Estimation of CO_2 Emission and Energy Consumption in Extraction of Metals

Survey Report

March 2003

Ecomaterials Center
National Institute of Materials Science
Independent Administrative Agency

Introduction

This report is a compilation of the results obtained from the "Surveys on the Estimation of Environmental Load Generated by Metallic Elements" that was commissioned by the Ministry of Environment based on its Global Environment Research System. The surveys were part of the "Research for Effective Predictions to Prevent Global Warming Arising from Material Technology Conversions" that was conducted in fiscal 2002 and 2003 by NIMS, the National Institute for Materials Science.

With such actions as the ratification of the Kyoto Protocol in June 2002, awareness of global warming policies has been increasing in Japan. Against this backdrop, data are urgently being compiled for LCA (life cycle assessments) that can be used to evaluate the CO_2 emissions of products and systems.

The objects of the present surveys were metallic elements that had not yet been subjected to data integration. The surveys were designed to acquire and compile data on material flow, energy consumption and CO_2 emissions that occur during the smelting and refining of these metals.

The data used in this report have been estimated independently by the National Institute for Materials Science based on publicly released papers and other literature. However, there were numerous cases in which the data obtained were not sufficient for the computations, so we cannot, by any measure, consider the database complete. Therefore, this report contains data and assumptions that were used in the computations, as well as compilations of data that served as a substitute for data that could not be obtained. Various people involved with this project, including researchers involved with smelting and refining, LCA researchers, and others, have corrected and added to the data. This should help to create a database that is accurate and easy to use. In this sense, we would appreciate it if you, the user, could give us feedback that could help us achieve this goal.

Finally, on behalf of everyone at NIMS, I would like to extend a note of thanks to the Nomura Research Institute for their assistance in compiling this report.

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1. Purpose and Contents of Investigation

1-1 Purpose of investigation

To construct a recycling-oriented society, a variety of projects such as recycling and countermeasures to global warming are being carried out at present, and various technologies have been developed. Current technologies or technologies whose alternatives are being considered have been required to be evaluated throughout the whole life cycle. As one evaluation method, a study using LCA (life cycle assessment) has been carried out. In LCA calculations, as data for the inventory of various materials are needed, a database, e.g., for metals and plastics, has been organized.

Because of this recent trend of times, studies on environmental load for principal metal materials such as iron, copper, aluminum, and zinc have already performed, and information about mass balance, energy consumption, etc., is available from some data sources. However, for other metal elements, such as rare metals, information of the smelting and refining methods has been collected separately, but integration of basic information to quantitatively understand their environmental load has not progressed.

Thus, the purpose of the present investigation is to grasp the material flow, electricity consumption, and amount of emission of CO_2 of metal elements except for principal metals (hereafter abbreviated as “non-principal metals”) in the smelting and refining processes and to organize these as basic information for estimation of the environmental load at the time of material transformation.

1-2 Contents of investigation

In the present investigation, existing information for the main steps in the smelting and refining processes of non-principal metals, such as iron, aluminum, zinc, and lead, has been collected and organized to estimate the material flow and environmental load.

The information organized in the present investigation is as follows:

1) Flow chart of the smelting and refining processes.
2) The name and amount of materials input (supplied) and output (emitted/produced) in each process (material flow).
3) The amount of energy consumption and CO_2 emission for each process.
4) Other information on apparatus, equipment, etc. used in metal smelting processes.
5) Integration of data which have been already collected and estimated and which will be required to be obtained in future.

1-3 Method of investigation

1-3-1 Integration of the big picture of metal smelting and refining processes

Various kinds of literature such as technical reports were collected, and tables for the main processes of smelting and refining of non-principal metals has been made.

By making such tables, it becomes possible to grasp the characteristic features of the respective steps such as a smelting method common to a family of elements.

1-3-2 Usage status of equipment in main processes

Tables have been made of the equipment used in the main smelting and refining processes. The power and amount of heavy oil used by the equipment have been summarized to estimate energy consumption. As data concerning the power etc. is not often described in literature and materials, some data are supplemented with product information provided by the producers.

1-3-3 Electricity consumption in electrolytic processes

In metal smelting processes, electrolytic processes like electrolytic refining, electrolytic winning and molten salt electrolysis are mostly adopted as the final step. Consumption amounts of electricity required for the electrolysis are approximately determined by the kind of metal element. To grasp the electricity consumption in the smelting processes in this investigation, the amounts of consumption due to electrolysis is summarized for each metal element in the table, along with the theoretical amounts of electricity consumption.

Also, as a matter of fact, the electricity consumption for the electrolysis depends on the operating conditions in the actual smelting and refining work sites. Thus, the electricity consumption summarized here should be understood as one example to obtain approximate values.

1-3-4 Preparation of data sheet for each element

In the present investigation, detailed data sheets have been made for 24 metal elements. Principal metals such as iron and aluminum are excluded from this investigation. Also, elements that are hard to obtain enough data about to make material flow sheets are not dealt with here.

(1) Process flow sheet

Of the smelting and refining processes of metal elements, the processes where energy is supplied and mass is distributed have been picked out as main processes, and they are summarized in a flow sheet.

The estimation of material balance, energy supply etc. shown below has been carried out on the basis of the sheet.

(2) Data of mass balance etc.

a. Material flow sheet

The substances put into and out of each main process have been figured out.

Material flow sheets showing how the mass of each substance flows have been made. Detailed material flow sheets are scarcely reported in the literature, so concentrations and quality of materials, intermediate and final products, etc. are used to estimate material flows in the present investigation.

In the material flow sheet, the unit is unified as weight (tons or kgs) for solid and volume (liters) for liquid (solvent or solution). To make the mass distribution clear, the weight is also written for liquids, if necessary.

b. Amount of energy supply

The type of supplied energy (electric and fuel) has been figured out for each main process.

The electric power has been estimated from the type, number, power, and operating rates of equipment used. Transformation from electric power to energy is made using 1 kWh = 3.6 MJ (based on Japanese Energy Statistics).

For fuel, the supplied energy is calculated from the supplied mass estimated using a calorific unit. The unit of energy is unified as J (joule).

c. Sources of information

Sources of data used for preparation of the flow sheet and for the estimation of material flow and energy supply are described.

Table 1. Table of elements for preparation of data sheet

I A	II A	III A	IV A	V A	VI A	VII A	VIII	VIII	VIII	I B	II B	III B	IV B	V B	VI B	VII B	
▨ Li	Be																
▨ Na	▨ Mg											Al	Si				
K	Ca	Sc	▨ Ti	V	▨ Cr	▨ Mn	Fe	▨ Co	▨ Ni	Cu	Zn	▨ Ga	Ge	As	Se		
Rb	Sr	Y	▨ Zr	▨ Nb	▨ Mo	Tc	Ru	Rh	Pd	▨ Ag	▨ Cd	▨ In	▨ Sn	▨ Sb	Te		
Ca	Ba	La*	▨ Hf	▨ Ta	▨ W	Re	Os	Ir	Pt	▨ Au	Hg	▨ Tl	Pb	▨ Bi			
		Ac*															

*Lantanoid	La	Ce		Nd		Sm	Eu								
*Actinoid				▨ U											

▨ Elements covered by a data sheet

1-3-5 Preparation statuses for data of mass balance, energy consumption and CO_2 emission

In the present investigation, the environmental load is estimated in each process for each element.

However, as the results are obtained from limited information, it should be noticed that processes having a lack of information have been excluded from the estimation of the amounts of energy consumption and CO_2 emission, because the estimation is impossible.

Therefore, in the preparation of data sheets for figuring out the material flow, the amounts of energy consumption, and the CO_2 emission, the following three categories have been introduced to integrate data in each process for each element: “data obtained”, “data not obtained but possible to estimate”, and “data not obtained but necessary to obtain.”

1-4 Remarks regarding notation of data sheets

In the data sheet for each element, not only the values cited from the literature but also the values estimated from the quality and concentrations of ores and intermediate products are described. The following notations are introduced therein to make clear the meaning of the values. An example of the notation for data of mass balance etc. is shown in Table 2.

[Notation]

1. Referred data from literature etc.	Expressed by [bold] font.
2. Calculated (estimated) values	Expressed by [normal] font.
3. Amounts of additives	Expressed by [+α] as other additives.
4. Increments resulting from additives	Expressed by [+], which means increments.
5. Substances which are subsequently supplied to the next process	Covered with a gray background.
6. Amount of metal element etc. dissolved in liquid	Expressed complementarily by a bracket ( ).
7. Supplied amounts of electric power, fuels, etc.	Expressed by J (joule) for each fuel.
8. Amount of CO_2 emission	Expressed by total amount (CO_2-t or kg).
9. Amount of supplied energy related to material production	Expressed by energy supplied to produce materials such as sulfuric acid and hydrochloric acid used for smelting. The names of materials are expressed in [ ] to indicate that the energy results from the material.
10. Amount of CO_2 emission related to material production	For CO_2 emitted in the production processes of materials such as sulfuric acid, the amounts itemized are expressed complementarily by a bracket ( ). (The unit is t-CO_2 or kg- CO_2.)
11. Recycling of materials	In data for material production, when only newly supplied amounts except for recycled amounts are taken up, the asterisk [*] is added on the right hand side of the value concerned. (*IV. Refer to the concept for wet type processes such as solvent extraction.)
12. Cases for which quantitative data are not available	Expressed by [amount is unclear] or [unclear].

Table 2 Notation for mass balance etc. in data sheet (an example)

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Oxidation roasting	Ore	**100.0 t**	**Ferro-XX**	34.0 t	Purity of XX in ore is 70%
	Cokes	**0.6 t**	Slag	66.6 t	
	Other additives (other additives)	+α			
	Limestone				
	Electric power	(unclear)			
	Heavy oil	12,200 GJ	[CO_2 emission]	420 t	
2) Dissolution	Ferro-XX	34.0 t	**Solution**	1804 L	Solubility of XX is assumed to be 100 %
	Sulfuric acid	**1804 L**	(including XX sulfate)	(42.3 t+)	
		(16.2 t)	Precipitants	7.9 t+	
	Other additives	+α			
	(other additives)				
	XX mother liquor				
	Electric power	690 GJ	[CO_2 emission]	530 t	
	[Production of sulfuric acid]	5,200 GJ*	(Including production of sulfuric acid)	(450 t*)	
Total	[Energy] (Including production of materials)	18,090 GJ 5,200 GJ*	[CO_2 emission] (Including production of material)	950 t (450 t*)	

1. Literature value

5. To next process

3. Additives

3. Breakdown of additives

2.Calculated value

8. Amount of CO_2 emission

6. Dissolved amount

4. Increment due to additives

7. Consumption of electricity and fuel

10. CO_2 emission from materials

11. Recycled

Note: The words with a gray background in the table correspond to the notation described in the previous page.

2. Refining Method for Each Element

		Li	Na	Be	Mg	Ti
		Sulfuric acid method	Down’s method		Electrolytic Dow method	Kroll’s method
	Starting materials	Raw ore	Industrial salt	Be(OH)$_2$	Dolomite	Rutile ore Synthetic rutile
Smelting	Separation of metal component					
	- Dry process					
	Roasting/ melting	Sulfuric roasting			Roasting	
	Sublimation refining					
	- Wet process					
	Solvent extraction (solvent leaching)			NH$_4$F		
	Removal of impurities from metals/ refining					
	- Wet process					
	Precipitation from solution (1)	Neutralization		Lead peroxides (Mn, Cr) $CaCO_3$, (Al)		
	Solvent extraction					
	Precipitation from solution (2)					
	Deposition of metallic compounds by concentration			Crystallization		
	- Dry process					
	Removal by oxidation					
	Removal by volatilization (distillation)					
	Removal by chlorination					
	Removal by sulfuration					
	Removal by parting (desilverization)					
	Transformation to easily separable compounds					
	- Transformation to alkaline compounds					
	- Transformation to chlorides	to LiCl			to MgCl$_2$	to TiCl$_4$
	- Transformation to oxides					
	- Transformation to other compounds					
	- Distillation					Distillation
	- Solvent extraction					
	Transformation to simple metal (crude metal)					
	Substitution precipitation (wet)					
	Substitution reduction (dry)			Reduction by Mg		Reduction by Mg
Refining	Refining of crude metal					
	- Removal by oxidation					
	- Removal by parting (desilverization)					
	Desilverization furnace (with a rotary burner)					
	- Removal by sulfuration					
	- Removal by chlorination					
	- Removal by dissolution					
	- Transformation and reduction to oxides etc.					
	- Electrolysis					
	- Diaphragm electrolysis					
	- Molten salt electrolysis	Molten salt electrolysis	Molten salt electrolysis		Molten salt electrolysis	
	- Electrolytic winning					
	- Removal by volatilization (distillation)					
	- Removal by sublimation refining					
	- Vacuum distillation/ vacuum melting			Vacuum melting (Mg)		Vacuum distillation (Mg)
	- Beam melting					
	- Zone melting					
	- Alkaline melting					

* The words written in brackets (   ) indicate elements to be separated and removed.

Zr	Hf	V	Nb	Ta
Kroll’s method				
Zircon sand ore	By-products in the smelting process of Zr	V ore, V_2O_5	Concentrates such as tantalite	Concentrates such as tantalite
		Roasting		
			Hydrogen fluoride	Hydrogen fluoride
		Water	MIBK (Fe,Mn,Si) Dilute sulfuric acid (Nb) Water	MIBK (Fe,Mn,Si) Dilute sulfuric acid (Nb) Water
Arc furnace (Si)				
		to alkaline compounds	Addition of NH_3	
Transformation to $ZrCl_4$				
	to Hf oxides	Transformation to V_2O_5	Transformation to Nb_2O_5	
		Transformation to chlorides		Transformation to K_2TaF_7
MIBK(Hf)				
Reduction by Mg	Reduction	Reduction by Mg	Aluminum thermite process	Substitution reduction by Na
				Aqua regia, HF, etc. (Fe, Ni, Cr)
				Removal of gaseous components (in vacuum)
Vacuum distillation (removal of excess Mg)	Vacuum distillation			
			Electron beam melting	

* The words written in a bracket (   ) indicate elements to be separated and removed.

(Continued)

		Cr	Mo	W
		Thermit process		
	Starting materials	Ferrochrome concentrate	Mo bisulfide concentrate (MOS_2)	Ferro-Mn scheelite ($MnWO_4$)
Smelting	Separation of metal component			
	- Dry process			
	Roasting/ melting	Cokes reduction	Roasting (oxidation)	Roasting (sometimes omitted)
	Sublimation refining			
	- Wet process			
	Solvent extraction (solvent leaching)	Sulfuric acid		Alkaline extraction by NaOH
	Removal of impurities from metals/ refining			
	- Wet process			
	Precipitation from solution (1)	Ammonium sulfate (Fe)		
	Solvent extraction		Ammonium (Fe, Cu)	
	Precipitation from solution (2)			$CaCl_2$ solution Highly concentrated hydrochloric acid + nitric acid Ammonium solution
	Deposition of metallic compounds by concentration	Recrystallization		Crystallization (deposition of A. P. T)
	- Dry process			
	Removal by oxidation			
	Removal by volatilization (distillation)			
	Removal by chlorination			
	Removal by sulfuration			
	Removal by parting (desilverization)			
	Transformation to easily separable compounds			
	- Transformation to alkaline compounds			
	- Transformation to chlorides			
	- Transformation to oxides			
	- Transformation to other compounds			
	- Distillation			
	- Solvent extraction			
	Transformation to simple metal (crude metal)			
	Substitution precipitation (wet)			
	Substitution reduction (dry)		Reduction in hydrogen gas flow	Reduction in hydrogen gas flow
Refining	Refining of crude metal			
	- Removal by oxidation			
	- Removal by parting (desilverization)			
	Desilverization furnace (with a rotary burner)			
	- Removal by sulfuration			
	- Removal by chlorination			
	- Removal by dissolution			
	- Transformation and reduction to oxides etc.			Oxidation /ion exchange refining / hydrogen reduction
	- Electrolysis			
	- Diaphragm electrolysis			
	- Molten salt electrolysis			
	- Electrolytic winning	Electrolytic winning		
	- Removal by volatilization (distillation)			
	- Removal by sublimation refining			
	- Vacuum distillation/ vacuum melting			
	- Beam melting			
	- Zone melting			
	- Alkaline melting			

* The words written in brackets (   ) indicate elements to be separated and removed.

Mn	Co	Ni	Ag	Au
MnO_2	Ni-Co mixed sulfides	Ni sulfide flotation concentrate	Copper/lead electrolytic slime	Crushed ore
Roasting (reduction)		Melting		
Sulfuric acid	Water		Sulfuric acid	Na cyanide
	Ammonia (Fe)			
	NaHS (Cu)			
	D2EHPA			
	Phosphonic acid			
	Co electrolytic tail solution			
Ammonia (Fe, As, Al, Si)		Cu electrolytic tail solution (Cu)		
Ammonium sulfide		Removal of $Co(OH)_3$ by chlorine		
			Removal by oxidation (Se)	
			Removal by oxidation (Sb)	
			Removal by oxidation (Pb)	
			Parting (Bi, Te)	
				Substitution precipitation by zinc powders
				Oxidation removal
			Electrolysis (Au)	Electrolysis
Electrolytic winning (diaphragm)	Electrolytic winning	Electrolytic winning		

* The words written in a bracket (   ) indicate elements to be separated and removed.

(Continued)

		Cd	Ga	In
	Starting materials	Roasting smoke ash of zinc and lead concentrates	Leaching slag of zinc concentrate	Pig iron slag
Smelting	Separation of metal component			
	- Dry process			
	Roasting/ melting			
	Sublimation refining			
	- Wet process			
	Solvent extraction (solvent leaching)	Sulfuric acid	Sulfuric acid	Sulfuric acid
	Removal of impurities from metals/ refining			
	- Wet process			
	Precipitation from solution (1)		Hydrogen sulfide	
	Solvent extraction		Tertiary fatty acid (Zn, Fe, Al) Ether (In)	
	Precipitation from solution (2)	Sulfuric acid (As)	NaOH (Fe)	Lead electrolytic solution (ZnO) Diluted sulfuric acid (Pb) Sodium sulfide (Cu, Sn)
	Deposition of metallic compounds by concentration			
	- Dry process			
	Removal by oxidation			
	Removal by volatilization (distillation)			
	Removal by chlorination			
	Removal by sulfuration			
	Removal by parting (desilverization)			
	Transformation to easily separable compounds			
	- Transformation to alkaline compounds			
	- Transformation to chlorides			
	- Transformation to oxides			
	- Transformation to other compounds			
	- Distillation			
	- Solvent extraction			
	Transformation to simple metal (crude metal)			
	Substitution precipitation (wet)	Substitution deposition by zinc		Substitution by zinc plate or Al
	Substitution reduction (dry)			
Refining	Refining of crude metal			
	- Removal by oxidation			
	- Removal by parting (desilverization)			
	Desilverization furnace (with a rotary burner)			
	- Removal by sulfuration			
	- Removal by chlorination			
	- Removal by dissolution			
	- Transformation and reduction to oxides etc.			
	- Electrolysis			Electrolysis
	- Diaphragm electrolysis			
	- Molten salt electrolysis			
	- Electrolytic winning		Electrolytic winning	
	- Removal by volatilization (distillation)	Distillation (Pb, Fe, Ta)		
	- Removal by sublimation refining			
	- Vacuum distillation/ vacuum melting			Vacuum distillation
	- Beam melting			
	- Zone melting			
	- Alkaline melting	Alkaline melting (Zn)		

* The words written in brackets (   ) indicate elements to be separated and removed.

Tl	Tl	Si	Ge	Sn
Lead electrolyte solution	Tl slag of Cd smelting	Quartzite SiO_2	Ge flotation concentrate GeO_2	Tin slag
				Roasting
	Warm water			
Sulfuric acid (Pb)	NaOH			
			Removal by distillation (S)	
			Transformation to $GeCl_4$	
			Transformation to GeO_2	
	Substitution by zinc plate			
		Reduction by carbon (arc electric furnace)	Reduction in hydrogen flow	Cokes reduction
Electrolysis	Electrolysis			Electrolysis
				Diaphragm electrolysis (stainless cathode)
			Zone melting	

* The words written in a bracket (   ) indicate elements to be separated and removed.

(Continued)

		As	As	Sb
			Production of high purity As (7N)	
	Starting materials	As_2O_3 in Cu smelting smoke ash	As_2O_3 in Cu smelting smoke ash	Antimonite
Smelting	Separation of metal component			
	- Dry process			
	Roasting/ melting	Roasting	Roasting	Roasting
	Sublimation refining	Sublimation refining	Sublimation refining	
	- Wet process			
	Solvent extraction (solvent leaching)			
	Removal of impurities from metals/ refining			
	- Wet process			
	Precipitation from solution (1)			
	Solvent extraction			
	Precipitation from solution (2)			
	Deposition of metallic compounds by concentration			
	- Dry process			
	Removal by oxidation			
	Removal by volatilization (distillation)			
	Removal by chlorination			
	Removal by sulfuration			
	Removal by parting (desilverization)			
	Transformation to easily separable compounds			
	- Transformation to alkaline compounds			
	- Transformation to chlorides		Transformation to $AsCl_3$	
	- Transformation to oxides			(Converter) Sb trioxide
	- Transformation to other compounds			
	- Distillation			
	- Solvent extraction			
	Transformation to simple metal (crude metal)			
	Substitution precipitation (wet)			
	Substitution reduction (dry)	Substitution reduction by carbon	Substitution reduction by hydrogen	(Reverberatory furnace) reduction
Refining	Refining of crude metal			
	- Removal by oxidation			Oxidation removal
	- Removal by parting (desilverization)			
	Desilverization furnace (with a rotary burner)			
	- Removal by sulfuration			Sulfuration removal (As)
	- Removal by chlorination			
	- Removal by dissolution			
	- Transformation and reduction to oxides etc.			
	- Electrolysis			
	- Diaphragm electrolysis			
	- Molten salt electrolysis			
	- Electrolytic winning			
	- Removal by volatilization (distillation)			
	- Removal by sublimation refining		Sublimation refining	
	- Vacuum distillation/ vacuum melting			
	- Beam melting			
	- Zone melting			
	- Alkaline melting			

* The words written in brackets (   ) indicate elements to be separated and removed.

Bi	Bi
Electrolytic method	Burks' method
Crude metal	Crude metal
With the silver refining process	With the silver refining process
Oxidation removal (Pb, Cu, As, Sb)	Substitution by zinc plate (Pb, Cu, As, Sb)
	Parting (Ag)
	Chlorination removal (Zn, Pb)
Electrolysis	

* The words written in a bracket (   ) indicate elements to be separated and removed.

3. Table of equipment etc. used in each main process

(1) Table of device and equipment used in concentration

Process	Name of device/ equipment	Power /kW	Dimensions etc. (unit: mm)	Data sources
Crushing	Brake crusher	187	176 rpm non-choke type 60”×48”	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 307
		75	261 rpm 760×380	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 307
		37	610×360	Shigen-to-Sozai, 109 (1993) No. 12
	Cone crusher	75	264 rpm, 1,200 ϕ	Shigen-to-Sozai, 109 (1993) No. 12
Grinding	Conical mill	225	2,400 ϕ×1,500 L	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800
		131	2,400 ϕ×900 L	Shigen-to-Sozai, 109 (1993) No. 12
		55	1,800 ϕ×750 L	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 721
		37	1,800 ϕ×450 L	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 721
	Impeller breaker	75		J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800
	Cylindrical ball mill	400	18.5 rpm, 3,000 ϕ× 3,000	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 304
	Tube mill	169	1,800 ϕ×4,200 L	Shigen-to-Sozai, 109 (1993) No. 12
Sorting	Gyrex screen	5.6	1,200W×3,000L	Shigen-to-Sozai, 109 (1993) No. 12
	Tyrox screen	5	1,200×2,400	Shigen-to-Sozai, 109 (1993) No. 12
	Sorter	7.5	2,400 ×6,000	Shigen-to-Sozai, 109 (1993) No. 12
	Paul sorter	7.5	5,500 ϕ×3,600W× 9,500L	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 303
	Sorter (Trommer)	75	20 rpm 1,550 ϕ×2,350	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 303
	Ellibtex Screen	11	20 rpm 1,560 ϕ×3,660	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 303
	Cyclone	37	782 rpm	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 304
	Magnetic separator (wet type)	1.5	2 drums, 600 ϕ×1,700 L	J. Mining & Metallurgical Institute of Japan, 86 985 (’70-enl), 307
	Wilfred table	2	1,800×4,500	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800
	Mineral jig	2	400×600	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800
	Flotation machine	3.7	255 rpm, 1,100W× 1,100L×1,956H	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 781
		22	255 rpm, 1,400 W× 1,400L×1,700H	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 781
Water washing	Drum washer	7.5	1,200 ϕ×1,500 ϕ× 1,400L	Shigen-to-Sozai, 109 (1993) No. 12
Sedimentation separation/ concentration	Thickener	3.7	10,000 ϕ×2,900H	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 781
		3	6,600 ϕ×2,400H	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800
Dehydration	Oliver filter	3.7	2,400 ϕ×4,300L, 6t/h	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 781
		2	1,800 ϕ×2,400L	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800
	Drum filter	3.7	3,250 ϕ×4,112L, 12t/h	J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 781
Conveyance	Shuttle conveyer	5		J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800
	Belt feeder	3		J. Mining & Metallurgical Institute of Japan, 86 991 (’70-10), 800

(2) Table of equipment used in smelting and refining processes

Process	Name of equipment	Dimensions/capacity	Performance etc.	Power etc.	Data sources
Crushing	Conical ball	2,400 ϕ×1,700	21 rpm	150 kW	J. Mining & Metallurgical Institute of Japan, 86 985 ('70-enl) p. 305
		2,400 ϕ×1,200	20 rpm	150 kW	J. Mining & Metallurgical Institute of Japan, 86 985 ('70-enl) p. 307
		3,200 ϕ×1,200	19 rpm	350 kW	J. Mining & Metallurgical Institute of Japan, 86 985 ('70-enl) p. 307
	Tube mill	1,800 ϕ×4,200		169 kW	Shigen-to-Sozai, 109 (1993) No. 12, p.1058
		1,800 ϕ×4,500		150 kW	Referred to some websites of manufacturing companies
		1,200 ϕ×2,400		37 kW	Referred to some websites of manufacturing companies
	Cylindrical ball mill	3,000 ϕ×3,000	18.5 rpm	400 kW	J. Mining & Metallurgical Institute of Japan, 86 985 ('70-enl) p. 305
	Rod mill	1,300 ϕ×3,000	30 rpm	45 kW	Referred to some websites of manufacturing companies
Classification	Rake sorter	2,450 ×6,700	21 spm, stroke:300mm	7.5 kW	J. Mining & Metallurgical Institute of Japan, 86 985 ('70-enl) p. 305
	Cyclone	Inner diameter, 380×height, 470 of cylinder	Pump revolution: 782 rpm	37 kW	J. Mining & Metallurgical Institute of Japan, 86 985 ('70-enl) p. 305
Leaching	Leaching cell	2.5 m^3		5.5 kW	Shigen-to-Sozai, 106 (1990) No. 5, 289
	Thickener	Inner diameter, 21,000×depth, 2,800			J. Mining & Metallurgical Institute of Japan, 96 1106 ('84-84) p. 267
		10,000 ϕ×2,900		3.7 kW	J. Mining & Metallurgical Institute of Japan, 86 991 ('70-10) p. 781
		12 mϕ, 150 m^3		1.5 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
		18 m		2.2 kW	J. Mining & Metallurgical Institute of Japan, 86 985 ('70-enl) p. 317
		20,000 ϕ, 3,048		2.3 kW	Shigen-to-Sozai, 109 (1993) No. 12, p. 1058
		18,000 ϕ×3,600		3.7 kW	Shigen-to-Sozai, 109 (1993) No. 12, p. 1058
Solid-liquid separation (dehydration)	Filter press	32 in			J. Mining & Metallurgical Institute of Japan, 96 1106 ('84-84) p. 257
		900×900			J. Mining & Metallurgical Institute of Japan, 96 1106 ('84-84) p. 259
			Filtering area: 2.33 m^2		Shigen-to-Sozai, 106 (1990) No. 5, 289
		770×4,500×1,300		1.5 kW	Referred to some websites of manufacturing companies
		600×2,500×1,200		0.4 kW	Referred to some websites of manufacturing companies
	Centrifugal dehydrator		Cake generation amount: 1,200-3,600 /h,	90kW	Referred to some websites of manufacturing companies
			700 rpm	55kW	Shigen-to-Sozai, 113 (1997) No. 6, p. 455
	Oliver filter	2,400 ϕ×4,300	6t/h, 0.25 rpm	3.7 kW	J. Mining & Metallurgical Institute of Japan, 86 991 ('70-10) p. 781
	Drum filter	3,250 ϕ×4,112	6t/h, 0.25 rpm	3.7 kW	J. Mining & Metallurgical Institute of Japan, 86 991 ('70-10) p. 781
	Belt filter	1,830×1,220	Filtering area: 2.33 m^2	0.75kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			Cake generation amount: 700-1,200 /h	3.7 kW	Referred to some websites of manufacturing companies
Leaching/ extraction	Mixer settler	80 L		2.2 kW	J. Mining & Metallurgical Institute of Japan, 96 1106 ('84-84) p. 257
	Agitator	8,500 ϕ×6,700		3.7 kW	Shigen-to-Sozai, 109 (1993) No. 12, p. 1058
	Stirrer	120 rpm, blade 500 ϕ×2		1.5 kW	J. Mining & Metallurgical Institute of Japan, 96 1106 ('84-84) p. 267
		120 rpm, blade 500 ϕ×2		2.2 kW	J. Mining & Metallurgical Institute of Japan, 96 1106 ('84-84) p. 267
		120 rpm, blade 500 ϕ×2		3.7 kW	J. Mining & Metallurgical Institute of Japan, 96 1106 ('84-84) p. 267
			Stirring in the 43 m^3 circulation tank	3.7 kW	Shigen-to-Sozai, 116 (2000) No. 5, p. 451
Drying	Band dryer		Effective area: 1.5Bm×12Lm	3.7 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			Effective area: 5.5 m^2	1.5 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			Drying efficiency: 24.5%	Heavy oil 265L/t-H_2O	Shigen-to-Sozai, 115 (1999) No. 5, p. 340
	Super rotary dryer		Drying efficiency: 72.1	Heavy oil 85L/t-H_2O	Shigen-to-Sozai, 115 (1999) No. 5, p. 340
	Air heating furnace		Hot air flow capacity: 19,400 Nm^3 (350°C)	Heavy oil 250L/h	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			Hot air flow capacity: 19,500 Nm^3 (230°C)	Heavy oil 170L/h	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
Pump	Circulating pump		2.17 m^3/min	5.5 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			3.0 m^3/min	37 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			13.0 m^3/min	110 kW	Shigen-to-Sozai, 116 (2000) No. 5, p. 451
	Supplying pump		5.0 m^3/min	90 kW	Shigen-to-Sozai, 113 (19997) No. 6, p. 455
	Vacuum pump		710 mmHg, 7.0 m^3	15 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
Compressor	Compressor		3.0 m^3/min	37 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
Fan	Exhaust gas fan		20,000 Nm^3/h (200°C)	37 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			9,000 m^3/h	5.5 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
			35,000 Nm^3/h (120°C)	150 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
	Air fan		10,000 m^3/h	55 kW	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
	Bug filter		Filtration area: 75m^3	22 kW	Shigen-to-Sozai, 109 (1993) No. 12, p.1058
Furnace	Rotary kiln	Inner size 3.5 mϕ×4.3 mL		55 kW, Bunker C: 180-800 L/h	J. Mining & Metallurgical Institute of Japan, 88 1011 ('72-75) p. 311
Casting	Foundry machine	1,880×4,000×1,650	100 t/h	181 kW	Shigen-to-Sozai, 113 (1997) No. 6, p. 479

4. Consideration of Wet Type Smelting Processes Such As Solvent Extraction etc.

There are some cases of wet-type smelting, in which a large volume of various solvents such as sulfuric acid, hydrochloric acid, and organic solvents are used for leaching, processing, solvent extraction, etc. from ores.

The entire amounts of these solvents are not necessarily consumed in each step of the smelting processes, but most of them are actually recycled. For example, in solvent extraction, solvents for extracting object metals are recovered after back extraction and reused. The solvents used for such back extraction are also collected and reused. At this time, the externally supplied amounts of the solvents to maintain the necessary amounts are "the actual consumption amount."

It is very hard to precisely grasp the picture of the actual consumption for all the elements to which wet type processing is applied, because information for that from the literature etc. is limited. However, the amounts of energy consumption and CO_2 emission related to the production process of the sulfuric acid, hydrochloric acid, etc. used could be overestimated, if the circulated amounts are also included.

Thus, data for wet type processing are set as follows:

(1) Material flow

In principle, the listed values include circulated amounts in addition to actual consumption, and if the circulated amounts exist, an asterisk should be appended to the data. (eg., 50.2 kL*).

(2) Energy consumption and CO_2 emission

Referring to wet type smelting processes for copper, energy consumption and CO_2 emission are as follows:

Table　Concept of energy consumption and CO_2 emission in wet type processes

Data items	Energy consumption and CO_2 emission
Data related to solvent stirring and circulation	The energy consumption is considered for all the amounts of solvents consumed and circulated.
Data related to solvent heating	The energy consumption is considered for all the amounts of solvents consumed and circulated.
Data related to production of consumed solvents etc.	Data for the amounts of consumed solvents, excluding the amounts of circulated ones from all the amounts, at the time of production are considered. (The rates described below are referred to those for Cu smelting processes.) 1. For the case using solvents in leaching processes from ores. Energy consumption, or CO_2 emission = those for all the amounts of solvents including the circulated ones × 1/200 2. For the case of solvent extraction processes, Energy consumption, or CO_2 emission = those for all the amounts including the circulated ones × 1/50 In both cases 1 and 2, an asterisk (*) is appended to the data to clarify that numerical data for the amounts excluding circulated ones are written.

For reference, N. Narita, *et al.*, "Lifecycle Inventory Analyses for CO_2 Emission in Electrolytic Copper Production System," Shigen-to-Sozai, vol. 117, No. 1 pp. 49-55 (2001).

5. Table of Energy Consumption in Electrolytic Processes

Electric power consumption in electrolysis can be theoretically derived from electric charge, the voltage of the electrolytic cell, and electric current efficiency which are characteristic of the chemical reaction for each element.

The electric power consumption estimated from the cell voltage and electric current efficiency for each element reported in various literatures is shown below.

It should be noted that the estimated values are only theoretical ones for the case that the cell voltage and electric current efficiency are set as follows. However, as there is not such a large difference between the values of actual electric power reported in the literature and the estimated ones, they can be used as a rough standard.

Table Examples of electric power consumption in electrolytic processes

Electrolytic method	Name of substance		Theoretical value of electric charge, Q kAh/t	Electrolytic cell voltage, Vt V	Electric current efficiency, εf %	Electric power consumption kWh/t
Electrolytic refining	Silver	Ag	248	1.7	93	453
	Indium	In	700	0.35	93	263
	Tin	Sn	903	0.15	85	159
	Gold	Au	408	1.0	99	412
	Lead	Pb	259	0.46	93	128
	Bismuth	Bi	385	0.2	93	83
Electrolytic winning	Chrome	Cr	1,546	4.2	45	14,429
	Manganese	Mn	976	4.7	60	7,645
	Cobalt	Co	910	3.1	92	3,066
				3.5	91	3,500
	Nickel	Ni	913	1.9	90	1,927
				3.0	93	2,945
				3.9	83	4,290
	Zinc	Zn	820	3.3	90	3,007
	Gallium	Ga	1,153	3.5	30	13,452
	Cadmium	Cd	477	2.4	94	1,218
	Tellurium	Te	420	1.7	95	752
	Thallium	Tl	393	1.2	90	525
Molten salt electrolysis	Lithium	Li	3,862	7.0	80	33,793
	Sodium	Na	1,166	6.9	83	9,693
	Magnesium	Mg	2,204	6.0	80	16,530
	Aluminum	Al	2,980	4.2	90	13,907
				4.0	90	13,377
	Calcium	Ca	1,338	25	74	45,510

Note: The unit production amount, t, indicates the quantity of electrolyzed metal.
Data source: produced by NRI using reference materials such as the Electrochemistry Handbook.

Electric energy consumption in material production processes W (kWh/t) = Q × Vt ÷ ε_f

6. Basic Units Used

In the present investigation, the basic units shown below are used to estimate the amounts of energy consumption, CO_2 emission etc. However, in the case that concrete values are obtained as energy- and CO_2 emission-reduced values from the literature etc., these basic units are not used, but instead the values in the literature are utilized.

Table Main basic units used

Item	Basic unit	Remarks	Data source
[Energy]			
Electric power	9,449 kJ/kWh Power generation efficiency 38.1%	Calorific power	Integrated Energy Statistics
Bunker A	38,911 kJ/L	Calorific power	Integrated Energy Statistics
Kerosene	37,238 kJ/L	Calorific power	Integrated Energy Statistics
Cokes	30,125 kJ/kg	Calorific power	Integrated Energy Statistics
Oil cokes	35,564 kJ/kg	Calorific power	Integrated Energy Statistics
Sulfuric acid	1,174 kJ/kg	At the time of production	NIMS Database
Hydrochloric acid	2,728 kJ/kg	At the time of production	NIMS Database
Caustic soda	11,493 kJ/kg	At the time of production	NIMS Database
Ammonia	13,375 kJ/kg	At the time of production	NIMS Database
MIBK	56,579 kJ/kg	At the time of production	NIMS Database
Hydrofluoric acid	19,444 kJ/kg	At the time of production	NIMS Database
Chlorine	7,720 kJ/kg	At the time of production	NIMS Database
Item	Basic unit	Remarks	Data source
[CO_2 emission]			
Electric power	0.3454 kg- CO_2/kWh	Electric power generation	Electric Almanac, 1999
Bunker A	2.6977 kg- CO_2/L	Combustion	Materials of the Ministry of Environment
Kerosene	2.5284 kg- CO_2/L	Combustion	Materials of the Ministry of Environment
Sulfuric acid	0.087 kg- CO_2/kg	At the time of production	NIMS Database
Hydrochloric acid	0.222 kg- CO_2/kg	At the time of production	NIMS Database
Caustic soda	0.938 kg- CO_2/kg	At the time of production	NIMS Database
Ammonia	1,365 kg- CO_2/kg	At the time of production	NIMS Database
MIBK	8.377 kg- CO_2/kg	At the time of production	NIMS Database
Hydrofluoric acid	1,722 kg- CO_2/kg	At the time of production	NIMS Database
Chlorine	0.630 kg- CO_2/kg	At the time of production	NIMS Database

* The cal (calorie) is converted to J (joule) using a factor of 4.184 kJ/kcal.

* The CO_2 emission of cokes and oil cokes are calculated separately, assuming that the content of fixed carbon is 80 % and that this is converted to CO_2 by combustion.

* Materials by Ministry of Environment: Execution plan manual for Article 8 Clause 1 in the law for countermeasures against global warning, August 1999.

Note)

(1) Lithium (Li)

1) Overview of smelting

a. Smelting method

The smelting of Li is generally carried out using brine as a starting material. Extraction of Li from raw mineral ore (the solvent extraction method, or the sulfuric acid method) is done only in a part of China. In the amount of Li resources produced, Chile is the first and the USA is the second, and the Li resources are produced from brine in both countries.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Brine method	Brine	Chemetal Foote (USA), FMC(USA), Chemetal GMBH (Germany), others	○
Solvent extraction method (Sulfuric acid method)	Lithium ore	State Owned (China)	○
Solvent extraction method (Lime method)	Lithium ore	-	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Used conformations		Main applications of final products	Domestic amount demanded (year 1998)
Lithium carbonate	Li_2CO_3	Additives for special glass, cover coat for ceramic wares, secondary batteries, etc.	4,700 t
Lithium bromide	LiBr	Refrigerate absorbent for absorption type refrigerators, medical use, etc.	3,600 t
Lithium hydroxide	LiOH	Iron and steel, car-related grease, additive for battery electrolyte, starting material for soaps etc., absorbent for carbon dioxide gas etc.	1,340 t
Lithium chloride	LiCl	Flux for light metal welding, absorbent for air dryer, medical use etc.	900 t
Metal lithium	Li	Anode material for lithium battery, polymerization catalyst for synthetic rubber, alloy, coolant for space atomic furnace, reducer etc.	180 t
Lithium hydride	LiH	Reducer, polymerization catalyst etc.	under 1 t
Lithium fluoride	LiF	Flux for welding, rocket fuel, neutron shielding material, fluorine electrolysis, electrode, etc.	not clear
Lithium oxide	Li_2O	Blanket material for nuclear fusion etc.	not clear
Lithium iodide	LiI	Solid electrolyte, etc. for fuel battery	not clear
Lithium silicate	LiSiO	Vehicle coating material etc.	not clear
Lithium hypochlorite	LiOCl	Bleaching agent, antiseptic for swimming pool etc.	not clear

Data source: from Data Book for Metals, 2000

2) Integration status of data such as mass balance

a. Brine method

Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1.Concentration		【INPUT】 -The substance concentrations in brine are assumed to be 7 times those in brine. (The concentrations of NaCl and Li in brine are 2.5% and 180 ppb, respectively.) -Evaporation is assumed to be induced in a concentration reservoir by only solar heat without supplying other energies. 【OUTPUT】 -Water content is assumed to be reduced by 70% on a weight basis. -What is crystallized by concentration is assumed to be only NaCl. -Crystallizing amounts of NaCl are estimated using its solubility. - The loss of Li is assumed to be zero.	【INPUT】 -Supplied amount of brine -Li concentration in brine -Concentrations of other impurity elements in brine 【OUTPUT】 -Concentration rate for brine 【Facility data】 -Specifications of the types and processing powers, etc. of equipment used -Operation conditions -Type and consumption amounts of supplied energy
2. Precipitation/ filtration		【INPUT】 -The amount of slaked lime added is assumed to be a theoretical value. 【OUTPUT】 - The yield of Li is assumed to be 95%. - All of the Mg in the concentrated brine is assumed to be removed.	【INPUT】 -The amounts of energy consumption and CO_2 emission for slaked lime at the time of production 【Facility data】 -Specifications of engine etc. of stirrer, pump etc. for precipitation/ filtration tank, Operation conditions, the number of equipments
3. Soda ash addition/ filtration		【INPUT】 -The yield of Li is assumed to be 95%. -The purity of Li carbonate is assumed to be 95%. -The amount of supplied soda ash is assumed to be a theoretical value. 【OUTPUT】 -The amount of CO_2 of soda ash emitted at the time of production is estimated.	【Facility data】 -Specifications for facilities, engines etc. of filtration tank etc. -Operation conditions -The number of pieces of equipment
4. Chlorination / Electrolytic winning	【OUTPUT】 - The grade of metallic Li is 99.8%.	【INPUT】 -The yield of Li is assumed to be 95%. -Only the amount of hydrochloric acid contributing to the reaction (a theoretical value) is taken up. -The energy consumption amount of hydrochloric acid at the time of production is estimated. -The amount of electric power consumption by electrolysis is estimated. 【OUTPUT】 -Mass balance is estimated based on the reaction formula. -The amount of CO_2 emitted at chlorination of lithium carbonate is estimated according to the reaction formula.	【OUTPUT】 -The yield of Li 【Facility data】 -The Operation conditions of the electrolytic cell

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in processes concerned.
【Facility data】: Data for equipment used in processes concerned.

