APPENDIX C
GEOCHEMICAL EVALUATION OF ROSEMONT KINETIC AND SHORT-TERM LEACH TEST DATA

C1.0 INTRODUCTION

An open pit copper mine and ore processing operation are planned for the Rosemont Copper Project (Rosemont) site, located approximately 30 miles southeast of Tucson, Arizona. Processing of approximately 546 million tons (Mt) of sulfide ore and 69 Mt of oxide ore is expected to generate up to 1,288 Mt of waste rock during the anticipated 20-25 year mine life. Consequently, a baseline geochemical characterization was prepared which focused on potential water quality impacts from the various mine facilities (e.g., waste rock and stack tailings storage areas). One of the primary goals of the baseline characterization study was to test a representative number of samples in order to adequately characterize the chemical behavior of rock that would be developed from mining (Tetra Tech, 2007). The geochemical baseline characterization utilized a phased approach to characterize mine materials using both kinetic testing and short-term leaching tests (STLTs). Kinetic tests were carried out using standard humidity cell tests (HCTs) (ASTM, 1996), while STLTs included the meteoric water mobility procedure (MWMP) (ASTM, 2003) and the synthetic precipitation leaching procedure (SPLP) (USEPA, 1986).

C2.0 TECHNICAL OBJECTIVE

The objective of this analysis is to evaluate the adequacy of existing kinetic and STLT data for providing the information needed to evaluate wall rock runoff source terms for use in the Rosemont pit lake model. A summary of the HCT and STLT methods used to characterize the rock types is provided. An evaluation of the data is also provided with respect to predicting chemical mass loading to the pit lake from wall rock runoff.

C3.0 SUMMARY OF TESTING METHODS

Geochemical testing of Rosemont materials included both kinetic testing and STLTs. This section provides a summary of the kinetic tests and STLTs which were conducted on various rock types which will ultimately comprise the pit walls and thus contribute to chemical mass loading of the anticipated pit lake.

C3.1 Kinetic Testing

Kinetic testing procedures are designed to accelerate the natural weathering processes for a material. Typically, kinetic tests are conducted to verify the extent of acid generation for samples whose acid-base accounting (ABA) results indicate uncertainty with respect to acid generation, or to determine the rates of acid production for samples which are known to be acid generating. Static ABA test results are first used to classify a sample as either inert, potentially-acid generating (PAG), or uncertain with respect to acid generation. Static ABA testing compares the acid generation potential (AGP) with the acid neutralization potential (ANP) to calculate a net neutralization potential (NNP = ANP-AGP). Theoretically, a sample would be acid generating if its NNP value is less than zero. In practice, however, the risk of acid generation is greatest for samples with NNP values less than -20 kg $CaCO_3$/ton rock (kg/t) and is the lowest when the NNP is greater than +20 kg/t (Price, 1997). The neutralization potential ratio (NPR = ANP/AGP) can also be used to assess the risk of acid generation, where an NPR greater than three (3) is considered to indicate a low risk for acid generation, and an NPR value less than one (1) indicates a high risk of acid generation (Price, 1997).

The Arizona Department of Environmental Quality (ADEQ) has a draft policy indicating that samples with an NPR greater than three (3) or with an NNP greater than zero and less than 0.3% sulfur are considered inert (ADEQ, 1999). Potentially-acid generating (PAG) materials are therefore defined by a negative NNP value with >0.3% sulfide-S and/or an NPR below one (1). Therefore, materials not classified as PAG according to the criteria of Price (1997), and which do meet the ADEQ criteria for inert materials, are considered uncertain with respect to acid generation.

Kinetic testing was carried out on 16 samples which displayed a range of NNP (-25.6 to 63.1 (kg $CaCO_3$/ton) and NPR (0.1 to 94.1) (Table C1). Testing was carried out using standard humidity cell tests (HCTs) (ASTM, 1996), where samples are placed into humidity cells and exposed to alternating periods of wetting and drying, followed by periodic leaching between cycles. The HCTs were carried out for a period of 25 to 35 weeks. The leachates are analyzed for constituents of interest (typically pH, sulfate, and metals) which can then be used to calculate rates of sulfide oxidation and metals release. Kinetic testing using HCTs is particularly useful in evaluating acid generation from samples which have been classified as PAG or uncertain.

Table C1 Static Testing Summary for Rosemont HCT Materials

Sample ID	Rock Type	NPR	NNP	Total Sulfur	Pyritic Sulfur (%)	Sulfate Sulfur (%)	Class
AR2000-02	Earp	5.7	10.5	0.55	0.66	0.19	uncertain
AR2003-03	Arkose	1.5	10.5	0.92	0.66	0.26	uncertain
AR2005-02	Arkose	1.2	4.7	1.21	0.94	0.27	uncertain
AR2009-03	Andesite	1.5	35	2.33	2.05	0.26	uncertain
AR2009-04	Epitaph	4.7	63.1	0.80	0.55	0.24	uncertain
AR2010-02	Arkose	1.3	3.8	0.57	0.44	0.13	uncertain
AR2010-03	Andesite	0.5	-25.6	2.01	1.67	0.34	PAG
AR2011-03	Andesite	0.8	-14.6	2.51	2.2	0.31	PAG
AR2013-01	Andesite	1.2	11.3	1.98	1.55	0.40	uncertain
AR2013-02	Andesite	2.1	37.1	1.36	1.06	0.30	uncertain
AR2013-03	Arkose	2.5	47.1	1.02	1.02	<0.01	uncertain
AR2014-02	Andesite	0.9	-17.1	4.77	3.92	0.81	PAG
AR2014-03	Andesite	2.4	42.1	1.22	0.95	0.23	uncertain
AR2014-05	Earp	94.1	10.4	0.32	0.37	<0.01	uncertain
A780-02 COMPOSITE	Bolsa	0.33	-6.1	0.42	0.29	0.13	PAG
A780-03 COMPOSITE	Bolsa	0.10	-8.7	0.45	0.31	0.13	PAG

C3.2 Short-Term Leaching Tests (STLTs)

The Meteoric Water Mobility Procedure (MWMP) is a common leaching test used to evaluate the potential for dissolution and mobility of certain constituents from a mine waste sample when exposed to meteoric water (ASTM, 2003). The MWMP incorporates a single-pass column deionized water leach (unspecified pH) over a 24-hr period. The ratio of solution:solid in the MWMP (1:1) is identical to the HCTs. Column leachates are filtered and analyzed for the constituents of interest. Twenty-three MWMP tests were run and included

- Nine (9) samples of Willow Canyon Formation Arkose;
- Six (6) samples of Willow Canyon Formation Andesite;
- Two (2) samples of Horquilla Limestone;
- Two (2) samples of Overburden;
- One (1) sample of Abrigo Formation;
- One (1) sample of Concha Limestone;
- One (1) sample of Quartz Monzonite Porphyry; and
- One (1) sample of Tertiary Gravel.

The Synthetic Precipitation Leaching Procedure (SPLP) is a different leaching test which was designed to determine the potential for constituent mobility from geologic materials when exposed to precipitation (USEPA, 1986). The SPLP is a batch testing procedure (as opposed to the MWMP column leach) which uses a solution:solid ratio of 20:1. The SPLP extraction solution is adjusted to a pH of 5.0 using a nitric/sulfuric acid mixture, and the sample is extracted for approximately 18 hrs. The resulting extracts are then filtered and analyzed for the constituents of interest. Sixty-seven samples of varying lithologies were submitted for SPLP testing, including

- Ten (10) samples of Willow Canyon Formation Arkose;
- Ten (10) samples of Horquilla Limestone;
- Seven (7) samples of Abrigo Formation;
- Six (6) samples of Bolsa Quartzite;
- Six (6) samples of Earp Formation;
- Six (6) samples of Epitaph Formation;
- Four (4) sample of Willow Canyon Formation Andesite;
- Four (4) samples of Colina Limestone;
- Four (4) samples of Escabrosa Limestone;
- Four (4) samples of Martin Formation;
- Two (2) sample of Overburden;
- Two (2) samples of Quartz Monzonite Porphyry;
- One (1) sample of Concha Limestone; and
- One (1) sample of Tertiary Gravel.

C4.0 SUMMARY AND EVALUATION OF KINETIC AND LEACHING TEST DATA

This section presents a summary of the HCT, MWMP, and SPLP results for the Rosemont geologic materials. A comparison of these results is then used to select the most appropriate testing method for defining chemical mass loading from wall rocks to the pit lake. Previous baseline testing results can be found in Appendix A of the Geochemical Characterization Addendum 1 Report (Tetra Tech, 2007).

C4.1 Materials Testing Evaluation

One of the most important aspects of geochemical characterization is ensuring that the materials being tested are representative of the overall population. As part of the initial Rosemont geochemical characterization program (Tetra Tech, 2007), a number of different rock types were characterized for ABA. A statistical evaluation of these data, in conjunction with additional data collection in 2008 and 2009, has shown that the majority of the rock types expected to comprise the pit walls have been adequately characterized (Appendix B in this report).

Subsequent to the initial geochemical characterization, a subset of samples was subjected to additional kinetic tests and STLTs, and these results are evaluated in Sections C4.2 through C4.4. A summary of the mean NNP for each rock type, and the corresponding range in NNP for the specific samples tested is provided in Table C2.

