LCD, low-temperature soldering and compound semiconductor: The sources, market, applications and future prospects of indium in Malaysia

by

Foo Nun Yong

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University of Malaya

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Signature of Author ....
Department of Materials Science and Engineering
August 11, 2006

Certified by ....
Thomas W. Eagar
Professor of Materials Engineering and Engineering Systems
Thesis Supervisor

Accepted by ....
Samuel M. Allen
POSCO Professor of Physical Metallurgy
Chair, Departmental Committee on Graduate Students

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ABSTRACT

Indium is a minor but very valuable metal. Decreasing supplies of indium from refining and increasing demands from LCD, low-temperature soldering and compound semiconductors have stimulated the indium price increase dramatically. Traditionally, indium is refined as a by-product of zinc refining. However, this type of indium extraction method is expected to last for the next 10-20 years and this opens a window to extract indium from other ores, especially from tin ore. Interestingly, extraction of indium from tin circuit can be considered as the major business and the pure tin metal is just considered as a by-product due to high indium price and low tin price. Relatively high estimated concentration levels of indium in Malaysian tin ore means that Malaysian tin refiners can withstand high degree of fluctuation of price in the free market due to hedge buying and speculation. Note that the business model for global indium market is duopoly or oligopoly but obviously not monopoly. Between duopoly and oligopoly, the most probable model is oligopoly. Thus, the potential competitors and partnership are also discussed here. Besides, LCD and low-temperature soldering and compound semiconductor are three main applications of indium which affect the indium price. The unique properties of indium for three major applications will be discussed from the material engineering prospective. A cost modeling spreadsheet has been built to estimate the cost of production of indium from tin and zinc ores under different conditions. Hence, the decision tree has been drawn based on the conditions of different indium concentration level and price. From the discussions on the sources, market, applications of indium, the future prospects for indium can be concluded. The outcomes of this work can be extended to cases outside of the geographical boundary of Malaysia by gathering some relevant information.

Thesis Supervisor: Thomas W. Eagar
Title: Professor of Materials Engineering and Engineering Systems

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Chapter 1: Introduction

1.0) Overview

Indium is an element from group III in the periodic table. It was discovered by two German chemists, Fernard Reich and Theoder Richter. The symbol for indium is **In** and its atomic number is 49. The orbital electronics configuration and orbital radii are (Kr)$5s^2 4d^{10} 5p^1$ and 13.82nm respectively. It is a rare, silvery-white, soft metal which physically looks like zinc and is chemically similar to aluminum. Indium has high ductility, high thermal conductivity and is a good electrical conductor. The boiling point of indium is much higher than the melting point. This feature can be used for extraction and refining of indium. At room temperature, pure indium will not react with oxygen or air. Besides, its level of toxicity is relatively low compare to many common metals. Some chemical properties are listed as below:

Property	Value
Density	7.30 g/cm^3
Atomic weight	114.82
Melting point	156.61^{0}C
Boiling point	2080^{0}C
Electronegativity	1.7
Specific heat	0.233 J/(g*K)
Isotopes	In^{115}(95.67%) In^{113}(4.33%)
Coefficient of linear expansion	24.8x10^{-6} ^{0}C^{-1}
Spectral wave lengths	λ_{In} = 451.14nm; 410.18nm
1st ionization potential	5.786eV

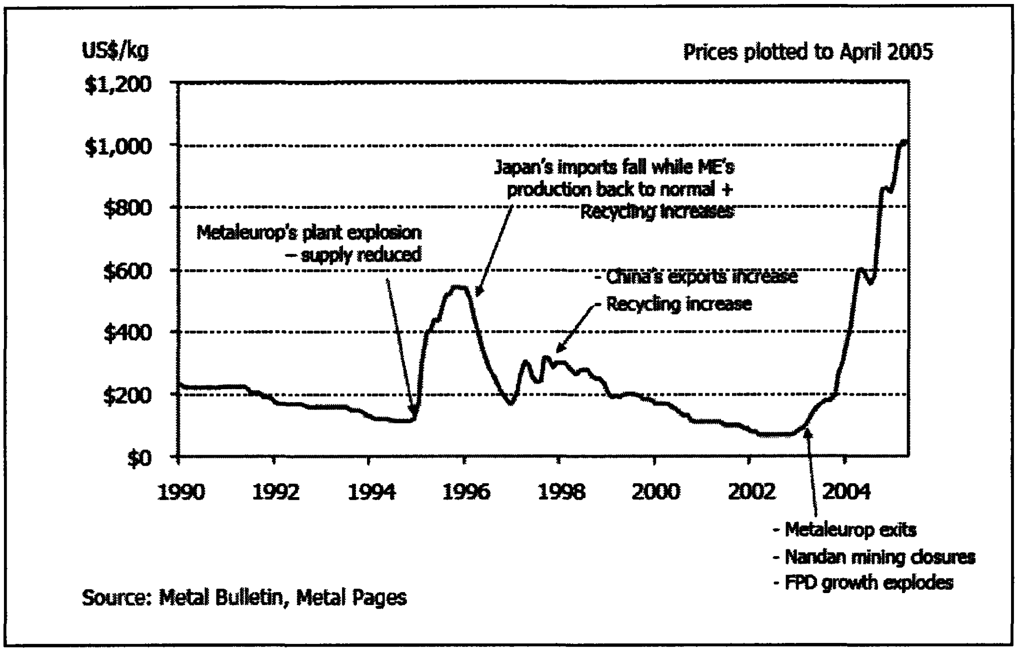
Table 1.1: Some chemical properties of indium

Currently, the world indium reserves are predicted by the estimation of the indium content of zinc reserves. [40, 41] The world reserve base for indium was estimated about 6000 tons in 2003. [24] These estimated reserves are expected to last about ten years under current trend of indium consumption. According to the Indium Corporation of

America, this estimation may be 3 times less than the actual indium reserve since the presence of indium in the tin, copper, lead and other ores are not taken into account. China refines indium more than other countries and Canada has been estimated as the world largest indium reserve country. The wide variety of size, structural styles and complex mineralogical intergrowths, which make the metal recovery more difficult and require advanced leaching techniques are the major barriers to determine the worldwide potential indium reserve.

About 70 percent of the world indium production has been used for display screen coating in 2005. The worldwide estimated indium consumption for low temperature melting point alloys and solders was 20 tons in year 2000. [40,41] It is expected the indium demands from the electrical and electronic companies will be increased because the European Union prohibited lead in electrical and electronic applications from July 1, 2006. Indium alloys are a good substitute for lead in low temperature soldering. In 2003, indium sold for about $320/kg. It is expected the price will be increased gradually because the demands are expected to increase. "Consumption of primary indium is expected to grow at around 4% per annual, whereas the growth in consumption of secondary material will increase by almost 19% per annual." [43] Meanwhile, according to the US Geological Survey Minerals Yearbook 2003, the demand for indium is projected to be 660 tons in 2006.

Indium price from 1990 to April 2005 is shown in the Fig 1.1. Indium was sold below USD 400/kg from 1990 to 2004, except for 1996. In 1996, the indium price had exceeded USD 500/kg because of supply of indium decreased due to the explosion of the Metaleurop's plant in 1995. However, Japan reduced its indium imports, recycling activities for indium increased and the indium production recovered to normal are the main driving force that causing indium price decreased. In 1998, indium price was further dropped since export of indium from China increased and the more indium had been recycled. In 2003, Metaleurop had exit from its indium extraction and Nandan mining had closed. Besides, the demands for liquid crystal display (LCD) and flat panel displays (FPDS) increased rapidly. All these factors stimulated indium price and indium was sold more than USD 1000/kg in 2005.



Source: Metal Bulletin, Metal Pages

Fig 1.1: Fluctuation of indium price from 1990 to April 2005 and some important factors affect its fluctuation

The demands for indium are expected to increase rapidly in the near future because many applications seem to rely on this metal. Indium tin oxide (ITO) coatings are used for making liquid crystal display (LCD), laptop computers and flat panel displays (FPDS). Indium is also applied to organic Light Emitting Diodes (LED). The indium coating can reflect the infrared light and reduce the rate of heat transfer in the glass. For low temperature soldering, alloys with indium give a lower range of soldering temperature. Indium also has some applications in the alkaline batteries, dental alloys, and nuclear control rods. Some applications are found in making photodiodes, laser, and optical communication systems. Interestingly, less than 55 cents out of $3000 is spent for indium material in making a 32-inch LCD screen. [4, 5] Thus, there is ample room for manufacturers to absorb expected price increases for indium. Now, the manufacturers are more concerned about the sustainability of the indium supply. Some substitutions for indium are suggested. For example, copper, tin and zinc are the compounds tested to substitute Indium-Tin-Oxide (ITO). However, the performance of the substitute has much poorer performance than the performance of indium. In other words, indium has very attractive advantages in these applications, compared to other elements.

The commercially available forms of indium in the market are powder, ingot, ribbon, wire, shot, plates and pellets. The currently commercial available compounds are Alkyls trimethyl indium [$In(CH_3)_3$], triethyl indium [In ($C_2H_5)_3$], triethyl indium [In ($C_6H_5)_3$], indium dichloride [$InCl_2$], indium hydroxide indium [$In(OH)_3$], indium nitrate [$In(NO_3)_3$], Indium oxides [In_2O_3, In_2O, and InO], indium phosphate [$InPO_4$], indium sulfide [In_2S_3], indium tricholoride [$InCl_3$], and indium trisulfide [$In_2(SO_4)_3$]. [34]

"Indium deposits encompass many different types of ore deposits, including volcanic- and sediment-hosted exhalative massive sulfide deposits, epithermal deposits, polymetallic base vein deposits, granite-related tin base metal deposits, and skarn deposits." [39] However, indium is mostly extracted from the sphalerite, a zinc-sulfide ore mineral. Only 1 part per million to almost 900 parts per million indium can be obtained from zinc ores. [25] Tin tungsten and coal may contain some level of indium content. However, less effort has been put into the extraction of indium from these ores because they are too costly and face technological constraints. Besides, indium also occurs in copper, lead and to a lesser extent in silver, cadmium and bismuth ores. [41] The minerals that can be found in Malaysia are tin, zinc, copper, silver, lead, tungsten, iron ores, antimony, zirconium, tantalum, mica, gold, barite, limestone, rare earths, bentonite, clays, coal, natural gas, crude petroleum, feldspar and thorium. [28] Thus, indium may occur in the tin, zinc, copper, silver, lead and tungsten cores in Malaysia's mines.

Indium can be obtained by primary production and recycling from the scrap. Normally, indium production in the world depends on the refining of the by-product of zinc ores and recycling from the scrap. However, much of the indium production in Russia is refined from tin cores. Russia also produces indium from zinc and copper mining. The tin reserves in Malaysia have been estimated as the world's second largest [40, 41, 46] and could potentially provide a significant source of indium. Tin contributed $289 million out of total export of major mines of $424 million in 2004. Note that the methods for tin production in Malaysia are gravel pump, open cast, re-treatment plant, dredging, panning and underground.

1.1) Motivation for the work

It is interesting to know how many indium reserves are in Malaysia. We know that indium is the by-product of tin, zinc, copper, silver, lead and tungsten ores and Malaysia has all these elements in its mines. Thus, it is reasonable to estimate Malaysia has some indium reserves. Traub & Moh had traced out relatively high level of indium in the Malaysian tin ore and published their paper in the third regional conference on geology and mineral resources of Asia on 1987. Thus, the second question we would like to know is whether it is economical to refine this valuable element in Malaysia. This project can draw the attention of the local authorities and investors around the world if Malaysia can contribute to world production of indium in the near future. In this work the world supply and demand chains and other factors that affect the prospects of indium will be provided.

1.2) Organization of the work

In this project, the sources of indium from the primary and secondary production and reserves will be outlined. This will be compared to other potential indium-contained mining in Malaysia and more attention will be given to the indium content in tin mining in the Chapter 2. The local industry demand and international market for indium will be analyzed and compared in Chapter 3. Meanwhile, different potential applications of indium and its compound in various areas will be summarized. Besides, the extraction and refining technologies will be discussed in the Chapter 4. The cost modeling for indium production for tin and zinc circuit in Malaysia will be figured out in the Chapter 5. Market analysis and a business model will be discussed in Chapter 6. Some other important issues related to indium like mining policy, lease application, mining works force, recycling and environmental, health and safety will be discussed in the Chapter 7. Finally, the significant applications and future prospects of indium in Malaysia will be discussed in the last chapter.

Chapter 2: Analysis on the potential indium-contained ores in Malaysia

2.0) Introduction

The Minerals industry in Malaysia can be divided into three groups, which are metallic, non-metallic and energy minerals. The main metallic minerals are tin, gold, bauxite, iron-ore and limonite. Limestone, clays kaolin, silica, sand and gravel, aggregates, feldspar and mica are the major non-metallic minerals. Coal is the only energy mineral. In 2004, the value of mineral production has been estimated to be RM2.23 billion, compared to RM 4 billion in 2003. [19] In other words, about 7.0 % of the rate of growth of gross domestic product (GDP) of Malaysia in 2004 was derived from the mining sector and 95% of the contribution was mainly from the oil and natural gas sector. [28] Domestic mineral production in 2004 experienced a drop of 13 per cent of total minerals output, compared with RM2.21 billion in 2003. Meanwhile, metallic minerals production in 2004 contributed 18 per cent share of the total mineral production value. Thus, the mining and quarrying sectors experienced growth of 4.1 per cent in 2004 due to higher production of crude oil and natural gas.

Before further discussion about the estimation of indium in mineral ore, it's important to have some idea how indium exists in nature. In natural systems, indium has a tendency to form compounds with other base metals, like copper and silver from Group I, zinc and cadmium from Group II, tin and lead from Group IV and bismuth from Group V in the periodic table. At the same time, indium is normally considered not a common rock-forming mineral because it is a mineral that is commonly included with the principal mineral or occupies a lattice site in a crystal. It is noted that indium-bearing deposits are generally found in the cal-alkaline, porphyritic felsic to intermediate volcanic and intrusive host rocks. Thus, several common alteration processes like silicafication, sericitization, chloritization and greisenization normally take an important role in the formation process of indium-bearing minerals. [39]

Table 2.1 shows the range of indium content in different types of minerals, and the chemical notation of their composition. The highest indium possible is found in the tin ore (cassiterite). In general, high indium concentration could be found in the cassiterite, sphalerite, chalcocyrite, and stannite. However, some types of minerals contain less than 100ppm indium. They are arsenopyrite, chalcocite, enargitee, pyrite and wolframite. Thus, it is rare to observe minerals at these trace levels using an electron microprobe.

Mineral	Composition	Indium content, ppm	Substituted by Indium
Arsenopyrite	FeAsS	0.3-20	-
Bornite	Cu_5FeS_4	1-1000	-
Cassiterite	SnO_2	0.5-13500	(Sn), Fe
Chalcocite	Cu_2S	0-100	-
Chalcopyrite	$CuFeS_2$	0-1500	Fe, Cu
Covellite	CuS	0-150	-
Enargite	Cu_3AsS_4	0-100	Cu, As
Galena	PbS	0.5-100	-
Pyrite	FeS_2	0-50	-
Sphalerite	(Zn,Fe)S	0.5-10000	Zn,Fe
Stannite	Cu_2FeSnS_4	0-1500	Sn,Fe
Tetrahedrite	$(Cu,Fe)_{12}Sb_4S_{13}$	0.1-160	Cu, Sb, (As)
Wolframite	$(Fe,Mn)WO_4$	0-16	-

Table 2.1: The range of indium content in different types of indium-bearing minerals and substituted elements. Source: pg158, Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14, VCH and Ulrich Schwarz-Schampera &Peter M. Herzig, Indium Geology, mineralogy, and economics, Springer

2.1) Estimation of the composition of indium in tin ores

From Table 2.1, we know that tin ores may contain the highest concentration of indium, compared to other types of ores. Vein stockwork deposits of tin contain the highest known concentrations of indium. It is rare to extract indium from tin deposits except in Russia. Besides, the "indium-bearing minerals including roquesite are associated with tin-bearing minerals and very often with bornite." [39]

Most of the tin deposits are mainly found from the State of Perak and Selangor in the Peninsular of Malaysia. In the Fig 2.1, the production of tin-concentrate in Malaysia from 1951-2005 has been shown. It is found that the production of tin-concentrate peaked at around year 1973 and the production dropped to less than 10,000 tonnes in the last ten years. The reasons are the exhaustion of high grade ground and also low tin price in the international market, the tin mining industry in Malaysia has been on the decline in recent years. [37] According to report from Malaysian Tin Bulletin, 2005, the number of operating mining areas in Malaysia was 26 and 23 in 2003 and 2004 respectively.

In 2003, the top ten tin producers were Rahman Hydraulic Tin Bhd. (Mine No. 2), Rahman Hydraulic Tin Bhd. Kota Bunyih Mill, S.E.K (M) Sdn. Bhd. (Padang Mine), Nariju Sama Sdn. Bhd. (No. 2), S.E.K (M) Sdn. Bhd. (Mine No 4), Nariju Sama Sdn. Bhd. (No. 62), Delima Industrie Sdn. Bhd., Nilai Cergas (M) Sdn. Bhd., Sheratin Sdn. Bhd. and Original Properties Sdn. Bhd. [20]

The depleted resources and lower ore grades in the tin mines are two main reasons that caused the production decline, although the price was higher. Malaysia Smelting Corp. Bhd. (MSC) was the only integrated tin producer after Escoy was shut down and it is one of the world main tin metal refiners. MSC had owned 2 smelters. They are a smelter in Butterworth, Malaysia and another one in PT Koba tin, Indonesia.

Table 2.2 shows the tin mining methods in Malaysia in 2003 and 2004. It is found that open cast, gravel pump and panning are the three major tin mining methods for tin production in 2003 and 2004. However, amang (retreatment) was used most frequently for the operating units. In 2004, tin production by open cast accounted for 40.5%, gravel pump 25.2%, panning 19.0%, amang (retreatment) 12.2%, dredging 3.1%.

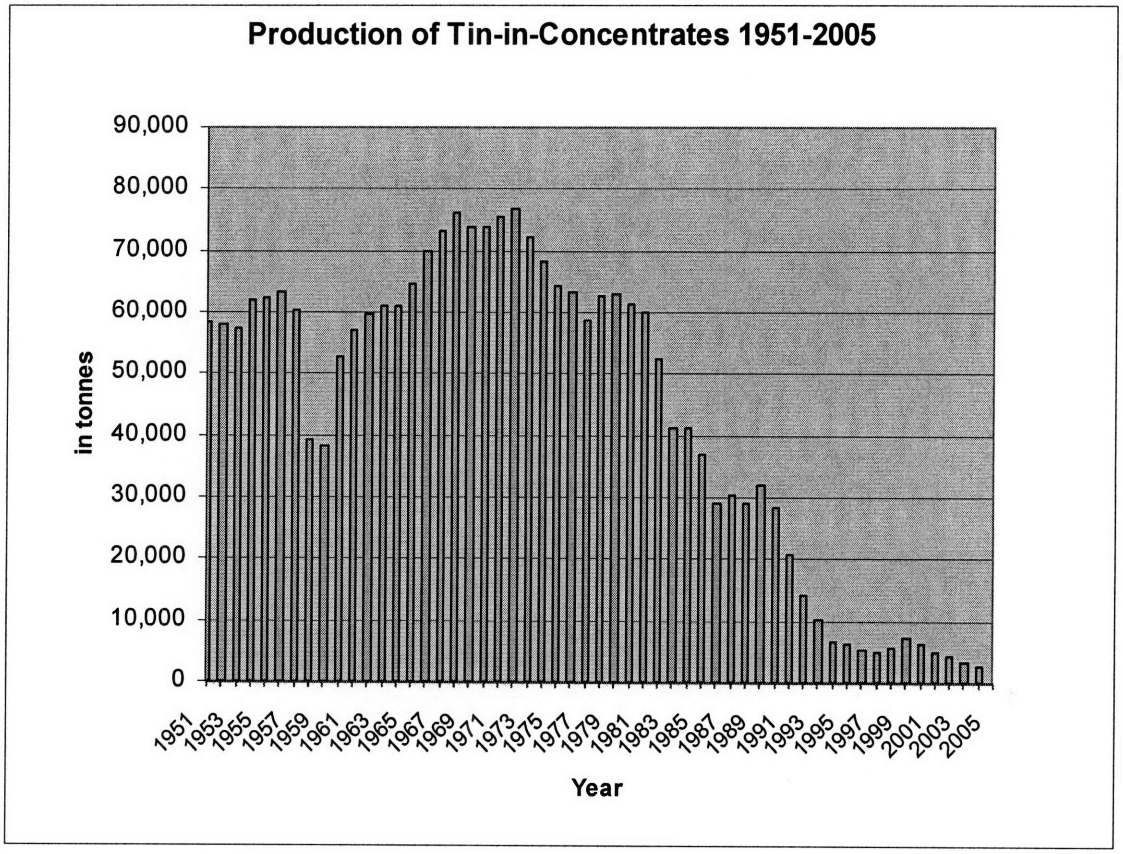


Fig 2.1: Production of tin-concentrate in Malaysia from 1951-2005

	2003		2004	
Mining methods	Production (Tonnes)	No. of Operating Units	Production (Tonnes)	No. of Operating Units
Open Cast	1419	15	1110	11
Gravel Pump	1124	9	692	9
Panning	513	-	520	-
Amang (Retreatment)	232	28	335	25
Dredging	70	2	86	1
Underground	0	0	0	0
Total	3358	54	2743	46

Table 2.2: Tin mining methods in Malaysia in 2003 and 2004
Source: Minerals and Geoscience Department, Malaysia

Some analyzed trace elements in some miscellaneous tin minerals had been reported by Traub & Moh in Third Regional Conference on Geology and mineral Resources of Asia, 1987. The tin samples were taken from different mine bases from Johor, Selangor and Perak. The trace elements in cassiterite, placer, stannites, wood tin, varmoffite and malayaite had been analyzed and the compositions are shown in the Table 2.3 to 2.6 respectively. Several notations are used here to represent different indium composition as contained in the tin ores in Malaysia. The symbols of *, **, *** and Θ show the concentration level of 0 to 100ppm, 100ppm to 1000ppm, 1000ppm or more and 10000 or more respectively.

In table 2.3, the analyzed trace elements in cassiterite (SiO_2) are shown. According to Traub & Moh, no indium is found from cassiterite in Malaysia. It is noted that six cassiterite tin samples had been tested. At the same time, the trace elements that may be contained in the cassiterite are Fe, Mn, V, W, Ti, Ge, Al, Mg, Cd, Cu, Ag and Bi. However, a range of concentration at 0-1000 ppm indium was traced in the cassiterite in Burma, Thailand, China and Japan. Thus, it is expected that cassiterite is not the type of tin ore in Malaysia that will attract our attention in searching for indium in Malaysia.

Notation: * approx. 0 – 100ppm
** approx. 100ppm – 1000ppm
*** approx. 1000ppm – or more
Θ approx. 10000 – or more

	Fe	Mn	Nb	Ta	V	Mo	W	Ti	Zr	Hf	Ge	Al	Be	Mg	Pb	Zn	Cd	Cu	Ag	In	Bi
1		*	*					*				*		*				*	*		
2					**			*									*	*			
3								*			**							*			*
4		*						*			**										
5		*					*	*				*					**	*			
6	***						*	*													*

Table 2.3: Analyzed trace elements in cassiterite (SiO_2)
1= Pegmatities, Waterfall mine, Johor
2= Klian Intan, Perak
3= Seng mines, Subang, Selangor
4= Hock Aun, Selangor
5= Ulu Klang, Selangor
6= Thye Sang, Salak South, Selangor
Source: Traub & Moh, Trace elements in tin ores (with special attention to Asian occurrences), Third Regional Conference on Geology and mineral Resources of Asia, 1987

The analyzed trace elements in placer deposits are shown in the Table 2.4. The range of indium was estimated at level of 100 – 1000ppm for the sample that taken from Sek, mine, Kampar, Perak. Other trace elements were found in the placer from Sek mine are Fe, V, Ti, Ge, Be, Pb and Cu. Germanium was found at high concentration level, from 1000 – 10000 ppm.

The ideal formula for stannite is Cu_2FeSnS_4. However, the iron in stannite is often partly substituted by zinc and forms Cu_2ZnSnS_4. Some stannites of Malaysian occurrences were tested using samples from Bylco Azira mine, Hock Aun mine and Hock Leong mine in Selangor and the result is shown in the Table 2.5. It is found that a concentration of 100 – 10000 ppm indium was traced out for the tin sample from Hock Leong Mine, Ampang, Selangor. At the same time, no indium was obtained from the tin samples from Bylco Azira mine and Hock Aun mine. Besides, all samples showed occurrences of high concentration of Sn, Fe and Cu. It is noted that Hock Leong mine in Ampang, Malaysia was closed for construction and housing purposes.

	Fe	Mn	Nb	Ta	V	Mo	W	Ti	Zr	Hf	Ge	Al	Be	Mg	Pb	Zn	Cd	Cu	Ag	In	Bi
a	*				**			*			***		*		*			*		**	

Table 2.4: Analyzed trace elements in placer (SiO_2)
a= Sek mine, Kampar, Perak

	Sn	Fe	Zn	Cd	Cu	Ag	In	Bi	Ge
1	Θ	Θ	***		Θ	**		*	**
2	Θ	Θ	Θ	**	Θ	Θ			***
3	Θ	Θ	Θ		Θ	Θ	***	*	***
4	Θ	Θ	***		Θ	***	**	*	***
5	Θ	Θ			Θ	*			**

Table 2.5: Analyzed elements in some stannites of Malaysian occurrences
1= Bylco Azira Mine, Puchong, Selangor
2= Hock Aun Mine, Selangor
3, 4, 5= Hock Leong Mine, Ampang, Selangor

In table 2.6, the analyzed trace elements in some miscellaneous tin minerals are shown. Indium had been traced out at concentration of 1000-10,000ppm for the wood tin samples from Sek mine, Kampar, Perak and Tekka, Perak, Malaysia. However, no indium was found for the varmoffite sample from Chenderiang, Perak and malayaite sample from Chenderiang, Perak.

	Fe	Zn	V	Mo	W	Ti	Ge	Al	Be	Cu	Ag	In	Be
1	*	*	**			**	***	Θ	*	***	*	***	
2	*				*			***	**	**			*
3	***	***				**	Θ	***		Θ	***	***	*
4	*							*	**	*			*
5	*							*	**				*

Table 2.6: Analyzed trace elements in some miscellaneous tin minerals
1= Wood tin, Sek mine, Kampar, Perak
2= Varmoffite, Chenderiang, Perak
3= Tekka, Perak, Malaysia
4= Malayaite , Chenderiang, Perak (non-fluorescent)
5= Malayaite, Chenderiang, Perak (fluorescent, intensive yellow)

2.2) Estimation of the composition of indium in other ores

Till today, no report about the composition of indium in zinc, copper, silver, lead and tungsten cores in Malaysia's mines has been found. Compared to tin ores in Malaysia, it is very hard to estimate the composition of indium in these ores. However, some information related to the production of copper and silver has been obtained and the discussion on copper and silver will be carried out in the following section. It is noted that a discussion for zinc, lead and tungsten cores will not be carried out since no significant data had been obtained from three main natural resources information providers in Malaysia; Minerals & Geoscience department Malaysia, Ministry of natural resources & environment Malaysia and Malaysian Chamber of Mines. Less attention should be paid to these ores in the efforts to search for indium since the production of these ores is insignificant or too small and the possible concentration of indium is relatively low.

2.2.1) Copper

No copper mining activity has been carried out in Malaysia after the Mamut Copper Mine in Ranau, Sabah was shut down in 1999. Table 2.7 shows the production of copper in Malaysia from 1995 to 2004.

Some statistics had been documented which showed that some base metals like copper, lead and zinc were found from the Central Belt area in Peninsular Malaysia. These base metals were associated with gold and silver. In Sabah, Tampang, Bidu, hills, Kiabau, Pinanduan, Gunung Nungkok and Bambangan are the locations which had been determined contain significant copper resource. Meanwhile, Bukit Jebong-Biawak, Kendai, Bau, Gunung Buri, Bukit Subong-Bukit Pan and Bukit Nimong are determined as the location that highly potential containing copper base metal in Sarawak. [21]

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Tonnes	20,267	20,219	18,821	13,907	4,600	-	-	-	-	-

Table 2.7: Production of copper in Malaysia from 1995 to 2004.
Source: Malaysian Minerals Yearbook 2004, Minerals& Geoscience department Malaysia and Ministry of natural resources & environment Malaysia

2.2.2) Silver

Silver was a by-product of gold mining in Pahang during 2004. Besides, it was also obtained as a by-product of copper mining in Sabah and gold mining in Sarawak. Silver production dropped dramatically followed by the shut down of the operation for the Mamut Copper Mine in Sabah in 1999 and gold mines in Sarawak. Note that no silver had been produced for 2002 and 2003. However, a small quantity of silver had been found within the silified volcanic rocks at Gunung pock and Semporna peninsular, Sabah. In the Table 2.7, the production of silver in Malaysia from 1995 to 2004 is shown.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Metallic minerals	^000gm	^000gm	^000gm	^000gm	^000gm	^000gm	^000gm	^000gm	^000gm	^000gm
Silver	11,079	9,720	9,647	7,285	2,744	4.5	3.1	-	-	363.72

Table 2.8: Production of silver in Malaysia from 1995 to 2004.
Source: Minerals& Geoscience department Malaysia

2.2.3) Zinc, lead and tungsten

It is noted that some indium may be contained in zinc, lead and tungsten ores. As stated in the Chapter 1, Malaysia has produced these ores. However, no further discussion will be carried out in this section due to lack of information provided by the authorities. However, it is sure that the production of these ores is just a by-product of other mining like tin and gold.

