Investigation of Microbial Bioremediation in a Gold Mill Tailings Pond*

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1. Introduction

Cameco Corporation's Contact Lake Operation was a small gold mine and mill located in central Saskatchewan approximately 45 km northeast of La Ronge. Untreated tailings slurry from the cyanide leach, carbon in pulp (CIP), mill were deposited in a partially dewatered lake (Turtle Lake) from December 1994 until June 1998. As expected, concentrations of cyanide and copper, the primary contaminants of concern, gradually built up over the first seventeen months of operation. There were no discharges from the tailings pond throughout this period and tailings supernatant was recycled to the mill for re-use as process water throughout the entire operating life of the mill. After cyanide and copper built up to approximately 45 - 50 mg/L in the tailings supernatant water, a dramatic decrease in both cyanide and copper concentrations occurred over a four month period. These reductions occurred despite the continued loadings being received from untreated mill tailings and the recycling of supernatant to the mill. Concentrations of cyanide and copper continued to decline over the rest of the operating period of the mill and continue to decline to this date. Microbial degradation was investigated as a possible explanation for the dramatic and continuing decrease in cyanide and copper concentrations in the tailings pond.

2. Methods

To determine if microbial degradation could be responsible for the changes in cyanide and copper concentrations, a three phase investigation was undertaken, with each phase building upon the results of the previous one.

2.1 Phase I

The first phase of the investigation involved microbiological characterization of the tailings pond. Samples of tailings solids and supernatant were collected in sterilized containers from several locations within the tailings pond. All samples from the mine site for this investigation (Phase I, II, and III) were packed with ice and transported to the laboratory within 48 hours. Microbiological characterization of the samples was conducted and included analysis for total coliforms (TC), fecal coliforms (FC), heterotrophic plate count (HPC) and total fungi count (TFC). The pour plate method was used for the determination of HPC and TFC in all samples using 1 mL aliquots for

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testing. The membrane filtration and most probable number methods were used for the determination of TC and FC in liquid and solids samples, respectively, using appropriate aliquots of each sample for testing. Cultures isolated from this work were maintained and in some cases used in Phase II and/or III.

2.2 Phase II

The purpose of the second phase was to isolate and identify potential cyanide and copper degrading microorganisms from the tailings pond samples. An enrichment culture technique was used to isolate microorganisms capable of growing in the presence of the cyanide and copper concentrations present in the Contact Lake tailings pond. Furthermore, the use of a cyanide containing enrichment medium allowed for the isolation of microorganisms capable of utilizing cyanide as a nitrogen source after other sources of nitrogen had been exhausted.

A mixed bacterial culture was established by inoculating 20 mL of nutrient broth (DIFCO Laboratories) containing 1 mL liquid from tailings solid with colonies obtained from samples (solids and supernatant) in Phase 1. This culture was incubated under aerobic conditions for 72 hours in a water bath at 35 C under agitation at 200 rpm. This mixed culture was used to set up three enrichment cultures in 250-mL Erlenmeyer flasks. Each flask contained 50 mL of enrichment medium and 1 mL of culture suspension from the mixed culture. Two control flasks received 50 mL enrichment medium only. Enrichment medium was prepared from the undiluted mill tailings which were filtered through a Whatman No. 1 filter to remove sediment and sterilized by membrane filtration (0.45 m nitrocellulose membrane, Gelman). The flasks were incubated for 4 weeks at 25 C under aerobic conditions at an agitation rate of 200 rpm. The growth of enrichment cultures was monitored by taking weekly samples and plating on a set of duplicate plates of Standard Plate Count Agar (Oxoid). At each sampling interval (0, 1, 2, 3, 4 weeks), an aliquot of 1 mL suspension was spread on each plate from individual enrichment culture flasks. Growth in control flasks was examined by plating 0.2 mL inoculum onto each plate. For the enrichment cultures, serial dilutions were made using sterile diluent (0.1% Bactopeptone in water), whereas control cultures were plated directly. Plates were incubated at 35 C for 48 hours and colonies (colony forming units) were counted manually using the Quebec Colony Counter.