Table C2 Statistical Summary for Materials Geochemical Testing

Rock Type	% of Pit Wall	NNP	HCT	MWMP	SPLP
		Mean	NNP Range for Test		
Willow Canyon Formation, Arkose	29.3	45 ± 36	4.2 to 47.1	-3.4 to 70.2	4.3 to 95.6
Horquilla Limestone	16.2	364 ± 242	NT [1]	410 to 467	169 to 766
Bolsa Quartzite	8.1	-0.75 ± 14	-6.1 to –8.8	NT	-6.2 to 22.7
Abrigo Formation	7.5	580 ± 100	NT	439	439 to 693
Epitaph Formation	7.4	519 ± 282	63.1	NT	175 to 928
Tertiary Gravel	6.4	41.7 ± 46.7	NT	4.0 to 17.4	4.0 to 17.4
Colina Limestone	4.8	393 ± 232	NT	NT	125 to 453
Earp Formation	4.0	110 ± 72	51.3 to 94.1	NT	14.4 to 169
Glance Conglomerate	3.8	625 ± 152	NT	NT	NT
Escabrosa Limestone	3.8	612 ± 354	NT	NT	203 to 874
Concha	2.9	650 ± 168	NT	570	740
Martin Formation	2.5	692 ± 148	NT	NT	572 to 876
Pre-Cambrian Granodiorite	1.0	NT	NT	NT	NT
Willow Canyon Formation, Andesite	0.9	36 ± 33	-25.6 to 42.1	-14.6 to 42.4	11.3 to 39.8
Scherrer	0.6	NT	NT	NT	NT
Quartz Monzonite Porphyry	0.5	11.3 ± 11.3	NT	0.3	10.1 to 12.2
Overburden	0.2	20.2 ± 15.4	NT	4.2 to 19	7.6 to 47

[1] NT = not tested.

This statistical summary shows that the range of sample NNP values for each test was within the mean NNP plus one (1) standard deviation for all samples of a given rock type. However, certain samples were biased toward a low NNP in order to evaluate the potential for acid generation by materials classified as PAG. For tests performed on only a single sample, the NNP of each sample was most often within one (1) standard deviation of the mean. Therefore, samples which were selected for additional kinetic tests and STLTs adequately represent the overall population for their respective rock type.

C4.2 Kinetic Testing

The results of weekly HCT sampling for pH, sulfate, acidity, and alkalinity for each of the 16 HCTs are shown on Illustrations C1 through C16. With the exception of the Bolsa Quartzite samples, pH levels were generally neutral to alkaline and sulfate levels gradually declined or remained stable throughout the 35-week testing period. Most metals were below detection limits in the HCT leachates; however, low concentrations of antimony, copper, manganese, arsenic, and selenium were detected in a few samples (Tetra Tech, 2007). Even though ABA testing results for these materials (Table C1) indicate that certain Rosemont rock types have the potential to generate acid, the HCT results provide no indication that sulfide oxidation and the subsequent release of metals and acidity is a significant mechanism controlling solution chemistry during weathering.

For example, one (1) sample of Willow Canyon Formation andesite (AR2010-03) displayed the most negative NNP value (-25.6 t/kt) and is classified as PAG (Table C1). The ABA results for this sample indicate that both sulfide-S (1.67%) and sulfate-S (0.34%) were present. Illustration C7 clearly shows that the pH of the humidity cell leachate remained neutral throughout the entire 35 weeks of testing. Both calcium and sulfate leaching rates fell slightly during the test period, while maintaining a calcium:sulfate ratio which is consistent with gypsum ($CaSO_4 \cdot 2H_2O$) dissolution. Any acid generation that may have occurred is masked by sulfate mineral dissolution. The constant low levels of acidity and iron are also consistent with simple sulfate mineral dissolution, rather than acid generation resulting from iron sulfide oxidation.

Another sample of Willow Canyon andesite (AR2014-02) displayed the highest total-S (4.77%) and sulfide-S content (3.92%), with a corresponding negative NNP, and was also considered PAG (Table C1). Similarly, the HCT results shown on Illustration C12 show that the pH of the cell leachate remained between 7.5 and 8.5 during the 35 weeks of testing. Again, the decrease in calcium and sulfate leaching rates over time, and the low constant levels of acidity and iron, are consistent with solution chemistry that is dominated by simple mineral dissolution, rather than iron sulfide oxidation.

The Bolsa Quartzite is the only material tested which generated net acidity during humidity cell testing. Unlike the andesite, arkose, and limestone materials which contain more reactive acid-neutralizing minerals, the neutralizing silicate fraction of the Bolsa Quartzite reacts more slowly. Therefore, net acidity associated with low pH values was generated in the humidity cells (Illustrations C15 and C16). These observations are consistent with the presence of 0.13% sulfate-S in the Bolsa Quartzite samples (Table C1).

C4.3 Meteoric Water Mobility Procedure (MWMP)

A comparison of the MWMP results to the HCT results provides further indication that mineral dissolution, rather than sulfide oxidation, is the dominant factor controlling constituent release from the Rosemont rocks. This conclusion is based on similarities between the leaching characteristics of short-term MWMP results as compared to long-term HCT results. Both testing procedures use a 1:1 ratio of solution:solid, which allows for a direct comparison of the two methods. However, the MWMP is a short-duration test (24 hr), compared to the long-duration (35 weeks) for HCTs.

The average calcium, magnesium, sulfate, and pH values at five (5) week intervals for the HCTs representing three (3) rock types are compared to the MWMP concentrations for the same rock types in Illustrations C17 through C19. The HCT data indicate that the initial flush (Week 0) generally produced elevated and variable constituent concentrations compared to the remaining five (5) week HCT rinsing intervals. The occurrence of high concentrations in the Week 0 leachates is a commonly-observed phenomenon caused by dissolution of soluble pre-existing reaction products, which sometimes requires three (3) to five (5) weeks to be completely flushed from the system (ASTM, 1996). From Week 5 forward, however, the concentrations of calcium, magnesium, and sulfate in the HCTs decreased and showed little variability (Illustrations C17 through C19).

The concentrations of major ions and pH in the arkose and andesite HCTs were within the range observed in the MWMP extracts (Illustrations C17 and C18). In other words, the solution composition which results from a simple 24-hr leaching is essentially the same as that produced by either early (Week 5) or late (35-week) HCT leachates. These observations suggest that short-term mineral solubility is the most important factor controlling the solution composition, not long-term weathering and release of oxidation products which is more typically demonstrated by decreasing pH, and increasing concentrations of iron, sulfate, and acidity. While no MWMP results exist for the Earp Formation limestone, the Earp HCT leachate compositions were very similar to the andesite and arkose HCT leachate compositions (Illustration C19).

C4.4 Synthetic Precipitation Leaching Procedure (SPLP)

The SPLP test is much more cost-effective when compared to MWMP, and therefore a larger number of samples was analyzed (SPLP, N = 59 and MWMP, N =19). The SPLP is a batch leach procedure which also differs from the MWMP column test in that the SPLP utilizes a solution:solid ratio of 20:1. Therefore, the SPLP procedure has the potential to dissolve more constituent mass from a sample compared to the MWMP, but the actual solution concentrations may be lower. For example, a comparison of the SPLP and MWMP results from four (4) different rock types is shown in Table C3. Examination of the major cation (calcium, magnesium, sodium, potassium) and anion (sulfate, chloride, fluoride) data for each rock type shows that their concentrations are more often than not higher in the MWMP solutions when compared to the SPLP solutions. However, when the results are expressed on a rock mass basis, the SPLP can be shown to release more chemical mass when compared to the MWMP (Table C4).

The SPLP was developed by the USEPA to determine the mobility of solid-phase constituents and the potential for groundwater contamination. The main advantage of using SPLP for geochemical characterization is that it provides a measure of the readily-dissolvable constituents from dried mine materials (e.g., wall rocks) (Maest and Kuipers, 2005). Furthermore, the higher SPLP solution:solid ratio (20:1) would be appropriate for modeling runoff-wall rock interaction compared to the MWMP solid:solution ratio of 1:1.

C5.0 SUMMARY AND CONCLUSIONS

Geochemical characterization of the Rosemont rocks which are anticipated to comprise the ultimate pit wall has been conducted using a variety of static tests, kinetic tests, and STLTs. A review of the static testing data indicates that some samples are classified as PAG based on their ABA characteristics. However, when the majority of these materials were subjected to long-term humidity cell testing, the leachate pH remains neutral and the trends in sulfate, iron, and acidity provide no indication of sulfide oxidation. Any sulfide oxidation products which may have been generated become masked by the dissolution of existing secondary weathering products.

Dissolution of Rosemont rocks is largely controlled by carbonate mineral solubility, an observation which is further supported by the chemical similarities between long-term HCT leachate compositions and those produced by selective short-term MWMP leaching. The abundance of SPLP data were subsequently chosen to simulate runoff compositions for the various wall rocks. Due to the low reactivity of acid neutralizing minerals in the Bolsa Quartzite, however, this rock type was shown to produce net acidity during humidity cell testing as a result of sulfide oxidation. Therefore, HCT data from the Bolsa Quartzite were also incorporated into the pit lake model to account for potential effects of acid generating materials.