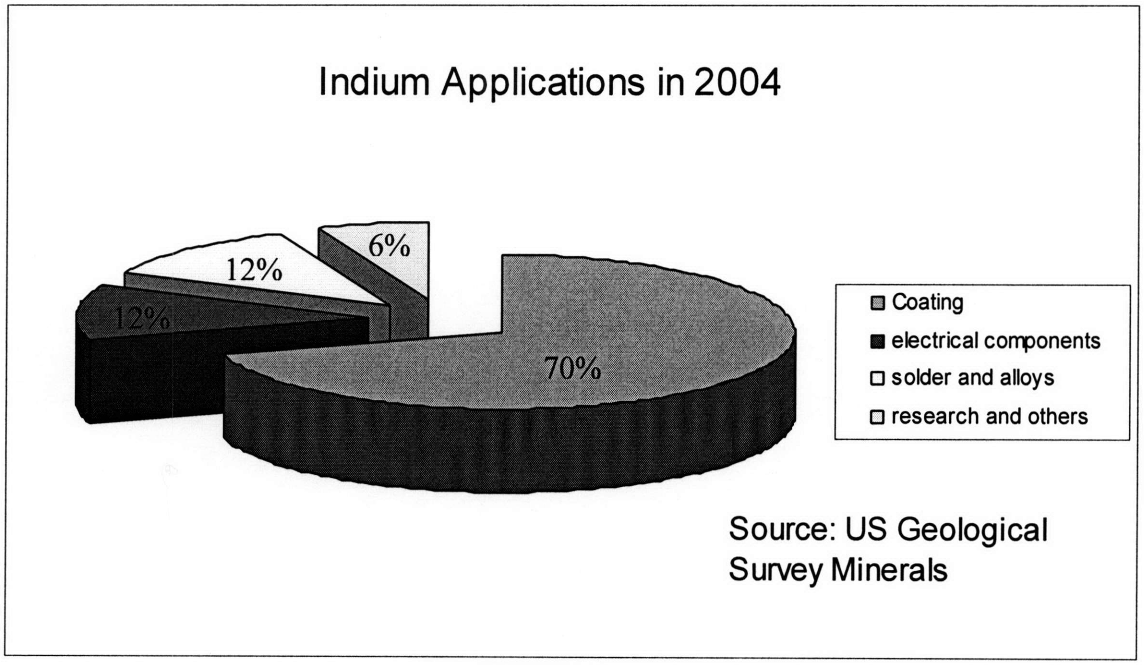
2.3) Discussion

In the efforts of searching for indium in Malaysia, tin ore should be our target since it has highest reserve base and possible indium concentration, compared to other ores. According to Traub & Moh, no indium is found from cassiterite in Malaysia. In the same time, placer, stannites and wood tin are the types of tin ores may bear high concentrations of indium. They may contain 100 – 10000 ppm of indium. The indium concentration in Polaris Northwest Territories (Canada) and Creek (Canada), Balmat, N.Y. are 0.027%, 0.010% and 0.004% by weight. This means indium concentration in Malaysian tin ore is relatively very high. In Chapter 5, the possibility to extract indium from tin circuit will be discussed.

Chapter 3: Potential applications of indium in Malaysia

3.0) Overview for indium applications

Indium is used for display coatings, electrical solders, alloys, and semiconductor. It is noted that 70 percent of indium production is used for coatings. Electrical components and solder alloys are the second largest portion of indium usage. Less than six percent is used other applications. Lead was banned for the electrical and electronics applications in the European Union after July 1, 2006. Use of lead-free soldering will become an environmental-friendly policy for more and more industries and countries soon. However, most of the lead free solders have a melting point higher than 200^0C. Many electronic components will be destroyed at this temperature. Thus, some of the indium-bearing alloys are good candidates for replacing the lead-based solders and it will be expected the demands of indium in electrical solder and alloys will increase. The world indium applications is shown in Fig3.1



Source: US Geological Survey Minerals

Fig 3.1: The world indium application in 2004.

If we want to trace the trend of indium use, observing the consumption of indium for different sectors in a long period is one of the methods. The world consumption of indium by sectors from 1975 till 2005 is shown in the Fig 3.2. It is found that the consumption of indium for thin coatings increased gradually after 1990. Meanwhile, a certain portion of indium production is used in electrical components and semiconductors. The application of indium in solders and alloys started around 1990 and the consumption has not changed much. According to Roskill, the total market for indium has expanded averaging over 10% annually for the past 5 to 6 years and is estimated that it will have similar growth rate in the near future.

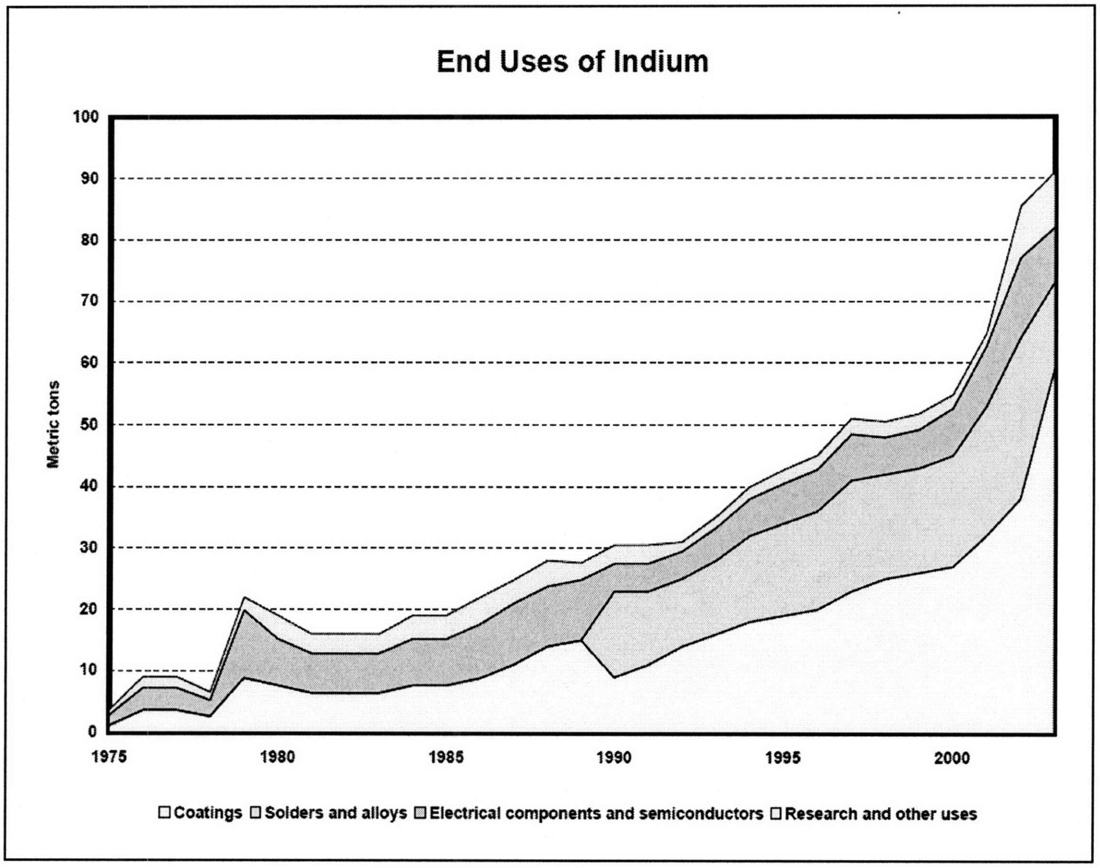


Fig 3.2: The end uses of indium from 1975 till 2005.
Source: G.R. Matos, J. D. Jorgenson, and M.W. George, US Geological Survey Minerals Commodity

The major consumption of indium from the refining production is applied for thin coatings on glass. "At forecast rates of growth, indium demand in ITO coatings will account for 745 tons/year by 2008, or approximately 85% of total demand." [43] This includes the applications in the liquid crystal display (LCD) and heat-reflecting windows coating. Thin coatings can be further categorized into two groups; electrically conductive and infrared reflecting. For electrically conductive coatings, indium is used in LCD's for watches, laptop, computers or television screens and other display instruments.

In addition, lots of indium compounds have been applied in semiconductor and optoelectronics. Although the total weight of indium is small in these applications, the indium used in this area must be very pure. Indium phosphide is used in laser diodes and optical circuitry. Indium antimonide and indium arsenide are applied in infrared detectors. As one of the indium compound, indium oxide can be doped and it can conduct electricity.

Thus, the further discussion of coating, soldering, semiconductors, photonics crystals and others are summarized as below. At the end of this chapter, a discussion for the potential applications of indium in Malaysia will be provided.

3.1) Thin Coating

Indium tin oxide (ITO) has some special properties for thin coating. The refractive index for ITO glass is 2.0, compared to the refractive index for the substrate glass of 1.52. The range of direct optical bandgap of ITO of 3.5 to 4.06eV was reported.

ITO can form a transparent yet electrical by conductive surface. The infrared waves are reflected back, but the waves within visible light and ultraviolet range can pass though the coated surface. Besides, it has low roughness and uniform transmission. Thus, it can be used for transparent electrodes in display technologies. ITO is applied in the thin film transistors for data conversion from electrical signal to optical signal in the liquid crystal (LCD), flat panel displays (FPDs) and plasma display panels (PDPs).

The components and operation of thin-film transistor (TFT) in light crystal display (LCD) is shown in the Fig 3.3 and 3.4 respectively. In a light crystal display, the alignment of light is altered using voltage since the liquid crystal can function as a shutter. For the thin-film transistor system in the LCD or others display technologies, the voltage of each pixel is determined by respective TFT and a liquid crystal material have been inserted in two glass plates. The polarizing filter is assembled on the outside of the glass and the whole display is sealed in plastic. There are two alignment plates or polarized plates. The backlight will be polarized in horizontal direction after it passes thought first polarized plate. When the TFT is turned on, a small voltage change will bias the liquid crystal molecules in an aligned polarized pattern and the light will be twisted. Meanwhile, the light will not be polarized if the TFT is powered off. The untwisted light will be blocked when it pass though the second alignment plate. Thus, only the twisted light of the powered on pixel will be emitted to surface. A color of emission light from each pixel is controlled by the color filter on the surface of display surface.

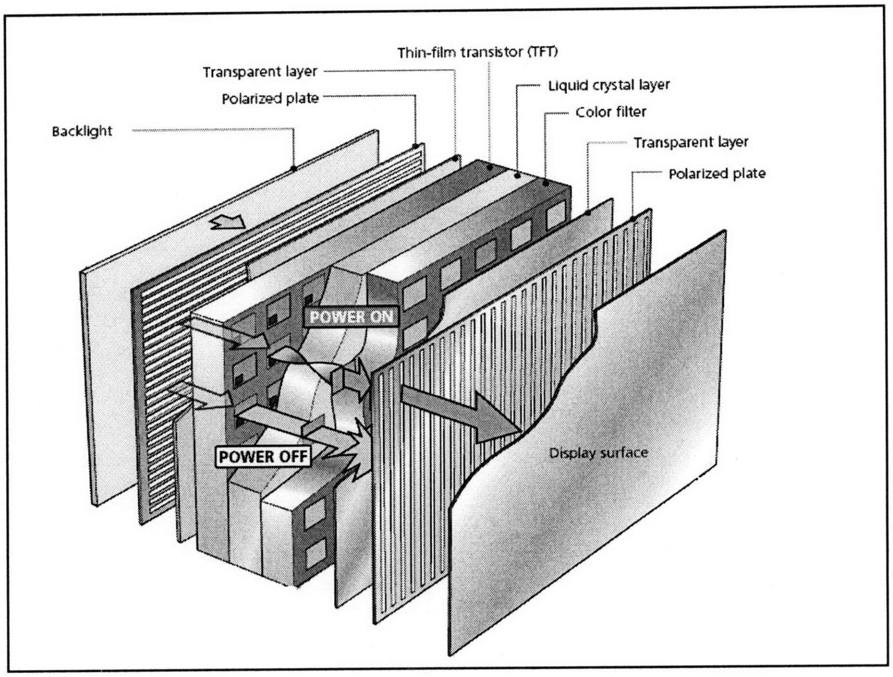


Fig 3.3: The components of TFT in LCD (Source: Ushio)

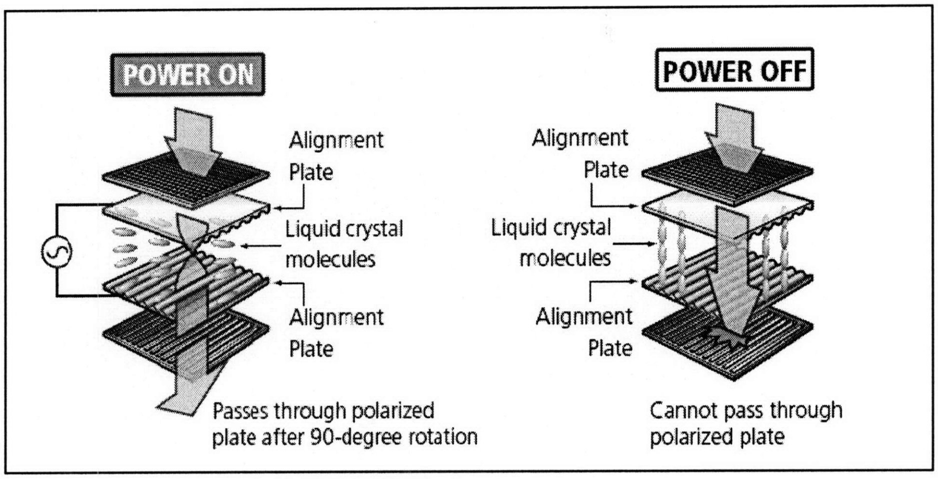


Fig 3.4: The operations of TFT in LCD (Source: Ushio)

ITO can be prepared by two ways. The first method is co-precipitation, which is the precipitation from an indium and tin solution. ITO powder can be obtained via this method. It can also be obtained by blending the oxides of indium and tin. The following reaction will normally take place to form indium tin oxide.

$$90\%\ In_2O_3 + 10\%\ SnO_2 \rightarrow (In_{0.9}Sn_{0.1})_2O_3.$$

Using physical vapor deposition technique, a very thin, stable, long life time and uniform ITO film can be deposited on a glass. The informality of ITO is an important parameter for high quality large area LCDs. Besides, the etching and lithography steps for the fabrication of the ITO film are very fast.

It is noted that the ITO is soluble in dilute mineral acids. But, it is insoluble in the many solvents. For example, xylene, naptha, acetone, methyl ethyl ketone, toluene and mineral spirits are unable to etch indium oxide. [1] Indium oxide can reflect infrared and this characteristic enables bulb to operate at higher temperature. As a result, the efficiency of the bulbs is increased.

Since the typical thickness of ITO layer is 1275Å to 1725Å, thus the transmittance of the light with wavelength of 550nm is expected more than 90%. Thus, ITO can be considered transparent because only large portion of the light can pass though the ITO layer. The effect of thickness for transmittance of ITO is shown in the Fig 3.5.

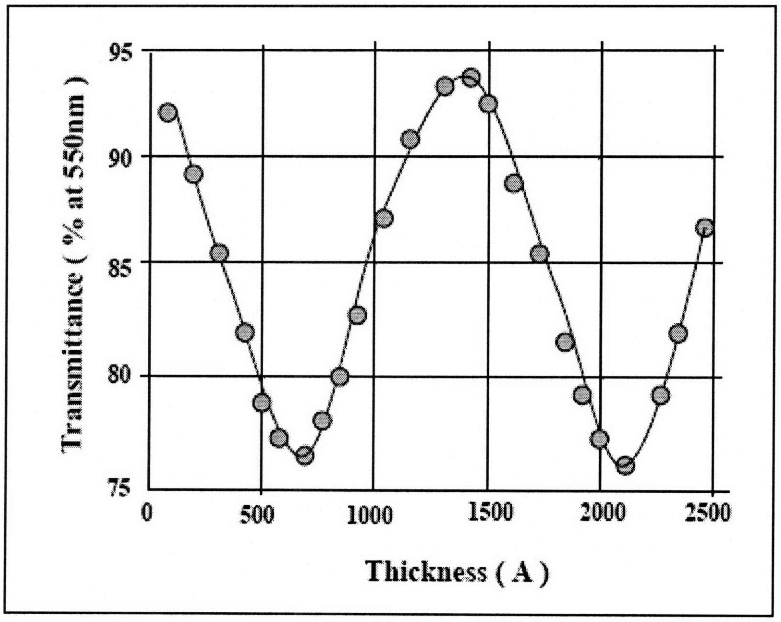


Fig 3.5: The transmittance response for different thickness of TFT in LCD at 550nm
Source: In-cha Hsieh, Chapter 3: TFTLCD Process, National Chung Cheng University

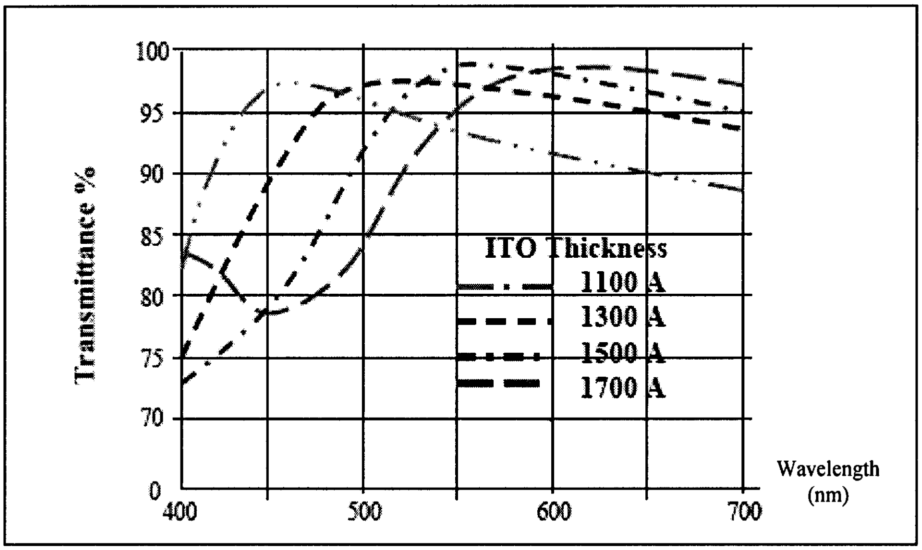


Fig 3.6: The transmittance response for different wavelengths of TFT in LCD
Source: In-cha Hsieh, Chapter 3: TFTLCD Process, National Chung Cheng University

Besides, the transmittance response for different wavelengths of TFT in LCD is shown in the Fig 3.6. This means if the wavelength of the transmitted light is fixed, then a proper thickness should be chosen in order to achieve high transmittance. This is also another reason the thickness uniformity of the ITO film is important parameter for LCD. If the thickness for the ITO film is higher, it will require a light source with a longer wavelength to maintain same transmittance of light.

3.2) Soldering

In the electronics industry, the eutectic tin-lead (Sn-Pb) solders are widely applied to attach electrical parts to the printed circuit boards. The coating or finish on the metal terminations on PCBs is done with this type of solders. It is because the lead can reduces the melting point of silver, surface tension of the molten solders, does not participate in the reactions with the circuit metallization. However, lead is very toxic for human body. Thus, lead-free soldering has been emphasized since last two decades.

Indium containing solders are considered one of the candidates for replacing eutectic Sn-Pb solders because the low melting point, softness, good wetting and ductility. "As early as 1935 it was noted that the addition of indium to low-melting alloys containing bismuth, lead tin, and cadmium caused the melting points to drop 1.45^{0}C at indium content of 19.1%." [17]

In additions, indium can functioned as the base material to improve some features of low-melting solders. For example, indium minimizes gold scavenging and forms a barrier to alkaline corrosion and thermal fatigue. Some indium-based solders are applied in microelectronics packaging and assemblies. In-Sn48 solder provides the low temperature soldering (117^0C) for glass-to-metal sealing and heat-sensitive assemblies. Indium is alloyed with other metals in order to decrease the melting point and maintain flexibility in of the solder temperature range. Some indium-containing lead-free solder alloys (below 200^0C) are showed as below:

Composition	Melting range (^{0}C)
Bi-33In	109 (E)
Sn-52In	118(E)
Sn-50In	118-125
Sn-20 Bi-10 In	143-193
Sn-20 In – 2.8 Ag	175-186

Table 3.1: Some low-temperature (below 200^0C) candidates for indium-contained lead-free solder alloys

Source: pg16, K.J. Puttlitz & K. A. Stalter, Handbook of lead-free solder technology for microelectronic assembies, Marcel Dekker, INC, 2004

Indium-containing alloys are not suitable for directly soldering to copper because intermetallic layers will be formed due to diffusion of indium atoms into copper. This problem can be solved by putting a layer of nickel between the two layers. However, a key concern for indium contained as a base metal is abundance of this metal. Compared to other metals, indium has a relatively high cost.

It is seen that indium and silver are much more expensive than other solder components. Zinc, copper, tin and bismuth have reasonable cost factors in comparison. However, indium-containing solders are attractive for low-soldering temperatures and some mechanical properties.

Element	Metals cost per pound (USD, Approximately)	Density at 25^0C (Ib/in^3)	Cost per standard volume (USD/ in^3)	Cost factor relative to Pb
Zinc (Zn)	0.50	0.258	0.129	0.70
Lead (Pb)	0.45	0.416	0.184	1
Antimony (Sb)	0.80	0.359	0.191	1.01
Copper (Cu)	0.65	0.324	0.211	1.15
Tin (Sn)	3.50	0.354	1.20	6.52
Bismuth (Bi)	3.40	0.354	1.20	6.52
Silver (Ag)	84.20	0.379	31.91	173.40
Indium (In)	125.00	0.264	33.00	173.30

Table3.2: Relative cost of candidate elements to replace lead in electronic assemblies based on volume. Source: pg14, K.J. Puttlitz & K. A. Stalter, Handbook of lead-free solder technology for microelectronic assemblies, Marcel Dekker, INC, 2004

3.3) Compound semiconductor and photonics crystals

3.3.1) Binary Semiconductor

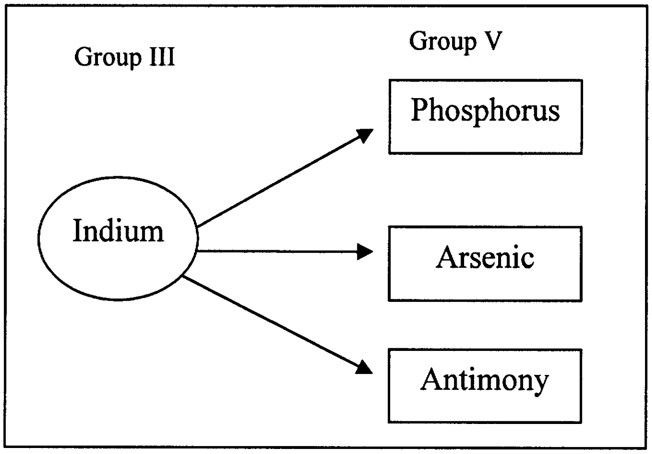


Fig 3.7: Combination of indium with three group V elements

Indium forms important compounds in semiconductor electronics and optoelectronics technology. Indium from group III can form semiconducting compounds with an element from group V. These include indium phosphide, indium arsenide and indium antimonide. Aluminum and gallium from group III can form compounds with these three same elements from group V. InP, InAs and InSb are all direct bandgap materials. A direct bandgap is needed for radiative emission of photons. These compounds are applied in fabricating photons detectors, LEDs and lasers. The bandgap energy, bandgap wavelength, refractive index, and enthalpy of formation of InP, InAs and InSb are shown in Table 3.3.

Material	Bandgap Energy at T=300K Eg (eV)	Bandagap Wavelength λ_g(μm)	Refractive index at T=300K	Enthalpy of formation ΔH(KJ/mol)
InP	1.35	0.92	3.5	-75.2
InAs	0.36	3.5	3.8	-57.7
InSb	0.17	7.3	4.2	-31.1

Table 3.3: The comparisons of bandgap energy, bandgap wavelength, refractive index, enthalpy and type of bandgap for InP, InAs and InSb

3.3.2) Quaternary Semiconductors

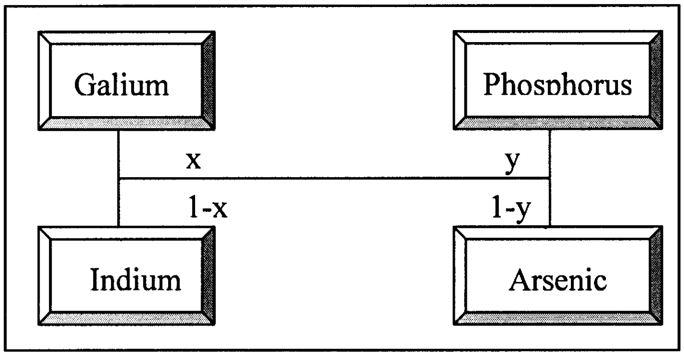


Fig 3.8: The compositions of $(In_{1-x}Ga_x)(As_{1-y}P_y)$

$(In_{1-x}Ga_x)(As_{1-y}P_y)$ is a quaternary compound which is formed from two elements from group III and another two from group V. Compared with the ternary semiconductors, this compound gives large degree of freedom for synthesis of the required properties. In other words, this provides the option to choose the bandgap width and the lattice constant by varying the compositional mixing ratios x and y. The range of energy bandgap for this quaternary compound is changed from 0.36eV to 2.26eV.

In other words, the wide range of direct bandgap for this quaternary compound can be tuned by varying the compositions of the compound. The emission wavelength can be tuned from 1.1 to 1.6μm. Normally, this compound is obtained by alloying GaAs on top of InP because a well matched lattice constant can be achieved. A linear relationship y = 2.16(1-x) is used in this case. This equation allows control of the compositions of $(In_{1-x}Ga_{x})(As_{1-y}P_{y})$ precisely.

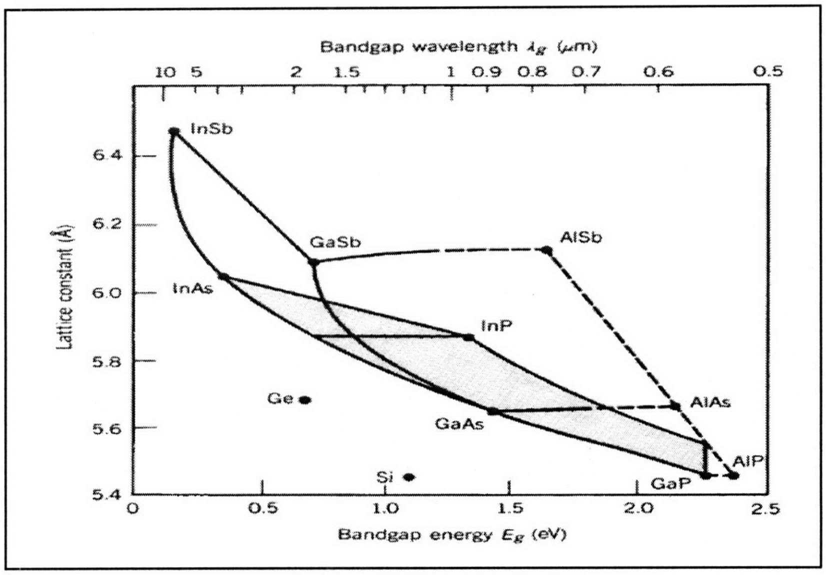


Fig 3.9: Graph of lattice constant versus bandgap wavelength for Si, Ge and some binary alloys. Source: Pg 550, B.E. A.Saleh & M. C. Teich, Fundamentals of photonics, John Wiley & Sons, Inc

The direct and indirect bandgap are represented using solid and dashed lines in Fig 3.9. The shaded area is bounded by possible composition combinations of InAs, InP, GaAs and GaP. Normally, InP is used and alloyed with different compositions of GaAs to obtain the required bandgap and lattice constant because it matches the requirement of larger bangap for alloying at same lattice constant. The absorption coefficient of InSb, InAs and InP are shown in Fig 3.9. Note that no photon will be emitted for photon energies below the bandgap energy. That is the reason for the presence of an onset for each material in the figure below. In other words, the excitation energy must be greater than certain energy level before emission happen.

