ARSENIC EMISSION CONTROL FROM PYROMETALURGICAL OPERATIONS

SUMMARY

As part of Environment Canada's action plan for "Reducing Arsenic Releases to the Environment in the Northwest Territories", W. R. Hatch Engineering Ltd. carried out an assessment of arsenic "Control Technology Options". The assessment reviewed literature relating to the chemical and thermodynamic properties of arsenic and its compounds as it relates to mining and metallurgical processes. The distribution of arsenic in various pyrometallurgical operations was determined for non-ferrous metal production. The behaviour of arsenic in roasting, smelting and converting operations was documented.

Arsenic occurs naturally in various mineralogical forms associated primarily with sulphur, iron, copper, nickel, cobalt and silver. The behaviour of arsenic in pyrometallurgical operations is characterized by the high vapour pressure of various arsenic compounds including the metal (As_4) the oxide (As_2O_3) and the sulphide (As_2S_3). As a consequence, arsenic is often vaporized and carried into the gas stream of various high temperature roasting, smelting or converting operations.

The control of arsenic in pyrometallurgical operations is generally related to one of the following:

1. Formation of non-volatile compounds of arsenic either in process or in the off-gas stream.
2. Condensation of volatile arsenic compounds in the gas phase by cooling.
3. Collection of inert or condensed arsenic particulate in electrostatic precipitators, baghouses, scrubbers or combinations thereof.

Current technology relating to non-ferrous smelters and gold arsenical concentrate roasters was reviewed. Current technology demonstrates that arsenic concentrations can be reduced to less than 1.0 mg/scm prior to sulphuric acid recovery or discharge to the

environment. Several gold roasting operations have either designed gas cooling-wet scrubbing into their flowsheets or have added these onto their current operations.

A number of gold producers which have refractory arsenical sulphide ores have installed alternate technologies to roasting. These alternatives have been reviewed with primary emphases on the autoclave pressure leaching of concentrates and the relative capital and operating costs.

The Giant Yellowknife Mine operation was reviewed in terms of equipment, operation and historical arsenic emission records. Current arsenic concentrations in stack gas approximate 24 mg As/scm. Basic gas cleaning equipment and procedures have not changed significantly over the last 20 plus years. The limitations of the present equipment prevent any major improvement in arsenic recovery.

Preliminary capital costs were obtained for tail gas cleaning by scrubber or wet electrostatic precipitator, estimated at $\$1.1 \times 10^6$ and $\$2.0 \times 10^6$ respectively. These options would reduce the stack gas arsenic to <1.0 mg/scm. Tail gas recovery of arsenic is estimated at +80% for an overall arsenic recovery of +99.95. Piloting may be required for some of the tail gas cleaning options.

ADDENDUM

Comments Received From Royal Oak Mines Inc., NWT Division

- On Page 56, length of the filtration bags should be 127 inches.
- On Pages 64, 66, 68, and 70, there is concern that the capital costs do not include allowances for mill shutdown while the new equipment is being installed.

Comment Received From Government of the NWT, Department of Renewable Resources, Environmental Protection Division

- On Pages 64, 66, 68, and 70, the capital costs include the costs of lining the existing stack. There is a possibility that Royal Oak Mines Inc. will install a taller stack as a result of a proposed Territorial Regulation governing sulphur dioxide.

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1.0 INTRODUCTION

W.R. Hatch Engineering have been contracted by Environment Canada to assess and report on current state-of-the-art air pollution control technology used in controlling arsenic releases from pyrometallurgical operations, including gold roasting. The background and purpose of the study was outlined in the contract, Project No. K2331-5-0001.

Objectives of the study were expanded to include a section on alternate technologies to roasting which have become available to the gold industry. The pressure autoclave hydrometallurgical treatment of gold bearing concentrates has been reviewed with reference to technology and capital and operating costs.

The assessment of fugitive control in the handling of arsenic bearing dusts has not been reviewed in this study.

2.0 THERMOCHEMICAL BEHAVIOUR OF ARSENIC IN METALLURGICAL SYSTEMS

The behaviour of the various minerals in the pyrometallurgical operations of roasting, smelting and converting is related to the stability of these minerals and of compounds formed in the thermo-chemical environment of the unit processes. The temperature and partial pressure of oxygen and sulphur determine the distribution of the arsenic in condensed and vapour phases.

Due to the relatively high vapour pressure of several compounds (As_2O_3, As_2S_3, As_4, $AsCl_3$) arsenic tends to concentrate in off-gas streams from the roasting, smelting and converting operations.

2.1 Arsenic Mineralogy in Non-Ferrous Metallurgy

Arsenic occurs in primary feeds to metallurgical processes in various mineralogical forms. The following lists the principal arsenic-sulphur containing minerals present in gold concentrates, copper concentrates, copper-nickel concentrates and lead-zinc concentrates.

Gold Concentrates	-	Arsenopyrite	-	FeAsS
Copper Concentrates	-	Enargite	-	Cu_3AsS_4
Copper-Nickel Concentrates	-	Niccolite	-	NiAs
	-	Gersdorfite	-	(Co,Ni)AsS
	-	Rammelsbergite	-	$NiAs_2$
	-	Skutterudite	-	$CoAs_3$

2.2 Thermochemistry and Phase Relationships in Arsenic Systems

Reaction of the feed compound can lead to the formation of various stable forms of arsenic under the temperatures and partial pressures of oxygen and sulphur in the given unit process. These include As_4, As_2S_3, As_2O_3, $FeAsO_4$ and CuAs some of which can exist in the solid, liquid or gaseous state under various pyrometallurgical environments. In some cases the kinetics of a given reaction may determine the species present in a plant stream under process conditions.

The Arsenic - Sulphur - Oxygen System

The behaviour of arsenic in the roasting of arsenopyrite is determined by the stability of the compounds formed. The predominant areas of the various gaseous compounds of arsenic in the system As-S-O are shown in Figure 2-1.

At low oxygen pressures which may be encountered in some partial roasting operations and reductive smelting operations arsenic may be in the vapour phase as As_4 or As_4S_4. Gokcen[1] has described the Arsenic System equilibrium phase diagram and the distribution of the various arsenic species.

As the oxygen partial pressure is increased, As_4O_6* becomes the stable volatile species. This is the operating region of most first stage gold roasting operations, which decompose arsenopyrite and evolve the arsenic in the gas phase. In most 2-stage roasting operations, the calcine from the primary roast is fed to a second stage where the remaining sulphur is oxidized at higher oxygen partial pressures.

High oxygen potentials lead to the formation of more stable, less volatile arsenates (As_2O_5) and are generally avoided in gold roasting operations.

* As_4O_6 is molecular formula for gaseous and common crystalline forms (As_2O_3 is an empirical formula)

The thermodynamics of roasting arsenopyrite has been studied and reviewed by Chakraborti etal[4].

The thermochemical arsenate-oxide equilibria in the system Fe-As-O at 800°K is shown in predominance area diagrams of Figures 2-2 and 2-3[3]. The formation of ferric arsenate ($FeAsO_4$) is prevented at low oxygen and consequently low As_4O_6 partial pressures. A reducing roast, partial roast, or kinetic factors of a fluid bed-flying roast would all tend to prevent the formation of ferric arsenate.

A review and tabulation of the thermodynamic data for the Fe-As-S-O system has been carried out.[4] Considerable discussion of the roasting of FeAsS concludes that in a strongly reducing environment ($PO_2 = 10^{-20}$ atm) arsenic may be volatilized as As_2S_3. As the oxygen potential is increased up to 10^{-1} atm arsenic is evolved as As_4O_6. A discussion of bed thickness in roasting operations is discussed in terms of oxidation of As_4O_6 to As_2O_5 or $FeAsO_4$.[4] The data may not apply to more stable forms of arsenic (Ni, Cu etc).

The thermodynamic properties of various nickel arsenides, niccolite (NiAs), rammelsbergite ($NiAs_2$) and maucherite ($Ni_{11}As_8$) in their reactions with O_2 to form NiO and As_4O_6 have been studied over the range 438 - 866°C.[5] Predominance area diagrams are shown in Figure 2-4 and Figure 2-5 for the Ni-As-O system at 800°K to simulate roasting conditions. The data show stepwise oxidation of NiAs to NiO but considering the presence of metastable equilibria, one would expect incomplete oxidation in a reducing or partial roast or in a fluid bed roast where the residence time was low. In such cases lower arsenides of nickel would likely remain in the calcine. Nickel is shown to be more arsenophyllic than iron and more aggressive conditions are required for decomposition of nickel arsenides.

2.3 Vapour Pressure of Various Arsenic Species

In the presence of oxygen, arsenides, sulphides or elemental arsenic may be oxidized to As_4O_6 and volatilized. Downstream temperature reductions may result in the condensation of As_4O_6 from the gas phase either as a separate product or combined with iron in the flue dust.

The vapour pressure-temperature equations for the various volatile arsenic species are summarized below.

Arsenious Oxide (As_2O_3)

The vapour pressure-temperature relationship for As_4O_6 has been studied by numerous authors. For the low temperature range, the equation for the vapour pressure of As_4O_6 (gas) derived by Brown and Page[6] from the data of Murray[7] has been used for the temperature range 70 - 180°C.

$$\log P\ As_4O_6\,(\text{atm}) = \frac{6080.6}{T(K)} + 9.9506$$

For temperatures above 180°C Figure 2-6 shows the vapour pressures for the equation.

$$\log P\ As_4O_6\,(\text{atm}) = \frac{5815.8}{T(K)} + 12.127$$

The latter as reported in the handbook of Chemistry and Physics (50th edition).

The vapour pressure-temperature relationship is given in Figure 2-6 and the actual concentrations are shown in Table 2-1. In the presence of oxygen, arsenides, sulpharsenides or elemental arsenic may be oxidized to As_4O_6 and volatilized.

Downstream temperature reductions may result in the condensation of As_4O_6 from the gas phase either as a separate product or combined with iron in the flue dust.

Arsenic (As)

The arsenic system has recently been reviewed.[1] The sublimation and vaporization pressures of arsenic are shown in Figure 2-7 with a vapour pressure of 1 atm at 883°K. As_4 is the primary vapour species at low oxygen and low sulphur partial pressures.

Arsenic Sulphide (As_2S_3)

The vapour pressure-temperature relationship is expressed by:

$\log p(\text{mmHg}) = -5100/T + 4.67$ (Kub,15) over the range 450 - 600°K

Vapour phase concentration of As_2S_3 are calculated as follows:

Temp °K	gAs_2S_3/m^3
600	0.0011
700	0.014
800	0.10
1000	1.51
1200	8.96

2.4 Distribution of Arsenic Reported in Pyrometallurgical Processes

A considerable amount of information exists in the literature on the behaviour of arsenic in arsenopyrite roasting and in copper smelting and converting.

2.4.1 Roasting

The conditions under which arsenious concentrates are roasted has a significant effect on the volatilization of arsenic. Arsenic may be removed in any of its volatile forms As_4S_4, As_2S_3, AsS, As_4, As_4O_6 etc. depending on the roasting conditions, sulphur and oxygen potentials, temperature and residence time. The thermodynamics of roasting arsenious concentrates has been discussed by several authors (References 2,3,5,8,9).

The thermodynamics of roasting arsenopyrite concentrates is shown in Figure 2-8. The primary reactions involve the oxidation of FeAsS as follows:

$$4\ FeAsS + 10\ O_2 \rightarrow 2\ Fe_2O_3 + As_4O_6 + 4\ SO_2$$

and under an excess of oxygen, formation of stable ferric arsenate:

$$As_4O_6 + 2\ O_2 + 2\ Fe_2O_3 \rightarrow 4\ FeAsO_4$$

Figure 2-9 shows Boliden data for the thermodynamic stability of iron arsenate, oxides and sulphides in the roasting of pyrite for sulphuric acid production.[2] The Boliden process is a single stage roast at 850°C. Roasting for gold recovery is normally carried out in two stages at lower temperature. Arsenic and sulphur removal are controlled by the oxygen partial pressure. Roasting at Giant Yellowknife is carried out at 500°C with about 0.4% oxygen in the off-gas. Arsenic and sulphur elimination are 91.6% and 87.9% respectively.[9]

Experimental data has shown that mildly oxidizing atmospheres sufficient to form As_2O_3 are more effective in the removal of arsenic than an inert atmosphere at 600°C.[4] The predominance area diagram for the Fe-As-O-S system is shown in Figure 2-8. At low oxygen potentials, the primary vapour phase is As_4 while above 10^{-15} atm O_2, As_4O_6 predominates at 700°C.

The rate of the various gas-solid reaction is increased by higher roasting temperatures and in fluid bed reactors, may limit the volatilization of arsenic.

The distribution of arsenic in roasting of nickel concentrates depends primarily on the temperature, residence time (kinetics), oxygen partial pressure and initial concentration of arsenic in the feed.

The behaviour of arsenic in copper roasting and smelting has been reviewed.[8] Information on arsenic distributions in nickel smelting is scarce. A comparison has been made of the arsenic distribution in the Inco flash smelting process and the conventional multi-hearth roasting - reverb smelting process.[10] Figures indicate a total of about 10% of the input arsenic is carried by dust and fume in both the roasters and reverb furnace. The form of the arsenic is not given. Arsenic evolved during a partial roast or reducing roast in a fluid bed would be expected to be considerably lower than this value due to the short residence time and low oxygen potential. This is in agreement with thermodynamic data on Ni-As-O [5], who state that one would not expect arsenic to be readily removed from nickel arsenides at O_2 partial pressures well into the NiO stability region since metastable equilibria can occur in which NiAs and NiO can coexist.

2.4.2 Smelting

In copper smelting, arsenic entering the reverberatory furnace distributes with an estimated 35% dissolved in matte, 50% in slag and 10% volatilized.[11] Studies on the distribution of arsenic between molten slag and matte indicate that arsenic is dissolved in the elemental form.[12] Lynch etal[11] found the distribution coefficient of arsenic between copper metal and slag to be 250 (metal/slag) at an oxygen pressure of 10^{-10} atm at 1200°C. Arsenic forms various Cu-As intermetallics with copper and has a high affinity for the molten metals.

Weisenberg et al[8] reviewed the distribution of arsenic in the various unit processes of copper smelters.

Copper plants which utilize roasters generally roast at temperatures between 540 and 620°C. Arsenic volatilization can range from 5.0 to 90% depending on (1) arsenic concentration in the feed, (2) type of roaster and (3) the oxygen and sulphur concentrations during roasting.

A survey of reverberatory copper smelters showed that

1. with high As feed (>0.2%), 55-75% of the arsenic leaves in the gas phase and 10-25% is slagged out.

2. with low As feed (<0.2%), 5-37% of the arsenic generally leaves in the gas phase and 16-55% is slagged out.

Electric furnace copper smelting with open bath yields distributions similar to reverberatory smelters. Where a cold calcine layer is maintained however, volatilization may be reduced.

The distribution of As in various copper smelters appears to vary widely depending on process parameters, (temp. etc.) and feed concentration. Low As concentrates (<0.2%) tend to volatilize less As with 4-10% elimination in fluid bed roasting, 25-30% eliminated in smelting and 25-30% eliminated in converting.

The influence of temperature on the partial pressure of As_2O_3 is discussed in relation to collection efficiencies for various devices. As in other pyrometallurgical operations, the volatility of arsenic (particularly As_4O_6) is the major factor in controlling As emissions. The influence of arsenic recycle in dusts has a significant effect on the overall arsenic elimination and distribution.

The distribution of arsenic was presented by Suzuki et al[13] in the Naoshima/copper smelter as follows:

	Stream	Arsenic(%)
IN	Concentrate	63.3
	Silica	8.6
	Misc Feeds	12.0
	Recycle	16.0
OUT	Rev. Slag	30.0
	Anode Copper	12.6
	Conv. Dust + Slime etc.	41.4
	Stack (Scrubber)	16.0

It is estimated that in the early stages of smelting, arsenic sulphide vaporizes and later in the process, metallic As_4 vaporizes. Copper metal has a high affinity for arsenic.

The fractions of arsenic reporting to the gas phase varies as the initial arsenic charged to the copper smelting furnace.[16] The figure taken from this work is shown as Figure 2-10.

Flash furnace smelting tests have been carried out by Inco on nickel concentrates.[10] Furnace off-gas contains 40% of the arsenic compared to about 22% in conventional roasting and reverb smelting. Thirty-eight percent of the arsenic is recovered in the settling chamber in similar proportion to copper and nickel which indicates that the arsenic is in the solid state on entering the chamber or condenses in a solid form at the chamber temperature (700°C). One would expect much higher collection efficiencies in a cottrell operating at 150°C.

2.4.3 Converting

In normal copper converting, approximately 70% of the As is volatilized with 16% reporting to slag. A relatively small amount reports to blister. Arsenic is volatilized early in the cycle before metallic copper can stabilize the arsenic. In the converting of high grade mattes the formation of metallic copper is accelerated with an increased stabilization of arsenic in the molten matte-metal phase. The distribution of arsenic and concentration in matte at the final converting stage is shown in Figure 2-11 for two SO_2 pressures.[14]

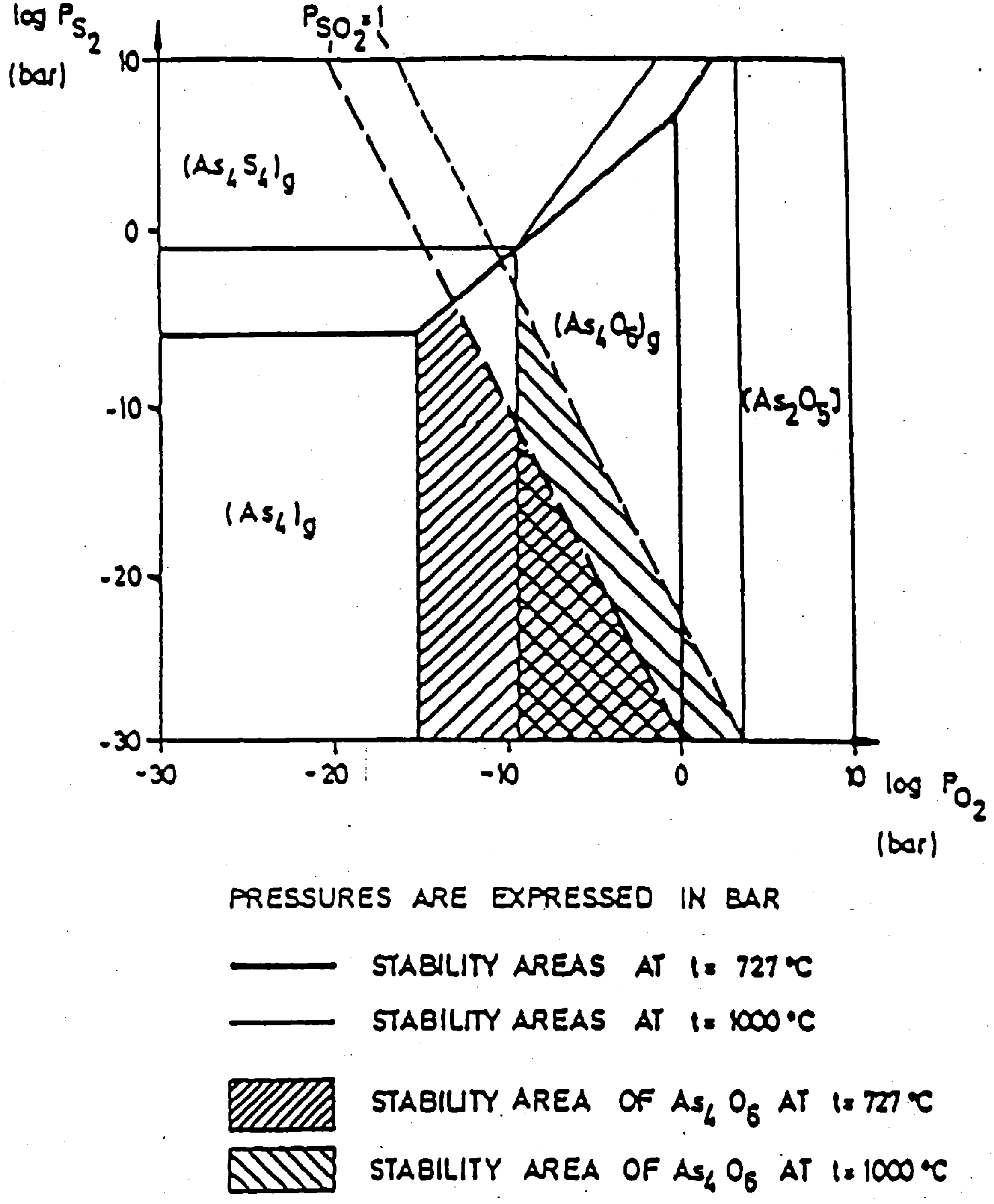
The excellent review of Piret et al[14] has summarized much of the work published on copper smelters.

