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Industrial flow of lead in China

MAO Jian-su(毛建素)[1], YANG Zhi-feng(杨志峰)[1], LU Zhong-wu(陆钟武)[2]

1. Department of Environmental Science, Policy and Management, School of Environment, Beijing Normal University, Beijing 100875, China
2. SEPA Key Laboratory on Eco-industry, Northeastern University, Shenyang 110004, China

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Abstract: The rules on industrial flow of lead were studied for theoretical foundation of nonrenewable resource conservation and environmental improvement. A model of lead flow in lead product life cycle was developed through lead flow analysis and was used to analyze the relationship between lead product system and its environment, thus the rules on industrial flow of lead were obtained. The results show that increasing eco-efficiency will favor both resource conservation and environmental improvement. Several indices were proposed to evaluate the lead flow. As for application, the lead-flow for China in 1999 was analyzed and the reasons for low eco-efficiency were identified. In the end, some countermeasures were proposed to improve eco-efficiency, and the future lead ore consumption and environment quality were forecasted.

Key words: lead-flow analysis; optimization of lead consumption; eco-efficiency; lead recycling rate; lead emission rate; evaluation index

1 Introduction

Lead is naturally deposit in the rocks of the lithosphere, and is transferred and cycled through the soils, atmosphere, hydrosphere, and biosphere by means of weathering of rocks, volcanic emissions, atmospheric sedimentation, water and wind erosion, and biological ingestion. These lead-flow processes are collectively termed the ‘natural’ lead flow[1]. In recent centuries, lead has been widely used in many industrial fields such as mechanical, electronic, and chemical engineering with a deeper understanding of its properties and a big progress in industrial technology[2]. To meet the human demand, it is needed to mine lead ore, then produce various lead products through series of processes, such as lead concentration, smelting and machining. An anthropogenic lead flow is thus been formed, which can be named the ‘industrial flow of lead’(IFL) because it is tightly related to industrial processes.

With rising lead consumption in the world, the present scale of IFL has far surpassed the environmental carrying capacity, which may result in unsustainable use of lead ore resource and worse environment quality due to an accumulation of lead pollutants. This situation has become particularly serious in China in recent years. Statistical data[3−4] indicate that the annual production and consumption of metallic lead have been increased rapidly, especially for the production of lead-acid batteries(LABs), which is the main lead product in China (Table 1). Meanwhile, the lead ore reserves of China seem to be exhausted, many lead ores had to be imported to meet the demand, and the imports of lead ore accounted for 1/3 of the total domestic demand in 2000. On the other hand, the anthropogenic lead flow has reached about 12 times higher than its estimated natural flow[5]. Thus, it is necessary to find ways to improve the relationship between China’s lead industry and its environment and to reduce the environmental impacts of the lead system.

LABs are the main lead products and account for around 70% of the total domestic lead consumption in China in 1999[6]. MAO and LU[7] studied the impacts of China’s LAB system on the lead ore resource, and MAO et al[8−9] analyzed the lead flow and the eco-efficiency of lead in lead-acid battery system. However,

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Corresponding author: MAO Jian-su; Tel: +86-10-58805523; E-mail: maojs@bnu.edu.cn

Table 1 Annual production of lead and lead-acid batteries, and domestic lead consumption in China

Year	Lead production/kt	Lead consumption/kt	Battery production/(GW·h)
1990	296.5	244.0	6.980
1991	319.7	249.9	5.146
1992	366.0	259.3	6.837
1993	411.9	299.6	7.773
1994	467.9	298.0	−
1995	607.9	447.7	7.080
1996	706.2	464.3	9.487
1997	707.5	529.9	−
1998	756.9	530.2	−
2000	918.4	525.0	10.394
2001	1 099.9	663.0	11.881

this study seemed insufficient to capture the system for the whole lead industry because more than one kind of lead product is produced throughout the overall system, and different product systems may impact the environment in different ways, thus the overall lead industry system may influence its environment in more complex way than an individual LAB system. Therefore, a theoretical study of the relationship between the system with various lead products and series of lead-related industries as a whole (the 'lead industry system' henceforth), and their corresponding environments will have significant importance for the environment.

As one of the largest country of the world in lead production and consumption, China accounted for 16.35% and 10.62% of the totals, respectively[3]. Thus, the status of the IFL in China will greatly influence the global lead ore resource and lead-related environmental quality. Therefore, the present study will have important and practical significance for lead ore conservation and environmental improvement.

In this paper, we studied the lead industry system in China, with an emphasis on the flow of lead within the system. Lead mining, concentration, smelting, and refining, as well as the manufacturing, use, disposal, and recovery of lead products are the main components of the system.

The study was composed of two parts: a theoretical study and a case study. In the theoretical study, we developed a model of the IFL based on the analysis of the industrial flow of lead and derived a quantitative relationship between a product's system and its environment, allowing us to formulate the fundamental rules for IFL. Based on these rules, we proposed several indices to evaluate IFL and the relationship between the lead industry system and its environment. In the case study, we analyzed China's IFL in 1999, evaluated its status, and identified the problems existed in lead industrial system by comparing the IFL for China's lead industry system with that of Sweden's lead-acid battery system. Moreover, we analyzed the main factors supporting these findings and proposed countermeasures for improvement of the IFL in China.

