Novel Evaluation Method of Elemental Recyclability from Urban Mine
—Concept of Urban Ore TMR—

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In this study, the total materials requirement (TMR) to recycle chemical elements from the urban ore by recycling (urban ore TMR, UO-TMR) has been compared with the TMR to extract the element from the natural ore by smelting (natural ore TMR, NO-TMR) in order to evaluate the urban ore grade on an equal footing with the natural ore. A framework of UO-TMR based on the NO-TMR framework is developed. To validate the developed framework, the UO-TMR of a laptop PC is estimated assuming gold, silver, copper, iron, aluminum, tantalum and indium are recycled. It is found that the UO-TMRs for gold, silver, copper, iron, aluminum and tantalum are lower than NO-TMR, but that for indium is higher. The ratio of "urban tailings" is at most 60% of the total, which is smaller than that of NO-TMR "tailings". In contrast to the contributions of energy and material inputs for the recycling process, the contribution of transportation is not very large. For the UO-TMR of indium, the contribution of materials for recycling process is extremely large. The availability and scalability of UO-TMR are also discussed. [doi:10.2320/matertrans.MBW200816]

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1. Introduction

Large amounts of valuable resources, such as rare metals in electric and electronic products, are said to be in "urban mines",¹ which is becoming a common term not only in the field of environmental studies but also among the general public. In Japanese urban mines, Halada² reported accumulated amounts of several chemical elements. For example, he estimated the following amounts, expressed as percentages of the world’s known deposits: gold 16% (6800 t), silver 22%, indium 61%, tin 42% and tantalum 10%. From the viewpoint of the urban mine, each waste product is considered to be "urban ore", and its effective utilization is a key issue for resource-poor countries such as Japan. However, one has to carefully consider whether the element should be smelted from crude (natural) ore or recycled from urban ore.

In the smelting process of an element, the concentration of the target element in natural ore is a general index for evaluating the ore grade. The development of a mineral deposit with higher elemental concentration is an important national strategy for resource-abundant countries and results in less energy, material inputs and cost for smelting, resulting in higher productivity. To further explain this concept, let us introduce the total material requirement (TMR)³ as one of the indices of material intensity,⁴ described below. TMR consists not only of direct and indirect material inputs (economic activities) but also of hidden flows (non-economic activities), as shown in the following.

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\text{TMR} = (\text{Direct Material Inputs}) + (\text{Indirect Material Inputs}) + (\text{Hidden Flows}),
\]

Although no one has confirmed whether TMR reflects environmental burden, it does imply a disturbance of the global environment.

Halada et al. estimated both “ore-TMR” that follows hidden flow such as overburden and waste rock to obtain metal ore⁵ and, based on the ore-TMR, the “TMR of metal” that considers the total amount of direct, indirect and hidden flows to obtain a metal, while taking into account the allocation.⁶ As shown in Fig. 1, it is found that the logarithm of the TMR of metal⁷ generally has a linear relationship with the elemental concentration in natural ore. This linearity is present because the amount of tailings, such as overburden and waste rock (hidden flows), is dominant compared with energy and material inputs (direct and indirect inputs). In other words, linearity indicates some equivalence of TMR to the elemental concentration in crude ore.

However, in the recycling process of an element in urban ore, it is not appropriate to evaluate its grade using the
elemental concentration. One reason is that the element in urban ore generally exists in many forms compared with the elements of natural ore. For example, aluminum exists as elemental aluminum, duralumin, Al-Cu, Mg, Mn, Si alloys, etc., in urban ore, but its form is primarily bauxite in natural ore. Another reason is that the recycling process of urban ore is different from the smelting process of natural ore; that is, the required energy and material inputs are different. Hence, to evaluate the urban ore grade on a scale comparable to that of natural ore, the TMR for obtaining an element from urban ore by recycling (urban ore TMR, UO-TMR) should be compared with the TMR for obtaining the element from natural ore by smelting (natural ore TMR, NO-TMR).

NO-TMR data has been estimated for almost all the elements by Halada et al. as shown in Fig. 1. However, no framework or even data has been developed for UO-TMR. Furthermore, for urban ore, since the amount that corresponds to tailing in natural ore is not expected to be dominant, it is impossible to estimate UO-TMR directly from the elemental concentration. Thus, the goal of this study is to develop the framework of UO-TMR, and then estimate UO-TMR according to this framework.

2. Development of Framework

2.1 Review of TMR

Before presenting the development of the framework, TMR-related research is briefly described. An important concept common to TMR is “hidden flow”, as mentioned above. From the viewpoint of hidden flow, material inputs per service unit (MIPS), proposed by Friedrich Schmidt-Bleek, should be explained. MIPS is the material intensity through the lifecycle of a product, and it reflects the total amount of involved natural resources for implementation of a product or service. Albert et al. reported the TMR for national economic activities in Germany, USA, Netherlands and Japan. Stefan et al. compared the change in TMR with economic growth around the world. In Japan, Halada reported the TMR of metal from natural ore, that is, NO-TMR. Also, Nakajima et al. reported the TMR of energy and various materials using the same framework as NO-TMR. In the following section, the framework of NO-TMR is examined, followed by development of the UO-TMR framework.