TABLE 2-1: VAPOUR PRESSURE - TEMPERATURE RELATIONSHIP FOR As_4O_6

Temp.(C)	Temp(K)	log p	As_4O_6 p(mm Hg)	As_4O_6 g/cu.m	As g/cu.m
90	363	-6.8005	0.00012	0.0021	0.002
100	373	-6.3514	0.00034	0.0058	0.0044
110	383	-5.9257	0.00090	0.0149	0.0113
120	393	-5.5218	0.0023	0.0369	0.028
130	403	-5.1378	0.0055	0.0871	0.066
148	421	-4.4927	0.0244	0.3683	0.279
170	443	-3.7754	0.127	1.825	1.382
180	453	-3.4724	0.256	3.586	2.716
200	473	-2.9049	0.946	12.69	9.610
220	493	-2.3834	3.144	40.46	30.64
240	513	-1.9025	9.513	117.6	89.09
260	533	-1.4577	26.490	315.3	238.8
289	562	-0.8787	100.49	1135.4	859.9
300	573	-0.6613	165.76	1835.2	1389.9
310	583	-0.4793	252.06	2742.8	2077.2
320	593	-0.3034	377.91	4042.9	3061.8
330	603	-0.1334	559.03	5881.4	4454.2
335	608	-0.0505	676.65	7060.3	5347.0
337	610	-0.0177	729.71	7589.0	5747.4
338	611	-0.0013	757.65	7866.6	5957.6

Range 90 -338 deg.C log P(atm)(As_4O_6) = - 6080.6/T(deg K) + 9.9506

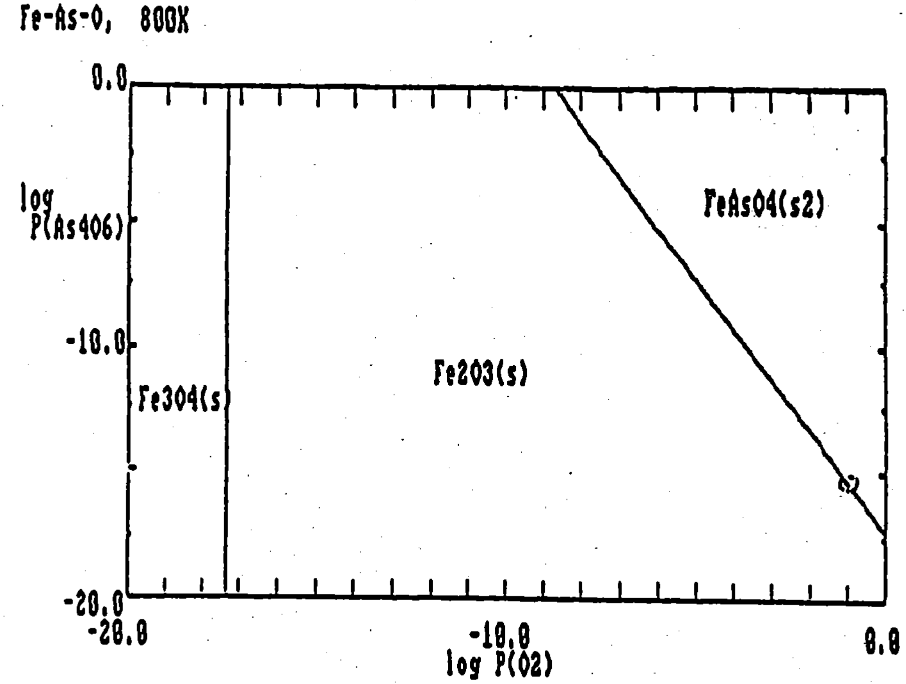
Fig. 2-1



Areas of predominance of gaseous arsenic compounds

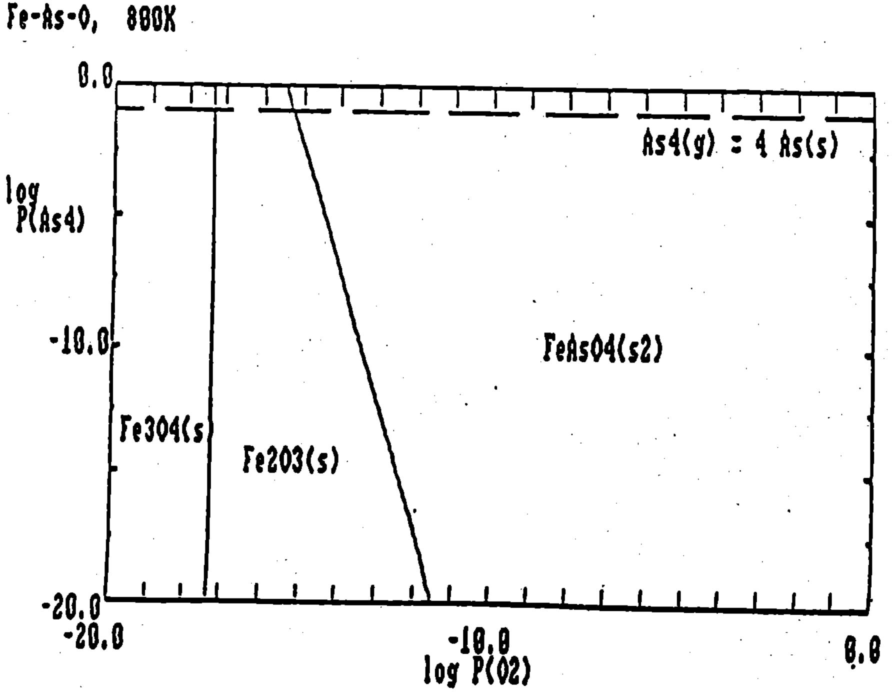
Reference 14 (Piret)

Fig. 2-2



Predominance area diagram in terms of log $P_{As_4O_6}$(atm) vs P_{O_2} (atm) for Fe–As–O at 800 K (527°C).

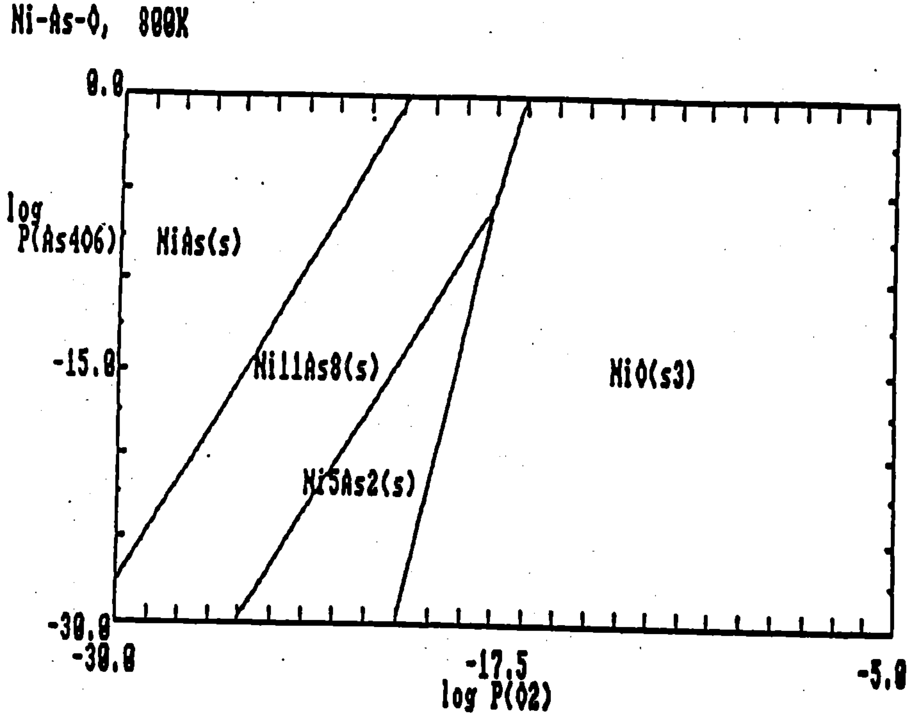
Fig. 2-3



Predominance area diagram in terms of log P_{As_4}(atm) vs log P_{O_2}(atm) for Fe–As–O at 800 K (527°C). Dashed line is saturation limit of As_4(g).

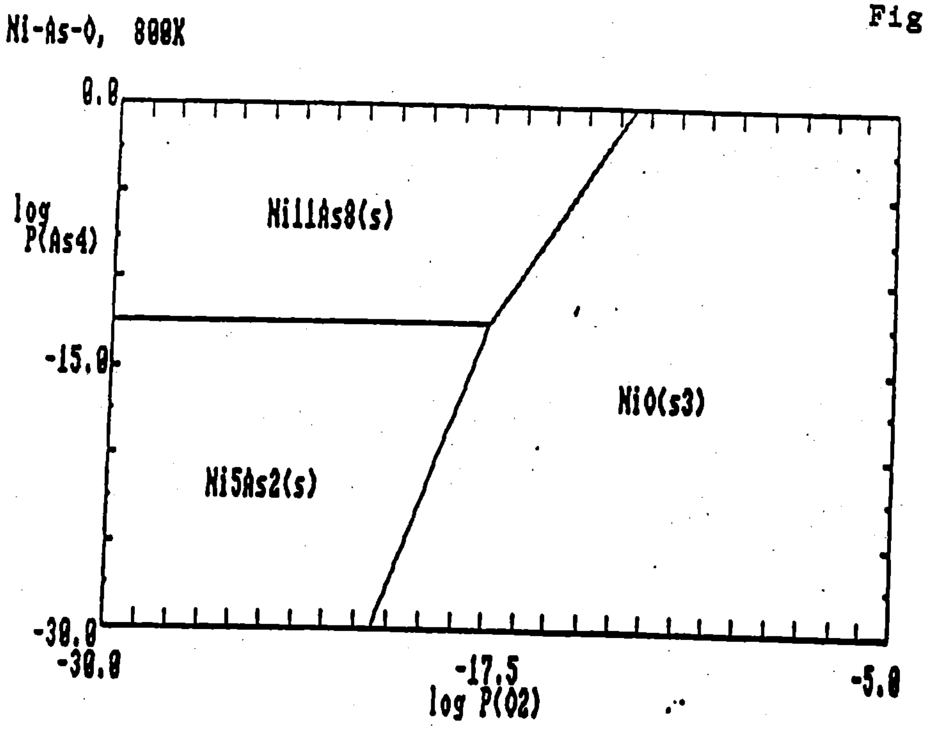
Reference 3 (Ske)

Fig.2 -4



Predominance area diagram in terms of log $P_{As_4O_6}$ (atm) vs log P_{O_2} (atm) for Ni-As-O at 800°K (527°C).

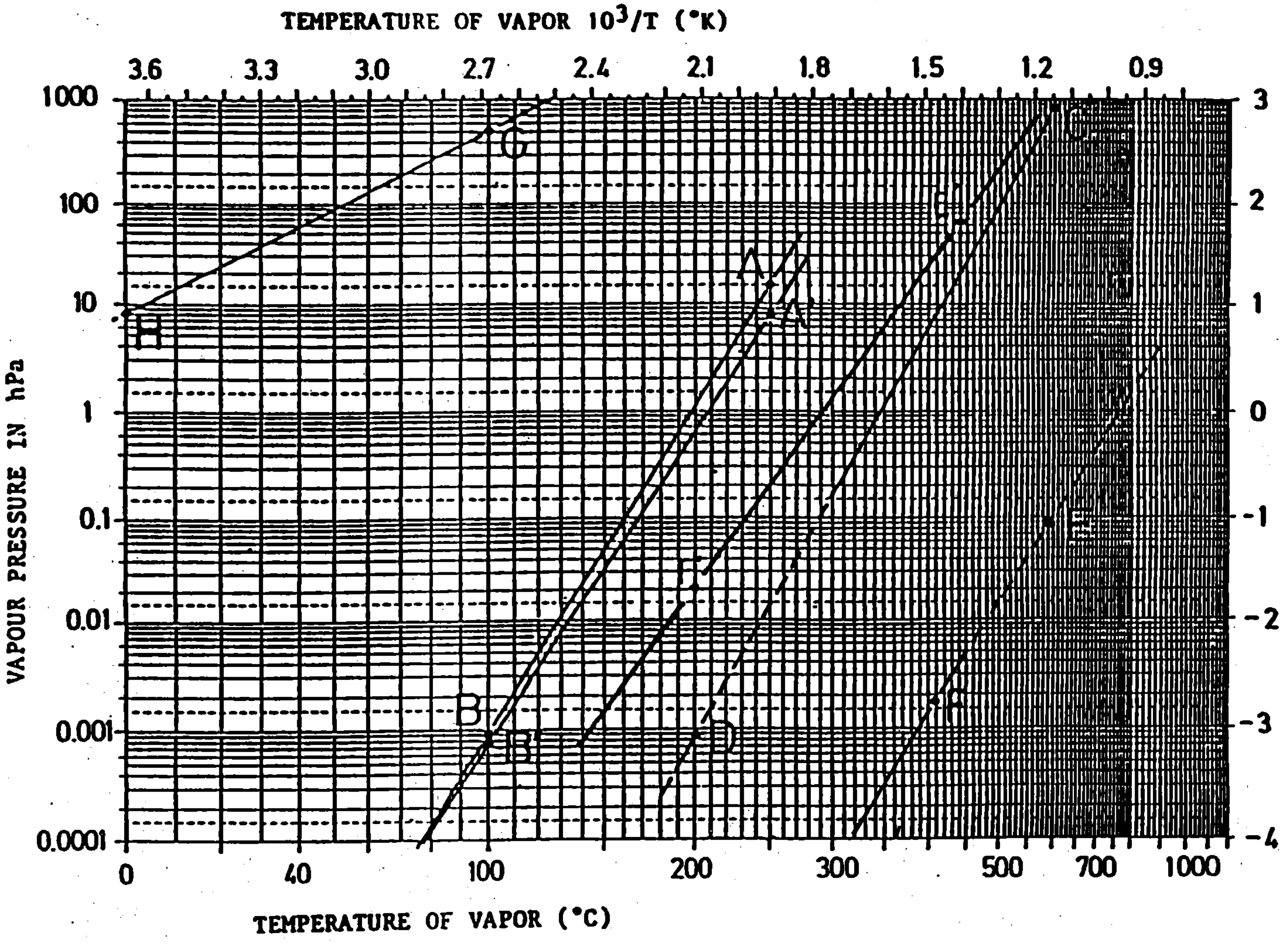
Fig. 2-5



Predominace area diagram in terms of log P_{As_4} (atm) vs log P_{O_2} (atm) for Ni-As-O at 800°K (527°C).