Since we specially emphasized the flow of lead in our study, the lead content in a material we used represented the quantity of the corresponding material.

2 Theoretical study

2.1 IFL model

2.1.1 IFL model of lead product system

In general, a lead product system is a series of processes in the product life cycle that starts from the natural resource (lead ore) and consists of several stages such as the production of primary materials, manufacturing of products, use of products and its recovery[10]. In order to obtain the rules for the behavior of lead flow in a system, we let lead itself to represent the product. Based on this assumption, the components of the product system can be simplified into the following phases: primary lead production (including mining, concentration, smelting and refining), manufacturing of the product, the use and recovery of the product.

Lead flows through every stage in a product life cycle, not only from the lead ore resource to the lead product, but also from lead scrap (as secondary resource for lead refining) to lead metals. While the lead passes through these stages, some of the lead will also flow into the environment as wastes or pollutants (emissions). Thus, the relationship between a product's system and its environment will appear as follows: 1) to provide products to society; 2) to consume lead ore (thus forming a load on the lead ore resource); 3) to emit lead wastes or pollutants into the environment (thereby causing an emission load). Both the load on the lead ore resource and the lead emission load are collectively considered the environmental impacts.

In order to study the relationship between a product system and its environment, we assumed as follows:

1) The life span of a product is $\Delta\tau$ years.

2) The time expense in various production processes can be ignored, since it is relatively very short compared to the product life span.

3) Each product becomes obsolete $\Delta\tau$ years after its production, and some of the obsolete products become scrap (termed 'old lead scrap') through a collection process.

4) All the scrap lead is recycled and refined as

secondary lead in the year when the scrap is formed.

Based on these assumptions, we may illustrate the lead-flow diagram for a product life cycle in Fig.1, which reflects the directions and distribution of the lead flow during every stage of the product life cycle. This flow obeys the "conservation law", in which inputs equal outputs[11] for every stage. In addition, the production of primary and secondary lead is combined into a single stage since they both belong to lead production, and are represented by stage Ⅰ in Fig.1.

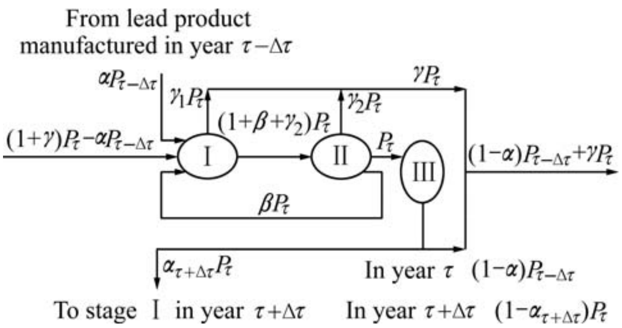

Fig.1 Lead-flow diagram for lead product life cycle: Stage Ⅰ Lead mining, concentration, smelting, and refining; Stage Ⅱ Lead product manufacturing; Stage Ⅲ Use of lead product

In Fig.1, we assume that the annual production of products changes yearly, and the productions in years τ and $\tau-\Delta\tau$ are P_x and $P_{\tau-\Delta\tau}$, respectively, with units of t/a. Similarly, it is clear that if the life-span of a product is $\Delta\tau$, then the products manufactured in year τ will become obsolete and form its old scrap in year $\tau+\Delta\tau$, and the scrap that becomes production inputs in year τ will come from the lead products produced in year $\tau-\Delta\tau$. Some of the obsolete products are collected and returned to the lead production stage through recycling processes. In order to simplify the formula, we may define the ratio of the old scrap lead that is recycled in year τ to the total production of products $\Delta\tau$ years ago as the recycling rate, and can represent this rate as α. Under these conditions, $\alpha_{\tau+\Delta\tau}P_\tau$ of old scrap lead will become inputs for lead production in year $\tau+\Delta\tau$, and $\alpha_\tau P_{\tau-\Delta\tau}$ will become the inputs in year τ. The subscript τ for the recycling rate in year τ is omitted in Fig.1 for simplicity.

Some other indices involved in Fig.1 are explained as follows.

β, the manufacturing recycling rate, is defined as the ratio of the scrap lead produced in the manufacturing of products (termed as "prompt scrap lead") that is recycled to the total production of lead products in the same year.

γ_1 and γ_2, the lead emission rates in stages Ⅰ and Ⅱ, respectively, are defined as the ratio of the lead emissions in the corresponding stage to the production of lead products in the same year. The sum of the two ratios is defined as the overall lead emission ratio and is represented by γ (i.e., $\gamma=\gamma_1+\gamma_2$).

The method we have used to describe IFL is called element flow analysis(EFA), which is one of the many kinds of material flow analysis(MFA)[11−14]. Some basic characteristics of EFA are as follows.

1) Only one element in the product studied is traced. (In the present study, that element is lead.)

2) The time interval between manufacturing and disposal of the products is considered.

3) Changes in the annual production of the products are considered.

LU[15] first proposed this method in 2000 and successfully used it to study scrap steel, iron emissions [16] and energy intensity[17]. MAO and LU[7] improved this method by focusing on the final products and taking the fiscal year as the statistical period to permit a more direct link with the social environment and to facilitate data gathering.

