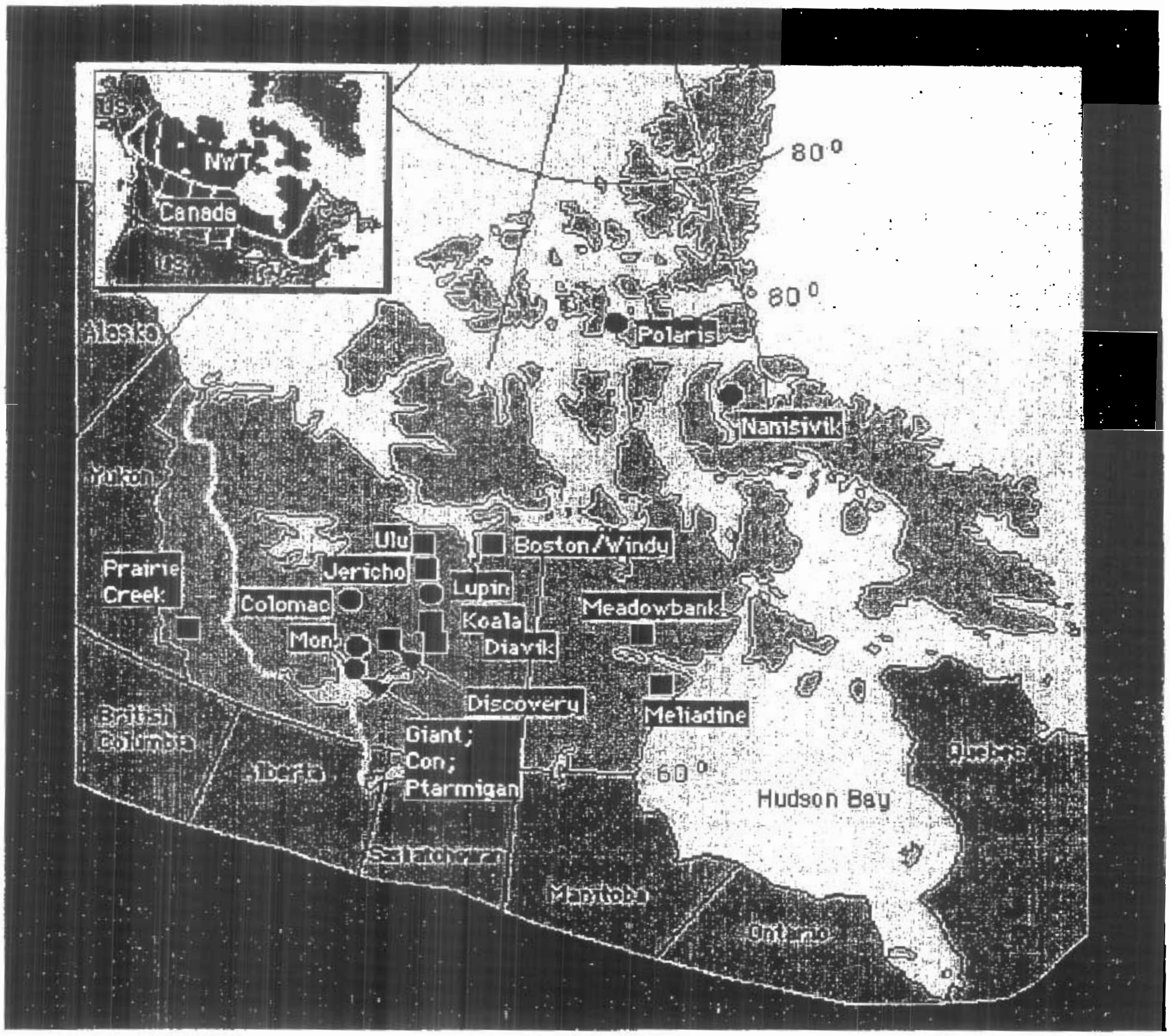


Figure 1 Location of the Ulu property with respect to Lupin Mine

These contentions, however, require validation by kinetic testing. Furthermore, geochemical kinetic tests will help to identify potential metal contamination problems early in the mining phase so that appropriate remedial schemes can be devised to reduce or eliminate the environmental risks. Thus, EBM-Lupin has retained Klohn-Crippen Consultants to design and conduct a kinetic test program with three primary goals as follows:

1) To validate ARD predictions based on geochemical static test data;
2) To demonstrate, where appropriate, that the local climatic conditions justify less conservative criteria for classifying potentially acid-generating material; and,
3) To identify potential metal leaching problems associated with the Ulu Project, if any.

1.2 Scope of Work

In consultation with environmental personnel at EBM-Lupin, a simulated weathering program involving humidity-cell testing of sulfide-rich (>1% total-S) material from Ulu under two temperature settings in the laboratory and under field conditions was designed. Both the laboratory and field columns have been run for 40 weeks. This report describes the details of the test work, documents the data obtained and discusses their implications. Where appropriate, supplementary data collection as the Ulu Project progresses is suggested.

