INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING-GREEN TECHNOLOGY Vol. 1, No. 2, pp. 145-152 APRIL 2014 / 145
DOI: 10.1007/s40684-014-0019-y

Industrial Demand and Integrated Material Flow of Terbium in Korea

Il Seuk Lee[1] and Jeong Gon Kim[2,#]

1 Center for Resources Information & Management Korea Institute of Industrial Technology, 07-34 Yeoksam-dong, Gangnam-gu, Seoul, South Korea, 135-918
2 Department of Materials Science & Engineering, Incheon National University, 12-1 Songdo-dong, Yeonsu-gu, Incheon, South Korea, 406-772
Corresponding Author / jyj309@incheoa.ac.kr, TEL: +82-32-835-8279, FAX: +82-32-835-0778

KEYWORDS: Terbium, Rare earth elements, Material flow analysis

The integrated material flow analysis methodology uses bottom-up flow analysis for primary and secondary resources and top-down flow analysis for the distribution structure. By combining the advantages of the top-down and bottom-up methods, the integrated material flow analysis Methodology can overcome the limitations of each method. Using the IMFAM, this study investigated the material flow of terbium in 2011, in Korea. Terbium was used to produce 3-wevelength fluorescent lamps, liquid crystal display back light unit, plasma display panel and so on. 7,239 kg of terbium was required to produce the intermediate product in Korea. Among total terbium used to produce intermediate products, 2,592 kg the part of the fluorescent lamp, 4,984 kg the part of flat panel display, which were used, 107 kg, was exported and 46 was put in collect stage. In the part of the 3-wevelength fluorescent lamp, terbium's use was expected to gradually increase for needs of consumers. But in the part of flat panel display, terbium's use is expected to gradually decrease. The use of terbium is expected to decrease in others. This MFA results represent the materials flow of terbium in Korea and can be used to predict demand through investigations on the demand industry.

Manuscript received: November 8, 2013 / Revised: February 6, 2014 / Accepted: February 11, 2014

NOMENCLATURE

1st flow = Primary resource flow
2nd flow = Recycling resource flow

1. Introduction

Due to the fast increase in the rare earth elements (REE) resource consumption of newly industrializing economies, crisis of resource depletion of finite natural resources is growing. The estimated demand for resources is exponentially increasing compared to the amount of resources that could be mined in the future. Therefore, many countries are doing much to acquire mineral resources, which are the core raw materials for industries.

Particularly among mineral resources, rare earth elements are highly deposited in certain parts of the world. China owns about 50% of their global reserves and produces over 86% of them.[3] China recently changed its trade policy for rare earth elements from export promotion to export restriction due to the increase in its domestic consumption. It is also strengthening its export restrictions based on promotion of its export allotment permission system. Worldwide countries that of producing key metal and mineral resources are increasing their impact on metal and mineral resources and exerting their power in 21st-century high-tech industries to maximize their country's interests.

Shown in Table 1 are the current world reserves of rare earth elements.[1] The global reserve of rare earth elements is 110,000,000 tons, and 50%, of it, which is 55,000,000 ton is deposited in China;

Table 1 World reserve of rare earth elements by country

Country	Reserves[kton]	Shares[%]
China	55,000,000	48.34
Russia	19,000,000	16.70
U.S	13,000,000	11.43
India	3,100,000	2.72
Australia	1,600,000	1.41
Brazil	48,000	0.04
Malaysia	30,000	0.03
Other	22,000,000	19.34
Total	113,778,000	100.0

about 17%, 19,000,000 tons in the Commonwealth of Independent States; and about 11%, 13,000,000 tons in the USA. These figures show a strong tendency toward unequal distribution.

Shown in Fig. 1 are the production quantities of rare earth elements by country. China produces over 97% of the world's rare earth elements in 2011, but was reduced to 86% with the start of rare earth elements production of Mt. Pass mine in USA. Its production has remained at around 120,000 tons since 2006; in 2010, 130,000 tons and in 2012 it produces 95,000 tons. While China accounts for the largest part of the world's production, the production of other countries has continued to dwindle, which has made them rely heavily on China's production [2,3,5] Terbium is a rare earth element with a silver-white color and excellent malleability and ductility, and is smooth enough to be cut with a knife.

Its main uses are as an additive to calcium fluoride, calcium tungsten and strontium molybdate, which are used as raw materials for electronic parts; and along with ZrO_2, as a crystal stabilization agent for fuel cells. It is also used as a magnetostrictive material (Terfenol-D)[21, 22] in naval sonar radar system detectors and as an actuator in sound bug systems.[15]