2.1.2 IFL model for complex lead product system

It is easy to understand that to meet various social demands on lead products, a lead industry system should include more than one product system. Thus, a series of product systems must be considered together to represent the overall lead industry system, and the system for each of these products acts as a subsystem of the overall system. If we assume that each subsystem concerns only one kind of product, and the annual production of that product is expressed by P_i, the load on the lead ore resource and the lead emission load can be expressed by R_i and Q_i, respectively. The overall lead industry system will thus have a total annual production of $P=\sum P_i$, a total load on the lead ore resource of $R=\sum R_i$, and a total lead emission load of $Q=\sum Q_i$. This model is illustrated in Fig.2, which reflects the relationship between the lead industry system and its environment.

2.2 Evaluation indices: external indices

In order to estimate the quantitative relationship between a product system and its environment, we have introduced the concept of eco-efficiency[18]. This concept defines the output of final products (the social benefit) per unit of environmental impact as the eco-efficiency of the product system. In this study, we focused on lead, and the eco-efficiency has two components: one is related to the consumption of lead ore, and is named the resource efficiency(RE) and represented by r; the other is related to lead emissions, and is termed the environmental efficiency(EE) and represented by q. RE and EE can be expressed as follows,

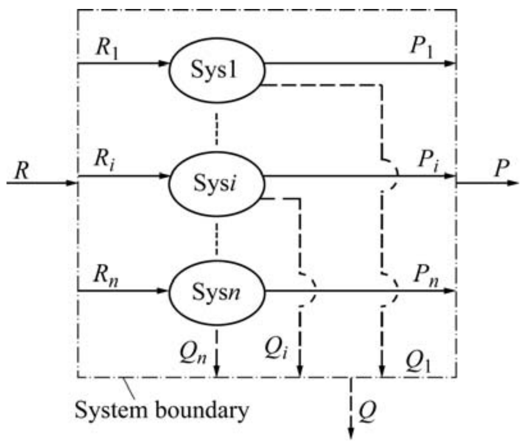

Fig.2 Conceptual model of relationship between lead industry system and its environment

respectively:

$$r=\frac{P}{R} \tag{1}$$

$$q=\frac{P}{Q} \tag{2}$$

where R and Q represent the load on the lead ore resource and the lead emission load per year, respectively. Both have the units of tons of lead content per year (t/a).

From Eqns.(1) and (2), we can see that a higher eco-efficiency means reduced consumption of lead ore, reduced lead emissions, or both simultaneously for a given level of output provided by a product system. Thus, increased eco-efficiency means better resource conservation and environmental protection. The above analysis shows that eco-efficiency forms the bridge between the product system and its environment, and can therefore be treated as an evaluation index for the IFL within a system.

2.3 Primary regulation

2.3.1 Resource efficiency

Fig.1 shows that for a single product system, a lead ore input of $(1+\gamma)P_{\tau}-\alpha P_{\tau-\Delta\tau}$ will produce P_{τ} of product. Based on Eqn.(1), we can derive the following equation for resource efficiency:

$$r=\frac{1}{1+\gamma-\alpha p} \tag{3}$$

where p represents the production ratio in a product life cycle and is defined as $p=P_{\tau-\Delta\tau}/P_{\tau}$. This value, which represents the ratio of the quantity of a product in year $\tau-\Delta\tau$ to that in year τ, is always positive.

Eqn.(3) shows that the RE of lead in a product's system is a function of the lead recycling rate (α), the lead emission rate (γ), and the production ratio (p) in the system. Further analysis shows that a higher recycling rate, a reduced lead emission rate, or a decreased production of the product will improve the RE of the product system.

For the lead industry system, the RE equals the total lead products produced by the system divided by the total lead ore consumption. Under the model illustrated in Fig.2, we obtain the following equation:

$$r'=[\sum f_{Pi}\cdot\frac{1}{r_i}]^{-1} \tag{4}$$

where f_{Pi} represents a fraction equal to the production of lead product i divided by total production of all lead products, and is expressed as $f_{Pi}=P_i/P$. The sum of all f_{Pi} in the system equals 1 (i.e., $\sum f_{Pi}=1$).

Eqn.(4) shows that the RE of lead in the lead industry system is tightly related to both the type of lead products and the individual RE in each product system. We thus conclude that in order to improve the RE of lead in the lead industry system, we must improve the RE of lead in each product system and optimize the lead consumption in the system by increasing f_{Pi} of the products with higher values of RE.

In practice, the RE of the lead industry system can also be expressed as Eqn.(3), and the corresponding parameters (such as the lead recycling rate, lead emission rate, and production ratio) can be treated as the nominal parameters of the lead industry system.

2.3.2 Environmental efficiency

Fig.1 also shows that the product system will produce $\gamma P_{\tau}+(1-\alpha)P_{\tau-\Delta\tau}$ of lead emissions into the environment while producing P_{τ} of products. Based on Eqn.(2), we can derive the EE of lead in a single product's system as follows:

$$q=\frac{1}{\gamma+(1-\alpha)p} \tag{5}$$

Eqn.(5) shows that the EE of lead in the product system is also a function of the lead recycling rate (α), the lead emission rate (γ), and the production ratio (p). Further analysis shows that a higher recycling rate, a reduced lead emission rate, an increase in the total production of lead products, or all three changes together will improve the EE of lead in the product system. Note that in this case, the influence of the production ratio (p) on EE is very different from that for RE.

