ENVIRONMENTAL STUDIES OF FLOODED OPENCUTS

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INTRODUCTION

In the course of uranium mining and extraction operations at Rum Jungle in the Northern Territory of Australia over the period 1953-70, processing materials were obtained from five opencuts and a sixth was excavated to just below the level of the ore body. In the monsoonal climate of Northern Australia, with its annual average rainfall of about 150 mm during the wet season, all opencuts became water-filled on the cessation of mining operations. Those in the Rum Jungle Mine area proper (Fig. 1) have become highly acidic and metal-polluted (Intermediate, White's and Dyson's Opencuts); the water in the other three opencuts (Rum Jungle Creek South, Mt Burton and Mt Fitch Opencuts) is neutral to slightly alkaline in reaction and the heavy metal content is negligible (Davy, 1975).

Intensive studies of environmental pollution in the Rum Jungle area were initiated by the Australian Atomic Energy Commission in 1973 and have continued up to the present time. Studies on the role of microbial populations in the generation of acidic and metallic pollution in sulfidic overburden heaps, tailings dams and flooded opencuts, were commenced in late 1974 in close collaboration with the A.A.E.C. teams. The findings here reported embody a preliminary examination of the microbial status of water samples taken from the Intermediate and White's Opencuts and associated water systems, early in a dry season (June, 1978).

An examination of water quality in respect of phsico-chemical characteristics in the Intermediate, White's and Rum Jungle Creek South Opencuts was carried out by the Water Resources Branch of the Northern Territory Administration in December, 1977. The results, which were made available through the A.A.E.C., enabled the selection of a limited number of sampling sites for a preliminary microbiological examination.

Prior to the commencement of mining operations in the Rum Jungle area, the East Branch of the Finnis River passed over the White's and Intermediate ore bodies: the water flow was subsequently diverted by the construction of a river diversion channel. A portion of the old bed of the East Branch lies between White's and Intermediate Opencuts and drains into a new channel, Copper Creek, which skirts the northern embankment of the Intermediate Opencut (Fig. 1).

During the operation of the processing plant at Rum Jungle, two small leaching heaps were constructed from the overlying, low-grade copper sulfide and oxidised ores of the Intermediate ore body. They are located between the two opencuts and continue to shed acidic, copper-bearing drainage waters into the various collection ponds and thence into the old bed of the river and Copper Creek.

When all uranium ore had been recovered from White's ore body, a considerable quantity of tailings from the processing plant was returned to the opencut, about half-filling it. No tailings or other residues were deposited in the Intermediate Opencut.

METHODS

Sampling points are located by reference to survey points established by the Water Resources Branch team, using compass and range finder. The sampling sites in the Intermediate Opencut and the associated water systems are shown in Fig. 2 and in White's Opencut in Fig. 3. Temperature and dissolved oxygen concentration at various depths were measured with standard equipment. Water samples were collected with a 2-litre capacity Friedinger-type water samples, and transferred to sterile containers for subsequent chemical and microbiological examination. The pH of each sample was determined at the point of sampling.