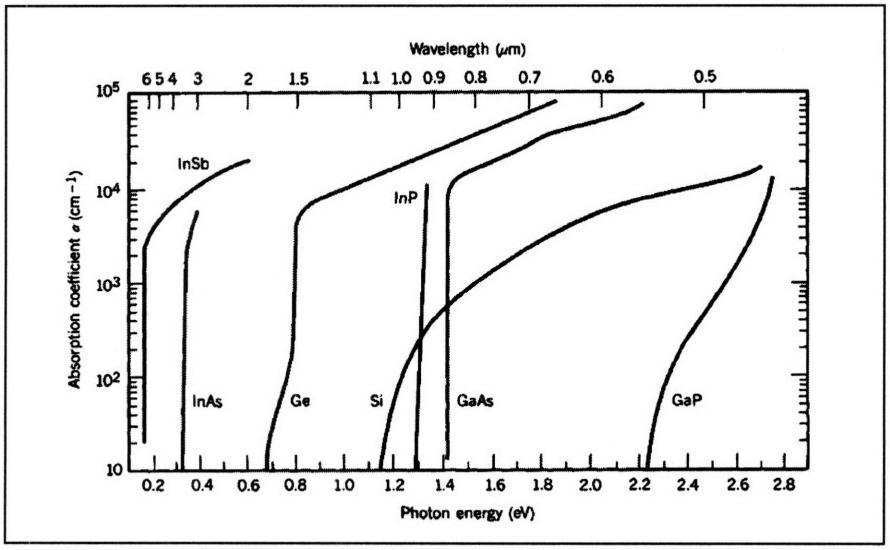


Fig 3.10: Graph absorption coefficient versus wavelength for some photonic crystal materials. Source: Pg575, B. E. A. Saleh & M. C. Teich, Fundamentals of photonics, John Wiley & Sons, Inc

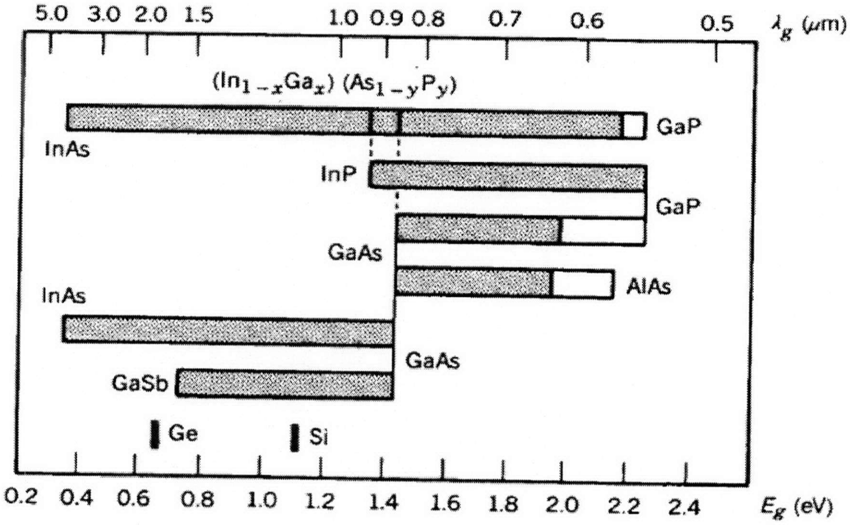


Fig 3.11: The range of wavelength for Ge, Si and some III-V binary, ternary and quaternary materials. Source: Pg 576, B. E. A. Saleh & M. C. Teich, Fundamentals of photonics, John Wiley & Sons, Inc

From Fig 3.11, we can observe the range of wavelengths for materials which still maintain the direct bandgap feature. The composition of the materials in the direct bandgap range is shaded in Fig 3.11.

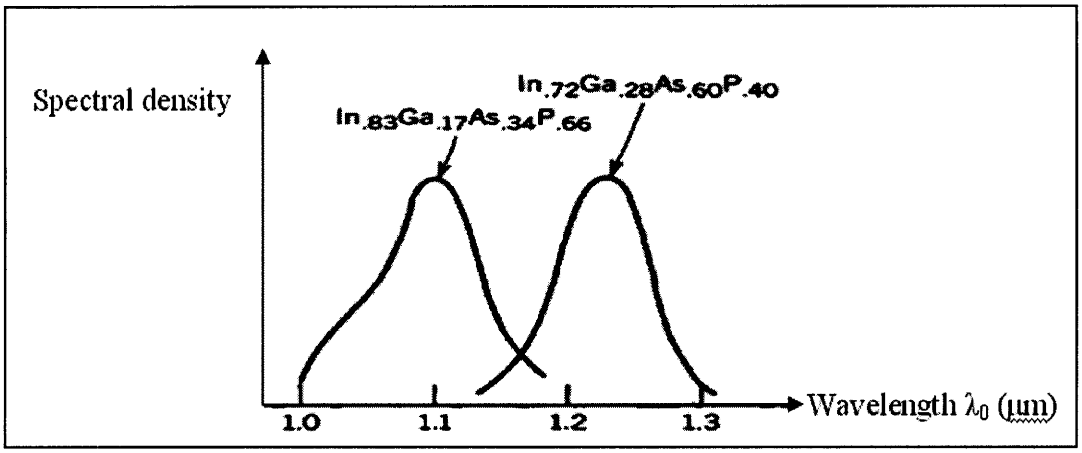


Fig 3.12: Graph spectral density versus wavelength for $(In_{1-x}Ga_x)$ $(As_{1-y}P_y)$. Source: Pg605, B. E. A. Saleh & M. C. Teich, Fundamentals of photonics, John Wiley & Sons, Inc

In particular, the spectral density of $(In_{1-x}Ga_x)$ $(As_{1-y}P_y)$ versus wavelength is shown in the Fig 3.12. It is shown that $(In_{0.83}Ga_{0.17})$ $(As_{0.34}P_{0.66})$ and $(In_{0.72}Ga_{0.28})$ $(As_{0.60}P_{0.40})$ have the highest spectral density at 1.1μm and 1.25μm respectively. Thus, $(In_{1-x}Ga_x)$ $(As_{1-y}P_y)$ is useful for fabrication of near infrared lasers.

In short, a double-heterostructure laser diode amplifier can be formed via grading $(In_{1-x}Ga_x)$ $(As_{1-y}P_y)$ with InP. The heterojunction potential barriers are formed on both sides of the p-n junction in the double-heterostructure. The potential well can block the diffusion of the minority carriers and they are generally confined in the active layer. The active layer and surrounding layers are $(In_{1-x}Ga_x)(As_{1-y}P_y)$ and InP respectively. To make sure of the lattice match, the right ratio of the x and y should be chosen. The advantages of the double-heterostructure are amplifier gain is increased and minimize the loss for absorption.

On the hand, $Ga_{0.5}In_{0.5}P$ is used for fabrication of visible band laser diodes. The wavelength of the emitted light is about 670nm. AlInP is used for continuous wave lasers and yellow color light is produced. Meanwhile, $(In_{1-x}Ga_x)$ $(As_{1-y}P_y)$ is normally applied in the near infrared lasers.

In short, indium plays an important role in the bandgap engineering of compound semiconductor and photonics crystals. By varying the composition of indium in the indium-containing materials, a suitable bandgap material can be created and the corresponding emission wavelength light can be produced.

3.4) Other uses

Indium is needed for manufacturing nuclear control rods for pressurized water reactors. Abrasive compounds can also be lubricated by using indium-palladium and indium-gold alloys. The presence of indium in the coating material will enhance some mechanical properties, like corrosion and abrasion resistance. Some application is found in vacuum technology due to the sealing ability of indium. It also can be used as a metal lubricant and for dental alloys. Note that the earliest application of indium is in the dental purpose. Besides, some research showed some indium containing compounds like indium-gallium-diselenide and copper-indium-diselenide were used for fabrication of higher power conversation efficiency solar cells. Some minor applications of indium will not discussed here.

3.5) Discussion for the potential applications of indium in Malaysia

A lot of multi-national electronics companies set up their branch offices in Malaysia. For example, Intel, Motorola, Samsung, and Texas Instruments have facilities in Malaysia. It is expected that the need for indium for soldering will increase if the soldering is changed to lead-free soldering. Besides, there are some companies manufacture LCD, television and other display instruments in Malaysia. It is noted that a pioneer company in the indium sales and refining, Indium Corporation of America had set up a branch in Malaysia. This shows that it must have some indium sales and consumptions in Malaysia.

Chapter 4: Reviews of some potential indium production technologies

4.0) Overview

Indium is the by-product of tin, zinc, copper, silver, lead and tungsten ores. Most of the world indium production is obtained as a by-product of zinc refining. This is because "indium is difficult to separate from copper, arsenics, antimony, lead and tin, and the pyrometallurgical processes are not well adapted for such separations." [36] The recovery of indium is commonly treated as a marginal business activity because the difficulties of separation from other metals. A large quantity of the tin or zinc ore is needed for treatment and only a few hundred grams/tons indium is extracted because the concentration indium is normally less than 1%. In other words, it is very low yield for indium extraction. As a result, the cost of extraction for indium increases significantly. However, indium has higher commercial value than the tin and zinc. Thus, the refiners may consider indium extraction as main activity and take extraction of tin or zinc as "by-product" business activity. This topic will be further discussed in the next chapter.

The commercial available grades for indium are 99.97% (3N), 99.99% (4N), 99.999% (5N), 99.9999% (6N), and 99.99999% (7N). The highest purity for sponge indium is 99.5%. Thus, sponge indium is normally required to be further refined for most of the indium applications. Note that the minimum required grade of indium in the semiconductor industry is 99.9999 % (6N).

"Major indium refiners in the world include Metallugie Hoboken-Overpelt NV in Belgium; Preussag AG in Germany; Socirte Miniere et Metallurgique Pennarroya S. A. in France; Mining and Chemical Products Ltd. in the United Kingdom; Nippon Mining Co. in Japan; and Cominco Ltd in Canada." [23]

4.1) Extraction of indium

There are several indium extraction technologies available. But, most of primary production of indium had been carried out from the zinc circuit due to economical reason. Besides, the recovery process is complex because indium has relatively high chemical affinity with its parent metals and tendency for dispersion in the process circuit. Thus, it cause the extraction cost for indium become high.

In the following section, the extraction process of indium from tin, zinc and lead circuits will be discussed here. In additional, some typical examples of the extraction process flows for each circuit will be given.

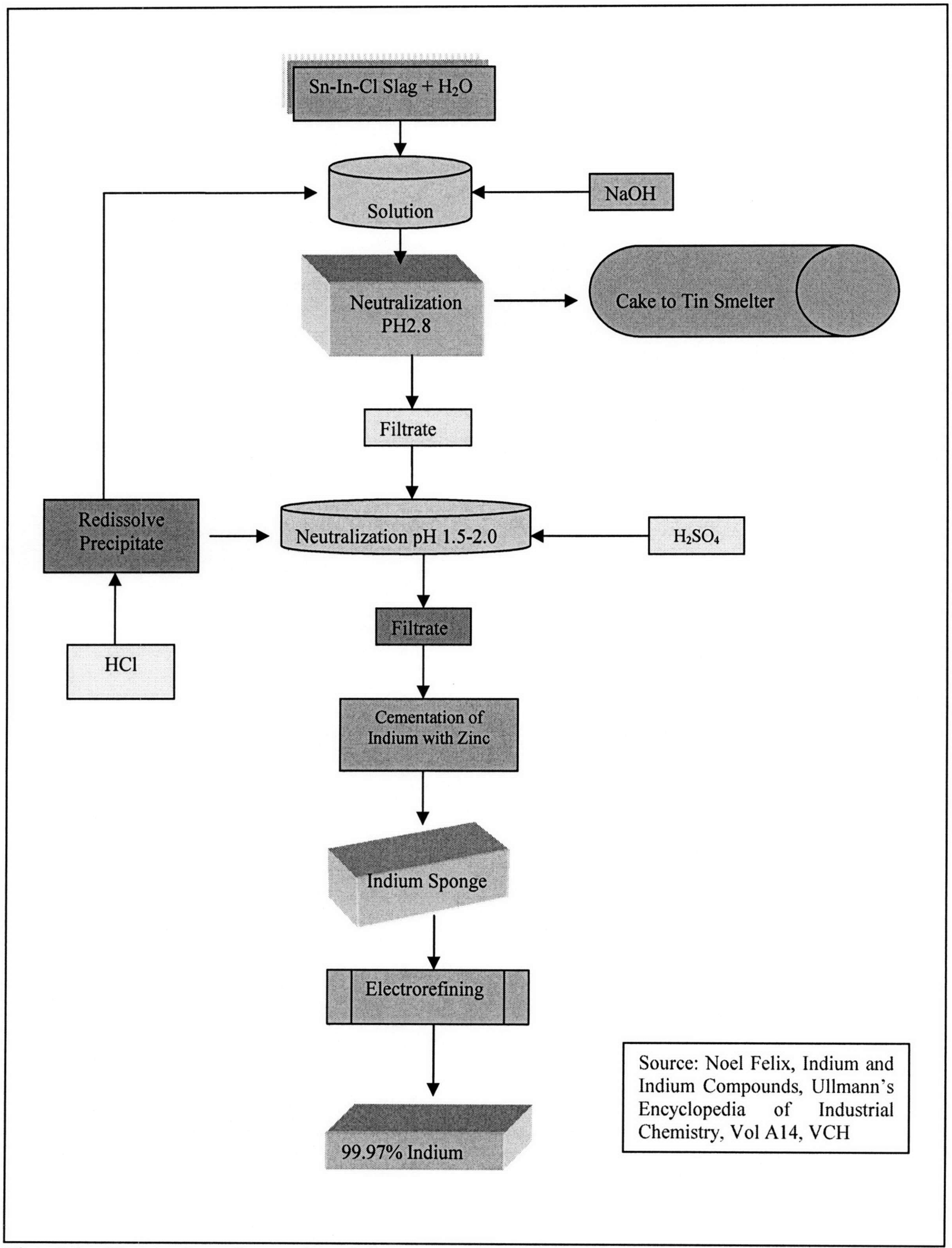
4.1 (a) Extraction of indium from tin circuits

Indium alloy is extracted from tin concentrate as an indium-lead-tin alloy. It is found that only 0.01 % indium in the tin concentrate and the above process need to be carried under a specialized vacuum refining apparatus. The raw indium can be obtained from the indium alloy in 20-ton melting pots. According to Novosibrisk City Guide, this method is can be applied to a primary indium concentration which has equal or more than 0.1 percent.

An indium recovery flow chart from the tin at Capper Pass, United Kingdom is shown in the Fig 4.1. Tin is chlorinated after electrorefining. Tin chloride slag is obtained and it is estimated that this slag has 2.7% of indium. Noted that an indium chloride solution is easily achieved by leaching the indium concentrates with or without an oxidant. Tributyl phosphate (TBP) or Methylisobutyl ketone (MIBK) is used as a solvent to separate tin and antimony from indium. But TBP is normally chosen because MIBK is very volatile, explosive and flammable. [36]

There are two neutralization stages in this indium recovery at Capper Pass, United Kingdom. The first neutralization stage is held at pH 2.8 and almost all of the tin will precipitate in this stage. Thus, the cake will be sent to the tin smelter. The pH of the second neutralization stage is maintained at 1.5 - 2.0. Sulfuric acid will be added into the second neutralization stage. Some indium may be found in the precipitate of the second neutralization. So it is normally being reused for another indium extraction. Thus, the precipitate is dissolved using hydrochloride solution. Then, this indium-containing solution could be recycled for further refinery.

From the cementation of indium with zinc, 95% of indium sponge is obtained. In order to achieve higher purity of indium, electrorefining is normally applied. Thus, 99.5% purity indium can be achieved after first and second electrorefining stages.



Source: Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14, VCH

Fig 4.1: Extraction from tin circuits ---- Indium recovery by Capper Pass, United Kingdom

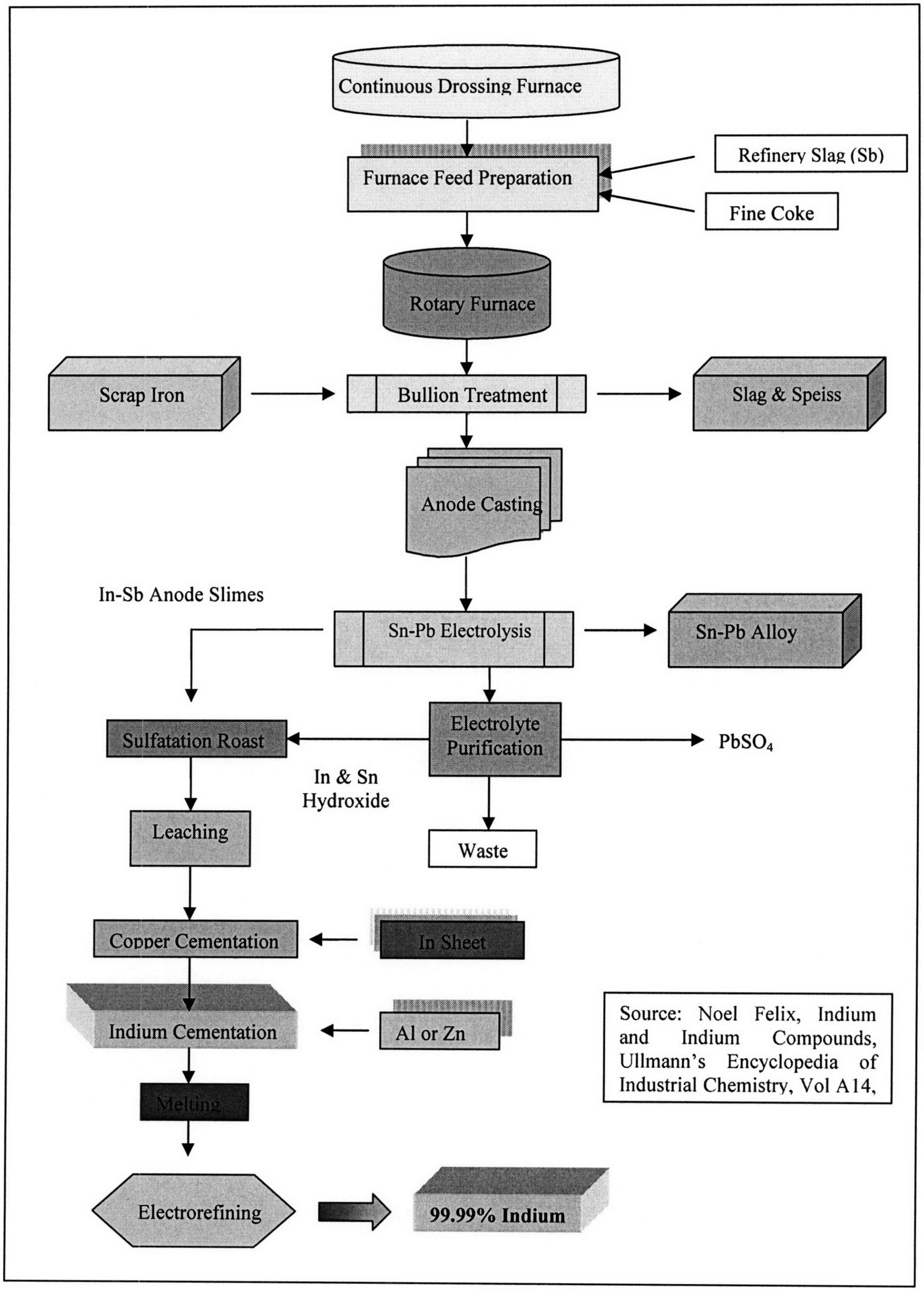
4.1 (b) Extraction of indium from Lead circuits

Fig 4.2 shows that indium production from lead circuits in the integrated lead-zinc smelter of Cominco, Canada. In the fumes of the continuous drossing furnace, accumulation of tin and indium is taken place. For the furnace feed preparation, the refinery slag of antimony and fine coke are mixed with the fumes in the furnace and then the mixture is melted in the rotary furnace.

Next, the scrap iron is injected in the Bullion treatment and it reacts with arsenic to produce iron speiss and slag. Thus, the arsenic is separated from the mixture of fumes. The anode casting for the residual tin-indium-antimony-lead alloy is carried out before the electrorefining. The tin-lead alloy is obtained from the solder cathode and indium-antimony is produced in anode slimes after the tin-lead electrolysis in a fluorosilicate solution.

The further electrolyte purification is applied to produce indium and tin hydroxides. Meanwhile, lead sulfate and waste is produced as by-products. The indium-antimony anode slimes are mixed with the indium and tin hydroxides and then roasted in the sulfuric acid. The sulfuric acid is leached with water to make sure that indium is dissolved.

The separation of copper can be done via cementation of copper onto the indium sheet. Aluminum or zinc is added into the indium solution to extract indium from its solution in the form of sponge. Normally the purity of indium sponge is not high. Thus, the sponge is melted and then it is electrorefined to achieve purity of 99.99%.



Source: Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14,

Fig 4.2: Indium production from lead circuits Cominco

4.1(c) Extraction of indium from zinc circuits

Most of the world's indium refining in carried out from zinc circuits. The production of indium from the process zinc smelting at the Kidd Creek zinc plant flow chart is shown in the Fig 4.3. In the neutral leach residue, germanium and indium are concentrated by using an electrolytic process for zinc refining. It is noted that the recovery of both metals will become harder if strong acid leaching is applied to extract the neutral leach residue with high concentrations of iron and silica.

The iron is found in the ferric state in the jarosite process of zinc refining. The steps involved in the jarosite processing factories are reductive leaching and copper precipitation, two stages of neutralization, and iron removal as hematite by autoclave oxidation-precipitation. Gypsum is obtained and purified by a neutralization process using ferrous sulphate solution and calcium carbonate. Finally, raw indium can be produced.

Recovery of indium from secondary zinc oxide is shown in Fig 4.4. Zinc oxide can be separated from the secondary oxide by pre-leaching in the dilute sulfuric acid. A residue with composition of 6% Zn, 50% Pb, 0.68% In is produced after leaching. The indium which is contained in the residue is then dissolved in dilute hydrochloric acid. The tin is separated from indium solution after it has been neutralized of pH 1.

The precipitation of indium is obtained if the indium solution is neutralized continuously. Sodium hydroxide and water are used for the leaching of the indium residue. The filtrate and crude indium hydroxide are obtained. This indium intermediate product is dissolved in the dilute hydrochloric acid and form indium solution. Purification of the indium solution is done with cementation of copper and arsenic with iron and copper-iron cement will be obtained. Next, the indium solution is further purified by cementation of tin and lead with indium. Indium cement is extracted from the cementation of indium with aluminum.

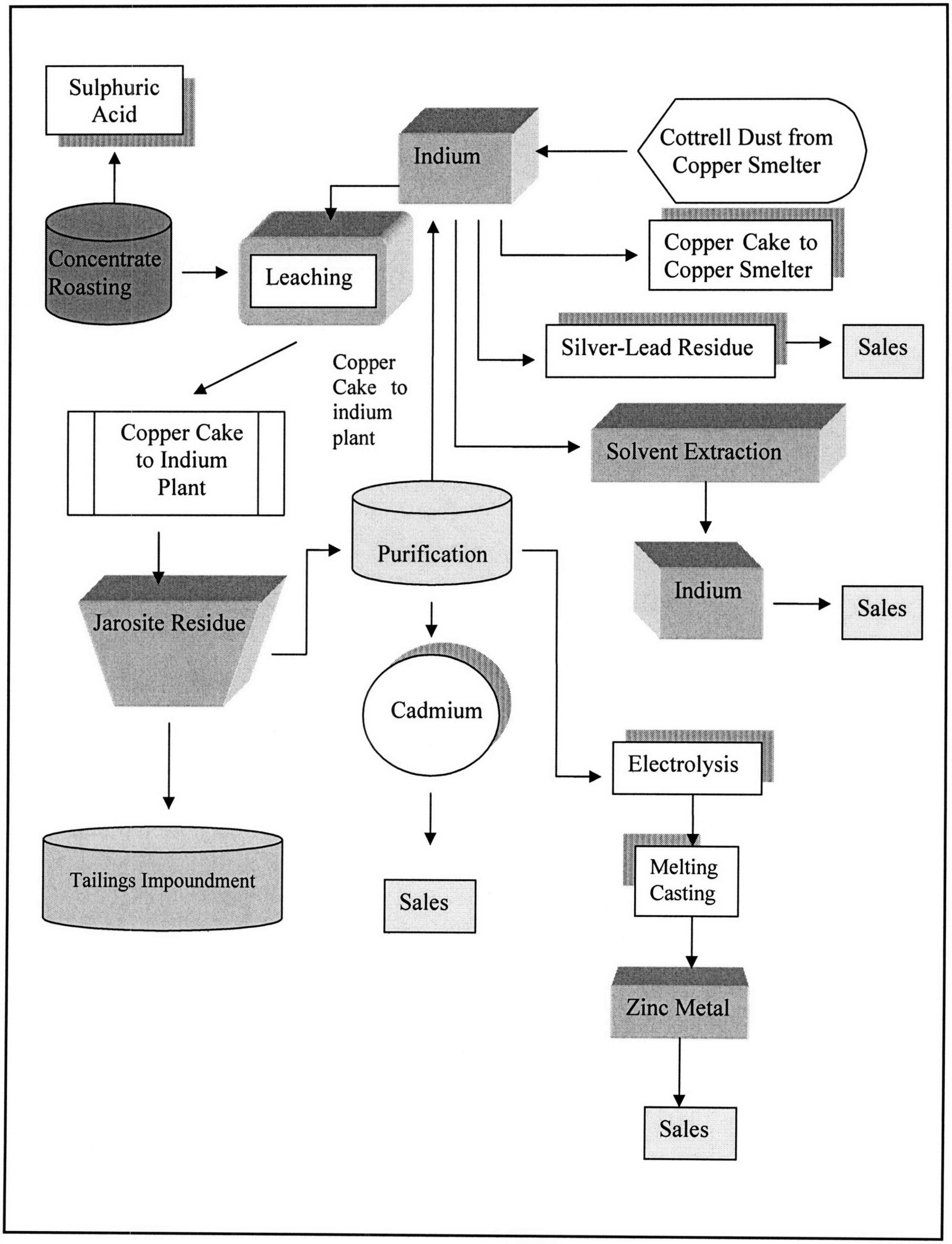
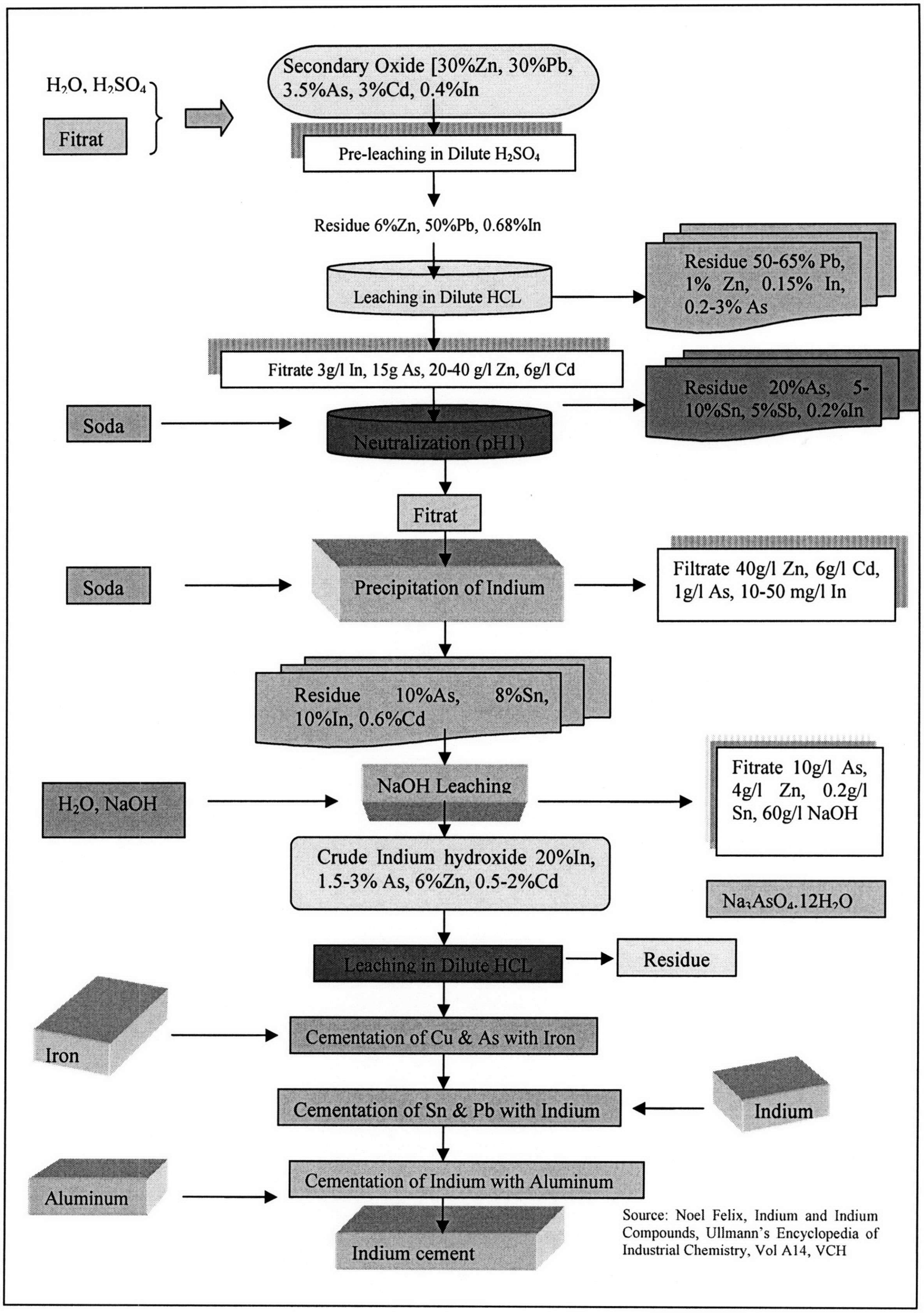


Fig 4.3: The production of indium from the process zinc smelting at the Kidd Creek zinc plant flow chart (Source: Falconbridge)

Meanwhile, Fig 4.5 shows that the indium recovery by Anaconda Copper Mining Company. Zinc calcine or zinc oxide fume is used for indium extraction. They are leached in the sulfuric acid. Indium can be obtained from the residue and bulk of zinc can be dissolved in the acid solution. The indium-contained alloy, dust, fumes, residues and slag from zinc and lead-zinc smelting are leached by using hydrochloric (HCL) or sulfuric acid (H_2SO_4).

