

Co-operative Research Centre for Coal in Sustainable Development

**COMPARATIVE EVALUATION OF LEACHABILITY TEST
METHODS AND ELEMENT MOBILITY FOR SELECTED
AUSTRALIAN FLY ASH SAMPLES**

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EXECUTIVE SUMMARY

Long-term management of solid wastes from coal utilisation, and guaranteeing sustainability of associated water resources, requires knowledge of how the different waste materials interact with water in different chemical situations. The extent to which individual chemical elements may be removed from particular ashes is traditionally evaluated by exposing the ash to water under specific conditions in laboratory leaching tests, and analysing the relative proportions of those elements extracted after a certain period of time. A number of different laboratory test procedures, however, have been used for this purpose, each based on a particular combination of operating procedures and chemical conditions.

As part of CCSD research into trace element mobilisation from coal utilisation wastes, a comparative evaluation was carried out of the extent to which the principal major and trace elements are released from a series of Australian fly ashes using different leaching test routines. The work was based on a more in-depth, element-specific evaluation of data derived from a previous study completed by CSIRO in 2000. The results have provided input to more comprehensive element mobility evaluation program, the initial results of which are reported separately, aimed at developing site-specific hydrogeochemical models of ash-water interactions for different emplacement or utilisation options.

The mobility of the individual elements from the fly ashes tested was found to vary significantly, depending on the test procedure used. While the other tests commonly produced similar results for each element, the widely used TCLP test procedure was found to indicate higher levels of leachability for many elements, especially from ashes that generate alkaline leachate solutions, than other laboratory test procedures. Separate CCSD research suggests that this variation reflects the pH conditions under which the test is conducted, which for the alkaline ashes is quite different to the pH established by equilibrium with water alone in the other leaching tests. The column leach test provides similar results for most elements to simpler tests based on shaking with water for shorter periods of time. Some elements, however, such as sulphur, appear not to be released as readily from the column tests, possibly because of re-precipitation in the lower parts of the leaching columns.

The reasons for the variation in response of particular elements in particular ashes to the different test procedures, and the extent to which the results of such tests are significant in practical situations, is currently being more fully evaluated as part of CCSD's trace element mobility and hydrogeochemical modelling programs.

INTRODUCTION

This report provides a comparative evaluation of data for major and trace element mobility from four different types of leaching tests applied to a series of nine Australian fly ashes in a study originally conducted by Killingley et al. (2000) for ACARP and the CRC for Black Coal Utilisation. That work was focused on testing of fly ash leaching characteristics using an extended-term column leaching test procedure, but also included a number of other laboratory leaching tests for comparative purposes. Although providing a tabulation of the data arising from the work program, several constraints prevented the final report on the project from presenting a more extended discussion of the comparison between the various test results, to identify differences between the outcomes of the various test procedures.

As part of the work program for Project 6.1 - Waste Management of the CRC for Coal in Sustainable Development, an evaluation of the data from this previous study was carried out, as a basis for understanding the factors affecting the mobility of different trace elements, and for further refining leachability test procedures for Australian fly ash materials. The results were also used to develop a further element mobility test program aimed at supporting development of appropriate hydrogeochemical models of ash-water interactions, the initial outcomes of which have been reported separately by Jankowski et al. (2003).

FLY ASH SAMPLES

A total of nine fly ashes were used for the study, representing combustion by-products from pulverised-fuel power stations in New South Wales, Queensland and Western Australia. The chemical composition of these fly ashes, based on data provided by Killingley et al. (2000), is summarised in Table 1. Further data on the mineralogy of these ashes, including their glass content and glass compositions, as well as their relation to the mineral matter in the feed coals, are given in a separate CCSD report by Ward and French (2003).

The samples in Table 1 are divided into two groups, those that yield a neutral to acidic pH on reaction with water and those that yield an alkaline pH. These subdivisions are based on the "initial pH" values reported from column leaching experiments by Killingley et al. (2000). The pH developed by ash-water interaction has also been identified as a significant factor in element leachability in more recent CCSD research, reported separately by Jankowski et al. (2003).

Killingley et al. (2000) suggested that the initial pH was related to several different aspects of ash composition, providing a correlation between the pH value and two different indicators of ash composition. These were based on whole-ash composition as follows:

- Index 1: $\text{CaO} + \text{MgO} / \text{SO}_3 + 0.4\text{Al}_2\text{O}_3$
- Index 2: $\text{CaO} + \text{MgO} / \text{SO}_3 + \text{P}_2\text{O}_5$

Plots of these indices against initial pH are given in Figure 1. Similar plots, based on the inferred chemical composition of the glass fraction of the ash, determined as described by Ward and French (2003), are given in Figure 2.

Table 1 also provides an indication of the average abundance and partitioning of the various elements among the ashes of each group. Based on these data, the chemical differences between the ashes in the two groups can broadly be compared as follows:

Acid-generating ashes	Higher in P Higher in Ba, Be, Cd, Co, Cr, Mo, Ni, Zn
Alkali-generating ashes	Higher in Ca, Mg, Na Higher in As, B, Mn, Sb

LEACHING TESTS USED IN THE STUDY

Four different leaching tests were used in the study. These are detailed more fully by Killingley et al. (2000). Three of the tests were batch processes based on agitating a sample of the ash with water or an appropriate solution for a certain time in a sealed container. The fourth was a column leach test, where water was passed through a packed ash column over an extended period of time (12-15 months) and the leachate collected periodically from the bottom of the column in each case.

The test procedures were:

Shake Test

This method follows the procedure of ASTM Method D-3987 and is meant to give an estimate of the mobility of inorganic constituents in the ash. A liquid to solid ratio of 20:1 was used and the sample was agitated for 18 hours. The resultant extract was filtered and analysed.

Simulated Groundwater Leaching Protocol (SGLP) Test

This is after US EPA Method 1312, in which simulated rain or reagent water is used. In this study a known mass of fly ash was extracted with a solution made up to simulate natural ground water. A liquid to solid ratio of 20:1 was used, and extraction took place in a standard bottle with mechanical agitation for 18 hours. The resultant extract was passed through a 0.6 to 0.8µm glass fibre filter and analysed.

Toxicity Characteristic Leaching Protocol (TCLP) Test

The Toxicity Characteristic Leaching Procedure (TCLP) was developed by the US EPA in 1984 and promulgated as EPA Method 1311. A known mass of ash was extracted with a buffered acetate solution, selected on the basis of the alkalinity of the ash sample. A solid to liquid ratio of 20: 1 was used, and extraction took place in a standard bottle with mechanical agitation for 18 hours. The resultant extract was passed through a 0.6 to 0.8µm glass fibre filter and analysed.

Column Leaching Test

A sample of fly ash exceeding 3 kg in mass was placed in a polycarbonate column 80 mm internal diameter and 980 mm long, and approximately 60 litres (twenty liquid/solid volumes) of de-ionised water passed through the ash in the column over a period of 12-15 months. Samples of the liquid were collected and analysed regularly throughout the period of treatment. The cumulative mass of each element extracted at the end of the process, provided in unpublished CSIRO data, was used in this comparative study.

EVALUATION OF LEACHING TEST DATA

The effectiveness of the various tests for the present study was evaluated using a common index: the relative amount of each element leached from each individual ash sample, expressed as a percentage of that element in the original (unleached) fly ash. This value was calculated for each leaching experiment on each sample, using data provided by Killingley et al. (2000). The resulting percentages, listed in Table 2, represent the leachability (or mobility) of the respective elements from each sample under each set of experimental conditions. Because each ash has different concentrations of the various elements, these values provide a better basis for comparison of leaching effectiveness than the absolute proportions of each element released into solution by the different test procedures.

Only those elements with significant abundance and of significant environmental concern have been evaluated for the present discussion. The trace element data concerned are highlighted by bold font in Tables 1 and 2. The same elements have also been evaluated in a series of follow-up leaching experiments under different environmental conditions, a preliminary report on which has been prepared by Jankowski et al. (2003). They will in due course provide the focus for further evaluation when the results of that study are fully available, and ultimately the foundation for a wider-ranging hydrogeochemical modelling process.

RESPONSE OF INDIVIDUAL TRACE ELEMENTS TO LEACHING TESTS

Arsenic

Arsenic in the individual fly ash samples shows a very variable response to the different leaching tests. For example, among the acid-generating ashes, between 9 and 20% of the As is leached from sample 15, whereas only 0.5 to 2% of the As is leached from sample 18. A similar variability occurs among the alkaline ashes; for example 3 to 25% of the As is

leached from sample 17 but (except for an anomalous TCLP result) only 0.2 to 1.4% of the As from sample 22 (Fig. 3a).

Only a relatively low proportion of the As is commonly leached from the ashes by shake tests in water. Data for samples 18, 23, 16, 21, and 22, for example (i.e. 5 of the 9 samples), all show that <1% of the As in the ash samples is released by the shake test technique. Although the shake test data for samples 17, 19 and 20 show leaching of somewhat higher percentages of the As in the respective ashes, the proportions released are still lower than those released by the other leaching methods. Only for sample 15, which seems to show a high overall level of As mobility, does the shake test release a higher proportion of the As in the ashes than the other techniques.

Tests using the simulated groundwater leaching protocol (SGLP) show levels of As leachability for the acid-generating ash samples (15, 18, 19 and 23) that are comparable to the respective shake test results. For the alkaline ashes, however (16, 17, 20, 21 and 22), SGLP testing shows a somewhat higher level of As leachability than shaking with water alone, the effect being more marked for samples 17 and 20.

For most ashes, the TCLP test indicates somewhat higher levels of As mobility than the other techniques, especially among the alkali-generating ash samples. The contrast is particularly marked for samples 16 and 22, where around 30 and 50% of the As is respectively indicated as being mobile, compared to no more than approximately 1% for the same samples using the other test procedures. Column leaching studies show similar levels of As mobility for most samples to those indicated by the shaking or SGLP procedures. In some cases (e.g. samples 18 and 19) the mobility is slightly higher, while in others (e.g. 15 and 16) significantly lower levels of As mobility are indicated by the column leaching data.

More recent CCSD studies (Jankowski et al., 2003) indicate that the mobility of As depends very significantly on the pH of the respective solutions, peaking in the middle of the pH range and decreasing at both low and high pH values. This may explain the variability in the response of As to the different leaching protocols, and is a factor that will be considered further in the CCSD's subsequent leaching and hydrogeochemical modelling studies.

Boron

Significant levels of B mobility are indicated for all of the ash samples studied. For the acid-generating ashes comparable levels of B mobility are indicated in each case by all of the test procedures, except for samples 15 and 23; the former showing a significantly higher level of B mobility in the TCLP and column leaches and the latter a markedly lower level of B mobility in the column leach test (Fig. 3b).