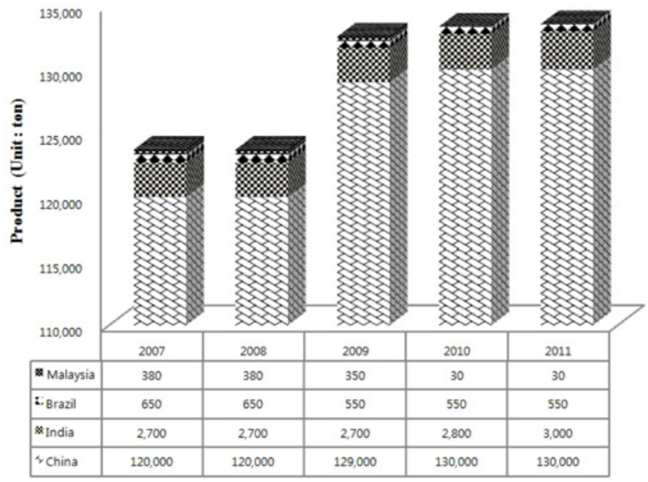

Fig. 1 Production quantities of rare earth elements by country[2]

Terbium oxide is used to emit green light in color TV tubes, which are three-band and five-band radiation lamps that use the emission property of an electromagnetic field. It is also used to improve the illumination intensity of fluorescent lamps or the clarity of X-ray screens, and to emit green light in the early of light emitting diod(LED) development.[7] In 2008, about 129,000 tons of the world's rare earth elements based on oxides were consumed.[8] About 60% of it was consumed by the catalyst, glass, lighting and metal industries, and the remaining 40%, by alloy elements, ceramic, magnet and other industries. Its consumption is increasing yearly by 4-10%.[4,9]

Table 2 shows the of rare earth elements consumption by usage.[11] The glass industry uses 28,400 tons (for polishing, 58% and for additives, 42%); the catalyst industry, 27,400 tons (for fluid decomposition, 72% and for catalysts, 28%); the Nd-Fe-B magnetic industry, 26,300 tons; the metallurgy and alloy elements industry, 23,600 tons; and other industries, 23,500 tons.

About 9,000 tons of rare earth elements are used to manufacture phosphors, and only 4.6% of such quantity is accounted for by terbium, which is used as a dopant in fluorescent agents. Moreover, 26,300 tons of rare earth elements are used for permanent magnets, of which only 0.2% is accounted for by terbium.[6]

Of the global terbium consumption as of 2008, 88.7% is for phosphor production (414 tons) and the remaining 12.3% (53 tons), is for the production of rare earth magnets.

As Korea imports most of its metal and mineral resources, it urgently needs to establish the groundwork for alleviating the effect of the fluctuation of global resource prices and the resource shortage crisis on its domestic industries and for building its national resource management system as well as improving its resource productivity to achieve a stable supply of resources.

In preparation for resource shortage due to the supply restriction policies of key mineral-producing countries and the soaring demand for resources, this study was conducted to determine the circulation of primary and recycled resources through a material flow analysis of terbium in 2011 and to acquire basic data for demand trend analysis and supply prospects analysis by surveying supply and demand trends in Korea.

Table 2 Rare earth elements consumption rates in 2008 by usage

End uses	CeO_2	La_2O_3	Nd_2O_3	Y_2O_3	Pr_6O_{11}	Dy_2O_3	Gd_2O_3	SmO	Tb_6O_7	Eu_2O_3	Other
Quantity used, in metric tons											
Automobile catalytic converters	6,840	380	228	-	152	-	-	-	-	-	-
Ceramics	840	1,190	840	3,710	420	-	-	-	-	-	-
Fluid catalytic cracking	1,980	17,800	-	-	-	-	-	-	-	-	-
Glass additives	7,920	2,880	360	240	120	-	-	-	-	-	480
Metallurgy, except batteries	5,980	2,990	1,900	-	633	-	-	-	-	-	-
Neodymium magnets	-	-	18,200	-	6,140	1,310	525	-	53	-	-
Battery alloys	4,040	6,050	1,210	-	399	-	-	399	-	-	-
Phosphors	990	765	-	6,230	-	-	162	-	414	441	-
Glass polishing	10,700	5,170	-	-	574	-	-	-	-	-	-
Other	2,930	1,430	1,130	1,430	300	-	75	150	-	-	75
Total	42,200	38,700	23,900	11,600	8,740	1,310	762	549	467	441	555

(The values are in metric tons of rare earth oxides and are rounded off to three significant digits. The percentages are rounded off to the nearest decimal. The values may not add up to the totals shown due to the independent rounding off. CeO_2 stands for cerium oxide; Dy_2O_3, dysprosium oxide; Eu_2O_3, europium oxide; Gd_2O_3, gadolinium oxide; La_2O_3, lanthanum oxide; Nd_2O_3, neodymium oxide; Pr_6O_{11}, praseodymium oxide; SmO, samarium oxide; Tb_6O_7, terbium oxide; Y_2O_3, yttrium oxide; REO, rare earth oxide; and -, no consumption.)

2. Integrated Material Flow Analysis

2.1 Integrated Material Flow Methodology

The integrated material flow methodology (IMFAM) uses the results of both top-down and bottom-up materials flow analysis methods. It combines the advantages of the two methods by applying the bottom-up method to the primary resources and secondary resources flow, in the material flow analysis, wherein reliable data acquisition is essential, and the top-down method to the distribution coefficient of material of intermediate and end products that lack field survey or actual statistical data.