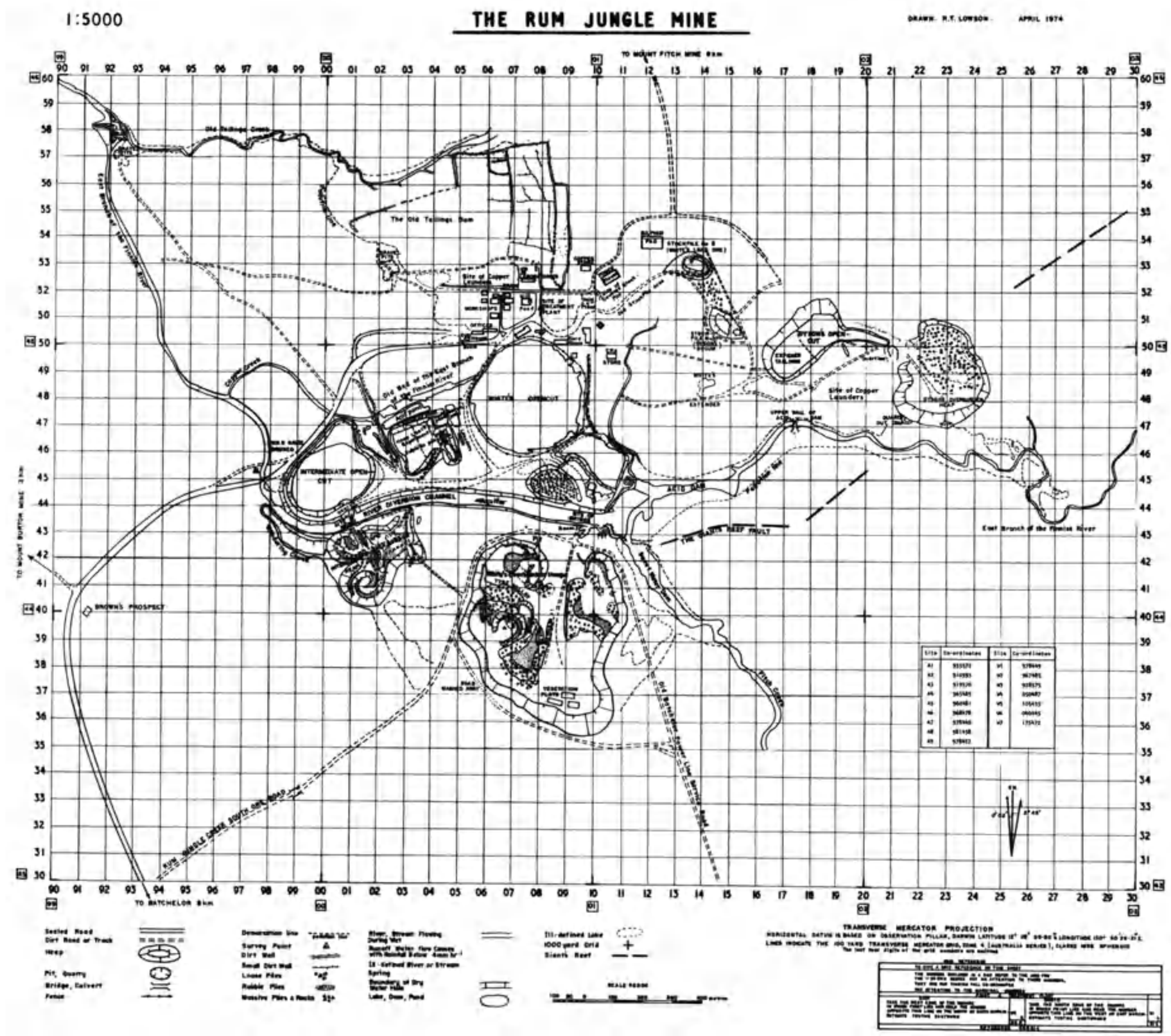


Figure 1: Map of Rum Jungle Mine area, Northern