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The Recovery of Metals from Secondary Sources, A Review-Part II

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1. Introduction

The author has written an article on the same topic in an early issue of this journal.[1] The author reviewed in that article the trend in metal production in the U.S. especially in relation to the metal recovery from scrap for the period of 1987-1991. The author pointed out that the trend of metal consumption has been shifted from more traditional metals to more advanced metals. It was observed also that the percent growth of many traditional metals showed downturn, while more advanced metals showed sharp increase in growth.

It was also noted that the production of many metals came from secondary sources. Table 1 shows the percent of recycled metals to meet the demand of these metals in the

Table 1. Apparent supply of metals and percentage of recycle in 1992-96[2] (in metric tons)

Metal	Recycled	Apparent Supply	% Rcecycled
Aluminum			
92	2,760,000	6.870,000	40
93	2,940,000	7,920,000	37
94	3,090,000	8,460,000	36
95	3.190,000	8,010,000	40
96	3,290,000	8.340,000	39
Chromium			
92	102,000	378,000	27
93	92,000	484,000	19
94	99,000	390,000	25.4
95	112,000	566,000	19.8
96	98,400	480,000	20 5
Copper			
92	1,280,000	3,030,000	42.2
93	1,290,000	3,260.000	39.6
94	1,330,000	3,510,000	37.9
95	1,320,000	3,410,000	38.6
96	1,300,000	3,700,000	35.1
Iron and Steel			
92	63,000,000	139,000,000	45
93	68,000,000	167,000,000	41
94	70,000,000	178,000,000	39
95	72,000,000	180,000,000	40
96	72.000,000	183,000,000	39

Table 1. Continued

Metal	Recycled	Apparent Supply	% Recycled
Lean			
92	916,000	1,330,000	69.1
93	893,000	1,380,000	64.7
94	931,000	1,540,000	60.5
95	972.000	1,580,000	61 5
96	1,090,000	1,630.000	66.8
Magnesium			
92	57,000	168,000	34
93	58,900	176,000	34
94	62,100	182.000	34
95	65,100	206,000	32
96	70,900	205,000	35
Nickel			
92	55,900	159,000	35.1
93	54,000	158,000	34.1
94	58,600	164,000	35.8
95	64.500	181,000	35 6
96	59,200	183,000	32.4
Tin			
92	13,700	37,300	37
93	11,100	43,300	26
94	11,700	41.900	28
95	11,600	43,300	27
96	11,000	37,700	29
Zinc			
92	366,000	1.280,000	28.7
93	355.000	1,370,000	26
94	361,000	1,400.000	25.9
95	353,000	1,460,000	24.2
96	379,000	1,450,000	26.1

U.S. for the period of 1992 and 1996.

It is clearly shown in Table 1 that the percentage of recycled metals to meet the demand in these metals is quite substantial. Furthermore, the percentage of the recycled portion is reasonably steady over the recent years.

In this paper, the production of metals including primary and secondary sources for the period of 1993~1997 will be reviewed. Also included in this review paper are primary production methods used in scrap recycling of important metals.

2. Aluminum

The importance of usefulness of aluminum is well recognized. Aluminum is the second most abundant metal occurred in the Earth crust and its application is the second to iron and steel. It is interesting to note that the consumption of this metal signifies the wealth and industrial nature of the country. The production of aluminum in the U.S. represents about 40% of the world production in the 1960s but this figure has been reduced to a little over 20% since the serge of the economy of European and Asian countries in the 90s.

In 1996, the total supply of aluminum in the U.S. including sources such as primary ores, scrap and importation was approximately 8.34 million metric tons. This is translated into a monetary value of about $13.1 billion of which $ 5.16 billion was accounted for recycled aluminum of about 3.29 million metric tons. Table 2 present the tonnage of aluminum produced during the 1993 and 1997 in the U.S. both from primary and secondary sources It also contains the price of aluminum ingot in cents per pound.

Aluminum consumption by about 25,000 firms in the U. S. is centered in the east central United States. The use in transportation accounts for about 32%, packaging 26%, building 16%, electrical 8%, consumer durables. 8% and other 10%.

The amount of aluminum imported from Russia has dropped from over 600,000 tons annually in 93-95 to about 400,000 tons in 96.