Table C3 Solution-Basis Comparison (mg/L) of MWMP and SPLP Testing for Four Rock Types

Material Type	Willow Canyon Formation-Andesite		Willow Canyon Formation-Arkose		Horquilla Limestone		Glance Conglomerate	
Test	**MWMP**	**SPLP**	**MWMP**	**SPLP**	**MWMP**	**SPLP**	**MWMP**	**SPLP**
Calcium	20.3	10.2	14.3	5.71	28.2	47.2	8.69	5.01
Magnesium	4.72	1.40	2.43	0.75	2.90	2.37	0.88	2.61
Sodium	15.8	4.46	15.4	4.86	10.8	2.13	5.29	0.80
Potassium	12.9	5.35	5.20	2.86	4.68	1.06	0.83	2.14
Sulfate	62.4	17.8	33.6	4.45	28.2	110	6.34	1.4
Chloride	3.09	0.57	4.05	0.86	24.4	2.34	0.88	0.88
Fluoride	1.03	0.29	0.79	0.26	1.09	0.51	0.17	0.10

Table C4 Mass-Basis Comparison (mg/kg) of MWMP and SPLP Testing for Four Rock Types

Material Type	Willow Canyon Formation Andesite	Willow Canyon Formation Andesite	Willow Canyon Formation Arkose	Willow Canyon Formation Arkose	Horquilla Limestone	Horquilla Limestone	Glance Conglomerate	Glance Conglomerate
Test	MWMP	SPLP	MWMP	SPLP	MWMP	SPLP	MWMP	SPLP
Calcium	20.3	204	14.3	114	28.2	944	8.69	100.2
Magnesium	4.72	28.1	2.43	15.0	2.90	47.4	0.88	52.2
Sodium	15.8	89.1	15.4	97.3	10.82	42.6	5.29	16
Potassium	12.9	107	5.20	57.2	4.68	21.2	0.83	42.8
Sulfate	62.4	357	33.6	89.1	28.2	2200	6.34	28
Chloride	3.09	11.5	4.05	17.2	24.4	46.8	0.88	17.6
Fluoride	1.03	5.78	0.79	5.3	1.09	10.2	0.17	2