2. METHODOLOGY

The detailed setup of laboratory humidity cells and field columns are described in the next two sections. All test materials used in the investigation originated from the Flood Zone of the Ulu deposit, where most recent exploration has been focused and where initial mining development will probably commence. The ore sample was made up of the +1.5 mm fraction of a 44 kg composite grading 0.25 oz/t Au and crushed to -6 mesh. The original sample was collected by EBM-Lupin geologists at the 25 m Level of the V5/V6 system. The tailings sample consisted of the -1.5 mm fraction of the same sample, which accounted for about 16% by weight of the composite. The waste rock subjected to kinetic testing was comprised of two parts by weight of Ulu-ARD-1 and one part by weight of Ulu-ARD-3, both of which were basalt and previously collected for preliminary ARD assessment from the Ulu site (Klohn-Crippen Consultants Ltd., 1996). All the test samples were fully characterized with respect to their geochemical composition (major and trace elements) and acid-base-accounting properties before and after the testing. The mineralogy of the test samples was also determined by petrographic examination prior to weathering.

2.1 Laboratory Humidity-Cell Testing

Two sets of humidity-cell experiments were conducted in the laboratory to assess the weathering behaviour of geologic materials from Ulu.

For weathering at room temperature (22 ± 2°C), a 2-kg subsample of each of the prospective ore, waste rock and tailings from Ulu was placed in a custom-made cylindrical cell as shown in Figure 2. Following an initial flush with 500 mL of deionized distilled water, the cell contents were subjected to enhanced weathering by pumping humid air through the cells. The test samples were flushed weekly with of de-ionized distilled water. The duration of flushing was about an hour for the ore and waste rock cells and two hours for the tailings cell. The weekly leachates were analyzed for pH, conductivity, Eh, sulfate, acidity, alkalinity and dissolved metals. To reduce the analytical costs, the weekly leachates were combined every other week after Weeks 20 prior to submission for analysis. The final rinse was conducted 10 weeks after the termination of humidity-cell testing to determine the influence of antecedent drying on leachate chemistry.

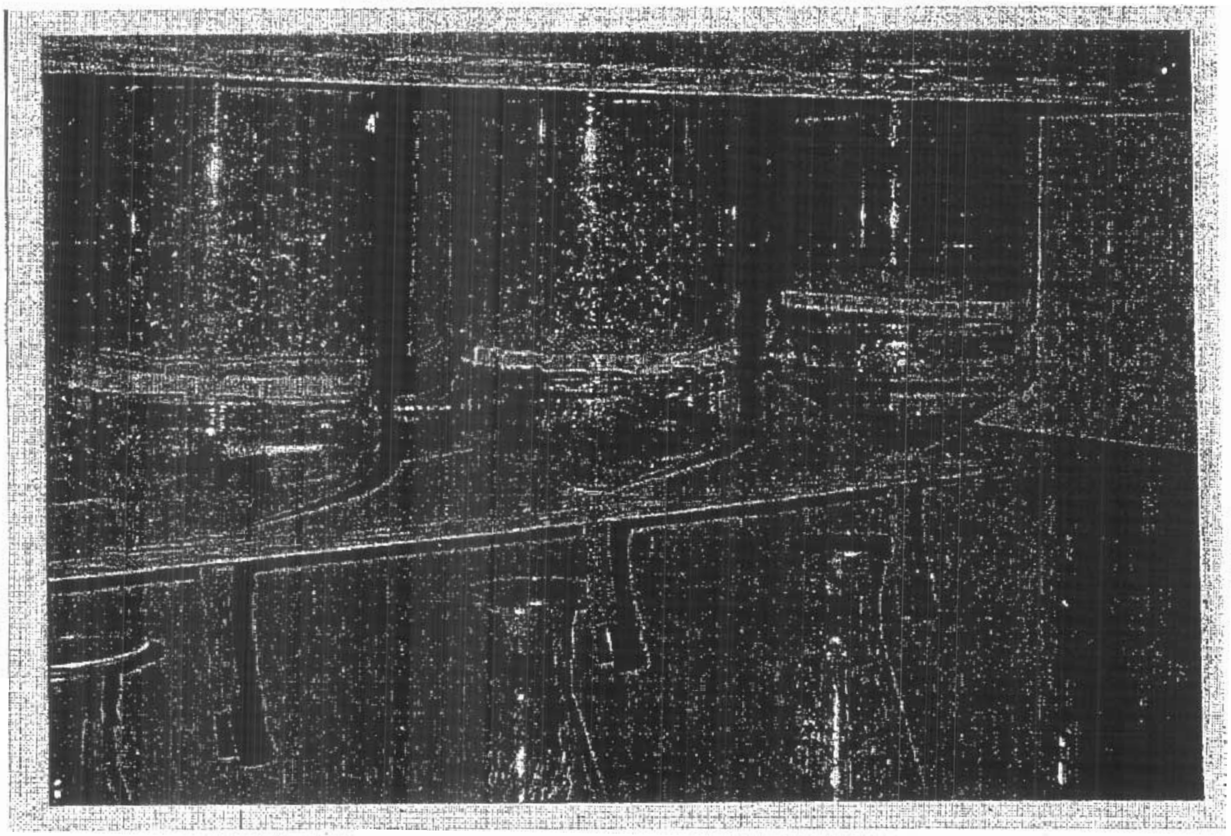


Figure 2 A photograph showing the room-temperature humidity cell setup.