Reference 3 (Ske)

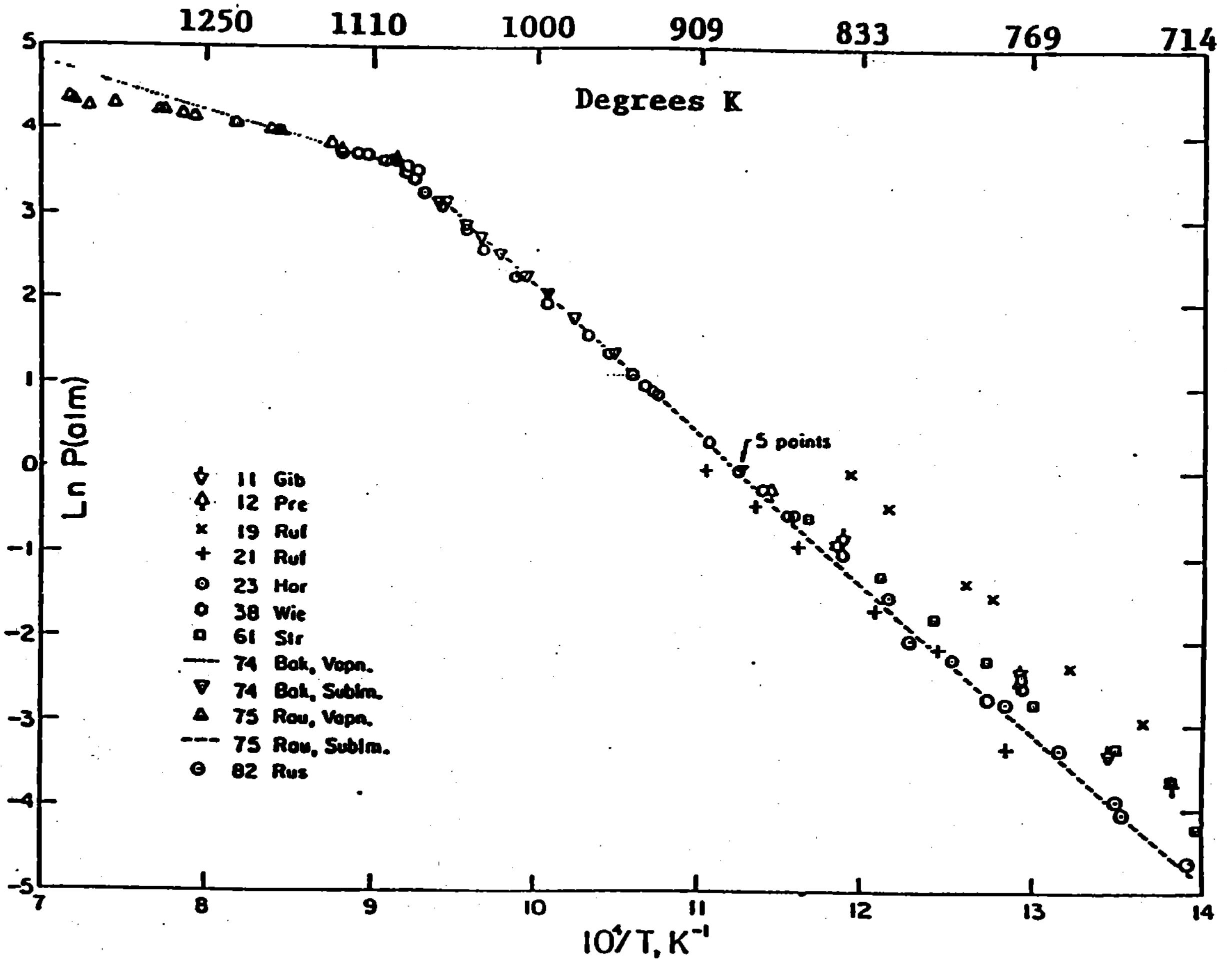
As_4O_6: A - B: Modification ortorombic (arsenolite), A'-B': Modification monoclinic (claudetite) **Fig.2-6**
As_4: C - D, $(As_2S_3)_2$: E - F, $AsCl_3$: G - H, As_4S_4: E' - F'



Vapor pressure of As and As-compounds as a function of temperature
Data from: Metallurgical Thermochemistry, 5th Edition, 1979, Kubachewski and Alcock

Fig. 2-7

Sublimation and Vaporization Pressures of As vs Temperature

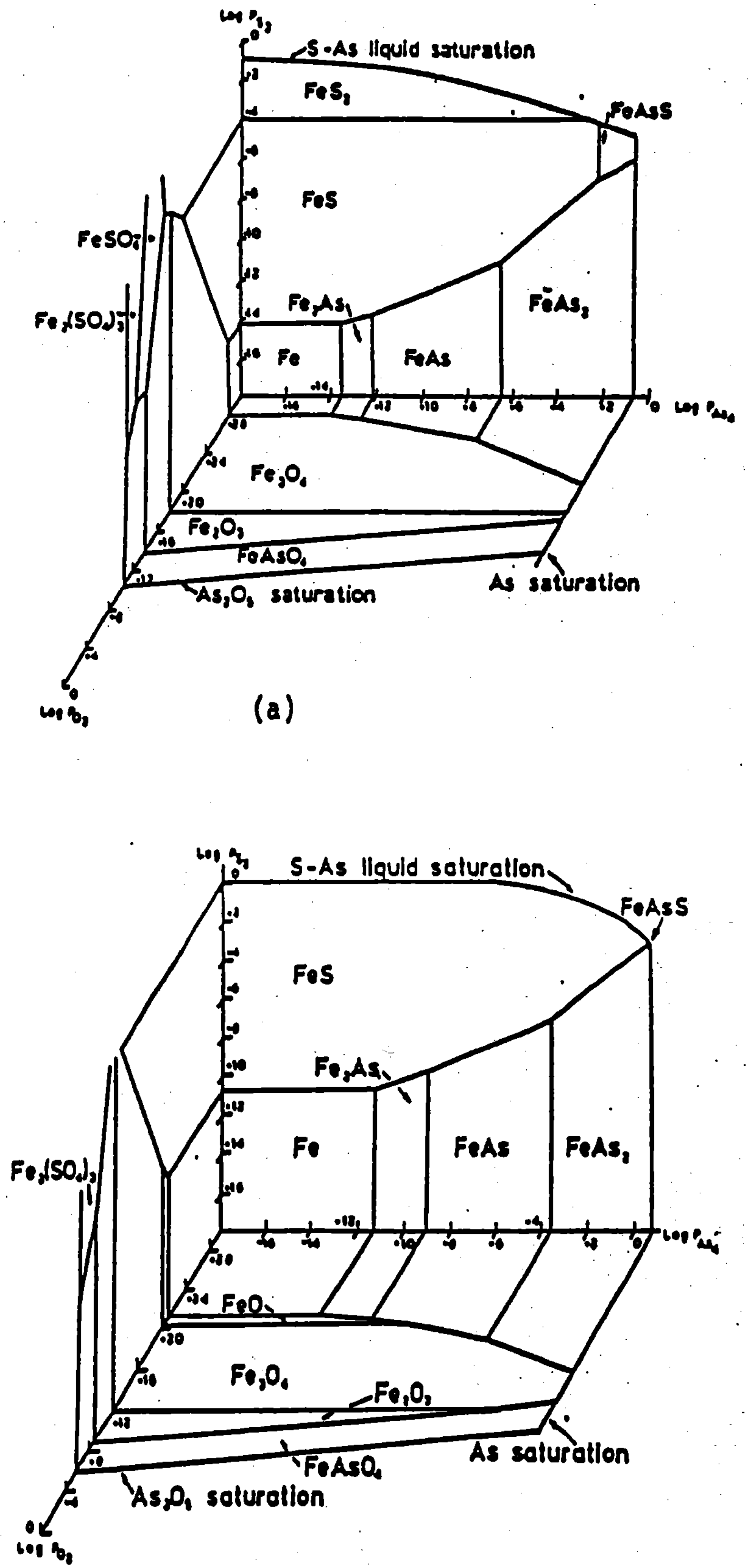


A datum point of [23Hor] and one of [75Rau] for supercooled liquid are not shown.

N.A. Gokcen, 1989.

Fig. 2-8

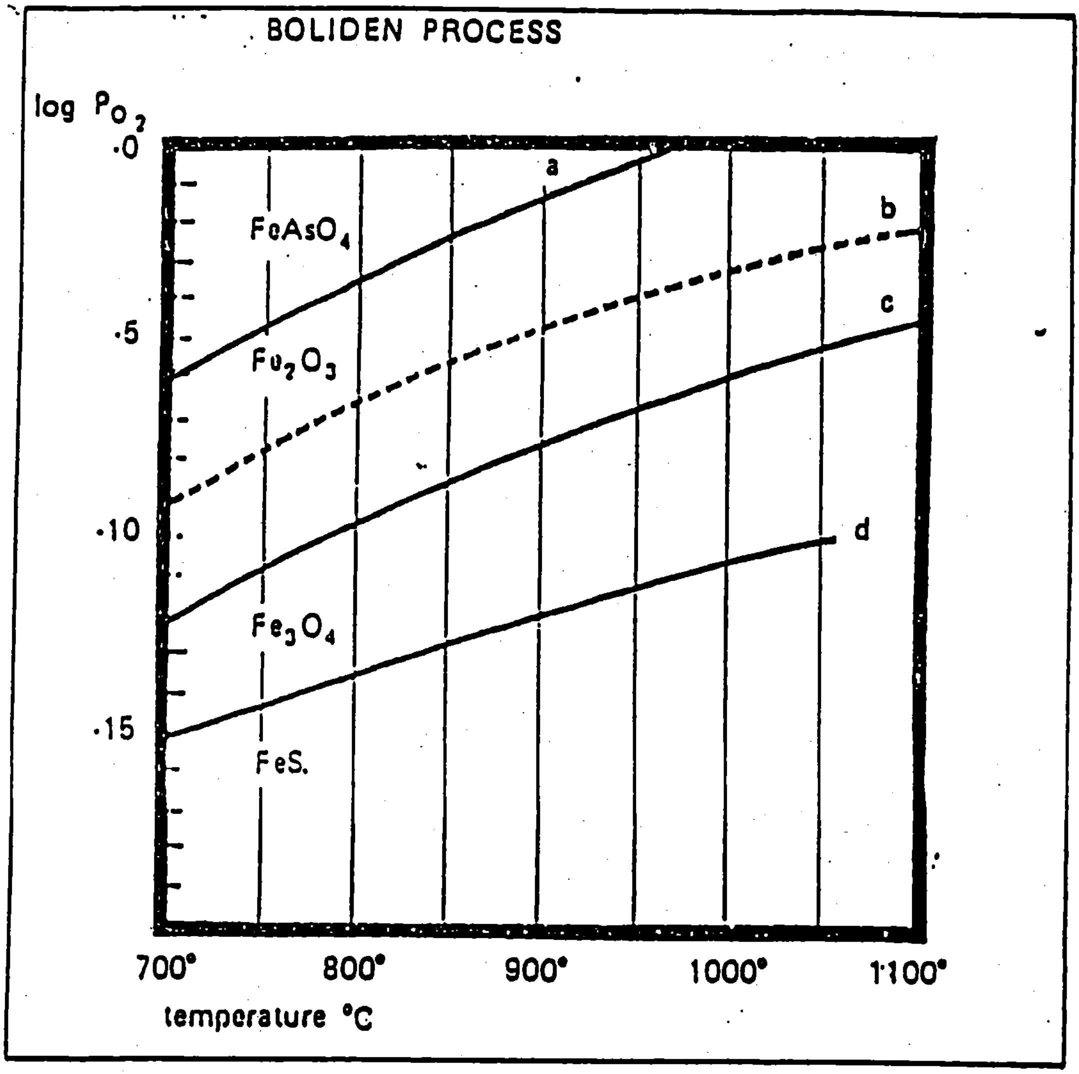
The three faces of the Fe-As-O-S predominance area diagram at (a) 798 K and (b) 973 K.



Reference 4 (Cha)

Fig. 2-9

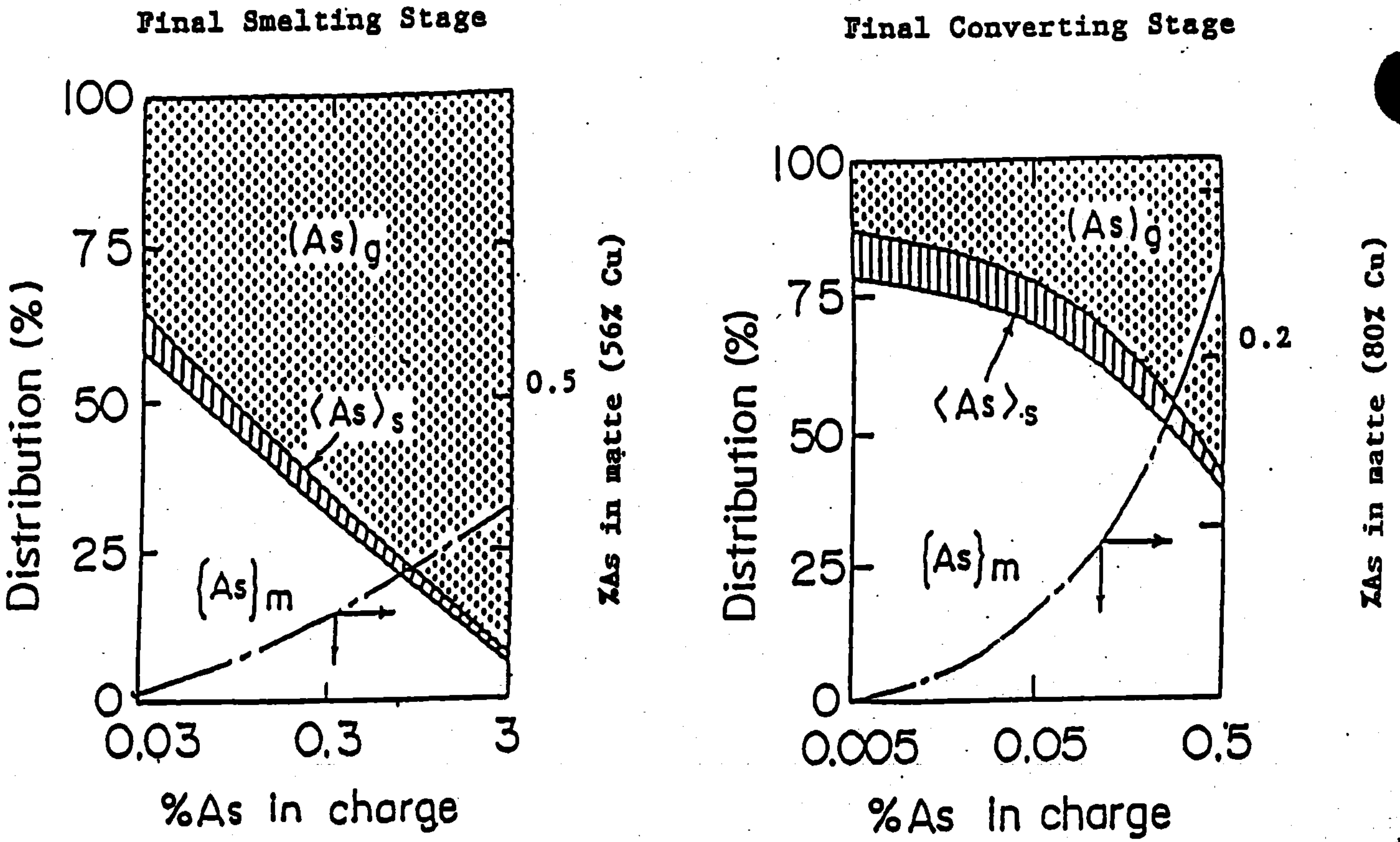
Boliden Process for Roasting Arsenical Pyrite



Reference 2 (Boliden)

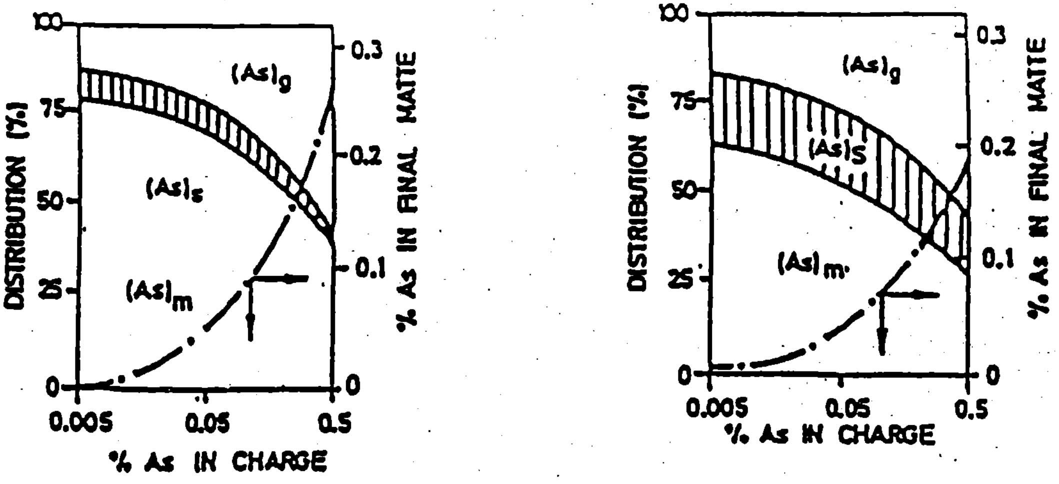
Distribution of Arsenic

Fig. 2-10



Ref. 16

Fig. 2-11



A. P_{SO2} = 0.1 bar

B. P_{SO2} = 1 bar

Distribution of As (%) and concentration in matte at final converting stage (30)

Ref.4 (Pir)

T = 1,250 °C

S = 1.0 (= PS-converting)

P_{SO2} = 0.1 bar (A)
1.0 bar (B)

% Cu in matte: 80

3.0 ARSENIC RECOVERY FROM PYROMETALLURGICAL OPERATIONS

3.1 Background

Arsenic is found as an impurity in many materials treated in numerous non-ferrous and ferrous metallurgical processes. Pyrometallurgical treatment of these materials is undertaken to produce, as efficiently and economically as possible, primary metal products free of impurities such as arsenic. Separating arsenic from metal values and developing methods of controlling emissions of arsenic (and other impurities) have been of great interest to process metallurgists for decades. Competition amongst metal producers to offer metals of higher and higher purity has prompted the development of processes which yield high purity products. At the same time, limiting emissions to meet local jurisdictional requirements is a priority.[14] A highly specialized example of the above is the processing of gold bearing arsenical materials to recover gold and an arsenical by-product.[9] Arsenical preservatives have been produced from these by-products and are known throughout the world.[23] Arsenic trioxide has sold for $2.20 per kilogram to preservatives producers. The supply has however, often exceeded demand and only the highest purity arsenic compounds have found a market.

The presence of arsenic in gold ores can produce a refractory mineral[41,44] from which gold is difficult to extract using conventional methods. Arsenic is only one of a number of contributors to refractoriness. The gold bearing component of refractory ores is amenable to gold recovery following an oxidation pre-treatment. Treating refractory arsenical gold ores often includes a thermal process to liberate the metal values. Effective pre-treatment of ore via heap leaching has not been developed. As a result, milling and concentration steps are typically required which limits treatment to ores with cut off grades in the range 0.07 to 0.08 oz/t. Upgrading or concentrating the refractory compound by flotation is often an effective means of reducing subsequent processing costs. Flotation tailings losses are off-set by reduced oxidative pre-treatment and subsequent gold recovery costs. A scavenging treatment of tailings may be possible to improve the overall gold recovery. Commercially proven options for treating refractory gold minerals are :

i) Roasting
ii) Pressure Oxidation (Leaching)
iii) Biological Oxidation

When base metals such as copper are recoverable, smelting in a TBRC or Sirosmelt furnace may be a viable option.[41] Alternatives to roasting refractory gold materials are discussed in Section 5. The following sections discuss arsenic processing and emissions from a variety of pyrometallurgical operations especially roasting techniques associated with gold recovery.

3.2 Roasting

3.2.1 Non Ferrous Roasting

Roasting of non-ferrous minerals has been used[14, 53] to pre-treat or modify a variety of minerals prior to a subsequent pyrometallurgical or hydrometallurgical treatment. Table 3-1 shows examples of oxidative roasting processes operated world-wide for recovery of various base metals. The processes produce calcines in sulphate, oxide, and mixed oxide-sulphide form. Heat liberated from oxidative roasting can often provide the necessary energy to sustain the process. Processes which are not autogenous operate with supplemental fuel additions. Roasting processes produce an off-gas which is cleaned to various degrees before discharge to atmosphere.

Table 3-1 illustrates gas cleaning for operations which have widely different concentrations of arsenic in the roaster feed. Some of these roasters have common gas cleaning elements that have been proven highly effective. The arsenic emitted to stack gas has been estimated based on the gas cleaning reported[65] in the literature and the requirements of sulphuric acid plants. Production of a marketable grade of sulphuric acid, from SO_2 in the off-gas, requires a high degree of gas cleaning in order to minimize product acid contamination and build-up on the catalyst beds. Sulphuric acid used for fertilizer production typically contains less than 1 ppm As. The gas cleaning requirements of sulphuric acid plants built over the last 20 years by companies such as Lurgi, Monsanto and Chemetics are shown in Table 3-2. It is estimated arsenic to stack is less than 1 mg/Nm^3 for recently designed sulphuric acid plants.

