MANGANESE

There was a small reduction of 26.47% when 10 mg/l of Ba^{2+} solution was added to the wastewater and addition of 20 mg/l did not produce any noticeable change but a gradual reduction of 31.09% and 36.13% in the concentration of manganese was noticed when 30 mg/l and 40 mg/l of Ba^{2+} solution respectively were added (Figure 60).

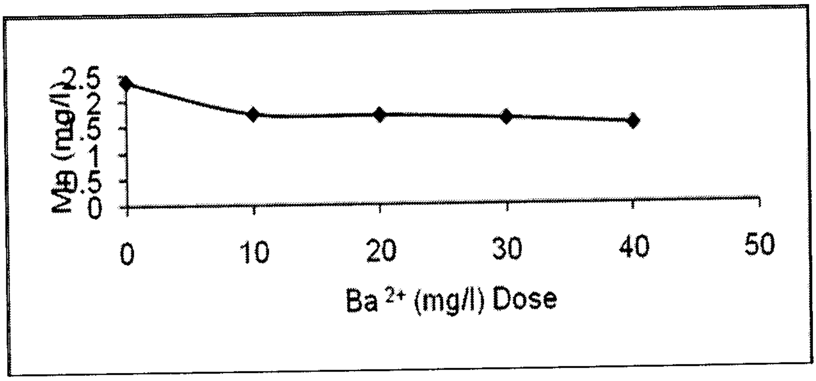

FIGURE 60. Dissolved manganese response to treatment of mine wastewater at NISIR, Lusaka.

NICKEL

When 10 mg/l of Ba^{2+} solution was added to the wastewater, there was a reduction of nickel by 76.12% and subsequent additions produced reductions of 77.61% from 20 mg/l of Ba^{2+}, 77.61% from 30 mg/l of Ba^{2+} and 79.10% from 40 mg/l of Ba^{2+} solution (Figure 61).

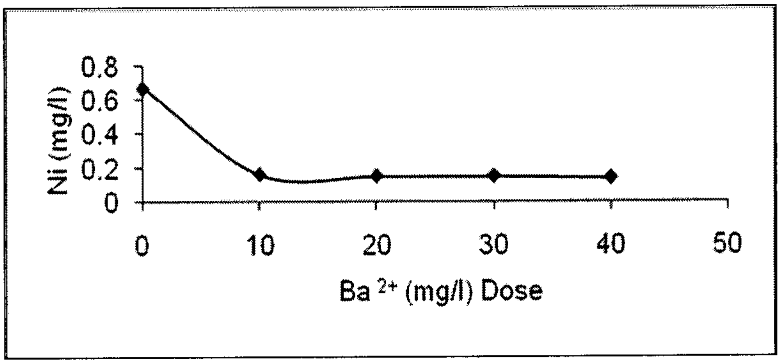

FIGURE 61. Dissolved nickel response to treatment of mine wastewater at NISIR, Lusaka.

LEAD

16.67% reduction was recorded when 10 mg/l of Ba^{2+} solution was added to the wastewater and addition of 20 mg/l Ba^{2+} produced the same effect as 10 mg/l of Ba^{2+}, 16.67 %. Subsequent addition of 30 mg/l of Ba^{2+} effected 33.33% reduction and 40 mg/l of Ba^{2+} effected 50% reduction (Figure 62).

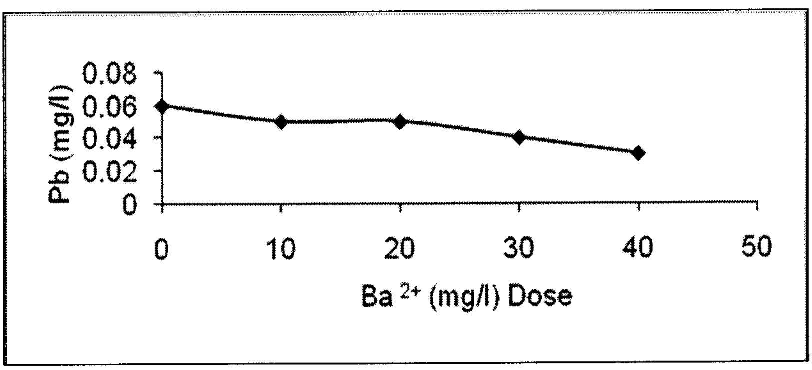

FIGURE 62. Dissolved lead response to treatment of wastewater at NISIR, Lusaka.

ZINC

There was no noticeable response of zinc to the treatment of wastewater with Ba $^{2+}$ solution because the zinc ions did not react with barium ion solution (Figure 63).

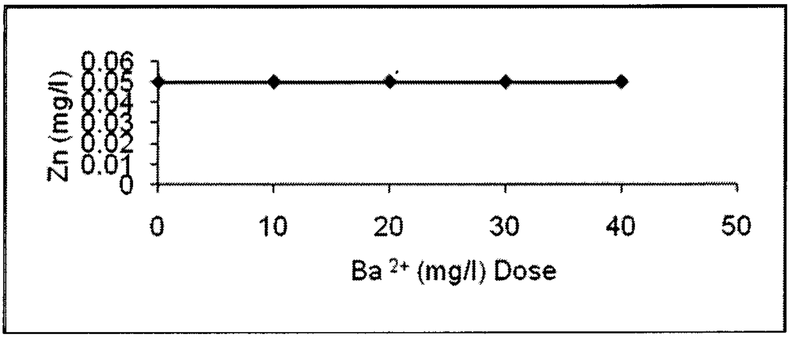

FIGURE 63. Dissolved zinc response to treatment of wastewater at NISIR, Lusaka.

RADIUM 226 (^{226}Ra)

When 10 mg/l of Ba^{2+} solution was added to the wastewater, a reduction of 8.60% was noticed. Addition of 20 mg/l of Ba^{2+} solution reduced ^{226}Ra by 62.37%. There was a major reduction by 95.70% when 30 mg/l of Ba^{2+} was added to the wastewater. 40 mg/l Ba^{2+} solution also produced the same reduction of 95.70% (Figure 64).

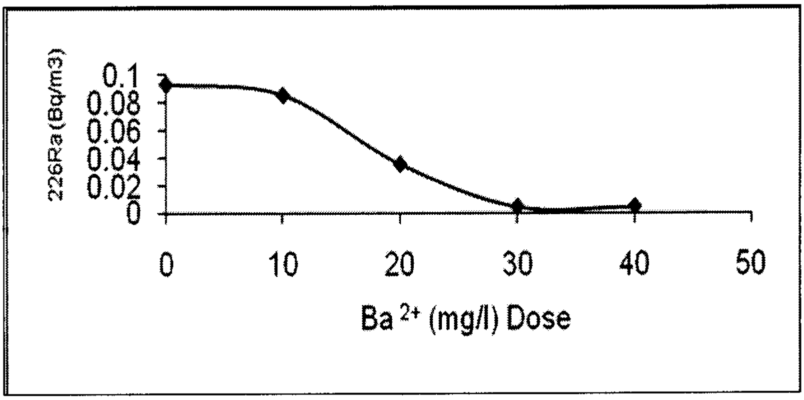

FIGURE 64. Dissolved radium 226 response to treatment of wastewater at NISIR, Lusaka.

The results obtained were expected, as the barium ions reacted with sulphates in wastewater to form a precipitate which later co-precipitated the radium 226 along side with other metallic ions and settled out of wastewater as sludge.

RADIUM 228 (^{228}Ra)

The initial addition of 10 mg/l of Ba^{2+} to the wastewater produced a reduction of 37.50% of radium-228. Addition of 20, 30 and 40 mg/l of Ba^{2+} produced 62.50% reduction in the concentration of ^{228}Ra (Figure 65).

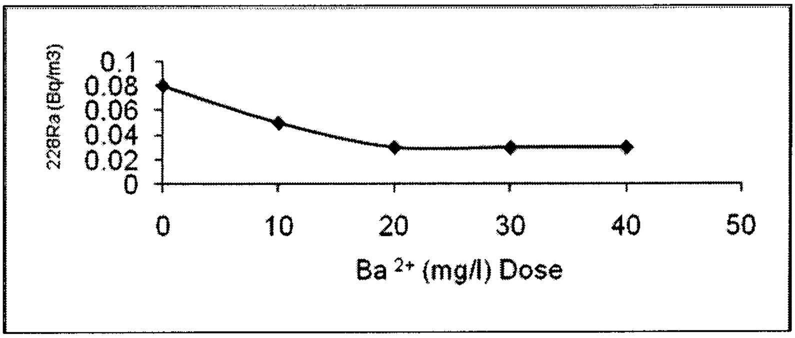

FIGURE 65. Dissolved radium 228 response to treatment of wastewater at NISIR, Lusaka.

7.3.2 BARIUM DOSE SENSITIVITY TEST RESULTS

(Path of Steepest Ascent (PSA) test 2)

From the response results of radium isotopes (^{226}Ra and ^{228}Ra) to Ba $^{2+}$ solution treatment (Table 9), it was observed that the effective reduction of radium isotopes occurred with the dose of 30 mg/l of Ba $^{2+}$ solution.Therefore, the wastewater was treated with incremental dosage of 28, 29, 30, 31 and 32 mg/l of Ba^{2+} with the view to observe the sensitivity of radium isotopes to small change of Ba $^{2+}$ dose. This was to aid at arriving atthe treatment dose for radium isotopes in mine wastewater (Table 10).

TABLE 10. Barium dose sensitivity results

Ba^{2+} dose (mg/l)	pH	SO_4^{2-} (mg/l)	Cu (mg/l)	Co (mg/l)	Fe (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)	^{226}Ra (Bq/m^3)	^{228}Ra (Bq/m
28	7.69	1445.76	0.10	0.55	1.00	1.49	0.13	0.04	0.05	0.035	0.03
29	7.69	1440.54	0.10	0.55	1.00	1.49	0.13	0.04	0.05	0.020	0.03
30	7.69	1439.47	0.10	0.55	1.00	1.49	0.13	0.04	0.05	0.010	0.03
31	7.69	1434.24	0.10	0.55	1.00	1.49	0.13	0.04	0.05	0.004	0.03
32	7.69	1429.57	0.10	0.55	1.00	1.49	0.13	0.04	0.05	0.004	0.03

7.3.2.1 GRAPHICAL PRESENTATION OF SENSITIVITY TESTS 2 RESULTS

SULPHATES

There was a gradual response of sulphates to small incremental change of Ba^{2+} solution (Figure 66).

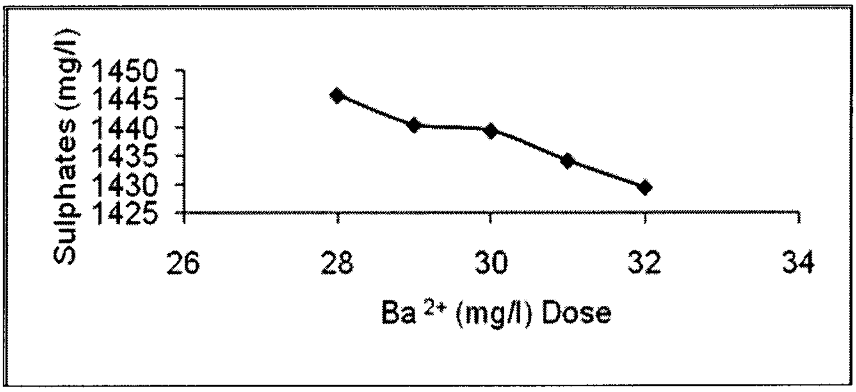

FIGURE 66. Sulphate response to sensitivity treatment of wastewater at NISIR, Lusaka.

HEAVY METALS (Cu, Co, Fe, Mn, Ni, Pb, Zn)

All heavy metals under investigation did not show any noticeable change to incremental addition of 28, 29, 30, 31 and 32 mg/l of Ba^{2+} to wastewater.

RADIUM 226 (^{226}Ra)

There was a corresponding steady decrease in the concentration of radium -226 with the incremental addition of 28, 29, 30, 31 and 32 mg/l of Ba^{2+} barium solution to the wastewater (Figure 67).

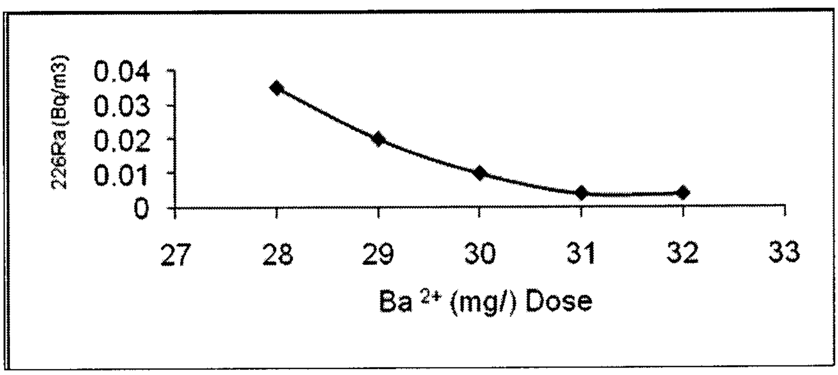

FIGURE 67. ^{226}Ra response to sensitivity treatment test of wastewater at NISIR, Lusaka.

RADIUM 228 (^{228}Ra)

There was no noticeable change after the incremental addition of 28, 29, 30, 31 and 32 mg/l of barium solution to the wastewater (Figure 68). This could be due to non free reactive ions present.

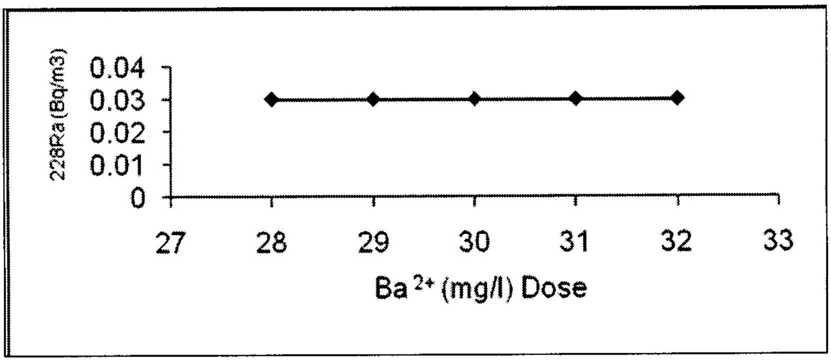

FIGURE 68. ^{228}Ra response to sensitivity tests of wastewater at NISIR, Lusaka.

From the sulphates (Figure 66) and radium-226 (Figure 67) results, it can be concluded that there was a reaction of sulphates and barium to form barium sulphate precipitate which later co-precipitated with radium-226.

7.4. SELECTION OF COAGULANT REAGENT RESULTS

It was observed that the mine wastewater settled faster after addition of ferric chloride than aluminum sulphate of same concentration. With addition of 6 mg/l of ferric chloride, the clarity of wastewater was reading 7 NTU while the same quantity of aluminum produced clarity of 12 NTU (Table 11 and 12).

TABLE 11. Aluminum Sulphate Coagulant settling tests at NISIR, Lusaka.

Al^{3+} (mg/l)	Turbidity (NTU)
0	31
2	27
4	13
6	12
8	10

TABLE 12. Ferric Chloride Coagulant settling tests at NISIR, Lusaka.

Fe^{3+} (mg/l)	Turbidity (NTU)
0	32
2	25
4	12
6	7
8	7

The treatment strategy developed in the laboratory at NISIR was a continuous process, therefore, it was important to use a coagulant that promotes fast settling of particles in a shortest period of time of the wastewater treatment process.