For low temperature (4 ± 1°C) weathering, a duplicate cell each of Ulu ore and waste rock was set up and run inside a refrigerator. The frequency of leachate collection and analysis was the same as that of the room-temperature weathering experiment. The room-temperature experiment represents the worst-case scenario for weathering of the Ulu material. A comparison of the results of the two sets of humidity-cell experiments will demonstrate the influence of temperature on acid generation and metal leaching.

2.2 Field Column Setup

To validate predictions based on laboratory test results and to assess the geochemical stability of prospective Ulu ore stockpiles under field conditions, two field columns each containing a 15-kg subsample of the ore composite was installed in an open area near the termination of the winter road at Lupin. Each field column consisted of two staggered 18-L plastic pails. The upper pail with a perforated bottom contained the 15-kg test sample and the lower pail served as a leachate collector. The system was held upright in a slot in a broad-base wood frame made up of two pallets tied together with iron wire. Instructions on column ~~maintenance and leachate collection~~ (Appendix II) were communicated to EBM-Lupin environmental personnel who were responsible for the respective tasks.

3. RESULTS AND INTERPRETATION

The raw data on pre- and post-weathering material characterization and the leachate chemistry for each of the laboratory and field columns are given in Appendix III. Salient observations pertaining to the Ulu ore, waste rock and tailings are summarized below:

3.1 Material Characterization

The geochemical properties of the test samples, including major and trace element composition and the acid-base accounting (ABA) characteristics, were determined both prior to and after the humidity-cell testing. Owing to the inherent limitation of petrographic examinations (i.e. large margin of error for quantitative analysis), the mineralogy of the test composite was assessed only prior to the testing.

3.1.1 Mineralogy

The mineralogy of the test composites are summarized in Table 1 while the detailed petrographic descriptions are given in Appendix III. Since the ore and tailings samples represent the different size fractions of the same bulk sample, it is not surprising to find the two composites having a similar mineralogical composition. However, there are significant differences in mineralogy between the ore and waste rock composites. The ore composite contains more quartz and biotite and less hornblende and plagioclase than the waste rock. Although the total sulfide content of the two composites is similar (i.e. within the error of visual estimates), pyrrhotite and arsenopyrite are the dominant sulfide minerals in the ore composite while pyrite predominates in the waste rock tested. All sulfides are fresh and carbonate is rare in all of the test composites.

Table 1 **Mineralogy of the Ulu ore, waste rock and prospective tailings used in humidity-cell testing**

Ulu ore	*Ulu waste rock*	*Prospective tailings*
25% quartz	15% quartz	22% quartz
20% plagioclase	28% plagioclase	25% plagioclase
1% K-feldspar	40% hornblende	1% K-feldspar
28% hornblende	5% biotite	28% hornblende
12% biotite	trace sericite	14% biotite
4% sphene	2% epidote	trace pyroxene, garnet
5% ilmenite	trace chlorite	trace epidote
0.5% carbonate	2% magnetite	2% sphene
2% pyrrhotite	3% ilmenite	2% ilmenite
2% arsenopyrite	2% rutile + sphene	0.5% carbonate
0.5% pyrite	2.5% pyrite	2% pyrrhotite
trace chalcopyrite	0.5% pyrrhotite	2% arsenopyrite
		1% pyrite
		trace chalcopyrite

3.1.2 Geochemistry

The ABA characteristics and the major and trace element composition of the test samples prior to and after the humidity-cell testing are compared in Table 2. The ABA data confirms the overall low carbonate content and the freshness of the sulfide minerals in the test samples. However, the tailings appears to contain more carbonates than the coarser-grained ore and waste rock composites. The abundance of hornblende in the waste rock composite is supported by the relative enrichment in Al_2O_3, CaO and MgO content and the paucity of arsenopyrite by the low As content for the waste rock. The gold mineralization is apparently associated with silicic and potassic alteration (in the form of quartz, biotite and K-feldspar) as reflected by the relative enrichment of K_2O and SiO_2 in the ore and tailings composites. The latter composites, as mentioned before, are derived from the same bulk ore sample.

Changes in geochemical composition as a result of the simulated weathering are, however, generally within the measurement errors of the analytical methods used in determining the various parameters. Thus, the consequence of weathering is better assessed by the evolving leachate chemistry than by changes in the geochemical composition of the test samples. A repeat analysis of the test samples suggests that the discrepant As analyses for the Ulu ore and waste rock samples (Table 2) are largely due to sample heterogeneity with respect to As distribution.