C6.0 REFERENCES

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ILLUSTRATIONS

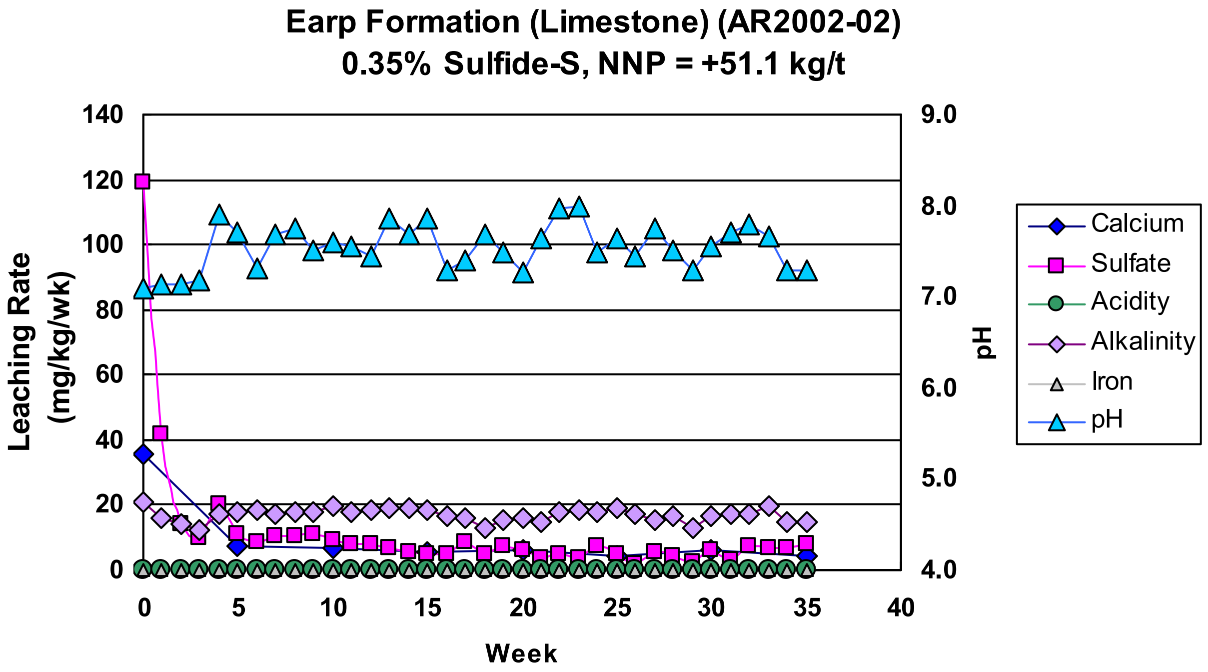

Illustration C1 Humidity Cell Test Results for Sample AR2002-02

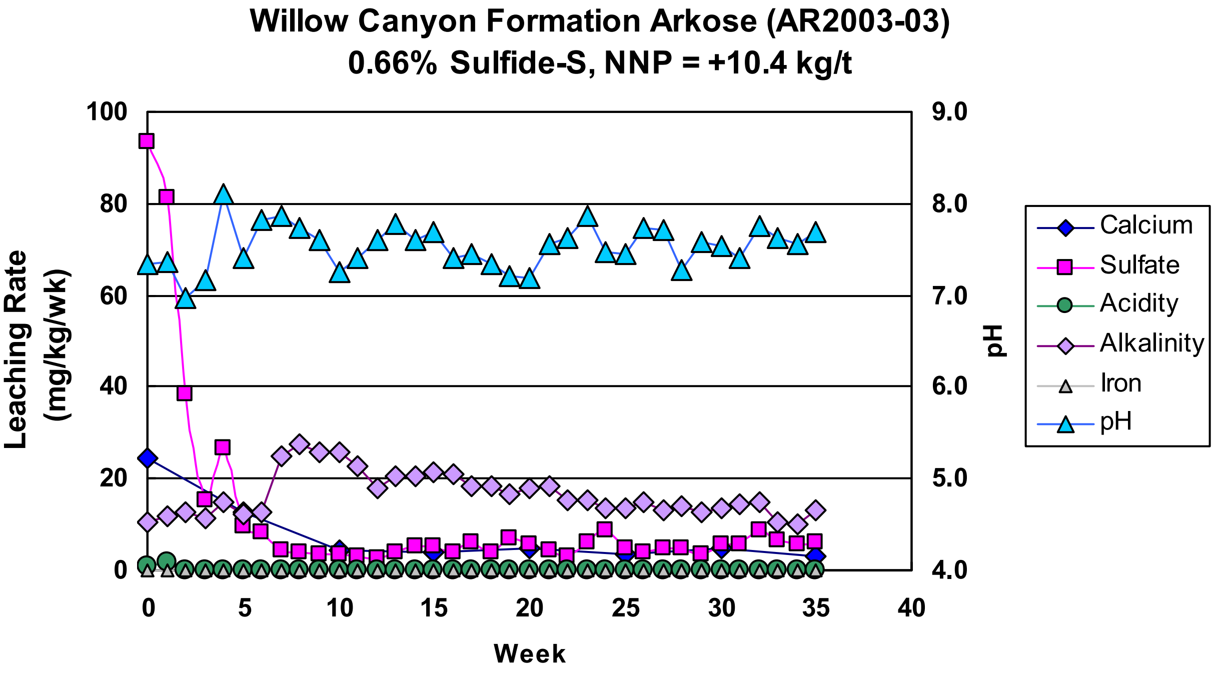

Illustration C2 Humidity Cell Test Results for Sample AR2003-03

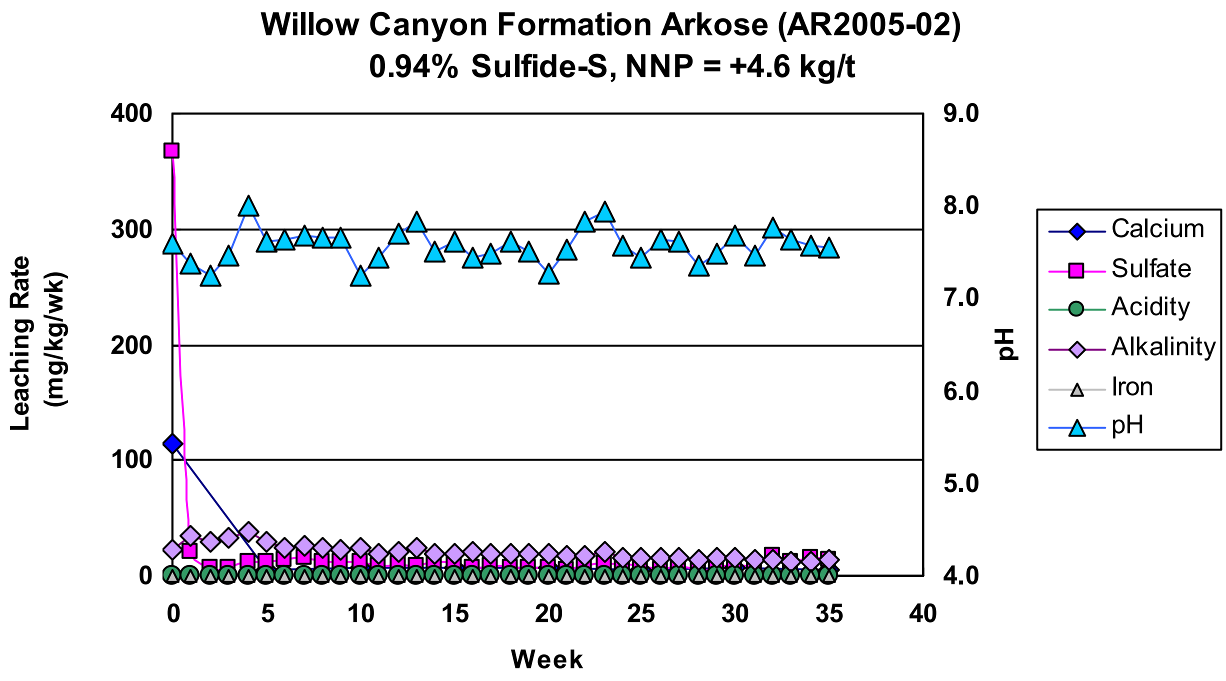

Illustration C3 **Humidity Cell Test Results for Sample AR2005-02**

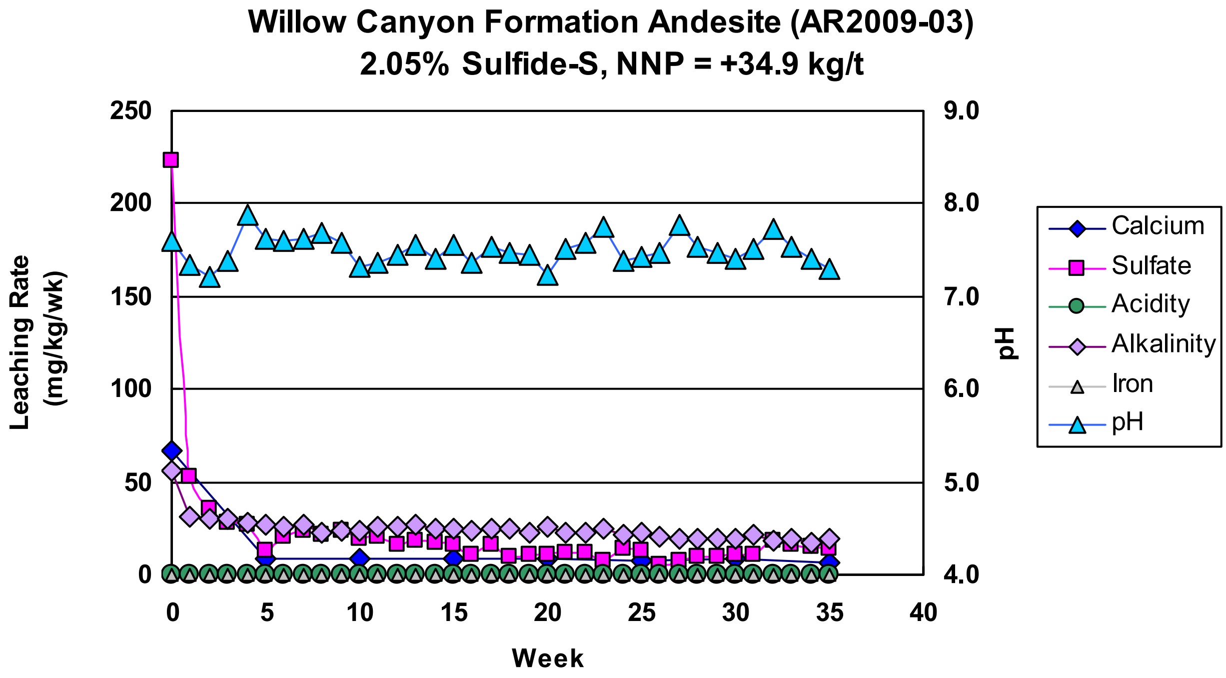

Illustration C4 **Humidity Cell Test Results for Sample AR2009-03**

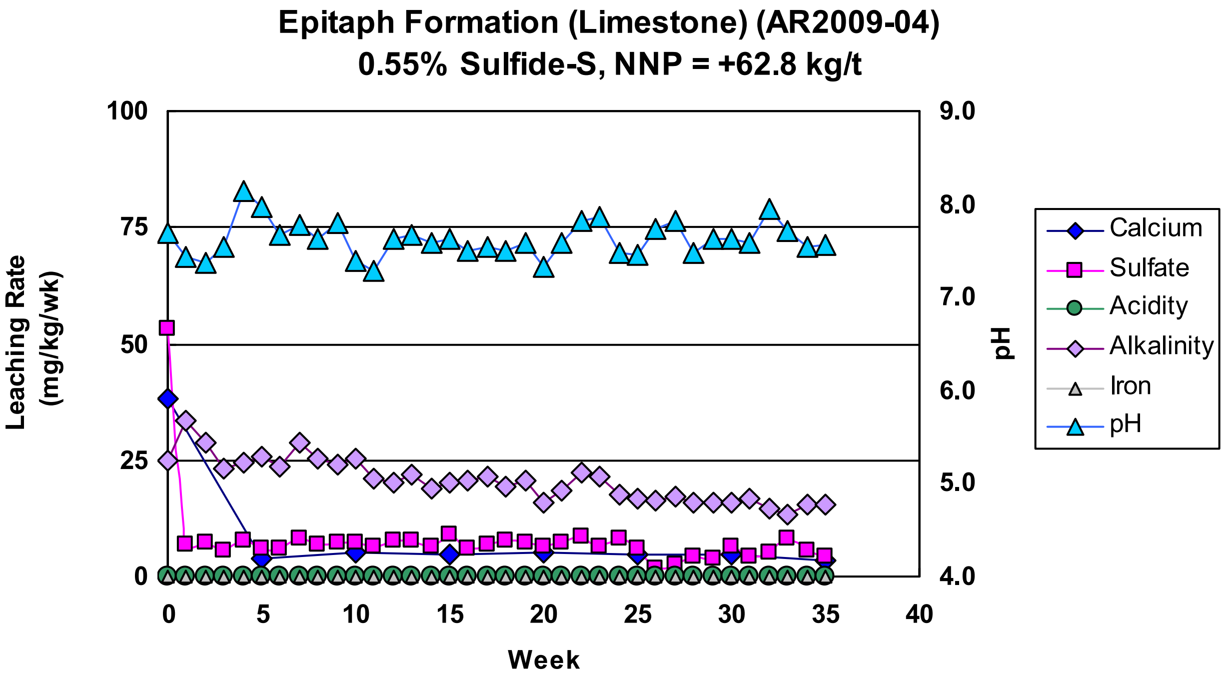
Epitaph Formation (Limestone) (AR2009-04)
0.55% Sulfide-S, NNP = +62.8 kg/t

Illustration C5 **Humidity Cell Test Results for Sample AR2009-04**

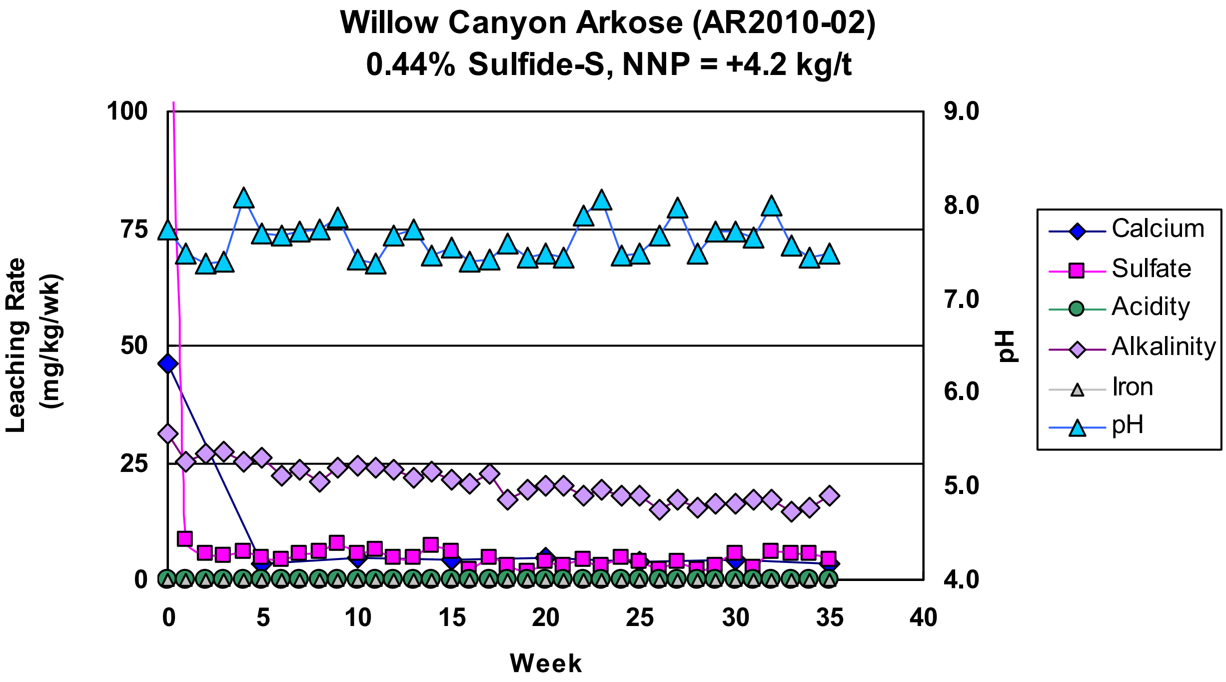
Willow Canyon Arkose (AR2010-02)
0.44% Sulfide-S, NNP = +4.2 kg/t