Table 2. Aluminum production in the U.S.[2]

(in thousand metric tons)

Production	1993	1994	1995	1996	1997
Primary	3,695	3,299	3,375	3,577	3,600
Secondary	1,630	1,500	1,510	1,570	1,700
Price (cents per pound)	53.3	71.2	85.9	71.3	75

Table 3. Smelter production of aluminum by country[2]

(in thousand metric tons)

Country	1996	1997
U.S.	3,577	3,600
Australia	1,372	1,390
Brazil	1,190	1,200

Table 3. presents the world smelter production in 1996 and 1997.

It is well known that aluminum is readily recycled from used beverage containers.[3] The recovery of aluminum from secondary sources is being carried out pyrometallurgically. When aluminum-bearing materials are subjected to melting, a special attention has been drawn because melting of aluminum oxides could be a problem. A flux usually containing NaCl-KCl with a small amount of fluorides such as KF, NaF or cryolite[4-6] is added to overcome such a problem.

3. Copper

Copper ranks third in world metal consumption following steel and aluminum. Obviously copper represents an important ingredient used in industrialized nations. The major copper consuming nations in 1990 were Western European countries accounting for about 29%, the U.S 19%, Japan 14%, Russia 10% and China 5.3%.

In 1996, the total supply of copper in the U.S. including sources such as primary ores, scrap and importation was approximately 3.7 million metric tons. This is translated into a monetary value of about $8.91 billion of which $3.12 billion was accounted for recycled aluminum of about 1.3 million metric tons. Table 4 presents the tonnage of copper produced during the 1993 and 1997 in the U.S. both from primary and secondary sources. It also contains the price of copper in cents per pound.

The major consumption of copper is found in building construction accounted for about 43%, followed by electric and electronic products, 24%, industrial machinery and e-

Table 4. Copper production in the U.S.[2]

(in thousand metric tons)

Production	1993	1994	1995	1996	1997
Primary	1,790	1,840	1,930	2,010	2,070
Secondary	543	500	442	428	420
Price (cents per pound)	91.6	111.0	138.3	109.0	108

Table 5. Mine production of copper and reserves by country[2]

China	439	440	18,000
Congo	29	40	10.000
Indonesia	507	525	11,000
Kazakstan	250	230	14,000
Mexico	341	360	15,000
Peru	572	580	7,000
Poland	422	420	20,000
Russia	520	520	20,000
Zambia	334	350	12,000
Other countries	1,330	1,360	40,000

quipment, 12%, transportation equipment, 12%, and consumer and general products, 9%. Primary copper was produced by about 35 mines operating in the U.S. in 996.

Table 5 presents the world mine production of copper in 1996 and 1997, and reserves:

Copper is recovered from secondary sources most frequently using pyrometallurgical technologies. The recovery of metals from electronic scrap represents most diverse strategies since it contains plastic in the amount of 30%, oxides, 30% consisting of silica, alumina and alkaline earth oxides[7] and metals consisting primarily of copper, 20%, iron, 8%, nickel, 2%, tine. 4%, lead, 2%, aluminum 2%, and zinc, 1%. In addition, it also contains gold, 0.1%, silver, 0 2% and palladium, 0.005%. which is often the economic drive for processing the electronic scrap.

It is interesting to note that based on the above composition and the price of these metals of May 1998,[8] the monetary value of each metal for one metric ton of electronic scrap amounts to about $377 for copper, $9,900 for gold, $397 for silver and $563 for palladium. The treatment of the electronic scrap has been described in the open literature[9-11] Researchers in the author's laboratory have developed a number of processes dealing with economical recovery of precious metals from various sources.[12-16]

4. Gold

The primary use of gold is found in the jewelry industry. Although the production amount of gold is relatively low, its high price makes gold fourth most valuable metal following steel, aluminum and copper in terms of revenue generation in the U.S. Since gold has extraordinary properties in electrical conductivity and corrosion resistance, gold emerged as an essential industrial metal used in computers, communication equipment, spacecraft, jet aircraft engines among many other applications. About 60~70% of gold is

Table 6.

Secondary	153	163	152	148	150
Price (dollars per ounce)	363.29	344 97	360.91	385 41	385.00

still used in the jewelry industry, 20~30% is used in electronic industry and 7% in dental applications In 1997, the total mine production of gold in the U.S. was valued at about $3 4 billion.

The major consumption of copper is found in building construction accounted for about 43%, followed by electric and electronic products, 24%, industrial machinery and equipment, 12% transportation equipment, 12%, and consumer and general products, 9% Primary copper was produced by about 35 mines operating in the U.S. in 1996.