The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

b. Solvent extraction method/sulfuric acid method

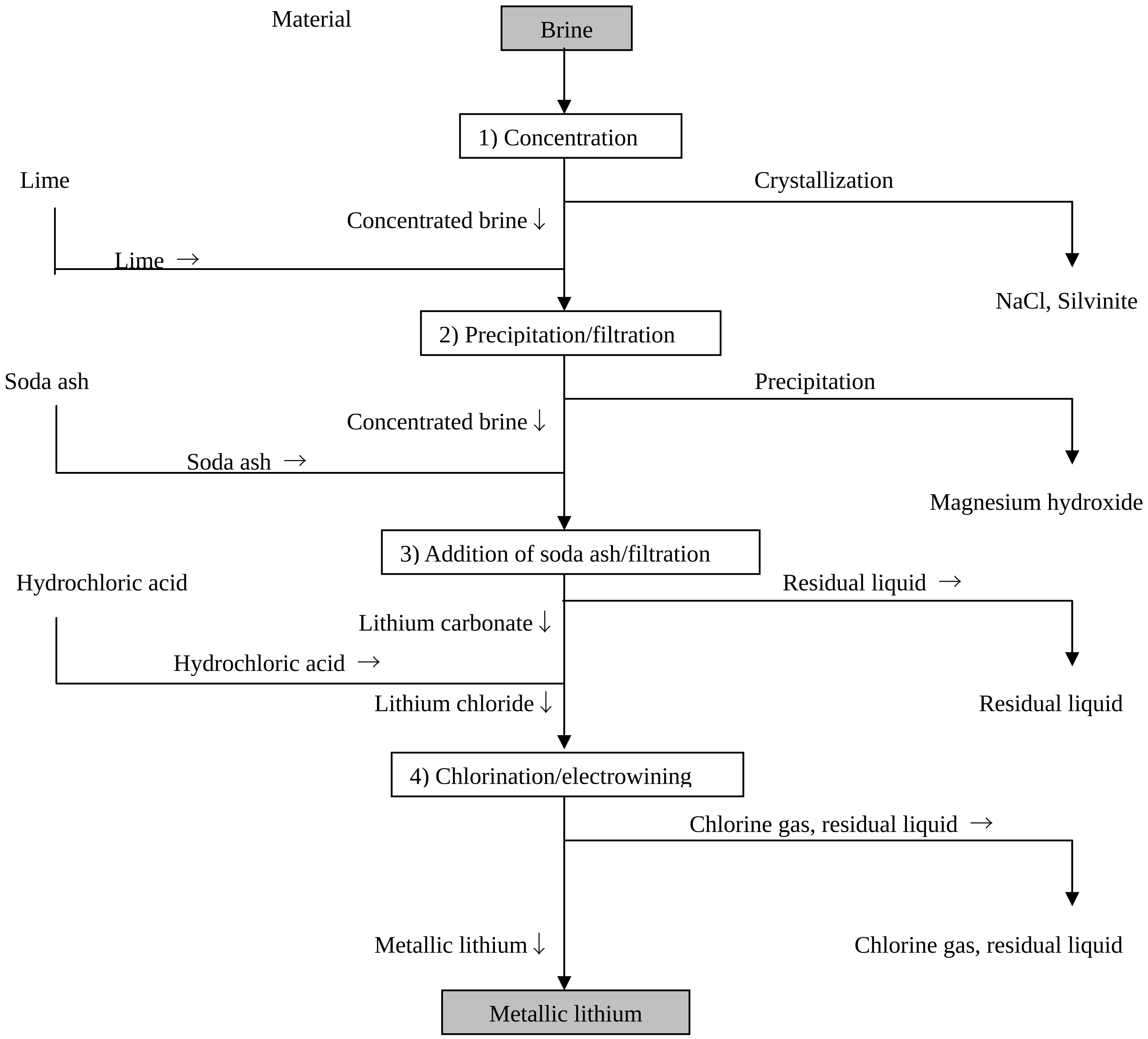
Process	Used data		Untaken data
	Data obtained from literature etc.	Data assumed and estimated in this report	
1. Gravity concentration/ flotation	【INPUT】 - The grade of LiO_2 in raw ore: 1.5% 【OUTPUT】 – The grade of α–type spodumene: 5-6%	【OUTPUT】 -The yield of α type spodumene from ore is assumed to be 90%.	【Facility data】 -Specifications for engines, processing power etc. of gravity concentrator/ floatation machine, operating rates, the number of pieces of equipment
2. Roasting		【OUTPUT】 - The loss of Li due to roasting is assumed to be zero.	【INPUT】 - Type and consumption amount of fuels supplied to roasting furnace 【Facility data】 - Specifications for engine, capacity, processing power, etc of roasting furnace - Operation conditions
3. Solvent extraction		【INPUT】 - For sulfuric acid, only the amount contributing to the reaction (a theoretical value) is considered. - The amount of energy consumption at the time of production of sulfuric acid is estimated. 【OUTPUT】 - The yield of Li is assumed to be 95%. - The amount of CO_2 emission at the time of production of sulfuric acid is estimated.	【INPUT】 - Total amount of sulfuric acid used as solvent - Type and consumption amount of energy required for solvent heating 【OUTPUT】 - The amount of residual liquid 【Facility data】 - Specifications of engines etc. of stirrers and pumps of extraction tank - Operation conditions, the number of pieces of equipment
4. Solution purification		【INPUT】 -For soda ash, the amount of energy consumption at the time of production is estimated. 【OUTPUT】 - The yield of Li is assumed to be 95%. - Mass balance is estimated based on the reaction formula. - For soda ash, the amount of CO_2 emission at the time of production is estimated.	【OUTPUT】 -Grade and yield of Li 【Facility data】 - Specifications of pump, engine of purification tank, processing power, etc - Operation conditions - The number of equipments
5 Electrowining	【OUTPUT】 - The grade of metallic Li: 99.8%	【INPUT】 - The yield of Li is assumed to be 95%. - For hydrochloric acid, only the amount contributed to reaction (a theoretical value) is taken up. - For hydrochloric acid, the amount of energy consumption at the time of production is estimated. - The amount of electric power consumption in electrolysis is estimated. 【OUTPUT】 - Mass balance is estimated according to reaction formula. - The amount of CO_2 emitted at chlorination of lithium carbonate is estimated according to reaction formula.	【INPUT】 - The total amount of hydrochloric acid used - Sort and consumption amount of energy required for solvent heating electrolytic tank 【OUTPUT】 - The amount of residual liquid (hydrochloric acid) - Yield of metal Li 【Facility data】 -Operation conditions of electrolytic tank

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in processes concerned.
【Facility data】: Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

(Note)

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes (1. Brine method)



Note: Silvinite = NaCl + KCl

Data source: produced by NRI according to Databook of Metals

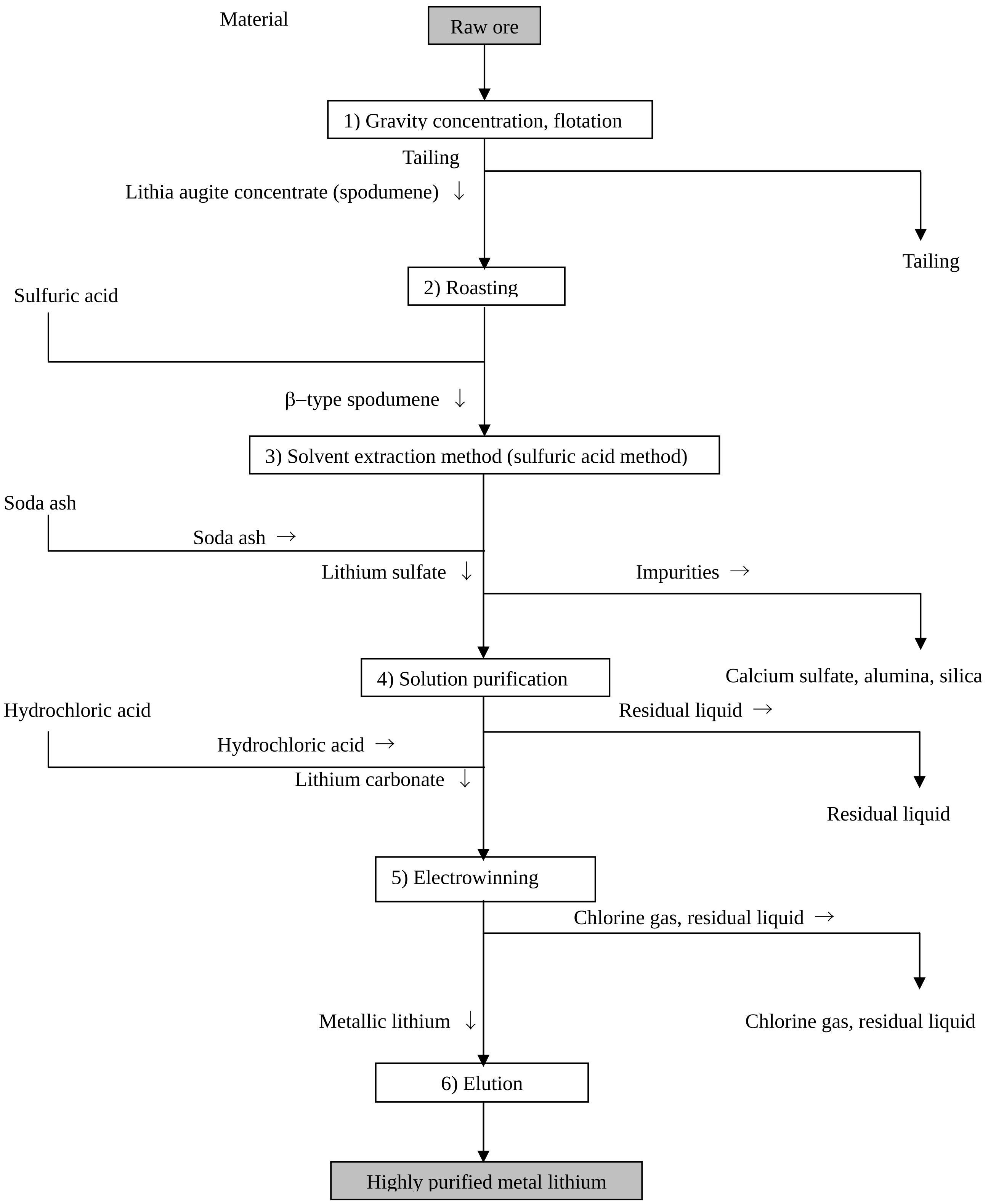
Mass balance data (1. Brine method)

The amounts of material/energy are those per raw ore of 10000t.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Concentration	Brine	10,000 t	Concentrated brine	3.336 t	- The substance concentrations in brine are assumed to be 7 times those in sea water.
	(content of Li)	(12.6 t)	(content of Li)	(12.6 t)	
			Crystallized NaCl	870 t	
			Evaporated water	5.793 t	- The loss of Li is assumed to be zero.
					- Evaporation is assumed to be induced only by solar heat.
	Electric power	(unknown)	[CO_2 emission]	(unknown)	- It is assumed that crystallization occurs only in NaCl.
2) Precipitation/ filtration	Concentrated brine	3,336 t	Concentrated brine	3,395 t	- The loss of Li is assumed to be zero.
	(content of Li)	(12.6 t)	(content of Li)	(12.6 t)	
	$Ca(OH)_2$	277 t	$Mg(OH)_2$	218 t	- The supplied amount of slaked lime is assumed to be a theoretical value.
					- All Mg is assumed to be removed.
	Electric power	(unknown)	[CO_2 emission]	(unknown)	
3) Addition of soda ash/ filtration	Concentrated brine	3,395 t	Lithium carbonate	67 t	- The yield of Li is assumed to be 95%.
	(content of Li)	(12.6 t)	(content of Li)	(12.0 t)	- The purity of Li_2CO_3 is assumed to be 95%.
	Soda ash	96 t	Residual liquid	3,425 t	- The added amount of soda ash is assumed to be a theoretical value.
					- The environmental load for the production of soda ash is considered.
	Electric power	(unknown)	[CO_2 emission]	78.6 t	
	[Soda ash production]	962 GJ	(content of soda ash production)	(78.6 t)	
5) Chlorination/ Electrolytic winning	Lithium carbonate	67 t	Metallic lithium	11.4 t	- Li_2CO_3 is chlorinated before electrowinning. (CO_2 is generated at this time.)
	(content of Li)	(12.0 t)	CO_2	36.04 t	
	Hydrochloric acid	151 kL (180 t)	Chlorine gas	61.0 t	- Mass balance is estimated based on the reaction formula.
	Other additives	+α	Residual liquid	151 kL (138 t +)	- Hydrochloric acid is considered only for the amount contributed to the reaction.
	(Other additives) Molten salt				- The yield of metal Li is assumed to be 95%. - The purity of metallic Li is assumed to be 99.8%. - The environmental load for the production of hydrochloric acid is considered. - Lithium chloride and potassium chloride in the molten salts are in equimolar ratio. - Electric power consumption for electrolysis: 35,000 kWh/t-electrolytic Li
	Electric power	3,761 GJ	[CO_2 emission]	213 t	- Voltage of electrolytic cell is 7V, and the electric current efficiency is assumed to be 80%.
	Hydrochloric acid production	490 GJ	(content of hydrochloric acid production)	(39.9 t)	- Including the amount of CO_2 emitted by the reaction.
Total	[Energy] (production of materials)	5,213 GJ (1,453 GJ)	[CO_2 emission] (production of materials)	292 t (118 t)	

Data source: produced by NRI using various data.
Reference: Data book of Metal

Flow diagram of processes (2. Solvent extraction method/Sulfuric acid method)



Data Source: produced by NRI using Data book of Metals

Mass balance data (2. Solvent extraction method/Sulfuric acid method)

The amounts of material/energy are those per raw ore of 100t.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Gravity concentration/ floatation	Raw ore	100.00 t	α-type spodumene	27.27 t	- The yield of lithium is assumed to be 90%.
	(content of Li)	(0.35 t)	(content of Li)	(0.31 t)	- The grade of raw ore Li_2O: approximately: about 1.5%
			Tailing	72.73 kt	- The grade of α−type spodumene Li is 5-6%.
	Electric power	(unknown)	[CO_2 emission]	(unknown)	
2) Roasting	α-type spodumene	22.27 t	β-type spodumene	22.27 t	- Transformation of α−type to β-type spodumene.
	(content of Li)	(0.31 t)	(content of Li)	(0.31 t)	
	Fuel	(unknown)	[CO_2 emission]	(unknown)	
3) Extraction by solvent	β-type spodumene	22.27 t	Lithium sulfate	4.76 t-dry	- The yield of Li is assumed to be 95%, when a little larger amount than the theoretical value is mixed.
	(content of Li)	(0.31 t)	(content of Li)	(0.30 t)	
	Sulfuric acid	7.48 kt (13.76 t)	Calcium sulfate, alumina, silica etc.	6.28 t	- Mass balance is estimated based on the reaction formula.
	Other additives	+ α			- Sulfuric acid is considered only for the amount contributed to reaction.
	(Other additives)				
	Slaked lime				- Slaked lime for washing
	Lime				- Lime for neutralization
	Electric power	(unknown)	[CO_2 emission]	1.2 t	-The environmental load for the production of sulfuric acid is considered.
	[production of sulfuric acid]	16.2 GJ	(content of sulfuric acid production)	(1.2 t)	
4) Solution purification	Lithium sulfate	4.76 t-dry	Lithium carbonate	3.07 t	- The yield of lithium is assumed to be 95%.
	(content of Li)	(0.30 t)	(content of Li)	(0.29 t)	
	Soda ash	4.59 t-dry	Residual liquid	6.28 t	- Mass balance is estimated according.
	Electric power	(unknown)	[CO_2 emission]	3.8 t	- The environmental load for the production of soda ash is considered.
	[production of soda ash]	45.9 GJ	(production of soda ash)	(3.8 t)	
5) Molten salt electrolysis	Lithium carbonate	3.07 t	Metallic lithium	0.27 t	- Li_2CO_3 is chlorinated before electrowinning. (CO_2 is generated at this time.)
	(content of Li)	(0.29 t)			
	Hydrochloric acid	6.91 kL (8.23 t)	CO_2 Chlorine gas	1.74 t 2.80 t	- Mass balance is estimated according to reaction formula.
	Other additives	+ α	Residual liquid	6.91 kL (6.49 t +)	- Hydrochloric acid is taken up only for the amount contributed to the reaction. - The yield of Li is assumed to be 95%. - The environmental load for the production of hydrochloric acid is considered. - Lithium hydrochloride and potassium chloride in the molten salts are in equimolar ratio.
	(Other additives) Molten salt				- Electric power consumption for electrolysis: 35,000kWh/t-electrolytic Li
	Electric power	90.6 GJ	[CO_2 emission]	6.9 t	- Voltage of electrolytic cell is 7 V, and the electric current efficiency is assumed to be 80%.
	[production of hydrochloric acid]	22.4 GJ	(production of hydrochloric acid)	(1.8 t)	- Including the amount of CO_2 emitted by the reaction
Total	[Energy]	175.1 GJ	[CO_2 emission]	11.8 t	
	(production of materials)	(84.5 GJ)	(production of materials)	(6.8 t)	

Data source: produced by NRI using various data.
Reference: Data book of Metal

(2) Sodium (Na)

1) Overview of smelting

a. Smelting method

Production of metallic sodium is presently done according to Downs' method where completely molten salt is directly electrolyzed. For Kastner's method using molten caustic soda as the raw material, the electric current efficiency is theoretically limited to be 50%, and thus only Downs' method is used at present.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Kastner's method (Electrolysis method of molten caustic soda)	Molten caustic soda	No companies at present	×
Downs' method (Direct electrolysis method for molten salt)	Industrial salt	Nippon Soda Co., Ltd. (Japan), Tosoh Corp. (Japan), etc.	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final products	
[Materials for chemical industry]	
[Metal reducer]	
[Thermal conductor]	Coolants for fast breeder reactor, heating pipe, car engine bulb, etc.
[Electrical use]	Sodium lump, permanent fuse, sodium sulfur buttery, etc.
[Atomic furnace use]	Coolants for fast breeder reactor

Data source: from Data Book for Metals, 2000

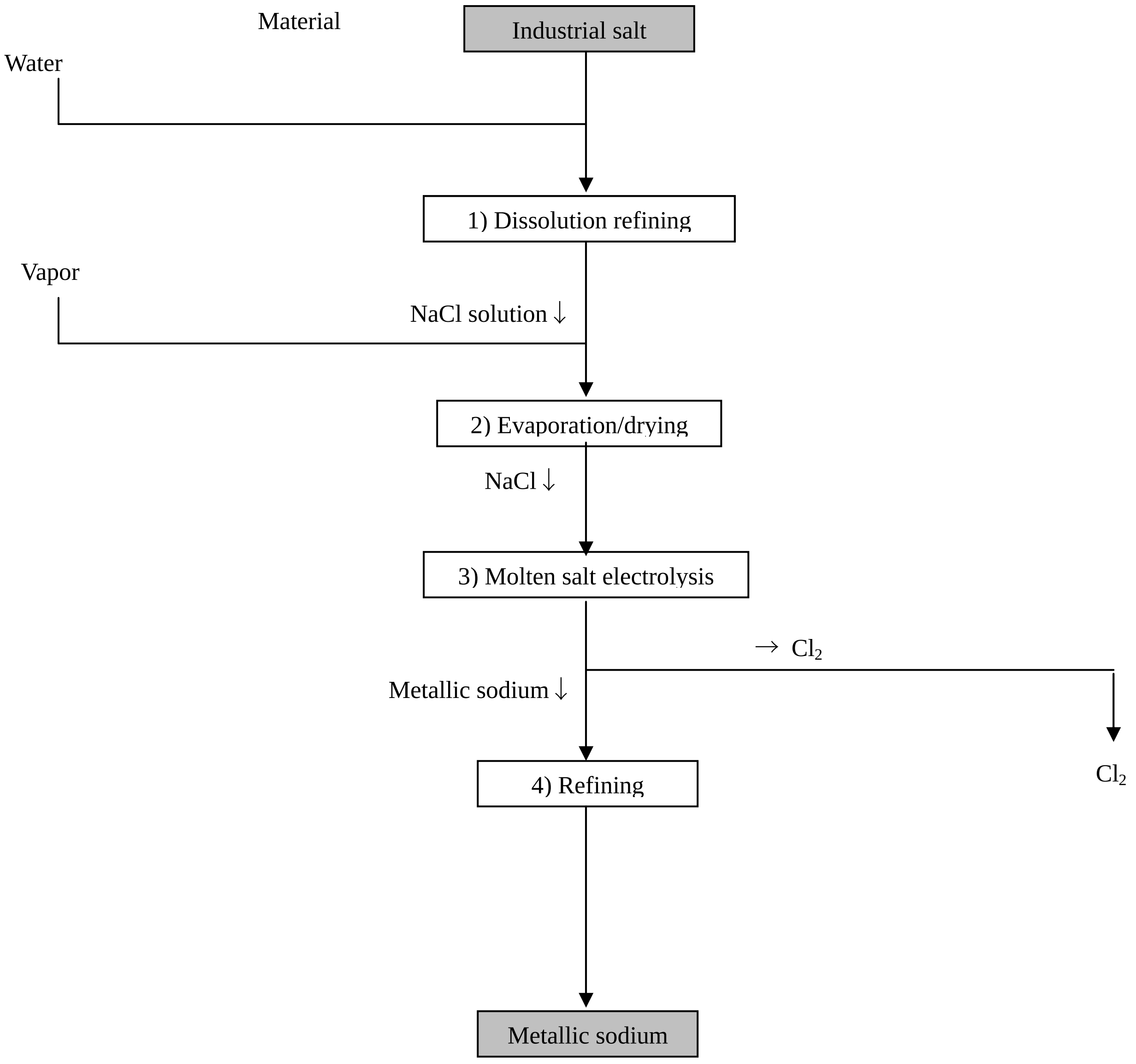
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1. Dissolution refining	【INPUT】 - Industrial salt (table salt) content of 99.0%. - Supplied amount of industrial salt	【INPUT】 - Solubility of salt is assumed to be 35.9 g/100 g-water (at 25°C), and 39.3 g/100 g-water (at 100°C). - Water is assumed to be oversupplied by 20%. - Energy required to heat water (from 25 to 100°C) is estimated on the assumption of heavy oil use. - Heat of dissolution for salt is not considered. 【OUTPUT】 - It is assumed that there is no water evaporation.	【FACILITY DATA】 - Specifications for engines and processing powers of stirrer and pump, etc. - Operation status
2. Evaporation/ drying	【OUTPUT】 - Amount of refined NaCl	【INPUT】 - Latent heat of water evaporation is considered as consumed energy. - Used fuel is assumed to be heavy oil A.	【FACILITY DATA】 - Specifications for engines of evaporation tank, dryer, etc., and processing power, etc. - Operation status - Type and consumption of supplied energy
3. Molten salt electrolysis	【FACILITY DATA】 - Cell temperature: approximately 600°C - Voltage of electrolytic cell: 6.9 V - Electric current efficiency: 83% - Electric power consumption for electrolysis: 10,600 kWh/t-electrolytic Na	【INPUT】 - Energy required to heat electrolytic cell is not considered. 【OUTPUT】 - The grade of metallic Na is assumed to be 99.5%. - The yield of Na is assumed to be 95%.	【INPUT】 - Type and consumption of energy required to heat electrolytic cell 【OUTPUT】 - Grade and yield of produced metallic Na
4. Refining	【OUTPUT】 - Amount of refined Na - The grade of refined Na is 99.8%. - Metal Ca and oxidized Na are predominant as impurities.	【OUTPUT】 - The grade and yield of metallic Na are assumed to be 100%.	【OUTPUT】 - Yield of metallic Na 【FACILITY DATA】 - Type of equipment used for refining - Specifications for engine of equipment and processing power, etc., and operation status - Type and consumption of supplied energy

Note: 【INPUT】:The amounts of materials, energy etc. supplied into the processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in the processes concerned.
【FACILITY DATA】:Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Electrochemistry Handbook

Mass balance data

The amounts of material/energy are those per refined metallic sodium of 1,000 kg.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Dissolution refining	Industrial salt Water	**3,000 kg** 9,069 kg	Sodium chloride solution	12,069 kg	- The industrial salt (table salt) content is 99 %. - Solubility of salt is assumed to be 39.3g/100g-water (at 100°C). - Water is assumed to be oversupplied by 20%. - Energy required to heat water (from 25 to 100°C) is estimated on the assumption of heavy oil used.
	Fuel	1.3 GJ	[CO_2 emission]	0.09 t	- Heat of dissolution of salt is not considered.
2) Evaporation/ drying	Sodium chloride solution	12,069 kg	Refined NaCl Water (evaporated portion)	2,600 kg 8,009 kg	- Latent heat of water evaporation is considered as consumed energy (on the assumption of heavy oil use).
	Vapor	(The amount is unknown.)	Residual liquid	1,460 kg	
	Fuel	18.1 GJ	[CO_2 emission]	1.25 t	
3) Molten salt electrolysis	Refined NaCl	2,600 kg	Metallic Na	1,003 kg	- The grade is assumed to be 99.5%. - The yield of Na is assumed to be 95%.
			Cl_2 gas Unrecovered Na etc.	1,539 kg 58 kg	- Cell temperature: approximately 660°C - Voltage of electrolytic cell: 6.9 V - Electric current efficiency: 83%
	Electric power	100.0 GJ	[CO_2 emission]	3.65 t	- Electric power consumption for electrolysis: 10,600 kWh/t-electrolytic Na
4) Refining	Metallic Na	1, 003 kg	Refined sodium Impure slag	**1,000 kg** 3.0 kg	- A grade of 99.8%. - Impurities are metallic Ca and Na oxide.
	Electric power	(unknown)	[CO_2 emission]	(unknown)	
Total	[Energy]	119.3 GJ	[CO_2 emission]	5.00 t	

Data source: produced by NRI using various data

References: Electrochemistry Handbook

Yajima et al. “Sodium production in Nihongi Plant, Nippon Soda Co., Ltd.”, J. Mining & Metallurgical Institute of Japan, 1997, 1122 (’81-8) 881, p.879

(3) Magnesium (Mg)

1) Overview of smelting

a. Smelting method

The main raw materials used for Mg smelting are seawater, dolomite and magnesite. Brine water with a high $MgCl_2$ concentration is also used for Mg smelting in the USA.

Seawater, with a concentration of approximately 0.13% of Mg, is the largest source of this material, which is refined by electrolysis of molten salt, $MgCl_2$.

The Mg content in dolomite ($MgCO_3$-$CaCO_3$) is in the range from 10 to 12.5%, whereas that in magnesite ($MgCO_3$) is in the range from 26 to 28%.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Electrolysis (I.G. Method)	Seawater, dolomite, magnesite	Norks Hydro (Norway), Norsk Canada (Canada), Russian corporations, others	×
Electrolysis (Dow Method)	Sea water	American corporations, etc.	○
Electrolysis (New Electrolysis Method)	Brine water	Magnesium Corp. of America (USA), Dead Sea magnesium (Israel), others	×
Thermal Reduction (Pidgeon Method)	Dolomite	Timmincco (Canada), Chinese corporations, others	×
Thermal Reduction (Magnetherm Method)	Dolomite	Northwest Alloys (USA), Sofrem (France), Chinese corporations, others	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final products		Domestic amount demanded (year 1998)
Additive for aluminum alloys (comprises 70% of domestic consumption)		19,707 t
Additive for nodular cast iron		1,659 t
Mg die cast		2,602 t
	Structural materials for aircraft/automobile parts, electric /electronic parts, etc.	
Cast Mg		228 t
Metallic powder, corrosion resistant, etc.		2,647 t
	Deoxidizing and desulfurizing agents for steel	
	Reducing agent for titanium, zirconium processing	
	Catalyst for fireworks, gun powder, organic compounds	
	Anticorrosion anode for oil tanks, pipelines, boilers, etc.	

Data source: from Data Book for Metals, 2000

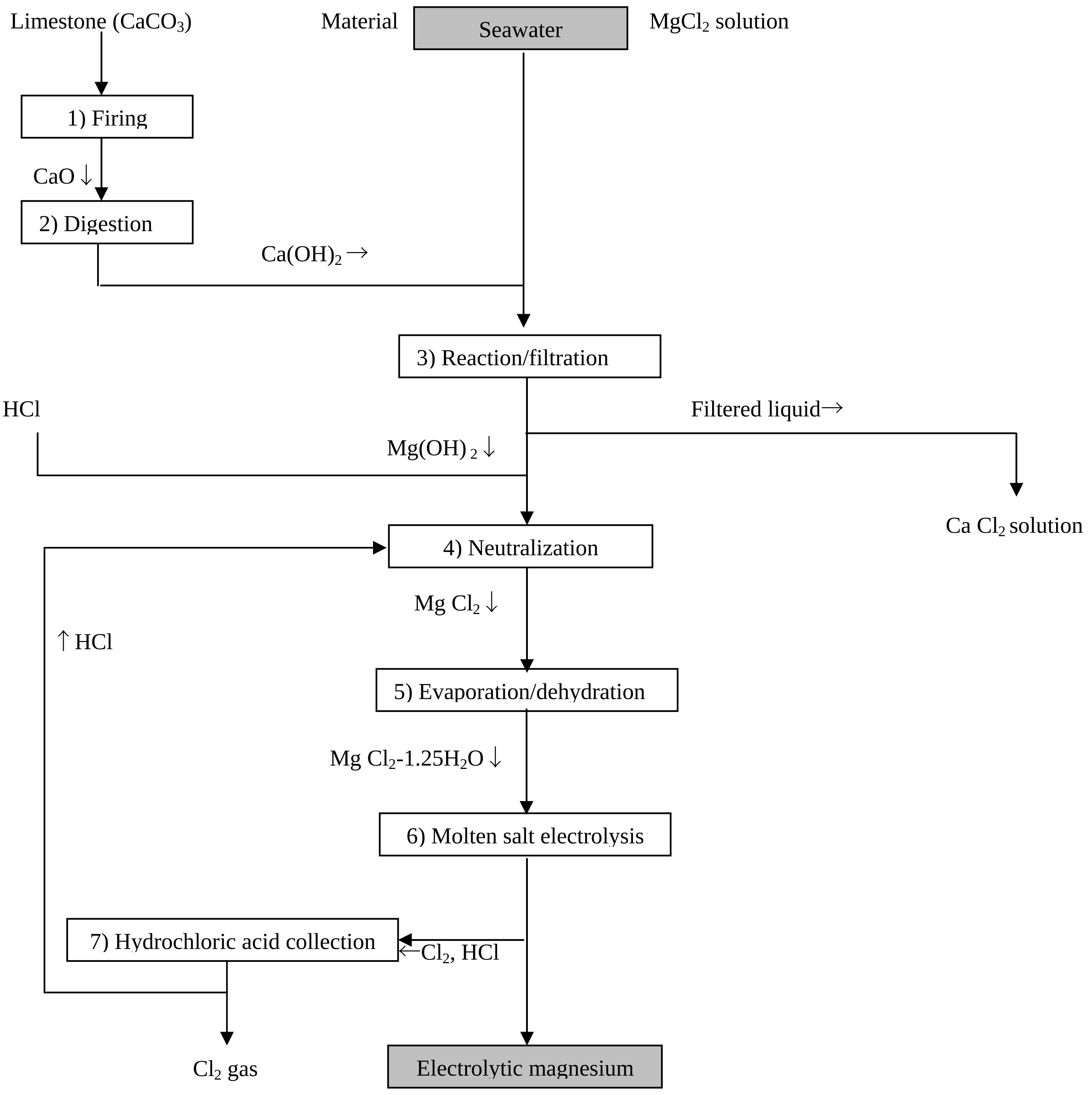
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature etc.	Data assumed and estimated in this report	
1. Firing	【Facility data】 - Using a calcining furnace	【INPUT】 - Used fuel is assumed to be heavy oil A. - Energy consumption of a calcining furnace is estimated to be 4000kJ/kg-limestone. 【OUTPUT】 - The amount of CO_2 emitted from the transformation of limestone into quicklime is estimated based on the reaction formula.	【Facility data】 - Specifications for processing capacity, etc. of the calcining furnace - Operation conditions - Type and amount of energy supplied
2. Consumption		【INPUT】 - The amount of used water is estimated as a theoretical value. 【OUTPUT】 -Mass balance is estimated based on the reaction formula.	【Facility data】 - Type of facility used - Specifications for power, processing capacity, etc. - Operation conditions - Type and consumption of energy supplied
3. Reaction / filtration	【INPUT】 - Mg concentration in seawater: 0.13 wt%	【INPUT】 - It is assumed that the amount of $Ca(OH)_2$ is 20% excess compared to the theoretical value. 【OUTPUT】 - The yield of Mg is assumed to be 95%. - The grade of $Mg(OH)_2$ is assumed to be 95%.	【Facility data】 - Type of facility - Specifications for power, processing capacity, etc. - Operation conditions
4. Neutralization	【OUTPUT】 - $MgCl_2$ concentration: 15 wt%	【INPUT】 - Heat of neutralization is not considered. - Energy consumption in producing hydrochloric acid is estimated (for newly supplied portion except for recovered hydrochloric acid). 【OUTPUT】 - It is assumed that there is no loss of Mg. - Amount of CO_2 emitted in producing hydrochloric acid is estimated.	【Facility data】 - Specifications for power, processing capacity, etc. of neutralization tank, stirrer, pumps, etc. - Operation conditions
5. Evaporation/ Dehydration		【INPUT】 - Latent heat of water evaporation is estimated as energy. - Used fuel is assumed to be heavy oil A. 【OUTPUT】 - It is assumed that there is no loss of Mg.	【OUTPUT】 - Grade and amount of magnesium chloride 【Facility data】 - Specifications for power, processing capacity, etc. of evaporator, dehydrator, etc. - Operation conditions - Type and amount of energy supplied
6. Molten salt electrolysis	【OUTPUT】 - Electrolytic Mg grade 99.9% - Electrolytic furnace energy consumption: 16.5 to 22 kWh/kg-Electrolytic Mg	【INPUT】 - The grade of hydrated magnesium chloride is assumed to be 99%. - Electric power consumption of electrolytic furnace is assumed to be 20 kWh/kg-electrolytic Mg. 【OUTPUT】 - It is assumed that all consumed graphite C is emitted as CO_2.	【INPUT】 - Supplied amount of hydrated magnesium chloride - Type and amount of energy required for heating an electrolytic cell. 【OUTPUT】 - The yield of electrolytic Mg
7. Recovery of hydrochloric acid		【OUTPUT】 - Amounts of chlorine and hydrogen produced in molten salt electrolysis are used to estimate the recovery amount of hydrochloric acid according to the reaction formula.	【Facility data】 - Specifications for type, power, processing capacity, etc. of the facility - Operation conditions - Type and amount of energy supplied

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.
【FACILITY DATA】:Data for equipment used in processes concerned
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: New Data Book for Metals, 2000

Mass balance data

The amounts of material/energy are those per 100,000 t of seawater.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Firing	Limestone	642 t	CaO	360 t	- Production of quicklime
			CO_2 gas	282 t	- Used fuel is assumed to be heavy oil A. - Energy consumption of a calcining furnace is estimated to be 4000 kJ/kg-limestone. - The amount of CO_2 emitted from the reaction is included.
	Fuel	2,569GJ	【CO_2 emission】	461 t	
2. Digestion	CaO	360 t	$Ca(OH)_2$	475t	- Production of slaked lime
	Water	116 t			
	Electricity	(unknown)	【CO_2 emission】	(unknown)	
3. Reaction/ filtration	Seawater	100,000 t	$Mg(OH)_2$	312 t	- It is assumed that Mg concentration in seawater is 0.13wt%.
	(content of Mg)	(130.0 t)	(content of Mg)	(123.5 t)	
	$Ca(OH)_2$	475 t	$CaCl_2$ solution	100,164 t	- All Mg is assumed to be present as $MgCl_2$. - The recovery rate of Mg is assumed to be 95%.
	Electricity	(unknown)	【CO_2 emission】	(unknown)	- It is assumed that the amount of $Ca(OH)_2$ is 20% excess compared to the theoretical value.
4. Neutralization	$Mg(OH)_2$	312 t	$MgCl_2$	3,225 t	- $MgCl_2$ concentration: 1.5wt%
	(content of Mg)	(123.5 t)	(content of Mg)	(123.5 t)	- The loss of Mg is assumed to be zero.
	HCl solution	2,913 t			- The environmental load for the production of HCl is considered (as a new addition excluding HCl recovered in 7.)
	Electricity	(unknown)	【CO_2 emission】	2.3 t	
	【Production of hydrochloric acid】	28 GJ	(Production of hydrochloric acid)	(2.3 t)	The neutralization heat is not considered.
5. Evaporation/ Dehydration	$MgCl_2$ solution	3,225t	$MgCl_2$-1.25H_2O	604 t	- The loss of Mg is assumed to be zero.
	(content of Mg)	(123.5t)	(content of Mg)	(123.5 t)	
			Water (evaporation)	2,331 t	- Using an evaporator
			Water (dehydration)	290 t	- Using dehydrating furnace Energy is estimated as the latent heat for water evaporation (assuming use of heavy oil A)
	Fuel	5,262GJ	【CO_2 emission】	365t	
6. Molten salt electrolysis	$MgCl_2$-1.25 H_2O(content of Mg)	604t (123.5t)	Electrolytic Mg	124t	- The grade of electrolytic Mg: 99.9%
			HCl, Cl_2	360t	
	Graphite electrode	60t	Others (gas, etc.)	181t	- Electric consumption of the electrolytic furnace: 16.5-22 kWh/kg-electrolytic Mg (here assumed to be 20 kWh)
	Electricity	23,362GJ	【CO_2 emission】	1.076t	- All consumed graphite is assumed to be emitted as CO_2.
7. Recovery of hydrochloric acid	HCl, Cl_2	360t	HCl	(unknown amount)	- Removal of Cl_2.
			Cl_2	(unknown amount)	
	Electricity	(unknown)	【CO_2 emission】	(unknown	
Total	【Energy】	31,221GJ	【CO_2 emission】	1,903t	
	(Production of raw material)	(28GJ)	(Production of raw material)	(2.3t)	

Data source: produced NIR using various data.

Reference: New Data Book for Metals, 2000

Japan Machinery Federation and the Japan Research and Development Center for Metals

Research and Survey Report on the Use of LCA Technique in Japan Materials Industry (March, 1996)

(4) Titanium (Ti)

1) Overview of smelting

a. Smelting method

The main raw materials used for metallic Ti (sponge titanium) are natural rutile mineral (TiO_2 as the main component) and synthetic rutile. Synthetic rutile is produced by artificial concentration of TiO_2, or addition of titanium slugs to the starting material.

The large-scale production of metallic titanium was made possible by the Kroll process involving Mg reduction, which is widely used currently.

Production of titanium oxide uses ilmenite mineral (main component $FeTiO_3$) as the main raw material.

Smelting method	Starting materials	Status	Smelting method adopted in the present report
Na Method (Hunter Method)	Rutile, Carbon, Slug	Being replaced by the Kroll process	×
Mg Reduction Method (Kroll Process)	Rutile (Synthetic rutile), Carbon	Current main smelting process (used in USA, CIS, China, Japan, etc.)	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of sponge titanium as final products	
Aeronautic-aerospace applications	Jet engine parts, mechanical parts, rockets and artificial satellites parts
Chemical-petrochemical applications	Materials for processing equipment (heat exchangers, reaction tanks, reaction towers, evaporator towers, etc.)
Electricity-water production	Electrothermic pipes for nuclear power, steam power, geothermal power generation plants, water recycling equipment, etc.
Ocean-energy applications	Exploration parts of oil and gas, materials for processing equipment for oil and LNG refining.
Construction-public works	Roofs, building exteriors, metallic parts, etc.
Transportation equipment	Parts for automobiles, etc.
Consumer goods	Communication and optic equipment (magnetic disc, etc.), medical materials, etc.

