ENVIRONMENTAL IMPACT AND RECLAMATION PLANNING FOLLOWING THE APRIL 25, 1998 ACCIDENTAL TAILINGS RELEASE AT THE BOLIDEN APIRSA MINE AT AZNALCÓLLAR, SPAIN

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ABSTRACT

An international Panel of Experts reviewed the environmental impact and reclamation planning of one of the most significant spills of mine tailings in history. On April 25, 1998, an embankment at the Apirsa mine near Aznalcóllar, Spain failed, spilling a large volume of fine, high sulphide tailings and acidic water into the Río Agrio, the Río Guadiamar and on to about 2,000 ha of farmland. A severe toxic effect was immediately observed in all aquatic animals in the affected zones. This was believed to be principally due to consumption of oxygen by ferrous iron, and to a limited extent due to suspended solids and dissolved metals, principally zinc.

The clean-up commenced shortly after the occurrence of the spill. The clean-up effort was split between the company (for the first 13 kms.) and the State of Andalusia and the National Government for the approximately 23 kms affected downstream. The panel concentrated its review on the first 13 kms.

The panel found that spill was cleaned up in a very efficient manner and that the land was essentially restored to former uses, principally agriculture. Factors that aided a very well planned restoration effort were an exceptionally dry and long summer and the high neutralization capacity of the agricultural soils. Factors that complicated the clean-up were the requirement to work around large numbers of trees, the porosity of soils in the river zones and the imprecision of soil contaminant contents before the spill.

INTRODUCTION

In the early morning of April 25, 1998, the east embankment of the tailings facility at the Boliden Apirsa zinc-lead-copper mine failed, releasing about 1.3 million cubic metres of fine sulphide tailings and up to 5.5 million tonnes of acidic, metal-containing tailings pond water (Boliden, October 1998; Eptisa, November 1998). Both contained potential contaminants such as Zn, Pb, Cu, As, and Cd.

The spill was caused by the failure of the foundation of a 27 metre high embankment containing fine, saturated tailings with a high percentage of pyrite content. Samples of tailings taken from the spill zone on May 9 contained the following:

Element	µg/g
As	4,600
Cd	28
Co	74
Cr	38
Cu	2,000
Fe	330,000
Mn	700
Mo	34
Ni	710
Pb	7,040
S (sulphide)	360,000
Sb	280
Zn	8,000

Table 1. Tailings Samples Contents.

The spilled tailings and water followed the course of the Agrio river, subsequently the Guadiamar river and reached the northern edge of the Doñana Park, about 45 kilometres south of the mine. Fast action by the government and local farmers prevented the spill from having a significant impact on this National park which has been designated an UNESCO world heritage site. Although there was no loss of human life in the spill, there was a significant and immediate environmental impact on agricultural resources and natural aquatic ecosystems. The loss of fauna caused by the spill was calculated at 37 tonnes of fish and 96 specimens of land vertebrates that were collected up to May 27 (Coopers & Lybrand, June 1998).

Initial toxicity was not, as perceived by the public, due to "toxic metals", but principally caused by four other factors - high oxygen demand caused by elevated levels of ferrous iron (which stripped out the dissolved oxygen), high acidity, high suspended solids and physical dispersion of aquatic species onto the land . Metal toxicity could have been a contributing factor for those species surviving the initial shock and this metal toxicity would have been principally caused by dissolved zinc. Other metals were precipitated after the acid waters were neutralized by the alkaline soils. Arsenic was precipitated as either calcium arsenate or iron arsenate. From stream water quality measurements 3 weeks after the spill, this potential toxicity was drastically reduced and fish had reappeared 6 weeks later in the Guadiamar river 13 km from the mine. Such an improvement in stream water quality gave the indication that the tailings remaining on the land surface were not oxidising and leaching contaminants into the surface water. This lack of leaching was due to the fact that rains had stopped, the black tailings on surface were rapidly drying and a small amount of neutralising potential delayed the onset of bacteria-catalysed acid drainage.

The reclamation strategy was put in place shortly after the spill event – tailings recovery started May 3. Responsibility for reclamation and cleanup area was divided into approximate thirds between the company and two levels of government. Apirsa was assigned responsibility for the northern or first 13 km down to the Sanlúcar bridge (Tramo Norte) where up to 70% of the tailings solids were estimated to have been deposited. The initial focus was to isolate contaminated water in the "Entremuros" wetland-reservoir north of Doñana Park, and to remove the tailings as soon as possible from the stream beds and riparian zones. Removal from farm lands as well as olive and fruit groves would follow.

Spilled tailings and contaminated soil were collected with mine equipment and road-compatible industrial equipment and transported to the mined-out Aznalcóllar open pit. By late November the clean-up of exposed tailings on the surface had been completed in all zones from the mine down to Doñana Park.

In early May, 3 main project teams began work on the reclamation and cleanup:

- Environmental Impact Assessment and Reclamation Planning
- Assessment of Mechanisms of Embankment Failure
- Future Tailings Disposal Options

The Expert Panel has been concerned with the first project teamwork area.

GEOLOGICAL BACKGROUND - MINERALIZATION AND MINING

The Aznalcóllar mining area is located on the eastern part of the Iberian Pyrite Belt, a 30 km long West-East metallogenic province, integrated by Palaeozoic metavolcanic-metasedimentary complex rocks ("Complejo Vulcano-Sedimentario"). Hundreds of occurrences of mineral deposits are located here, many of them having been subject to mining operations in the past, and a few are presently being exploited.