Table 7. presents the world mine production and reserves of gold:

It is interesting to note that in the history of gold mining, about 123.000 tons have been mined which is compared to the estimated world reserves of 89,000. Of 123,000 tons mined, about 34,000 tons is official stocks held by central banks of many countries and about 71,000 tons is privately held as coin, bullion, and jewelry.

Gold is extracted traditionally using cyanide in the primary industry. However. since the rate of dissolution in cyanide-bearing solutions is very slow and cyanide is toxic, other chemical reagents such as aqua regia[18] is used in the treatment. However, the cost of reagents in such a system is usually high and post treatment involving with the recovery of various metals in the leach liquor can be complicated. Researchers in the author's service centers, 21%, transportation primarily automotive production, 14%, construction, 13%, cans and containers. 4% and others, 48%.

Table 7. Mine production and reserves of gold by country[1,17]

(in metric tons)

Country	Mine production		Reserves
	1996	1997	
U.S	318	325	5,600
Australia	289	290	4.000
Brazil	63	75	800
Canada	164	150	1,500
China	145	125	NA
Russia	120	135	3.000
South Africa	498	490	18,500
Uzbekistan	72	65	2,000
Other countries	580	650	9,300

Table 8. Iron and steel production in the U.S.[2]

(in million metric tons)

Production	1993	1994	1995	1996	1997
Prig iron	48.2	49.4	50.9	49 4	53.8
Steel	88 8	91.2	95 2	95.5	96.7
producer price index	108.2	113 4	120.1	115.7	116.8

Table 9. Production of iron and steel and reserves by country[2]

(in million metric tons)

Country	Pig iron	Raw steel	Crude ore reserves
U.S.	49.3	96.0	16,000
Australia			18,000
Brazil	24.6	26.2	11,000
Canada			12,000
China	113	106	25,000
European Union	96 6	157	
Japan	78 6	105	
Korea	22.4	41 4	34,300
Russia	36.9	48.6	5,400
India			

In 1996, the total supply of iron and steel in the U.S. including sources such as primary ores, scrap and importation was apporximately 183 million metric tons This is translated into a monetary value of about $23.9 billion of which $6. 82 billion was accounted for recycled iron and steel of about 72 million metric tons. Table 8 presents the tonnage of iron and steel produced during the 1993 and 1997 in the U. S. both from primary and secondary sources. It also contains the producer price index for steel mill products based on 100 for the year 1982.

Table 9 presents world production of pig iron and steel in 1997 and also listed are crude iron ore reserves.

5. Lead

The value of lead produced in U.S. mines in 1997 was about $440 million. It should be noted however, that the lead produced from scrap was more than that produced from primary sources. The transportation industries are the principal users of lead, consuming about 71% of it for batteries, fuel tanks, solder, seals, and bearings. The use in electrical, electronic, and communications accounts for about 23% and the balance was used in ballast and weights, ceramics and crystal glass, tubes and containers, type metal, foil, wire, and specialized chemicals.

Table 10. Lead production in the U.S.[2]

(in thousand metric tons)

Production	1993	1994	1995	1996	1997
Primary	335	351	374	326	340
Secondary	838	877	963	1,060	1,100
Price (cents per pound)	31.7	37.2	42.3	48.8	47

Table 11. Mine production of lead and reserves by country[2]

(in thousand metric tons)

Country	Mine production		Reserves
	1996	1997	
U S.	436	450	7,000
Australia	522	530	18,000
Canada	241	190	4,000
China	500	450	6,000

In 1996, the total supply of lead in the U.S. including sources such as primary ores, scrap and importation was approximately 1.63 million metric tons. This is translated into a monetary value of about $1.75 billion of which $1.17 billion was accounted for recycled lead of about 1.1 million metric tons. Table 10 presents the tonnage of lead produced during the 1993 and 1997 in the U.S. both from primary and scecondary sources. It also contains the price of lead in cents per pound.

Table 11 presents the world mine production of lead in 1996 and 1997, and reserves:

Its strong acid resistant property allows lead to be used often in pipes. However, its toxicity one of the major problems which discourage people to use lead in water pipes. Substitution of plastics has reduced the use of lead in building construction, electrical cable covering, cans, and containers in recent years.

The recovery of lead from lead batteries is traditionally carried out in rotary furnaces.[19] After removal of plastics associated with batteries, the lead paste is subjected to smelting at around 1000°C with coke as a reductant and sodium carbonate flux and iron borings to fix sulfur. Hydrometallurgical treatment of lead batteries has also been tested.[20,21] In this process, lead is converted to soluble lead compounds such as $PbSO_4$ and PbO_2 which are then subjected to dissolution and then the leach liquor is subjected to electrowinning.