Territory, Australia. Reproduced

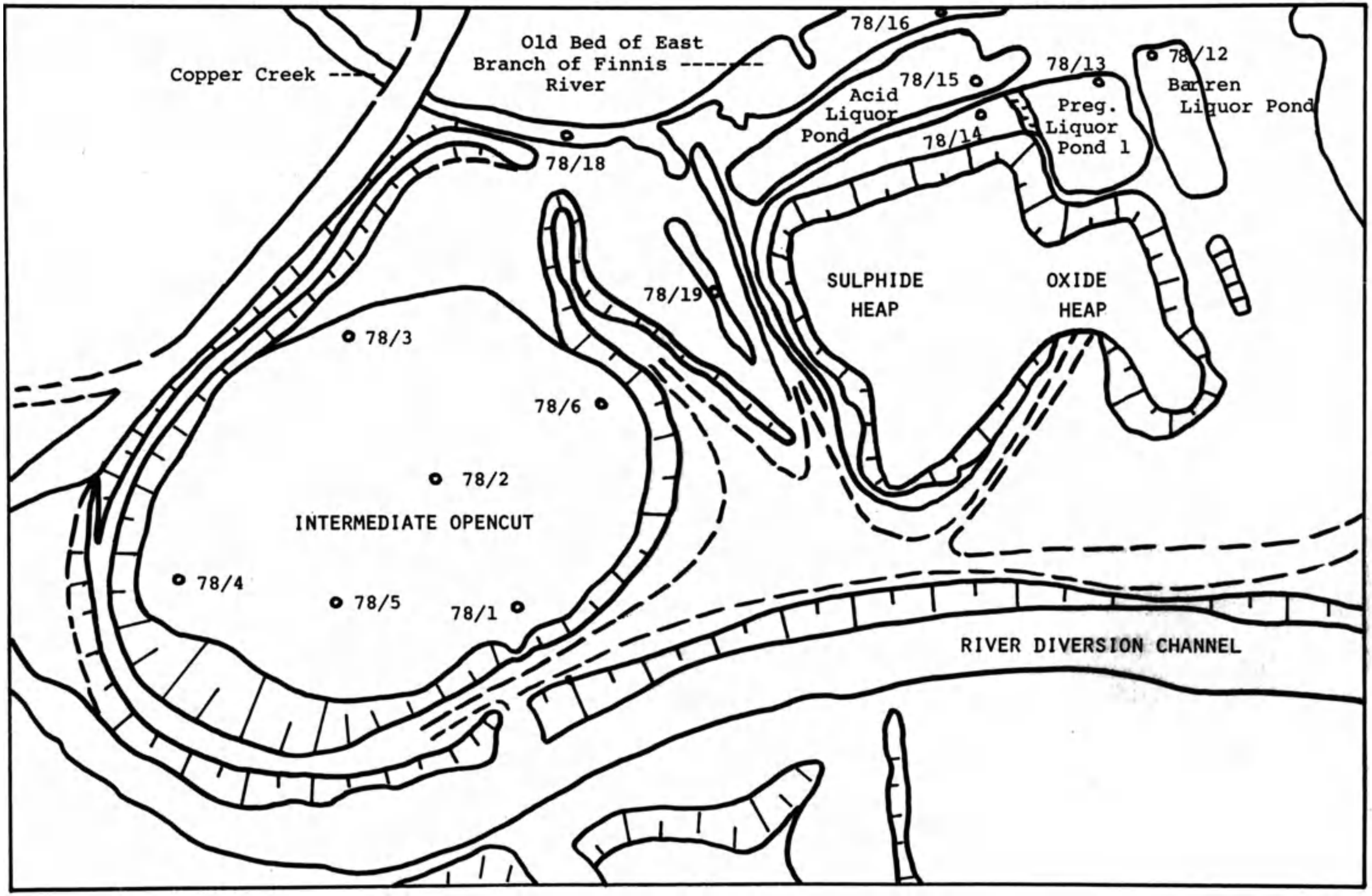
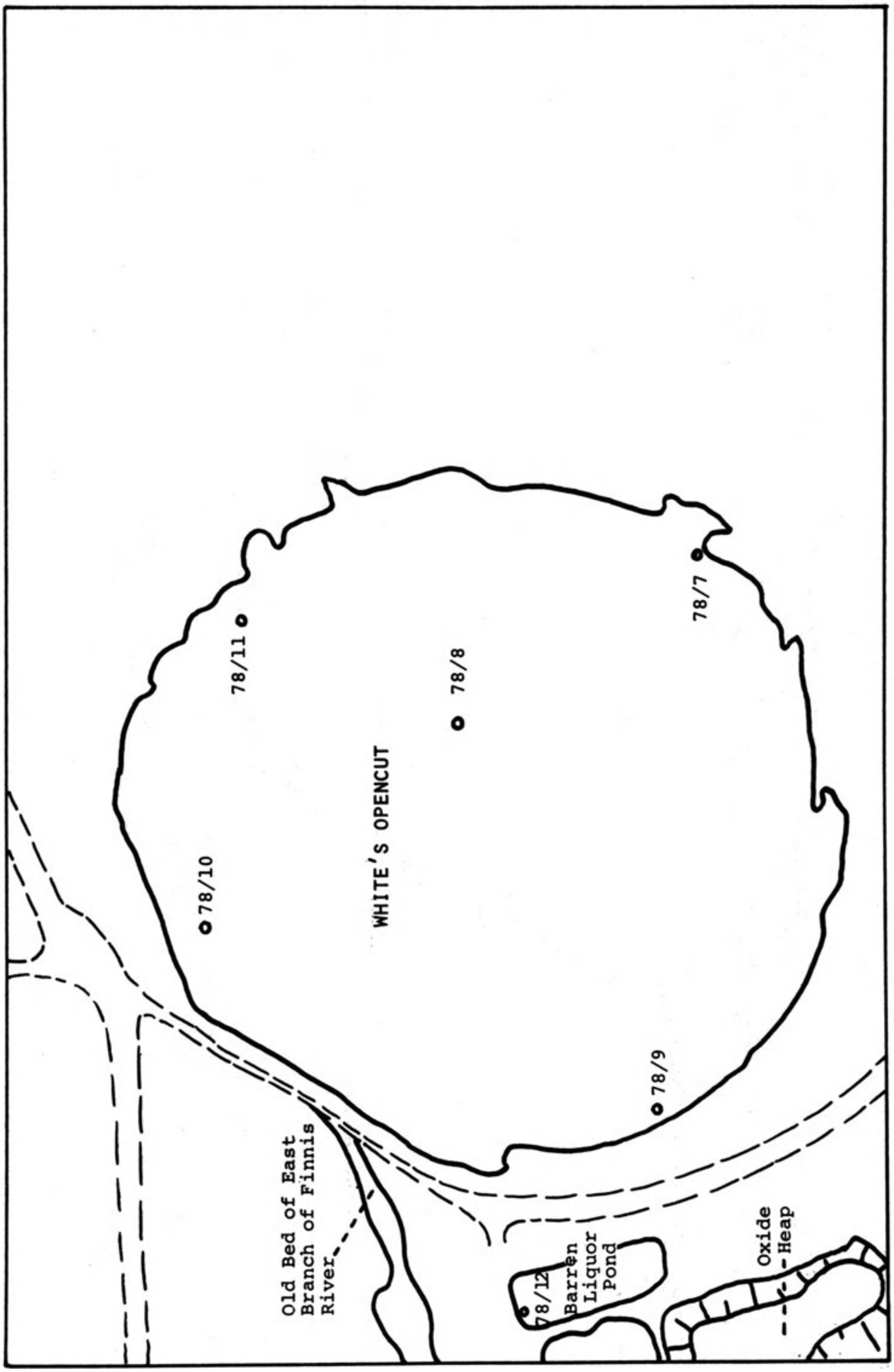