As a consequence of the weathering processes affecting the pyrite outcrop bodies and the wastes produced by more than 5,000 years of mining activities (from Tartesians, Phoenicians, Romans, and later modern man), the Tertiary and Quaternary sediments contain a relatively high background of heavy metals and arsenic.

For the same reason the surface water runoff occasionally includes an elevated content of dissolved metals. In any case, the chemistry of such water is variable with time according with meteorological and hydrological changes (dry and wet periods, runoff yield, ground water out flow, and use for irrigation).

This elevated metals background is present in the area not only from the last few years of mining activity but from a long time ago. It is evident that heavy metal availability had provided the trophic food chain with a relatively high content in some heavy metals for thousands of years.

RECENT, LOCAL MINING ACTIVITY

The Aznalcóllar deposit was first investigated by the Peñarroya company in 1956. In 1960, a company Andaluza de Piritas, S. A. (APIRSA) was formed to investigate the feasibility of exploiting a large low to medium grade polymetallic deposit, but it was not until 1979 when production began. Two types of ores were mined, a pyroclastic copper ore and a complex pyrite ore. In order to separate the two types of tailings and provide for the possibility of future sulphur recovery, a two-compartment tailings pond was developed. Tailings were deposited under water in the ponds to prevent sulphide oxidation from the start in 1979. The area of the ponds was about 200 hectares with the pyrite section about 24% of area and volume.

Boliden acquired the APIRSA property in 1987 and immediately began to improve environmental management at the site. This included a clay cover on a very large acid-generating rock pile, collection of contaminated seepage and the installation and operation of a state-of-the-art mine water treatment plant capable of delivering 1,500 m^3/hr of very low metal level water. Not only has this treatment plant provided very high quality water to the Agrio river, it provided a steady flow which helped to sustain the aquatic ecosystem in the dry months of typical summers.

PRE-SPILL SOIL CONDITIONS IN THE GUADIAMAR RIVER BASIN

In the northern zone, the predominant system is a well-drained eutric or calcareous unit followed by a well-drained coarse-textured unit. The river bed itself comprises flood plain materials that have very low buffering capacity a high degree of porosity.

The sediments of calcareous marles had neutralized the acidity from the Agrio river. In the neutralization process, metals, including heavy metals were precipitated.

The repercussions on the agrosystem were limited to the alluvial floodplain. Soil here is a calcaric fluvisol, low organic matter content with uneven distribution through the profile, sedimentary textural strata, and rich in alkaline-earth carbonates, mainly $CaCO_3$. Under those conditions of calcareous soils with poor drainage, biochemical incorporation of contaminants into the soil-water-plant system appears to have been minimized as a consequence of natural buffering. It has been observed that there have been examples of severe soil erosion caused by the spill in these low terraces in spite of the smooth slopes.

Recent investigations of interactions between acid mine waters and local soils demonstrated the buffering capacity of soils and their ability to immobilize metals (Soil-Water Investigations in the Los Frailes Mining Area -Holmström, Land & Carlson, June 1998).

A review of recent studies before the spill showed elevated metals in top 0-5 cm of soils of the Guadiamar river valley:

Zn: 115 – 4200 mg/kg
Pb: 8 – 126 mg/kg
Cu: 43 – 1339 mg/kg (42-99 in top layers)
Cd: 0.9 – 13 mg/kg (3-6 in top layers)

It was recognized that the use of these old data had some limitations – sampling techniques, and analytical procedures may be questioned. However, these and other data indicated a substantial baseline of metal content that had been naturally placed and was distributed resulting in naturally elevated levels of heavy metals in soils. Historical sources included previous naturally elevated levels of heavy metals in soils, historic mining-related activity, atmospheric deposition, and agriculture (fertilizers).

	pH	Cu	Pb	Cd	Zn	Mn	Fe	Sulphate
1993	5.92	0.86	0.05	0.16	32.0	9.5	0.53	1230
1994	6.23	0.28	<0.05	0.063	17.8	9.5	0.98	1150
1995	7.30	0.11	"	0.051	15.5	7.8	0.17	1090
1996	7.40	0.02	"	0.017	6.5	3.8	0.23	1000
1997	7.43	0.01	"	0.019	4.3	2.3	0.19	730

Table 2. Average Water Quality (mg/l) in the Guadiamar River (El Guijo Station).

SURFACE WATER QUALITY AND QUANTITY

There was a significant amount of baseline water quality available. The quality of this data was difficult to interpret since analytical techniques have improved with time. Some examples of data available include the average water quality at the El Guijo Station on the Guadiamar River as shown in Table 2.

These improvements in water quality reflect the improvements made at the Apirsa mine site.

GROUNDWATER

In the area affected by the water and tailings spill there are three main aquifers:

- The Agrio-Guadiamar shallow alluvial aquifer,
- The Aquifer 27 which currently includes the Hydrogeological Units 05-51 (Almonte-Marismas) and 05-50 (Aljarafe), a Plioquaternary aquifer, and
- The Aquifer 26 currently the Hydrogeological Unit 05-49 (Niebla-Posadas), a Miocene aquifer.

The Agrio-Guadiamar shallow alluvial aquifer locally covers the Aquifer 27 and the Aquifer 26. At times, the alluvial aquifer is gaining water, and other times it is a losing water from the Aquifer 27 according to the dry and rainy periods but also depending on pumping operations in both aquifers. In many existing hydrogeological cross sections there is evidence of the hydrological relations.