The failure of conventional gold recovery processes in cases of gold bearing arsenical materials prompted the development of pre-treatments as discussed in Section 3.1. The roasting process yields a calcine amenable to gold recovery using conventional cyanide leaching technologies. An overview of technological developments[17, 18, 20, 28, 48] is included to put the transition to current techniques and their limitations into perspective.

3.2.2 Gold Roasters

Table 3-3 summarizes gold roasting operations and their associated gas cleaning circuits. Roasting of refractory gold minerals was first practiced in Australia and later in South Africa in the first decade of this century. In many older references, there is little mention of gas cleaning except with respect to the recovery of gold values contained in the dust and fume emitted from the roasting process[17, 19].

Fluid bed roasting was developed in the 1920's in Germany[53] and was quickly recognized as a more intense form of roasting with process emissions concentrated in the off-gas. Removal of arsenic from refractory minerals using fluid bed roasting was reported about fifty years ago[53] and continues to be investigated[25]. The benefits of a two stage roast for optimum arsenic removal was reported in detail in the 1940's[29]. A generic flowsheet of two stage roasting is shown in Figure 3-1. Gold is generally best liberated by removing most of the arsenic and sulphur.[29, 48, 49, 83] Particulate containing the gold is generally separated from gaseous arsenious oxide using an electrostatic precipitator. The arsenious oxide is subsequently condensed by direct or indirect cooling with the high grade As_2O_3 collected, usually in a baghouse filtration. Residual arsenic, mostly in the vapour state may be removed by further cooling and wet scrubbing of the gas. Certain ores do not lend themselves to making concentrates which necessitates treating the whole ore[33, 37, 38, 77, 78, 98, 104] in a fluid bed roaster (or other process). A number of these roasters operate in the Carlin district of Nevada.

The use of two ESP's in series, first hot and second warm to capture arsenic trioxide, was implemented by Boliden[115]. Boliden later developed wet gas cleaning alternatives[42, 51, 60, 110] The two ESP's in series approach was also implemented at Giant Yellowknife and New Consort with a subsequent switch to baghouse technology for improved arsenic recovery. Stack dust loss estimates of 5 to 9 percent (excluding arsenic in the gas phase) of the roaster output were reported by Giant Yellowknife[17] using two ESP's in series.

The use of bag house technology[61] to capture arsenic trioxide, shown in Figure 3-1, came into favour in the 1950's. Arsenic emissions from the Giant Yellowknife roaster were reported at 75 mg/Nm^3 when operating the bag house at 230 degrees F. Reducing the baghouse temperature to 220 degrees F, reduced the arsenic trioxide concentration in the stack gas to its current level[71] of 23 mg/Nm^3. Proposed Canadian standards were developed in 1979 based on results obtained from baghouse systems installed at Campbell Red Lake Mines Ltd. and Dickenson Mines Ltd.[72] The proposed standard was 20 mg/Nm^3.

Baghouses capture arsenic trioxide precipitated from hot flue gas by chilling the gas with air mixed carefully[61,18, 9] to avoid cooling to the acid mist dewpoint. Mixes of water and air can be used as well as indirect cooling in a heat exchanger. Recovery of arsenic trioxide is limited by the vapour pressure of As_2O_3 in the baghouse, which approximates 10 to 40 mg/m^3 depending on the gas temperature. Arsenic capture is also related to the quality and condition of the bag filters.

Large amounts of arsenic trioxide have to be disposed of in secure holding areas when baghouses are used. Underground stopes in permafrost was the choice of some operators and is currently used by Giant Yellowknife Mines. Sales of impure arsenic trioxide are minimal, hence, up-grading to produce a marketable product was investigated. The WAROX process was developed to produce a high purity arsenic trioxide from baghouse dust. The refining relied on the volatile nature of arsenic trioxide to separate it from minor constituents. Arsenic trioxide markets are also unstable and with inconsistent sales, inventories of baghouse dust[9] have grown over the years.

As discussed in Section 2, the vapour pressure of arsenic trioxide at baghouse temperatures is significant and limits the recovery to about 99.5 percent under ideal conditions. To recover arsenic from the gas exiting a baghouse, some gas conditioning is required.

It was reported that chilling the gas in a water scrubber and collecting the mist in a wet ESP[60] can significantly reduce the arsenic trioxide content. Operators at the New Consort Mine report[39] that:

"The mist precipitator acts as a policeman for arsenic that has escaped the baghouse "

Table 3-3 shows that the baghouse is the final gas cleaning step in many operations. In instances were scrubbers or acid plants clean roaster gases, arsenic emissions are very low. The latest gold roaster commissioned by Newmont in Nevada, in 1995, has a very complex gas cleaning circuit, shown in Figure 3-2. Included are mercury removal and catalytic conversion of carbon monoxide to carbon dioxide to meet emission regulations.

The roasting operation at Golden Bear Mines, British Columbia treats arsenical concentrates in a fluidized bed roaster.[128] Gas cleaning includes cyclones, a bag filter and a wet scrubber, which cools the gas to about 70°C. Alkaline scrubbing effectively removes SO_2 and As_2O_3. Stack sampling has consistently given arsenic concentrations less than 1.0 mg/m^3 (North American Metals Corp.). Scrubbing in aqueous acid media will effectively remove arsenic without collecting SO_2. Some SO_3 mist will be captured.

Section 4 discusses control options for gold roasters with a variety of current established technologies.

3.3 Smelting

Smelting of ferrous and non-ferrous metals inherently separates volatile components from the main metal stream due to the high temperatures needed to form the liquid metal, matte, slag and speiss phases[14, 21, 22, 105]. The vapour pressure of various arsenic compounds at smelting temperatures tends to transfer these and other volatile compounds into the atmosphere above the molten bath phases characteristic of smelting operations. The atmosphere above the bath is vented into an off-gas handling system.

As noted in Section 2, arsenic behaviour during smelting depends on the affinity of arsenic for the condensed phase as well as its tendency to volatilize. This volatile behavior of arsenic has been recognized for many decades. Arsenic produced in the US, in the first half of this century, was principally a by-product of copper and lead smelting[22]. Arsenic was also produced by subliming arsenical sulphides or treating scrubbing residues[26]. Metallic arsenic was recovered by reacting the oxide in a retort with charcoal[22]. The arsenic vapour condensed in a cooler connected to the retort. Metallic oxide as thermally sublimed in a muffle, reverberatory or roasting furnaces fired with coke gas or oil. The recovery of arsenic was reported by cooling flues, baghouses and hot Cottrell precipitators (ESP's). The technology used to clean flue gases has been available for decades[22, 47, 50, 59]. Gas cleaning developments to recover arsenic trioxide efficiently have been refinements in many instances[108].

Table 3-4 shows examples of off-gas cleaning systems for smelting operations in various parts of the world. Smelter unit operations operate with increased intensity due to improvements such as flash furnace development and oxygen enrichment. The concentration of SO_2 in the off-gas from recently designed smelters is sufficient to manufacture sulphuric acid. This process requires a high degree of gas cleaning as discussed in Section 3.2. Materials recovered in the gas cleaning circuits of modern smelters have to be processed themselves. This results in interesting recycle loops of arsenic bearing materials[14] or fixation circuits[27, 68, 100]. A generic flowsheet outlining the complexity of recycles in smelters with effective gas cleaning circuits is shown in Figure 3-3. Sludge materials are treated to recover high purity arsenic in certain smelters[26, 84]. Thep1434 percent of the arsenic in the feed volatilized during primary smelting was discussed in Section 2. The wide range of arsenic concentrations reflects its dependence on factors such as temperature, weight distribution and gas flow conditions. This complicated behaviour of arsenic makes modelling arsenic distribution difficult.

The complex behaviour of arsenic is described in an overall flowchart for the copper smelter in Naoshima shown in Figure 3-4. In this instance, two primary smelters operate in parallel with recycle arsenic totalling about 14 percent of the feed arsenic. Arsenic is managed in this case by treating converter dust separately and scrubbing the off-gas to produce a sludge. The concept of treating materials collected in gas cleaning systems separately to avoid build-up by recycling was also adopted by Kennecott in their new smelter in Utah. Metallurgical complexes, i.e. Boliden, at times combine off-gases from various processes and treat the blended gas in acid plants or liquid SO_2 plants [42, 51, 110].

Roasting, compared to smelting, is essentially a once through process, with few impurity recycles, which makes dealing with arsenic in roasters generally a more direct matter.

Although many non-ferrous smelters recover arsenic by gas cleaning prior to acid production, a number vent the off-gas to stack after collecting particulates in electrostatic precipitators. The gas may be cooled to only 150 to 200°C at which temperature arsenic trioxide has a high vapour pressure and theoretically could retain arsenic at concentrations of 0.4 to 13.0 grams/m^3. In the presence of excess air however, arsenic trioxide vapour may react with various metal oxides in the off-gas. These are collected in the ESP as particulates and limit the discharge of arsenic to the atmosphere (see Section 2.0).

3.4 Converting

Table 3-5 illustrates the difficulty in economically controlling emissions from Peirce-Smith converting operations. The off-gas is produced intermittently and the SO_2 concentration fluctuates. The major smelters in Canada vent converter off-gases to atmosphere after gas cleaning which is essentially particulate removal. Gaspe Copper in Murdochville has treated converter gas in a sulphuric acid plant.

Arsenic is distributed between the condensed, liquid and gaseous phases during converting as discussed in Section 2. A common outlet for arsenic is the converter slag if it is cleaned of metal values and discarded at a land fill site. The metal or matte product from a smelter also contains arsenic which is typically eliminated further during refining as in the case of blister copper.

Arsenic in the off-gas is not typically as concentrated as in the case of gold roasting operations treating arsenopyrite. During converting, arsenic tends to prefer to associate with metal oxides in the flue dust which reduces its activity and the vapour pressure of arsenic in the gas. This is discussed in more detail in Section 2. As a result, temperature-vapour pressure relationships for arsenic can vary greatly depending on concentration and other compounds present. This tends to reduce the arsenic emissions from smelter stacks if particulate recovery is efficient.

Attempts to model the behaviour of arsenic during converting at TSUMEB's smelter have been inadequate[54] due to the difficulty of accounting for the affinity of arsenic for the condensed phases. A low matte grade tends to promote the volatilization of arsenic[14] due to the delay in forming a copper phase. Converting low grade matte results in 75 to 90 percent of the arsenic transferring to the gas phase. Converting higher grade flash furnace matte results in 40 to 50 percent of the arsenic reporting to the gas phase as discussed in Section 2.

3.5 Sintering

Sintering of base metal minerals has had to contend with volatile impurities emitted from the process due to the high temperatures and large gas volumes associated with this process. Sintering is typically used to agglomerate minerals prior to smelting. The agglomeration helps contain the minerals within a smelting furnace until smelting reactions occur. Sintering has been replaced by flash furnaces and roaster/electric furnace smelting processes. Sintering is still practiced in lead and lead/zinc operations which employ blast furnace technology for successful recovery of metal values.

Maximum removal of arsenic is considered beneficial during sintering since subsequent removal is usually difficult[14]. The burden to control arsenic emissions falls to the gas cleaning circuits treating sintering off-gases. Examples of sintering operations and their gas cleaning trains are shown in Table 3-6.