Figure 2: Sampling points in the Intermediate Opencut and associated water systems.


WHITE'S OPENCUT
78/7
78/8
78/9
78/10
78/11
78/12
Old Bed of East
Branch of Finnis
River
Barren
Liquor
Pond
Oxide
Heap

Within two hours of sampling, aliquots of each sample were membrane-filtered and both filtrate and separated microbial populations cooled to 4^{o} for transport to Sydney. Chemical analysis and the enumeration of various microbial population types were carried out by the methods described by Khalid and Ralph (1976b) and Goodman and Ralph (1978).

RESULTS AND DISCUSSION

The physico-chemical and microbiological data respectively for the samples taken from the Intermediate Opencut are shown in Tables 1 and 2, and the similar data for the White's Opencut samples in Tables 3 and 4. The associated water systems data are set out in Tables 5 and 6.

Intermediate Opencut

The water solubles content of the samples ranged from 3780 ppm to 6760 ppm with no discernible patterns of distribution. The bottom samples did not contain a markedly higher solute concentrations than other samples taken in particular vertical profiles. The pH of samples ranged from 3.5 to 2.6, the most acidic areas being sites 78/4 and 78/6. The former site is that of the exit point of the original river bed; the latter is the closest point to the old leaching heaps. It will be noted that the soluble iron content of all samples was equal to or less than 1 ppm while the copper contents ranged between 85 and 165 ppm and zinc content between 4 and 7 ppm. A semi-quantitative examination of samples by an energy dispersive X-ray analytical system indicated high levels of magnesium, calcium and manganese, and lower levels of aluminium, silicon and chloride. The temperature profiles show a consistent slight fall from surface to bottom. Dissolved oxygen concentrations show the same pattern without sharp breakpoints.

Although the levels of soluble iron were very low, *T.ferrooxidans* populations were detected in every samples. The numbers increased markedly in the bottom samples. Sulfur-oxidizing organisms grown at pH 3.5 were detected in only two samples (78/2/12.5 and 78/2/58; middle of opencut) but those growing at pH 4.8 on thiosulfate were relatively abundant. At every site these organisms were plentiful in the bottom samples except in 78/1/1 where they occurred near the surface. Sulfur oxidizers growing at pH 6.2 on thiosulfate were not as widespread as those growing at pH 4.8 although the bottom samples from sites 78/4, 78/6 and especially 78/2 contained substantial populations.

It is interesting to note that sample 78/2/58, which is the bottom sample from the centre of the opencut, contained extremely high sulfur-oxidizing bacterial populations and also high numbers of acidophilic heterotrophs which in the main occurred only in samples at depth. The only non-acidophilic heterotrophs detected were in the bottom samples at site 78/6.

Unicellular organisms belonging to the algal genus *Chlorella* were found throughout the water of the opencut. Green colonies were isolated on acidophilic-heterotroph and thiosulfate (pH 4.8) agar plates.