The alluvial unconfined aquifer is located along the Agrio-Guadiamar plane from Aznalcóllar to Villamanrique de la Condesa (about 34 km long with an average width of 2 km and a thickness between 10-20 m). This aquifer was affected by direct inflow of acid water and tailings through some inundated holes and wells. This aquifer did not possess a protective layer of soil with low permeability and could be affected in the long term by leakage of contaminated water through the alluvial.

Precise data on pre-spill ground water quality in the alluvial aquifer were not available. Zinc can be used as an indication of groundwater quality. In the alluvial aquifer at the confluence of the Agrio and Guadiamar rivers, the zinc levels were reported to be 0.05 to 35 mg/l in 1993 in samples taken by Instituto Tecnológico Geominero de España (Recovery Plan, Water Appendix July 1998). These data can be misleading since the aquifer can be recharged by the river in flood during the wet season, and discharged during the dry season.

Data on well water after the spill also leads to imprecise conclusions. Wells outside the flooded area (in the area north of the Sanlúcar bridge) showed a mean zinc level of 0.11 mg/l, while those in the affected zone showed a mean zinc concentration of 85 mg/l. Many of these wells had tailings in them. The black line marking the maximum flood level quickly showed which wells had been flooded by tailings. The use of Zn/Cd ratios was also important in estimating which wells were affected. It would be expected that the flood zone would be the zone of highest baseline metal content. One well, high enough not to be flooded by tailings showed a zinc level of 11.7 mg/l which might indicate the ground water was slightly contaminated by the spill or natural ground water concentration might have been at this level.

Potential aquifer contamination may remain a significant long-term issue for the public and authorities. The issues regarding the interaction of aquifers with surface waters are very complex. The Panel recommended that Apirsa consider acquiring the services of accredited expert in Hydrological-Hydrogeological services to examine the issues.

DETAILS OF PHYSICAL, CHEMICAL AND BIOLOGICAL IMPACT OF THE SPILL

The details of the spill were well documented by Boliden Apirsa and others. As is common in events of this nature, media descriptions included "toxic wave", "lethal concentrations of heavy metals", etc.

The following elements were identified as "Contaminants of Concern: Zn, Pb, As, Cu, Co, Al, Cr, Tl, Cd, Co, and Hg. Contaminants of concern were released in both liquid and solid form. The concentrations of these elemental contaminants in the liquid phase analyses are shown in Table 3.

"Red water", typical of the results of acid generation, was visible in early May at several locations in the spill zone. This was caused by the oxidation of ferrous iron oxidation (some places were still greenish blue in early May). This represented the oxidation of the original tailings water, not fresh oxidation. By July, all of these ponds had dried up or had been drained leaving a zinc-rich white salt on the surface.

A comparison of Table 1 with Table 3 shows that lower-than-expected metal contents were observed in the zone north of the Sanlúcar bridge. This is likely explained by the segregation by size in the spill release process, coarser lower-metal fractions settling out before the fine fractions, and the mixing in of embankment materials and soils in the spill release process.

Element	mg/l	Tonnes @ 5.5 million m^3 water
Cu	17	94
Pb	3.5	20
Zn	450	2,500
Fe (ferrous)	85	470
Mn	100	550
Cd	1.3	7.2
Ni	0.8	4.4
Co	0.8	4.4
Cr	0.07	0.39
As	0.18	0.99
Hg	<.001	-
SO_4	5000	28,000

Table 3. Tailings water contents.

The >1 metre thick zones that were in the upper river channel were composed of coarse sulphides, while the material on the flood plain was finer. For example the tailings material on cotton fields near the maximum extent of the black tailings plume were very fine, thickness less than 10 mm and were mixed with soils sediments from upstream. This had the beneficial effect of adding neutralization capacity to the tailings downstream that assisted in preventing or delaying the onset of acid conditions.

The tailings mineralogy was reported (Boliden, July 1998) as being predominantly pyrite with minor quartz, mica sphalerite, galena and arsenopyrite. The northern basin of the tailings contained "pyroclastic" tailings that were reported (Eptisa, November 1998) as being sized at 80% less than 450 :M. The Panel believed these results may have been representative of tailings deposited near the embankments only.

The 10 tailings samples had little to no neutralization potential (NP 0 to 50) and were extraordinarily high potential acid producers (AP 980 to 1200). According to accepted formulas, the spilled tailings could produce over 40 million tonnes of acidity. Humidity cell tests on samples taken from the field were performed for a short time. These tests showed a delay in significant acid production, but a rapid generation of acidity and metals release, particularly zinc, after a few weeks. Based on simple mass-balance considerations, it was calculated that the neutralization potential of about 1.5 metres of soil would be consumed by the acidity from 10 cm of tailings.

Initial availability of metals depends on the oxidation of sulphide $S^{=}$ into sulphate SO_4

Mineral habit and associations play a major part in the evolution of sulphides to sulphates, soluble metals and acidity. Euhedral pyrite grains with no impurities or inclusions are slow to oxidize even in aggressive conditions. Galvanic reactions can greatly affect the reactions, the production of acidity and metals in the leachate. In general terms, the reaction priorities are: sphalerite>arsenopyrite>pyrrhotite>galena>pyrite

Field conditions in the spill zone of the Guadiamar River had been feared to be "the world's largest humidity cell". However, international experience at tailings sites where the pyrite content is high, tailings are very fine and neutralizing potential is low, have shown some surprisingly low reaction rates. Little sulphide-based acid generation was observed in the field. In the opinion of the Panel Experts this was because:

1. The fine tailings remained water saturated for days to weeks, effectively blocking oxygen penetration,
2. The coarser, more porous material closer to the mine contained some neutralization potential,
3. Some alkalinity was added from the soil to the finer tailings in the erosion process and this increased with distance from the mine,
4. The tailings dried out in the hot dry climate; almost no rain fell between the time of the spill and final removal.