Five colonies were randomly picked as putative cyanide degrading cultures from the plates of 4th week enrichment cultures (three from culture #4 and one each from the other two cultures) and transferred to fresh Standard Plate Count Agar (SPCA) plates. Each of the five isolates was taxonomically identified using the API system (bioMerieux Vitek, Inc. Missouri, USA). Cyanide tolerance capacity of these cultures was further confirmed by their growth on SPCA medium supplemented with potassium ferricyanide (237 mg cyanide/mL). The isolated cultures were maintained by regular subculturing on SPCA medium supplemented with the filter sterilized mill tailings samples.

All cyanide, copper, and ammonia results reported here were analyzed at the Saskatchewan Research Council (SRC), Analytical Services Laboratory in Saskatoon, Saskatchewan. Samples were preserved appropriately before being shipped to SRC. Samples for total cyanide were preserved with NaOH to pH >12 and analysed by an automated colorimetric procedure using pyridine-pyrazolone and chloramine T with in-line distillation and UV digestion (Environment Canada NAQUADAT No. 06604). Total copper analysis on nitric acid preserved (pH <2) samples was conducted by Inductively Coupled Plasma Atomic Emission Spectroscopy. Sulphuric acid preserved (pH <2) samples were analysed for total ammonia as nitrogen by an automated phenate method (*APHA, 1995*).

2.3 Phase III

Cyanide degrading bacteria isolated in Phase II were tested in degradation trials. In addition to these bacterial isolates, an original inoculum (mixed culture) from Phase II and a fungal culture, isolated as a laboratory contaminant, were also tested. All cultures used in Phase III were grown under aerated conditions on a shaker at room temperature (22-24 C).

Seed inoculum was prepared by culturing the isolates in 30 mL of tryptic soy broth (TSB, DIFCO Laboratories) and incubating overnight at room temperature on a shaker at 200 rpm. The degradation trials were conducted by adding 15 mL of the culture suspension in the broth to 250 mL of the filter sterilized mill tailings in a 500 mL erlenmeyer flask. Flasks were incubated on a shaker with an agitation rate of 200 rpm at room temperature. A total of eight cultures were tested including four *Shewanella putrefaciens* isolates, one *Staphylococcus hominis*, one original mixed culture (ie., before enrichment culturing), one fungus (*Cladosporium sp.*), and one control. The control flasks contained filter sterilized mill tailings (250 mL) only. Four flasks were prepared for each culture at the start of the degradation trials and one flask was used for each of the four intervals: 0, 1, 2, and 4 weeks for analyses.

3. Results

3.1 Phase I

Microbial characterization (Phase I) of the tailings pond solids and supernatant samples indicated that most microbial activity was likely to be from heterotrophic bacteria as they were the most abundant and there were very low counts of coliforms and fungi (Table 1). A common trend in these results was that the greater number of microorganisms (bacteria and fungi) were found in solids samples compared to liquid (supernatant) samples. It was also noted that microbial numbers within the tailings pond were greatest at the sample location nearest the tailings deposition point. The presence of total and fecal coliforms was also found to be restricted to the sampling location nearest the tailings deposition point. The presence of coliforms at this location is not unexpected given the co-deposition of sewage and mill tailings.

Table 1

Phase I Results - Microbial Enumeration

	Solids		Supernatant	
	Range	Mean	Range	Mean
Heterotrophic[1] (HPC) Plate Count	1200-28800	10528	11-85	29
Total Fungi[1] (TF) Count	2-160	27	2-7	4
Total Coliforms[2] (TC)	<30 - 1900	418	<1 - 230	24
Fecal Coliforms[2] (FC)	<30 - 1900	418	<1	<1

[1] HPC and TF - results expressed as colony forming units per 1 mL sample.

[2] TC & FC - results expressed as colony forming units per 100 mL sample (liquid samples) or most probable number per 100 mL sample (for solids samples).

3.2 Phase II

Results from the weekly enumeration of the enrichment cultures from Phase II are given in Table 2. The mean bacterial count for the enrichment cultures decreased over the first two weeks and then increased in weeks three and four to a level equal to that at initiation. The bacterial counts for the two control flasks demonstrated the effectiveness of the filter sterilization performed on the mill tailings which were used in preparation of the enrichment medium.