7.5. PRECIPITATION OPTIMIZATION RESULTS

The precipitation and flocculation optimization experiments made extensive use of factorial designs to screen variables efficiently and to give estimates of the independent effect of each variable.

Barium dose was fixed at 31.0 mg/l as Ba^{2+} determined from sensitivity tests (Table 10) during bench scale tests and the mixing speed and time was set at 70 rpm and 10 minutes respectively, there was a reduction of ^{226}Ra from 0.92 Bq/m^3 to 0.035 Bq/m^3 and ^{228}Ra from 0.08 Bq/m^3 to less than 0.03 Bq/m^3.

In the second trial test, the speed was set at 35 rpm and mixing time of 10 minutes, the reduction of ^{226}Ra was 0.02 Bq/m^3 and ^{228}Ra was less than 0.03 Bq/m^3 (Table 13).

TABLE 13. Radium precipitation optimization at NISIR, Lusaka.

A	B	C	D	E
Ba^{2+} dose (mg/l)	**Mix Speed (rpm)**	**Mix Time (minutes)**	**^{226}Ra (Bq/m^3)**	**^{228}Ra (Bq/m^3)**
31	70	10	0.035	<0.03
31	35	10	0.020	<0.03
31	**70**	**20**	**<0.003**	**<0.03**
31	35	20	0.004	0.08

In the third trial test, mixing speed was 70 rpm and mixing time of 20 minutes, the reduction of ^{226}Ra was less than 0.003 Bq/m^3 and ^{228}Ra was also less than 0.03 Bq/m^3.

The last test was keeping the mixing speed at 35 rpm and mixing time at 20 minutes, the reduction of ^{226}Ra was 0..4 Bq/m^3 and ^{228}Ra was 0.08 Bq/m^3. Therefore, the greatest reduction of both ^{226}Ra and ^{228}Ra to less than 0.003 and 0.03 Bq/m^3 respectively achieved when the mixing speed was set at 70 rpm and mixing time of 20 minutes.

7.6 REMOVAL EFFICIENCY OF THE PROPOSED TREATMENT STRATEGY AT MCM, KITWE.

From the results obtained from the laboratory treatment of mine wastewater (TTF) composite sample, 31 mg/l of Ba^{2+}, with 6 mg/l of Fe^{3+} as a coagulant at mixing speed of 70 rpm with mixing time of 20 minutes were added and the efficiency of the proposed treatment strategy was calculated.

7.6.1 METALLIC IONS DECONTAMINATION RESULTS

First the decontamination of heavy metals from mine wastewater was calculated by adding the sum of all metallic ions under investigation before treatment (BT) and after treatment (AT) as indicated in Table 14.

TABLE 14. Total dissolved metallic ions (mg/l) before and after treatment of wastewater at NISIR, Lusaka.

Element	**Before Treatment (BT)**	**After Treatment (AT)**
Copper	1.33	0.10
Cobalt	3.14	0.61
Iron	1.27	1.03
Manganese	2.38	1.64
Nickel	0.67	0.15
Lead	0.06	0.04
Zinc	0.05	0.05
TOTAL	**8.90**	**3.62**

Decontamination Factor (D.F) for metallic ions after treatment was

therefore, D.F = BT / AT

= 8.90 / 3.62

= **2.46**

Therefore, the percentage removal of heavy metals after treatment was

59.33% which is not very different from **59.21%** obtained before treatment of the wastewater with Ba^{2+} solution. This simply meant that the treatment of mine wastewater with 31 mg/l Ba^{2+} did **NOT** have any noticeable effect on metallic ions under investigation.

7.6.2. RADIONUCLIDES DECONTAMINATION RESULTS

The same approach of summing the dissolved radionuclides before and after treatment (Table 15) was employed in the determination of the efficiency the proposed treatment strategy.

TABLE 15: Total dissolved radionuclides (Bq/m^3) before and after treatment of wastewater at NISIR, Lusaka.

Radio nuclides	Before Treatment (BT)	After Treatment (AT)
^{226}Ra	0.093	0.003
^{228}Ra	0.030	0.030
TOTAL	**0.123**	**0.033**

Decontamination Factor, D.F for radio nuclides after treatment was

therefore, D.F = BT / AT

= 0.123 / 0.033

= **3.73**

The percentage removal of radio nuclides after treatment was **73.17%** which was almost twice the efficiency of **43.09%** for the current treatment strategy at MCM, Kitwe. This meant that the treatment strategy employed at laboratory scale was very effective for radio nuclides treatments than metallic ions treatment.

CHAPTER EIGHT

8.0 PROCESS DESIGN FOR FULL SCALE TREATMENT PLANT AT MCM IN KITWE

OVERVIEW

From the bench scale treatment tests, it was possible to design a full scale treatment plant at Mopani Copper Mine (MCM) in Kitwe to treat 75000 m^3/day of mine wastewater. This involved drawing up the process flow sheet, developing the process design criteria, calculating the material balances and the plant layout. The hydraulic profile was not calculated but was estimated from the current treatment plant at MCM.

8.1 TREATMENT PROCESS FLOW SHEET

The proposed treatment plant will consist of two reactors in series, a vessel for rapid mixing of ferric chloride, two flocculators and two clarifiers (Figure 69). The basis for this selection was based on the large volume (75000 m^3/day) of wastewater generated at Mopani Copper Mines in Kitwe.

The wastewater was mixed with the barium chloride (31 mg/l as Ba^{2+}) and fed to the first reactor fitted with a pH probe to monitor the pH of the wastewater. Hydrated lime was added to it to bring the pH to the range of 8 – 9 at which the removal of radio nuclides was effected. To achieve homogeneity of the solution, the wastewater was fed to the second reactor to complete the precipitation process with detention time of 20 minutes..

From the precipitation stage, the wastewater was fed to the rapid mixing vessel for approximately 2 minutes rapid mixing where the coagulant ferric chloride (6mg/l as Fe^{3+}) was added to aid flocculation of the precipitate, barium-radium sulphate – $RaBa(SO_4)_2$.

The next stage in the process was the flocculation process of the formed precipitate with the detention time of 20 minutes. This was promoting building up of the precipitate in mass for easy separation in the next stage of the process although the results were not as good as those obtained under batch experiments. This was because aggregation time needed to be increased under continuous flow conditions.

The final stage in the treatment process was the clarification of the wastewater where the precipitate was separated as sludge from the effluent and the effluent was discharged to the drainage. During the test 4 samples were taken for radium and heavy analyses (Table 15 and 16) and results demonstrated that dissolved radium isotopes target of 0 Bq/m^3 could be met under continuous- flow conditions, but at a very low flow rate 0.5 l/min.

The proposed treatment process at MCM will be automated to regulate the pH of the mine wastewater to the range between 8 and 9 at which optimum precipitation of radionuclides occurs. In the event that the pH falls to acidic levels, the lime will automatically be discharged into the reactor to promote precipitation.

Schematic diagram for the proposed mine wastewater treatment process at MCM, Kitwe.

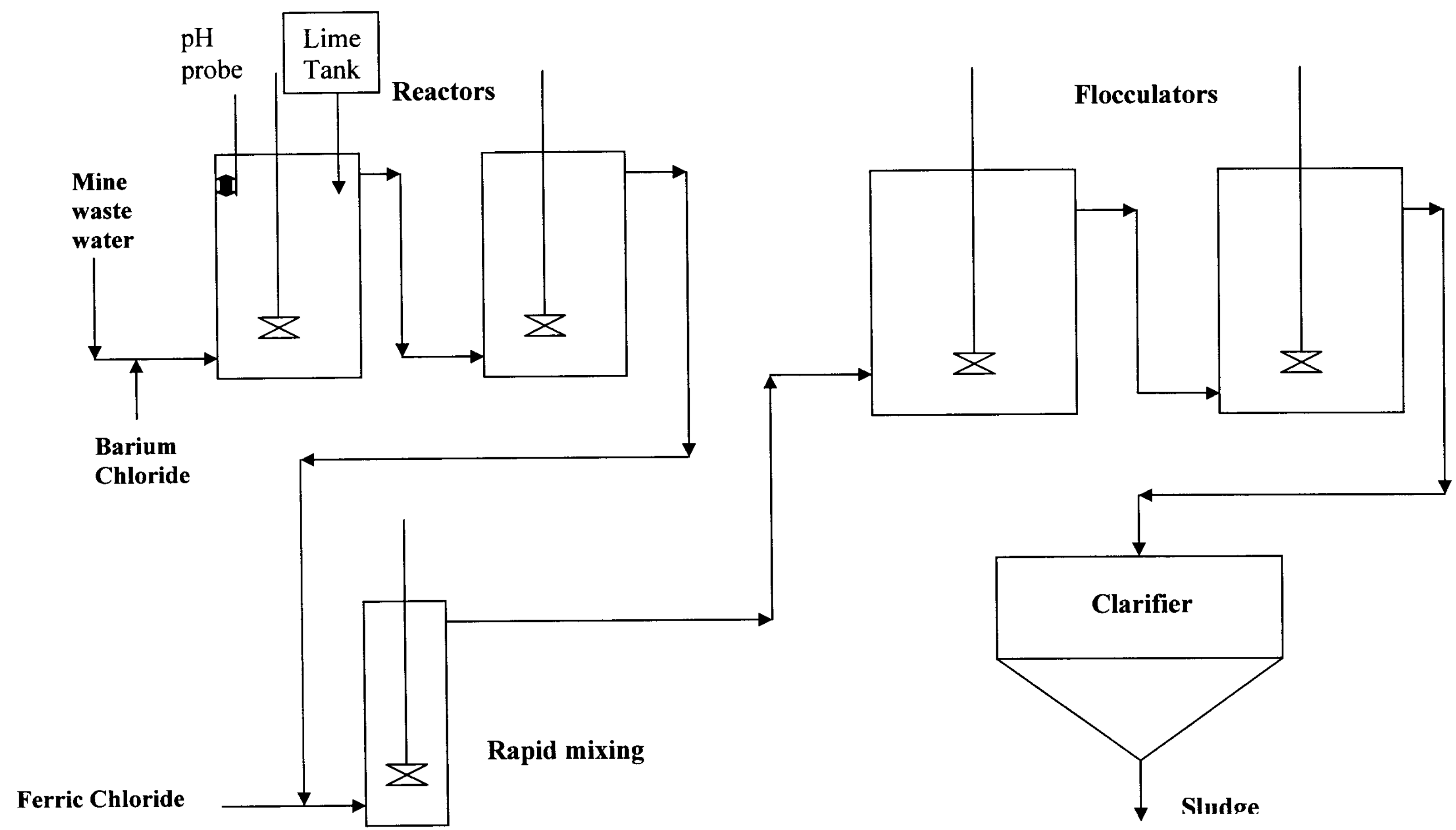

FIGURE 69. Schematic diagram for the proposed mine wastewater treatment process at MCM, Kitwe.

8.2 PROCESS DESIGN CRITERIA FOR CONTINUOUS FLOW PROCESS

From the laboratory tests, the optimal operating conditions to achieve maximum decontamination of dissolved radio nuclides from mine wastewater are given in Table 16.

TABLE 16. Optimal Operating Parameters for radionuclides removal at NISIR, Lusaka.

Operation	Parameter	Setting
Precipitation	Ba^{2+} dose	31 mg/l
	Detention time	20 minutes
Rapid mixing	Coagulant and dose	Fe^{3+} @ 6mg/l
	Detention time	2 minutes
Flocculation	Detention time	20 minutes
Clarification	Detention time	60 minutes

To design a treatment plant for Mopani Copper Mines to treat 75000 m^3/day (0.87 m^3/sec) of wastewater, the sizes of the physical facilities was required. These are briefly described below.

8.2.1 REACTOR VOLUME

Assuming steady state operations where there are no accumulations, the volume of the Continuous Stirred Tank Reactors (CSTR) was calculated using the following design equation:

$$V = F_{AO}\, X / (-r_A) \quad \text{.......} \quad (1)$$

Where;

V = Volume of the reactor

F_{AO} = the molar flow rate at which A is fed to the system

X = the convention

$-r_A$ = the rate of reaction

From the laboratory tests, the total activity (^{226}Ra & ^{228}Ra) in the feed was 0.123 Bq/m^3, the total activity in the discharge was 0.034 Bq/m^3, total activity removed (reacted) was 0.089 Bq/m^3 (0.123 - 0.034).

Therefore, conversion (x) of radio nuclides in the precipitation reaction was;

= Activity of radionuclide reacted / Activity of radionuclide fed

= 0.089 / 0.123

= **0.72**

The reaction rate constant ($-r_A$) for co-precipitation of barium ions is 1000 pCi/l to 3 pCi/l in 15 minutes (1.1 1 pCi/l.sec) (Schmidtke and Smith, 1983).

Converting Curies (Ci) per litre to Becquerel per cubic meter.

Given that 1 Ci = 3.7 *10^{10} Bq.
The reaction rate of 1000 pCi to 3pCi was therefore equivalent to 37000 Bq/m^3 to 111 Bq/m^3 in 15 minutes. Therefore, the rate of reaction ($-1/r_A$) was 40.99 Bq/m^3 .sec.

The activity of radio nuclides flowing into the reactor was 0.123 Bq/sec (Table 15).

Therefore, the volume of the reactor was;

$$V = F_{AO} X / (-r_A)$$

$$V = 40.99 \text{ m}^3\text{.sec/Bq} * 0.123\text{Bq/sec} * 0.72$$

$$= 5.67 \text{ m}^3$$

$$\approx \underline{\mathbf{6.0\ m^3}}$$

But taking into consideration the free-board of 0.5 m^3 in reactor (volume above the reactor not occupied by material), the actual volume of the reactor becomes **6.5 m^3**

Given reactor volume of the reactor = 6.0 m^3 with diameter of 1.5 m, therefore the height of the tank will be:

The height of the reactor will be:

$$V = \pi r^2 h$$

$$h = 3.68 \text{ m} \approx 3.7 \text{ m}$$

The diameter of the cylindrical reactor is 1.5 meters.

Therefore, the dimension of the reactor will be; 3.5 m * 1.5 m (Figure 70).

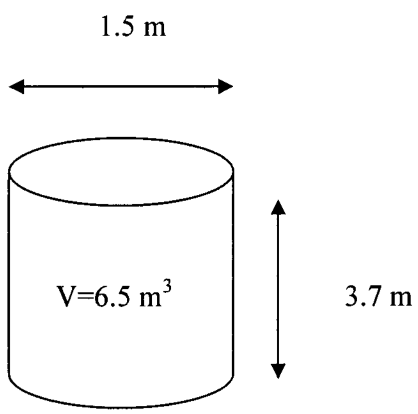

FIGURE 70. Sketch of the proposed Continuous Stirred Tank Reactor at MCM, Kitwe.

The total volume of 2 reactor tanks in series becomes:

$$= \mathbf{13.0\ m^3}$$

8.3 RATE OF FLOW OF FEED (WASTEWATER) INTO THE REACTOR

The maximum mine wastewater generated per day at Mopani Copper Mine is 75000 m^3/day (0.87 m^3/sec). From laboratory bench scale of Continuous Stirred Tank Reactor (CSTR) tests, the optimum residence time in the reactor was 20 minutes (1200 seconds). Therefore, the rate of flow of feed into the reactor will be:

Volumetric flow rate = Volume / Residence Time

$= 6.5 m^3 / 1200$ sec

$= 5.42 * 10^{-3} m^3/sec$

$\approx$ 5.4 liters/sec

Therefore, the rate of flow of feed into the reactor will be **$5.4 * 10^{-3} m^3/sec$.**

8.3.1 RAPID MIXING VESSEL VOLUME

Assuming constant rate of flow of feed in the treatment process, $5.4 * 10^{-3} m^3/sec$, the volume of the rapid mixing vessel with residence time of 2 minutes will be:

Feed Rate = Volume of vessel / Residence Time

Therefore, the volume of the vessel will be:

$V = 120 \text{ sec} * 5.4 * 10^{-3} m^3/sec$

$= 0.6 m^3$

= 600 litres

The dimensions of the vessel will be:

Given vessel volume = $0.6 m^3$ and diameter of 0.5 m.

The height of the vessel will be:

$V = \pi r^2 h$

$h = 3.06$ m

$\approx$ 3.0 m

The dimension of rapid mixing vessel will be of height 3.0 m, volume of $0.6 m^3$ and 0.5 m in diameter (Figure 71).

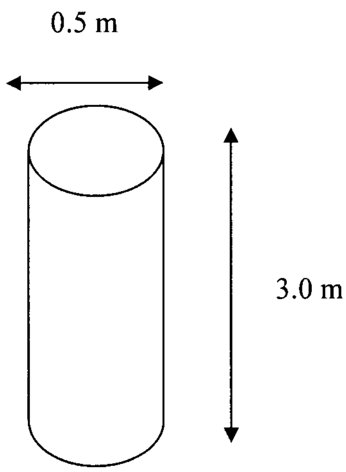

FIGURE 71. Sketch of the proposed rapid mixing tank at MCM, Kitwe.

8.3.2 FLOCCULATION VESSEL VOLUME

The estimated residence time in the flocculators of 20 minutes, therefore, the volume of the flocculators will be:

Volume = Volumetric Flow Rate (m^3/sec) * Residence Time (sec.)
= 1200 sec * 5 * 10^{-3} m^3/sec
= **6.0 m^3**

The dimension of the flocculation tanks will be as in Figure 72;

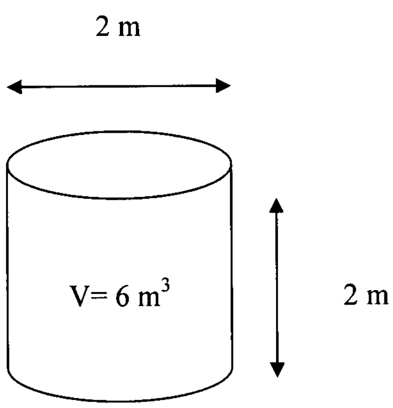

FIGURE 72. Sketch of the proposed flocculator vessel at MCM, Kitwe.

8.3.3 SEDIMENTATION TANK CAPACITY - UPFLOW

The overflow rate of sedimentation tanks is usually given a value from 20 to 30 m^3/m^2.day (Morley, 1979).

Maintaining constant flow rate of feed at $5 * 10^{-3}$ m^3/sec and detention time of 60 minutes, the volume of the tank was calculated as follows:

Surface area = $[5 * 10^{-3}\ m^3/sec * 24 * 3600\ sec]/ 20\ m^3/m^2$.

$= \mathbf{21.6\ m^2}$

$\approx \mathbf{22\ m^2}$

The tank is circular; therefore, surface area $= \pi D^2 /4$

Therefore, diameter of the sedimentation tank will be; = **5.2 m**

And since the tank will consist of a 1 m deep cylinder followed by a cone (Morley, 1979), then, initially, the depth of the cone will be:

$H = [5.2 /2]/ \tan 30^o$

$= \mathbf{4.5\ m}$

If the depth is made 4.5 m, then there will be a flat-bottomed inverted cone with a width on the flat of about 0.2 m. Therefore, the volume of the cone (detention time of 1 hour) will be calculated as follows:

The total volume of sedimentation tank required will be:

Volume = Detention Time * Flow rate of feed

$= 3600\ sec * 5 * 10^{-3}\ m^3/sec$

$= \mathbf{18\ m^3}$

The volume of the cylindrical top part will:

Volume $= \pi * r^2 h$

$= 8.17\ m^3$

$\approx \mathbf{8\ m^3}$

The volume of the conical bottom will be as given in Figure73.

$= 18 - 8\ m^3$

$\mathbf{= 10\ m^3}$

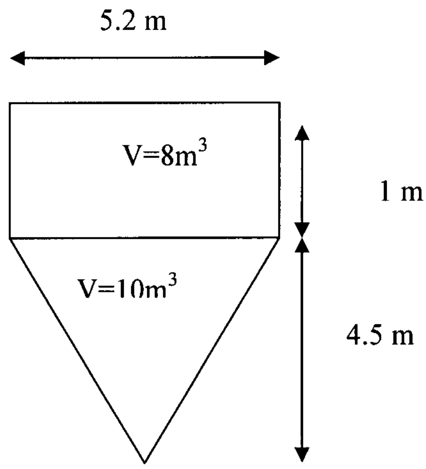

FIGURE 73. Sketch of proposed sedimentation tank at MCM. Kitwe.

8.4 MATERIAL BALANCE FOR THE PROCESS

To aid the co-precipitation of radium, barium chloride was chosen as an agent. During laboratory testing, the capabilities of this agent were proven. The chemical reaction is as follows;

$$\mathbf{BaCl_2 \leftrightarrow Ba^{2+} + 2Cl}$$

Firstly, the barium chloride dissolves in water. The next step of the reaction is the co-precipitation of radium and barium ions as sulphates (in the case of radium reaction, it is not stoichiometric) (IAEA-TECDOC-1472, 2005).

$$\mathbf{Ba^{2+} + SO_4^{2-} \quad = \quad BaSO_4}$$
$$\mathbf{BaSO_4 + Ra^{2+} \quad = \quad BaRa\ (SO4)^{2+}}$$
$$\mathbf{BaRa\ (SO_4)^{2+} + SO_4^{2-} \quad = \quad BaRa\ (SO_4)_2} \quad \text{(mesothorium)}$$

Since the co-precipitation of radium 226 to barium sulphate was not stoichiometric, the calculation of material balance was based on the mass of the heavy metals and radionuclides in the feed and in the output.

The material balance was based on the baseline data generated from laboratory scale Continuous Stirred Tank Reactor (CSTR) mine wastewater treatment tests. This data can be used to scale-up to the full scale treatment plant with the capacity to treat 75,000 m^3/day of mine wastewater at MCM, Kitwe.

Applying the law of mass conservation;

Input = Output + Accumulation

Data available

Total dissolved heavy metals in feed = 8.9 mg/l

Total dissolved radionuclides in feed = 0.173 Bq/m^3

Heavy metals removed after treatment = 59.33%

Radionuclides removed after treatment = 73.17%

Converting the activity (Bq/m^3) to mass for radionuclides given that 1 Curie of activity is equivalent to $3.2 * 10^6$ g (Kaplan, 1972).

Since $1 \text{ Ci} = 3.7 * 10^{10}$ Bq

Therefore,

$$1 \text{ Bq} = 0.865 * 10^{-4} \text{ gm}$$

Therefore, 0.173 Bq//m^3 is equivalent to $1.5 * 10^{-5}$ mg/l

Basis for material balance was 100 kg of mine wastewater and assuming the wastewater density is 1000 kg/m^3 and the results are summarized in Table 18.

Input (TTF) composition before treatment

Radio nuclides input = $1.5 * 10^{-5}$ mg/l which is equivalent to $1.5 * 10^{-5}$ ppm.

Therefore, in 100 kg mine wastewater, we have;

$1.5 * 10^{-9}$ kg of radionuclides.

Heavy metals input = 8.9 mg/l equivalent to 8.9 ppm. Therefore, in 100 kg of wastewater, we have;

$8.9 * 10^{-4}$ kg of heavy metals

Output composition after treatment

Effluent Overflow (TTO)

Radio nuclides output = $2.85 * 10^{-6}$ mg/l (Table 15) which is equivalent to $2.85 * 10^{-6}$ ppm.

Therefore, in 100 kg mine wastewater, we have;

$2.85 * 10^{-10}$ kg of radionuclides discharged to water courses.

Heavy metals output = 3.62 mg/l (Table 14) equivalent to 3.62 ppm. Therefore, in 100 kg of wastewater, we have;

$3.62 * 10^{-4}$ kg of heavy metals discharged to the water courses.

The material balance befpre and after treatment is summarized in Table 17.

Radionuclides

Input = $1.5 * 10^{-9}$ kg

Output = $2.85 * 10^{-10}$ kg

Heavy metals

Input = $8.9 * 10^{-4}$ kg

Output = $3.62 * 10^{-4}$ kg

TABLE 17. Material balance of components in mine wasteswater on 100 kg basis.

Component	Input (kg)	Output (kg)
Radionuclides	$1.5 * 10^{-9}$	$2.85 * 10^{-10}$
Heavy metals	$8.9 * 10^{-4}$	$3.62 * 10^{-4}$

<u>Material Balance on the 75000 m^3/day at MCM, Kitwe</u>

Mass discharge of wastewater per day will be;

Mass discharge =Volumetric * Density of wastewater

= 0.87 m^3/sec * 1089 kg/m^3

= 947.43 kg/sec

Input

Radio nuclides = 947.43 kg /sec * ($1.5*10^{-9}$ /100) = $1.42 * 10^{-7}$ kg/sec

Heavy metals = 947.43 kg/sec * ($8.9 * 10^{-4}$ / 100) = $8.4 * 10^{-2}$ kg/sec

Output

Radio nuclides = $(1.42 * 10^{-7}$ kg/sec) * 73.17 % = $1.04 * 10^{-6}$ kg/sec

Heavy metals = $(8.4 * 10^{-2}$ kg/sec) * 59.33% = $4.98 * 10^{-1}$ kg/sec

The material balance for the proposed 75,000 m^3/day treatment plant at MCM, Kitwe is summarized in Table 18.

TABLE 18. Material balance for the proposed treatment plant at MCM, Kitwe.

Component	Input (kg/sec)	Output (kg/sec)
Radionuclides	$1.42 * 10^{-7}$	$1.04 * 10^{-6}$
Heavy metals	$8.4 * 10^{-1}$	$4.98 * 10^{-1}$

8.5 PROCESS PLANT LAYOUT

Plant layout refers to the spatial arrangement of the physical facilities required to achieve a given treatment objective in most economical flow of materials and personnel around the site. The overall plant layout includes the location of the control and administrative buildings.

Among other factors considered when laying out a treatment plant were as follows:

(i) geometry of the available treatment plant sites,
(ii) topography,
(iii) soil and foundation conditions,
(iv) location of the influent sewer,
(v) location of the point of discharge,
(vi) transportation access,

(vii) types of processes involved,

(viii) effects of the length of process piping on treatment,

(ix) process performance and efficiency,

(x) reliability and economy of operation,

(xi) aesthetics,

(xii) environmental control, and

(xiii) an additional area for future plant expansion.

For the proposed treatment plant at MCM in Kitwe, the plant layout to achieve the objective of removing radio nuclides in mine wastewater (Figure 74) was arrived at by taking into considerations all the units of operations employed at laboratory scale at NISIR, Lusaka.

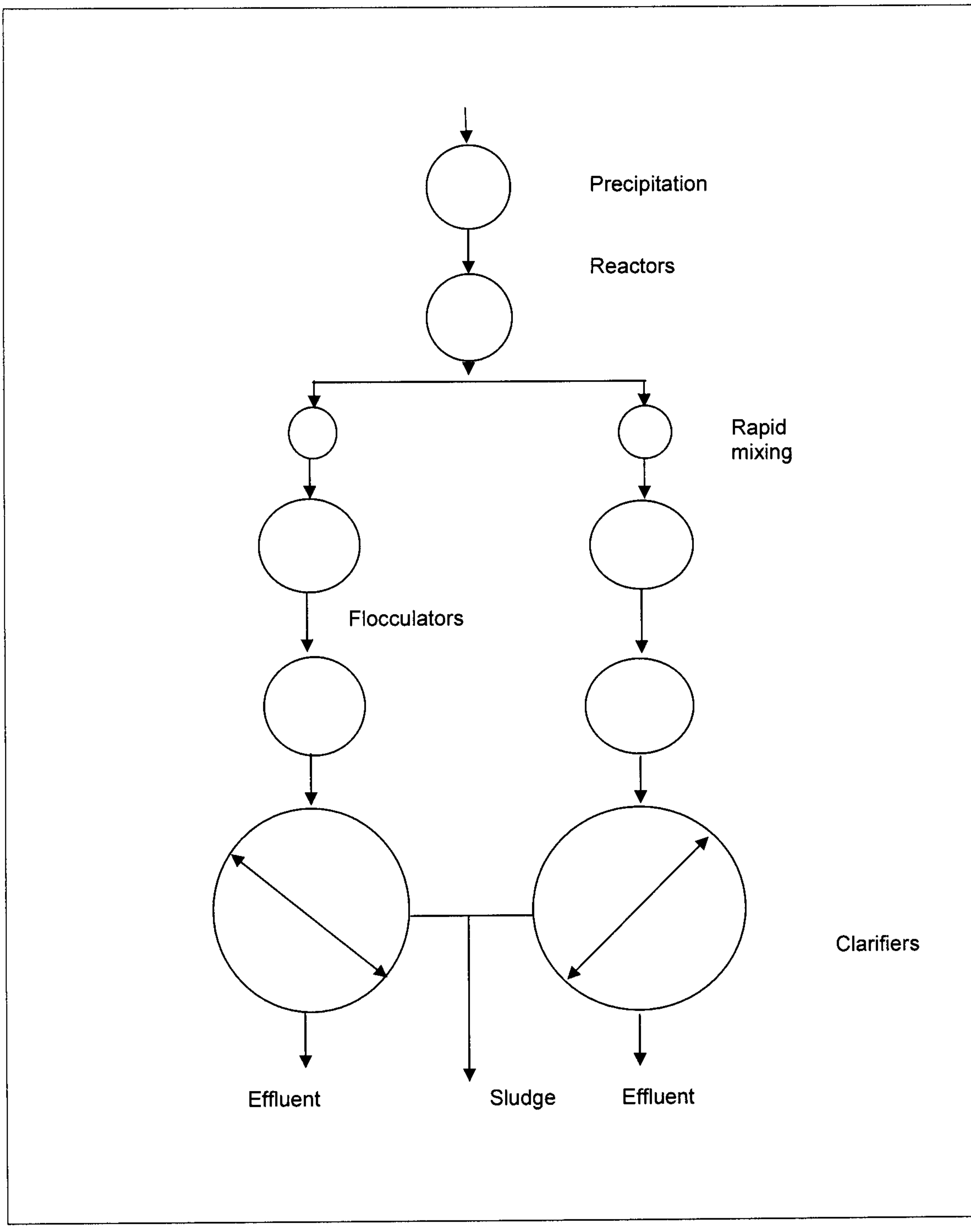

FIGURE 74. Plant layout for the proposed treatment plant at MCM, Kitwe.

8.6 MATHEMATICAL MODELLS FOR UNITS OF OPERATION FOR THE TREATMENT PROCESS OF MINE WASTEWATER AT MCM, KITWE.

OUTLINE

Wastewater treatment processes are inherently dynamic because of the large variations in the influent wastewater flow rate, concentration and composition. Moreover, these variations are to large extent not possible to control.

Mathematical models and computer simulations are essential to describe, predict and control the complicated interactions of the processes. Models are excellent method of conceptualizing knowledge about a process and to convey it to other people.

The number of reactions that are involved in a process maybe very large and an accurate description of such a system can therefore result in highly complex models, which may not be very useful from a practical, operational point of view.

This dissertation contains mathematical models that can be employed to scale-up the treatment process for any volume of mine wastewater at MCM using barium chloride. These models are for the three major units of operation namely; continuous stirred tank reactor for precipitation, coagulation / flocculation and sedimentation processes.

The functions of the three models are:

i. The model for the reactor to calculate the different reactor capacities to treat different concentrations of the radionuclides and heavy metals in mine wastewater.

i. The model for the coagulation/ flocculation to calculate different detention times for the coagulant for different concentration levels of radionucludes and heavy metals.

ii. The model for sedimentation tank to calculate different capacities of the tank for different volumes of mine wastewater.

8.7 MODELLING STRATEGY

Modeling of any system occurs in five rather distinct steps, as illustrated in Figure 75 (Murthy *at. al.*, 1990).

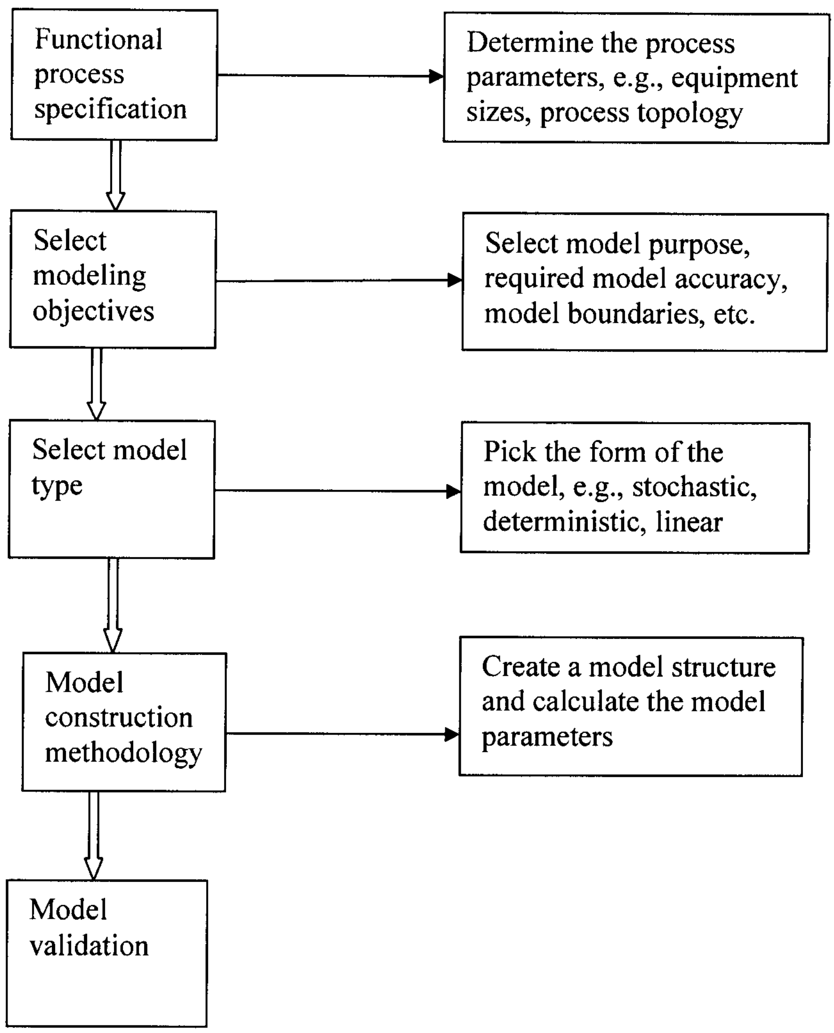

FIGURE 75. An overview of general modeling process. Adapted from Murthty *at.el.*, 1990.

8.8 MODELLING THE CONTINUOUS STIRRED TANK REACTOR (CSTR)

OUTLINE

Chemical reactor design is based on the modeling of reactors and of the reactions that take place in them. The model of a chemical reactor must be sufficiently simple and accurate in bringing out the quantitative aspects of the process. Any mathematical description of a chemical reactor relies heavily on balance equations which express the general laws of conservation of mass and energy.

8.9 MODEL FOR TWO CSTR TANK REACTORS IN SERIES

When a product is to be turned out in large quantities and of a consistent quality, continuous stirred-tank reactor (CSTR) operating under steady–state conditions is considered.

Consider two CSTR in series of perfectly mixed liquid and that a chemical reaction takes place in the liquid in each tank.

Component A reacts irreversibly and at a specific reaction rate k to form a product, component B by first-order reaction occurring in the liquid.

Assuming that the temperatures and holdups (volumes) of the two tanks can be different, but both temperatures and the liquid volumes are assumed to be constant (isothermal and constant volume holdup). Density is assumed constant throughout the system, which is a binary mixture of A and B.

With these assumptions in mind, we formulate a model (Figure 76). If the volume and density of each tank are constant, the total mass in each tank is constant.

Thus, the total continuity equation for the first reactor is

$$d(\rho V_1)/dt = \rho F_o - \rho F_1 = 0 \quad \ldots\ldots 1$$

$$\text{or } F1 = F_o$$

Likewise total mass balances on tank 2 give;

$$F_2 = F_1 = F_o = F$$

Where;

F is the flow rate (m^3/min), and

V is the volume of the tanks (m^3)

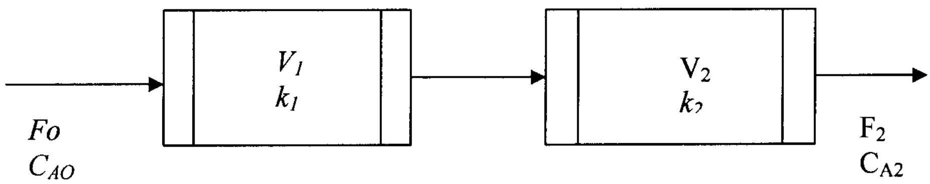

FIGURE 76. Two CSTRs in series in the treatment process at NISIR, Lusaka.

Keeping track of the amounts of reactant A and product B in each tank and knowing the total mass of material in each tank, only one component continuity equation is required. Arbitrarily reactant A is chosen, the equations describing the dynamic changes in the amounts of reactant A in each tank are (with units of kg.mol of A/min)

$$V_1.dC_{A1}/dt = F(C_{AO} - C_{A1}) - V_1 k_1 C_{A1} \quad \ldots\ldots 2$$

$$V_2.dC_{A2}/dt = F(C_{A1} - C_{A2}) - V_2 k_2 C_{A2} \quad \ldots\ldots 3$$

The specific reaction rates k_n is given by the Arrhenius equation.

$$k_n = ae^{-E/RTn} \quad \ldots\ldots 4$$

Where n = 1, 2, (number of stage number)

The volumes, V_n, can be pulled out of the time derivatives because they are constant. The flows are equal to *F* but can vary with time and isothermal operation is assumed.

The two first-order nonlinear ordinary differential equations given in equations 2 and 3 are the mathematical model of the system.

The parameters that must be known are V_1, V_2, k_1, and k_2. The variables that must be specified before these equations can be solved are F and C_{AO}. They can be time-varying, but they must be known or given functions of time. They are the ***forcing functions***.

The freedom of the system can be checked by specifying the three equations and, with the parameters and forcing functions and their three unknowns or dependent variables: C_{A1} and C_{A2}..

If the throughput F is constant and the holdups and temperatures are the same in all tanks, equations 2 and 3 becomes

$$dC_{A1}/dt + (k + 1/r)\, C_{A1} = 1/r.C_{A0} \quad \ldots\ldots 5$$

$$dC_{A2}/dt + (k + 1/r)\, C_{A2} = 1/r.C_{A1} \quad \ldots\ldots 6$$

where r = V/F with units of minutes.

There is only forcing function or input variable, C_{A0}

8.10 MODEL FOR COAGULATION / FLOCCULATION PROCESS

OUTLINE

Coagulation consists of mixing a chemical with the incoming water in order to promote the aggregation of small colloidal particles into a larger mass or floc so that they will be easier to remove by a sedimentation or filtration process. The coagulant is mixed first to form a solution in a rapid mix tank, of detention period 1-3 minutes, or in a turbulent area of the plant such as the hydraulic jump after a weir. After mixing with the incoming water the solution is led into a coagulant tank or into a combined coagulant / sedimentation tank. There the mixing rate is much slower and in the conditions prevailing the colloidal particles form a floc which settles to the bottom of the sedimentation tank.

8.11 MODEL FOR COAGULATION TANKS IN SERIES

The tanks in series, each serving a different function (Figure 77). The first tank is a flash mix tank with a clear water inflow and a concentrated coagulant supply. The wastewater of the flash mix tank is fed into a coagulant tank, where it mixes with the incoming water and reacts with the coagulant to produce a chemical floc nucleus which then, over a short period of time, generates a floc by collecting suspended particles from the inflow. This latter accumulation occurs in a flocculant tank. The timing is organized on the basis of minutes.

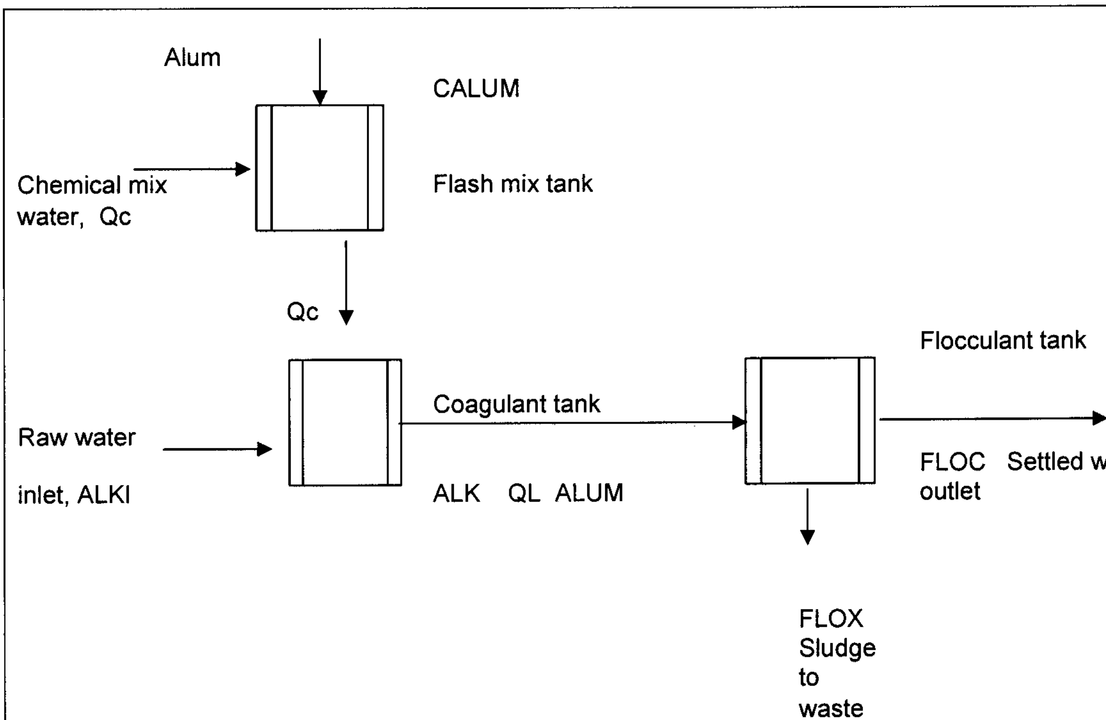

FIGURE 77. Tank layout and programme variables for coagulation and flocculation programme, NISIR, Lusaka.

The detention time in the flash mix tank (D_{FM}) is given by:

D_{FM} = Volume of tank (m^3)/ Volumetric flow rate (m^3/min)

The time flash mix (T_{FM}) is given by:

$T_{FM} = 1/D_{FM}$

The detention time of the coagulant in the coagulant tank is given by:

D_{CO} = Volume of coagulant tank / Volumetric flow rate in tank

The time for coagulation (T_{CO}) is given by:

$T_{CO} = 1/ D_{CO}$

The flow will consist of the raw water plus the liquid from the flash mix tank.

The flocculant tank volume will be:

D_{FL} = volume of the Tank / volumetric flow rate in tank

Where;

D_{FM} = Detention time in flash mix

T_{FM} = Rate of flow in flash mix tank

D_{CO} = Detention time in coagulator tank

Tco = Rate of flow in coagulator tank

D_{FL} = Detention time in the flocculator tank

TFL = Flow rate in the flocculator tank

The flash mix tank is treated as a non-biological CSTR; the variable name used is ALUM:

DALUM = (CALUM – ALUM) * T_{FM}

ALUM = INTGRL (ALOI, DALUM)

CALUM is the input concentration. If the input is in the form of a powder, it would be necessary to calculate the ALUMI as in units/time at flow per unit time.

The coagulant tank has as inflow ALUM, and the raw water ALK. The reaction here is a first –order reaction but there is also inflow and outflow and, there are two reactions:

DALK = (ALKI – ALK) * T_{CO} – K3*Y* ALUM

DALUM = (ALUMI – ALUM) * T_{CO} – K3*ALUM

The Y is used to adjust for less alkalinity being destroyed than ALUM.

8.12 SEDIMENTATION PROCESS MODEL

OUTLINE

Since sedimentation is a well-known physical process which occurs naturally in water, as evidenced by the presence of alluvial plains, it is not surprising that it was readily adopted for the removal of suspended matter from wastewater.

In spite of this long history, the prediction of the performance of sedimentation tanks, particularly when treating heterogeneous suspensions, is not an established practice. In many cases it would appear that variations in the nature of the suspension are likely to have greater effects on the sedimentation process than differences in tank design or operation.

The basic concept of the removal of suspended particles from a fluid by gravitation forces is one which is deceptively simple and which lends itself to mathematical approach. Thus the formulation of Stoke's law,

$$V_S = \frac{gd^2(S_s - 1)}{18\upsilon}$$

Where,

V_s = settling velocity
g = acceleration due to gravity
S_s = specific gravity of particle
P_w= density of water
d = diameter of particles
v = kinematics viscosity of water

permits the calculation of theoretical setting velocities for spherical discrete particles under quiescent laminar flow conditions. The effect of particle shape on settling velocity is not likely to be significant at the velocities normally encountered in water treatment. The limitations as to discrete particles and quiescent conditions are much more restrictive (James, A. 1978).

8.13 MODEL FOR UPWARD FLOW SEDIMENTATION TANKS

Upwards flow tanks have their flow upwards from the bottom in a hoppered bottom tank which normally is square, or circular. The side slope of the hopper bottom is of the order of 60 ° and at this slope sludge will not cling but slides to the bottom of the tank when no inflow occurs. The inflow is usually led to the centre of the tank (Figure 78), and discharged into a vertical tube.

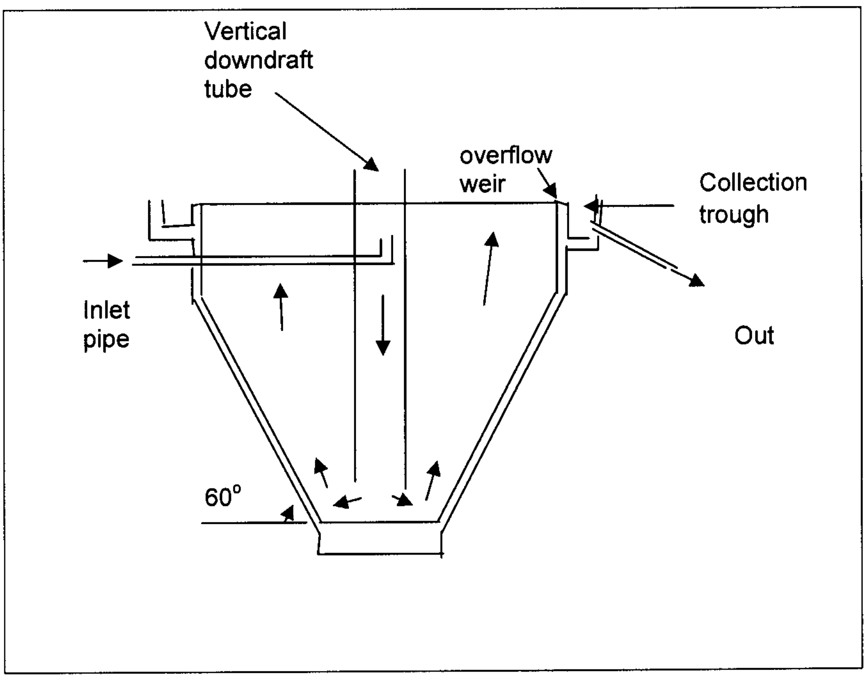

FIGURE 78. An example of a typical upward flow sedimentation tank.

Flow is down the tube, out the end and upwards into the expanding areas of the tank. As the flow rises, the diameter of flow increases and the vertical velocity decreases. Somewhere in the upward flow its velocity equals that of the suspended particles settling and a concentration of particles occurs which causes a situation to occur akin to the flow of particles through pipes with resultant interferences; this is called hindered settling. It means that the particle accumulation is such that water is displaced as it settles and, because of particle density, the water has to move through smaller passages which restrict the flow and cause a loss efficiency, which is caused by energy transfer and power dissipation.

This power dissipation can be likened to the effect of stirring, and under the conditions where it will promote the growth of a floc, the removal rate is enhanced:

$$U_h / U_s = fe^4 \text{ approximately}$$

Where;

U_h = hindered settling velocity

U_s = unhindered settling velocity

fe=porosity, i.e. volume (space) in volume of suspension

Porosity can be calculated from concentration:

$$D = M/Vol$$

$$Vol = M/D$$

$$fe = (1\text{-}C/D/10^6)$$

Where;

D = density (ML^{-3})

M = mass (M)

Vol = volume (L^3)

fe = porosity

C = concentration (mg/litre)

The surface area required will be:

Surface Area = Discharge/ Velocity gradient

$$A = Q/V$$

The tank with circular; therefore,

$$\text{Surface area} = \frac{\pi D^2}{4}$$

The diameter of the tank is:

$$D = \sqrt{\frac{4 * A}{\pi}}$$

And since the tank will consist of a 1m deep cylinder followed by a cone, then, initially, the depth of the cone will;

$$H = \frac{Radius}{\tan 30^{o}}$$

The volume of a cone will be given by;

$$Vi = \frac{H * (A_1 + A_2 + \sqrt{A_1 A_2}}{3}$$

Where;

Vi = volume of the cone

H = height of the cone

A_1= surface area of tank

A_2 = area of a cone

The total volume of the tank will be:

Volume of a cylindrical part of the tank plus area of the cone

$Vt = V_1 + Vc$

Where;

Vt = Total Volume

V_1 = Volume of cylindrical part

Vc = Volume of cone

The detention time in the tank will be:

Time = Total Volume of the tank/ Volumetric Discharge

T = Vt / Q

CHAPTER NINE

9.0 ENVIRONMENTAL MONITORING PROGRAMME FOR RADIONUCLIDES AND HEAVY METALS IN MINE WASTE WATER AT MCM, KITWE

The primary objectives of environmental monitoring surveys in normal situations are the:

i. Assessment of the adequacy of controls on the release of radionuclide and toxic materials
ii. Assessment of the actual or potential exposure to man and the environment or at a minimum, the estimation of the probable upper limits of such exposure; and
iii. Demonstration of compliance with regulations.

The proposed monitoring programme will outline the sampling procedures, sampling sites, sampling time, and analyses of samples, recording of results and the budget (Table 19).

Sampling Procedures

Automatic samplers should be used for continuous sampling at preset time interval to form a composite sample. These samplers should in-situ measure the pH, conductivity and temperature of the samples. For heavy metals and radio nuclides, samples should be preserved using strong acids like 10% nitric acid. Samples should be kept for at least one month after analysis in case of a query.

Sampling Site

For monitoring the performance of the proposed treatment plant, composite samples should be taken from both inlet and outlet of the treatment plant where there is sufficient velocity to keep the effluent solids in suspension. Other samples can be taken at discharge points for individual unit of operations to monitor their performance.

Frequency of Sampling

The frequency of sampling for radio nuclides monitoring as recommended by the International Atomic Energy Agency (IAEA) safety series No. 44 was initially quarterly (every three months), then the frequency of sampling could be reduced or increased depending on the concentration levels of radio nuclides. For heavy metals monitoring, weekly sampling was highly recommended so that intervention measures can be put in place immediately when high concentration levels are noticed.

Reporting of Results

The results should include the name of sampling site, date of sampling, date of analyses, analytical result and uncertainty. The results obtained should compare with the regulatory limits. Where regulatory limits are exceeded, intervention measures should be instituted.

Monitoring Budget

Table 19. Budget for environmental monitoring programme for the proposed treatment plant at MCM, Kitwe.

Material	Quantity	Unit Cost	Total cost (ZMK)
1. Chemicals	5 litres	80,000.00	400,000.00
2. Analyses costs	20 samples	300,000.00	6,000,000.00
3. Transport costs	1 trip	500,000.00	500,000.00
4. pH meter	02	1,500,000.00	3,000,000.00
5. Automated Sampler	02	6,000,000.00	12,000,000.00
6. Labour costs	2 persons	6,000,000.00	12,000,000.00
7. Sampling containers	20 * 5 litres	25,000.00	500,000.00
8. Stationery	20 reams	25,000.00	500,000.00
TOTAL COST			**34,900,000.00**

CHAPTER TEN

10.0 ECONOMIC EVALUATION OF A 75,000M^3/DAY MINE WASTEWATER TREATMENT PLANT AT MOPANI COPPER MINES.

OUTLINE

The major significance in the selection and design of alternatives wastewater treatment facilities, especially to the client, is the question of costs- not only initial construction cost but also annual operation and maintenance costs.

There was need to make quick, rough, cost estimates to decide between alternative designs and project evaluation. The accuracy of an estimate depends on the amount of design detail available, the accuracy of the cost data available; and the time spent on preparing the estimate.

The cost of materials and labour has been subject to inflation since Elizabethan times. All cost-estimating methods use historical data, and are themselves forecasts of future costs. Some method has to be used to update old cost data for use in estimating at the design stage, and to forecast the future construction cost of the plant.

In this study, the economic evaluation of the proposed treatment plant was done by estimating the fixed and variable costs based on the current market price of materials multiply by the cost index to take care of the inflation.

10.1 LOCATION

The location of the treatment plant can sit where the current wastewater tailing thickeners are situated at the concentrator at Nkana mine of MCM.

10.2 COSTS AND BUDGET

The method usually used to update historical cost data makes use of published cost indices which take care of the inflation in the country. These relate present costs to the past costs, and are based on data for material and energy costs (Table 20).

TABLE 20. Budget for constructing a proposed treatment plant at MCM,Kitwe.

MATERIAL	QTY	UNIT COST (ZMK)	TOTAL COST (ZMK)
VARIABLE COSTS			
1. Barium Chloride	2355 kg	50,000.00	117,750,000.00
2. Ferric Chloride	450 kg/	35,000.00	15,750,000.00
3. Lime	2500 kg	15,000.00	37,500,000.00
4. Utilities (Power)			2,500,000.00
5. Miscellaneous materials 10% maintenance			1,000,000.00
Variable cost			**174,500,000.00**
FIXED COSTS			
6. Process Vessels			
Precipitation Tank (2m *2m)	2	10,000,000.00	20,000,000.00
Rapid mixing (0.6m*2.5m)	2	10,000,000.00	20,000,000.00
Coagulation Tank (2m * 2m)	4	10,000,000.00	40,000,000.00
Sedimentation Tank (5.2m*5.5m)		20,000,000.00	20,000,000.00
Lime Tank (2m * 2m)	1	10,000,000.00	10,000,000.00
Subtotal			**110,000,000.00**
7. Process Piping			
Steel pipes 6" (vessel connector)	20	350,000.00	7,000,000.00
Steelpipes18"(dischargeto dams)	2	750,000.00	1,500,000.00
GI pipes ¾" (reagent delivery)	25	100,000.00	25,000,000.00
Subtotal			**33,500,000.00**

8. Construction Open Channel			
Cement	5 *tons*	45,000,000.00	180,000,000.00
River sand	15,000 *t*	90,000.00	1,350,000,000.00
Steel bars 12 Y	200	120,000.00	24,000,000.00
Steel bars 18 Y	200	125,000.00	25,000,000.00
Subtotal			**1,579,000,000.00**

9. Equipment			
Electric motors 07 kW	2	750,000.00	1,500,000.00
Centrifugal pumps 10 HP	2	20,000,000.00	40,000,000.00
Electric stirrers 2 HP	10	1,500,000.00	15,000,000.00
pH Regulator	2	20,000,000.00	40,000,000.00
Subtotal			**96,500,000.00**
10. Design & Engineering			100,000,000.00
11. Equipment erection			50,000,000.00
12. Operating labour (OL)	6	2,500,000.00	15,000,000.00
13. Plant overheads 65% of labour			9,750,000.00
14. Miscellaneous materials			5,000,000.00
15. Laboratory costs 20% of OL			3,000,000.00
16. Insurance 2% of fixed capital			3,670,000.00
17. Maintenance costs/year			9,000,000.00
Subtotal			**195,420,000.00**
Grand Fixed Cost			**2,014,420,000.00**

Direct treatment costs = Variable costs + Fixed costs

= 174,500,000.00 + 2,014,420,000.00

Therefore, the annual operating cost, **K 2,188,920,000.00**

At the exchange rate of USD 1 = K4, 000.00

estimates were used for project cost evaluation and firm quotations for equipment, and a detailed breakdown and estimation of the construction cost.

Given the following indexes:

First quarter index for 2006 – 793

First quarter index for 2007 - 863

There, the cost of constructing a Treatment Plant at Mopani Copper Mines in one year (2007) was going to be:

863/793 * 2,188,920,000.00

= **ZMK 2,380,000,000.00 (USD 845,000.00)**

CHAPTER ELEVEN

11.0. CONCLUSIONS AND RECOMMENDATIONS

This study represents, in many respects, pioneering work aimed at providing insights into aspects of pollution of aquatic environment by mine wastewater. While focusing on heavy metals and radionuclides, the study attempted to apply existing theories and techniques to provide original clarification and propose recommendations that make a distinct contribution to the knowledge and understanding of the subject under investigation.

The major conclusions and recommendations of the study are as follows:

11.1 CONCLUSIONS

i. **Determination of radionuclides and heavy metals content in mine wastewater in relation to the Environmental Council of Zambia Standards.**

Under the Environmental Protection and Pollution Control Act of 1990, it can be concluded that the discharged effluent exceeded the regulatory limits of "No discharge of radioactive material" to the environment although this not achievable.

The dissolved radio nuclides were 0.04 Bq/m^3 for ^{226}Ra and less than 0.03 Bq/m^3 for ^{228}Ra were discharged to the streams whereas 0.196 Bq/m^3 of ^{226}Ra and 0.07 Bq/m^3 of ^{228}Ra were discharged to tailing facilities.

Dissolved manganese was 2.16 mg/l when the regulatory limit is 1.0 mg/l. For the discharge to the tailing dump sites (tailing thickener underflow), 42.9% of elements measured were above the regulatory limits, dissolved copper (1.58 mg/l), cobalt (2.80 mg/l), and manganese (5.04mg/l) were above the regulatory limits.

ii. **Treatment of mine wastewater for radionuclides and heavy metals.**

It is possible to treat heavy metals and radio nuclides in mine wastewater using barium chloride. The mine wastewater was subjected to chemical treatment with maximum dose of 40 mg of barium chloride (as Ba^{2+}), dissolved copper reduced from 1.33 mg/l to 0.09 mg/l, cobalt reduced from 3.14 mg/l to 0.61 mg/l, iron reduced from 1.27 mg/l to 1.03 mg/l, manganese reduced from 2.38 mg/l to 1.52mg/l, nickel reduced from 0.67 mg/l to 0.14 mg/l, lead reduced from 0.67 mg/l to 0.03 mg/l, ^{226}Ra reduced from 0.093 Bq/m^3 to 0.004 Bq/m^3, ^{228}Ra reduced from 0.08 Bq/m^3 to 0.03 Bq/m^3. All in all, there was a reduction of 59.32% in heavy metals and 75.61% in radio nuclides.

iii. **Design of a treatment process for radionuclides and heavy metals removal.**

It was concluded that the optimum operating parameters to effect 59.32% reduction in heavy metals and 75.61% reduction in radio nuclides were 31 mg/l (Ba^{2+}) with 6 mg/l of ferric chloride (Fe^{3+}) as a coagulant with mixing speed of 70 rpm and mixing time of 20 minutes was successfully developed.

From the results of the batch treatment trials, the concepts of similitude and response surface methodology were used to develop a heavy metals and radio nuclides removal process. Scale-up to full scale was accomplished by means of reaction kinetics data in conjunction with geometric, dynamic and chemical similitude. The use of factorial experimental designs made it possible to examine several process variables in an efficient manner.

iv. **Safe disposal of treated/ recovered natural radionuclides and heavy metals.**

The toxic and radioactive sludge produced after treatment of the wastewater was concretized with Portland cement in the ratio 3:1 (as per recommendation for concrete production) to form a concrete matrix for safe disposal. This method of disposal can withstand adverse weather conditions to prevent dispersion of toxic heavy metals and radio nuclides into the environment.

v. **Establishing of a routine, continuous monitoring programme for radionuclides and heavy metals in mine wastewater**

The monitoring programme of weekly and monthly sampling for heavy metals and for radio nuclides respectively as recommended by the International Atomic Energy Agency was adequate enough to send early warning signs for poor performance of treatment plant and also to implement remedial actions to normalize the situation.

vi. **Economic evaluation of a 75000 m^3/day of mine wastewater treatment plant at Mopani Copper Mines**

The economic evaluation to compare the economic performance of the treatment plant with other alternative processes was not done due to lack of information on the sales income from copper and cobalt as this treatment plant is an integral part of the entire production process. However, the cost of constructing and operating a treatment plant in 2007 at Mopani Copper Mines was calculated to be ZMK 3,380,000,000.00 (USD 845,000.00) and that for environmental monitoring programme was K 34, 900,000.00 (USD 9,971).

11.2 RECOMMENDATIONS

From this study, the following are the recommendations:

(a) The Government of Zambia through the Environmental Council of Zambia (ECZ) should revise the "**NO** discharge of radioactive material" clause in the Environmental Protection and Pollution Control Act of 1990 because this not attainable in Zambia considering the nature of the ore where copper and cobalt are mined. It is relatively uraniferrous area and uranium is not recovered as a by-product but discharged to the environment.

(b) Research should also be done to find a suitable or a combination of reagents to effectively remove both radionuclides and heavy metals by more than 80% from mine wastewater.

(c) The Government should make it mandatory for all mine operators to incorporate the state-of-art treatment plants as an integral part of production processes.

(d) The mine operators should be encouraged to promote the practice of cleaner production strategies in mining activities by way of recycling process water to reduce the volume of wastewater discharged to the water courses.

(e) Routine monitoring of mine wastewater received in water courses for radionuclides and heavy metals is highly recommended for quick intervention in case of pollution.

(f) The mine operators should be encouraged to make available records of profits generated from copper and cobalt sales in order to economically evaluate the type of treatment plant to build.

(g) This type of study should be extended to other mines on the copperbelt to assess the overall extent of environmental pollution due to mining activities.

REFERENCES

1. Backstrom, M., and Johnsson, B., 1996. A sediment study in the Kafue River, Zambia. Master Thesis, Lulea University of Technology, SWEDEN.
2. Bergstrom, J., Hollaway,J.and Zulu,E., 1992. "Environmental Effects of Mining in the SADC Region ", Mining Sector Coordinating Unit"pp 34
3. Biegler,L.T., I.E.Grossman and A.W. Westerberg, 1997. Systematic methods of chemical process design. New Jersey.: Prentice Hall PTR.
4. Clemmy, H., and J. Coles, 1975. "A Geological Guide to Rokana Division" Technical Report, 12-19 NCCM LTD Kitwe
5. Coulson, J.M., and J.F Richardson (ed), 1993. Chemical Engineering Design. 6 vols., 2 nd ed. Butterworth Heinemann.
6. SRK Consulting, 2003. "Environmental Impact Assessment for Mopani Copper Mines." Technical Report Volume 1. Mopani Copper Mines Kitwe.
7. Extreme Health, 2003. "Toxic Heavy Metals: Sources and specific effects." Extremehealthusa.com/source.html. Google website.
8. Fair, G.M., T.C. Geyer and D.A. Okun. 1968. Water and Wastewater Engineering. Vol. 2. New York.: John Wiley and Sons, Inc.
9. Evans, A. M.(ed.), 1993. Ore geology and Industrial Minerals. 3ed. Blackwell Science Ltd.
10. Hayumbu, P., E.M Malikana and M.M. Hussain, 1990. "Preliminary survey of radon levels in some copper/cobalt/pyrite underground mines in Zambia." Techinical Report. NISIR, Lusaka.
11. Henry, G.T., and G.W. Heinke(ed.), 1996. Environmental Science & Engineering." 2nd ed. Prentice Hall.
12. International Atomic Energy Agency. 1990. "The environmental behavior of radium" Technical Report Series No. 310. Volume 2. IAEA.
13. International Atomic Energy Agency. 1992. "Chemical Precipitation Processes for the Treatment of Aqueous Radioactive Waste." Technical Report Series No. 337. IAEA.
14. International Atomic Energy Agency. 2001. "Handling and Processing of Radioactive Waste from Nuclear Applications." Technical Report Series No. 402. IAEA.

15. International Atomic Energy Agency. 2003. "Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technically Option for Mitigation." Technical Series No. 402 IAEA.
16. International Atomic Energy Agency. 2005. "Naturally Occurring Radioactive Materials (NORM IV)." Proc. Conf., IAEA –TECDOC-1472 IAEA.
17. Isaksson, S., and A. Safevestad. 1996. Environmental Effects from mining Industry on the sediment quality in the Kafue River, Zambia-a geochemical investigation of a tropical river. Master Thesis, Division of Applied Geology, University of Lulea, SWEDEN.
18. Kaplan, I. (ed.), 1972. Nuclear Physics. 2nd ed. Wesley Publishing Company.
19. Kasonde, J. M., 1990. "Environmental pollution of Kafue River due to mining activities on the Copperbelt." Technical Report – 90- NCSR, Zambia.
20. Kribek, B., and I. Nyambe. 2004, "Impact assessment of mining and processing of copper and cobalt ores on the environment in the copperbelt, Zambia." Final Technical Report 04 - Ministyr of Environment of the Czech Republic.
21. LennTech. 1998. "Heavy Metals", HH Delft, The Netherlands, Google website.
22. Lund, H. F., (ed.), 1971. Industrial Pollution Control Handbook. 1st ed. McGraw Hill.
23. Mendelson, F., 1961. The geology of the Northern Phodesia Copperbelt. London: MacDonald and Co Ltd.
24. Morley, D.A., 1979. Mathematical Modeling in Water and Wastewater Treatment, London: Applied Science Publisher Ltd.
25. Murthy, M.N., 1967. Sampling Theories and Methods, Montreal : Statistical Publishing Society.
26. Nkandu, C., 1996. "Environmental Research in Zambia." Technical Report -96- Ministry of Mines, Zambia.
27. Pettersson, U & Ingri, J., 1993. "The effect of mining activities on water quality in the Kafue River, Copperbelt, Zambia." Master's Thesis. Division of Applied Geology, University of Lulea. SWEDEN.
28. Poland. Decree of the President, 1989. Atomic Energy Agency, Zarzadzenie Prezesa PPA zdina 19 maja 1989 w sparawie zasald zaliczania odpadow do odpado'w promieniotwo'rczch, Monitor Polski nr 18, Warsaw (in Polish).

29. Reeves, W.H., 1963. The geology and mineral resources of Northern Rhodesia. Volume 1. London: N . Rhodesia Geological Survey Bull.

30. Schmidtke, N.W., and D.W. Smith. 1983.. Scale-up of Water and Wastewater Treatment Processes." Boston: Butterworth Publishers.

31. Smordis B., 2000. "Biomonitoring of Atmospheric Pollution (with Emphasis on Trace Elements)." TECDOC -1152-IAEA.

32. Tchobanoglous, G., 1972. Wastewater Engineering Treatment/Disposal/Reuse. New York: McGraw Hill.

33. Thomro, Sweco, Swedish Geological lab, 2005. "Geochemical and Radiation Characteristics", ZCCM, Zambia, pp 3.

34. United States Environmental Protection Agency (USEPA), 1975. Standard Methods for Examination of Water and wastewater. 14^{th} ed. American Public Health Association.

35. United States Environmental Protection Agency, 1999. Technologically Enhanced Naturally Occurring Radioactive Materials in the Southwestern Copper belt of Arizona. Technical Report - 99- USEPA.

36. United States Nuclear Regulator Commission, 1995. Code of Federal Regulations. 10 cer 20, UPNRC, Washington, DC, Appendix B.

37. Williams, J. M., 1996. Environmental Science and Engineering. 2^{nd} ed. New Jersey: Prentice Hall.

38. Zambia Consolidated Copper Mines, 1982. "A review of Factors Relevant to the Reported Incidence of cattle Losses on Farms Bordering the Mwambashi River." Pollution Control Department. ZCCM.

39. ZCCM. HI., (2003). "Preparation of phase 2 of a consolidated Environmental Management Plan", Topic Reports Volume 1, ZCCM, Zambia.

40. ZCCM.HI. 2000. "Copperbelt Environmental Project." Technical Report 00-ZCCM.HI.

APPENDIXES

APPENDIX I

ENVIRONMENTAL PROTECTION AND POLLUTION CONTROL ACT OF 1990

THIRD SCHEDULE (Regulation 5 (2))

SECOND SCHEDULE

(Regulation 3 and 4)

PRESCRIBED FEES

	K
Application for licence to Discharge effluent	100,000.00
Application for licence to withdraw water for treatment of effluent	100,000.00

THIRD SCHEDULE

(Regulation 5 (2))

TABLE OF STANDARDS (LIMITS) FOR EFFLUENTS AND WASTE WATER

Column 1 PARAMETER	*Column 2* EFFLUENT AND WASTE WATER INTO AQUATIC ENVIRONMENT
A. Physical	
1. Temperature (Thermometer)	40 °C at point of entry
2. Colour (Hazen Units)	20 Hazen units
3. Odour and Taste (Threshold odour number)	Must not cause any deterioration in taste or odour as compared with natural state
4. Turbidity (NTU scale)	15 Nephelometer turbidity units
5. Total suspended solids(Gravimetric method)	100 mg/L must not cause formation of sludge or scum in receiving water
6. Settleable matter sedimentation in 2 hours (Imhoff funnel)	0.5 mg/L in two hours. Must not cause formation of sludge in receiving water
7. Total Dissolved Solids (Evaporation @ 105 C and Gravimetric method)	3000 mg/L The TDS of waste water must not adversely affect surface water
8. Conductivity (Electrometric method)	4300 μS/cm
B. Bacteriological	
9. Total Coliform/100 ml (Membrane Filtration method)	2500°
10. Faecal Coliform/100ml (Membrane Filtration method)	5000°
11. Algae /100 ml (Colony counter)	1000 cells
C. Chemical	
12. pH (0-14 scale) (Electro-metric method)	6.0 - 9.0
13. Dissolved oxygen mg Oxygen / Litre (Modified Winkler method and membrane electrode method)	5 mg/L after complete mixing extreme temperature may result in lower values

Column 1 PARAMETER	*Column 2* EFFLUENT AND WASTE WATER INTO AQUATIC ENVIRONMENT
A. Physical	
14. Chemical Oxygen Demand (COD) (Dichromat method)	COD based on the limiting values for organic carbon 90 mg 0_2/L average for 24 hours
15. Biochemical Oxygen Demand (BOD) (Modified Winkler method and Membrane Electrode method)	50 mg 0_2/L (mean value over 24 hours period) According to circumstances in relation to the self cleaning capacity of waters
16. Nitrates (NO3 as nitrogen) (Spectrophotometric method and electrometric method)	The nitrates burden must be reduced as far as possible according to circumstances: water course 50 mg/L; Lakes 20 mg/L
17. Nitrite (NO2 as nitrogen/L Spectrophotometric sulphanilamide)	2.0 mg NO_2 as N/L
18. Organic Nitrogen (Spectro-photometric method N-Kjeldal)	5.0 mg/L Mean* (* the % of nutrient elements for degradation of BOD should be 0,4 - 1 % for phosphorous (different for processes using algae)
19. Ammonia and Ammonium (Total) (NH_3 as N/L) (Nesslerization method and Electrometric method)	The burden of ammonium salts must be reduced to 10 mg/L (depending upon temperature, pH and salinity)
20. Cyanides (Spectrophoto-metric method)	0.2 mg/L
21. Phosphorous (Total) (PO4 as P/L) (Colori-metric method)	Treatment installation located in the catchment area of lakes: 1.0 mg/L; located outside the catchment area: reduce the load of P as low as possible (PO_4 = 6 mg/L
22. Sulphates (Turbidimetric method)	The Sulphate burden must be reduced to 1500 mg/L
23. Sulfite (Iodometric method)	0.1 mg/L (presence of Oxygen changes SO_3 to SO_4)
24. Sulphide (Iodometric and electrometric method)	0.1 mg/L (depending on temperature, pH and dissolved O_2)
25. Chlorides Cl/L (Silver nitrate and Mercuric nitrate)	Chloride levels must be 800 mg/L
26. Active chloride Cl2/L (Iodometric method)	0.5 mg/L
27. Active Bromine (Br2/L)	0.1 mg/L
28. Fluorides F/L (Electro-metric method and Colori-.metric method with distillation)	2.0 mg/L
C. Metals	
29. Aluminium compounds (Atomic Absorption method)	2.5 mg/L
30. Antimony (Atomic absorption method)	0.5 mg/L
31. Arsenic compounds (Atomic Absorption method)	0.05 mg/L
32. Barium compounds (water soluble concentration) (Atomic Absorption method)	0.5 mg/L
33. Beryllium salts and compounds (Atomic Absorption method)	0.5 mg/L

Column 1 **PARAMETER**	*Column 2* **EFFLUENT AND WASTE WATER INTO AQUATIC ENVIRONMENT**	
A. Physical		
34. Boron compounds (Spectro photometric method-curcumin method)	0.5 mg/L	
35. Cadmium compounds (Atomic Absorption method)	0.5 mg/L	
36. Chromium Hexavelant,Trivalent (Atomic absorption method)	0.1 mg/L	
37. Cobalt compounds (Atomic Absorption method)	1.0 mg/L	
38. Copper compounds (Atomic Absorption method)	1.5 mg/L	
39. Iron Compounds (Atomic Absorption method)	2.0 mg/L	
40. Lead compounds (Atomic Absorption method)	0.5 mg/L	
41. Magnesium (Atomic Absorption method and flame photometric method)	500 mg/L	
42. Manganese (Atomic Absorp tion method)	1.0 mg/L	
43. Mercury (Atomic Absorption method)	0.002 mg/L	
44. Molybdenum (Atomic Absorption method)	5.0 mg/L	
45. Nickel (Atomic Absorption method)	0.5 mg/L	
46. Selenium (Atomic Absorption method)	0.02 mg/L	
47. Silver (Atomic Absorption method)	0.1 mg/L	
48. Thallium (Atomic Absorption method)	0.5 mg/L	
49. Tin compounds (Atomic Absorption method)	2.0 mg/L	
50. Vanadium compounds (Atomic Absorption method)	1.0 mg/L	
51. Zinc compounds (Atomic Absorption method)	10 mg/L	
D. Organics		
52. Total hydrocarbons (Chromatographic method)	10.0 mg/L	
53. Oils (Mineral and Crude) (Chromatographic method and Gravimetric method)	5.0 mg/L	
54. Phenols (steam distillable)	0.2 mg/L	
(Colorimetric method) (Non-steam distilled)	0.05 mg/L	
55. Fats and saponifiable oils (Gravimetric method and chromatographic method)	20 mg/L	
56. Detergents (Atomic) (Atomic Absorption Spectrophometric)	2.0 mg/L (Detergents should contain at least biodegradable compounds)	
57. Pesticides and PCB's (Total) (Chromatographic method)	0.5 mg/L	
58. Trihaloforms (Chromatographic)	0.5 mg/L	
E. Radioactive Materials		
58. Radioactive materials specified by International accepted Atomic Energy Agency	No discharge accepted	Not permitted

APPENDIX II

NEUTRON ACTIVATION ANALYSIS RESULTS

ELEMENTS (mg/kg)		SAMPLING SITES TTF	TTU
Na		295 ± 7	0.17 ± 0.004
K	%	0.301 ± 0.009	< 200
Ca	%	0.53 ± 0.02	1.5 ± 0.04
Sc		0.64 ± 0.04	2.87 ± 0.1
Cr		3.7 ± 0.4	4.3 ± 0.2
Mn		< 200	23 ± 2
Fe	%	0.221 ± 0.009	620 ± 20
Co		61 ± 2	1.09 ± 0.05
Cu		222 ± 6	250 ± 20
Zn		< 0.9	< 0.6
Ga		0.89 ± 0.03	750 ± 30
Ge		< 50	24.2 ± 0.9
As		4.5 ± 0.2	4.8 ± 0.2
Se		0.41 ± 0.05	< 300
Br		0.155 ± 0.006	12.1 ± 0.3
Rb		7.6 ± 0.4	1.54 ± 0.1
Sr		17 ± 3	< 0.8
Y	%	< 30	51 ± 4
Zr		< 15	60 ± 7
Mo		1.5 ± 0.2	< 0.9
Ru		< 0.15	78 ± 6
Pb		< 1.5	5.3 ± 0.8
Ag		< 0.15	< 0.4
Cd		< 0.6	< 10
In		< 0.5	< 1
Sn		< 15	< 30
Sb		0.13 ± 0.005	0.27 ± 0.03
Te		< 0.4	< 4
Cs		0.131 ± 0.01	0.93 ± 0.05
Ba		56 ± 3	350 ± 20
La		1.7 ± 0.04	9.4 ± 0.3
Ce		3.2 ± 0.3	24 ± 3
Pr		0.39 ± 0.05	< 3
Nd		1.5 ± 0.2	11 ± 2
Sm		0.273 ± 0.007	1.51 ± 0.04
Eu*	ng/g	43 ± 2	0.28 ± 0.05
Gd		< 0.8	3.91 ± 0.1
Tb	ng/g	34 ± 4	0.22 ± 0.02
Dy	%	< 0.15	< 3
Ho	ng/g	< 40	< 0.4
Er		< 1.5	< 3
Tm		< 0.1	< 90
Yb		0.124 ± 0.005	0.77 ± 0.03
Lu	ng/g	< 5	< 15
Hf		0.19 ± 0.02	1.28 ± 0.07
Ta	ng/g	52 ± 4	0.34 ± 0.02
W		0.176 ± 0.006	0.8 ± 0.08
Re	ng/g	< 8	< 30
Os		< 1.5	< 40
Ir	ng/g	< 9	< 0.15
Pt		< 0.4	< 2
Au	ng/g	1.7 ± 0.2	< 6
Hg		< 1.5	< 0.2
Th		0.82 ± 0.03	4.9 ± 0.2
U		0.37 ± 0.02	2.23 ± 0.1

ELEMENT (mg/kg)		SAMPLING SITE TTO
Na		42.9 ± 1
Si	%	< 70
Ar		< 60
K		145 ± 4
Ca	%	< 0.15
Sc	ng/g	< 1.5
Cr		< 0.15
Mn		1.46 ± 0.06
Fe		< 9
Co		3.13 ± 0.08
Ni		< 800
Cu	ng/g	< 8
Zn		< 0.4
Ga	ng/g	< 9
Ge		< 4
As	ng/g	< 4
Se		< 0.1
Br		0.19 ± 0.005
Rb		< 0.8
Sr		8.3 ± 1
Y		< 400
Zr		< 4
Mo		< 0.15
Ru	ng/g	< 70
Pd	ng/g	< 60
Ag		< 60
Cd		< 0.2
In		< 0.3
Sn		< 7
Sb	ng/g	60 ± 2
Te		< 0.6
Cs	ng/g	< 15
Ba		< 5
La	ng/g	< 4
Ce	ng/g	< 90
Pr	ng/g	< 70
Nd		< 0.6
Sm	ng/g	< 0.5
Eu	ng/g	< 0.2
Gd		< 0.15
Tb	ng/g	< 6
Dy		< 0.2
Ho	ng/g	< 3
Er	ng/g	< 50
Tm	ng/g	< 50
Yb	ng/g	< 15
Lu	ng/g	< 6
Hf	ng/g	< 10
Ta	ng/g	< 10
W	ng/g	< 6
Re	ng/g	< 1.5
Os	ng/g	< 30
Ir	ng/g	< 1.5
Pt	ng/g	< 0.15
Au	ng/g	< 0.3
Hg	ng/g	< 40
Th	ng/g	< 15
U	ng/g	54 ± 2

APPENDIX III

CHARACTERIZATION OF MINE WASTEWATER RESULTS

PHYSICAL PARAMETERS RESULTS

TABLE 22: Tailing Thickener Feed (TTF) Physical Parameter Results at Mopani Copper Mines, Kitwe.

Date of Sampling	pH	Temp. °C	Cond. mMho/cm	TSS mg/l	TDS mg/l	TS mg/l	Density Kg/m^3	Flow rate m^3/day
1st Trip								
29/9/05	7.37	26.6	3890	95.00	2790	2885.00	1050	59,616
30/9/05	7.57	28.3	3643	94.03	2567	2661.03	1048	60,032
Mean	**7.47**	**27.45**	**3766.5**	**94.52**	**2679**	**2773.02**	**1049**	**59,824**
Dev.	**0.14**	**1.20**	**174.70**	**0.69**	**157.68**	**158.37**	**1.41**	**294.16**
2nd Trip								
22/11/05	4.32	35.1	4010	97.00	2865	2962.00	1058	58,854
23/11/05	9.03	34.6	5018	110.27	3153	3263.27	1060	60,102
Mean	**6.68**	**34.85**	**4514.00**	**103.64**	**3009**	**3112.64**	**1059**	**59,478**
Dev.	**3.33**	**0.35**	**712.76**	**9.38**	**203.65**	**213.03**	**1.41**	**882.47**
3 rd Trip								
2/8/2006	11.62	30.1	3880	123.32	2361	2484.32	1165	58,876
3/8/2006	9.39	29.7	5460	136.19	2681	2817.19	1023	61,123
Mean	**10.51**	**29.9**	**4670**	**129.76**	**2521**	**2650.76**	**1094**	**59,999**
Dev.	**1.58**	**0.28**	**1117.23**	**9.100**	**226.27**	**235.37**	**100.41**	**1,588**
4th Trip								
18/12/06	7.51	31.0	3380	137.23	2319.0	2456.23	1046	59,678
19/12/06	9.63	33.4	3140	141.27	2198.1	2339.37	1263	59,765
Mean	**8.57**	**32.2**	**3260**	**139.47**	**2258.55**	**2397.80**	**1155**	**59,721**
Dev.	**1.50**	**1.70**	**169**	**3.16**	**85.49**	**82.63**	**153.44**	**61.52**
Overall Mean	**8.31 ± 1.66**	**31.10 ± 3.16**	**3154. 68 ± 2084.49**	**109.31 ±18.29**	**2658.89 ±313.69**	**2733.55 ±297.12**	**1089.25 ±47.89**	**59755.50 ±217.70**

TABLE 23: Tailing Thickener Underflow (TTU) Physical Parameter Results at Mopani Copper Mines, Kitwe.

Date of Sampling	pH	Temp. °C	Conductivity mMho/cm	TSS mg/l	TDS mg/l	TS mg/l	Density Kg/m³	Flow rate m³/day
1st Trip								
29/9/05	8.19	28.4	4210	98.00	2778.60	2876.60	1360.0	9,387.90
30/9/05	8.03	27.8	3340	150.71	2204.40	2355.11	1230.5	
Mean	**8.11**	**28.10**	**3775**	**124.36**	**2491.50**	**2615.86**	**1295.25**	
Dev.	**0.11**	**0.42**	**615.2**	**37.27**	**406.02**	**368.75**	**91.57**	
2nd Trip								
22/11/05	8.11	34.8	3120	109.80	2059.20	2169.00	1069.4	
23/11/05	9.01	36.0	5110	110.17	3372.60	3482.77	1090.0	
Mean	**8.56**	**35.40**	**4115**	**109.10**	**2715.90**	**2825.89**	**1079.7**	
Dev.	**0.64**	**0.85**	**1407**	**0.26**	**928.71**	**928.86**	**14.6**	
3rd Trip								
2/8/2006	8.21	32.5	4100	169.31	2706.00	2875.31	1270.0	
3/8/2006	10.23	33.1	3820	203.42	2521.20	2724.62	1243.4	
Mean	**9.22**	**32.8**	**3960**	**186.37**	**2613.60**	**2799.97**	**1256.7**	
Dev.	**1.43**	**0.42**	**198**	**24.12**	**130.67**	**106.55**	**18.8**	
4th Trip								
18/12/06	8.35	30.9	2850	143.67	1881.00	2024.67	1157.6	
19/12/06	9.40	31.9	2050	151.71	1353.00	1504.71	1228.7	
Mean	**8.88**	**31.4**	**2450**	**147.69**	**1617.00**	**1764.69**	**1193.2**	
Dev.	**0.74**	**0.7**	**566**	**5.69**	**373.35**	**367.67**	**50.3**	
Overall Mean	**8.69 ±0.47**	**31.93 ±3.04**	**3575 ±762.77**	**141.88 ±33.64**	**2359.50 ±503.43**	**2501.60 ±500.09**	**1206.21 ±94.25**	**9387.90**

TABLE 24. **Tailing Thickener Overflow (TTO) – Physical Parameters Results at Mopani Copper Mines, Kitwe.**

Date of Sampling	**pH**	**Temp. °C**	**Conductivity mMho/cm**	**TSS mg/l**	**TDS mg/l**	**TS mg/l**	**Density Kg/m³**	**Flow rate m³/day**
1st Trip								
29/9/05	7.30	29.4	4090	25.30	2699.40	2724.70	990.0	12268.80
30/9/05	7.85	28.4	4330	17.02	2857.80	2874.82	1000.0	12096.00
Average	**7.58**	**28.90**	**4210**	**21.16**	**2778.60**	**2799.76**	**995**	**12182.24**
Dev.	**0.39**	**0.71**	**169.71**	**5.86**	**112.01**	**106.15**	**7.07**	**122.19**
2nd Trip								
22/11/05	7.40	33.8	3650	30.22	2409.00	2439.22	995.0	12157.13
23/11/05	8.46	34.8	2960	18.13	1953.60	1971.73	995.0	12314.08
Mean	**7.93**	**34.3**	**3305**	**24.18**	**2181.30**	**2205.48**	**995.0**	**12235.61**
Dev.	**0.75**	**0.71**	**488**	**8.55**	**322.02**	**330.57**	**0**	**110.98**
3rd Trip								
2/8/2006	10.30	28.9	5760	41.21	3801.60	3842.81	1000.5	11321.04
3/8/2006	9.43	30.8	4860	98.11	3207.60	3305.71	998.6	10432.21
Mean	**9.87**	**29.85**	**5310**	**69.66**	**3504.60**	**3574.26**	**999.6**	**10876.63**
Dev.	**0.62**	**1.34**	**636**	**40.23**	**420.02**	**379.79**	**1.34**	**628.50**
4th Trip								
18/12/06	10.00	31.5	2950	23.13	1947.00	1970.13	1000.0	11540.76
19/12/06	8.35	30.9	2850	15.98	1881.00	1896.98	990.5	12610.33
Mean	**9.18**	**31.2**	**2900**	**19.56**	**1914.00**	**1933.56**	**995.25**	**12075.55**
Dev.	**1.17**	**0.42**	**70.7**	**5.06**	**46.67**	**51.72**	**6.72**	**756.30**
Overall Mean	**8.64 ±1.07**	**31.06 ±2.36**	**3931.25 ±1069.94**	**33.64 ±24.09**	**2594.63 ±706.16**	**2859.83 ±686.36**	**996.21 ±2.26**	**11842.51 ±647.35**

CHEMICAL PARAMETERS

NON-METALLIC IONS

TABLE 25: Tailing Thickener Feed Chemical Parameter (non-metallic ions) Results at Mopani Copper Mines, Kitwe.

Date of sampling	Total Hardness mg/l	Total Alkalinity mg/l	HCO_3^- mg/l	CO_3^{2-} mg/l	OH^- mg/l	NO_3^- mg/l	SO_4^{2-} mg/l	PO_4^{3-} mg/l	Cl^- mg/l
1st Trip									
29/9/05	1250	114.43	22.8	91.2	-	54.08	1471.56	ND	159.95
30/9/05	1817	98.94	17.4	80.6	-	47.16	1382.16	ND	143.67
Mean	**1533.50**	**106.69**	**20.1**	**85.9**	**-**	**50.62**	**1426.86**		**151.81**
Dev.	**400.93**	**10.90**	**3.80**	**7.50**		**4.90**	**63.22**		**11.50**
2nd Trip									
22/11/05	1940	74.88	-	-	-	27.02	1705.88	ND	123.96
23/11/05	1994	73.33	-	-	-	29.90	1378.11	ND	127.14
Mean	**1967**	**74.11**				**28.46**	**1541.99**		**125.55**
Dev.	**38.18**	**1.00**				**2.04**	**231.77**		**2.25**
3rd Trip									
2/8/2006	1158	109.51	-	-	-	40.25	1746.51	ND	170.12
3/8/2006	1975	88.67	-	-	-	51.26	1985.31	ND	154.06
Mean	**1566.50**	**99.09**				**45.76**	**1865.91**		**162.09**
Dev.		**14.74**				**7.78**	**168.86**		**11.36**
4th Trip									
18/12/06	1543	105.33	-	-	-	37.45	1332.01	ND	133.76
19/12/06	1731	99.67	-	-	-	38.42	1894.43	ND	142.65
Mean	**1637.00**	**102.50**				**37.94**	**1613.22**		**138.21**
Dev.	**132.84**	**4.00**				**0.69**	**397.69**		**6.29**
Overall Mean	**1676.00 ±198.74**	**95.60 ±14.66**	**20.10 ±3.80**	**85.90 ±7.50**	**-**	**40.70 ±9.69**	**1611.99 ±185.88**	**-**	**144.26 ±15.84**

TABLE 26: **Tailing Thickener Underflow Chemical Parameter (non metallic ions) Results at Mopani Copper Mines, Kitwe**

Date of sampling	Total Hardness mg/l	Total Alkalinity mg/l	HCO_3^- mg/l	CO_3^{2-} mg/l	OH^- mg/l	NO_3^- mg/l	SO_4^{2-} mg/l	PO_4^{3-} mg/l	Cl^- mg/l
1st Trip									
29/9/05	1700	86.64	-	63.84	22.80	16.19	1207.51	0.06	239.92
30/9/05	1756	91.14	-	69.23	21.91	16.73	1187.41	0.06	241.17
Mean	**1728.00**	**88.89**		**66.54**	**22.36**	**16.46**	**1197.46**	**0.06**	**240.55**
Dev.	**39.60**	**3.18**		**3.81**	**0.63**	**0.38**	**14.21**	**0**	**0.08**
2nd Trip									
22/11/05	1020	46.80	28.08	18.72	-	20.81	1850.27	0.03	131.96
23/11/05	1140	45.11	25.75	19.36	-	21.17	1641.23	0.04	129.87
Mean	**1080**	**45.96**	**26.92**	**19.04**	**-**	**20.99**	**1745.75**	**0.04**	**130.92**
Dev.	**84.85**	**1.20**	**1.65**	**0.45**		**0.25**	**147.81**	**0.01**	**1.48**
3rd Trip									
2/8/2006	1546	76.23	33.23	27.43	-	18.54	1022.03	0.06	232.11
3/8/2006	1553	71.87	31.25	25.33	-	19.34	1981.34	0.05	213.43
Mean	**1549.50**	**74.05**	**32.24**	**26.38**		**18.94**	**1501.69**	**0.06**	**222.77**
Dev.	**4.95**	**3.08**	**1.40**	**1.48**		**0.57**	**678.33**	**0.01**	**13.21**
4th Trip									
18/12/06	1631	53.45	27.34	19.87	-	17.33	1241.23	0.05	211.23
19/12/06	1534	63.57	26.32	20.33	-	18.23	1345.76	0.04	213.11
Mean	**1582.50**	**58.51**	**26.83**	**20.10**	**-**	**17.78**	**1293.50**	**0.05**	**212.17**
Dev.	**68.59**	**7.16**	**0.72**	**0.33**	**-**	**0.64**	**73.91**	**0.01**	**1.33**
Overall Mean	**1485.00 ±280.92**	**66.85 ±18.65**	**28.66 ±3.10**	**33.02 ±22.58**	**22.36 ±0.63**	**18.54 ±1.92**	**1434.60 ±243.21**	**0.05 ±0.01**	**201.60 ±48.56**

TABLE 27:Tailing Thickener Overflow-Drain Chemical Parameter (non-metallic ions) Results at Mopani Copper Mines, Kitwe