Practically no acid generation was observed (red water or depressed pH in the wet zones) very low levels of metals and arsenic would have been released from the solid tailings. However in zones where small pockets of tailings were wet and oxidized, acid generation was clearly visible and sustainable. There was no doubt that rainy conditions would have duplicated the significant oxidation observed in laboratory tests.

The Panel observed that the great fear of metals release caused by acid generation did not occur between the time of the spill and the completion of cleanup in the Tramo Norte in

November. The principle source of bioavailable contamination was limited to the soluble metals in the pore water. This solubility decreased as pH rose and metals were precipitated or absorbed. The Panel reviewed the surface water quality data and selected zinc as an indicator of metal mobility

The apparent rapid recovery in water quality confirmed that residual tailings in contact with the wet zones were not significantly oxidizing. However, with the very low flows, and almost no rain, oxidation products and porewater residues were not being mobilized. An increase in heavy metal loading, principally zinc, to Guadiamar River was expected when the rains arrived.

OBSERVATIONS EIGHT MONTHS AFTER THE SPILL

As the end of November, the cleanup of the tailings in the zone above the Sanldcar bridge had been completed. Minor amounts of tailings remained around the trunks of fruit, olive and eucalyptus trees. The Administrations of Andalusia and the National government had completed the cleaning and shipment of tailings and contaminated soils from the river zones and farmland in the zones below the Sanlúcar bridge.

As of late December, 5.5 million cubic metres of tailings and soil had been excavated and dumped into the open pit. No significant rains had occurred since May (a little in October). What little rain that had fallen promoted some natural greening of many cleaned areas, but the hydroseeded river banks had not shown any significant growth.

The "Green Corridor" concept had gained increased acceptance, particularly with the Government agencies. It was understood that a significant proportion of the affected land in the lower zone had been purchased and it was the governments' intention to purchase all affected land and turn this land over to the public for park and natural wild-life use.

It had been planned to add organic(sewage) and alkaline (from paper-making and sugar manufacturing) wastes to all agricultural zone soils. The amendments would have been tilled into the soils using agricultural equipment. No decision had been taken on the removal of the haulage roads and the breaking up of the compacted soil. The use of these road zones for agriculture or Green Corridor purposes would require some action.

Both governments' and Apirsa contractors were cleaning the flooded wells to acceptable water quality useful for irrigation. Lime (calcium hydroxide) was being added to well water to precipitate metals, the mixture stirred and pumped out into a dugout 50 metres from the well.

Some difficulty was being experienced in meeting irrigation water quality objectives set by the authorities for Mn (0.25mg/l) and sulphate (250 mg/l). Also wells closest to the mine appear to have been affected by acidic groundwater that may have originated as historical seepage from the wastes at the mine site.

The piezometer wells that the Panel observed being installed in July had been purged and were being sampled. Initial data was available from one set of piezometers (C-1 to 5) This set exhibited no significant levels of metals (Cu, Pb, Zn, Fe), but one showed Mn at 1.5 mg/l. Sulphate ranged from 650 to 960 mg/l. Given that the reported pH was 7.1 to 7.3, low metals could be expected. It was uncertain whether other piezometers exhibit high sulphate levels or whether the sulphate levels are naturally high in the ground water

The river authorities (Confederación Hidrográfica del Guadalquivir) had not permitted the reuse of any of the wells in the affected zone. Sediment traps had been installed under the direction of the river authority in the Guadiamar below the Sanlúcar bridge.

An ecological and human health risk assessment of the spill event had been contracted to a consulting company. The restoration of the natural ecosystem remained a priority, but the very dry weather presented a challenge.

Ensuring that metal uptake does not exceed established criteria and ensuring the long term health of the ecosystem appeared to be significant challenges. One of the challenges would be the establishment of normal conditions. The Agrio-Guadiamar River basins will be in a state of flux for some time as river channels are reestablished; surface erosion diminishes, a new municipal wastewater treatment plant is commissioned, and the Green Corridor is established.

SELECTION AND ORGANIZATION OF RECLAMATION STRATEGIES.

The original Statement of Intent (by Boliden Apirsa) for the Recovery Plan for the Guadiamar River Basin included the following principles:

- "It is the overall objective of Boliden Apirsa S.L. to undertake the recovery planning to standards which reflect the regulatory requirements within Andalucía, Spain and the European Union and to other relevant international standards; and
- It is also the objective of Boliden Apirsa S.L. to promote the recovery of the affected area to as close as possible to the pre-existing conditions and land use as is technically achievable and economically justified.

Recovery to pre-existing conditions had been an appropriate objective, but was, and remains not fully achievable. The process of surface cleaning soils of tailings permanently altered the landscape. Instead, the primary objective could have been to restore the previous soil functions, and this was ultimately the accepted objective. Metals levels may be elevated, but their bioavailability may be sufficiently controlled by natural means or by soil amendments. The Panel agrees that the return to agricultural uses is reasonably possible, but will depend on the type of agriculture, soil contamination and the contaminants' bioavailability, and the ultimate acceptability.

The Panel was in agreement with the strategy of removing all the visible tailings solids on the surface (and the strategy of reclamation aimed at returning the land to former uses, principally agriculture). This compares to an alternate strategy that would remove the land formerly covered with tailings from agricultural production and establish a "Green Corridor".

Based on information available, the Panel believed that there was a good probability that the cleaned soil would have chemical and physical characteristics comparable to those that existed before the spill. In-situ remediation, such as the addition of alkalinity and/or absorbing organics was appropriate where a small amount of tailings remain after surface cleaning.