The two aforementioned methods in the integrated material flow analysis (MFA) methodology are described in Fig. 2. The bottom-up method is used for the domestic supply-demand analysis based on the domestic ore, metal ingot production and the amount of imports and exports; but if the resources are put in the end production stage, the calculation from the inputted amount or the ratio of the resources among internal industries requires the determination of the amount of material flow in domestic all industries and products, which makes it difficult to use the bottom-up method. In this case, a material flow between industries can be calculated using the top-down method.

Such an integrated material flow analysis allows the analyst to select the advantages of either the top-down or bottom-up method, and helps resolve the problems with each method.

The proposed integrated methodology can solve problems with the top-down and bottom-up MFA methods. The integrated material flow is defined in eight stages.

Such an integrated material flow analysis allows the analyst to select the advantages of either the top-down or bottom-up method, and helps resolve the problems with each method.

The proposed integrated methodology can solve problems with the top-down and bottom-up MFA methods. The integrated material flow is defined in eight stages.

Raw material stage: The stage in which the ores produced domestically or abroad, and the secondary resources inputted in the recycling stage, are produced as ingots by removing their impurities

First process stage: The stage in which the ingots from the raw material stage go through the processing stage and are manufactured in the form of plates, plating, poles, wires or compound etc.

Intermediate product stage: The stage in which intermediate stage products from the first processed products are manufactured to use or produce the end product

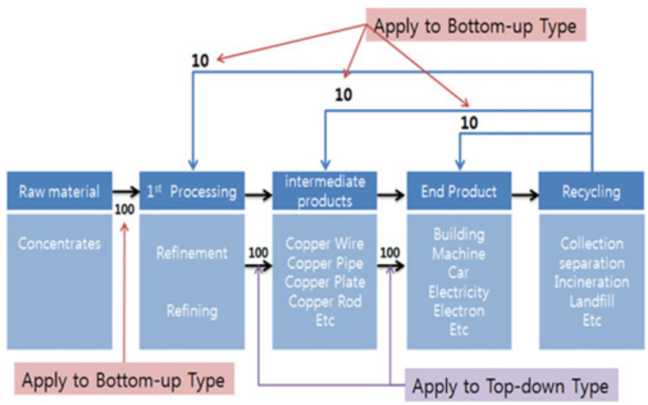

Fig. 2 Schematic of integrated materials flow methodology

End product stage: The end product such as the construction, automobile, electronic, or other industries, in which intermediate stage are finally inputted as representative products of each industry

Use/accumulation stage: The stage in which the manufactured end products in the current year are consumed and used. The manufactured end products until last year are accumulated by considering the durability of each end product, and the used products are collected for recycling

Collection stage: The stage in which used products are collected and processed to be recycled as secondary resources

Recycling stage: The stage in which the collected products are inputted in the recycling process

Disposal stage: The disposal of not recovered resource from the collection stage and from the recycling stage

2.2 Terbium Flow in Korea

2.2.1 Raw Materials Stage

In Korea, there is no company that owns a rare earth elements smelting and refining plant. However, the Korean mineral resources corporation and some other companies, having recognized the importance of rare earth elements, are researching and examining the feasibility of putting up such a separation and refining plant.

In 2011, there was no supply of rare earth ore related to terbium in Korea. While Hongcheon Jaeun mine in Jaeun-ri, Duchon-yeon, Hongcheon-gun, Gangwon[17] exists, its R_2O_3 class is low at 2.13% m and its potential reserve is only about 20,181 ktons. Due to its low economic value, it is not being developed.

The statistical survey and field research conducted by Korea international trade association[16] showed that terbium-related basic inorganic chemicals was not being imported and exported by Korea.

In KITA's statistics, terbium ingots do not exist as independent harmonized commodity description and coding system Korea (HSK) code, Table 3 shows the HSK codes that are related to rare earth elements.

KITA's terbium-related HSK code is 2805302000, which is grouped with europium and gadolinium, and the amounts of its exports and

Table 3 HSK codes associated with rare earth elements

HS-Code	Item
2805 30	Rare Earth Elements Metals · Scandium and Yttrium
2805 30 1000	Cerium group
2805 30 2000	Terbium group
2805 30 3000	Erbium group
2805 30 4000	Yttrium
2805 30 5000	Scandium
2805 30 9000	Other

Table 4 Import and export of the Tb group

	Weight[kg]	
2011	Import	1
	Export	-
2010	Import	2
	Export	-
2009	Import	1
	Export	-
2008	Import	1
	Export	-
2007	Import	553
	Export	-

imports are shown in Table 4.[16]

In 2011, only 1 kg of it was imported; and while it was difficult to determine the exact amount of the element that was imported, it was considered to have been terbium, a representative rare earth element, and was inserted as such.

Since terbium-related basic inorganic chemicals and ingots that are circulated among secondary resources are either supplied or recycled in the recycling stage, they are not used as raw materials. Recycled terbium, which is circulated among secondary resources, is used to produce intermediate products. The amount of terbium supply in the raw materials stage is only 1 kg.