Five putative cyanide degrading cultures were isolated from the enrichment cultures. The isolates were identified to species level based on morphological characters, physiological tests and the API system. Results of these tests are given in Table 3. Four of the bacterial isolates were identified as *Shewanella putrefaciens* and one as *Staphylococcus hominis*. These cultures were used in the Phase III degradation studies.

A fungal culture isolated as a contaminant in the laboratory during early biodegradation work was identified, by microscopic examination, as *Cladosporium sp.* This fungus is a plant pathogen and therefore considered a contaminant of the tailings pond samples. However, as it demonstrated a tolerance for the cyanide and copper concentrations in the tailings pond, it was also studied for its potential biodegradation abilities in Phase III under similar aerobic conditions as for the bacterial cultures.

Table 2

Total Aerobic Bacterial Count in Enrichment Culture for Four Week Incubation

Flask Identification	Counts (CFU) per mL of sample				
	Week 0	Week 1	Week 2	Week 3	Week 4
Control #1	<1	2	<1	<1	<1
Control #2	<1	<1	4	<1	<1
Culture #3	6.85×10^7	1.06×10^7	5.80×10^5	1.58×10^5	5.70×10^4
Culture #4	1.35×10^7	1.11×10^7	8.45×10^5	1.40×10^7	7.50×10^7
Culture #5	1.85×10^7	1.63×10^7	6.15×10^5	1.00×10^5	5.00×10^5
Mean (Culture 3-5)	3.35×10^7	1.27×10^7	6.80×10^5	4.92×10^6	3.78×10^7

Table 3

Microbiological Identification Data

I.D.#	Cameco #1	Cameco #2	Cameco #3	Cameco #4	Cameco #5
Colony Morphology	Gram (-) rods	Gram (-) rods	Gram (-) rods	Gram (-) rods	Gram (+) cocci
Media	TSA	TSA	TSA	TSA	TSA
Growth	35 C	35 C	35 C	35 C	35 C
Size	Large	Large	Large	Large	Large
Pigmentation	Creamish	Creamish	Creamish	Creamish	White
Elevation	Convex	Convex	Convex	Convex	Flat
Edge	Fuzzy	Fuzzy	Fuzzy	Fuzzy	Round
Physiology					
Catalase	+	+	+	+	+
Oxidase	+	+	+	+	+
Growth*	++++	++++	++++	++++	+
Result	Shewanella putrefaciens	Shewanella putrefaciens	Shewanella putrefaciens	Shewanella putrefaciens	Staphylococcus hominis

* growth on *Pseudomonas* medium

3.3 Phase III

A summary of results from the Phase III degradation trials is provided in Table 4 and a plot of the cyanide and copper concentrations over the four week trials is given in Figure 1. As these results demonstrate, all degradation trial flasks showed dramatic reductions in total cyanide, and to a slightly lesser extent, total copper concentrations. Per cent reductions for total cyanide over the four-week test, ranged from 98.04 to 99.83% and from 67.30 to 93.42% for total copper. In comparison, the control flask showed a 13.58% reduction in total cyanide concentrations over the four-week test. Total ammonia as nitrogen levels for each treatment at the end of the four-week degradation trials are also given in Table 4. Although ammonia concentrations were not determined for each treatment on day zero, the final levels can be referenced to an initial value of 12.3 mg/L. This is the result of a single analysis conducted on the filter sterilized tailings (corrected for addition of microbial culture) used in the degradation trials. Although no quantitative conclusions should be made from these results, they do indicate that a substantial increase in total ammonia levels occurred over the course of the degradation trials.

A meaningful comparison of the reductions in copper between the inoculated flasks and the control was not possible due to sampling difficulties and unexplainable fluctuations in control flask copper concentrations. The week one control flask copper and cyanide values were lower than week two or four results (Table 4). It is believed that the formation of a precipitate in week one flasks is responsible for the lower values in week one. A precipitate was observed in the week one control flasks and remained stuck to the flask wall while sampling. Therefore, the retention of copper and cyanide in this precipitate would explain the low values measured in the week one flask. This explanation is further supported by the copper and cyanide values for weeks two and four when no such precipitate was observed in these control flasks. We are unable to offer an explanation for the elevated copper values in the week four flask.