The technique of using commercial earthmoving equipment was an excellent strategy – fast, moderately low safety risk, and efficient. The Panel agreed that alternative methods of tailings recovery, such as hydraulic transport, were justifiably rejected for several reasons including the potential to spread soluble contamination, promotion of acid generation and the lack of adequate water supply.

A strategy of leaving some of the tailings in place had been considered but rejected. Primary zones for leaving undisturbed were difficult-to-clean wetland and gravel pit areas. At no time were areas obviously covered by tailings to be left uncleaned.

Continuous improvement was a principle of the July 1998 recovery plan. Examples included the development of efficient methods to remove contaminated soil from around trees without injuring these trees. Nevertheless, many trees were removed and these were mainly eucalyptus varieties not native to Spain. Special care was taken to protect oaks. Haulage roads were developed along the Guadiamar River which were later twinned to improve safety. Where tailings were still wet in the river valley, these tailings were removed in small increments to provide drying and maximize loading capacity. Cleaned areas inspected by the Panel showed very little evidence of residual tailings.

Hot, dry conditions were at once both a benefit and a challenge. There was no visual evidence of acidification of the tailings in the field. The dust generated by trucks and excavation equipment was a challenge in spite of continuous watering of roadways

Gravel quarries and wet zones contaminated with tailings were a special challenge. This challenge was finally overcome by constant innovation and the persistence by the equipment operators. Because of higher soil permeability and mixing during excavations, it was not possible to reach the clean-up efficiency achieved on the agricultural lands.

The Panel agreed that the use of the mined-out open pit was an excellent place to dispose of tailings-soils mixtures. Concerns had been raised about the leakage of soluble contaminants from the open pit, but this was later shown to be a low risk possibility in detailed studies.

The visual and measured results of the tailings removal in the Tramo Norte are truly impressive. The Panel congratulates the company for a truly massive, complex and financially demanding clean up program over 8 months.

The Panel had concerns about the development or definition of appropriate recovery standards. The Panel suggested that proposals for reclamation criteria be made and then actually tested in the field to see how well they could be achieved. In August, the Panel agreed that a risk assessment approach be adopted in reaching decisions concerning the appropriate recovery method for soils. The Panel agreed that the establishment of baseline conditions that existed before the spill represented a major technical challenge. Significant baseline contamination was known to have existed (before Boliden) and the Panel suggested that the company should not be expected to remove baseline contamination regardless of national or international standards. Site specific, risk-based criteria are much more appropriate.

Composted sewage sludge, originally planned to be added to soil, was rejected after quality tests. However, alkaline wastes from sugar manufacturing were being added on the basis of alkalinity needs to help in reestablishing soil characteristics.

Hydroseeding was done on the steep banks of the river from the mine to the Sanlúcar bridge. Fast germinating, indigenous species were used. Since there had been no rains to start the growth until late December, erosion by heavy rains remained a concern.

The Panel agreed that the quick establishment of vegetative cover could be achieved through planting grasses. Planting legumes as *Medicago sativa* as a single cover may not have been an option since the germination time is rather long and the initial growth is not very fast. This would result in a significant risk of erosion at the beginning of the rainy season. Studies have demonstrated the value of some *Lollium multiflorum, Cynoden dactilon, Agrostis tenuis* and *Trifolium repeus* cultivars in revegetating contaminated soils.

Although the alkaline soils, which tend to be dominant in the impacted zone, did not require increased alkalinity, the treatment with calcium hydroxide or limestone could have been tested on a limited scale to determine whether or not this would speed up the precipitation of metals. Little is known about the properties of the alkaline wastes from the sugar refining that were used.

LABORATORY AND FIELD INVESTIGATIONS

There was evidence to suggest that many of the soils and sediments of this region were abnormally high in metals long before the spill occurred. The field sampling and cleaning showed that heavy metals and arsenic were higher in the upper 10 to 20 cm of soil. Exceptions to this were the gravel-rich zones of the river beds where metal levels often did not decrease with depth. Laboratory tests by the University of Lülea confirmed that alkaline soils would precipitate metals and buffer acidity. The Panel recommended additional tests on capacity of alluvial soil to further define the absorptive and buffering capacities.

It is believed that future efforts should concentrate on methods of stabilizing metals in the soil, whether historically or added as a result of the tailings spill. Laboratory and field tests were initiated to provide evidence that the alkaline, calcareous soil systems in the Guadiamar River valley can, even though containing elevated metals levels, function properly and ensure normal crop quality.

The purpose of the laboratory study was to provide basic data for ecological risk assessment. The crops were limited to only three of the crops normally grown in the affected zone – sunflowers, wheat and corn. The testing of agricultural crops, such as forage, rice and fruit crops was suggested. Although such testing might be at odds with the concept of a Green Corridor, additional greenhouse tests related to phytotoxicity and metal uptake might have been an opportunity to cooperate with the authorities and agencies during the current monitoring and restoration phase. Field tests on metals uptake were started after permits were received from the Consejería de Medio Ambiente on December 12.

It was also recommended that *in situ* surface infiltration and permeability tests would help determine the potential of a displacement of pollutants. The classification of pollutants could be completed using the following categories:

- water soluble
- soluble in diluted acetic acid
- interchangeable to pH 7 and to the soil's pH
- extractable using DTPA
- released while oxidizing organic matter
- included in oxyhydroxides

Additional investigations were warranted to investigate if contaminated tailings water has infiltrated aquifers. In some cases, the water could have gone through subjacent, non-saturated sediments and ultimately reach connecting water-bearing beds, (aquifers).

