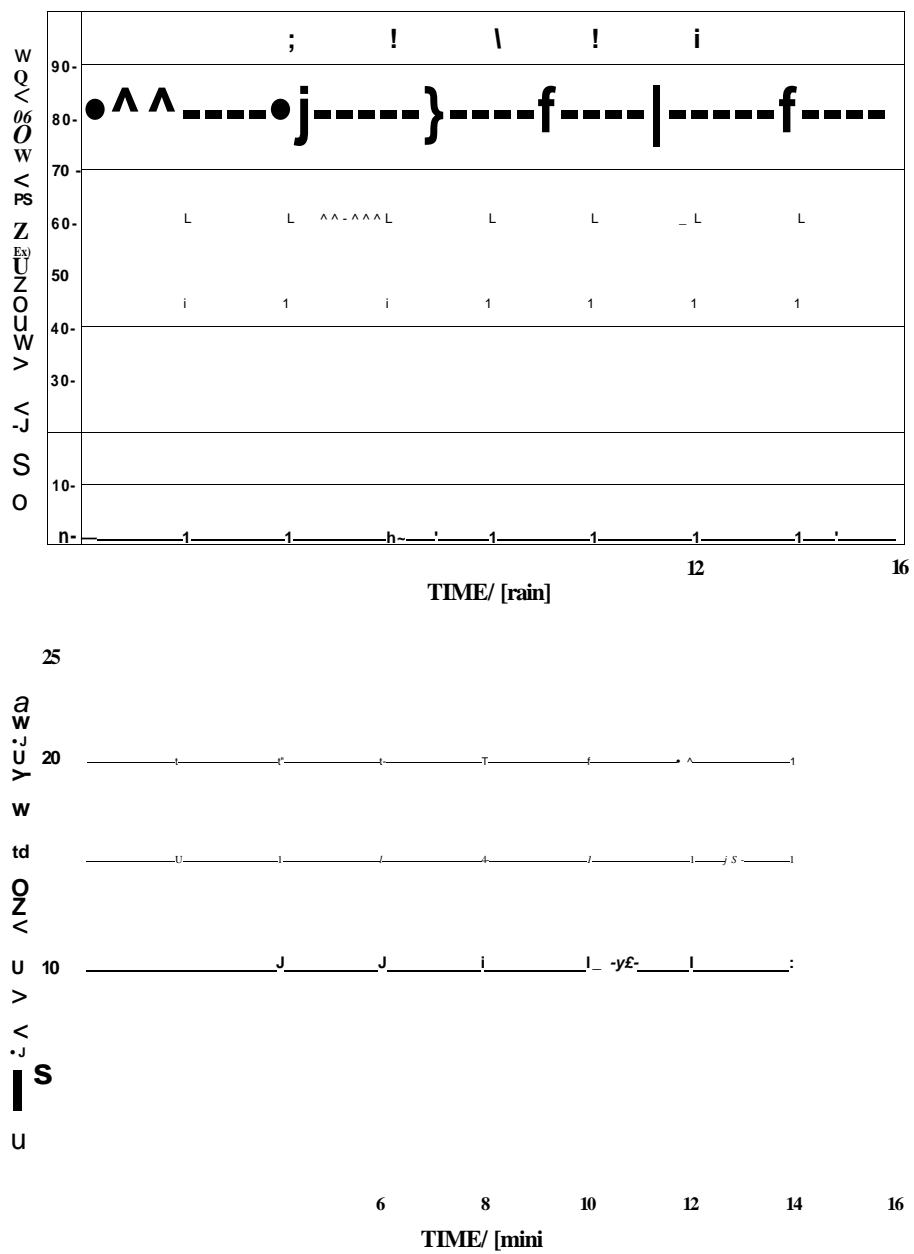
Time/ [min]	Mass Recycled/ [g]	Cumulative Mass Recycled/ [g]	Percentage Recycled, relative to total gangue added
0.00	0.00	0.00	0.00
2.00	32.20	32.20	0.59
3.00	18.23	50.43	0.93
5.00	64.99	115.41	2.13
7.00	84.82	200.23	3.70
10.00	253.91	454.15	8.39
15.00	641.35	1095.50	20.24



**Figure 11—75.** Cumulative recovery—time profile for a solid concentration of 10.00 % in cell two of the SBFA



**Figure 11—76.** Cumulative recovery—grade curve for a solid concentration of 10.00 % in cell two of the SBFA.



**Figure 11—76.** Variation in the cumulative concentrate grade for a solid concentration of 10.00 % in cell two of the SBFA.