Table 2 A comparison of pre- and post-test sample characterization data

a) ABA data

Sample #	Paste pH	%Total S	Sulfate-S %	Acid Pot. kg/t CaCO3	Neut. Pot kg/t CaCO3	NNP kg/t CaCO3	NP/AP	Carb-NP kg/t CaCO3
B1, Ulu ore								
Pre-test	8.70	1.14	<0.01	35	32	-3	0.9	6
Post-test @4 deg.C	9.21	1.14	<0.01	35	31	-4	0.9	5
Post test @ room T	8.97	1.22	<0.01	38	25	-13	0.7	5
B2, Ulu waste rock								
Pre-test	9.32	1.17	<0.01	36	28	-8	0.8	4
Post-test @4 deg.C	9.31	1.19	<0.01	37	28	-9	0.8	6
Post test @ room T	9.16	1.17	<0.01	36	25	-11	0.7	4
B3, Prospective tails								
Pre-test	8.12	1.63	<0.01	51	49	-2	1.0	9
Post test @ room T	8.56	1.55	<0.01	48	45	-3	0.9	8

b) Geochemistry

Sample #	% Al2O3	% CaO	% Cr2O3	%Fe2O3	% K2O	% MgO	% MnO2	% Na2O	% P2O5	% SiO2	% TiO2	% LOI	Total %
B1, Ulu ore													
Pre-test	11.98	6.54	<0.01	15.77	1.34	3.07	0.21	2.30	0.21	55.05	1.88	1.39	99.74
Post-test @4 deg.C	11.70	6.54	<0.01	15.98	1.33	3.23	0.21	2.39	0.20	54.60	1.87	0.72	98.77
Post-test @ room T	11.58	6.58	<0.01	15.82	1.40	3.38	0.20	2.19	0.18	54.81	1.87	0.67	98.68
B2, Ulu waste rock													
Pre-test	13.34	8.24	<0.01	14.80	0.79	5.46	0.21	2.33	0.17	50.56	1.46	1.57	98.93
Post-test @4 deg.C	13.16	8.40	<0.01	14.96	0.69	5.56	0.22	2.49	0.16	50.43	1.44	1.56	99.07
Post-test @ room T	12.99	8.17	<0.01	15.01	0.74	5.58	0.22	2.56	0.19	50.22	1.47	1.65	98.80
B3, Prospective tails													
Pre-test	10.48	5.91	<0.01	15.30	1.46	2.94	0.20	2.17	0.18	56.36	1.66	2.00	98.66
Post-test @ room T	10.78	6.04	<0.01	15.71	1.35	2.94	0.20	1.97	0.19	56.45	1.69	1.28	98.65
	ppm Ag	ppm As	ppm Ba	ppm Cd	ppm Co	ppm Cr	ppm Cu	% Fe	ppm Ni	ppm Pb	ppm Sr	ppm V	ppm Zn
B1, Ulu ore													
Pre-test	<0.2	7780	90	<0.5	31	38	60	4.71	11	2	8	119	86
Post-test @4 deg.C	<1	9590	100	10	35	50	60	5.37	20	<5	10	120	65
Post-test @ room T	<1	9870	100	10	35	60	75	5.64	12	5	10	140	90
B2, Ulu waste rock													
Pre-test	<0.2	556	70	<0.5	37	59	103	4.58	36	<2	20	120	44
Post-test @4 deg.C	<1	90	80	<5	35	60	110	4.71	40	<5	20	120	40
Post-test @ room T	<1	90	80	<5	40	80	125	4.89	37	<5	20	120	40
B3, Prospective tails													
Pre-test	0.8	>10000	90	<0.5	37	47	75	5.77	13	6	12	132	84
Post-test @ room T	<1	10670	100	10	35	50	80	6.03	14	10	5	120	90

3.2 Leachate Chemistry

The humidity-cell test results are described below according to sample types. The kinetic data derived under different experimental conditions are also summarized and compared at the end of each presentation.

3.2.1 Weathering of Ulu Ore

The Ulu ore composite chosen for detailed study has been tested under three sets of conditions: laboratory humidity-cell testing at 4°C and at room temperature (22°C) and column leaching under field conditions. The time series of selected parameters measured from the leachate (pH, acidity, alkalinity, sulfate, conductivity, dissolved As and Zn) and the derived production rates for sulfate, dissolved As and Zn and the cumulative sulfate and alkali production for each scenario are depicted with corresponding figures.

Low temperature weathering at 4°C: The leachate pH has remained near neutral at a value of 7.6 ± 0.3 throughout the testing and the measured alkalinity has always exceeded acidity (Figure 3a). The dissolved sulfate concentration appears to follow a decreasing trend with time except for the final leachate of Week 40. The sulfate increase suggests the formation of efflorescence during the long antecedent drying period between Weeks 30 and 40. The efflorescence is dissolved during the final rinse which also gives rise to higher acidity and conductivity readings at Week 40. The overall sulfate release rate on a per mass basis, however, shows a prominent decreasing trend with time (Figure 3b). This reflects a continuously decreasing sulfide oxidation rate, possibly caused by coating of the reacting sulfides with oxidation products like iron oxyhydroxide.