Data source: from Data Book for Metals, 2000

2) Integration status of data such as mass balance

The amounts of material/energy are those per refined metallic sodium of 1,000 kg.

Process	Used data		Untaken data
	Data obtained from literature etc.	Data assumed and estimated in this report	
1. Chlorination	【INPUT】 - TiO_2 grade in raw material: 90-96% 【OUTPUT】 - $TiCl_4$ grade: 98% 【Facility data】 - Use of fluidization furnace for chlorination - availability factor: 40.4% (1992) - Reaction temperature: 1,000°C	【INPUT】 - Production energy of chlorine is estimated only for newly added chlorine except for the recovered amount of chlorine. - Theoretical amount of coke used was estimated based on the reaction formula. 【OUTPUT】 - Ti yield is assumed to be 90%. - CO_2 emission is estimated from coke combustion.	【INPUT】 - Consumed amount of coke - Energy supplied other than coke 【OUTPUT】 - Yield of $TiCl_4$
2. Distillation	【OUTPUT】 - Refined $TiCl_4$ grade: 99.9% 【Facility data】 - 30 steps - Processing capacity: Max: 72,000 t/year	【OUTPUT】 - Yield of refined $TiCl_4$ is assumed to be 95%.	【OUTPUT】 - Yield of refined $TiCl_4$ 【Facility data】 - Specifications for power, processing capacity, etc. - Operation conditions - Type and consumption of energy supplied
3. Magnesium reduction	【OUTPUT】 - The grade of sponge titanium: 99.92-99.99% - The yield of sponge titanium 【Facility data】 - Reduction/separation process in a furnace - Rate of operation: 39.5% (1992) - Heating at 1,000°C - Electricity consumption: 3,000 kwh/t-Ti sponge - 1 batch of 10 t: 180 hours - Processing capacity: Max. 380 t/year-furnace	【OUTPUT】 - The grade of sponge Ti is assumed to be 99.93%.	【OUTPUT】 - Yield of Ti sponge
4. Refining	【Facility data】 - Use of a vacuum arc melting furnace with consumable electrode - Electricity consumption: 2,000 kwh/t-Ti sponge	【OUTPUT】 - It is assumed that only impurities are removed, and there is no Ti loss.	【OUTPUT】 - Yield of Ti ingot - Grade of ingot
5. Magnesium electrolysis	【OUTPUT】 - Amounts of chlorine and Mg losses 【Facility data】 - 40 furnaces used - Electricity consumption: 12,000 kwh/t-Ti sponge		

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.

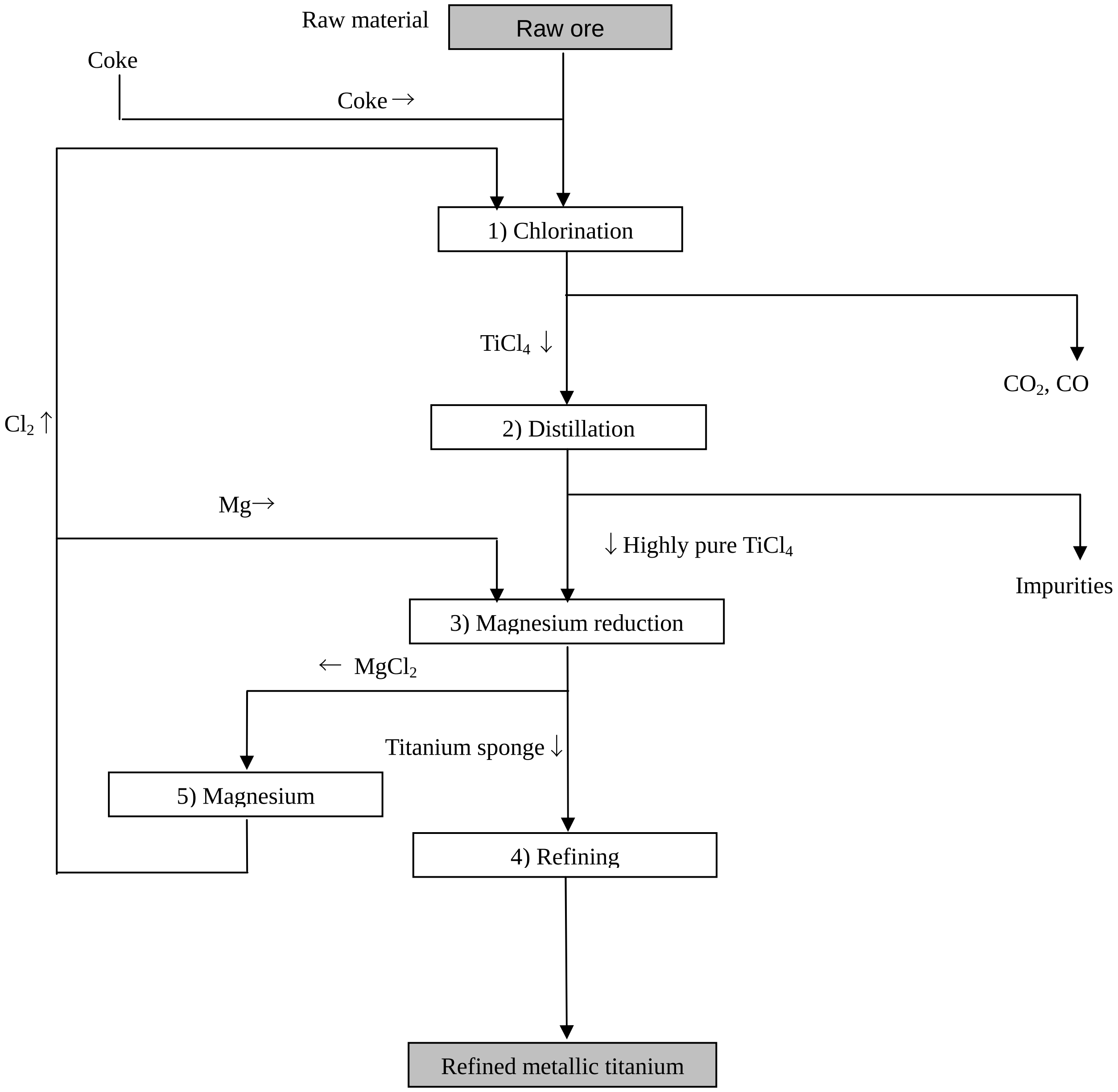
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.

【FACILITY DATA】:Data for equipment used in processes concerned.

The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: A. Moriya et al., “Titanium Production in Sumitomo Sitix Ltd.,” Shigen-to-Sozai 109 (1993), No. 12, p.1064

Mass balance data

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Chlorination	Raw ore	1,032 t	$TiCl_4$	2,129 t	- Raw ore: rutile, synthetic rutile
	(Content of Ti)	(585 t)	(Content of Ti)	(526 t)	- The yield of Ti is assumed to be 90%.
	Coke	165 t	CO_2	385 t	- Operation rate: 40.4% (1992)
	Cl_2	1,592 t	CO	141 t	- The grade of TiO_2 in raw material: 90-96%
					- The grade of TiO_4: 98%
					- Reaction at approximately 1,000°C
					- Max: 60,000 t-$TiCl_4$/year
	Coke	4,985 GJ	【CO_2 emission】	514 t	- Only energy supplied for chlorine production is considered, except for those of chlorine recovered.
	【Production of chlorine】	1,580 GJ	(Production of chlorine)	(129 t)	- Including CO_2 emission from coke.
2. Distillation	$TiCl_4$	2,129 t	High purity $TiCl_4$	1,982 t	- The grade of $TiCl_4$: 99.9%
	(Content of Ti)	(554 t)	(Content of Ti)	(500 t)	- Yield: 95%
	Other additives	+α	Impurities	146 t +	
					- Distillation tower: 30 steps, Max: 72,000 t/year
	(Other additives) Mineral oil				
	Electricity	(unknown)	【CO_2 emission】	(unknown)	
3. Magnesium reduction	High purity $TiCl_4$	1,982 t	Titanium sponge	**500 t**	- Reduction/separation process in a furnace is used.
	(Content of Ti)	(500 t)	(content of Ti)	(500 t)	
	Mg	761 t	$MgCl_2$	1,940 t	- Operation rate: 39.5% (1992)
			Cl_2	37 t	- The grade of Ti: 99.92-99.99%
			Mg (non reacted)	266 t	- Separation by vacuum distillation
					- Heating at 1,000°C
					- Electricity consumption: 3,000 kwh/t-Ti sponge
					- 1 batch of 10 t: 180 hours
	Electricity	14,173 GJ	【CO_2 emission】	518 t	- Max: 380 t/year-furnace
4. Refining	Titanium sponge	**500 t**	Titanium ingot	500 t	- The method of vacuum arc remelting with consumable electrode
	(Content of Ti)	(500 t)	Residual impurities	0.4 t +	- It is assumed that only impurities are removed and that there is no Ti loss.
	Other additives	+α			
	(Other additives) Scrap in the process				
	Electricity	9,449 GJ	【CO_2 emission】	345 t	- Electricity consumption: 2,000 kwh/t-Ti sponge
5. Magnesium electrolysis	$MgCl_2$	1,940 t	Mg	756 t	- Mg: reusing for reduction
	Cl_2	37 t	Cl_2	1,387 t	- Cl_2: for streaming chlorination furnace
	Mg (non reacted)	266 t	Mg loss	**5 t**	- Constituting more than 70% of all electricity consumption during the refining process for Ti sponge production.
			Cl_2 loss	**125 t**	
	Electricity	56,693 GJ	【CO_2 emission】	2,072t	- Electricity consumption for 40 furnaces: 12,000 kwh/t-Ti sponge
Total	【Energy】	86,880 GJ	【CO_2 emission】	3,450 t	
	(Production of raw material)	(1,580 GJ)	(Production of raw material)	(129 t)	

Data source: produced by NRI using various data.

Reference: A. Moriya et al., “Titanium Production in Sumitomo Sitix Co., Ltd.,” Shigen-to-Sozai 109 (1993), No. 12, p.1064

H. Fukuyama et al., “Production of Sponge Titanium and Ingot in Toho Titanium Co., Ltd.,” Shigen-to-Sozai 109 (1993), No. 12, p.1057

(5) Chromium (Cr)

1) Overview of smelting

a. Smelting method

The main raw materials are chromium ore etc. Metallic chromium is not found in nature.

Smelting methods are classified into two kinds: the aluminum reduction method (dry method) and the electrolytic method (wet method), which are most widely used for industrial production.

The aluminum reduction method utilizes the thermite reaction, and the purity of the metallic chromium obtained is in the range of approximately 97 to 99%.

The electrolytic method makes it possible to produce highly pure chromium, which cannot be obtained through the dry method.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Aluminum reduction method (dry method)	Chromium mineral (chromite)	Nihon Denko (Japan), Delachaux (France), London & Scandinavian Metallurgical (England)	×
Silicon reduction method (dry method)	Chromium mineral (chromite)	Currently not used at industrial level	×
Carbon reduction method (dry method)	Chromium mineral (chromite)	Currently not used at industrial level	×
Sulfuric acid electrolysis method (wet method)	Chromium mineral (chromite)	Elkem Metals (USA), *acquired by Eramet (France)	○
Chromic acid electrolysis method (wet method)	Chromium mineral (chromite)	Unknown	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final products	
Super alloys	Aircraft, atomic energy equipment, turbines, engine parts, etc.
Non-ferrous alloys	Automobile parts, aircraft components, structural components, etc.
Welding rod	Chemical plants, etc.
Target materials	Hard disc, liquid crystal, etc.
Others	Dyes, pigments, adhesives, magnetic heads, etc.

Data source: from Data Book for Metals, 2000, and the website of the Metal Mining Agency of Japan

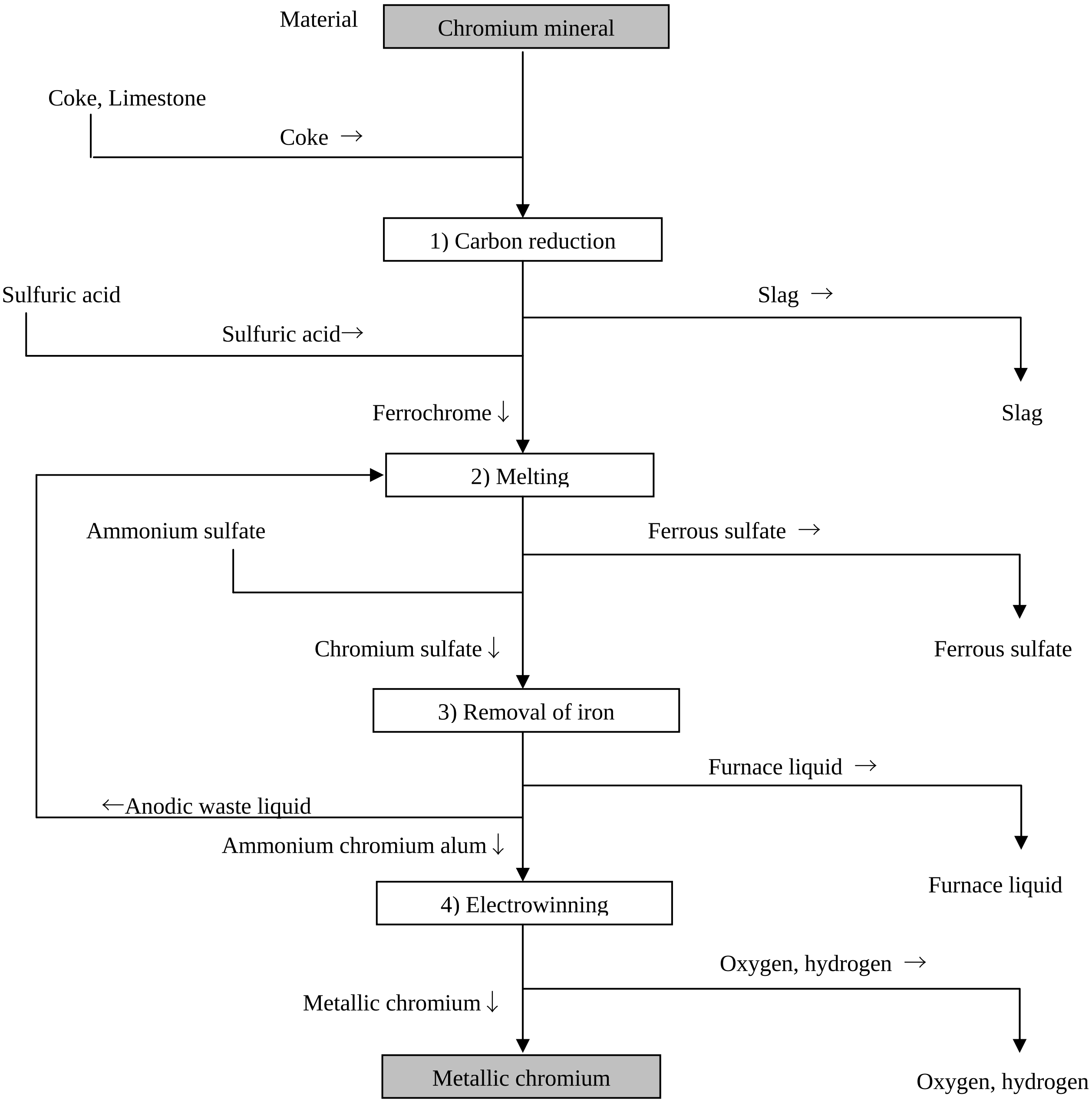
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1. Carbon reduction	〔INPUT〕 - Cr_2O_3 grade in chromium mineral: 68% 〔OUTPUT〕 - Cr grade in ferrochrome: 68.5% 〔Facility data〕 - Electric furnace	〔INPUT〕 - For cokes supplied, only the amount contributing to the reaction (a theoretical value) is taken up. - A fixed carbon content in coke is assumed to be 80%. 〔OUTPUT〕 - The yield of Cr is assumed to be 90%. - CO_2 emission during coke reduction is estimated. (Complete combustion is assumed.)	〔INPUT〕 - Supplied amount of coke 〔OUTPUT〕 - The yield of ferrochromium 〔Facility data〕 - Specifications for power, processing capacity, etc. - Operation conditions
2. Melting	〔Facility data〕 - Melting is carried out at over 100°C. - Stirrer and ball mill are used.	〔INPUT〕 - Sulfuric acid supplied is estimated as pure consumption excluding the circulating amount. (Wet smelting of copper was used as reference for material balance). - Energy consumption was estimated for production of sulfuric acid. 〔OUTPUT〕 - It is assumed that Cr is completely separated. - The amount of CO_2 released is estimated on production of the sulfuric acid used for melting. 〔Facility data〕 - It is assumed that A stirrer (rated power 2.2 kW) and A ball mill (150 kW) are used. - A stirrer and a ball mill are assumed to run for 10 days (24 hours/day) based on the processing amount.	〔INPUT〕 - Supplied and circulated amounts of sulfuric acid, and its concentration - Reused amount of waste solution obtained from the electrowinning process. 〔OUTPUT〕 - Amount of solution after dissolution - Cr concentration in solution after dissolution - The extracted rate of Cr 〔Facility data〕 - Specifications for power, processing capacity, etc. - Operation conditions
3. Removal of iron		〔INPUT〕 - Only the amount of ammonium sulfate contributing to the reaction (a theoretical value) is estimated. 〔OUTPUT〕 - It is assumed that Cr is completely separated.	〔INPUT〕 - Supplied amount of solution and Cr concentration - Supplied amount of ammonium sulfate and energy consumption for production 〔OUTPUT〕 - Amount of residual solution after removing iron, and Cr concentration - The yield of Cr - Amount of CO_2 emitted during producing ammonium sulfate supplied 〔Facility data〕 - Type of used equipment - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy
4. Electrolytic winning	〔OUTPUT〕 - Metallic Cr grade: 99.47% 〔Facility data〕 - Required electric power: 18,500 kWh/t-metallic Cr - Electrolysis time: 72 hours	〔OUTPUT〕 - The yield of Cr is assumed to be 85% for all smelting processes after carbon reduction.	〔INPUT〕 - Supplied amount of solution in electrowinning 〔OUTPUT〕 - Amount of anodic waste liquid reused for dissolving process - Amount of consumed solution - The yield of Cr on electrowinning

Note: 〔INPUT〕:The amounts of materials, energy etc. supplied into processes concerned.
〔OUTPUT〕:The amounts of substances produced and emitted in processes concerned.
〔Facility data〕:Data for equipment used in processes concerned.
The data indicated by 〔INPUT〕, 〔OUTPUT〕, and 〔Facility data〕 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Masatoshi Sugimori, “Electrowinning of Metallic Chromium,” Special Metals and Smelting Technology for High-Technological Industry, Kagaku-to-Kogyo Co., Ltd.

Mass balance data

The amounts of material/energy are those per raw ore of 100 t.

Process	INPUT		OUTPUT		Remarks
	Supplied materials, etc.	Supplied amounts	Products	Amounts of products	
1. Carbon reduction	Chromium mineral	100.0 t	Ferrochrome	61.1 t	- Cr_2O_3 grade in chromium ore: 68%
	(content of Cr)	(46.5 t)	(content of Cr)	(41.9 t)	- Cr grade in ferrochrome: 68.5%
	Coke	16.1 t	Slag	42.1 t+	- For coke, only the amount contributed to the reaction is taken into account.
	Other additives	+α			- It is assumed that all carbons in coke are released as CO_2
	(Other additives)				- Yield of Cr is assumed to be 90%.
	Limestone				
					- Use of electric furnace
					- It is assumed that fixed carbon content in coke is 80%.
	Coke	485 GJ			- CO_2 emission during coke reduction is considered.
	Electricity	(Unknown)	【CO_2 emission】	47.2 t	
2.Melting	Ferro-chrome	61.1 t	Solution	72.0 t-dry +	- Solution contains chromium sulfate and ferrous sulfate.
	(content of Cr)	(41.9 t)	(content of Cr)	(41.9 t)	
	Anodic waste liquid	9.17 t	Residue	3.67 t	- It is assumed that Cr is completely separated.
	Sulfuric acid	2.90 kL* (5.3 t)			- Solution is prepared to remove non-metallic substance.
	Other additives	+α			- Solubilizing at over 100°C.
					- Use a stirrer (assumed power 2.2 kW)
	(Other additives)				- Use a ball mill (assumed power 150 kW)
	Chrome alum mother liquid				- Operation time is assumed as 10 days (24 hours/day).
					- For production of sulfuric acid, only consumption except for circulating amount is taken up (copper smelting data used as reference).
	Electricity	345 GJ	【CO_2 emission】	12.6 t	
	【Production of sulfuric acid】	0.03 GJ*	(Content of sulfuric acid Production)	0.002 t*	
3. Removal of iron	Solution	72.0 t-dry	Ammonium chromium alum	74.9 t	- It is assumed that Cr is completely separated.
	(content of Cr)	(41.9 t)	(content of Cr)	(41.9 t)	
	Ammonium sulfate	3.00 kL (5.31 t)	Residue in solution	2.36 t-dry	- For ammonium sulfate, only the amount contributed to the reaction is taken into account.
	Electricity	(unknown)	【CO_2 emission】	(Unknown)	
4. Electrolytic winning	Ammonium chrome alum	74.9 t	Metallic chromium	39.8 t	- The grade of metallic Cr is 99.47%. - The yield of Cr from the smelting process is assumed to be 85%.
	(content of Cr)	(41.9 t)	(content of Cr)	(39.5 t)	
			Hydrogen	1.5 t	- Anodic waste liquid is reused into solutbilization process
			Oxygen	24.5 t	
			Anodic waste liquid	9.17 t	- Required electric power: 18,500kWh/t-metallic chromium
	Electricity	6,913 GJ	【CO_2 emission】	253 t	- Electrolysis time: 72 hours
Total	【Energy】	7,743GJ	【CO_2 emission】	313t	
	(Production of raw material)	(0.03 GJ*)	(Production of raw material)	(0.002 t*)	

Data source: produced by NRI using various data.

Reference: Masatoshi Sugimori, Electrowinning of Metallic Chromium," Special Metals and Smelting Technology for High-Technological Industry, Kagaku-to-Kogyo Co., Ltd.

(6) Manganese (Mn)

1) Overview of smelting

a. Smelting method

The main mineral resources for metallic manganese are manganese oxide ore, rhodochrosite, and manganese silicate ore, and manganese oxide ore is the most commonly used.

Most of the smelting is carried out by electrolysis (wet method). The thermite reaction (aluminum reduction) method and the electric furnace smelting method are also used.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Electrolytic method (wet method)	Manganese oxide ore	Elkem Metals (USA), Kerr Mcgee (USA), Manganese Metal (South Africa). Russia, Chinese and other companies	○
Electric furnace method (dry method)	Manganese ore (Manganese oxide ore, etc.)	Unknown	×
Thermite/aluminum reduction method (dry method)	Manganese oxide ore	Unknown	×

Data source: from Databook for Metals, 2000

b. Status of domestic utilization

Main applications of final products	Notes
Additive for special steel (large diameter pipes, steels for thick sheets, etc.)	Domestic consumption in 1998 was 19,700 t. This is the most common application of metallic manganese
Additive for aluminum and non ferrous alloys	—
Welding rods	—
Chemical uses	—
Others	—

Data source: from Data Book for Metals, 2000.

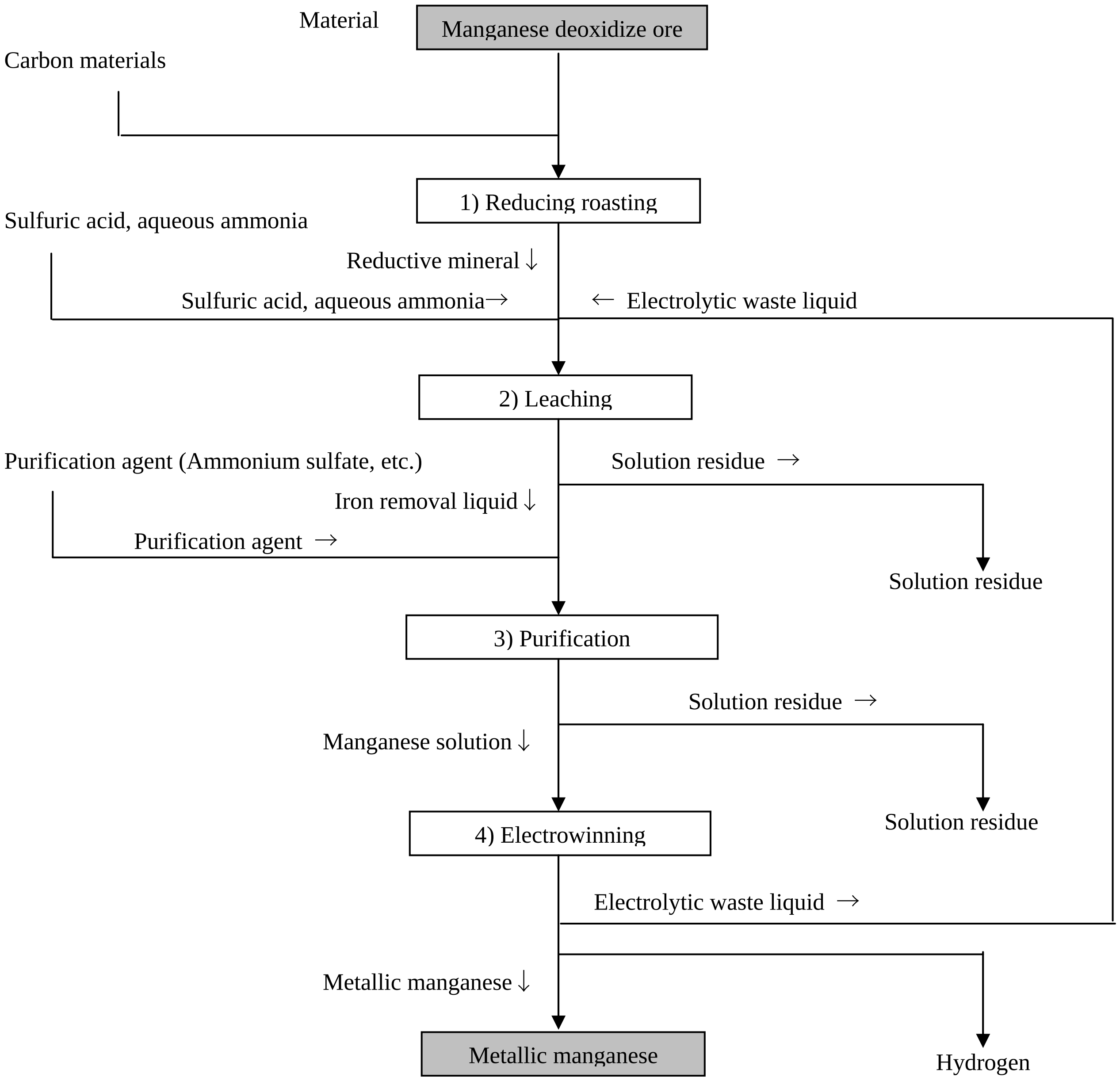
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature etc.	Data assumed and estimated in this report	
1. Reducing roasting	【INPUT】 - The grade of MnO_2 mineral: 48.85% - Use of reduction furnace and roller mill	【INPUT】 - For cokes supplied, only the amount contributing to the reaction (a theoretical value) is taken up. - Fixed carbon content in coke is assumed to be 80%. 【OUTPUT】 - The yield of Mn is assumed to be 90%. - CO_2 emission during coke burning is estimated.	【INPUT】 - Supplied amount of coke 【OUTPUT】 - The yield of Mn - The grade of Mn in a reductive ore. 【FACILITY DATA】 - Specifications for power, processing capacity, etc. - Operation conditions - Type and consumption of energy supplied
2. Leaching		【OUTPUT】 - The yield of Mn is assumed to be 99%. - It is assumed that only iron is removed. 【FACILITY DATA】 - It is assumed that a stirrer (rated power 2.2 kW) is used. - It is assumed that a filter press is used. - For a filter press, a filter press (rated power 150 kW) is used. - The equipment is assumed to run for 25 days/month (24 hours/day).	【INPUT】 - The quantity of leaching liquid after leaching 【OUTPUT】 - The solution concentration after leaching - The yield of Mn 【FACILITY DATA】 - Type of equipment used - Specifications for power, processing capacity, etc. - Operation conditions - Type and consumption of energy required for heating leaching liquid
3. Purification		【OUTPUT】 - The yield of Mn is assumed to be 99%. - It is assumed that elements to be separated are Zn, Ni, Co, As, and Mo. 【Facility data】 - It is assumed that a stirrer (rated power 2.2 kW) and a filter press (0.4 kW) are used. - The equipment is assumed to run for 10 days/month (24 hours/day).	【OUTPUT】 - The concentration of Mn solution after purification - The yield of Mn 【Facility data】 - Type of used equipment - Specifications for power, processing capacity, etc. - Operation conditions
4. Electrolytic winning (Use of diaphragm)	【OUTPUT】 - The grade of metallic Mn: 99.96% - Monthly production 【Facility data】 - Electric power efficiency: 60-63 % - Electrolysis time: 72-96 hours - Electric consumption for electrolysis: 8,000 kWh/t-electrolyte Mn	【OUTPUT】 - The returning amount of electrolytic waste liquid into the leaching process is estimated based on electrolysis data in chromium smelting.	【INPUT】 - Energy required for heating during electrolysis 【OUTPUT】 - The yield of Mn - The returning amount of electrolytic waste liquid into the leaching process

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.
【Facility data】:Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Hiroshi Tsukuta, "Production of Electrolytic Metallic Manganese in Chuo Denki Kogyo," Shigen-to-Sozai, 109 (1993) No. 12 p. 1091-

Mass balance data

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials, etc.	Supplied amounts	Products	Amounts of products	
1. Reducing roasting	MnO$_2$ ore	802 t	Reductive ore	530 t	- The grade of MnO$_2$ mineral: 48.85% - The yield of Mn in a total smelting process is assumed to be 85%. - The yield of Mn is assumed to be 90%. - For carbon materials, only the amount contributed to the reaction is taken into account. - It is assumed that all carbons contributed to the reaction are released as CO$_2$ - Reducing furnace and roller mill are used. - CO$_2$ emission during coke burning is considered.
	(content of Mn)	(392 t)	(content of Mn)	(353 t)	
	Carbon materials (Coke)	108 t	Slag	294 t	
	Coke	3,260 GJ			
	Electricity	(Unknown)			
	Fuel	(Unknown)	【CO$_2$ emission】	317 t	
2.Leachting	Reductive ore	530 t	Iron removal liquid	572 t	- The yield of Mn is assumed to be 99%. - It is assumed that only iron is removed. - Sulfuric acid and aqueous ammonia are used to supply required amount of electrolytic waste liquid. - Slime formed at the anode during electrowinning or dioxide manganese ore are used as oxidizing agents - It is assumed that there is no loss of electrolytic waste liquid - It is assumed that A stirrer (rated power 2.2 kW) and filter press (0.4kW) are used. - Operation time is assumed as 25 days/month (24 hours/day).
	(content of Mn)	(353 t)	(content of Mn)	(349 t)	
	Electrolytic waste liquid	73 t 2.90 kL*	Residue in solution	31 t+	
	Other additives	+α			
	(Other additives) Sulfuric acid Aqueous ammonia Oxidizing agent				
	Electricity	14.7 GJ	【CO$_2$ emission】	0.54 t	
3. Purification	Iron removal liquid	572 t	Manganese solution	572 t	- Ammonium sulfide and others are used as purification agent. - The yield of Mn is assumed to be 99%. - It is assumed that elements to be separated are Zn, Ni, Co, As, and Mo. - It is assumed that a stirrer with power of 2.2kW is used. - It is assumed that a filter press with power of 0.4kW is used. - Operation time is assumed as 10 days/month (24 hours/day).
	(content of Mn)	(349 t)	(content of Mn)	(346 t)	
	Purification agent	+α	Residue on purification	0.2 t+	
	Electricity	5.9 GJ	【CO$_2$ emission】	0.22 t	
4. Electrolytic winning (Use of diaphragm)	Manganese solution	572 t	Metallic manganese	**333 t**	- The grade of metallic Mn is 99.96%. - Electrolytic waste liquid goes to permeation process (2). - It is estimated based on the material balance during electrowinning for chromium smelting. - It is assumed that all electricity losses are contributed to hydrogen reaction - Electricity efficiency: 60-63% - A part of the hydrogen is adsorbed into metallic Mn. - Electrolysis time: 72-96 hours - Electricity consumption for electrolysis: 8,000 kWh/t-Electrolyte Mn.
	(content of Mn)	(346 t)	(content of Mn)	(333 t)	
			- Electrolytic waste liquid	73 t	
			- Hydrogen	8 t	
			- Oxygen	158 t	
	Electricity	25,197 GJ	【CO$_2$ emission】	921 t	
Total	【Energy】	25,338GJ	【CO$_2$ emission】	934 t	

Data source: produced by NRI using various data.

Reference: Hiroshi Tsukuta, “Production of Electrolytic Metallic Manganese in Chuo Denki Kogyo,” Shigen-to-Sozai, 109 (1993) No. 12 p. 1091-

Hitoshi Shigemura et al., “Electrolytic Refining of Nickel,” Special Metals and Smelting Technology for High-Technological Industry, 58-, Kagaku-to-Kogyo Co., Ltd.

(7) Cobalt (Co)

1) Overview of smelting

a. Smelting method

Raw materials for cobalt are mainly copper-cobalt sulfide or oxide ores, cobalt-containing pyrite, and cobalt sediments obtained as a by-product during the refining of nickel.

Smelting of copper-cobalt sulfide ore produces cobalt together with copper. Major producing countries such as Congo and Zambia make one third of cobalt production in the world.

Cobalt production from cobalt sediments resulting from nickel smelting is carried out by corporations such as Sumitomo Metal Mining, whose produced amount corresponds to about a half of the world's cobalt production.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Sulfatizing roasting method (simultaneous with copper mining)	Copper-cobalt sulfide ore	ZCCM (Zambia)	×
Electrolysis method of oxide ore (simultaneous with copper mining)	Copper-cobalt oxide ore	Gecamines (Congo)	×
Solvent extraction/Electrolytic winning (simultaneous with nickel mining)	Impurities on nickel smelting	Sumitomo Metal Mining (Japan)	○
Pressurized leaching smelting method	Laterite ore	West Australia companies, etc.	×
(Unknown)	Cobalt-containing pyrite	OMG (Finland)	×
Oxidizing roasting method	Arsenite ore	INCO (Canada)	×
Bio-chilling method	Cobalt-containing iron sulfide	Kasese (Uganda)	×

Data source: Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final metallic cobalt products	products	Domestic amount demanded (year 1998)
Special steels	High-speed steel, tools, parts for machine tools, aircraft engine parts, gas turbine parts, etc.	682 Mt
Magnetic materials	Permanent magnet, TV, acoustic materials, magnetic discs, etc.	334 Mt
Ultra-hard tools	Cutting tools, anti-abrasive tools, etc.	344 Mt
Catalyst	-	214 Mt
Pipe/plate/rod/wire	-	425 Mt
Others	Pigments, under-coating for enamel, etc.	420 Mt

Data source: Data Book for Metals, 2000, Website of the Metal Mining Agency of Japan.

2) Integration status of data such as mass balance

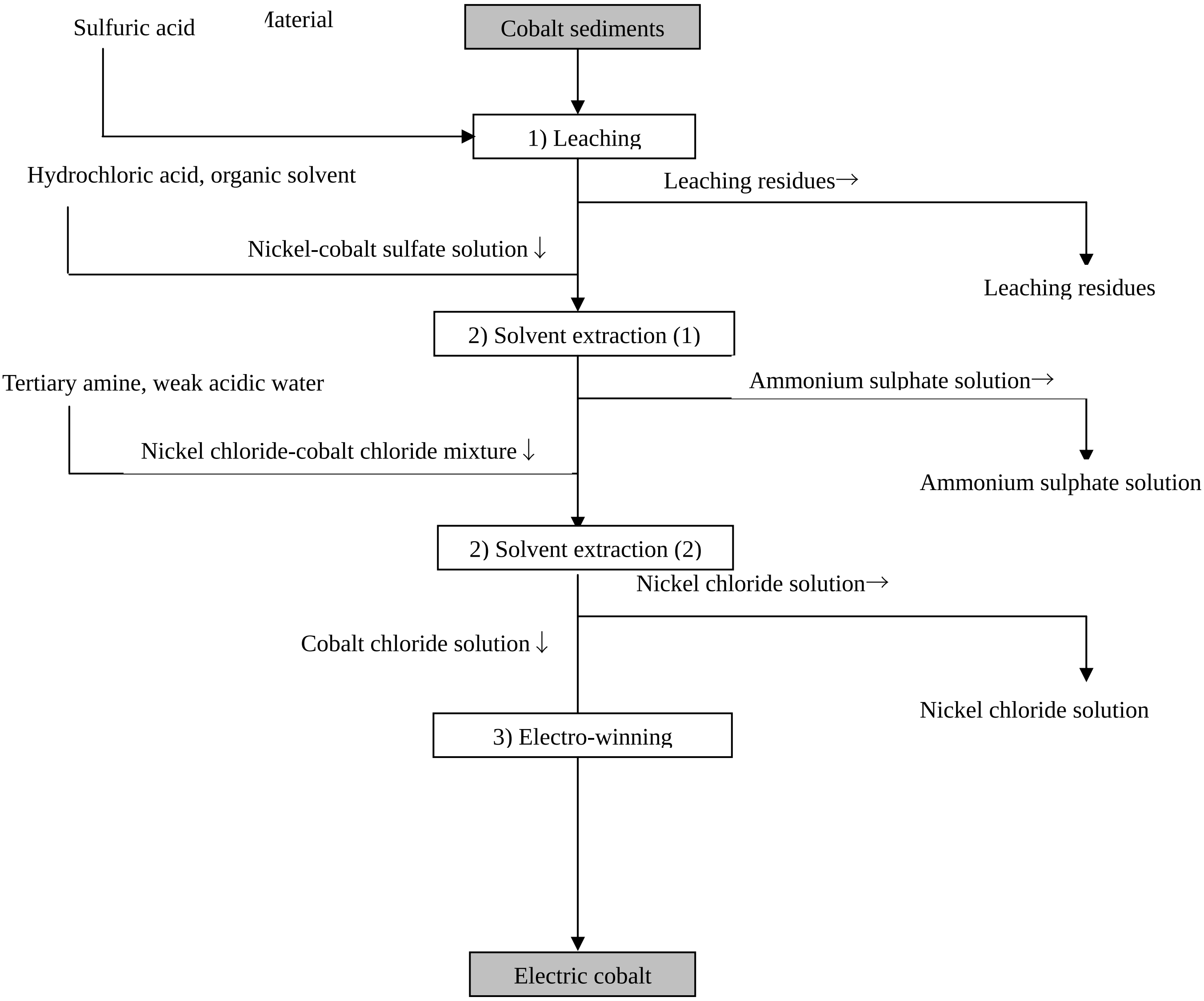
Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1. Leaching	【INPUT】 - Co sediments Ni grade: 29.3% Co grade: 6.5%	【INPUT】 - For sulfuric acid supplied, only a net consumption is estimated excluding the recycling amount. (The wet smelting of copper is used as reference for mass balance.) - Energy consumption is estimated for production of sulfuric acid. 【OUTPUT】 - The amount of CO_2 released during production of the consumed sulfuric acid is estimated. 【Facility data】 - It is assumed that A stirrer (rated power 2.2 kW) and Eight press filters (0.4kW) are used. - The equipments are assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount, recycling amount, and concentration of sulfuric acid 【OUTPUT】 - The recovery rate of Co - Amount of the leaching solution - The Co concentration in the leaching solution - Amount of leaching residues 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of energy required for heating of the leaching solution
2. Solvent extraction (1), (2)		【INPUT】 - For hydrochloric acid and aqueous ammonia supplied, only a net consumption is estimated excluding the recycling amount. (The wet smelting of copper is used as reference for mass balance.) - Energy consumption is estimated for production of sulfuric acid and aqueous ammonia. 【OUTPUT】 - It is assumed that cobalt is completely separated. - The amount of CO_2 released during production of the consumed sulfuric acid and aqueous ammonia is estimated. 【Facility data】 - Two stirrers are assumed to be used (rated power 2.2 kW). - The equipments are assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount, recycled amount, and concentration of hydrochloric acid and aqueous ammonia 【OUTPUT】 - The recovery rate of Co - Amount of the extract (cobalt chloride solution) - Co concentration in the extract - Amount of the extracted residues. - Co concentration in the extracted residues - Amount of the extract used for Co electrowinning 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating of the extract
3. Electrolytic winning	【OUTPUT】 - Electric Co grade: 99.92% - Monthly production of electric Co 【Facility data】 - Electric power consumption for electrolysis: 3,400 kWh/t-electrolytic Co	【OUTPUT】 - The yield of Co is assumed to be 99%.	【OUTPUT】 - The recovery rate of Co - Amount of residues after electrolysis and Co concentration

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.
【Facility data】:Data for equipment used in processes concerned.