A greater degree of variability is noted for boron mobility based on the test results for the alkali-generating ash samples. In all cases the TCLP procedure shows a significantly higher level of B mobility than the other test data, with three times as much B typically being released compared to the other techniques. The samples tend to fall into two groups in the other leach tests. The first group comprises samples 16 and 22, which have lower levels of boron release than the second group consisting of samples 17, 20 and 21.

Cadmium

Although the overall concentration of Cd in the ashes is relatively low (<1.5 ppm), the test data suggest that it displays a somewhat variable degree of mobility, especially among the alkali-generating ash samples. Of the acid-generating ashes, samples 15 and 19 show comparable values of leachability by all of the different test methods (Fig. 4a). Sample 18 has much lower levels of Cd mobility, except in the TCLP test in which it is comparable to

samples 15 and 19. Sample 23 is unusual in having a much higher overall level of Cd mobility, which increases monotonically from the shake test through to the column test.

For the alkali-generating ashes, the TCLP results are significantly higher than those of the other test procedures. In one case (sample 21) the proportion of Cd indicated as being leached from the ash (112%) appears to exceed the total amount of Cd actually present. Except for these high TCLP values, however, comparable proportions of mobile Cd are indicated for each alkaline ash (typically 1 to 3%) by each of the other test procedures and are consistently lower than those of the acid-generating ashes (except for sample 18 with which they are comparable).

Cobalt

The cobalt occurring in the fly ashes studied appears to be virtually immobile under any of the test procedures (Fig 4b). The results for the alkali-generating ashes are similar with all being low (generally less than 0.1%), except that the TCLP results invariably show significantly higher Co mobility values (typically around 1.5 to 2.5%) than the other test results. The acid-generating ashes show a greater spread between samples (from almost nil to 3%), but the results are generally comparable between the different leach tests for each sample.

Chromium

The chromium in the ashes studied is also virtually immobile under the different test procedures, especially for the acid-generating ash samples (Fig. 5a). All of the acid-generating ashes have Cr mobility values of less than 1%, except for sample 23, where a Cr leachability of between 2 and 3% is indicated by the TCLP and the column leaching data. Similar low Cr leachabilities (<1%) are indicated for two of the alkali-generating ashes, samples 16 and 22, except for a SGLP value of 1.9% in the sample 22 data. Two others (17 and 20) have Cr leachabilities around 1.5%, although sample 20 has a TCLP value of more than 3% and a column test value of only 0.6%. Data for the other ash, sample 21, indicate Cr mobility values of 5 to 7% (with the TCLP data at the upper end of the range), except for column leaching experiments that indicate only 2.5% of the Cr being released in mobile form.

Copper

In contrast to chromium, copper shows some degree of mobility in the acid-generating ashes, but is virtually immobile (except for the TCLP data) in the alkali-generating samples (Fig. 5b). Significant levels of Cu mobility are indicated by different test procedures for samples 15 and 19, with 3-6% of the Cu being leached from sample 15 and 2-4% from sample 19 by all except the column leaching technique. The column leaching values for Cu are significantly lower for these two samples, at 0.8% and 0.4% respectively. By contrast, the column leaching data indicate a Cu leachability of 4.3% for sample 23, although values of only 0.8 to 1.4% are indicated for that sample by the other test results.

As with many other elements, the TCLP data for the alkali-generating ashes show significantly higher levels of Cu mobility than the other test results. This is particularly notable with sample 22, where over 30% of the Cu is apparently leached from the ash by the TCLP technique yet less than 0.1% of the Cu is removed by the other leaching procedures. The TCLP results for the other alkali-generating samples also show significantly higher levels of Cu removal than the other protocols, with values between 0.5 and 2.5% compared to the typical values of <0.1% indicated by the other test data.

Molybdenum

The test data for molybdenum shows an extremely variable level of mobility for the acid-generating ashes, depending on the test procedure, but a more uniform and relatively high degree of mobility for the alkali-generating ashes, regardless of the leaching protocol used (Fig. 6a).

Mobilisation of a very high proportion of the Mo in the acid-generating ashes is indicated by the column leaching tests, with between 33% (sample 18) and 80% (sample 23) of the Mo in the ashes being removed by the column leaching experiments. These values are significantly higher than the values indicated by the other leaching protocols, although a wide range of (lower) Mo leachability values is also indicated for each sample by the non-column test procedures. With sample 19, for example, the proportion of the Mo in the ash mobilised by the different test procedures is 0.7% (shake test), 2.2% (SGLP), 8.4% (TCLP) and 51% (column). For all but sample 18, the shake and SGLP tests indicate significantly lower mobilities than the TCLP data, which in turn indicate a lesser mobility than the column leach results. For sample 18, the shake test data provide the second-highest mobility levels after the column leaching tests, and the TCLP results give the lowest mobility values.

The data indicate that between 20 and 60% of the Mo is released from the alkali-generating fly ashes. Although some variability still exists, the results from each test procedure are somewhat more uniform for each individual sample than for the acid-generating ashes in the series. Samples 21 and 22 show a steady increase in leachability in passing from the shake to the column test, whereas sample 16 exhibits a steady decrease. Samples 17 and 20 have comparable values in all tests, apart from the TCLP test in which there is a significant decrease in leachability.

Nickel

Nickel is indicated by the data to have a relatively low level of mobility, particularly for the alkali-generating ash samples (Fig. 6b). Of the acid-generating ashes, samples 15, 19 and 23 have similar leachability values of 1-1.5% in contrast to sample 18, which has very low (less than 0.3%) leachability values, comparable to those of the alkali-generating ashes. For each sample the leachability values are essentially the same for all tests.

Low levels of Ni mobility (<1%) are also indicated by the shake, SGLP and column leaching procedures for the alkali-generating ashes. However, as with many other elements, the TCLP data indicate a significantly higher (although still quite low) level of Ni mobility, with 1 to 4% of the Ni being removed from the alkali-generating ash samples.

Lead

All test procedures indicate that the lead in the ash samples, whether acid- or alkali-generating, is completely immobile (Fig. 7a). Less than 0.15% of the Pb is leached from all of the ashes by any of the test procedures.

Selenium

Selenium is one of the more mobile trace elements in the series studied, with more than 60% of the Se being leached from some ashes by some test protocols (Fig. 7b). However, its response to the different tests is also very variable, with Se leachabilities from 7.5% to over 60% being indicated from some individual samples (e.g. sample 16) by different test procedures.

Although it is difficult to discern a consistent pattern in the test data for either sample set, the acid-generating ashes appear to display some gross trends. The SGLP results are generally lower than the shake test results, the effect being more pronounced for samples 18 and 19. The TCLP results are significantly higher for samples 15, 18 and 23 and less so for sample 19. The column leach results are higher still with the exception of sample 18, which shows a decrease with respect to the TCLP result.

The data for the alkali-generating ashes is considerably more variable. Samples 16 and 22 have low leachability values in the shake test and display a marked increase in the SGLP test. In contrast, samples 17, 20 and 21 have high shake test values and either similar (sample 17) or slightly increased (samples 20 and 21) SGLP values. The TCLP test results display the greatest variability, with samples 17 and 20 showing a marked decrease in leachability values in comparison to the increase exhibited by samples 16 and 21. The TCLP result for station 22 is comparable to the SGLP value. The column data, however, indicate relatively low Se leachability for three of the alkali-generating ashes (samples 16, 21 and 22), and higher values for samples 17 and 20 comparable to the shake and SGLP test results.

RESPONSE OF MAJOR ELEMENTS TO LEACHING TESTS

Table 2 shows that negligible proportions of silicon, aluminium, iron and titanium were leached from the ashes studied, regardless of the testing procedure used. A possible exception was silicon (Si), of which a small but measurable proportion (approximately 0.3%) was leached from three of the alkali-generating ashes (samples 16, 21 and 22) by the TCLP technique. Small proportions of Si, again representing 0.2 to 0.3% of the total in the respective ashes, were also leached from two of the acid-generating samples, 15 and 19, by the column leach procedure.

Calcium

Significant proportions of the Ca in the ashes was mobilised by the various leaching tests (Fig. 8a). For the acid-generating ashes the total proportion leached was up to around 10%, with the shake, SGLP and TCLP tests showing similar results for three of the four samples studied (15, 19 and 23). For the fourth sample (sample 18), the shake and SGLP data were almost identical, but the TCLP results were slightly higher. The column leaching results showed similar to slightly higher Ca mobility for all of the acid-generating ashes compared to the shake and SGLP tests, although the differences, where present, are probably not significant. Only with sample 18, where the shake and SGLP tests indicated very low Ca mobilities, do the TCLP and column leach data depart significantly from the other test results.

Similar to slightly higher proportions of the Ca in the alkali-generating ashes (up to around 15%) are mobilised by the shake, SGLP and column leach tests. Again, although there is some degree of variation, no particular trend is evident among the results of the different tests for each individual sample. However, the data show that a significantly higher proportion of the Ca (25 to 35%) is leached from four of the alkali-generating ashes (samples 16, 20, 21 and 22) by the TCLP technique. For the remaining alkaline ash, however (sample 17), the TCLP procedure indicates a significantly lower Ca mobility level.

Magnesium

With the exception of the TCLP data for the alkali-generating ashes, similar results are shown for Mg mobility from each individual sample by all of the tests in the program (Fig. 8b). Small but possibly significant proportions (2 to 4%) of the Mg in two of the acid-generating ashes (samples 15 and 19) were mobilised equally by all four test procedures; much smaller,

essentially negligible proportions (<1%) were mobilised, again more or less equally, from the other two acid-generating samples.

Negligible proportions (mostly less than 0.1%) of the Mg were mobilised from all of the alkali-generating ashes by the shake and SGLP tests, and in all but one case (sample 17) by the column leaching process. Significant proportions of Mg, however, up to 15% in two instances (samples 21 and 22), were mobilised from these ashes by the TCLP technique. Although the two acid-generating samples from which significant Mg was released were also among those yielding significant proportions of mobile Ca, there does not seem to be any particular correlation between Ca and Mg mobility for most of the ash samples studied.

Sodium

Significant proportions (up to 25%) of the Na in some of the ashes are removed by the different leaching processes (Fig. 9a). Na was not tested in the TCLP study, but the other tests each indicated similar proportions of Na removed from the respective ash samples. Only in one instance (sample 16) is there a significant difference, with 2-3% of the Na leached by the shake and column tests but only 0.02% released by the SGLP technique.

Potassium

With the exception of samples 15 and 19 (which show significantly higher leachability values), all samples show similar low leachability values (Fig. 9b) of less than 1.0%. Consistent results are indicated by each of the four tests for the acid-generating ash samples. The leachability of potassium from these samples varies from around zero (sample 18) to around 4.5% (sample 19), mirroring to some extent the Mg mobility pattern.

Similar, although invariably low (<1%) levels of K mobility are also indicated by all tests, including the TCLP procedure, for each of the alkali-generating ash samples. Only in one instance (sample 22) does a particular test result (the column leach data) seem to depart significantly from the other mobility indicators.