**Table 11—128. Summary of the SBFA model input parameters for a solid concentration of 15.00 % in cell two of the SBFA**

<b>Model Parameters</b>	<b>Parameter Description</b>	<b>Units</b>	<b>Value</b>
<b>M(0)</b>	Total mass limestone charged into SBFA	grams	265.295
<b>M<sub>1</sub>(a)</b>	Limestone in cell one at time a	grams	265.295
<b>M<sub>1</sub>(b)</b>	Limestone in cell one at time b	grams	123.323
<b>M<sub>2</sub>(b)</b>	Limestone in cell two at time b	grams	141.972
<b>a</b>	Startup time a, related to first cell in SBFA	min	0.000
<b>b</b>	Startup time a, related to second in SBFA	min	1.218
Rf <sub>1</sub>	Froth recovery for cell one	—	0.974
Rf <sub>2</sub>	Froth recovery for cell two	—	0.922
A <sub>1</sub>	Cross sectional area of cell one	m <sup>2</sup>	0.176
A <sub>2</sub>	Cross sectional area of cell two	m <sup>2</sup>	0.065
Q <sub>1</sub>	Air flow rate in cell one	m <sup>3</sup> • min <sup>-1</sup>	0.205
Q <sub>2</sub>	Air flow rate in cell two	m <sup>3</sup> • min <sup>-1</sup>	0.049
n <sub>1</sub>	Flotation kinetic scaling parameter related to cell one		0.885
H <sub>2</sub>	Flotation kinetic scaling parameter related to cell two		2.998

**Table 11—129. Summary of data for a duplicate test at a solid concentration of 15.00 % in cell two of the SBFA**

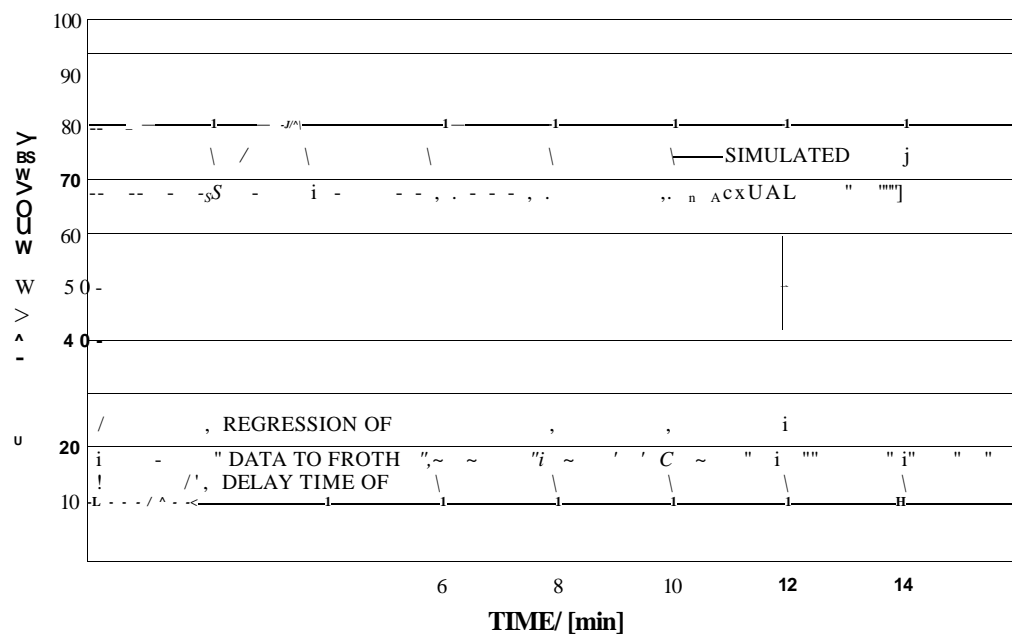
<b>Time/ [min]</b>	<b>Mass Before Acid Dissolution/ Isl</b>	<b>Mass After Acid Dissolution/ [g]</b>	<b>Mass Limestone/ [g]</b>	<b>Cumulative concentrate Grade/ [-]</b>	<b>Cumulative Limestone Recovery/ H</b>	<b>Simulated Limestone Recovery/ H</b>
0.50	117.00	28.70	88.30	75.47	33.28	33.13
2.00	145.20	51.70	93.50	69.34	68.53	64.25
3.00	49.40	24.90	24.50	66.21	77.76	75.98
5.00	65.20	42.80	22.40	60.70	86.21	87.64
7.00	63.10	51.40	11.70	54.65	90.62	91.92
10.00	52.10	46.00	6.10	50.10	92.92	93.81
15.00	50.30	49.10	1.20	45.68	93.37	94.28
<b>Tailings</b>	8335.55	8316.00	17.59	—	—	—

