



# Scale-up procedures for gold-adsorption systems.

## Part 1: Adsorption kinetics

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### Synopsis

*Little is reported in the literature that is directly useful for the interpolation of film coefficients for the in-pulp adsorption circuits used in gold metallurgy. This can create a problem if the design or operation of these circuits is to be optimized by the use of simulation techniques. To address this problem, a study was undertaken on the influence of mixing intensity, scale, and geometry on the film coefficient in adsorption systems typical of the carbon-in-pulp plants used for gold extraction. This, the first paper deals with the influence of these factors on the film coefficient and shows that the specific power to just disperse the carbon in the slurry is an important variable. This variable is also strongly dependent on mixing intensity, scale, and geometry—a dependence that is dealt with in the second paper in the series. From the*

### Introduction

Adsorption processes in gold metallurgy rely on the transfer of gold-bearing species in solution to solid particles—either granules of activated carbon or beads of ion-exchange resin. The extraction economics are strongly dependent on the rate at which such transfer occurs, which is influenced by diffusional processes in the solution and/or within the adsorbent particles.

Film diffusion is particularly important in resin-based systems. Ahmed *et al.*<sup>1</sup> suggest that, with some resins, film diffusion is the only rate-controlling mechanism while, with others, film diffusion is rate-controlling at low gold loadings and exerts less influence at higher loadings.

For carbon-based systems, the picture is not clear. In the systems that he tested, Le Roux<sup>2</sup> showed that, at high concentrations of gold in solution, intra-particle diffusion was rate-controlling, but film diffusion played a more significant role as the gold concentration decreased. Most gold plants operate with gold concentrations well below those used in Le Roux's experiments, and film diffusion is therefore expected to be important in most of the carbon-in-pulp (CIP) and carbon-in-leach (CIL) processes used in these plants.

Unless the rate of gold adsorption onto the carbon is controlled by intra-particle diffusion alone, the value of the film coefficient is needed for any simulation study of the operation. In practice, this presents a problem because the film coefficient is sensitive to the intensity of mixing and to the scale and geometry of the adsorption vessel. What this means is that, to measure the film coefficient applicable to a given operation, the measurement must be conducted at the relevant scale and under the mixing conditions that are expected in that operation. This is the recommended procedure if the value of the coefficient is needed only under the expected mixing conditions.

This procedure is not adequate, however, if variations in design and operating conditions are to be investigated, or if it is not practical to conduct the measurements under operating conditions. In either case, what is required is a scale-up procedure that will allow reliable interpolation of the value of the film coefficient for systems having different scales and mixing conditions.

Most of the work that has been done on this problem has focused on systems that are much simpler than those that occur in gold-adsorption plants. In general, the experimental work has been conducted on systems in which the adsorbate is a solution that behaves in a Newtonian manner and in which the adsorbent tends to settle at low mixing intensity. Most adsorption systems in gold extraction are in-pulp processes in which the adsorbate is a slurry and is not Newtonian in behaviour. Further, at low mixing intensities, the adsorbent may settle or float, depending on the relative densities of the slurry and the carbon or resin particles.

To the authors' knowledge, no comprehensive study of the influence of scale and mixing conditions on the film coefficient in systems relevant to gold plants has been reported in the literature. This paper is a contribution in this direction. The study is targeted specifically at the CIP process. However, it is considered that the findings will apply equally well to any in-pulp process.

### Theory

The nomenclature used is listed at the end of the paper.

#### Adsorption kinetics

The rate of transfer of gold from a bulk solution to the surface of carbon particles is given by

$$R = k_f A (C - C^*), \quad [1]$$

where  $R$  is the mass-transfer rate of gold through the film (grams of gold per unit mass of carbon per second)

$k_f$  is the film mass-transfer coefficient or film coefficient (metres per second)

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# Gold-adsorption systems: Adsorption kinetics

*information obtained, practical scale-up procedures were developed. These procedures are considered to be applicable to resin-in-pulp as well as to carbon-in-pulp plants.*

$A$  is the external surface area of the carbon particles (square metres per unit mass of carbon)

$C$  and  $C^*$  are respectively the concentrations of gold in the bulk solution and at the solution-carbon interface (grams of gold per cubic metre of solution).

$C^*$  is determined by the gold loading at the surface of the carbon particles through the appropriate isotherm expression. When film diffusion is rate-controlling, this loading is the mean loading for the particle. When intraparticle diffusion exerts some influence, the loading at the surface is determined by intra-particle diffusion effects<sup>1,2</sup>.

### Mixing theory

In a mechanically agitated adsorption system, the intensity of mixing is related to the agitator speed,  $N$  (r/min). The greater the speed, the greater the intensity of mixing and the greater the power that must be supplied in order to maintain the speed of the agitator. The power supplied,  $P$ , is related to the agitator speed through equation [2]. In the assessment of mixing performance, reference is frequently made to the power per unit mass of the slurry or specific power,  $E$ , or to the torque per unit volume or specific torque,  $Q$ . These terms are defined in equations [3] and [4].

$$P = P_0 \rho_s N^3 D^5 \tag{2}$$

$$E = \frac{P}{V \rho_s} \tag{3}$$

$$Q = \frac{60P}{2\pi N} \tag{4}$$

where  $D$  is the impeller diameter

$P_0$  is the power number (dimensionless) that relates the actual and the theoretical power

$V$  is the volume of slurry

$\rho_s$  is the density of the slurry.

It is well known<sup>3</sup> that any increase in the intensity of mixing increases the film coefficient by increasing the convective component of mass transfer from the bulk solution to the surface of the carbon. This is shown in Figure 1. The mixing intensity also affects the extent to which the carbon particles are dispersed in the adsorption system, and this can have a very dramatic impact on the  $k_f A$  term. When the agitation intensity is insufficient, some of the carbon particles will tend to settle on the bottom of the vessel if their density is greater than that of the fluid, or will tend to float if their density is lower than that of the fluid. In either case, some of the exterior surface of the adsorbent phase is not available for mass transfer, and low values of the term  $k_f A$  result.

