METALLURGY OF THE WILLIAMS CREEK OXIDE COPPER DEPOSIT

WESTERN COPPER HOLDINGS LIMITED
THERMAL EXPLORATION COMPANY

MAY 1994

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May 2, 1994

Western Copper Holdings Limited
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ATTENTION: Mr. Ken McNaughton, P. Eng.

Dear Ken,

I am pleased to submit the summary report on the metallurgy of the Williams Creek oxide copper ore. The report includes all the leaching testwork conducted prior to the three full height columns, which are being reported separately, as well as the initial solvent extraction testwork conducted in 1990. I believe that the teswork on the leaching of copper from the ore has progressed to the point where we are able to design a leach cycle with predictable copper extraction rate, % extraction and acid consumption.

It has been a pleasure to work on this project and I trust that you will find the report to be adequate for your purposes.

Yours Truly,
BEATTIE CONSULTING LTD

Dr. M.J.V. Beattie, P. Eng.

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VOLUME 2

SECTION 1

SUMMARY

Testwork on the acid leaching of copper from the Williams Creek deposit has demonstrated that the deposit is amenable to copper recovery by this process. Testwork conducted on samples from surface trenches as well as on composite samples prepared from drill core has demonstrated the following:

1. The copper extraction rate increases with decreasing particle size. The optimum feed size for leaching, taking into account the complexity of the required crushing circuit, the minimization of fines which will impede solution flow through the leach pile, and the copper extraction rate and ultimate recovery, appears to be minus 2 cm, obtained by closed circuit crushing.

2. The agglomeration of the ore with 5 kg/tonne sulphuric acid prior to placing the material onto the leach pile is beneficial in terms of initiating favourable conditions for copper leaching throughout the pile. The agglomeration also binds the fines generated during crushing onto the coarse particles so that good solution flow occurs throughout the pile. Based on observations made during the testwork, the use of an agglomeration drum is recommended.

3. The samples tested to date contain 85 to 90 % of the copper in an acid soluble form. Essentially all of this acid soluble copper can be leached from the rock if sufficient leach time is allowed. Based on the testwork to date it appears that an ultimate copper extraction of 80 to 85 % of the total copper is achievable over a leach period of 90 to 100 days. At this extraction, the acid consumption can be expected to be in the order of 25 to 30 kg/tonne when treating material included in the high grade reserves. These parameters are being verified by means of a column tests which are comparable in height

to a full lift. The results of these full height tests are being summarized in a separate report.

4. Based on a feed grade of 1.4 % Cu and the above leach cycle, the average PLS grade will be 3.4 g/L Cu. The grade is several times this figure during the first few days of operation of a new lift and then decreases. An average grade is maintained by integrating the operation of several leach areas.

4. Solvent extraction testwork conducted on solution samples from the leaching testwork has defined the design and operating parameters for this part of the circuit which can be considered to be typical for the industry. Final verification of these parameters will result from ongoing testwork.

SECTION 2

INTRODUCTION

The Williams Creek copper deposit, located northwest of Whitehorse, Yukon contains a zone of non - sulphide copper mineralization. The metallurgical development of this mineral resource has been directed at the use of heap leaching followed by conventional solvent extraction and electrowinning for copper recovery. Testwork has utilized both bulk samples obtained from surface trenches and composite drill core samples from various sections of the deposit. The present report is a compilation of all the testwork conducted from 1990 until May 1993. The main focus of the report is on the leaching testwork which has been conducted to establish copper extraction and acid consumption since the solvent extraction and electrowinning sections of the process are readily defined once the pregnant leach solution has been characterized.

The majority of the leaching testwork has been conducted by Process Research Associates of Vancouver, B.C. under the direction of Dr. M.J.V. Beattie, P. Eng. Throughout the test program, the results of the tests and the direction of the continuing program were discussed with Mr. Ken McNaughton, P. Eng. of Western Copper Holdings Ltd. In addition to the testwork included in the present report, three column tests having a height comparable to a full lift in the proposed commercial operation have been conducted as well as a bulk pilot test including solvent extraction and copper electrowinning. The results of this additional testwork is being reported separately.

SECTION 3
SUMMARY OF TESTWORK CONDUCTED

3.0 Introduction

The following section outlines the composition of the samples used for the various parts of the metallurgical development program conducted on Williams Creek as well as the procedures used for the testwork. The details of the analytical procedures used are included in Appendix G.

Prior to the comprehensive testwork which is detailed in the present report being commenced, several scoping tests had been conducted by Coastech Research. These tests utilized a high grade (2.8% Cu) sample and demonstrated that in excess of 90% of the copper in the sample was acid soluble. The column test utilized a very high initial acid concentration of 94 g/L H_2SO_4 and this contributed to a high net acid consumption for the test of 48 kg/tonne. The Coastech report is included in Appendix A.

3.1 Bacon, Donaldson Leaching Testwork (1990 and 1992)

Preliminary leaching studies were conducted at the laboratories of Bacon, Donaldson & Associates Ltd. of Vancouver, B. C. in 1990. These tests consisted of bottle roll tests as well as column tests on surface bulk samples to demonstrate that the Williams creek deposit is amenable to heap leaching. Additional testwork was conducted by Bacon Donaldson early in 1992 on samples from within the deposit to demonstrate that this deeper material could also be leached successfully. The reports detailing the Bacon, Donaldson studies are included as Appendix A.

3.1.1 Sample Description

The testwork conducted in 1990 utilized two bulk surface samples weighing approximately 1300 kg each. The samples were identified as "Blue" and "Orange" composite and as received contained fragments up to 3-4 inches in diameter. Complete sample preparation details are included in the reports in Appendix A. Both samples were relatively high grade, assaying 1.65 and 1.54 % Cu of which 93 to 95 % was in non - sulphide form.

The BDA testwork conducted in 1992 utilized drill hole assay rejects obtained from Chemex Labs Ltd. In the discussion of results in this report, these samples are referred to as "the Chemex samples". The rejects were combined to provide composites representing different levels within the deposit as well as high grade and low grade sections. The designations for these samples and their copper contents are summarized in Table 3.1. The details of the sample make-up and preparation are included in Appendix A.

TABLE 3.1

BDA 1992 Test Sample Assays

SAMPLE	% Cu_T
+2700 low grade	0.48
+2700 high grade	1.58
-2700 +2500 low grade	0.32
-2700 +2500 high grade	1.36
-2500 +2300 low grade	0.54
-2500 +2300 high grade	1.56
South End	1.22
+2500 S	1.56

Sulphide assays of the samples included in Appendix A indicate that the copper exists primarily in non-sulphide forms.

3.1.2 Description of Tests

1990 Program

- bottle roll tests of different size fractions of trench sample composites "orange" and "blue"
  - 1990 L1 through L6

- ammonia leach of bottle roll test of combined composite

- 2 column tests of 50:50 blend of composite orange and composite blue
  - BDA Column 1
  - BDA Column 2

1992 Program

- Bottle roll tests on various samples to test leaching variability across deposit. These tests were conducted with fresh acid solution added to each cycle of the test.

- Bottle roll tests on High Grade and Low Grade Composites with solvent extraction of PLS prior to recycle of solution to the next cycle of the test. The solvent extraction utilized LIX 84 in kerosene and the raffinate pH was adjusted to 1.8 if needed, prior to being returned to the test.

- The South End sample was subjected to an acid leach followed by a second stage leach inoculated with bacteria to determine if oxidation of residual sulphide could be achieved in this way in order to maximize the total copper extraction.

- The residue from leaching of the high grade composite was leached with a cyanide solution to establish the feasibility of recovering gold and silver from the copper leach tailing.

3.2 1992 - 1993 Leaching Program

Detailed metallurgical testwork on drill hole rejects was conducted in 1992 and 1993. While a few confirmatory bottle roll tests were conducted at Lakefield Research, the majority of the work was conducted at the laboratories of Process Research Associates Ltd. of Vancouver, B.C. The laboratory work was conducted by Mr. Peter Tse of Process Research under the supervision of Dr. Morris J. V. Beattie, P.Eng. of Beattie Consulting Ltd.

This current phase of metallurgical development for the Williams Creek deposit included bottle roll tests and column tests as well as auxiliary testwork. All the present work is detailed in this report.

3.2.1 Sample Description

The initial bottle roll tests conducted in the current program utilized the same Chemex samples as were used for the 1992 BDA testwork. The detailed metallurgical testwork was performed on composites prepared from drill core. The drill hole composites corresponded to the same intervals used to prepare the assay reject samples for the 1992 test program at Bacon, Donaldson. The details of which drill hole samples were utilized for each composite, together with the location of the samples within the deposit are included in Appendix B.

The drill core was received at the laboratory in 92 plastic bags. Each bag was weighed and one small piece of core was removed for possible future mineralogical studies. The drill core consisted of a one-half split of core having a diameter of approximately 5 cm. Each bag was examined and any pieces of core which had a length greater than 5 cm was broken with a hammer so that the top size of all the material became approximately 5 cm by 5 cm. The individual samples were then combined into seven composites as detailed in Appendix B.

Each of the seven composites was blended by coning and quartering. Three 25 kilogram portions were removed from each composite for size reduction and bottle roll testwork. One portion was tested without further reduction, the second portion was reduced to minus 2 cm and the third portion was reduced to minus 1 cm before testing. An assay sample was split from the minus 1 cm portion and the results of the analyses are summarized in Table 3.2.

TABLE 3.2

Analyses of Composite Samples

COMP. NO.	SAMPLE DESCRIPTION	Au oz/ton	Ag oz/ton	Cu_T %	Cu_{ox} %	Fe_T %	Fe_{ox} %	S^{-2} %
1	+ 2700 L	.007	.05	0.48	0.38	3.86	3.88	0.13
2	+ 2700 H	.020	.20	1.44	1.43	3.60	3.68	0.12
3	2500 - 2700 L	.006	.06	0.32	0.32	3.76	3.80	<.01
4	2500 - 2700 H	.020	.06	1.36	1.24	3.74	3.76	0.12
5	2300 - 2500 L	.007	.14	0.50	0.49	3.50	3.38	<.01
6	2300 - 2500 H	.025	.26	1.31	1.30	3.46	3.46	<.01
7	South End	.013	.10	1.29	1.28	3.60	3.60	0.04

Following the initial bottle roll testing of these composites, the remaining material was all crushed to minus 2 cm. The minus 2 cm material was used to prepare additional composites for subsequent testing as follows:

High Grade composite - composites 2, 4, 6
Low Grade composite - composites 1, 3, 5
South End composite - composite 7

Following crushing to minus 2 cm, a portion of each composite was screened into a series of size fractions which were assayed as summarized in Table 3.3.

During the course of the test program additional quantities of the composites had to be prepared from time to time to fill the needs of the testwork. During the preparation of the sample for the "S" series of four column tests, two pails of sample from the high and low grade composites were inadvertently reversed. The effect of this sample mixing is that the feed to the high grade column S2 was lower and the feed to the low grade column S1 was higher in copper than would have been expected.

TABLE 3.3

Analyses of Composites by Size Fraction

FRACTION cm	WEIGHT %	% Cu	% Cu_{ox}	% oxide	Au, oz/ton
Low Grade					
- 2 + 1.3	35.5	0.38	0.30	78.9	0.005
- 1.3 + 1	18.1	0.40	0.34	85.0	0.005
- 1 +0.6	13.7	0.40	0.36	90.0	0.005
- 0.6 + 6m	11.3	0.42	0.36	85.7	0.005
-6m	21.3	0.64	0.54	84.4	0.006
Total		0.45			0.005
High Grade					
- 2 + 1.3	28.4	1.28	1.12	87.5	0.020
- 1.3 + 1	17.1	1.28	1.10	85.9	0.017
- 1 + 0.6	15.0	1.20	1.08	90.0	0.025
- 0.6 + 6m	12.8	1.15	0.96	84.2	0.018
- 6m	26.7	1.79	1.56	87.2	0.027
Total		1.39			0.022
South End					
- 2 + 1.3	29.5	1.02	0.90	88.2	0.010
- 1.3 + 1	17.0	1.10	0.96	87.3	0.010
- 1 + 0.6	13.3	1.05	0.92	87.6	0.011
- 0.6 + 6m	11.8	1.10	0.98	89.1	0.015
- 6m	28.4	1.74	1.55	89.1	0.010
Total		1.25			0.011

3.2.2 Description of Tests

1. Bottle Roll Tests (L1 - L27)

These tests were generally conducted with 2 kilograms of feed and at 50% solids. Tests on minus 5 cm material utilized 5 kilogram samples and the confirmatory tests conducted by Lakefield on the Chemex samples used 1 kilogram charges. The rock and acid solution were combined in a bottle on rollers and were rotated slowly. The bottles and roller assembly are shown in Figure 3.1. The test conditions and detailed results are included in Appendix C. After each time interval the bottle was removed from the rolls and the solution was removed by filtration. An aliquot was taken for analysis and the balance was treated by solvent extraction.

Solvent extraction throughout the test program was conducted with Acorga M5460. A 20% by weight solvent was prepared by adding Acorga to the diluent Shell Sol DMS which is a purified grade of Kerosene. Prior to using the solvent it was conditioned by extracting copper from a solution containing in excess of 5 g/L Cu.

Copper extraction from test samples was achieved by adding a 1:1 ratio of pregnant leach solution to the solvent and mixing for 3 to 5 minutes. After allowing the solvent to separate from the solution, the raffinate was drawn from the bottom of the tank. To strip copper from the solvent, a 1:1 ratio of 188 g/L sulphuric acid was used. The acid strip solution was re-used until it became concentrated in copper, judged by an intense blue color.

Following solvent extraction the raffinate was returned to the bottle. Sulphuric acid was added to adjust the pH of the raffinate to meet the test conditions.

At the completion of the test, the sample was filtered and then washed by repulping with fresh water followed by filtration.

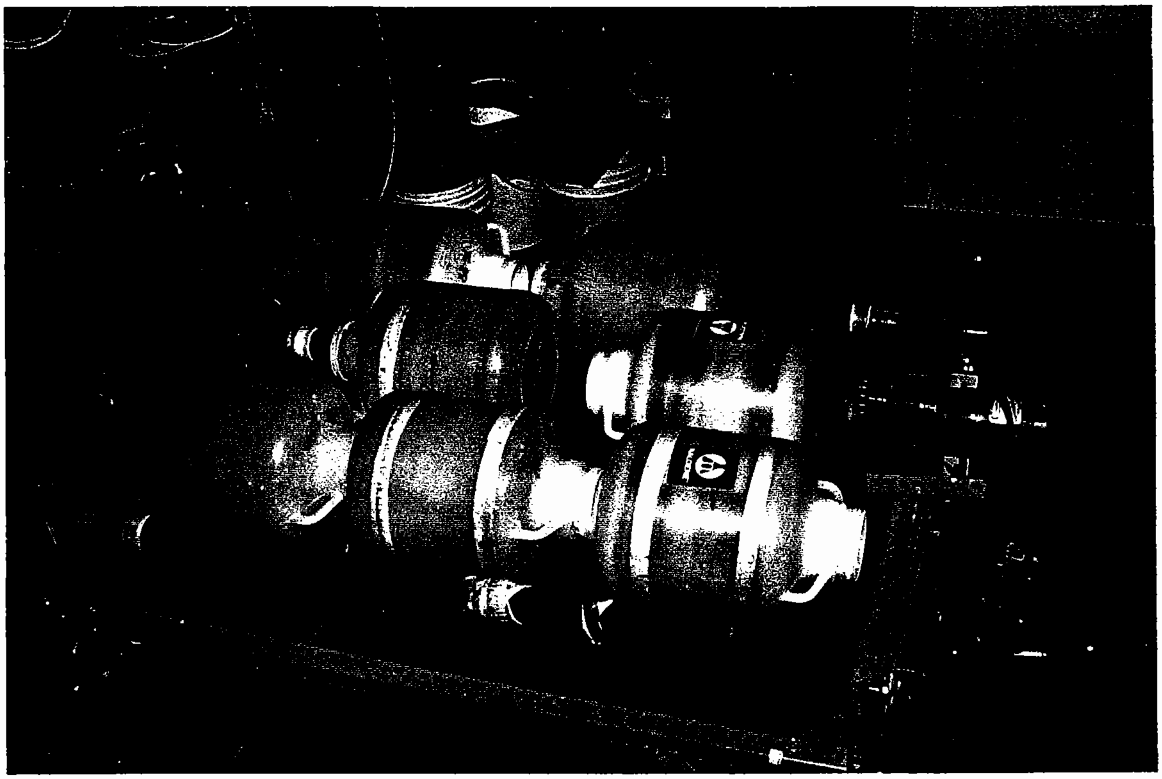

Figure 3.1

Bottle Roll Assembly

In addition to testing different composites, the following variables were studied:

- particle size
- initial acid concentration
- total acid addition
- leach time

2. Mini Column Tests (M1 - M3, M5, M6)

Mini column tests were carried out in columns having a 7.6 cm diameter by 1.2 m tall. The agglomeration procedure used throughout the test program consisted of spraying an acid solution (150 - 300 g/L H_2SO_4) onto the crushed ore so that it was uniformly wetted as shown in Figure 3.2. The ore was rolled back and forth several times, as in Figure 3.3, in order to achieve agglomeration. For each test the agglomerated ore was placed into the column and allowed to cure overnight before leaching was started. The feed solution was pumped to the top of the column with the drip point being moved from day to day to ensure complete wetting of the column contents.

The starting conditions for the columns varied as summarized in Table 3.4. The details of operating conditions, sample analyses and extractions are included in Appendix D. All extractions for these and other columns included in this report are based on the calculated feed assay to the column, derived from solution and residue analyses. All the mini column tests utilized the high grade composite.

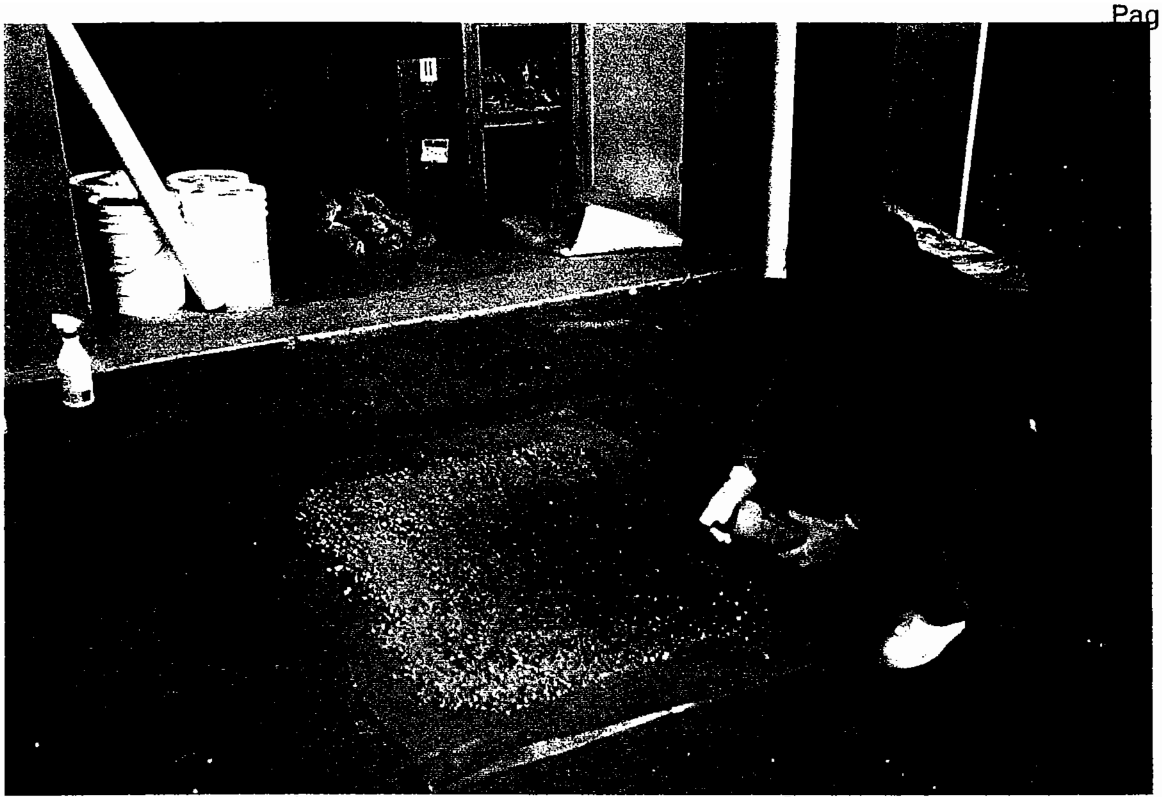

Figure 3.2 Spraying of solution over ore sample.

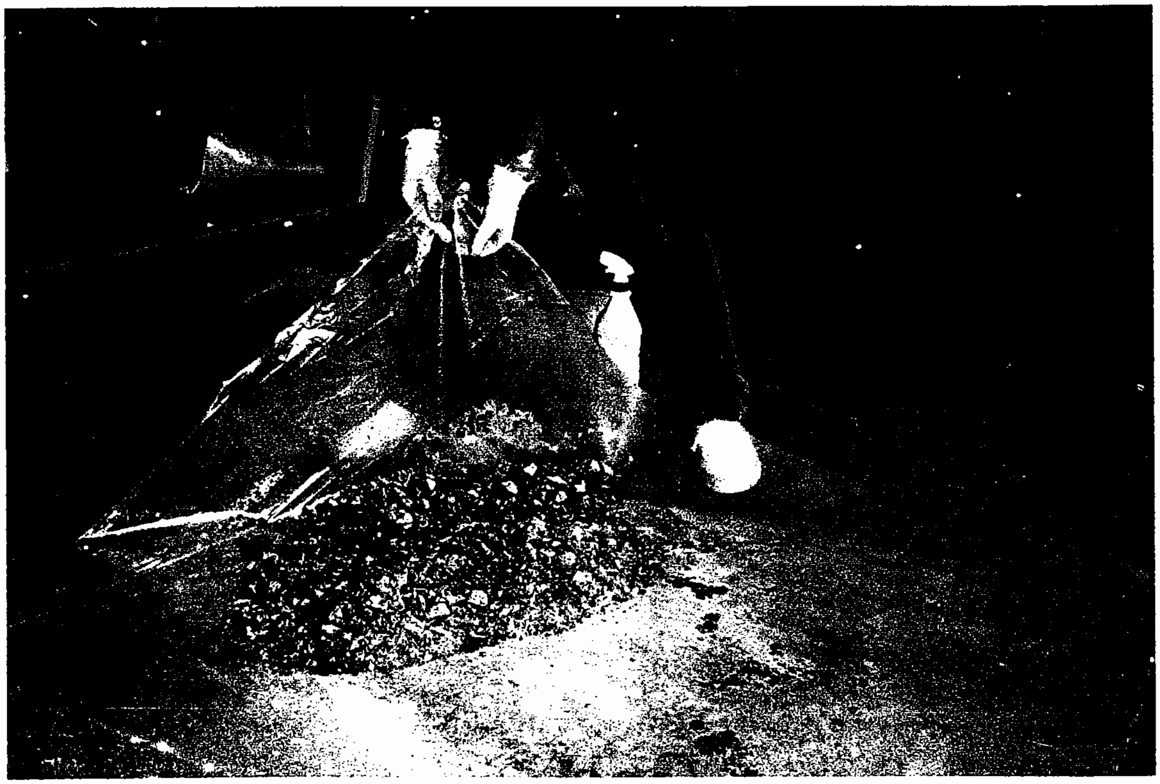

Figure 3.3 Rolling of wetted sample for agglomeration.