For the leaching of trace elements, only the profiles for As and Zn are shown in Figure 3 because other trace elements were mostly undetectable except for rare excursions which could have resulted from analytical error. Both the measured dissolved As concentration and the derived As release rate decrease with the progress of the testing, suggesting a diminishing arsenopyrite oxidation rate with time. On the other hand, both the dissolved Zn content and the calculated Zn release rate appear to increase with the progress of the experiment except during the final rinse at Week 40. Given the low initial Zn content of the test sample, the apparent increase in Zn leaching could be a cumulative effect of laboratory contamination. Alternatively, if the Zn occurred as sphalerite embedded in other sulfides with a higher electrode potential (e.g., pyrite and chalcopyrite), preferential Zn leaching could have taken place as a result of galvanic interactions (Kwong, 1995). The observed decrease in Zn release during the final rinse again suggests coating of the source mineral with secondary oxidation products during the long antecedent drying period (10 weeks).

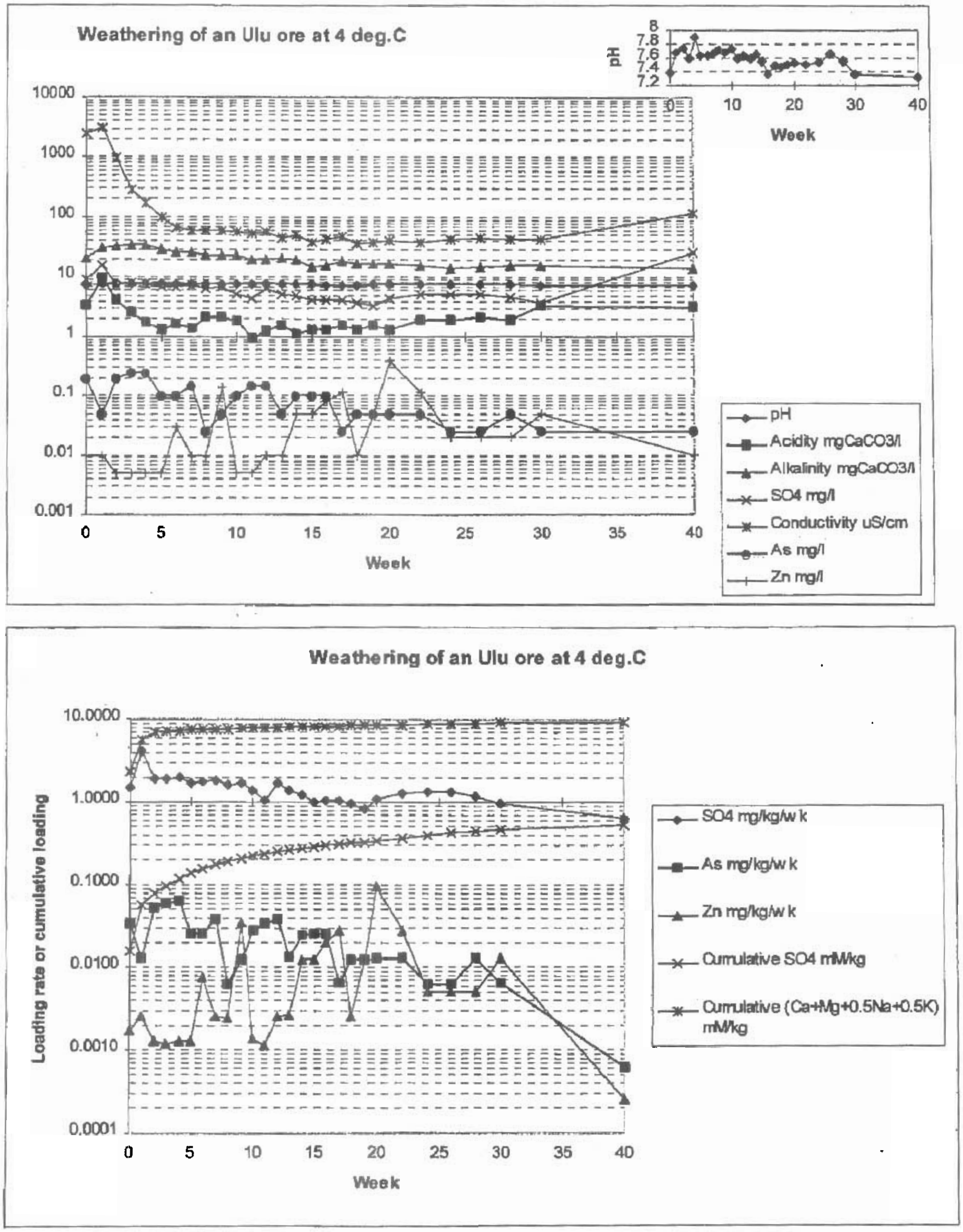
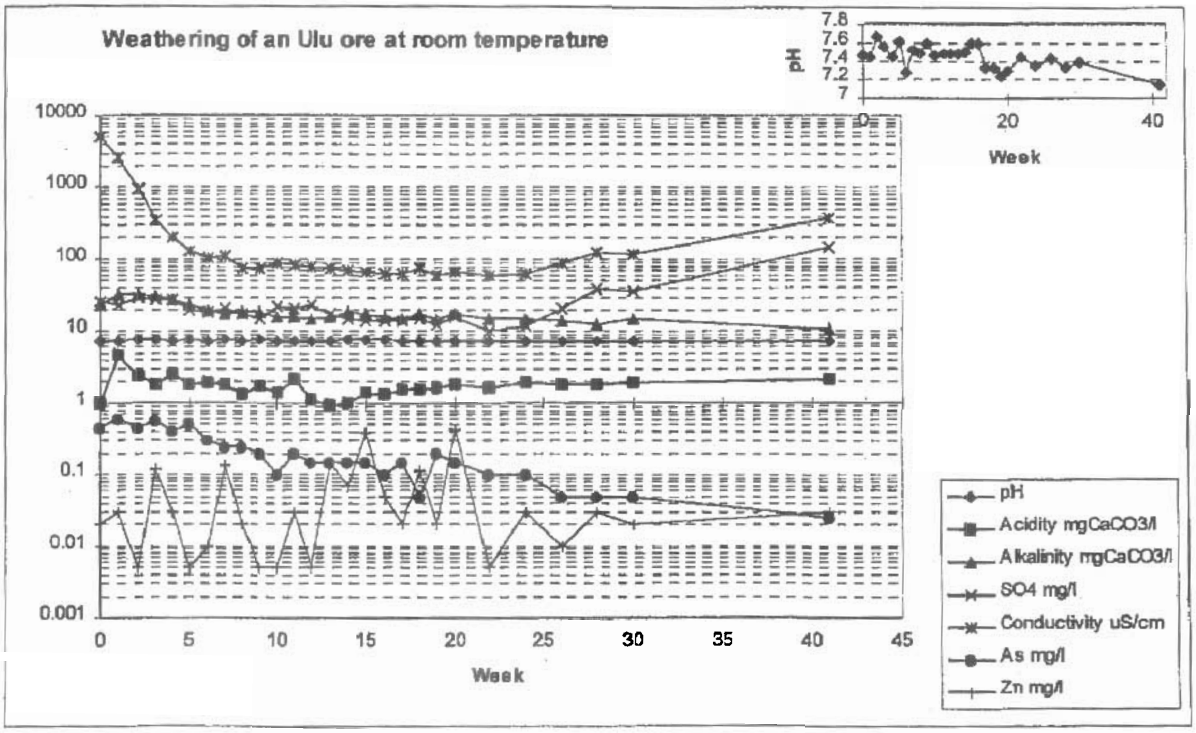