All bottom samples contained viable cells of the anaerobes *Desulfovibrio* and *T.denitrificans* (except 78/3/3 in which *T.denitrificans* could not be detected). Although the dissolved oxygen concentration in the bottom samples was not less than 2.0 ppm, as measured just above the sediment, anaerobic or micro-aerophilic conditions must occur close under the sediment surface.

White's Opencut

The results show a considerable difference in both physico-chemical factors and microbial distribution between the samples from the Intermediate and White's Opencuts. In White's Opencut, the water solubles content of the samples ranged from 7160 ppm to 14,540 ppm; that is, the spread of concentrations is much more marked and all samples contained a higher level of solutes than any from the Intermediate Opencut. Further, the concentration of solutes in White's Opencut samples was highest in the bottom samples, and in all areas except 78/9, the concentration in the micro-aerophilic zone was higher than in the upper aerobic zone. This oxygen zonation is a significant feature of the waters of White's Opencut and has been previously observed by the A.A.E.C. workers and the Water Resources Branch team. The interface is relatively sharp with aerobic conditions (D.O. about 6 ppm) in the upper 4-4.5 m and dropping markedly in a metre or less to micro-aerophilic conditions (D.O. 2.0 - 0.7 ppm) below 5-5.5 m depth.

TABLE 1

INTERMEDIATE OPENCUT WATER SAMPLES - PHYSICO-CHEMICAL DATA

Sample No.[a]	Temp. (°C)	D.O. (ppm)	pH	Total Solids (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)
78/1/1	26.8	7.4	3.1	6180	0.75	145	6
10	25.9	8.0	3.2	6760	1.0	125	4
12.5	25.0	5.2	3.2	4680	0.5	100	5
15/S	24.0	3.8	3.1	5400	nd	165	6
78/2/1	25.5	7.4	3.25	4400	0.6	120	6
10	24.0	4.3	3.2	4940	0.5	113	6
12.5	24.0	3.7	3.4	5360	0.5	120	6
58/S	23.5	3.8	3.5	6280	0.5	95	7
78/3/1	25.2	7.1	3.0	4360	0.75	125	7
2	25.2	7.4	3.0	3840	0.5	135	7
3/S	25.1	7.0	3.1	4100	0.75	125	6
78/4/1	25.3	6.0	2.7	3780	0.75	110	6
10	25.2	6.3	2.9	3940	0.5	95	6
12.5	24.0	4.5	3.0	4940	0.5	105	6
15/S	24.0	4.5	3.2	4180	nd	105	7
78/6/1	25.2	5.4	2.9	4200	0.7	125	6
12.5	24.5	5.1	2.8	5000	0.5	113	6
15	23.5	2.6	3.0	4920	0.5	113	7
28/S	23.2	2.0	2.6	5440	0.75	85	7

[a] Sample Code: Year/Location No./Depth in metres/S - Sediment

[b] nd = Not detected

TABLE 2

INTERMEDIATE OPENCUT WATER SAMPLES -
MICROBIOLOGICAL DATA

Sample No.	D.O. (ppm)	pH	Microbial Populations - Cells $ml^{-1} \times 10^{-3}$								
			A	B	C	D	E	F	G	H	J
78/1/1	7.4	3.1	0.05	nd	14.5	0.02	2.2	nd	-	-	0.72
10	8.0	3.2	0.006	nd	nd	nd	nd	nd	-	-	nd
12.5	5.2	3.2	0.008	nd	0.07	nd	nd	nd	-	-	1.18
15/S	3.8	3.1	5.35	nd	0.41	0.2	0.6	nd	+	+	1.16
78/2/1	7.4	3.25	0.02	nd	0.64	nd	nd	nd	-	-	0.86
10	4.3	3.2	0.03	nd	0.01	nd	nd	nd	-	-	0.03
12.5	3.7	3.4	0.04	nd	3.5	0.02	nd	nd	-	-	8.0
58/S	3.8	3.5	1.3	nd	500	500	500	nd	+	+	nd
78/3/1	7.1	3.0	0.002	nd	nd	nd	nd	nd	-	-	0.1
2	7.4	3.0	0.01	nd	nd	nd	nd	nd	-	-	nd
3/S	7.0	3.1	4.15	nd	1.2	0.43	0.42	nd	+	+	0.02
78/4/1	6.0	2.7	0.02	nd	nd	nd	nd	nd	-	-	nd
10	6.3	2.9	0.01	nd	nd	nd	nd	nd	-	-	nd
12.5	4.5	3.0	0.007	nd	0.57	0.04	0.21	nd	-	-	2.2
15/S	4.5	3.2	2.0	nd	10.0	5.6	11.0	nd	+	+	0.27
78/6/1	5.4	2.9	0.006	nd	nd	nd	nd	nd	-	-	nd
12.5	5.1	2.8	0.02	nd	0.01	nd	nd	nd	-	-	0.01
15	2.6	3.0	0.01	nd	nd	nd	nd	nd	-	-	nd
28/S	2.0	2.6	2.4	nd	8.5	2.0	5.5	0.05	+	+	nd