The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Source: Yukio Ishikawa, Nickel and Cobalt Smelting at Besshi Plant (Sumitomo Metal and Mining), Sigen to Sozai 109 (1993), No.12, pp 1072-1076

Mass balance data

The amounts of material/energy are those per month.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Leaching	Cobalt sediments	209.4 t	Leaching solution	82.9 kL	- Ni grade in cobalt sediments: 29.3%
	(content of Co)	(13.6 t)	(content of extracts)	(86 t+)	- Co grade: 6.5%
	Sulfuric acid	82.9 kL	(content of Co)	(12.5 t)	
		(152.5 t)	Leaching residues	276 t-dry+	- Eight press filters (rated power 0.4 kW) and one stirrer (2.2 kW) are assumed to be used.
	Other additives	+α			- The equipment is assumed to run for 25 days/month (24 hours/day).
	(Other additives) Hydrogen sulfide Caustic soda				- Hydrogen sulfide: copper-removing agent - Caustic soda: iron-removing agent
	Electric power	30.6 GJ	[CO_2 emission]	1.2 t	- For sulfuric acid production, electric consumption is estimated for only newly supplied amount excluding those for recycling amount.
	[Production of sulfuric acid]	0.9 GJ*	(production of sulfuric acid)	(0.07 t*)	
2) Solvent extraction (1), (2)	Leaching solution	82.9 kL	Cobalt chloride	22.9 t-dry+	- A part of the cobalt chloride solution is used for smelting of cobalt oxide.
	(content of extracts)	(86 t+)	(including Co)	(12.5 t)	
	(content of Co)	(12.5 t)			- It is assumed that Co is completely extracted.
	Aqueous ammonia	115.9 kL	Extraction residues	235.7 kL	
		(108.3t)	(including nickel chloride)	(31.8 t+)	- For hydrochloric acid and ammonia, amounts required chemical reactions are estimated. (Recycled portions are not included.)
	Hydrochloric acid	36.9 kL			
		(43.9 t)	(including ammonium sulfate)	(68.6 t)	
	Other additives	+α			
	(Other additives) VA acid, tertiary amine, slightly acid water				- The mass balance is calculated from reaction equations. - 13 mixer settlers (it is assumed that two stirrers, rated power 2.2 kW, are used.)
	Electric power	24.9 GJ	[CO_2 emission]	1.7 t	- The equipments are assumed to run for 25 days/month (24 hours/day).
	[Production of hydrochloric acid]	0.6 GJ*	(including chloride production)	(0.05 t*)	- VA acid and amines are used as extracting agents.
	[Production of aqueous ammonia]	7.2 GJ*	(including aqueous ammonia production)	(0.73 t*)	- Kerosene and xylene are used for diluting of VA acid and amines respectively.
3) Electrolytic winning	Cobalt chloride	8.0 t-dry	Electric cobalt	4.3 t	- The grade of electric cobalt: 99.92%
	(content of Co)	(4.4 t)	(including Co)	(4.3 t)	- The yield of cobalt is assumed to be 99%.
			chlorine gas	3.6 t	- Chloride gas is recycled into the nickel smelting process.
			liquid residues	0.08 t-dry	
	Electric power	139 GJ	[CO_2 emission]	5.1 t	- The equipments are assumed to run for 25 days/month (24 hours/day). - Electric power consumption: 3,400 kWh/t-electrolytic Co
Total	[Energy]	203 GJ	[CO_2 emission]	8.0 t	
	(production of materials)	(8.7 GJ*)	(production of materials)	(0.8 t*)	

Data source: produced by NRI using various data.

Reference: Yukio Ishikawa, Nickel and Cobalt Smelting at Besshi Plant (Sumitomo Metal and Mining), Sigen to Sozai 109 (1993), No.12, pp.1072-1076

Nagaki Ono, Industrialization of Separation and Refining of Nickel-Cobalt Using the Solvent Extraction Method, MMIJ journal, 95 1098 (79-80, pp 441-44

Note: Aqueous ammonia in the solvent extraction process 2) is used for pH adjustment during extraction. After being collected as ammonium sulfate solution, it is reused as ammonia.

(8) Nickel (Ni)

1) Smelting Conditions

a. Smelting Method

The raw materials for metallic nickel are laterite (oxide ore) and sulfide ores, and the former has large amounts of reserves. Various wet smelting methods, such as the Nicaro method or the pressurized sulfuric acid leaching method, have been developed for laterite ore, whereas sulfide ores are mainly smelted by dry methods.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Hybinette method	Sulfide ore	INCO (Canada), Sumitomo Metal Mining (Japan), others	×
Sherritt Gordon method	Sulfide ore	WMC (Australia), others	×
Elkem method, etc.	Oxide ore (garnierite)	Morro de Nickel (Brazil), others	×
Nicaro method, etc.	Oxide ore (laterite)	Nicaro Freeport Queens Nickel ( ), others	×
Automatic smelting method/ Matte electrolysis method	Nickel sulfide mineral concentrate	–	×
MCLE method	Nickel matte	Sumitomo Metal Mining (Japan)	○
Carbonyl method	Ni-Cu mineral concentrate	INCO (Canada)	×
Pressurized sulfuric acid leaching method	Oxide ore (laterite)	Australian corporations, etc.	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final products	Products	Domestic amount demanded (year 1998)
Special steels	Aircraft machinery parts, construction materials, heat-resistant material parts, etc.	41,404 t
Magnetic materials	Speakers, motors, etc.	3,464 t
Non-ferrous alloys	Electronic and communication equipment, etc.	3,494 t
Metal plating	Steel boards for automobiles, electric appliances, bicycle parts, etc.	5,624 t
Catalyst	Oil refining, oil processing, etc.	605 t
Battery	Nickel/hydrogen cells, fuel cells, etc.	4,160 t
Others	Magnetic cards, etc.	6,643 t

Data source: from Data Book for Metals, 2000 and the web site of the Metal Mining Agency of Japan.

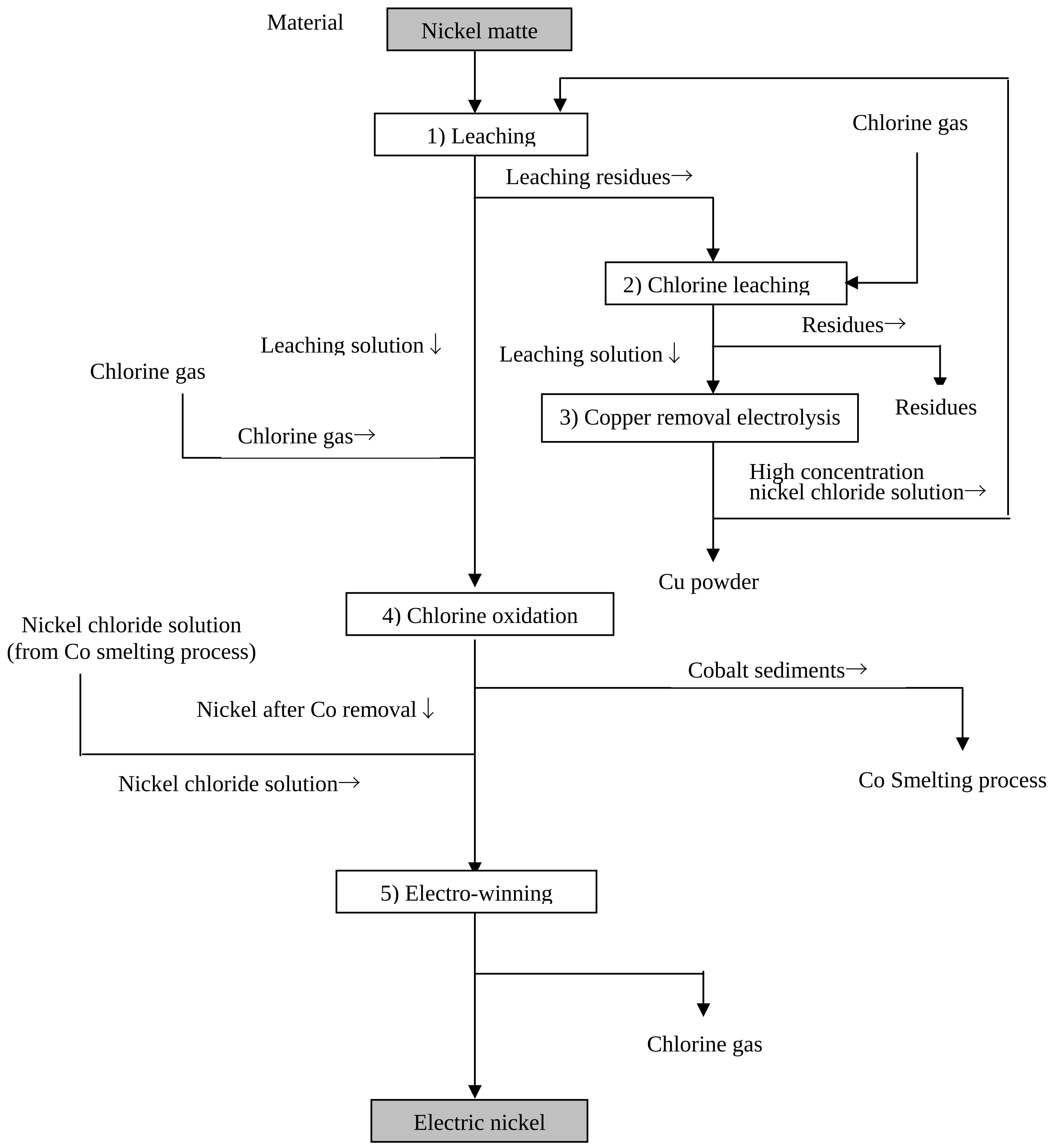
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1. Leaching	【INPUT】 - Ni grade of Ni matte: 73.6% - Monthly input of nickel matte 【OUTPUT】 - Ni content in residues: 1% 【Facility data】 - Temperature: 60°C - Retention time: 6-8 hours	【Facility data】 - It is assumed that one stirrer (rated power 5.5 kW) is used. - It is assumed that one filter press (rated power 0.4 kW) is used. - The equipment is assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount of nickel chloride solution 【OUTPUT】 - Amount of leaching solution - Amount of residues - Recovery rate of Ni 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating of the leaching solution
2. Chlorine leaching	【INPUT】 - Ni content in residues: 1% 【OUTPUT】 - Ni content in leaching solution: 50% 【Facility data】 - Temperature: 110°C - Retention time: 4-6 hours	【OUTPUT】 - Leaching rate of Ni: 99% 【Facility data】 - It is assumed that one stirrer (rated power 2.2 kW) is used. - It is assumed that one filter press (rated power 0.4 kW) is used. - The equipment is assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount of chlorine 【OUTPUT】 - Leaching rate of Ni - Amount of residues and Ni grade after leaching 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating of the leaching solution
3. Cu removal electrolysis	【OUTPUT】 - Ni content in Cu powder: 1% 【Facility data】 - Current density: 300-400 A/m^2 - Electric power consumption for electrolysis: 346 MWh/month	【OUTPUT】 - Chloride gas produced during electrolysis is not considered	【INPUT】 - Supplied amount of chlorine leaching solution 【OUTPUT】 - Amount of nickel chloride and Ni grade - Amount of Cu powder 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of energy required for heating of the electrolytic solution
4. Chlorine oxidation	【OUTPUT】 - Co content in nickel solution after cobalt removal: 0.004%	【OUTPUT】 - Ni yield is assumed to be 99%. - The process of producing hydrochloric acid from surplus chlorine gas is not considered 【Facility data】 - It is assumed that A stirrer (rated power 2.2 kW) and a filter press (0.4kW) are used. - The equipments are assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount of chlorine gas 【OUTPUT】 - Amount of nickel solution and Ni grade after Co removal - Recovery rate of Ni - Amount of Co sediments 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy
5. Electrolytic winning	【OUTPUT】 - The grade of electrolytic Ni: 99.98% 【Facility data】 - Electric power consumption for electrolysis: 2,000 kWh/t-electrolytic Ni	【OUTPUT】 - The Ni yield is assumed to be 99%.	【INPUT】 - Amount of nickel chloride solution 【OUTPUT】 - The yield of Ni - Emission amount of chlorine gas - Amount of residual liquid and Ni grade after electrolysis

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in processes concerned.
【Facility data】: Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



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Source: Yukio Ishikawa, Nickel and Cobalt Smelting at Besshi Plant (Sumitomo Metal Mining), Sigen to Sozai 109 (1993), No.12, pp. 1072-1076

Ni (Nickel)

Mass balance data

The amounts of material/energy are those per month.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Leaching	Nickel matte	2,744 t	Leachate	2,525 t-dry	- Ni grade of nickel matte: 73.6%
	(content of Ni)	(2,020 t)	(content of Ni)	(2,017 t)	- Leachate to process (4)
	Nickel chloride solution	334 t-dry	Residues	553 t+	
	Other additives	+α			- Temperature: 60°C
					- Flow time: 6-8 hours
	(other additives)				- Additives as copper removal agent
	Matte				- Use of one stirrer with power of 5.5kW is assumed.
					- Use of one press filter with power 0.4kW is assumed.
	Electric power	33 GJ	[CO_2 emission]	1.22 t	- Operation is assumed to run for 25 days/month (24 hours/day)
2) Chlorine leachihg	Residues	553 t	Chlorine leachate	547 t-dry	- Main residual compound is sulfur
	Chlorine gas	271 t	Residues	276 t	- Residual Ni grade: 1%
					- Temperature: 110°C, Ni
					- Leaching yield: 99%
					- Flow time: 4-6 hours
					- Use of one stirrer with power of 2.2 kW is assumed.
					- Use of press filter with power of 0.4kW is assumed.
	Electric power	15 GJ	[CO_2 emission]	0.54 t	- Operation is assumed to run for 25 days/month (24 hours/day)
3) Copper removal electrolysis	Chlorine leachate	547t-dry	Nickel chloride solution	334 t-dry [For leaching (1)]	- Ni content in chlorine leachate: 50%
			Cu powder	101 t	- Ni content in Cu powder: 1%
			Chlorine gas	112 t	- Electric density: 300-400 A/m2
	Electric power	3.269 GJ	[CO_2 emission]	120 t	- Electric power consumption for electrolysis: 346kWh/month
4) Chlorine oxidation	Leachate	2,525 t-dry	Nickel after Co removal	4,338 t-dry	- Ni yield of 99% is assumed.
	(content of Ni)	(2,017 t)	(content of Ni)	(1,997 t)	- Co content in pure Ni fluid: 0.004%
	Chlorine gas	2.022 t	Cobalt sediments	209 t+	
	Other additives	+α			- Cobalt sediments to Co smelting process
	(other additives)				- Hydrochloric acid produced from surplus chlorine gas
	Active Ni powder				
	Nickel carbonate				
					- It is assumed that A stirrer (rated power 2.2 kW) and a filter press (0.4kW) are used.
	Electric power	15GJ	(CO_2 emission)	0.54 t	- Operation is assumed to run for 25 days/month (24 hours/day)
5) Electrolytic winning	Nickel after Co removal	4,338 t-dry	Electric nickel	1,978 t	- Electric nickel grade: 99.98%
	(content of Ni)	(1,997 t)	(content of Ni)	(1,977 t)	- Ni yield of 99% is assumed.
	Nickel chloride	31.8 t-dry	chlorine gas	2,392 t+	- Nickel chloride solution is a residual fluid from Co smelting process
	Other additives	+α			
	(other additives)				
	Chloride bath				
	Electric power	37,370 GJ	[CO_2 emission]	1,366 t	- Electric power consumption for electrolysis: 2,000kWh/t-electrolytic Ni
Total	[Energy]	40,702 GJ	[CO_2 emission]	1,488 t	

Data source: produced by NRI using various data.

Reference: Yukio Ishikawa, Nickel and Cobalt Smelting at Besshi Plant (Sumitomo Metal and Mining), Sigen to Sozai 109 (1993), No.12, pp 1072-1076

(9) Ga (Gallium)

1) Overview of smelting

a. Smelting Method

Gallium is not present in nature as pure ore. Main raw materials for metallic gallium are derived from bauxite (Bayer fluid produced during alumina processing) or from zinc ore (residues from wet smelting). Bauxite contains between 10^{-2} and 10^{-3} % of gallium. Sphalerite contains between 10^{-2} and 10^{-3} % of gallium.

In Japan, Dowa Mining Co., Ltd. uses a selective ion exchange resin (chelate resin) to collect gallium from the zinc ore domestically produced.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Carbon dioxide gas method	Bayer fluid produced during alumina processing	Alcoa (USA), others	×
Resin adsorption method	Bayer fluid produced during alumina processing	Sumitomo Chemicals (Japan), others	×
Elkem method	Collection dust from Al electrolysis	Elkem (USA), others	×
Amalgam method	Iron scrap containing gallium (from the wet zinc smelting process)	Eagle Picher Industries, Inc. (USA), others	○
Dowa Mining improved method	Zinc ore (black ore)	Dowa Mining (Japan)	×
Chlorination method	GaAs scrap	Sumitomo Metal Mining (Japan)	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final products	Products
Semiconductors	Device materials, light emission diodes, transistors, integrated circuits, semiconductor laser, solar batteries, etc.
Optic-electronics	Electronic devices for microwave applications, etc.
Alloys	Low melting point alloys, dental alloys, super conductivity materials, etc
Others	Ski wax, etc.

Data source: from Data Book for Metals, 2000, and a website of the Metal Mining Agency of Japan.

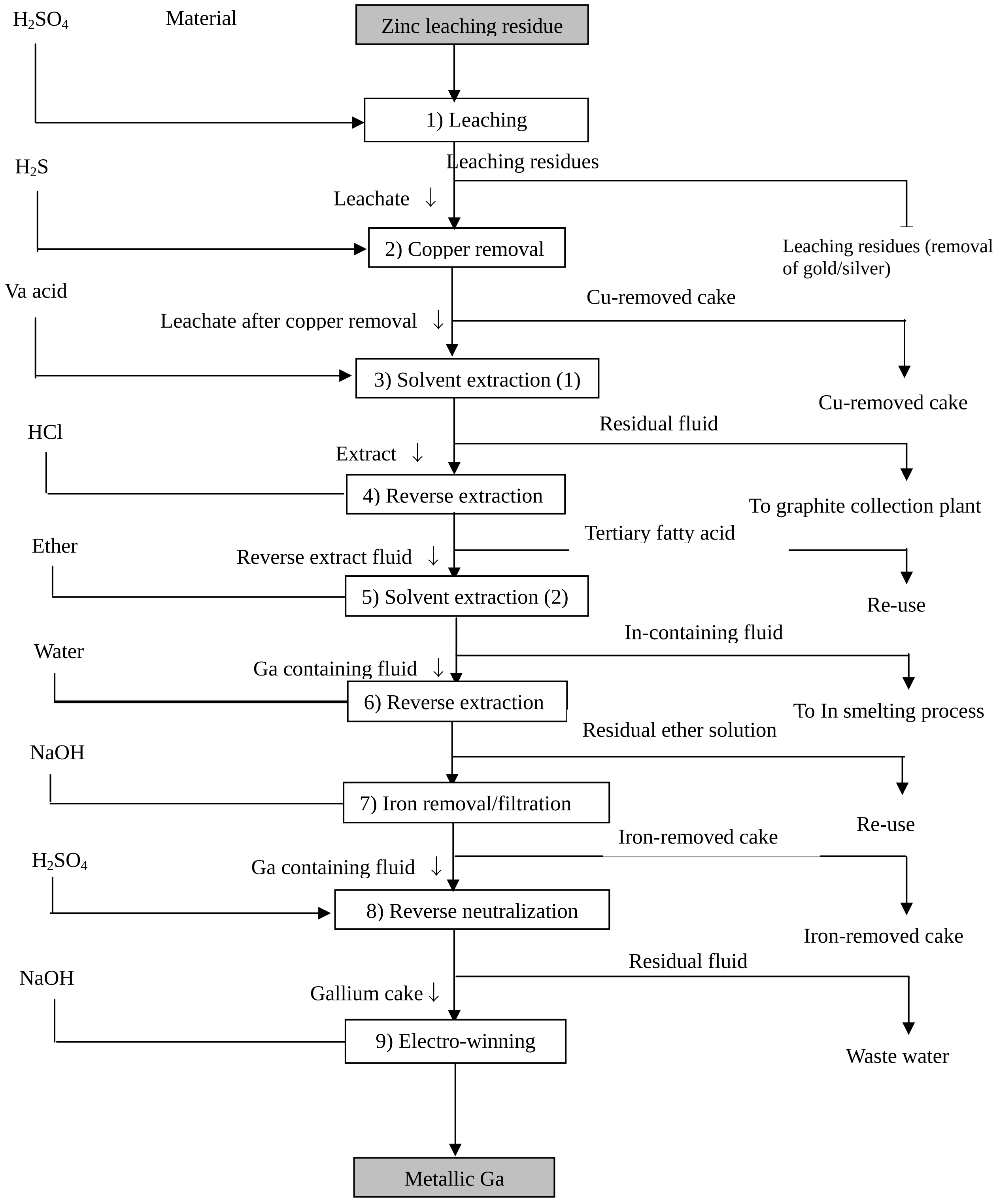
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1. Leaching	【OUTPUT】 - The grade of Ga in the residues: 0.09% - Ga concentration in the leachate: 0.27 g/L	【OUTPUT】 - Leaching yield is assumed to be 90% 【Facility data】 - It is assumed that a centrifugal machine (rated power 55 kW) and a stirrer (2.2 kW) are used. - The equipments are assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied and circulating amount of sulfuric acid 【OUTPUT】- Leaching rate (collection rate), amount of leaching residues of Ga 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption of supplied energy
2. Copper removal		【OUTPUT】 - Mass balance was estimated by assuming that copper is completely removed as CuS and that no Ga is lost. 【Facility data】 - It is assumed that a stirrer (rated power 2.2kW) and a press filter (rated power 0.4kW) are used, and that the equipments run for 25 days/month (24 hours/day).	【INPUT】 - Supplied and circulated amount of hydrogen sulfide 【OUTPUT】 - The amount of Cu-removed cake, and amount of leachate after copper removal 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption of supplied energy
3. Solvent extraction (1)	【OUTPUT】 - Ga extraction rate: 90% - Ga concentration in the extracted tailing solution: 0.027 g/L	【INPUT】 - The supplied amount of VA acid is estimated based on the extracted fluid (estimated). 【OUTPUT】 - The amount of extract is estimated when Ga concentration in it is assumed to be 2.5 g/L. 【Facility data】 - It is assumed that a stirrer (2.2kW) is used. - The equipment is assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied and recycled amount of VA acid 【OUTPUT】 - Ga concentration in the extract 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption of supplied energy
4. Reverse extraction		【INPUT】- The supplied amount of hydrochloric acid is estimated as pure consumption excluding the circulating amount. (Cu wet smelting used as reference). The energy consumption is estimated for production of hydrochloric acid. 【OUTPUT】 - The Ga extraction rate is assumed to be 95%. 【Facility data】 - It is assumed that a stirrer (1.5kW) is used, and that the equipment runs for 15 days/month (24 hours/day).) - The CO_2 emission during hydrochloric acid production is estimated	【INPUT】 - Supplied and recycled amount of hydrochloric acid 【OUTPUT】 - The amount of reverse extraction liquid and extraction tailing - Ga concentration 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption amounts of supplied energy
5. Solvent extraction (2)		【OUTPUT】 - The Ga extraction rate is assumed to be 95%. - Ga concentration in ether is assumed to be 30 g/L 【Facility data】 - It is assumed that a stirrer (1.5kW) is used. - The equipment is assumed to run for 10 days/month (24 hours/day).	【INPUT】- Supplied and recycled amount of ether 【OUTPUT】 - The amount of Ether fluid and extraction tailing fluid - Ga concentration 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption amounts of supplied energy
6. Reverse extraction		【OUTPUT】 - The Ga extraction rate is assumed to be 97%. - The concentration of Ga in reverse extract is assumed to be 35g/L 【Facility data】 - It is assumed that a stirrer (rated power 1.5kW) is used and that the equipment runs for 5 days/month (24 hours/day).	【INPUT】 - Supplied and circulating amount of reverse extract 【OUTPUT】 - Amounts of extract and residual fluid, and the Ga concentration 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption amounts of supplied energy
7. Iron removal-filtering		【INPUT】 - The amount of caustic soda is estimated to be 20% excess - The energy consumption is estimated for production of caustic soda. 【OUTPUT】 - The loss of Ga is assumed to be zero	【INPUT】- Supplied amount of caustic soda 【OUTPUT】 - Amounts of Fe-removed cake and Ga including fluid, Ga concentration 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption of supplied energy
8 Reverse neutralization	【OUTPUT】 - Ga grade in the Ga hydroxide: 34%	【OUTPUT】 - The loss of Ga is assumed to be zero	【INPUT】 - Supplied and recycled amount of sulfuric acid 【OUTPUT】 - The amount of Ga hydroxide, residual fluid, Ga concentration, Ga yield 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption of supplied energy
9. Electrolytic winning	【OUTPUT】 - The grade of metal Ga: 99.99% 【Facility data】 - Power consumption for electrolysis: 15,000 kWh/t-electrolytic Ga	【OUTPUT】 - The yield of Ga is assumed to be 97%.	【INPUT】 - The amount of electrolyte solution 【OUTPUT】 - The amount of residues after electrolysis 【Facility data】 - Specifications for power, processing capacity, etc. -Type and consumption of supplied energy

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.
【Facility data】:Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Source: Hideki Abe, “Smelting of Gallium and Indium”, J. Min. Metall. Inst. Jpn., 93 1070 (1977-4) 323-

Mass balance data

The amounts of material/energy are those per month

	Input		Output		
Process	Supplied materials etc.	Supplied amounts	Products	Amounts of products	Remarks
1) Leaching	Zinc leaching residues	323 t	Leachate	969 kL	- Ga grade in residues: 0.09%
	(content of Ga)	(291 kg)	(content of Ga)	(262 kg)	- The leaching rate is assumed to be 90%.
	Sulfuric acid	969 kL	(Amount of leachate excluding Ga)	(291 t)	- Ga concentration in leachate: 0.27g/L - It is assumed that centrifugal machine (rated power 55kW) and stirrer (2.2kW) are used, and that the equipments are run for 25 days/month (24 hours/day).
			Leaching residue	32 t	
	Electric power	24.9 GJ	[CO_2 emission]	1.02 t	
	(production of sulfuric acid)	1.4GJ*	(sulfuric acid production)	(0.11 t*)	- Environmental impact of sulfuric acid production is considered.
2) Copper removal	Leachate	969 kL	Leachate after copper removal	969 kL	- The loss of Ga is assumed to be zero.
	(content of Ga)	(262 kg)			- Copper is removed as sulfide
	Hydrogen sulfide	2.1 t	(content of Ga)	(262 kg)	- It is assumed that a stirrer (rated power 2.2 kW) and filter press (0.4kW) are used.
			Copper-removed cake	5.8 t	- The equipment is assumed to run for 25 days/month (24 hours/day).
	Electric power	14.7GJ	[CO_2 emission]	0.54 t	
3) Solvent extraction (1)	Leachate after copper removal	969 kL	Extraction liquid	75 kL	- VA acid: Versastic acid
	(content of Ga)	(262kg)	(content of Ga)	(236 Kg)	- Extraction rate: 90%
	VA acid	94 kL	Extracting tailing fluid	969 kL	- Zinc is removed.
	Ammonia gas	+α			- It is assumed that a stirrer (rated power 2.2kW) is used. - The equipment is assumed to run for 25 days/month (24 hours/day). - Environmental impact of VA acid production is not considered
	Electric power	12.5 GJ*	[CO_2 emission]	0.46 t	
4) Reverse extraction	Extraction liquid	94 kL	Reverse extraction liquid	75 kL	- Assuming extraction yield of 95%
	(content of Ga)	(236 kg)	(content of Ga)	(224 kg)	
	Hydrochloric acid	75 kL	Reverse extracting tailing fluid	94 kL	- It is assumed that a stirrer (rated power 1.5kW) is used. - The equipment is assumed to run for 15 days/month (24 hours/day).
	Electric power	5.1GJ	[CO_2 emission]	0.22 t	
	(Hydrochloric acid production)	0.4GJ*	(hydrochloric acid production)	(003 t*)	- Environmental impact of hydrochloric acid production is considered.
5) Solvent extraction (2)	Reverse extraction liquid	75 kL	Ether solution	7.1 kL	- The extraction rate is assumed to be 95%
	(content of Ga)		(content of Ga)	(213 kg)	- The Ga concentration in ether solution is assumed to be 30g/L
	Ether	(224 kg)	Extraction tailing liquid	75 kL	
		7.1 kL			- It is assumed that a stirrer (rated power 1.5kW) is used, and that the equipment is run for 10 days/month (24 hours/day). - Environmental impact of ether production is not considered
	Electric power	3.4GJ	[CO_2 emission]	0.12 t	
6) Reverse extraction	Ether solution	7.1 kL	Reverse extraction liquid (water phase)	5.9kL	- Ether: IPE (isopropyl ether)
	(content of Ga)	(213 kg)			- The extraction rate is assumed to be 97%
	Water	5.9 kL	(content of Ga)	(206 kg)	- It is assumed that a stirrer (1.5kW) is used.
			Ether solution	7.1 kL	- The equipment is assumed to run for 5 days/month (24 hours/day).
	Electric power	1.7GJ	[CO_2 emission]	0.06 t	
7) Iron removal-filtration	Reverse extraction liquid (water layer)	5.9 kL	Ga containing solution	5.9 kL	- The loss of Ga is assumed to be zero.
	(content of Ga)	(206 kg)	(content of Ga)	(206 kg)	- Iron is removed under high temperature, high pressure. Only iron is removed
	Caustic soda	1.7 t	Iron removal cake	1.2 t	
	Electric power	(unknown)	[CO_2 emission]	1.60 t	- Caustic sod is 20% excess
	(caustic soda production)	19.6GJ	(including caustic soda production)	(1.60 t)	- Energy consumption by caustic soda production is considered
8) Reverse neutralization	Ga-containing solution	5.9 kL	Gallium hydroxide	606 kg	- $Ga(OH)_3$ is separated by pH adjusting.
	(content of Ga)	(206 kg)	(content of Ga)	(206 kg)	- Ga grade in the Ga hydroxide: 34%
	Sulfuric acid	+α	Residual liquid	5.9 kL+	- The loss of Ga is assumed to be zero.
	Electric power	(unknown)	[CO_2 emission]	(unknown)	
9) Electrolytic winning	$Ga(OH)_3$	606 kg	Metallic Gallium	200 kg	- grade of metallic Ga: 99.99%
	(content of Ga)	(206 kg)	Others	406 kg	- The yield of Ga is assumed to be 97%
	Electrolytic solution	1.5 kL			- Electrolytic solution: caustic soda - Voltage of tank: 3.5 V, electric density: 2,000A/m^2, average current efficiency: 30%, electrolysis temperature: 45-50°C - Electric power consumption for electrolysis: 15,000 Wh/t-Electrolyte Ga
	Electric power	28.3GJ	[CO_2 emission]	1.04 t	
Total	[Energy]	112 GJ	[CO_2 emission]	5.1 t	
	(materials production)	(21 GJ*)	(materials production)	(1.7 t*)	

Data source: produced by NIR using various data.

Reference: Hideki Abe, “Smelting of Gallium and Indium”, J. Min. Metall. Inst. Jpn., 93 1070 (1977-4 323
Hitoshi Masuda “Gallium, Indium electrolysis”, Kagaku Kogyosha Co, Chemical Industry, 30-38,pp72

(10) Zirconium (Zr)

1) Overview of smelting

a. Smelting method

Main ores acting as raw materials for metallic zirconium are zircon sand (ZrO_2, SiO_2, $ZrSiO_4$) and baddeleyite. Zircon sand is the most widely used raw material.

In accordance to the hafnium separation process, smelting methods are classified into two separation systems: separation by solvent extraction using hydrochloric acid-MBIK solvent and separation by distillation of chloride (hafnium tetrachloride) or Kroll process.

95% of the produced metallic zirconium is used for nuclear energy applications.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Hydrochloric acid-MBIK method	Zircon sand	Oremet-Wah Cheng (USA), Westinghouse Electric Company (USA)	○
Chloride distillation method (Kroll process)	Zircon sand	CEZUS (France)	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	products	Domestic amount demanded (year 2000 estimated)
Pipes material	Fuel cladding, fuel application materials, etc	450 t
Board material	Channel box, etc.	180 t
Rod material	Control rods, etc.	50 t

Demand as alloys for nuclear energy applications
Data source: from Data Book for Metals, 2000 and home page of the Metal Mining Agency of Japan.

2) Integration status of data such as mass balance

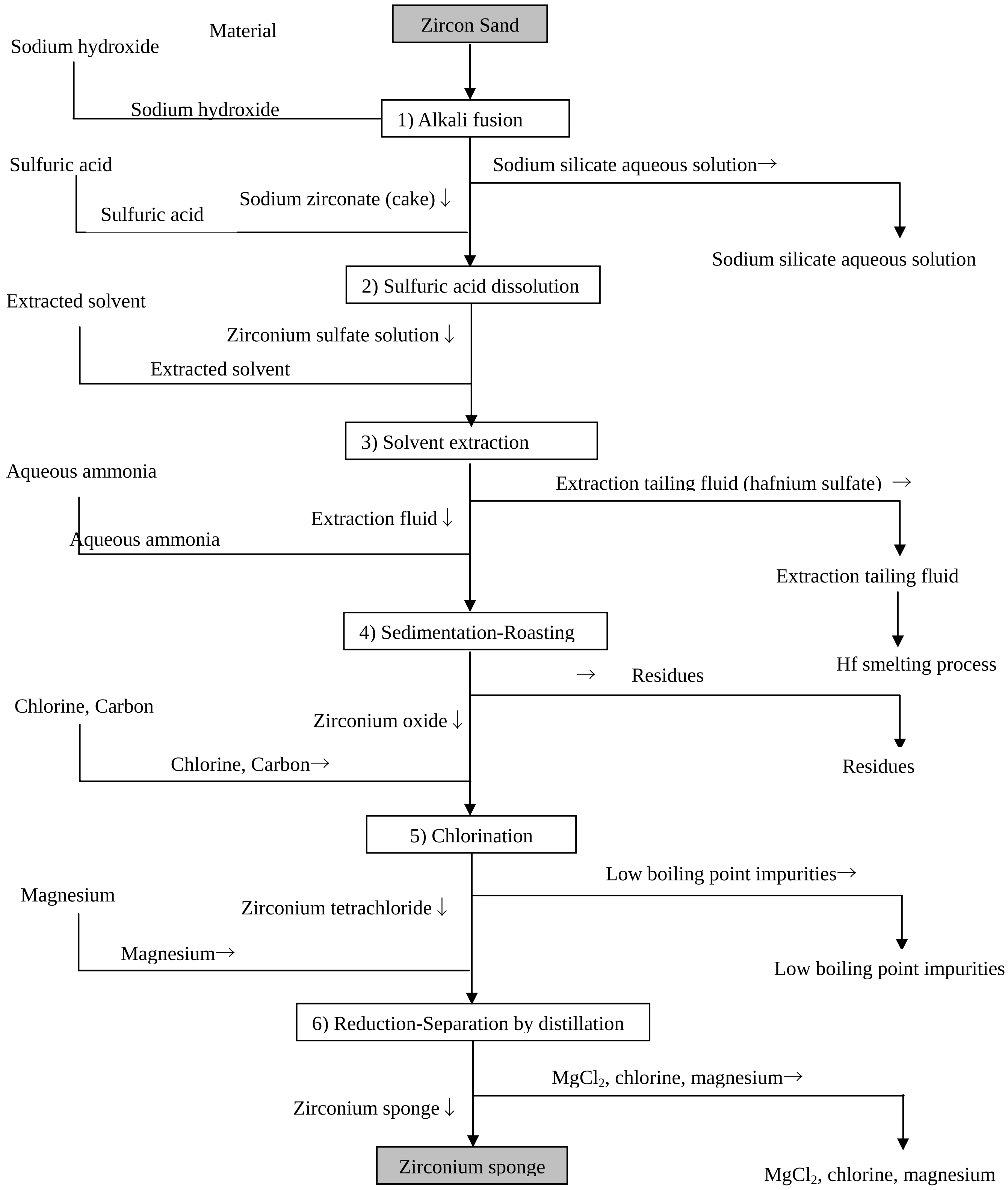
Process	Used data		Untaken data
	Data obtained fro literature, etc.	Data assumed and estimated in this report	
1. Alkali fusion		【INPUT】 - ZrO_2 concentration in Zr sand is assumed to be 64% for calculations. - Energy consumption is estimated for production of caustic soda. 【OUTPUT】 - SiO_2 is assumed to be completely separated. - The yield of Zr is assumed to be 98% - The amount of CO_2 released during production of the caustic soda is estimated.	【INPUT】 - Supplied amount of Zr sand; Grade of Zr - Supplied amount of Na(OH) 【OUTPUT】 - Amount of sodium zirconate; Grade of Zr. - Amount of soda silicate separated 【Facility data】 - Specifications for type, power, processing capacity, etc. of a used facility - Type and consumption of supplied energy - Type and consumption of energy for heating during fusing process
2. Sulfuric acid dissolution		【INPUT】 - Sulfuric acid supplied was estimated as pure consumption excluding the circulating volume. (Wet smelting of copper is used as reference for the material balance). - Energy consumption is estimated for production of sulfuric acid. 【OUTPUT】 - Zirconium soda is assumed to be completely dissolved. - The amount of CO_2 released during production of caustic soda used is estimated 【Facility data】 - It is assumed that a stirrer (rated power 1.5 kW) is used for 5 days/month (24 hours/day).	【INPUT】 - Amounts of sulfuric acid supplied and recycled 【OUTPUT】 - The amount of dissolved soda zirconate - The volume of solution; Zr concentration 【Facility data】 - Type of equipment used - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy - Type and consumption of energy for heating during dissolution process
3. Solvent extraction		【OUTPUT】 - Mass balance is estimated based on the solvent extraction data for Ta smelting - The extraction rate of Zr is assumed to be 99% 【Facility data】 - It is assumed that a stirrer (rated power 1.5 kW) as a mixer settler is used. - The equipment is assumed to run for 5 days/month (24 hours/day).	【INPUT】 - The amount of extraction fluid supplied, recycled 【OUTPUT】 - The amount of extracted fluid, Zr concentration - The amount of extraction tailing fluid, Zr concentration, Zr extraction yield 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption amounts of supplied energy - Type and consumption of energy for heating
4. Sedimentation - Roasting	【Facility data】 Approx.800°C	【OUTPUT】 - The yield of Zr is assumed to be 98%.	【INPUT】 - The supplied amount of aqueous ammonia 【OUTPUT】 - The amount of zirconium oxide, the grade of Zr - The amount of evaporated solution and residues, Zr concentration - The yield of Zr 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy
5. Chlorination	【Facility data】 Fluid chlorination at 1,000-1,300°C	【INPUT】 - Energy consumption for production of sulfuric acid is estimated. 【OUTPUT】 - Mass balance is estimated based on the data for chlorination process in titanium smelting. - The grade of Zr oxide is assumed to be 93%. - The grade of Zr tetrachloride is assumed to be 98%. - The amount of CO_2 released during production of hydrochloric acid used is estimated.	【INPUT】 - Supplied amounts of chlorine and carbon 【OUTPUT】 - The amount of Zr tetrachloride, grade of Zr - The amount of impurities and Zr concentration 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy
6. Reduction-Separation by distillation	【OUTPUT】 The grade of Zr: 99.6% 【Facility data】 - Electric furnace used - 800-850°C	【OUTPUT】 - Mass balance is estimated based on the data for reduction process during titanium smelting - The grade of Zr oxide is assumed to be 93% - The yield of Zr in the overall smelting process is assumed to be 90%.	【INPUT】 - The supplied amount of Mg. 【OUTPUT】 - Amounts of Mg chloride, produced chlorine, and collected Mg; the yield of Zr 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.
【Facility data】:Data for equipment used in processes concerned.