If the agitation intensity is gradually increased, a point is reached when all the particles are just fully dispersed in the fluid phase. This point is termed the 'just-dispersed' point, and is marked by a significant change in the relationship between agitation intensity and the composite term  $k_f A$ . At agitation intensities below this point, any increase in agitation intensity results in an increase in both  $k_f$  and  $A$ . Above the point, only  $k_f$  increases with increased agitation intensity. The just-dispersed point is therefore marked by a break in the curve, as shown in Figure 1.

Both the position of the just-dispersed point and the slope of the curve above this point can be strongly influenced by the scale and geometry of the mixing systems. The mixing in larger-scale systems tends to be less intense than in smaller-scale systems, and the just-suspended point tends to occur at lower agitation speeds<sup>4</sup>.

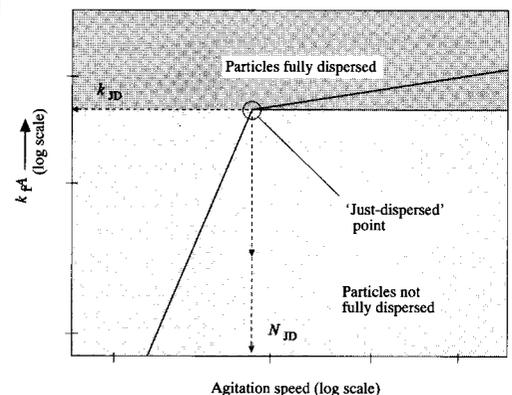


Figure 1—Influence of mixing intensity on  $k_f A$

## Mass-transfer correlations

For systems that are geometrically similar (i.e. systems in which the ratios of all the geometric dimensions are the same), mass-transfer data can be correlated by the use of expressions of the form of equation [5]. In the well-known Gilliland-Sherwood equation, the values of  $b$  and  $c$  are  $1/2$  and  $1/3$  respectively. Many similar expressions are reported in the literature for a variety of different adsorption systems<sup>3-7</sup>. Many of these include additional terms to describe the influence of geometry or other relevant factors.

$$Sh = a (Re)^b (Sc)^c, \quad [5]$$

where  $a$ ,  $b$ , and  $c$  are parameters

$Sh$ ,  $Re$ , and  $Sc$  are respectively the Sherwood, Reynolds, and Schmidt numbers defined as

$$Sh = \frac{k_f X_1}{d_s}, \quad Re = \frac{u X_2}{\nu}, \quad Sc = \frac{\nu}{d_s}. \quad [6]$$

In these equations,  $d_s$  and  $\nu$  are respectively the molecular diffusion coefficient for the adsorbing species and the kinematic viscosity of the adsorbate.  $X_1$  and  $X_2$  are characteristic linear dimensions, different workers defining them in different ways.  $X_1$  in the Sherwood number is usually taken to be the particle diameter or the impeller diameter. In the Reynolds number,  $X_2$  is usually defined as the diameter of either the particle or the impeller.

The term  $u$  in equation [6] is the mean superficial slip velocity between the adsorbent particle and the bulk fluid. Its definition presents something of a problem. An attempt has been made to evaluate this term from first principles using the Kolmogoroff theory of turbulence<sup>8</sup>. (This theory models the distribution of turbulent eddies in the fully turbulent region.) The treatment yields a mean slip velocity that is related to the specific power input as shown in expression [7]. In this case, the Reynolds number takes the form indicated.

$$u \propto (ED)^{1/3}; \quad Re = \frac{D^{4/3} E^{1/3}}{\nu}. \quad [7]$$

Another approach that is commonly taken is to consider that the mean slip velocity will be related to the tip speed of the impeller ( $\pi ND/60$ ). In this case, the characteristic dimension  $X_2$  in the Reynolds number is the impeller diameter,  $D$ , and the resulting expression — equation [8] — is termed the impeller Reynolds number:

$$u \propto \pi ND / 60; \quad Re = \frac{ND^2}{\nu}. \quad [8]$$

Mass-transfer correlations can be used to predict the values of film coefficients if reliable values for the parameters  $a$ ,  $b$ , and  $c$  are known. For gold-adsorption systems, this approach is usually not immediately useful. Firstly, the systems tend to be more complex than those that were used for the evaluation of the parameters. Secondly, there is usually some uncertainty about the physical properties of the system, particularly the values of  $d_s$  and  $\nu$ . However, the correlations do have utility for gold-adsorption systems as a basis for the development of scale-up equations. This approach is considered shortly.

## Influence of mixing intensity in a given vessel

When the mixing intensity in a given adsorption vessel varies, the impact on the film coefficient can be predicted from the mass-transfer correlations. Because the power or the agitator speed is the only factor that varies, the expressions simplify to

$$k_f \propto N^f; \quad k_f \propto E^g. \quad [9]$$

If the exponents in the Gilliland-Sherwood equation apply, the values of the parameters  $f$  and  $g$  will be  $1/2$  and  $1/6$  respectively.

## Scale independence of $k_{JD}$

Nienow *et al.*<sup>4</sup> suggest a design procedure for adsorption systems that is based on the scale independence of the film coefficient at the just-dispersed point. The procedure is based on three observations.

The first of these is that the exponent  $g$  in equation [9] is small. Consequently, it is usually not economical to design a mixing system to operate much above the just-dispersed point. Large increases in power would be required to achieve only small increases in film coefficient and hence in adsorption rates. Accordingly, he suggests that mixing systems should be designed to operate just above this point. Therefore, the appropriate film coefficient for use in design is the coefficient at the just-dispersed point.

The second observation is that, at the just-dispersed point, the mean slip velocity should be a minimum and should be related to the terminal settling velocity of the particles in the adsorbate. The argument arises from a simple model of the dispersion process in systems where particles tend to settle and so need to be suspended. The argument is based on the idea that, for the particle to remain just suspended off the bottom of the tank, the adsorbate in that region must have an upward velocity at least equal to the settling velocity of the particles. The just-dispersed condition is viewed as that point at which the average upward velocities at the tank bottom are equal to the particle settling rates.

Nienow then suggests that the Reynolds number for the particles can be estimated by the use of the experimentally determined value of the settling rate in equation [7], after which equation [5] or a relevant equivalent can be used in the estimation of the associated film coefficient.