2.2.2 First Process Stage

The terbium production in the first process stage was used to conduct a material flow analysis for phosphors, which included terbium or terbium oxide.

Terbium oxide that was included in the composite oxide was imported. And terbium oxide, the form was Tb_4O_7.

Depending on the type of support, terbium-included phosphors are categorized into phosphate phosphors, silicate phosphors, aluminate phosphors and borate phosphors. Based on their usage, they are categorized into plasma phosphors, phosphors for giant-screen display tubes, phosphors for X-ray intensifying screens and phosphors for orthochromatic films. The first process stage was conducted based on the usage.

Terbium ingots from raw materials stage were sent to the process where terbium oxides were produced. There were no basic inorganic chemicals that contained terbium, which was sent to the first process stage. However, 1 kg of terbium ingots was supplied. The field survey of related companies showed that the net amount of terbium included in imported terbium chemicals was 1,021 kg.

Imported terbium chemicals, produced as phosphors was used to manufacture the backlight units (BLU) for liquid crystal display (LCD) panels and plasma display panels (PDP).

Terbium is used with phosphors' dopant for display device. As shown in Fig. 3, when terbium prices soared in the second half of 2010, the field survey confirmed that no more terbium were not utilized to produce of general fluorescent lamps[17].

The use of three-band fluorescent lamps is increasing because they offer the highest illumination among fluorescent lamps. The survey on the companies that produce or import fluorescent lamps showed that over 70% of the fluorescent lamp market was accounted for by three-band fluorescent lamps in 2011.

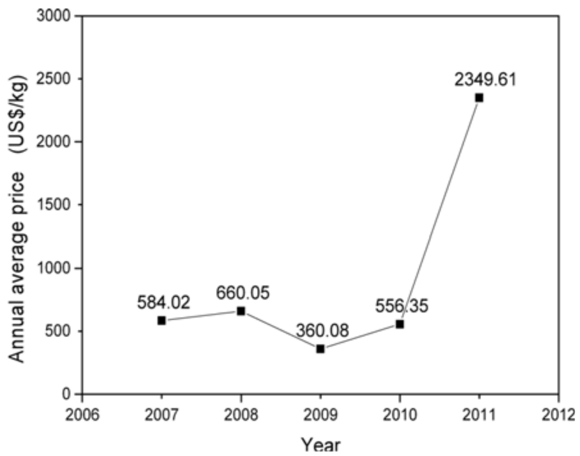

Fig. 3 Terbium price changes

To examine the amount of phosphors used in three-band fluorescent lamp, the types and amount used of phosphors used by three-band lamp manufacturers were surveyed. We confirmed that only the three-wavelength lamp was produced in Korea through the survey and both general fluorescent lamps and three-band fluorescent lamps were imported from their foreign plants.

The amount of phosphors used in three-band fluorescent lamp was calculated using Eq. (1).

$$Amount\ of\ phoshors\ in\ one\ fluorescent\ lamp = \frac{Amount\ of\ phosphors\ used\ in\ 2011}{Production\ of\ fluorescent\ lamps(in\ units)} \quad (1)$$

Amount of phosphors used by manufacturing company in 2011
Where, ni = Yearly consumption of i phosphors

$$Yearly\ phosphor\ consumption = \sum_{n=1}^{i}(n_1+n_2+n_3+...)$$

Production of fluorescent lamps - Production of fluorescent lamps in 2011 by the manufacturing company

The survey showed that there was about 0.6305 g of phosphors in one three-band fluorescent lamp, and the results of Eqs. (2) and (3) showed that 0.0136763 g of terbium is used in one fluorescent lamp.

$$Ratio\ of\ Tb\ to\ phosphors(\%) = \frac{Tb\ content}{Molecular\ weight\ of\ phosphors\ with\ Tb} \times 100 \quad (2)$$

$$Amount\ of\ Tb = Phosphor\ consumption \times \frac{1}{3} \times of\ Tb\ to\ phosphors(\%) \times 100 \quad (3)$$

The total number of fluorescent lamps produced in Korea in 2011 was 78,440,000 units.[18] All the required phosphors were imported and the terbium consumption rate was about 1,074 kg.

The production ratio of cold cathode fluorescent lamps (CCFL) to LEDs in 2011, as shown in Table 5, was 51:49. The LCD TV production ratio based on CCFLs[12] was used. The field survey showed that LED BLU did not contain terbium.

Tables 6 and 7 are the production and export quantities of LCD and PDP TVs in Korea, in 2011.[14]

Using the aforementioned data and those from the business's annual reports 2011 of LCD and PDP TV manufacturers, the production cost per unit was calculated and used to be estimated the numbers of LCD and PDV TVs manufactured. The export, import and consumption numbers in Korea for the year of 2011 is shown in Table 8. The KITA statistical data were used for the amount of imports.