6. Pt-group Metals

The primary use of pt-group metals is found in the au-

Table 12. Mine production in 1997 and reserves of platinum and palladium by country[2] (in kilograms)

Country	Mine production		Reserves (PGM)
	Platinum	Palladium	
U.S.	2,500	8,300	570,000
Canada	8,300	5,300	311,000
Russia	18,500	50,000	6,220,000
South Africa	117,000	49,000	62,800,000
Other countries	148,000	116,000	70,600,000

tomotive industry, which represents about 38%. Other uses are found in electrical and electronic, 29%. dental and medical, 9%, chemical, 4%, petroleum refining, 5%, and other, 15%. The major platinum producing country is South Africa, 60%. Russia, 10%, the United Kingdom, 10%, Germany. 5%, and other, 15% The U.S. only one active pt-group metals mine located in Montana, which produced about 11,000 kilograms of PGM, primarily palladium in 1997.

In 1997, the amounts of platinum, palladium and rhodium imported for consumption in the U.S were about 76, 95 and 7 metric tons respectively. In comparison, about 63 metric tons of PGM was recovered from scrap in the same year.

Table 12 presents the world mine production and reserves of platinum and palladium:

7. Silver

Silver is an industrial metal compared to gold. Its primary use, approximately 50% of the total consumption is found in the manufacture of photographic products Other uses include electrical and electronic products, 21%, electroplated ware, sterlingware, and jewelry, about 9% and other uses, 20%. In 1997. silver was produced from 76 mines in the U. S. with estimated value of $238 million.

Table 13 presents U.S. silver production for the period of 1991~1995.

The price of silver has been relatively low for sometime. The price of silver has been increasing steadily in recent

Table 13. Silver production in the U.S.[17] (in metric tons)

Production	1991	1992	1993	1994	1995
Mine	1,860	1,800	1,640	1,480	1,500
Refinery: Primary	1,880	2,160	1,790	1,810	1,800
Secondary	1,700	1,760	2,020	1,700	1,700
Price (dollars per ounce)	4.04	3.94	4.30	5.29	5.30

Table 14. Mine production and reserves of silver by country[2] (in metric tons)

Country	Mine production		Reserves
	1996	1997	
U.S	1,570	1,600	31,000
Australia	1,020	1,100	29,000
Canada	1,230	1,200	37,000
Mexico	2,500	2,500	37,000
Peru	1,970	2,000	25,000
Other countries	6,910	6,900	120,000

years. The most current price, based on May of 1998 Metals Week, is $6.17 per ounce.

Table 14 presents the world mine production and reserves of silver·

8. Zinc

The value of zinc produced in U.S mines in 1997 was about $1.1 billion. more than twice that of lead. About 54% zinc consumed was found in galvanizing, 19% in zinc-base alloys, 13% in brass and bronze, and 14% in other uses.

In 1996, the total supply of zinc in the U.S. including sources such as primary ores, scrap and importation was approximately 1.45 million metric tons. This is translated into a monetary value of about $1 64 billion of which $388 million was accounted for recycled zinc of about 0.379 million metric tons. Table 15 presents the tonnage of zinc produced during the 1993 and 1997 in the U S both from primary and secondary sources. It also contains the price of zinc in

Table 15. Zinc production in the U.S.[2] (in thousand metric tons)

Production	1993	1994	1995	1996	1997
Primary	240	217	232	226	235
Secondary	141	139	131	140	145
Price (cents per pound)	46 2	49.3	55.8	51.1	81

Table 16. Mine production of lead and reserves by country[2] (in thousand metric tons)

Country	Mine production		Reserves
	1996	1997	
U.S.	628	635	19,000
Australia	1,071	1,100	39,000
Canada	1,235	1,200	15,000
China	1,010	1,000	33,000
Mexico	378	380	6,000

cents per pound

The price of zinc has dropped in recent months approximating 63 cents per pound at the May of 1998 price.

Table 16 present the world mine production of zinc in 1996 and 1997, and reserves: therefore the treatment usually involves thermal reduction to volatilize zinc together with lead and cadmium. Hydrometallurgical routes often involve direct dissolution of zinc among other metals and metal values are subsequently recovered by traditional methods such as electrowinning, solvent extraction, chemical precipitation and cementation.

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