The *S. hominis* culture showed the greatest per cent reduction in total cyanide concentrations but also had the lowest per cent reduction for copper. The fungal culture (*Cladosporium sp.*) showed the greatest reduction in copper concentrations. This culture and the mixed culture had greater reductions in copper than any of the single species bacterial cultures. The total cyanide concentrations at the end of the four week degradation trial in the *S. putrefaciens* #3, *S. hominis* #5, and mixed culture were below the regulatory agency imposed discharge limits (1.0 mg/L monthly mean) for the site. These dramatic reductions were achieved despite starting concentrations of nearly 400 mg/L total cyanide. All of the total copper concentrations at the end of the degradation trials were at least an order of magnitude greater than regulatory discharge limits (0.30 mg/L monthly mean).

4. Discussion

The results of this investigation have demonstrated that a number of specialized microorganisms were present in the Contact Lake tailings pond, which were tolerant of significant cyanide and copper concentrations. Generally, a greater number of microorganisms were found in samples of the (subaqueous) tailings solids than in samples of tailings pond supernatant (liquid). Also, greater numbers were found in the samples closest to the tailings deposition point, perhaps implying a relationship or even dependence on cyanide in the tailings.

Table 4. Phase III Results - Biodegradation of Cu and CN

Treatment	Time	Total CN (mg/L)	% Degradation (CN)	Total Cu (mg/L)	% Degradation (Cu)	Total Ammonia as Nitrogen (Mg/L)
Control	0 day	346		180		
	1 week	155	55.20	63	65.00	
	2 week	340	1.02	220	-ve	
	4 week	299	13.58	530	-ve	10
S. putrefaciens#1	0 day	578		162		
	1 week	162	71.97	59	63.58	
	2 week	92	84.08	21	87.03	
	4 week	11.3	98.04	18	88.88	45
S. putrafaciens#2	0 day	328		156		
	1 week	144	56.09	62	60.25	
	2 week	59.1	81.98	59	62.17	
	4 week	1.27	99.74	51	67.30	43
S. putrafaciens#3	0 day	378		156		
	1 week	117	69.04	59	62.17	
	2 week	77.2	79.57	59	62.17	
	4 week	0.952	99.74	50	67.94	46
S. putrafaciens#4	0 day	444		152		
	1 week	147	66.89	64	57.89	
	2 week	83.1	81.28	13	91.44	
	4 week	2.260	99.49	47	69.07	49
S. hominis#5	0 day	386		156		
	1 week	138	64.24	44	71.79	
	2 week	12.00	96.89	61	60.89	
	4 week	0.650	99.83	51	67.30	48
Mixed culture	0 day	372		160		
	1 week	119	68.01	57	64.37	
	2 week	33.3	91.04	61	61.87	
	4 week	0.885	99.76	19	88.12	47
Cladosporium sp.	0 day	346		152		
	2 week	21.2	93.87	130	14.47	
	4 week	1.130	99.67	10	93.42	48