Phosphorus

With the exception of the TCLP results for the alkali-generating ash samples (especially samples 16, 17 and 22), all of the tests for all of the samples show only very limited phosphorus mobility characteristics (Fig. 10a). Mobility of up to around 0.5% of the P is indicated for two of the acid-generating ashes (samples 15 and 19). Except for the TCLP results from the alkali-generating ashes, all of the other data indicate release of less than 0.2% of the P from the other ash samples. The TCLP data for three of the alkali-generating ashes (samples 16, 17 and 22), however, indicate P mobilities of up to almost 20%, a figure quite inconsistent with the other test data.

Sulphur

Mobility of a large proportion of the sulphur in the ash is indicated for most samples by the different test procedures and the behaviour is highly variable for both the alkali and acid generating ashes (Fig. 10b). The shake test results display a range from less than 10% for sample 18 to more than 80% for samples 15 and 19 in spite of all three being acid-generating ashes. The alkali-generating ashes show a similar large spread of 15% to nearly 70% of sulphur being leached.

Most samples show an increase in the SGLP test results, the effect being most marked for the alkali-generating ashes samples 16, 21 and 22 and less so for samples 15, 18, 19 and 20, the first three being acid-generating ashes. Samples 17 and 23 show a comparative decrease in SGLP values. TCLP values tend to be higher still with the exception of samples 17 and 20, both of which decrease. The column leach values generally show a sharp decrease to values of less than 25%, except for samples 15 and 18, which show only a slight decrease. Sample 17 is the only sample to show a slight increase in their column leach result to 52%. These anomalous results for the column leach tests may reflect re-precipitation of S elsewhere within the columns, a situation not experienced in the other tests where the ash was continually agitated in the leaching medium. No other element, however, seems to show a similar low level of leachability from the column tests, and hence the reasons behind the anomaly cannot at this stage be satisfactorily explained.

CONCLUSIONS

The mobility of elements from the fly ashes tested may vary significantly, depending on the test procedure. TCLP testing tends to produce higher levels of leachability for many elements, especially from ashes that generate alkaline leachate solutions, than the other test procedures. This probably reflects the contrast in the pH conditions under which the test is conducted, relative to the pH established by equilibrium with water alone in the other leaching tests. The reason for the variation, and the extent to which the results are significant in practical situations, is currently being more fully evaluated as part of the CCSD's more extensive element mobility program.

The column leach test provides similar results for most elements to the simpler shake and SGLP test procedures. However, some elements, such as sulphur, appear not to be released as readily from the column tests, possibly because of re-precipitation in the lower parts of the leaching columns. Although the principle of such tests more closely approximates the conditions typically found at ash emplacement sites, the difference in results achieved does not seem to justify their adoption as a routine test procedure.

Further work to establish the chemical controls on element leachability, and the time-dependent aspects of the leaching process, are currently under way as part of the CCSD's waste management research program. Preliminary results of this investigation have already been reported (Jankowski et al., 2003), and further outcomes will be communicated as they come to hand.

References

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Table 1: Concentration of trace and major elements in ash samples studied (data from Killingley et al., 2000)

Power Station	Acid Generating				Acid Average mg/kg	Alkali Generating					Alkali Average mg/kg	Element Dist'n
	15 mg/kg	19 mg/kg	18 mg/kg	23 mg/kg		16 mg/kg	17 mg/kg	20 mg/kg	21 mg/kg	22 mg/kg		
As	11	7.24	5.74	12.4	9.1	22.3	12.1	5.35	6.58	43.5	18.0	Alkali
B	11	16	7.4	25	14.9	56	75	60	89	80	72.0	Alkali
Ba	3520	4310	3510	393	2933.3	1190	393	768	653	510	702.8	Acid
Be	24	22	13	22	20.3	4.5	8.5	9.3	3.9	5.6	6.4	Acid
Cd	1.34	0.734	0.384	0.404	0.7	0.52	0.444	0.386	0.25	0.345	0.4	Acid
Co	100	97	77	11	71.3	35	11	29	5.6	38	23.7	Acid
Cr	130	122	122	49.6	105.9	69.2	45.2	26.5	18	72	46.2	Acid
Cu	93.8	68.9	82.1	51.6	74.1	93	47.4	99.1	28.1	151	83.7	Even
Ge	10	8.5	9.5	40	17.0	7	10	20	5	10	10.4	Even
Hg	0.0759	0.05	0.0627	0.0183	0.1	0.234	0.118	0.0651	0.152	0.215	0.2	Even
Li	27.9	24.9	23.8	180	64.2	90.5	58.2	50.5	47.9	106	70.6	Even
Mn	225	190	488	87.5	247.6	1630	321	103	899	413	673.2	Alkali
Mo	21	18	5.9	8.1	13.3	6.1	6.1	9.1	4.9	9.5	7.1	Acid
Ni	242	240	165	41.2	172.1	52.9	24.4	18	10.5	70.2	35.2	Acid
Pb	80	63	81	59	70.8	49	68	59	48	48	54.4	Even
Sb	0.97	1.1	0.94	2.9	1.5	1.4	3.9	3.5	3.1	2.9	3.0	Alkali
Se	3.01	2.07	1.09	5.15	2.8	2.26	3.49	2.87	2.48	3.69	3.0	Even
Sn	7	6	5.9	10	7.2	4.9	10	4.6	5.7	11	7.2	Even
V	156	143	125	128	138.0	164	109	274	48.5	172	153.5	Even
W	6.5	6	5.5	4.5	5.6	5	6	3	5.5	3	4.5	Even
Zn	282	283	196	108	217.3	140	124	105	67.2	142	115.6	Acid
Zr	250	700	200	600	437.5	300	400	700	250	450	420.0	Even

Power Station	Acid Generating				Acid Average mg/kg	Alkali Generating					Alkali Average mg/kg	Element Dist'n
	15 mg/kg	19 mg/kg	18 mg/kg	23 mg/kg		16 mg/kg	17 mg/kg	20 mg/kg	21 mg/kg	22 mg/kg		
Si	242000	240000	246000	283000	252750	188000	289000	265000	262000	240000	248800	Even
Al	127000	119000	106000	134000	121500	147000	121000	140000	108000	133000	129800	Even
Fe	60700	62000	85800	7070	53893	90900	19900	11400	48300	34900	41080	Even
Ca	9030	9830	8290	2630	7445	27400	6320	8100	21400	24500	17544	Alkali
Mg	4250	4000	4620	1710	3645	8870	3610	5950	6050	6220	6140	Alkali
Na	1430	1010	1020	1060	1130	2390	3930	5650	5870	1020	3772	Alkali
K	4980	4080	3260	22000	8580	6660	12600	3790	14600	8460	9222	Even
Ti	9420	7980	9140	7090	8408	10300	5430	9840	4930	8820	7864	Even
P	7360	10500	3980	719	5640	3760	964	420	648	1770	1512	Acid
S	1020	1730	272	384	852	948	343	776	522	848	687	Even

Table 2a: Percentages of elements leached from acid-generating fly ashes

P Stn No	15				18				19				23			
	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %
As	20.00	13.27	11.82	8.67	0.63	0.51	1.46	2.08	4.97	4.97	4.28	10.77	0.65	0.30	5.48	1.64
B	23.55	23.73	50.00	43.01	5.01	11.76	6.35	9.10	12.94	14.38	6.88	8.78	26.24	25.16	26.40	3.62
Ba	0.03	0.20	0.34	0.38	0.05	0.22	3.30	0.08	0.02	0.14	0.20	0.17	0.10	0.48	1.48	2.27
Be	1.33	5.00	0.25	0.21	0.04	0.05	0.23	0.01	1.32	0.68	0.77	0.19	0.40	0.91	0.45	0.69
Cd	8.21	9.70	8.96	10.41	1.30	1.56	11.72	1.37	11.58	12.26	10.90	12.37	24.75	27.23	32.18	38.61
Co	1.20	1.20	1.50	1.06	0.01	0.00	0.16	0.01	2.99	2.68	2.68	2.46	0.62	0.45	0.45	0.80
Cr	0.69	0.50	0.28	0.12	0.02	0.03	0.02	0.02	0.32	0.25	0.10	0.07	0.32	0.20	2.00	2.65
Cu	5.86	6.71	3.41	0.76	0.01	0.05	0.06	0.07	3.34	4.06	2.22	0.43	1.41	0.76	0.85	4.32
Ge	6.50	3.90	4.20	9.53	0.42	0.38	1.89	2.02	3.88	2.59	2.35	8.62	8.00	5.75	9.00	16.41
Hg	32.94	26.35	2.64	11.80	39.87	31.90	31.90	6.61	50.00	4.00	8.00	24.82	136.61	109.29	21.86	43.10
Li	4.30	3.94	0.00	3.61	0.08	0.08	0.13	0.35	5.82	0.00	7.35	7.83	1.79	1.67	1.89	4.16
Mn	1.88	1.88	1.71	1.78	0.00	0.00	0.24	0.03	3.84	3.68	3.44	3.95	0.77	0.73	0.65	1.09
Mo	0.52	0.52	10.38	74.75	17.80	6.95	4.41	33.73	0.72	2.17	8.39	50.95	2.96	1.85	17.53	80.84
Ni	1.05	1.02	1.16	0.94	0.01	0.06	0.27	0.03	1.60	1.58	1.58	1.58	1.07	1.29	0.87	1.25
Pb	0.01	0.03	0.07	0.02	0.01	0.01	0.01	0.00	0.06	0.03	0.13	0.04	0.01	0.02	0.02	0.06
Sb	0.62	1.65	3.09	8.74	0.32	0.32	0.74	3.65	0.64	1.36	2.91	13.87	1.34	1.59	4.48	15.97
Se	23.26	19.60	33.22	58.98	16.51	7.34	28.44	24.16	31.40	7.73	9.18	35.01	2.14	1.75	7.77	45.16
Sn	0.00	28.57	0.03	0.06	0.00	33.90	0.03	0.03	0.00	0.03	0.10	0.07	0.01	20.00	0.06	0.05
V	0.22	0.24	1.03	4.16	0.40	0.57	0.51	2.18	0.38	0.56	0.91	7.45	0.14	0.11	1.13	1.00
W	0.06	0.62	0.28	10.14	0.62	1.09	0.16	8.71	0.03	0.18	0.18	4.76	0.22	0.73	1.64	1.66
Zn	2.84	2.98	2.47	2.32	0.02	0.14	0.67	0.02	13.43	10.88	9.89	11.83	1.22	0.85	1.22	1.87
Zr	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Initial pH				3.9				7.2					3.5			3.8