The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Source: Yuhei Kokubo, Smelting of zirconium and hafnium at Japan Mining (Central Laboratory) Co., Ltd., J. Min. Metal. Inst. Jpn., 97, 1122 (‘81-88) p. 877-

Zr (Zirconium)

Mass balance data

The amount of material/energy is those per month.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Alkali fusion	Zircon sand	16.5 t	Sodium zirconate	16.5 t	- The total yield of all zirconium smelting process is assumed to be 90%.
	(Content of Zr)	(7.8 t)	(Content of Zr)	(7.7 t)	
	Sodium hydroxide	11.0 t	Sodium silicate	11.1 t+	- The yield of alkali fusion process is assumed to be 98%.
	Other additives	+α			
	(Other additives)				
	Water				
					- All of the SiO_2 is assumed to be removed.
	Electric power	(unknown)	[CO_2 emission]	10.3 t	- Silicate is separated through water leaching.
	(Production of caustic soda)	126.6 GJ	(Portion of caustic soda production)	(10.3 t)	- Environmental load of caustic soda production is considered.
2) Sulfuric acid dissolution	Sodium zirconate	16.5 t	Zirconium sulfate solution	5.6 kL	- It is assumed to be completely dissolved.
	(Content of Zr)	(7.7 t)	(Content of Zr)	(7.7 t)	- It is assumed that a stirrer (rated power 1.5 kW) is used
	Sulfuric acid	5.6 kL	(others)	(19.1 t)	
		(10.3 t)			- The equipment is assumed to run for 5 days/month (24 hours/day).
					- Environmental load of sulfuric acid production is considered. (Newly added amount except for recycled portion is estimated based on copper smelting data.)
	Electric power	1.7 GJ	[CO_2 emission]	0.1 t	
	(sulfuric acid production)	0.06 GJ*	(including sulfuric acid production)	(0.004 t*)	
3) Solvent extraction	Zirconium sulfate solution	5.6 kL	Extract	3.4 kL	- Amine (tri-n-octylamine) diluted with n-paraffin and alcohol is used as an extract.
	(Content of Zr)	(7.7 t)	(Content of Zr)	(7.6 t)	- Mass balance is estimated based on the solvent extraction during Ta smelting.
	(other)	(19.1 t)	(others)	(18.1 t)	
					- The yield of Zr is assumed to be 99%.
	extracting solvent	3.4 kL	Extract tailing	5.6 kL (1.1 t)	- It is assumed that a stirrer (rated power 1.5 kW) as mixer settler is used to run for 5 days/month (24 hours/day).
	Electric power	1.7 GJ	[CO_2 emission]	0.1 t	
4) Sediments-Roasting	Extraction fluid	3.4 kL	Zirconium oxide	10.1 t	- The yield of Zr is assumed to be 90%.
	(Content of Zr)	(7.6 t)	(including Zr)	(7.5 t)	- Approx. 800°C
	(other)	(18.1 t)	Residues	8.0 t+	
	Aqueous ammonia	+α			
	(Fuel)	(unknown)	[CO_2 emission]	(unknown)	
5) Chlorination	Zirconium oxide	10.1 t	Zirconium tetra-chloride	18.1 t	- Mass balance was estimated based on the chlorination process during Ti smelting.
	(Content of Zr)	(7.5 t)	(Content of Zr)	(7.1 t)	
	Chlorine	11.0 t	Low boiling point impurities	4.2 t	
	Carbon	1.1 t			- grade of zirconium oxide: 93%
					- grade of zirconium tetrachloride: 98%
	Electric power	(unknown)	[CO_2 emission]	7.0 t	- Fluid chlorination at 1,000-1,300°C
	(Production of chlorine)	85.3 GJ	(Amount of chlorine production)	(7.0 t)	- Environmental load of chlorine production is considered.
6)Reduction-Distillation	Zirconium tetra-chloride	18.1 t	Zirconium sponge	7.1 t	- Mass balance was estimated based on the reduction process of Ti smelting
			(Content of Zr)	(7.1 t)	
	(Content of Zr)	(7.1 t)	$MgCl_2$	14.5 t	
	Magnesium	5.7 t	Chlorine	0.3 t	- Zr grade: 99.6%
			Mg (unreacted)	2.0 t	- Reduction at 800-850°C
	Electric power	(unknown)	[CO_2 emission]	(unknown)	- Electric furnace is used.
Total	[Energy]	215 GJ	[CO_2 emission]	17.4 t	
	(Production of materials)	(212 GJ*)	(Production of materials)	(17.3 t*)	

Data source: produced by NRI using various data.

Reference: Yuhei Kokubo, Smelting of Zirconium and Hafnium at Japan Mining (Central Laboratory), J. Min. Metall. Inst. Jpn., 97 1122 ('81-8) p. 877-

6) Considerable heat is required for magnesium reduction.

(11) Niobium (Nb)

1) Overview of smelting

a. Smelting method

Metallic niobium is sometimes found in combination with tantalum in nature. Currently, pyrochlore ore (containing both tantalum and niobium) is the main source of the material. Niobium also occurs in other ores, such as columbite and tantalite, usually as Nb_2O_5.

Smelting of metallic niobium is carried out through pulverization and ore sorting of the pyrochlore, followed by magnetic beneficiation and floatation. Concentrated material is, then, converted in highly pure oxide by solvent extraction, and finally thermite reduction process is applied to the material.

Smelting method	Starting materials	Smelting situation	Smelting method adopted in the present report
Solvent extraction/Reduction by NbC or C	Pyrochlore ore, tantalite ore, etc.	The most widely used	○
Thermite reduction/Chlorination	Pyrochlore ore	Teledyne Wah Chang Albany (USA), etc.	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final products	Products
Super conductive materials	Nb-Ti alloys, Nb_3Sn chemical compounds, etc.
Corrosion resistant materials	Hafnium doped niobium alloys, etc.
Electronic industrial materials	Sodium lamps, etc.

Data source: from Data Book for Metals, 2000 and the website of the Metal Mining Agency of Japan.

2) Integration status of data such as mass balance

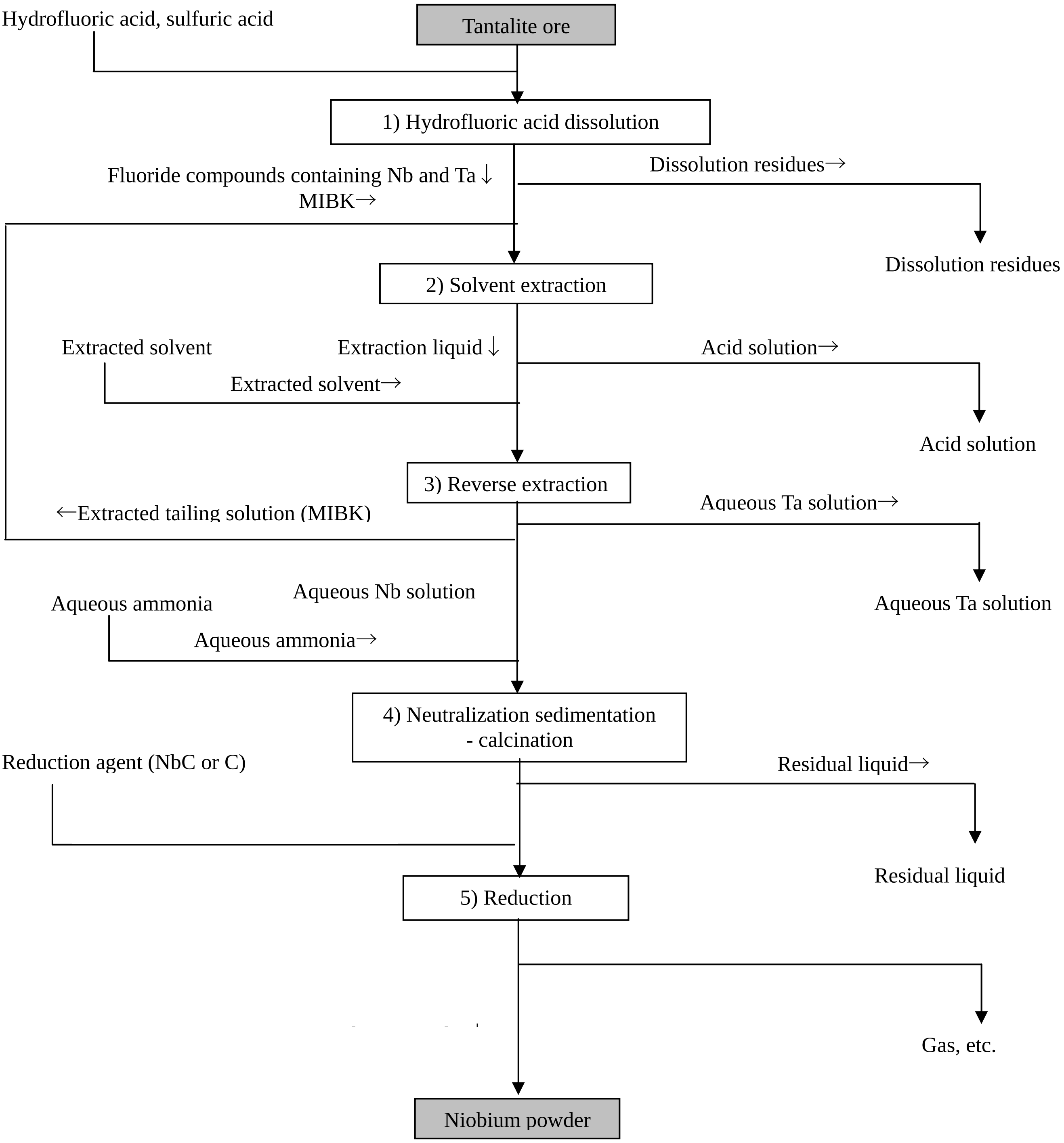
Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1. Hydrofluoric acid dissolution	【INPUT】 - Nb grade in the ore: 14% - Ta grade in the ore: 41% 【OUTPUT】 - Ta concentration in hydrofluoric acid solution: 17.3 g/L 【Facility data】 Dissolution temperature: 60°C	【INPUT】 - The grade of ore is assumed to be medium to high. - Hydrofluoric acid supplied is estimated as pure consumption excluding the circulating amount (Copper wet smelting is used as reference for mass balance). - Energy consumption for production of hydrofluoric acid is estimated. 【OUTPUT】 - The average solubilities of Ta and Nb are assumed to be 90%. - CO_2 emission during hydrofluoric acid production is estimated.	【INPUT】 - The amount of hydrofluoric acid supplied and recycled - The amount of sulfuric acid supplied 【OUTPUT】 - The solubility of Nb - The amount of solution - The undissolved residues 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of added energy - Type and consumption of energy for heating of solution, etc.
2. Solvent extraction		【INPUT】 - MIBK supplied is estimated as pure consumption excluding the circulating amount. (Copper wet smelting used as reference for mass balance). - Energy consumption for production of MIBK is estimated. 【OUTPUT】 - The extraction yield of Ta is assumed to be 95%. - The extraction yield of Nb is assumed to be 90%. - CO_2 emission during MIBK production is estimated.	【INPUT】 - The amount of MIBK supplied and recycled 【OUTPUT】 - The extraction rate of Nb - The amount of extraction, Nb concentration - The amount of acidic waste solution, Nb concentration 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy - Type and consumption of energy for heating of extraction, etc.
3. Reverse extraction		【OUTPUT】 - It is assumed that Ta and Nb are completely separated. - The reverse extraction yields of Ta and Nb are assumed to be 95%	【INPUT】 - The amount of dilute sulfuric acid and water supplied 【OUTPUT】 - The amount of Nb aq. solution, Nb concentration, and yield of Nb - The amount of Ta aqueous solution, Ta concentration - The amount of extraction tailing liquid, Nb and Ta concentration 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of added energy - Type and consumption of energy for heating of extraction liquid
4. Sediment neutralization -calcination		【OUTPUT】 - The yield of Nb is assumed to be 95%	【INPUT】 -The amount of aqueous ammonia supplied 【OUTPUT】 - The yield of Nb - The amount of Nb pentoxide supplied, the grade of Nb - The amount of residual liquid, amount of evaporated liquid, Nb concentration 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy
5. Reduction	【OUTPUT】 - Nb powder grade: 99.7% 【Facility data】 - Reduction was carried out twice at 1,700-2,300°C	【OUTPUT】 - The yield of Nb is assumed to be 95%.	【OUTPUT】 - The yield of Nb - The amount of other gases 【Facility data】 -Specifications for power, processing capacity, etc. - Type and consumption of supplied energy

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.
【Facility data】:Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

Nb (Niobium)

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Source: Toshio Miura, "Smelting of Niobium and Tantalum at Sankin Rare Earth Co., Ltd. " MMIJ Journal, 1997 (81-88) p 869-

Rare metals, Hideo Kaneko, et al., Morikita Publishers Co., Ltd.

Mass balance data

The amounts of material/energy are those per raw tantalite ore of 10 t.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Hydrofluoric acid dissolution	Tantalite ore	10 t	Nb, Ta containing solution	213 kL+	- The grade of tantalite ore is assumed to be medium to high.
	(including Ta)	(4.1 t)	(including Ta)	(3.7 t)	
	(including Nb)	(1.4 t)	(including Nb)	(1.3 t)	- Ta grade in ore: 41%
	Hydrofluoric acid	213 kL	(excluding the above)	(4.1 t)	- The average solubility is assumed to be 90%.
	Sulfuric acid	+α			- Sulfuric acid is used for pH adjustment.
			Dissolution residues	1.0 t	- Ta concentration in hydrofluoric acid: 17.3 g/L
					- Dissolution temperature: 60°C
	Electric power	(unknown)	[CO_2 emission]	1.8 t	- Energy consumption for hydrofluoric acid production is estimated taking into account only newly added material except for circulating amount (copper smelting data is used as reference for mass balance).
	(Hydrofluoric acid production)	20 GJ*	(including hydrofluoric acid production)	(1.8 t*)	
2) Solvent extraction	Na and Ta mixed solution	213 kL	Extraction liquid	346 kL	- Ta extraction yield: 95%
			(including Ta)	(3.5 t)	- Nb extraction yield: 90%
	(including Ta)	(3.7 t)	(including Nb)	(1.1 t)	
	(including Nb)	(1.3 t)	Acid waste solution	213 kL	- Continuous operation
	MIBK	346 kL			- Energy consumption for MIBK production is estimated taking into account only newly added material except for circulating amount (copper smelting data is used as reference for mass balance).
	Electric power	(unknown)	[CO_2 emission]	46 t	
	(MIBK production)	314 GJ*	(including MIBK production)	(46 t*)	
3) Reverse extraction	Extraction liquid	346 kL	Nb aqueous solution	(unknown)	- Ta and Nb are completely separated from the differences in solubility based on the different acid concentrations.
	(including Ta)	(3.5 t)	(including Nb)	(1.1 t)	
	(including Nb)	(1.1 t)	Ta aqueous solution	(unknown)	
	Dilute sulfuric acid	(unknown)	(including Ta)	(3.3 t)	- The reverse extraction yields of Ta and Nb are assumed to be 95%.
	Water	(unknown)	Tailing extract	346 kL	
					- Dilute sulfuric acid: for Nb reverse extraction
					- Water: for Ta reverse extraction
	Electric power	(unknown)	[CO_2 emission]	(unknown)	- Continuous operation
4) Neutralizing sedimentation - calcination	Nb aqueous solution	(unknown)	Niobium penta-oxide	3.0 t	- The yield of this process is assumed to be 95%.
	(including Nb)	(1.1 t)	(including Nb)	(1.0 t)	
	Aqueous ammonia	+α	Residues	(unknown)	
	Electric power	(unknown)	[CO_2 emission]	(unknown)	
5) Reduction	Niobium penta-oxide	3.0 t	Niobium powder	1.0 t	- Grade of Nb powder: 99.7%
	(including Nb)	(1.0 t)	Others (gas, etc.)	2.0 t+	
	Other additives	+α			- Reduction (vacuum heating) is carried out twice (1700-2300ºC).
	(Other additives)				
	Reducing agent				- Assuming 2000ºC
	Electric power	(unknown)	[CO_2 emission]	(unknown)	- The yield of this process is assumed to be 95%.
Total	[Energy]	334 GJ	[CO_2 emission]	48 t	
	(production of materials)	(334 GJ*)	(production of materials)	(48 t*)	

Data source: produced by NIR using various data.

Reference: Toshio Miura, “Niobium and Tantalum Smelting at Sankin Rare Earth Co., Ltd.” MMIJ Journal, 97 1122(81-8) pp 869-
Lectures on Metallurgy (Kinzoku Kogaku Koza) “Non-Ferrous Smelting”
Hideo Kaneko, “Rare metal,” Morikita Publishers Co., Ltd.

(12) Molybdenum (Mo)

1) Overview of smelting

a. Smelting Method

Metallic molybdenum is found in such minerals as molybdenite and wulfenite, and molybdenite is most used as the main source. It is also recovered as by-product of copper mining or from oil refining catalyst.

The process for smelting of metallic molybdenum starts with calcination of the molybdenum mineral (molybdenite) to obtain oxides, followed by ammonia dissolution and sedimentation by nitric acid, and metallic molybdenum is finally obtained by reduction (hydrogen reduction, etc.).

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Calcination/Oxidation extraction/Hydrogen reduction	Molybdenite	Japan New Metals, Toshiba, etc.	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications of final products	Products
Light bulbs	Supports for tungsten filaments in incandescent electric bulbs Halogen lamps for automobiles
Materials for vacuum tube	Electron tube (anode), zirconium insulating getter, materials for X-ray tubes, materials for magnetron, etc.
Others	Semiconducting materials, etc.

Data source: from Data Book for Metals, 2000 and home page of the Metal Mining Agency of Japan.

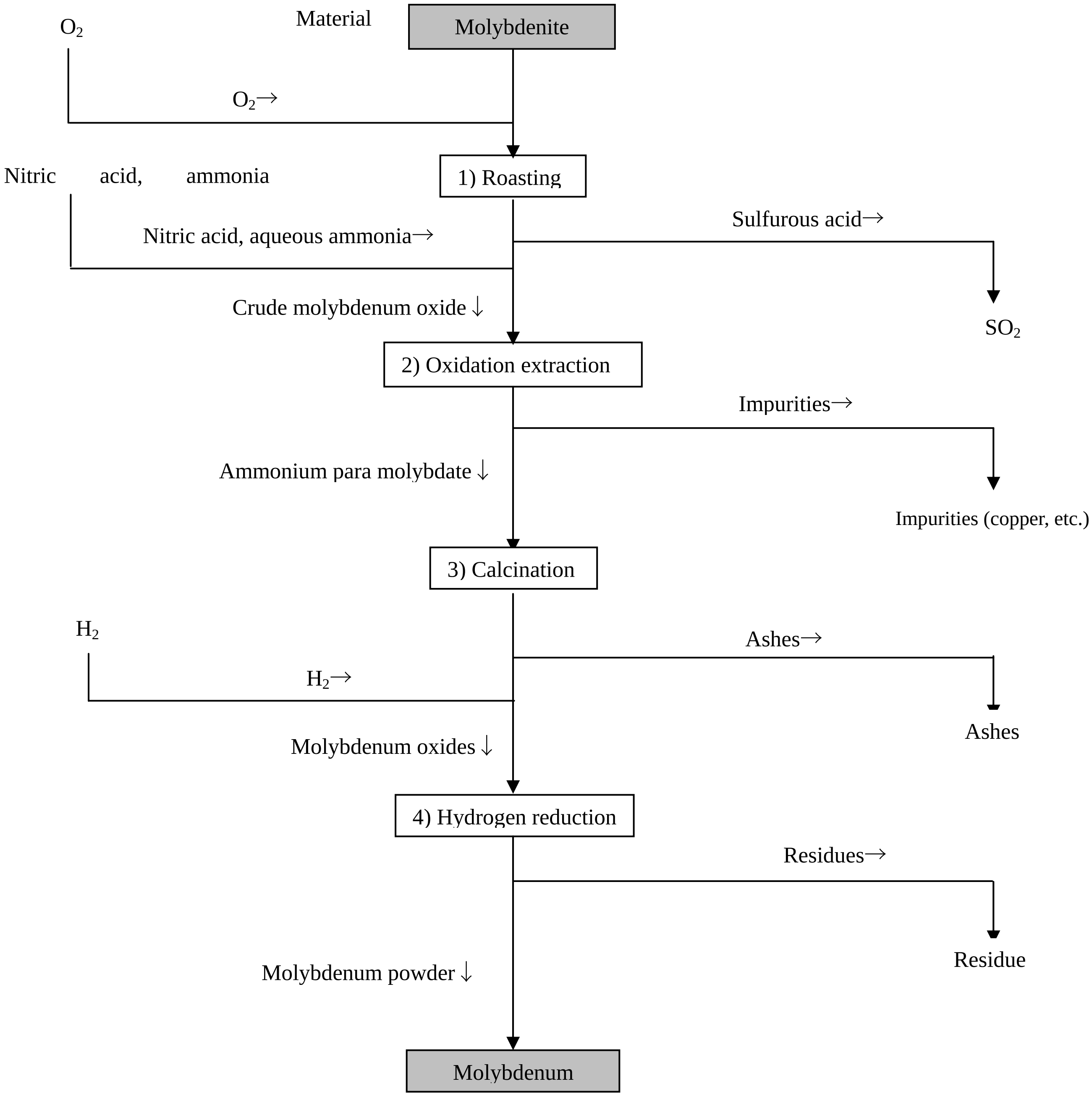
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report	
1. Roasting		【INPUT】 - Oxygen is estimated as the amount contributing to the reaction (theoretical value). 【OUTPUT】 - The yield of Mo is assumed to be 90%. - Mass balance is estimated based on the reaction formula.	【INPUT】 - Supplied amount and grade of ore 【OUTPUT】 - The amount and grade of Mo oxide - Emission of SO_2 gas 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy
2. Oxidation extraction		【INPUT】 - Aqueous ammonia supplied is estimated as pure consumption excluding the circulating amount (copper wet smelting is used as reference for mass balance). - Energy consumption for production of aqueous ammonia is estimated. 【OUTPUT】 - The yield of Mo is assumed to be 90%. - Mass balance is estimated based on the reaction formula. - The impurities are assumed to be only Fe, Cu, and S for calculation - CO_2 emission is estimated for production of aqueous ammonia 【Facility data】 - It is assumed that a stirrer (rated power 2.2 kW) is used and that the equipment is run for 25 days/month (24 hours/day).	【INPUT】 - The supplied and recycled amounts of nitric acid and aqueous ammonia 【OUTPUT】 - The amount of extraction, and Mo concentration - The amount of ammonium para-molybdate - The amount of impurities 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy - Type and consumption of energy for heating of extraction liquid, etc.
3. Calcination		【OUTPUT】 - Mass balance is estimated based on the reaction formula. - The loss of Mo is assumed to be zero for calculation.	【OUTPUT】 - The amount of molybdenum oxides, Mo grade - Mo yield - The amount of ash 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy
4. Hydrogen reduction	【OUTPUT】 - Grade of Mo powder: 99.8%	【OUTPUT】 - The yield of Mo from the overall smelting process is assumed to be 85%.	【INPUT】 - The amount of hydrogen supplied 【OUTPUT】 - The amount of residues - Mo yield 【Facility data】 - Specifications for power, processing capacity, etc. - Type and consumption of supplied energy

Note: 【INPUT】:The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】:The amounts of substances produced and emitted in processes concerned.
【Facility data】:Data for equipment used in processes concerned.
The data indicated by【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Source: Hiroshi Doi, Tungsten and molybdenum production at Japan New Metals Co., Ltd., Shigen to Sozai, 109 (1993), No. 12, p 1150-

Mo (Molybdenum)

Mass balance data

The amounts of material/energy are those per month.

Process	Input		Output		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1) Roasting	Molybdenite	25.0 t	Crude molybdenum oxide	18.8 t	- The yield of Mo from the overall process is assumed to be 85%.
	(including Mo)	(11.7 t)	(including Mo)	(10.6 t)	
	O_2	12.8 t	SO_2	19.0 t	- The yield of Mo is assumed to be 90%. - Mass balance is estimated based on the reaction formula. - Only oxygen contributing to the reaction is considered.
	Fuel	(unknown)	【CO_2 emission】	(unknown)	
2) Oxidation extraction	Crude molybdenum oxide	18.8 t	Ammonium para-molybdate	18.6 t-dry	- Mass balance is estimated based on the reaction formula.
	(including Mo)	(10.6 t)	(including Mo)	(10.5 t)	
	Nitric acid	(unknown)	Impurities (Cu, etc.)	13.2 t	- Nitric acid: removing impurities
	Aqueous ammonia	40.6 kL	Ammonia	2.2 t	- The impurities are assumed to be only Fe, Cu, S for calculation.
	(10% solution)	(38.8 t)	Water	2.1 kL	
				(2.1 t)	- The yield of Mo is assumed to be 99% - It is assumed that a stirrer (rated power 2.2 kW) is used. - The equipment is assumed to run for 25 days/month (24 hours/day). - Environmental load of aqueous ammonia production is considered (only newly supplied material except for the circulating amount is taken into account with copper smelting used as reference for mass balance).
	Electric power	12.5 GJ	【CO_2 emission】	0.59 t	
	【Production of aqueous ammonia】	1.3 GJ*	(Including aqueous ammonia production)	(0.13 t*)	
3) Calcination	Ammonium para-molybdate	18.6 t-dry	Molybdenum oxide	15.0 t	- Mass balance is estimated based on the reaction formula.
	(including Mo)	(10.5 t)	(including Mo)	(10.5 t)	
			Ashes	3.6 t	
	Fuel	(unknown)	【CO_2 emission】	(unknown)	
4) Hydrogen reduction	Molybdenum oxide	15.0 t	Molybdenum powder	**10.0 t**	- Grade of powder molybdenum: 99.8%
	(including Mo)	(10.5 t)	(including Mo)	(10.0 t)	
	Hydrogen	0.6 t	Residues	5.7 t	
	Fuel	(unknown)	【CO_2 emission】	(unknown)	
Total	【Energy】	13.8 GJ	【CO_2 emission】	0.59 t	
	(production of materials)	(1.3 GJ*)	(production of materials)	(0.13 t*)	

Data source: produced by NIR using various data.

Reference: Hiroshi Doi, Production of tungsten and molybdenum at Japan New Metals Co., Ltd., Shigen to Sozai, 109 (1993), No. 12, p 1150-

(13) Silver (Ag)

1) Overview of smelting

a. Smelting method

A silver ore is usually produced with gold-silver deposit, or lead-zinc, or copper deposit.

In Japan, it is often obtained as a by-product of the smelting or refining of copper, lead, or zinc ore, and the most general method is refining of copper electrolysis slime.

Smelting method	Starting materials	Main producers Name of company	Smelting method adopted in the present report
Smelting from silver ore	Silver ore	-	×
Smelting method from Copper electrolytic slime	Copper electrolytic slime	Sumitomo Metal Mining	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Domestic amount demanded (year 2001)
Photographic materials	1,663 t
Silver nitrate for other use	150 t
Point connector	202 t
Silver solder	111 t
Plating	-
Extension material	194 t
Jewelry	-
Others	637 t

Data source: Yearbook of Non-Ferrous Metals Statistics, 2001, Ministry of Economy, Trade and Industry

2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report	
1. Solvent extraction /filtration /drying	【INPUT】 - The grade of Ag in copper electrolytic slime: 10.5% 【OUTPUT】 - Decopperizing rate: 90%	【INPUT】 -The latent heat of evaporation is estimated on the assumption that 10wt% moisture is dehydrated from extraction precipitation. 【OUTPUT】 - Only Cu is assumed to be removed. - The yield of Ag from slime is assumed to be 90%. 【Facility data】 - Electric consumption of a band dryer (3.7kW), a filter press (1.5kW), or a stirrer (2.2kW) is estimated. - It is assumed that they are used for 20 days/month (24 hours/day). (The rated power is all assumed.)	【INPUT】 - Amounts of dilute sulfuric acid supplied and circulated 【OUTPUT】 - The yield of Ag, amount of sedimentation, grade of Ag. -The water content in sedimentation, amount of moisture evaporation - The amount of extract, Ag concentration. 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy. - Type and consumption of energy for heating extract
2. Roasting (Oxidation refining)	【Facility data】 - Use of rotary kiln	【OUTPUT】 - Mass balance is estimated by assuming that only selenium is removed.	【OUTPUT】 - The amount of roasted sedimentation, the grade of Ag. - The yield of Ag, the amount of selenium dioxide. 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy. - Type and consumption of energy for heating extract
3. Melting sedimentation (Reduction dissolution)	【INPUT】 - The grade of Ag in lead electrolytic slime: 16% 【Facility data】 - Girod-type electric furnace - Secondary voltage: 73V - Secondary electric current: 7,230 A - 2,760 kWh/batch	【Facility data】 - It is assumed that they are used for 2 batches/day (25 days/month). 【OUTPUT】 - The yield of Ag is assumed to be 95%.	【INPUT】 - Supplied amount of lead electrolytic slime. 【OUTPUT】 - The yield of Ag - The amount of noble lead, the grade of Ag - The amount of fused slag, Ag concentration 【Facility data】 - Operational status
4. Volatilization	【Facility data】 - Rocking type volatile furnace	【OUTPUT】 - The loss of Ag is assumed to be zero. - Mass balance is estimated by assuming that only selenium is removed by volatilization. - Heating energy of noble lead and evaporation heat of Sb are considered as consumption energy (specific heat of noble lead substitutes for the value of Ag)	【OUTPUT】 - The amount of removed Sb. - The amount of noble lead after removing Sb. 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy
5. Chlorination removal of lead	【INPUT】 - The grade of Ag in noble lead: 21.7%. 【OUTPUT】 - The grade of Ag in noble lead fed: 28.4%	【OUTPUT】 - The loss of Ag is assumed to be zero. - Mass balance is estimated by assuming that only lead is removed.	【INPUT】 - Supplied amount of chlorine gas 【OUTPUT】 - The yield of Ag, the amount of noble lead fed. - Removed amount of $PbCl_2$ 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy.
6. Parting	【OUTPUT】 - The grade of silver anode: 92.5% - The grade of Bi in Bi lead oxide: 70% 【Facility data】 - BBOC furnace (use of kerosene) - 15 GJ/t-Ag anode - Equipment is used to run for 20 days/month (22 hours/day).	【OUTPUT】 - Mass balance is estimated based on the grade, etc.	【OUTPUT】 - The yield of Ag - The amount of Ag anode. - The amount of slag or Bi lead oxide.
7. Electrolysis	【OUTPUT】 - The grade of electrolytic silver: 99.99% 【Facility data】 - Electric power consumed in electrolytic furnace: 500 kWh/t - Electrolytic Ag - Equipment is used to run for 25 days/month (22 hours/day)	【OUTPUT】 - Mass balance is estimated based on the grade, etc.	【INPUT】 - Supplied amount of anode 【OUTPUT】 - The yield of Ag - The amount of sedimentation, the grade of Ag

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in process concerned.
【Facility data】: Data for equipment used in process concerned.
The indicated by 【INPUT】, 【OUTPUT】, 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO2 emission are large.

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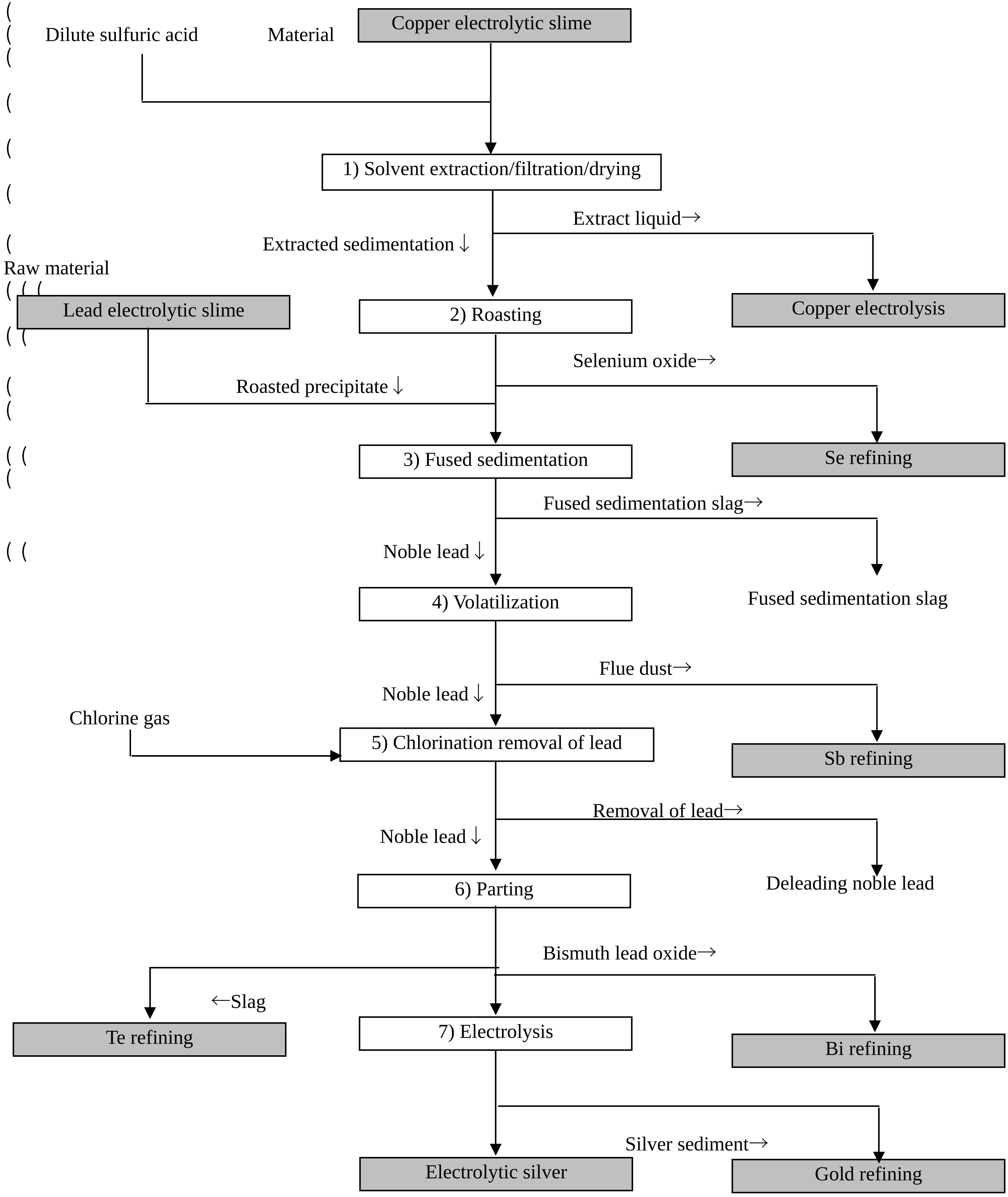
Flow diagram of processes



Data source: Kenichi Moriyama, "Noble Metal Smelting in Copper Smelting Plants in Sumitomo Metal Mining Co., Ltd.," Sigen to Sozai, 109 (1993), No.12

Ag (Silver)

Mass balance data

The amounts of material/energy are those per month.

	INPUT		OUTPUT		
Process	Supplied materials etc.	Supplied amounts	Products	Amounts of products	Remarks
1. Solvent extraction /filtration /drying	Copper electrolytic slime	120 t	Extracted sedimentation	106 t	- Decopperizing rate: 90% - The grade of Ag in copper electrolytic slime: 10.5% - It is assumed that only Cu is removed. - The yield of Ag in the slime is assumed to be 90%. - Latent heat of evaporation is estimated by assuming that 10% moisture of the sedimentation weight is dried and evaporated. - It is assumed that a band dryer (rated 3.7 kW), a filter press (rated 1.5 kW), and a stirrer (rated 2.2 kw) are used for 20 days/month (24 hours/day).
	(including Ag)	(12.6 t)	(including Ag)	(12.6 t)	
	Dilute sulfuric acid	(unknown)	Extract liquid	(unknown)	
			(Decopperrized amount)	(14.1 t)	
	Electric power	33.6 GJ			
	Heavy oil	23.9 GJ	【CO_2 emission】	2.9 t	
2. Roasting (oxidation refining)	Extraction sediment	106 t	Roasted sedimentation	100 t	- Use of rotary kiln - It is assumed that only Se is removed.
	(including Ag)	(12.6 t)	(Ag)	(12.6 t)	
			Selenium dioxide	6.2t	
	Electric power	(unknown)			
	Heavy oil	(unknown)	【CO_2 emission】	(unknown)	
3. Fusion sedimentation (reduction resolution)	Roasted sedimentation	100 t	Noble lead	110 t	- Girod-type electric furnace - 2,760 kWh/batch - Equipment is used for 2 batches/day and 25 days/month. - Secondary voltage: 73V - Secondary current: 7,230A
	(including Ag)	(12.6 t)	(including Ag)	(22.7 t)	
	Lead electrolytic slime	70 t	Fused sedimentation slag	60 t	
	(including Ag)	(11.2 t)	【CO_2 emission)		
	Electric power	1,304GJ		47.7 t	
4. Volatilization	Noble lead	110 t	Noble lead after removing Sb	105 t	- Rocking type volatilization furnace - The loss of Ag is assumed to be zero. - It is assumed that only Sb is removed by volatilization. - Heating energy of noble lead (25→2000℃) and evaporation heat of Sb are considered as consumption energy. - The loss of energy is not considered. - Specific heat of noble lead substitutes for the value of Ag.
	(including Ag)	(22.7 t)	(including Ag)	(22.7 t)	
			Removed Sb	5 t	
	Heavy oil	216.9 GJ	【CO_2 emission】	15.0 t	
5. Chlorination removal of lead	Noble lead after removing Sb	105 t	Deleading noble lead	80 t	- The loss of Ag is assumed to be zero. - It is assumed that only lead is removed. - The grade of Ag in supplied noble lead: 21.7% - The grade of Ag in deleading noble lead: 28.4%
	(including Ag)	(22.7 t)	(including Ag)	(22.7 t)	
	Chlorine gas	8 t	Removal of lead ($PbCl_2$)	33 t	
	Heavy oil	(unknown)	【CO_2 emission】	(unknown)	
6. Parting	Deleaded noble lead	80 t	Silver anode	24 t	- The grade of Ag anode: 92.5% - The grade of Bi in bismuth lead oxide: 70% (Source: Sgen-to-Sozai, 110 (1994) No.5, 422-) - BBOC furnace: 15 GJ/t-Ag anode - Equipment is used for 20 days/month (22 hours/day). - Use of kerosene
	(including Ag)	(22.7 t)	(including Ag)	(22.4 t)	
			Slag	51 t	
			Bismuth lead oxide	5 t	
	Electric power	(unknown)			
	Heavy oil	363.0 GJ	【CO_2 emission)	24.6 t	
7. Electrolysis	Silver anode	24 t	Electrolytic silver	21 t	- The grade of electrolytic silver: 99.99% - Equipment is used for 25 days/month (22 hours/day). - Consumed electric power of electrolytic furnace: 500 kWh/t-electrolytic Ag
	(including Ag)	(22.4 t)	Silver sedimentation	3 t	
	Electric power	101.2 GJ	【CO_2 emission】	3.7 t	
Total	Energy	2,042GJ	【CO_2 emission】	93.9 t	

Data source: produced by NRI using various data.

Reference: Kenichi Moriyama, “Noble Metal Smelting in Copper Smelting Plants in Sumitomo Metal Mining Co., Ltd.,” Sigen-to-Sozai, 109 (1993) , No.12

Yukinori Abe, et al, Some improvements at noble metal plants, Takehara smelting works, Sigen-to-Sozai, 110 (1994) No.5, 422

(14) Cadmium (Cd)

1) Overview of smelting

a. Smelting method

The main ores for cadmium are Cd sulfide ores, although the amount of production is small. Most metallic Cd is produced as byproducts in the smelting of zinc concentrates using materials such as smoke ash and dusts.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Dry method	Purified slag solution obtained at the time of zinc smelting	Toho Zinc Co., Ltd., Mitsui Mining and Smelting Co., Ltd., Nippon Mining and Metals Co., Ltd., etc.	○ (Combination of dry and wet methods in the present report.)
Wet method	Zn-Cg metal obtained at the time of zinc smelting		

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Domestic amount demanded (year 1998)
Plating	1 t
Alloy	52 t
Pigment	20 t
Vinylchloride stabilizer	0 t
Battery	2,016 t
Others	162 t

Data source: from Data book for Metals, 2000

2) Integration status of data such as mass balance

a. The process without roasting

Process	Used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report.	
1.Leaching	【INPUT】 - Cd concentration in flue dust: 4.0% 【Facility data】 - Use of a stirrer	【OUTPUT】 - Leaching rate is assumed to be 85%	【INPUT】 - Supplied amount of flue dust - Supplied and circulating amounts and concentration of sulfuric acid 【OUTPUT】 - Amount of leaching liquid, Cd concentration. - The amount of leached residue, Cd concentration, leaching rate of Cd. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating of leaching liquid
2.Condensation sedimentation		【INPUT】 - The amount of soda ash is estimated as a theoretical value required for carbonization. - Energy consumption in producing soda ash is estimated. 【OUTPUT】 -The yield of Cd is assumed to be 90% - CO_2 emission in producing soda ash is estimated. 【Facility data】 -It is assumed that a thickener (rated power 3.7 kW) is used to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount of soda ash 【OUTPUT】 - The amount of Cd carbonate, Cd concentration. - The amount of residual solution, Cd concentration. - Recovery rate of Cd. 【Facility data】 - Specification of engine, processing power etc., - Type and consumption of supplied energy. - Type and consumption of energy required for heating of leaching liquid
3. Removal of impurity by solvent	【Facility data】 - Use of a stirrer	【OUTPUT】 - The yield of Cd is assumed to be 95%.	【INPUT】 - Supplied and circulating amounts, and concentration of sulfuric acid. 【OUTPUT】 - The amount of solution, Cd concentration. - The amount of impurity removal, Cd concentration. - Recovery rate of Cd. 【Facility data】 - Specification of engine, processing power, etc. - Type and consumption of supplied energy. - Type and consumption of energy required for heating of leaching liquid
4. Substitution reduction	【Facility data】 -Use of a filter press -Use of a stirrer	【OUTPUT】 - The yield of Cd is assumed to be 97%. - The grade of Cd sponge is assumed to be 94%.	【OUTPUT】 - Recovery rate of Cd - The amount of Cd sponge, the grade of Cd 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy. - Type and consumption of energy required for heating of leaching liquid
5. Dissolution		【OUTPUT】 - The yield of Cd is assumed to be 75%. - The grade of fused Cd is assumed to be 95%.	【OUTPUT】 - The amount of fused Cd, the grade of Cd. - The recovery rate, the amount of dross and the grade of Cd. 【Facility data】 - Specifications of type, engine, processing power etc. Type and consumption of supplied energy.
6. Fusion	【OUTPUT】 - 60 t/month of fused metal is produced.	【OUTPUT】 -The loss of Cd is assumed to be zero.	【INPUT】 - Supplied amount of Zn-Cd alloy 【OUTPUT】 - The grade of Cd in molten metal. - The recovery of Cd. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy
7.Distillation	【OUTPUT】 - The grade of crude Cd: 97% 【Facility data】 - Use of a small rectification column -Equipment is used for 15 days/month. - Processing amount: 4 t/day -Distillation temperature: 600℃	【OUTPUT】 -The mass balance is estimated based on the Cd grade.	【OUTPUT】 - The amount of crude Cd, the recovery rate of Cd. - The amount of residue, the grade of Cd. 【Facility data】 - Type and consumption of supplied energy.
8.Alkali fusion	【OUTPUT】 - The grade of Cd: 99.998%	【OUTPUT】 -The mass balance is estimated based on the Cd grade.	【INPUT】 - Supplied amount of NaOH. 【OUTPUT】 - The amount of metal Cd, the recovery rate of Cd - The amount of impurity, Cd concentration. 【Facility data】 - Specifications of type, engine, processing power, etc. - Type and consumption of supplied energy.