Table 5 Exports Ratio of LCD TV back light unit category

	Q2 '11 [%]	Q3 '11 [%]	Q4 '11 [%]	Q1 '12 [%]	Q2 '12 [%]	Q3 '12 [%]	Q4 '12 [%]
CCFL	57.3	51.0	44.7	40.8	35.1	31.9	29.7
Direct Type LED	1.3	1.0	0.5	3.8	8.3	12.7	17.0
Edge Type LED	41.4	480	54.8	55.3	56.6	55.4	53.4

The field survey confirmed that the amount of phosphors used in lamps for CCFL-type LCD TVs was 0.05 g per lamp. The field survey on the company that produces CCFL BLU showed that 22 lamps are used in a 46” TV.

As for CCFL-type LCD TVs, their phosphors content per unit (46”) was about 1.1 g, of which green phosphors that contained terbium accounted for 0.3667 g. The net terbium content of these green phosphors was 6.8%. The survey showed that the Korea production ratio of CCF lamps was 44.4%, and the terbium content of CCFL-type LCD TVs was about 164 kg.

According to the survey on PDP TV, the average phosphors content of a 50” PDP TV was 100 g. To realize RGB (red, green, blue) colors, each color was evenly used by 33.3%. The molecular weight of the green phosphors was 155.6628 g, of which that of terbium was 0.05 Mole or about 5.1%. The terbium content per PDP TV was 1.701598 g. The PDP TV production in Korea is over 99%.

The amount of terbium used in PDP TV production was 4,659 kg, of which 1,022 kg was provided in the pre-process and 3,637 kg was imported.

The total supply of terbium in the first process stage is 5,897 kg, which was included in the phosphors used for LCD BLU, PDP panels and fluorescent lamps.

2.2.3 Intermediate Product Stage

The intermediate product stage is the stage in which intermediate products are produced to yield the end products, and was produced from the first process stage.

The intermediate products were LCD TV BLUs, PDP panels and flat display panels. They are used in lighting and particularly in three-band fluorescent lamps, in addition to photographic chemicals such as orthochromatic films and X-ray sensitization screens.

Various types of terbium oxide-related phosphors with different terbium contents are manufactured in or imported by Korea. Due to the characteristics of phosphors, their components and construction methods are so diverse that it was difficult to determine their exact data for this study.

Of the total demand for CCF lamps for LCD TVs, 44.4% was manufactured in Korea and the remaining 55.6% was imported from Vietnam and China. The amount of terbium in imported CCF lamps for LCD TV production was 206 kg. The imported LCD CCF lamps were used to manufacture BLUs in Korea.

In this study, a survey was conducted on three-band fluorescent lamps that was imported and exported by Korea. Fluorescent lamps are both intermediate and end products. In the intermediate product stage, their flow stops; and after their use, they are sent to the collection stage.

The amount of exports and imports of fluorescent lamps were shown in Table 9.[16]

The amount of terbium included(2,592 kg) in three-band fluorescent lamps, was calculated from, the amount of terbium included(107 kg) in the exported three-band fluorescent lamps, the amount of terbium supplied(1,073 kg,) from the first processed product stage and the amount of terbium included(1,626 kg) in the imported three-band fluorescent lamps.

The production of tubes for color TVs and computer monitors in Korea was discontinued in June 2006. After Korea announced that it had nine production lines in April 2009, it closed its factories in Tianjin, China and in Mexico and Brazil, and its additional two lines in Malaysia by the end of December 2012. Korea also has a factory in

Table 8 Estimated productions of LCDs and PDPs in 2011

		Production	Export	Import	Domestic
LCD	CCFL	14,889,395	13,861,655	1,027,695	2,055,435
	LED	14,305,497	13,318,061	987,393	1,974,829
Sum		29,194,892	27,179,716	2,015,088	4,030,264
PDP		2,710,835	2,195,396	296,129	811,568

Table 9 Exports and imports of fluorescent lamps

Year	Export	Import
2003	25,058,934	52,259,796
2004	12,351,572	68,719,650
2005	11,278,787	96,548,146
2006	11,164,577	111,315,929
2007	12,428,019	115,331,037
2008	14,653,847	109,384,702
2009	19,210,093	89,933,038
2010	16,874,094	103,489,658
2011	7,787,066	118,864,366

Table 6 Production of flat panel display devices in Korea

	‘09	‘10	2011					2012								
			9	10	11	12	SUM	1	2	3	4	5	6	7	8	9
LCD	29,099	31,809	2,609	2,973	2,502	2,382	29,485	2,106	2,111	2,364	2,415	2,499	2,317	2,469	2,570	2,555
PDP	1,666	1,962	156	162	149	103	1,745	116	116	125	120	126	98	105	134	143
OLED	436	661	232	238	247	240	1,781	262	254	273	252	318	351	356	394	365
CRT	228	198	11	10	1	0	125	0	0	0	0	0	0	0	0	0
SUM	31,429	34,630	3,008	3,383	2,899	2,725	33,136	2,484	2,481	2,762	2,787	2,943	2,766	2,930	3,098	3,063