For the lead industry system, EE equals the total products produced by the system divided by the total lead emissions into the environment. Based on the model illustrated in Fig.2, we obtain the following equation:

$$q' = [\sum f_{Pi} \cdot \frac{1}{q_i}]^{-1} \tag{6}$$

where q_i represents the EE of lead in the system for product i and f_{Pi} has the same meaning as in previous equations.

Eqn.(6) shows that the EE of the lead industry system is tightly related to the type of lead products in the overall system and the individual EE of lead in each product system. We thus conclude that in order to improve the EE of lead in the lead industry system, we must improve the EE of lead in each subsystem and optimize the lead consumption in the system by increasing the fraction (f_{Pi}) of products with higher values of EE.

In practice, the EE of lead industry system can be expressed as Eqn.(5), with the corresponding recycling rate, lead emission rate, and production ratio used as the same nominal parameters described in the previous section.

2.3.3 Relationship between EE and RE

By combining Eqn.(3) with Eqn.(5), we can describe the relationship between EE and RE:

$$\frac{1}{q} - \frac{1}{r} = p - 1 \tag{7}$$

Eqn.(7) shows that the relationship between EE and RE is tightly related to the production ratio (i.e., the ratio of the production in year $\tau - \Delta\tau$ to that in year τ). Further analysis shows that EE will equal RE when the production of lead products remains constant, whereas the RE will be less and greater than EE, respectively, with increasing and decreasing production of lead products. These results are mainly due to the expansion or shrinkage of the product system under different situations. That is, the system expands with increasing production, and consumes more lead ore while emitting less lead into the environment, thus the value of RE is less than that of EE. Conversely, the system shrinks with decreasing production, and consumes less lead ore while emitting more lead into the environment, thus the value of RE is greater than that of EE.

2.4 Evaluation indices: internal indices

The above analysis on Eqns.(3) and (5) shows that the lead recycling rate, lead emission rate, and production ratio in the product life cycle are the internal factors that affect the eco-efficiency of lead in a specific product system. Because they reflect the links among the internal components of the product system, they can thus be termed the driving factors of eco-efficiency. These three factors can thus be treated as internal indices for evaluating the lead flow within the product system.

For the lead industry system, Eqns.(4) and (6) reveal that the composition of the products (or the structure of lead consumption) and the individual eco-efficiency in each product system are the internal factors that drive the eco-efficiency of the system, and can thus be treated as the internal evaluation indices for lead flow in the lead industry system as well.

Because the production ratio in the product life cycle is related to the life span of lead product, and different life spans result in different production ratios for the same annual growth in production, For instance, if we assume that the annual growth rate of production is 0.10, the production ratio will be 0.7 when the life span is 3 a, whereas the ratio will be 0.6 when the life span is 4 a. The average life span of lead products or the individual product life span can be treated as internal evaluation indices for the lead flow in the lead industry system as well.

3 Case study: industrial flow of lead in China

3.1 Brief description of lead flow in China

The case study described in this section is based on the statistical data for all of Chinese lead-related industries in 1999. It is reported that the domestic consumption of refined lead in 1999 is about 525 kt[3]. Of this amount, 66.8% was used in the manufacturing of LABs, 11.6% was used in construction materials and cables, and the remaining 21.6% was used in chemical engineering[19].

During the process of manufacturing LABs, every 1 t of lead inputs produces an average of 0.920 0 kt of LABs, 0.035 6 t of scrap lead that would be promptly recycled, and 0.044 4 t of lead emissions into the environment[7]. The average life-span of Chinese LABs has been estimated as 3 a[20].

During the manufacturing of lead-related construction materials and cables, the lead utilization rate ranges from 0.85 to 0.95[21]. In the present case study, we chose a value of 0.87 (87%). An estimated 11.26% of the lead input for these processes is transformed into scrap lead that is promptly recycled, and the remaining 1.74% is dissipated into the environment as lead emissions. The average life span of these lead products was estimated as 15 a[21].

During the production of lead products used in chemical engineering, the lead utilization rate is estimated as 0.9524 (95.24%), and the remaining 4.76% is dissipated into the environment as lead emissions.

These lead products cannot be recycled after their uses, and most of the lead will be permanently dissipated into the environment; thus, the average life span of these products is considered to be 0 year.

It was estimated that 110.84 kt scraps were recycled in 1999, of which 82.01% represented obsolete LABs, 0.54% represented obsolete lead-related construction materials and cables, and the remaining 17.45% represented scrap lead that was promptly recovered for reuse during the manufacturing of lead products[6]. The overall recovery rate in secondary lead smelting and refining changed from 80% to 88%[22]. We used a value of 82.31% for the calculations in the present case study. Thus, 91.23 kt of secondary refined lead was recovered in total. The remaining domestic lead consumption would be primary refined lead, at an estimated total of 433.77 kt.

During the production of primary lead, many processes are involved, including mining, concentration, smelting, and refining. The recovery rate in lead mining and concentration averaged 83.82% in 1999, versus 93.49% for lead smelting and refining[3]. Therefore, the production of 433.77 kt of primary refined lead would consume 553.54 kt of lead ore.

Based on the above analysis, the industrial flow of lead in China in 1999 is illustrated in Fig.3.