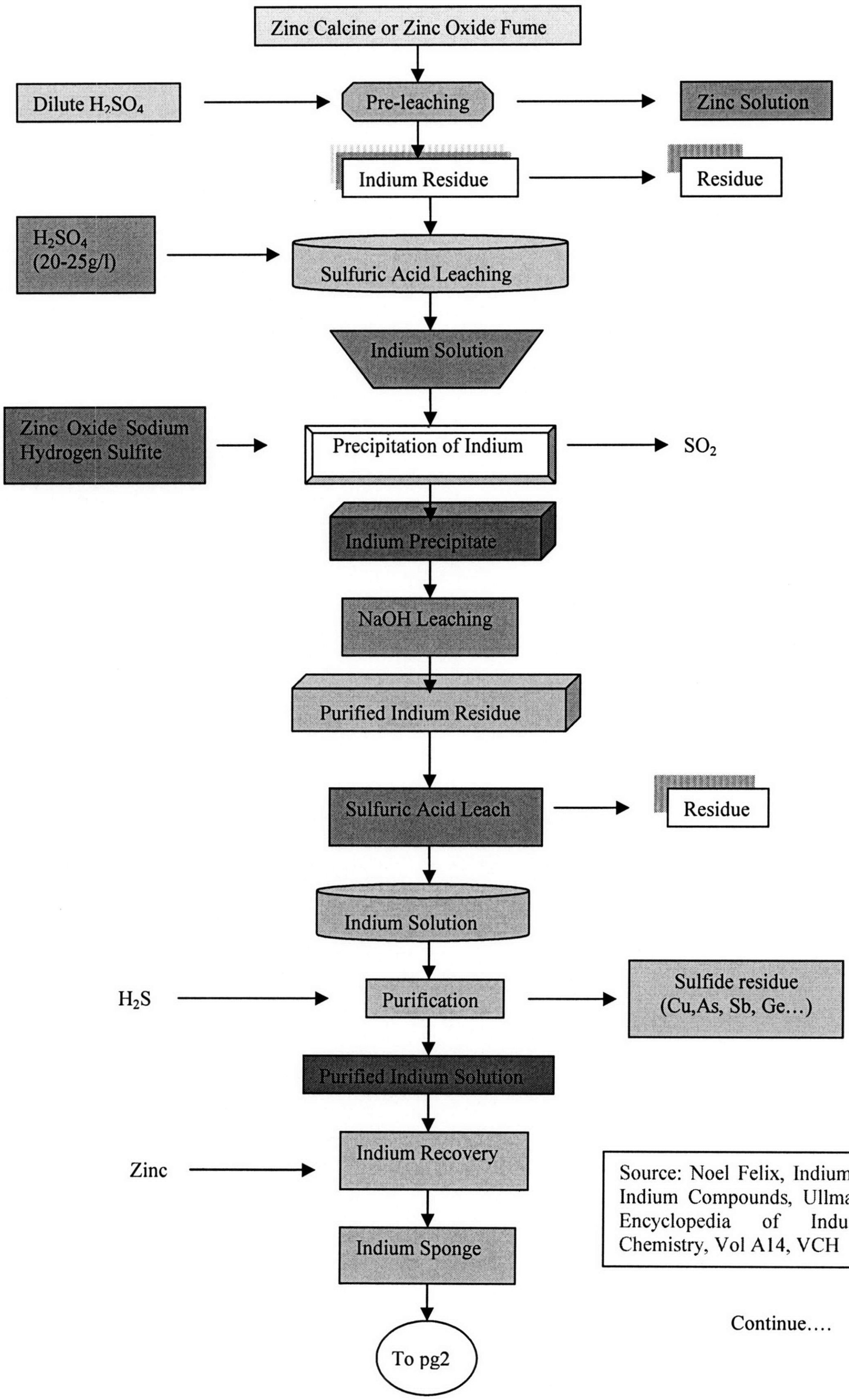
Next, indium residue is leached in 20-25 g/l sulfuric acid solutions. Indium is dissolved and some residues are separated in the sulfuric acid leaching stage. Zinc oxide and sodium hydrogen sulfite are used to obtain precipitation of indium and sulfur oxide. Zinc can be separated from the indium precipitate by using leaching with concentrated sodium hydroxide, water washing and followed by dilute sulfuric acid. Indium solutions can be purified by adding hydrogen sulfide. At the same time, the heavy metals like copper, arsenic and germanium are removed in form of a sulfide residue. Indium sponge can be extracted from this purified indium solution using zinc. Addition of zinc can produce 95% indium in the crude indium sponge.

The indium can be melted with sodium hydroxide to form indium metal or further purified if higher purity is required. For second method, the indium sponge is leached in hydrochloric acid. Next, sulphate ions can be separated by using barium chloride. Note that some heavy metals may contain in the sulphate ions free of indium chloride solution. Thus, hydrogen sulfide and sodium hydroxide are added into the indium chloride solution and purified indium solution is obtained. 99.99% purity of indium can be produced via electrorefining after filtration.



Source: Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14, VCH

Fig 4.4: Recovery of indium from secondary Zinc Oxide



Source: Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14, VCH

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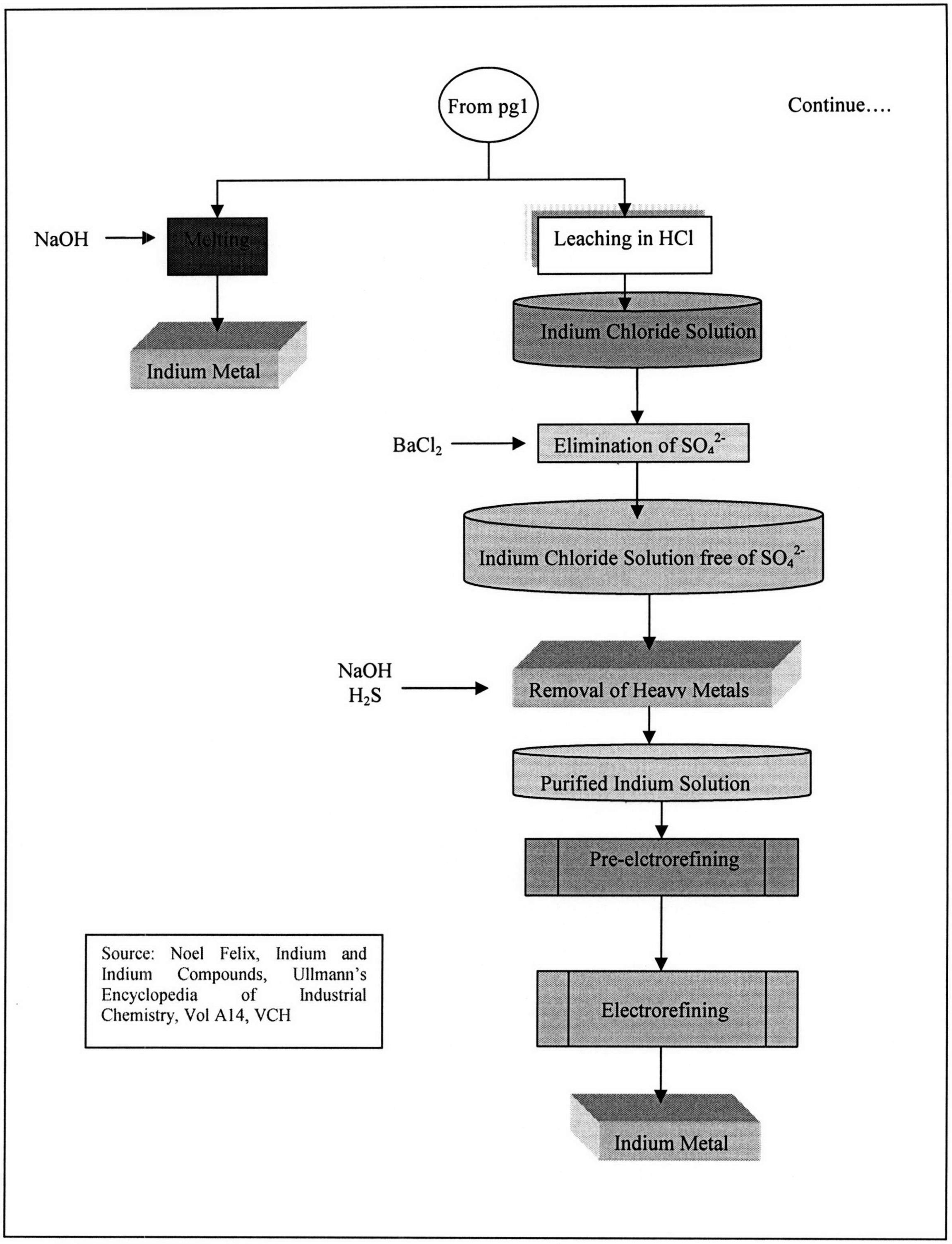


Source: Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14, VCH

Fig 4.5: Indium Recovery by Anaconda Copper Mining Company

4.2) Refining of indium

It is impossible to produce 100% pure metals. Some degree of metallic and nonmetallic impurities will be present in the indium. The metallic impurities are silver, copper, lead, antimony, tin, cadmium, titanium, zinc, iron, aluminum and gallium. Sulfur, chlorine, oxygen, selenium and nitrogen are the possible nonmetallic impurities in indium. Higher purity of indium can be obtained via refining processes. In commercial refining processes, electrorefining is one of the most important indium refining techniques. Multistage electrorefining, zone refining or electrorefining must be supplemented by vacuum distillation are normally applied in order to achieving purities up to 99.99%. Sometimes, zone refining and electrorefining which is supplemented by vacuum distillation are used.

Cotton-bagged indium anodes and pure indium cathodes are normally used in indium electrorefining. The function of the cotton bag is to avoid the metallic impurities mixing with the bulk electrolyte and degrading the purity of the indium deposit. These impurities are collected in anode slime form. The common electrolyte is a chloride solution. Sulfate solution, cyanide solution, fluoroborate ssolution, and sulfamate solution are also possible electrolytes. [27]

4.3) Recent indium production research and developments

It is expected that more and more research and developments on the indium production due to more demands on indium and the worries about the sustainability of the indium supply. The mixture of hydroxyquinolines (Kelex 100 and LIX 26) is applied to produce indium from acidic alkaline aqueous solutions. To leach lead-containing residue by using sulfuric acid, Di-(1-thyhexyl) phosphoric acid (D2EHPA) and tributyl phosphate (TBP) in kerosene are applied to separate arsenic, cadmium, zinc, copper, antimony, and iron. This method can be applied to the tin-containing sulfuric acid solution by addition of soluble fluorides. [27]

Some researchers carried out the extraction study of indium by using triphenylarsine oxide (TPASO), tripod phenolic ligands or monothiophosphinic acid. Besides, a solvent extraction method for indium by using LIX 973N were documented by F.J. Alquacil. Some methods related to the liquid-liquid extraction of indium from aqueous acid solutions by acid organophosphorus compounds were documented. A selective separation of indium experiment from a dilute solution using solvent-impregnated resin that containing Di(2-ethylhexyl) phosphoric acid was conducted by J.S. Liu et al.

High indium price in the recent day attract many attentions from the refiners. Some electronic manufacturer, especially for the liquid crystal display (LCD) and other display instruments manufacturers, put lots of efforts to recycle indium from indium-bearing scrap units. For example, Sharp had developed a technique related to recycling indium from indium tin oxide (ITO) in the LCD panels. More discussions on this matter will be carried out in the recycling section.

4.4) Conclusion

The uncertainty of indium-containing level in the different ores and low level of containing in part-per-million had caused the cost for indium extraction very high. Most of the world indium refineries are carried out using zinc circuit, except for few countries like Russia. Relatively high extraction cost has blocked the extraction effort from these circuits. However, it is expected that this situation may change if a dramatically rise of indium price and demands. Besides, the world indium reserve base in the zinc mines is estimated to last about ten years under current trend of indium consumption. Thus, tin and lead circuit may also be used for the extraction of indium in future. In addition, high indium price will motivate refiners, especially tin and zinc refiners can extract indium from tin and zinc ores respectively. At the same time, more indium production research and developments are suggested in order to extract this minor but valuable metal in more economical way.

Chapter 5: Cost Modeling

5.0) Introduction

In the previous chapters, information related to the world indium supply and demand chain, estimation of indium in Malaysia's mines, unique properties of indium and its applications and extraction technologies were discussed. In this chapter, whether it is economical to extract indium from Malaysia's mines will be discussed. There are several questions that may be raised. How does the high indium price affect the zinc refiner's decisions to extract indium from low indium contained zinc ores? How much will the Malaysian tin miners need to invest in indium extraction from the tin circuit? Thus, a cost modeling spreadsheet has been built up to answer these questions. In this chapter, the sensitivity analysis, cost analysis in different scenarios and strategy analysis will also be discussed.

5.1) Assumptions

There are a couple of assumptions which have been made to simplify the cost modeling spreadsheet. Some explanations for the values used in the cost modeling will be given. The assumptions are listed as below:

1. Electricity consumption for whole factory is 5000kWhr per day
2. A 'typical' extraction efficiency is taken as 80%
3. Assume more electrical energy is needed for extraction from tin circuit than extraction from zinc circuit. Thus an energy adjustment factor is used. (1 for zinc circuit and 3.5 for tin circuit)
4. The flow rate for each process is steady and constant.
5. Direct labor loading and unloading is assumed as 0.20 hour.
6. Accounting life of machine is 20 years
7. Building recovery life is 30 years
8. Capital recovery rate is 18 % (Used 72 rule for 4 years capital recovery rate)
9. Discount rate is 35%
10. Machines cost is set at $8,000,000
11. Working days is set 240

12. Number of technical staff, executive, and non-technical staffs are 20, 10 and 85 respectively.
13. Current total market/ demand to indium is 650,000kg
14. Probabilities for low, medium and high market are assumed.
15. Price 1 and Price 2 are varied to observe the change of the strategy summary. The strategy summaries give the hints for our decision in phase 1 and phase 2 and the expected values (EV).

Electricity consumption in a factory is generally a few thousands kWhr per day and the expense of an annual electricity bill usually costs several hundred thousands to few millions dollars. Here, 5000kWhr per day was used. The indium extraction efficiency is set at 80% since it is hard to extract all the indium contained in the ores. Besides, it is expected that more electrical energy is needed to extract indium from tin circuit than extracting from the zinc circuit. Thus, the energy adjustment factor for zinc circuit and tin circuit are 1.0 and 3.5 respectively.

The flow rate of chemicals for each process step is expected to be steady and constant. This assumption is usually considered reasonable after the all the process in the long run. The process is expected to be fully controlled by advanced control systems. However, some direct labor loading and unloading is expected. From the point of view of taxation, there are usage periods for the building and machines. Thus, the accounting life for the machines and building recovery life are 20 years and 30 years respectively. A typical capital recovery rate in refiners is 4 years. Using "72 Rules", the capital recovery rate is set at 18 %. Due to the time value of money, a discount rate of 35% is used to calculate the investment. Besides, a lump sum of Machines cost that excluded the installation fee is set at $8,000,000.

The number of working days in companies is determined by the government and the company. The typical annual working days are 220 – 300 days. Here, 240 days are used for our annual working days. Technical staffs, executives, and non-technical staffs are needed to ensure the operation in factory run smoothly. The number of technical staffs, executives, and non-technical staffs are 20, 10, and 85 respectively.

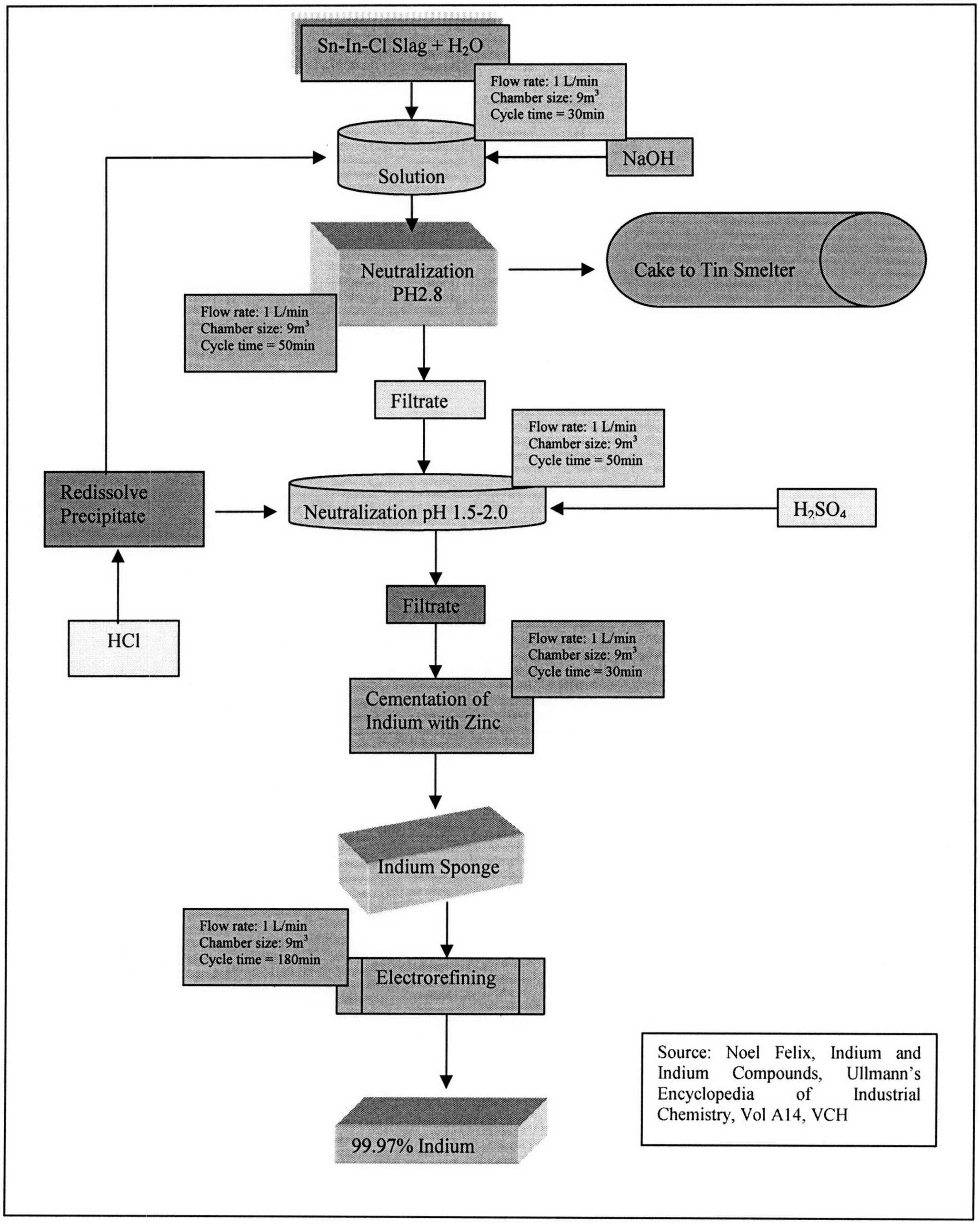
From previous chapter, it is also noted that the total market in 2005 is about 600 tonnes. Thus, it is assumed the total market is 650 tonnes in 2006. There are uncertainties for the future indium market, so the probabilities for low, medium and high market are assumed to figure out the strategy to exploit the indium market. Price 1 and Price 2 are varied to test how the variation of indium price affects our decisions. Thus, the decision in phase 1 and phase 2 and the expected values (EV) can be obtained.

In addition, the cost for producing 1kg of tin was about \$4.74 and \$5.00 in 1998 and 1999 respectively. (Metal Bulletin, 1998 ad Metal Bulletin Monthly, 1999) During 1998 and 1999, the closed mines were reopened and new mines had been developed and opened due to the improved profit margin from the tin mining. Thus, the cost for tin and zinc ores are estimated at one-third of the free market price tin and zinc respectively.

5.2) Process Flow

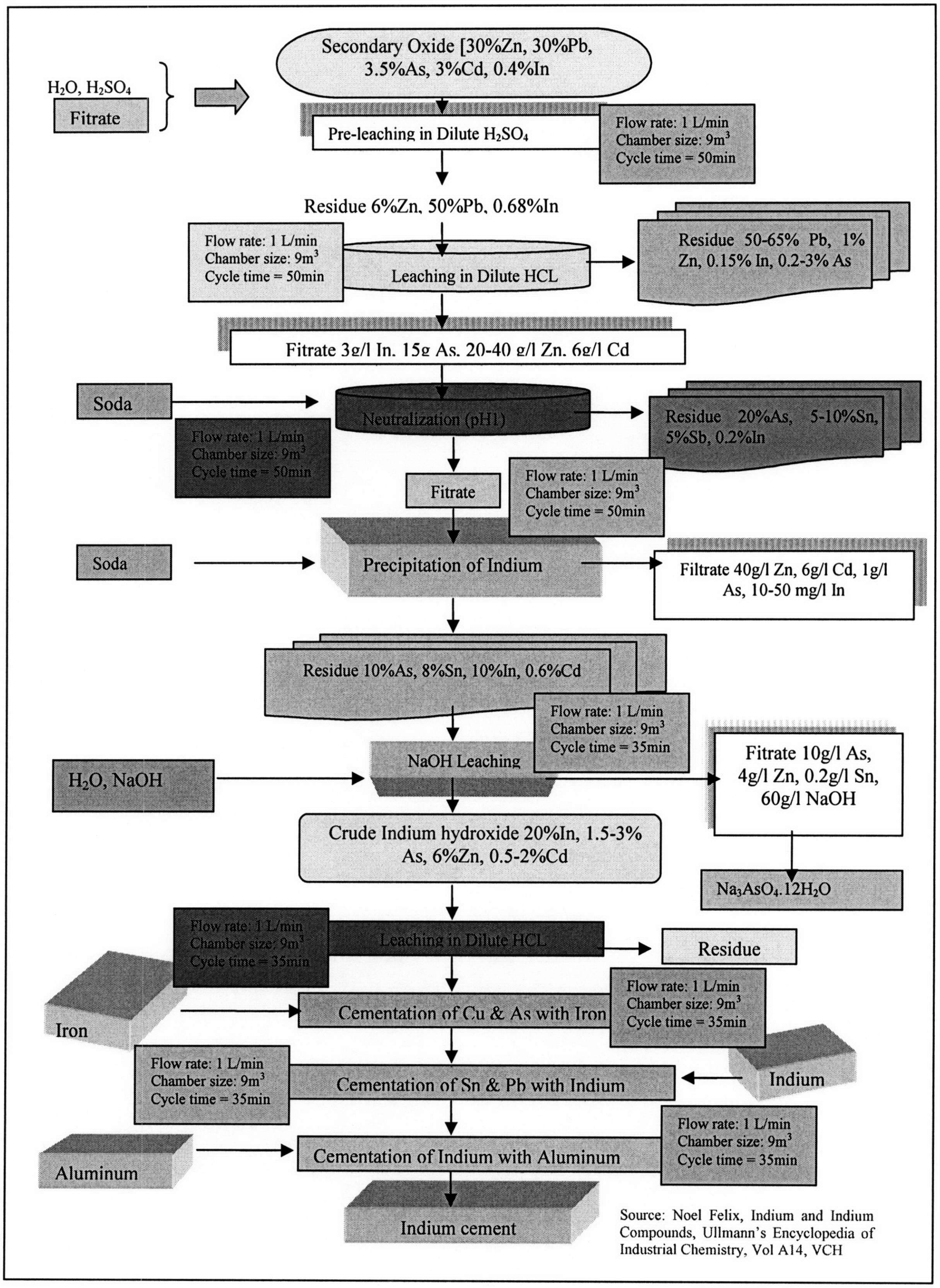
Process flows had been discussed in the Chapter 4. Here, the process flows for the indium recovery from tin circuits in the Capper Pass and the process flow for the recovery of indium from secondary zinc oxide are chosen for the cost modeling. The estimated process flow rate and chamber size for each step are shown in the Fig 5.1 and Fig 5.2 respectively. The detailed explanation about these process flows were provided in the Chapter 4.

As we assumed in the previous section, the flow rate for each process is steady and constant. Here, the flow rate for each step is set at 1L/min. Besides, the chamber size is considered the same for all processes, which is $9m^3$. However, the time needed for the extraction steps are expected to be different. Thus, the assigned values of the cycle time are set and are stated in the Fig 5.1 and Fig 5.2 respectively. These three process parameters play an important role in determining the materials cost.



Source: Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14, VCH

Fig 5.1: Process flows for the indium recovery from tin circuits in the Capper Pass, United Kingdom with stating the estimated flow rate, chamber size and cycle time for each process steps



Source: Noel Felix, Indium and Indium Compounds, Ullmann's Encyclopedia of Industrial Chemistry, Vol A14, VCH

Fig 5.2: Process flow for the recovery of indium from secondary zinc oxide with stating the estimated flow rate, chamber size and cycle time for each process steps

5.3) Formulae:

Some relationships were used to link the input, process parameters and production cost. The important formulae are shown as below:

5.3.1) Variable costs:

(a)Material cost

1. Material cost per year = Annual Ore input x ore price per year + Total cost for raw materials other than ore ($/kg) x 60 x Required operating time produced (Hours/year) / Effective cycle time (min)
2. Material cost per kg of indium produced = Material cost per year / Annual indium production
3. Total cost for raw materials except ore ($/kg) = (Σ Flow rate of each process x cycle for each step + Chamber size) x Price for each materials per litre

(b) Energy cost

1. Energy cost per year = Price of electricity x Annual energy consumption
2. Energy cost per kg of indium produced = Energy cost per year/ Annual indium production

(c)Labor cost

1. Annual labor cost = Σ salary of staffs each month x 12
2. Labor cost per kg of indium produced = Annual labor cost/ Annual indium production

5.3.2) Fixed cost:

(a) Machines cost

1. Total Investment for machines cost = Indium extraction machines cost x number parallel streams x (1 + installation cost (% of machines))
2. Machine cost per year = Normalized the total investment for machines cost into annual payment for a loan based on constant payment and capital recovery rate over machine life time

   = PMT (rate, total investment for machines cost, present value)

3. Machine cost per kg of indium produced = Machine cost per year/ Annual indium production

(b) Tooling cost

1. Total Investment for Tooling cost = Total cost for stirring tools and other tools (Replaced)
2. Annual tooling cost = Normalized the total investment for tooling cost into annual payment for a loan based on constant payment and capital recovery rate over product life time= PMT (rate, total investment for tooling cost, present value)
3. Tooling cost per kg = Tooling cost per year/ Annual indium production

(c) Fixed overhead cost

1. Annual Fixed overhead cost = Σ (Annual machines cost + Annual tooling cost + Annual building cost) x Overhead burden in % of Fixed Cost
2. Fixed overhead cost per kg of indium produced = Fixed overhead cost per year/ Annual indium production

5.3.3) Others

1. Total Investment for building space cost = Price for building space per sq feet x Required building space in sq meter x 0.0929
2. Annual building space cost = Normalized the total investment for building space into annual payment for a loan based on constant payment and capital recovery rate over building life time= PMT (rate, total investment for building space, present value)
3. Building space cost per kg of indium produced = building space cost per year/ Annual indium production
4. Annual maintenance cost = Σ (Annual machines cost + Annual tooling cost + Annual building cost) x maintenance cost in % of investment
5. Maintenance cost per kg of indium produced = maintenance cost per year/ Annual indium production

5.4) Results

Some parameters in the cost modeling spreadsheet had been changed to carry out a sensitivity analysis. Besides, some graphs have been generated in expected ranges to show the outcomes of the model and relevant explanations of the graphs are also provided.

The cost breakdown for extraction of tin and zinc ores are shown in the Fig 5.3 and Fig 5.4 respectively. The results are obtained by setting indium concentration at 0.5% and the annual process rate is 50,000,000 kg tin ore. It is found that the two main cost contributors are materials and labor. Note that more than 85% of the total cost is the materials cost. It is reasonable because the indium concentration is only 0.5% and a large quantity of tin or zinc ore is required in the process. Compared to the labor cost for tin circuit, the labor cost for zinc circuit has higher faction of total cost than because tin ore is more expensive than zinc ore.