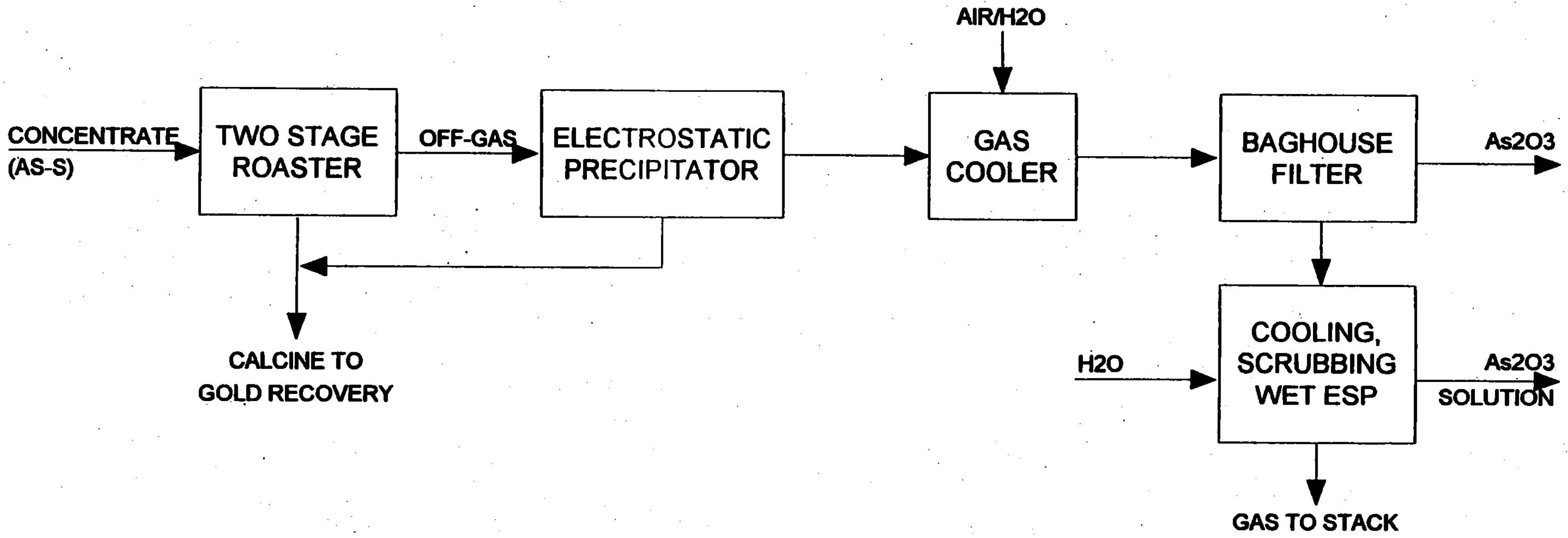


FIGURE 3-1 . FLOWSHEET OF A GENERIC GOLD ROASTING/GAS CLEANING OPERATION

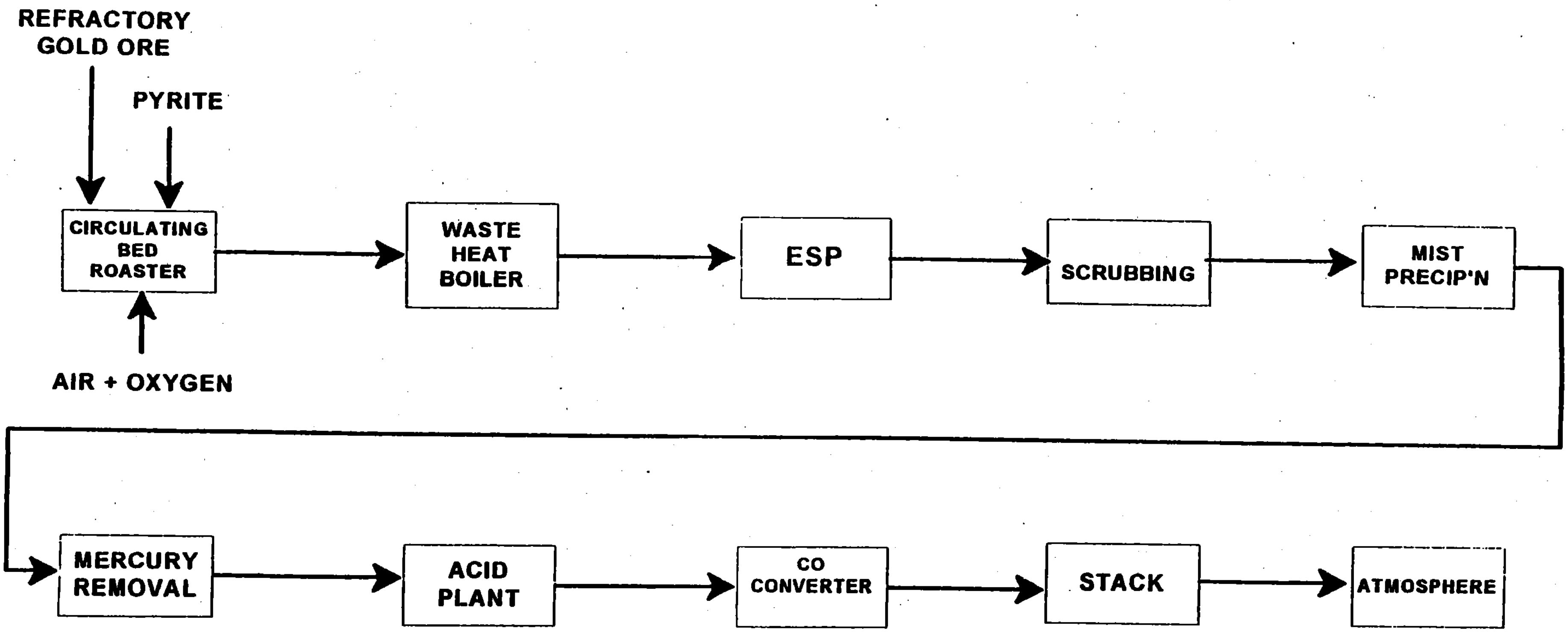


FIGURE 3-2 GOLD ROASTING CIRCUIT NEWMONT NEVADA - COMMISSIONED FALL 1995

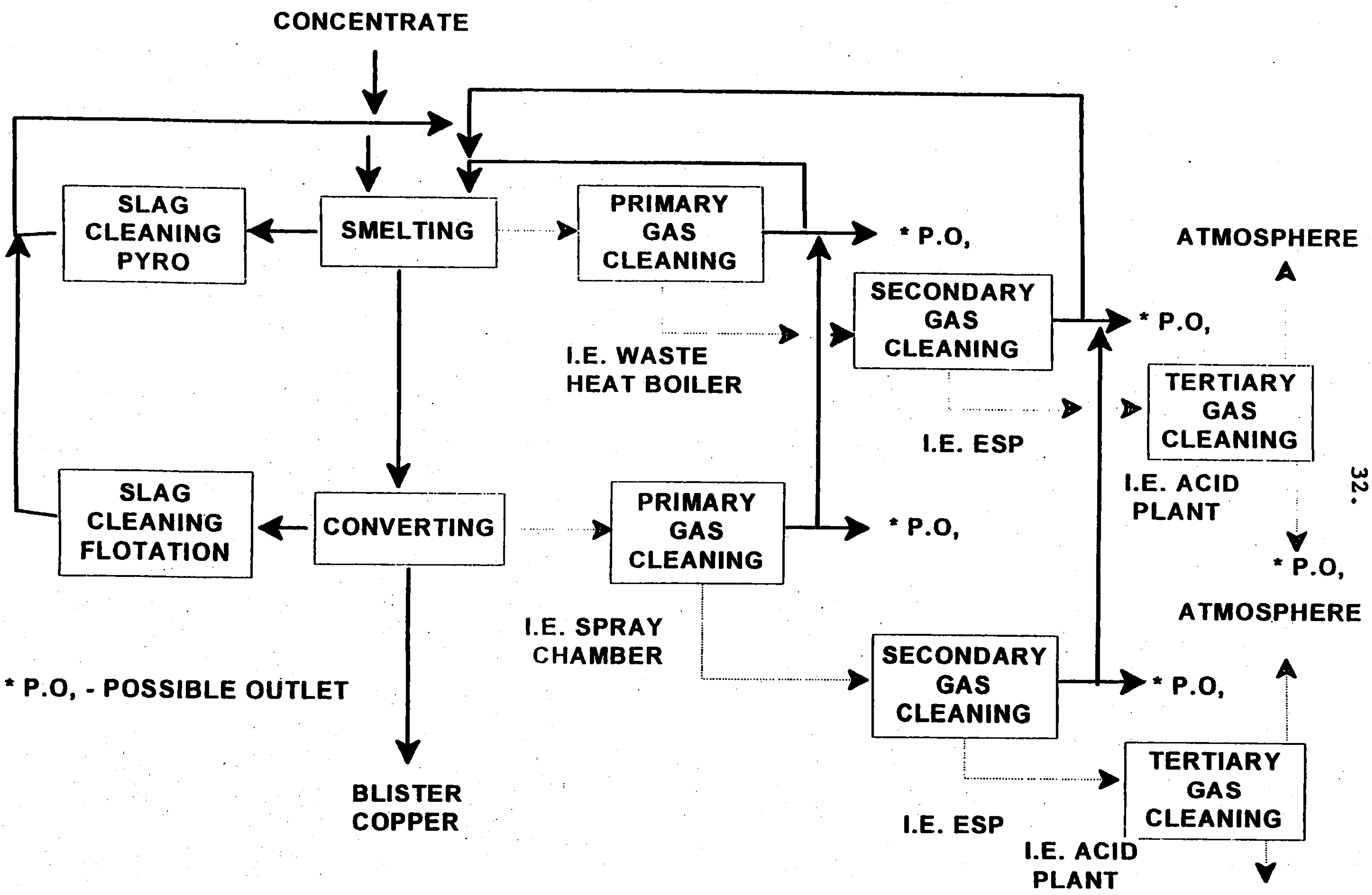
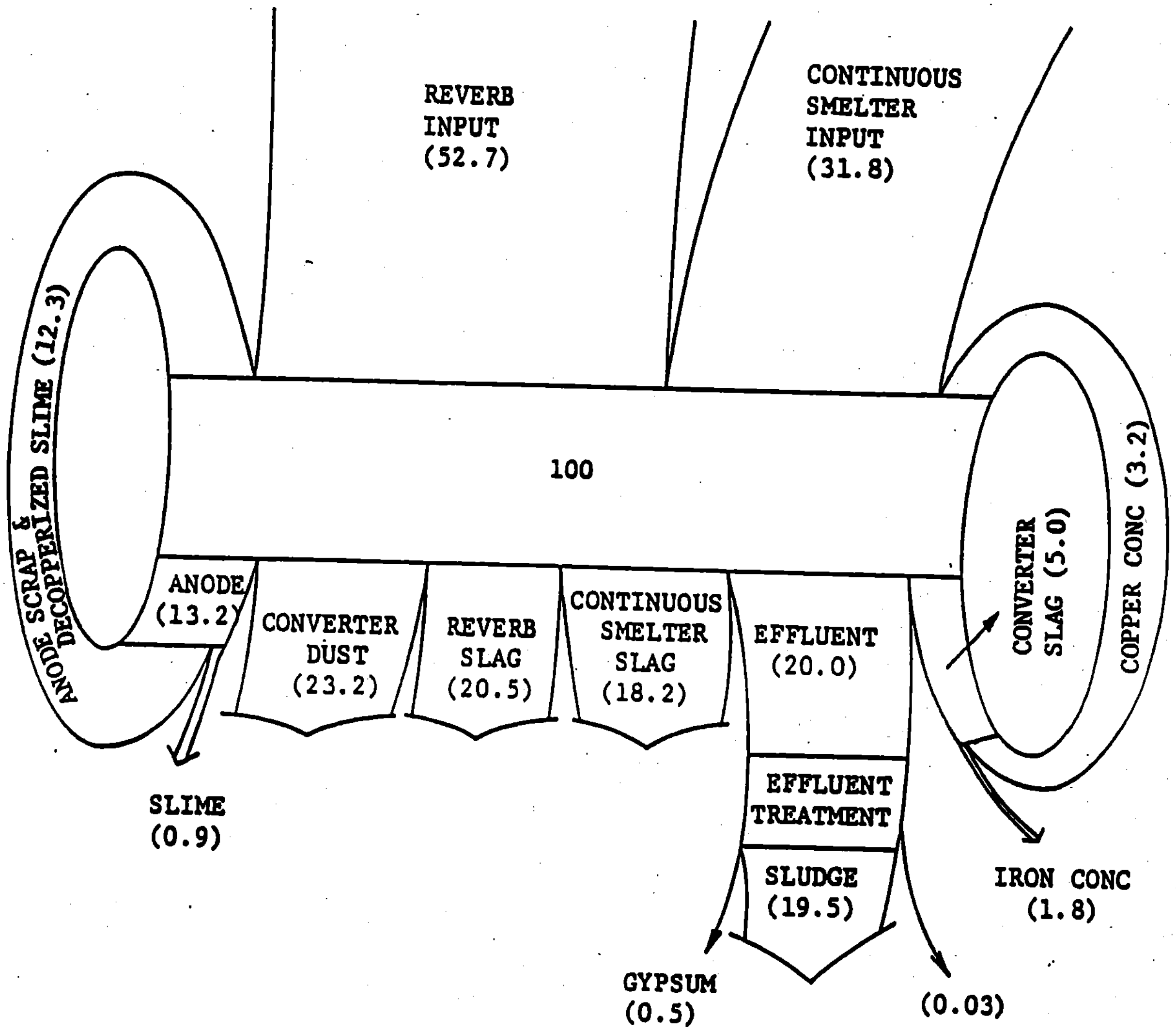


FIGURE 3-3 GENERALIZED SMELTER FLOWSHEET SHOWING RECYCLES AND ARSENIC OUTLETS

Figure 3-4

ARSENIC BALANCE IN THE NAOSHIMA SMELTER



(Reference 121)

TABLE 3-1 COMPARISON OF GAS CLEANING FOR VARIOUS ROASTING OPERATIONS PRODUCING BASE METALS

ROASTING OPERATION	NO. OF STAGES	ROAST TYPE	MATERIAL ROASTED	LOCATION	CAPACITY MTPD	GAS CLEANING UNITS	ESTIMATED ARSENIC TO STACK mg/Nm3	Reference
Falconbridge	1	Partial	Cu-Ni Conc.	Sudbury	1060	Cycl., ESP, Scrub., Mist Ppt., AP, Stack	<1	108
INCO	1	Dead	FeS	Sudbury Ontario		WHB, Cycl., ESP, Scrub., Mist Ppt., AP, Stack	<1	118
Kidd Creek	1	Dead	Zn Conc.	Timmins Ontario		WHB, Cycl., ESP, Scrub., Mist Ppt., AP, Stack	<1	127
Cominco	1	Dead	Zn Conc.	Trail BC		Cycl., ESP, Scrub., Mist Ppt., Hg Rem'l, AP, Scrub., Stack	<1	94, 125
Can. Electrolytic Zinc	1	Dead	Zn Conc	Valleyfield Quebec		Cycl., ESP, Scrub., Mist Ppt., Hg Removal, AP, Stack	<1	126
Pasar	1	Partial		Philippines	200	N/A		14
Boliden	1	Dead	Py	Ronnskar Sweeden		Cycl., hot ESP, cold ESP, Stack	>400	115
Quimigal	2	Dead	Py Conc.	Barreiro Portugal		N/A		14
Boliden	1	Partial	Mixed Sulphides	Ronnskar Sweeden		Cycl., ESP, Scrub., Mist Ppt., AP, Stack	<1	110

ABBREVIATIONS

WHB	(Waste Heat Boiler)	Mist Ppt	(Mist Precipitator)
Cycl.	(Cyclone)	AP	(Acid Plant)
ESP	(Electrostatic Precipitator)	MTPD	(Metric Tonnes Per Day)
Scrub.	(Scrubbers)	N/A	(Not Available)

TABLE 3-2
GAS CLEANING FOR SULPHURIC ACID PRODUCTION IN SMELTERS

IMPURITY	SCRUBBER TYPICAL INLET mg/Nm3	SCRUBBER TYPICAL OUTLET mg/Nm3	ACID CONTENT ppm	ESTIMATED GAS TO STACK mg/Nm3
Chloride as Cl fume	125	1.2		
Fluorides as F fume	25	0.25		
Arsenic as As_2O_3 fume	200*	1.2	0.5	< 1
Lead as Pb fume	200	1.2		
Mercury as gas	2.5	0.25		
Selenium as gas	100	50		
Particulate	1000	1.2		
Acid Mist as H_2SO_4		50		

* Noranda's Horne smelter (57) reported instantaneous values of 947 mg/Nm3 arsenic trioxide at the scrubber inlet and an arsenic in acid product of 0.5 ppm.

TABLE 3-3A COMPARISON OF GAS CLEANING FOR VARIOUS ROASTING OPERATIONS PRODUCING GOLD

ROASTING OPERATION	NO. OF STAGES	MATERIAL ROASTED	LOCATION	CAPACITY MTPD	GAS CLEANING UNITS	ESTIMATED ARSENIC TO STACK mg/Nm3	Reference
Giant Yellowknife	2	AsPy Stibnite	Yellowknife NWT	180	Cycl. ESP, Baghouse, Stack	23	9,71,17
Campbell Red Lake *	2	AsPy, Py Po	Balmerton Ontario	55	Cycl. ESP, Baghouse, Stack	>15	18,19,20
Dickenson Mine *	1	AsPy, Py Po	Balmerton Ontario	60	Cycl., Hx, Hot Baghouse, Warm Baghouse, Stack	> 15	70
Kerr Addison *	1	Py Conc.	Kirkland Lake Ont.	80	WHB, Cycl., Stack	>70	70
Golden Bear *	1	Mixed: Py incl. carbon	Muddy Lake BC		Cycl., ESP, Scrub., Stack	0.2	98, priv. comm.
Cortez Gold	1		Nevada	N/A	n/a	<10	14
El Indio	1 (MH)	Cu Conc.	La Serena Chile		Cycl., HX, ESP, Baghouse Stack	>15	58 ,81,14
Transvaal Gold Mining (1959)	1	Cu pyrite	E. Transvaal S. Africa	14	Cycl., Scrub., Mist Ppt., AP, Stack	< 1	52
New Consort ** (1988)	2	As pyrite	E. Transvaal S. Africa	100	Cycl., ESP, Baghouse, Scrub., Mist Ppt., AP, Stack	< 1	39
Newmont Gold	1	Mixed Py incl. carbon	Nevada	xxx	WHB, ESP, Mist Ppt., Hg Twr., Dble AP, CO catalyt. oxidiz., Stack	< 1	76, 78

* Not in Operation Dec. 1995

** Boliden single stage was installed and abandoned in favour of a 2 stage

Abbreviations Listed in Table 3-1

TABLE 3-3B COMPARISON OF GAS CLEANING FOR VARIOUS ROASTING OPERATIONS PRODUCING GOLD

ROASTING OPERATION	NO. OF STAGES	MATERIAL ROASTED	LOCATION	CAPACITY MTPD	GAS CLEANING UNITS	ESTIMATED ARSENIC TO STACK mg/Nm3	Reference
Kalgoolie Mining	1	Py and Tellurides	Fimiston W. Austrailia	75	Cycl., ESP.	>100	14
Danly	2 in one shell	AsPy/Py	Gatoorna Zimbabwe	47	Cycl., Dust Pot, Stack	>1000	30
North Kalgurli	1	Py	Fimiston W. Austrailia	75	Spray Chamb., ESP, Stack	>100	14
Harmony Mine	1	Py	Orange Free State, S. Afr.	240	AP, Stack	<1	14
Lancefield Mine Windarra Project	2	AsPy	Austrailia	80	Hx, ESP, Baghouse	10	36, 31
Darasun		AsPy	- USSR	14	Cycl., ESP, Cold Box Stack	>1000	24
Big Springs		Py Ore incl. Carbon	USA	N/A	N/A	<10	14
Jarret Canyon		Py Ore incl. Carbon	USA	N/A	N/A	<10	14

NOTE:
Emissions as per date of reference.
Several plants not currently operating.
Abbreviations listed in Table 3-1

TABLE 3-4 COMPARISON OF GAS CLEANING FOR VARIOUS SMELTING OPERATIONS PRODUCING BASE METALS

SMELTING OPERATION	FURNACE PRODUCT	SMELTER TYPE	MATERIAL SMELTED	LOCATION	CAPACITY MTPD	GAS CLEANING UNITS	ESTIMATED ARSENIC TO STACK mg/m3	Reference
Horne Smelter	Cu Matte	Noranda Reactor	Cu Conc.	Noranda PQ	1850	Hood, ESP, AP, Stack	<1	57, 123
Inco Smelter	Cu Matte	Flash Fce	Cu Conc.	Sudbury Ont.	1100	Spray Chamber, Scrub., AP, Stack	<1	122
Falconbridge Smelter	CuNi Matte	Roaster	CuNi Conc.	Sudbury Ont	1060	Cycl., ESP, Scrub., Mist Ppt., AP, Stack	<1	119
Naoshima Smelter	Cu Matte	Reverb. & Continuous	Cu Conc.	Naoshima Japan	1480	Cycl., ESP, Scrub., Mist Ppt., AP, Stack	<1	121
Sumitomo Refinery	Arsenic Metal	Refinery	Arsenic Sludge	Japan	<10	Scr., Mist Ppt., Scrub., Stack	<5	84
Hudson Bay Mining	Cu Matte	Reverberatory Furnace	Cu Conc.	Flin Flon Manitoba	N/A	Esp, Baghouse, Stack	N/A	verbal com.

* Electric furnace off-gas is not treated in the acid plant
Abbreviations listed in Table 3-1

TABLE 3-5 COMPARISON OF GAS CLEANING FOR VARIOUS CONVERTING OPERATIONS PRODUCING BASE METALS

SMELTING OPERATION	FURNACE PRODUCT	CONVERTER TYPE **	MATERIAL CONVERTED	LOCATION	MATTE CAPACITY* MTPD	GAS CLEANING UNITS	ESTIMATED ARSENIC TO STACK mg/Nm3	Reference
INCO Smelter	Blister Cu	PS	Cu Matte	Sudbury Ont.	192	Hood, ESP, Stack	N/A	117
Horne Smelter	Blister Cu	PS	Cu Matte	Noranda PQ	1698	Hood, ESP, Stack	N/A	116
TSUMEB	Blister Cu	PS	Cu Matte	- Africa	N/A	Hood, ESP, Stack	N/A	54
Hudson Bay Mining	Blister Cu	PS	Cu Matte	Flin Flon Manitoba	485	Hood, ESP, Baghouse Stack	N/A	117
Gaspe Copper	Blister Cu	PS	Cu Matte	Murdochville PQ	578	Hood, ESP, Scrub., Mist Ppt., AP, Stack	<1	117
Kennecott Copper	Blister Cu	Continuous	Cu Matte	Salt Lake City Utah	N/A	WHB, ESP, Scrub, Mist Ppt., AP, Stack	<1	117
Falconbridge	CuNi Matte	PS	Cu/Ni Matte	Falconbridge Ont.	354	Hood, ESP, Stack	N/A	117

* Nominal plant capacity for active converters
** PS refers to Peirce - Smith
Abbreviations listed in Table 3-1

TABLE 3-6 COMPARISON OF GAS CLEANING FOR VARIOUS SINTERING OPERATIONS

SINTERING OPERATION	FURNACE PRODUCT	SINTERING TYPE	MATERIAL SINTERED	LOCATION	CAPACITY MTPD	GAS CLEANING UNITS	ESTIMATED ARSENIC TO STACK mg/Nm3	Reference
Brunswick Mining	Blast Fce Feed	Down Draft Strand	Pb Conc.	Belledune NB	1100	Hood, ESP, Scrub., Mist Ppt., AP, Stack	<1	124
Falconbridge*	Blast Fce Feed	Down Draft Strand	CuNi Conc.	Sudbury Ont.	1500	Hood, Cyclone, Stack	N/A	120
Algoma Steel *	Blast Fce Feed	Strand	Iron Ore	Wawa Ont.	N/A	Hood, n/a, Stack	N/A	
Cominco	Blast Fce Feed	Down Draft Strand	Pb Conc.	Trail B.C.	1450	Hood, Scrub., Mist Ppt., Liq. SO2 Pt., Stack	<1	125

* No longer in operation
Abbreviations listed in Table 3-1

4.0 GENERIC ARSENIC CONTROL OPTIONS AND EXPECTED ARSENIC RECOVERIES

Arsenic control options considered were divided into two principal categories as shown in Figure 4-1 :

- Processes which treat the roasting baghouse tail gas and,
- Processes which are alternate treatments to roasting

Alternatives to roasting are discussed in Section 5.

Treating the tail gas is a viable option. Current technologies designed to address the removal of residual amounts of contaminants from process gas streams are well established. The technologies investigated were:

- scrubbing
- gas conditioning followed by electrostatic mist precipitation
- activated carbon adsorption

Tail gas scrubbing offered by Turbotak in Waterloo Ontario was considered due to the compact, high intensity sprays available in their equipment. Scrubbing inherently cools the gas to precipitate the arsenic and collects about 80 percent on fine water droplets. The main energy consumer in this form of scrubbing is compressed air used for water atomization. The scrubbing step is followed by mechanical mist elimination. The process gas proceeds to the stack via a booster fan. A stack liner is required due to the moist nature of the gas. Table 4-1 compares arsenic recoveries using tail gas scrubbing and the other options. Capital and operating cost are presented in Section 6. Details of the equipment are shown in Appendix I. Turbotak have indicated a willingness to operate a pilot scrubber at a site such as Giant Yellowknife to confirm their predictions.

Significant tail gas arsenic removal is possible by conditioning the gas by cooling in a low pressure drop venturi scrubber followed by treatment in a wet electrostatic precipitator. Gases from the wet mist precipitators proceed to the stack using a booster fan. A stack liner is also included. The tail gas recovery of arsenic following baghouse collection is estimated at 95 percent using this technology producing an overall arsenic recovery of >99.9% and an As_2O_3 concentration of <1.0 mg/m^3 in the stack gas. By adding additional mist precipitator modules, the arsenic recovery from the tail gas could be increased to 97 percent. Collecting the acid mist (i.e. SO_3) will be a bonus using this approach. A version of this equipment is offered by Environmental Corrections Inc. (California) as shown in Table 4-1. Details of the equipment are presented in Appendix I.

A second version of the gas conditioner-mist precipitator combination is available from Biothermica in Montreal. This is an integrated design from France. This equipment is used on municipal incinerators. The arsenic recovery after baghouse collection forecast is 90 percent as shown in Table 4-1.