Figure 3 **Time series of selected parameters determined during humidity-cell testing of an Ulu ore at 4°C.**

Weathering at room temperature (22°C): The overall appearance of the time series for leachates collected in the room temperature experiment (Figure 4) is similar but not identical to that of the low temperature experiment. The leachate pH has remained near neutral at a value of about 7.4 ± 0.3. The dissolved sulfate concentrations initially follows a decreasing trend but reverses course after Week 26. The reason for the sudden change in sulfate release is not clear. However, the increase in sulfate concentration is accompanied by increases in measured acidity and conductivity (Figure 4a) and is therefore unlikely due to measurement errors. Nonetheless, the decrease in sulfate production rate derived from the final rinse data collected at Week 41 (Figure 4b) still supports the formation of efflorescence material during the long antecedent drying period (11 weeks).

While the net values are higher compared to those obtained in the low temperature experiment, both the leachate As concentration and the As release rate on a per mass basis decreases with the progress of the weathering simulation. On the other hand, dissolved Zn appears to follow a slowly increasing trend although the reduced release rate during the final rinse reflects coating effects with prolonged antecedent drying.



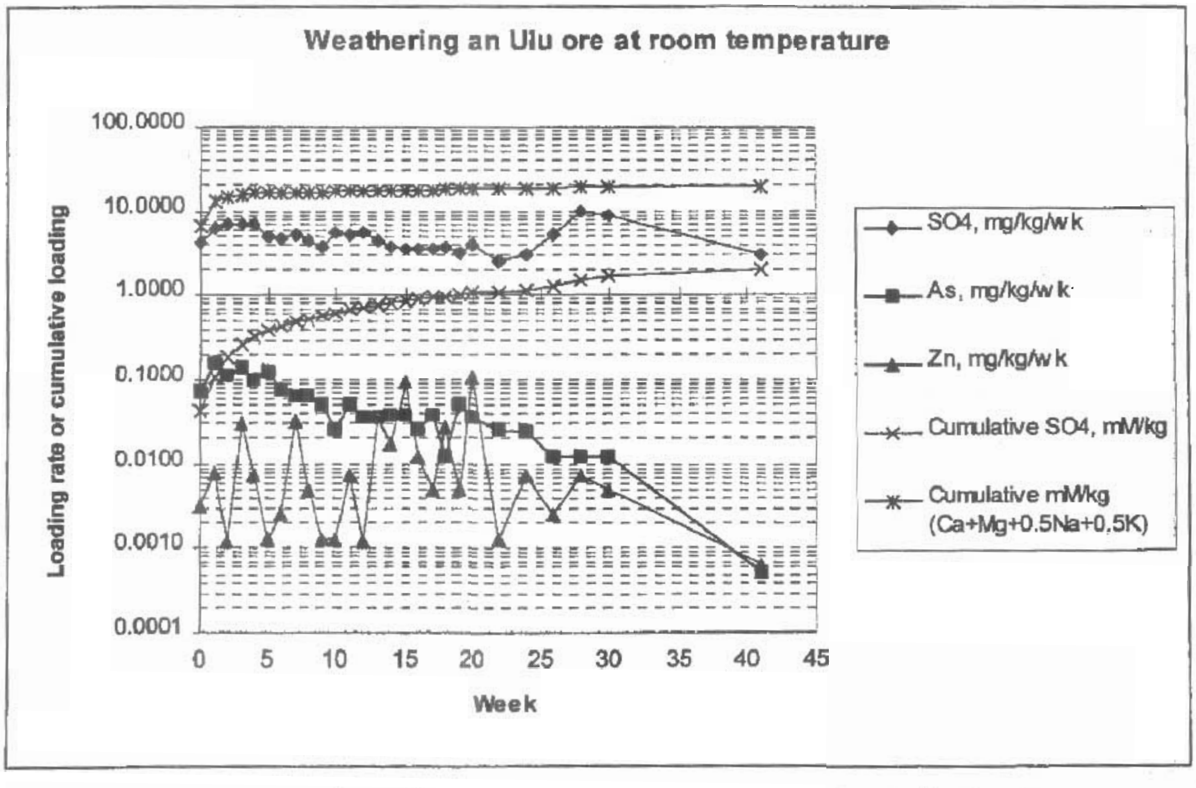


Figure 4 **Time series of selected parameters determined during humidity-cell testing of an Ulu ore at room temperature**

Column leaching under field conditions: The leachate chemistry of the two duplicate field columns are depicted in Figure 5. Since the site conditions are such that the ground remains frozen eight months of the year, it has been possible only to collect three leachate samples from each of the field columns during the thaw period from June to September. As shown in Figure 5, the two sets of leachate samples have very similar composition except possibly for the dissolved Zn concentrations, which are all close to the analytical detection limit. The leachate samples are all characterized by a near-neutral pH value of 7.6 ± 0.2 and a measured alkalinity exceeding acidity. They also show anomalous conductivity measurements ranging from 2000 to 9000 µS/cm. Correspondingly high dissolved Na concentrations (360 to 1630 mg/l) are noted in the leachate analyses (Appendix III). Apparently, salt water has been used as drilling fluid in drilling the Ulu portal for bulk ore sampling (David Hohnstein, personal communication, December, 1997). The observed high dissolved Na and conductivity in the leachate samples thus result from the leaching of adsorbed salt in the ore composite instead of in-situ weathering of the constituent minerals. A comparison with the leachate chemistry of the laboratory cells shows that the adsorbed salt is essentially leached within about five flushing events for the laboratory cells; the salt contaminant is however not completely removed in three flushing events for the field columns.

Since there are only three data points for each parameter depicted in Figure 5 and the volume of leachate collected in each sampling event is different, no apparent trends for temporal changes in leachate chemistry can be established. However, a close examination of the calculated loading rates suggests that the dissolved sulfate, As and Zn release rates on a per mass basis are considerably higher between August and September than during the rest of the year. In other words, the bulk of the sulfide oxidation could have occurred during the short summer months when the test samples are totally thawed and the air temperature is presumably at its peak.