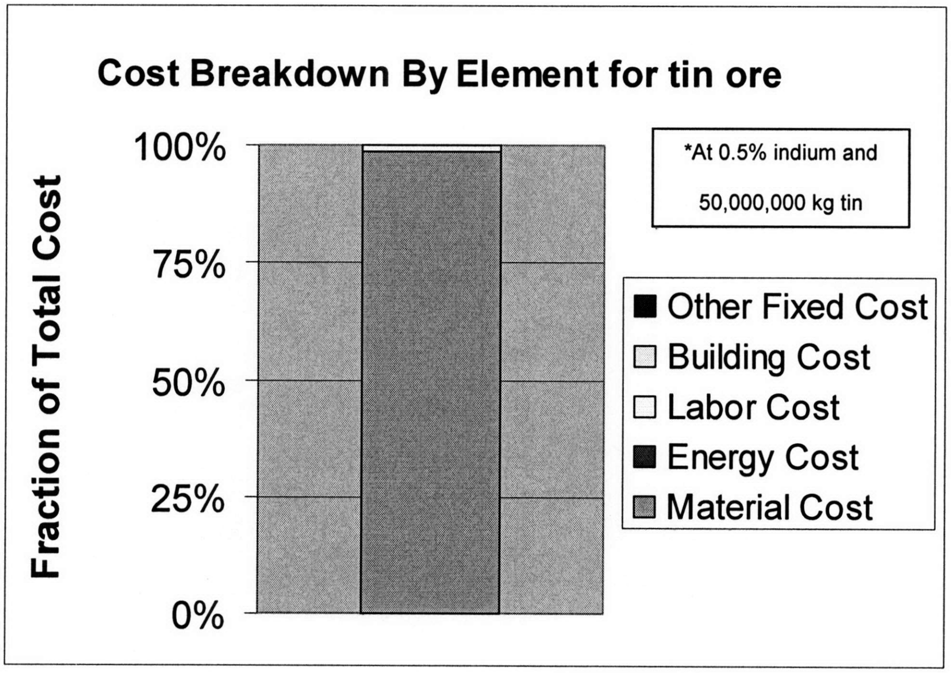


Fig 5.3: Cost breakdown for extraction of tin ore

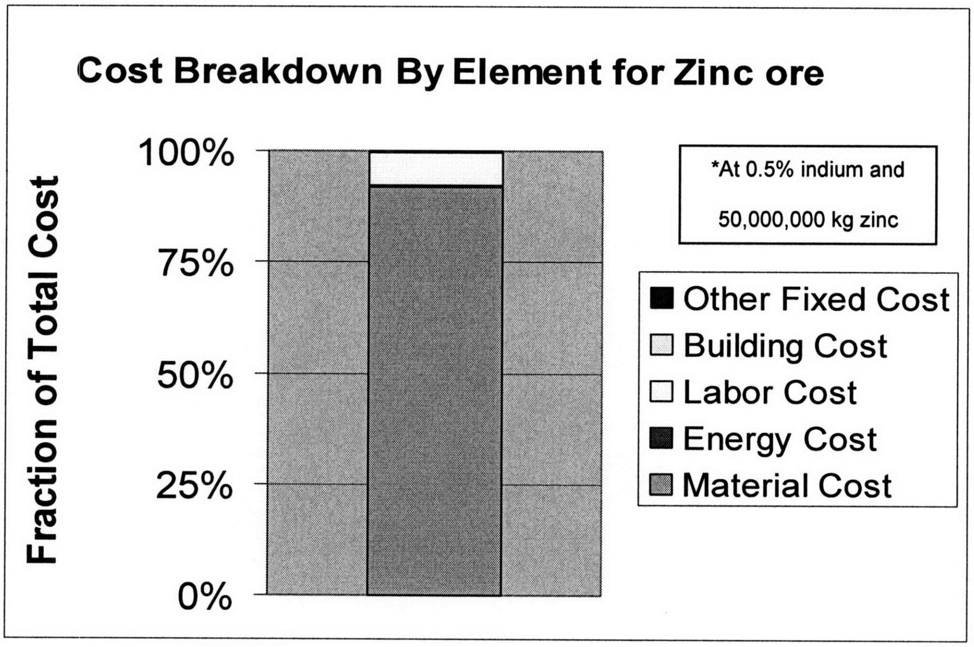


Fig 5.4: Cost breakdown for extraction of zinc ore

The effect of process rate on unit cost from extraction of tin ore is shown in Fig 5.5 and Fig 5.6 respectively. The indium concentration is assumed at 0.5% or 5000ppm. It is found that the fixed cost can be neglected in the calculation of unit production cost of indium for both tin and zinc ores. For the process rate below than 10,000,000 kg/year, the unit production cost for indium is decreasing when the process rate is increasing. It is true for zinc circuit and tin circuit. However, the indium unit production cost does not change much if we increase the process rate beyond 10,000,000 kg/year. It is noted that economics of scale happen for extraction process when it is cheaper to extract indium from zinc or tin ores in quantity. In other words, indium unit production cost will remains at about $700 and $100 for tin and zinc ores if the indium concentration is found at 0.5% or 5000ppm for tin and zinc respectively, even the process rate is doubled.

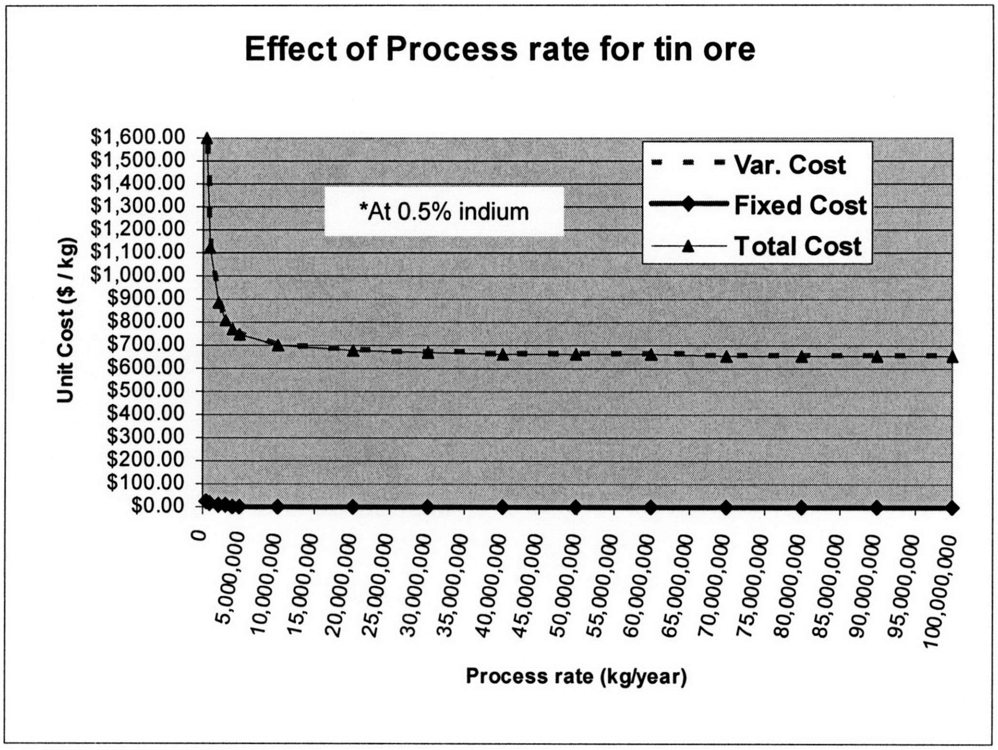


Fig 5.5: Effect of process rate for extraction of tin ore

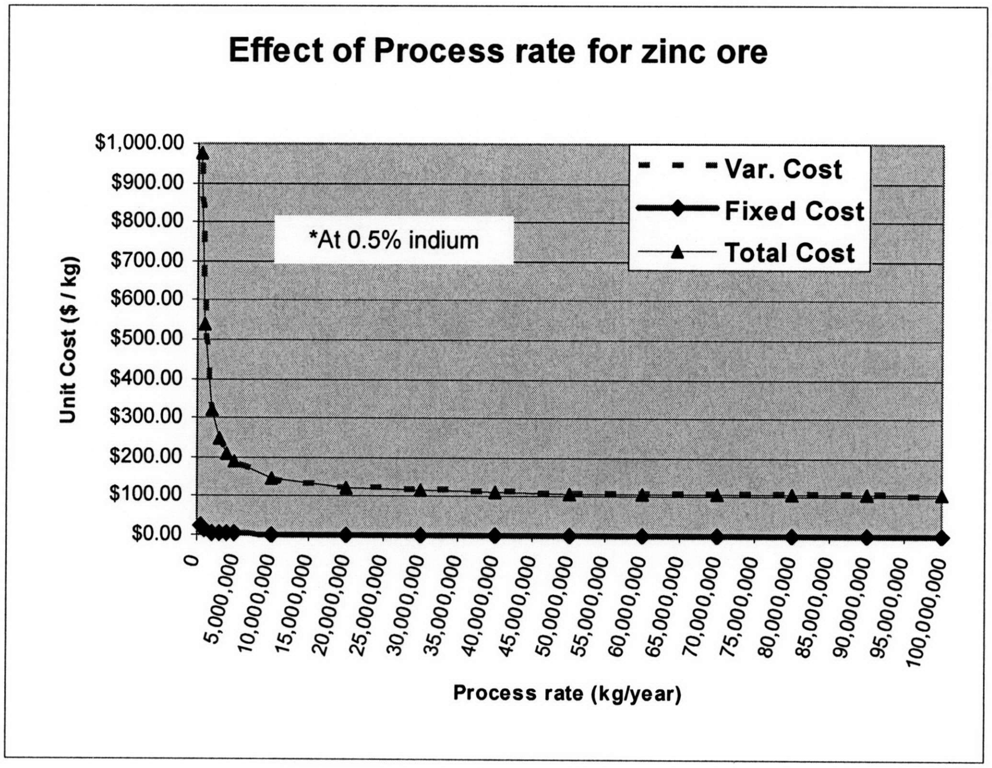


Fig 5.6: Effect of process rate for zinc ore

In Fig 5.7, comparison of the effect of indium concentration for extraction of tin and zinc ores is shown. The indium unit cost is obtained by varying the indium concentration accordingly. The annual process rate is set at 50,000,000kg. The unit production cost for indium decreases dramatically when the indium concentration increases from 1500ppm and 3000ppm for zinc and tin ore respectively. If the indium concentration exceeds 1500ppm and 3000ppm for zinc and tin ores respectively, the indium unit production cost will be reduced at a much slower rate. The lowest indium unit production cost from tin and zinc ores are \$300 and \$55. That is also the reason why most of world indium production is obtained from zinc circuit since the indium price is below \$250 most of time.

However, this situation might be different if the indium price reaches \$1000/kg. It becomes economical to carry out indium extraction from tin ore. Since it is foresee that the indium price will remain at about \$1000/kg, it is economical to extract indium from zinc ore if indium concentration is as low as 500ppm. Meanwhile, it becomes economical to extract indium from tin ore if the indium concentration exceeds 3000ppm.

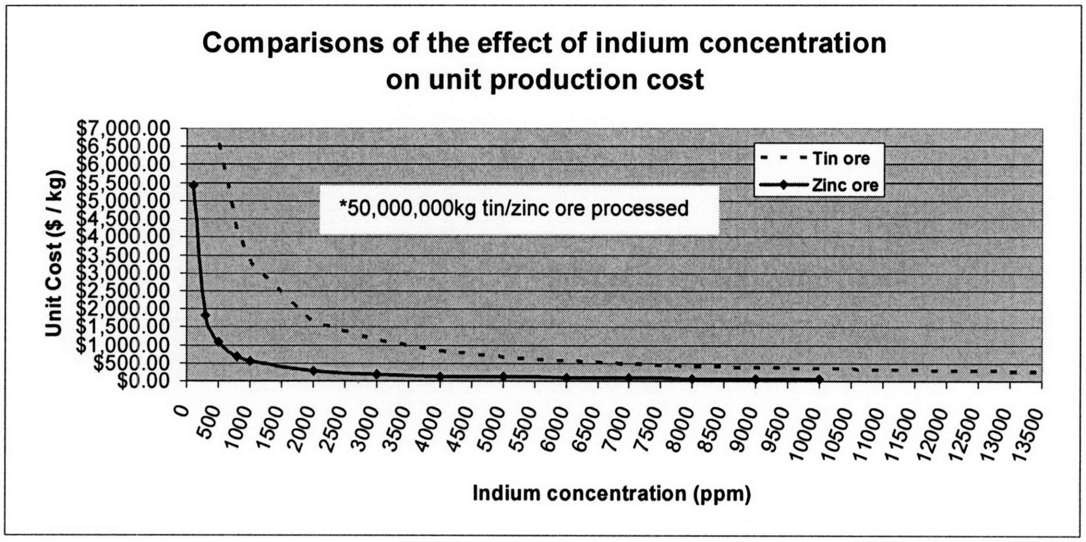


Fig 5.7: Effect of indium concentration for extraction of tin and zinc ores

The effect of process rate of tin and zinc ores in different extraction efficiencies are shown in the Fig 5.8 and Fig 5.9 respectively. For the tin ore, every 5% improvement of extraction efficiency will reduce the unit cost about \$30-40. Meanwhile, \$5-\$15 of the unit cost can be reduced by improving 5% of the extraction efficiency. In other words, improvement in the indium extraction efficiency for the tin circuit has a larger impact on the unit cost for same process rate than the zinc circuit.

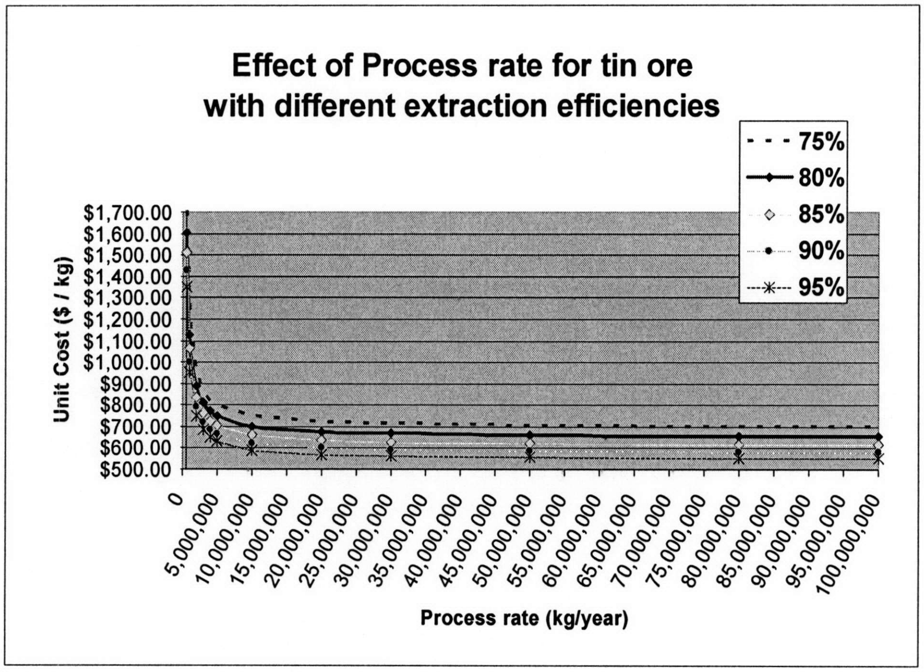


Fig 5.8: Effect of process rate of tin ore with different extraction efficiencies

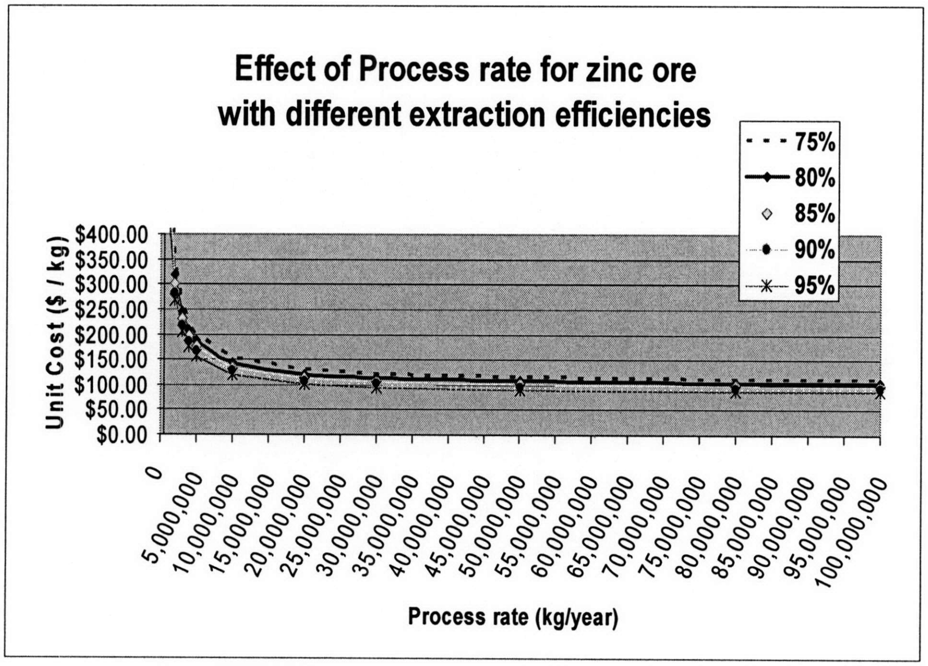


Fig 5.9: Effect of process rate of zinc ore with different extraction efficiencies

The effect of process rate of tin and zinc ores with different indium concentrations are shown in the Fig 5.10 and Fig 5.11 respectively. It is found that the indium unit cost for tin circuit is more sensitive to the indium concentration level, as compared to the zinc circuit. However, the unit cost does not change much after the composition of indium reaches 6000ppm. For zinc ore, higher indium composition in the zinc ore can reduce the unit cost slightly when the indium composition exceed than 4000ppm.

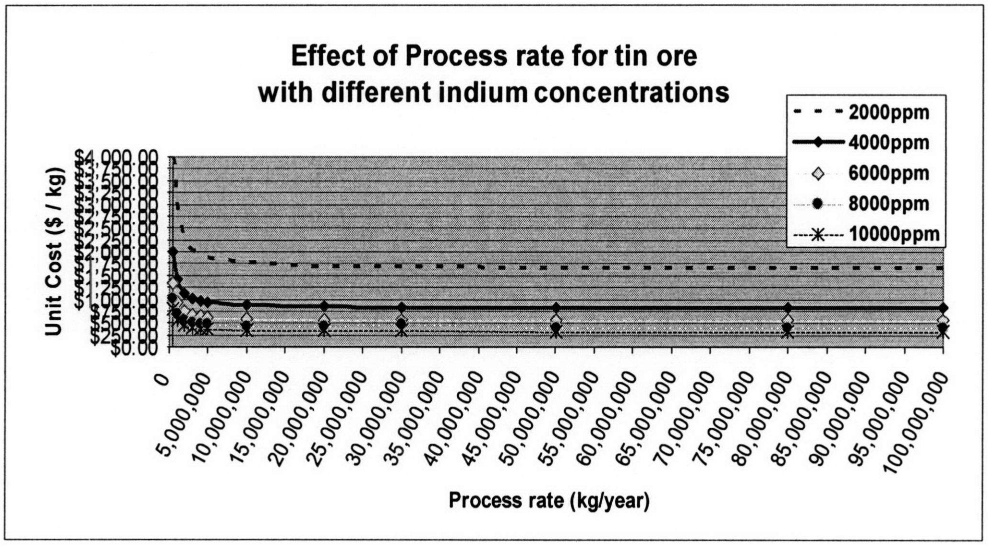


Fig 5.10: Effect of process rate of tin ore with different indium concentrations

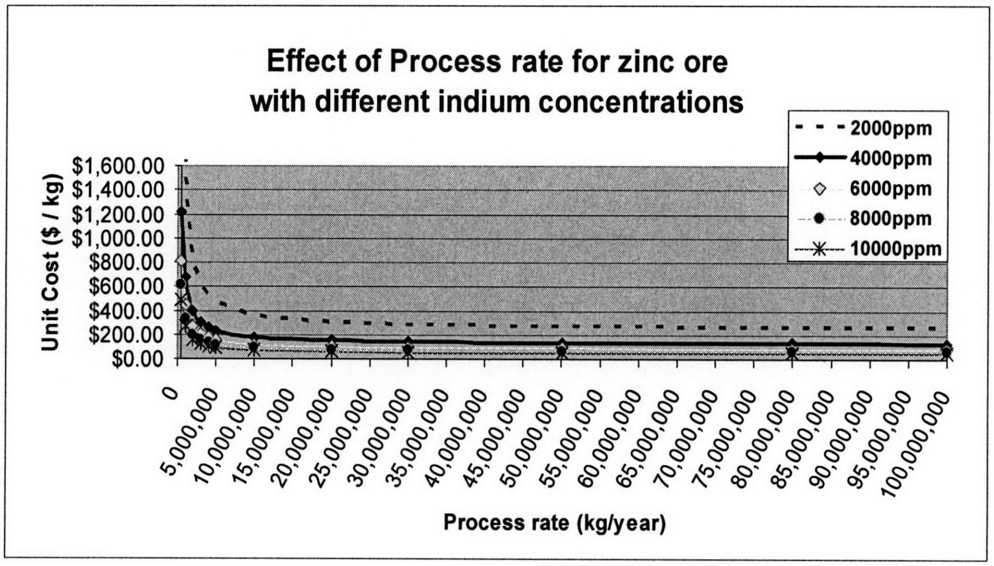


Fig 5.11: Effect of process rate of zinc ore with different indium concentrations

The graphs above are merely considering the profit from extraction of indium. Some other compositions might exist in the tin and zinc ores. Fig 5.12 is generated by taking the economic impacts from the largest quantity in the tin and zinc ores respectively, which are tin and zinc. It is found that the indium unit cost for the tin circuit will decrease dramatically and the unit cost is reduced to about $200/kg if the annual process rate exceeds 10,000,000kg. The profit from zinc has little effect on the indium production overall since the zinc market price is low.

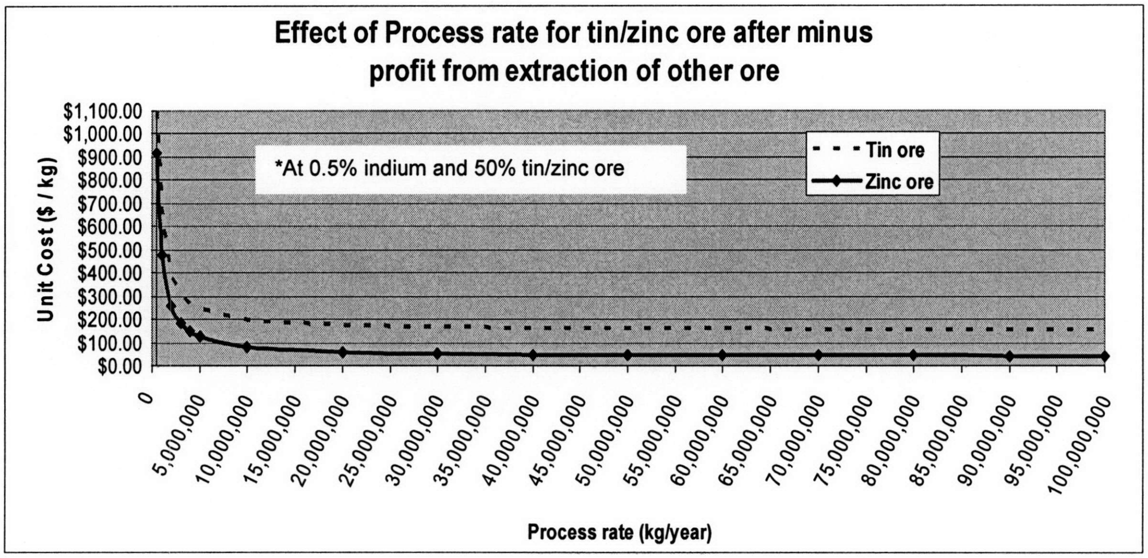
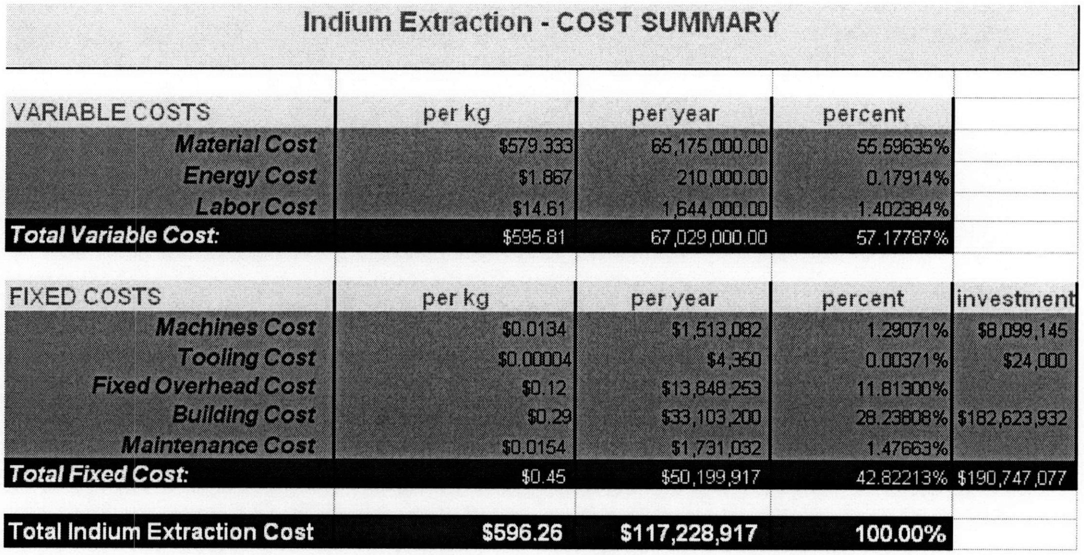


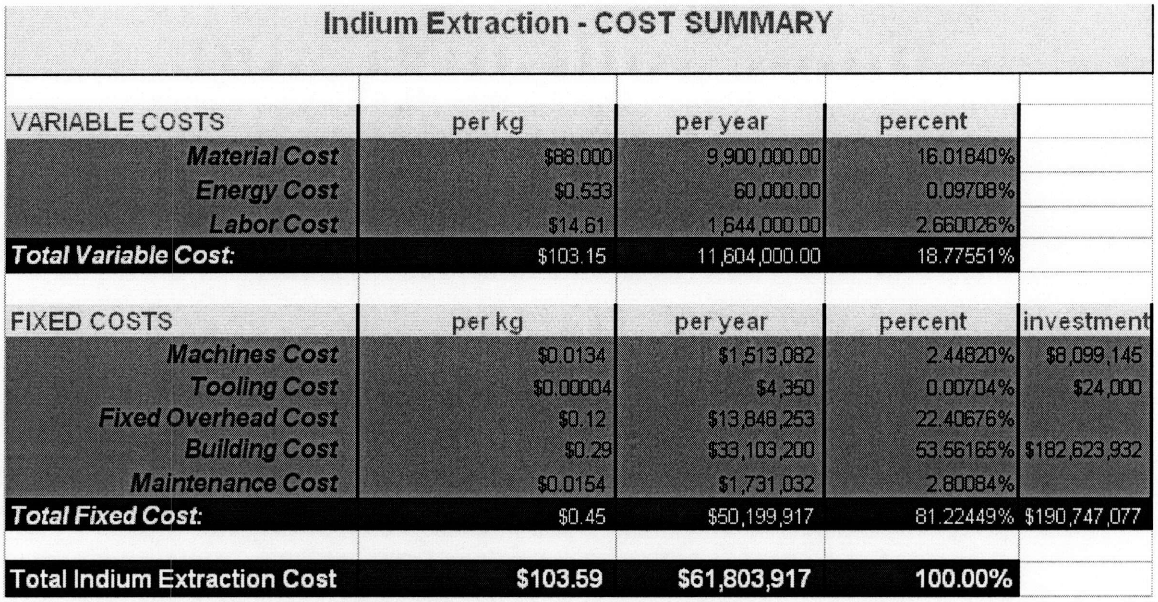
Fig 5.12: Effect of process rate on unit cost of indium for extraction from tin and zinc ores with taking consideration of market value of tin and zinc ores



Indium Extraction - COST SUMMARY

VARIABLE COSTS	per kg	per year	percent	
Material Cost	$579.333	65,175,000.00	55.59635%	
Energy Cost	$1.867	210,000.00	0.17914%	
Labor Cost	$14.61	1,644,000.00	1.402384%	
Total Variable Cost:	$595.81	67,029,000.00	57.17787%	
FIXED COSTS	per kg	per year	percent	investment
Machines Cost	$0.0134	$1,513,082	1.29071%	$8,099,145
Tooling Cost	$0.00004	$4,350	0.00371%	$24,000
Fixed Overhead Cost	$0.12	$13,848,253	11.81300%	
Building Cost	$0.29	$33,103,200	28.23808%	$182,623,932
Maintenance Cost	$0.0154	$1,731,032	1.47663%	
Total Fixed Cost:	$0.45	$50,199,917	42.82213%	$190,747,077
Total Indium Extraction Cost	**$596.26**	**$117,228,917**	**100.00%**	

Fig 5.13: Indium concentration level at 0.5 % or 5000ppm for tin circuit at annual process rate of 25,000,000kg



Indium Extraction - COST SUMMARY

VARIABLE COSTS	per kg	per year	percent	
Material Cost	$88.000	9,900,000.00	16.01840%	
Energy Cost	$0.533	60,000.00	0.09708%	
Labor Cost	$14.61	1,644,000.00	2.660026%	
Total Variable Cost:	$103.15	11,604,000.00	18.77551%	
FIXED COSTS	**per kg**	**per year**	**percent**	**investment**
Machines Cost	$0.0134	$1,513,082	2.44820%	$8,099,145
Tooling Cost	$0.00004	$4,350	0.00704%	$24,000
Fixed Overhead Cost	$0.12	$13,848,253	22.40676%	
Building Cost	$0.29	$33,103,200	53.56165%	$182,623,932
Maintenance Cost	$0.0154	$1,731,032	2.80084%	
Total Fixed Cost:	$0.45	$50,199,917	81.22449%	$190,747,077
Total Indium Extraction Cost	**$103.59**	**$61,803,917**	**100.00%**	

Fig 5.14: Indium concentration level at 0.5% or 5000ppm for zinc circuit at annual process rate of 25,000,000kg

5.5) Discussion

High indium price can motivate the zinc refiner's decisions to extract indium for lower indium containing zinc ores. This should motivate refiners to extract indium from tin ore, which was not economical to do that previously. We know that zinc and tin are the metals that have low market value. Now, we can extract indium as the main business activities and extract zinc and tin as a "by-product" activity.

In additions, the cost modeling spreadsheet also shows that the Malaysian tin miners are required to spend about $190million for the investment in indium extraction from tin circuit. It is expected the capital can be recovered in 4 years since the capital recovery rate is 18% per year. Materials cost contributes most of the total cost for indium refinery from either tin ore or zinc ore. That's the reason why variable cost is almost equal to total required cost for indium extraction.

Higher indium extraction rate can reduce the unit cost greatly for the tin circuit. Compared to tin ore, indium unit cost for zinc ore is less sensitive to the indium concentration. However, when the indium composition level exceeds 6000ppm and 4000ppm for tin and zinc ore respectively, the unit cost can be deducted at a much slower rate. It is expected that the indium unit cost will not be altered much when the annual process rate exceeds 10,000,000 kg and 20,000,000kg for tin and zinc ores respectively.

Thus, more research on the extraction of indium from tin ore are encouraged. The economics of scale for the annual process rate is estimated to be about 10,000,000 kg and 20,000,000kg.