Illustration C6 **Humidity Cell Test Results for Sample AR2010-02**

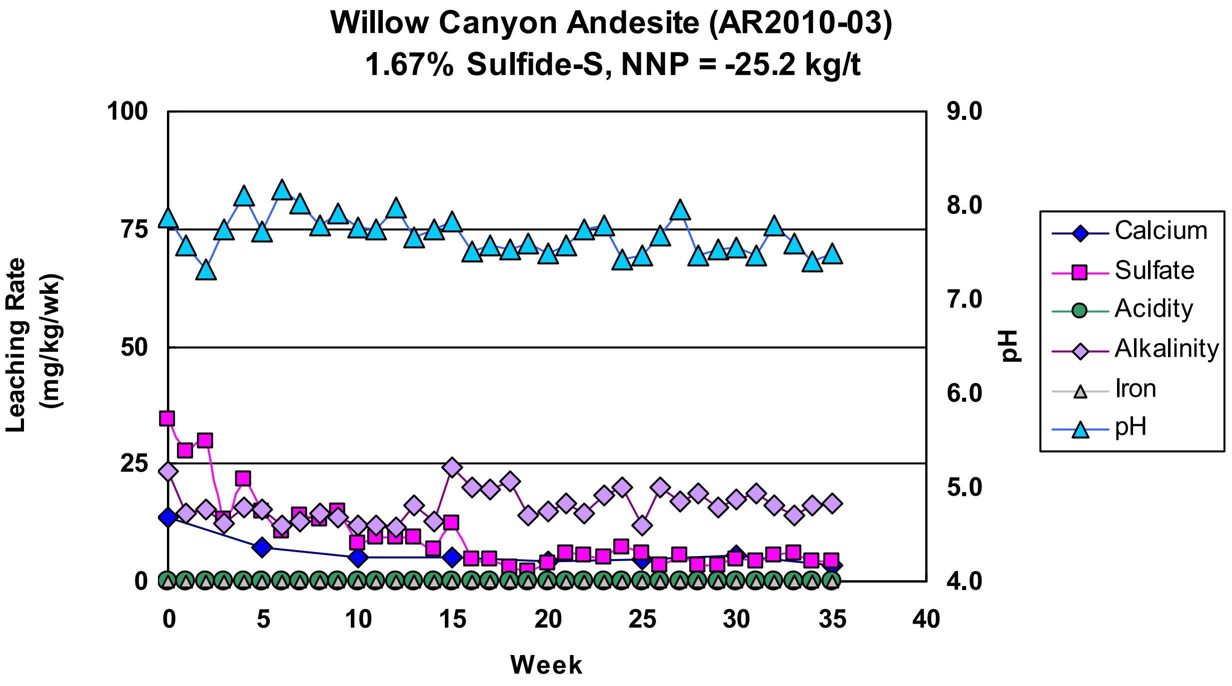

Illustration C7 **Humidity Cell Test Results for Sample AR2010-03**

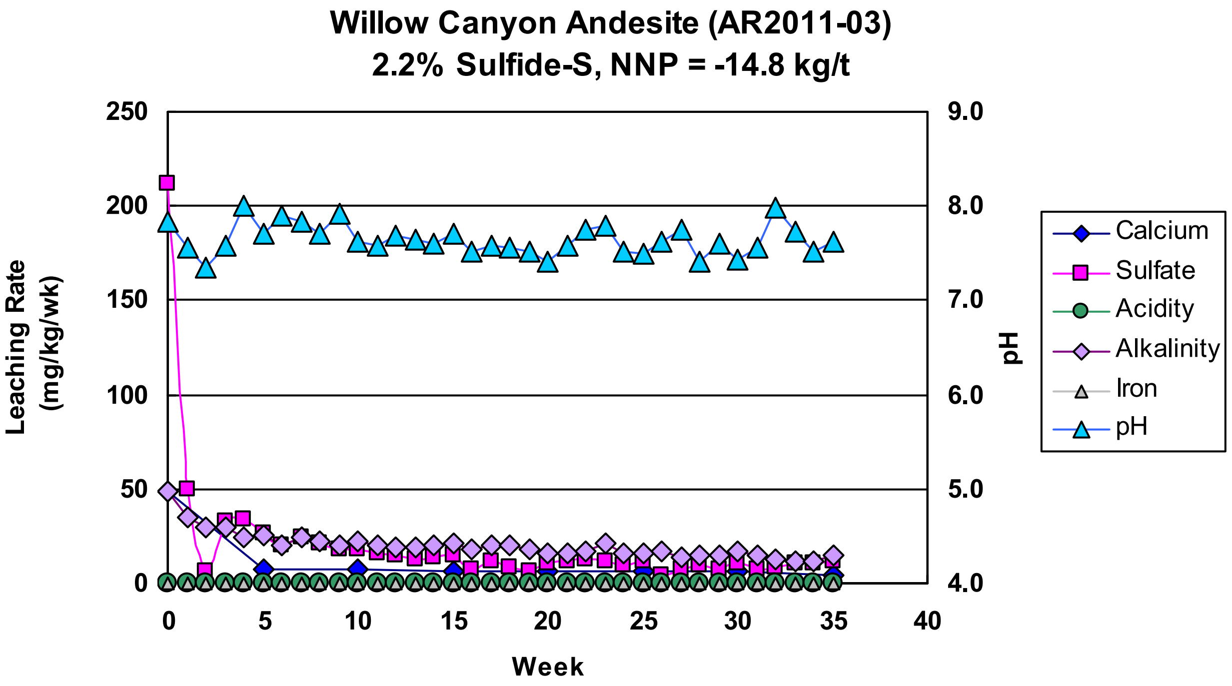

Illustration C8 **Humidity Cell Test Results for Sample AR2011-03**

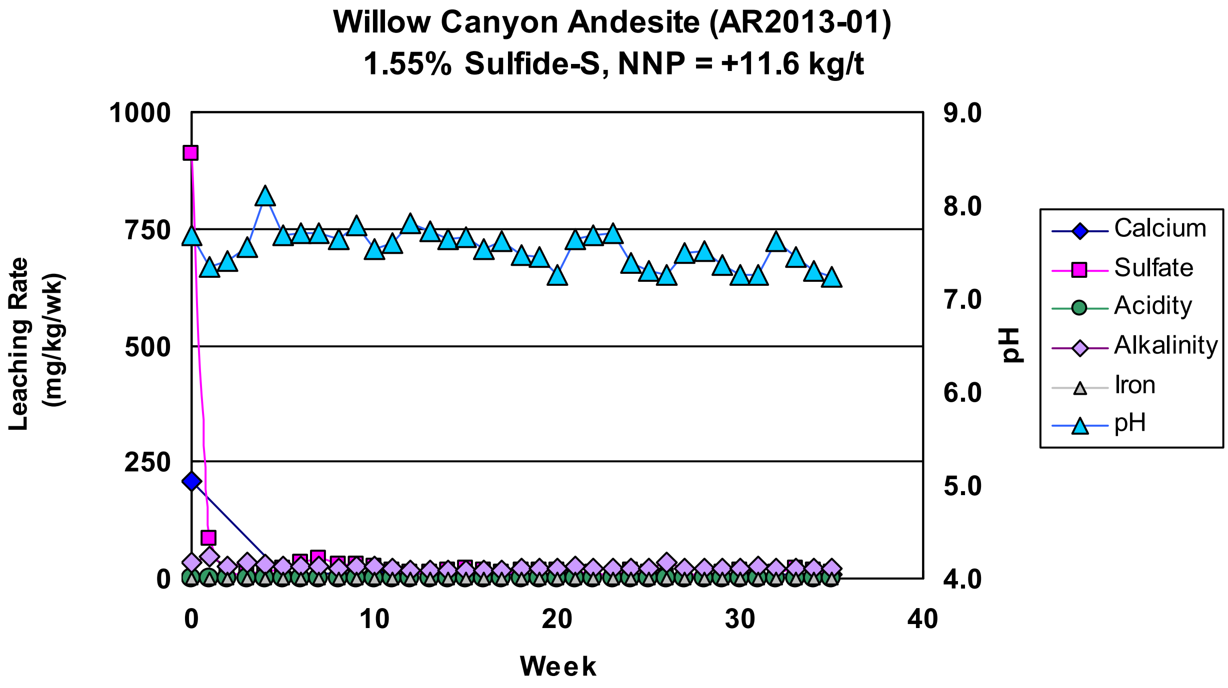

Illustration C9 Humidity Cell Test Results for Sample AR2013-01