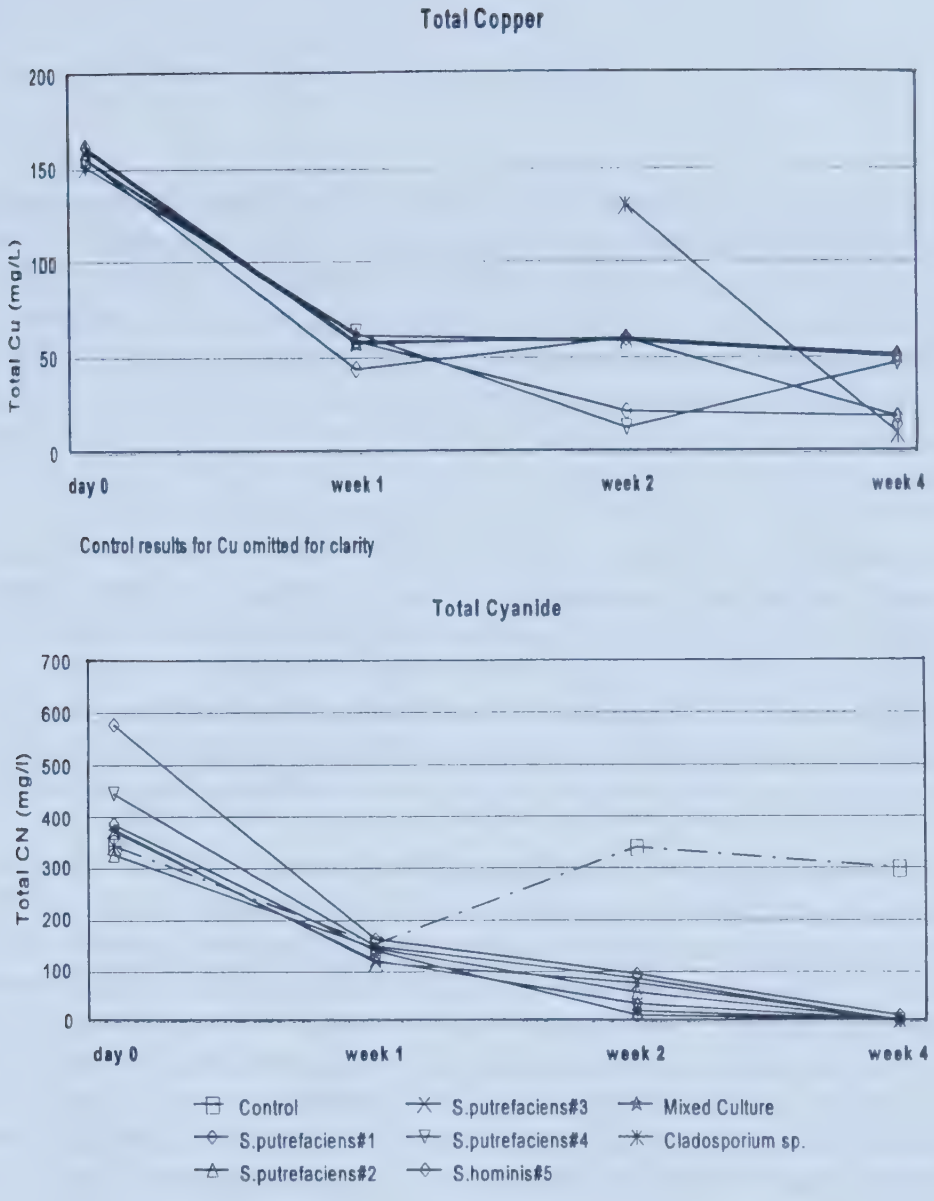

FIGURE 1

Phase III Results - Plots of copper and cyanide concentrations over 4 week degradation trials

By using enrichment culture techniques, specialized microorganisms capable of utilizing cyanide as a nitrogen source were isolated from tailings pond samples. Although non-cyanide nitrogen sources were initially present during enrichment culturing, it is believed that the incubation time was long enough for these to be exhausted, thereby providing the advantage to microorganisms capable of utilizing cyanide as a nitrogen source. Numerous other authors have successfully used enrichment culturing to isolate cyanide utilizing microorganisms (*Harris and Knowles, 1983. White et. al., 1988, Kang and Kim, 1993, Thompson et. al., 1995a*).

Two species of bacteria were isolated as potential cyanide degraders. *Staphylococcus hominis* is a gram positive cocci and is an opportunistic human pathogen. Its presence is attributable to the sewage which was co-deposited with mill tailings. It is interesting to note the very low numbers of total and fecal coliforms in all of the tailings samples, indicating an intolerance of coliform bacteria to conditions in the tailings pond. The second bacterium, identified as *Shewanella*

putrefaciens, is a gram negative, rod-shaped bacteria. It is very common in a wide range of environments including aquatic reservoirs (freshwater, marine, sewage), industrial sludges (mining, oil and gas), soils, and some food products (*Khashe and Janda, 1998*). While *S. putrefaciens* has occasionally been implicated as a human pathogen, it is reported to be most frequently recovered from non-human sources (*Khashe and Janda, 1998*). Therefore, it is uncertain whether the presence of *S. putrefacients* in the tailings pond is a remnant from before the lake (now tailings pond) was dewatered or it was introduced as a result of sewage disposal during operations.

In addition to the two bacterial species, a fungus, *Cladosporium sp.* was also found to be tolerant of the high cyanide and copper concentrations in the mill tailings. However, this fungus is a plant pathogen and a tailings pond is not considered its likely habitat and therefore it was considered a laboratory contaminant. Regardless of this, it demonstrated not only a tolerance for cyanide and copper but also a biodegradation ability under similar aerobic conditions as tested for the bacterial cultures. This ability is not unusual as numerous other fungi have been reported to biodegrade cyanide *(Nazy and Knowles, 1981, Nazy et. al., 1983, Allen and Strobel, 1966*).