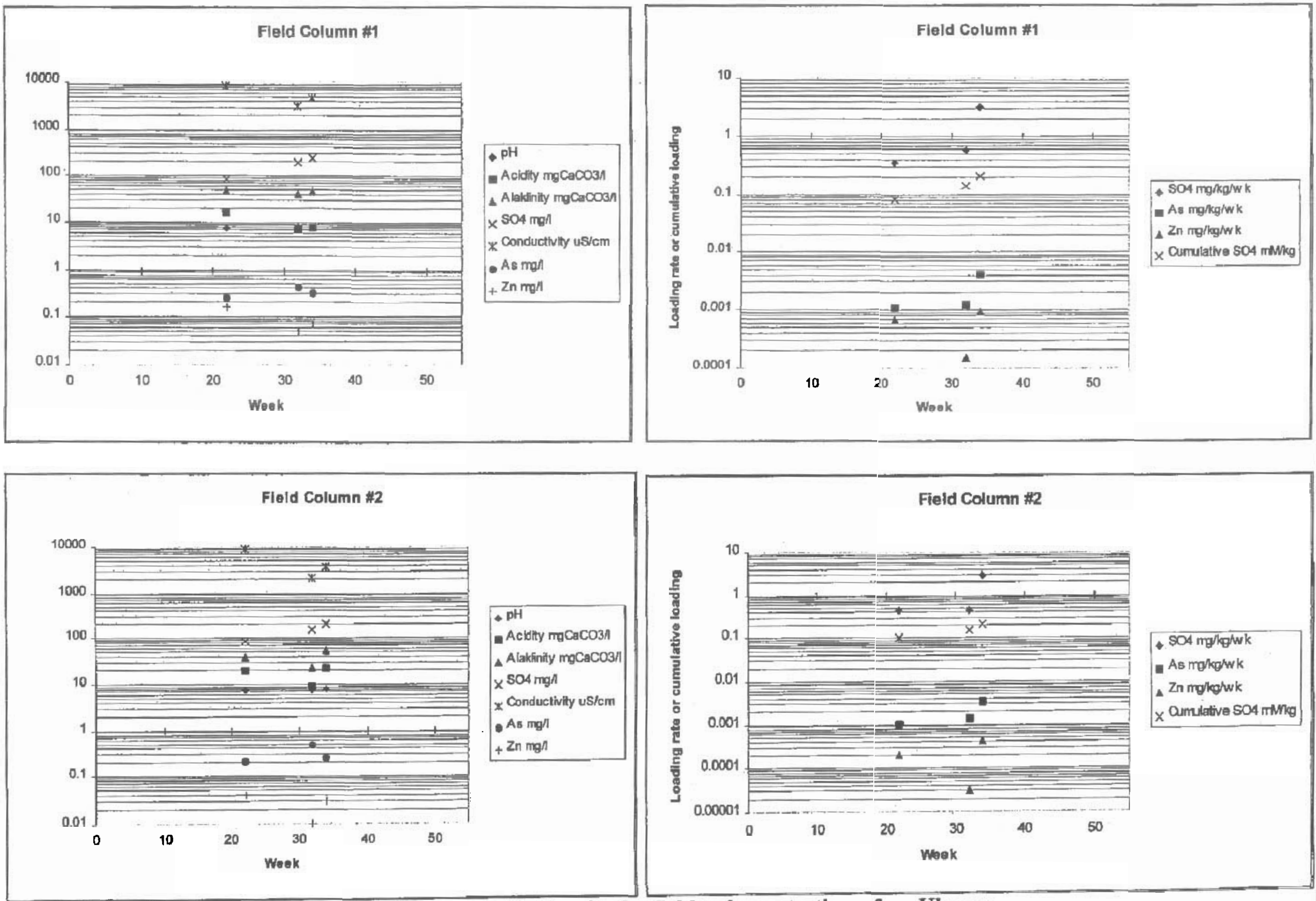


Figure 5 Variation of selected parameters with time in the field-column testing of an Ulu ore.

Comparing the results of weathering of the Ulu ore under different conditions: The consequences of weathering the Ulu ore for the three scenarios described above are compared in Table 3. For the humidity-cell testing in the laboratory, the sulfide-S depletion rate is calculated based on the average sulfate release rate measured between Weeks 10 and 30. Since the sulfate production rates appear to slowly decrease with time (Figures 3a and 4a), this may result in an underestimate of the time required to deplete all the sulfides. For the field columns, the sulfide-S depletion rate is obtained by dividing the cumulative sulfate release to date (assumed to be the yearly production) by 52 weeks. The neutralization potential (NP) depletion rate is calculated from the total weekly release, on a molar basis, of Ca+Mg+0.5Na+0.5K. The factor of 0.5 is used for Na and K because the two alkali metals can compensate only for half of the acid produced by the complete oxidation of one mole of sulfide-S. Since the ore composite has apparently been contaminated with salt water, the average of the NP depletion rates measured from Weeks 10 to 30 (when all the remnant salts have been leached) is used to estimate the time required for complete depletion of the NP available in the ore composite. The estimated time represents the lag time for net acid generation because the sample NP will be totally depleted prior to the complete oxidation of the sulfides. Since the field columns still contain remnant salts, similar calculations cannot be made for the weathering of non-sulfide minerals under field conditions.

Table 3 **A comparison of the results of weathering of an Ulu ore under different conditions**

	Humidity cell at 4°C	Humidity cell at 22°C	Field Columns #1 / #2
S depletion rate (mM/kg/week)	0.012	0.052	0.004 / 0.004
NP depletion rate (mM $CaCO_3$/kg/week)	0.060	0.116	not calculated due to remnant salt
Time for total S depletion (years)	563	132	1707 / 1726
Time for total NP depletion (years)	102	53	not calculated
As loading rate (mg/kg/week)	0.001 - 0.063 decrease with time	0.001 - 0.153 decrease with time	0.001 - 0.004 / 0.001 - 0.003
Zn loading rate (mg/kg/week)	0.0002 - 0.0961 erratic	0.0006 - 0.1061 erratic	0.0002 - 0.0009 / 0.0002 - 0.0004

From the data presented in Table 5, it is evident that the sulfides contained in the Ulu ore tested oxidize four times as fast at room temperature as at 4°C, which is in turn three times faster than sulfide oxidation under field conditions. Even at room temperature with 100% humidity and weekly flushing, the test sample will not give rise to net acid generation in at least 50 years. For the release of both As and Zn from the test composite, temperature does not appear to affect the overall loading rate as much as the removal of oxidation products by frequent flushing.

3.2.2 Weathering of Ulu Waste Rock

Subsamples of the Ulu waste rock composite was subjected to humidity-cell testing in the laboratory under low (4°C) and room temperature (22°C) conditions. The time series for the same set of parameters as described above for the weathering of the Ulu ore are depicted in Figures 6 and 7, respectively. Salient observations are summarized below: