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PREDICTION, PREVENTIVE AND REMEDIAL ACTION AGAINST ACID MINE DRAINAGE (PRAMID)

by'

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ABSTRACT

PRAMID aimed at the development of an integrated environmental management methodology and mine closure strategy for the efiective control and mitigation of the Acid Mine Drainage (AND) phenomenon in polymetallic sulphide mines. The Kassandra mines in Macedonia, Greece were used as the case study. AMD is generated by the oxidation of sulphide minerals under the combined action of oxygen, water and indigenous oxidising bacteria. The acidic waters generated have high concentrations of metals and pollute the soils, surface and ground waters. The main sources of AMD are underground and open-pit mining works, waste rock dumps, and processing wastes; the sources generally remain active and pollute the environment for decades or even centuries after mine ciosure.

A generic methodology for the prediction, prevention and remediation of the AMD phenomenon was developed including the following; identification of AMD sources, sampling and characterisation; drainage monitoring; static and kinetic tests for predicting the AMD potential and quality; chemical modelling of the reactions involved; drainage prediction from spoils versus time. Within the project several preventive technologies were tested, such as the application of alkaline additives and covers. Remediai technologies developed include innovative neutralisation schemes with magnesia in combination with sulphate reducing bacteria, and passive treatment schemes with anoxic limestone drains and anaerobic wetlands. These findings provided the basis for the development of a mine closure strategy. The expertise and methodologies acquired within the project, already transferred to the endorsing Kassandra Mines, can potentially be used by other similar sulphide mines, in order to aid sustainable development in the mining sector in Europe.

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1. INTRODUCTION

1.1 Objectives

PRA.MID is a focused fhridarnental research project addressing the acid mine drainage environmental problem faced by virtually ail polymetallic sulphide mines. The project aims at:

- the development of an integrated method for the effective prediction, prevention and mitigation of the Acid Mine Drainage (AMD) phenomenon in polyrnetallic sulphide mines and processing operations, and
- the elaboration of appropriate mine closure strategies in order to minimise long-term environmental problems in redundant sulphide mines.

The control and abatement methodology developed is intended to be of a generic nature; the *Kassandra Mines,* a galena- sphalerite- pyrite producer at Macedonia, Greece was examined as the case study.

The Project had two research partners: The Laborato~ of Metallurgy, Department of Mining and Metallurgical Engineering, NTational Technical University of Athens, Greece (NTUA) acting as the project co-ordinator and the Department of Mineral Resources Engineering, Imperial College of Science, Technology and Medicine, London, UK (IC); Hellenic Chemicals and Fertilisers, (HC&FC) owners and operators of the Kassandra Mines Complex until December 1995 and Knight Piesold and Partners @P&P), UK, a Consulting-Engineering Company participated in the project as the endorsing companies,

The objectives of PRAMID were implemented by tackling the issues shown in the project work programme, Figure 1,

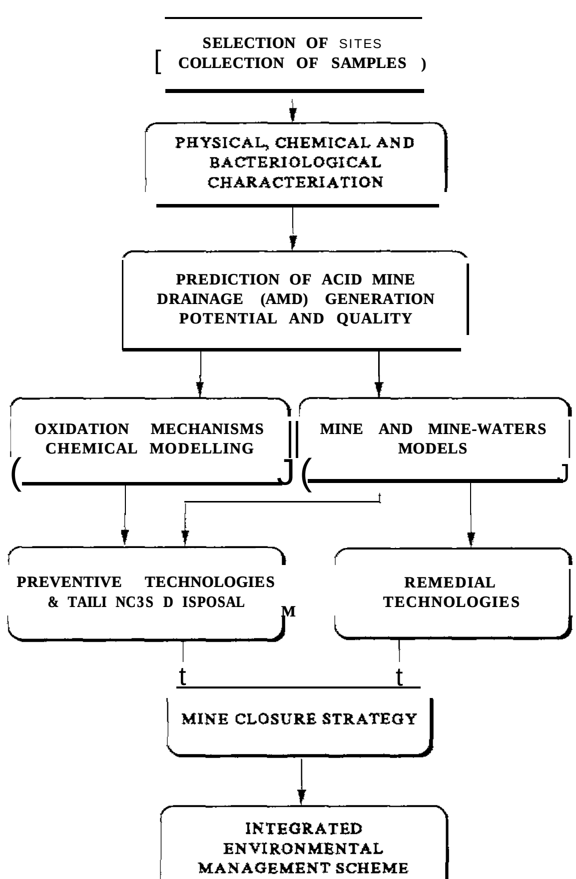

Figure 1: PRAMID project flow diagram

Chen the focused fundamental nature of the project more emphasis was given in the development, evaluation and comparison of state-of-the art technologies. Also an effort was made for transfer in Europe the experience from countries like Canada and the US& where the acid mine drainage problem has been faced for years. Finally, it must be pointed out that the aim of the study was not to resolve the ail the tailings and water management issues of the Kassandra mines.

1.2 Kassandra Mines Complex

The Kassandra Mines used as the case study consist of the Mavres Petres and Madem Lakkos mines in Stratonion and the Olympias mine. In 1993 the Stratonion ROM production amounted to 300,000 t, averaging: Pb: 8.OYO, Zn:6.5%, S:22.0%, Ag: 155 @t while for Olympias it was 130,000 t with: Pb:4.0%, Zn:5.5%, S:17.1?40, As:3.8°A, Ag: 130 g/t and Au: 10 g/t, In Stratonion, the sulphide mining / processing activities were started by HC&FC in the early 1950's and with the present ore reserves they are expected to last until the end of the century, In Olympias mining commenced in 1976; coniirmed ore reserves are presently estimated at 14 Mt, enough for 25 years operation. The mining method used in the past was sub-level caving. However, since, 1989, the cut-and-fill method has been applied in both mines, using the coarse flotation tailings fraction mixed with cement as backfilling material.

Galena and sphalerite concentrates are recovered in both the Stratonion and Olympias processing plants but in Olympias an auriferous arsenical pyrite concentrate is also separated and stockpiled. In the past, standard pyrite was produced in the Stratonion plant; currently the pyrite is rejected with the tailings.

2. TECHNICAL DESCRIPTION AND RESULTS

An overall review of the research work performed by the participating partners is presented in the following sections:

2.1. Selection of sites. Collection of samples

This task covered the identification and selection of potential sources of AMD within the mining areas, the collection of samples, and assessment of the current environmental conditions. The areas examined within the PRAMID project as potential sources of acid mine drainage include flotation tailings dams in the Stratonion and Olympias mines (code-named STAFLOT and OLTAP), Stratonion waste rock and pyrite concentrate stockpile (STAROCK and STAPYC). Moreover, the Stratonion mine, whose operations are expected to cease by the end of 1990's was selected as the case study for the development of the mine closure strategy.

After a systematic sampling campaign, more than 140 solid samples, both bulk and drill-core, were collected from the selected sites providing an adequate, if not complete, description of the deposited material and characteristic properties were measured.

2.2 Detailed physical, chemical and bacteriological characterisation of the samples. Estimation of current environmental conditions

<u>Composite samples formation - Chemical and mineralogical characterisation</u>

Composite samples were formed, representing the wastes deposited at the selected sites, and their chemical and mineralogical composition was determined. These composites formed the test materials examined in the AMD generation studies.

Physical / Geote.chnical properties of wastes with laboratory and in-situ measurements

The properties determined included: *particle size distribution, bulk and particle density rnoistwe, porosity andpemeability;* these parameters known to significantly influence the rate of acid drainage generation and the migration of the resulting acidic waters. The geotechnical data, were employed in the design of the kinetic studies and modelling so as to simulate the actual site conditions.

Water monitoring

A water monitoring programme was established for the Stratonion mine in order to elucidate the correlation between the quality of the waters and the on-going oxidation in the underground works. On-site measurements of pH/EMF, conductivity and flow-rates on a monthly basis, plus chemicaI analyses on a quarterly basis were carried out for a period of more than two years. The streams were classified according to their acidity, metal content and flow-rates.

Characterisation of the indigenous bacterial population

A study of the Stratonion mines waters indicated that the bacteria present were predominantly strains of *ThiobaciWs ferrooxidans* and *thiooxiahns* with the occasional occurrence of *Leptospirihw2 ferrooxiahs.*

Monitoring boreholes

Piezometers, eight in total, were installed in selected locations of the waste disposal areas, STAFLOT, STAPYC and OLTAP, to evaluate the current state of the environment and to establish the correlation between laboratory, model and field results regarding the mechanisms of acid mine drainage generation.

2.3 **Prediction of acid mine drainage generation and quality**

State-of-the-art predictive laborato~ tests, including static and kinetic tests were applied to assess the potentiaI for acid generation and the drainage quality from the waste stockpiles under study.

Static tes~s are low-cost laboratory scale procedures, developed to measure the balance between the acid generating and alkaline minerals of a given material and therefore to determine its potential to produce acidity when exposed to atmospheric conditions, In order to develop a generic methodology for the prediction of ARD potential, a number of *static tests* including the Acid-Base Accounting (ABA), B, C. Research initial (BCR) and the Net Acid Production test (NAP) were tested and their results were compared, Static tests were performed on a number of geological formations as well as on different wastes and processing tailings stemming from the Kassandra mines.

Kinetic tests including the B.C. Cordlrrnation test, lysimeters and leaching columns were applied to samples such as STAPYC, STAFLOT and OLTAP E. S. which according to the static tests exhibited potential for acid generation. With kinetic tests, the quality of the drainage emanating from the sulphide wastes under study was evaluated, taking into account parameters such as the temporal relationships involved in acid mine drainage, the geotechnical characteristics of the waste as well as the meteorological conditions prevailing in the study area.

The results of the predictive tests study are summarised in Table 1. E was seen that with the three static test techniques examined, the classification of the examined solids regarding their potential to generate acidity remains in general the same. Furthermore, the static test results were found to be in agreement with kinetic data and on-site measurements. However, behaviour of the fine STAFLOT flotation tailings was not accurately predicted by static tests; despite its high sulphur content, the low permeability of this stockpiled material does not allow the massive generation of acidity. Thus, it is deduced that in addition to its chemical properties, the geotechnical characteristics of a given waste also significantly effect the potential for acid drainage formation in the disposal facilities. Furthermore, the waste rock material stockpiled at the STAROCK site was quite inhomogenous in nature and the composite sample showed significant variation in suIphur content in the different size fractions obtained after wet sieving. Although the STAROCK material was predicted to be non acid generating, according to the static tests, field observations indicated on-going oxidation activity in the waste rock stockpile. It is thus concluded that the selection of a representative sample should be the primary consideration before conducting predictive tests.

Tabk 1
AMD prediction results

Sample	Static test	S %	NNP kg CaCO#	AMD Generation	Kinetic results	Field data
t = =	ABA BCR NAP	14.8	-327.9 -337.9 *-107.1*	Yes Yes *Yes*	No	No
F PYC	ABA BCR NAP	*46.7*	*-1476.4* *NA$* -733.6	*Yes* Yes	*Yes*	*Yes*
ROCK	ABA BCR ATM	4.4	293.2 274.8 > 0	No No *No*		Yes***
FOLTAP E.S	ABA BCR NAP	*6,5*	*271,0* *243.7* > 0	*NO*** ~ T No	No	No
OLTAP 1?.S	ABA BCR NAP	2.5	172.7 145.8 > 0	No No No	No	No

* Not applicable, ** Zone of uncertainty, *** Occasionally

2.4 **Determination of the prevailing oxidation mechanisms. Chemical modelling**

Fundamental studies of the oxidation mechanisms

Oxidation tests in a giass reactor were carried out to examine the effect of ferric iron on the dissolution of arsenopyrite for pH: 1.0 and 2.0 at ambient temperature, Based on the analysis of As(III)/As(V) and Fife in solution, the oxidation of arsenopyrite was found to obey the following equation:

$$2FeAsS + 14Fe3+ + 7H_j0 + 16Fe^{2+} + 2As0.j + S,0_3^{2-} + 14H' \quad (1)$$

The relationship between initial ferric sulphate concentration and the initial rate of leaching for the ditlerent experiments is shown in Figure 2.

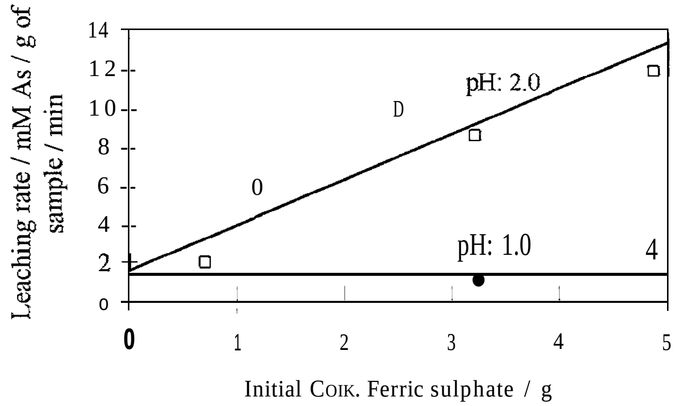

Figure 2: Correlation between the initial concentration of ferric sulphate and the leaching rates at pH: 1.0 and 2.0, temperature:20 *C,

The slopes indicated a rate of 2.4 x 10-~ and 0.4 x 10-4 rnM As/g of sample/g of initial ferric concentrationh-ninute for pH 2.0 and 1.0 respectively. The decrease in dissolution rate with increasing acidity is as expected in view of the proposed leaching reaction.

Chemical modelling

The Reactive Acid Tailings Assessment Programme (RATAP), developed within the Canadian MEND programme was tested and used as a tool for AMD modelling.

A preliminary evaluation of the RATAP computer model was carried out using data available from the STAPYC column test. Furthermore, the model was applied in the simulation of the STAFLOT and OLTAP disposal areas. The predicted values obtained by RATAP were consistent with those of the kinetic experiments and cordkrned that the simulated average acidity generated by the STAFLOT stockpile was not high.

The simulated effect of increasing the pyrite content of the OLTAP, W.S tailings on the amount of acidity generated on an annual basis, is given in Figure 3. Three 3.5 m laboratory leaching columns were set up, in which pyrite concentrate was added to Olympias tailings to correspond with the simulations. The experimental results confirmed that only small amounts of acidity were generated even in the case where pyrite w-as increased by 10 times.

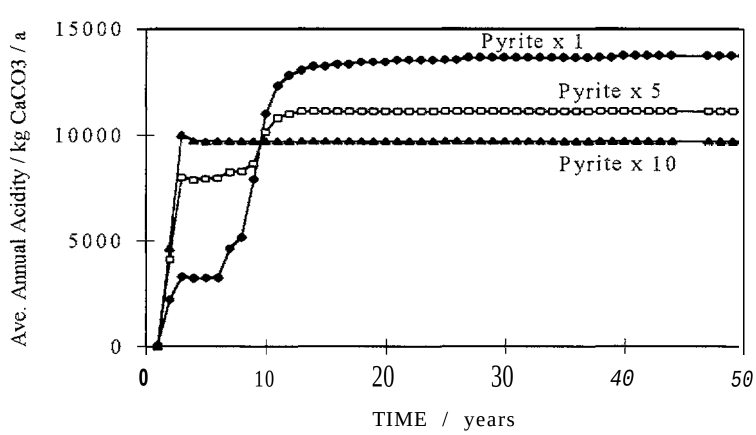

Figure 3: Average annual acidity for Olympias Tailings for 3 different pyrite contents

2.5 IWduation and devthpment of mine and mine-water models

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A 3D geostatistical model was developed in order to determine the underground areas within the Stratmkm mine where intense sulphide oxidation activity occurs or which possess a high potential for acid generation. For model validation, the qualities of the mine waters were assessed as related to their Ori=gins.

The dii%-ent steps for the development of the model included: compilation of geological logging horn exploratory drllhcdes from the wider Stratm.ion area; the construction of geological cross-sections, to optimally estimate the initial values of the numericaI model parameters; assignment of experimentally defined NW values to the geological formations including CH@iboiite, amphilmlitic gnei.w, bioti"tic gneiss, marble, aphle, pyrite, H% (kixed s7.@k'a'e minera!isation) and keratite; and structural amdysis of the NNl? distribution.

The output of the model, in the form of horizontal cross-sections, was superimposed on the Stratonion mine plans in order to produce maps of the NW? distribution on the main levels of the underground mining works. To validate the aeguracy of the estimation and also to improve the prediction capability, the following information was also included in the model output: [a) Stratonion mine waters flow paths, including their acidities and flmvrates, (b) mine voids and 'backfilled mining areas. In Fi=~re 4 the characteristic areas of A&ID generation potential identified using the 3D model are presented. These maps are a vaIuable too} far both the elucidation of the acid mine waters origin and the design of mine closure strategy.

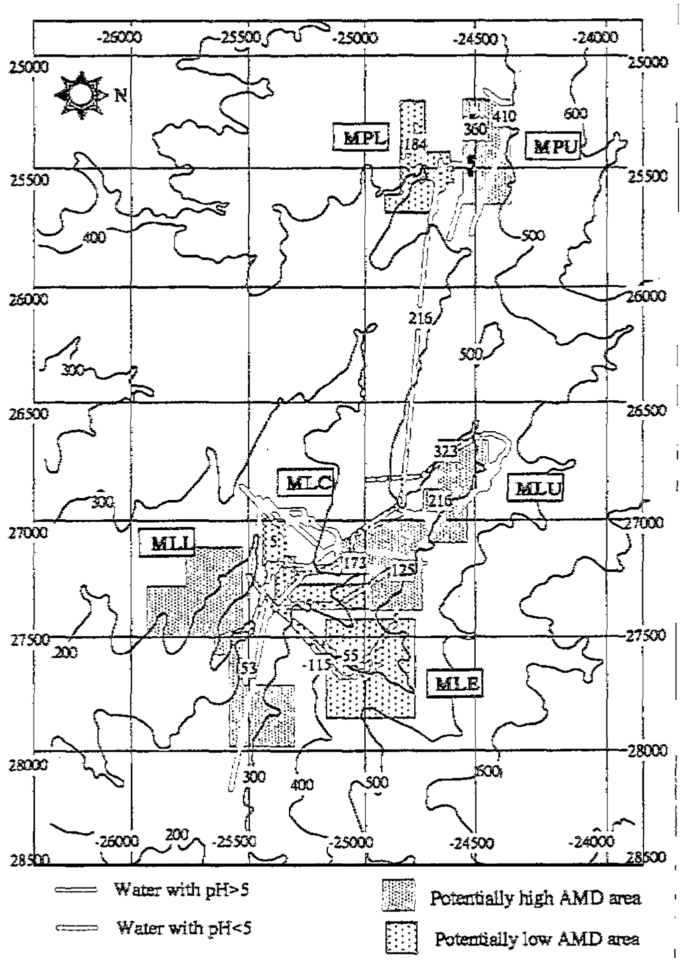

Figure 4: Schematic representation of i~aracteristic areas **in** the Stratonion mine.

Environmental Simulation Pro~ramme CESP)

Mine water monitoring data were employed to derive an equilibrium chemistry model of the Stratonion waters using the Environmental Simulation Prograrnme (ESP) developed by OLI Systems. The agreement between the field data and the model is considered satisfactory; the model is capable of predicting the changes in composition as the water progresses through the flow network in the mine. Moreover, the model is a usefil tool to predict changes in the chemical composition of the waters once the mine is closed. The mine water network was divided into three separate areas: Mavres Petres and Madem Lakkos, the latter having been sub-divided into two parts, the +63 and -63 levels, based on the assumption that once pumping has ceased, the water table will rebound to level +63 as the maximum height. The prediction of water quality for the summer season, assuming that the July 95 sampling campaign results are typical of that period of the year, is given in Table 2.

Table 2

ESP predicted metals concentrations in the Stratonion mine waters, mg/1

Area	pH	Fe(II)	Fe(III)	Pb	Zn	Mn	S0,	Q (m'/h)
Mavres Petres	4.4	4.8	0.0	0.5	7.3	14.7	570.7	144.9
M, bkkos +63	2.1	663.8	95.3	0.6	290.5	338.6	5931.8	49,2
M. h.kkos -63	3.0	51,6	0.1	0.7	49,2	8.6	1414.1	92.8

2.6 Evaluation and development of preventive technologies

Aikaline additives

The effect of limestone addition on the mitigation of acid mine drainage generation from pyritic wastes was examined. Laboratory lysimeter tests were performed on the pyrite concentrate stockpile (STA.PYC) in which limestone was added by mixing (SL 1) or layering (SL2). The mechanisms involved in the system regarding acid generation-neutralisation and secondary mineral formation were examined based on the drainage chemistry and analyses of the solid residues.

The effects of limestone addition on the drainage quality afier 300 days of testing are illustrated in Table 3.

Table 3

Drainage quality of limestone amended and control tests after 300 days (analyses in mg,d)

Lysirneter	pH	S04	Fe	Zn	As	Pb	Ca
Control	2.3	4500	920	50	20	-	-
SL 1 (mixture)	**7.3**	**1480**	<0.1	**15**	**<1**	<0.5	660
SL2 (layer)	3.0	1810	94	27	1	<0.5	590
Permissible levels for industrial effluent discharge*	6.0-8.5		15	2.0	0.5	0.1	

*Greek legislation 573, vol B, 24/9/86

Previously reported applications of the use of limestone for the amendment of mine wastes have been for wastes with sulphur contents ranging between 1- 10"/O. The findings of this study suggested that limestone could be also effectively applied for pyrite-rich materials if it is properly ground and homogeneously mixed.

Mixing pyrite with limestone amounting to only 5’?40 of the contained acidity, resuh ed in drainage with near neutral pH and Fe levels within the permissible environmental limits; fi,u-thermore the rate of pyrite oxidation was reduced by 53Y0. Based on these findings, this limited amount of limestone would suffice to neutralise the produced drainage for a period of 3 years. However, when limestone was added as a layer, the alkaline potential, i.e. 15% of the contained acidity was not effectively utilised to neutralise the acidity produced. The pH of the leachate remained acidic with an average value of 3,1, however the sulphate production was reduced by 33% against the control run.

It was thus deduced that the inhibition of acid generation in pyritic waste is not solely determined by the addition rate of alkaline materials. The homogeneous distribution of acid generating or neutralising materials significantly contribute to the relative effectiveness of this measure in controlling acid generation, Further testwork is necessary to confirm the feasibility of preventing acid generation from pyritic wastes by adding limestone in small fractions of the stoichiometric requirements.

Soil covers

RATAP computer model was applied in order to assess the effectiveness of soil covers as a measure to prevent AMD generation in the STAPYC stockpile, Two different covers were considered: a two layer cover consisting of coarse sand covered by compacted till and a four layer cover consisting of a coarse sand / compacted till / coarse sand 1 soil sequence. Figure 5 shows that both the two and four layer covers can decrease the average generation of acidity by almost 50% and 66% respectively, however, the actual potential for acid generation remains high over the long term. The implication is that safe design criteria should be adopted when layered soil covers are designed.

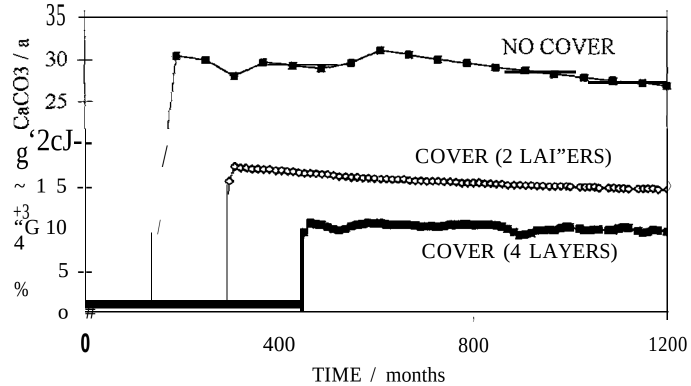

Figure 5: Simulated effect of placing layered soil covers on the STAPYC stockpile.

2.7 Evaluation of remedial technologies

Comparative study between lime and mamesia neutralisation

For this study factorial design was applied to synthetic solutions consisting of Fe, Mn and As, the main metal ion contaminants of the Stratonion mine waters. With magnesia the control of the final pH was more accurate and the volume of the sludge produced was significantly reduced. The settling properties of the gypsum containing sludge were poorer than these obtained with magnesia. However, the final Mg and sulphate levels in solution are significantly higher than the environmental limits for disposal. Furthermore, precipitation with magnesia present higher cost and slower kinetics than lime. Based on research findings and published data, a combination of limestone/lime is suggested for the neutralisation of acidic, metal 1 aden solutions.

Precipitation of heavy metals with bio-hydrogen sulphide

A process for the treatment of acid mine water involving the use of sulphate reducing bacteria (SRB] to precipitate heavy metals was developed. **As** illustrated in Figure 6, the scheme consists of four” basic steps. Firstly, Fe and As are removed as hydroxides by pH control using NaOH or $Mg(OH)_2$. This step results in the disposal of the non-valuable metals as a sludge of reduced volume, stable for safe environmental disposal. In the second stage, the biogenerated H_2S reacts with the dissolved metals and Cu and **Zn** precipitate as sulphides. The third stage involves the precipitation of Mn as sulphide in order to eliminate H_2S from the solution to be fed to the bioreactor. The final stage of the process involves the biogeneration of H_2S by the reduction of sulphate in the effluent by the SRB. The Upflow Anaerobic SIudge 131anket reactor (UASB) is used for the H_2S generation; the advantage of this type of reactor is its simplicity and robustness.

The results confirmed the feasibility of the concept. Precipitation of +99% was obtained for all the metal ions present. It was concluded that the w-ater quality resulting from the process can easily meet environmental regulations and potentially saleable metal concentrates of high grade can be generated. Furthermore, the overall volume of sludge generated is minimised by using sodium hydroxide/magnesia in the precipitation of iron and arsenic ions. Taking into account that to test biological systems, it is necessary to operate the flow circuit for several months at steady state, ftlrther work is necessary to conduct a full economic evaluation of the proposed process.

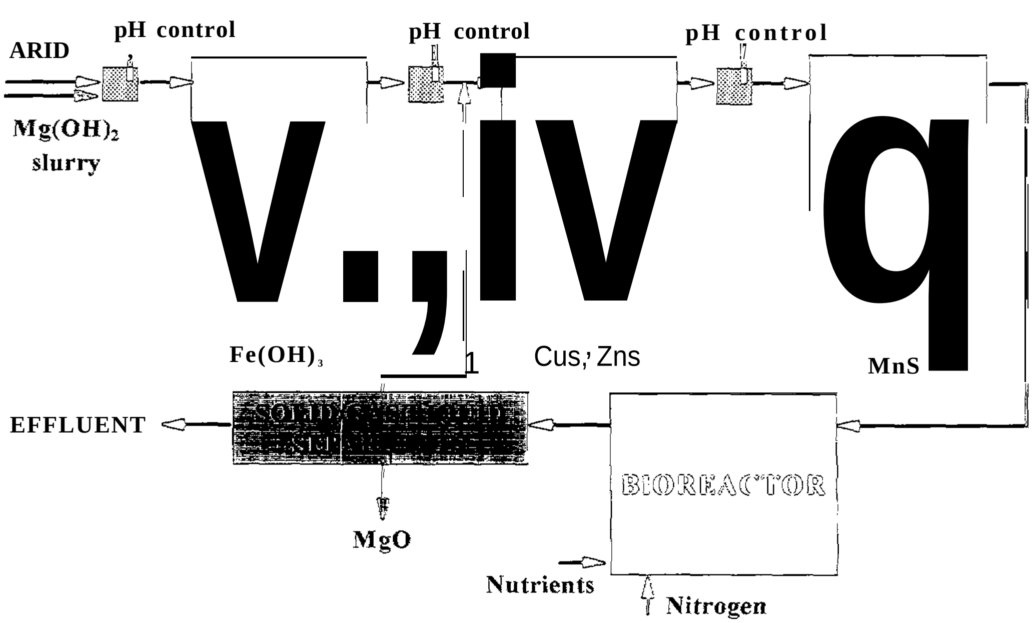

Figure 6: AND treatment scheme

Passive Treatment schemes - Anoxic Limestone Drains

To evaluate the applicability of Anoxic Limestone Drains (ALDs) as a method for the pre-treatment of metal laden acidic mine waters, “proof-of-principle laboratory tests, both static and dynamic, were carried out. The aim of this study w& to determine the effect of the mine water composition on the alkalinity generation potential and the kinetics of the system.

Synthetic acidic solutions simulating the average quality of the Stratonion mine waters were examined, Fe^{3+}/Fe^{2+}, $\sim^{2+}$, Zn^{2+} and $A1^{3}$’ being the major contaminants. The effect of ferrous/ferric iron and alurninium on limestone dissolution and the overall petiormance of ALJls was specifically addressed.

For all solutions examined, irrespectively of their initial composition, the effluent recovered after the static ALD tests had an alkaline pH, with varying net alkalinities. Kinetic runs were then conducted in order to confirm the static results regarding the rate of limestone dissolution and the alkalinity generation potential of ALDs.

From the research findings summarised in Table 4, it was concluded that Anoxic Limestone Drains can be effectively employed for the pre-treatment of acidic drainage solutions containing Fe^{2+} and/or Mn^{2+} andfor Zn^{2+}. When metal levels in solution remained above 200 mgy’1, the efiluents exhibited net acidity due to the contained mineral acidity.

The performance of ALDs is significantly impaired in the presence of Fe^{3+} andlor $A1^{3+}$, or increased levels of DO along with Fe^{2}’, G&en the low pH of hydrolysis of both Fe^{3+} and AI’+, the limestone is rapidly coated with hydroxide precipitates, the calcite dissolution rate decreases and the production of alkalinity virtually ceases.

Table 4

Static and kinetic tests results (pH influent: 2.6, analyses in mg/1)

Treatment	pH	Acidits*		Mk.				Z n, +			f
	Ef.	In.	E f	Ef.	Ef.		E f	Ef.	Ef.	Ef.	E
3T.4TIC TESTS, Contact time 5 days											
Control	8,0	124	**0.0**	97							
Fe^{z+} :500	6,4	1009	694	85	432						
Fe^{3+}: 500	6,5	1414	0.0	426							
As^{5+}: 20	8.2	293	31	127						16	
Fe^{2+}/As^{5}’: 500/20	6,5	1014	589	128	413					**0.0**	
iw^{3+}: 50	7.0	55-7	0.0	203					0.0		
Fe/MdZn/As/Cu .500/250/300120/25	6.7	2214	1600	83	423		287	250		**0.0**	0.2
KINETIC TESTS, Retention Time 4h											
Fe^{2+} :500	6.6	1075	790	94	506						
Fe^{3+}: 500	2.8	1415	650	0,0		246					
Al^{3+}: 50	4.2	529	172	0.0					36		
Fe^{2}’,Mn^{2+}/Zn^{2+} 500/250/300	6.5	19s4	1821	54	507		260	305			

* analyses, mg CaC03/1

Sizing *of ALDs*

For sizing an anoxic limestone drain, the amount of limestone needed for the continuous operation of the system, for a certain period of time, should be estimated. This estimation is based on the following parameters: water flow-rate, calcite content of limestone, limestone dissolution, desired life of the ALD.

The assumption that the contained acidity should be all neutralised by limestone was not confirmed by the static and kinetic test results, since in highly contaminated waters the effluent remained net acidic. Thus, the amount of limestone that is going to dissolve, is mainly depended on the amount of alkalinity that is going to be produced. It is suggested that the alkalinity to be added in the system should be the sum of two individual values. The first component is the maximum theoretical alkalinity (MTA) that can be added under the specific conditions of the ALD (closed system) and is determined from thermodynamic data assuming that the partial pressure of $C0_2$ equals to 0.05 atm. According to these calculations, MTA in Anoxic Limestone Drains amounts to 300 mg/1 (Stumm and Morgan, 1978). The second component refers to the neutralisation of the acidity within the system associated with the partial precipitation of metals, mainly as carbonates or hydroxides.

2.8 **Mine closure strategy**

Research findings obtained in this project together with the results of relevant studies reported in the literature and the background data provided by the Kassandra Mines were assessed so as to elaborate a post closure strategy for the Mavres Petres and Madem Lakkos mines, and other similar sulphide operations where acid mine drainage presents a potential long term environmental problem. The overall closure scheme includes methods and techniques to minimise AMD generation, and mitigate its eflect as well as to monitor its long-term environmental impact.

Alternative measures that should be taken to control and abate acid mine drainage generation in the waste disposal sites under study are given in Table 5,

Table 5

Remediation options for the examined waste disposal sites

REM!3DIATION OPTIONS]	ADVANTAGES	DISADVANTAGES
Pyrite concentrate stockpile, STAPYC		
Leave in place and cover Install dr&age systems RecontourlRevegetate	I - Reduce oxidation and metal release rate - Minimise erosion and tMIISpOI_t Of solids	f - Cost of cover/ rehabilitation - May still require long-term drainage collection and treatment
Reprocess	- Additional income should reprocessing prove economical	- Cost requirements
Fine$otatiofl tailings, STAFL(X		
Leave in place and cover Flatterubuttress slopes Recontour/ Install spillway Drainage systems	- Physical stability - Reduce rate of oxidation and metal leaching	- Cost of coverf rehabilitation - Long-term monitoring /treatment
Waste rock, STAROCK		
Leave in place and cover Install drainage systems Recontour/ Revegetate	- Reduce oxidation and metal release rate	- Cost of cover/ rehabilitation - Long-term monitoring
Classtilcation to segregate the sulphides	- Reduce the amount of acid generating rock - Minimise risk associated with on site utilisation of waste rock	- Operatiom'transport cost - SipplemenEuy 'measures for the management of the sulphides fraction - Long-term monitoring

The underground mine workings are the major AMD source at the Stratonion mine. The water monitoring data along with the predictions of the 3D model provided the input to determine the high risk areas, where special measures should be taken during mine decommissioning. In order to develop an alternative water management scheme, the quality of waters originating from the characteristic areas after mine closure and the relative contribution of the major acidic streams on the final effluent quality was also predicted with the ESP model. It was concluded that even for the case where all the acidic streams are isolated, the mine water quality would not meet environmental standards for direct discharge to natural receivers.