Since a lot of assumptions are made in this cost modeling, some differences with real business are expected. However, the shape of the graph for extraction cost tin and zinc ores are expected to be correct. This means the real situations are expected have same tendency with the generated graphs. Thus, the results of this spreadsheet can be easily corrected if the real business data are obtained.

Chapter 6: Market Analysis and Business model

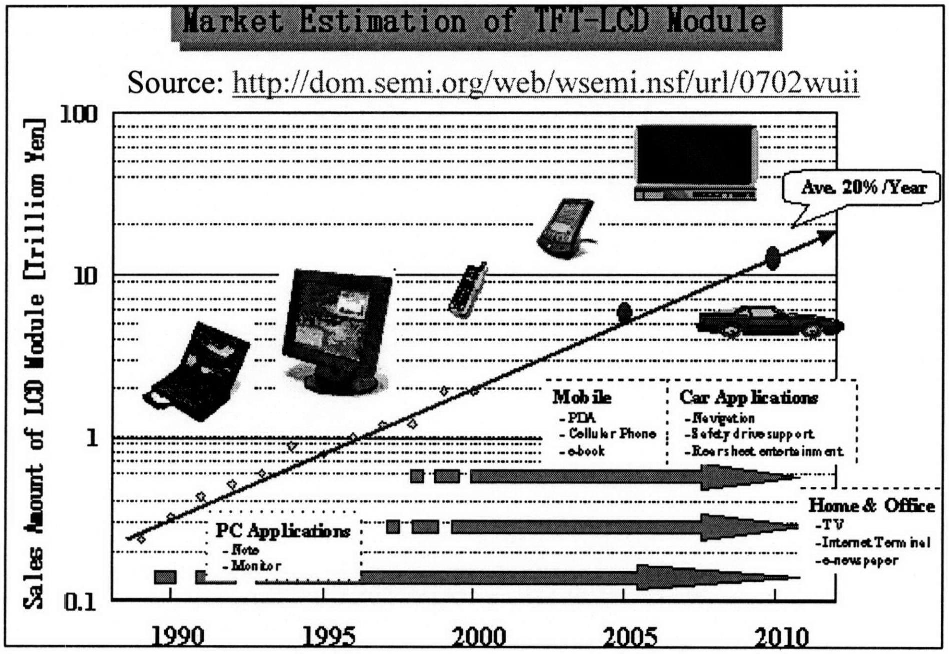
6.0) Introduction

Globalization has brought the indium world market closer and closer. This means that the production or consumption in one country might influence world price. It is noted that about 70% of world indium production has been consumed in thin film coatings. This reflects the fact that the demand from thin film coatings application affects the world indium price. Thus, the market estimation on TFT-LCD is an important analysis tool to trace out the trend of the price for indium. Here, some market estimation reports for TLT-LCD will be discussed.

In this chapter, a business model for indium extraction will be discussed. Some supporting articles will be given to support some arguments. In addition, a decision tree for the indium business will be provided to show some strategies which should be taken in phase 1 and 2.

6.1) TFT-LCD market estimation

The demands from the application of thin film coatings, especially for LCD markets have huge impacts on the price. Compared to other countries, Japan is the largest indium consumer country. In the Fig 6.1, TFT-LCD market estimation from Semicond has been shown. It shows that the average annual growth rate for TFT-LCD market is projected into 20%. The TFT-LCD modules are mainly applied in PC monitors, mobile phones, cars and so on. In 2010, the sales amount of TFT-LCD market is estimated projected to 10 trillion yen.

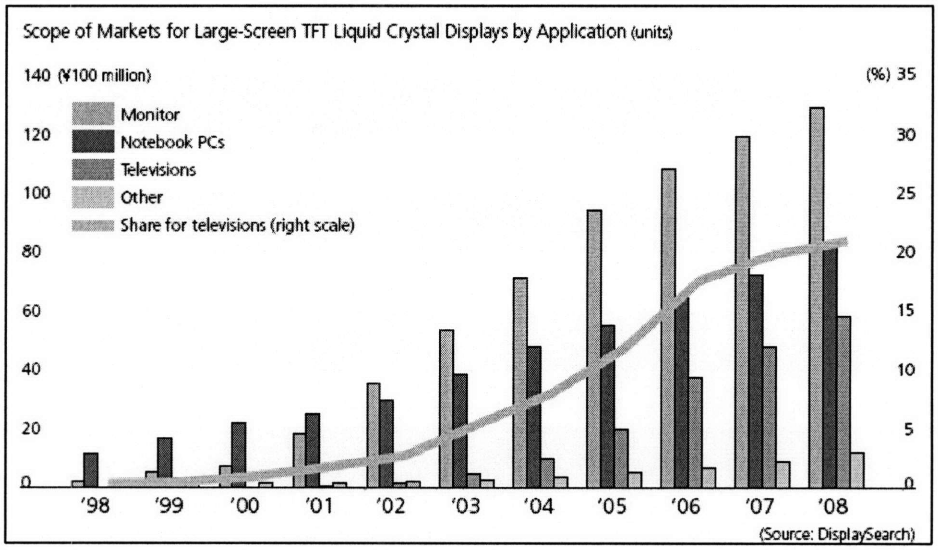


Source: http://dom.semi.org/web/wsemi.nsf/url/0702wuii

Fig 6.1: TFT-LCD market estimation

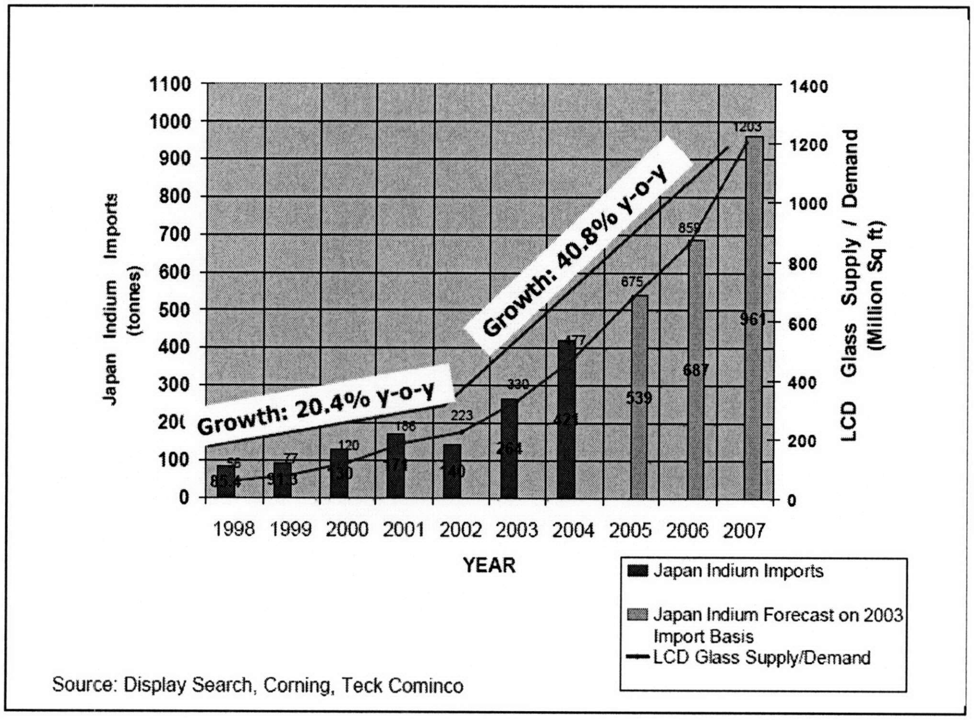
Another well-known LCD estimation source is DisplaySearch.com and it has outlined a similar market trend for LCD. The market for large-screen TFT liquid crystal displays by application has been shown in the Fig 6.2. The large-screen TFT liquid crystal displays can further be divided into applications in monitors, notebook personnel computers, televisions and others. Monitors and notebook personnel computers are two major applications in the LCD market. It is found that the applications of the large-screen TFT liquid crystal displays are estimated to grow at a steady rate in the next two years.

As the highest indium consumer country, Japan has a large influence on the world indium price. Thus, an analysis of Japan's indium import is important. Fig 6.3 shows Japan's indium imports from 1998 to 2004 and the forecasted import for 2005 to 2007. Besides, the LCD supply and demand are shown in the same figure. Parallel to the growth in LCD, it is found that Japan's indium import grew at a steady rate from 1998 to 2004, except 2002. The growth rate for LCDs is 20% for 1998-2002 and it increased to 40% in 2003-2004. Similar growth rate is expected to be continuing until 2007.


Scope of Markets for Large-Screen TFT Liquid Crystal Displays by Application (units)

(Source: DisplaySearch)

Fig 6.2: Scope of market for large-screen TFT liquid crystal display by applications



Source: Display Search, Corning, Teck Cominco

Fig 6.3: Japan's indium imports from 1998 to 2004 and the forecasted import for 2005 to 2007

In the Fig 6.4, the main electronic factories that invest in large LCD fabrication capacity are shown. The main LCDs manufacturers are Arima Display Corp., AU Optronics (AUO), Samsung Electronics, LG Philips, Samsung Electronics, BOE Technology Co. Ltd., Chi Mei Optoelectronics, Chunghwa Picture Tubes, HannStar

Display Co, Innolux, Sharp Corp. This reflects that the demand and supply of LCDs will be increased since these main LCD manufacturers are upgrading their LCD producing facilities. More information related to LCD can be found in the Appendix C.

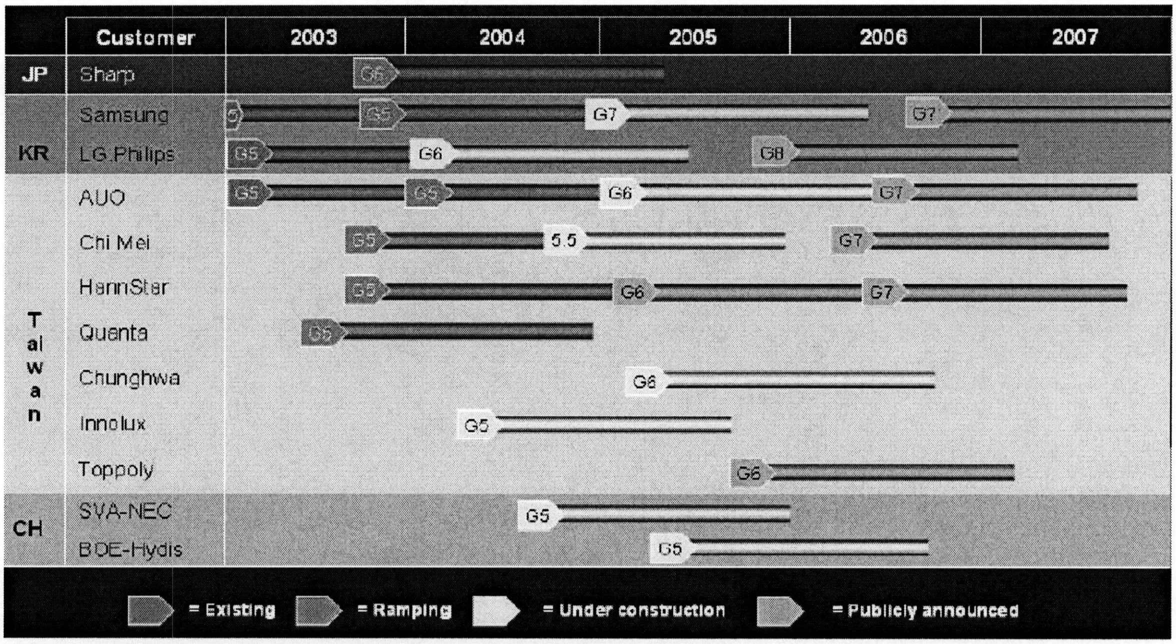


Fig 6.4: Customer investing in large fabrication capacity

Source: Corning, Teck Cominco

6.2) Business Model

The potential indium contained in the Malaysian tin mines is estimated based the indium concentration report by Traub & Moh. They figured out the possible indium concentration range in Malaysian tin mines is from 100ppm to 10000ppm. In last chapter, it is expected to be economical to refine indium from the tin ore in Malaysia. From the cost modeling spreadsheet, it is profitable to extract indium if the indium concentration is more than 300ppm. To discuss of possible business model in a convenient way, it is assumed a company which named as Indium Corporation of Malaysia will be set up.

According to USGS, there is 1,000,000 metric tones tin base in Malaysia. Using these figures, following simple calculations are carried out.

Tin Base in Malaysia = 1,2 00,000 metric tonnes =1,2 00,000,000kg (USGS)
5000ppm indium means 6,000 tonnes available
1000ppm indium means 1200 tonnes available
500ppm indium means 600 tonnes available
100ppm indium means 120 tonnes available

Assume that we have the indium concentration level of 1000ppm and the market price is $1000/kg. This means 1,200 tonnes indium is available and this is also equivalent to USD $1.2 billion! This shows a big business opportunity for the Indium Corporation of Malaysia to extract indium from tin circuit. This means that extraction of indium from tin circuits becomes our major business and the tin ore is considered as a by-product since indium is more valuable than tin.

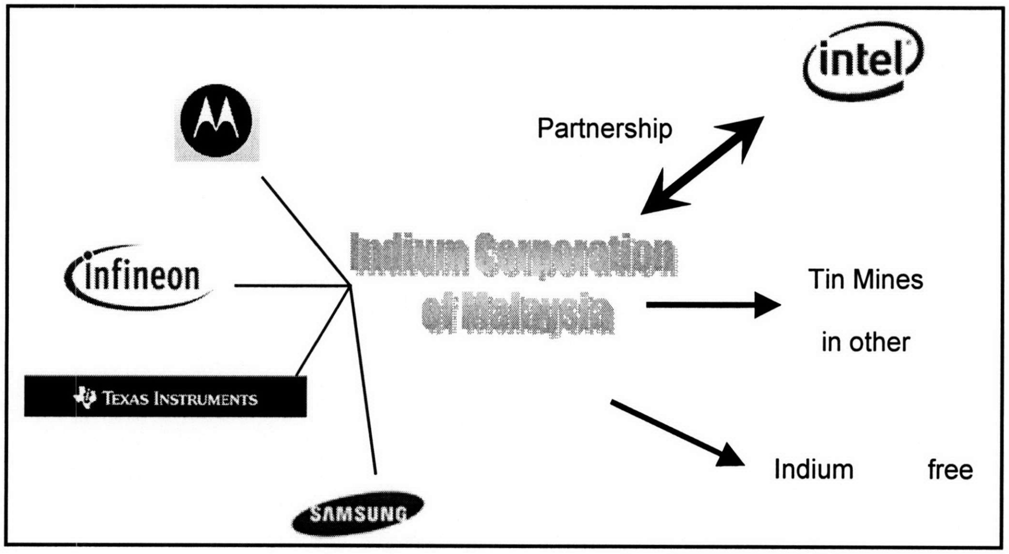


Fig 6.5: A suggested business model for Indium Corporation of Malaysia

A business model for Indium Corporation of Malaysia is suggested in the Fig 6.5. As an initiator for this project, Intel is expected to create a major partnership with Indium Corporation of Malaysia. Intel might invest some money and hold some shares of Indium Corporation of Malaysia. Besides, the requirements of lead free soldering forces the electronics manufacturing factories to change their soldering and this enhance the possibility that they start to use indium alloy solders. Motorola, Infineon, Texas

Instruments and Samsung may become the potential customers for Indium Corporation of Malaysia. In additions, the refined indium is also sold in the indium free market. We can also expand our indium business in corporation with the tin mines in other countries based on the knowledge and experiences we gained from extraction operation in Malaysian tin mines.

6.3) Competitors --- monopoly, duopoly, oligopoly?

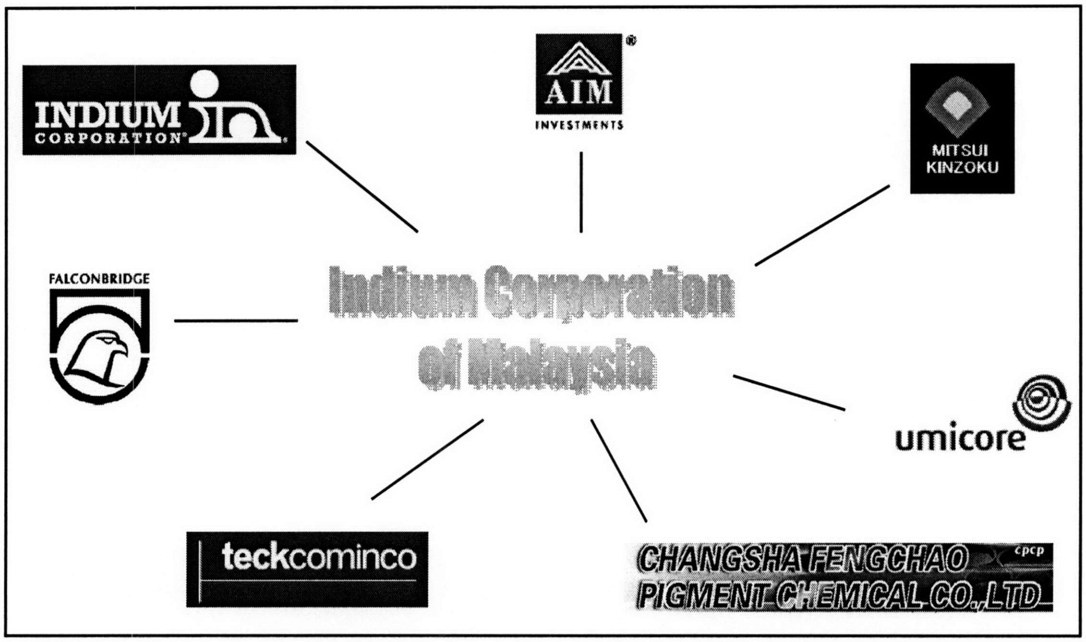
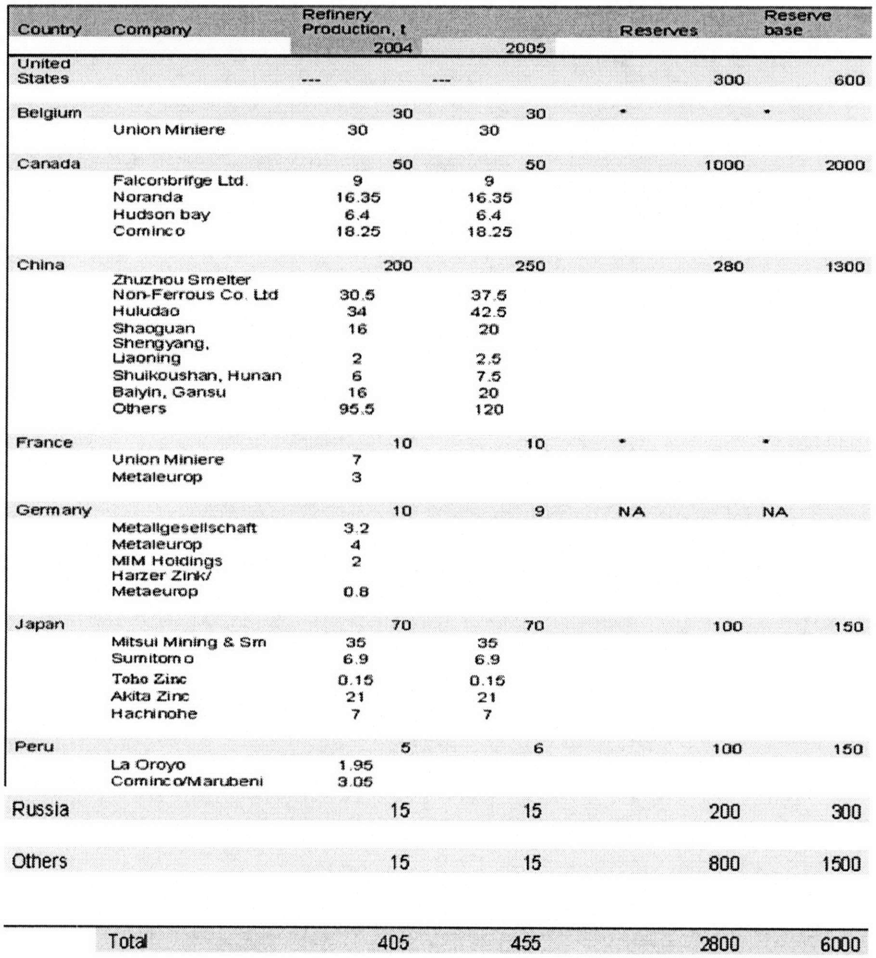


Fig 6.6: Some competitors for the Indium Corporation of Malaysia

In business, it is important to know who will be our potential competitors. In Fig 6.6, some potential competitors for the Indium Corporation of Malaysia are shown. They are AIM, Alfa Aesar, Belmont Metals Inc., Indium Corporation of America, Asahi Pretec Corp., Dowa Mining Co. Ltd., Japan Energy Corp., Mitsui Kinzonku, Umicore, ChangSha Fengchao pigment Chemical Co. LTD, Dongwu Nonferrous Metals Mine, Teckcominco and Falconbridge and so on. It is noted that “all of the output of indium from the Kidd Creek smelter operated by Falconbridge in Canada is shipped to Indium Corporation of America for further refining. All Falconbridge’s indium production is marketed by Indium Corporation of America”. [43] An estimate idea for the production capacity of each company is outlined here. It is estimated by making the following assumptions. The refining of indium is done by extraction from zinc ores and the indium production is directly proportional to the production of zinc. Only special attention is given to Russia. Some data is adjusted based on supporting data. The total refining volume for each country was obtained from USGS. The estimated data does not reflect the actual indium production for each company. However, it is clear that no one company can monopolize the market.

The world indium production for some main producers and their production data are shown in Fig 6.6. Besides, the indium price strongly depends on the demand of ITO and reduction in refining capacity. Increasing demand from low-temperature use may be another factor. However, greater recycling activities can increase the production volume and then decrease price.



Country	Company	Refinery Production, t 2004	2005	Reserves	Reserve base
United States		---	---	300	600
Belgium		30	30	*	*
	Union Miniere	30	30		
Canada		50	50	1000	2000
	Falconbrifge Ltd.	9	9		
	Noranda	16.35	16.35		
	Hudson bay	6.4	6.4		
	Cominco	18.25	18.25		
China		200	250	280	1300
	Zhuzhou Smelter Non-Ferrous Co. Ltd	30.5	37.5		
	Huludao	34	42.5		
	Shaoguan	16	20		
	Shengyang, Liaoning	2	2.5		
	Shuikoushan, Hunan	6	7.5		
	Baiyin, Gansu	16	20		
	Others	95.5	120		
France		10	10	*	*
	Union Miniere	7			
	Metaleurop	3			
Germany		10	9	NA	NA
	Metallgesellschaft	3.2			
	Metaleurop	4			
	MIM Holdings	2			
	Harzer Zink/ Metaeurop	0.8			
Japan		70	70	100	150
	Mitsui Mining & Sm	35	35		
	Sumitomo	6.9	6.9		
	Toho Zinc	0.15	0.15		
	Akita Zinc	21	21		
	Hachinohe	7	7		
Peru		5	6	100	150
	La Oroyo	1.95			
	Cominco/Marubeni	3.05			
Russia		15	15	200	300
Others		15	15	800	1500
	Total	405	455	2800	6000

Fig 6.7: The estimated refinery production for some indium refinery companies
Source: US Geological Survey Minerals and ILZSG, Brook Hunt Associate

They most probable increase the indium sale price if they observed some increase of demand of indium consumption and decrease of indium refining. However, they might not have any 'agreements' among the indium refiners. When they foresee shortage of indium supply may happen, they will adjust their indium sale price after one of the refiners did that. Thus, we can say that the business model for global indium market is duopoly or oligopoly but obviously not monopoly. Between duopoly and oligopoly, the most probably model is oligopoly.

In Fig 6.7, the world indium supply and demand is shown. According the estimation of Teck Cominco, it will have a deficit of more than 200 metric tonnes between the supply and demand in 2007. Thus, it is expected that the indium price will at least maintain at $1000/kg till next year.

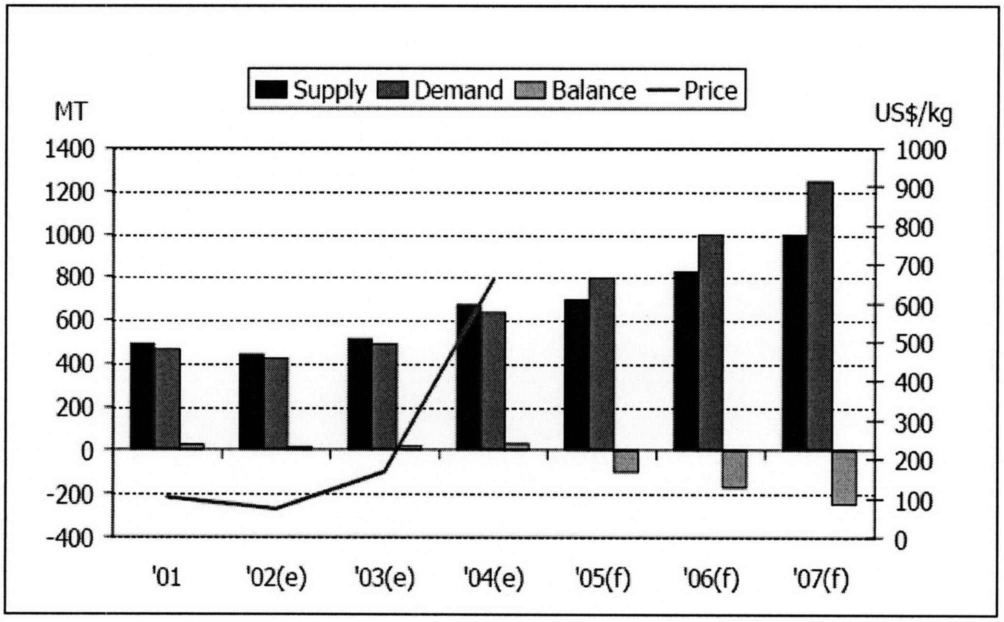


Fig 6.8: Indium – world supply and demand
Source: Teck Cominco, Metal Bulletin, Metal Pages

6.4) Supporting statements

The following paragraphs are taken from *American Metal Market* and *Metal Bulletin* which can be used to support the arguments.

- *"The price of indium has smashed through the $1,000-a-kilogram mark on surging demand from Japanese consumers and tightening stocks following a shutdown of Chinese indium smelters and refiners. Indium is now changing hands at $1,000 to $1,050 per kg in the free market, up from $960 to $1,000 previously. The metal is expected to hit a high of $1,100 per kg before year-end as indium's* *main users-producers of flat-panel, plasma and liquid crystal displays-start to ramp up production ahead of Christmas, traders said. "Demand for indium is rampant at the moment as production of flat-screen TVs charges ahead," one U.S. trader said. "Japanese consumers had been holding off from buying material in order to get prices down, but they're back in the market in a big way."" (Source: American Metal Market. Vol. 113, no. 33-5, pp. 1, 4. 26 Aug. 2005)*

- *"For the third time in 1987 major indium producers increased their list prices for indium. Arconium Corp. in America took the lead by raising its price from $3.35 to $4.00 per troy oz on 2 Mar. and was followed by Belgium's MHO which put its price up to BFr 4600 per kg and Indium Corp increasing its list price to $3.95/troy oz. The producers have not increased the price uniformly despite their insistence that spiralling prices are not good for the metal's long-term consumption prospects." (Source: Metal Bulletin, no. 7166, pp. 9. 6 Mar. 1987)*

6.5) Some IP related to indium extraction from tin circuit [Source: US Patent Office]

From the website of US Patent Office, there are four patented indium extraction process are found related to indium extraction from tin circuit. Note that the protection for the patents will be last because they were already filed more than 20 years. Three patents are filed on 1980, so there is no more protection on these patents already. Note that one of the patents for the recovery for indium processes is still under patent protection and 2-3% of IP fee is normally required if we wish to use it. Thus, Indium Corporation of Malaysia will use the patent no (2) to (4) for indium refinery from the tin circuit and no IP fee is needed.

Four patents related to the indium extraction from tin circuit are shown as below.

PAT. NO.	Title	Filed date
■ 1)5,344,567	Recovery of indium by solvent extraction using trialkylphosphine oxides	**June 29, 1993**
■ 2)4,292,284	Solvent extraction recovery process for indium	**June 27, 1980**
■ 3)5,108,497	Treatment of indium dusts	**September 5, 1990**
■ 4)4,292,284	Solvent extraction recovery process for indium	**June 27, 1980**

One of the IP Patents; "Patent No: 4,292,284: Solvent extraction recovery process for indium" is used to show the claims of a typical indium extraction from tin circuit.

- *What is claimed is:*

  1. A process of recovering indium, comprising the steps of adjusting the pH of an aqueous solution containing indium ions to 0.25-4.5, bringing the aqueous solution into contact with an organic solvent solution prepared by diluting an extracting reagent containing a monoalkylphosphoric acid and/or a dialkylphosphoric acid and a trialkylphosphoric acid in 1:2-5 by volume ratio with a phase-stabilizing water-immiscible organic solvent to extract the indium ions in the organic solvent solution and then bringing the organic solvent solution into contact with an aqueous sulfuric acid-acidic solution containing 100-500 g/liter free sulfuric acid to back-extract the indium ions into the aqueous sulfuric acid-acidic solution to provide an indium concentrate.

  2. The process as claimed in claim 1 wherein the pH of an aqueous solution containing indium ions is adjusted to 0.25-1.5.

  3. The process as claimed in claim 1 wherein the pH of an aqueous solution containing indium ions is adjusted to 0.25-1.0.