CLEAN-UP OBJECTIVES – GENERIC VERSUS RISK - BASED CRITERIA

Various generic criteria could be applied. The preferred, internationally-accepted methodology is however a risk-based approach. This approach incorporates:

- the specific uses and characteristics of the site;
- appropriate ecological and human factors; and
- data from greenhouse and field tests.

This approach is known to be economical but protective of human health. Initial risk-based screening criteria are shown below. These are summarized in Table 4.

The Panel reviewed the rationale for development of the above criteria and disagreed with some of the assumptions

	Agriculture	**River**
As	488	200
Cd	50	9
Cu	250	162
Pb	500	474
Zn	1000	651

Table 4. Los Frailes Screening Criteria, mg/kg.

but found the overall results within acceptable ranges. On December 18, 1998 the Consejería de Medio Ambiente established intervention limits (Concentraciones Límites de Intervención) for the area affected by the accidental spill. These limits are shown in Table 5.

	Less Sensitive Zones (agriculture and river) mg/kg	**Sensitive Zones** (recreation, eg playgrounds) mg/kg
Zinc	1200	700
Cadmium	10	5
Copper	500	250
Lead	500	350
Arsenic	100	50

Table 5. Soil Metal Limits Established by Medio Ambiente, December 1998.

CONTAMINATION POTENTIAL FROM RESIDUAL TAILINGS

Estimates of residual tailings could not be reasonably estimated by chemical analyses since the baseline conditions were not well known. Assuming that 1% of the tailings remained, the Panel calculated that approximately 9,000 cubic metres would be left mixed with soils in the zone north of the Sanlúcar bridge. Release of contaminants of concern can occur in three ways, leaching into the ground water, accumulation in plants and/or direct uptake by animals and man. Risk assessment based on actual field and laboratory tests was suggested.

Because the tailings particles are dense, the restoration of the river channel by natural processes will result in some pockets of concentrated tailings. If left exposed during the next dry season, some minor excavation might be justified to prevent pockets of acidified tailings from accumulating. Also, some tailings may have been accidentally buried in the river and riparian zones and may become exposed during the rainy season.

As noted previously, most of the soils are buffering and will prevent any significant acid generation from contained tailings as long as well mixed together. Metal and arsenic release will be very slow as indicated by the few tests done to date. The only exception would be the acid soils near the mine site that may promote the release of heavy metals. Arsenic is indicated to be relatively immobile, stabilizing at around 10.g/l.

WATER – ENVIRONMENTAL IMPACT AND RECOVERY PLAN

It was expected that some of the soluble components left by the spill would be remobilize when the rains arrived. However, leaching tests on agricultural soil samples suggested that the mobilization will be limited to zones of acidic soils, zones that have been rendered acidic, or coarse river sediments with limited potential to retain metals. The potential for acidification of buried tailings should be small since the mine water treatment plant water contains significant alkalinity, and no concentrated zones of tailings are known to exist.

Available information indicated that acidity in the tailings spill was rapidly neutralized by natural sources as $CaCO_3$ present in the soil and interchangeable sodium contained in the clay and organic complexes. This neutralization potential will continue to be available for a long time in the future.

The water quality in the Guadiamar River had returned to pre–accident levels. The need for water treatment in the Guadiamar River is uncertain. It is foreseen that although the acidity may be neutralized by the carbonate content of the soils, zinc may be mobilized. If treatment is needed, lime could be added to the river to precipitate metals and the sludge collected in settling basins constructed along the river. The treatment plant at the south end of the Entremuros region could be used again if the zinc content of collected water reaches levels considered to be toxic.

However, it was agreed that the use of Best Available Technology (BAT) similar to that installed at the mine site to handle the whole river flow in flood conditions is not economically or technically practical. It would be instructive to construct some small-scale (tonnage size) experiments and to do some geochemical modeling to predict the evolution of water quality in the Guadiamar River in the future.

The Panel believed that zinc removal using passive biological-based technologies could be considered in the future, but concerns would remain about the accumulation of contaminated sediments and their disposal.

The Panel suggested a program for investigating the interaction between remaining tailings, the unsaturated soil, the ground water and the surface waters be given additional consideration. This issue is possibly one of long term importance to the public and the authorities regulating land and water use.

RISK ASSESSMENT FOR POST REMEDIATION

Although the concept of developing risk-based criteria for remedial guidance was suggested at an early date, the remedial actions were carried out by zone on a priority basis. The Panel agreed with this strategy. As discussed previously, the objective was to remove all visible tailings before the rainy season led to further spread of contamination.

The first step in the risk assessment process that was taken in September 1998. This report is a good first step towards risk based criteria by which the effectiveness of the cleanup can be judged. Spanish or other criteria based on conservative assumptions are not necessarily relevant or applicable to this area. One key issue here was the question of bioavailability. The environmental toxicity of metals and metalloids depends on the bioavailable fraction rather than on the total metal content. Soil pH is a key factor and metal toxicity is generally reduced at neutral or alkaline pHs relative to the toxicity at acid pH. Thus, the buffering capacity of local soils and sediments is a key factor that must also be considered in the development of risk-based criteria. Fixation with oxyhydroxides and organics can also be important. In addition, the interaction between metal species may affect toxicity. For example, the toxicity of cadmium is reduced through the presence of elevated zinc.