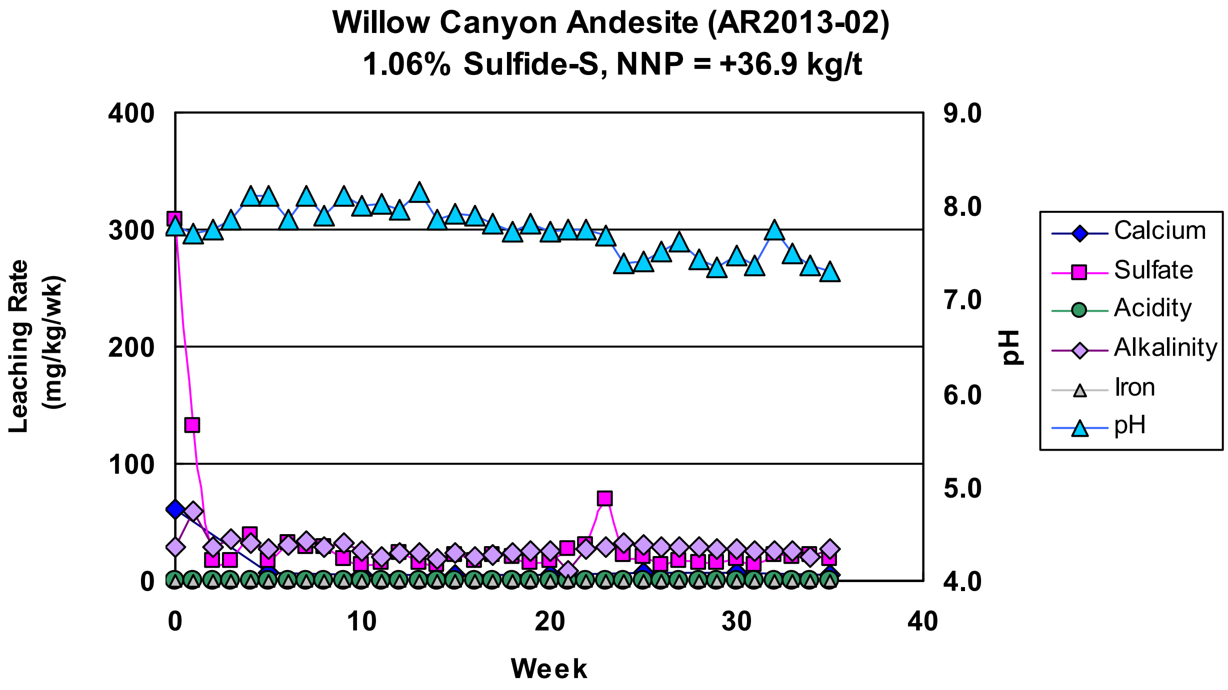

Illustration C10 Humidity Cell Test Results for Sample AR2013-02

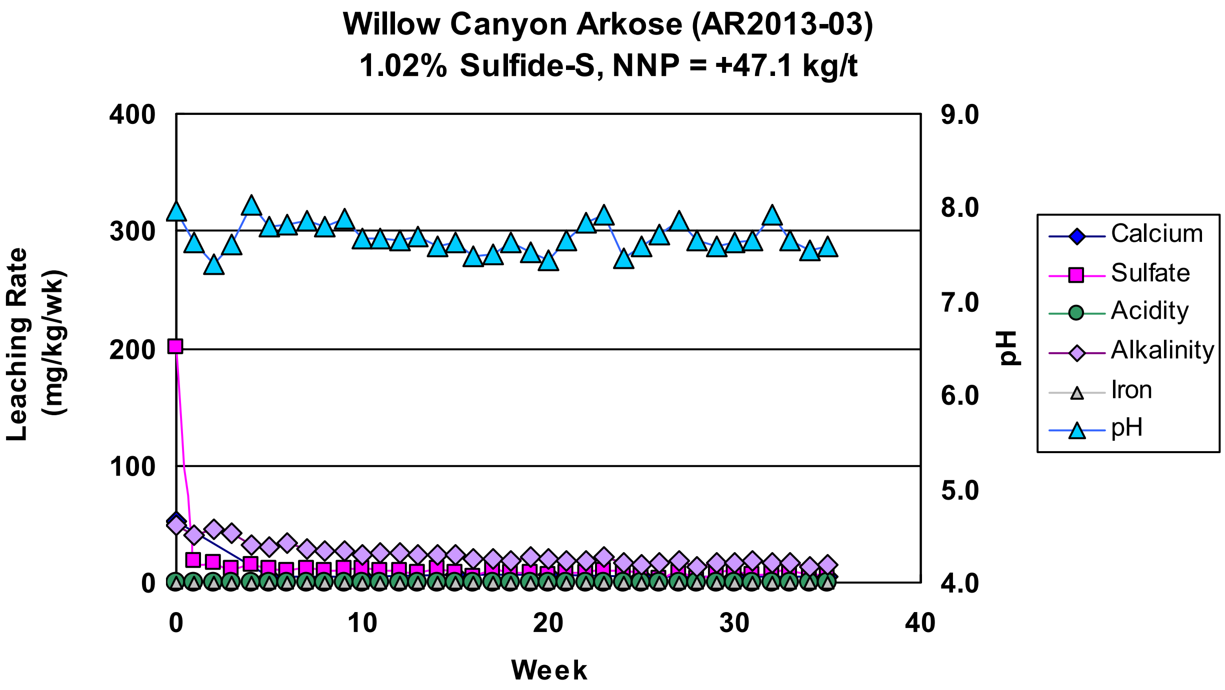

Illustration C11 **Humidity Cell Test Results for Sample AR2013-03**

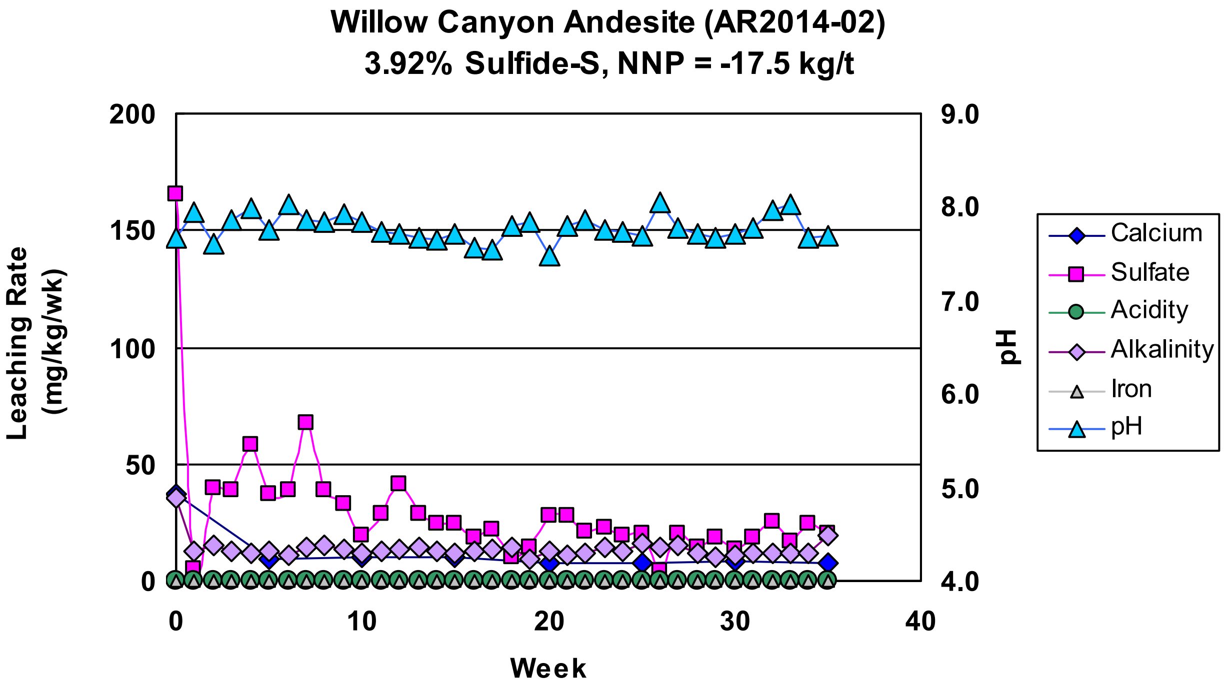

Illustration C12 **Humidity Cell Test Results for Sample AR2014-02**

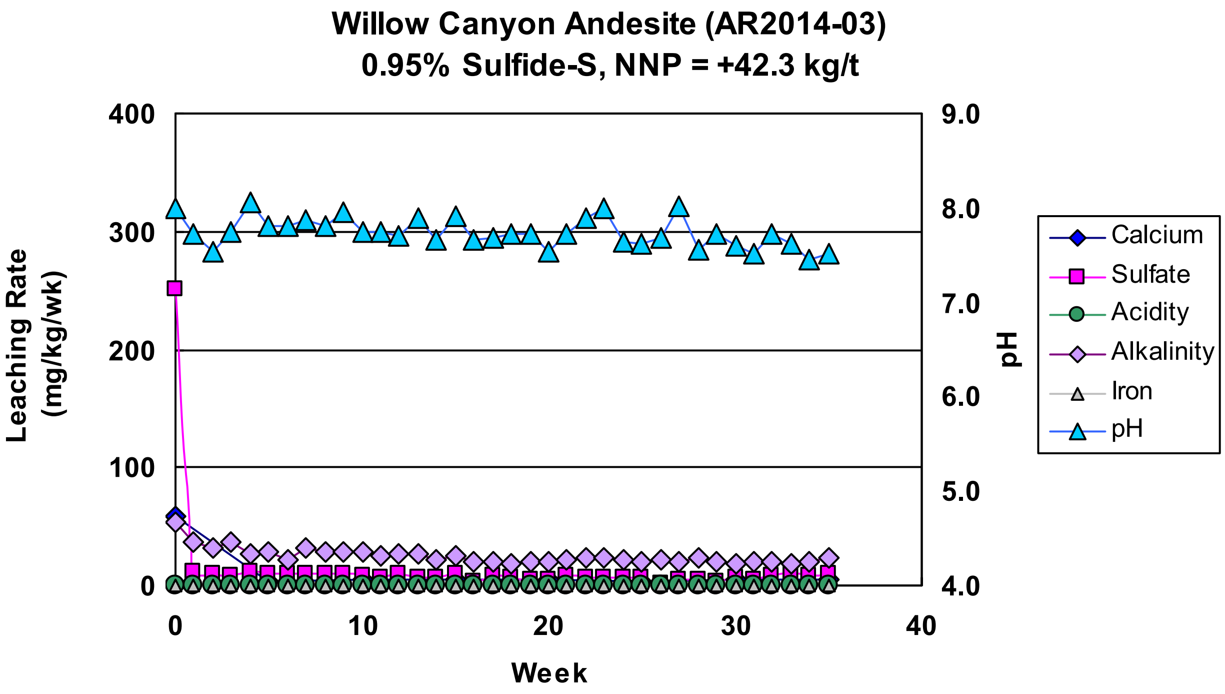