Arsenic in the vapour state can be removed by passing the tail gas through a slurry of activated carbon. The forecast arsenic recovery is over 90 percent. Operating costs are highest for this option since the carbon must be replaced on a regular basis. An additional scrubbing tower using an activated carbon slurry added to the Biothermica unit provides for an extra degree of arsenic removal. The costs associated with this option are shown in Section 6.

Capital costs were developed based on vendor equipment budget quotations to treat gases from a site such as Giant Yellowknife[71]. These costs are shown in Section 6 and the vendor data in Appendix I.

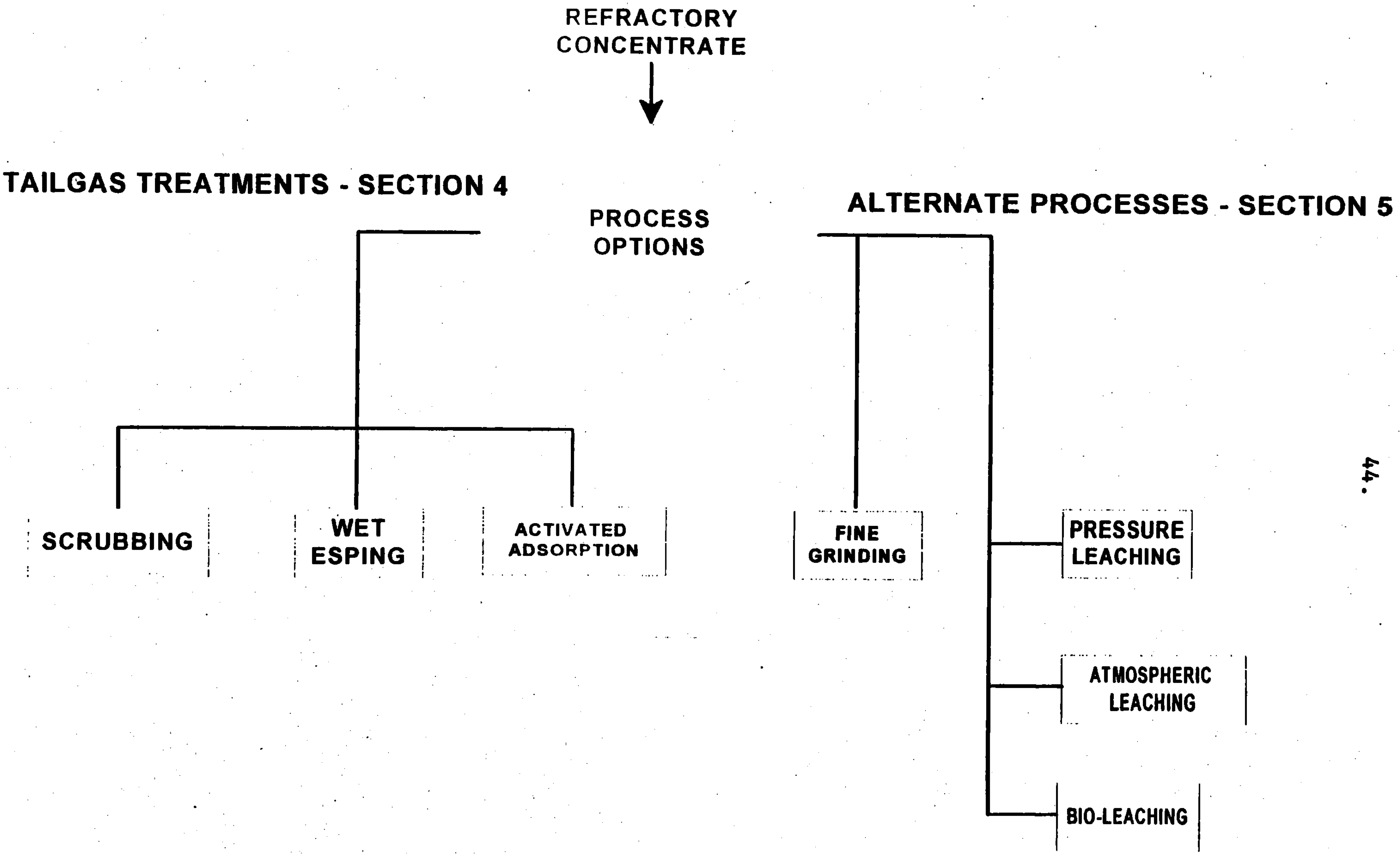


FIGURE 4-1 ARSENIC CONTROL OPTIONS FOR GOLD ROASTING

TABLE 4-1 COMPARISON OF TAIL GAS CLEANING OPTIONS

ITEM	UNITS	TURBOTAK SCRUBBER	ENV. CORR. MIST PPT.	BIOTHERMICA LAB	BIOTHERMICA OPTION 3 PLUS CARBON ADSORBTION
EQUIPMENT DESCRIPTION		Scrub., Ancil. Tks, Pumps, Fan, Mech. Mist Elim., Stack Liner	Scrub., Ancil. Tks, Pumps, 4 Mist Ppt, Fan, Stack Liner	Scrub., Ancil. Tks, Pumps, Mist Ppt, Fan, Stack Liner	Scrub., Ancil. Tks, Activated carbon Scrub., Pumps, Mist Ppt, Fan, Stack Liner
ARSENIC REMOVAL FROM TAIL GAS	%	90	95	90	>90
STACK ARSENIC CONCENTRATION	mg/m3	<1.0	<1.0	<1.0	<5.0
PILOTING AVAILABLE		YES	NO	YES	YES

5.0 ALTERNATE TECHNOLOGIES FOR GOLD RECOVERY FROM ARSENICAL SOURCES

5.1 Background

Alternatives to roasting as a means to treat refractory minerals have been investigated and reported[33, 45, 68, 69, 76, 90, 96, 101] which improve Au recovery and or meet emission requirements. Figure 4-1 shows alternatives to roasting as:

- Pressure Leaching
- Atmospheric Leaching
- Bioleaching
- Fine Grinding

The first three operations are commercially demonstrated and are discussed in the following Sections. Fine grinding is an approach reported by Metprotech[92, 114] in South Africa. Commercial applications could not be identified hence this approach will not be discussed further.

Process options are reviewed in the following sections of the report.

5.2 Pressure Leaching

A number of gold mills employing roasting to treat refractory minerals have evaluated or switched[32, 35, 75, 79, 85] to a hydrometallurgical approach. Figure 5-1 shows a generic flow sheet for pressure oxidation. Table 5-1 lists examples of gold mills which have adopted pressure oxidation to treat refractory feeds. As with roasting, the main purpose of pressure leaching is to break down arsenic bearing sulphide minerals to permit conventional leaching of gold.

Pressure leaching involves reacting feed with oxygen at 1800 to 2200 kPa and temperatures in the range 180 to 210 degrees C. in autoclave reactors. The solid residue after oxidation[102] contains a mix of ferric arsenate, ferric oxide, basic ferric sulphates, jarosites, arsenic in ferric oxyhydroxides, gangue, precious metals and sometimes elemental sulphur. Arsenic in solution is treated in a neutralization circuit. The ultimate tailings from this process contain ferric arsenate, calcium arsenate, complex arsenates and adsorbed arsenic on ferric oxyhydroxides.

The stability of arsenic in gold mine wastes produced by pressure leaching have been investigated. The precipitation of a range of compounds such as ferrous and ferric arsenate, barium arsenate, titanium arsenate, magnesium-ammonium arsenate, and arsenic sulphide have been suggested for removing arsenic from waste water. The two major compounds which form in commercial operations are calcium and ferric arsenate. The other major component is ferric oxyhyroxide.

Capital costs relating to the installation of pressure leaching circuits are documented.[68,69,76,79] The Campbell Red Lake retrofit projected capital costs at $23.6 million (C) (1990) including licensing and tailings area preparation. Capacity was rated at 71 tonnes concentrate per day.[32] Major capital expenditures are involved in converting from roasting to pressure leaching of refractory gold concentrates. A thorough study of capital and operating costs must be carried out along with studies to determine gold recovery. Preliminary test work has been carried out on the pressure oxidation and recovery of gold from Giant Yellowknife concentrates.[85]

5.3 Biological Leaching

An alternative to chemical leaching is biological leaching which employs bacteria to modify the refractory minerals for gold leaching. Oxidation of sulphides by Thiobacillus Ferrooxidans is a natural phenomenon and can be observed in most sulphide orebodies[41]. The bacteria behave as catalysts and, under ambient conditions, can accelerate the oxidation reaction by factors of several hundred thousand to a million.

In bacterial oxidation, selective oxidation is well documented[36]. High gold extractions are possible with only partial oxidation of arsenopyrite and little oxidation of pyrite.

Observations of bacterial attack along grain boundaries, where gold often resides, may explain this. Selective oxidation by bacteria can reduce requirements for oxygen, lime and limestone. A consequence of this phenomenon is that unoxidized sulphides are disposed of in tailings compounds. Long term stability of sulphides in tailings needs to be ensured so that acids are not formed leading to heavy metal pollution.

In bio-oxidation as in pressure oxidation, the sulphide minerals are reacted to form a variety of compounds, such as sulphates, as described in Section 5.2. Oxidation of one ton of sulphur requires two tonnes of oxygen. This oxygen requirement is the same for whole ore or concentrate treatments. For concentrates, considerable cooling or pulp dilution is necessary to maintain the process temperature in the range 32 to 37 degrees C for Thiobacillus Ferrooxidans. The cooling requirement can negate the advantages of treating concentrates instead of ore. A further design consideration is the oxygen mass transfer. In bio-oxidation, oxygen transfer is slow compared to other processes. The implication is that power costs to provide oxygen increase more rapidly with increasing sulphur in the feed than for other processes. Neutralizing sulphur in process tailings is significant and expensive. Neutralization at an Australian bio-leach plant were over 35 percent of the total operating costs[36].

The optimum form of arsenic for stable storage is the pentavalent species. This form produces a more stable, crystalline ferric arsenate. Bio-oxidation can produce a trivalent arsenic for disposal which requires an additional process step to produce pentavalent arsenic in a stable form for tailings disposal.

A summary of bio-oxidation plants is shown in Table 5-2. Plants have been built in the US, Brazil and South Africa and considered for other sites. Bio-leaching was evaluated for Dickenson Mines in northern Ontario[35]. Operations in Nevada, at U.S. Gold, were maintained through both summer and winter seasons[36]. There are no reports of bio-leaching in arctic regions.

Successful operations have been reported at Fairview in South Africa where bio-leaching replaced roasting. At Sao Bento, near Belo Horizonte, Brazil, capacity of the existing pressure leach plant will be supplemented with a bio-oxidation facility installed in tandem with the autoclaves to take advantage of the synergisms between the two processes.

The cost of a bio-leaching plant, to replace the existing roasting operation at a site such as Giant Yellowknife, would cost approximately $35 million. Operating costs are estimated to be similar to current costs with the exception of tailings neutralization treatment lime/limestone costs which increases the pre-treatment cost to $98 per tonne from $78 per tonne.

5.4 Atmospheric Leaching

Low pressure or atmospheric leaching has been developed as an alternative to pre-treatments previously discussed. Process equipment is simplified by avoiding, for example, the use of autoclaves. Examples of this pre-treatment approach are : Nitrox Process and the Redox (formerly Arseno) process. Both these processes are based on nitric acid as the leaching agent.

Many reviews of pre-treatments for refractory minerals describe atmospheric leaching as a process which holds potential but has not been demonstrated beyond the detailed feasibility study stage. The Redox process is to be used at the Cinola site in British Columbia and at Snow Lake in Manitoba.

The overall chemistry of the two process cited above is similar but there are distinctive differences in operating temperatures, pressure and the means of recirculating nitric acid. The Nitrox process uses soluble calcium nitrate to recirculate nitric acid. On lower sulphide feeds, the Redox process uses air regeneration of nitric acid and atmospheric leach vessels.

A summary of operations using this technology is shown in Table 5-3. Capital costs for commercial plants have not been reported in the literature. Estimates suggest a Nitrox plant for a situation such as the one at Giant Yellowknife would be 1.2 times the capital cost of a pressure leach plant.

FIGURE 5-1: GENERIC PRESSURE OXIDATION FLOWSHEET

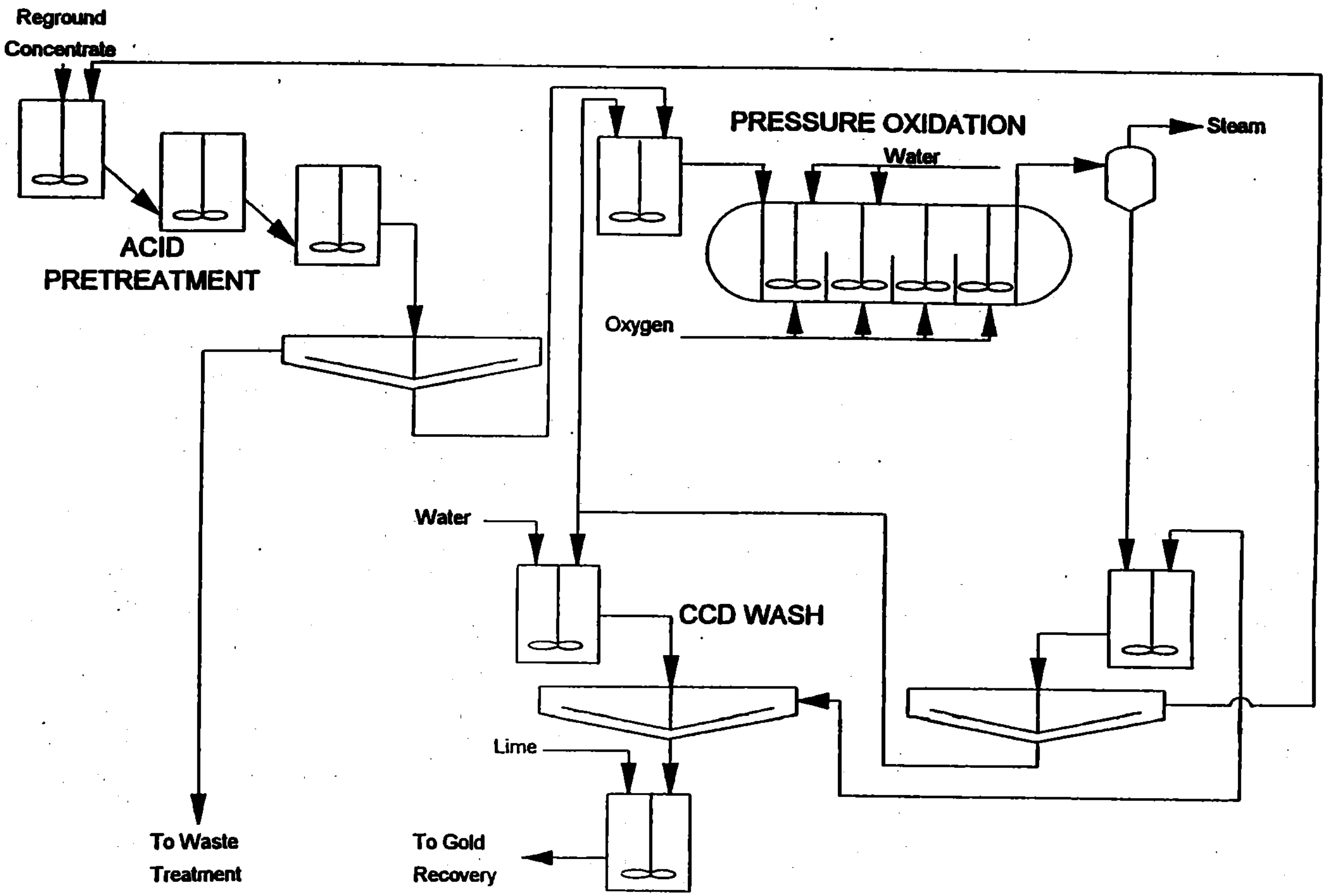


TABLE 5-1 SUMMARY DESCRIPTIONS OF PRESSURE LEACHING OPERATIONS

OPERATION	LOCATION	CAPACITY MTPD	REFERENCES
Con Mine (Miramar)	Yellowknife NWT	96	100
McLaughlin (Homestake)	Calif.		14
Goldstrike (Barrick)	Carlin Nevada	1363	69
Sao Bento (Gencor)	Brazil		102
Getchell (FRM)	Nevada		102

TABLE 5-2 SUMMARY DESCRIPTION OF BIO-OXIDATION PRE-TREATMENT OPERATIONS

OPERATION	MATERIAL LEACHED	LOCATION	CAPACITY MTPD	REFERENCES
Fairview Mine Gencor	Py/AsPy	South Africa	12	41
U.S. Gold		Tonkin Springs Nevada	1500	41

TABLE 5-3 SUMMARY DESCRIPTION OF ATMOSPHRIC LEACHING OPERATIONS

OPERATION	MATERIAL LEACHED	LOCATION	CAPACITY MTPD	REFERENCES
Cinola (City Resources)	Vein Sulphides	Queen Charlotte Islands B.C.	pilot scale	41
Snow Lake (Sikaman Resources)	Arsenical Tailings		pilot scale	41

6.0 ARSENIC EMISSION CONTROL AT THE GIANT YELLOWKNIFE MINE

6.1 Background

The Giant Mine is located just north of the city of Yellowknife in the Northwest Territories. The mine commenced production in 1947. The mine was previously owned by Falconbridge Limited and Pamour Resources Limited with its current owner Royal Oak Mines Inc. (Kirkland Washington) operating the facility since 1990. Several excellent descriptions of the operation are found in the literature covering the roasting and gas cleaning circuits. (L. Connell, B. Cross, Ref. 9 and references therein.). Additional information was supplied by Royal Oak personnel.

The ore was found to be refractory in that a considerable portion of the gold was locked in pyrite and arsenopyrite minerals and was not amenable to conventional cyanide leaching processes. Roasting operations commenced in 1949 with an Edwards type hearth roaster which was replaced in 1952 by a two-stage slurry roaster. In 1958 a larger two-stage fluid bed slurry roaster was installed with a baghouse for improved collection of arsenic. Mill tonnage approximated 1000 t/d with the flotation concentrate comprising the feed to the roasters.

Flotation concentrates are thickened to 75% solids and sprayed into the first stage of the roaster. Air is introduced through tuyeres at the bottom of the roaster to oxidize sulphide and sulphide-arsenide minerals at low oxygen partial pressures. At a temperature of 925^0 F, arsenopyrite is decomposed and most of the arsenic is volatilized as As_2O_3 . The roast is autogenous with no additional heat required. The first stage calcine is transferred to the second stage where the temperature is held at 925^0 F using spray water and additional air is supplied to oxidize sulphur associated with pyrite and other minerals.

6.2 Gas Cleaning Circuit

The gas cleaning circuit is shown in Figure 6-1.