With an assumption of 3 a LAB life span, the obsolete LABs recycled in 1999 would be manufactured in 1996. Based on the data in Table 1, the production of LABs in 1996 was about 291.67 kt of lead content, where it is assumed that the data in Table 1 represent 77% and 78% of the total national production of LABs in 1996 and 1999, respectively, and that both the LAB life-span and the LAB specific energy (a coefficient used to convert the production of LABs from energy units into a lead content) remained constant. Because 90.90 kt of obsolete LABs was recovered in 1999, the remaining 200.77 kt of obsolete LABs had not been recycled (or had not been included in the statistical data) and were thus treated as lead losses into the environment. For the product system related to construction materials and cables, with an estimated production in 1984 of 55.3 kt, the old scrap lead from these products recovered in 1999 was about 0.6 kt, and we thus estimated that about 54.70 kt of obsolete lead-related construction materials and cables had not been recycled (or had not been included in the statistical data) and was thus treated as lead losses into the environment. All lead used in chemical engineering products was considered to be lead losses into the environment.

3.2 Data sources

The sources of the data related to Chinese IFL in 1999 are listed in Table 2.

3.3 Evaluation of IFL in China

3.3.1 Evaluation indices

1) Eco-efficiency

For the lead industry system in 1999, Fig.3 shows that the total consumption of lead ore is 553.54 kt, and the total production of lead products is 483.62 kt. 524.89 kt of lead is lost into the environment, which includes 200.77 kt of obsolete LABs, 54.70 kt of discarded lead-related construction materials and cables, 108.00 kt

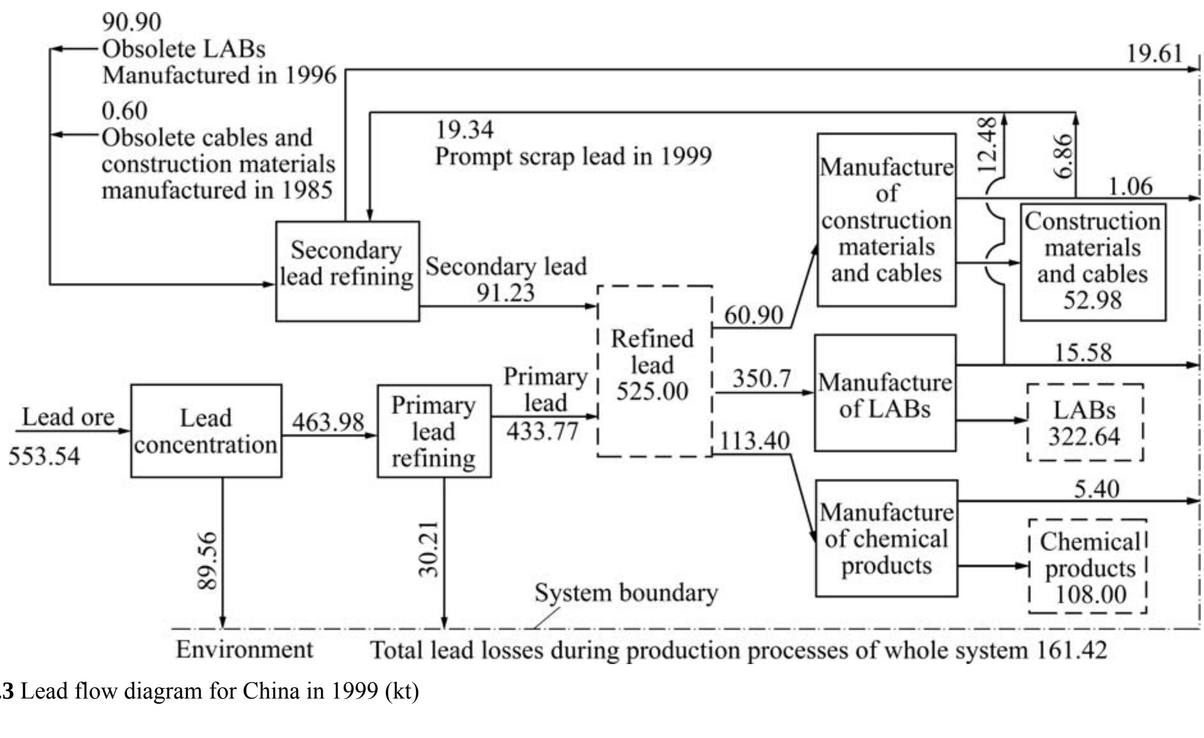

Fig.3 Lead flow diagram for China in 1999 (kt)

Table 2 Sources of data for case study

Data type or name	Data source	Agency responsible for compiling data
Recovery rate in lead mining	China investigation report on exploitation and utilization of lead-zinc mineral resource 2000	Beijing General Research Institute of Mining and Metallurgy
Recovery rate in lead concentration, smelting, and refining	China nonferrous metals industry yearbook (1990-2001)	Editorial Staff of Yearbook of Nonferrous Metals Industry
Data related to scrap lead and lead recycling	Published literature or actual manufacturing data	Partly provided by the China Association for Metals Recycling
Data related to battery manufacturing	Report on the environmental impacts for some lead-acid battery companies	Research Institute of Environment Science
Battery performance and profiles	China statistic report on lead-acid batteries	Shenyang Research Institute of Storage Battery
Annual production of lead-acid batteries	China machinery industries yearbook China power and electrical equipment yearbook	Editorial Staff of Yearbook of Machinery Industries Editorial Staff of Yearbook of Machinery Industries, Power and Electrical Equipment
Export of lead-acid batteries and scrap lead	China foreign trade yearbook	Editorial Staff of China Foreign Trade Yearbook

of chemical engineering products, and 161.42 kt of lead emissions in production-related processes. Using Eqns.(1) and (2), we calculated the RE and EE of lead in the lead industry system of China as follows:

$r'=0.874$ and $q'=0.921$

These results could also be obtained by estimating the eco-efficiency of lead for each product system and summing up the values using Eqns.(4) and (6). The results are the same, which indicates that the calculation is correct.