  4. The process as claimed in claim 1 wherein the dialkylphosphoric acid is di(2-ethylhexyl)phosphoric acid.

  5. The process as claimed in claim 1 wherein the trialkylphosphoric acid is tributylphosphoric acid.

  6. The process as claimed in claim 1 wherein the phase-stabilizing water-immiscible organic solvent comprises one or more of aliphatic hydrocarbons, aromatic hydrocarbons or alkylaromatic hydrocarbons.

6.6) Decision Tree

From the discussions above, it is noted that indium concentration level and price are two main factors that able to determine business decision and future prospects for Indium Corporation of Malaysia. The decision tree for two phases has been outlined in Fig 6.9. It is expected that the whole duration for this business plan is 10 years, which is 5 years for each phase.

If the indium concentration level is higher than 10000ppm, it is found that Indium Corporation of Malaysia can survive, although the price is as low as $250/kg. This means that the business activities can be expanded on second phase, even if the indium price is $200/kg. However, the indium price will most unlikely decrease to this level in the next few years due to low refinery activities and increasing demands. Similar business decisions will be made if the indium concentration level is 5000ppm and the price fluctuates around $500/kg to $1000/kg.

Indium Corporation of Malaysia will continue its business and expand its business in conditions in phase 1 and phase 2 respectively if the indium concentration level is 7000ppm and the price is $200/kg to $500/kg. Similar business decisions are applied to the case of indium concentration of 4000ppm and the market is from $500/kg to $1000/kg.

If the indium concentration level is as low as 1000ppm, the indium refinery from tin circuit is most likely to be closed even if the price exceeds $1000/kg. Such a low indium price does not provide incentives for indium extraction activities using tin circuit. From the cost modeling spreadsheet, Indium Corporation of Malaysia will start to be motivated to carry out the indium refinery activities if the indium concentration is more than 3000ppm since the cost refinery is about $1000/kg without taking consideration of other composition of ores in the tin ore. The decisions for phase 1 and 2 are shown in Fig 6.9.

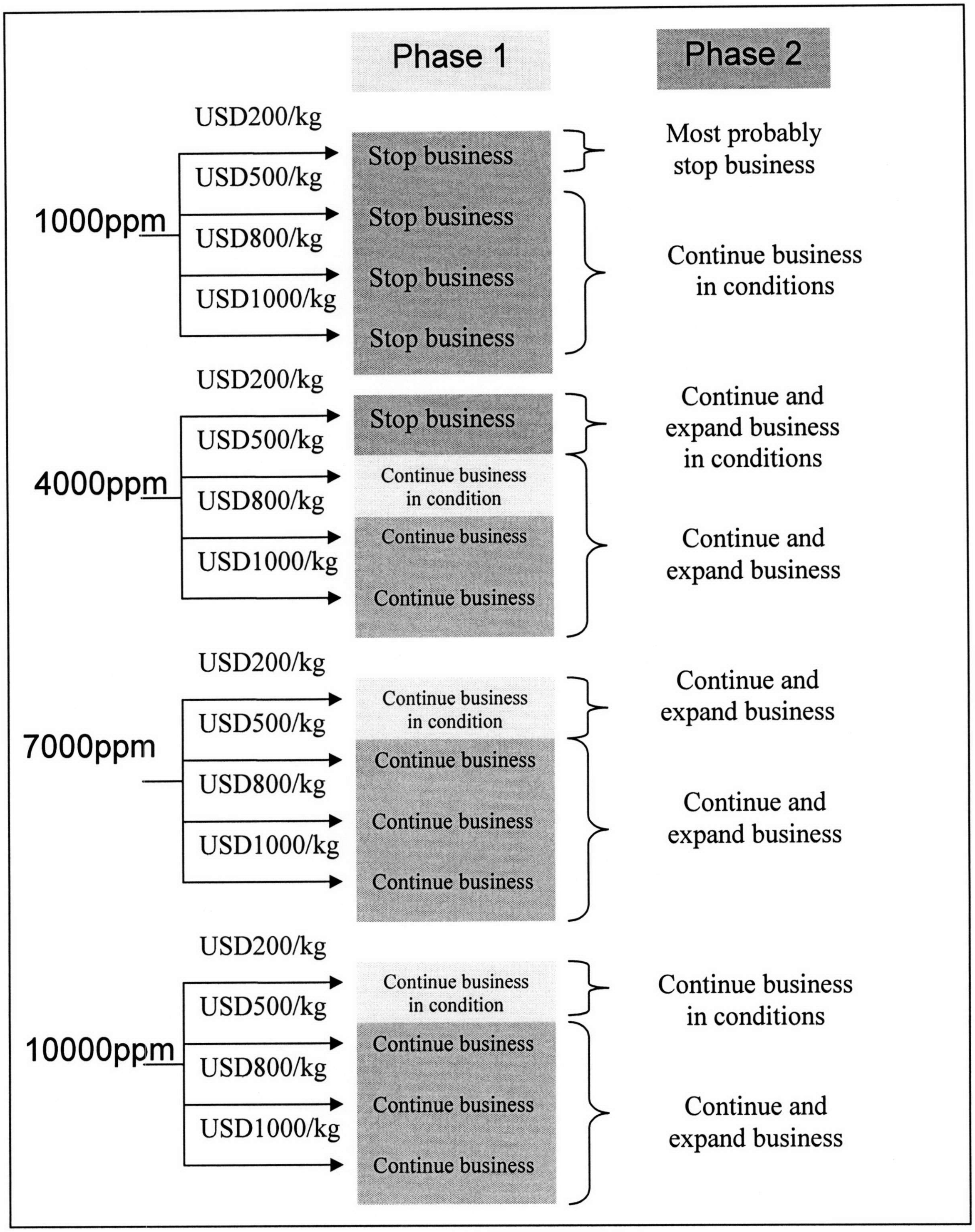


Fig 6.9: Decision tree for Indium Corporation of Malaysia

Chapter 7: Others issues

7.0) Introduction

There are some additional issues which may determine the position of indium. These include mining policy, lease application, mining work force, recycling and environmental, health and safety. In this chapter, a brief discussion on these issues will be provided.

7.1) Mining policy and lease application process

The mineral resources are owned by the State. Malaysia has 13 states, which are Johor, Kedah, Kelantan, Negeri Sembilan, Pahang, Perak, Perlis, Selangor, Terengganu, Malacca, Penang, Sabah and Sarawak. Three federal territories are Kuala Lumpur, Putrajaya and Labuan. Thus, the licenses for the exploration activities and mining rights are approved and issued by the authorities of the governments of each State and federal territories under the Federal Government. Besides, the miners are required to pay 3 to 7% of royalties to respective states government.

As reported in the Malaysian tin bulletin (2004), the state governments have been urged by the Federal Government in order to develop the mining sector cooperatively and they are motivated to issue more mining licenses to stimulate the mining sector in Malaysia.

The miners have to follow certain procedures before they wish to build a mine in Malaysia. A flow chart of the standard procedure to build a mine is shown in the Fig 7.1. It is noted that the environmental impact will be taken in consideration before and after the close of the mine. The process for application of quarrying and Mining and process for change authority for mining are shown in the Fig 7.2 and Fig 7.3 respectively. It is found that they have similar application flow. The new application flow is less complicated than the old application flow.

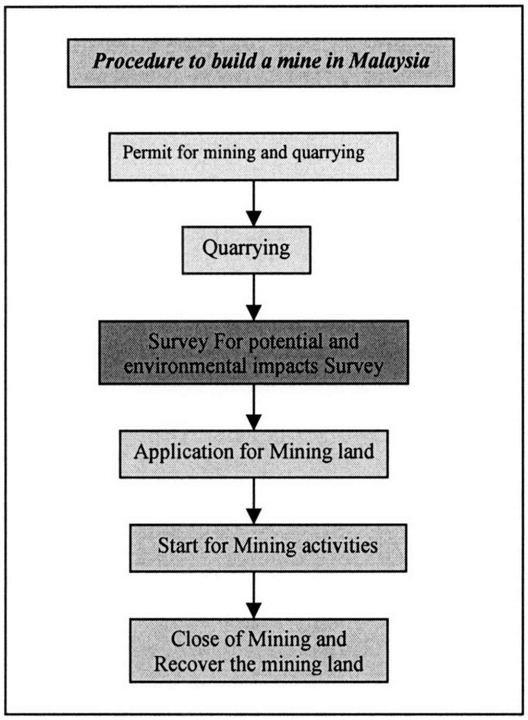


Fig 7.1: Procedure to build a mine in Malaysia
Source: Minerals& Geoscience department Malaysia

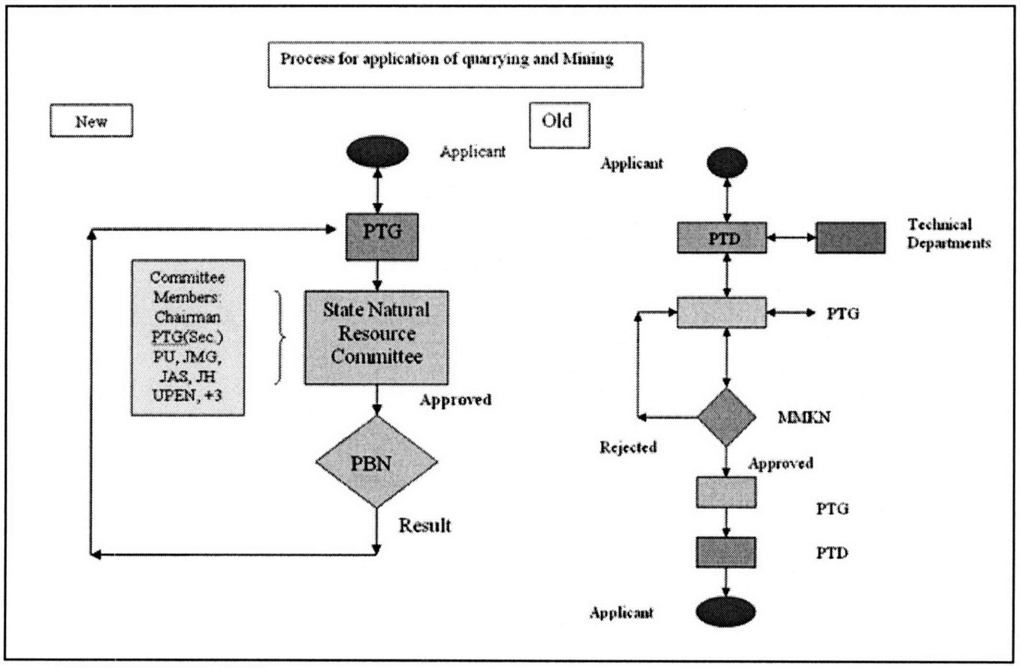


Fig 7.2: Process for application of quarrying and Mining.
Source: Minerals& Geoscience department Malaysia

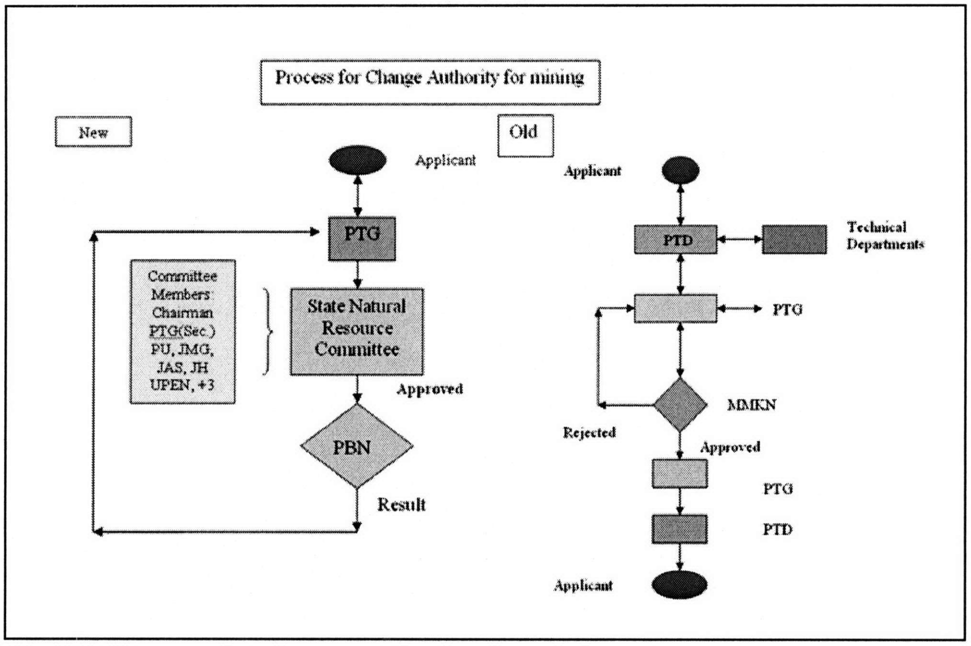


Fig 7.3: Process for change authority for mining.
Source: Minerals& Geoscience department Malaysia

In 2005, China's government had shut 30 small smelters in Hunan province since detection and spilling toxic waste was found in the local river for the factories that extract indium from zinc slag.

7.2) Mining works force

Discipline	Dist. Hon Fellow	Hon Fellow	Hon Member	Fellow	Member	Graduate	Incorporated	Affiliate	Associate	Student	Total
Geological	0	0	0	0	1	2	0	2	0	0	5
Geotechnical	0	0	0	0	1	4	0	1	0	0	6
Metallurgy	0	0	0	0	8	1	0	0	0	0	9
Mineral processing	0	0	0	0	1	4	0	0	0	0	5
Mineral Resources	0	0	0	0	0	2	0	0	0	0	2
Mining	0	0	0	0	6	39	4	0	0	0	49
Mining& Metallurgy	0	0	0	0	1	0	1	0	0	0	2

Table 7.1: Membership of The Institution of Engineers Malaysia from various disciplines that related to mining works force. Source: pg64, Membership of the institution as at 2.1.2004, 45th Annual Report, The Institution of Engineers Malaysia

From table 7.1, the total numbers of member and graduates for each mining related engineering discipline are less than 10, except for the mining discipline. There are 78 registered engineers available in the mining work force in 2004. It is expected that this number will not change dramatically in near future. Thus, the mining work force may not be enough to support indium mining and extraction.

7.3) Recycling

Indium is a minor metal and its abundance is limited. Recycling is one method to produce indium. In 2004, about 47% of the indium world supply was obtained from recycling. [10] In other words, indium recycling activities will have a great influence on the indium price. Note that the indium-containing alloys are readily reclaimed due to their low melting point. This means any scrap that contains indium metal or indium alloys or chemicals should be safely collected, stored, and returned to the refiners for recycling.

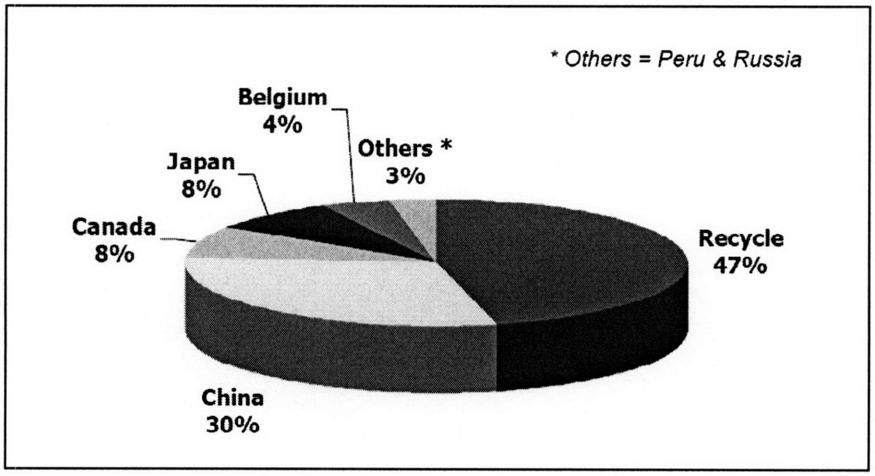


Fig 7.4: Total world indium production including recycling
Source: Roskill, Antaike, Teck Cominco

It is noted that the abundance of indium in the earth's crust is in quantities about 300% more than that of silver. However, the rate of extraction for silver is approximately 60 times more than the extraction rate of indium. "While extraction efficiency is greater for silver, the relative abundance and current extraction rates of indium versus silver are still a telling story." [79]

According to Roskill, the rate of recycling in 2003 is just over 40% and it is projected to be about 60% by 2008. Meanwhile, the USGS's metal recycling report showed that about 50% of the application in indium tin oxide in 2005 is provided by the recycled indium source, and this recycling rate is also forecasted to increase in the next few years.

Note that strong demand and steady price increases can encourage more recycling activities for indium. An example will illustrate this situation. The higher price of indium in 1995 was set due to strong demand from thin film applications. This motivates significant efforts for the recycling of indium in 1996. The price then settled back followed by increased supply and successful implementation of the recycling program from the indium-containing compounds and scrap of indium-tin-oxide and the recycling rate became steady.

There are two types of indium recycling levels; pre-consumer recycling and post-consumer recycling. The pre-consumer recycling is to reclaim the scrap or the indium containing materials from the manufacturing wastes before passing to the consumer's hand. The LCD manufacturing techniques like Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) may leave lots of waste on the wall of the chambers. Thus, this indium containing waste can be reclaimed and recycled. Meanwhile, post-consumer recycling collects the indium-bearing products which had been used by the consumer. For example, Sharp developed an indium recycling technique. The used LCD panel is broken into small pieces and then an acid solution is used to dissolute the glass cullet. This is post-consumer recycling. The indium supply chain has been continuously enhanced by improvements in terms of the indium recycling technologies and networking of recycling programs. "In the rapidly growing LCD market, greater than 85% of non-deposited indium is reclaimed and returned to the supply chain." [51]

Only 15% of the ceramic ITO sputtering particles will be deposited at the glass. Low target utilization rate mean that a lot of ITO sputtered particles resides on the chamber walls and dissolves in the etching solution. [4, 5] According to Roskill, about 60% of the world indium consumption is estimated to be obtained from the recycling by 2008.

7.4) Environmental, health and safety

Pure indium has very small or no environmental risks. However, indium normally reacts and forms a compound with other elements. Note that its alloys may contain toxic effects to the environment. For example, hydrochloric acid solution can be formed by indium trichloride and this indium trichloride contained acid solution is hazardous to the environment.

Currently, no case related to the irritating effects on skin has been documented, as well as no industrial poisoning. In other words, no systemic effects in the human body exposed to indium have been reported [27]. However, ionic indium can harm the kidneys and liver. Normally ingestion and inhalation are the expected routes of entry to the human body. Hence, our respiratory system may be affected by indium. Lungs, skin and eyes can by irritated by indium. As a consequence of high level exposure, permanent damage of the lungs or death may happen. Thus, a standard limit value set by the American Conference of Governmental Industrial Hygienists (ACGIH) is below 0.1 mg/m^3. This value has been set because of some injury due to the indium salts, particularly the pulmonary effects. However, no limit has been set for the permissible indium in water.

The toxicity metric comparisons for indium and some metals are shown in the Table7.2. It is found that indium is neither bio-accumulative nor a carcinogen. Currently, no limit has been set for EPA drinking standard. However, the Occupational Safety and Health Administration (OSHA) had set a limit value of 0.1 mg/m^3. Unfortunately, birth defects have been found for lab animals under exposure a certain levels of indium. This raised some worries about the toxicity of indium, especially birth defect for babies if their mothers have been exposed to indium.

Metal	Bio-accumulative	Carcinogen	Birth Defects	EPA Drinking Standard (mg/L)	OSHA (mg/m^3)
Lead	Yes	Yes	Yes	0.015	0.05
Silver	Yes	No	No	0.05	0.01
Antimony	No	Yes (Cal EPA)	No	0.006	0.5
Indium	No	No	Yes (Lab animal)	None	0.1
Bismuth	No	No	No	0.05	None
Copper	No	No	No	1	0.1
Tin	No	No	No	None	2

Table 7.2: Toxicity metric comparisons for indium and some metals. Source: Ku, O. Ogunseitan, J-D Saphores, A. Shapiro&J. M. Schoenung, Lead-Free Solder: Issues of toxicity, Availability and Impacts of Extraction, 2003 Electronics Components and Technology Conference, IEEE

Table 7.3 shows the results for testing for the effect of indium on mouse and rat mortality. It is noted that indium nitrate, indium chloride and metallic indium were used in these tests.

Parameter	Effect value	Concentration and condition	Species
Mortality	50%	Nitrate, Oral dose = 3350 mg/kg body	Mouse
Mortality	50%	Chloride, intraperitonal dose =1.8mg/kg body	Rat
Mortality	50%	Metallic, oral dose=4200mg/kg body	Rat

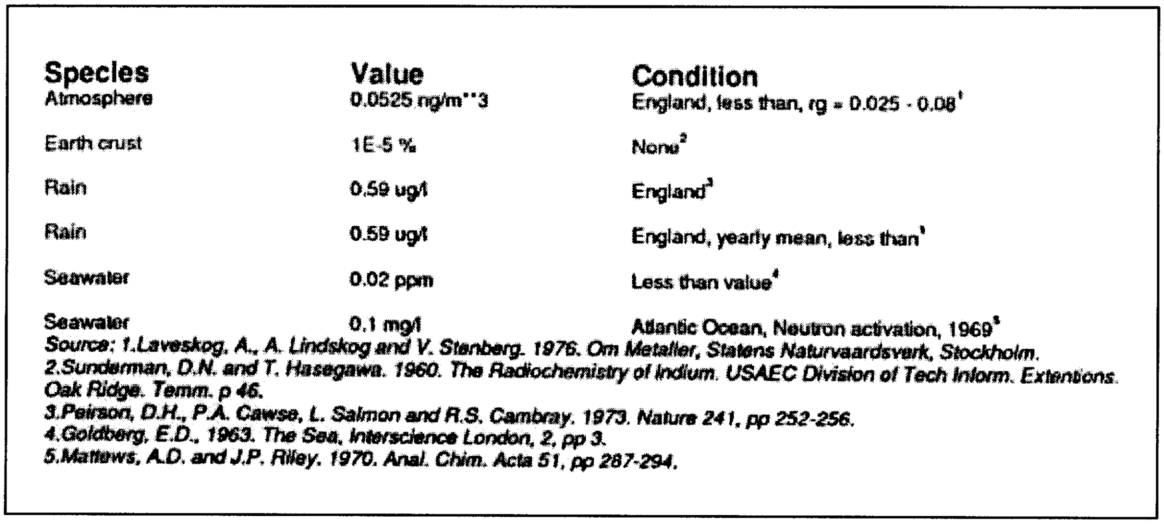
Table7.3: Effect of indium. Source: S.E. Jorgensen, S.N. Nielsen, L.A. Jorgensen, Handbook of ecological parameters & ecotoxicology, Elsevier

The results of excretion indium testing are shown in the Table 7.4. Excretion is a process that eliminates waste materials or unused substances from the body. In these experiments, animals, mouse or the lung of the rat were used. 40% to 100 % of indium dose had been applied. There were different methods to put indium into the tested animals. They included oral intake, injection, urinary and decal excretion, oral dose with urine or feces and the intratracheal injection. None of excretion testing of indium on human body has been found.

Species	Value	Condition
Animal	100% of dose	Oral intake
Animal	40% of dose	Injection, urinary and decal excretion
Mouse	52% of dose	Oral dose, ionic In, with urine
Mouse	53% of dose	Oral dose, colloidal In, with feces
Rat, lung	60% of dose	In 16 days, intratracheal injection

Table 7.4: Excretion Indium. Source: S.E. Jorgensen, S.N. Nielsen, L.A. Jorgensen, Handbook of ecological parameters & ecotoxicology, Elsevier

There are some low concentrations of indium that have been obtained in our surroundings. Some researchers proved that the existence of a background concentration in atmospheric, rain and seawater. The values of the background concentration of indium are shown in Table 7.5. It shows that there is 0.0525 ng/m^3 and 10^{-5}% or 0.05ppm in the atmosphere and earth crust respectively. Besides, rain may contain 0.59 µg/l of indium. Meanwhile, a concentration of 0.02 ppm indium might be found in seawater. At the same time, the research conducted by A.D. and J.P. Riley showed that the value of indium concentration in seawater is 0.1mg/l.



Species	**Value**	**Condition**
Atmosphere	0.0525 ng/m**3	England, less than, rg = 0.025 - 0.08[1]
Earth crust	1E-5 %	None[2]
Rain	0.59 ug/l	England[3]
Rain	0.59 ug/l	England, yearly mean, less than[1]
Seawater	0.02 ppm	Less than value[4]
Seawater	0.1 mg/l	Atlantic Ocean, Neutron activation, 1969[5]

Source: 1.Laveskog, A., A. Lindskog and V. Stenberg. 1976. Om Metaller, Statens Naturvaardsverk, Stockholm.
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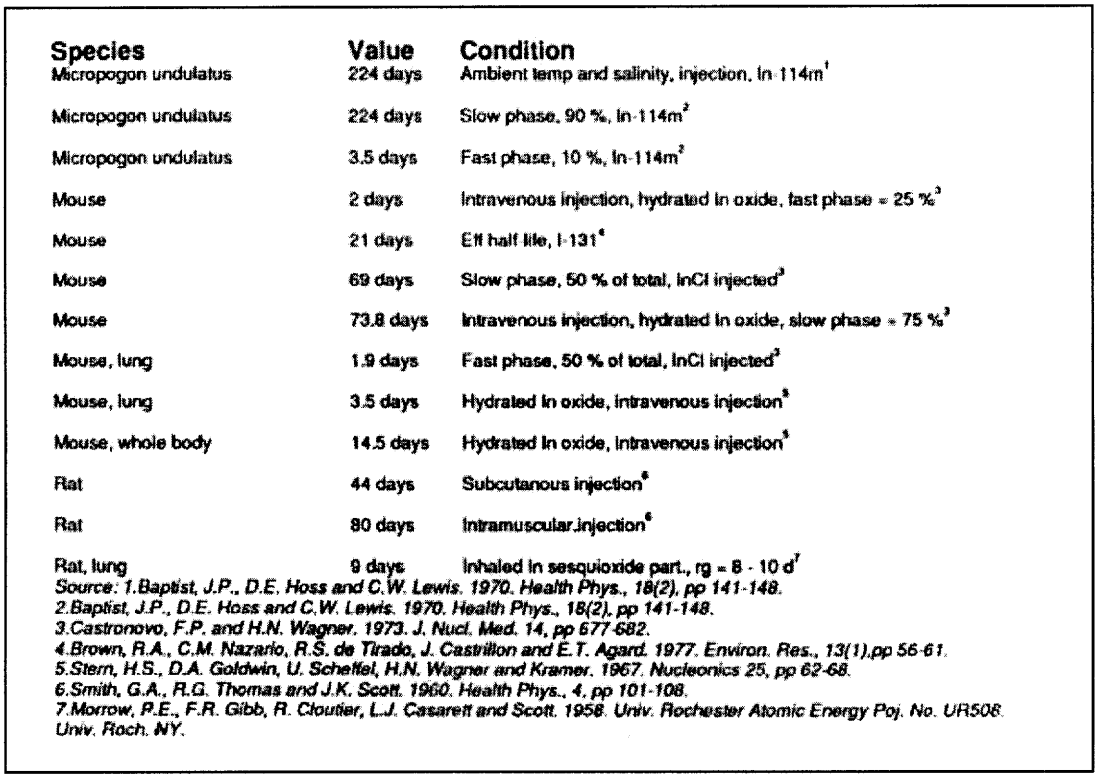
Table 7.5: Background concentration indium. Source: S.E. Jorgensen, S.N. Nielsen, L.A. Jorgensen, Handbook of ecological parameters & ecotoxicology, Elsevier

In Table 7.6, the biological half-life of indium in different species are shown. The species included micropogon undulatus, mouse, the lung of a mouse and rat. In the testing in micropogon undulates, the biological half-life time of indium is 224 days in the slow phase or ambient temperature and salinity and it is 3.5 days in the fast phase. Meanwhile, there were about 2 days to 80 days of biological half-life time of indium for mouse and mouse in different conditions. Until today, no testing of biological half-life of indium on human beings has been reported. Thus, it is expected the biological half-life time of indium is 2 to 80 days if the indium has been taken into our body accidentally.



Species	Value	Condition
Micropogon undulatus	224 days	Ambient temp and salinity, injection, In-114m[1]
Micropogon undulatus	224 days	Slow phase, 90 %, In-114m[2]
Micropogon undulatus	3.5 days	Fast phase, 10 %, In-114m[2]
Mouse	2 days	Intravenous injection, hydrated In oxide, fast phase = 25 %[3]
Mouse	21 days	Eff half life, I-131[4]
Mouse	69 days	Slow phase, 50 % of total, InCl injected[3]
Mouse	73.8 days	Intravenous injection, hydrated In oxide, slow phase = 75 %[3]
Mouse, lung	1.9 days	Fast phase, 50 % of total, InCl injected[3]
Mouse, lung	3.5 days	Hydrated In oxide, intravenous injection[5]
Mouse, whole body	14.5 days	Hydrated In oxide, intravenous injection[5]
Rat	44 days	Subcutanous injection[6]
Rat	80 days	Intramuscular.injection[6]
Rat, lung	9 days	Inhaled in sesquioxide part., rg = 8 - 10 d[7]

Source: 1.Baptist, J.P., D.E. Hoss and C.W. Lewis. 1970. Health Phys., 18(2), pp 141-148.
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Table 7.6: Biological half-life time of indium
Source: S.E. Jorgensen, S.N. Nielsen, L.A. Jorgensen, Handbook of ecological parameters & ecotoxicology, Elsevier

7.5) Discussion

Today, environmental issues become more and more important. Thus, government of Malaysia also regulated some corresponding rules and enforced these rules strictly to ensure the environmental impacts are minimized. Thus, the potential indium miners should be alert for these environmental issues. Recycling is one of way to reduce and reuse the indium-bearing waste. Although no poison case due to indium has been documented, but it does not mean we should underestimate a potential poison to human body since some reports showed that indium has side effects to the human body. Furthermore, some experiments on animals also proved that it has some degree of poison. Thus, indium recycling program should be encouraged because it can not only contribute indium production, but also reduce potential danger to our body and environment.