Major Elements	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %
Si	0.04	0.01	0.02	0.18	0.01	0.01	0.02	0.05	0.03	0.01	0.00	0.32	0.00	0.00	0.00	0.04
Al	0.07	0.09	0.03	0.05	0.00	0.00	0.02	0.00	0.11	0.14	0.06	0.02	0.07	0.03	0.04	0.16
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.02
Ca	6.00	5.50	5.18	9.00	0.71	0.54	4.04	1.98	9.51	8.62	7.08	10.79	3.72	3.31	3.52	5.90
Mg	1.74	1.85	1.64	2.07	0.16	0.19	0.64	0.59	3.35	3.23	3.23	3.80	0.50	0.44	0.39	0.84
Na	6.64	6.41		5.05	0.88	3.25		1.99	26.63	25.64		25.33	1.38	1.25		1.98
K	1.27	1.33	1.57	1.21	0.04	0.08	0.45	0.10	3.87	3.55	4.51	3.41	0.22	0.10	0.19	0.65
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P	0.54	0.56	0.29	0.24	0.04	0.08	0.59	0.16	0.29	0.39	0.12	0.50	0.03	0.03	0.11	0.10
S	80.29	84.80	90.98	84.44	7.87	14.49	17.02	8.59	82.66	91.33	93.06	21.42	65.10	44.27	53.13	1.30

Table 2b: Percentages of elements leached from alkali-generating fly ashes

P Stn No	16				17				20				21				22			
	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %
As	0.28	1.43	29.60	0.04	2.89	11.57	23.14	15.27	4.49	14.21	4.86	8.94	0.62	3.50	13.53	6.05	0.15	1.38	50.57	0.19
B	2.14	9.11	29.11	12.11	22.53	28.40	45.47	38.15	25.33	40.00	45.33	25.32	21.24	41.69	80.00	28.16	1.63	15.88	65.50	14.11
Ba	0.44	1.54	0.64	0.98	0.06	0.07	0.56	0.16	0.28	0.96	1.42	0.36	0.51	0.74	3.06	1.40	0.95	1.15	1.88	12.33
Be	0.13	0.04	0.04	0.04	0.06	0.02	0.45	0.05	0.10	0.02	0.49	0.05	0.18	0.13	1.46	0.12	0.14	0.04	0.04	0.06
Cd	0.96	0.38	6.73	0.50	1.13	1.13	3.60	2.22	3.63	0.52	14.51	1.70	2.40	0.80	112.00	5.50	2.32	1.16	31.88	1.83
Co	0.01	0.01	0.94	0.01	0.00	0.03	0.82	0.06	0.03	0.01	1.79	0.01	0.09	0.04	2.32	0.20	0.01	0.01	1.37	0.01
Cr	0.20	0.35	0.19	0.01	1.22	1.55	1.70	1.49	1.55	1.43	3.62	0.56	5.28	6.17	7.78	2.61	0.58	1.89	0.46	0.47
Cu	0.01	0.02	1.33	0.01	0.04	0.04	0.58	0.06	0.02	0.02	2.42	0.01	0.07	0.14	0.69	0.08	0.02	0.01	31.79	0.05
Ge	0.14	0.10	7.14	0.04	1.00	3.40	19.50	9.84	0.10	0.23	15.00	0.10	0.10	0.40	48.00	2.75	0.05	0.09	46.00	0.18
Hg	10.68	0.85	0.85	0.98	21.19	1.69	15.25	10.74	38.40	3.07	3.07	8.18	16.45	13.16	9.21	10.07	11.63	0.93	0.93	3.27
Li	3.43	0.00	0.00	2.90	1.03	0.00	1.53	1.00	0.69	0.00	0.00	1.64	0.42	0.61	1.27	24.46	1.04	0.00	1.66	3.01
Mn	0.00	0.00	1.16	0.00	0.00	0.01	1.05	0.04	0.00	0.02	2.91	0.10	0.00	0.00	0.62	0.01	0.00	0.00	1.13	0.02
Mo	35.57	32.79	27.54	19.83	47.54	45.90	27.38	51.06	60.44	59.56	14.07	62.27	33.67	40.82	48.37	53.62	16.00	29.47	42.11	54.19
Ni	0.04	0.05	1.25	0.05	0.08	0.08	1.48	0.32	0.11	0.11	3.00	0.17	0.19	0.95	3.90	0.97	0.03	0.04	2.62	0.08
Pb	0.01	0.00	0.00	0.01	0.00	0.00	0.02	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.14	0.02	0.02	0.10	0.10
Sb	0.21	2.93	4.29	0.55	4.62	4.87	4.62	13.70	3.43	5.71	5.71	9.69	0.00	6.13	12.26	5.48	0.03	4.14	12.41	1.96
Se	12.39	44.25	61.95	7.45	34.38	34.38	13.47	40.75	38.33	48.78	13.94	32.13	32.26	40.32	63.31	18.11	7.86	27.10	28.18	7.49
Sn	0.00	0.04	0.04	0.02	0.01	0.04	0.03	0.03	0.00	0.07	0.04	0.07	0.09	124.56	0.05	0.08	0.01	0.36	0.07	0.05
V	0.14	0.63	5.49	0.27	1.24	2.39	4.77	6.92	2.92	5.62	1.68	6.96	0.47	2.56	8.25	7.42	0.07	0.81	9.30	1.87
W	8.80	8.40	0.76	8.35	19.17	20.00	2.67	42.80	21.67	24.00	0.33	21.77	10.00	16.55	3.64	10.25	3.67	7.33	2.80	9.74
Zn	0.06	0.08	1.27	0.01	0.06	0.09	1.31	0.05	0.17	0.12	2.62	0.02	0.17	0.54	2.60	0.10	0.03	0.15	3.38	0.05
Zr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Initial pH				10.5				9.8				11.3				12.4				12.4

Major Elements	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %	Shake %	SGLP %	TCLP %	Colmn %
Si	0.01	0.03	0.28	0.00	0.00	0.02	0.08	0.06	0.01	0.02	0.05	0.06	0.01	0.04	0.32	0.12	0.00	0.03	0.27	0.02
Al	0.01	0.13	0.01	0.17	0.06	0.09	0.02	0.04	0.03	0.09	0.08	0.01	0.01	0.06	0.09	0.08	0.00	0.08	0.00	0.03
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	3.87	8.61	25.55	2.18	8.04	10.38	2.47	11.54	12.02	15.06	23.83	8.82	8.64	14.39	35.51	11.44	8.24	10.08	36.73	15.19
Mg	0.00	0.00	3.08	0.01	0.04	0.34	7.73	1.20	0.00	0.03	1.31	0.12	0.00	0.01	14.56	0.05	0.00	0.01	15.14	0.01
Na	2.62	0.02		2.00	0.84	0.71		0.80	1.95	1.96		1.98	0.75	0.82		1.36	1.55	0.88		2.59
K	0.39	0.35	0.78	0.43	0.12	0.10	0.04	0.19	0.21	0.23	0.43	0.29	0.11	0.11	0.36	0.62	0.28	0.15	0.21	1.06
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P	0.04	0.10	15.08	0.04	0.06	0.17	14.00	0.09	0.07	0.09	0.42	0.06	0.26	0.11	0.71	0.16	0.02	0.04	18.02	0.04
S	36.92	66.35	76.48	14.21	67.06	65.01	45.19	52.85	61.98	74.36	68.81	20.13	51.92	69.73	84.48	16.92	14.27	47.41	63.56	8.67