2) Composition of lead products

Fig.3 shows that the production of lead products in 1999 totals 483.62 kt, of which the productions of LABs, construction materials and cables, and chemical engineering products total 322.64, 52.98, and 108.00 kt, respectively. We thus can estimate the contributions of these three kinds of lead product to the total production of lead products as 66.71%, 10.95%, and 22.34%, respectively.

3) Production ratio

Substituting the values of r' and q' into Eqn.(7), we can obtain p'=0.942. Because this value is less than 1, the production of lead products in China increases yearly.

4) Lead emission rate

Fig.3 shows that the total lead emissions into the environment during production processes in 1999 is 161.42 kt. Based on the definition of the lead emission rate in the first part of this paper, γ'=0.334, which indicates that 0.334 t of lead emissions will occur during production processes for every 1 t of lead products.

5) Lead recycling rate

Substituting the values of r', p', and γ' that we obtained earlier in this section into Eqn.(3), α'=0.202, which indicates that only 20.2% of the total lead products were recycled in 1999. If we substitute the values of q', p', and γ' into Eqn.(5), we also derive α'= 0.202, which confirms that the above calculation is correct.

In the same way, we can estimate the IFL in each lead product system by distinguishing its data from those of the other products. For instance, we could analyze the data for collected obsolete LABs, the scrap lead created during the manufacture of LABs, and the refining of this scrap lead for reuse in the LAB system. Such work is always very complex. For the present study, we summarized the evaluation indices for the LAB system, the construction materials and cables related system, the chemical engineering products system, and the lead industry system as a whole in Table 3.

3.3.2 Discussion

Table 3 shows that the different product systems have different eco-efficiency values. The eco-efficiency of the LAB system is the highest, with higher values in both RE and EE than not only the average for the lead industry system but also the values for the other two product systems. In contrast, the eco-efficiency of the construction materials and cable system is on the middle level, and is lower than the average for the lead industry system (the lower EE in this system is mainly due to its decreased production), whereas the eco-efficiency of the chemical engineering system is the lowest and is lower than the average for the lead industry. Further analysis shows that the different eco-efficiencies result mainly from different abilities to recycle in various lead products. Ayres sorted the use of materials into three classes[12].

1) Uses that are economically and technologically compatible with recycling under present prices and regulations and termed as type Ⅰ uses, such as the use of lead in LABs in the present study, where the lead recycling rate in China reaches 0.312.

2) Uses that are not economically compatible with recycling but recycling is technically feasible and termed as type Ⅱ uses, such as the use of lead in construction materials and cables in the present study, where the lead recycling rate in China is only 0.011.

3) Uses for which recycling is inherently not feasible, such as the use of lead in chemical engineering products and termed as type Ⅲ uses, where the lead recycling rate is zero.

Of these three lead product systems in this study, the LAB system is the one with the most possibility to harmonize with its environment. The relatively small difference among the eco-efficiencies of the three lead product systems is mainly resulted from their similar lead emission rates (Table 3). The production ratio in the LAB system is the lowest of the three systems, which indicates that the production of LABs increases fastest compared with the other products. In addition, the contribution of LABs to the total production of lead products has been increased in recent years.

To improve the eco-efficiency of lead in the lead industry system, we have two main options. First, we can increase the contribution of LABs to the total production of all lead products and gradually reduce the use of lead in the other systems. Second, we can improve the eco-efficiency of the LAB system.

In order to assess the potential for improving China's lead industry system, we compared the evaluation indices for China's LAB system with those for Sweden (Table 4), where the data for Sweden has been estimated based on the data provided by KARLSSON [23].

Table 4 shows that both the RE and the EE of lead in Swedish LAB system reach 79.02, which represents 82.31 and 74.76 times the corresponding values for China. The main reasons for this difference are as follows.

1) The lead recycling rate for Sweden has reached 0.99, which means that nearly all of the obsolete LABs are recycled. In contrast, the corresponding rate for China is only 0.312, which means that nearly 70% of the obsolete LABs is not recycled.

2) The lead emission rate for Swedish LAB system is only 0.002 655, which means that there are almost no lead emissions from the system. In contrast, Chinese emission rate is 0.324, which means that nearly 33% of the lead inputs used in the LAB system is lost into the environment.

3) The production of LABs in Sweden has remained constant for at least 5 a (a period equal to one LAB life span in Sweden), whereas production in China has increased rapidly during the same period.

3.4 Analysis of causes and proposed improvements

The previous analysis indicates that to improve the eco-efficiency of lead in Chinese lead industry system, attention should be focused on increasing the lead recycling rate and reducing the lead emission rate. Thus, additional discussion of the causes of Chinese low recycling rate and high emission rate is necessary to propose improvements in the system.