Table 3.4

Summary of Operating Conditions for Mini Columns

TEST NO.	CONDITIONS
M1	- minus 2 cm feed - no acid to agglomeration - leach with 15 g/L H_2SO_4 solution
M2	- minus 2 cm feed - 5 kg/t H_2SO_4 to agglomeration - leach with raffinate to pH 1.8
M3	- minus 2 cm feed - 10 kg/t H_2SO_4 to agglomeration - leach with raffinate to pH 1.8
M5	- minus 2 cm feed - pretreatment as M2 - increase initial flowrate M2 - increase acid addition over M2
M6	- minus 1 cm feed - operate as M5

The physical arrangement of mini columns M1 to M3 is shown in Figure 3.4 with solution being pumped to the top of the column and the PLS collecting in the pails underneath.

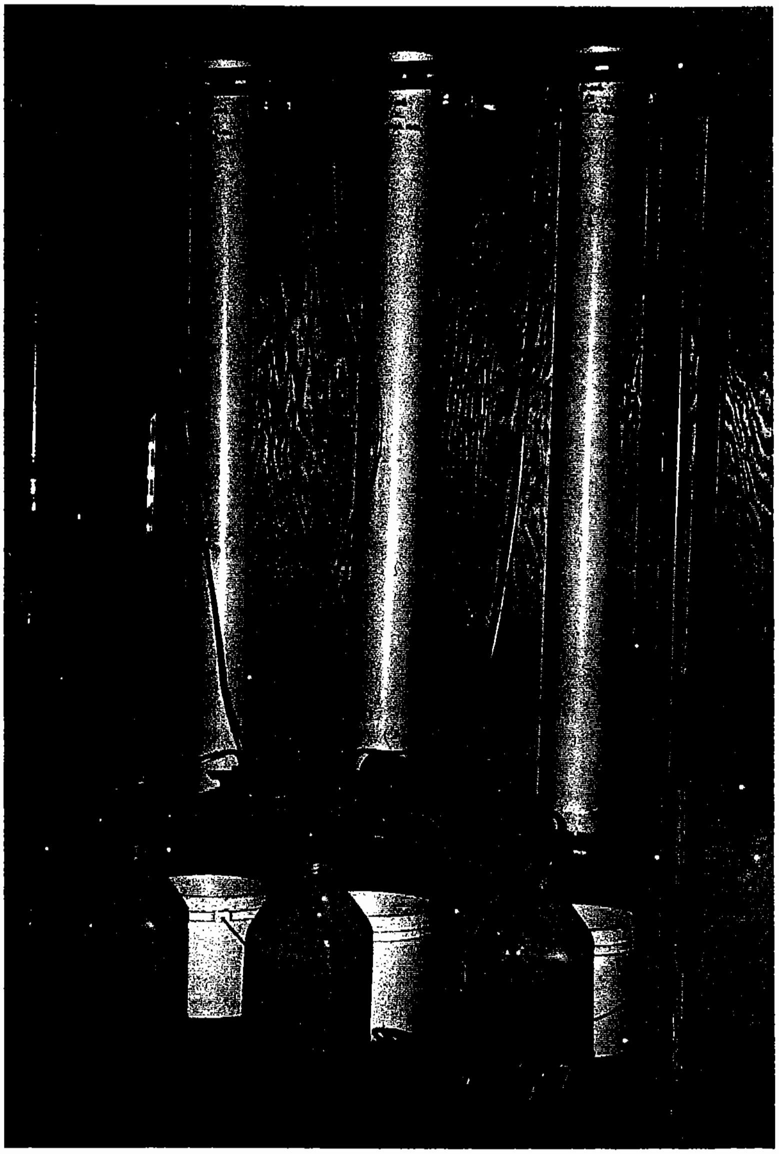

Figure 3.4 **Set up of mini column tests.**

While Table 3.4 summarizes the starting conditions for the tests, the operating conditions over the duration of the tests varied considerably as the influences of various parameters were studied. The details of operation, including when fresh solution versus recycled raffinate was used as feed are included in Appendix D.

3. 15 cm Column Tests (S1 to S4)

A set of four column tests was conducted using columns which were 15 cm in diameter and 3.2 m tall. Each column utilized approximately 86 kilograms of minus 2 cm feed. The operating parameters for the columns were as follows:

- pretreat ore with 5 kg/tonne H_2SO_4
- initiate leach with raffinate adjusted to pH 1.5
- recycle raffinate after pH adjusted to 1.5
- initiate leach with flowrate of 0.015 gal/ft^2/min (0.036 m^3/h/m^2) and decrease flowrate to 0.005 gal/ft^2/min when PLS grade drops to 1.5 g/L Cu.

As the tests progressed, some variations in recycle pH and flowrates were investigated. The sample used for each test is indicated in Table 3.5. The test details are included in Appendix E.

The column set-up with feed and product buckets and recycle pumps is shown in Figures 3.5 and 3.6.

Table 3.5

15 cm Columns Description

TEST NO.	FEED
S1	Low grade composite Inoculated with bacteria
S2	High grade composite Inoculated with bacteria
S3	High grade composite No bacteria
S4	South End composite Inoculated with bacteria

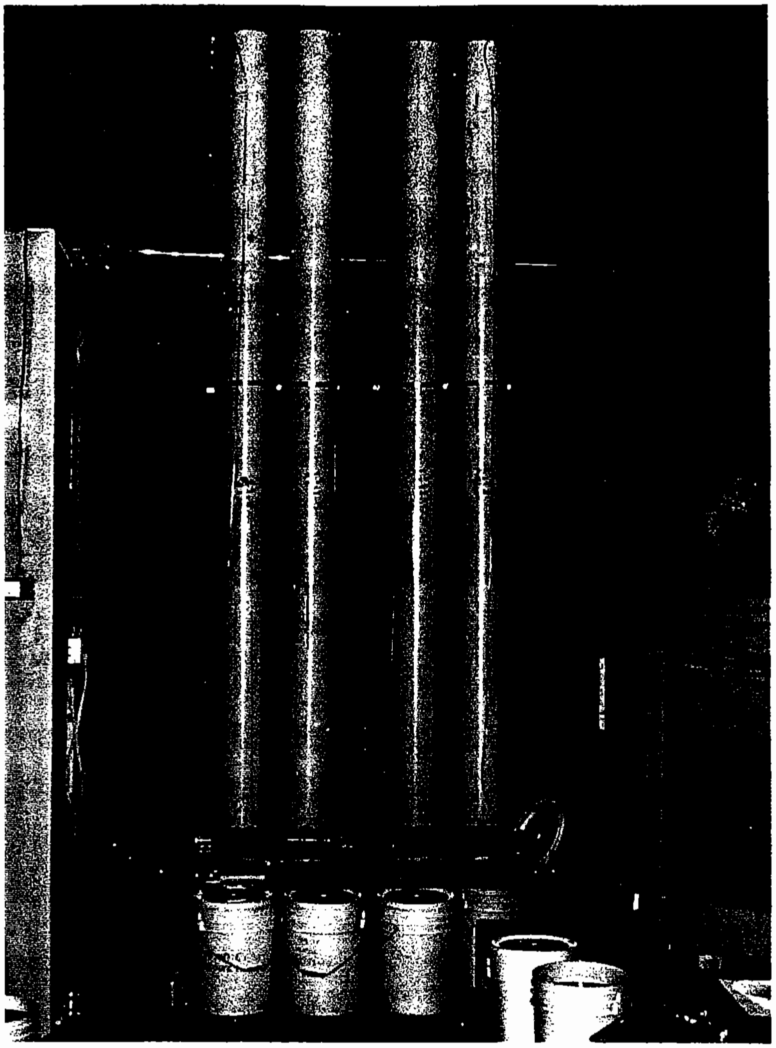

Figure 3.5
Column test set up.

Figure 3.6
Base of columns with pumps.

4. Flood Tests (F1 to F11)

A set of tests was conducted utilizing 15 cm diameter columns and sized fractions of the composite samples. In these tests the leach solution was pumped into the bottom of the column and allowed to overflow just above the top of the rock so that the rock was continually flooded. The arrangement of these columns is shown in Figure 3.7.

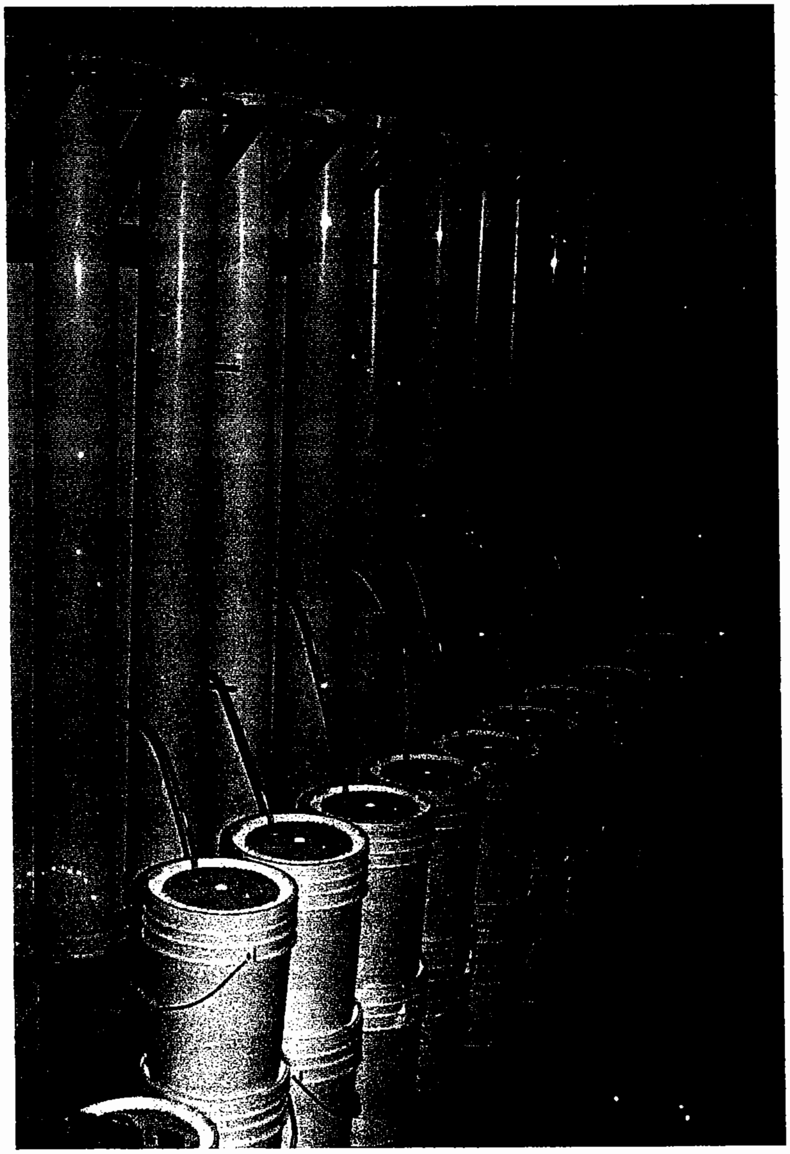

Figure 3.7

Flood Column Arrangement

It can be seen in Figure 3.4 that the overflow connections are part-way up the columns since only enough of the sized fractions to partially fill the columns was available.

The feed to each column was agglomerated with 5 kg/tonne H_2SO_4 as described previously, prior to being loaded in the columns. The agglomerated ore was allowed to sit in the columns for one day prior to being flooded with 15 g/L H_2SO_4 solution by pumping solution into the bottom of the column. The details such as feed rates, acid concentration etc. for all the flood columns are included in Appendix F. The pregnant solution was treated for copper removal by means of solvent extraction prior to having more sulphuric acid added and being recycled to the feed.

While the operating conditions for the columns were approximately the same, one column (F11) was operated at about three times the solution flowrate as the other columns so that the effect of flowrate on copper extraction and acid consumption could be observed.

The duration of the flood tests varied since the coarse fractions leached more slowly than the fines. Since the -6 mesh material was not considered to be suitable for column testing, bottle roll tests (B1 - B3) were conducted on these fractions. The detailed results for these bottle tests are included in Appendix F.

5. Percolation Tests (P1 - P5)

A set of tests was conducted utilizing 15 cm diameter columns and sized fractions of the composite samples. In these tests the feed solution was pumped to the top of the column and was then allowed to percolate down over the ore. Prior to being placed into the columns, the sized ore fractions had been agglomerated as previously. The arrangement of these columns is shown in Figure 3.8, together with one flood column.

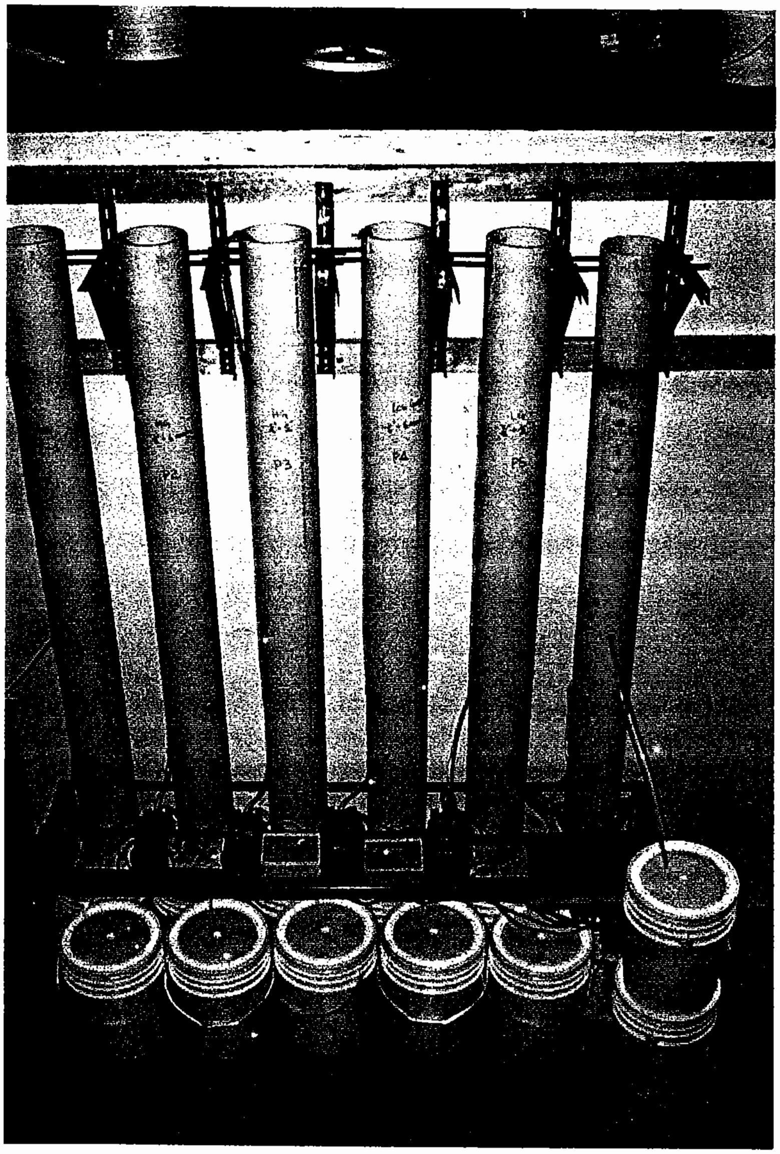

Figure 3.8

Percolation Column Arrangement

The pregnant solution was treated by means of solvent extraction prior to being recycled to the feed. Sampling was done on a daily basis for the first week then every second day for the next week and finally every four days to the end of the test. The test details are included in Appendix F.

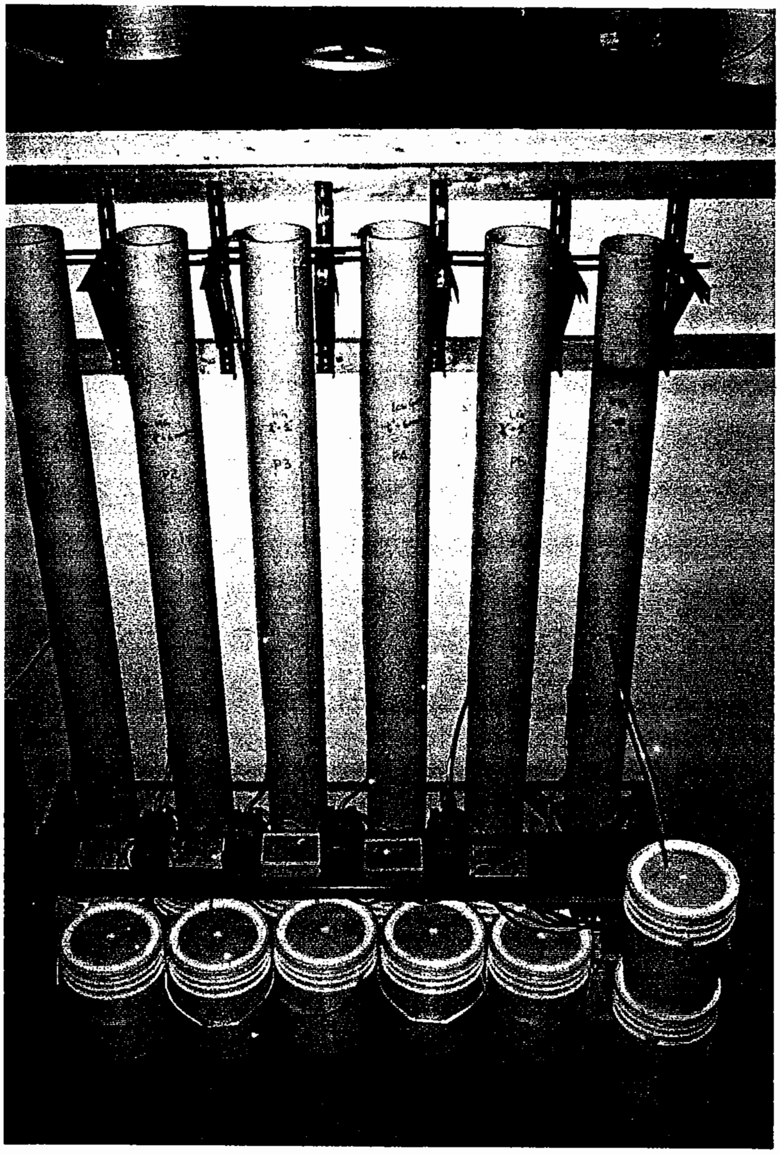

Figure 3.8

Percolation Column Arrangement

The pregnant solution was treated by means of solvent extraction prior to being recycled to the feed. Sampling was done on a daily basis for the first week then every second day for the next week and finally every four days to the end of the test. The test details are included in Appendix F.

Both the flood tests and percolation tests were conducted as part of a study recommended by Brown & Root Braun Inc. to provide baseline data for the development of a leach kinetics model for the Williams Creek deposit.

3.3 Solvent Extraction

Solvent extraction testwork has been conducted by ICI Specialty Chemicals. The initial testwork and circuit design was performed in 1990 using solutions from the Bacon, Donaldson test program. The detailed test results and recommendations of this study are included in Appendix G. A second study was conducted by ICI in July 1993 using solutions from the testwork conducted at Process Research Associates.

All solvent extraction testwork consisted of small-scale bottle tests with analysis of the products to develop extraction and strip isotherms.

SECTION 4
RESULTS

4.1 Bottle Roll Testwork

Bottle roll tests provide a rapid and relatively inexpensive method to screen differences between samples or operating procedures. Throughout the development of the Williams Creek project, bottle tests have been used to achieve these objectives and to establish the basic operating parameters for subsequent column leach testwork. Throughout this report, copper extraction is given as a percentage of total copper in the sample.

4.1.1 Effect of Particle Size

The initial bottle roll tests conducted by BDA in 1990 on the "Blue" and "Orange" trench composites, demonstrated that the oxide copper was amenable to leaching with sulphuric acid solutions. The results summarized in Figures 4.1 and 4.2 show copper extraction as a function of time for various crush sizes. While a considerable degree of particle abrasion and degradation can be expected in bottle roll tests, the top size of particles in the test was sufficiently unchanged for differences in extraction resulting from size to be observable. The particle size distribution for products from the tests are summarized in Figures 4.3 and 4.4.

Although the top sizes used for the samples of the two composites were the same, leached tails from the test using the Blue sample are finer than the Orange composite leach tails. The Orange products also show a greater variation in particle size, consistent with the broader range of copper extractions shown in Figure 4.2 compared to Figure 4.1. The coarsest (+ 3.8 cm) fractions leach more slowly than the finer fractions. These preliminary tests demonstrated that an extraction of 80% was achievable with a top size if 2 cm within a reasonable leach time.