Under laboratory conditions, all of the inoculated degradation trial flasks showed very large reductions in total cyanide (>98%) and total copper (67-93%) concentrations over the four-week test period. In comparison, the control samples, which were not inoculated, only showed a marginal reduction (13.58%) in total cyanide concentrations over the four-week test period. This indicates that the reductions in total cyanide were a result of biodegradation rather than other physical or chemical factors associated with the test procedure such as ultraviolet degradation, shear stress, or complexation or adsorption to other constituents in the sample matrix. The biodegradation of cyanide by microorganisms has been reported in numerous environments including river sediments, soils, coal tar sludge, sewage plant sludges, and heap leach waste piles (*Harris and Knowles, 1983, Castric, 1981, Kang and Kim, 1993, Raef et. al., 1977, Knowles, 1976, Thompson et. al., 1995*a). Furthermore, engineered systems have been designed and used specifically for the bioremediation of cyanide containing mine wastes, primarily at heap leach operations (*Thompson and Jones, 1993*), and other industrial waste waters (*Richardson, 1987, Ingvorsen and Godtfredsen, 1988*).

While all of the inoculated degradation trial flasks showed significant reductions in total copper, results from the control flasks were ambiguous. As a result, the copper reductions observed in the inoculated flasks can not definitively be attributed to the presence of the microorganisms. However, the simultaneous removal of metals, including copper and selenium, and cyanide degradation by specialized bacteria has been demonstrated in biodegradation studies involving mining wastes (*Fischer et. al., 1995, Adams et. al., 1996*). *Fischer et. al.* also reported some anomalous copper results in biotreatment studies involving simultaneous copper removal and cyanide degradation by a consortium of microbes. They also stated that when cyanide is biologically removed from solution, metals may also be precipitated by several possible mechanisms, including: adsorption on cell membranes, chelation, ligand depletion, or sulphide precipitation mediated by sulphate-reducing bacteria. *Thompson et. al., (1995b)* also found that

metals were removed from solution, remineralized, and deposited on the surfaces of spent ore particles during biodetoxification of a heap leach pad. In this investigation, biologically catalysed precipitation reactions are the most likely mechanism for the reduced copper levels given the use of filter sterilized mill tailings (i.e., no particulate matter or bacterium other than test inoculum). However, the simultaneous biomineralization of copper and biodegradation of cyanide could certainly occur in the tailings pond at the Contact Lake Operation.

The mechanisms involved in microbial cyanide biodegradation are not completely understood and a determination of the mechanism responsible for the results reported here was beyond the scope of this investigation. However, significantly higher ammonia concentrations were observed at the end of the degradation trials than in the original mill tailings used for these degradation trials. This suggests that the cyanide was metabolized by the microorganisms and used as a nitrogen source to support the growth of the organism rather than simply assimilating it. The literature indicates a number of possible reactions responsible for cyanide metabolism by microorganisms including substitution/addition, hydrolysis, oxidation, and reduction (*Raybuck, 1992, Mosher and Figueroa, 1995*).

5. Conclusions

In conclusion, microbial characterization of gold mill tailings pond samples (supernatant and solids) revealed a number of microorganisms which were tolerant of the elevated concentrations of metals and cyanide in the tailings pond. By the use of enrichment culturing techniques, two species of bacteria (*Staphylococcus hominis* and *Shewanella putrefaciens*) were isolated from the tailings pond samples and considered to be potential biodegraders of cyanide and copper. Degradations trials conducted using these two bacterial isolates, an original inoculum (mixed culture), and a fungal culture (*Cladosporium sp.*) isolated as a laboratory contaminant showed considerable reductions in total cyanide and copper concentrations for all trials. These bacteria and fungus were able to tolerate the very high concentrations of total cyanide (328-578 mg/L) and total copper (152 - 162 mg/L) in full strength mill tailings at the beginning of the trials and reduced levels to as low as 0.65 mg/L total cyanide and 10 mg/L total copper. To our knowledge, *S. hominis*, *S. putrefaciens*, and *Cladosporium* sp. have not previously been reported to biodegrade cyanide or copper. Results of this investigation demonstrated that a process of microbial bioremediation was a viable explanation for the dramatic reductions observed in Contact Lake Operation tailings pond cyanide and copper concentrations. The results also demonstrated that the disposal of sewage in the tailings pond was partially, if not fully, responsible for the presence of bacteria capable of degrading cyanide and copper.