A *Thiobacillus ferrooxidans*.

B Sulfur oxidisers (growing on thiosulfate at pH 3.5).

C Sulfur oxidisers (growing on thiosulfate at pH 4.8).

D Sulfur oxidisers (growing on thiosulfate at pH 6.2).

E Acidophilic heterotrophs (Manning's glucose-salts-YE medium).

F Non-acidophilic heterotrophs (Nutrient agar).

G *Desulfovibrio* spp.

H *T.denitrificans*.

J *Chlorella* spp.

TABLE 3

WHITE'S OPENCUT WATER SAMPLES - PHYSICO-CHEMICAL DATA

Sample No.	Temp. (°C)	D.O. (ppm)	pH	Total Solids (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)
78/7/1	23.5	6.2	2.4	9880	125	75	5
4	23.5	6.0	2.2	9640	125	85	6
5	25.5	1.3	2.1	12800	225	115	6
8/S	27.0	0.7	1.8	13420	325	80	6
78/8/1	24.0	6.3	2.5	8740	125	103	6
4.5	23.5	6.2	2.6	7520	125	100	6
6	26.5	1.5	2.4	10900	250		
40/S	25.0	1.3	2.2	14540	525	80	6
78/9/1	24.0	6.0	2.6	8100	200	120	5
4	23.2	5.8	2.5	8460	150	100	6
5	25.0	1.2	2.5	7440	100	135	6
8/S	25.2	1.1	2.3	13400	400	75	6
78/10/1	24.8	6.0	2.6	7260	125	70	6
4	23.3	5.9	2.6	7160	150	138	6
5	24.8	1.1	2.4	8940	200	80	6
12/S	25.0	2.0	2.2	14020	500	90	6
78/11/4	23.3	5.7	2.5	5800	125	80	6
5	24.8	1.2	2.4	7360	225	80	6
14/S	25.0	0.8	2.2	11700	500	90	6

TABLE 4

WHITE'S OPENCUT WATER SAMPLES - MICROBIOLOGICAL DATA

Sample No.	D.O. (ppm)	pH	Microbial Populations - Cells $ml^{-1} \times 10^{-3}$								
			A	B	C	D	E	F	G	H	J
78/7/1	6.2	2.4	0.04	nd	0.12	nd	nd	nd	-	-	0.24
4	6.0	2.2	0.05	nd	0.16	nd	nd	nd	-	-	0.38
5	1.3	2.1	0.05	nd	1.24	nd	nd	nd	-	-	0.38
8/S	0.7	1.8	1.65	nd	79	nd	0.12	nd	+	-	8.1
78/8/1	6.3	2.5	0.05	nd	0.12	nd	0.03	nd	-	-	0.24
4.5	6.2	2.6	0.16	nd	0.02	nd	nd	nd	-	-	0.02
6	1.5	2.4	0.60	nd	0.25	nd	nd	nd	-	-	0.22
40/S	1.3	2.2	2.25	nd	25	nd	nd	0.1	+	-	0.16
78/9/1	6.0	2.6	0.16	nd	0.03	0.02	nd	nd	-	-	0.02
4	5.8	2.5	0.12	nd	0.04	nd	nd	nd	-	-	0.02
5	1.2	2.5	0.08	nd	0.12	1.0	nd	nd	-	-	nd
8/S	1.1	2.3	815	nd	500	nd	0.37	0.05	+	-	2.5
78/10/1	6.0	2.6	0.2	nd	nd	nd	nd	nd	-	-	nd
4	5.9	2.6	0.05	nd	0.07	0.04	nd	nd	-	-	0.04
5	1.1	2.4	0.08	nd	0.07	nd	nd	nd	-	-	0.08
12/5	2.0	2.2	19.5	nd	10	nd	nd	nd	-	-	1.0
78/11/4	5.7	2.5	0.07	nd	nd	nd	nd	nd	-	-	nd
5	1.2	2.4	0.22	nd	0.1	nd	nd	nd	-	-	nd
14/S	0.8	2.2	33.2	nd	2.0	nd	nd	nd	+	-	0.25

A *Thiobacillus ferrooxidans*.