**Table 11—130. Summary of model parameters for a solid concentration of 15.00 % in cell two of the SBFA**

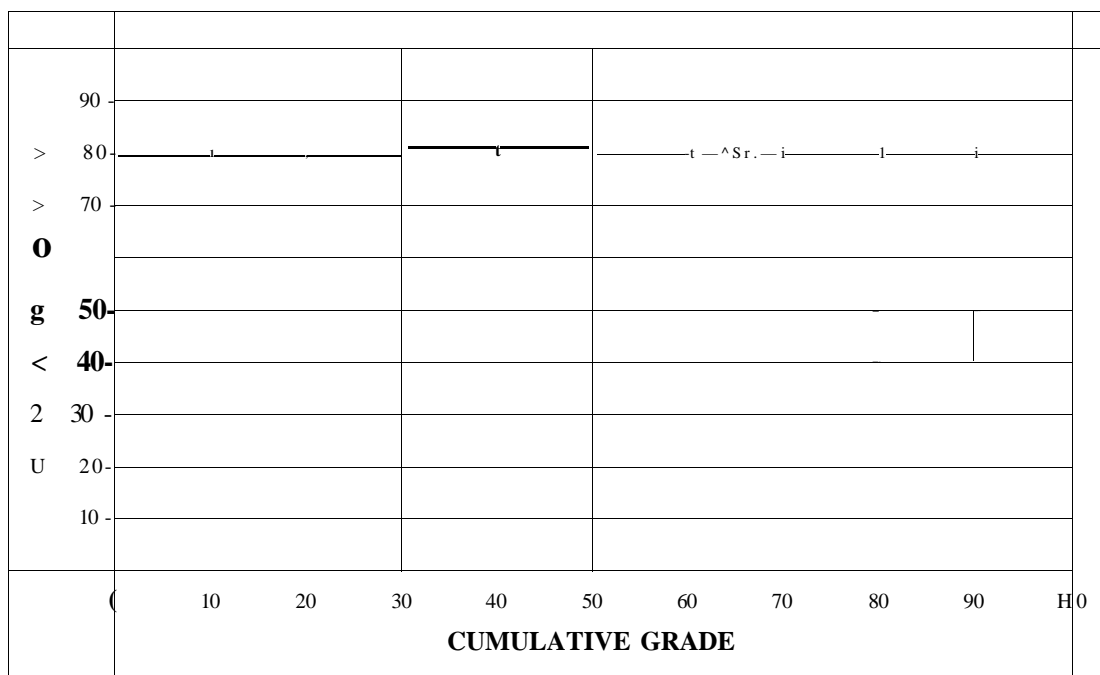
<b>Parameter</b>	<b>Units</b>	<b>Model estimate</b>
$\lambda^{\text{MAX}}$	—	94.323
<b><i>h</i></b>	min"	0.513
$k_2$	min" <sup>1</sup>	1.065
$v$	min	0.000
SER	—	2.319
$r^2$	—	0.990
Residual	—	0.003

**Table 11—131. Summary of cumulative gangue recycled for a solid concentration of 15.00 % in cell two of the SBFA**

<b>Time/ [min]</b>	<b>Mass Recycled/ [g]</b>	<b>Cumulative Mass Recycled/ [g]</b>	<b>Percentage Recycled, relative to total gangue added</b>
0.00	0.00	0.00	0.00
2.00	123.66	123.66	1.44
3.00	158.39	282.05	3.28
5.00	185.60	467.65	5.43
7.00	221.35	689.00	8.00
10.00	428.89	1117.89	12.98
15.00	995.25	2113.14	24.54