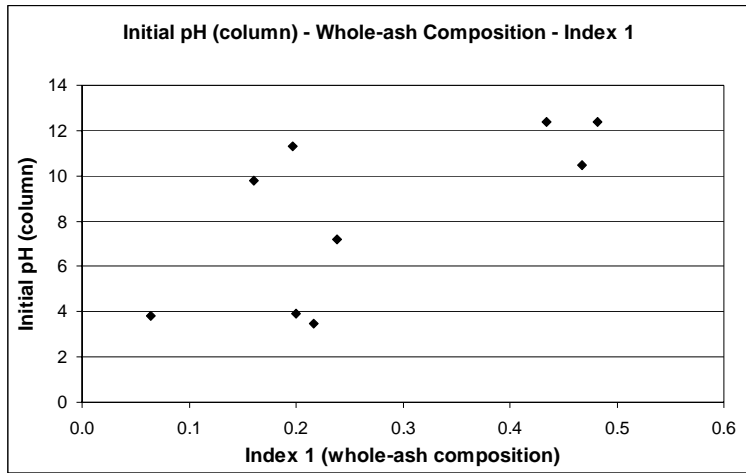


Figure 1a: Ash composition index 1 against initial column pH

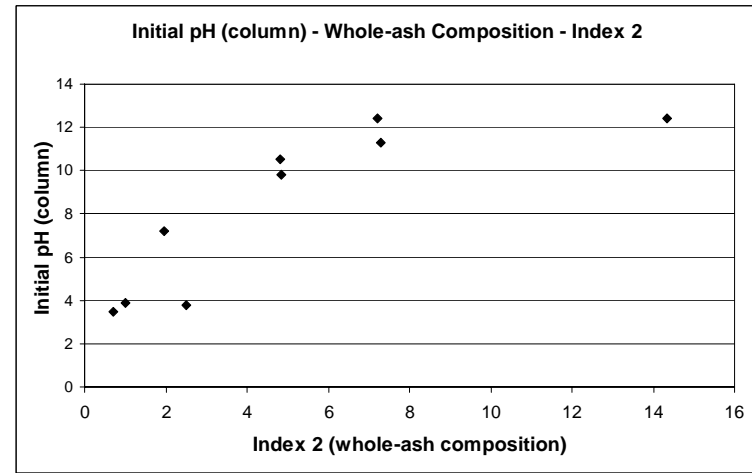


Figure 1b: Ash composition index 2 against initial column pH

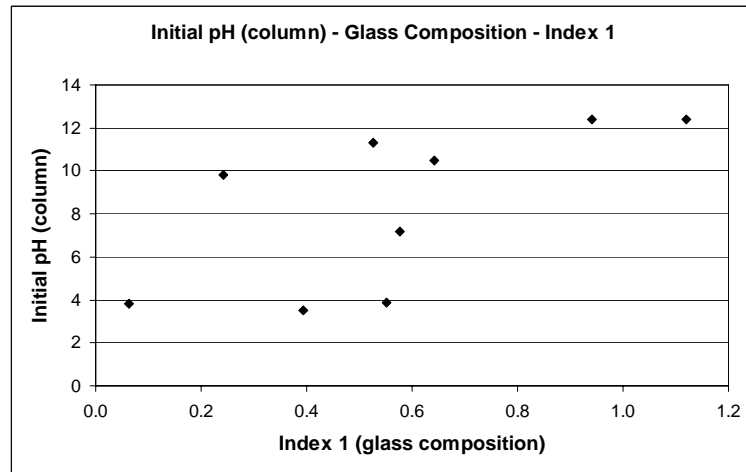


Figure 2a: Glass composition index 1 against initial column pH

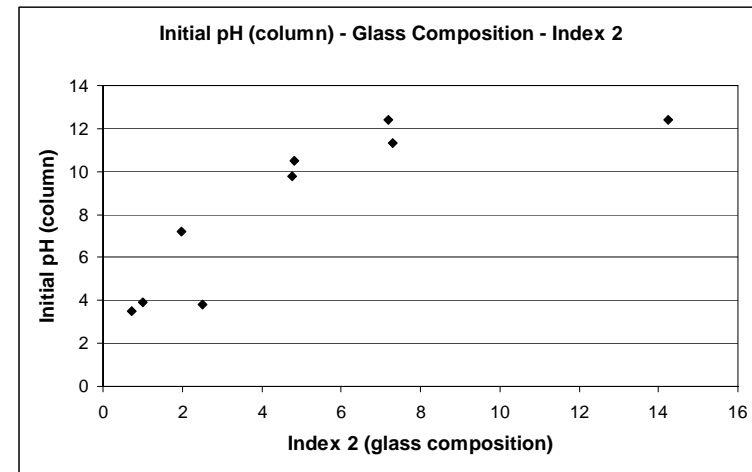


Figure 2a: Glass composition index 2 against initial column pH

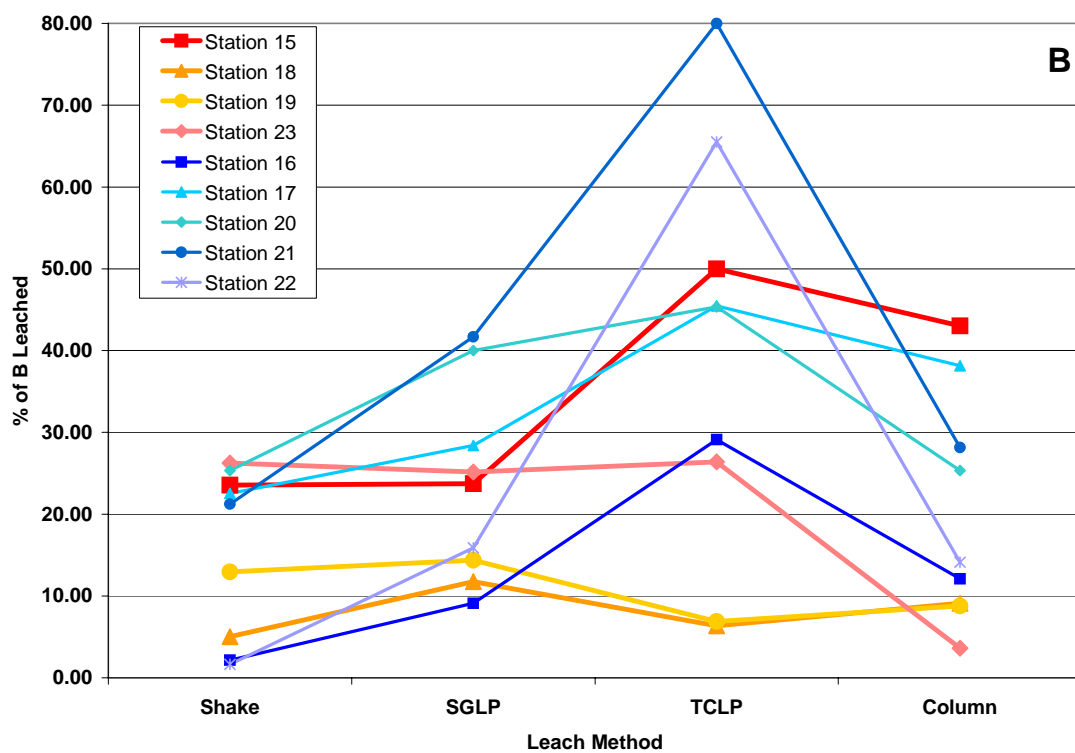
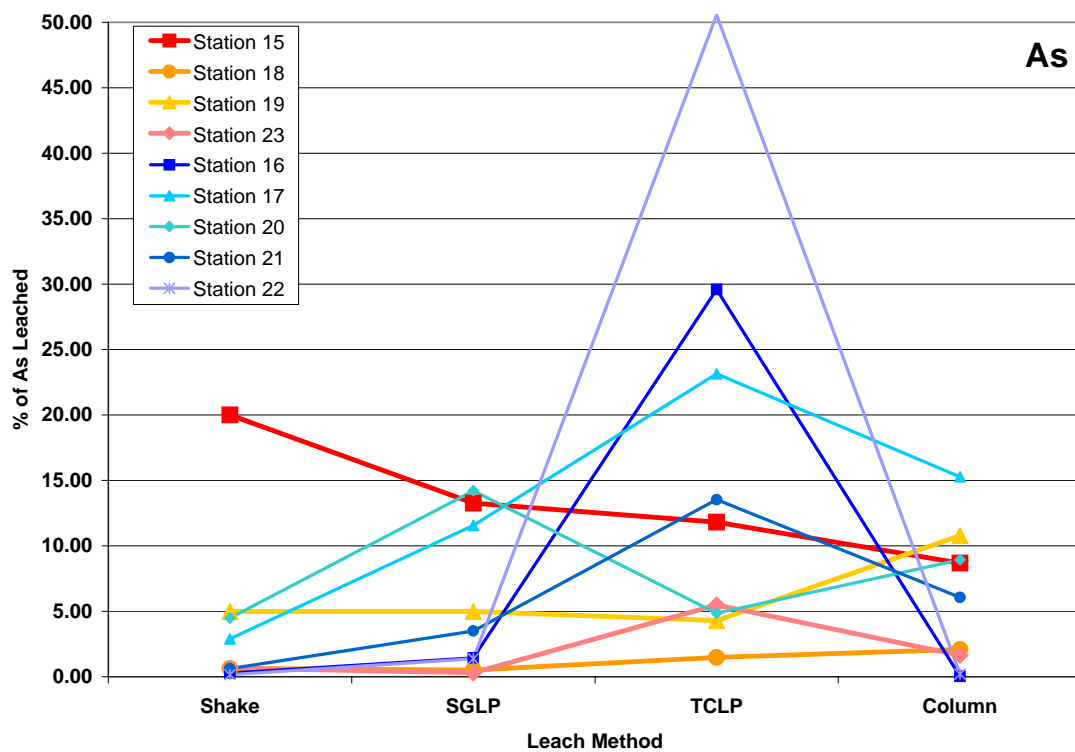


Figure 3. Comparative leaching data for A) arsenic and B) boron.

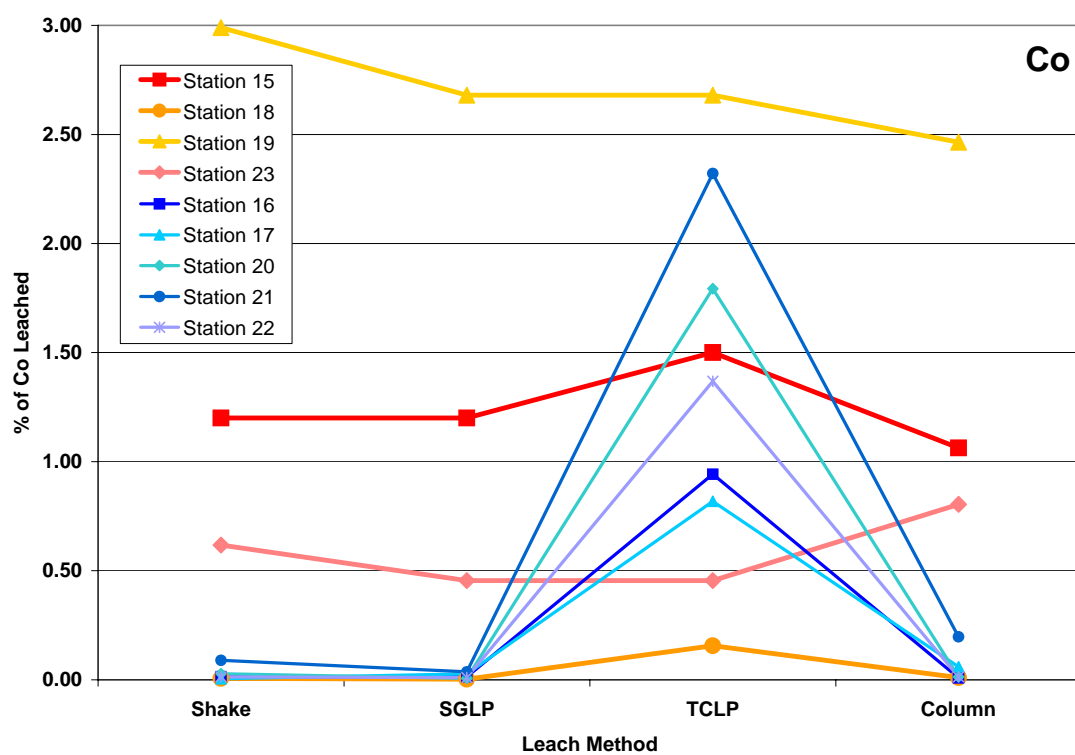
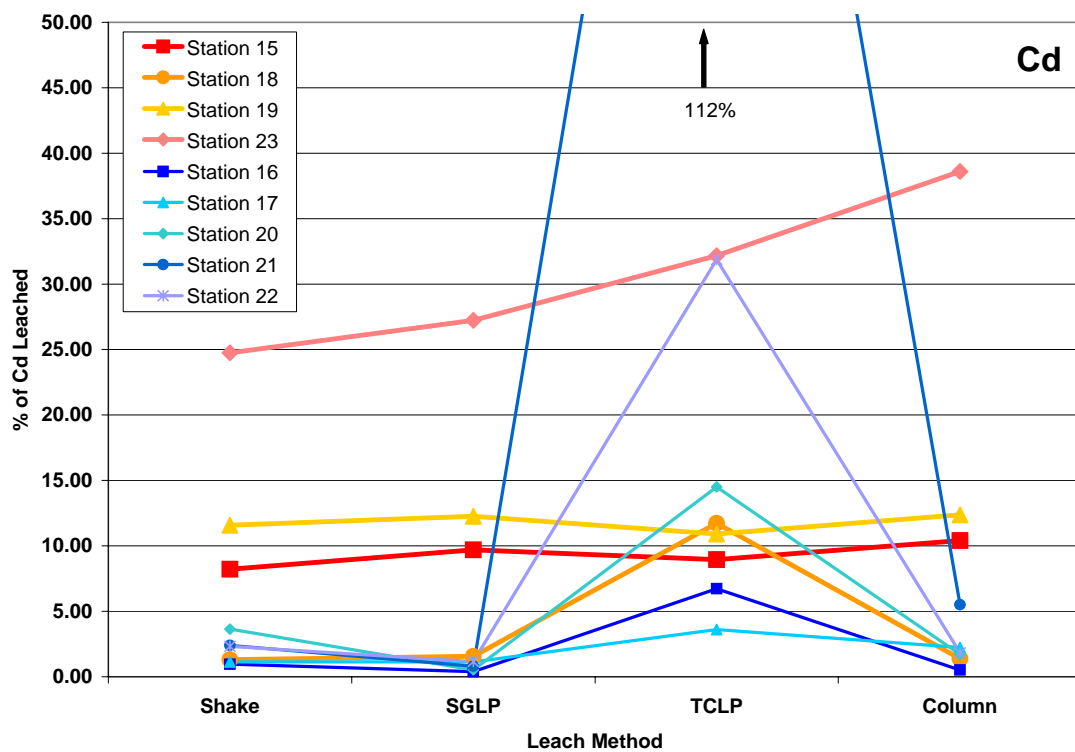


Figure 4. Comparative leaching data for A) cadmium and B) cobalt.