Table 7 Exports of flat panel display devices in Korea

	‘09	‘10	2011					2012								
			9	10	11	12	SUM	1	2	3	4	5	6	7	8	9
LCD	31,003	34,940	2,884	2,898	2,823	2,549	31,671	2,481	2,524	2,783	2,850	2,855	2,762	2,743	2,951	3,033
PDP	1,921	2,218	176	182	167	116	1,959	131	132	141	135	143	111	121	152	161
OLED	589	869	283	282	282	273	2,277	301	294	340	293	370	408	414	458	425
CRT	242	204	11	10	1	0	126	0	0	0	0	0	0	0	0	0
SUM	33,755	38,231	3,354	3,372	3,273	2,938	36,033	2,913	2,950	3,264	3,278	3,368	3,281	3,278	3,561	3,619

Shenzhen, China, in Seremban, Malaysia and in Manaus, Brazil. It is believed that there are no CRT-related production facilities in Korea.

The use of terbium as a photographic chemical is for X-ray sensitizing screens, which make image clear when exposed to X-ray.

However, with the digitization of X-ray devices, there is now little demand for the films used for X-ray shots, so it was difficult to determine its consumption. Moreover, the orthochromatic film is coated with a photographic emulsion, i.e., silver halide, with an added pigment that has a wide scope of light sensitization and is sensitized even to green or yellow with a long wavelength around 600 μm. Since it could offer a high contrast, it was mainly used for photoengraving. However, with the digitalization of printing devices, its use has gradually decreased so that the amount of its consumption could not be determined in 2011.

Shown in Table 10 is the consumption of terbium by the scope of each product in the intermediate product stage.

Three-band fluorescent lamps do not go from the intermediate to end stage. But they go to the usage and accumulation stage. The production in the PDP panel manufacturing process is about 99%, with 1% defects that were sent to the collection stage.

2.2.4 End Products Stage

In the end products stage, materials flow analysis (MFA) was conducted using the statistical and field survey data of the related companies that were supplied from the intermediate to the end products stage. The products that were processed in the intermediate products stage were used to product TVs, computers and other devices that consisted of the electric and electronic components.

The amount of terbium supplied in the intermediate products stage for LCD TVs in Korea was 371 kg, and the amount included in imported LCD TVs was 26 kg. The total terbium export amount was 346 kg. The amount of terbium included in LCD TVs supplied in the Korea domestic market was 51 kg. As shown in Table 8, the amount of terbium supplied in the intermediate products stage in PDP TVs, was 4,613 kg; in imported PDP TVs, 504 kg; and in exported PDP TVs, 3,736 kg. Therefore the amount of terbium included in PDP TVs supplied in the Korea domestic market was 1,381 kg.

The flow of terbium in photographic chemicals seems to have disappeared due to the digitalization of the market. While there should still be some flow related to orthochromatic films, its amount is expected to be very small, and expected to be used in the intermediate products stage of printing work instead of being included in the end product.

The amount of terbium included in end products in Korea was 1,432 kg, about 18.5% of the total terbium consumption in Korea of 7,729 kg. This figure excludes the terbium consumption for three-band fluorescent lamps.

Table 10 Consumption by product in the intermediate product stage

		The amout of supply in the previous stage[kg]	Import [kg]	Export [kg]	Supply [kg]	Recycle [kg]
CCF Lamp		165	206	0	0	0
Flat panel display	LCD panel	0	0	0	371	0
	LED panel	0	0	0	0	0
	PDP panel	4,659	0	0	4,613	460
Light		1,073	1,626	107	2,592	0
Chemical products used in photography		0	0	0	0	0
Total		5,897	1,832	107	7,576	460

2.2.5 Use/Accumulation Stage

The use and accumulation stage is where the amount of terbium used in the field or at home is determined. The use of terbium is limited. Of the world's terbium oxide consumption, 467 tons, as reported by USGS in 2008, 88.7% was used for phosphors, and the remaining 11.3%, for rare earth element magnets. The amount of terbium of the total consumption of rare earth elements was merely 0.4%.[6]

Some rare earth elements that are used for phosphors are expensive, and their price fluctuates fast. As such, the industry is either searching for other alternatives or using low-cost rare earth elements to create phosphors.

The demand for phosphors that contain rare earth elements changes fast according to changes in industrial environment.

The industry with the highest use and accumulation of terbium in Korea is the lighting industry. The amount of terbium used and accumulated in improved three-band fluorescent lamps is 2,592 kg. Three-band fluorescent lamps account for more than 70% of the domestic fluorescent lamp market by field survey. As consumers require high-quality lighting devices, the demand for terbium is expected to grow.

The amount of terbium accumulated in display devices is about 1,381 kg in PDP TVs and 51 kg in LCD TVs that use CCFLs, totaling an amount of 1,432 kg. As the market demands higher-quality displays for TVs, the demand for LEDs for BLUs in LCD TVs is expected to increase. Therefore the use and accumulation of terbium in displays device are expected to decrease, because terbium is not used for LED TV.