**Figure 11—78.** Cumulative recovery—time profile for a solid concentration of 15.00 % in cell two of the SBFA.



**Figure II—79.** Cumulative recovery—grade curve for a solid concentration of 15.00 % in cell two of the SBFA.



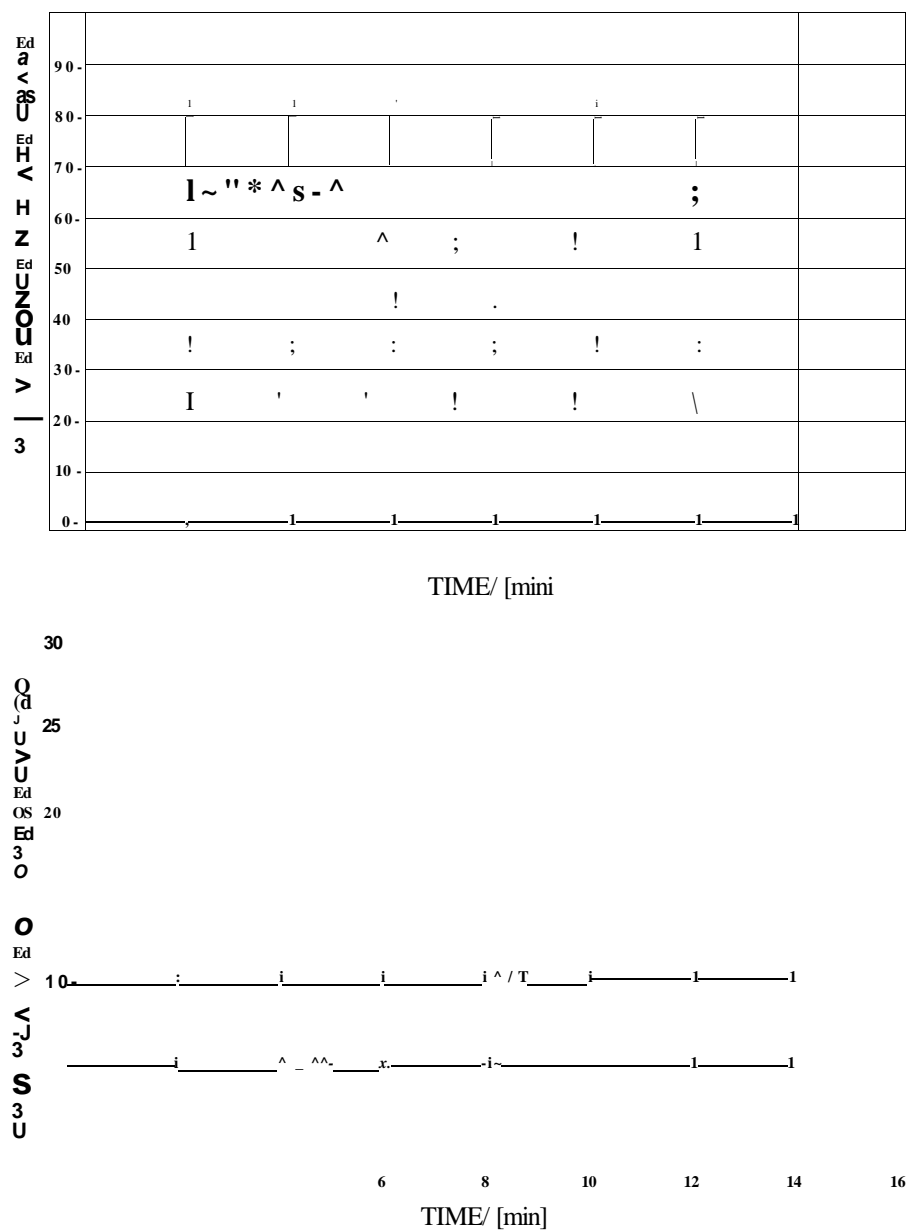


Figure 11—80. Variation in the cumulative concentrate grade for a solid concentration of 15.00 % in cell two of the SBF A.

**Table 11—132. Summary of size analysis data for the concentrate obtained from the SBFA having a pulp with 5.00 % solid by mass in cell one**

<b>Total Mass Of Tailings/</b>		2634.90		
<b>[g]</b>				
<b>Total Mass Of Concentrate/</b>		167.30		
<b>[g]</b>				
<b>Particle Diameter/ [µm]</b>	<b>Concentrate</b>		<b>Tailings</b>	
	<b>Limestone Mass/ [g]</b>	<b>Gangue Mass/ [g]</b>	<b>Limestone Mass/ [g]</b>	<b>Gangue Mass/ [g]</b>
268.328	0.985	0.362	5.639	7.676
230.217	3.270	0.281	0.655	3.155
195.346	14.740	2.774	0.291	49.711
164.317	8.700	0.163	0.239	8.638
144.914	9.167	2.657	0.000	82.634
132.288	15.569	9.305	0.007	283.257
115.109	6.395	3.180	0.100	411.360
102.956	6.938	4.109	0.090	182.724
94.868	14.806	10.465	0.020	517.209
82.158	9.488	4.324	0.500	548.606
63.048	14.284	6.771	0.142	435.851
48.836	8.099	5.159	0.686	99.311
41.352	2.851	1.998	0.600	4.759
0.000	0.000	0.000	0.000	0.000