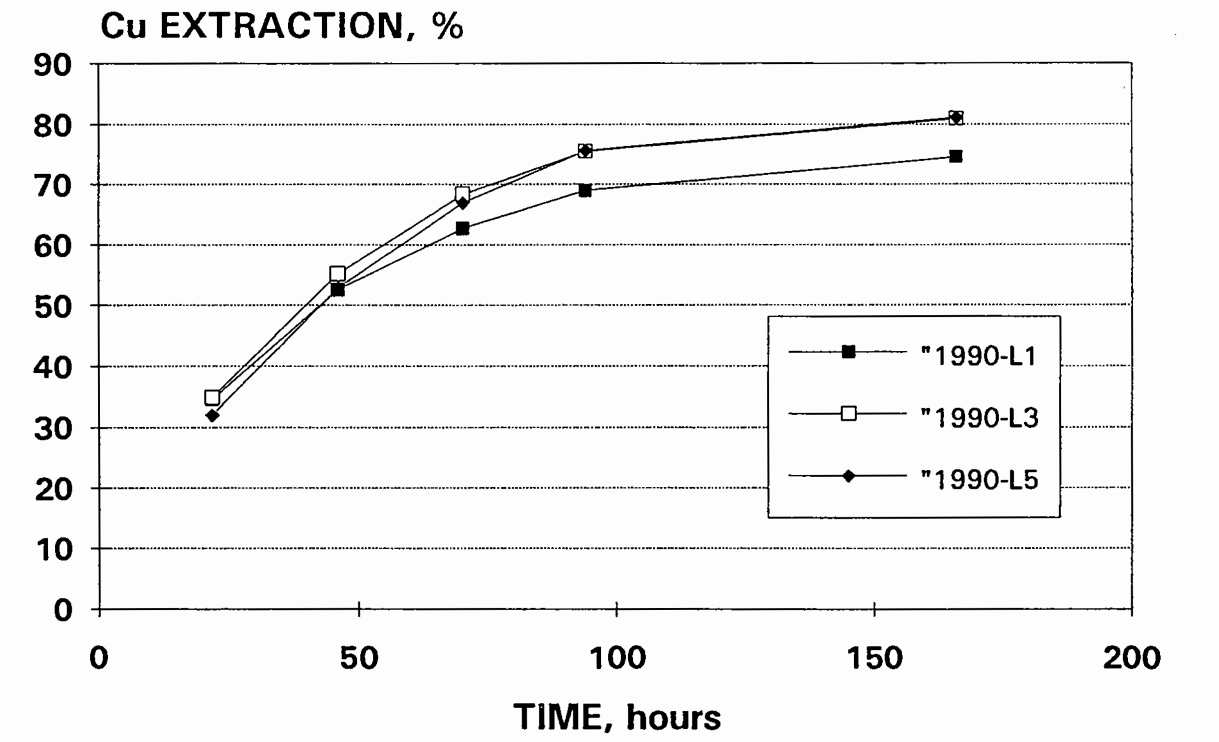

Figure 4.1 BDA Bottle Roll Results

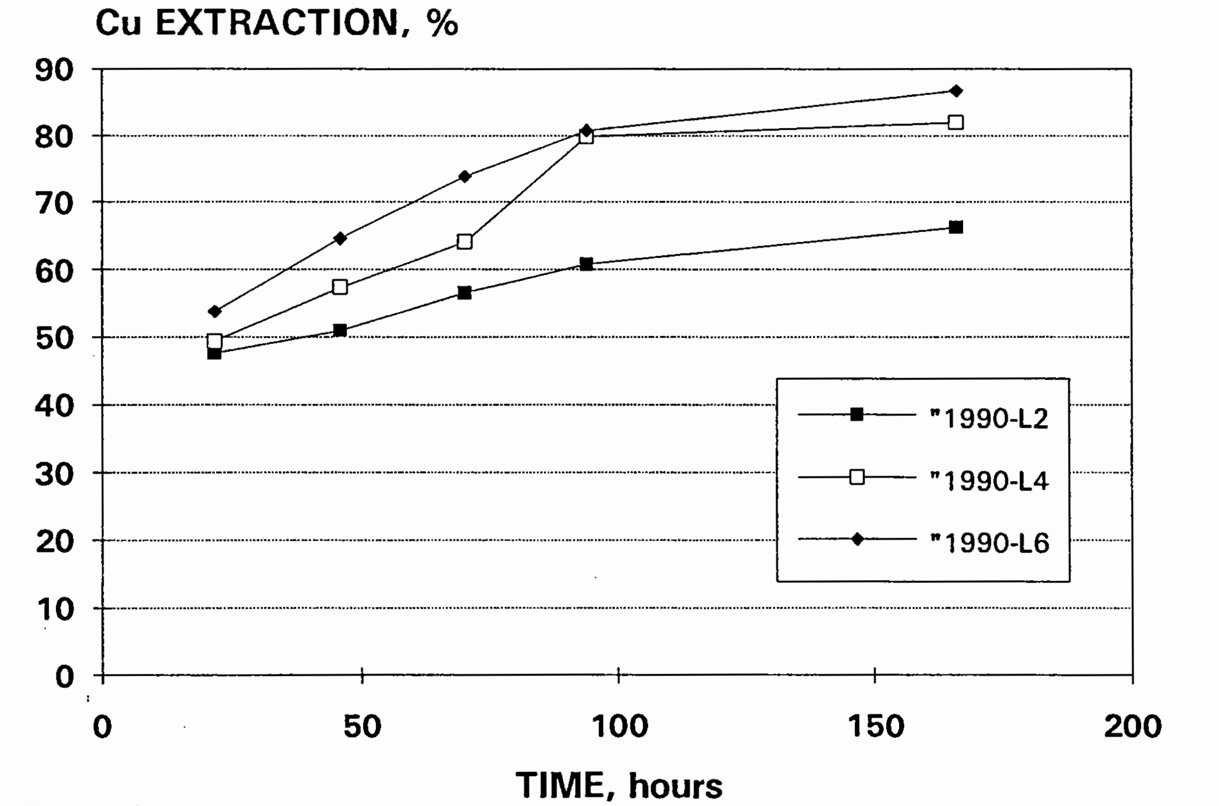

Figure 4.2 BDA Bottle Roll Results

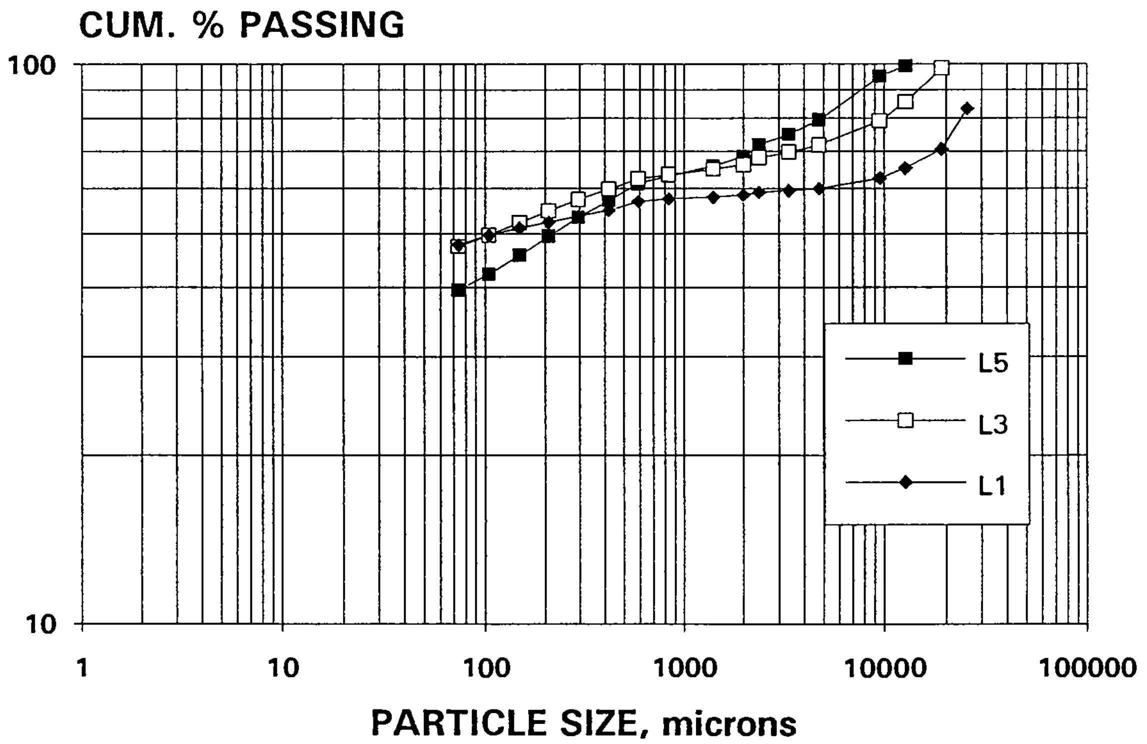

Figure 4.3 Size Analysis of Bottle Products

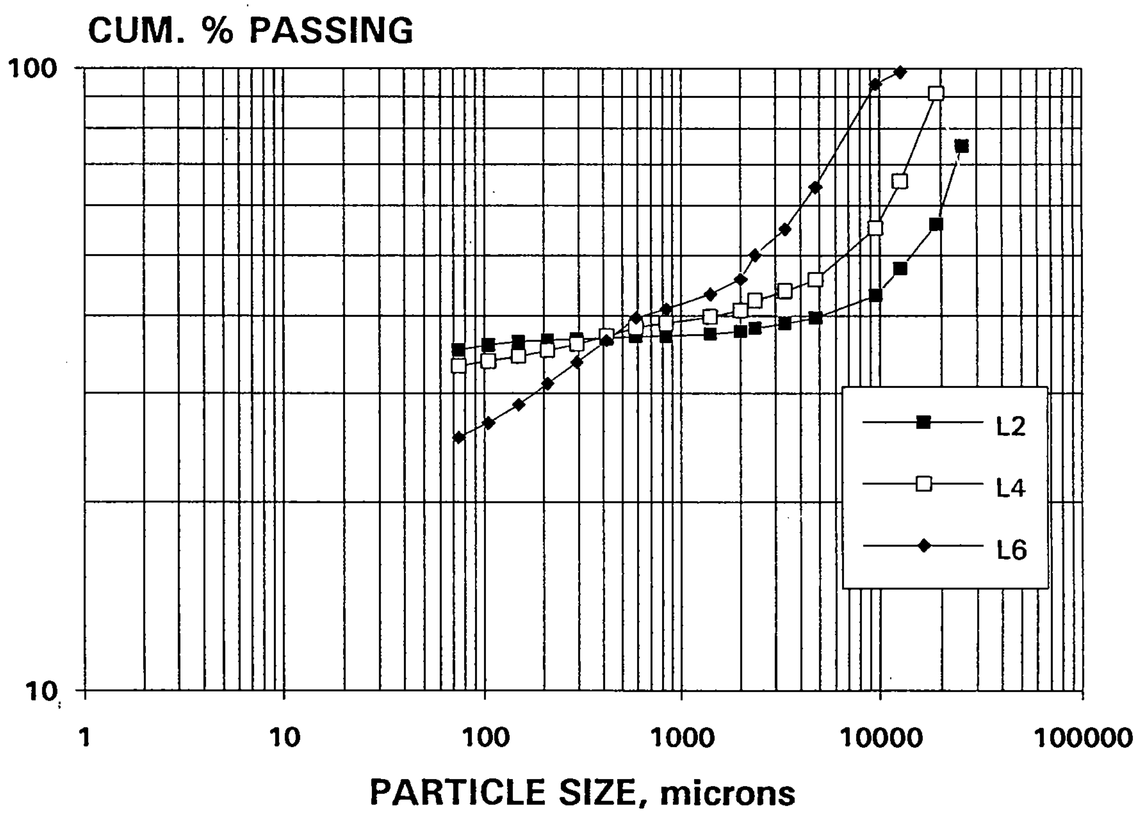

Figure 4.4 Size Analysis of Bottle Products

The encouraging results of the preliminary tests lead to the development of an in-depth metallurgical program. In the first stage of this program the effect of crush size was studied by means of a series of bottle roll tests. Table 4.1 summarizes the results of tests on several samples at different sizes. All tests included in Table 4.1 consisted of 93 hour tests with an initial acid concentration of 15 g/L H_2SO_4 and solvent extraction of pregnant solutions prior to being returned to the test.

Table 4.1

Bottle Roll Test Results for Drill Core Composites

COMPOSITE	SAMPLE	RESIDUE ASSAY, % Cu			% EXTRACTION		
	I.D.	-5 cm	-2 cm	- 1 cm	- 5	- 2	- 1
1	+ 2700L	0.54	0.22	0.22	23.8	54.6	49.8
2	+ 2700H	1.06	0.98	0.55	32.5	47.6	63.9
3	2500 - 2700L	0.17	0.26	0.22	25.8	35.5	32.6
4	2500 - 2700H	0.82		0.54	31.0		58.7

Although there are some variations in the results the general trend is for increased extraction as the crush size becomes finer, particularly from minus 5 cm to minus 2 cm. Since the bottle tests are of a relatively short duration, the results may not indicate differences in ultimate achievable extraction but rather may illustrate differences in extraction kinetics as a function of particle size. For all the tests, copper extraction was proceeding when the tests were ended.

The extractions shown in Table 4.1 are considerably lower than the 80% + values demonstrated by the BDA tests in 1990 and 1992. They are also lower than the extractions of 64% to 77% achieved in the current testwork on the Chemex high grade samples (L2, L4, L6). The reason for these variations in extraction become apparent when the size distributions for the various test products are compared. Table 4.2 summarizes the size distribution for several of the bottle roll products, together with the copper extraction achieved in each test. It is apparent from the results that high copper extraction correlates with a high proportion of fines in the test product. A secondary effect is the acid concentration during the test as discussed in the next section. The nature of the crushed samples for the current work can be seen in Figure 4.5.

Figure 4.5

Appearance of crushed samples

Table 4.2

Size Analyses of Bottle Roll Products

FRACTION	CUMULATIVE WT.% PASSING			
	BDA BOTTLE	CHEMEX SAMPLE	- 2 cm	- 10 mesh
2.5 cm	100			
2 cm	91.1		91.3	
1.3 cm	65.6		58.7	
1 cm	55.3		49.4	
4 mesh	45.7		31.1	
6	43.8			
8	42.3		22.3	
10	40.8			
14	39.8			
20	38.9	68.7	14.8	62.8
28	38.3			
35	37.0			
48	36.0	52.1	9.1	35.7
65	35.1	46.1	7.3	28.5
100	34.4	40.7	5.9	22.8
150	33.8	35.7	4.6	17.9
200	33.2	31.5	3.8	14.3
Cu extraction, %	82.3	70.0	66.5	81.4*

* 24 hour result

Table 4.2 also includes results for a blend of composites 2, 4 and 6 which had been crushed to minus 10 mesh prior to leaching. Note that the extraction of 81.4% for the -10 mesh sample was achieved in just 24 hours of leaching while the other results are all after 93 to 96 hours leaching.

A test was conducted to determine the possible effect of waste being mixed with the ore on acid consumption. A sample of waste rock from the deposit was placed in a bottle with a 15 g/L sulphuric acid solution at 50 % solids for 24 hours. The final acid concentration was 3.64 g/L, corresponding to an acid consumption of 11.2 kg/tonne. Under similar conditions, the ore samples consumed 15 to 20 kg/tonne acid.

4.1.2 Effect of Acid Concentration

The initial bottle tests conducted by BDA used an acid concentration of 15 g/L H_2SO_4. After each cycle, the pregnant solution was replaced with fresh acid solution of this strength. All testwork from the 1992 BDA work on, has utilized solvent extraction (SX) to remove copper from the pregnant solution prior to the solution being returned to the bottle. The use of the SX step appeared to result in a substantial decrease in acid consumption with some reduction in copper extraction kinetics. This effect is apparent from the results summarized in Table 4.3.

The higher acid consumption shown for the low grade samples compared to the high grade is consistent with the result of acid base accounting tests. Low grade material generally has a higher neutralization potential than the high grade material.

TABLE 4.3

Bottle Roll Results with Fresh Solution and Raffinate

TEST NO.	SOLVENT EXTRACTION	SAMPLE	Cu EXTRACTION %	H_2SO_4 kg/t
BDA L2	N	+2700 H	86.1	46.0
BDA L4	N	2500-2700 H	85.5	44.7
BDA L6	N	2300-2500 H	87.2	37.7
BDA L11	Y	High grade composite	78.7	13.6
BDA L1	N	+2700 L	75.2	56.3
BDA L3	N	2500-2700 L	86.6	55.6
BDA L5	N	2300-2500 L	84.3	58.6
BDA L10	Y	Low grade composite	70.0	15.6

Typical copper extraction and acid consumption curves for a test (L2) with fresh acid solution additions to each cycle are shown in Figure 4.6. It is apparent that much of the acid has been consumed after 80% or so of the copper was extracted. The acid consumption is therefore at least in part a function of how the test is conducted.

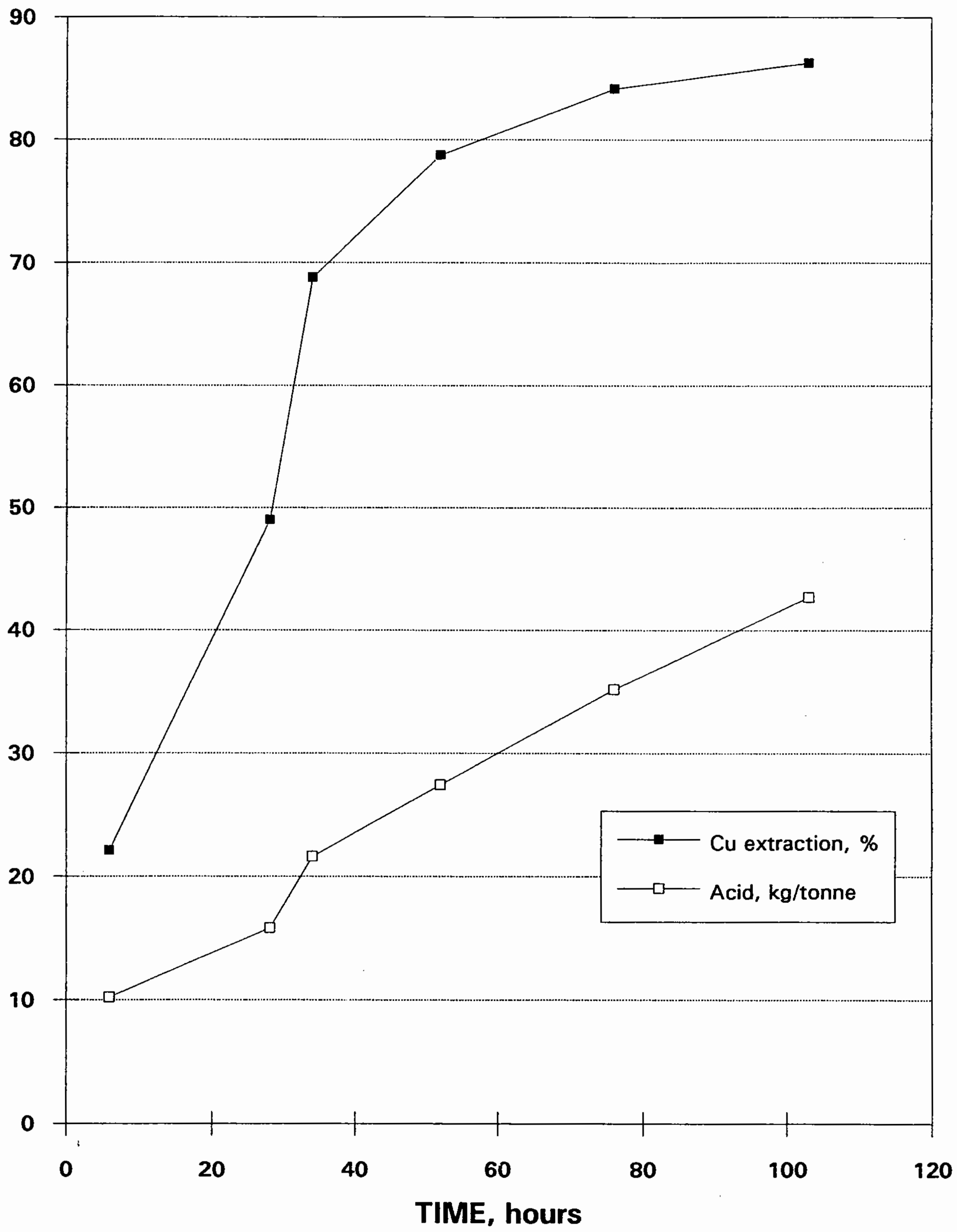

Figure 4.6 Bottle Test L2 (1992) Results

A test series was conducted using high grade and low grade Chemex samples with varying initial acid concentrations and a total leach time of 96 hours. Further acid additions were made during the test if the raffinate pH increased to a value greater than 1.8. The results of these tests are summarized in Table 4.4 and show increasing copper extraction corresponding to increased acid addition.

TABLE 4.4

Effect of Acid Consumption on Copper Extraction from Chemex Samples

TEST NO.	INITIAL H_2SO_4 g/L	Cu Extraction %	H_2SO_4 Consumption kg/tonne
Low grade			
L1	10	54.4	13.4
L3	15	62.0	16.2
L5	20	68.2	22.8
High grade			
L2	10	64.3	13.5
L4	15	69.0	14.4
L6	20	77.7	19.3

Confirmatory tests on the Chemex samples were conducted by Lakefield Research (Tests: Lake 1-4). The tests were started with 15 g/L sulphuric acid solution and the pH of the slurry was decreased to 1.8 after 30 minutes or 90 minutes of leaching time. The results included in

Appendix C are comparable to those shown in Table 4.4 although the increased acid additions made to the Lakefield tests make a direct comparison difficult. The results of the various tests performed on the Chemex samples are summarized in Figure 4.7. It is apparent from these results that there is a direct correlation between acid addition and copper extraction.

For both composites the BDA tests were acid starved and yet gave increased copper extraction over the other tests. The exact reason for this variation cannot be established although it is known that the BDA tests were conducted at high roll speeds compared to the other tests. It is postulated that the high roll speed resulted in increased particle degradation, exposing more copper to the solution.

Similar results are shown in Table 4.5 for tests conducted on samples crushed to -2 cm. Note that these tests only achieved partial extraction due to the short duration of the test. As for the Chemex samples, increased acid addition correlates with increased copper extraction.

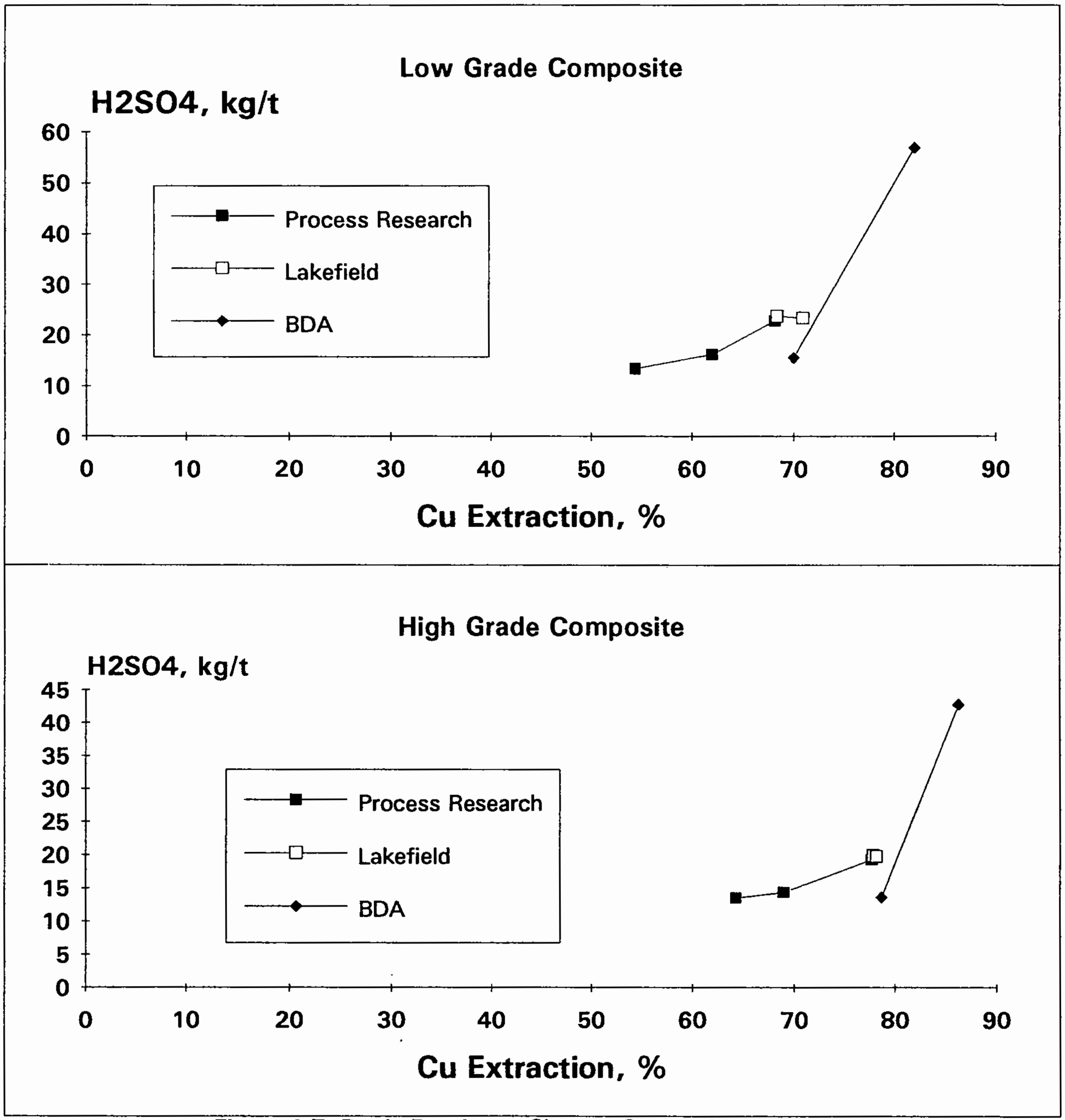

Figure 4.7 Bottle Results on Chemex Composites

TABLE 4.5

Effect of Acid Addition on Copper Extraction from minus 2 cm Material

COMPOSITE	TEST NO.	INITIAL H_2SO_4 g/L	Cu EXTRACTION %	H_2SO_4 Kg/tonne
+2700 L	L21	15	54.6	14.3
	L18	20	60.6	20.5
+2700 H	L22	15	47.6	13.9
	L19	20	50.9	19.4
2500-2700L	L23	15	35.5	12.4
	L20	20	39.5	19.0

4.2 BDA Column Tests

Two column tests were conducted by BDA on the surface trench samples. Since both tests achieved copper extractions of greater than 80% in 12 to 60 days they were judged to be successful and serve as a benchmark against which to judge all subsequent column tests.