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in process concerned.
【Facility data】: Data for equipment used in process concerned.
The indicated by 【INPUT】, 【OUTPUT】, 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

b. The process with roasting

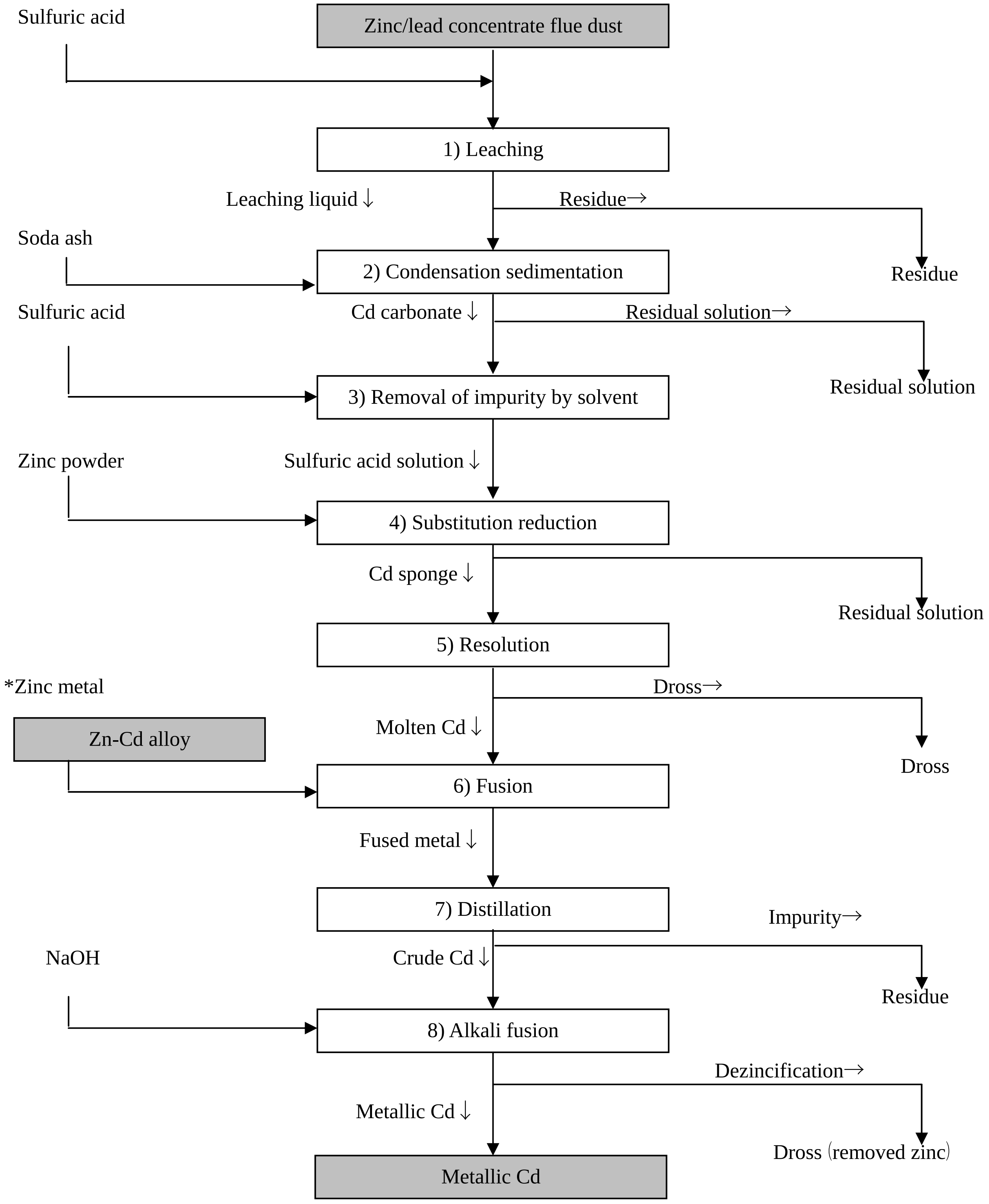
Process	Used data Data obtained from literature, etc.	Data assumed and estimated in this report.	Untaken data
1. Roasting	【INPUT】 - The amount of raw material dust: 360 t. - Supplied amount of sulfuric acid: 120 t. 【Facility data】 - Rotary kiln - Roasting temperature: 430℃ - Retention time: 2 hours - Heavy oil: 36 kL/month - Electric power: 95,000 kWh/month - Total energy source unit: 431 G cal/t-Cd metal	【INPUT】 - The energy consumption in producing sulfuric acid is estimated. 【OUTPUT】 - The yield of Cd is assumed to be 95%. - CO_2 emission in producing sulfuric acid is estimated.	【OUTPUT】 - The amount of roasted cake, grade of Cd. - The recovery rate of Cd - Generation amount of residue, gas, etc.
2. Leaching	【OUTPUT】 - Cd concentration in leaching liquid: 50g/L 【Facility data】 - Leaching temperature: 40℃ - Leaching hour: 5 hours/time - Use of edge mill	【OUTPUT】 - Cd leaching rate is assumed to be 90%. 【Facility data】 - A stirrer (rated power 2.2kW) is assumed to run. - An edge mill (rated power 150kW) is assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount of water 【OUTPUT】 - The amount of leaching liquid - The leaching rate of Cd - The amount of residue, Cd concentration 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating of leaching liquid
3. Solution purification		【OUTPUT】 - The loss of Cd is assumed to be zero.	【OUTPUT】 - The amount of solution purification, Cd concentration - The amount of cake, Cd concentration - Cd recovery rate 【Facility data】 - Specifications of engine, processing power etc. - Type and consumption of supplied energy.
4. Substitution reduction	【OUTPUT】 - The grade of Cd sponge: 98.4% 【Facility data】 - Zinc plate substitution - Substitution hour: 42 hours	【OUTPUT】 -The mass balance is estimated based on the grade of Cd.	【OUTPUT】 - The amount of Cd sponge, Cd yield - The amount of residual solution, Cd concentration. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy
5. Dissolution /distillation	【OUTPUT】 - The grade of Cd: 99.999% 【Facility data】 - Continuous vacuum distillation	【OUTPUT】 - The mass balance is estimated based on the grade of Cd.	【OUTPUT】 - The amount of impurity - The yield of Cd 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in process concerned.
【Facility data】: Data for equipment used in process concerned.
The indicated by 【INPUT】, 【OUTPUT】, 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

(Note)

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes (a. The process without roasting)



Data source: Mikiya Tanigawa, "Production of High-Purity Cadmium Using Dry Method," J. Min. Metal. Inst. Jpn. 90 1035 (74-75) 359-

Mass balance data (a. A case without roasting)

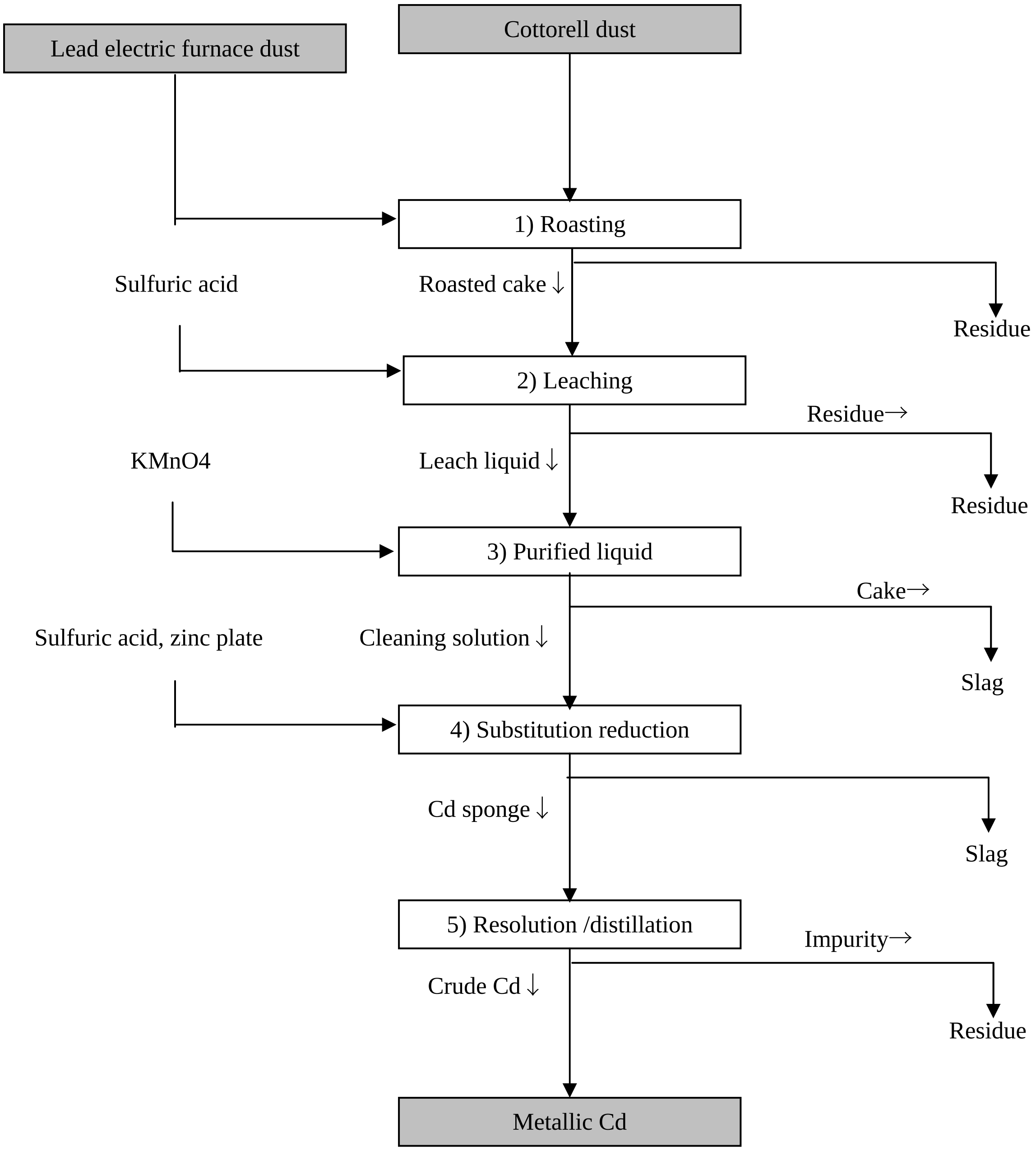
Monthly amount of material and energy

	INPUT		OUTPUT		Remarks
Process	Supplied materials etc.	Supplied amounts	Product	Amounts of products	
1. Leaching	Zinc-Lead concentrate flue dust	1,500 t	Leaching product	(unknown)	- Cd concentration in flue dust.: 4.0%
	(including Cd)	(60.0 t)	(including Cd)	(51.0 t)	- Leaching rate is assumed to be 85%.
	Sulfuric acid	(unknown)	(Leaching product excluding Cd)	(1,224 t)	
			Residue	225 t	- Use of stirrer
	Electric power	(unknown)	【CO_2 emission】	(unknown)	
2. Condensation sedimentation	Leaching product	(unknown)	Crude Cd carbonate	78.2 t	- The yield of Cd is assumed to be 90%.
	(including Cd)	(51.0 t)	Residual solution	(unknown)	- A thickener (3.7 kW) is assumed to be used.
	Soda ash	48.1 t			- Environmental load during soda ash production is considered.
	Electric power	21 GJ	【CO_2 emission】	40.1 t	- Equipment is used for 25 days/month (24 hours/day).
	【Soda ash production】	481GJ	(including production of soda ash)	(39.3 t)	
3. Removal of impurity by solvent	Crude Cd carbonate	78.2 t	Sulfuric acid solution	(unknown)	- The yield of Cd is assumed to be 95%.
	Sulfuric acid	(unknown)	(including refined Cd carbonate)	(70.4 t)	- Removal of As.
	Electric power	(unknown)	【CO_2 emission】	(unknown)	- Use of a stirrer
4. Substitution reduction	Sulfuric acid solution	(unknown)	Cd sponge	45.0 t	- The yield of Cd is assumed to be 97%.
	(including refined Cd carbonate)	(70.4 t)	Residual solution	(unknown)	- Use of zinc powder
					- Use of a filter press
	Electric power	(unknown)	【CO_2 emission】	(unknown)	- Use of a stirrer
5. Dissolution	Cd sponge	45.0 t	Fused Cd	33.4 t	- The yield is assumed to be 75%.
			Dross	11.6 t	
	Electric power	(unknown)	【CO_2 emission】	(unknown)	
6. fusion	Fused Cd	33.4 t	Fused metal	**60.0 t**	- The grade of fused Cd is assumed to be 95%.
	Zn-Cd alloy	26.6 t			
	electric power	(unknown)	【CO_2 emission】	(unknown)	
7. Distillation	Fused metal	60.0 t	Crude Cd	31.7 t	- Use of a small rectification column
			Residue	28.3 t	- The grade of crude Cd: 97%
					- Equipment is used for 15 days/month.
					- The amount of treatment: 4 t/day
	Electric power	(unknown)	【CO_2 emission】	(unknown)	- The distillation temperature: 600℃
8. Alkali fusion	Crude Cd	31.7 t	Metallic Cd	30.7 t	- The grade of Cd: 99.998%
	NaOH	(unknown)	Impurity	0.9 t	- Dezincification process
	Electric power	(unknown)	【CO_2 emission】	(unknown)	
Total	【Energy】	502 GJ	【CO_2 emission】	40.1 t	
	(including production of raw material)	(481 GJ)	(including production of raw material)	(39.3 t)	

Data source: produced by NRI using various data.

Reference: Mikiya Taniguchi, "Production of High-purity Cadmium Using Dry Method," J. Min. Metal. Inst. Jpn. 90 1035 (74-75)

Flow diagram of processes (b. The process with roasting)



Reference: Akira Kusanagi, et al., "Rationalization in Cadmium Smelting Process in Mikkaichi Smelter," J. Min. Metal. Inst. Jpn. 93 1070 ('77-4) p.319-

Mass balance data (a. A case with roasting)

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Roasting	(Cottorell dust)	(216 t)	Roasted cake	362 t	- Selective sulfation of CdO, PbO - The yield of Cd is assumed to be 95 %. - Equipment is used for 25 days/month (24 hours/day). - Roasting temperature: 430℃ - Retention time: 2 hours - Rotary kiln: use of heavy oil - Heavy oil: 95,000 kWh/month - Total energy source unit: 431 Gcal/t-Cd metal - Environmental load during sulfuric acid production is considered.
	(Lead electric furnace dust)	(144 t)	(including Cd)	(48.5 t)	
	Total dust	**360 t**	Residue, gas, etc	118 t	
	(including Cd)	(51.0 t)			
	Sulfuric acid	**120 t**			
	Electric power	898 GJ	【CO_2 emission】	133.1 t	
	Heavy oil	1,401 GJ	(including sulfuric acid production)	(3.1 t)	
	【Sulfuric acid production】	42 GJ			
2. Leaching	Roasted cake	362 t	Leaching liquid	872 kL	- Lead sulfate is removed. - Leaching temperature: 40℃ - Leaching time: 5 hours/one time - The leaching rate of Cd is assumed to be 90%. - A stirrer (150 kW) is assumed to run. - An edge mill is assumed to run for 25 days/month (24 hours/day). - Energy required for water heating is not considered.
	(including Cd)	(48.5 t)	(including Cd)	(43.6 t)	
	Water	872kL	(Leaching product excluding Cd)	(812 t)	
			Residue	136 t	
	Electric power	863 GJ	【CO_2 emission】	31.5 t	
3. Purified solution	Leaching liquid	872 kL	Purified solution	872 kL +	- Tl is removed. - Cd loss is assumed to be zero.
	(including Cd)	(43.6 t)	(including Cd)	(43.6 t)	
	Other additives	+ α	Cake	1.6 t	
	(Other additives) $KMnO_4$				
	Electric power	(unknown)	【CO_2 emission】	(unknown)	
4. Substitution reduction	Purified solution	872 kL +	Cd sponge	44.3 t	- Zinc plate substitution - Substitution time: 42 hours - The grade of Cd sponge: 98.4%
	(including Cd)	(43.6 t)	(including Cd)	(43.6 t)	
			Residual solution	872 kL	
			(including Cd)	(0.02 t)	
	Electric power	(unknown)	【CO_2 emission】	(unknown)	
5. Resolution/ distillation	Cd sponge	44.3 t	Cd product	**40.0 t**	- The grade of Cd product: 99.999% - Continuous vacuum distillation method
	(including Cd)	(43.6 t)	Impurity etc.	4.3 t	
	Electric power	(unknown)	【CO_2 emission】	(unknown)	
Total	【Energy】	3,204 GJ	【CO_2 emission】	164.6 t	
	(including raw material production)	(42 GJ)	(including raw material production)	(3.1 t)	

Data source: produced by NRI using various data

Reference: Akira Kusanagi et al., "Rationalization in Cadmium Smelting Process in Mikkaichi Smelter," J. Min. Metal. Inst. Jpn. 93 1070 ('77-4) p.319-

(15) Indium (In)

1) Overview of smelting

a. Smelting method

Ores including In as the main component are not known. In is mostly included in the ores of lead, zinc, etc, and thus is produced as a byproduct in the smelting of these metallic elements.

For the smelting of metallic In, the solvent extraction method is used.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Solvent extraction method	Zinc smelting	Metaleurope. SA(Fr.), Indium Corp. of America (U.S.), Nippon Mining & Metals, Sumitomo Metal Mining, Dowa Mining	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Products	Domestic amount demanded (year 1998)
Compound semiconductor	Semiconductor laser, infrared detector, etc.	5 t
Transparent electrode	Liquid crystal TV, solar cell, etc	58 t
Fluorescent substance	Monochrome CRT, etc.	4 t
Bonding materials	Adhesives for spattering target	6 t
Low melting alloy	Solder fuse etc.	3 t
Dental alloy	-	4 t
Point connector materials	-	4 t
Bearing	Airplane, motor vehicle, etc.	1 t
Battery	-	4 t

Data source: from Data Book for Materials, 2000, Metal Mining Agency of Japan (web site) etc.

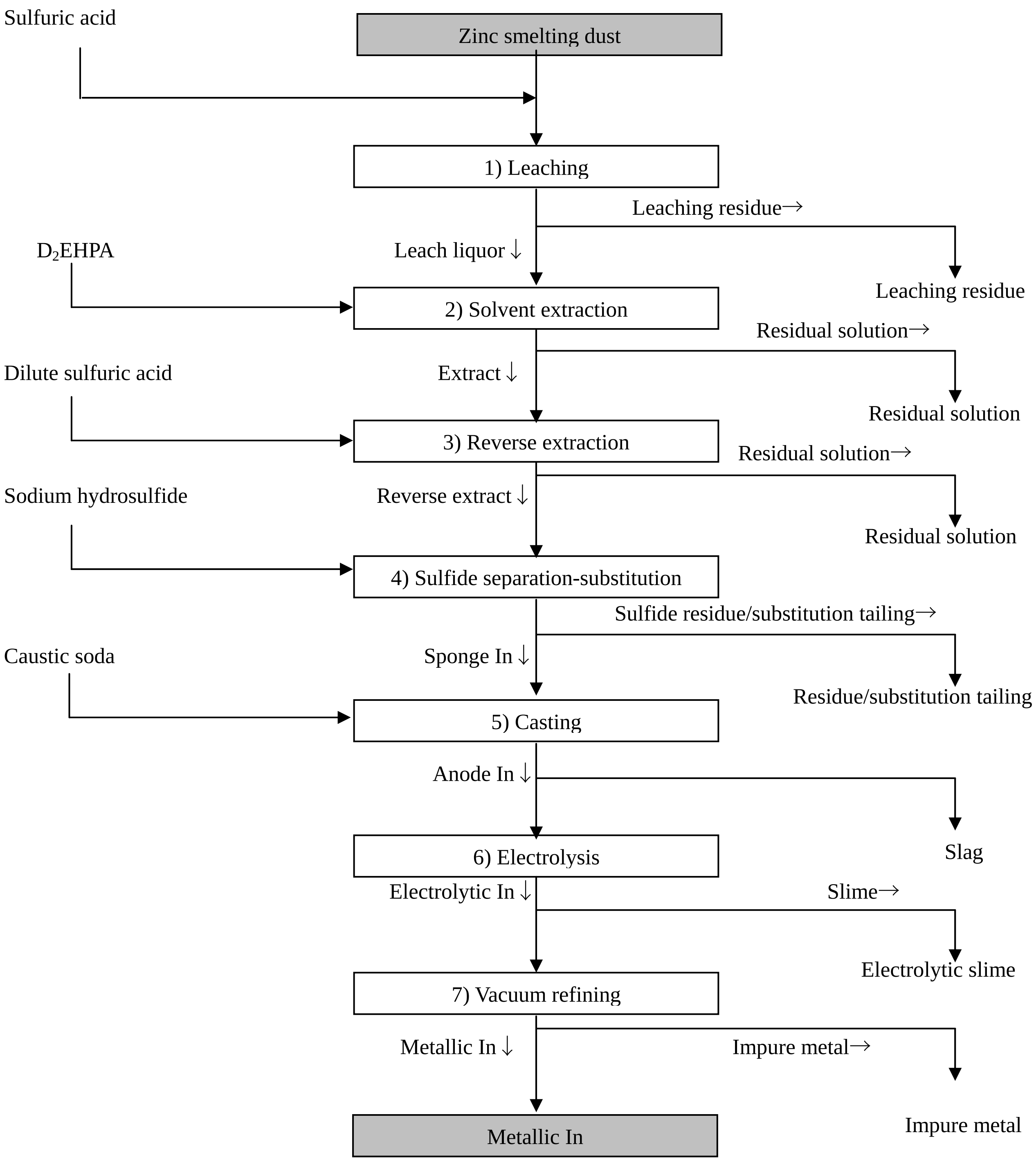
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report	
1. Leaching	【INPUT】 - Supplied amount of dust : 800 t/month - The grade of In in dust: 0.2% **【OUTPUT】** - Average leaching rate of dust: 92.5%, In leaching rate: 85%, - In concentration in leaching liquid: 2g/L	**【INPUT】** - The amount of dilute sulfuric acid is counted backward from In leaching concentration. The amount of circulation is not considered. **【OUTPUT】** - In yield is assumed to be 85% **【Facility data】** - A stirrer (rated power 2.2 kW) and a filter press (0.4kW) are assumed to run for 25 days/month (24 hours/day).	**【INPUT】** - The amount of sulfuric acid. **【OUTPUT】** In recovery rate - The amount of leaching liquid - Residue **【Facility data】** - Specification of engine, processing power etc. - Type and consumption of supplied energy. - Type and consumption amounts of energy required for heating of leaching liquid.
2. Solvent extraction	**【OUTPUT】** - In extraction rate is 97% - In concentration in extraction liquid: 30g/L **【Facility data】** - Use of stirrers (2.2 kW) and 7 mixer settlers	**【INPUT】** - The energy during production of D_2EHPA extraction liquid is not considered. **【OUTPUT】** - The amount of solution is counted backward from In extraction concentration. **【Facility data】** - Equipment is assumed to run for 25 days/month (24 hours/day).	**【INPUT】** - The amount of extraction liquid - The amount of energy consumption at the time of production. of extraction liquid **【OUTPUT】** - The amount of extraction liquid - The amount of residual solution, solution concentration. **【Facility data】** - Type and consumption of supplied energy required for extraction liquid heating.
3. Inversion extraction	**【OUTPUT】** - Inversion extraction rate is 97 % - The grade of In in inversion extraction liquid: 35g/L	**【INPUT】** - The amount of energy consumption at the time of production of dilute sulfuric acid is estimated. (The acid concentration is estimated to be 250 g/L) **【OUTPUT】** - CO_2 emission at the time of production of dilute sulfuric acid is estimated. **【Facility data】** - A stirrer (rated power 1.5 kW) is assumed to run for 15 days/month (24 hours/day).	**【INPUT】** - The amount of inversion extraction liquid **【OUTPUT】** - The amount of inversion extraction liquid - The amount of residual solution, solution concentration **【Facility data】** - Specification of engine, processing power etc. - Type and consumption of supplied energy - Type and consumption of supplied energy required for heating of inversion extraction liquid.
4. Sulfide separation/ substitution	**【OUTPUT】** - The amount of In in tailing liquid: 0.8g/L	**【INPUT】** - The amount of energy consumption at the time of production of sodium hydrogen sulfide is estimated. **【OUTPUT】** - Amounts of residue and required sodium hydrogen sulfide (theoretical amount) are estimated on condition that As is removed to become As_4S_4 by assuming that the grade of As in extraction liquid is 0.05 g/L. - CO_2 emission at the time of production of sodium hydrogen sulfide is estimated. **【Facility data】** - A stirrer (rated power 1.5 kW) is assumed to run for 15 days/month (24 hours/day).	**【INPUT】** - The amount of sodium hydrogen sulfide **【OUTPUT】** - The grade and the amount of sponge In - The amount of residue and the grade of In. - Tailing liquid **【Facility data】** - Specification of engine, processing power etc. - Type and consumption of supplied energy - Type and consumption of supplied energy required for heating of solution
5. Casting	**【OUTPUT】** - The grade of In: 99.5% - The yield of In: 75%	**【INPUT】** - The amount of energy consumption at the time of production of caustic soda is estimated. **【OUTPUT】** - The amount of CO_2 emission at the time of production of caustic soda is estimated.	**【INPUT】** - The amount of caustic soda **【OUTPUT】** - The amount of anode In - The amount of slag, the grade of In in slag. **【Facility data】** - Specification of engine, processing power etc. - Type and consumption of supplied energy.
6. Electrolysis	**【OUTPUT】** - The grade of In: 99.98% - The yield of In: 95% **【Facility data】** - Electric furnace energy consumption: 300 kWh/t-electrolytic In	**【OUTPUT】** - Mass balance is estimated based on the grade and the yield of In.	**【OUTPUT】** - The amount of electrolytic In. - The amount of slime, the grade of In
7. Vacuum refining	**【OUTPUT】** - The grade of In: 99.99% **【Facility data】** - Heating In to 1,000℃ under reduced pressure.	**【INPUT】** - Energy consumption is assumed to be energy required for heating electrolytic In. - Energy loss is not considered. **【OUTPUT】** - Mass balance is estimated based on the grade and the yield of In.	**【OUTPUT】** The amount of metallic In. - The amount of impurity, the grade of In **【Facility data】** - Specification of engine, processing power etc. - Type and consumption of supplied energy.

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in process concerned.
【Facility data】: Data for equipment used in process concerned.
The indicated by 【INPUT】, 【OUTPUT】, 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Koji Yamaguchi et al., “Production of Indium by Solvent Extraction Method,” J. Min. Metal. Inst. Jpn. 96 1106 (80~84) 257-

Mass balance data

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Leaching	Zinc smelting dust	800 t	Leach liquor	740 kL	- Grade of In in dust: 0.2%
	(Including In)	(1,600 kg)	(Including In)	(1,360 kg)	- Average leaching rate of dust: 92.5%
	Dilute sulfuric acid (Zinc electrolytic tailing)	740 kL	(the amount of leaching except for In)	(739 t)	- In leaching rate: 85% - Running for 25 day/ month (24 hour/day)
			Leaching residue	60 t	- A stirrer (rated power 2.2kW) is assumed to be used. - A filter press (0.4kW) is assumed to be used.
	Electric power	12.5GJ	【CO_2 emission】	456 kg	
2. Solvent extraction	Leaching liquid	740 kL	Extract	44 kL	- Extraction rate: 97%
	(Including In)	(1,360 kg)	(Including In)	(1,319 kg)	- Extraction solvent: D_2EHPA
	Extract	44 kL	Residual solution	740 kL	- In concentration in extract: 30g/L - A stirrer (2.2kW) and 7 mixer settlers are assumed to run for 25 day/month (24 hour/day) - Energy amounts for D_2EHPA production and heating liquid are not considered.
	Electric power	12.5 GJ	【CO_2 emission】	456 kg	
3. Reverse extraction	Extraction liquid	44 kL	Reverse extract	37 kL	- Inversion extraction rate: 97%
	(Including In)	(1,319 kg)	(Including In)	(1,280 kg)	- Inversion extraction solvent: dilute sulfuric acid (acid concentration: 250 g/L)
	Reverse extract	37 kL	Residual solution	44 kL	- A stirrer (1.5kW) is assumed to run for 15 days/month (24 hour/day).
	Electric power	8.5 GJ	【CO_2 emission】	327 kg	- The environmental load for production of sulfuric acid is considered.
	【Sulfuric acid production】	0.21 GJ	(Sulfuric acid production)	(16 kg)	- Heating liquid is not considered.
4. Sulfide separation /substitution	Reverse extract	37 kL	Sponge In	1.250kg	- Removal of As, Bi, etc.
	(including In)	(1,280 kg)	Sulfide residue	3 kg	- Substitution of aluminum plate
	Sodium hydrosulfide	1.4 kg	Substitution tailing	37kL	- A stirrer is assumed to be rated power 1.5kW. - A filter press (0.4kW) is assumed to run for 10 days/month (12 hours/day).
	Electric power	2.2 GJ	【CO_2emission】	80 kg	- Liquid is not heated.
	【Sodium hydrosulfide production】	0.22 GJ	(Including production of sodium hydrosulfide)	1.4 kg	- The environmental load for production of sodium hydrosulfide (NaSH) is considered.
5. Casting	Sponge In	1,250 kg	Anode In	938 kg	- The grade: 99.5%, or more
	Caustic soda (flux)	625.2 kg	Slag	938 kg	- The yield : 75% - The environmental load of caustic soda is considered.
	Electric power	(unknown)	【CO_2 emission】	586 kg	
	【Sodium hydroxide production】	7.2 GJ	(Sodium hydroxide production)	(586 kg)	- Energy for casting is not included.
6. Electrolysis	Anode In	938 kg	Electrolytic In	887 kg	- The grade: 99.98%, or more
			Slime	51 kg	- The yield : 95%
	Electric power	2.5 GJ	【CO_2 emission】	92 kg	- Electric power consumption of electrolytic furnace: 300 kWh/t-electrolytic In
7. Vacuum refining	Electrolytic In	887 kg	Metallic In	887 kg	- The grade: 99.99%, or more
			Impurity	0.1kg	- Zinc etc. is volatilized to remove by heating to 1,000 ℃ under reduced pressure. (Electricity is used.)
	Electric power	0.2 GJ	【CO_2 emission】	7.3 kg	
Total	【Energy】	45.7 GJ	【CO_2emission】	2,004 kg	
	(Including raw material production)	(7.4 GJ)	(Including raw material production)	(604 kg)	

Data source: produced by NRI using various data.

Reference: Shuntaro Ono et al., “Recovery of In in Annaka Smelter,” J. Min. Metal. Inst. Jpn., 90, 1035 (’74-75) 377-

Koji Yamaguchi et al., “Production of Indium by Solvent Extraction Method,” J. Min. Metal. Inst. Jpn. 96 1106 (’80~84) 257-

Hitoshi Masuda, “Electrolyses of Gallium and Indium,” Kagakukogyo, 30-8, p.72, published by Kagakukogyo Co., Ltd.

(16) Tin (Sn)

1) Overview of smelting

Smelting method

The raw ore of metallic Sn is SnO_2. Sn smelting is usually performed by electrolyzing crude Sn which is obtained by processing SnO_2 concentrates with dry methods using blast-, reverberating -, or electric-furnaces etc.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the presence report
Dry /electrolytic methods	Cassiterite, tin slag	Mitsubishi Materials, Mitsui Kinzoku, etc.	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Domestic amount demanded (FY 2001)
Tin plate	-
Electric wire	296,303 t
Elongated copper product	1,658,928 t
Solder/copper alloy block	10,537,841 t

Data source: Yearbook of Minerals and Non-Ferrous Metals Statistics FY2001, Ministry of Economy, Trade and Industry

2) Integration status of data such as mass balance

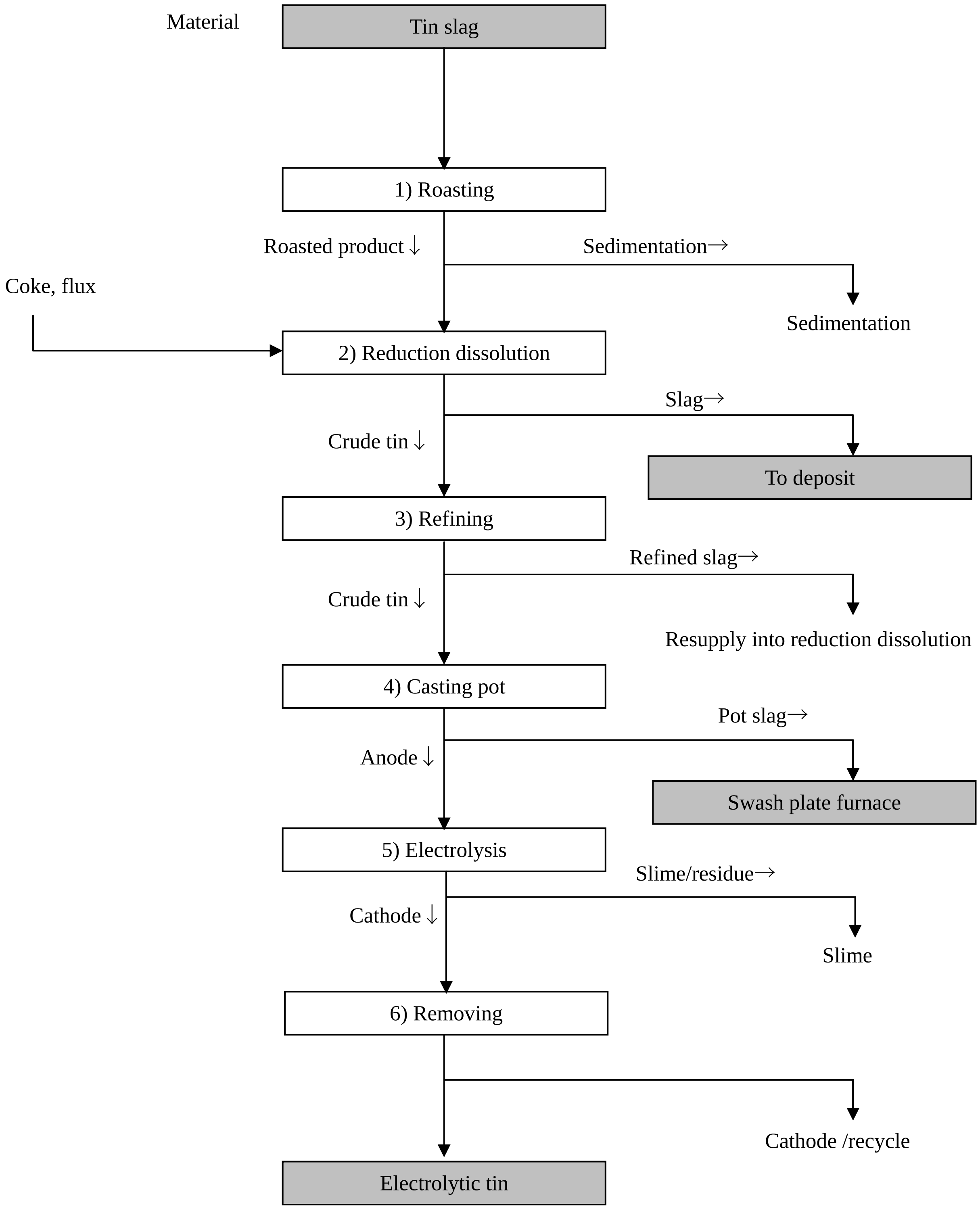
Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report.	
1.Roasting	【Facility data】 - Use of rotary kiln - Heavy oil 35 L/hour (average)	【INPUT】 - Mass balance is calculated by assuming that 10% of Tin slag is emitted as sedimentation, gas, etc. by roasting. 【Facility data】 - It is calculated by assuming to run for 4 day/month (24hours/day).	【INPUT】 - Supplied amount of tin slag, the grade of Tin. 【OUTPUT】 - The recovery rate of tin - The amount of roasted products, the grade of Tin. - The amount of sedimentation, the grade of tin - The amount of gas. 【Facility data】 - Operational status
2. Reduction dissolution	【OUTPUT】 - The grade of Sn in crude Tin: 90 % - The grade of Sn in slag: 12.5% 【Facility data】 - Use of electric furnace - Batch method - One cycle/3 hours, 1350 kWh/cycle	【INPUT】 - The grade of Sn in roasted product is assumed to be 65 %. 【OUTPUT】 - The yield of Sn from roasted product is assumed to be 70%. 【Facility data】 - It is assumed to run for 2 cycles/day and 20 days/month.	【OUTPUT】 - The amount of coarse tin - The amount of slag - The recovery rate of tin 【Facility data】 - Operational status
3. Refining	【OUTPUT】 - The grade of Sn in crude tin: 90 % - The grade of Sn in refined slag: 12.5 %	【OUTPUT】 - Mass balance is estimated by assuming that the grade of crude tin is 95%.	【OUTPUT】 - The amount of crude tin, the grade of tin. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy
4. Casting pot	【OUTPUT】 - The grade of Sn in anode:97.55% - The grade of Sn in pot slag: 85% 【Facility data】 - Use of casting machine	【OUTPUT】 - Mass balance is estimated based on the grade of tin.	【OUTPUT】 - The amount of anode - The amount of pot slag 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy
5. Electrolysis	【INPUT】 - The amount of heavy oil used: 60L-electrolytic tin (Hot air removing machine) 【OUTPUT】 - The grade of electrolytic tin: 99.996% - The grade of tin in slime: 27.4% 【Facility data】 - Consumption of electric power for electrolysis: 200 kWh/t-electrolytic Sn	【OUTPUT】 - Mass balance is estimated based on the grade of tin.	【OUTPUT】 - The amount of slime

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in process concerned.
【Facility data】: Data for equipment used in process concerned.

The indicated by 【INPUT】, 【OUTPUT】, 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Hideomi Saito, et al., “Smelting of Tin in Ikuno Manufacturing Co., Ltd.,” Sigen to Sozai 109 (1993) No.12 141-

Mass balance data

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Roasting	Tin slag	188.3 t	Roasted product	169.5 t	- Use of rotary kiln
			Sedimentation, gas, etc.	18.8 t	- Heavy oil: 35 L/hour (average)
					- It is assumed that 10% of tin slag is processed.
	Heavy oil	131 GJ	【CO$_2$emission】	9.1 t	- Running for 4 days/month (24 hours/day)
2. Reduction dissolution	Roasted sedimentation	169.5 t	Coarse tin	85.7 t	- Electric furnace: batch method
			Slag	83.8 t	- 1 cycle/3 hour, 1,350 kWh/cycle
					- It is assumed to run for 2 cycles/ day (20 days/month).
	Electric power	510 GJ	【CO$_2$emission】	18.7 t	
3. Refining	Crude tin	85.7 t	Crude tin	71.4 t	- The grade of coarse tin: 90%
			Refined slag	14.3 t	
	Heavy oil	(unknown)	【CO$_2$emission】	(unknown)	
4. Casting pot	Crude tin	71.4 t	Anode	56.9 t	- The grade of Sn in anode: 97.55%
			Pot slag	14.5 t	- The grade of Sn in pot slag: 85%
					- Use of casting machine
	Electric power	(unknown)	【CO$_2$emission)	(unknown)	
5. Electrolysis	Anode	56.9 t	Electrolytic tin	**55.0 t**	- The grade: 99.996%
			Slime	1.9 t	- Electric power consumption for electrolysis: 200 kWh/t electrolytic Sn
					- Consumption of heavy oil (by hot air remover) is equal to 60 L/ton of electrolytic Sn, J. Min. Metal. Inst. Jp., 97 1122 (81-8) p.775
	Electric power	104 GJ			
	Heavy oil	128 GJ	【CO$_2$emission】	12.7 t	
Total	【energy】	873 GJ	【CO$_2$emission】	40.4 t	

Data source: produced by NRI using various data.

Reference: Hideomi Saito, et al., “Smelting of Tin in Ikuno Manufacturing Co., Ltd.,” Sigen to Sozai 109 (1993) No.12 141-

(17) Antimony (Sb)

1) OVERVIEW OF SMELTING

a. Smelting method

The main raw ores of metallic Sb are sulfide and oxide minerals. The most important ore is stibnite (Sb_2S_3), and the Sb smelting is mostly done using Sb_2S_3 as the raw material. There are dry and wet methods for smelting, and at present, the dry type is dominant. The Sb oxide reduction method is usually used as the dry type one.