B Sulfur oxidisers (growing on thiosulfate at pH 3.5).

C Sulfur oxidisers (growing on thiosulfate at pH 4.8).

D Sulfur oxidisers (growing on thiosulfate at pH 6.2).

E Acidophilic heterotrophs (Manning's glucose-salts-YE medium).

F Non-acidophilic heterotrophs (Nutrient agar).

G *Desulfovibrio* spp.

H *T. denitrificans*.

J *Chlorella* spp.

TABLE 5

ASSOCIATED WATER SYSTEMS -
PHYSICO-CHEMICAL DATA

Sample No. and Location	pH	Total Solids (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)
78/12 Barren Liquor Pond	2.8	4320	100	425	3
78/13 Pregnant Liquor Pond 1	2.1	7940	400	750	5
78/14 Pregnant Liquor Pond 2	2.6	107140	8250	25000	30
78/15 Acid Liquor	2.6	9480	300	700	5
78/16 Old Bed of East Branch of Finnis River	3.0	7640	25	205	5
78/18 Pond - Copper Creek	3.0	7520	52	171	6
78/19 Sample Ditch	2.9	22220	300	1170	13
78/17 Rum Jungle Creek S. - Composite sample	7.1	5800	nd [a]	nd [a]	nd [a]

[a] nd = not detected

TABLE 6

ASSOCIATED WATER SYSTEMS - MICROBIOLOGICAL DATA

Sample No. and Location	pH	Microbial Populations - Cells $ml^{-1} \times 10^{-3}$								
		A	B	C	D	E	F	G	H	J
78/12 Barren Liquor Pond	2.8	0.02	nd	nd	nd	nd	nd	-	-	nd
78/13 Pregnant Liquor Pond 1	2.7	0.6	nd	0.37	nd	nd	nd	-	-	nd
78/14 Pregnant Liquor Pond 2	2.6	75	nd	3.6	nd	1.2	nd	-	-	nd
78/15 Acid Liquor Pond	2.6	0.02	nd	0.81	nd	nd	nd	-	-	nd
78/16 Old Bed of East Branch of Finnis River	3.0	0.05	nd	nd	nd	0.4	nd	-	-	0.6
78/18 Pond - Copper Creek	3.0	0.03	nd	7.5	nd	nd	nd	-	-	nd
78/19 Sample Ditch	2.9	5.5	nd	nd	nd	0.09	nd	-	-	0.04
78/17 Rum Jungle Creek S. Opencut - Composite sample	7.1	nd	nd	nd	nd	nd	nd	-	-	nd

A *Thiobacillus ferrooxidans*.

B Sulfur oxidisers (growing on thiosulfate at pH 3.5).

C Sulfur oxidisers (growing on thiosulfate at pH 4.8).

D Sulfur oxidisers (growing on thiosulfate at pH 6.2).

E Acidophilic heterotrophs (Manning's glucose-salts-YE medium).

F Non-acidophilic heterotrophs (Nutrient agar).

G *Desulfovibrio* spp.

H *T.denitrificans*.

J *Chlorella* spp.

Unlike the Intermediate Opencut samples, the samples from White's Opencut showed a high soluble iron content (100 - 252 ppm) with the highest concentrations in the bottom samples Also, except for site 78/9, the concentration of iron in the samples below the oxygen concentration interface was almost double that of samples taken immediately above the interface. The soluble copper levels (70 - 135 ppm) and zinc levels (5 - 6 ppm) were similar to those found in the Intermediate Opencut samples. EDAX examinations showed high levels of magnesium, aluminium, calcium and manganese and lower levels of sodium, silicon, silver and chloride.

The pH of the water samples was significantly lower than in the Intermediate Opencut (2.6 1.8) and decreased from surface to bottom at every sampling site. It is noteworthy also that the temperature profile, while of the same dimensions as that in the Intermediate Opencut, consistently showed higher values at depth than at the surface.

Thiobacillus ferrooxidans populations occurred in all samples with the highest levels in the bottom samples. That from sample site 78/9 contained the highest numbers of the majority of microorganism types with *T.ferrooxidans* the most abundant.