The copper extraction as a function of time for both tests is summarized in Figure 4.8. Column no. 1 was leached with a 15 g/L H_2SO_4 solution until day 54, at which time the concentration was decreased to 10 g/L. As can be seen from Figure 4.9, the acid consumption for column no. 1 was fairly linear over the test duration and the pH of the pregnant solution decreased steadily.

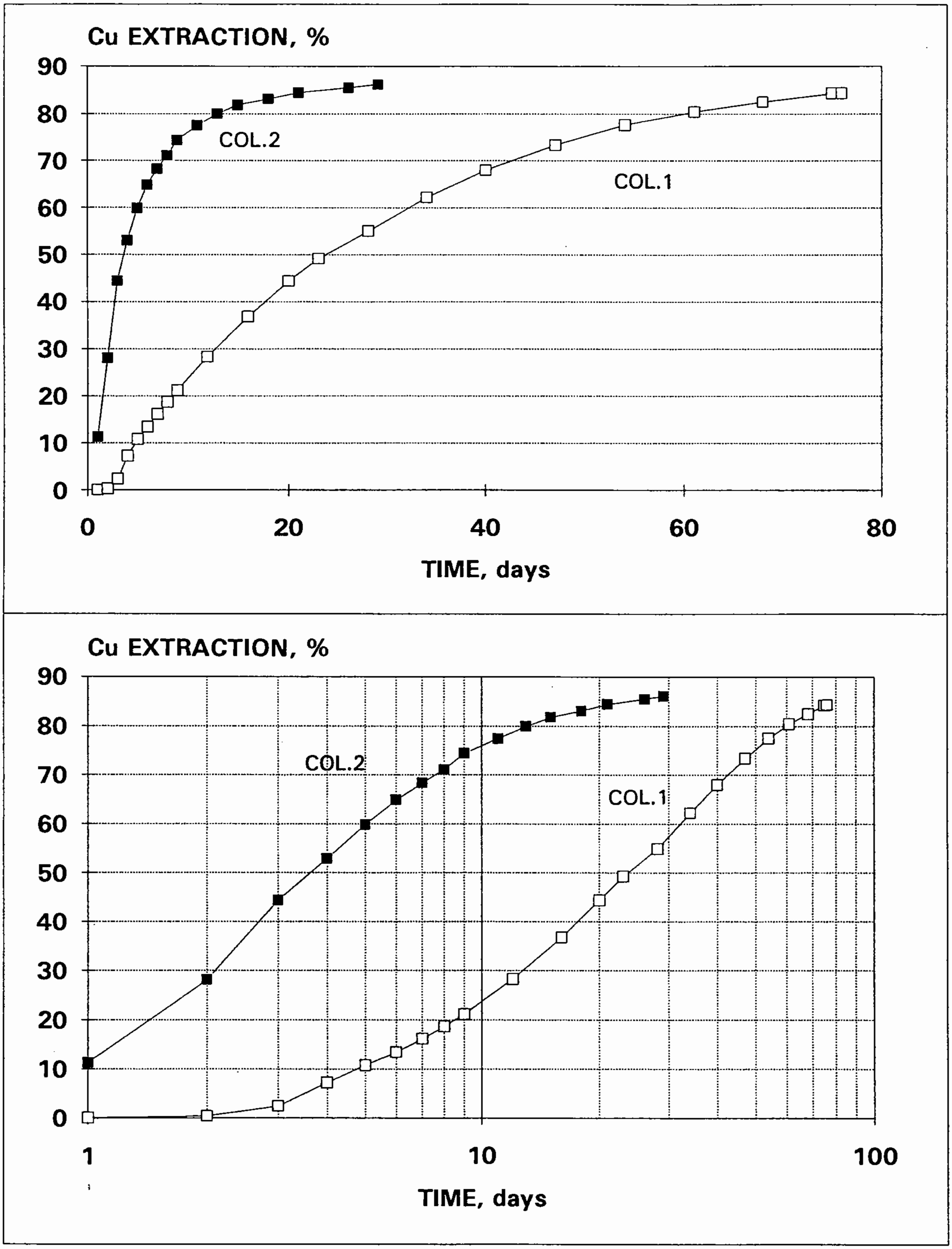

Figure 4.8 BDA column test results.

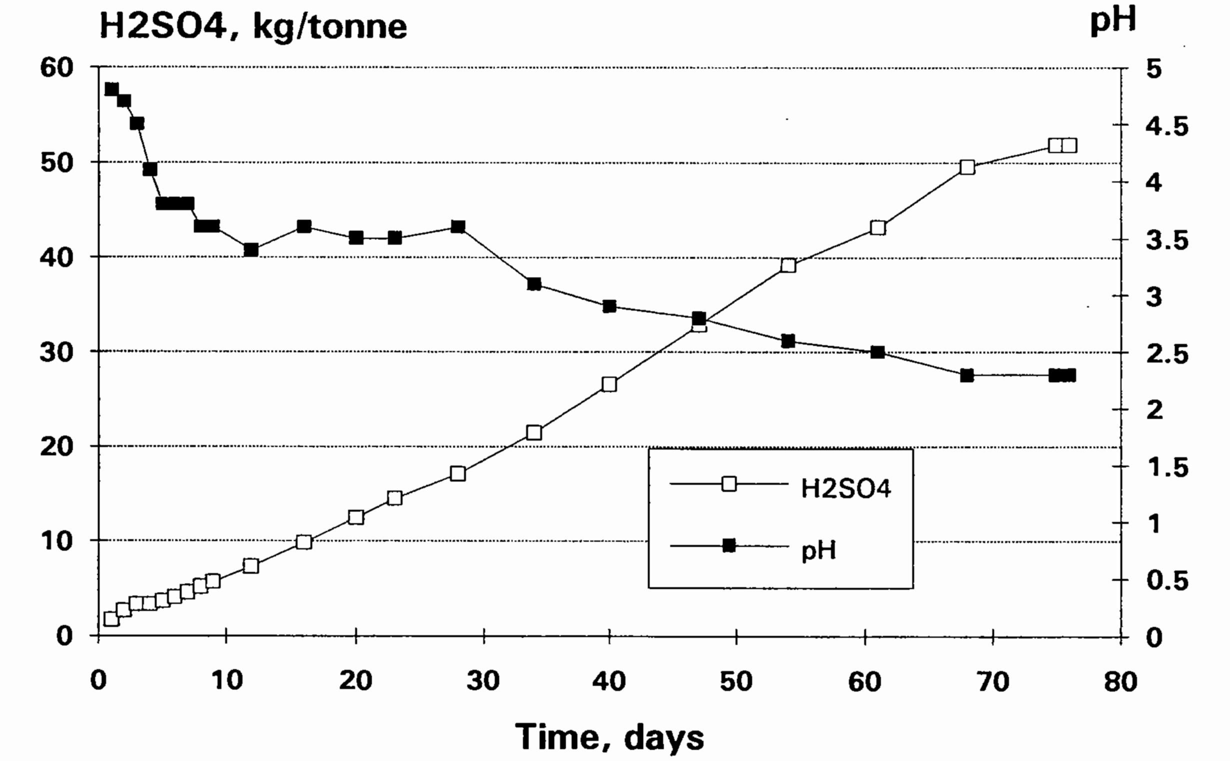

Figure 4.9 Acid consumption and pH for BDA column1

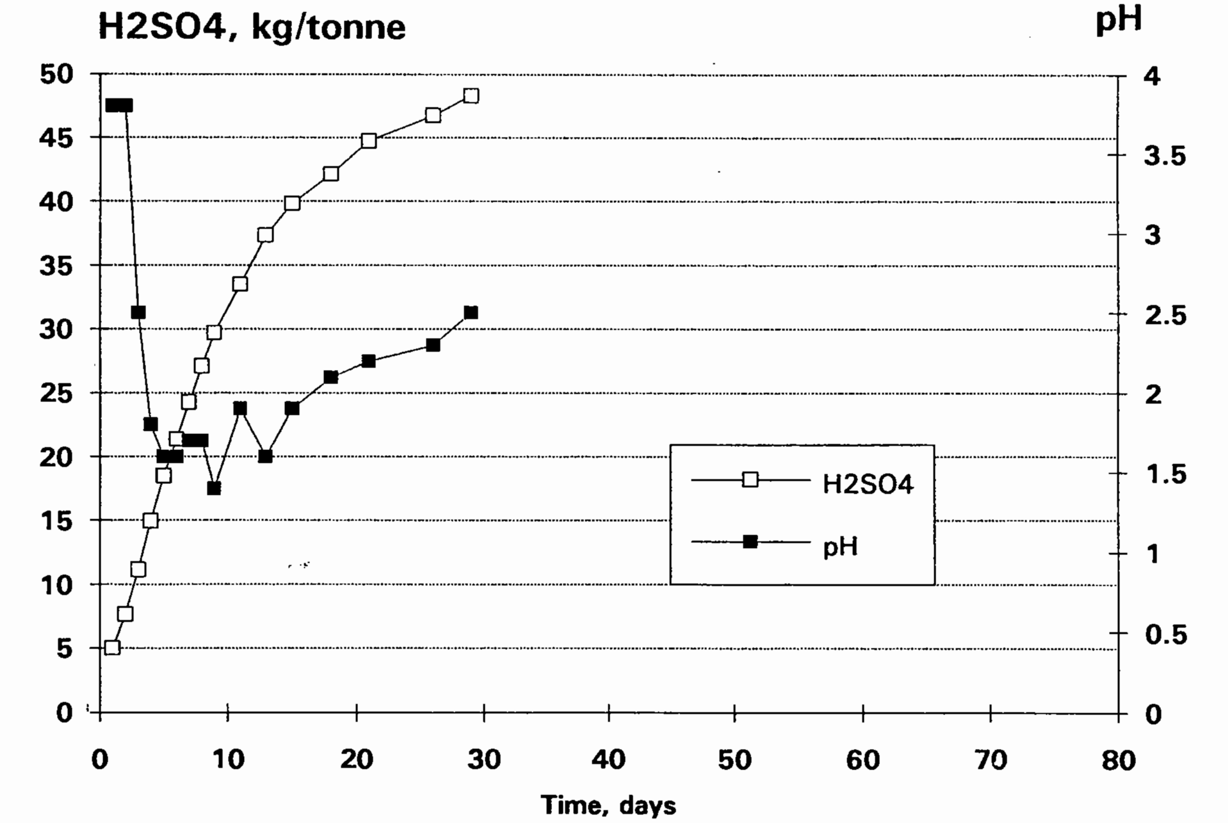

Figure 4.10 Acid consumption and pH for BDA column 2.

Although the pregnant solution pH was over 4 for the first few days of the test, there was no detrimental effect of this high pH on ultimate copper extraction. The flowrate for the entire tests was near the industry normal of .012 $m^3/h/m^2$.

For column 2, the initial flowrate was five times the normal flowrate and it was decreased periodically through the test duration so that it was at the normal rate by the end of the test. The initial acid concentration was 20 g/L H_2SO_4 which was decreased to 15 g/L on day 6 and to 10 g/L on day 15. The shape of neither the copper extraction curve in Figure 4.8 nor the acid consumption curve in Figure 4.10 was affected by these changes in operating conditions. The effect of changing the feed acid concentration on the pregnant solution pH is readily apparent in Figure 4.10. The acid consumption per kilogram of copper extracted reached a minimum at approximately 40% copper extraction and increased steadily after this point as can be seen in Figure 4.11. Decreasing the acid concentration of the feed solution to 10 g/L near the end of the test did not decrease the acid consumption per unit of copper. Even lower solution acidity may be appropriate near the end of a leach cycle.

The net effect of the high flowrate, high acid conditions at the outset of column 2 has been to give a much higher rate of copper extraction with comparable acid consumption. While the residue from column 2 had a somewhat finer average particle size than those from column 1, as can be seen from Figure 4.12, the difference is not judged to be significant enough to account for the large increase in copper extraction rate shown by column 2.

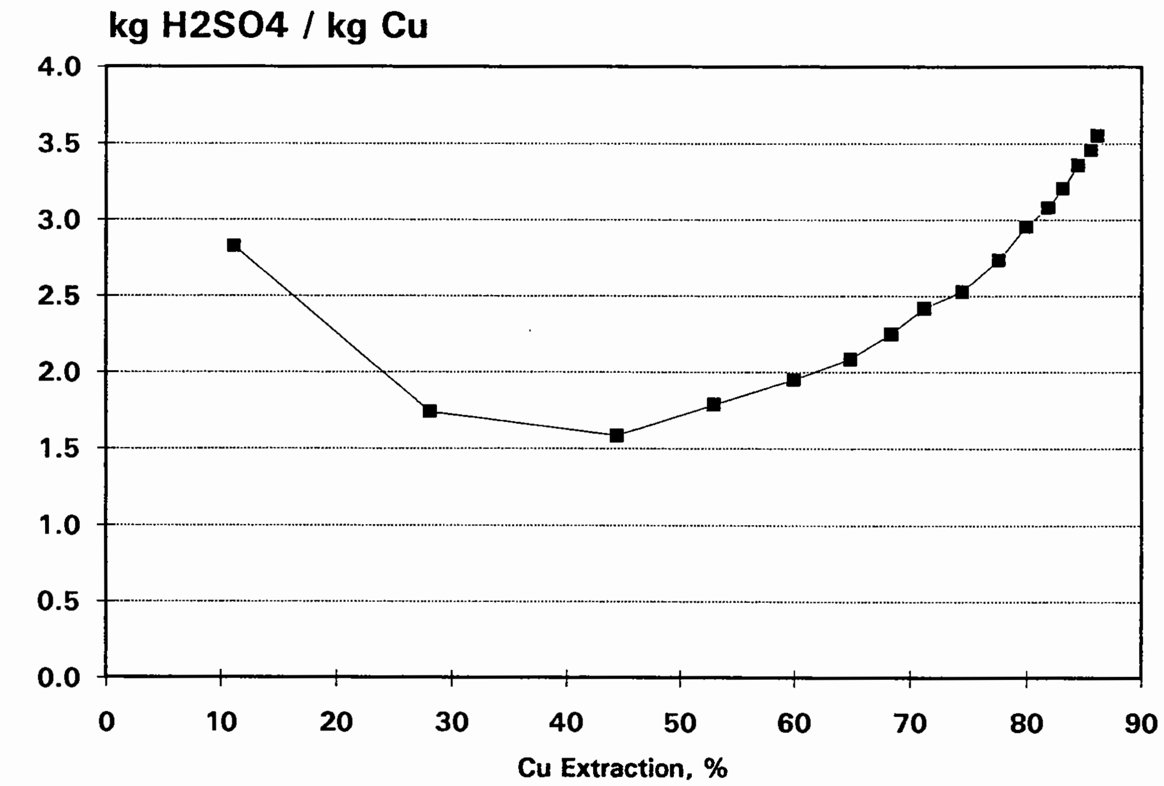

Figure 4.11 Acid consumption for BDA column 2

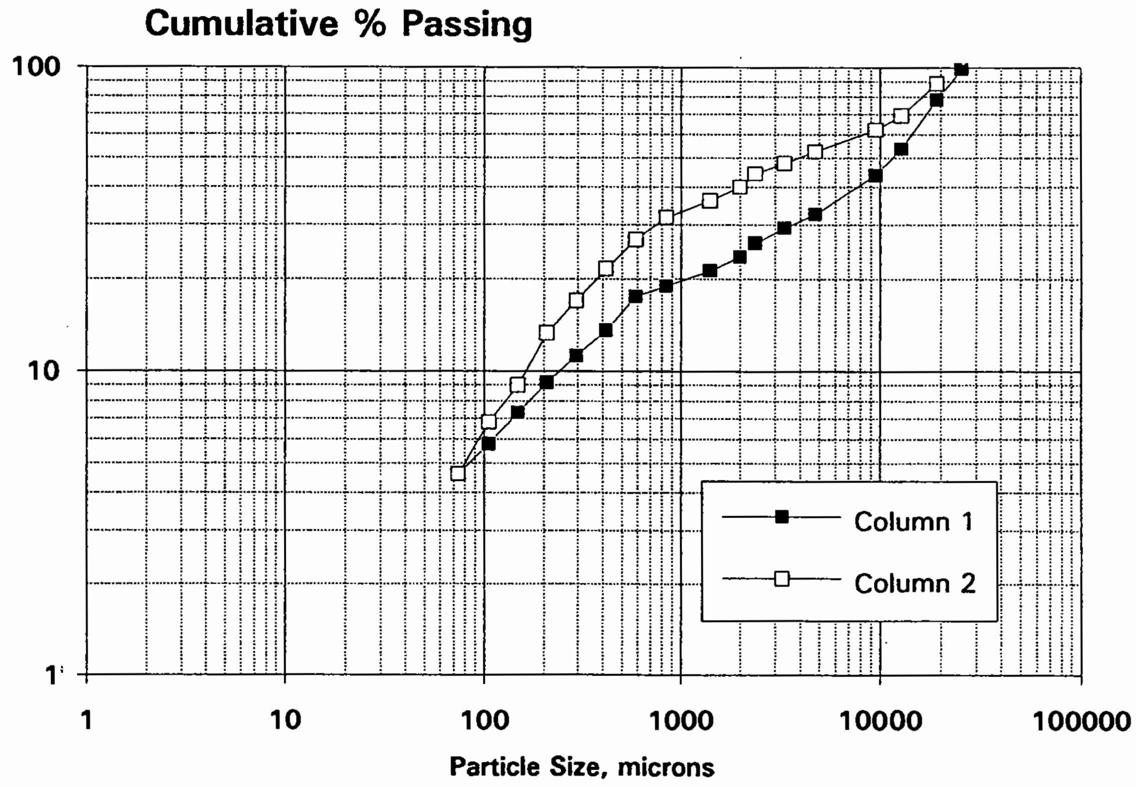

Figure 4.12 Size distribution of BDA column tailings.

4.3 Mini Column Tests

Mini column tests were conducted as a means to screen variables without the particle abrasion and degradation which is inherent in bottle roll tests. The first series of mini columns was conducted to study the effect of varying acid addition to the agglomeration stage while the second series studied the effect of crush size on leaching behaviour. In addition to these principal parameters, the operating conditions for the columns were varied as time proceeded in order to determine which variables controlled leaching kinetics and acid consumption.

4.3.1 Agglomeration Conditions

Three levels of acid addition to the agglomeration step were studied as follows:

Test No.	Acid, kg/tonne
M1	0
M2	5
M3	10

The results for the first 5 days in Figure 4.13 show that increasing the acid to the agglomeration stage results in higher initial copper leaching rates, as would be expected. Beyond day 5 the conditions for the three columns were varied and the three extraction curves converged, showing complex behaviour relative to each other. It was concluded from these results that although the acid addition to the agglomeration stage had an influence on the initial leach rate, other variables such as solution flowrate and feed solution acid concentration could be equally well used to control the overall copper leaching performance. For all subsequent column leaching testwork an acid addition of 5 kg/tonne was made to the agglomeration stage.

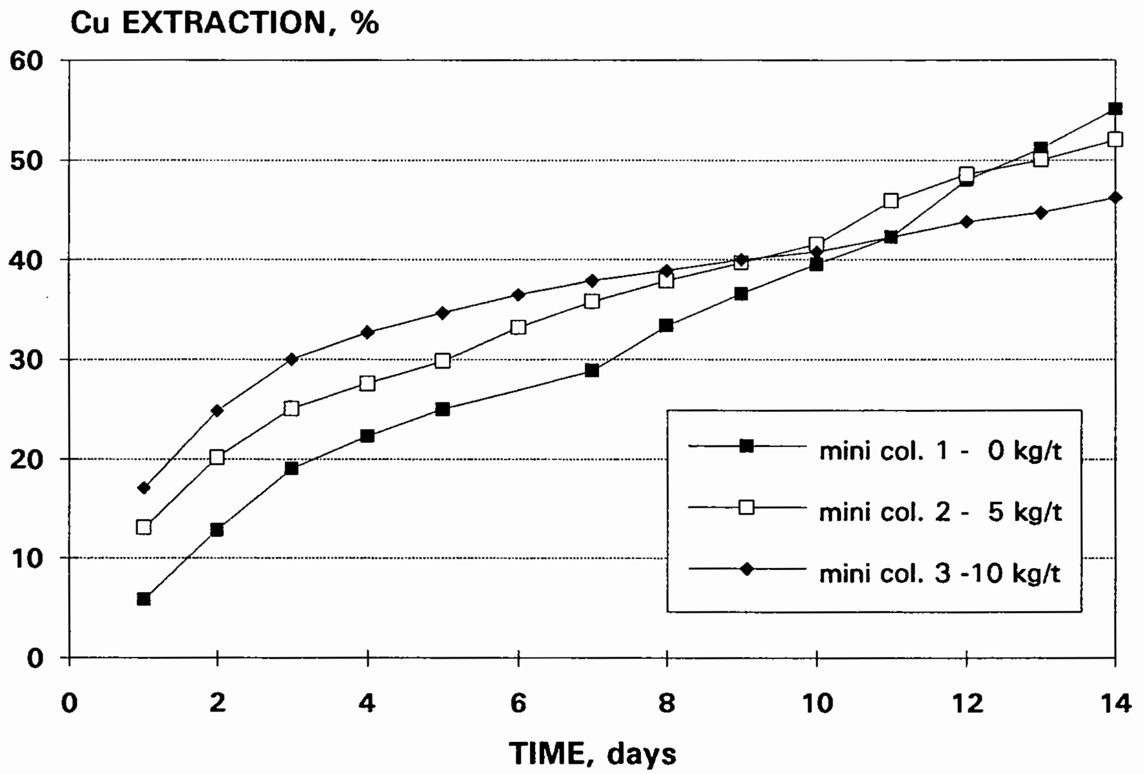

Figure 4.13 Effect of acid to agglomeration on Cu extraction.