Date of sampling	Total Hardness mg/l	Total Alkalinity mg/l	HCO_3^- mg/l	CO_3^{2-} mg/l	OH^- mg/l	NO_3^- mg/l	SO_4^{2-} mg/l	PO_4^{3-} mg/l	Cl^- mg/l	DO mg/l
1st Trip										
29/9/05	1560	91.20	91.20	-	-	64.13	1131.94	0.06	159.95	5.3
30/9/05	1709	90.14	90.14	-	-	65.66	1209.18	0.06	163.19	5.2
Average	**1634.50**	**90.67**	**90.67**			**64.90**	**1170.56**	**0.06**	**161.57**	**5.25**
Dev.	**105.36**	**0.75**	**0.75**			**1.08**	**54.62**	**0**	**2.29**	**0.07**
2nd Trip										
22/11/05	1220	51.48	88.96	-	-	16.72	1018.19	0.09	159.95	5.1
23/11/05	1288	57.89	78.09	-	-	17.06	1211.28	0.08	148.14	5.2
Mean	**1254**	**54.68**	**83.53**			**16.89**	**1114.74**	**0.09**	**154.05**	**5.15**
Dev.	**48.08**	**4.53**	**7.69**	-	-	**0.24**	**136.54**	**0.01**	**8.35**	**0.07**
3rd Trip										
2/8/2006	1587	88.18	90.62	-	-	54.83	1628.12	0.03	148.94	5.3
3/8/2006	1785	87.54	89.34	-	-	49.45	1976.45	0.05	151.23	5.4
Mean	**1686**	**87.86**	**89.98**	-	-	**52.14**	**1802.29**	**0.04**	**150.09**	**5.35**
Dev.	**140.01**	**0.45**	**0.91**			**3.80**	**246.31**	**0.01**	**1.62**	**0.07**
4th Trip										
18/12/06	1133	110.34	89.09	-	-	38.45	1019.33	0.10	161.29	5.0
19/12/06	1522	109.32	90.81	-	-	33.56	1985.44	0.08	163.23	5.0
Mean	**1327.50**	**109.83**	**89.95**	-	-	**36.01**	**1502.39**	**0.09**	**162.26**	**5.0**
Dev.		**0.72**	**1.22**	-	-	**3.46**	**683.14**	**0.01**	**1.37**	**0**
Overall Mean	**1475.50 ±216.45**	**85.76 ±22.91**	**88.53 ±3.35**	-	-	**42.49 ±20.76**	**1397.50 ±319.54**	**0.07 ±0.03**	**156.99 ±5.92**	**5.19 ±0.15**

METALLIC IONS

TABLE 28: Tailing Thickener Feed Chemical Parameter (metallic ions) Results at Mopani Copper Mines, Kitwe

Date of Sampling	T Cu mg/l	D Cu mg/l	T Co mg/l	D Co mg/l	T Fe mg/l	D Fe mg/l	T Mn mg/l	D Mn mg/l	T Pb mg/l	D Pb mg/l	T Ni mg/l	D Ni mg/l	T Zn mg/l	D Zn mg/l
1st Trip														
29/9/05	3.06	0.31	0.46	0.04	83.83	0.16	14.28	0.18	0.05	0.03	1.34	0.50	0.09	0.07
30/9/05	4.01	0.53	0.37	0.07	71.67	0.34	12.24	0.33	0.07	0.05	1.16	0.47	0.10	0.04
Mean	**3.54**	**0.42**	**0.42**	**0.06**	**77.75**	**0.25**	**13.26**	**0.26**	**0.06**	**0.04**	**1.25**	**0.49**	**0.10**	**0.06**
Dev.	**0.70**	**0.20**	**0.10**	**0.02**	**8.60**	**0.13**	**1.44**	**0.11**	**0.01**	**0.01**	**0.13**	**0.02**	**0.1**	**0.02**
2nd Trip														
22/11/05	74.06	2.39	22.28	1.71	405.80	2.60	15.65	2.58	0.36	0.03	1.30	0.52	0.08	0.03
23/11/05	42.74	2.94	18.13	1.48	115.80	2.04	17.50	2.72	0.08	0.07	1.50	0.38	0.04	0.06
Mean	**58.40**	**2.67**	**20.21**	**1.60**	**260.80**	**2.32**	**16.58**	**2.65**	**0.22**	**0.05**	**1.40**	**0.45**	**0.06**	**0.05**
Dev.	**22.15**	**0.39**	**2.93**	**0.16**	**205.06**	**0.40**	**1.31**	**0.10**	**0.20**	**0.03**	**0.14**	**0.10**	**0.03**	**0.02**
3rd Trip														
2/8/2006	36.05	2.83	1.86	1.05	91.03	1.49	17.44	5.87	0.09	0.02	2.01	1.64	0.12	0.04
3/8/2006	54.32	1.12	1.59	1.07	77.96	1.03	15.19	3.92	0.12	0.03	1.99	0.93	0.07	0.03
Mean	**45.19**	**1.98**	**1.73**	**1.06**	**84.50**	**1.26**	**16.32**	**4.90**	**0.11**	**0.03**	**2.00**	**1.29**	**0.10**	**0.04**
Dev.	**12.92**	**1.21**	**0.19**	**0.01**	**9.24**	**0.33**	**1.59**	**1.38**	**0.02**	**0.01**	**0.01**	**0.50**	**0.04**	**0.01**
4th Trip														
18/12/06	5.11	1.21	15.32	2.33	107.47	6.38	16.34	4.16	0.09	0.05	1.21	0.92	0.13	0.07
19/12/06	4.41	1.12	17.84	3.75	121.43	7.17	12.74	2.20	0.04	0.01	1.09	0.82	0.07	0.04
Mean	**4.76**	**1.17**	**16.58**	**3.04**	**114.45**	**6.78**	**14.54**	**3.18**	**0.07**	**0.03**	**1.15**	**0.87**	**0.10**	**0.06**
Dev.	**0.50**	**0.06**	**1.78**	**1.00**	**9.87**	**0.56**	**2.55**	**1.39**	**0.04**	**0.03**	**0.09**	**0.07**	**0.04**	**0.02**
Overall Mean	**27.97 ±27.71**	**1.56 ±1.02**	**9.74 ±10.12**	**5.04 ±7.41**	**134.38 ±85.78**	**2.65 ±2.88**	**15.18 ±1.57**	**2.75 ±1.92**	**0.12 ±0.07**	**0.04 ±0.01**	**1.45 ±0.38**	**0.78 ±0.39**	**0.09 ±0.02**	**0.05 ±0.01**

TABLE 29: Tailing Thickener Underflow (TTU) Chemical Parameter (metallic ions) Results at Mopani Copper Mines, Kitwe

Date of Sampling	T Cu mg/l	D Cu mg/l	T Co mg/l	D Co mg/l	T Fe mg/l	D Fe mg/l	T Mn mg/l	D Mn mg/l	T Pb mg/l	D Pb mg/l	T Ni mg/l	D Ni mg/l	T Zn mg/l	D Zn mg/l
1st Trip														
29/9/05	0.31	0.06	0.05	0.01	0.15	0.03	17.12	0.10	0.02	0.02	0.42	0.29	0.05	0.03
30/9/05	0.54	0.03	0.07	0.02	0.13	0.01	11.67	0.08	0.04	0.03	0.36	0.18	0.03	0.02
Mean	**0.43**	**0.05**	**0.06**	**0.02**	**0.14**	**0.02**	**14.40**	**0.09**	**0.03**	**0.03**	**0.39**	**0.24**	**0.04**	**0.03**
Dev.	**0.16**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**3.85**	**0.01**	**0.01**	**0.01**	**0.04**	**0.08**	**0.01**	**0.01**
2nd Trip														
22/11/05	12.71	2.11	13.41	9.08	3.50	1.50	26.48	9.09	0.29	0.17	0.37	0.20	0.04	0.03
23/11/05	15.55	3.07	11.96	5.68	4.32	1.95	23.87	7.06	0.18	0.11	0.29	0.19	0.04	0.04
Mean	**14.13**	**2.59**	**12.69**	**7.38**	**3.91**	**1.73**	**25.18**	**8.08**	**0.24**	**0.14**	**0.33**	**0.20**	**0.04**	**0.04**
Dev.	**2.01**	**0.68**	**1.03**	**2.40**	**0.58**	**0.32**	**1.85**	**1.44**	**0.08**	**0.04**	**0.06**	**0.01**	**0**	**0.01**
3rd Trip														
2/8/2006	9.09	2.09	7.10	2.22	2.54	1.67	20.11	5.21	0.09	0.03	0.55	0.22	0.06	0.05
3/8/2006	7.34	1.10	5.11	2.19	2.06	0.91	17.87	4.19	0.12	0.01	0.43	0.20	0.06	0.06
Mean	**8.22**	**1.60**	**6.11**	**2.21**	**2.30**	**1.29**	**18.99**	**4.70**	**0.11**	**0.02**	**0.49**	**0.21**	**0.06**	**0.06**
Dev.	**1.24**	**0.70**	**1.41**	**0.02**	**0.34**	**0.54**	**1.58**	**0.72**	**0.02**	**0.01**	**0.09**	**0.01**	**0**	**0.01**
4th Trip														
18/12/06	10.78	2.08	4.13	2.02	2.85	0.93	16.72	6.23	0.04	0.01	0.51	0.22	0.09	0.07
19/12/06	9.93	2.05	3.93	1.13	1.98	0.64	18.11	8.31	0.03	0.01	0.46	0.20	0.12	0.06
Mean	**10.36**	**2.07**	**4.03**	**1.58**	**2.42**	**0.79**	**17.42**	**7.27**	**0.04**	**0.01**	**0.49**	**0.21**	**0.11**	**0.07**
Dev.	**0.60**	**0.02**	**0.14**	**0.63**	**0.62**	**0.21**	**0.98**	**1.47**	**0.01**	**0**	**0.04**	**0.01**	**0.02**	**0.01**
Overall Mean	**8.29 ±5.78**	**1.58 ±1.10**	**5.72 ±5.28**	**2.80 ±3.19**	**2.19 ±1.55**	**0.96 ±0.74**	**18.10 ±4.54**	**5.04 ±3.60**	**0.11 ±0.10**	**0.05 ±0.06**	**0.43 ±0.08**	**0.22 ±0.02**	**0.06 ±0.03**	**0.05 ±0.02**

TABLE 30: **Tailing Thickener Overflow-Drain Chemical Parameter (metallic ions) Results at MCM, Kitwe.**

Date of Sampling	T Cu mg/l	D Cu mg/l	T Co mg/l	D Co mg/l	T Fe mg/l	D Fe mg/l	T Mn mg/l	D Mn mg/l	T Pb mg/l	D Pb mg/l	T Ni mg/l	D Ni mg/l	T Zn mg/l	D Zn mg/l
1st Trip														
29/9/05	0.30	0.11	0.61	0.38	0.08	0.07	42.70	0.25	0.03	0.01	1.53	0.44	0.01	0.01
30/9/05	0.39	0.09	0.71	0.33	0.04	0.02	26.83	0.30	0.05	0.02	1.68	0.33	0.01	0.01
Mean	**0.35**	**0.10**	**0.66**	**0.36**	**0.06**	**0.05**	**34.77**	**0.28**	**0.04**	**0.02**	**1.61**	**0.39**	**0.01**	**0.01**
Dev.	**0.06**	**0.01**	**0.07**	**0.04**	**0.03**	**0.04**	**11.22**	**0.04**	**0.01**	**0.01**	**0.11**	**0.08**	**0**	**0**
2nd Trip														
22/11/05	1.15	0.97	0.90	0.79	4.20	1.80	1.70	1.55	0.74	0.15	2.37	0.20	0.02	0.01
23/11/05	1.11	0.82	0.98	0.55	5.32	1.11	1.09	0.91	0.67	0.09	1.10	0.34	0.02	0.01
Mean	**1.13**	**0.90**	**0.94**	**0.67**	**4.76**	**1.46**	**1.40**	**1.23**	**0.71**	**0.12**	**1.74**	**0.27**	**0.02**	**0.01**
Dev.	**0.03**	**0.11**	**0.06**	**0.16**	**0.79**	**0.49**	**0.43**	**0.45**	**0.05**	**0.04**	**0.90**	**0.10**	**0**	**0**
3rd Trip														
2/8/2006	0.92	0.57	0.84	0.41	4.06	2.98	33.90	4.74	0.51	0.06	1.32	0.99	0.02	0.02
3/8/2006	0.99	0.65	0.93	0.65	2.07	1.09	23.98	1.77	0.34	0.12	1.54	0.98	0.02	0.01
Mean	**0.96**	**0.61**	**0.89**	**0.53**	**3.07**	**2.04**	**23.94**	**3.26**	**0.43**	**0.09**	**1.43**	**0.99**	**0.02**	**0.02**
Dev.	**0.05**	**0.06**	**0.06**	**0.17**	**1.41**	**1.34**	**0.06**	**2.10**	**0.12**	**0.04**	**0.16**	**0.01**	**0**	**0.01**
4th Trip														
18/12/06	1.72	0.88	0.62	0.46	1.43	0.98	16.32	3.76	0.06	0.01	0.96	0.34	0.02	0.02
19/12/06	2.50	1.09	0.83	0.51	0.95	0.87	17.98	3.94	0.07	0.03	1.21	0.94	0.02	0.01
Mean	**2.11**	**0.99**	**0.73**	**0.49**	**1.19**	**0.93**	**17.15**	**3.85**	**0.07**	**0.02**	**1.09**	**0.64**	**0.02**	**0.02**
Dev.	**0.55**	**0.15**	**0.15**	**0.04**	**0.34**	**0.08**	**1.17**	**0.13**	**0.01**	**0.01**	**0.18**	**0.42**	**0**	**0.01**
Overall Mean	**1.14 ±0.73**	**0.81 ±0.13**	**0.65 ±0.40**	**0.51 ±0.13**	**2.27 ±2.07**	**1.12 ±0.85**	**19.32 ±13.97**	**2.16 ±1.68**	**0.31 ±0.32**	**0.06 ±0.05**	**1.47 ±0.28**	**0.57 ±0.32**	**0.02 ±0.01**	**0.02 ±0.01**

DISSOLVED RADIONUCLIDES RESULTS

TABLE 31. Dissolved radionuclides in TTF (Bq/m^3) at MCM, Kitwe

Sampling Date	Dissolved Radionuclides	
	^{226}Ra	^{228}Ra
30/9/2005	0.097 ± 0.01	0.18 ± 0.01
25/11/2005	0.115 ± 0.01	< 0.03
4/8/2006	0.065 ± 0.01	< 0.03
21/12/2007	0.093 ± 0.01	< 0.03
Overall Mean	**0.093 ± 0.02**	**0.068 ± 0.08**

TABLE 32. Dissolved radionuclides in TTU (Bq/m^3) at MCM, Kitwe

Sampling Date	Dissolved Radionuclides	
	^{226} Ra	^{228} Ra
30 / 9/ 2005	0.176 ± 0.02	0.08 ± 0.07
25 / 11 / 2005	0.212 ± 0.02	0.10 ± 0.03
4/ 8 / 2006	0.230 ± 0.02	< 0.03
21 / 12 / 2006	0.174 ± 0.02	0.04 ± 0.03
Overall Mean	**0.198 ± 0.03**	**0.07 ± 0.02**

TABLE 33. Dissolved radio nuclides in TTO (Bq/m^3) at MCM, Kitwe

Sampling Date	Dissolved Radionuclides	
	^{226} Ra	^{228} Ra
30 / 9/ 2005	0.043 ± 0.01	< 0.03
25 / 11 / 2005	0.015 ± 0.01	0.05 ± 0.02
4 / 8 / 2006	0.037 ± 0.01	< 0.03
21 / 12 / 2006	0.065 ± 0.01	< 0.03
Overall Mean	**0.040 ± 0.02**	**< 0.03**

SUSPENDED RADIONUCLIDES RESULTS

TABLE 34. Suspended Radionuclides (Bq/kg) at MCM, Kitwe.

PARAMETERS	SAMPLING SITE		
	TTF	TTU	TTO
^{224}Ra	66.10 ± 5.75	69.80 ± 4.7	38.60 ± 4.7
^{226}Ra	80.25 ± 3.75	104.00 ± 4.5	57.85 ± 3.65
^{228}Ra	73.90 ± 4.6	80.80 ± 5.1	41.90 ± 4.5
K-40	1720.00 ± 69	451.00 ± 29	96.00 ± 18