Table II—133. Summary of size analysis data for the concentrate obtained from the SBFA having a pulp with 7.50 % solids by mass in cell one

Total Mass Of Tailings/ [g]		3862.88		
Total Mass Of Concentrate/ [g]		204.10		
Mean Particle Diameter/ [f*m]	Concentrate Limestone Mass/ [g]	Concentrate Gangue Mass/ [g]	Tailings Limestone Mass/ [g]	Tailings Gangue Mass/ [g]
268.328	0.999	0.828	4.331	11.264
230.217	2.919	1.409	0.960	4.625
195.346	10.605	10.742	0.426	72.878
164.317	8.764	2.039	0.351	12.664
144.914	7.860	6.551	0.000	121.146
132.288	17.505	12.814	0.011	415.267
115.109	6.322	5.348	0.736	603.072
102.956	6.985	6.481	0.133	267.882
94.868	16.575	14.228	0.029	758.252
82.158	10.092	6.743	1.104	804.281
63.048	2.688	22.975	0.208	638.977
48.836	2.511	13.649	1.006	145.595
41.352	2.002	3.907	0.636	6.977
0.000	0.000	0.000	0.000	0.000

**Table 11—134. Summary of size analysis data for the concentrate obtained from the SBFA having a pulp with 10.00 % solids by mass in cell one**

<b>Total Mass Of Tailings/</b>	5568.00			
<b>[g]</b>				
<b>Total Mass Of Concentrate/</b>	318.80			
<b>[g]</b>				
<b>Particle Diameter/ [µm]</b>	<b>Concentrate Limestone Mass/ [g]</b>	<b>Concentrate Gangue Mass/ [g]</b>	<b>Tailings Limestone Mass/ [g]</b>	<b>Tailings Gangue Mass/ [g]</b>
268.328	0.690	2.163	6.242	16.235
230.217	2.760	4.001	1.383	6.666
195.346	8.466	24.876	0.615	105.040
164.317	5.065	11.809	0.505	18.253
144.914	5.838	16.672	0.000	174.608
132.288	15.269	32.088	0.015	598.526
115.109	9.300	8.928	1.061	869.210
102.956	10.335	10.697	0.191	386.099
94.868	25.314	22.799	0.042	1092.871
82.158	3.012	23.283	0.080	1159.529
63.048	1.567	38.518	0.001	921.010
48.836	2.245	22.996	0.000	209.896
41.352	0.607	8.624	0.092	10.058
0.000	0.000	0.000	0.000	0.000

**Table 11—135. Summary of size analysis data for the concentrate obtained from the SBFA having a pulp with 15.00 % solids by mass in cell one**

<b>Total Mass Of Tailings/</b>		8610.60		
<b>[g]</b>				
<b>Total Mass Of Concentrate/</b>		542.30		
<b>[g]</b>				
<b>article Diameter/ [urn]</b>	<b>Concentrate Limestone Mass/ [g]</b>	<b>Concentrate Gangue Mass/ [g]</b>	<b>Tailings Limestone Mass/ [g]</b>	<b>Tailings Gangue Mass/ [g]</b>
268.328	4.121	0.732	9.6531	57.640
230.217	9.222	2.278	2.1393	23.665
195.346	37.956	18.762	0.9504	372.920
164.317	23.286	5.419	0.7814	64.803
144.914	24.797	13.495	0.0000	619.905
132.288	69.981	10.576	0.2621	2124.871
115.109	20.710	10.298	0.0000	146.019
102.956	22.471	13.307	0.0000	72.336
94.868	67.510	14.333	0.0653	3879.992
82.158	30.727	14.004	0.0000	588.100
63.048	21.811	46.377	0.1538	329.330
48.836	1.782	41.155	0.0000	327.654
41.352	14.181	1.522	1.6559	3.363
0.000	0.000	0.000	0.000	0.000