3.4.1 Reasons for low recycling rate

Figs.1 and 2 indicate that the recycling rate of the lead industry system relates mainly to the types of lead

Table 3 Summary of evaluation indices for several lead product systems in China

Item	Product profile/%	Resource efficiency	Environmental efficiency	Lead recycling rate	Lead emission rate	Production ratio	Life span/a
Lead-using industry	100.00	0.874	0.921	0.202	0.334	0.942	4
Lead-acid batteries	66.71	0.960	1.057	0.312	0.324	0.904	3
Construction materials and cables	10.95	0.751	0.727	0.011	0.342	1.044	15
Chemical engineering products	22.34	0.736	0.736	0.000	0.359	1.000	0

Table 4 Comparison of lead flow in lead-acid battery systems of China and Sweden

Country	Resource efficiency	Environmental efficiency	Lead recycling rate	Lead emission rate	Production ratio	Life span/a
China	0.960	1.057	0.312	0.324 000	0.904	3
Sweden	79.020	79.020	0.990	0.002 655	1.000	5

products in the system, the domestic consumption of these products, the collection of obsolete lead products for recycling, and the trade of lead scrap, as well as the availability of the data used and other factors[24].

Fig.3 shows that in 1999 the contributions of LABs, construction materials and cables, and chemical engineering products to the total production of lead products in China amounted to 66.71%, 10.95%, and 22.34% of the total, respectively. Because the lead recycling rate in the construction materials and cables system is only 0.011 (Table 3) and the lead used in chemical engineering is not recyclable, both can be effectively ignored in the present case study. Thus, we can deduce that 33.29% of the total lead in the lead product system was lost into the environment in 1999.

The annual production and domestic consumption of LABs for the recent 10-year period are summarized in Table 5, which indicates that about 7.62% of the obsolete LABs cannot be recycled back into China's LAB system because of the export of LABs.

Table 5 Production and export of lead-acid batteries in China

Year	Production/(GW·h)	Export/(GW·h)	(Export/production)/%
1986	3.220	0.158	4.91
1987	5.072	0.477	9.40
1988	4.550	0.007	0.15
1989	–	–	–
1990	6.980	0	0
1991	5.146	1.968	38.24
1992	6.837	0.020	0.29
1993	7.773	0.014	0.18
1994	–	0.022	–
1995	7.080	0.011	0.16
1996	9.487	0	0
Average			7.62

The trade of lead scraps from 1990 to 2000 is summarized in Table 6, which shows that the trade of lead scraps is very little compared with the total amount of lead products (for instance, an average of 0.983 kt vs 483.62 kt of lead products produced in 1999), and has been nearly balanced in recent years. Thus, we may ignore the influence of the trade of lead scrap on the lead recycling rate in this study.

MA[25] and YANG and MA[26] reported that there were about 300 secondary lead refineries in China in 1999, among which only three could be considered large-scale, and they together produced about half of the total secondary lead in China. They also reported that most of these facilities were privately owned and were operated on a small scale. About half of the obsolete LABs was collected and recovered by these private refineries, and their data may not be fully accounted in the recorded statistics. Many small companies were engaged in the collection of obsolete LABs in China in 1999, such as the supply and marketing systems of business, individuals or small groups that collect obsolete LABs for secondary lead refineries, of which the individuals played a dominant position in the collection and gathering of obsolete LABs. In other words, no national or regional network existed for the collection of obsolete LABs, and this work is still done by individual, uncoordinated operations[25]. This situation potentially decreases the recycling rate by 0.202. Consequently, we can estimate that about 18.69% (i.e., the result of 1−0.3329−0.0762−0.202−0.202) of the obsolete lead products in 1999 were not recovered and were thus lost into the environment.

Table 6 Trade of scrap lead in China

Year	Export/kt	Import/kt	Net import/kt
1990	6.132	1.690	−4.442
1991	5.250	0.140	−5.110
1992	1.500	5.712	4.212
1993	0.621	7.322	6.701
1994	1.510	5.793	4.283
1995	0.589	5.690	5.101
1996	0.152	0.820	0.668
1997	0.061	0.204	0.143
1998	1.751	0.007	−1.744
1999	1.060	–	–
2000	0.037	0.050	0.013
Average			0.983

From the above discussion, we can conclude that the main reasons for the low lead recycling rate in China are the use of non-recyclable lead, which still contributes strongly to the total, and the inefficient collection of obsolete lead products.

3.4.2 Reasons for high emission rate

Fig.3 shows that 161.42 kt of lead was lost in various production-related processes in Chinese lead industry system in 1999. Further analysis of this total is summarized in Table 7, which shows that most of the lead losses occurred during lead concentration, followed by refining, then manufacturing.

The recovery rate during lead concentration is only 81% to 86%, which is 5% to 15% lower than the recovery levels in other countries[27]. This is mainly because of the poor quality of Chinese lead ore resources, with lead-zinc para-generated, many metals concomitant,

Table 7 Lead losses during production processes in Chinese lead industry system in 1999

Item	Lead loss/kt	Percentage of total/%
Lead concentration	89.56	55.48
Primary lead refining	30.21	18.72
Secondary lead refining	19.61	12.15
Manufacturing of lead products	22.04	13.65
Total	161.42	100.00

and a complex distribution of metals in the minerals. Chinese lead ore usually has a low lead to zinc ratio (1:2.6) and contains more than 50 kinds of useful metals (e.g., copper, silver, gold) in a complex distribution that makes the concentration process unusually difficult [27].