The third observation that is relevant is that the slip velocity at the just-dispersed point should be a characteristic of the particle-adsorbate system and not dependent on geometry or scale. This must be true if the link between the slip velocity at the just-dispersed point and the settling velocity is valid. Because the settling velocity is a property of the particle-fluid system, and not of the geometry, the patterns of fluid flow at the bottom of any flat-bottomed tank must be the same at the just-suspended point. If the fluid-flow patterns are the same, and the adsorbate and particles are the same, then the mass-transfer rates should also be the same. The important conclusion from this line of argument is that the value of the film coefficient at the just-suspended point should be independent of the geometry in flat-bottomed tanks. In consequence, its value can be measured in a laboratory or pilot plant and should be the same at any scale.

Nienow *et al.*<sup>4</sup> showed that, for the systems he tested, the assumption was a good one. His tests covered 40 different impeller-vessel configurations. Coetzee and Cloete<sup>9</sup> also found it to be a reasonable assumption for a system involving resin in solution.

*Scale-up equations*

The approach adopted when scale-up equations are used envisages two adsorption systems: a prototype and a model. Measurements are conducted on the model system, and the data obtained are interpolated by means of the scale-up equations to give an estimate of the film coefficient in the prototype system. So that all the variables that do not depend on scale and mixing intensity are eliminated, the chemical and physical properties of the slurry and the particles are the same in both systems. In addition, geometric effects are eliminated to some degree in that the model is made geometrically similar to the prototype. The reliability of the interpolation depends on how well the scale-up equations describe the influence of scale and mixing on the film coefficient.

Scale-up equations can be developed from the mass-transfer correlations that have already been described. The correlations are modified by the combination into a proportionality constant of all the variables that are not dependent on scale and mixing intensity. Depending on how  $X_1$ ,  $X_2$ , and the Reynolds number are defined, this leads to a variety of expressions of the form of equation [10], from which scale-up expressions of the form of equation [11] can be developed. The subscripts 'model' and 'proto' in this equation refer to the values associated with the two adsorption systems, and  $h, j, m$ , and  $n$  are parameters. Additional terms may be required if they occur in the original correlation equation.

$$k_f \propto \frac{Re^b}{X_1} = \frac{(NDX_2)^b}{X_1} \quad [10]$$

$$\frac{k_{f, \text{proto}}}{k_{f, \text{model}}} = \left\{ \frac{N_{\text{proto}}}{N_{\text{model}}} \right\}^h \left\{ \frac{D_{\text{proto}}}{D_{\text{model}}} \right\}^j \quad [11]$$

$$= \left\{ \frac{E_{\text{proto}}}{E_{\text{model}}} \right\}^m \left\{ \frac{D_{\text{proto}}}{D_{\text{model}}} \right\}^n$$

**Experimental**

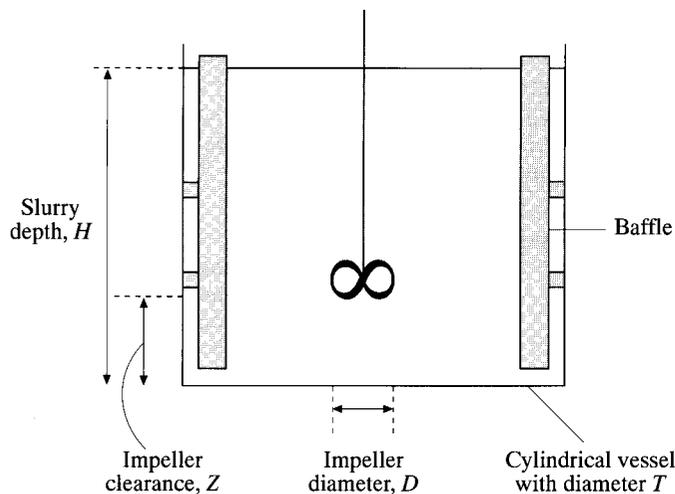
To investigate the nature of the influence of the relevant factors on the film coefficients in gold in-pulp adsorption systems, kinetic experiments were conducted under a variety of adsorption conditions. The film coefficients were determined under mixing conditions where the speed and power input were carefully measured. The experiments were specifically designed so that the only factors that were varied in the various tests were scale, geometry, and mixing intensity. The compositions, temperature, and pH of the slurry were the same in all the tests. The type, loading, preparation, and size distribution of the carbon particles and their concentration in the slurry were kept constant. To simplify matters further, a standard mixer geometry was used, as indicated in Figure 2. The only geometric factors that were varied in the study were the ratios of tank to impeller diameters,  $TID$ . The majority of the tests were conducted using hydrofoil impellers having a pitch of 20 degrees. The diameters of the vessels used were 185, 305, 330, 690, and 1200 mm. Specific details of the experiments are given elsewhere<sup>10</sup>.

*Adsorption chemistry in the experiments*

The adsorption system studied is relevant to CIP practice in South Africa. Filter-plant residue from Western Deep Levels was used to make up the slurry. The size distribution of the solids in the residue was as follows:

Size, $\mu\text{m}$	150	90	75
Cumulative % passing	97,5	79,6	72,2.

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### Relevant geometric ratios for the adsorption system tested:

Slurry depth,	$H = T$
Impeller clearance, $Z$	$= 0,25 T$
Number of baffles	$= 4$
Width of baffles	$= 0,10 T$
Height of baffles	$= T$
Baffle clearance	
Off tank bottom	$= 0,075 T$
Off tank wall	$= 0,02 T$

Figure 2—Geometry of the adsorption system used

To ensure that the chemistry of the solution would not change from test to test, the standard recipe of the Anglo American Research Laboratory (AARL)<sup>2</sup> was used for the solution in each test, i.e. calcium chloride (3,2 g/l) and sodium cyanide (200 mg/l) buffered with boric acid (3,1 g/l) and sodium hydroxide (1,75 g/l) to give a pH value of about 10 in each experiment. All the tests were conducted at ambient temperatures in a laboratory.