2.2 Framework of NO-TMR

To produce an element, not only direct material and energy inputs such as ore and reductant are required, but also indirect material and energy inputs, such as energy for transportation, are needed. Using typical (crude) steelmaking as an example, coke and concentrated ore to produce pig iron correspond to indirect inputs, whereas pig iron and energy for heat generation correspond to direct inputs. The indirect inputs induce other indirect inputs such as energy for the coke production and for transportation of concentrated ore from mines.

It should be noted that the source of concentrated ore is crude ore, which is mined with a large amount of overburden and waste rock, etc., (i.e., tailings). Since tailings are overlooked in the marketplace, they do not appear in economic statistics; hence, tailings are also called “hidden flow”. In energy production, crude oil as a typical energy source is generally produced with a large amount of sand, which is a hidden flow. As a matter of practice, hidden flows exist for almost all materials and energy. However, in the framework of NO-TMR, the different compositions of tailings among various mines are not considered.

In the smelting process, by-products are frequently produced. Although no clear treatment method of by-products has been established through life cycle assessments (LCAs), the employment of system expansion or allocation methods that disclose the calculation manner are considered reasonable and proper. In the case of NO-TMR estimation, Halada allocated the shared input and hidden flow for by-products in monetary proportion.

2.3 Framework of UO-TMR

In the recycling of an element from urban ore, the generation of waste products is denoted the starting point of the evaluation. That is, the amounts of direct inputs, indirect inputs and hidden flows after the starting point are included. In steel recycling using an electric arc furnace, the direct inputs include crude steel, steel scrap recovered from waste products, electricity for the furnace; indirect inputs include the pig iron to produce the crude steel, energy for shredding the waste products and energy to transport the waste products, etc. These indirect inputs induce further indirect inputs, as in the smelting process of natural ore. Here, unreclaimed parts of which are defined as “urban tailings” in this study, in contrast to the terms overburden, waste rock and tailings, etc., defined for natural ore. The urban tailings are considered hidden flow. The summation of not only the direct and indirect inputs but also the urban tailings and hidden flows accompanied by both inputs is the UO-TMR. As with NO-TMR, difference in the compositions of the urban tailings are not considered, and shared inputs and hidden flows are allocated by recycled elements.

Figure 2 illustrates the proposed framework of UO-TMR, and Fig. 3 shows the system boundary of the UO-TMR estimation. In the following section, UO-TMR is estimated along with the proposed framework.

3. Test Estimation of UO-TMR based on the Framework

3.1 Target urban ore, data and assumptions

The UO-TMR of gold, silver, copper, iron, aluminum, tantalum and indium in a laptop PC weighting 1930 g is estimated as a test case. The composition was determined from literature except for tantalum, neodymium and titanium which were measured in this study using energy dispersive X-ray analyzer (0.31, 0.62, 0.18 g/laptop-PC, respectively).

In the transportation process, it is assumed that the amount of waste product in each prefecture is proportional to the number of households in the prefecture and the waste product is transported to the closest recycling plant actually accepting laptop PCs. Such plants are located in Hokkaido, Chiba, Aichi, Kyoto and Fukuoka prefectures. The transportation
distance is estimated using the support system for driving plan, “SMAP ver.3”. Here, the prefectural capital is used as the reference point of the estimation. Based on the assumptions, the average transportation distance per unit laptop PC from consumer to recycling plants is estimated to be 130 km.

In the recycling process for gold, silver, copper, iron and aluminum, it is assumed that well-established conventional recycling processes are applied. After the separation processes, iron is recycled using an electric arc furnace, and aluminum and primary wire-shaped copper are re-melted. Mixtures including gold, silver and copper from printed circuit board were subjected to the copper recycling process, resulting in the recycling of gold and silver as by-products. The specific energy and material consumption data are estimated based on Morii’s report and the NIMS-EMC MDE report, respectively. In the recycling of tantalum from tantalum capacitors and indium from liquid crystal displays (LCDs) etc., we assume Mineta’s process for tantalum, and the patented process by Sharp Co., Ltd. for indium.

For shredding and separation processes, it is assumed from interview investigation that a recycling plant using a shredder (1 unit, 100 kW of electricity consumption), cyclones (2 units, 5 kW for each), magnetic separation (1 unit, 10 kW), a trammel (1 unit, 10 kW) and others (60 kW in total) can process 450 tons of waste laptop-PC per month.