The off-gas from the roasters is combined, cycloned to remove coarse particulate and then passed through an electrostatic precipitator (ESP). Arsenious oxide in the vapour state passes through the ESP at 600^0 F. The ESP is a Type K, rod curtain collector. The dust settles in the collection hoppers and is discharged by screw conveyors to the quench tank for subsequent gold recovery. Tail gas from the precipitator is cooled by dilution with ambient air causing arsenious oxide to condense as fine particulate from the gas phase. Up until 1977 the gas was cooled to 230^0 F which limited the As_2O_3 concentration in the vapour phase to about 15 mg/m^3. Since then the temperature has been lowered to about 220^0F, lowering vapour concentration of As_2O_3 to about 10 mg/m^3. The fluegas particulate stream is filtered in a Dracco baghouse to remove particulate As_2O_3. Each of the eight compartments contains 300, five inch diameter by 10 ft long filtration bags. Arsenic trioxide shaken from the bags is collected in V-shaped hoppers and discharged by means of 4 screw conveyors. The efficiency of particulate collection in the baghouse is dependant on several variables namely, bag quality, shaking cycle and maintenance of the system. A homopolymer Acrylic Dralon T bag has been used recently in the baghouse. In the early 1980's the shaking cycle was changed from a timed 45 minute control to a pressure drop control. When the pressure drop across the baghouse reaches 2 inches of water, the individual compartments are shaken in sequence. The frequency of shaking was reduced from 32 to 4 cycles per day, reducing the amount of fine As_2O_3 which passes through the bag during the shaking cycle. The filtered gas is drawn into a variable speed fan and discharged to the atmosphere via a 9 ft. diameter by 150 ft acid brick stack.

6.3 Arsenic Emission at Giant Yellowknife

Arsenic emission data and notes relating to specific tests are given in Appendix 2. Values obtained by Giant (Royal Oak) 1990-1993 show an average arsenic concentration of 25 mg/scm. Values reported by an independent contractor 1991-1993 average 24 mg/scm arsenic. The results show a normal variability which reflects the stack sampling variance and variance within the plant operations. The reported results of the 1983 EPS tests are an average of three tests, some on different days.

The standard reference method, used in most tests since 1983 is that published by Environment Canada; "Measurement of Emissions of Arsenic from Gold Roasting Operations, Report EPS 1-AP-79-1". Both particulate and gaseous arsenic are captured in the test train.

The emissions are dependant on two factors.

1. the concentration of arsenic in the gas phase
2. the concentration of arsenic as particulate.

Arsenic concentration in the gas phase passing through the baghouse is dependant on the gas temperature, approximating 7 mg/scm (10 mg As_2O_3/scm). Gas temperature control in the baghouse is via single thermocouple measurement and control of the incoming air damper. Variations of +/- 15^0 F are normal at the thermocouple which will cause vapour phase fluctuations in arsenic.

Arsenic in particulate form is dependant upon a number of physical and operating parameters. The quality and porosity of the filter bag, the frequency of shaking and the regular maintenance of the bags, detection of tears or pinholes all factor into the particulate emission. Given a vapour concentration of 7 mg As/scm and an average total emission of 24 mg/scm, a particulate value of 17 mg/scm appears reasonable.

The concentration of arsenic reported reflects an average value over the duration of the stack test (typically 160 min). This value will depend on the factors mentioned above. The sampling period may or may not include a bag shaking cycle.

6.4 Arsenic Control Strategies and Alternatives

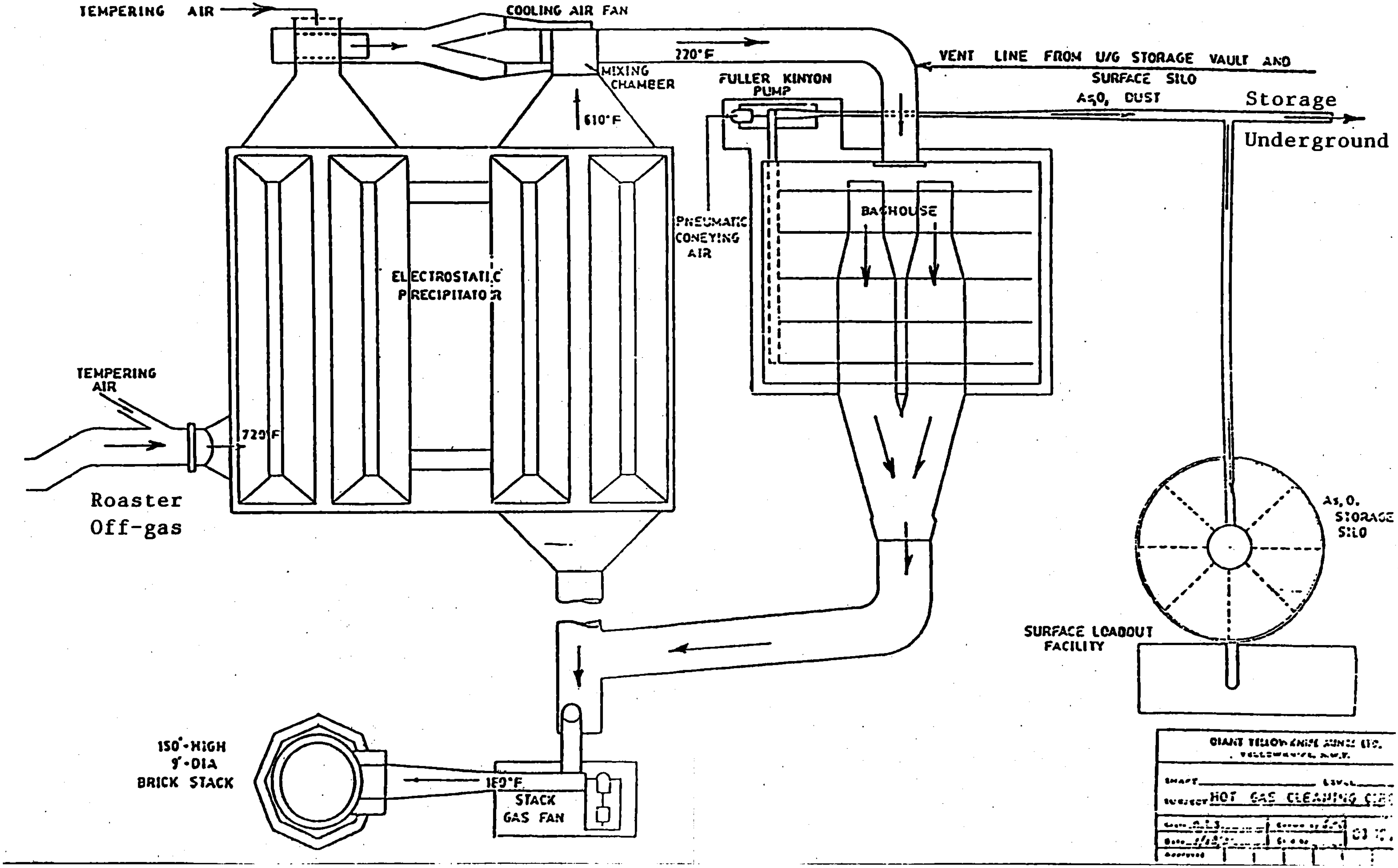
The present method of arsenic control has been documented. The major pieces of equipment and the method of control has not changed since the mid 1970's. No major piece of equipment has been changed or added to the gas cleaning process.

In our opinion, only minor improvements can be made to reduce arsenic emissions to the environment using the current equipment and control philosophy. With limitations on lowering temperature (SO_2 dew point) some minor modifications related to bag quality appear to be an option for increased particulate capture. Under present operating conditions, consistently meeting a stack concentration of 25 mg As/scm would be a challenge. With improvements in bag technology and management practices this may be reduced to 15-20 mg As/scm., but may require additional emission test work to confirm whether such values could be maintained on a consistent basis.

GAS CLEANING FLOWSHEET _ GIANT YELLOWKNIFE MINE

Figure 6-1

(Reference 9)



7.0 CAPITAL AND OPERATING COSTS FOR ARSENIC CONTROL OPTIONS

Section 4 outlined options for reducing arsenic emissions to atmosphere by adding a gas cleaning unit after the baghouse for roasting operations such as at Giant Yellowknife. The options investigated were wet scrubbing, wet electrostatic precipitating and activated carbon absorption. Capital and operating costs are summarized in Table 7-1. Applicable taxes and permits are excluded.

Wet Scrubbing

Turbotak Inc., of Waterloo Ontario, provided a conceptual scrubber design to reduce arsenic in the tail gas for a Giant Yellowknife type operation. The basis for the design is the flowsheet shown in Figure 7-1. The data for the baghouse exhaust gas condition was extracted from a recent report[71] from Giant Yellowknife. The estimated arsenic recovery is discussed in Section 4.

The scrubber consists of a number of high intensity sprays which knock out the arsenic by both cooling and scrubbing the gas. A layout sketch of the scrubber is shown in Appendix I as part of a preliminary proposal. The estimate includes a booster fan, stack liner, pumps and tanks needed to operate the scrubber. An enclosure is included for weather protection. The capital cost for the scrubber is shown as a factored type estimate shown in Table 7-2. The operating cost is shown in Table 7-3.

Turbotak would be prepared to demonstrate the scrubbing process by installing their pilot scrubber at site and operating it to determine the optimum scrubbing conditions for the process. Details of the pilot unit and a conceptual program are included in Appendix I.

Wet Electrostatic Precipitation

Environmental Corrections Inc.

Significant arsenic removal is possible using a combination of gas conditioning to transfer arsenic from the gaseous to solid phase followed by electrostatic precipitation. Estimated performance data is shown in Section 4. This combination of gas cleaning equipment is available from Environmental Corrections Inc. of Sun Valley, California. A description of the two stages is presented in Appendix I.

The estimate includes a booster fan, stack liner, pumps and tanks needed to operate the scrubber. An enclosure is included for weather protection. A capital cost for the wet electrostatic cleaning is shown as a factored type estimate in Table 7-4. Operating costs are shown in Table 7-5.

Biothermica Inc.

An alternative to the two staged unit available from Environmental Corrections Inc. is an integrated gas conditioner and electrostatic gas cleaner developed in France for municipal incinerators. The device is intended to clean up process gases that have been subjected to standard cleaning techniques. The design is by LAB Inc. (France) and is available in Canada from Biothermica Inc. in Montreal. The expected arsenic recoveries achievable using this approach were discussed in Section 4.

The estimate includes a booster fan, stack liner, pumps and tanks needed to operate the scrubber. An enclosure is included for weather protection. The capital cost estimated for a LAB Inc. unit at a Giant Yellowknife type operation is shown in Table 7-6. The associated operating cost is shown in Table 7-7.

Activated Carbon Adsorption

Activated carbon can be used to clean roasting tail gases of components such as arsenic trioxide. Biothermica offers a unit which is similar to the LAB Inc. unit but includes an additional scrubbing tower using a slurry containing activated carbon. This step increases the overall arsenic removal. However, the carbon is not easily regenerated hence there is an on-going need to provide make-up carbon. Details of the Biothermica equipment are shown in Appendix I. Table 7-8 shows the capital cost for installing an activated carbon scrubber as part of the LAB Inc. unit. Operating costs are shown in Table 7-9.

TABLE 7-1 COMPARISON OF TAIL GAS CLEANING OPTIONS

ITEM	UNITS	TURBOTAK SCRUBBER	ENV. CORR. MIST PPT.	BIOTHERMICA LAB PROCESS	BIOTHERMICA OPTION 3 PLUS CARBON ADSORBTION
EQUIPMENT DESCRIPTION		Scrub., Ancil. Tks, Pumps, Fan, Mech. Mist Elim., Stack Liner	Scrub., Ancil. Tks, Pumps, 4 Mist Ppt, Fan, Stack Liner	Scrub., Ancil. Tks, Pumps, Mist Ppt, Fan, Stack Liner	Scrub., Ancil. Tks, Activated carbon Scrb., Pumps, Mist Ppt, Fan, Stack Liner
ARSENIC REMOVAL	%	90	95	90	>90
CAPITAL COST INSTALLED	C$ thous	1,181	2,016	2,044	2,206
OPERATING COST	C$ thous Per Annum	198	168	169	206
OPERATING COST	C$ Per Kg As Captured	69	55	59	72

TABLE 7-2

CAPITAL COST ESTIMATE - OPTION 1
TURBOTAK SCRUBBING

		thous. $
1	Purchased equipment costs (supplier quotes)	374
2	Equipment installation (include freight and taxes)	56
3	Process piping (include materials and labour)	150
4	Electrical (include materials and labour)	40
5	Instrumentation	40
6	Process buildings (include mechanical services and lighting)	60
7	Auxiliary buildings (include mechanical services and lighting)	nil
8	Plant services (include water, sewers, compressed air etc.)	50
9	Site improvements	nil
10	Field expenses (related to construction management)	25
11	Project Management (include engineering and construction)	150
12	Contingency (20 %)	236
13	Total Capital Cost	1181

TABLE 7-3

DIRECT OPERATING COSTS - OPTION 1
TURBOTAK SCRUBBING

ITEM	UNITS	ANNUAL $	COST/kg As
OPERATING			
MANPOWER	0.25 Men/Shift	20000	
ELECTRICITY (pumps etc.)***	0.1 $/kWh	33600	
COMPRESSED AIR **	500 cfm	71400	
WATER *	25 L/min Evap.	0	
CONSUMABLES water conditioning	allowance	25000	
MAINTENANCE			
MANPOWER	1.5 % Capital	18000	
SUPPLIES	1.5 % Capital	18000	
TAILINGS DISPOSAL	Existing	0	
INSURANCE (1% capital)		12000	
TOTAL		198000	69.20

* Water required totals 45 USGPM.

** Compressed air requires 85 kW at $0.1/ kWh.

*** Booster fan, pumps and heat tracing allowance of 40 kW

TABLE 7-4

CAPITAL COST ESTIMATE - OPTION 2 ENVIRONMENTAL CORRECTIONS WET PRECIP.

		thous. $
1	Purchased equipment costs (supplier quotes)	828
2	Equipment installation (include freight)	150
3	Process piping (include materials and labour)	150
4	Electrical (include materials and labour)	120
5	Instrumentation	80
6	Process buildings (include mechanical services and lighting)	60
7	Auxiliary buildings (include mechanical services and lighting)	nil
8	Plant services (include water, sewers, compressed air etc.)	50
9	Site improvements	nil
10	Field expenses (related to construction management)	25
11	Project Management (include engineering and construction)	150
12	Contingency (20 %)	403
13	Total Capital Cost	2016

TABLE 7-5

DIRECT OPERATING COSTS - OPTION 2
ENVIRONMENTAL CORRECTIONS WET PRECIP.

ITEM	UNITS	ANNUAL $	COST/kg As $/kg
OPERATING			
MANPOWER	0.25 Men/Shift	20000	
ELECTRICITY	0.1 $/kWh	60000	
COMPRESSED AIR	50 cfm	7000	
WATER	free issue	0	
CONSUMABLES	water conditioning	0	
MAINTENANCE			
MANPOWER	1.5 % Capital	30300	
SUPPLIES	1.5 % Capital	30300	
TAILINGS DISPOSAL	Existing	0	
INSURANCE (1% capital)		20000	
TOTAL		167600	55.44

TABLE 7-6

CAPITAL COST ESTIMATE - OPTION 3 BIOTHERMICA WET PRECIP.

		$ (thous.)
1	Purchased equipment costs (supplier quotes)	850
2	Equipment installation (include freight and taxes)	150
3	Process piping (include materials and labour)	150
4	Electrical (include materials and labour)	120
5	Instrumentation	80
6	Process buildings (include mechanical services and lighting)	60
7	Auxiliary buildings (include mechanical services and lighting)	nil
8	Plant services (include water, sewers, compressed air etc.)	50
9	Site improvements	nil
10	Field expenses (related to construction management)	25
11	Project Management (include engineering and construction)	150
12	Contingency	409
13	Capital cost Total	2044

TABLE 7-7

DIRECT OPERATING COSTS - OPTION 3
BIOTHERMICA WET PRECIP.

ITEM	UNITS	ANNUAL $	COST/kg As
OPERATING			
MANPOWER	0.25 Men/Shift	20000	
ELECTRICITY	0.1 $/kWh	60000	
COMPRESSED AIR	50 cfm	7000	
WATER	free issue	0	
CONSUMABLES	water conditioning	0	
MAINTENANCE			
MANPOWER	1.5 % Capital	30660	
SUPPLIES	1.5 % Capital	30660	
TAILINGS DISPOSAL	Existing	0	
INSURANCE	1% Capital	20400	
TOTAL		168720	58.91

TABLE 7-8

CAPITAL COST ESTIMATE - OPTION 4
BIOTHERMICA ACTIVATED CARBON ADSORPTION

		$ (thous.)
1	Purchased equipment costs (supplier quotes)	925
2	Equipment installation (include freight and taxes)	170
3	Process piping (include materials and labour)	170
4	Electrical (include materials and labour)	125
5	Instrumentation	85
6	Process buildings (include mechanical services and lighting)	65
7	Auxiliary buildings (include mechanical services and lighting)	nil
8	Plant services (include water, sewers, compressed air etc.)	50
9	Site improvements	nil
10	Field expenses (related to construction management)	25
11	Project Management (include engineering and construction)	150
12	Contingency (20%)	441
13	Total Capital Cost	2206

TABLE 7-9

DIRECT OPERATING COSTS - OPTION 4 BIOTHERMICA CARBON ADSORBTION

ITEM	UNITS	ANNUAL $	COST/kg As
OPERATING			
MANPOWER	0.25 Men/Shift	20000	
ELECTRICITY	0.1 $/kWh	63000	
COMPRESSED AIR	50 cfm	7000	
WATER	free issue	0	
CONSUMABLES	carbon	50000	
MAINTENANCE			
MANPOWER	1.5 % Capital	33090	
SUPPLIES	1.5 % Capital	33090	
TAILINGS DISPOSAL	Existing	0	
INSURANCE	1% Capital	22000	
TOTAL		206180	72.00

8.0 CONCLUSIONS

Roasting technology for treating refractory gold concentrates has be practiced for over 50 years. Fundamental conditions associated with gas cleaning operations determine the extent to which arsenic can be recovered from the off-gas discharged to the environment.

New technologies have been developed which can further reduce arsenic air emissions.. The new technologies are available as a result of continued demand for improved environmental emission controls. A number of new roasting plants have been commissioned in the last 10 years, providing an effective route to gold recovery and meeting stricter environmental regulations.

It is possible to use existing technologies to achieve roasting tail gas cleaning. These processes can significantly reduce arsenic emissions to atmosphere and require modest capital expenditures. Operating costs are also modest and would include the marginal cost associated with operating existing tailings disposal facilities.

Alternative pre-treatment processes which could replace roasting are commercially available and would curtail atmospheric emissions. Installation of one of these process would require significant capital expenditures and operating costs at least as expensive as those associated with roasting. These processes would also require significant development to ensure that concentrates, such as those from an operation such as Giant Yellowknife, could be successfully treated for acceptable gold recovery.