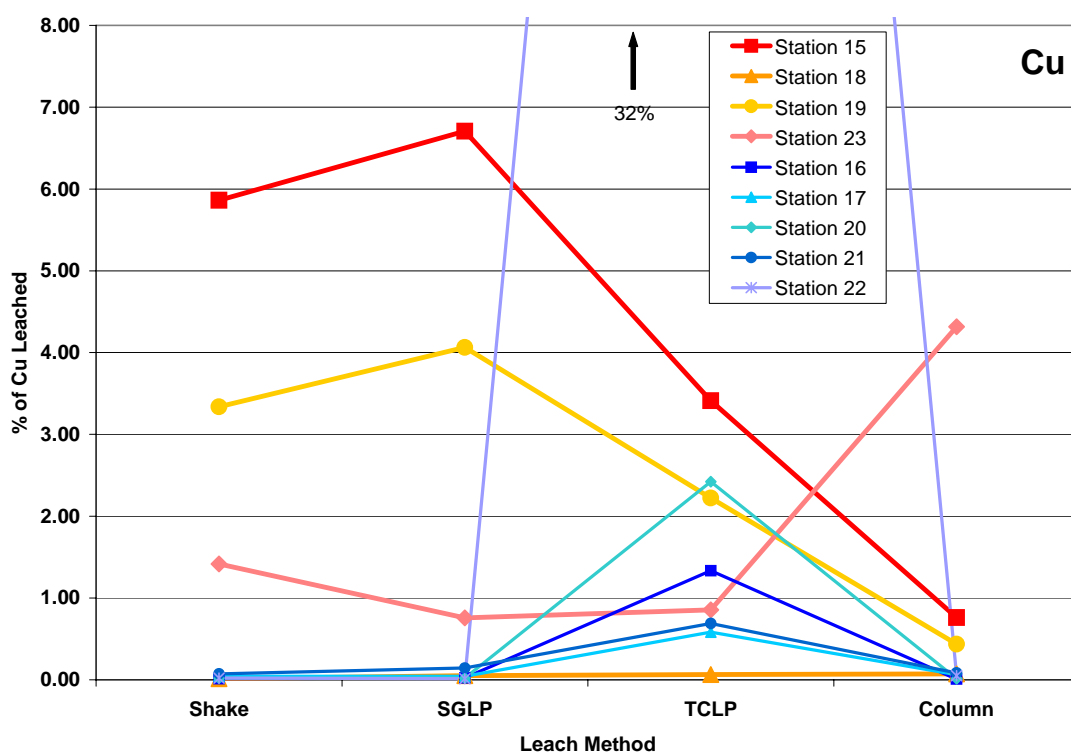
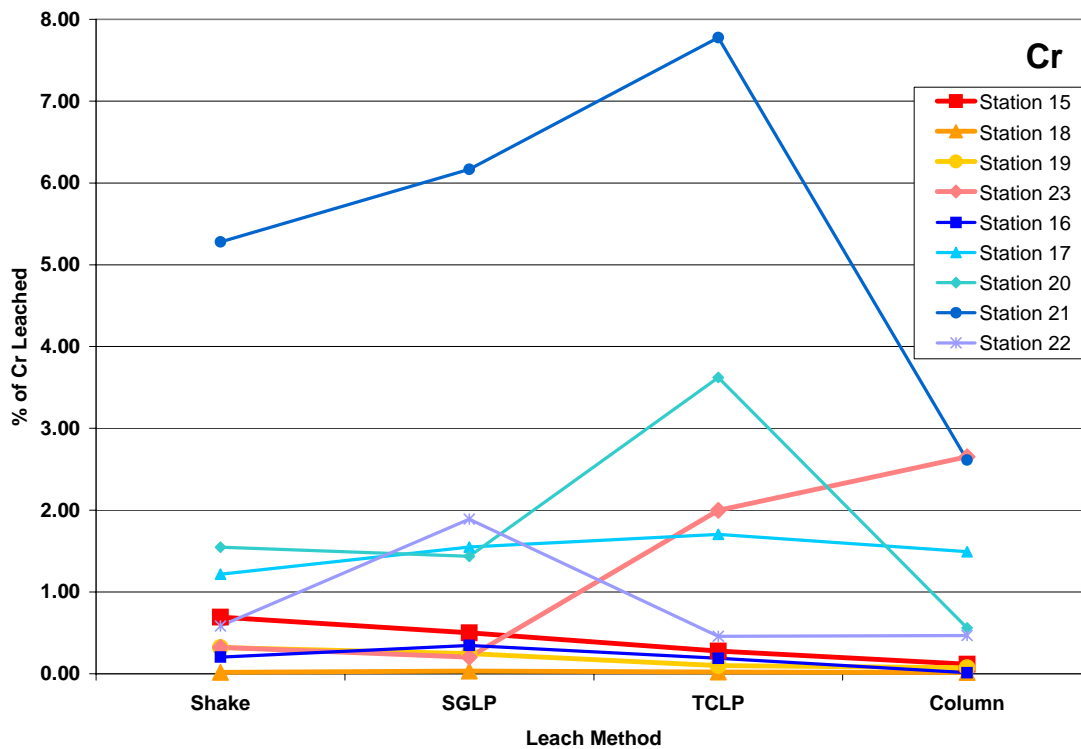


Figure 5. Comparative leaching data for A) chromium and B) copper.

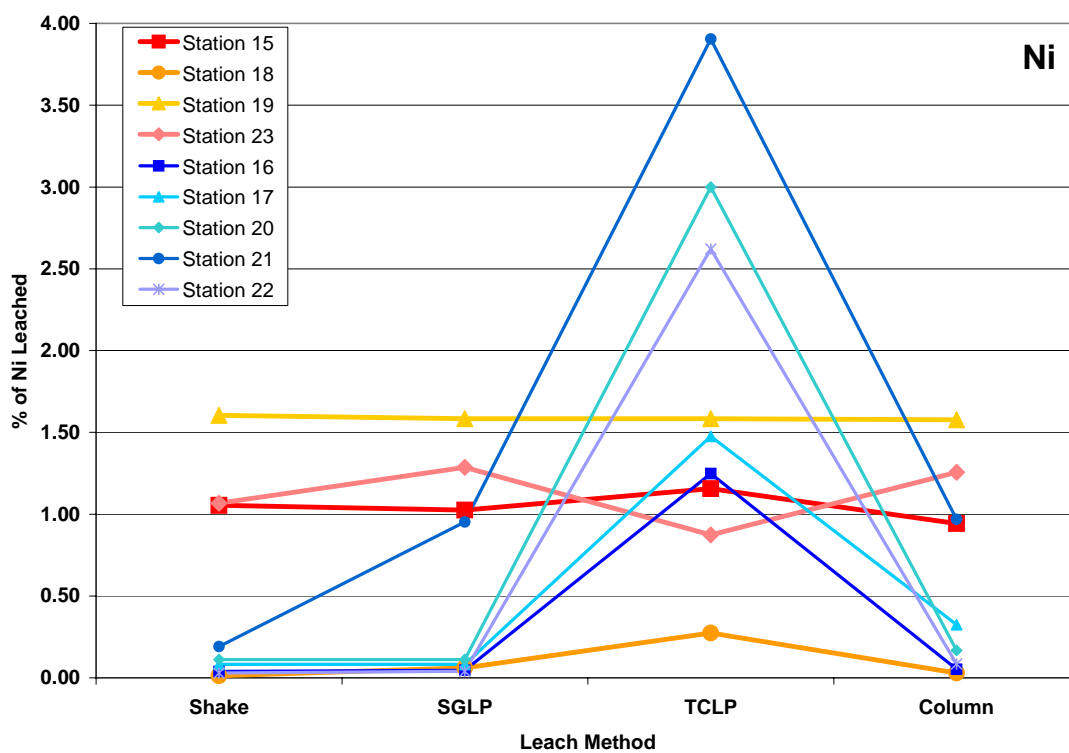
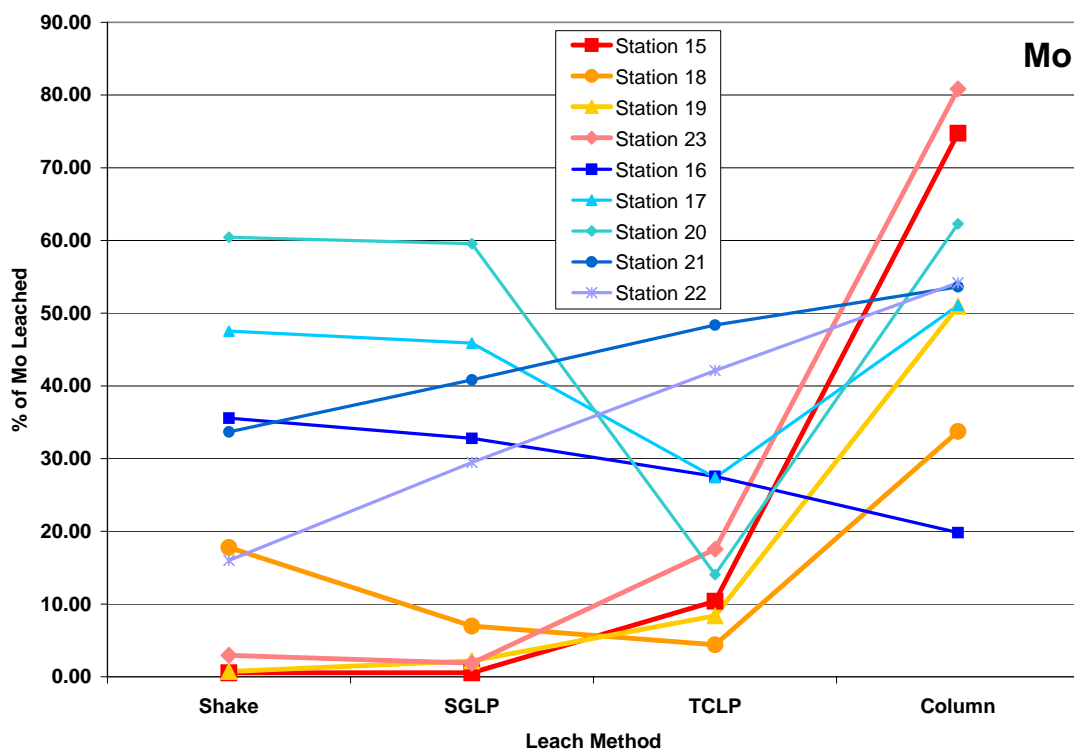


Figure 6. Comparative leaching data for A) molybdenum and B) nickel.