Chapter 8: Conclusion and Future works

8.0) Conclusion

The uncertainty of indium-containing level in the different ores and low level of indium concentration are two main factors that caused the cost for indium extraction very high. Currently, most of indium is refined from zinc circuit, except for a few countries like Russia. Most of the extraction efforts from these circuits have been blocked due to relatively high extraction cost. However, high indium price and demands may encourage more and more refiners to do that. We may face shortage of indium supply next twenty years if the indium refiners not carry out refinery from ores other than zinc. From this reasoning, tin circuit is highly expected as a good resource. In addition, the cost modeling showed that it is profitable to extract indium from tin at current price.

More indium production research and developments for indium extraction from tin circuit are suggested in order to extract this minor but very valuable metal in more economical way. Improvements of extraction efficiency can reduce cost production.

Many experiments on other kinds of transparent conductive oxide have been carried out to search for a suitable substitute candidate for ITO. However, none of recent experimental results on the transparent conductive oxides like ZnO has showed as good as an ITO film. In other words, LCD manufacturers need to use ITO due to its unique properties. If any transparent conductive oxide that substitutes to ITO with comparative properties, this can decrease indium price dramatically. However, this is unlikely happen next few years since lots of this type of conductive oxide is in the experimental stage.

In short, it is seem that the demand for indium has increased rapidly over the past decade since a lot of demands from LCD, low-temperature soldering and compound semiconductor. Besides, there are relatively few suppliers; hence any disruption in the supply can create large price fluctuations due to hedge buying and speculation. Surprisingly, indium can be considered as main product of the tin extraction and the tin become by-product because indium price is currently more than 100 times higher than tin price. Most importantly, the indium supply from the zinc circuit is expected decrease in the next few years and to be eliminated very soon.

8.1) Future work

When additional or new information or data is available, it is important to revise the estimated data since these estimates are dubious. Although research works are mainly focus on the boundary of Malaysia, the methods used in whole thesis works are applicable to other countries. In other words, the results or information provided in this work can be easily adapted outside of Malaysia by gathering relevant data. If the accurate production data for each indium producers is important, then this data should be collected and compiled in the long run. The current cost modeling spreadsheet can be modified if the additional information is obtained in order to obtain more accurate output.

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Appendix A: Tin mining right in force in 2004

(Source: Malaysian Minerals Yearbook 2004, Minerals& Geoscience department Malaysia and Ministry of natural resources & environment Malaysia)

Lease Holder	Location	Area (Hectres)	Period of Lease Expiry Date
Johor			
Giant Distinction Sdn Bhd	Ulu Sg. Johor, Johor	21	18/6/2006
Kota Tinggi Mg Sdn Bhd	Kota Tinggi, Johor	79.81	15/3/2009
Toh Eng Chew & Rakan-rakan	Bakri, Muar, Johor	4	24/2/2005
Negeri Sembilan			
Sua Grensing Estate Sdn. Bhd. (Maju Daki Contruction Sdn. Bhd)	Linggi, Negeri Sembilan	36.7	17/8/2001-17/8/2006
Pahang			
Nilai Cergas (M) Sdn Bhd	Sg. Lembing, Hulu Kuantan, Pahang	1,561	26/9/1990-2005
Sy. Ratna Putra Sdn Bhd	Sg. Timun, Rompin, Pahang	323	14/7/2005
Jenwen Sdn Bhd	Sg. Semantut, Bentong, Pahang	30.35	14/4/2001-17/4/2006
Kamarruddin B Mohd Yusof	Rompin, Pahang	20.2	15/11/2002-14/11/2006
Perak			
Pesuruhjaya Tanah Persekutuan	Kampar, Perak	119.04	7/2/2005
Raja Ekram Ibni Sultan Yusuf&	Kampar, Perak	91.03	Permanent
Dato Mohd Hashim B Abdul Shukor			
Nilai Saujaana (M) Sdn Bhd	Blanja, Perak	46.41	8/1//2005
Syarikat Permodalan Kebangsaan	Teja, Perak	1.4856	24/3/2005
New Lahat mines Sdn Bhd	Ulu Kinta, Perak	44.52	24/9/2009
Harison Bt Dato Hj. Abd. Raffar, Abd Talib B.		135.2	2/8/2005
Fahmi, Puteh Bt Osman	Sg. Raja, Perak		
Ever Bright Mining Corp (M) Sdn Bhd	Tg. Tualang, Perak	36.06	6/6/2011
Salmiah Bt Ishak,	Bidor, Perak	60.43	4/10/2006

Mohd Arshad B. Abdullah			
Timah Dermawan Sdn Bhd	Btg. Padang, Perak	71.08	23/1/2004
Pakatan Perak Bina Sdn Bhd	Batang Padang, Perak	80.89	27/12/2010
Malaysian Mining Corporation Bhd	Pasir Panjang Ulu, Perak	70.79	30/1/2004
Malaysian Mining Corporation Bhd	Kg. Gajah, Perak	7	23/2/2009
Hj. Abdullah B. Hj. Mohamad	Pengkalan Baru, Perak	379.1	4/1/2011
DYMM Paduka Seri Sultan Azian Shah	Pengkalan Baru, Perak	28.5	31/12/2013
Rahaman Hydraulic Tin Bhd	Pengkalan Hulu, Perak	28.5	31/12/2013
Rahaman Hydraulic Tin Bhd	Pengkalan Hulu, Perak	671.25	31/12/2013
Timah Dermawan Sdn Bhd	Batang Padang, Perak	8.4	12/8/2006
Timah Dermawan Sdn Bhd	Batang Padang, Perak	3.5	12/8/2006
Ehsan Delima Sdn Bhd	Batang Padang, Perak	0.45	30/6/2009
Ehsan Delima Sdn Bhd	Batang Padang, Perak	0.45	30/6/2009
Ehsan Delima Sdn Bhd	Batang Padang, Perak	21.02	30/6/2010
Bharum B. Uda Mat Jali	Kinta	23.06	17/6/2004
Selangor			
Robangan Bt. Ahmad & Rakan(Sheratin Sdn Bhd)	Sungai Tinggi, Ulu Yam, Selangor	27.06	1999-8/3/2004
KPSB (Magnaprise Sdn Bhd)	Batang Berjuntai, Selangor	106.59	21/7/2000-20/7/2010
KPSB (Magnaprise Sdn Bhd)	Batang Berjuntai, Selangor	13.41	21/7/2000-20/7/2011
Tetuan K. L. Larut Sdn Bhd(Excel Performance)	Batang Berjuntai, Selangor	299.51	21/7/2000-20/7/2012
KPSB(Petaling Tin Bhd)	Tanjung Duabelas, Selangor	268.41	expiring 19/7/2004
KPSB(Petaling Tin Bhd Dredge No. 7&9)	Tanjung Duabelas, Selangor	281.66	6/10/1983-5/10/2004
KPSB	Tanjung Duabelas, Selangor	212.06	Expiring 14/9/2005
KPSB (Imuda Sdn Bhd)	Tanjung Duabelas, Selangor	90.89	expiring 10/9/2007
KPSB (Kuala Langat Mining Sdn Bhd)	Tanjung Duabelas, Selangor	96.7	Expiring 10/9/2007
KPSB	Tanjung Duabelas, Selangor	80.95	Expiring 14/11/2014

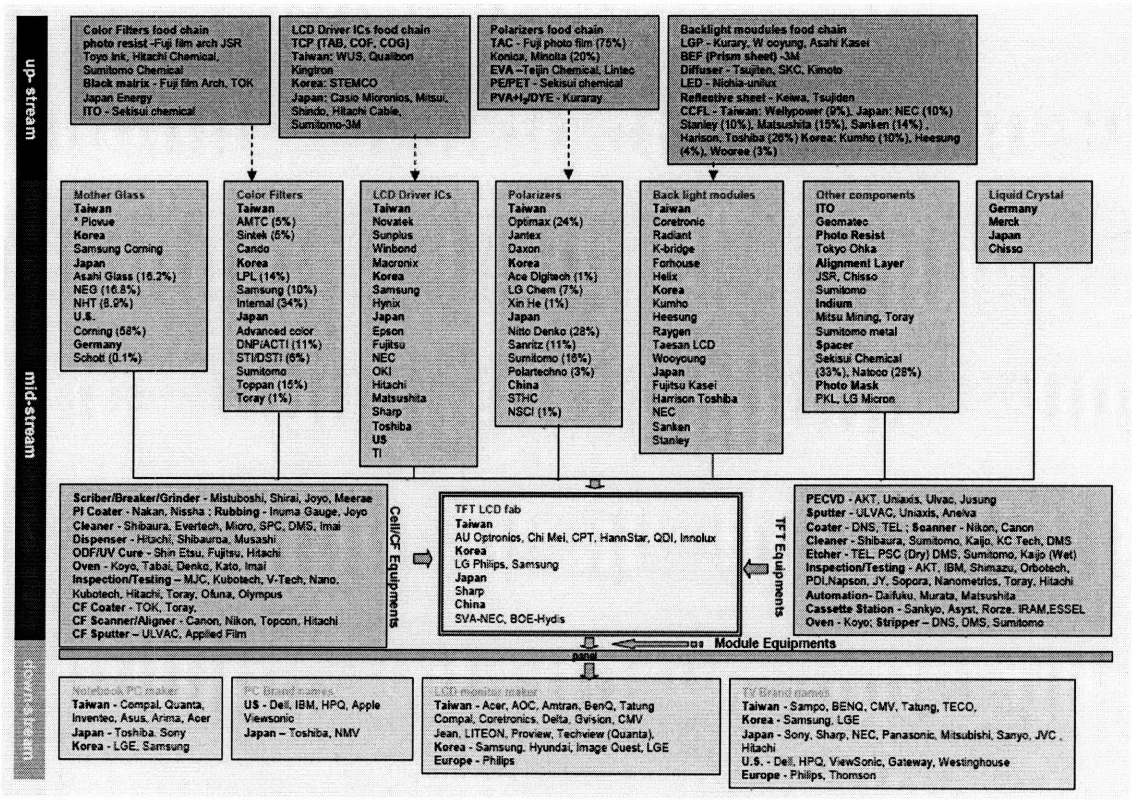
Syarikat Dayapi Lombong Bijih Sdn Bhd (Dayapi Lombong Bijih Sdn Bhd)	Tanjung Duabelas, Selangor	243.2	28/3/1995-27/3/2005
Swasta Rasmi	Tanjung Duabelas, Selangor	87.37	Expiring 27/3/2005
KPSB (Delima Industries Sdn Bhd)	Tanjung Duabelas, Selangor	324	16/1/1999-18/4/2004
Terengganu			
Ismail Abdul Rahman	Tebak, Kemaman, Terengganu	7	17/5/2008
Yong Moi Fong	Tebak, Kemaman, Terengganu	65	11/4/2005
Syarikat Ismail Adik Beradik	Tebak, Kemaman, Terengganu	39	15/1/2009
Sri Wangan Sdn Bhd	Sg. Batu, Hulu Paka, Dungun, Terengganu	31.16	25/12/2007

Appendix B: List of indium-related mineral names, abbreviations (Abbre.), and formulas:

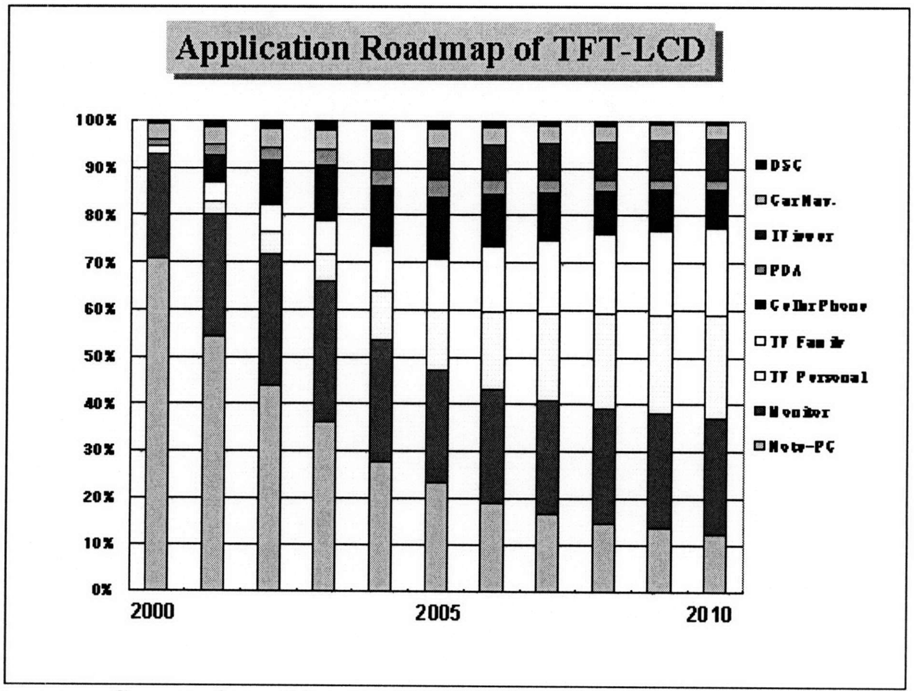
Source: Pg217, Ulrich Schwarz-Schampera &Peter M. Herzig, Indium Geology, mineralogy, and economics, Springer

Minerals	**Abbre.**	**Formula**
Native indium	in	In
Dzhalindite	dz	$In(OH)_3$
Indite	ind	$FeIn_2S_4$
Laforetitee	laf	$AgInS_2$
Roquesite	rq	$CuInS_2$
Sakuraiite	sk	$(Cu,Zn,Fe,Ag)_3(In,Sn)S_4$
Tolovkite	tvk	InSbS
Yanomamite	ynm	$InAsO_4*2H_2O$
Yixunite	yx	ptIn
Unnamed	-	In_2Pt
Unnamed	-	$InPt_3$

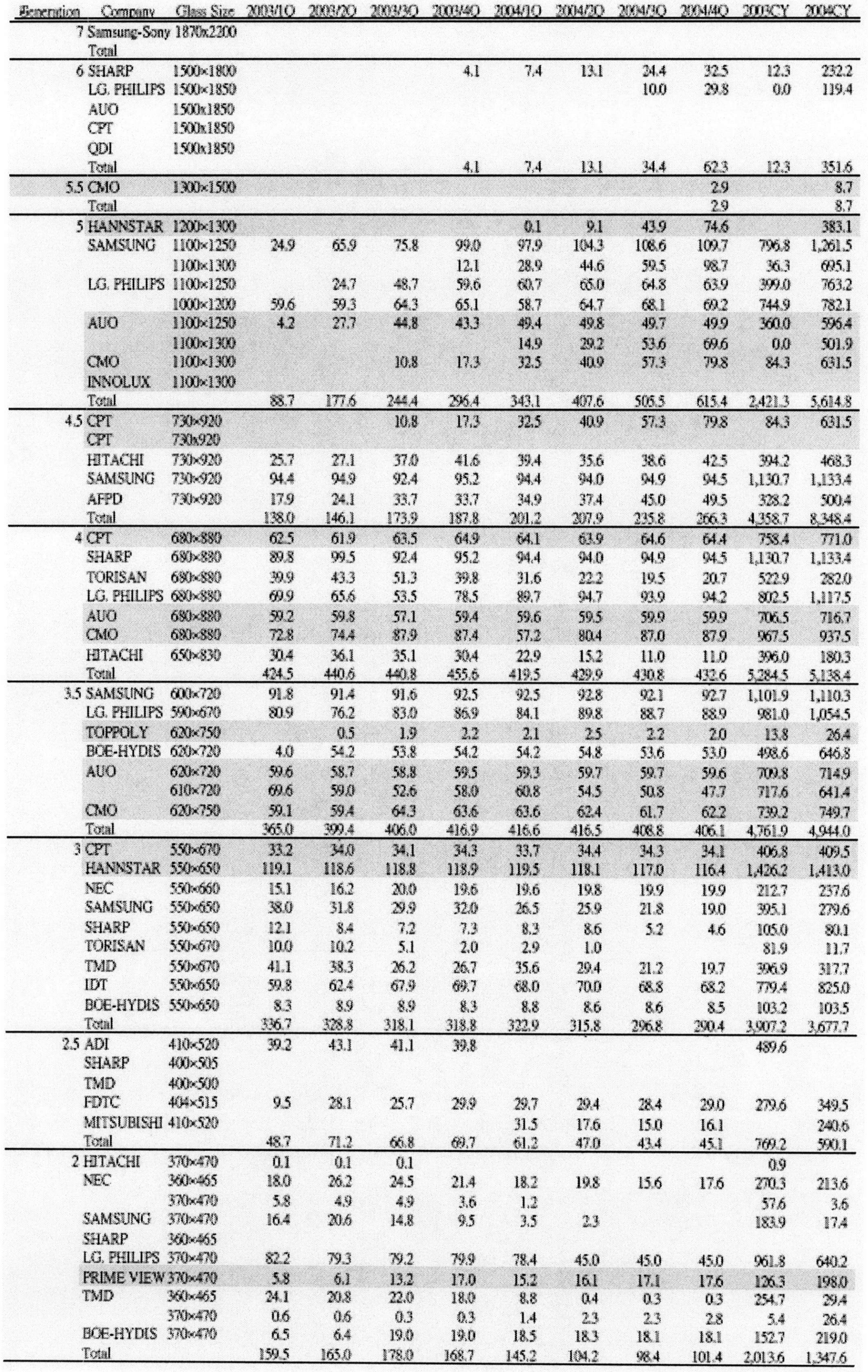
Appendix C: LCD



The world supply chain for the flat plane displays (FPDs)
Source: In-cha Hsieh, Chapter 3: TFTLCD Process, National Chung Cheng University



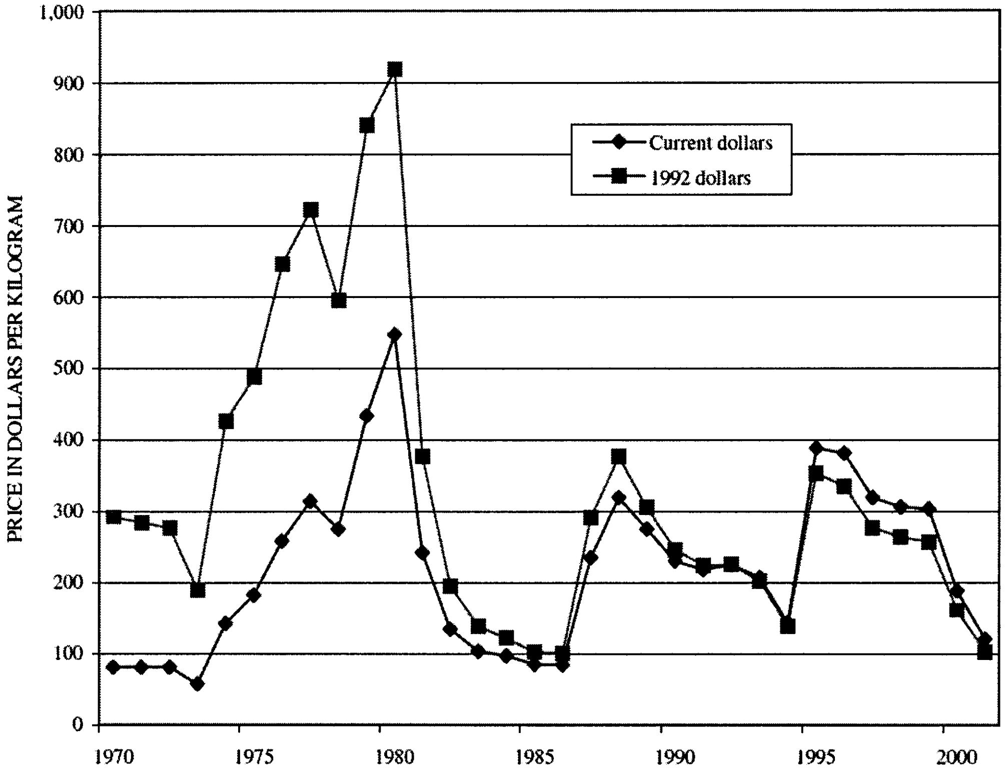
Source: http://dom.semi.org/web/wsemi.nsf/url/0702wuii



Generation	Company	Glass Size	2003/1Q	2003/2Q	2003/3Q	2003/4Q	2004/1Q	2004/2Q	2004/3Q	2004/4Q	2003CY	2004CY
7	Samsung-Sony	1870x2200										
	Total											
6	SHARP	1500×1800				4.1	7.4	13.1	24.4	32.5	12.3	232.2
	LG. PHILIPS	1500×1850							10.0	29.8	0.0	119.4
	AUO	1500x1850										
	CPT	1500x1850										
	QDI	1500x1850										
	Total					4.1	7.4	13.1	34.4	62.3	12.3	351.6
5.5	CMO	1300×1500								2.9		8.7
	Total									2.9		8.7
5	HANNSTAR	1200×1300					0.1	9.1	43.9	74.6		383.1
	SAMSUNG	1100×1250	24.9	65.9	75.8	99.0	97.9	104.3	108.6	109.7	796.8	1,261.5
		1100×1300				12.1	28.9	44.6	59.5	98.7	36.3	695.1
	LG. PHILIPS	1100×1250		24.7	48.7	59.6	60.7	65.0	64.8	63.9	399.0	763.2
		1000×1200	59.6	59.3	64.3	65.1	58.7	64.7	68.1	69.2	744.9	782.1
	AUO	1100×1250	4.2	27.7	44.8	43.3	49.4	49.8	49.7	49.9	360.0	596.4
		1100×1300					14.9	29.2	53.6	69.6	0.0	501.9
	CMO	1100×1300			10.8	17.3	32.5	40.9	57.3	79.8	84.3	631.5
	INNOLUX	1100×1300										
	Total		88.7	177.6	244.4	296.4	343.1	407.6	505.5	615.4	2,421.3	5,614.8
4.5	CPT	730×920			10.8	17.3	32.5	40.9	57.3	79.8	84.3	631.5
	CPT	730x920										
	HITACHI	730×920	25.7	27.1	37.0	41.6	39.4	35.6	38.6	42.5	394.2	468.3
	SAMSUNG	730×920	94.4	94.9	92.4	95.2	94.4	94.0	94.9	94.5	1,130.7	1,133.4
	AFPD	730×920	17.9	24.1	33.7	33.7	34.9	37.4	45.0	49.5	328.2	500.4
	Total		138.0	146.1	173.9	187.8	201.2	207.9	235.8	266.3	4,358.7	8,348.4
4	CPT	680×880	62.5	61.9	63.5	64.9	64.1	63.9	64.6	64.4	758.4	771.0
	SHARP	680×880	89.8	99.5	92.4	95.2	94.4	94.0	94.9	94.5	1,130.7	1,133.4
	TORISAN	680×880	39.9	43.3	51.3	39.8	31.6	22.2	19.5	20.7	522.9	282.0
	LG. PHILIPS	680×880	69.9	65.6	53.5	78.5	89.7	94.7	93.9	94.2	802.5	1,117.5
	AUO	680×880	59.2	59.8	57.1	59.4	59.6	59.5	59.9	59.9	706.5	716.7
	CMO	680×880	72.8	74.4	87.9	87.4	57.2	80.4	87.0	87.9	967.5	937.5
	HITACHI	650×830	30.4	36.1	35.1	30.4	22.9	15.2	11.0	11.0	396.0	180.3
	Total		424.5	440.6	440.8	455.6	419.5	429.9	430.8	432.6	5,284.5	5,138.4
3.5	SAMSUNG	600×720	91.8	91.4	91.6	92.5	92.5	92.8	92.1	92.7	1,101.9	1,110.3
	LG. PHILIPS	590×670	80.9	76.2	83.0	86.9	84.1	89.8	88.7	88.9	981.0	1,054.5
	TOPPOLY	620×750		0.5	1.9	2.2	2.1	2.5	2.2	2.0	13.8	26.4
	BOE-HYDIS	620×720	4.0	54.2	53.8	54.2	54.2	54.8	53.6	53.0	498.6	646.8
	AUO	620×720	59.6	58.7	58.8	59.5	59.3	59.7	59.7	59.6	709.8	714.9
		610×720	69.6	59.0	52.6	58.0	60.8	54.5	50.8	47.7	717.6	641.4
	CMO	620×750	59.1	59.4	64.3	63.6	63.6	62.4	61.7	62.2	739.2	749.7
	Total		365.0	399.4	406.0	416.9	416.6	416.5	408.8	406.1	4,761.9	4,944.0
3	CPT	550×670	33.2	34.0	34.1	34.3	33.7	34.4	34.3	34.1	406.8	409.5
	HANNSTAR	550×650	119.1	118.6	118.8	118.9	119.5	118.1	117.0	116.4	1,426.2	1,413.0
	NEC	550×660	15.1	16.2	20.0	19.6	19.6	19.8	19.9	19.9	212.7	237.6
	SAMSUNG	550×650	38.0	31.8	29.9	32.0	26.5	25.9	21.8	19.0	395.1	279.6
	SHARP	550×650	12.1	8.4	7.2	7.3	8.3	8.6	5.2	4.6	105.0	80.1
	TORISAN	550×670	10.0	10.2	5.1	2.0	2.9	1.0			81.9	11.7
	TMD	550×670	41.1	38.3	26.2	26.7	35.6	29.4	21.2	19.7	396.9	317.7
	IDT	550×650	59.8	62.4	67.9	69.7	68.0	70.0	68.8	68.2	779.4	825.0
	BOE-HYDIS	550×650	8.3	8.9	8.9	8.3	8.8	8.6	8.6	8.5	103.2	103.5
	Total		336.7	328.8	318.1	318.8	322.9	315.8	296.8	290.4	3,907.2	3,677.7
2.5	ADI	410×520	39.2	43.1	41.1	39.8					489.6	
	SHARP	400×505										
	TMD	400×500										
	FDTC	404×515	9.5	28.1	25.7	29.9	29.7	29.4	28.4	29.0	279.6	349.5
	MITSUBISHI	410×520					31.5	17.6	15.0	16.1		240.6
	Total		48.7	71.2	66.8	69.7	61.2	47.0	43.4	45.1	769.2	590.1
2	HITACHI	370×470	0.1	0.1	0.1						0.9	
	NEC	360×465	18.0	26.2	24.5	21.4	18.2	19.8	15.6	17.6	270.3	213.6
		370×470	5.8	4.9	4.9	3.6	1.2				57.6	3.6
	SAMSUNG	370×470	16.4	20.6	14.8	9.5	3.5	2.3			183.9	17.4
	SHARP	360×465										
	LG. PHILIPS	370×470	82.2	79.3	79.2	79.9	78.4	45.0	45.0	45.0	961.8	640.2
	PRIME VIEW	370×470	5.8	6.1	13.2	17.0	15.2	16.1	17.1	17.6	126.3	198.0
	TMD	360×465	24.1	20.8	22.0	18.0	8.8	0.4	0.3	0.3	254.7	29.4
		370×470	0.6	0.6	0.3	0.3	1.4	2.3	2.3	2.8	5.4	26.4
	BOE-HYDIS	370×470	6.5	6.4	19.0	19.0	18.5	18.3	18.1	18.1	152.7	219.0
	Total		159.5	165.0	178.0	168.7	145.2	104.2	98.4	101.4	2,013.6	1,347.6

Source: In-cha Hsieh, Chapter 3: TFTLCD Process, National Chung Cheng University

Appendix D:The average price for 99.97% indium from 1970 to 2000



Source: Brown, 1999, 2000b

Appendix E: Supporting article

Indium price falls as metal supply increases

American Metal Market, March 15, 2006 by Sean Barry

NEW YORK -- The price of indium has inched lower as Chinese producers release more stocks onto the market to cash in on high prices, according to market participants.

The specialty metal had raced up in recent weeks, and many Chinese producers are now looking to sell into the spot market as the price holds around $1,000 per kilogram, trade sources said. The free-market price of indium tin oxide (ITO) is between $970 and $1,020 per kilogram currently vs. $990 to $1,040 previously.

"Prices have come off a bit as liquidity in the market improves. Some holders of material in China are looking to cash in," one U.S. trader said. "Once the price heads over $1,000, the market seems to correct a little bit." Another trade source reported improved liquidity and said some offers were being made at the mid- to low-$900 level.

But the drop in prices could be a temporarily blip as major electronic companies based in Japan look to build up inventories after their fiscal year ends March 31, traders said.

A slight increase in activity on the spot market has been reported in the past week and a firming in demand is expected. "All the major consumers are now looking to replenish stocks after the fiscal year ends," the U.S. trader said, "and we're starting to see more activity." Demand for indium is expected to outstrip supply this year as major electronic companies ramp up production of flatscreen televisions.

The market is facing a deepening supply shortage during the year as no new production is scheduled to come on stream and China continues to crack down on smaller producers because of environmental concerns.

The recent withdrawal of operating licenses from 13 privately owned indium smelters by Shaoguan's city government in China's southern Guangdong province has underlined the tightening market conditions, according to traders.

Meanwhile, germanium has nudged higher as demand from infraredbased product manufacturers firms, traders said. The metal has moved up $20 to a range of $620 to $670 per kg. "The supply-demand fundamentals have been in balance for a while, but we're now starting to see more demand from the infrared sector," another trader said. "We're also seeing new applications coming into the market like solar panels and computer chips."