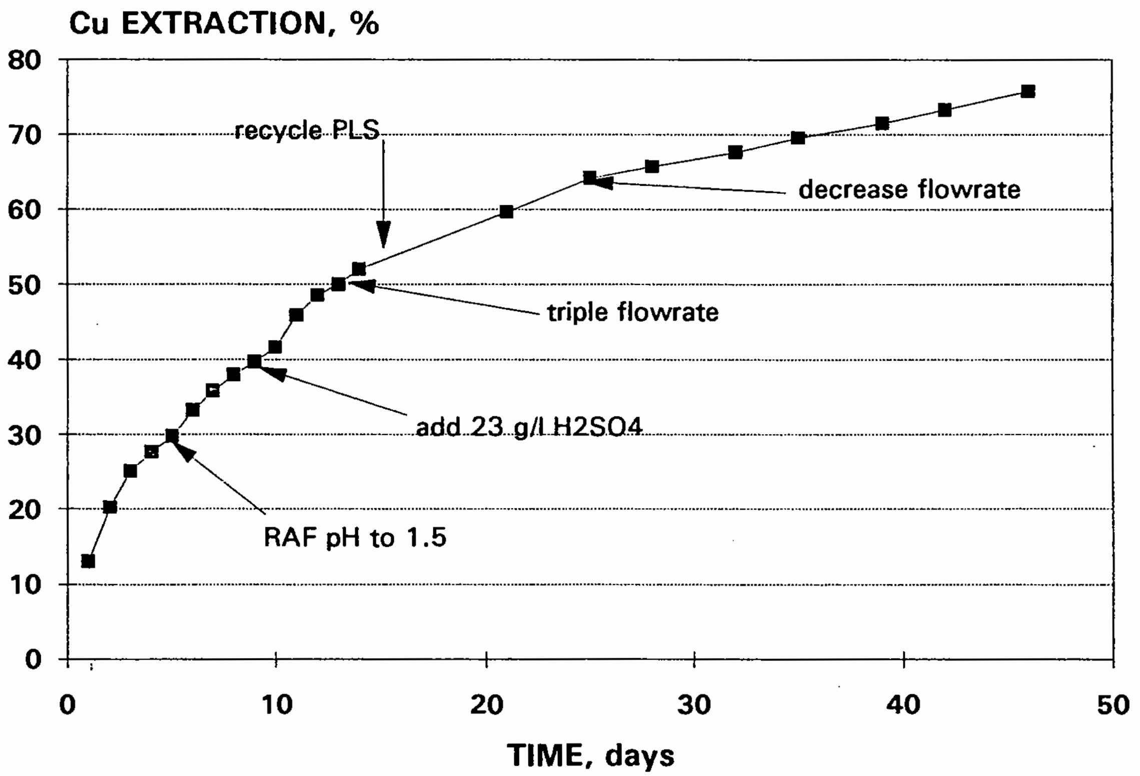

Figure 4.14 Variations in procedure for test M2.

4.3.2 Operating Conditions

The influence of some of the operating parameters on copper extraction rate can be seen from Figure 4.14 which summarizes the results from mini column no. 2. The increased acid additions made on days no. 5 and 9 resulted in temporary increases in the extraction rate. This increase tended to taper off within a few days so that the overall curve has a fairly constant profile.

The effect of acid addition on leaching rate is also evident for mini column 1 in Figure 4.13. The acid additions made after day 7, accelerated the leaching rate. The rate shows an additional sharp increase after day 11 at which time the solution flowrate was increased by a factor of five times. The increase in copper extraction rate was not proportional to the dramatic increase in acid consumption. This observation is consistent with the results for column 2 where tripling the flowrate on day 13 had only a minor effect on copper leaching rate.

It appears that the benefit to leaching rate resulting from high solution flowrates such as was observed in BDA column no. 2 is only realized at the outset of leaching when abundant leachable copper is exposed. It may also only be observable in tall columns which may benefit from a rapid migration of an acid front through the leach pile.

The acid consumption per kg copper in test M2 is shown in Figure 4.15 with the results for BDA column 2 included for comparison. The two curves have a similar form although column M2 shows a higher acid consumption across the entire range of extractions.

From day 15 on the pregnant solution from mini column 2 was recycled with acid addition to maintain the feed solution at pH 1.5 and only periodic solvent extraction for copper removal. Copper leaching proceeded at a reasonable rate indicating that there was no build-up of materials which are deleterious to leaching.

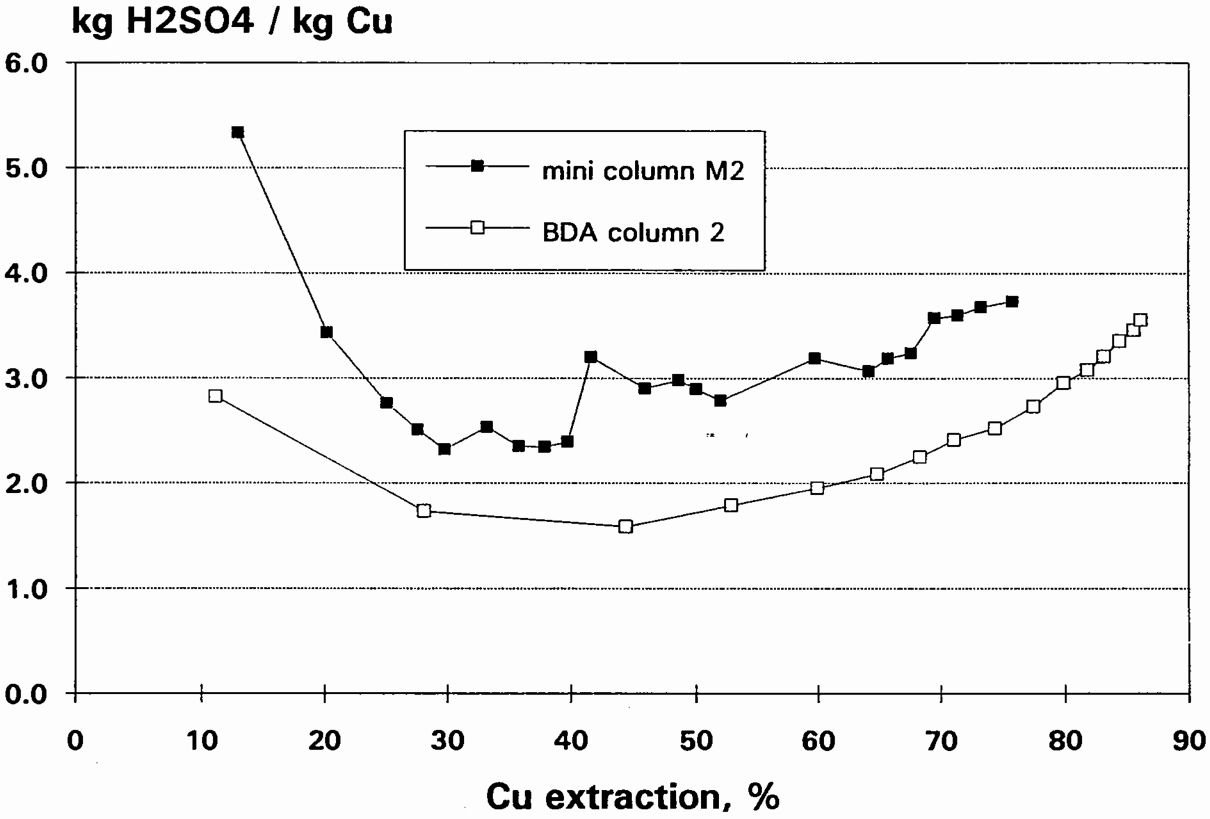

Figure 4.15 Acid consumption for mini column M2.

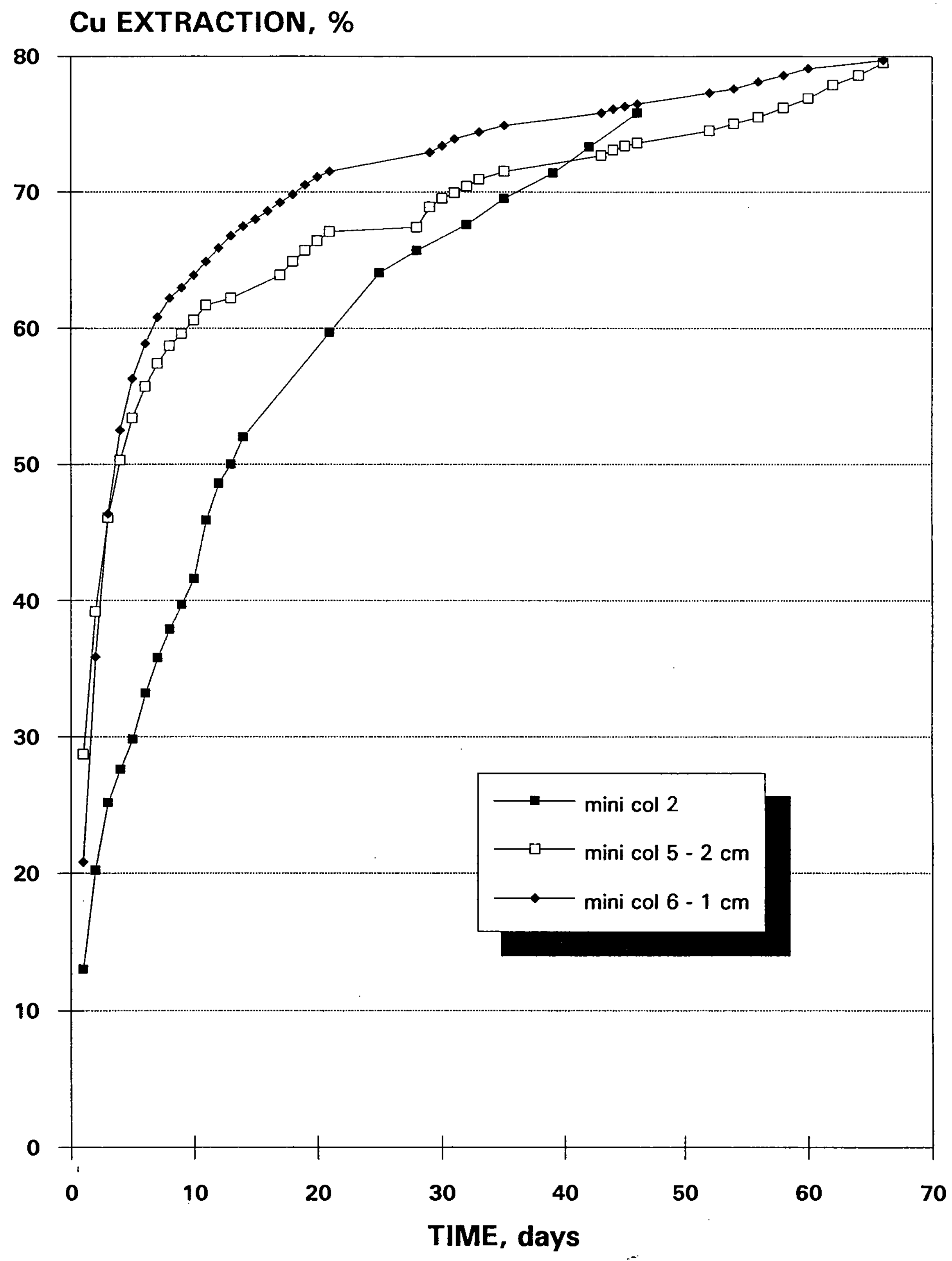

Figure 4.16 Effect of crush size on copper extraction.

TABLE 4.6

Copper Assay of Feed and Tailings Fractions from Column M5

FRACTION	FEED		TAILINGS			
			TOP		BOTTOM	
	WEIGHT %	Cu, %	WEIGHT %	Cu, %	WEIGHT %	Cu, %
+ 1.6 cm	31.0	1.67	35.6	0.50	26.8	0.72
- 1.6 + 1	38.8	2.60	28.0	0.26	30.1	0.34
- 1 + 0.6	15.3	1.46	9.2	0.15	11.3	0.19
- 0.6+ 20 m	9.5	1.74	11.4	0.09	14.8	0.11
-20+32	1.2	2.30	1.9	0.16	2.1	0.19
-32+65	1.8	2.56	5.3	0.17	5.4	0.20
-65	2.5	3.26	8.6	0.23	9.4	0.22
TOTAL		2.07		0.31		0.37

The results show that leaching has progressed to a greater degree at the top of the column than at the bottom. Considering the fact that the column was only 1.2m tall, the effect can be expected to be more pronounced when leaching a full lift.

As expected, the copper extraction is greater for the fine fractions than for the coarser particles. The same observation is made for the column M6 results which are summarized in Table 4.7. For both tests there appears to have been some decrepitation of the solids since the tailings size distributions are finer than the feed distributions.

TABLE 4.7
Copper Assay for Feed and Tailings Fractions from Column M6

SIZE FRACTION	FEED		RESIDUE		EXTRACTION %
mesh	WEIGHT %	Cu, %	WEIGHT %	Cu, %	
+4	37.7	1.58	35.9	0.55	66.9
-4+20	32.7	1.28	29.8	0.10	92.9
-20+32	6.1	1.46	6.8	0.12	90.8
-32+65	9.6	1.52	11.4	0.14	89.1
-65+100	3.2	1.64	3.6	0.15	89.7
-100+200	4.9	1.78	5.1	0.15	91.2
-200	5.9	2.54	7.3	0.16	92.2
TOTAL		1.54		0.28	

In addition to maximizing the rate of copper extraction, it is important to minimize acid consumption. The results for tests M5 and M6 shown in Figure 4.17 indicate that this minimization of acid consumption was not achieved by using a fine crush size which actually had an increased consumption compared to the coarse crush. This result was not expected since bottle roll tests on fine materials (ie. the Chemex samples or material crushed to -10 mesh) had required significantly less acid than material crushed to minus 2 cm for comparable copper extractions. Since the percolation problems experienced in column 6 make it apparent that fine crush sizes cannot be heap leached, differences in acid consumption due to varying particle size do not seem to be exploitable.

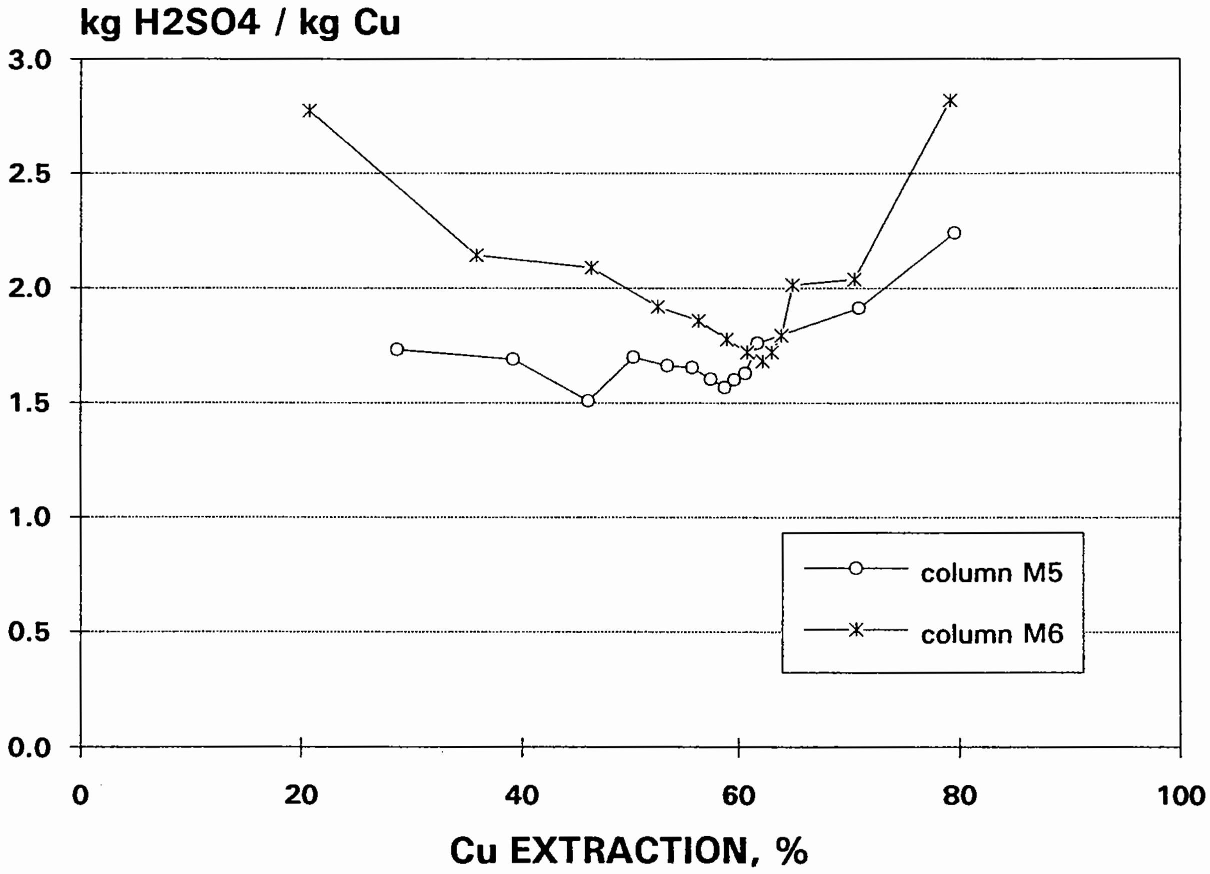

Figure 4.17 Acid consumption for mini columns 5 and 6.

4.3.4 Iron Dissolution

As well as dissolving copper, the acid solution dissolves iron and other metals from the rock. In test M5 the iron concentration in solution increased to as high as 19.5 g/L. The iron values for the PLS in test M5 as a function of pH, are shown in Figure 4.18.

Although there is a trend towards lower iron concentrations with increasing pH, the trend is very broad. This broad trend is consistent with the solution potentials which indicate that the majority of the iron is in the ferrous state.

Since the solvent extraction reagents are highly selective against iron, solution concentrations in the order of 10 g/L Fe are not expected to pose any operational problems. If PLS pH is maintained at a level of 2 or greater, the dissolved iron will precipitate as it becomes oxidized. In addition to avoiding excessive build-up of iron, this precipitation will serve to release the acid associated with the dissolved iron.

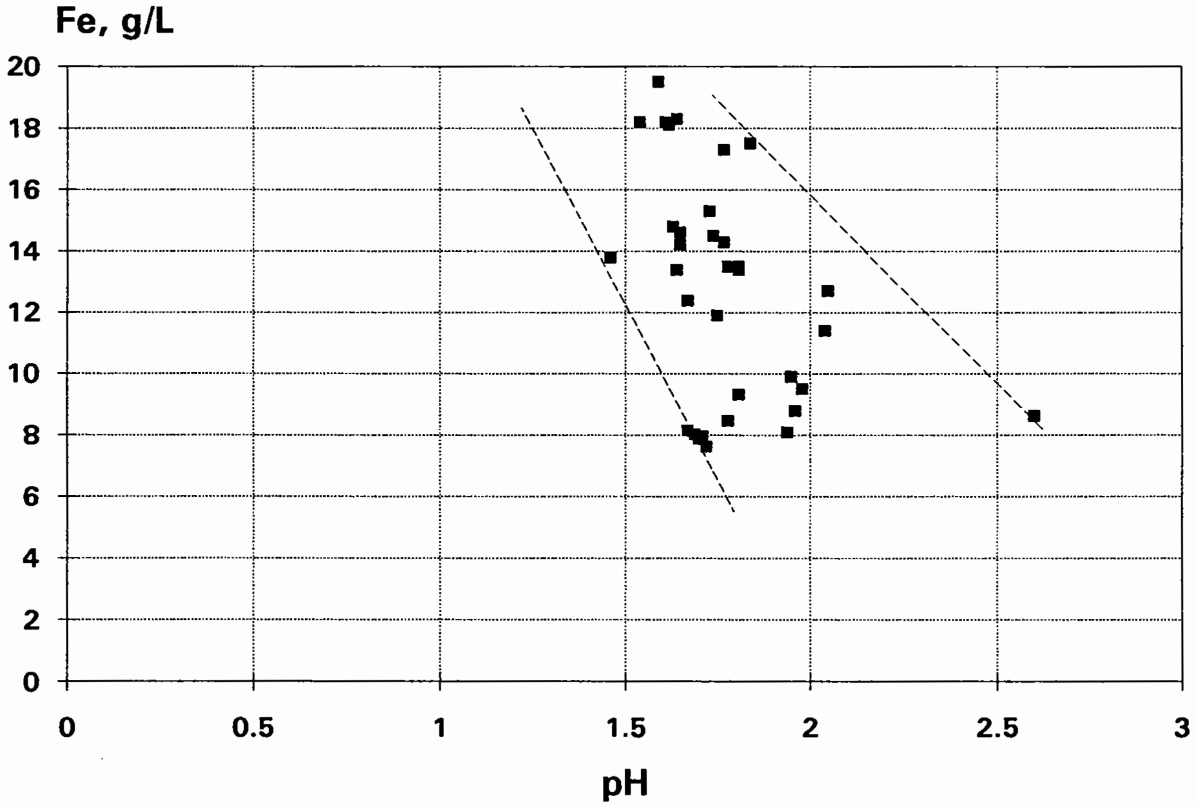

Figure 4.18 Iron concentration as function of pH for test M5.

4.4 Column Tests

4.4.1 Composite Samples

Tests were conducted on the three composite samples:

Low Grade
High Grade
South End

These tests included the full particle size range below 2 cm and the columns were loaded to their full 3 meter height. The feed to each column was agglomerated with 5 kg/t H_2SO_4.

One of the objectives of these tests was to determine whether the acid consumption could be minimized by limiting the addition rate of acid to the columns.

The tests were started with raffinate solution from previous testwork which was diluted with fresh water to provide sufficient volume for the tests and was then adjusted to pH 1.8 prior to use. The starting solution therefore contained 3.5 g/L H_2SO_4. During the initial part of the test the raffinate produced from each column only had acid added when the pH exceeded 1.8. The tests therefore operated with little or no acid additions during the first week to ten days of leaching.

The results for these tests, together with those for BDA column no. 1, are shown in Figure 4.19.