A large sample of virgin carbon in the size range 1,0 to 2,36 mm was washed with water and in 5 per cent hydrochloric acid, and was then thoroughly rinsed in water and dried at 110°C. In each test, the carbon concentration was 5 g/l, the required mass of carbon being soaked in water a day before each test.

The dry density of the carbon was about 760 kg/m<sup>3</sup>. The specific exterior surface area of the carbon was estimated from this value on the assumption that the particles were spherical. In practice, adsorption performance is modelled by use of the composite term  $k_f A$  so that the errors associated with the assumption of sphericity are cancelled.

### Measurement of the film coefficient

The film-transfer coefficient for each adsorption condition was measured in a standard batch kinetic experiment. The gold slurry was stirred well in the adsorption vessel, and the gold concentration of the solution was determined at intervals after the carbon had been added.

To facilitate accurate determination of the film-transfer coefficient, the experimental conditions were chosen so that film diffusion would be rate-controlling. To do this, the following three precautions were observed.

- ▶ The initial gold concentration selected was low (5 p.p.m. or less). Le Roux<sup>2</sup> had shown that, at these initial concentrations, the intra-particle diffusion effects are not likely to be significant during the first half hour or so of adsorption.
- ▶ The adsorption was measured over a short period of time just after the carbon had been added to the adsorption vessel. Five samples were taken over a ten-minute period.
- ▶ Virgin carbon was used to ensure, firstly, that the term  $C^*$  in equation [1] was initially zero and, secondly, that all the carbon particles had the same gold loading at the start of the experiment.

Under these experimental conditions, equation [1] and the gold balance for the system yielded equation [12]. Le Roux<sup>2</sup> had shown that little error is introduced if  $C^*$  is assumed to be zero over the initial period of adsorption. In this case, the film-transfer coefficient, or the product  $k_f A$ , can be determined by simple regression of equation [13]:

$$\frac{dC(t)}{C(t) - C^*} = -\frac{k_f A M}{V} dt \quad [12]$$

$$\ln \frac{C(t)}{C_0} = -\frac{k_f A M}{V} t, \quad [13]$$

where  $C(t)$  is the gold concentration in solution at time  $t$

$M$  and  $V$  are respectively the mass of carbon and the volume of solution in the adsorption vessel.

### Measurement of power input

A load cell measured the restraining force on a torque arm so that the applied torque,  $\tau$ , could be determined. The power required to maintain the desired agitator speed was determined from this by use of equation [14]:

$$P = 2\pi \frac{N}{60} \tau. \quad [14]$$

Turbulence in the vessels caused the readings of force to fluctuate. In the smaller rig (used for the test with vessel diameters of 185, 303, and 330 mm), heavy electronic damping of the signal from the load cell was necessary to enable the mean restraining force to be measured reliably. In the two larger vessels, mechanical damping of the torque arm by a spring and dash-pot arrangement was needed in addition to electronic damping.

*Determination of the just-dispersed point*

The mixer speed, power, and specific power at the just-dispersed point (respectively  $N_{JD}$ ,  $P_{JD}$ , and  $E_{JD}$ ) can be determined<sup>11</sup> by varying the agitator speed and observing the bottom of the tank (or the surface of the fluid if the adsorbent particles float). Coetzee and Cloete<sup>9</sup> and Chudacek<sup>12</sup> measured the concentration of solids near the tank bottom to establish when the just-dispersed condition was reached. The measurement of the film coefficient as a function of agitator speed or power (Figure 1) can also be used<sup>9</sup>. This was the method employed in the study described here. Coetzee and Cloete<sup>9</sup> showed, for resin in solution systems, that the different methods give similar results.

**Results**

Initial tests indicated that the film coefficient could be measured with good precision. The relative standard deviations on replicate tests ranged between 3,3 and 5,2 per cent.

The kinetic data were described very well by equation [13]. The correlation coefficients for the seventy-nine tests conducted were all greater than 0,972, and all but six were greater than 0,99. These results support the assumption that the film diffusion was rate-controlling during the experiments. As shown in Figures 3 and 4, the experimental procedure gave results that distinguished quite clearly the effect of agitator speed on the film coefficient.

Figure 4 indicates that the data were sufficiently consistent and accurate to define the relationships between the film coefficient and the mixing intensity in the region of interest. To determine the relevant parameters, including  $k_f$  and  $N_{JD}$ , each set of data was fitted to a simple bi-linear model—equation [15]. The values of  $P_{JD}$  and  $E_{JD}$  were estimated by the same approach. The high values of the correlation coefficients obtained, all greater than 0,995, indicate that the relevant parameters for each data set could be estimated with confidence.

$$\begin{aligned}
 k_f &= \alpha + \beta N : N \leq N_{JD} \\
 k_f &= \delta + \gamma N : N > N_{JD}.
 \end{aligned}
 \tag{15}$$

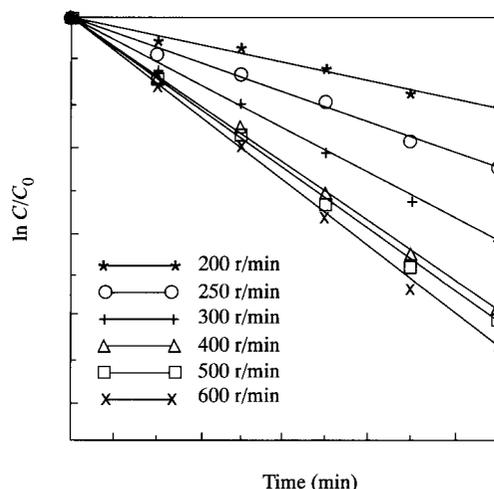


Figure 3—Batch kinetic curves for the vessel with a diameter of 305 mm and an impeller (hydrofoil) diameter of 142 mm