In the smelting and refining processes, MA and YANG[22] and YANG and MA[26] reported that about half of the lead (including both the primary and the secondary) was smelted and refined by small-scale enterprises through outdated technology. Most of these enterprises still utilized traditional sintering and blast-furnace, which means the technology during the 1980s in the advanced countries has been replaced by more advanced processes.

In the manufacturing of lead products, JIANG[21] reported that the lead utilization rate is usually about 0.85 to 0.95. Based on the data obtained in this study, it is estimated that about 41.38 kt of lead was not utilized efficiently in these processes, of which 46.74% (i.e., 19.34 kt of lead) was promptly recycled as lead scrap, while the remained one was dissipated into the environment as emissions, or was omitted from the statistical data. JIANG[21] also reported that much of the lead scrap was collected and transferred to lead refineries by individuals, and thus accurate data were very difficult to obtained.

3.4.3 Possible countermeasure to improve eco-efficiency

To improve the lead recycling rate, several countermeasures might be adopted[24−28].

1) To improve the types of lead products produced by the overall system (or the lead consumption) so as to increase the contribution of LABs, which has the highest eco-efficiency, to the total production of lead products, while gradually eliminating the use of lead in non-recyclable products.

2) To take advanced management method and treat lead wastes as resources[29]. To implement laws, regulations, and mechanisms for lead recycling so as to lead recycling of lead scrap to more effective paths[30]. Thus, we could gradually enclose the system in terms of the flow of lead[31].

3) To extend the responsibility of LAB companies so that they can sell services instead of only products [32−33], or levy a tax upon the consumers of lead products[34] and charge them for lead emissions into the environment[35], thereby encouraging the recycling of obsolete lead products.

To reduce lead emissions, we suggest that China should develop or introduce new technology for lead mining, concentration, smelting, and refining; improve the management of companies involved in lead production and implement a special license for these companies that strictly stipulates the production scale, technology used, and measures required for environmental protection; eliminate the use of outdated technology by small-scale companies; and promote the spread of clean production technology for lead. Thus, we could improve the overall rate of lead utilization and reduce lead emissions.

3.4.4 Forecast for Chinese LAB system

MA[36] reported that a technical policy for the prevention of pollution resulted from obsolete lead-acid batteries has been implemented. The situation for Chinese lead industry system is thus expected to be improved in the coming years.

If Chinese lead industry system can be improved, the following targets will be realized within 20 years:

1) LABs will represent 95% of the total lead products; other products contribute only 5% of the total.

2) Both the RE and EE of lead in the LAB system will reach 60, whereas those for other systems will reach 1.

Then, the eco-efficiency of lead in China would rise to 15.19 by around 2020, which means that for the same total production of lead products as in 1999 (i.e., 483.62 kt), the following changes would occur.

1) The production of LABs would increase to 459.44 kt (i.e., 1.499 times the present level), which means an annual average growth rate of 2.495%. Simultaneously, the production of other lead products would decrease to 24.18 kt (i.e., only 15% of their present level), which means an annual average growth rate of −4.25%.

2) The consumption of lead ore will decrease to 1/15.19 of the present value (i.e., to 36.44 kt of lead ore per year). This will alleviate the growing scarcity of lead ore.

3) Lead emissions will decrease to 1/15.19 of the present level, which is lower than the environmental carrying capacity (i.e, the estimated natural flow;

RBSDCAS 2000). Thus, the current overload of lead pollutants in the environment will be eliminated and the environmental quality will gradually be improved.

4 Conclusions

1) A model of the industrial flow of lead in the lead product system was developed based on the application of element flow analysis. This model served as the foundation of a quantitative case study on the relationships of lead flow between the lead product system and its natural and socio-economical environments.

2) We developed evaluation indices for the industrial flow of lead. We used the eco-efficiency (including RE and EE) as external indices to reflect the relationship between the lead product system and its environment, and used the types of lead products, the lead recycling rate, the lead emission rate, and the production ratio as the internal factors that drive the lead flows and thus are treated as internal indices.

3) Three countermeasures can improve the eco-efficiency of an individual lead product system or the lead industry system as a whole, i.e. to increase the contribution of LABS to the total lead products; to increase the lead recycling rate and to reduce the lead emission rate.

4) The current state of Chinese IFL in 1999 was studied. The results show that the RE and the EE in both LAB system and lead industry system as a whole are only around 1, which indicates a level of around 1/80 of that achieved by Swedish LAB system. The main reasons for this difference were Chinese low lead recycling rate and high lead emission rate.

5) Additional reasons for Chinese low eco-efficiency of lead (i.e., the reasons for the low lead recycling rate and higher lead emissions) were also studied. The main reasons for low lead recycling rate are the low contribution of LABs to the total lead products and inefficient management of the recycling of lead scraps. The main reasons for the high lead emission rate are the poor quality of lead ore resource, and an abundance of small-scale lead-related plants using outdated technologies. Several countermeasures were proposed to improve this situation and the future status of lead ore resource and environment quality was forecasted to be improved substantially within 20 years by implementation of these countermeasure.

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