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Conference Program / Table of Contents

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8:00 AM	Field Tour Departure (no delays)	
7:00 - 10:00 PM	Wine and Cheese, Registration	
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8:25 – 10:05	**Saskatchewan Policy** – Saskatchewan Room 'B' Session Chair: Lorne Veitch – Saskatchewan Agriculture and Food, Lands Branch, Swift Current	
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3:05 – 3:25 Rare Plant Rescue During Pipeline Construction *(Erigeron compositus* Pursh. var. *glabratus* Macoun, Fern-leaf Fleabane on the 1998 Foothills Pipe Lines Expansion Project.)
David Walker, Walker and Associates ..... n/a

Session D: **Soils and Restoration**– Saskatchewan Room 'C'
Session Chair: Mike Solohub – Department of Soil Science, University of Saskatchewan

1:45 - 2:05 Soil information resources for the prairies.
Alvin Anderson and Glenn Padbury, Agriculture and Agri-Food Canada ..... n/a

2:05 – 2:25 Setting reclamation standards: When is soil decompacted?
Richard Johnson, Alberta Research Council 175

2:25 – 2:45 Using oily waste to restore productivity in a severely eroded loamy sand.
M.C.P. Jarvis[1,3], V.O. Biederbeck[2], K.G. Hanson[2], T.A. Fonstad[3] ;[1] Imperial Oil Resources, [2] Semiarid Prairie Agricultural Center, and [3], University of Saskatchewan 68

2:45 – 3:05 Remediation of potash slime tails through use of cross-linked polyacrylamide hydrogel.
Kathleen Cameron, University of Saskatchewan 169

3:05 – 3:25 Fifteen years of subsoil/mine spoil development on a

Use of ecological management planning in Western Saskatchewan
Wayne Pepper and Jim Ireland, ERIN Consulting Ltd. 136

11:15 – 12:00 2) Focus Session - Legal Considerations in the Environmental Sector

Julian Bodnar, Barrister and Solicitor (Stevenson Gillis Hjelte Tangjerd) ..... n/a

Gary Meschishnick, Barristor and Solicitor Wallace Meschishnick Clackson Zawada ..... n/a

12:00 – 1:30 **Lunch** – Saskatchewan Room 'A'

1:30 – 3:10 **Concurrent Sessions**

Session A: **Remediation** – Saskatchewan Room 'C'
Session Chair: Lisa Groves – EnviroTest Labs

1:30 – 1:50 Phytoremediation as an in-situ technique for the restoration of oil-contaminated sites.
C.M. Frick, J.J. Germida, and R.E. Farrell, University of Saskatchewan 95

1:50 – 2:10 Integration of toxicity testing and chemical analyses for site assessment and remediation.
Deib Birkholz, Enviro-Test Laboratories and Stephen Goudey, HydroQual Laboritories Ltd. 98

2:10 – 2:30 Evaluating soil amendments for brine spill remediation.
Ken Greer, Western Ag. Consulting and Jeff Schoenau, University of Saskatchewan ..... n/a

2:30 – 2:50 Decommissioning and reclamation of an abandoned herbicide plant.
Ralph Bock, Saskatchewan Environment and Resource Management ..... n/a

2:50 – 3:10 Surface water management with the Little River Pond Mill.
Kathleen Cameron, Sunset Solar Systems Ltd. 99

Session B: **Ecosystem Restoration** – Saskatchewan Room 'B'
Session Chair: Corinne Tchorzewski – Saskatchewan Environment and Resource Management, Sustainable Land Management Branch

1:30 – 1:50 Physical restoration of the Kingsmere River in Prince Albert National Park.
Michael Fitzsimmons, Prince Albert National Park and Guy Melville, Saskatchewan Research Council 138

1:50 – 2:10 Fire management for Prince Albert National Park - planned and random ignition prescribed burns.