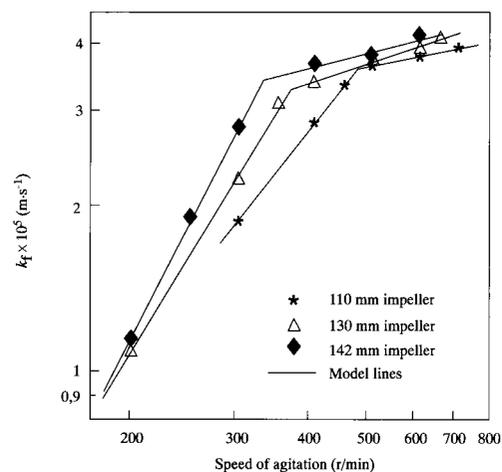


Figure 4—Film coefficients versus agitator speed for the vessel of 305 mm diameter with hydrofoil impellers

**Discussion**

*Influence of mixing intensity on the film coefficient*

Values for  $g$ , the exponent on  $E$  in equation [9], have been reported by various workers. Oldshue<sup>3</sup> reported values between 0,05 and 0,2, Nienow<sup>13</sup> values from 0,12 to 0,2, Letterman *et al.*<sup>7</sup> a value of 0,149, and Coetzee and Cloete<sup>9</sup> values of 0,167, 0,203, and 0,265.

In the work reported here, the exponent was found to vary between 0,074 and 0,162 (Table I), and the mean value was 0,123 with a relative standard deviation of 3,5 per cent. These values are at the lower end of the range found by others.

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Table I

## $k_{JD}$ and the exponent on E (specific power)

Vessel diameter, mm	Impeller type and diameter, mm	$k_{JD} \times 10^5$ (from power data) $m \cdot s^{-1}$	Exponent on E
185	Hydrofoil/110	3,65	0,103
305	Hydrofoil/110	3,66	0,077
	130	3,38	0,153
	142	3,41	0,097
330	Hydrofoil/110	3,62	0,156
	130	3,84	0,074
	142	3,52	0,145
690	Hydrofoil/275	3,64	0,136
1200	Hydrofoil/480	3,27	0,162
185	45° pitched/75	3,61	0,107
185	Flat blade/75	3,61	0,100

Because only 3 or 4 data points were available for each of the adsorption conditions tested, some scatter in the values of the exponent was expected. No discernable pattern was apparent. Consequently, little can be said about the dependence of the exponent on scale and geometry other than that any variation that might exist occurs in a narrow range.

### Scale independence of $k_{JD}$

The data generated in this study suggest that, for the gold-adsorption systems tested, the film coefficient at the just-dispersed point is essentially independent of scale and the  $T/D$  ratio. As will be seen shortly, it also appears to be independent of impeller type.

The relative scale independence of  $k_{JD}$  for the system tested is shown in Table I and Figure 5. The mean value of the coefficient at this point was found to be  $3,52 \times 10^{-5} m \cdot s^{-1}$  from the speed data in equation [13], and  $3,55 \times 10^{-5} m \cdot s^{-1}$  from the power data. The relative standard deviations associated with these measurements were 4,62 and 4,94 per cent respectively. Since replicate measurements of the film coefficient gave relative standard deviations of between 3,3 and 5,2 per cent, it can be seen that the differences between the measured values of  $k_{JD}$  are not statistically significant. In addition, a pairing comparison shows that, at a 95 per cent confidence level, there is no difference between the values of  $k_{JD}$  when estimated from correlations of  $k_f$  against speed or from correlations of  $k_f$  against power.

If note is taken of Nienow's recommendation that mixing systems should be designed to operate just above the just-dispersed point, the findings mentioned are of great importance. What they indicate is that, at this point, the film coefficient that will apply on a large scale can be determined on a laboratory or pilot scale.

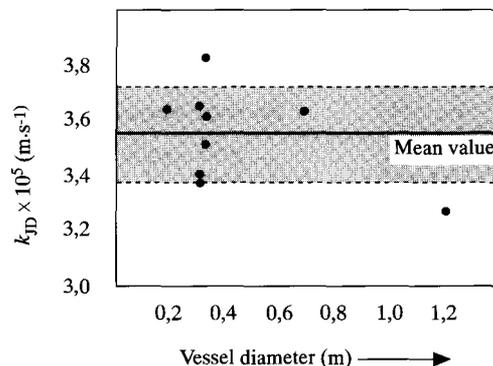


Figure 5—Scale dependence of  $k_{JD}$  determined from power versus  $k_f$  data (the shaded area indicates the 5 per cent error band about the mean)

A note of caution should be sounded at this point. The conclusions stated here are based on tests that were carried out over a rather limited range of scales and in small agitators, with diameters of 0,185 to 1,2 m. Closer examination of Figure 5 suggests that there may be a very slight reduction in  $k_{JD}$  with increased scale. Over the small range of scales tested, this reduction, if real, is less than the expected experimental error. However, if the trend is real, the value of  $k_{JD}$  in a full-scale plant may be slightly lower than in geometrically similar vessels on a laboratory scale.

### Scale-up equations

As a first step in an examination of possible scale-up expressions for the gold-adsorption systems tested, regression analyses were conducted on all the mass-transfer data for the hydrofoil tests above the just-dispersed point. Several expressions were investigated. The better correlations that were found are presented in Table II.

Several points emerge from Table II. Firstly, it is apparent that the film coefficient correlates most strongly with the specific power and less strongly with the agitator speed. Correlations against tip speed and specific torque were very much poorer. Secondly, it is interesting that a very strong correlation exists between the film coefficient and the specific power alone. The strength of the correlation will be appreciated from an examination of Figure 6, where all the data for the hydrofoils are shown in one diagram.

It is not clear whether the three-parameter correlation (expression 1 in Table II) is statistically more meaningful than the two-parameter correlation involving specific power alone (expression 2). A significance test (described in the Addendum) showed that the three-parameter expression is a better model than the two-parameter expression, but that this can be stated only with 95 per cent confidence, and not 99 per cent confidence.

### Acknowledgements

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### References

1. AHMED, F.E., YOUNG, B.D. and BRYSON, A.W. Comparison and modelling of the adsorption kinetics of gold cyanide onto activated carbon and resin in a silica slurry. *Hydrometallurgy*, vol. 30. 1992. pp. 257-275.