The initial leach rates for these tests were higher than observed for BDA column 1 since the initial flowrate for the columns was three times the rate used for the BDA column and sufficient acid was obtained from the solvent extraction step. As the acid concentration in the recycle solution fell, the leaching rate

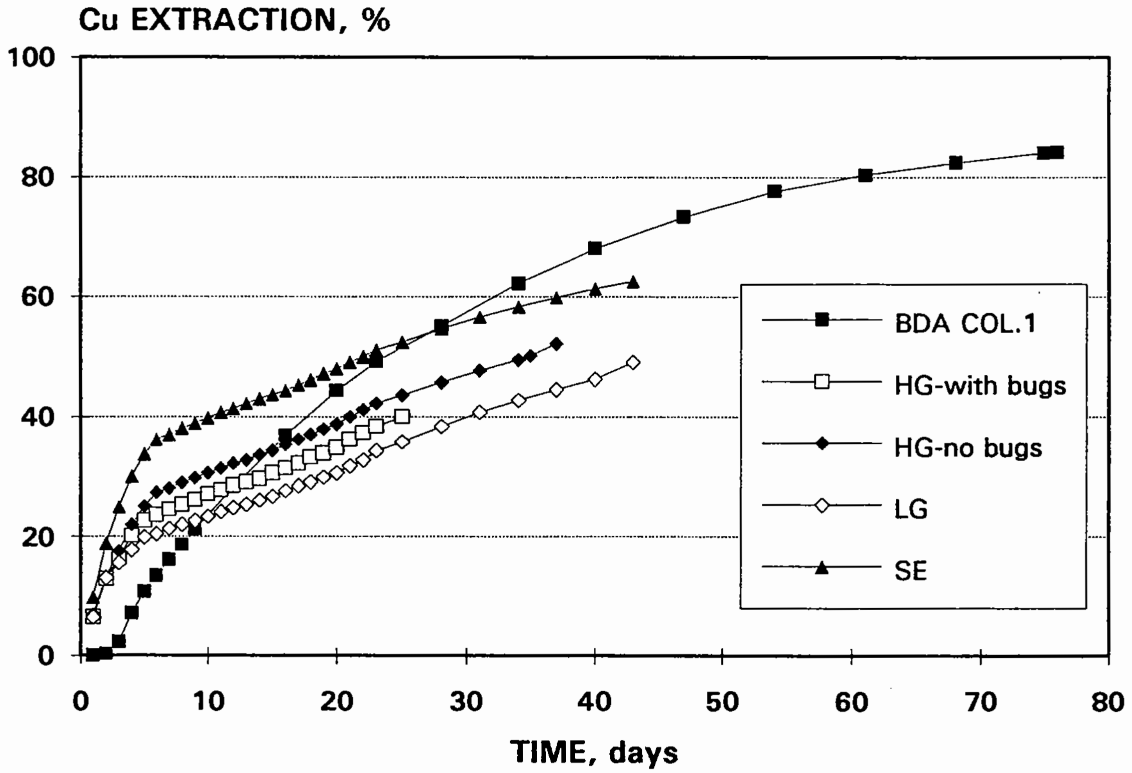

Figure 4.19 Copper extraction vs time for composite samples.

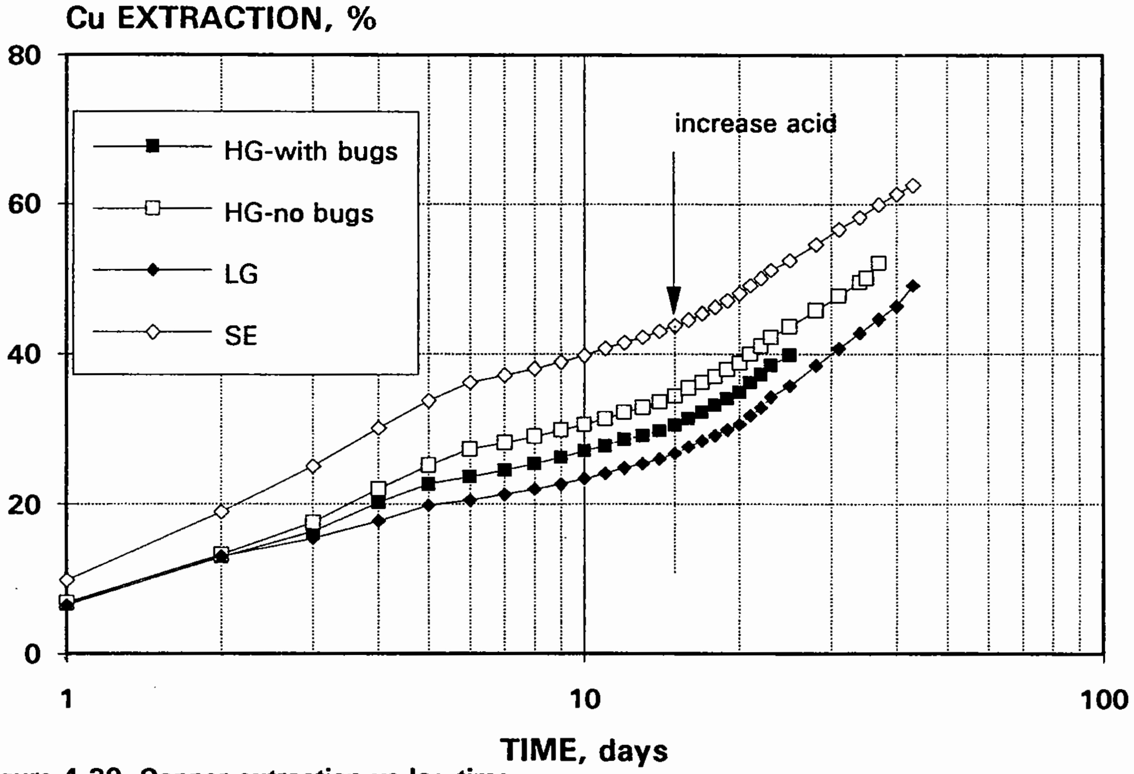

Figure 4.20 Copper extraction vs log time.

dropped off drastically by day 5 to 6. The rate decrease was most dramatic for the low grade composite which not only contains the least soluble copper but is also the highest acid consumer. The South End sample gave the best leaching response as was observed during the 1992 BDA bottle roll testwork. There is little apparent difference between columns S2 and S3 which were both conducted on the high grade composite. Column S2 had bacteria added to the test while S3 did not. It is possible that the sulphide content of the material is too low to support a viable population of bacteria.

Since the samples seemed to be leaching very slowly, on day 15 it was decided to add 0.5 kg/t H_2SO_4 to each column every day, regardless of the recycle pH. This addition is equivalent to approximately 9 g/L H_2SO_4. The result of the increased acid addition is an upward inflection in the extraction curves. The increase in extraction rate is more apparent in the log plots shown in Figure 20.

The effect of the variation in acid addition strategies on acid consumption for test S3, is apparent in Figure 21. Since a small amount of copper was extracted on day 1, the initial consumption per kg copper is very high. Then, as no acid was added for the first 11 days, the consumption decreases steadily with the accompanying decrease in copper extraction rate observed in Figures 4.19 and 4.20. The acid added from day 15 onward does not result in a proportional increase in copper extraction so the acid consumption per unit of copper increases dramatically, particularly at the end of the test when an addition of 2.5 kg/t was made for two successive days. The acid consumption per unit of copper in these tests was higher than for the previous test results shown in Figures 4.15 and 4.17, at comparable copper extractions. A preferable strategy appears to be to add more acid at the start of the test and then to control acid additions by maintaining the pH of the feed solution.

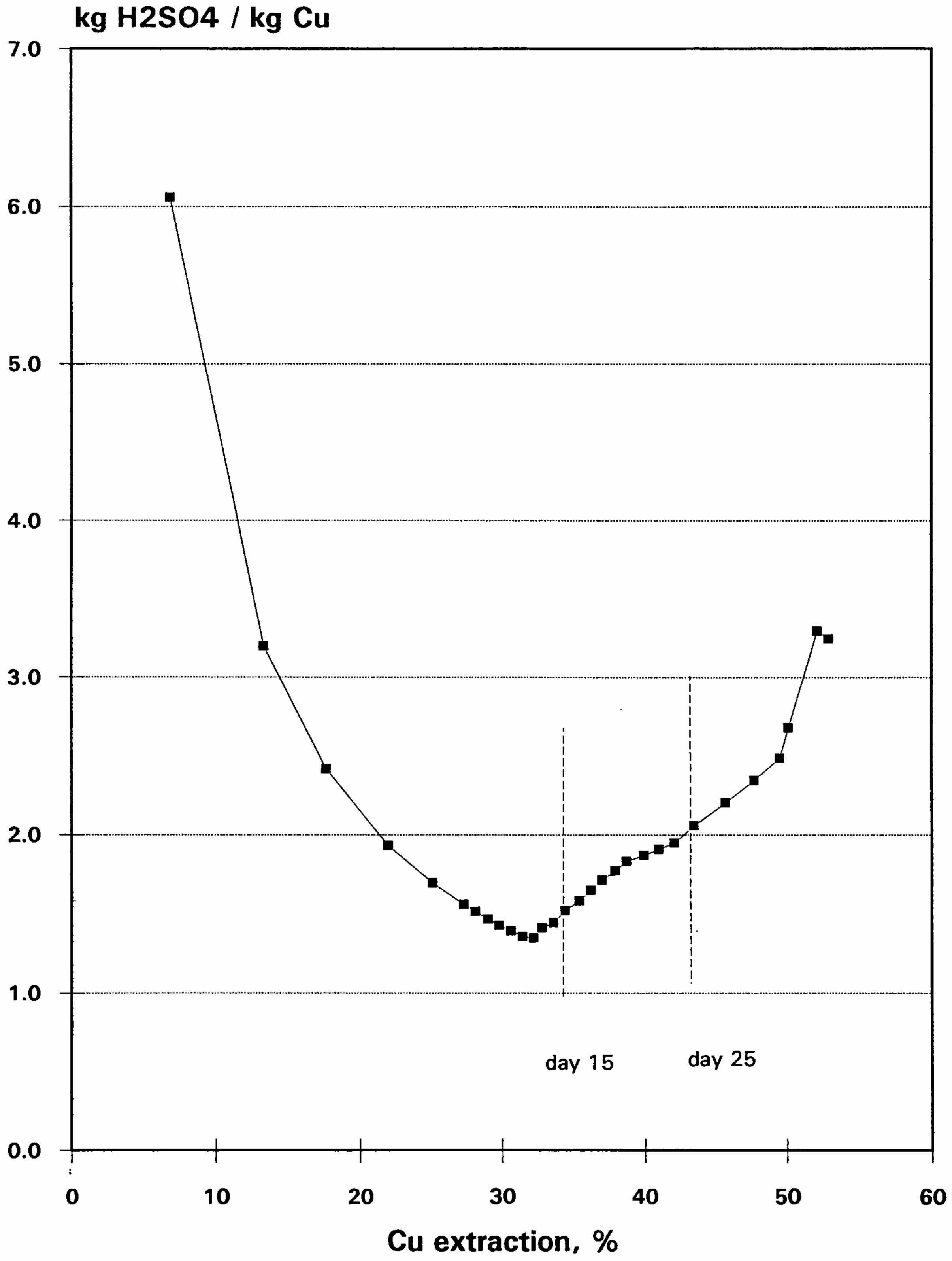

Figure 4.21 Acid consumption for column test S3.

The PLS grade in these tests shows the typical pattern of being very high at the outset of the test (2-8 g/L Cu) and then decreasing to approximately 1 g/L as the test progresses. Increasing the initial acid addition can be expected to increase the copper concentration in the initial "spike". Also, as the height of material is increased to that of a full lift, the PLS grade will remain at a high level for an extended period compared to the present test. It is projected that the PLS grade will remain at 1 g/L Cu or better until the extraction exceeds 80%.

As each column test was ended, the solids were carefully dumped out so that variations in leaching from the top to bottom could be analyzed. The tailings from each column were split into three approximately equal portions representing the top, middle and bottom of the columns. The complete size analyses for each section of the columns are included in Appendix E. Figure 4.22 summarizes the size distribution for the top section of the four columns. The low grade composite is seen to have the coarsest size distribution and the South End sample the finest. These variations in size distribution in part explain some of the differences in leaching behaviour exhibited by the composites.

The size distributions for the column products were analyzed for evidence of fines migration to the bottom of the column. A typical variation for the three sections of a column is shown in Figure 4.23. The top and bottom sections are seen to be finer than the middle section. The data are not convincing that any migration has occurred. It is probable that the top of the column experienced greater particle degradation than the other sections since this section was leached more completely.

The copper analyses for the sections of the columns are summarized in Table 4.8. In each case it is apparent that leaching was progressing downward from the top of the column. In the case of column 2, almost no leaching had occurred at the bottom of the column. These results are consistent with observations made when the column was dismantled. The bottom section of this column still contained visible malachite on the surface of the rock fragments. These results are particularly significant in view of the fact that increased acid additions as the test progressed

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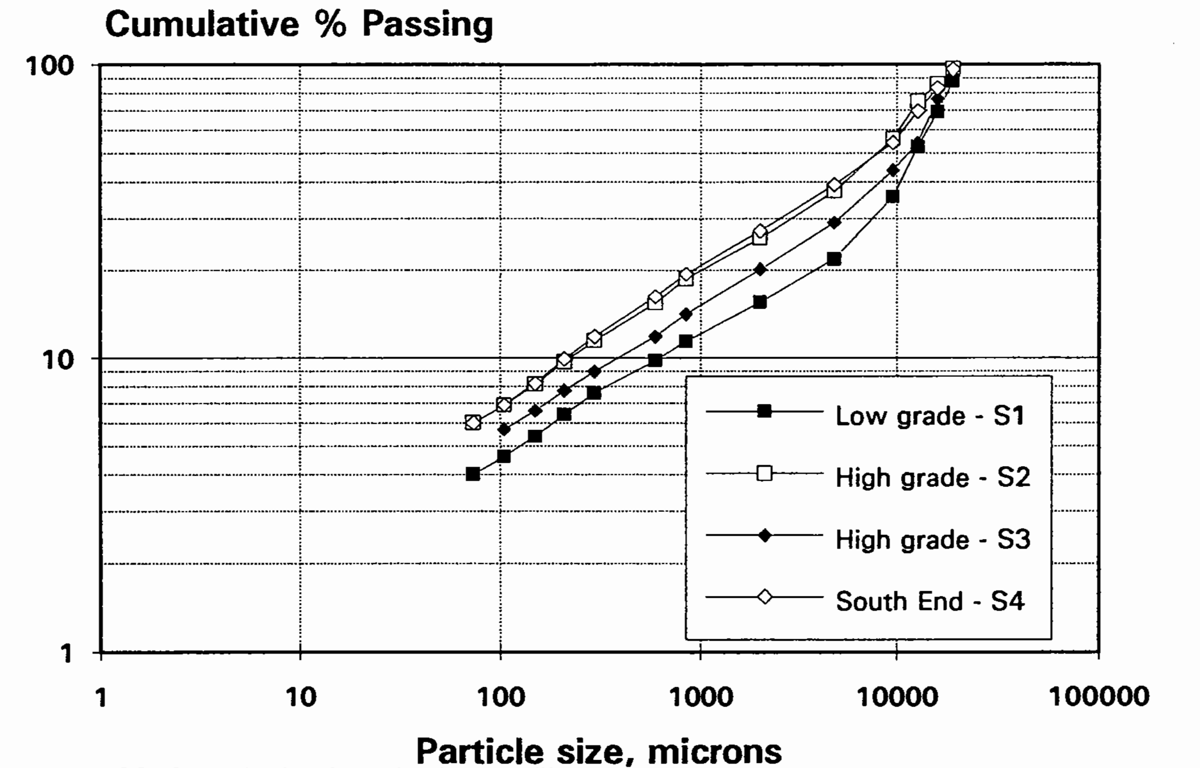


Figure 4.22 Size distribution of column tailings.

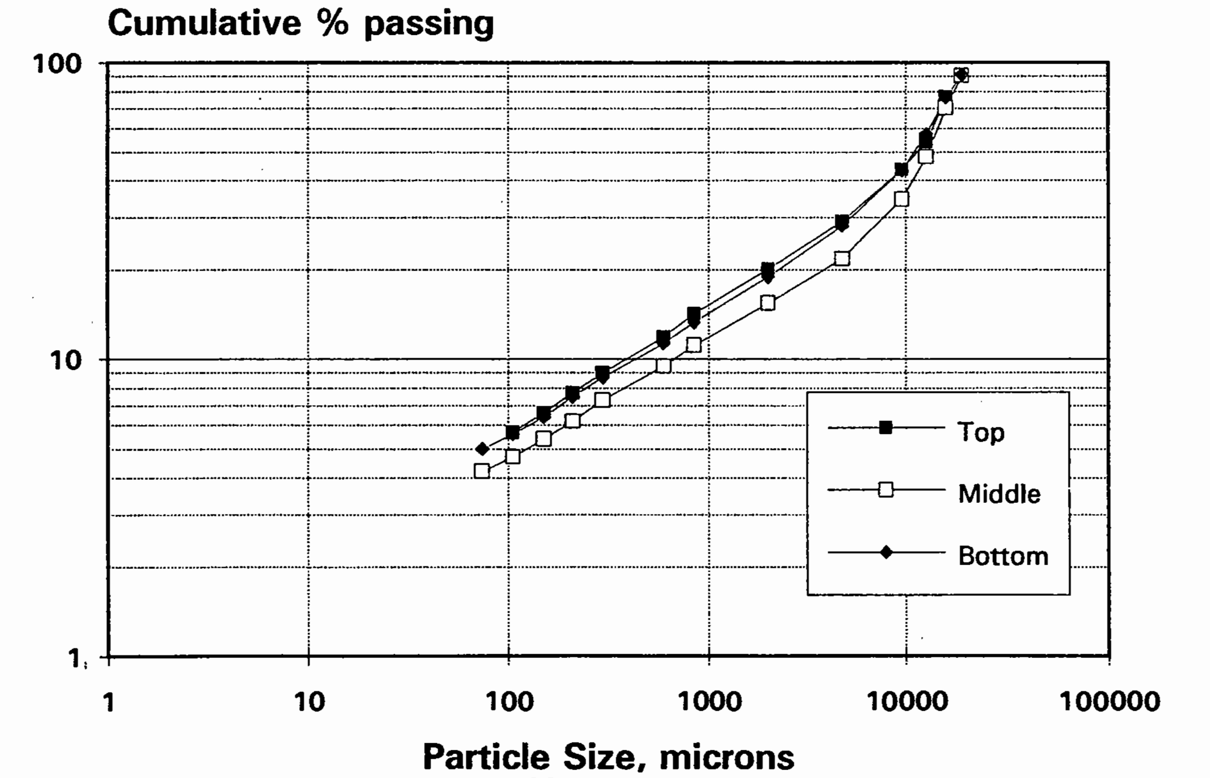


Figure 4.23 Size variation within column S3.

failed to leach this copper which readily dissolved when the rock chips were placed in an acid solution. It appears from these results that high copper extraction with minimal acid consumption is best achieved by ensuring high acid availability at the start of the leach cycle as was done in BDA column no. 2.

TABLE 4.8

Analyses of Column Tailings

SAMPLE	WEIGHT %	Cu %	% DISTRIBUTION
COLUMN S1			
TOP	25.4	0.16	11.7
MIDDLE	32.4	0.31	28.9
BOTTOM	42.2	0.49	59.4
COLUMN S2			
TOP	34.3	0.41	21.1
MIDDLE	39.4	0.65	38.4
BOTTOM	26.3	1.03	40.6
COLUMN S3			
TOP	34.5	0.38	19.9
MIDDLE	36.0	0.77	42.1
BOTTOM	29.5	0.85	38.0
COLUMN S4			
TOP	36.4	0.25	21.6
MIDDLE	35.6	0.49	41.3
BOTTOM	28.0	0.56	37.1

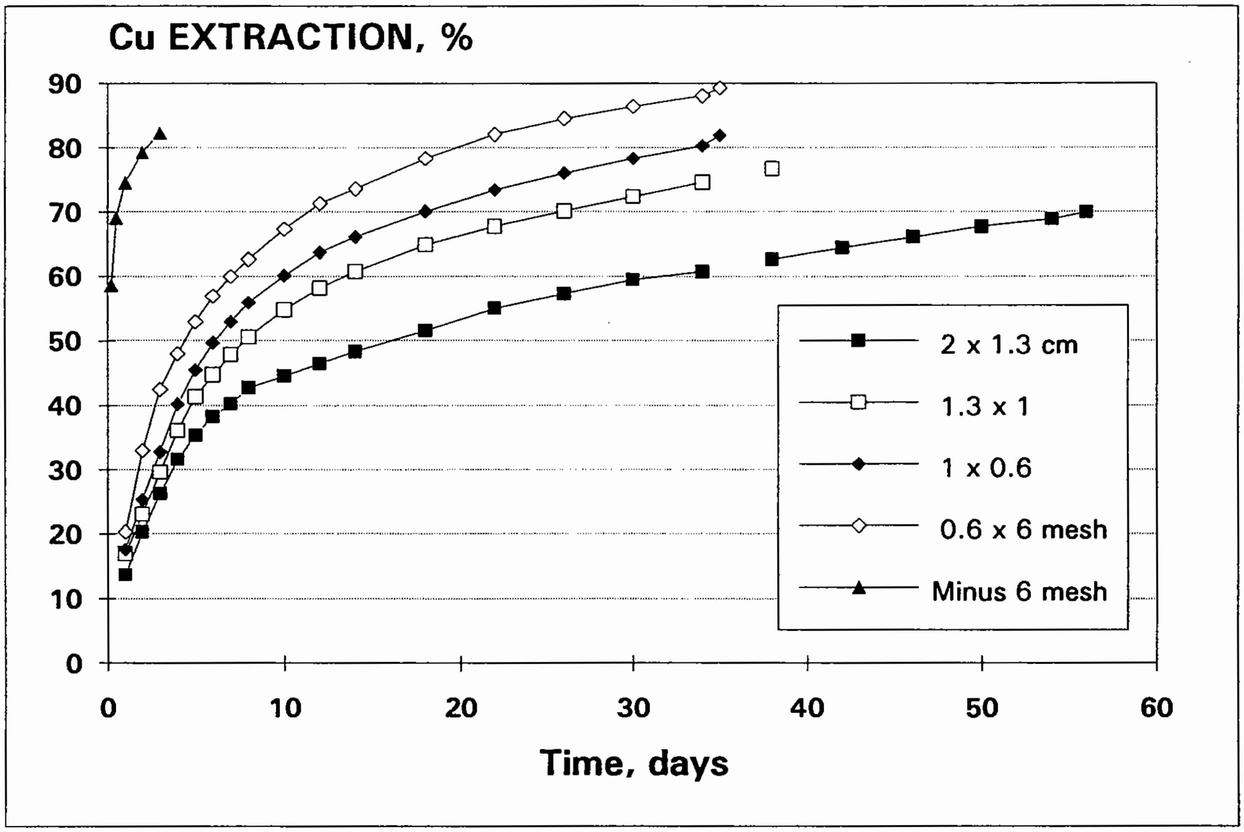
4.4.2 Flood Tests

Flood tests were conducted on size fractions from 2 cm to 6 mesh of the High Grade, Low Grade and South End composites according to procedures described in section 3.2.2. Since the minus 6 mesh material would not be amenable to column leaching, it was subjected to a bottle roll test.

The test results are summarized in Figures 4.24 through 4.26 which include both an extraction vs linear time and vs log time plot for each composite. The results for each composite show a similar pattern of progressively longer times being required for achieving 80% extraction as the particle size becomes coarser. As for previous tests, the South End samples leached the fastest and the Low Grade samples leached the slowest. The log time plots are fairly linear for all the tests apart from minor fluctuations due to variation in daily flowrate.

For the high grade composite the 2 x 1.3 cm fraction requires a significantly longer leach time than the 1.3 x 1 cm fraction. In addition to the longer time requirement the slow leach kinetics for the coarse fraction results in increased acid consumption. While the 1.3 x 1 cm fraction consumed 32 kg/t H_2SO_4 to achieve 70% copper extraction, the 2 x 1.3 cm fraction consumed 41.5 kg/t for the same extraction.

The effect of solution flowrate on copper extraction and acid consumption was determined for the 2 x 1.3 cm High Grade fraction. The solution flowrate for test F11 was approximately three times that of F3. As can be seen from the results shown in Figure 4.27, while there is some increase in rate with the higher solution flowrate, the effect is minimal. The increased leach rate observed for BDA col. 2 with high flowrate is apparently due to leaching of the fines present in that test. At comparable copper extractions the acid consumption per tonne ore is lower for the high flowrate condition as shown in Figure 4.28. This effect is even more pronounced on a kg acid per kg Cu basis since the feed grade to the high flowrate test was somewhat greater than for the low flow test.



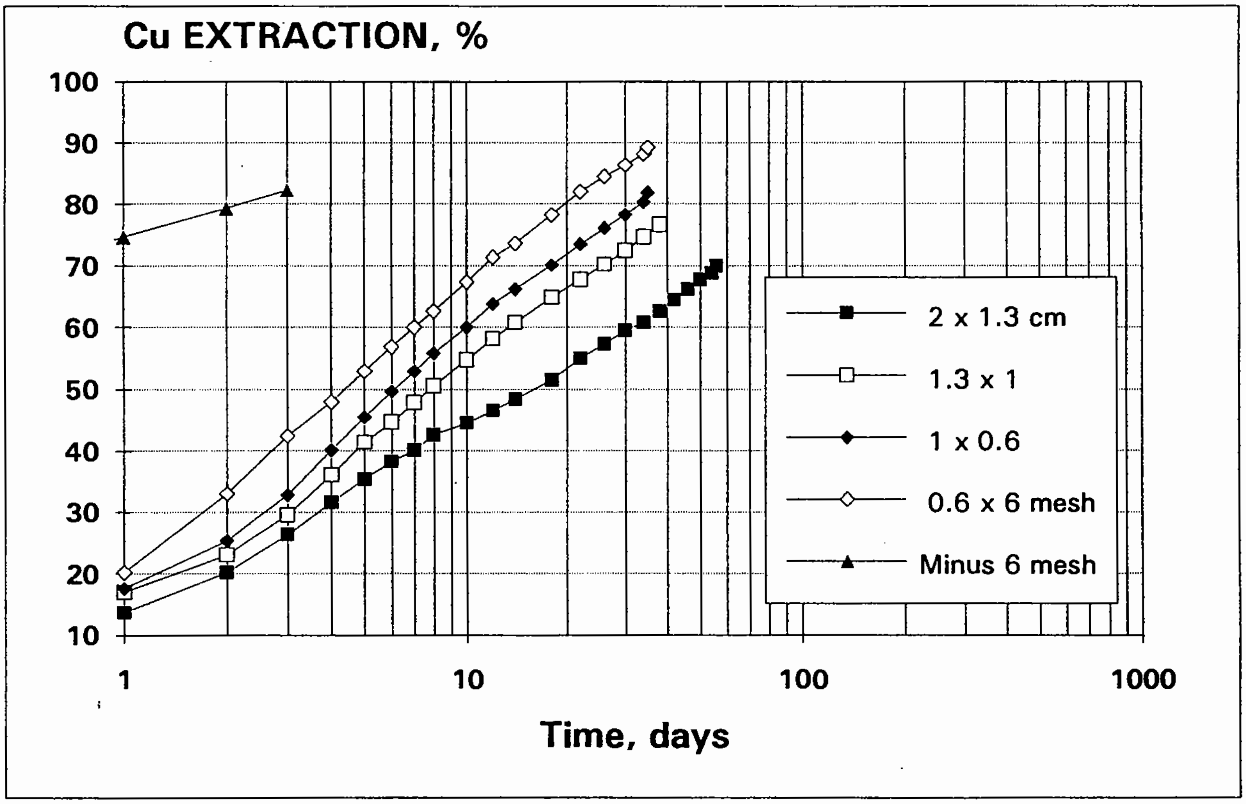
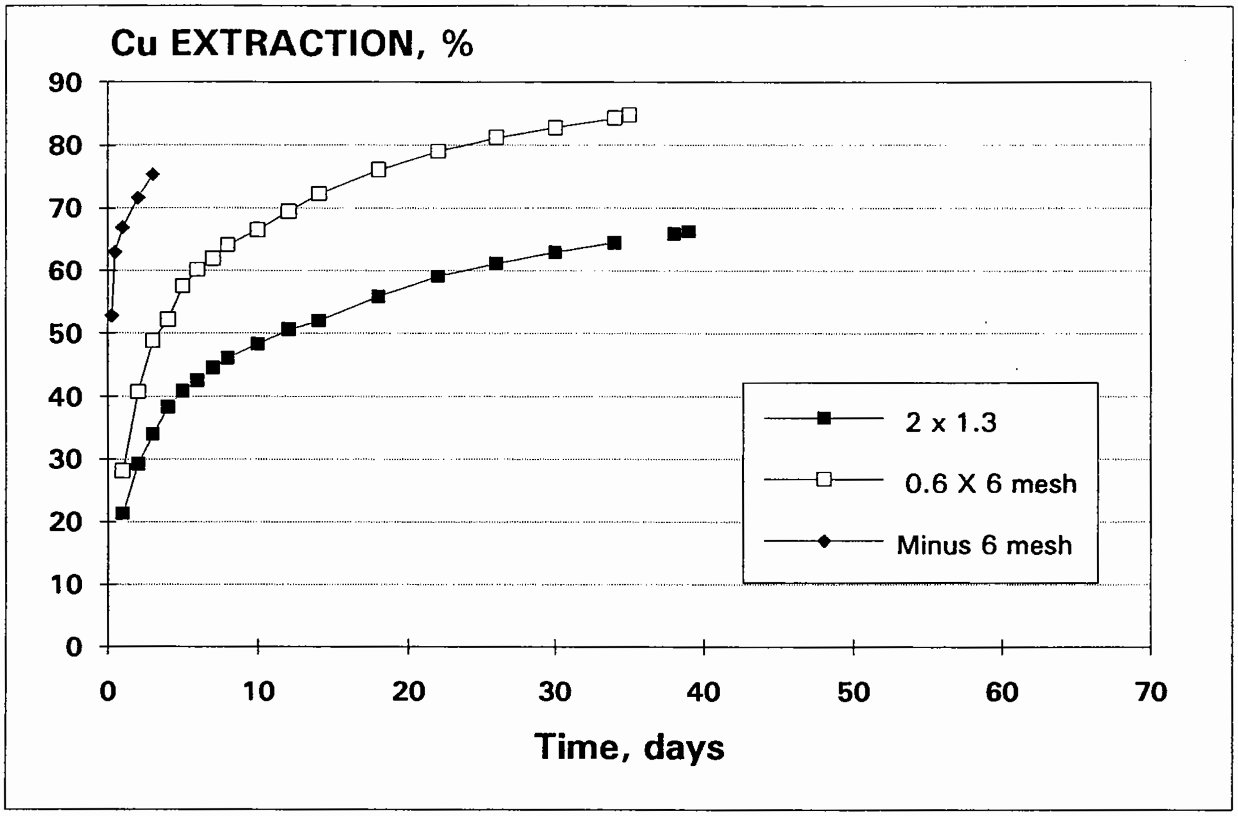


Figure 4.24 High grade composite flood results.



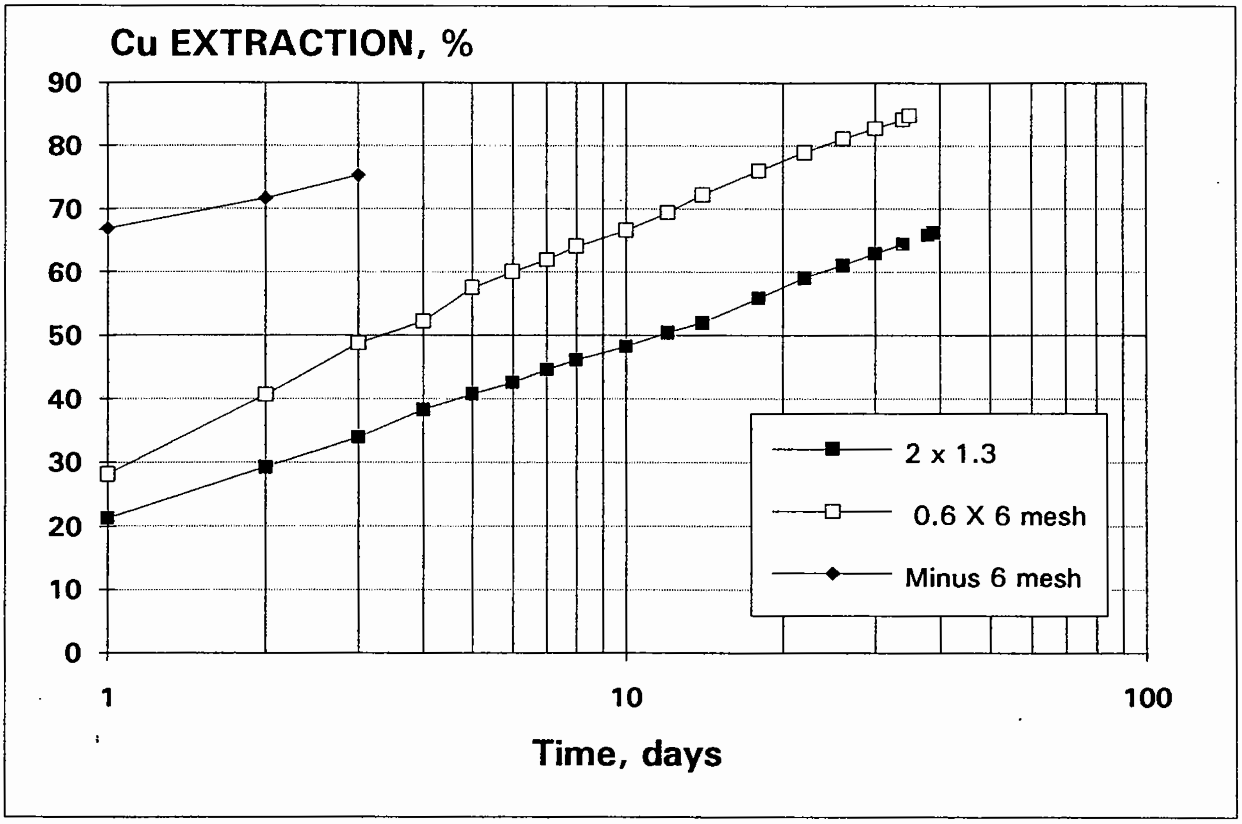
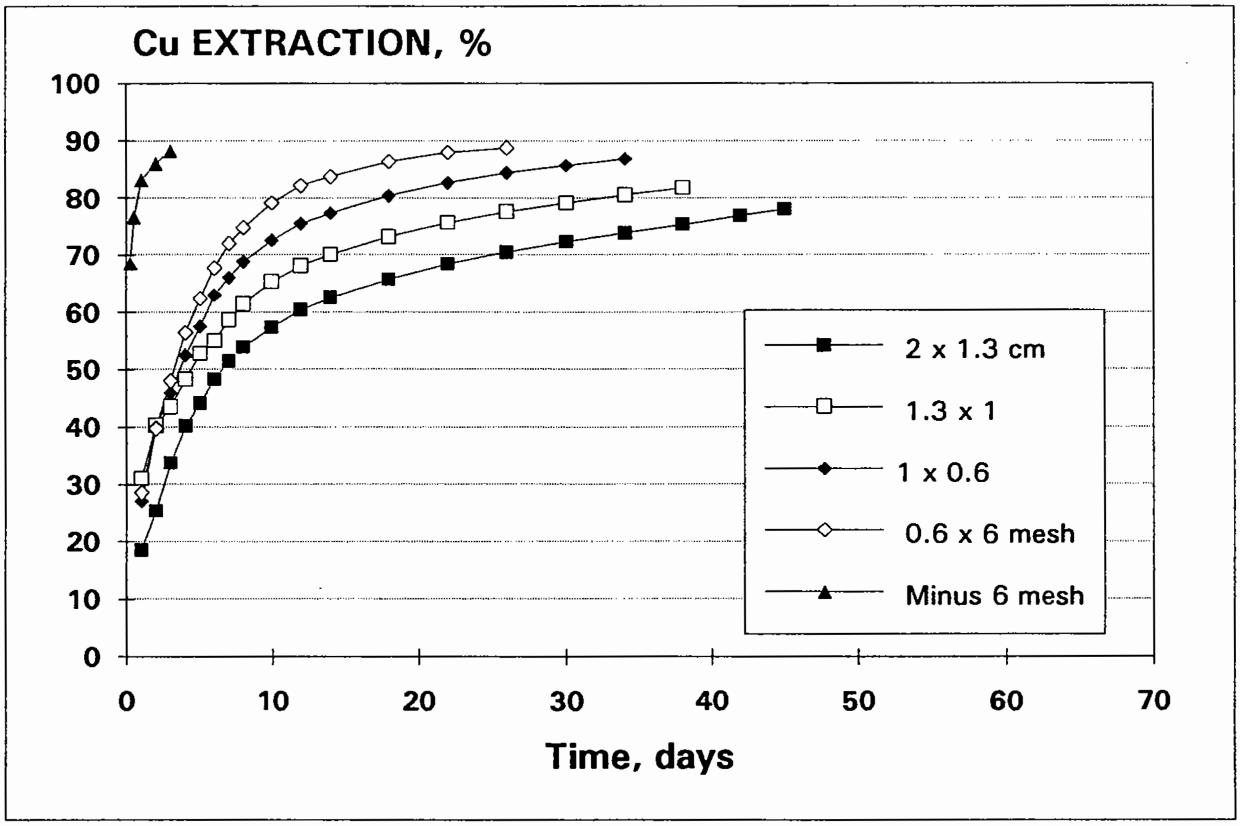


Figure 4.25 Low grade composite flood results.



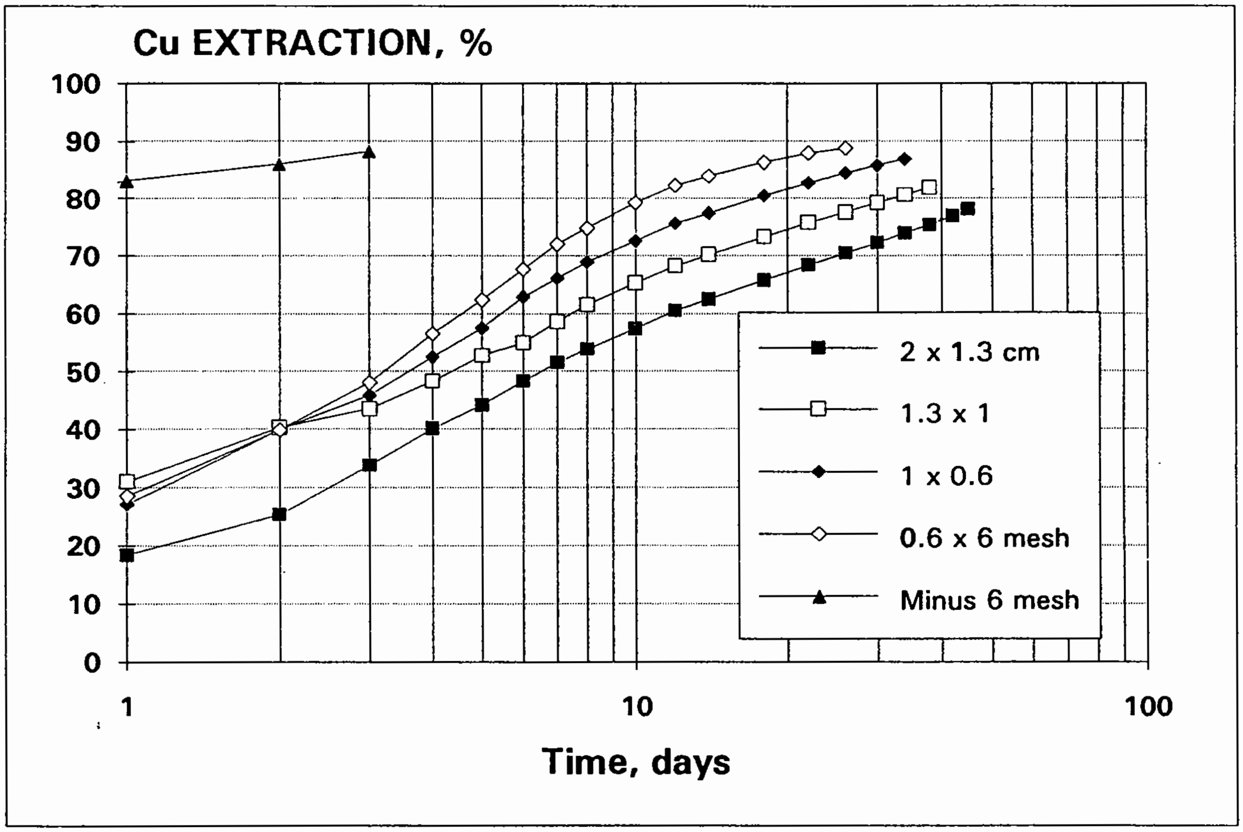


Figure 4.26 South end composite flood results.

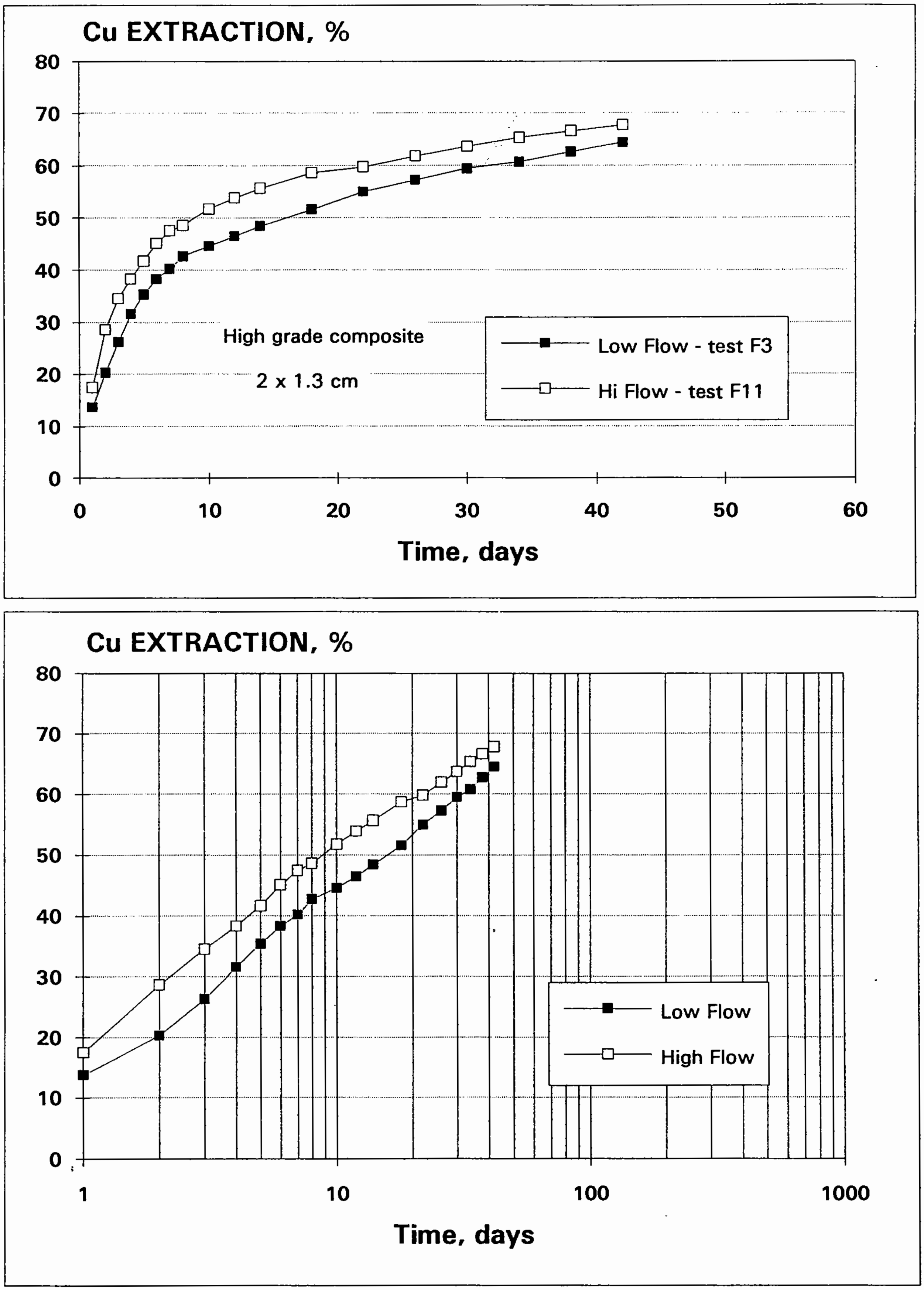


Figure 4.27 Effect of flowrate on flood leaching of high grade.