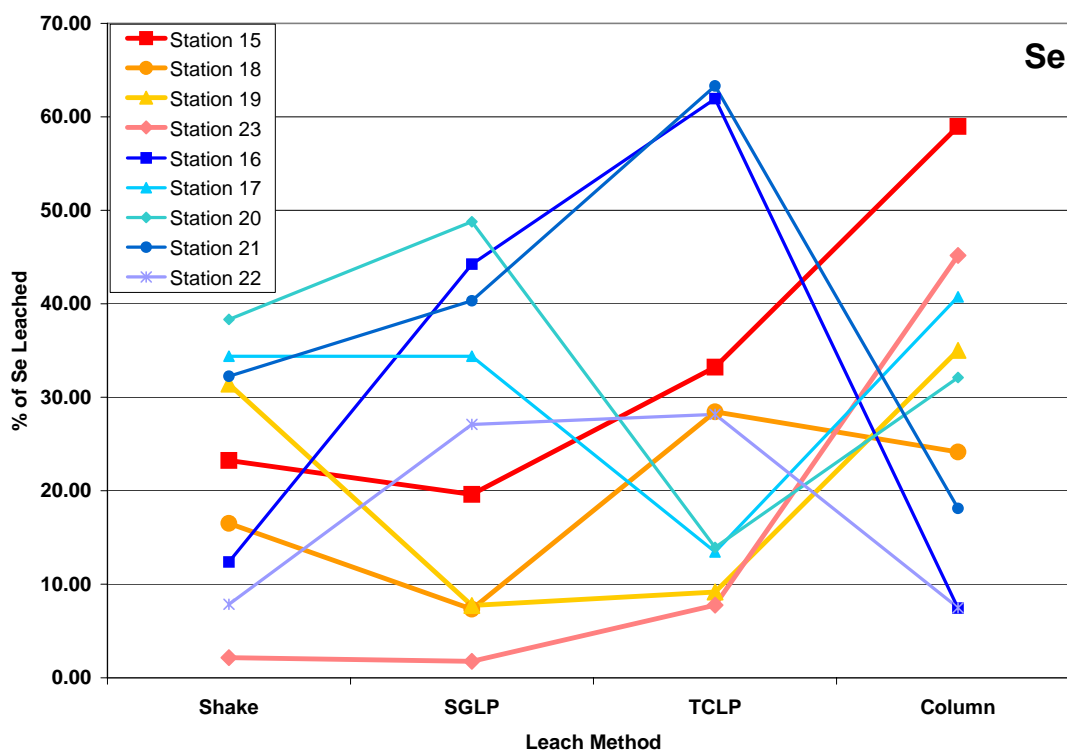
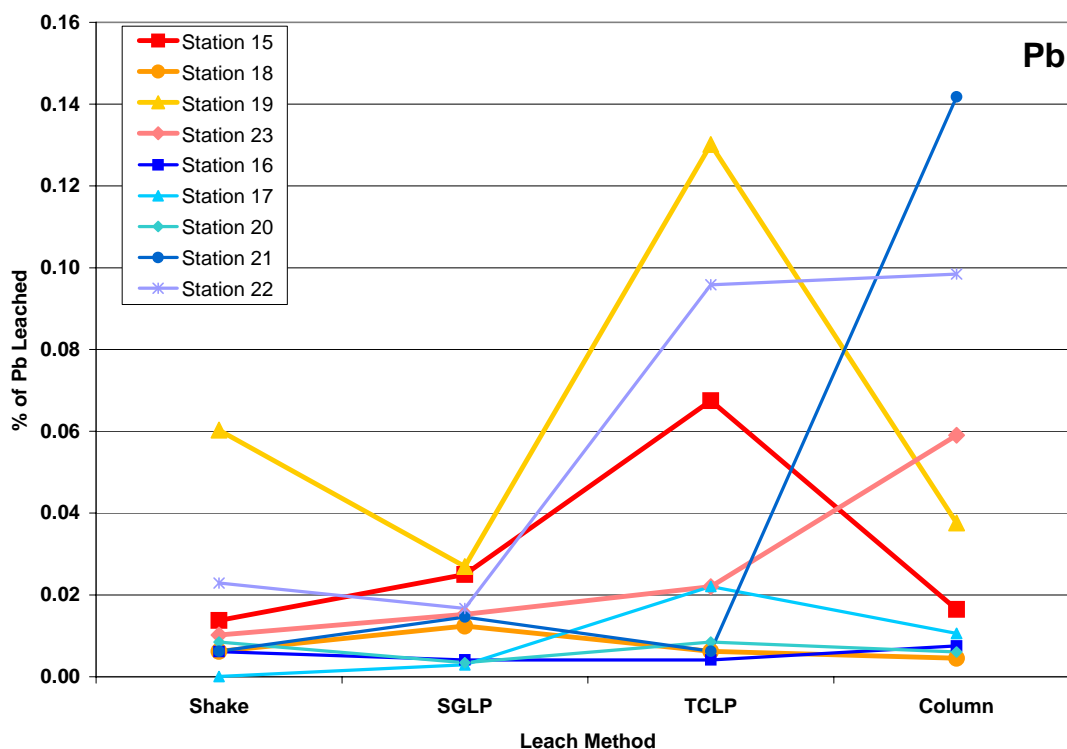


Figure 7. Comparative leaching data for A) lead and B) selenium.

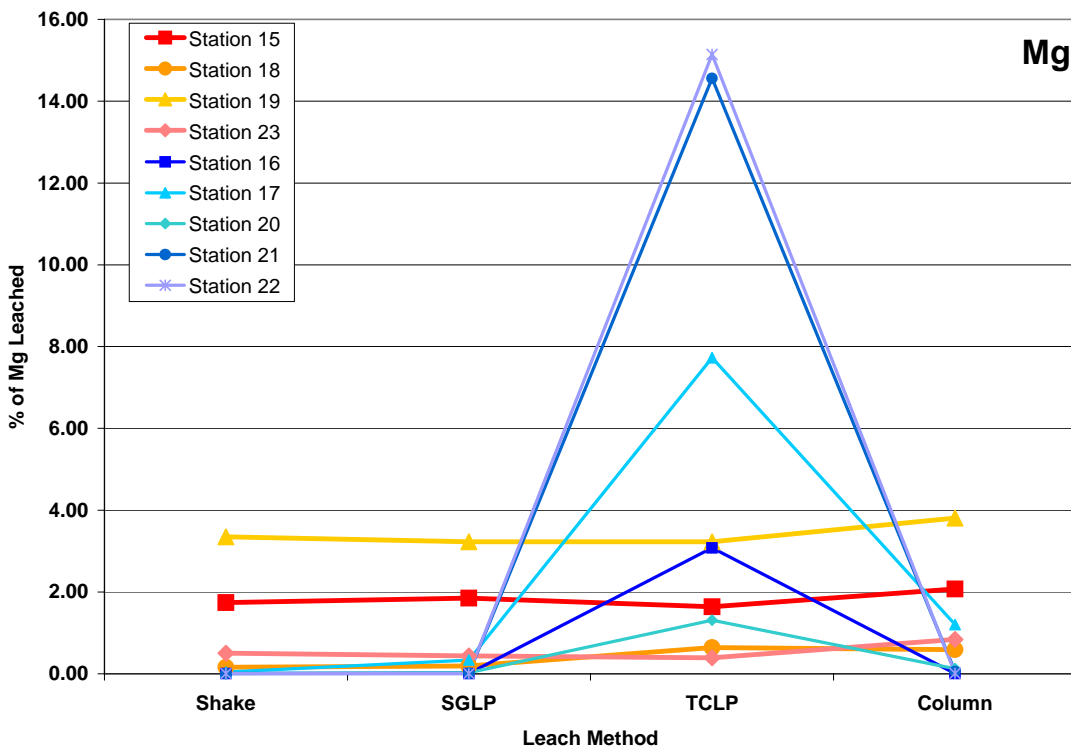
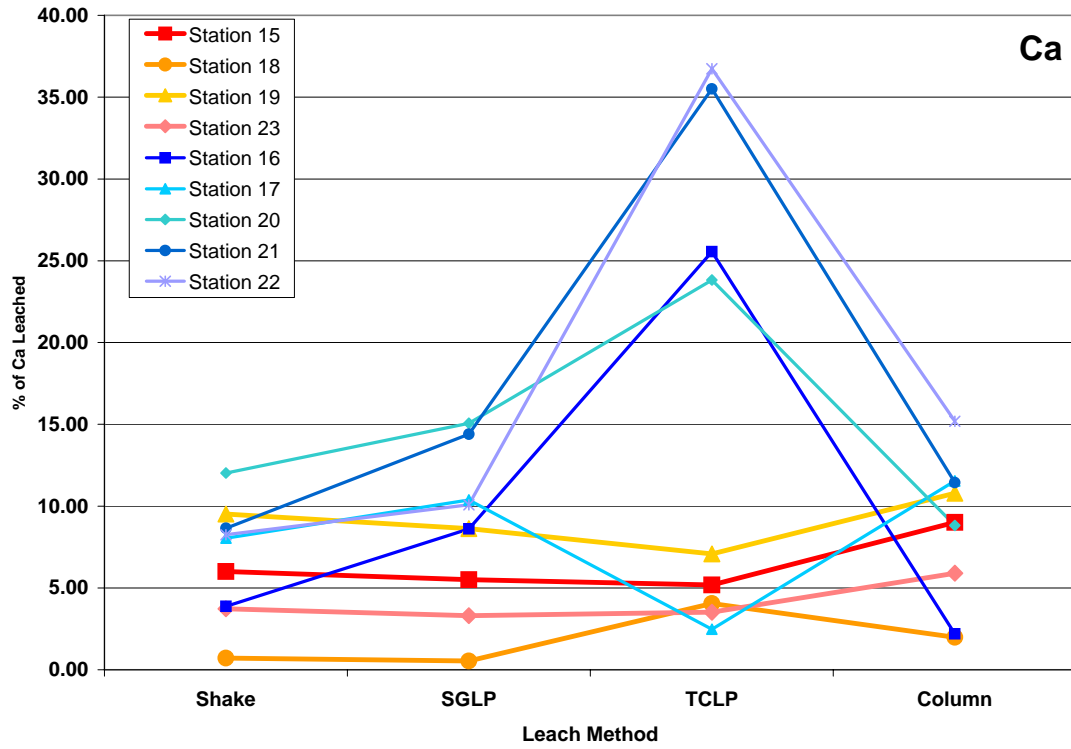


Figure 8. Comparative leaching data for A) calcium and B) magnesium.