**Table II**  
**Correlations for film coefficients of the hydrofoil impellers**

Expression	Correlation equation	Correlation coefficient*
1	$k_f \propto E^{0,114} (T/D)^{0,073}$	0,908
2	$k_f \propto E^{0,104}$	0,893
3	$k_f \propto N^{0,115} (T/D)^{-0,131}$	0,821
4	$k_f \propto N^{0,167} D^{0,062}$	0,773
5	$k_f \propto N^{0,10} T^{-0,011}$	0,753

\* The correlation coefficients for all the other correlations tested were less than 0,75

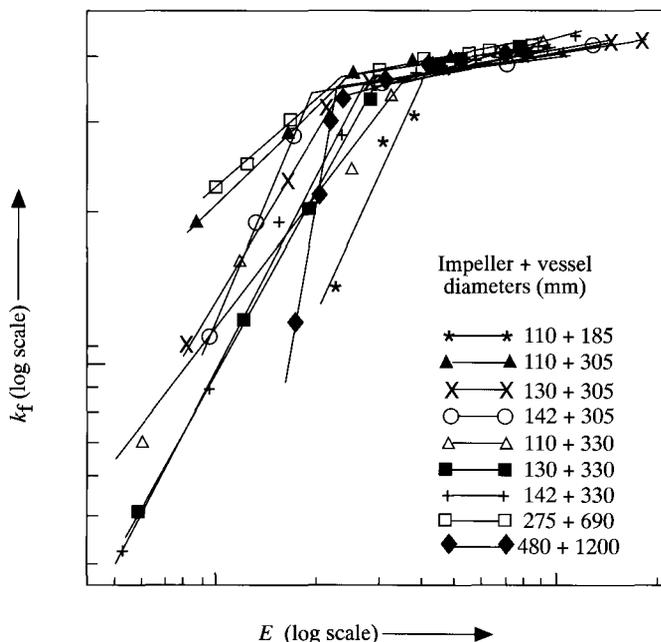


Figure 6— $k_f$  versus  $E$  for the hydrofoil impellers

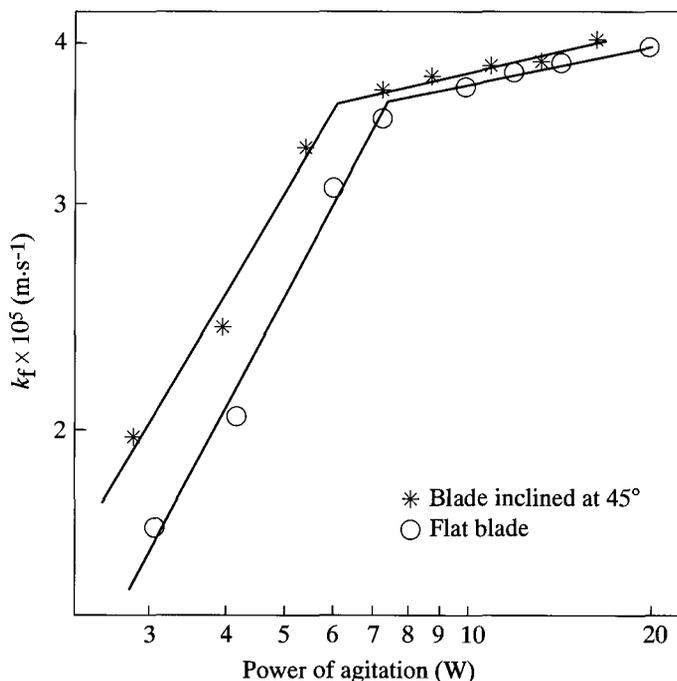


Figure 7— $k_f$  versus power for inclined- and flat-bladed impellers

*Influence of impeller type*

A limited number of tests were conducted to establish the relationship between the film coefficient and the mixing intensity for impellers of two different types: impellers with flat blades and impellers with blades pitched at 45 degrees, each type having six blades and a diameter of 75 mm. The tests were conducted in the tank of 185 mm diameter, the system geometry being the same as in the tests using hydrofoil impellers. The results are illustrated in Figure 7, and are compared with those of the hydrofoil tests in Figure 8.

Two things are immediately apparent from Figure 8.

Firstly, the values of  $k_{jD}$  are very similar to those for the hydrofoils (Table I). This observation is very interesting and gives strong support to Nienow's suggestion that hydrodynamic conditions in the mixer at the just-dispersed point must be characteristic of the particle-adsorbate system and largely independent of the mixer geometry.

The second important observation from Figure 8 is that the slopes of the curves for the two impellers are very similar to those for the hydrofoils. (The relevant data are also presented in Table I, where they are compared with the data for the hydrofoil impellers.) This is a little surprising in that many workers<sup>3, 4, 13</sup> have noted that the exponent in equation [9] is strongly influenced by the geometry of the system. What is more, the flat-bladed impeller is very different in its mixing action from that of the other impellers tested<sup>4</sup> and, as a consequence, a rather different relationship between  $k$  and  $E$  is expected when the geometry is different.

Figure 8 shows that the variable that changes most with changes in the adsorption system is  $E_{jD}$ . Even in the hydrofoil tests, a noticeable scale dependence of  $E_{jD}$  was discerned. (This dependence is examined more closely in the next paper in the series.)

The observations that  $E_{jD}$  is very scale-dependent, while  $k_{jD}$  and  $g$  are not, suggests a very simple model for the scale dependency of the film coefficient in gold-adsorption systems. The model is presented as equation [16] and is depicted graphically in Figure 9.

$$k/k_{jD} = (E/E_{jD})^x \tag{16}$$

where  $x$  is a parameter.

# Gold-adsorption systems: Adsorption kinetics

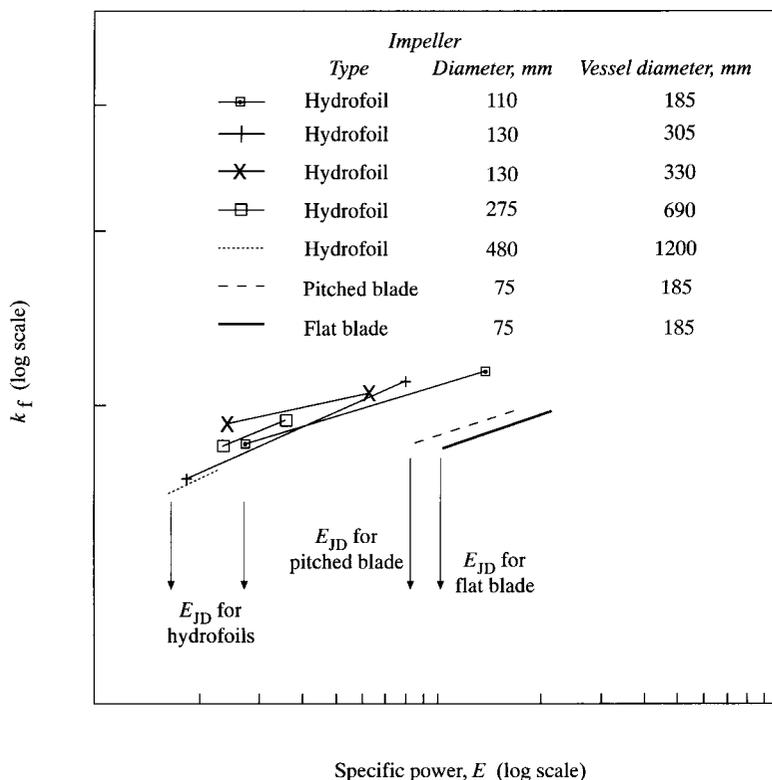


Figure 8— $k_f$  versus  $E$  for three types of impeller

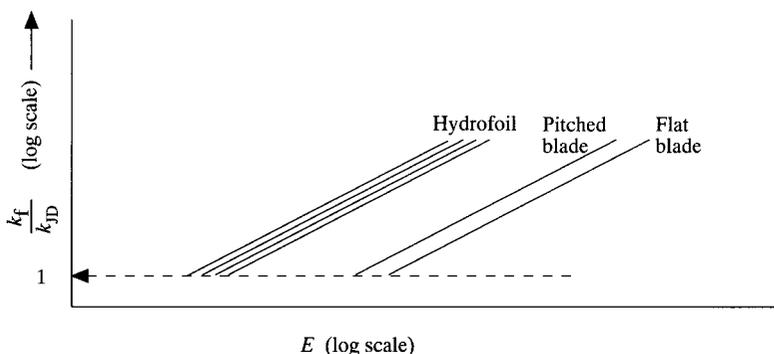


Figure 9—Simple model for the relationship between  $k_f$  and  $E$

- LE ROUX, J.D., BRYSON, A.W., and YOUNG, B.D. A comparison of several kinetic models for the adsorption of gold cyanide. *J. S. Afr. Inst. Min. Metall.*, vol. 91, no. 3. 1991. pp. 95–103.
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The model describes the hydrofoil data almost as well as expressions 1 and 2 in Table II, the correlation coefficient being 0,886 as compared with 0,908 and 0,893 respectively. The use of the *F*-test to give a more sensitive indication of the relative merits of the models (Addendum) reveals that, although the correlation coefficients are fairly close and equation [16] has only a single parameter, this equation is not as good a model as either expression 1 or 2 in Table II. However, in addition to its simplicity, this model has the considerable advantage of being able to describe the influence of geometric effects through their influence on  $E_{JD}$ . Provided that scale and geometry affect the exponent on specific power no more than has been found in

this study, equation [16] should provide a very adequate basis for the interpolation of film coefficients.

## Constraints

Caution must be exercised in the use of the data presented here in situations very different from the experimental conditions reported. The correlations and data presented apply to CIP adsorption systems having a specific geometry (Figure 2). In addition, the range of vessel diameters tested was not large—0,185 to 1,2 m. Further, the particles of adsorbent tended to float at low agitation intensity, an adsorption situation that has received very little attention in the literature<sup>8</sup>. It is known that such systems require more energy to disperse the particles of adsorbent<sup>8</sup>, and they may very well differ in other ways from systems in which the particles have a tendency to settle.

In addition, the in-pulp adsorption systems that were investigated are rather different from the systems employed in most mass-transfer investigations reported in the literature. This may explain why some of the parameter values and trends found in this work differ from those reported by others.

## Conclusions

Useful progress has been made in the understanding of the factors affecting the scale dependence of film-transfer coefficients in gold in-pulp adsorption systems. Note should be taken of the following points.

- The film coefficient correlates most strongly with the specific power input.
- The experimental technique used in this study provides data that are sufficiently precise to allow reliable estimates to be made of film coefficients and scale-up parameters.
- The data generated show that, for CIP adsorption systems, the exponent in the relationship between the film coefficient and the specific power input was similar to that found by other workers for different adsorption systems. What is more, the data indicate that, for the gold-adsorption systems tested, the value of this exponent appears to be relatively independent of scale,  $T/D$  ratio, and impeller type.
- The film coefficient at the just-dispersed point was found to be essentially independent of scale (over the range tested) and of the ratio of tank to impeller diameters. It was also found to be independent of the type of impeller used, though only three types were tested. The film coefficient at this point can be estimated reliably from either the agitator speed or the power data.

# Gold-adsorption systems: Adsorption kinetics

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- The implication of the observations made is that, for gold in-pulp adsorption systems, only one factor is strongly dependent on scale and geometry, namely the power input (or agitator speed) needed to just disperse the carbon particles.

The study has shown that at least three scale-up procedures can be followed for the interpolation of the values of the film coefficient in gold-adsorption systems. These are summarized below. When these procedures are used, special note should be taken of the constraints controlling their applicability, as outlined earlier.