RECLAMATION MONITORING AND QUALITY CONTROL

Analytical quality control was an issue during the initial phases of the water quality measurement programs. Early problems with QA/QC for all sampling and measurements were quickly overcome. Many agencies and companies other than those sponsored by Apirsa were involved in sampling and analytical measurements. The Panel was concerned that these agencies may have reported data from sampling and measurement programs that lacked adequate QA/QC. Such data is now available and is widely used by various groups. In general, the Panel was satisfied that Apirsa and its contractors have used recognized sampling, recording, storage and analytical protocols.

The Panel acknowledged that discussion of social-economic factors was beyond the scope of the Panel Terms of Reference. However, the Panel suggested that technological solutions can be best realized with the co-operation of affected stakeholders such as government agencies and landowners. The best technological solutions can only be put in place with public acceptance.

The Panel expressed concern that there appeared to be a limited exchange of information between the Boliden Apirsa group, the local and federal government agencies and organizations that were involved in the recovery of areas downstream from the accident. These agencies are understood to have generated a considerable amount of data characterizing soils, the spill and its impact on the ecosystem.

The split of the recovery effort into 3 separate administrative areas was an effective way of making the best use of available resources, and this dual-track approach appeared to work well. The Panel was pleased that all parties, including Apirsa were working more closely during the monitoring phase.

THE GREEN CORRIDOR

The "Green Corridor" concept has positive aspects, particularly with respect to public perception. However, Apirsa was correct to continue to clean surface soils and wells so that former uses could be restored. This will reduce the public and official perception that the affected zone was and remains "toxic".

The Green Corridor concept also presents some challenges. Within the Green Corridor are all of the affected wells. New wells outside the affected area could be constructed but would need detailed hydrological investigations. The Green Corridor may need a constant supply of water that normally does not exist in the summer. The responsibility for restriction of access of farm animals such as goats would need to be clearly and robustly enforced. The Panel suggested that this should not be Boliden Apirsa's responsibility.

A healthy Green Corridor would depend on a constant supply of fresh surface water. The water treatment plant at the mine can be expected to operate for a very long time, at least decades but the present mine owner and any successors should not be expected to provide an "ecological flow" indefinitely.

RECOMMENDATIONS AND OBSERVATIONS

1. A very complex job has been successfully done (by both the governments and Boliden Apirsa) in recovering the estimated 1.3 million cubic metres of spilled tailings. Both have committed extensive financial, technical and people resources to the clean-up.
2. The visual impact of the results of the clean-up were very impressive. In the upper zone, Boliden Apirsa made a very strong effort to restore the landforms and minimise the removal of productive soil. It was difficult to find any significant evidence of tailings solids remaining on the surface.
3. The organization of the planning and cleanup effort was innovative and resourceful. The principle of continuous improvement was applied to the reclamation planning and environmental assessment as well as the actual reclamation.
4. The Panel commends the Environmental Impact Assessment and Reclamation Planning group at Boliden Apirsa for preparing detailed Recovery Plans, and soliciting peer review of these plans. Although not all of the Panel's suggestions concerning these Plans were accepted, Boliden Apirsa is to be congratulated for presenting a wide array of complex technical issues in Plans that met the needs of the various stakeholders.
5. The planning and reclamation activities have been accomplished in spite of some considerable challenges:
   - there was no model available to pattern the work after;
   - the cleanup task appeared insurmountable at the beginning;
   - there was extensive national and international media and interest group attention;
   - permits needed to do the essential work often took considerable time to acquire;
   - there were many non environmental, economic and political agendas; and
   - there was an urgent need to recover tailings solids before they were subject to autumn rains.
6. The planning anticipated that the cleanup of solid tailings needed to be finished by October. It must be emphasized that the weather co-operated magnificently during the clean-up, extending the major recovery operations into November. The very long and dry summer allowed all the needed reclamation work to be done and prevented any significant acid generation in the dispersed wastes.
7. There is no doubt that the land, surface water and ecological resources were severely affected at the time of the spill. However, the Panel believed that it remains reasonable to expect that the land can be restored to its former use, principally agriculture. If it is decided that the Green Corridor is to be established, the ecological resource and diversity should be improved from that before the spill event. This would be a positive legacy of the event.
8. The water quality of the Agrio-Guadiamar Rivers was severely affected immediately after the accident. Boliden Apirsa conducted a thorough sampling and analysis program that measured a quick recovery of water quality. Early problems with sample Quality Assurance/Quality Control (QA/QC) were quickly overcome. The Panel recommended that it is very important to monitor water quality during the rainy season and in the future. The Panel observes that a routine water sampling program, with high levels of QA/QC, downstream of an industrial operation would have been valuable.