No extreme acidophilic sulfur oxidizers were isolated, but the majority of sites yielded sulfur oxidizers at pH 4.8, some in very high numbers as in samples 78/7/8 and 78/9/8. It is interesting to note that at every site except 78/10, the levels of these organisms increased by an order of magnitude from the sample directly above the interface to the sample immediately below it. Again, the bottom samples supported the highest population levels. Higher pH sulfur oxidizers were detected in only three samples. Acidophilic and non-acidophilic heterotrophs were scarce, being found in only three and two samples respectively.

Desulfovibrio spp. were detected in the bottom samples from every site except 78/10, but unlike the samples from the Intermediate Opencut those from White's Opencut did not contain *T.denitrificans*. The pH of the bottom sediments in White's Opencut is probably too low for the growth of this organism.

The occurrence of *Chlorella* in virtually all samples, including the bottom sediments, is surprising. It has been noted, however, that these organisms, from both opencuts, can develop green colonies under conditions of minimal illumination and may be capable of heterotrophic growth in the dark.

Associated Water Systems

The associated water systems comprising the old collection ponds of the leaching heaps, the old bed of the East Branch and Copper Creek contain small volumes of water as compared with the two opencuts and during the dry season may almost completely dry up. The leachin heaps are still yielding iron, copper, zinc and other metals at a low rate and this circum stance together with the evaporative effect no doubt explains the very high soluble metal content at some sampling points (e.g. 78/14, with 8 and 25 g l^{-1} of iron and copper, respectively). EDAX analysis of the sample from 78/14 showed substantial levels of magnesium, aluminium, silicon, phosphorus, calcium, manganese and nickel).

T.ferrooxidans was present in all samples and sulfur oxidizers (pH 4.8), acidophilic heterotrophs and *Chlorella* were present in a number of samples.

By comparison with the samples from the opencuts and the associated water systems, Tables 5 and 6 contain data on a composite sample from the Rum Jungle Creek South Opencut. It will be noted that although the water solubles concentration is comparable to that from the Intermediate Opencut samples, no soluble iron, copper or zinc were detected. The pH was at neutrality and no bacterial populations were isolated on any of the media employed.

CONCLUSION

It might be expected that the water quality in a flooded opencut would deteriorate and become polluted with acid and soluble metal salts if:

(i) Exposures of sulfide-bearing materials occur in the walls and/or the floor,

(ii) The opencut acts as sump for polluted water from ground drainage systems or the drainage from nearby sulfidic overburden heaps, or

(iii) Sulfidic tailings or residues from extractive processes have been dumped into the opencut and subsequently become water-covered.

The first two factors could apply in the case of the Intermediate Opencut; all three are likely contributors to the deterioration of water quality in White's Opencut. The level of the autotrophic sulfur- and iron-oxidising populations in both opencuts suggests that sulfidic material is still in process of biodegradation and that the final levels of acidic and metallic pollution have not yet been reached. Earlier data on the copper concentrations in both opencuts (Davy, 1975; Khalid and Ralph, 1976) indicate that a significant increase has occurred over the past three years.

In the Intermediate Opencut, the substantial population levels of *T.ferrooxidans* and of sulfur-oxidizing bacteria in the bottom samples suggests some remaining exposures of sulfides; the aerobic status and the pH level would favour continued biodegradation. In White's Opencut, the significant iron levels but low *T.ferrooxidans* populations in the aerobic region above the oxygen concentration interface suggests a slow penetration of ferrous iron into this zone. The high levels of *T.ferrooxidans* populations and of some sulfur-oxidizers in the deeper, micro-aerophilic regions gives rise to the speculation that these organisms could be facilitating the oxidation of residual sulfides in the tailings layer, using ferric iron as an electron acceptor (Brock and Gustafson, 1976). The higher temperature at the bottom of White's Opencut is probably maintained by metabolic heat generation and induces an upward convective flow which carries ferrous iron from the micro-aerophilic zone to the surface aerobic regions.

This preliminary examination has been fruitful in providing a general picture of the microbial status of the two most polluted opencuts and is useful as a basis for the planning of long-term, systematic investigation of the mechanisms by which deterioration of water quality in flooded opencuts occurs. It is clear that the dumping of sulfidic tailings into an opencut may be a most dubious procedure and that an oxygen-depleted water cover provides no guarantee that microbially-catalysed degradation of sulfides will not continue to occur.

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