Measures that should be taken to reduce the extent of acid generation and pollution migration in underground mining works include: backfilling of mined out areas; installation of bulkheads; construction of diversion channels; segregation of highly polluted acidic streams from relatively "clean" circumneutral waters.

The separate passive treatment of certain acidic streams was also reconumended, as an alternative to the existing neutralisation schelme, shown in Figure 7.

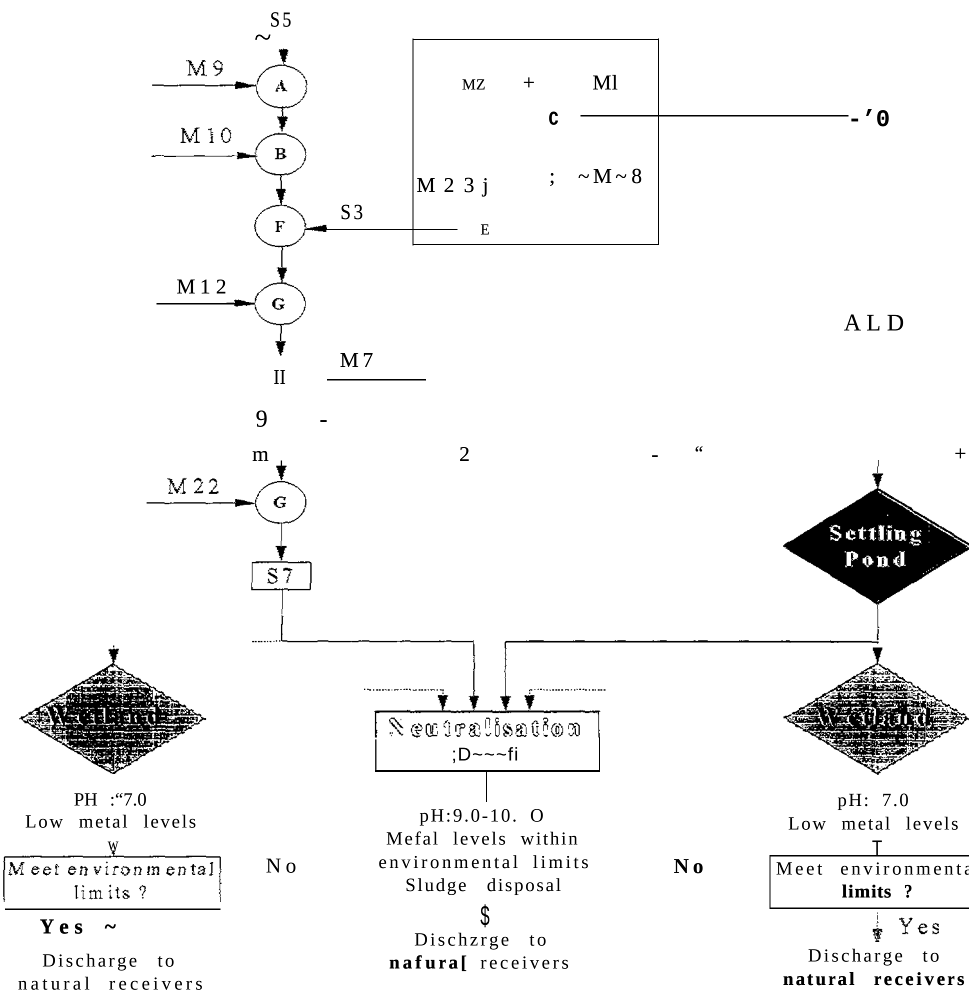

Figure 7: Proposed mine waters treatment scheme

2.9 lDeveIopment of an integrated environmental management scheme

Techniques and methods developed and applied within the project, including sampling, characterisation of mini~g wastes, environmental mcmitoring, prediction and chemical modelling of the acid drainage generation consist the first part of this protocol. Another part of this methodology covers the evaluation of available preventive techniques as defined from laboratory testing and computer simulation. Finally the optimisation of acidic water treatment. was assessed with the potential application of low-cost active and passive schemes developed within the project.

Similar mining areas within Europe where the methodology developed within the project could be applied include: LAVRION, (3R; WHEW JANE, UK; AVC)CA, IE; SALSKNE> FR; WISMUTH, RAMMELSBURG, DE; ALMAGRERA, RIO TINTO & THARSIS, ES; NEVES CORVO, PT; OUTCICUMPU, FI; SILVERGRUN> SE; BURGAS, BU.

3. CONCLUSIONS

For the completion of the PRAMID project a considerable effort was paid by NTUA IMPCOL and the endorsing companies, HC&FC and KP&P, to meet the main objectives of the project and more specifically to cover the areas regarding the “Development of a mine closure strategy” and the “Development of an integrated method for the effective prediction, control and mitigation of Acid Mine Drainage phenomenon in polymetallic sulphide mines”. These objectives set by the PRAMID group were met within schedule, as a result of the constructive co-operation of the members of the consortium. During the execution of the individual tasks including site characterisation, environmental monitoring, prediction and chemical modelling of Acid Mne Drainage potential and quality, a considerable effort was made for technology transfer and critical assessment of the state-of-the art methods. Regarding the evaluation and development of preventive and remedial methods, emphasis was placed on assessment of the applicability of cost-effective techniques to sites where acid mine drainage consists a serious threat to the environment. The main conclusions derived from the execution of the different stages of the project are summarised below:

A *comprehensive review* of the Kassandra mines records and numerous site visits were undertaken for the *selection oj sites* to be examined, as potential sources of acid drainage, and complete *characterisation of* the wastes under study was then performed. Due to the complex situation encountered in this sulphide mine with more than forty years of operation, during which the environmental legislation has varied significantly, the duration of the tasks related to the characterisation of deposited wastes and monitoring of the current environmental conditions was extended and additional man-power was allocated, given that this set of data provided the basis for the next stages of the project.