**Procedure A.** Measure the values of the film coefficient,  $k_{\text{meas}}$ , and the specific power input,  $E_{\text{meas}}$ , under convenient conditions in an adsorption system that is geometrically similar to the system of interest. For the desired value of  $E_{\text{scale}}$  (the specific energy input at a different scale), use equation [17] to predict  $k_{\text{scale}}$  (the film coefficient at that scale and mixing intensity). The values of the exponents in this equation should be checked experimentally if the impeller type and geometry are very different from those on which the expression is based—notably 20 degree hydrofoil impellers and the geometry shown in Figure 2. In addition, the expression assumes that both  $E_{\text{scale}}$  and  $E_{\text{meas}}$  are greater than the specific powers at the associated just-dispersed points ( $E_{\text{JD, scale}}$  and  $E_{\text{JD, meas}}$ ).

$$\frac{k_{\text{scale}}}{k_{\text{meas}}} = \left( \frac{E_{\text{scale}}}{E_{\text{meas}}} \right)^{0.114} \left( \frac{T/D_{\text{scale}}}{T/D_{\text{meas}}} \right)^{0.073} \quad [17]$$

**Procedure B.** At a convenient scale, measure the value of the film coefficient at the just-dispersed point. Assume that, at a different scale, the coefficient will have the same value at the power input required at that scale to just disperse the adsorbent particles.

**Procedure C.** Use the same experimental procedure as in Procedure B to determine  $k_{\text{JD}}$ , but use equation [18] to predict the value of  $k_{\text{scale}}$ . If the adsorption system is very different from that reported in this study, then the value of the exponent should be determined experimentally at any convenient scale.  $E_{\text{JD, scale}}$  (the specific power to just disperse the particles at the scale of interest) must be obtained from some other source.

$$\frac{k_{\text{scale}}}{k_{\text{meas}}} = \left( \frac{E_{\text{scale}}}{E_{\text{JD, scale}}} \right)^{0.096} \quad [18]$$

Procedure C is the more elegant and the more general of the three. A feature of the procedures described is the need to obtain an estimate of  $E_{\text{JD, scale}}$ . Methods for the evaluation of this variable and the nature of its scale dependence are the subject of the next paper in this series.

## Nomenclature

Parameters:  $a, b, c, f, g, h, j, m, n, x, \alpha, \beta, \lambda$

Subscripts: scale indicates values at the desired scale  
 proto indicates values in the prototype  
 meas indicates measured values  
 model indicates values in the model.

Variables:

$A$	Superficial area of the carbon phase per unit mass of carbon
$C, C^*, C_0$	Respectively the gold concentration in solution, at the surface of the carbon particles, and at the start of a batch kinetic test
$d_s$	Molecular diffusion coefficient
$D$	Impeller diameter
$E$	Specific power input
$k_f$	Film-transfer coefficient
$N$	Rotational speed of agitator
$M$	Mass of carbon
$P$	Power input
$P_0$	Power number
$Q$	Specific torque
$R$	Adsorption rate
$Re$	Reynolds number
$Sc$	Schmidt number
$Sh$	Sherwood number
$t$	Time
$u$	Superficial slip velocity
$V$	Volume of solution
$X_1, X_2$	Characteristic linear dimensions in the Sherwood and Reynolds numbers respectively
$\rho_s$	Slurry density
$\nu$	Kinematic viscosity
$\tau$	Torque

## Addendum: Evaluation of the relative merits of different models describing the same data but having a different number of parameters

Consider that model A, which has  $Ma$  parameters, yields a sum of squared residuals equal to  $S_A$ , while model B, having  $Mb$  parameters, yields a sum of squared residuals equal to  $S_B$ . There are  $N$  data points. If the value of  $\lambda_{AB}$ , equation [A1], is greater than the relevant value of the statistic  $F_{(Ma-Mb), (N-Ma)}$  (Table A1), then model A provides a better description of the data than does model B1:

$$\lambda_{AB} = \frac{(S_A - S_B)/(Ma - Mb)}{S_A/(N - Ma)} \quad [A1]$$



# CONFERENCE ON

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papers



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OCTOBER  
1996

**HIDDEN  
WEALTH**

**Unlocking values from low grade and refractory ores and wastes**

## CONFERENCE OBJECTIVE

This International Metallurgical Conference on the treatment of low-grade and 'refractory' ores and wastes provides a forum for the exchange of knowledge and experiences between extractive metallurgists on a worldwide basis.

The date of the Conference coincides not only with the 1996 Electra Mining Exhibition, but runs concurrently with the Surface Mining Conference 1996, the latter bearing a close relationship to the 'Hidden Wealth' theme with valuable synergistic effects.

## CONFERENCE PROGRAMME

The conference will consist of three days of technical proceedings together with a range of post-conference tours and technical visits. The technical presentations will aim to cover the widest range of topics relating to the processing of low-grade ores and 'refractory' ores and wastes.

## CONFERENCE THEME

'Hidden Wealth' refers to those metallic values which, for mineralogical, chemical, spacial distribution, small particle size, spasmodic occurrence, or other reasons are difficult to recover economically, and require specific cost effective metallurgical treatment.

The theme is intended to cover all low-grade operations of noble or base metals, and the processing of 'refractory' ores and wastes, regardless of grade. Ores of complex mineralogy are also covered as they present recovery difficulties in their own right.

## CALL FOR PAPERS

Papers are invited on any aspect relating to the Conference. Papers may be categorized broadly under the following headings:

- Low-grade base metal ores, slags and residues, beneficiation and metal recovery.
- Low-grade and refractory gold ores and residues, beneficiation and metal recovery.
- Low-grade industrial minerals beneficiation.
- Complex sulphide ores, beneficiation and metal recovery.
- Ferro-alloy slags, beneficiation and metal recovery.
- Environmental issues relating to the treatment of low grade and refractory ores and wastes.

Prospective authors are invited to submit titles and abstracts of their papers, in *English*, and to indicate the topic under which the paper should be categorized. The abstracts should be no longer than 500 words and should be submitted to:

The Conference Secretariat, 'Hidden Wealth, 1996'.  
SAIMM, P.O. Box 61127, Marshalltown 2107, South Africa.

The date for submission of abstracts has been extended, enquiries may be made over telephone  
Tel: 27 (11) 834-1273/7  
or by facsimile 27 (11) 838-5923.

## KEY DATES

- |              |                                       |
|--------------|---------------------------------------|
| 30 Nov 1995  | Submission of papers                  |
| 30 Mar 1996  | Final circular and registration forms |
| 2-4 Oct 1996 | Conference                            |

## VENUE AND DATE

National Exhibition Centre, Johannesburg,  
2 to 4 October 1996