For the allocation of shared inputs and flows, two possible formulas are considered. One is allocation by the number of recycled elements, and the other is allocation by the monetary value of recycled elements. Since Halada and Nakajima implemented a formula based on monetary value, we also employ it for comparison in this study. The detailed calculation method will be presented in a later publication.

3.2 Results of the estimation

Figure 4 shows the estimated UO-TMR compared with NO-TMR. As shown in the figure, UO-TMRs are lower than NO-TMRs except for indium. This result indicates that the grades of all the elements excluding indium in the product are higher than those in natural ore. It is interesting that although

![Fig. 2 Schematic diagram of proposed framework of UO-TMR.](image)

![Fig. 3 System boundary of UO-TMR estimation.](image)

![Fig. 4 The estimated UO-TMR compared with NO-TMR.](image)
the elemental concentration of indium (45 ppm) in the product is greater than that in natural ore (10 ppm), the estimated UO-TMR of indium (17000 t/t) is greater than the NO-TMR of indium (4500 t/t).

Figure 5 shows the breakdown of the estimated UO-TMR. The ratios of urban tailings are, at most, 60% of the total and are relatively low compared with the ratios of tailings in the NO-TMR, and the contribution of the transportation is rather small, whereas the contributions of energy and material inputs for the recycling process are very large.

It is notable that in indium process, the contribution of material inputs for the recycling process is extremely large. This could be because the recycling technique for indium is still in development. Also, the indium in an LCD is spread thinly on a huge glass panel, and so excessive amounts of acid and organic solvent are required to leach the indium.

4. Discussion

4.1 Application of UO-TMR

It is shown that the elemental grade in the urban ore can be evaluated by applying the procedures of the NO-TMR. Furthermore, we can quantify how much a recycling process should be improved with the UO-TMR. In the case of indium recycling, the main reason for a huge UO-TMR shown in Fig. 5 is the excessive amount of acid and organic solvent required for leaching indium tin oxide. To improve the recycling process, the materials inputs must be reduced. For example, the acid and organic solvent could be re-used more than ten times at most. Given the current recycling process, indium in LCDs should not be recycled. The figure also reflects the fact that tantalum is only slightly recycled in Japan, but it may be worthwhile to recycle. Finally, although the ECNOE is essentially same as the UO-TMR, it is thought that the elemental concentration seems to be a more easily understandable unit (or index) than TMR for non-expert people.

4.2 Elemental Concentration of Natural Ore Equivalent, ECNOE

In the first section, the linear relationship between NO-TMR and the elemental concentration in crude ores was shown. In this study, we estimated UO-TMR, and it can be reduced to another elemental concentration in the following manner.

Assuming that the elemental concentration in natural ore is 100% when NO-TMR is equal to 1, the relationship between NO-TMR and the elemental concentration in crude ores, as shown Fig. 1 can be recalculated as follows;

$$\log(\text{NO-TMR}) = -0.982 \log(x) + 2 \quad (2)$$

where $x$ indicates the elemental concentration in natural ore. If we substitute UO-TMR for NO-TMR in eq. (2), the obtained “$x$” is the reduced elemental concentration of the urban ore. It can be called the “elemental concentration of natural ore equivalent” (ECNOE).

Figure 6 shows a comparison of the ECNOE with the elemental concentration in natural ore. As shown in this figure, the higher the elemental concentration is, the higher the possibility of recycling becomes. It is found that the elemental grade of gold in a laptop PC is 50 times greater than that in natural ore, but elemental grade of indium is 0.3 times at most. Given the current recycling process, indium in LCDs should not be recycled. The figure also reflects the fact that tantalum is only slightly recycled in Japan, but it may be worthwhile to recycle. Finally, although the ECNOE is essentially same as the UO-TMR, it is thought that the elemental concentration seems to be a more easily understandable unit (or index) than TMR for non-expert people.

5. Conclusion

In this study, it was clarified that the total material requirement for obtaining elements from urban ore by recycling (urban ore TMR, UO-TMR) can be compared with the TMR for obtaining elements from natural ore by smelting (natural ore TMR, NO-TMR) to evaluate the urban ore grade on the same basis used for natural ore. The framework of UO-TMR is developed based on that of NO-TMR. It is found for laptop PCs that the UO-TMR for gold, silver, copper, iron,
aluminum and tantalum is lower than the NO-TMR for each element, except the UO-TMR for indium is higher primarily because the recycling process requires large material inputs. From the breakdown provided by the UO-TMR, it is found that the ratio of urban tailings, which is at most 60% of the total, is relatively small compared with ratio of tailings in NO-TMR. Also, the contribution of transportation is rather small, whereas the contributions of energy and material inputs for the recycling process are great. “Elemental Concentration of Natural Ore Equivalent” (ECNOE), which can be induced from the UO-TMR, is proposed as an understandable index.

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