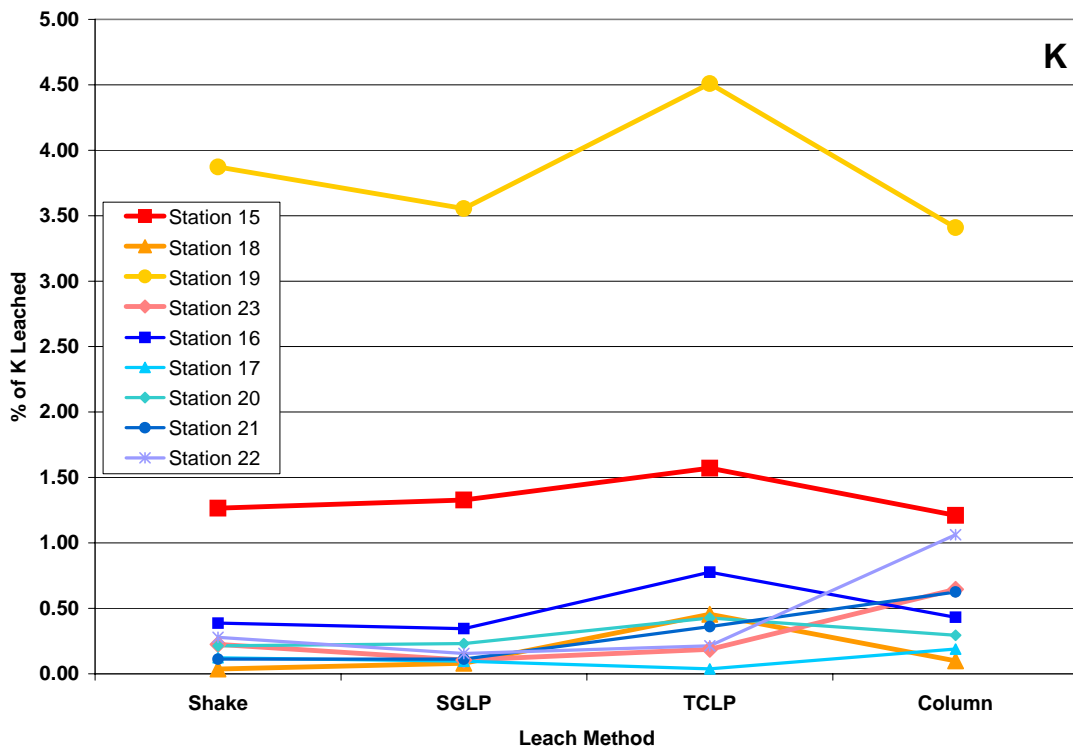
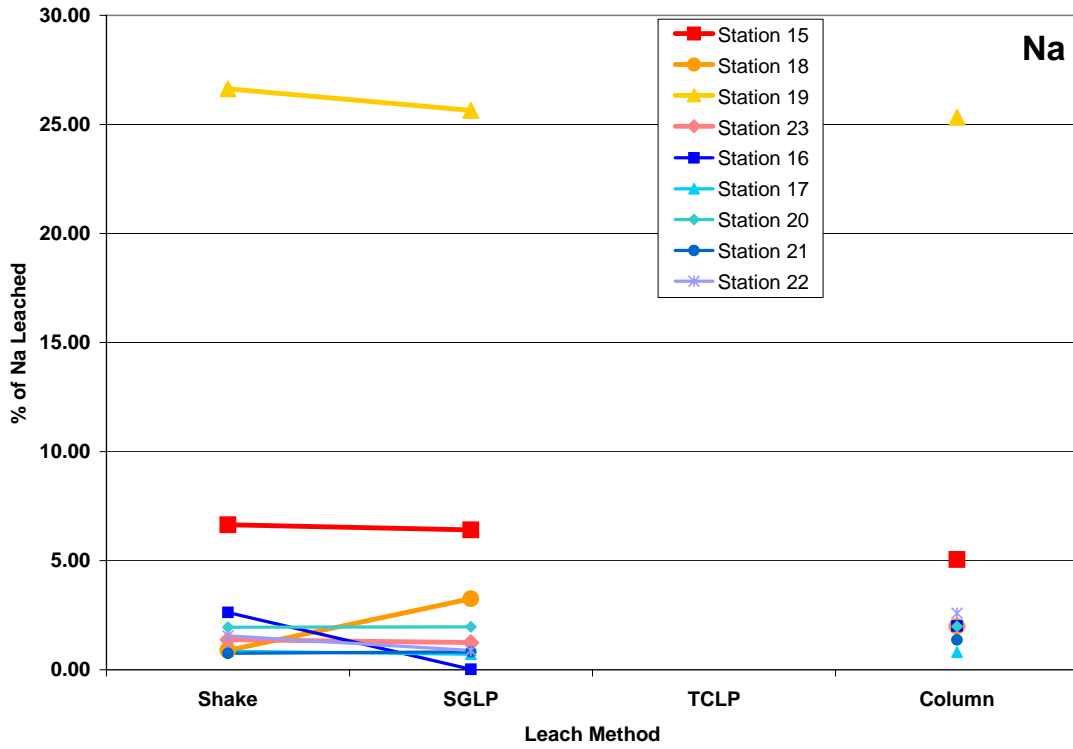


Figure 9. Comparative leaching data for A) sodium and B) potassium.

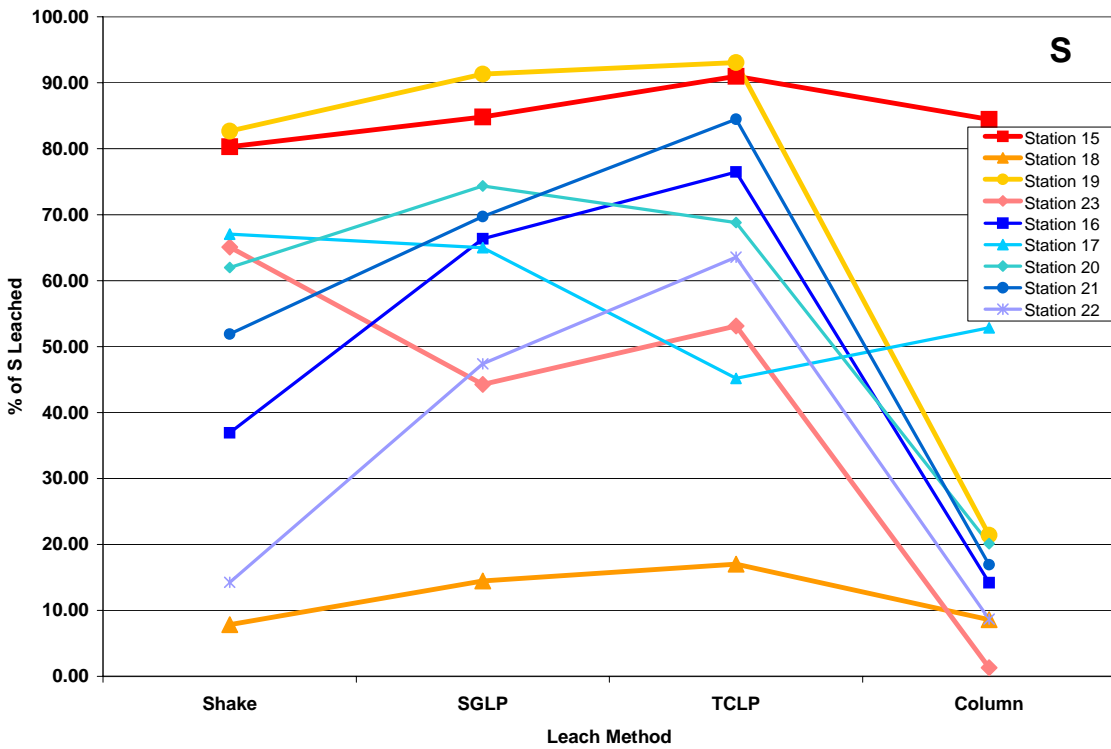
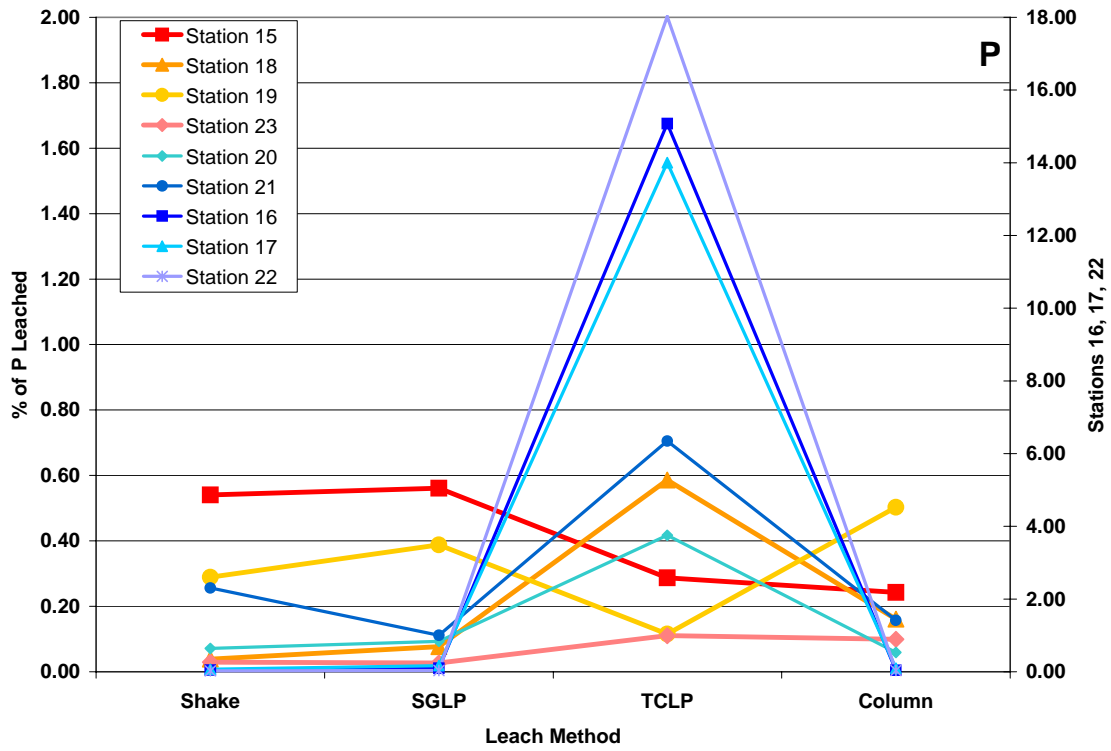


Figure 10. Comparative leaching data for A) phosphorus and B) sulphur.