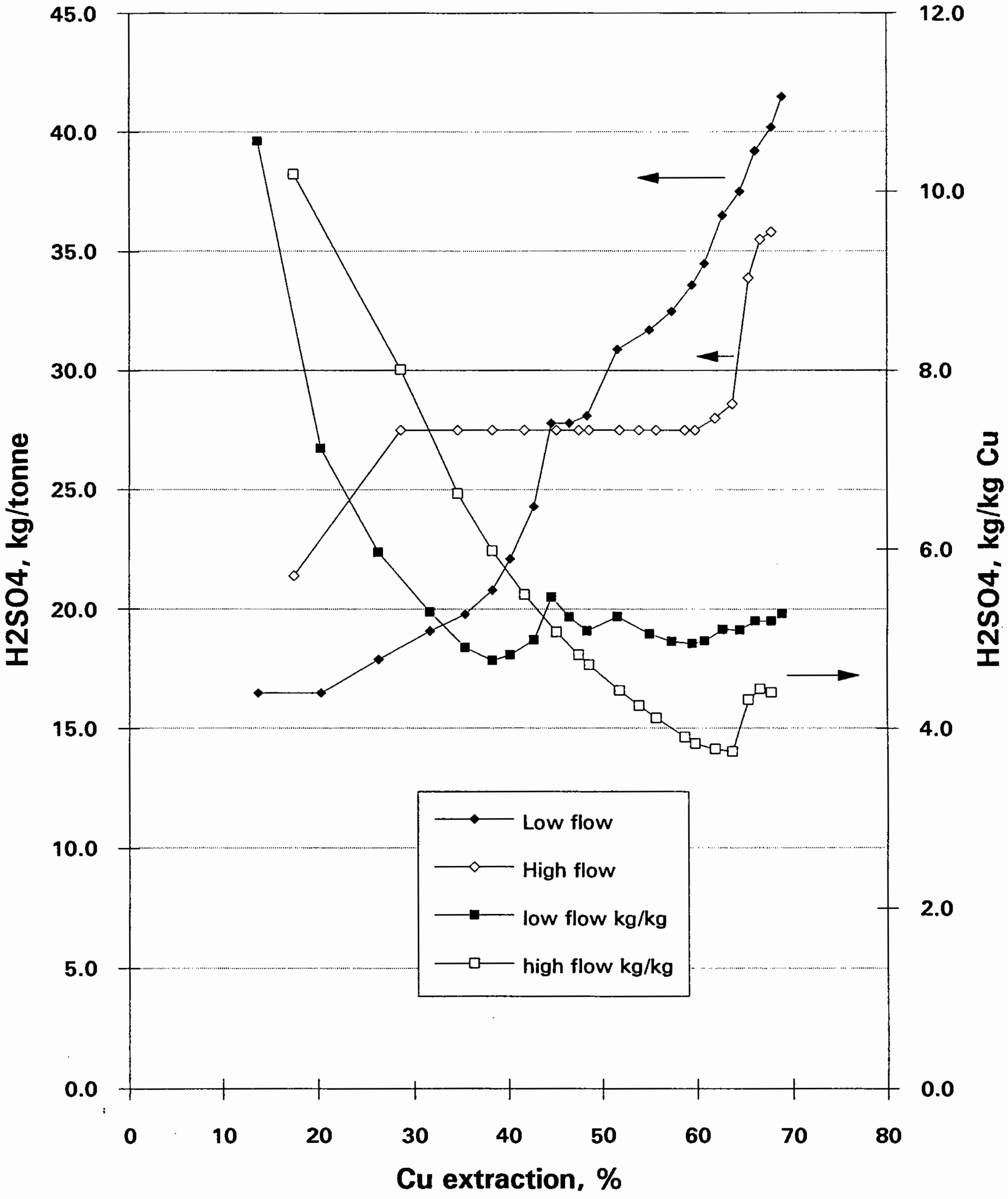


Figure 4.28 Effect of flowrate on flood test acid consumption.

The tailings from each column were screened at the bottom size of the interval which they represented in order to evaluate the breakdown of particles. This step was undertaken since it was visually apparent that decrepitation had occurred with only minor amounts of undersize being present in the feed to each test. The results in Table 4.9 confirm that this breakdown was extensive.

TABLE 4.9

Proportion of Fraction Reporting to Undersize after Leaching

TEST NO.	COMPOSITE	BOTTOM SIZE cm/MESH	% PASSING
F1	LG	1.3	26.4
F2	LG	6 m	45.2
F3	HG	1.3	15.8
F4	HG	1	25.2
F5	HG	0.6	6.0
F6	HG	6 m	17.2
F7	SE	1.3	34.8
F8	SE	1	31.3
F9	SE	0.6	18.5
F10	SE	6 m	27.1

Bottle roll tests on the -6 mesh High Grade fraction were conducted with initial acid concentrations of 15 and 60 g/L H_2SO_4. The results shown in Figure 4.29 indicate a much higher extraction rate when more acid is available. The acid consumption went from 22 kg/tonne at 15 g/L to 49.2 kg/t at 60 g/L.

The settling of the product from the bottle roll tests was evaluated qualitatively to determine if vat leaching was a viable option. The fines from the low grade and high grade samples settled quite well, while the south end material settled somewhat more slowly. In each case there was a sharp interface between the slurry and the supernatant. The supernatant in each case was clear with only minor suspended particles.

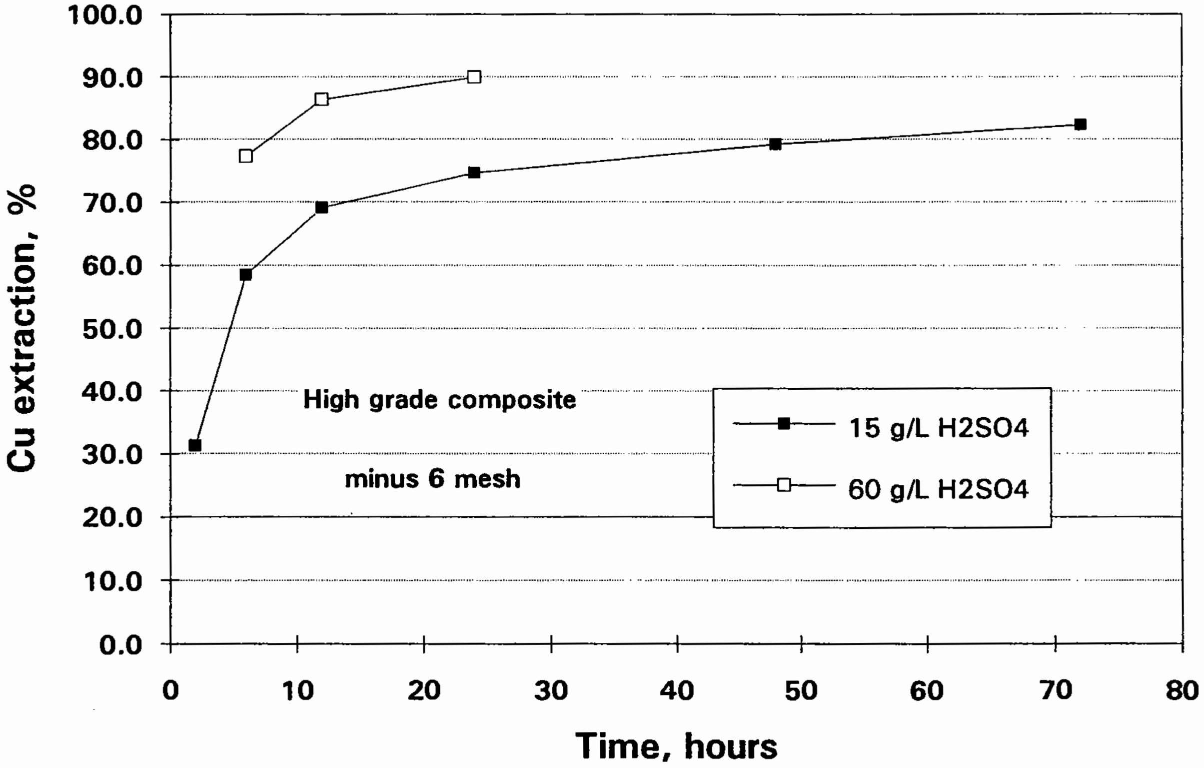


Figure 4.29 Effect of bottle roll acid concentration on Cu extraction.

4.4.3 Percolation Tests

A series of percolation tests was performed on selected size fractions of the three composites. The tests were all conducted in a similar manner with 5 kg/tonne H_2SO_4 to agglomeration, a target solution flowrate of 0.012 $m^3/h/m^2$ and a feed pH of 1.5. The results of the tests are summarized in Figure 4.30. The results of these tests confirm those of the flood tests and other previous tests with the 2 cm x 1.3 cm fractions for the Low Grade and High Grade composites leaching much more slowly than the finer fractions and the South End sample leaching very quickly.

The results in Table 4.10 show the degree of particle breakdown during leaching which, as for the flood tests, was extensive.

TABLE 4.10

Proportion of Fraction Reporting to Undersize after Percolation Leaching

TEST NO.	COMPOSITE	BOTTOM SIZE INCHES/MESH	% PASSING
P1	SE	1.3	25.6
P2	HG	6 m	25.4
P3	HG	1.3	14.7
P4	LG	6 m	30.8
P5	LG	1.3	17.9

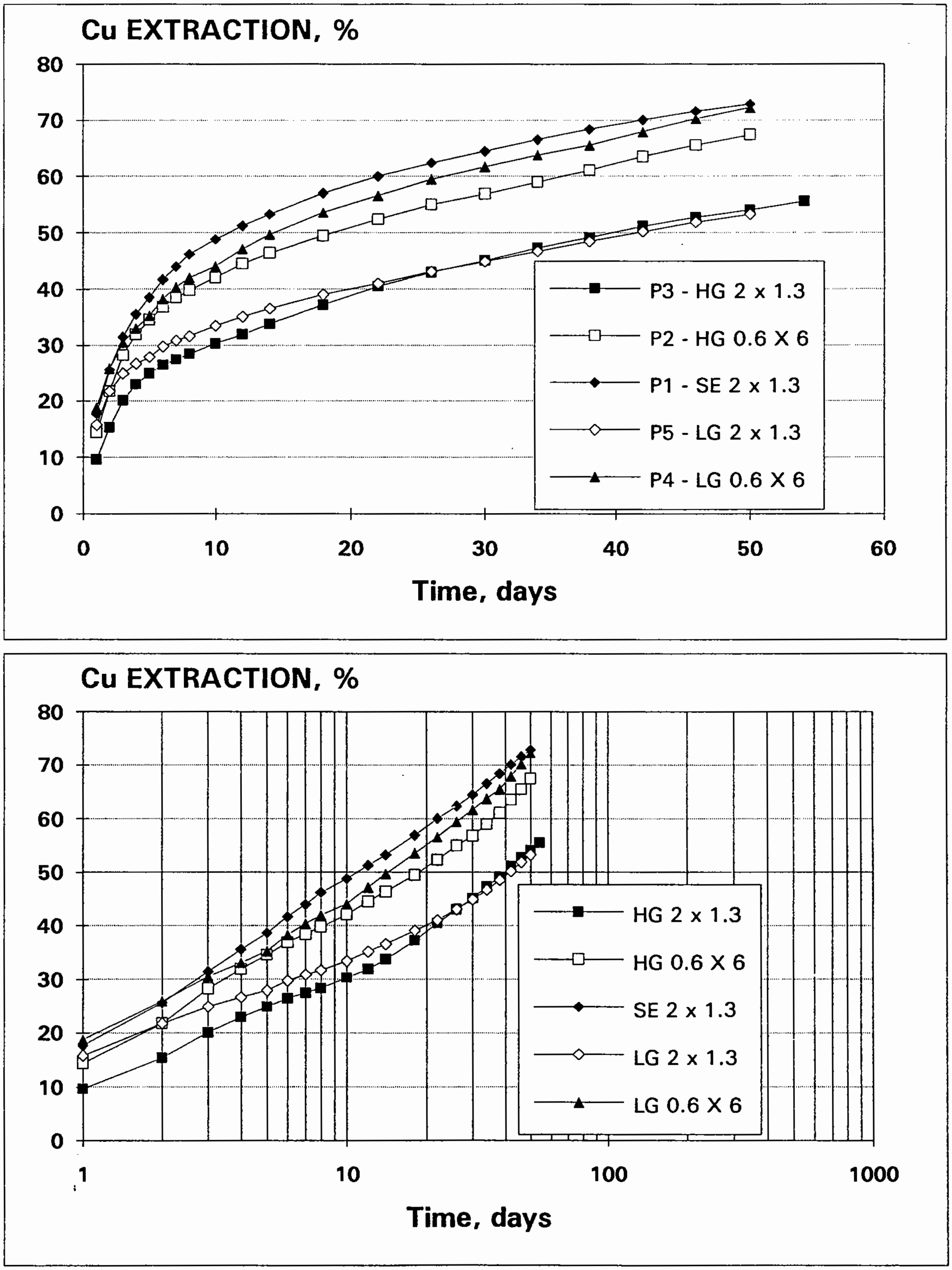


Figure 4.30 Percolation test results on size fractions.

4.5 Solvent Extraction

The solvent extraction process is conducted in two stages. The first stage, extraction, removes the copper from the pregnant solution producing a raffinate solution for recycle to the leaching operation and an organic loaded with copper. In the second stage, stripping, the loaded organic is contacted with a high acid recycle solution from electrowinning. This second stage produces a depleted organic for recycle to the extraction stage and a high copper feed for the electrowinning circuit. The number of units included in each stage is affected by factors such as the copper and acid content of the pregnant liquor. There is generally a trade-off between capital and operating cost for the solvent extraction circuit. A series circuit generally results in a higher capital cost and higher copper extraction but lower reagent consumption than a series-parallel circuit. The testwork conducted by ICI (Appendix H) investigated several circuit configurations and provides data which can be used for cost studies.

The reagent used for the solvent extraction is dependent on the copper concentration in the PLS. For the Williams Creek solutions, ICI have recommended the use of Acorga M-5774.

The solvent extraction of the solution from the various column tests was observed to result in the production of crud. An analysis of a crud sample is included as Table 4.11. The high loss on ignition value results from the presence of the organic phases which were not driven off during low temperature drying of the sample. The analysis of the inorganic components indicates that the material consists of approximately 64% silica with the other major components being alumina and iron oxide.

An interesting observation made during the testwork was that when a sample of pregnant solution was frozen and then allowed to thaw, it became quite viscous. It appeared that the dissolved silicates became polymerized by the freezing. If the same observation is made in the field, there may be a benefit to removing the crud prior to solvent extraction.

The viscosity of several leach solutions was determined with a capillary viscometer. The results of these determinations are included in Table 4.12.

Table 4.11

Analysis of Crud Sample

ELEMENT	%
SiO_2	8.74
Al_2O_3	1.19
Fe_2O_3	1.29
MgO	0.39
CaO	0.23
Na_2O	0.07
K_2O	0.35
P_2O_5	0.139
TiO_2	0.296
MnO	0.048
BaO	0.089
Cr_2O_3	0.023
SrO	0.005
LOI	86.3

Table 4.12

Viscosity Determination of Leach Solutions

SOLUTION	Cu, g/L	s.g.	Viscosity, cP
L4 - 2 hour	5.4	1.0168	1.04
L12 - 24 hour	2.68	1.0144	1.12
C5 day 86	0.61	1.0808	1.54

4.6 Trace Elements

Over the course of the program, various pregnant and raffinate solution samples have been analyzed for trace elements by means of multi element ICP analyses. The results of these analyses are included in Appendix J.

Appendix J also includes trace element analyses for a raffinate sample from bottle test L19, together with an analysis for the same solution after it was neutralized from pH 1.8 to pH 7.0 through the addition of lime. An ICP analysis of the solids formed during neutralization of the solution together with the results of a SWEP test on the solids are also included.

Appendix J further includes the results of acid base accounting tests on the various composites and several leach tails.

The solution from mini-column M6 was analyzed by ICP-MS for rare earth elements following 66 days of circulation through the ore. The results of this analysis are summarized in Table 4.12. This solution also contained 390 ppb uranium.

Table 4.12

Rare Earth Analysis of Pregnant Solution from column M6

ELEMENT	ppb
Scandium	840
Yttrium	1200
Lanthanum	1400
Cerium	2900
Praseodymium	450
Neodymium	1600
Samarium	330
Europium	90
Gadolinium	350
Terbium	47
Dysprosium	240
Holmium	54
Erbium	150
Thulium	20
Ytterbium	140
Lutetium	21

SECTION 5

DISCUSSION

The objective of the metallurgical test program has been to establish the principal design parameters for heap leaching of the oxide ore together with SXEW for copper recovery. The principal parameters in this regard are the following:

- crush size of the ore to be leached
- pretreatment parameters
- copper leaching rate (residence time on leach pile)
- ultimate % copper extraction
- acid consumption

The results presented in section 4 have been analyzed in order to establish the above parameters. The results have also been reviewed by Brown & Root Braun of Houston, Texas and their report is included as Appendix I .

5.1 Crush size.

The initial evaluation by bottle roll testing of various crush sizes covered a broad range from 3.8 cm to 1 cm with only one intermediate size at 2 cm. The results of this work indicated that while there did not appear to be a significant difference between the 1 cm and 2 cm sizes, using a top size of 3.8 cm resulted in a significantly slower extraction rate. Subsequent testwork therefore focussed on testing material which had a top size of 2 cm or less.

The testwork utilizing mini-columns indicated that a top size of 1 cm would be too fine since at this size the column became impermeable part way through the leach cycle. Such loss of permeability has not been observed with any of the columns using material crushed to passing 2 cm, even though decrepitation of the particles has been shown to occur during leaching.

The flood tests and percolation tests confirmed that the -2 + 1.3 cm size fraction leached slower than the finer size fractions although given enough time, a copper extraction of 80% or better could be achieved.

In evaluating the results of the testwork conducted to date it has been noted that the size distribution of the feed to most of the tests has some differences to that which would be expected in a closed circuit commercial operation. Table 5.1 presents a "typical" size distribution for material crushed in closed circuit to a top size of 2 cm as well as the distributions for the feed to several tests. The material tested to date has a greater proportion of + 1.3 cm material and minus 6 mesh material than the typical distribution. The implication of the increased fines content is that a higher initial leach rate would be expected, compared to that experienced with the typical distribution. However, the significantly increased coarse (+1.3 cm) content would result in a longer leaching time being required to achieve the ultimate copper extraction.

Table 5.1

Variations on size distribution.

Size fraction	Weight % in fraction		
	Typical commercial	HG flood test feed	Column S3 tails
+ 1.3	16	28.4	42.3
- 1.3 + 1	24	17.1	14.4
- 1 + 0.6	26	15.0	11.2
- 0.6 + 6m	19	12.8	7.0
- 6m	15	26.7	24.0

It can be concluded that since the Williams Creek ore will be crushed to minus 2 cm in closed circuit, the top few size fractions of the size distribution will match the typical distribution. The minus 6 mesh fraction can be expected to contain in the order of 25% of the feed weight. The agglomeration procedure should take into account this high fines content, particularly since it has been demonstrated that excessive fines can result in a loss of heap permeability.

5.2 Agglomeration

The pretreatment of the ore by agglomeration with acid solution has two principal objectives. One objective is to neutralize the alkaline components in the ore so that the leaching solution will not be excessively neutralized as it passes through the leach pile. The second objective is to bind the fines to the coarser particles in order to minimize the migration of the fines to the bottom of the leach pile.

The results of the mini-column testwork indicated that while there was an increase in the initial leach rate with increasing acid to the agglomeration step, this increased rate did not persist for the duration of the leach cycle. Variations in solution application rate and acidity can more than overcome the effects of acid addition to the agglomeration step.

An acid addition of 5 kg/tonne was adopted as the standard for most of the testwork. This addition seems to be adequate to give the effects of agglomeration without resulting in excessive acid consumption.

The method of addition of the acid to the crushed ore is often through the use of drips or sprays onto the conveyor belt carrying the ore to the leach dumps. For the Williams Creek ore, it appears that the use of an agglomeration drum is likely justified since considerable mixing of the wetted ore was required to get effective adherence of the fines. The results of mini-column M6 indicate that the presence of excessive fines in the leach pile will result in the pile becoming impermeable. Since the oxide mineralization is friable and results in the production of considerable fines, effective binding of this material to the coarse particles will be mandatory. Highly effective agglomeration can only be achieved by means of drum agglomeration.

5.3 Leaching rate.

The rate at which copper is leached from the rock initially is dependent on particle size, solution application rate and acid availability. As leaching progresses the readily available copper is removed first and the rate becomes largely dependent on the diffusion of solutions into and out of the rock particles. At this second stage, particle size is therefore largely controlling on leach rate.

The results of the flood tests and percolation tests demonstrate the dependence of leach rate on particles size. It is apparent that the leach rate will be maximized by minimizing the proportion of particles in the coarser size fractions (-2cm + 1.3cm). Closed circuit crushing to minus 2 cm will achieve this objective with minimum fines production. Based on the results of the mini-column tests and the six inch column tests it appears that a copper extraction of 80% to 85% will be achieved in under 100 days of leaching with a 2 cm particle size.

There appears to be an advantage to using a higher solution flowrate at the start of a leach cycle and then decreasing this rate as leaching proceeds. The higher flowrate ensures that the material is wetted to the maximum extent and promotes the rapid migration of the acid front through the leach pile. Practical considerations with emitter systems will limit the achievable variation in solution flowrate to a factor of about two. An initial solution application rate of 0.010 gal/min/ft^2 should be made until the pH and copper content of the pregnant solution decrease significantly. At this point the rate should be decreased to 0.005 gal/min/ft^2. This strategy is being tested in the 18 foot column which is underway at the time of this report.

While the use of an increased initial flowrate maximizes the leach kinetics, no increase in leach rate is obtained from increases in the flowrate later in the leach cycle. This observation is consistent with the extraction being diffusion controlled at this stage.

For ore which contains 1.4 % Cu and which is leached for 20 days at the high initial flowrate, followed by an additional 70 days at the lower flowrate and which attains a copper extraction of 85%, the average PLS grade will be 3.4 g/L Cu. The grade will be very high, 10 to 20 g/L, for the first few days and will then drop off to a near average value.

5.4 Ultimate Copper Extraction

The ultimate or maximum percent copper extraction is dependent on the mineralogy of the material being leached as well as on the duration of leaching. The copper mineralization in the samples tested to date has been amenable to acid leaching with 85 to 90% being acid soluble.

There is no evidence to date to suggest that any significant proportion of the sulphide copper will be extracted within a normal leach cycle, even with the intentional addition of bacteria as was tested in one six inch column test.

The ultimate copper extraction will depend primarily on the length of the leaching cycle. For a multiple lift configuration the extraction from the top lift will be less than from the bottom lift. The overall extraction has to be balanced against acid consumption since excessive acid consumption near the end of the cycle could exceed the value of the copper being extracted.

The results to date suggest that a copper extraction of 80 to 85% will be the optimum economic value, based on total copper content and the acid requirement.

5.5 Acid consumption

At the same time as the copper extraction rate and ultimate copper extraction are optimized, the acid consumption has to be minimized since it represents a substantial cost to the operation. Sufficient acid must be supplied to neutralize the basic components in the ore and to solubilize the copper. The testwork has indicated that it is most useful to supply a high acid concentration at the start of a leach cycle and then to decrease the concentration as leaching proceeds. In this way the kilograms of acid per kilogram of copper extracted is minimized.

In a multiple lift configuration, the most effective strategy will be to partially leach the first lift and then to allow the low acid pregnant solution from the upper lift to complete the leaching process. At the same time, the acid concentration to the upper lift must be reduced as leaching proceeds. For BDA column no. 2 for instance, the acid concentration in the feed solution was decreased, from an initial value of 20 g/L to 10 g/L as leaching proceeded. Even with this decrease, the acid consumption per unit of copper extracted was increasing in the latter stages of the test. Leaching will proceed at this stage with only a few grams per litre of acid in the feed solution and by reducing the acid concentration to low levels at the end of the leach cycle the acid consumption will be minimized.

There has been some variation noted in acid consumption for the different samples tested, with the low grade ores exhibiting a higher acid consumption than the high grade ores. For the high grade composites it appears that an acid consumption in the order of 25 to 30 kg/tonne will be experienced for an 80 to 85% copper extraction.

5.6 Copper recovery

Copper recovery from the Williams Creek leach solutions is to be by solvent extraction followed by electrowinning. The leach solutions do not contain any elements which will be detrimental to the solvent extraction process. The results of solvent extraction tests conducted by ICI Specialty Chemicals are included in Appendix H. Based on the results of their testwork, several alternate circuit configurations, all standard for the industry, were proposed for consideration.