Smelting method	Starting materials	Smelting method adopted in the present report
Dry method (Sb oxide reduction method)	Sulfide mineral	○
Wet method (Ferrous sedimentation method)	High grade sulfide mineral	×
Dry method (Smelting furnace method)	Sulfide mineral	×
Wet method	Sulfide mineral	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Products	Domestic amount demanded (year 2001)
Special steel	-	116,301 t
Batteries	Products for vehicles, etc.	203,787 t
Antimonial lead casting	Products for chemical device and equipment, etc.	99,132 t
Cable and wire	-	10,338 t
Others	Lubricant, flame retardant agent of polymer resin, etc.	200,648 t

Data source: 2001.Ministry of Economy, Trade and Industry, Yearbook of Minerals and Non-Ferrous Metal Statistics, Web site of the Metal Mining Agency of Japan, etc.

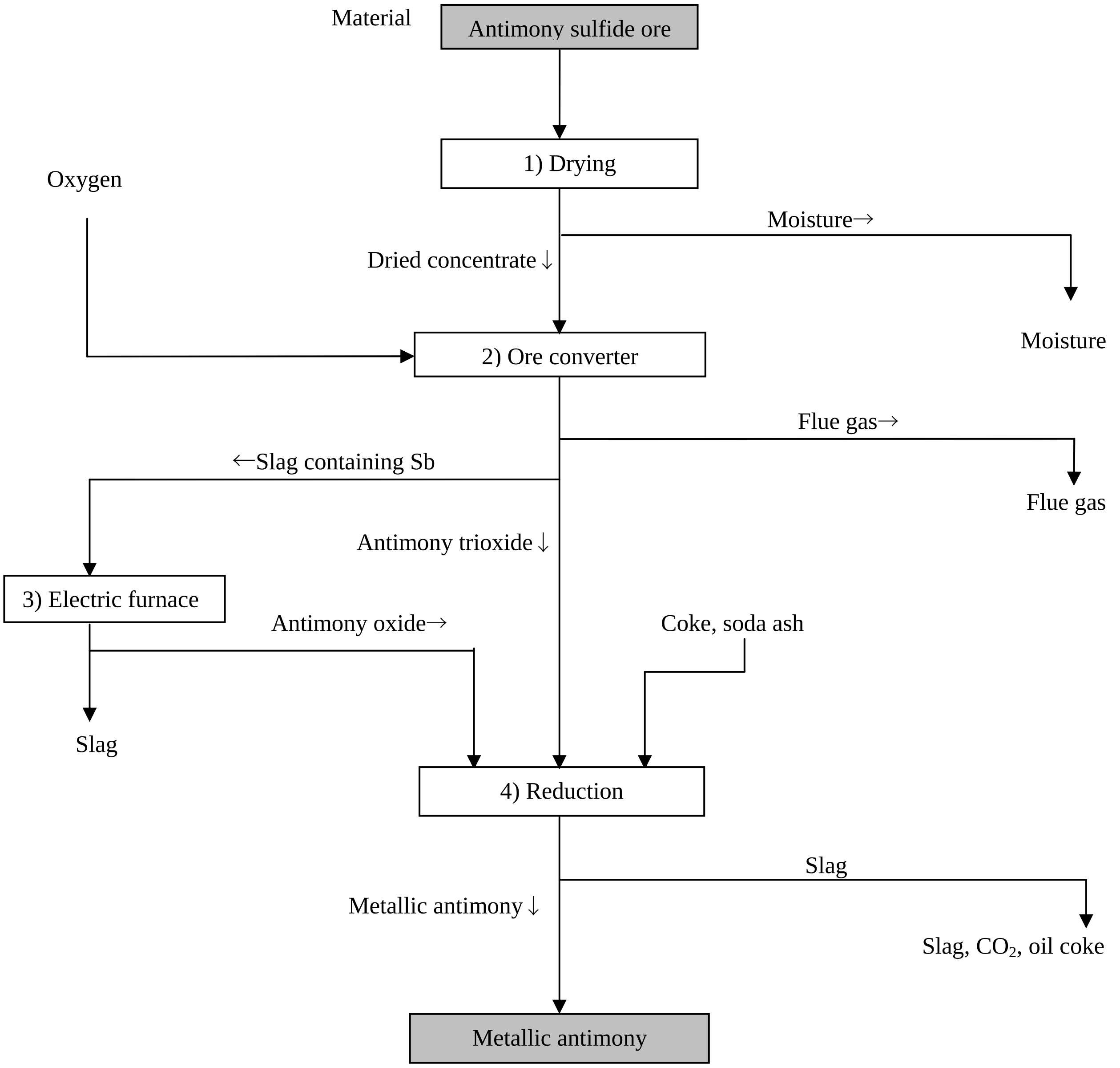
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report	
1. Drying	【INPUT】 - The grade of Sb in ore: 61.5% 【Facility data】 - Use of band dryer	【INPUT】 - Latent heat of water evaporation is estimated as the consumed energy. The loss of energy is not considered. - Heavy oil is used for heating.	【INPUT】 - Supplied amount of ore 【OUTPUT】 - The recovery rate of Sb - The amount of dried refining ore, the grade of Sb - The amount of moisture evaporated 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy.
2. Ore converter	【OUTPUT】 - The grade of Sb trioxide: 79.48% - The grade of Sb in slag: 40% 【Facility data】 - Rotary furnace using LPG - Processing power of the rotary furnace: 30 t/30 hours	【INPUT】 - Latent heat of water evaporation is estimated as the consumed energy. The loss of energy is not considered. - Heavy oil is used for heating. - The amount of oxygen is estimated as consumption by oxidation.	【OUTPUT】 - The recovery rate of Sb - The amount of Sb trioxide - The amount of slag including Sb 【Facility data】 - Specifications of engine, etc. - LPG consumption
3. Electric furnace		【OUTPUT】 - The yield of Sb is assumed to be 99%	【OUTPUT】 - The recovery rate of Sb - The amount of Sb trioxide - The amount of slag 【Facility data】 - Specifications of engine, processing power, etc. - Electric consumption, and type and consumption of other supplied energy.
4. Reduction	【OUTPUT】 - The grade of metallic Sb: 98.79% - The grade of Sb trioxide: 71.75% 【Facility data】 - Reverberatory furnace: use of heavy oil	【INPUT】 - Sb trioxide is estimated as a summation used for rotary and electric furnaces. - The carbon content of coke is assumed to be 80%, which is emitted as CO_2. - The energy of soda ash consumed is estimated at the time of production. 【OUTPUT】 - The CO_2 emission from soda ash consumed is estimated at the time of production.	【OUTPUT】 - The recovery rate of Sb - The grade of slag 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.
【Facility data】: Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Source: Junichi Mizokuchi, "Production of antimony compounds in Nakase Smelting Factory, Nihon Seiko Co., Ltd.," Sigen to Sozai, 109 (1995) No. 12, p. 1198-

Mass balance data

The amounts of material/energy are those per batch of converter.

	INPUT		OUTPUT		
Process	Supplied materials etc.	Supplied amounts	Products	Amounts of products	Remarks
1. Drying	Antimony sulfide ore	3.9 t	Dried concentrate	3.7 t +	- The grade of Sb: 61.5%
	(including Sb)	(2.4 t)	(including Sb)	(2.4 t)	- Use of band dryer
	Other additives	+ α	Moisture	0.22 t	- Latent heat of water vaporization is considered as energy. Heavy oil is used for heating.
	(Other additives)				
	Slaked lime				
	Heavy oil	0.50 GJ	【CO_2emission】	34.4 kg	
2. Ore converter	Dried concentrate	3.7 t	Antimony trioxide	2.7 t	- The processing power per cycle operation of ore converter is 30t/30 hours. Slag is removed every cycle by tilting the converter.
	(including Sb)	(2.4 t)	(including Sb)	(2.2 t)	
	Oxygen	1.1 t	Sb containing slag	0.60 t	
			Flue gas	1.42 t	
					- The grade of antimony trioxide: 79.48%
					- The grade of Sb in slag: 40%
					- Rotary furnace: use LPG
	LPG	(unknown)	【CO_2emission】	(unknown)	
3. Electric furnace	Sb containing slag	0.60 t	Antimony trioxide	0.29 t	- The yield of Sb in Sb containing slag is assumed to be 99%.
	(including Sb)	(0.23 t)	(including Sb)	(0.23 t)	
			Slag	0.31 t	- The grade of antimony trioxide: 79.48%
	Electric power	(unknown)	【CO_2emission】	(unknown)	
4.Reduction	Antimony trioxide	3.0 t	Metallic antimony	**2.2 t**	- The supplied amount of antimony trioxide is total value for ore converter and electric furnace.
	(including Sb)	(2.4 t)	(including Sb)	(2.2 t)	
	Oil coke	**0.22 t**	Slag	**0.32 t +**	
	Soda ash	**0.10 t**	Antimony trioxide	**0.27 t**	- Oil coke: as a reducing agent
	Other additives	+ α	(including Sb)	(0.19 t)	- Soda ash: as a solvent
			CO_2	0.49 t	- The grade of metallic antimony: 98.79%
	(Other additives)		Oil coke (unreacted)	0.03 t	
	Caustic soda				- The grade of produced antimony trioxide: 71.75%
					- Caustic soda: use for high purity metal production
					- Reverberatory furnace: use heavy oil
					- The environmental load for the soda ash production is considered.
	Electric power	(unknown)			- The carbon content of coke is assumed to be 80%, which is completely emitted as CO_2.
	Oil coke	7.82 GJ	【CO_2emission】	1,120 kg	
	Heavy oil	(unknown)	(including soda ash production)	(82 kg)	- The amount of CO_2 produced from Sb reduction is estimated as emission.
	(Production of soda ash)	1.00 GJ			
Total	【energy】	9.32 GJ	【CO_2emission】	1,154 kg	
	(including raw material production)	(1.00 GJ)	(including raw material production)	(82 kg)	

Data source: produced by NRI using various data.

Reference: Junichi Mizokuchi, “Production of antimony compounds in Nakase Smelting Factory, Nihon Seiko Co., Ltd.,” Sigen to Sozai, 109 (1995) No. 12, p. 1198-

(18) Hafnium (Hf)

1) Overview of smelting

a. Smelting method

Hafnium is included in the zirconium ore as HfO_2. Metallic hafnium is produced as a by-product of the zirconium smelting.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
By-product of zirconium smelting	Tailing extract of Zr smelting (hafnium sulfate)	Wah Chang (USA), Westinghouse (USA), CEZUS (France), etc.	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Concrete product
Nuclear reactor materials	Control rod, etc.
Electrode tip	Cutting of metallic materials, electrode tip for welding, etc.
Additives	Super-strong heat resisting alloy including Ta, Mo, W, Nb, etc. (Aircraft engine parts)
Corrosion resisting materials	Chemical plant, chemical instrument, etc.
Electronics	X-ray tube, rectifier tube, negative electrode for high-voltage discharge tube, optical fiber materials, etc.

Data source: from Data Book for Metals, 2000, Metal Mining Agency of Japan (web site) etc.

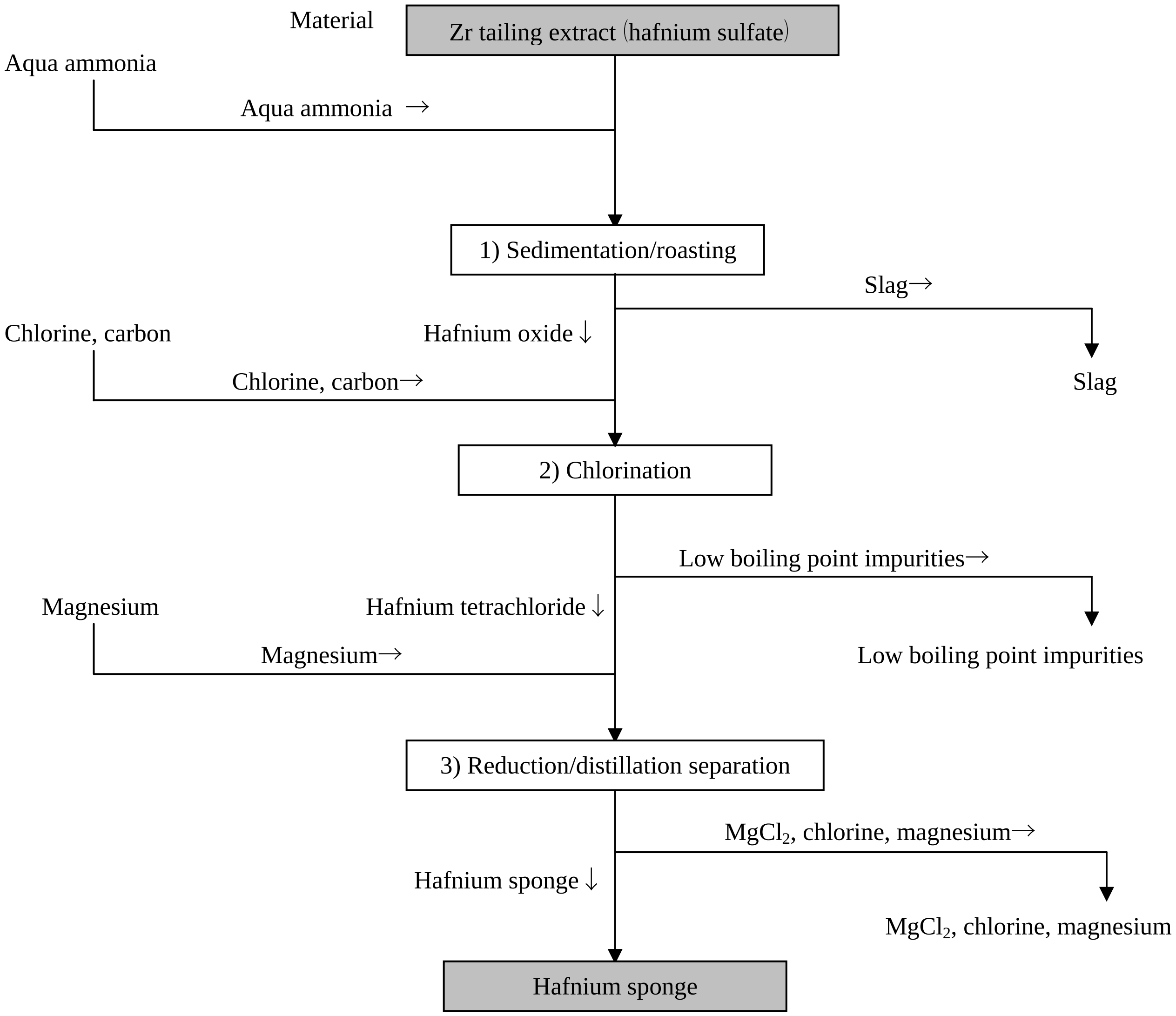
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report	
1. Sedimentation/ roasting		【OUTPUT】 - The yield of Hf is assumed to be 98%. - The amount of Zr tailing extract (sulfuric acid) is estimated as the pure consumption excluding the circulating amount by referring to the mass balance of Zr. - The grade of hafnium oxide is assumed to be 90%	【INPUT】 - The amount of tailing extract, Hf concentration 【OUTPUT】 - The recovery rate of Hf - The amount of hafnium oxide, the grade of Hf - The amount of slag, the grade of Hf 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy
2. Chlorination		【INPUT】 - Mass balance is calculated by referring to the chlorination process of Ti smelting. - The amount of chlorine is assumed to be only amount contributing to the reaction (a theoretical value). The loss is not considered. - The energy consumption is estimated at the time of production of chlorine consumed. 【OUTPUT】 - The yield of Hf is assumed to be 97% - The grade of Hf tetrachloride is assumed to be 93% - The CO_2 emission is estimated at the time of production of chlorine consumed.	【INPUT】 - Supplied amount of chlorine - supplied amount of carbon 【OUTPUT】 - The recovery rate of Hf - The amount of hafnium tetrachloride, the grade of Hf - The amount of impurity, the grade of Hf 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy
3. Reduction/ distillation separation	【OUTPUT】 - The grade of Hf sponge: 95.3% - The CO_2 emission is estimated at the time of production of chlorine consumed. 【Facility data】 - Use of electric furnace	【INPUT】 - Mass balance is calculated by referring to the reduction process of Ti smelting. 【OUTPUT】 - The yield of Hf is assumed to be 98% - The grade of Hf sponge is assumed to be 93%	【INPUT】 - Supplied amount of Mg 【OUTPUT】 - The recovery rate of Hf - The amount of Hf sponge - The generated amount of chlorine - The amount of non-reacted Mg 【Facility data】 - Specifications of engine, power processing ability, etc. - The type and consumption of supplied energy

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.
【Facility data】: Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Yuhei Kokubo, “Smelting of zirconium and hafnium in Nippon Kogyo Co., Ltd. (the central laboratory),” J. Min. Metal. Inst. Jpn./97, 1122 (81-8) p. 877-

Mass balance data

Monthly amount of material and energy

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amount of products	
1. Sedimentation/ roasting	Zr tailing extract	5.6 kL	Hafnium oxide	273.2 kg	- The yield of Hf is assumed to be 98%.
	(including Hf)	(225.3 kg)	(including Hf)	(220.8 kg)	
	(Others)	(0.8 t)	Slag/water vapor	779.3 kg+	- Hf in extract exists as $HfO(SO_4)_2$ ion.
	Aqueous ammonia	+ α			
	Electric power	(unknown)			
	Fuel	(unknown)	【CO_2emittion】	(unknown)	
2. Chlorination	Hafnium oxide	273.2 kg	Hafnium tetrachloride	402.4 kg	- Mass balance is estimated based on the chlorination process of Ti smelting. - The yield of Hf is assumed to be 97%. - The grade of hafnium oxide is assumed to be 90% - The grade of hafnium tetrachloride is assumed to be 93%.
	(including Hf)	(220.8 kg)	(including Hf)	(213.7 kg)	
	Chlorine	178.1 kg	Low boiling point impurities	69.2 kg	
	Carbon	20.2 kg			
	Electric power	(unknown)	【CO_2emittion】	109.3 kg	- The environmental load for chlorine production is considered.
	【Chlorine production】	1.3 GJ	(including chlorine production)	(109.3 kg)	
3. Reduction/ distillation separation	Hafnium tetrachloride	402.4 kg	Hafnium sponge	219.4 kg	- Mass balance is estimated based on the reduction process of Ti smelting. - The yield of Hf is assumed to be 98% - The grade of Hf: 95.3% - The yield of Hf from main raw material, zirconic sand, is assumed to be 90% in Zr smelting
	(including Hf)	(213.7 kg)	(including Hf)	(209.0 kg)	
	Magnesium	94.0 kg	$MgCl_2$	239.5 kg	
			Chlorine	4.6 kg	
			Mg (unreacted)	32.9 kg	
	Electric power	(unknown)	【CO_2emittion】	(unknown)	- Use of electric furnace
Total	【energy】	1.3 GJ	【CO_2emittion】	109.3 kg	
	(including raw material production)	1.3 GJ	(including raw material production)	(109.3 kg)	

Data source: produced by NRI using various data.

Reference: Yuhei Kokubo, “Smelting of zirconium and hafnium at Nippon Kogyo Co., Ltd. (the central laboratory),” J. Min. Metal. Inst. Jpn./97, 1122 (81-8) p. 877-

(19) Tantalum (Ta)

1) Overview of smelting

a. Smelting method

The main ores of Ta are Tantalite and Columbite. Recently, rather than from Ta ores, production is usually done from by-products in Sn smelting etc. (slag) and artificial concentrates. In many cases, Ta and Nb coexist in ores.

As smelting methods, the fluorine dissolution method due to MIBK for the crude dissolution of ores, the solvent extraction method to refine the raw materials, and the reduction method using an alkaline metal (metallic Na) to obtain Ta powders are mainly used.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Fluorine dissolution method/MIBK extraction/alkali metal reduction	Tantalum ore (low to high quality ores)	Most generally used	○
Alkali fusion/fractional crystallization method/electrolytic method	Tantalum ore (high quality ore)	-	×
Chlorination method/electrolytic method, etc.	Tin tailing Tin slag	Most generally used as supplied sources other than ores	×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Products
Powder for condenser	-
Super hard tools	Carbon tantalum, etc.
Rolled products	-
Electronics	Wire, foil, etc.
General industry	Heat resisting and corrosion resisting materials, rod, tube, etc.
Others	Optical lens, heat resisting and corrosion resisting materials, etc.

Data source: from Data Book for Metals, 2000, Metal Mining Agency of Japan (web site), etc.

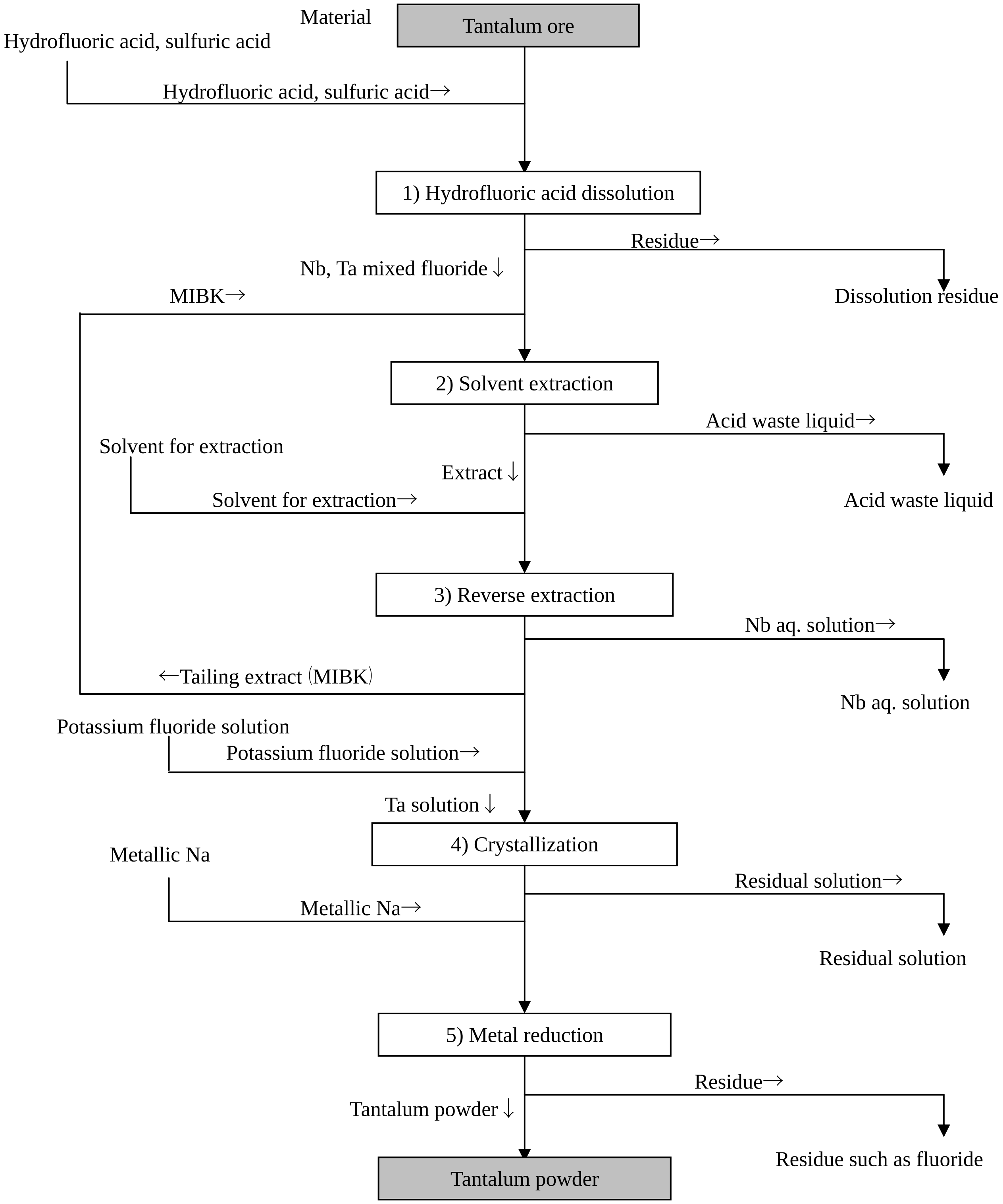
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report.	
1. Hydrofluoric acid dissolution	【INPUT】 - The grade of Ta in ore: 41% 【OUTPUT】 - The average solubility of Ta and Nb is assumed to be 90% - Ta concentration in the solution: 17.3 g/L 【Facility data】 - Dissolution temperature: 60℃	【INPUT】 - Tantalum ore is assumed to be high or middle grade. - The supplied amount of hydrofluoric acid is estimated as the pure consumption excluding the circulating amount. (Mass balance is estimated by referring to the data of wet copper smelting method.) - Energy consumption of hydrofluoric acid is estimated at the time of production. 【OUTPUT】 - The average solubility of Ta and Nb is assumed to be 90%. - The CO_2 emission from hydrofluoric acid is estimated at the time of production.	【INPUT】 - Supplied and circulating amounts of hydrofluoric acid - Supplied amount of ore. 【OUTPUT】 - Solubility of Ta, the amount of solution. - The amount of residue, concentration of Ta 【Facility data】 - Specifications for engine and processing power - Type and consumption of supplied energy. - Type and consumption of energy required for heating solution
2. Solvent extraction	【Facility data】 - Continuous operation	【INPUT】 - MIBK supplied is estimated as the pure consumption excluding the circulating amount. (Mass balance is estimated by referring to the data of wet copper smelting method.) - The energy consumption of MIBK is estimated at the time of production. 【OUTPUT】 - The extraction rate of Ta is assumed to be 95%. - The extraction rate of Nb is assumed to be 90%. - The CO_2 emission from MIBK is estimated at the time of production.	【INPUT】 - Supplied amount of MIBK. 【OUTPUT】 - Extraction rates of Ta and Nb. - The amount of extract - The amount of acid waste liquid, concentration of Ta 【Facility data】 - Specifications for engine and processing power. - Type and consumption of supplied energy. - Type and consumption of energy required for heating solution, etc.
3. Reverse extraction	【Facility data】 - Continuous operation	【OUTPUT】 - The extraction rate of Ta or Nb is assumed to be 95%.	【INPUT】 - Supplied and circulating amounts of dilute sulfuric acid and water 【OUTPUT】 - Extraction rates of Ta and Nb - The amount and concentration of Ta aqueous solution - The amount and concentration of Nb aqueous solution - The amount of extract tailing, concentration Ta and Nb 【Facility data】 - Specifications for engine and processing power. - Type and consumption of supplied energy. - Type and consumption of energy required for heating extract, etc.
4. Crystallization	【OUTPUT】 - The grade of Ta in K_2TaF_7: 46.3%	【INPUT】 - The amount of potassium hydrofluoride only contributing to the reaction is calculated as a theoretical value. 【OUTPUT】 - The yield of Ta is assumed to be 95%.	【INPUT】 - Supplied amount of potassium hydrofluoride 【OUTPUT】 - The amount of K_2TaF_7 - The yield of Ta. - The amount of waste liquid, concentration of Ta - The amount of acid waste, Ta concentration. 【Facility data】 - Specifications for engine and processing power. - Type and consumption of supplied energy.
5. Reduction of metal	【OUTPUT】 - The grade of Ta powder: 99.74%	【INPUT】 - The theoretical value of metallic Na is calculated based on the reaction formula. 【OUTPUT】 - The yield of Ta is assumed to be 95%.	【INPUT】 - The amount of metallic Na 【OUTPUT】 - The amount of tantalum powder. - The yield of Ta. - The amount of residue. 【Facility data】 - Specifications for engines and processing power - Type and consumption of supplied energy.

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.
【Facility data】: Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Reference: Toshio Mitsui, Smelting of tantalum and niobium in Sankin Rare Earth Co., Ltd., J. Min. Metal. Inst. Jpn/97 1122 (81-88) p.869-
Kinzoku Koza, "Smelting of Nonferrous Metals"

Mass balance data

The amounts of material/energy are those per raw ore of 10 t.

	INPUT		OUTPUT		
Process	Supplied materials etc.	Supplied amounts	Products	Amounts of products	Remarks
1. Hydrofluoric acid dissolution	Tantalum ore	10 t	Mixture of Nb and Ta	213 kL+	- Tantalum ore is assumed to be high or middle grade. - The grade of Ta in ore: 41% - Average solubility is assumed to be 90%. - Sulfuric acid is used for pH adjustment. - Ta concentration in hydrofluoric acid: 17.3 g/L - Solubility temperature: 60 ℃ - The energy of hydrofluoric acid production is considered. (The amount newly supplied, excluding the circulating amount, is calculated using the copper smelting data.)
	(including Ta)	(4.1 t)	(including Ta)	(3.7 t)	
	(including Nb)	(1.4 t)	(including Nb)	(1.3 t)	
	Hydrofluoric acid	213 kL	(Others)	(4.1 t)	
	Sulfuric acid	+ α	Residue	1.0 t	
	Electric power (Production of hydrofluoric acid)	(unknown) 20 GJ*	【CO$_2$emission】 (including hydrofluoric acid production)	1.8 t (1.8 t*)	
2. Solvent extraction	Mixture of Nb and Ta	213 kL	Extraction liquid	346 kL	- The extraction rate of Ta is assumed to be 95% - The extraction rate of Nb is assumed to be 90% - Continuous operating - The energy of MIBK production is considered. (The amount newly supplied, excluding the circulating amount, is calculated using the copper smelting data.)
	(including Ta)	(3.7 t)	(including Ta)	(3.5 t)	
	(including Nb)	(1.3 t)	(including Nb)	(1.1 t)	
	MIBK	346 kL	Acid waste	213 kL	
	Electric power (MIBK production)	(unknown) 314 GJ*	【CO$_2$emission】 (including MIBK production)	46 t (46 t*)	
3. Reverse extraction	Extract	346 kL	Tantalum aq. solution	(unknown)	- Ta and Nb are assumed to be completely separated using the difference in specific gravity. - Reverse extraction rates of Ta and Nb are assumed to be 95%. - Dilute sulfuric acid: for reverse extraction of Nb - Water: for reverse extraction of Ta - Continuous operating
	(including Ta)	(3.5 t)	(including Ta)	(3.3 t)	
	(including Nb)	(1.1 t)	Niobium aq. solution	(unknown)	
	Dilute sulfuric acid	(unknown)	(including Nb)	(1.1 t)	
	Water	(unknown)	Tailing extract	346 kL	
	Electric power	(unknown)	【CO$_2$emission】	(unknown)	
4. Crystallization	Tantalum aq. solution	(unknown)	K_2TaF_7	6.8 t	- The grade of Ta in potassium tantalum fluoride: 46.3 % - The yield of Ta is assumed to be 95%
	(including Ta)	(3.3 t)	(including Ta)	(3.2 t)	
	Potassium fluoride	3.7 t	Waste liquid	(unknown)	
	Electric power	(unknown)	【CO$_2$emission】	(unknown)	
5. Reduction of metal	K_2TaF_7	6.8 t	Tantalum power	3.0 t	- The grade of Ta powder: 99.74% - The yield of Ta is assumed to be 95%
	(including Ta)	(3.2 t)	Residue (fluoride, etc.)	6.1 t	
	Metallic Na	2.2 t			
	Fuel	(unknown)	【CO$_2$ emission】	(unknown)	
Total	【energy】 (including raw material production)	334 GJ (334 GJ*)	【CO$_2$ emission】 (including raw material production)	48 t (48 t*)	

Data source: Data source: produced by NRI using various data.

Reference: Toshio Mitsui, Smelting of tantalum and niobium in Sankin Rare Earth Co., Ltd., J. Min. Metal. Inst. Jpn/97 1122 (81-88) p.869-

Kinzoku Koza, “Smelting of Nonferrous Metals”

(20) Tungsten (W)

1) Overview of smelting

a. Smelting method

The tungsten ores are roughly divided into scheelite ($CaWO_4$) and wolframite. The grade of these raw ores is usually low. Thus, various sorting methods are applied and used repeatedly to raise the grade, and metallic tungsten is obtained by reducing through WO_3.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Reducing through APT	Wolframite, scheelite	Sandvikens jernverks AB (Sweden), London Scandinavian Metallurgical Co., Ltd. (England), etc.	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Products
Super-hard alloy and tools	Cutting, wear resistance, corrosion resistance, mine civil engineering etc.
Special steels	High-speed steel, heat resistant steel, tool steel, etc.
Metallic tungsten products	Lighting, electric and electronic components, resistance materials, electrode for electrochemistry
Alloys	Alloy containing Ni, Co, Fe, etc.
Chemical products	Catalyst, pigment

Data source: from Data Book for Metals, 2000, Metal Mining Agency of Japan (web site) etc.

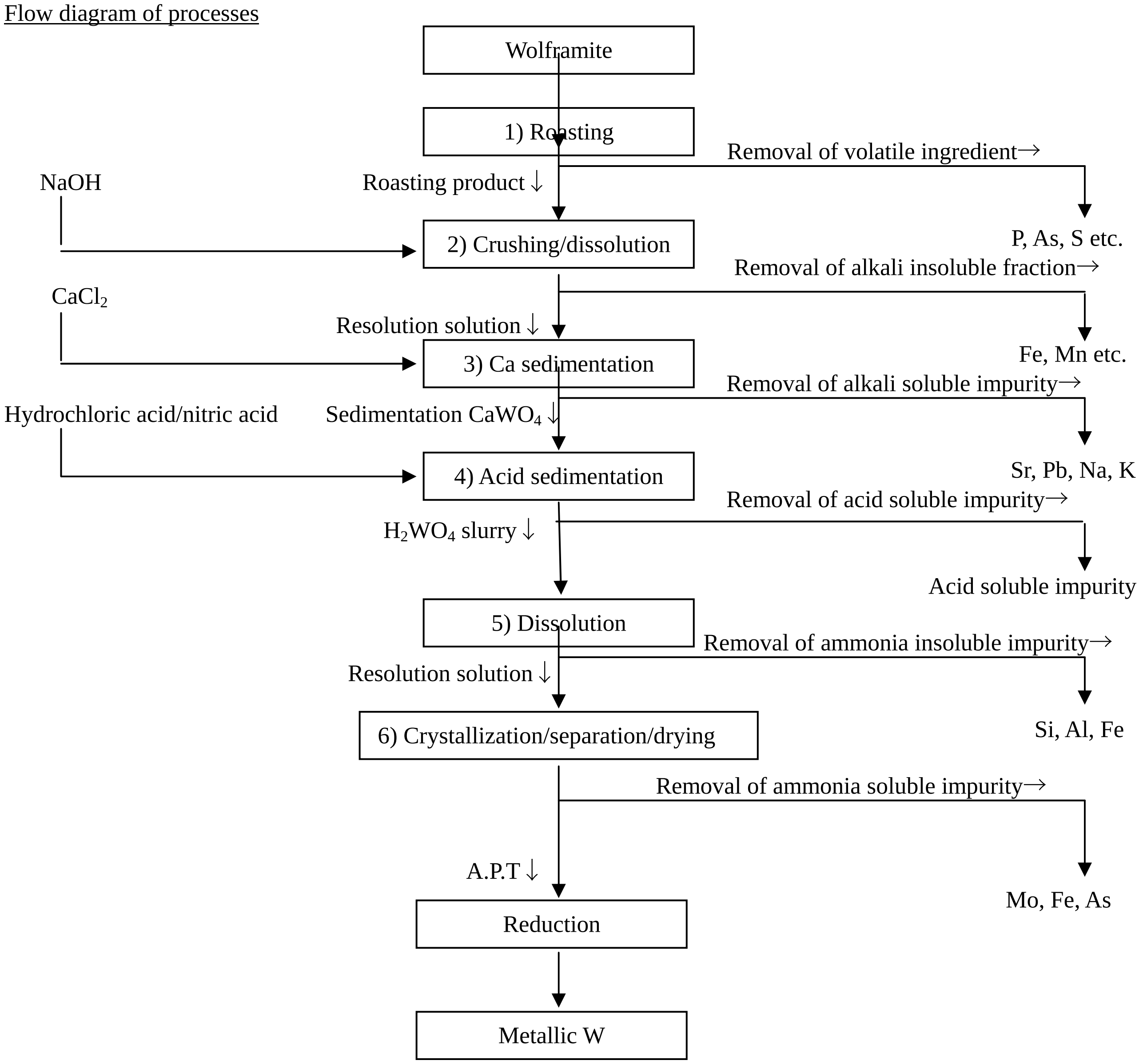
2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report.	
1. Roasting	【Facility data】 - Use of rotary kiln	【INPUT】 - The grade of W in ore is assumed to be 55%. 【OUTPUT】 - The loss of W is assumed to be zero.	【INPUT】 - Supplied amount of ore - The grade of ore 【OUTPUT】 - The amount of roasted product, the grade of W - The amount of residue, the concentration of W 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy.
2. Crushing/ dissolution	【OUTPUT】 - Extraction rate of W: 99.7% 【Facility data】 - Use of rod mill and ball mill	【OUTPUT】 - Mass balance is estimated based on the extraction rate of W. 【Facility data】 - A rod mill (45 kW), a ball mill (rated power 150 kW), a stirrer (rated power 2.2 kW), and an Oliver filter (rated power 3.7 kW) are assumed to run for 25 days/month (24 hours/day).	【INPUT】 - Supplied amount of NaOH. 【OUTPUT】 - The amount of solution, the concentration of W - The amount of residue, the grade of W 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy - Type and consumption of energy for heating of solution
3. Ca sedimentation		【INPUT】 - The amount of $CaCl_2$ is estimated as a theoretical value based on the reaction formula. 【OUTPUT】 - The yield of W assumed to be 95% 【Facility data】 - A stirrer (rated power 1.5 kW) is assumed to run for 15 days/month (24 hours/day).	【INPUT】 - Supplied amount of $CaCl_2$ 【OUTPUT】 - The amount of sedimentation, the grade of W - The amount of residual solution, the concentration of W 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy
4. Acid sedimentation		【INPUT】 - The theoretical amount of hydrochloric acid is estimated based on the reaction formula by assuming the acid concentration of 35%. - The energy consumption of supplied hydrochloric acid is estimated at the time of production. 【OUTPUT】 - The yield of W is assumed to be 95%. - The CO_2 emission from consumed hydrochloric acid is estimated at the time of production. 【Facility data】 - A stirrer (rated power 1.5 kW) is assumed to run for 15 days/month (24 hours/day).	【INPUT】 - Supplied and circulated amounts and concentration of hydrochloric acid 【OUTPUT】 - The amount of slurry, the grade of W - The amount of residual solution, the concentration of W 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy
5. Dissolution		【INPUT】 - The amount of aqua ammonia is estimated based on the reaction formula. 【OUTPUT】 - The yield of W is assumed to be 95%. 【Facility data】 - Agitator 1 unit (rated power 1.5 kW), filter press 1 unit (rated power 0.4 kW) are assumed to run for 10 days/month (24 hours/day).	【INPUT】 - Supplied amount of aqua ammonia 【OUTPUT】 - The amount of solution, the concentration of W - The amount of residue, the grade of W 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy
6. Crystallization/ separation/ drying		【OUTPUT】 - Mass balance is estimated based on the reaction formula. - As 90% of water evaporates by drying, the latent heat of the evaporation is considered as a consumed energy. 【Facility data】 - A stirrer (rated power 1.5 kW) and a centrifuge (rated power 55 kW) is assumed to run for 10 days/month (24 hours/day).	【OUTPUT】 - The amount of APT, the grade of W - production of ammonia - The amount of residual solution and evaporated liquid 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy.
7. Reduction	【Facility data】 - Use of rotary reduction furnace	【OUTPUT】 - Mass balance is calculated based on the reaction formula.	【OUTPUT】 - The amount of impurity. 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy.