Illustration C13 **Humidity Cell Test Results for Sample AR2014-03**

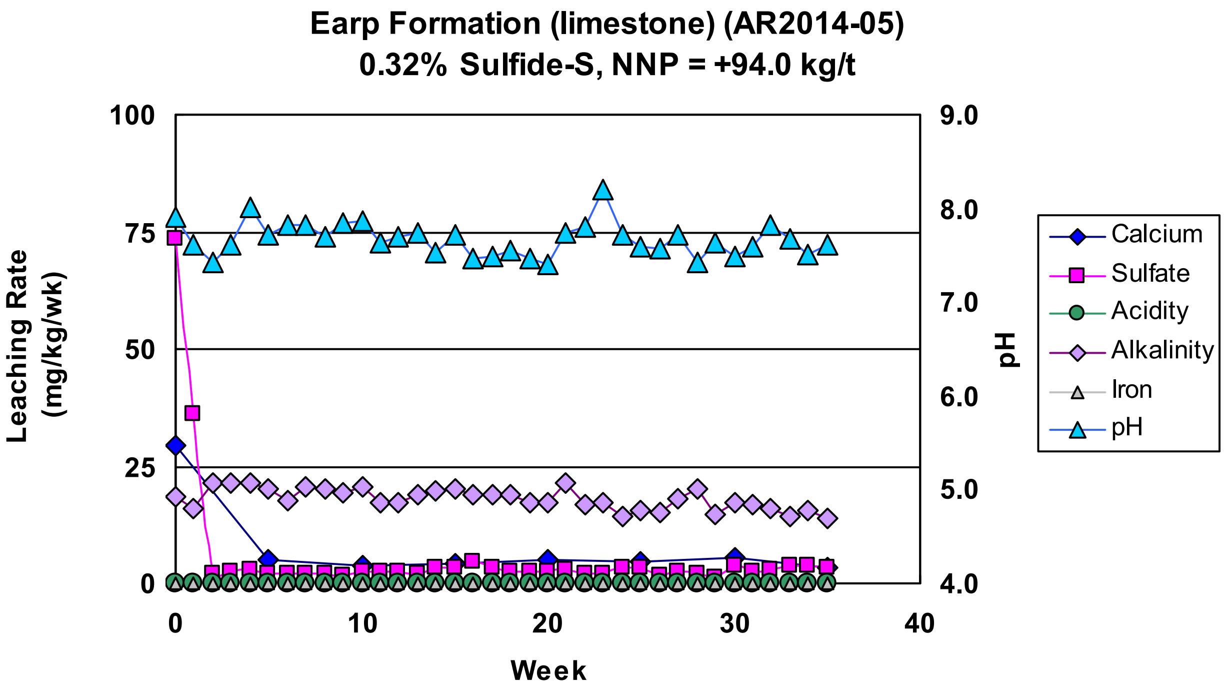

Illustration C14 **Humidity Cell Test Results for Sample AR2014-05**

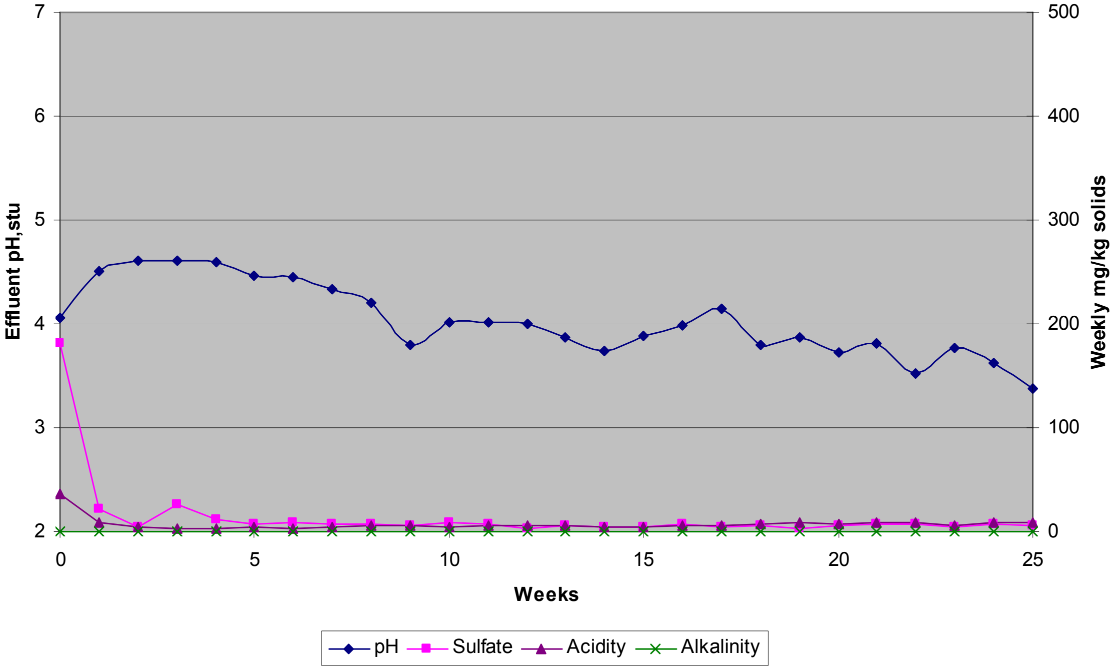

Illustration C15 **Humidity Cell Test Results for Sample A780-02 Bolsa Composite**

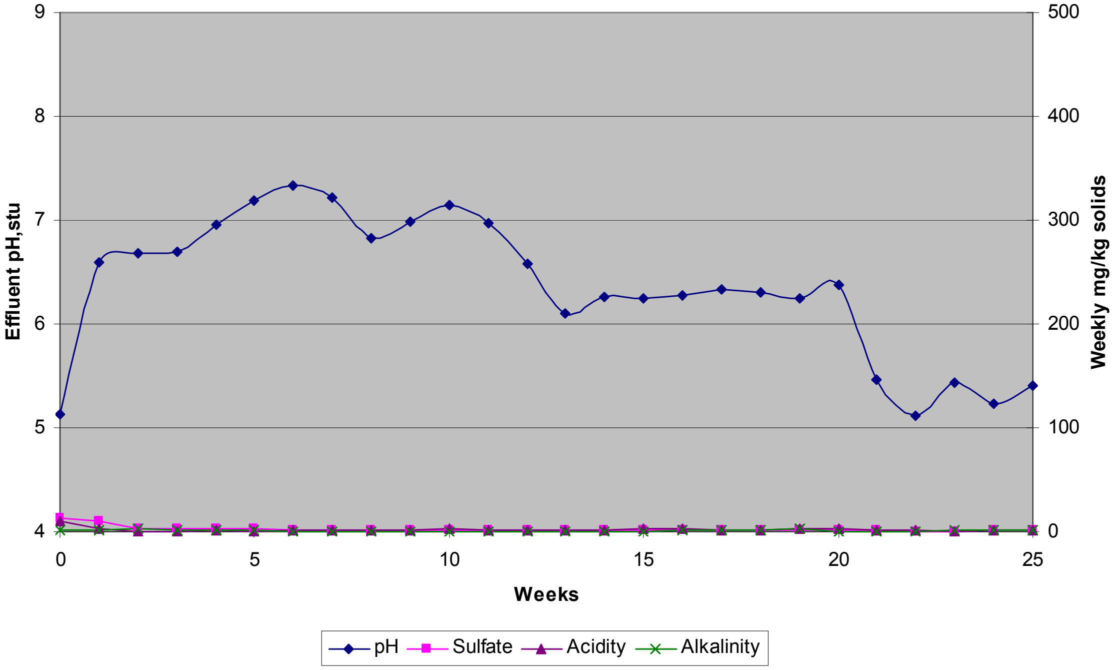

Illustration C16 **Humidity Cell Test Results for Sample A780-03 Bolsa Composite**