9. Although considerable amount of surface and groundwater data was available, the Panel suggests the inclusion of and comparison with Central Government and Andalucian Government sources would have been more illustrative in determining the environmental impact of the spill.
10. The Panel notes that considerable environmental improvements had been made or were being made by the company at the Boliden Apirsa Mine before the spill occurred on April 25, 1998. These included the diversion of clean water around the mine site, the improved collection of contaminated seepage from the mine site and wastes, the installation of a soil cover on the waste rock piles, and the installation and operation of a state-of-the art water treatment plant. This water treatment plant had the extra benefit of providing a steady flow of high quality (with excess alkalinity) water to the Río Agrio during the dry season.
11. The split of responsibility between the government agencies and Boliden Apirsa well served the objective of getting the tailings solids returned to the mine site before the autumn rains started. The Panel recommended and was pleased to observe closer co-operation during the monitoring phase.
12. The issue of baseline metal contents (immediately before the spill) was and remains critical. The Panel recommended that a series of forensic studies be initiated to determine the baseline conditions. The purpose would be to add quality information to the existing databases and to have samples on hand for evidence in potential scientific or legal disputes. The sampling was needed for:
   - determination of sediment metal content upstream of the mine site (e.g. reservoir);
   - assessment of metal contents in Río Agrio sediments near the mine site (the panel acknowledges this may be difficult since acidic plumes are evident downstream of the waste rock ;
   - estimation of historical pH by sampling sediments for subfossilized chironomid head capsules;
   - determination of historical metal deposition of sediment columns in the Entremuros region (preferably in undisturbed areas). The possibility exists that the extensive clean-up observed by the Panel in December may have been based to a considerable extent on removing contamination that may have been historically deposited.
   - age determination and dissolved contents of groundwater. The fate of the dissolved contents in the tailings water appeared to be poorly understood.
13. The Panel recognised that the spill event, geopolitical and ecological circumstances were well suited to fostering exaggeration of the effects of the spill. The Panel believes that metals in the environment is the focus and the preliminary evidence showed that metal contamination being measured existed in significant part before the spill. In addition, mining and natural conditions (before Boliden) had led to the systemic dispersion of metal-laden acidic waters.
14. The Panel observed that the great fear of metals release caused by acid generation did not occur between the time of the spill and the completion of cleanup in December. Dry conditions, fine materials and the availability of neutralizing minerals prevented significant acid production. The principle source of bioavailable contamination would have been limited to the soluble metals in the pore water. This metal solubility decreased as pH rose and metals were precipitated or absorbed.
15. The Panel had identified a need to quantify the residual impact of the remaining tailings. It had been suggested that field lysimeters be constructed to test the impact of tailings remaining on the land or a small amount of tailings would be mixed in with surface soil. This would have been a complex task since metal contamination can arise from three sources – baseline metal contents, residual soluble metals from tailings pond water and solid tailings particles from the spill. The Panel understands that permits were not available for these field tests. Nevertheless, the Panel recommended a suite of samples be collected and retained in case leaching tests are needed to compliment the bioavailability tests.
16. The Panel strongly supported the need to develop and use site specific, risk-based criteria as a basis for evaluating the effectiveness of the cleanup and the hazards, if any, arising from residual contamination.
17. The northern zone had been cleaned (and recleaned) to meet the lowest possible metal levels for metals and arsenic content in soils. The Panel was satisfied with the pragmatic approach taken to date and recommended the completion of the risk-based assessment of the results on human health and ecology. The application of soil criteria from other jurisdictions was not appropriate considering the historical mining activities and natural distribution of metals from the sulphide deposits of the Iberian pyrite belt. In any event, the development of scientifically defensible criteria that account for bioavailability will be of great benefit in anticipated negotiations concerning whether the cleanup has been adequate.
18. Hydroseeding of the river banks in the northern zone (Tramo Norte) was an appropriate strategy. Additional measures to stabilise the existing (unnatural, man-made stream) channel could have been done to minimise erosion before the rains arrived. Sedimentation barriers suggested by the authorities may be ineffective since they would be quickly filled with coarse material

during the first heavy rains. However, such barriers could reduce the river gradients between barriers.

19. Because some buried tailings make be exposed as the natural river channels are reestablished, the Panel recommended that the company or those responsible in the future should be prepared to undertake some minor tailings recovery following the current rainy season.
20. The monitoring phase, now in progress, may need to include some additional remediation for minor amounts of tailings recovery or erosion control in the future.
21. The Panel suggested that the monitoring phase should last several years until the conditions of metal dispersion and uptake, and a firm inventory of the metal contamination in soils and water are well understood.
22. The biological monitoring program was comprehensive and well structured to meet technical and scientific needs.
23. The Panel suggested a program for investigating the interaction between remaining tailings, the unsaturated soil, the ground water and the surface waters be given additional consideration. This issue is possibly one of long term importance to the public and the authorities regulating land and water use.
24. The Panel suggested that the greenhouse studies should be expanded to include fruit, rice, berry crops and forage grasses. Also tests to determine the effect of the addition of the alkaline industrial wastes should be considered. The Panel understood that the addition of sewage sludge had been considered but rejected.
25. An acceleration of the groundwater monitoring and measurement program was recommended to get the data needed to compare ground water quality, well water contents and irrigation water objectives.
26. Potential aquifer contamination may remain a significant long-term issue for the public and some regulators. The issues regarding the interaction of aquifers with surface water are very complex and needed to be studied.
27. To reduce future liability concerns, it was recommended that water quality be monitored (with pumping) for extended periods of time, before the original uses (irrigation and drinking water) be considered.
28. Future rains may flush out some soluble metals from sediments, most likely zinc. If necessary the water treatment plant at the south end of the Entremuros could be restarted. In situ treatment along the river does not appear to be justified. The encouragement the establishment of natural wetlands was recommended, provided the wetlands remain viable (wet) during the dry season. The Panel agreed that the use of Best Available Technology (BAT) similar to that installed at the mine site to handle the whole river flow in flood conditions is not economically or technically practical.
29. The "Green Corridor" concept had positive aspects and some challenges. Within the proposed Green Corridor are all of the affected wells. New wells outside the affected area could be constructed but would need detailed hydrological investigations. The Green Corridor may need a constant supply of water that normally does not exist in the summer. The responsibility for restriction of access of farm animals such as goats would need to be clearly and robustly enforced.
30. The public information and exchange program had low visibility; such a program might be useful in achieving "closure".
31. The Panel believes that Boliden Apirsa can be justifiably proud of the results of the clean-up that have been achieved in the Tramo Norte.

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