2.2.6 Collection Stage

The collection stage is the stage in which after-use products or damaged products are collected. The amount of terbium supplied to the use and accumulation stage is 4,024 kg. Since it was impossible to determine the amount of terbium supplied to the collection stage, EPR (Extended Producer Responsibility) has been used instead.

Shown in Table 11 is the recycling responsibility by product and packing material from the 2011 EPR, as presented by the Korean government.

It is estimated that 301 kg, the included terbium in display devices and 739 kg, the terbium included in three-band fluorescent lamps were collected, while 46 kg of scrap was produced during processing of PDP panel from the intermediate product. The collected amount of terbium was 1,086 kg. These figures are based on the compulsory collection ratio proposed by the Korean government. The actual amounts would be higher.

2.2.7 Recycling and Disposal

The recycling and disposal stage is the stage in which the collected

Table 11 Recycling responsibility by product and packing material in 2011

Item		Rate of recycling responsibility in 2011[%]
Metal Can	Steel Can	0.771
	Aluminum Can	0.771
Glass bottle		0.765
Carton		0.340
Lubricating Oil		0.708
Tire		0.758
Fluorescent Lamp		0.285
Electronics	Television	0.210
	Refrigerator	0.250
	Washing Machine	0.285
	Air Conditioner	0.024
	Personal Computer	0.140
	Audio	0.185
	Mobile Phone	0.230
	Copy Machine	0.150
	Facsimile	0.150
	Printer	0.150

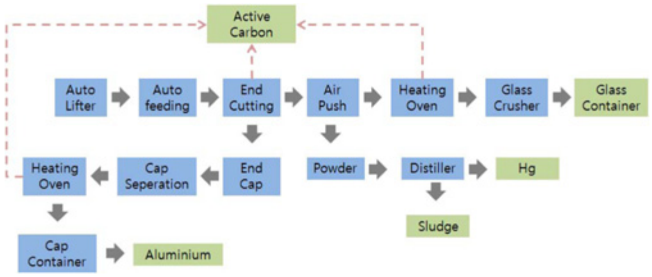

Fig. 4 Fluorescent lamp recycling process

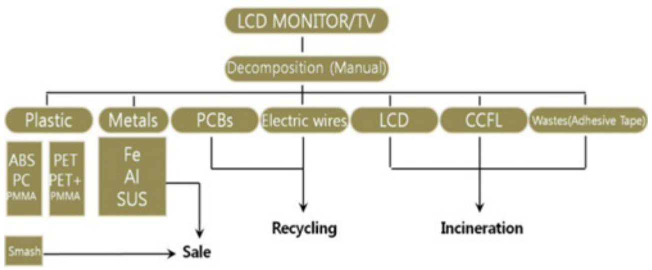

Fig. 5 LCD products recycling process

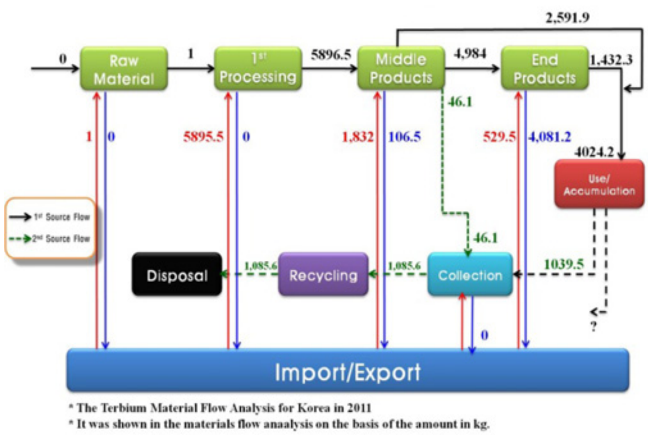

Fig. 6 Material flow analysis of terbium in Korea

products are inputted in the recycling process and disposed of not recovered resource.

Of the terbium collected in 2011, 1,086 kg did not go to the recycling process and all were sent to the disposal stage. The fluorescent lamps collected in Korea are processed as shown in Fig. 4.[19] The cathodes of the lamps are cut and separated into cathodes and glass parts before the process. Using compressed air, the powder adhered to the glass is removed and the separated powder is collected, put in a distiller and heated to remove the Hg. And then the residual sludge was landfilled.

Through the recycling of fluorescent lamps, phosphors are disposed of as sludge. Due to their economic values and environmental issues, phosphors are not yet recycled.

LCD/PDP TVs recycle are processed as shown in Fig. 5.[20] LCD/PDP TVs are disassembled by hand and separated into plastic, metal, printed circuit board (PCB), electrical lines, LCD panels, CCFLs and other parts, each of which is treated with a different process.

LCD/PDP panels, CCFLs and other wastes are incinerated, and LCD/PDP panels and CCFLs are recycled into glass by subcontractors. The sludge generated in the process is incinerated and landfilled.

Because glass, various chemicals and metal substances are coated in layers on LCD/PDP panels via sputtering and are also coated with adhesives, it is difficult to separate and disassemble these panels. As such, these panels are currently incinerated and the sludge is landfilled. Only glass is recycled.