The transfer, critical evaluation and subsequent application of experimental techniques, methods and numerical models related to the *prediction* of AMD generation is considered to be filly developed. The scope of work of the prediction task was expanded compared to the project’s work programme; the main static and kinetic test techniques reported in relevant studies were compared so as to propose a reliable low-cost methodology of broad applicability. Concerning the static tests examined it was concluded that the BC Research Initial test seems to more closely simulate the actual conditions prevailing during the generation of acid mine drainage. However, it is time consuming and requires more elaborate equipment than Acid Base Accounting. It is thus suggested that in order to predict the relative AMD potentiai of a large number of samples, the standard screening method that should be used is the Acid Base Accounting method. For field applications and samples with low sulphur content, the Net Acid Production test may be employed as an alternative. The results of the static tests techniques were in most cases in agreement with kinetic test data and on-site measurements. However the behaviour of the fine flotation tailings was not accurately predicted by static tests; despite its high sulphur content, the low permeability of the stockpiled material does not allow the massive generation of acidity. It is thus evidenced that in addition to its chemical properties, the geotechnical characteristics of a given waste also significantly effect the potential for acid drainage formation in the disposal facilities. From the experience of this study it is concluded that static tests, and more specifically the ABA method, can be used for the characterisation of wastes, tailings and geological formations, however kinetic tests are also needed to confirm static test results and predict the drainage quality.

Chemical modelling of the prevailing acid generation mechanisms coni%med that the importance of ferric ions and T. *ferrooxiahns* in acid mine drainage cannot be over emphasised, Once these two factors are present, physical parameters such as permeability, aeration, water penetration, then play an important controlling role over the way that the reactants and products are transported to the surfaces of reactive sulphides. Thus the various manifestations of mine drainage seen in different areas are due to the differing physical characteristics of the sites, although the chemistry of AMD is generally always the same. The RATAP computer model also seems successfi.dly to predict the acidity generated by sulphidic tailings, All the predictions generated by RATAP in this project were validated either through kinetic. experiments or through field experience.

The development of *mine and mine* **water** *models,* showed that a 3D stochastic numerical model of the distribution of NNP values in the underground mine may be used as a tool for monitoring AMD in new and existing mines, since the application of the model in the Stratonion mine produced reasonable results regarding the location of acid drainage sources, In order to improve the accuracy of the model and reduce the size of the unit blocks, additional geological logging should be incorporated in the data base, Furthermore, the Stratonion mine water model seems capable of predicting the changes in composition as the water progresses through the network. These tools were fimther used in the mine closure to predict the quality of mine waters after the mine decommissioning.

Regarding the *evaluation* of *preventive technologies,* the research findings suggested that limited amounts of limestone could be effectively applied to pyrite-rich materials, if the limestone is properly ground and homogeneously mixed. Moreover, the RATAP computer model predi~ted that layered soil covers offer another option to diminish the acidity generated from tailingslstockpiles; however the actual potential to generate AMD remains high over the longer term.

Given the extent and severity of acid drainage formation in the Stratonion mine, attention was paid to the evaluation of *remedial* technologies, both active and passive. Concerning the active methods, i.e. neutralisation with lime and magnesia, it was concluded that in situations where storage of sludge is not at a primary consideration, the disadvantages of magnesia, i.e. increased Mg, $S0_4$ levels in the final solution, and increased cost, outweigh the advantages and thus the use of iime, combined with limestone, is suggested as the best option. Biochemical methods are also considered to be promising alternatives but tiu-ther work is necessary to conduct a fill economic evaluation of the proposed process. Alternatively passive methods, i, e., anoxic limestone drains, aerobic wetlands and compost wetlands, are considered as low-cost and low-maintenance treatment schemes, Anoxic Limestone Drains can be effectively employed for the pre-treatment of acidic drainage solutions containing Fe^{2+} andlor Mn^{2}' and/or Zn^{2+} but their operation is limited in the presence of Fe^{3+}, $A1^{2}$' or increased concentrations of dissolved oxygen. It is thus concluded that, under specific conditions, AIDs can be effectively used as a pre-treatment stage, with significant decrease in the overall cost of the treatment scheme.

The research findings obtained and the background data provided by the Kassandra Alines were assessed to develop a *post ciosw-e s@ategv* for the Mavres Petres and Madem Lakkos mines, and other similar sulphide operations where acid mine drainage presents a potential long term environmental problem. The Stratonion water monitoring data along with the predictions from the 3D model provided the input in order to define the high risk underground mining areas where special measures should be taken. The final effluent flowrate and quality after mine closure, as well as the effect of acidic streams on the overall water quality, predicted by ESP model were evaluated in order to develop an alternative water management scheme. The overall closure scheme included methods and techniques to minimise AMD generation, and to mitigate its effect as well as to monitor its long-term environmental impact.

Development of an integrated environmental management scheme; Techniques and methods developed and applied within the project, including sampling, characterisation of mining wastes, environmental monitoring, prediction and chemical modelling of the acid drainage generation, are an important component of this protocol. Another part of this methodology is the evaluation of available preventive techniques as defined from laboratory testing and computer simulation. Finally the optimisation of acidic water treatment is addressed with the potential application of low-cost active and passive schemes developed within the project.

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