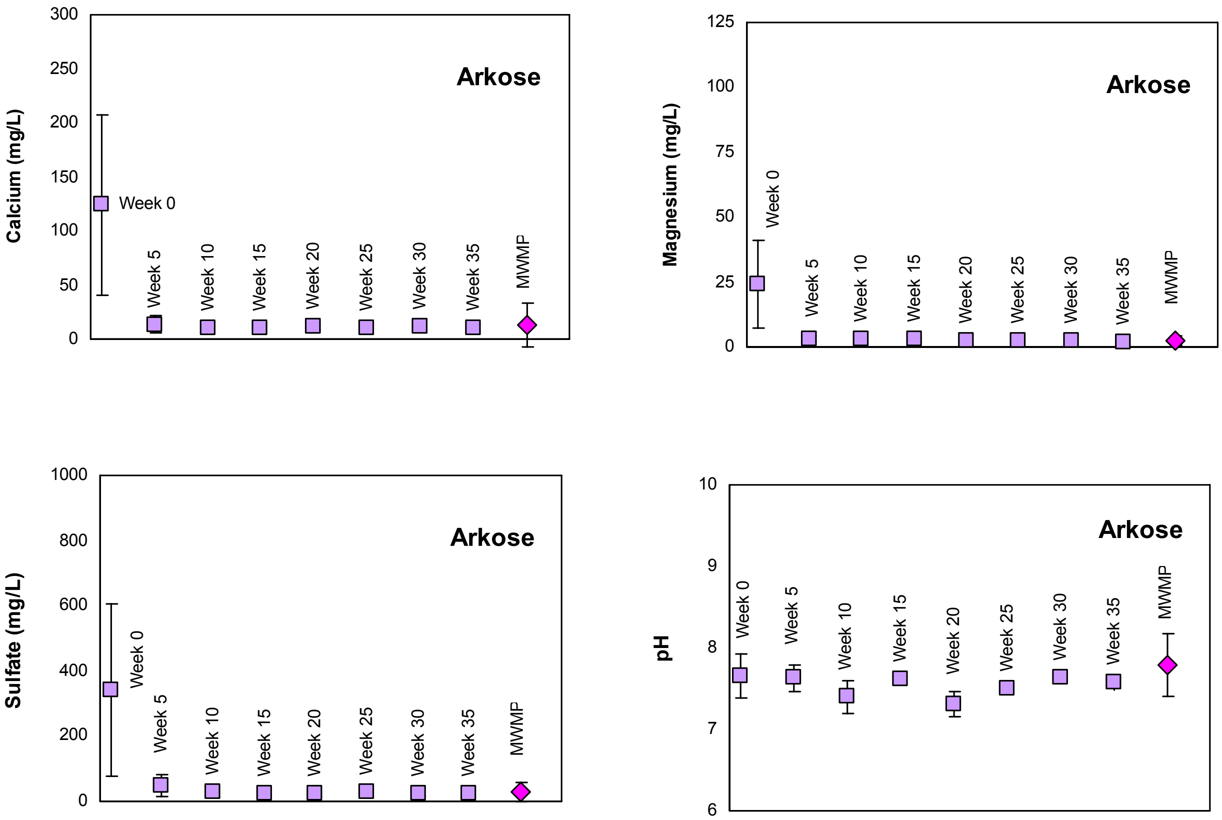

Illustration C17 **Comparison of Major Ion and pH Data from Willow Canyon Arkose HCT and MWMP Testing**

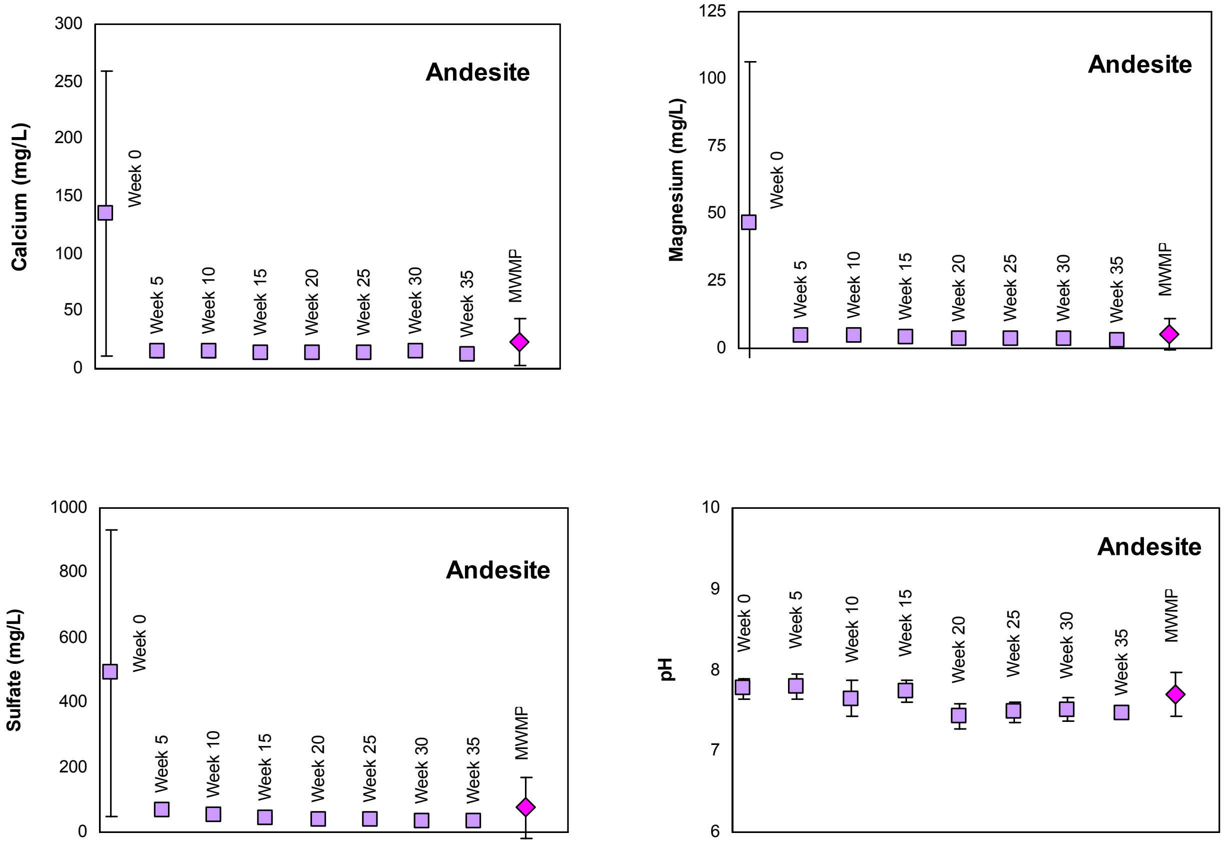

Illustration C18 **Comparison of Major Ion and pH Data from Willow Canyon Andesite HCT and MWMP Testing**

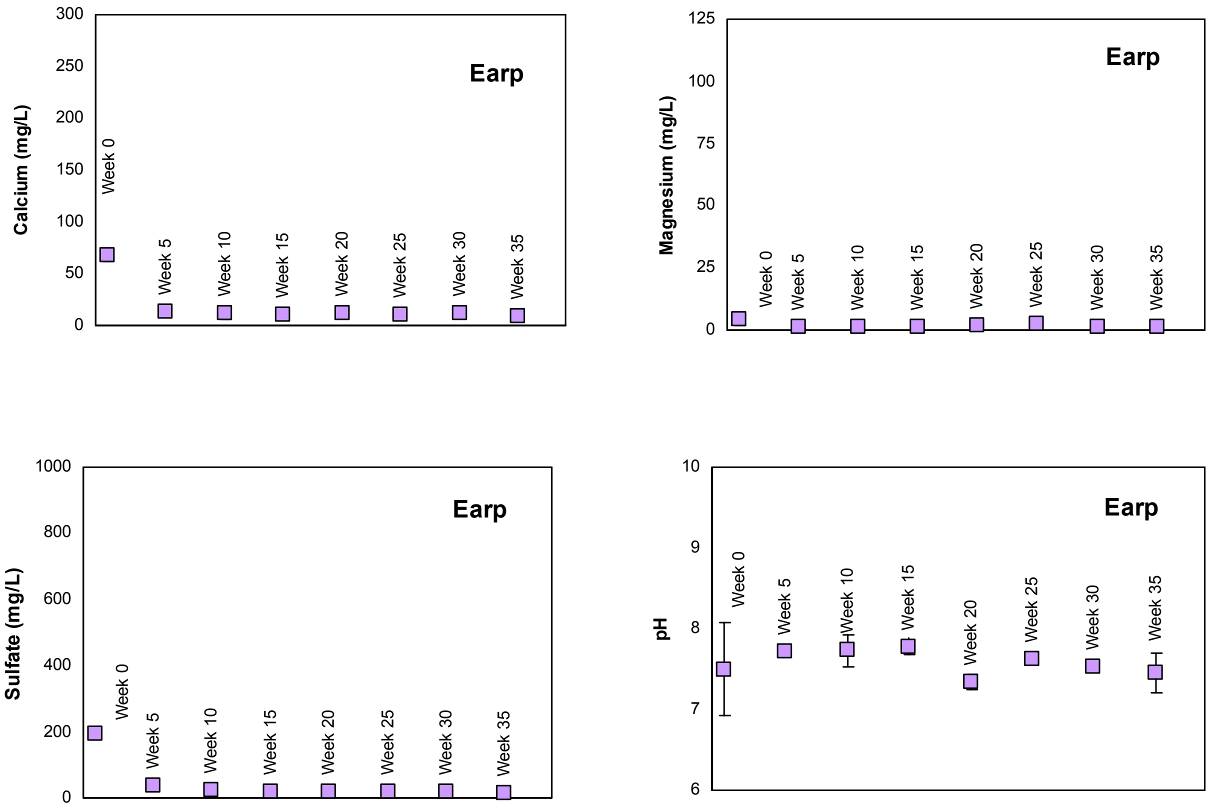

Illustration C19 Selected Major Ion and pH Data from Earp Formation (Limestone) HCTs