The amount of disposed terbium was 1,086 kg.

As shown in Fig. 6, material flow analysis of terbium can be summarized in Korea in 2011.

3. Conclusions

Korea did not import or export rare earth elements minerals. To produce phosphors in the first processing stage, Korea imported 1,021 kg terbium oxide and 4,875 kg, phosphors. The manufactured and imported phosphors were supplied to the intermediate products stage to manufacture PDP panels, LCD TV BLUs and three-band fluorescent lamps.

In the intermediate products stage, 1,832 kg of CCF lamps and three-band fluorescent lamps were imported. The amount of used and accumulated terbium, in Korea by included in end products was 4,024 kg, of which 1,040 kg was collected in Korea. However, due to the economic value of the hazardous substances in the sludge, it was not recycled and disposed. Nevertheless, we recognize that the world's terbium supply will continue to decrease due to China's export restrictions, foreigners' investment restrictions and raw material and basic material export restrictions. Therefore it is necessary to consider material flow analysis, for stocking up on, and developing alternatives and recycling plans in Korea.

ACKNOWLEDGEMENT

This work was supported by a grant from the Project of Fundamental Construction for Resource Productivity funded by the Ministry of Trade, Industry and Energy, Republic of Korea

REFERENCES

1. U.S. Geological Survey, “Mineral Commodity Summaries,” Paper No. 129, 2011.
2. U.S. Geological Survey, “Mineral Commodity Summaries,” Paper No. 129, 2012.
3. U.S. Geological Survey, “Mineral Commodity Summaries,” Paper No. 129, 2013.
4. Cordier, D. J. and Hedrick, J. B., “Minerals Yearbook, RARE EARTHS,” U.S. Geological Survey, Paper No. 60.15, 2008.
5. Cordier, D. J., “Minerals Yearbook, RARE EARTHS,” U.S. Geological Survey, Paper No. 60.15, 2009.
6. Goonan, T. G., “Rare Earth Elements - End Use and Recyclability,” U.S. Geological Survey Scientific Investigations, Report No. 2011-5094, 2011.
7. Hammond, C. R., “The Elements,” in Handbook of Chemistry and Physics, 81st ed., CRC Press, 2000.
8. Tse, P. -K., “China’s Rare Earth Industry,” U.S. Geological Survey, Paper No. 5, 2011.
9. Cordier, D. J. and Hedrick, J. B., “Rare Earths,” 2010.
10. Papp, J. F., Bray, E. L., Edelstein, D. L., Fenton, M. D., Guberman, D. E., and et al., “U.S. Geological Survey Minerals Yearbook,” Paper No. 60, 2008.
11. Goonan, T. G., “Rare Earth Elements - End Use and Recyclability,” U.S. Geological Survey Scientific, Investigations Report, Report No. 2011-5094, Paper No.3, 2011.
12. NPD DisplaySearch, “Quarterly Large Area TFT LCD Shipment Report - Advanced LED. 2.8,” 2012.
13. Korea Mineral Resources Information Service, “The Current Status of Mineral Resources Reserve,” http://www.kores.net/ mcInfo/ infomineral_l.do.html (Accessed 28 Feb. 2014)
14. Korea Display Industry Association, “Market Tendency, Monthly Focus,” 2012.
15. Wikimedia Foundation, Inc., “Terbium,” http://en.wikipedia.org/ wiki/Terbium.html (Accessed 28 Feb. 2014)
16. Korea International Trade Association, Korea, “International Trade Association Statistics,” http://stat.kita.net/top/state/main.jsp?lang _gbn=null&statid=kts.html (Accessed 28 Feb. 2014)
17. Korea Mineral Resources Information Service, “Rare Earth Element Market tendency,” http://www.kores.net/mcInfo/ infomineral_l.do. html (Accessed 28 Feb. 2014)
18. National Statistics Office, “Production in the Mining and Manufacturing Industries by Item,” http://kosis.kr/statisticsList/ statisticsList_01List.jsp?vwcd=MT_ZTITLE&parmTabId=M_01_0 1#SubCon.html (Accessed 28 Feb. 2014)
19. Korea Lighting Recycling Corporation, “Fluorescent lamp recycling process,” http://www.rlamp.co.kr/subpage.php?p=m32.html (Accessed 28 Feb. 2014)
20. Korea Association of Electronics Environment, “LCD products recycling process,” 2013.
21. Witthauer, A., Kim, G. -Y., Faidley, L., Zou, Q., and Wang, Z., “Design and Characterization of a Flextensional Stage Based on Terfenol-D Actuator,” Int. J. Precis. Eng. Manuf., Vol. 15, No. 1, pp. 135-141, 2014.
22. Kwak, Y. K., Kim, S. H., and Ahn, J. H., “Improvement of Positioning Accuracy of Magnetostrictive Actuator by Means of Built-in Air Cooling and Temperature Control,” Int. J. Precis. Eng. Manuf., Vol. 12, No. 5, pp. 829-834, 2011.