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APPENDIX 1

SUPPLIER QUOTATIONS

Turbotak Canada Inc.
Air Pollution Control Systems

550 Parkside Drive
Suite A-14
Waterloo, Ontario
N2L 5V4
Tel: (519) 885-5513
Fax: (519) 885-6992

Preliminary Proposal

No. SPC96-183

Project: J.A. Kurtis & Associates
140 Mavety ST.
Toronto, ON
M6P 2L9

Date: January 19, 1996

Ref: Giant Yellowknife

All applicable taxes, duty and brokerage fees are extra.
F.O.B.: Waterloo, Ontario.
Freight will be charged to client at cost.
Shipment: 16 weeks from receipt of drawing approval.
See Terms and Conditions attached.

<u>Terms</u>:
25% with purchase order
75% on delivery of equipment

For the <u>DESIGN AND SUPPLY ONLY</u> of one (1) Turbotak Scrubber System

TOTAL BUDGET PRICE $248,800.00

The quoted price above is budgetary only and is subject to change at any time without notice.

Reviewed by:

R.A. Allan, P.Eng.
Vice President Engineering

Prepared by:

Carl Bender
Proposals Coordinator

Turbotak Air Pollution Control Systems

Suite A-14, 550 Parkside Drive
Waterloo, Ontario, CANADA, N2L 5V4
tel 519-885-5513, fax 519-885-6992

FAXED
DATE: ....
TIME: ....

TO:	J.A. Kurtis & Associates		
ATTENTION:	Allan Kurtis		
FAX #:	416 763 6012	**DATE:**	January 17, 1996
FROM:	Egbert van Everdingen	**TOTAL PAGES:**	
SUBJECT:	Tail gas scrubber for Giant Yellowknife Project		

Dear Sir,

Attached is our proposal for the Giant Yellowknife project for controlling arsenic emissions, and for a pilot scale test. The scrubber quoted is based on supply of a typical particulate/acid gas scrubber; actual design would be based on results of a pilot test, as discussed with Bob Allan. A field pilot program would require 1-2 weeks on site to collect operating data (scrubbing liquid & energy consumption, attainable removal efficiency, etc.), and would cost in the order of $50,000.00. Please review the enclosed and call if you have any further questions.

Regards,

No.: SPC96-183

Scrubber Operating Data

Inlet Gas Conditions

Gas Volume (ACFM)	36,619
Gas Temperature (°F)	220
Gas Humidity (% v/v)	5
Particulate Concentration (mg/Nm^3)	10
SO_2 Concentration (ppmv wet)	12,500

Expected Outlet Gas Conditions

Gas Volume (ACFM)	32,005
Gas Temperature (°F)	109
Gas Humidity	saturated
Particulate Concentration (mg/Nm^3)	1
SO_2 Concentration (ppmv wet)	TBA

Operating Parameters

Pressure Drop Across Scrubber ("H_2O)	2.5
Total Liquid Flow Rate to Scrubber (USgpm)	
- Evaporative Loss	6.5
- Scrubbing Liquid	38
Liquid Flow Rate to Entrainment Separator	16
Design Compressed Air Consumption (SCFM)[1]	415
Fan Horsepower (BHP)	

---

[1] To be optimized during scrubber commissioning.

Supply

Mechanical Supply

The scrubber system will consist of the following components:

One (1) **Particulate Removal/Gas Contacting Chamber**
- 316L stainless steel construction
- internal baffle plate
- bolted inspection hatch
- integral slurry tank
- flanged for connection to duct from process and to scrubber inlet duct
- nozzle ports for mounting Turbotak nozzles

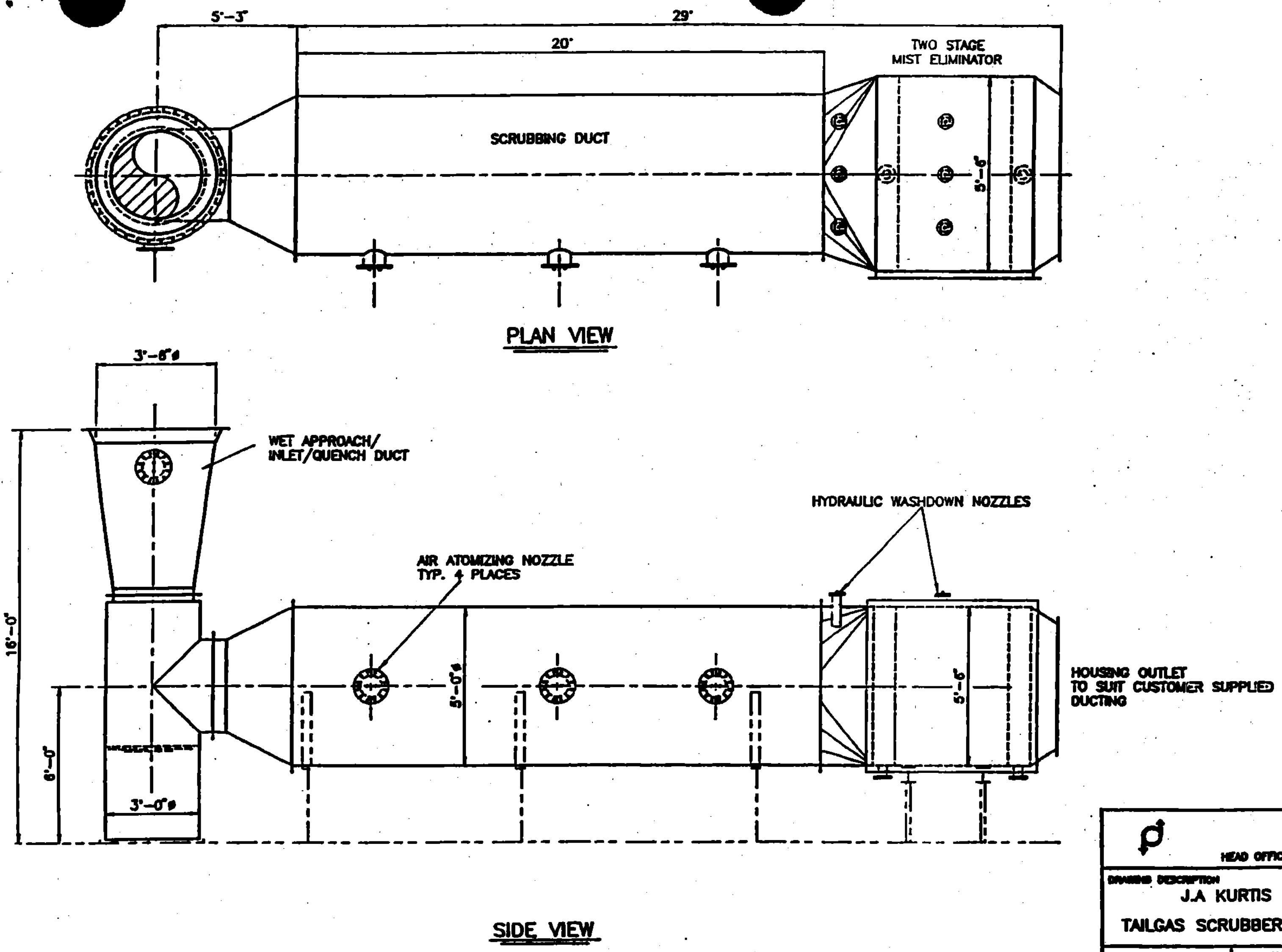
One (1) **Scrubber Duct**
- 316L stainless steel construction
- flanged at both ends
- bolted inspection/access hatch
- nozzle ports for mounting Turbotak nozzles

Turbotak Air Atomizing Nozzles
- 316L stainless steel construction
- mounted in scrubber inlet duct and contacting chamber inlet and outlet ports
- internal piping included

One (1) **Entrainment Separator Housing**
- 316L stainless steel construction
- internal banks of entrainment separation media
- spray bars with hydraulic spray nozzles
- bolted access hatch
- bottom drain connections

One (1) **Scrubber Control System** - to regulate compressed air and liquid flows to scrubber nozzles and water flow to entrainment separators. The following equipment will be pipe mounted for location at nozzle ports:
- magnetic flowmeters for flow indication to each nozzle
- compressed air regulators with gauges for air pressure control
- individual manual shutoff valves for liquid and air to each nozzle and entrainment separator
- individual manual throttling valves for liquid flow control
- stainless steel piping for air and liquid lines

Two (2) **Operating and maintenance instructions for each scrubber**, including parts lists, start-up and shut-down procedures.



TURBOTAK

HEAD OFFICE – WATERLOO,ONTARIO,CANADA

DRAWING DESCRIPTION

J.A KURTIS – GIANT YELLOWKNIFE

TAILGAS SCRUBBER SYSTEM – GENERAL ARRANGEMENT

DRAWN: JHM	DATE: JAN10/96	SCALE: NONE	SHT 1 OF 1
CHKD:	DATE:	APPRD:	DATE:

ACAD FILE No. 961831.dwg	DWG. No. SPC96–183–01	REV. A
PLOTTING: 1=48		

A		ISSUED FOR GENERAL INFORMATION ONLY
EV.	DATE	DESCRIPTION

BIOTHERMICA

Montreal, January 31, 1996

Mr Allan Kurtis
J.A. KURTIS & ASS.
140 Mavety Street
Toronto, Ontario
M6P 2L9

fax: (416) 763.6012
tel: (416) 763.4230

REF: Gas scrubbers for Giant Yellowknife Project

OBJECT: Preliminary process and budget price

Dear Sir,

As per your request and our recent phone conversation, we are proposing the following solution:

An EDV Spray Tower operated at a low pH for quenching and absorption of As_2O_3. The acidity of the scrubbing liquid would be brought by partial capture of SO_3. If this is not sufficient, acid addition may be needed.

The EDV Scrubber is a proprietary technology from LAB INC, France, that we commercialize in Canada. The particularity of the scrubber is its very high efficiency for fine particles, its low energy consumption and it is virtually impossible to plug.

For this application, a total pressure drop is expected to be in the magnitude of 8 in w.g. The system would also include the LAB droplet separator.

As we have no similar installation in this process (LAB has many installations in chemical processes very close to that one) we suggest to make a small pilot test on the actual installation. The expected outlet concentration of As_2O_3 is 1.0 mg/Nm^3 but the pilot test would confirm the outlet guaranteed concentration.

This pilot test would cost about 150,000 $ to 200,000 $ US dollars.

.../2

The total cost ot the final solution is estimated at 500,000 $ to 1,500,000 $ US dollars depending on the:

- need to put a new I.D. fan
- need to put a new stack
- need to treat the SO_3 more effectualy
- need to provide on acid supply system.
- need to add air electric filtering element

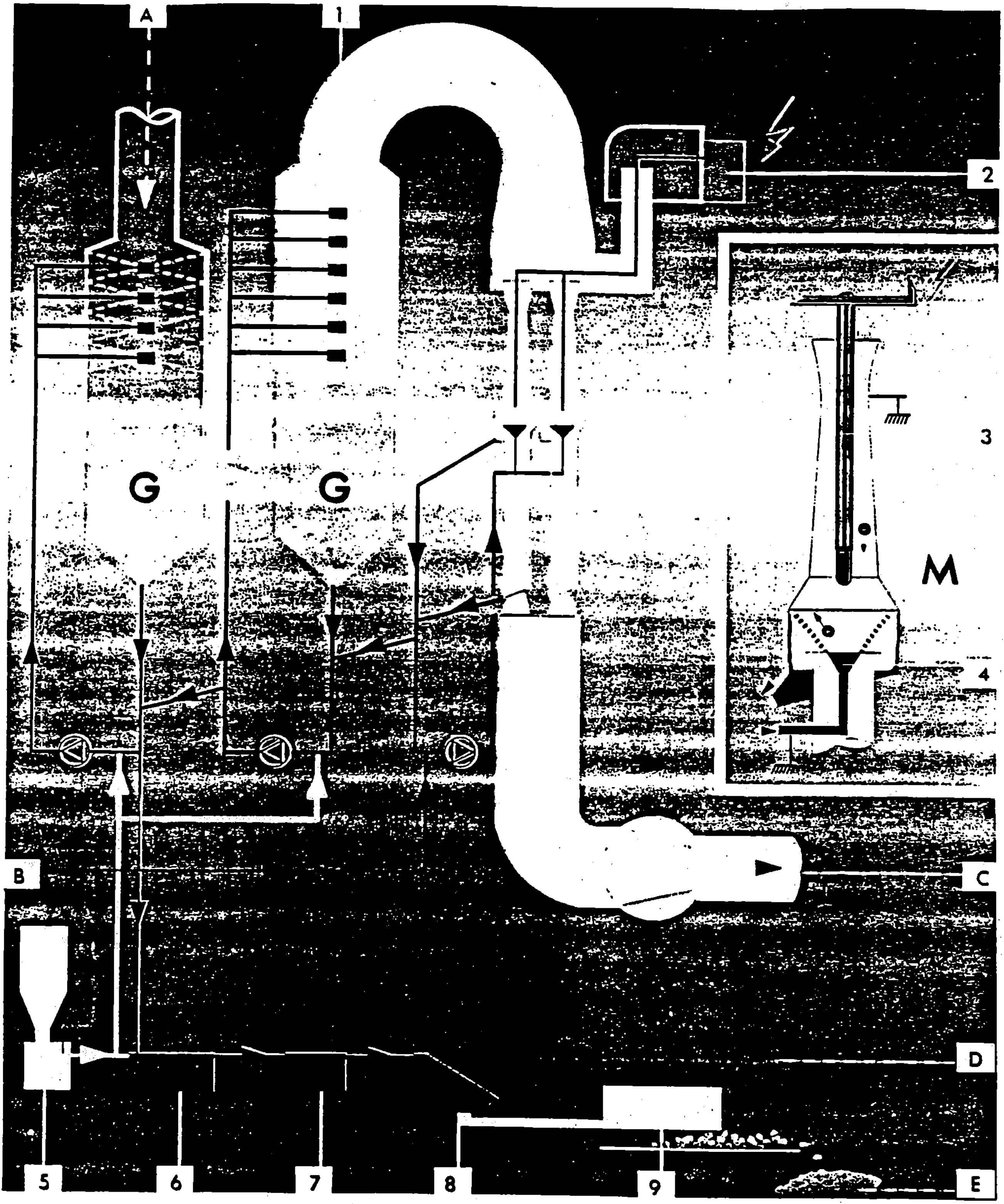
The time frame for the project is as follows:

- pilot testing: next summer/fall
- final solution: summer 1997

Hoping this to be satisfactory.

Gerard Goseelin, P.Eng.,
Vice-president

GG/mco



G GRANILAB
M MODULE

A Gaz brut
B Eau neuve
C Gaz épuré
D Eau claire
E Gâteau

1 Pulvérisateur LAB - G
2 Alimentation H.T.
3 Electrode H.T.
4 Pulvérisateur LAB - F

5 Préparation neutralisant
6 Neutralisation
7 Floculation
8 Décantation
9 Déshydratation

ENVIRONMENTAL CORRECTIONS, INC.
11285 PENROSE STREET • SUN VALLEY, CALIFORNIA 91352 • (81
(213
FAX (213) 87

QUOTATION

Date February 1, 1996

Quotation No. Q-96-02-01

J.A. KURTIS & ASSOCIATES
140 Mavery St.
Toronto Ontario, M6P 2L9
Canada

PROJECT: GREAT YELLOWKNIFE

(416) 763-4230 fax (416) 763-6012

Your Inquiry No. your letter d
Jan. 05/96

In response to your inquiry, we submit the following quotation: (See Terms & Conditions on Reverse Sic

QUANTITY	DESCRIPTION	PRICE
	Environmental Corrections, Inc. is pleased to bid the manufacturing and supplying of the following:	
4	ESP units for efficiency of 95%	488,000.0
6	ESP units for efficiency of 98%	692,000.0
1ea.	Pretreated Scrubber and Fan (no Duct)	52,700.00
	A) Specification -- 29000 SCFM B) Customer to install E.C.I. to supervise C) All FRP construction	
	(Drawings and full proposal to follow)	
	Tax Not Included in Quoted Price	

TERMS	F.O.B.	ESTIMATED SHIPPING DATE
1/3 down, net 30	Sun Valley	10 weeks

By

APPENDIX 2

GIANT YELLOWKNIFE STACK EMISSIONS

ARSENIC EMISSIONS FROM GIANT MINE ROASTER
RESULTS OF STACK TESTING

DATE		EMISSION RATES				FLOW	TESTER
		TOTAL		PART.	VAPOUR		
		(mg/cu m)	(kg/day)	(mg/cu m)	(mg/cu m)	(cu m/h)	
May 27	1981	6.7	8.8	0.1	6.6	54,500	Giant
May 28	1981	6.7	7.5	0.3	6.4	52,500	Giant
June 24	1981	4.4	6.5	1.1	3.3	61,300	Giant
July 14	1981	5.5	8.3	2.2	3.3	63,200	Giant
July 31	1981	5.8	8.1	N/A	N/A	58,400	Giant
* August 7	1981	18.4	27.2	18.1	0.3	61,500	Giant
August 20	1981	18.9	24.0	N/A	N/A	53,000	Giant
August 21	1981	9.3	11.2	N/A	N/A	50,100	Giant
August 25	1981	14.1	17.3	N/A	N/A	51,000	Giant
** Dec. 15	1982	10.2	13.2	0.1	10.1	54,200	Giant
July 5	1983	15.8	17.0	N/A	N/A	44,900	EPS
July 7	1983	19.0	21.8	N/A	N/A	47,700	EPS
July 8	1983	37.0	40.8	N/A	N/A	46,000	EPS
July 11	1983	29.7	28.1	N/A	N/A	39,400	EPS
July 12	1983	23.0	25.7	N/A	N/A	46,400	EPS
July 13	1983	25.3	28.8	N/A	N/A	47,400	EPS
** Nov. 19	1985	14.4	27.1	5.5	8.9	78,000	Giant
Nov. 18	1986	16.3	24.3	1.5	14.8	62,000	Giant
Sept. 28	1988	158.1	185.0			48,800	Giant
Oct. 5	1988	198.8	232.8	60.2	138.6	48,600	Giant
** Oct. 11	1989	24.0	26.4	2.3	21.7	45,300	Giant
** August 17	1990	34.3	37.1	2.3	32.0	45,000	Giant
** June 24	1991	16.3	15.2	0.5	15.8	38,700	Giant
*** August 29	1991	[illegible]	59.0	N/A	N/A	95,000	Contractor
October 30	1991	23.0	25.9	N/A	N/A	46,900	Contractor
October	1993	23.0	29.2			39,900	Giant
Sept. 13	1995	[illegible]	3.2	N/A	N/A	45,000	Contractor

* These values for arsenic in Particulate and Vapour may have been switched in the report from Giant.

** The results of these tests are suspect because Giant did not follow the EPS protocol for sampling.

*** Giant disputes these results for daily mass emissions and stack flow. They believe that the contractor erred by a factor of two.