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.
【Facility data】: Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



A.P.T: $5(NH_4)_2O/12WO_3/5H_2O$

Data source: Shoji Hayashibara, “Smelting of Tungsten in Toshoiba Yokohama Metal Factory,” J. Min. Metal. Inst. Jpn, 97 1122 (81-88) 243-

Mass balance data

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Roasting	Wolframite	68.3 t	Roasting product	57.8 t	- The grade of ore is assumed to be 55%.
	(including W)	(35.1 t)	Removal of impurity	6.0 t	- The loss of W is assumed to be zero. - Sulfur is removed.
	Fuel	(unknown)	【CO_2emission】	(unknown)	- Use of rotary kiln
2. Crushing/ dissolution	Roasting product	57.8 t	Solution	(unknown)	- The extraction rate of W: 99.7%
	NaOH aq. solution	(unknown)	(including Na_2WO_4)	(55.9 t)	- A rod mill (45 kW), a ball mill (150 kW), a stirrer (2.2 kW) and an Oliver filter (3.7 kW) are assumed to run for 25 days/month (24 hours/day).
			Residue	1.9 t	
	Electric power	1,139 GJ	【CO_2emission】	41.6 t	
3. Ca sedimentation	Solution	(unknown)	Sedimentation	57.8 t	- The yield is assumed to be 95%.
	(including Na_2WO_4)	(55.9 t)	(including $CaWO_4$)	(52.1 t)	- A stirrer (1.5 kW) is assumed to run for 15 days/month (24 hours/day).
	$CaCl_2$	20.1 t	Residual solution	(unknown)	
	Electric power	5.1GJ	【CO_2 emission】	0.19t	
4. Acid sedimentation	Sedimentation	57.8 t	H_2WO_4 slurry	47.7 t	- The yield is assumed to be 95%.
	(including $CaWO_4$)	(52.1 t)	(including H_2WO_4)	(42.9 t)	- Ca component in residual solution is recycled.
	Hydrochloric acid	37.7 t	Residual solution	47.8 t+	
	Nitric acid	+ α			
					- A stirrer (1.5 kW) is assumed to run for 15 days/month (24 hours/day).
	Electric power	5.1GJ	【CO_2 emission】	8.5 t	
	(Hydrochloric acid production)	103 GJ	(including hydrochloric acid production)	(8.4 t)	
5. Dissolution	H_2WO_4 slurry	47.7 t	Solution	6.3 kL	- The yield is assumed to be 95%
	(including H_2WO_4)	(42.9 t)	(including $(NH_4)_2WO_4$)	(46.3 t)	- A stirrer (1.5 kW) and a filter press (0.4 kW) are assumed to run for 15 days/month (24 hours/day).
	Aqua ammonia	6.3 kL	Residue	4.8 t	
	Electric power	4.3 GJ	【CO_2 emission】	0.16 t	
6. Crystallization/ separation/ drying	Solution	6.3 kL	APT	42.6 t	- A.P.T.:
	(including $(NH_4)_2WO_4$)	(46.3 t)	Ammonia	5.5 t	- $5(NH_4)_2O/12WO_3/5H_2O$
	Consumption for hydration	(1.2 t)	Residual solution	5.0 kL	- It condenses to 1/10 by drying
			(including dried and evaporated moisture)	(4.5 kL)	(It is assumed to use heavy oil.) - A stirrer (1.5 kW) and a centrifuge (55 kW) are assumed to run for 10 days/month (24 hours/day)
	Electric power	128 GJ			
	Heavy oil	10.2 GJ	【CO_2emission】	5.4 t	
7. Reduction	APT	42.6 t	Metallic W	30.0 t	- Hydrogen reduction (hydrogen is circulated.)
			Others	12.6 t	- Use of rotary reduction furnace
	Fuel	(unknown)	【CO_2 emission】	(unknown)	- Running for 24 hours/day
Total	【energy】	1,395 GJ	【CO_2 emission】	56 t	
	(including raw material production)	(103GJ)	(including raw material production)	(8.4 t)	

Data source: Data source: produced by NIR using various data.

Reference: Data source: Shoji Hayashibara, “Smelting of Tungsten in Toshoiba Yokohama Metal Factory,” J. Min. Metal. Inst. Jpn, 97 1122 (81-88) 243-

(21) Gold (Ag)

1) Overview of smelting

a. Smelting method

As smelting methods for Au, the water sorting method utilizing specific gravity difference, the mixing method with mercury, and the cyanide method utilizing dissolution due to potassium cyanide solutions are usually used. Also, in Japan, gold and silver silicate ores are used as fluxes for the dry type smelting of copper and lead, leading to the production of Au as the byproduct. For refining, the electrolytic method is used.

Smelting method	Starting materials	Overview of smelting	Smelting method adopted in the present report
Washing method (Gravity separation)	Sand including alluvial gold	There is no example today.	×
Amalgam process	Gold and silver ores (mud ore)	-	×
Cyanide process/electrolytic method	Gold and silver ores (placer ore)	-	○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final products	Products
Electrical and electronic equipment/communications instrument	Print circuit boards, personal computers, cellular phones, electrical components, etc.
Dental instrument	Artificial dentures, etc.
Jewelry	Rings, necklaces, etc.
Arts and crafts	Religious tools, gold cups, etc.
Medals	Commemorative medal, etc.
Others	Gold leaves and foils, ceramics etc.

Data source: from Data Book for Metals, 2000, Web site of the Metal Mining Agency of Japan, etc.

2) Integration status of data such as mass balance

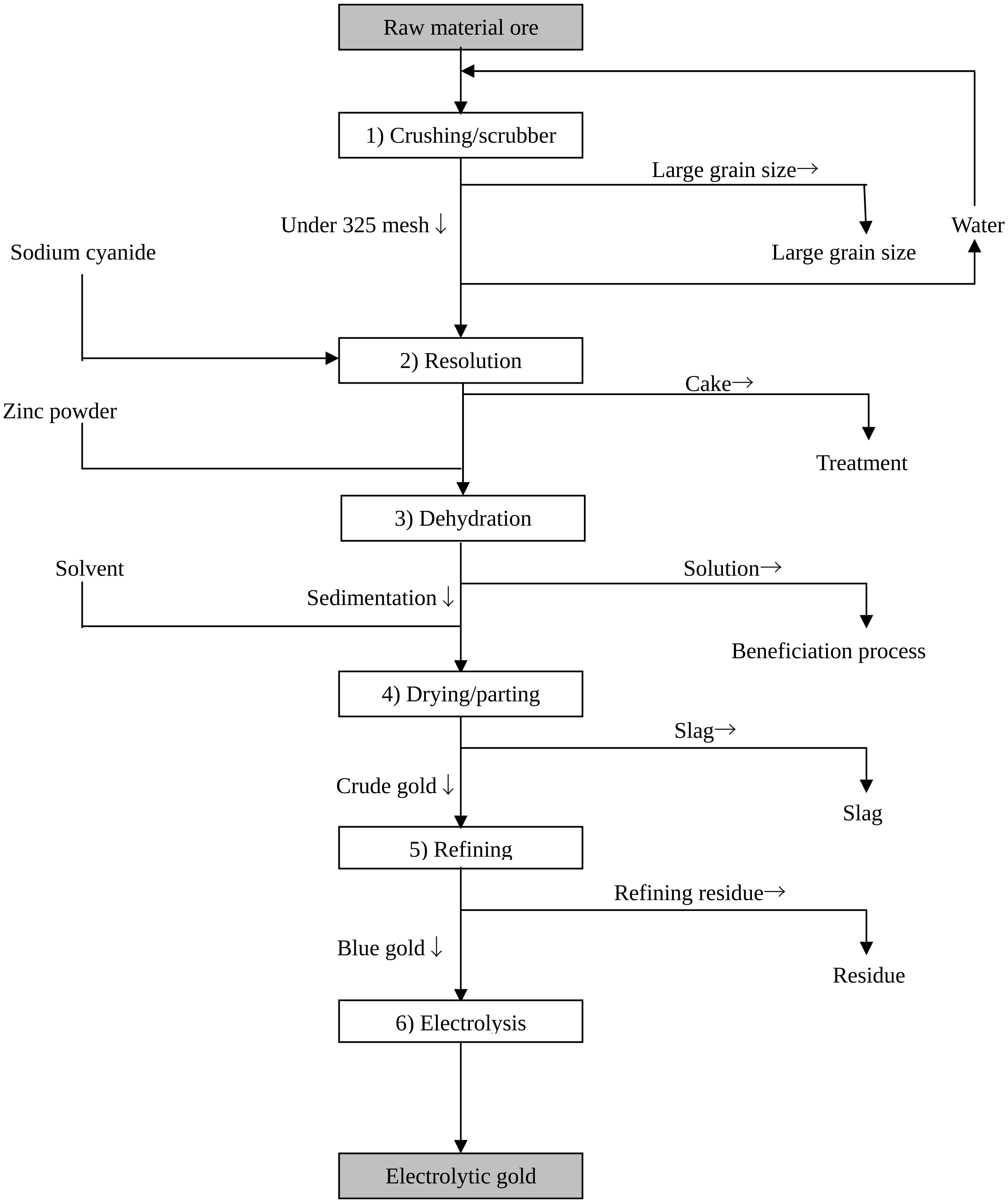
Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report.	
1. Crushing/ grinding	【INPUT】 - The grade of Au in raw ore: 7.0 g/t 【OUTPUT】 - The yield of gold is 90%	【Facility data】 - Electric consumption is estimated by assuming that crushing/grinding process is performed for 15 days/month (24 hours/day).	【INPUT】 - Supplied amount of water 【OUTPUT】 - The amount of smelting sludge, the grade of Au 【Facility data】 - Type and consumption of supplied energy except electric power consumption.
2. Resolution	【OUTPUT】 - Au concentration in solution: 3.2 g/t - The grade of Au in the cake: 0.33 g/t - The solubility of Au: approximately 95% 【Facility data】 - Six stirrers （rated power 3.7 kW） are used.	【OUTPUT】 - The mass balance is estimated based on the concentration of solution, etc. 【Facility data】 - Six oliver filters (rated power 3.7 kW) and a tube mill (rated power 150 kW) is assumed to run for 15 days/month (24 hours/day).	【INPUT】 - Supplied amount of sodium cyanide - Supplied amount of lead sulfate 【OUTPUT】 - The amounts of dissolved solution and cake 【Facility data】 - Specifications for engines, processing power, etc. - Type and consumption amounts of supplied energy - Type and consumption of energy required for heating solutions
3. Substitution/ dehydration	【OUTPUT】 - The yield of Au: 99% - The grade of Au in sedimentation: 2.44%	【INPUT】 - Supplied amount of zinc powder is estimated by assuming that the concentration is 3 N.	【INPUT】 - Supplied amount of zinc powder 【OUTPUT】 - The amount of sedimentation. - The amount of solution 【Facility data】 - Specifications for engines, processing power, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating solutions
4. Drying/parting	【OUTPUT】 - The grade of Au in crude gold: 6.1% 【Facility data】 - Six rotary kilns are used. - roasting temperature: 750℃ - A tilting furnace is used for separate slag. - Dissolution temperature: 1,100~1,200℃. - Heavy oil is used in the furnace.	【OUTPUT】 - The yield of Au is assumed to be 95%. 【Facility data】 - Drying is assumed to be performed by preheating of roasting furnace. - Two bug filters (rated power 22kW) are assumed to run for 15 days/month (24hour/day).	【OUTPUT】 - The amount of crude gold - The amount of sedimentation, the grade of Au - The amount of slag, the grade of Au 【Facility data】 - Specifications for engines, processing power, etc. - Type and consumption of supplied energy.
5. Refining	【OUTPUT】 - The grade of Au in blue gold: 19.95% 【Facility data】 - A refining furnace (heavy oil) is used.	【Facility data】 - A refining furnace is assumed to run for 15 day/month (24 hours/day).	【OUTPUT】 - The amount of blue gold - The amount of refining residue, the grade of Au. 【Facility data】 - Specifications for engines, processing power, etc. - Type and consumption of supplied energy.
6. Electrolysis	【OUTPUT】 - The grade of electrolytic gold: 99.99% 【Facility data】 - Electric power consumption of electrolytic furnace: 420 kWh/t-electrolytic Au	【OUTPUT】 - The yield of Au is assumed to be 90%. - All impurities are removed as slime.	【OUTPUT】 - The production of electrolytic gold - The amount of slime, the grade of Au

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.
【Facility data】: Data for equipment used in processes concerned.

The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Satoshi Uchino, "Smelting of Gold and Silver and Production of By-products in Kushikino Mine," J. Min. Metal. Inst. Jpn. 97 1122 ('81-8) 757

Mass balance data

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Crushing/ grinding	Raw ore (including Au) Water	**11,200 t** (78.4 kg) 57,120 t	Smelting sludge (including crushed ore) (including Au) (Water content) Over-325 mesh ore Supernatant solution	16,320 t (9,520 t) (70.6 kg) (6,800 t) 1,680 t 50,320 t	- Specific gravity in smelting sludge: 1.4 - The grade of Au in raw ore: 7.0g/t - The yield of gold: 90% (※) - The yield of under-325 mesh ore: 85% (※) - Supernatant solution is returned to the grinding process. - 15day/month, 24hour/day is operated.
	Electric power	3,274 GJ	【CO$_2$ emission】	119.7 t	
2.Dissolution	Smelting slag (including Au) Sodium cyanide solution Lead nitrate	16,320 t (70.6 kg) 15,412 t 4.7 t	Dissolved solution (including Au) Cake	20,936 t (67.0 kg) 10,800 t	- Au concentration in dissolved solution: 3.2 g/t (※) - The grade of Au in cake: 0.33 g/t - The solubility of Au: approximately 95% - Stirrers: 3.7 kW (6 units) - Oliver filter: 3.7 kW (Assuming to use 6 units) - Tube mill: 150 kW (Assuming to use 1 unit) - It assumes to run for 15 days/month (24 hours/day).
	Electric power	661.3 GJ	【CO$_2$ emission】	24.2 t	
3. Substitution/ dehydration	Dissolved solution (including Au) Zinc powder	20,936 t (67.0 kg) 33.4kg	Sedimentation (including Au) Solution	2,608 kg (63.6 kg) 20,934 t	- Substituted by zinc powder - Supplied amount of zinc is 3 N. - The yield of Au: 99% - The grade of Au in sedimentation: 2.44%
	Electric power	(unknown)	【CO$_2$ emission】	(unknown)	
4. Drying/ parting	Sedimentation (including Au) Solvent (Solvent) Sodium bicarbonate Borax Silica sand	2,608kg (63.6kg) + α	Crude gold (including Au) Roasted sedimentation Slag	994 kg (60.5 kg) 85 kg 1,529 kg +	- The grade of Au in crude gold: 6.1% - The yield of Au is assumed to be 95%. - Remaining heat of roasting furnace is used for drying. - Roasting: Use of 4 rotary kilns - Roasting temperature: 750℃ - Separation of slag: Use of tilting and rotating fusion furnace - Temperature of fusion furnace: 1,100-1,200℃ - Roasting/dissolution: Use of heavy oil - Bug filter: 22 kWh (2 units) - It is assumed to run for 15 days/month (24hours/day).
	Electric power Heavy oil	149.7GJ (unknown)	【CO$_2$ emission】	5.5 t	
5. Refining	Crude gold (including Au)	994 kg (60.5 kg)	Blue gold (including Au) Refining residue	**291 kg** (58.0 kg) 704 kg	- Refining furnace - The grade of Au in blue gold: 19.95% - It is assumed to run for 15 days/month (24 hours/day).
	Heavy oil	(unknown)	【CO$_2$ emission】	(unknown)	- Use of heavy oil
6. Electrolysis	Blue gold	291 kg	Electrolytic gold Slime	52.2 kg 238 kg	- The grade of electrolytic gold: 99.99% - The yield of Au is assumed to be 90% - Electric power consumption for electrolytic furnace: 420kWh/t-electrolytic Au
	Electric power	0.2 GJ	【CO$_2$ emission】	0.01 t	
Total	【Energy】	4,085GJ	【CO$_2$ emission】	149.3t	

Data source: Data source: produced by NRI using various data.

Reference: Satoshi Uchino, “Smelting of Gold and Silver and Production of By-products in Kushikino Mine,” J. Min. Metal. Inst. Jpn. 97 1122 (’81-8) 757-
Hiroshi Miyakawa, “Smelting of Gold and Silver in Kushikino Mine Co. Ltd.,” Sigen to Sozai 109 (1993) No.12
Takashi Kawasaki, “Current Status of Cyanidation in Oguchi Smelting Company,” J. Min. Metal. Inst. Jpn. 87 997 (’71-Extra issue) 301-
Yoshimichi Moriguchi, et al., “Kounomai Cyanidation Smelting Factory,” J. Min. Metal. Inst. Jpn. 86 991 (79-10) 749-

(22) Thallium (Tl)

1) Overview of smelting

a. Smelting method

For the production of metallic thallium, byproducts from the smelting process of lead, zinc, copper, etc. are usually used as starting materials. In Japan, a small amount of Tl is produced from slag in the zinc smelting process and from electrolytic waste solutions etc. in the lead smelting process.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Alkaline leaching/electrolytic extraction	Thallium slag (byproduct of zinc smelting)	Nippon Mining and Metals, Mistui Kinzoku, Sumitomo Metal Mining, etc.	○
Electrolytic extraction	Lead electrolytic solution		×

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications for final products	Products
Thallium sulfate	Rat poison, etc.
Thallium oxide, thallium fluoride	Low-melting glass, etc.
Additive elements to alloy	Electronic materials, special fuses, low-coagulating thermometer, optical fiber, optical instrument, etc.

Data source: The web site of Metal Mining Agency of Japan, etc.

2) Integration status of data such as mass balance

Process	used data		Untaken data
	Data obtained from literature, etc.	Data assumed and estimated in this report.	
1. Leaching	【OUTPUT】 - The leaching rate of Tl: 90% 【Facility data】 - The leaching temperature: 80℃	【INPUT】 - The grade of Tl in its slag is assumed to be 45%. - The amount of caustic soda is calculated based on the concentration of leach solution. 【Facility data】 - A stirrer (rated power 5.5 kW) and a filter press (rated power 0.4 kW) are assumed to run for 10 days/month (1 day/24 hours).	【INPUT】 - Supplied amount of Tl slag, the grade of Tl - Supplied amount of caustic soda. 【OUTPUT】 - The leaching rate of Tl - The amount of leach solution, the concentration of Tl - The amount of leaching residue, the grade of Tl 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating of leach solution
2. Substitution	【OUTPUT】 - The substitution rate of Tl: 99.7% - The grade of sponge Tl: 99.3%	【Facility data】 - A pump (rated power 1 kW) and a filter presses (rated power 0.4kW) are assumed to be used.	【OUTPUT】 - The amount of sponge Tl - The amount of residue, the concentration of Tl 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption amounts of supplied energy. - Type and consumption of energy required for heating of leaching solution
3. Dissolution/ casting		【OUTPUT】 - The grade of anode Tl is assumed to be 99.8%.	【OUTPUT】 - The recovery rate of Tl - The amount of anode Tl, the grade of Tl - The amount of slime, the grade of Tl 【Facility data】 - Specifications for engine, processing power, etc. - Type and consumption of supplied energy.
4. Electrolytic refining	【OUTPUT】 - The grade of electrolytic Tl: 99.99% 【Facility data】 - Voltage of electrolytic cell: 1.2V - Current density: 57.5 A/m^2 - Electric power consumption for electrolysis: 600 kWh/t-electrolytic Tl	【OUTPUT】 - The yield of Tl is assumed to be 95%.	【OUTPUT】 - The amount of sedimentation, the grade of Tl

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.

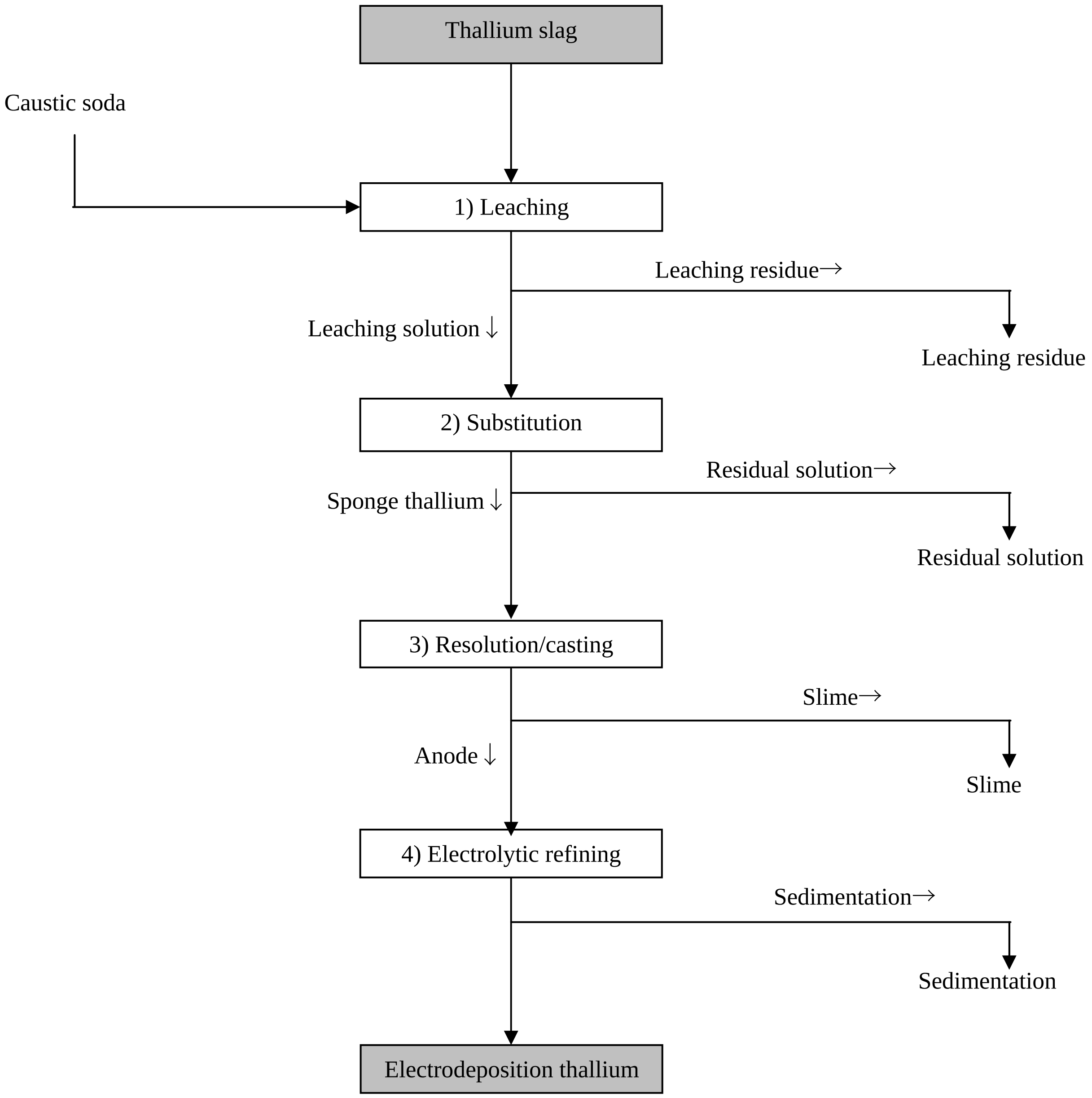
【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.

【Facility data】: Data for equipment used in processes concerned.

The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes



Data source: Chikashi Suenaga, et al., “Production of Metallic Thallium in Saganoseki Smelting Works (in Japanese),” Shigen to Sozai, 106 (1990) No.5 289-

Mass balance data

The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Leaching	Thallium slag (including Tl) Solution of caustic soda	384.1 kg (172.9 kg) 15.6 kL	Leaching solution (including Tl) (The amounts of leaching solution excluding Tl) Leaching residue	15.6 kL (155.6 kg) (27.0 kg) 201.5 kg	- The leaching rate of Tl: 90% - Leaching temperature: 80℃ - Stirrer: rated power 5.5kW - A filter press (rated power 0.4kW) is assumed to run for 10 days/month (24 hours/day). - Environmental load is not considered for the production of caustic soda. - Electric power is used for heating. - Heat of dissolution is not considered.
	Electric power	15.0 GJ	【CO$_2$emission】	547.3 kg	
2. Substitution	Leaching solution (including Tl) (The amounts of leaching solution excluding Tl)	15.6 kL (155.6 kg) (27.0 kg)	Sponge thallium Residual solution (The dissolved amount in residual solution)	156.2 kg 15.6 kL (26.4 kg)	- Substitution rate: 99.7% (substitution of zinc plate) - The grade of sponge thallium: 99.3% - Dissolved components in the residual solution contain impurities. - The power of circulation pump is assumed to be 1 kW - A filter press (rated power 0.4kW) is assumed to be used. - The solution is not heated
	Electric power	0.82 GJ	【CO$_2$emission】	30.1 kg	
3. Dissolution/ casting	Sponge thallium	156.2 kg	Anode thallium Slime	147.6 kg 8.6 kg	- The grade of anode thallium is assumed to be 99.8% - Run for 15 days/month (24 hours/day) - Electric power is used for heating. - Energy for heating and dissolving thallium is estimated. However, the energy loss is not considered. - Energy for the casting machine is not considered.
	Electric power	0.01GJ	【CO$_2$emission】	0.3 kg	
4. Electrolytic refining	Anode thallium	147.6 kg	Electrolytic thallium Sedimentation	140.0 kg 7.6 kg	- The grade of electrolytic thallium: 99.99% - The yield of electrolysis is assumed to be 95%. - Cell voltage: 1.2 V - Current density: 57.5 A/m$_2$ - Electric power consumption for electrolysis 600 kWh/t-electrolytic Tl - Data source: Denki-kagaku binran (Electrochemical manual)
	Electric power	0.79 GJ	【CO$_2$emission】	29.0 kg	
Total	【energy】	16.6 GJ	【CO$_2$emission】	606.8 kg	

Data source: produced by NRI using various data.

Reference: Chikashi Suenaga, et al., “Production of Metallic Thallium in Saganoseki Smelting Works (in Japanese),” Shigen to Sozai, 106 (1990) No.5 289-

(23) Bismuth (Bi)

1) Overview of smelting

a. Smelting method

Bismuth is usually produced as a byproduct in the smelting process of lead and copper concentrates. In Japan, it is produced as a byproduct in the lead smelting process.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Burks/chlorination method	Crude bismuth (by-product of lead/copper smelting)	Asarco (USA), Industrials Penoles (Mexico), Centoromin Peru (Peru), Toho Zinc, Dowa Mining, Mistui Mining & Smelting, etc.	○
Electrolytic method	Crude bismuth (by-product of lead/copper smelting)		○

Data source: from Data Book for Metals, 2000

b. Status of domestic utilization

Main applications to final product	Products
Metal industry field	Low boiling point alloys, aluminum additives, malleable cast iron additives, etc.
Chemical industry field	Drugs and medicines, cosmetics, catalysts, etc
Electronic industry field	Ferrite additives, condenser additives, semiconductor, etc.

Data source: from Data Book for Metals, 2000

2) Integration status of data such as mass balance

a. Burks/chlorination method

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report.	
1. Primary refining	【INPUT】 - The grade of crude Bi: 93.6% 【OUTPUT】 - The grade of Bi in primary refined metal: 95.8%	【OUTPUT】 - Mass balance is estimated based on the grade of Bi in refined metal.	【INPUT】 - The supplied amount of crude Bi. 【OUTPUT】 - The yield of Bi - The amount of primary refined metal - The amount of dross, the grade of Bi. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy.
2.Desilverization	【INPUT】 - Supplied amount of zinc: 30 kg/product Bi-t 【OUTPUT】 - The grade of Bi in desilverized metal: 99.8%	【OUTPUT】 - Mass balance is estimated based on the grade of Bi in desilverized metal.	【INPUT】 - The supplied amount of zinc 【OUTPUT】 - The yield of Bi - The amount of desilverized metal. - The amount of desilverized dross, the grade of Bi. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy
3. Dezincification/ unlead	【INPUT】 - Supplied amount of chlorine gas: 40 kg/product Bi-t	【OUTPUT】 - Mass balance is estimated by assuming that all impurities, Pb and Zn, are removed.	【INPUT】 - The supplied amount of chlorine gas 【OUTPUT】 - The yield of Bi - The amount of unlead metal, the grade of Bi. - The amount of unlead dross, the grade of Bi. - The amount of dezincified dross, the grade of Bi. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy.
4. Secondary refining	【OUTPUT】 - The grade of refined Bi: 99.99%	【OUTPUT】 - Mass balance is estimated based on the grade of Bi.	【OUTPUT】 - The amount of dross, the grade of Bi. - The yield of Bi 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy.

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.

【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.

【Facility data】: Data for equipment used in processes concerned.

The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

b. Electrolytic method

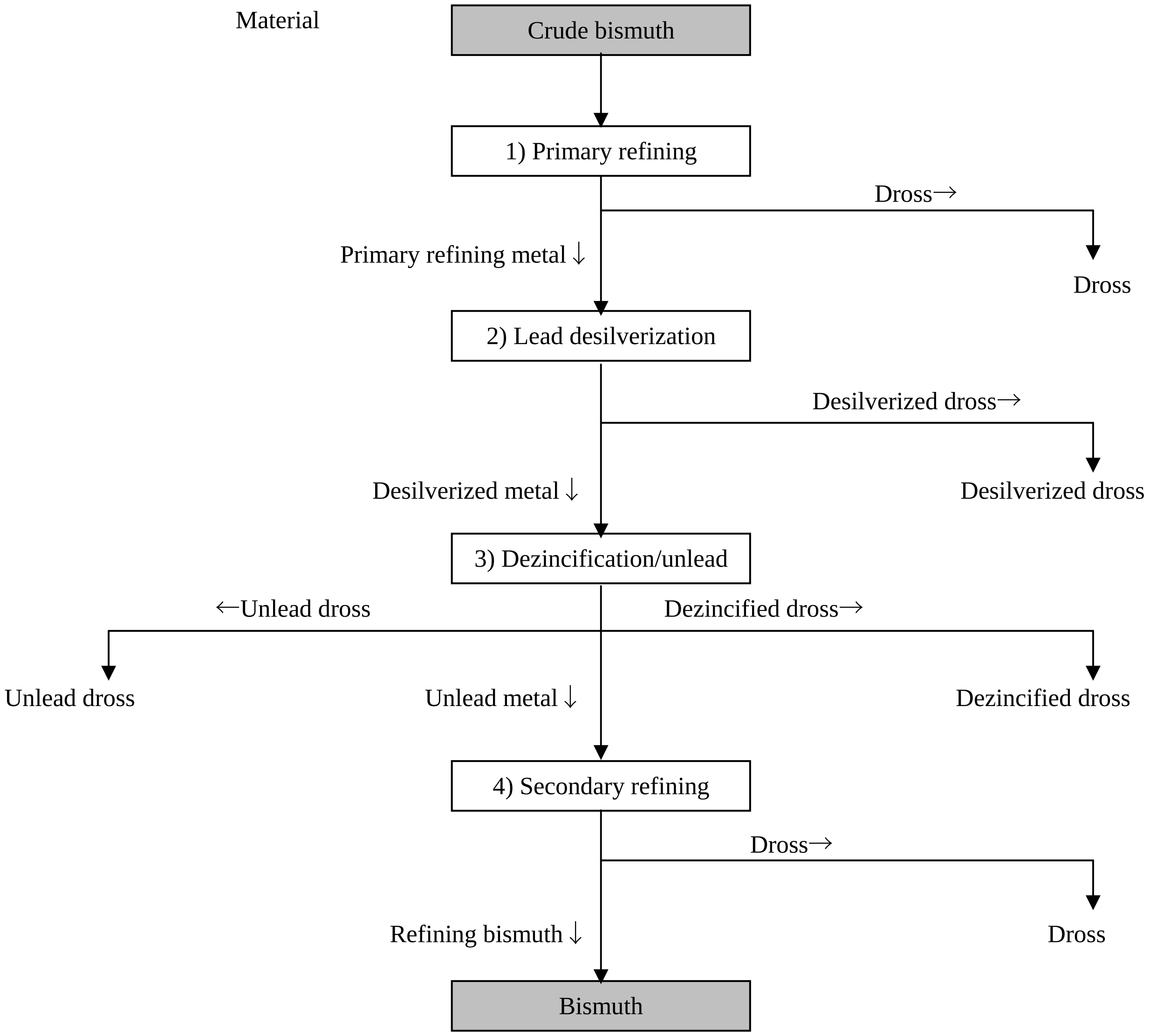
Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report.	
1. Primary refining	【INPUT】 - The grade of crude Bi: 96.5% 【OUTPUT】 - The grade of Bi in the anode: 98.2%	【OUTPUT】 - The mass balance is estimated based on the Bi grade.	【INPUT】 - Supplied amount of crude Bi. 【OUTPUT】 - The yield of Bi - The amount of anode - The amount of dross, the grade of Bi 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy.
2. Electrolysis	【INPUT】 - The circulating amount of electrolytic solution: 20 L/min 【OUTPUT】 - The grade of electrolytic Bi : 99.9% 【Facility data】 - Electric current of the cell: 850 A - Current density: 500 A/m^3 - Voltage of the cell: 0.2 V - Current efficiency: 93% - 25-day continuous run - Total electrolysis cells: 16 - Electric power consumption of electrolytic furnace: 100 kWh/t-electrolytic Bi	【OUTPUT】 - The mass balance is estimated based on the Bi grade.	【INPUT】 - Supplied amount of sulfuric acid. 【OUTPUT】 - The yield of Bi. - The amount of slime - The amount of anode scrap, the grade of Bi -The amount of lead sulfate. 【Facility data】 - Specification of engine, processing power, etc. - Type and consumption of supplied energy.
3. Secondary refining	【OUTPUT】 - The grade of refined Bi: 99.99%	【OUTPUT】 - The mass balance is estimated based on the Bi grade.	【OUTPUT】 - The yield of Bi. - The amount of refined Bi. - The amount of dross, the grade of Bi. 【Facility data】 - Specifications of engine, processing power, etc. - Type and consumption of supplied energy

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in process concerned.
【Facility data】: Data for equipment used in process concerned.
The indicated by 【INPUT】, 【Facility data】, 【OUTPUT】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO_2 emission are large.

(Note)

3) Flow diagram of processes and integration of mass balance data

Flow diagram of processes (a. Burks/chlorination method)



Data source: Shoichi Asahina, et al., "History of Bismuth Refining in Kunitomi Smelting Works (in Japanese)," J. Min. Metal. Inst. Jpn., 90, 1035 (1974-75) p.373-

Mass balance data (a. Burks/chlorination method)

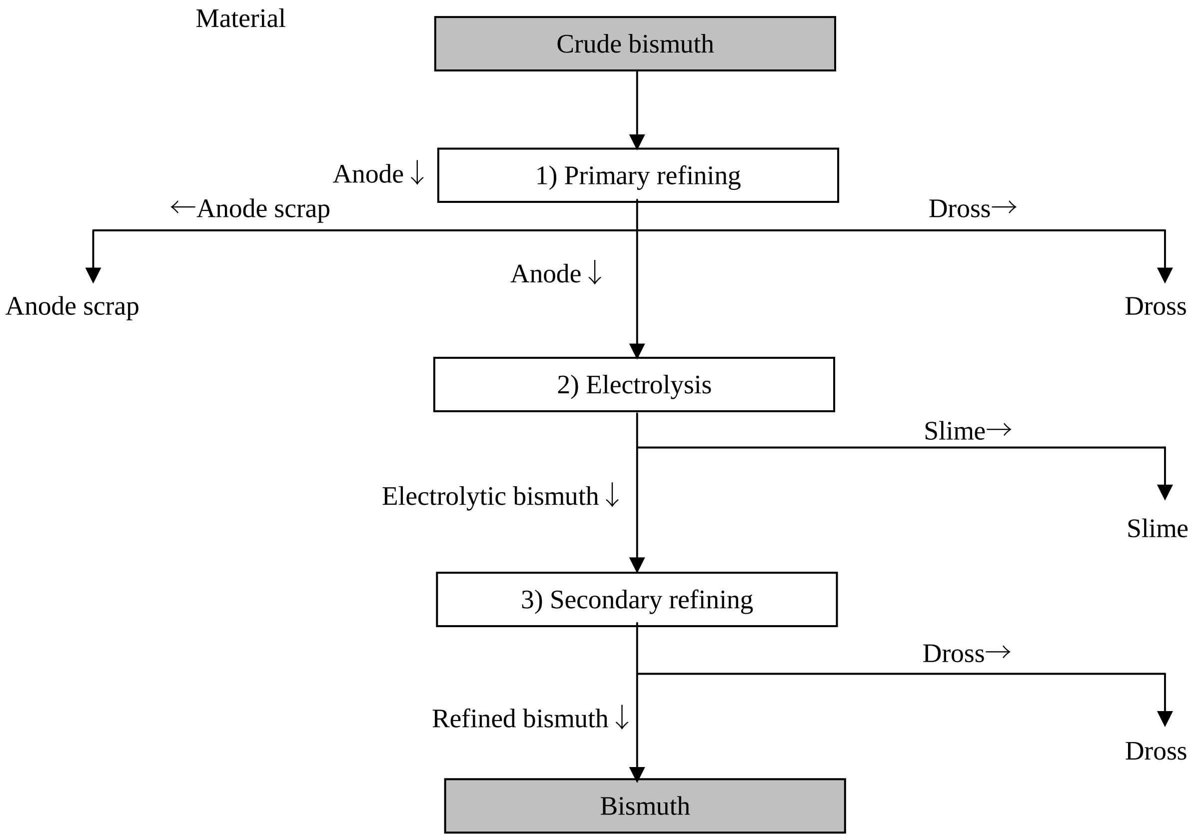
The amounts of material/energy are those per month.

Process	INPUT		OUTPUT		Remarks
	Supplied materials etc.	Supplied amounts	Products	Amounts of products	
1. Primary refining	Crude bismuth and other additives	33.9 t + α	Primary refined metal Dross	33.2 t + 0.78 t +	- Removing process of Cu, As, and Sb - The grade of Bi in primary refined metal: 95.8%
	(Other additives) Caustic soda Sulfur powder Niter				
	Electric power	(unknown)	【CO_2emission】	(unknown)	
2. Desilverization	Primary refined metal Zinc	33.2 t 0.86 t	Desilverized metal Desilverized dross	32.7 t 1.86 t	- The grade of Bi in desilverized metal: 99.8%
	Electric power	(unknown)	【CO_2emission】	(unknown)	
3. Dezincification/ unlead	Desilverized metal Chlorine gas	32.7 t 1.14 t	Unlead metal Unlead dross Dezincified dross	30.7 t 1.12 t 1.95 t	- Pb is assumed to be completely removed. - Zn is assumed to be completely removed.
	Electric power	(unknown)	【CO_2emission】	(unknown)	
4. Secondary refining	Unlead metal Other additives	30.7 t + α	Refined bismuth Dross	**28.6 t** 2.1 t +	- The grade of refined Bi: 99.99%
	(Other additives) Caustic soda Sulfur powder Niter				
	Electric power	(unknown)	【CO_2emission】	(unknown)	
Total	Sulfur powder Caustic soda Niter Zinc Chlorine	**0.29 t** **3.29 t** **0.86 t** **0.86t** **1.1 t**			
	Electric power Fuel	**328 GJ** (unknown)			
Grand total	【energy】	328 GJ	【CO_2emission】	12.0 t	

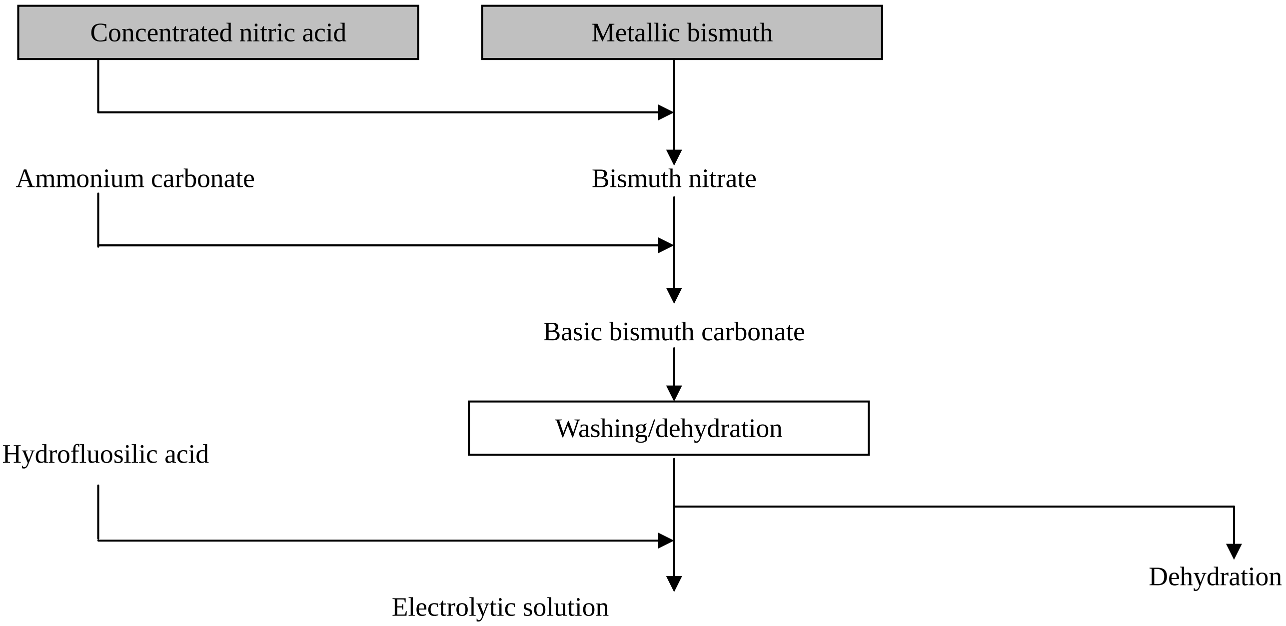
Data source: produced by NIR using various data.

Reference: Shoichi Asahina, et al., “History of Bismuth Refining in Kunitomi Smelting Works (in Japanese),” J. Min. Metal. Inst. Jpn., 90, 1035 (1974-75) p.373-

Flow diagram of processes (b. Electrolytic method)



[Manufacturing process of electrolytic solution]



Data source: Shoichi Asahina, et al., "History of Bismuth Refining in Kunitomi Smelting Works (in Japanese)," J. Min. Metal. Inst. Jpn., 90, 1035 (1974-75) p.373-

Mass balance data (b. Electrolytic method)

The amounts of material/energy are those per month.

	INPUT		OUTPUT		
Process	Supplied materials etc.	Supplied amounts	Products	Amounts of products	Remarks
1. Primary refining	Crude bismuth	33.70 t	Anode	33.12 t+	- Removing process of Cu, As, and Sb
	Other additives	+ α	Dross	0.58 t+	- The grade of Bi in crude bismuth: 96.5%
	(Other additives)				
	Sulfur powder				
	Caustic soda				
	Niter				
	Hydrofluosilic acid				
	Nitric acid				
	Ammonium carbonate				
	Heavy oil	(unknown)	【CO_2emission】	(unknown)	
2. Electrolysis	Anode	**33.12 t +**	Electrolytic Bismuth	26.64 t	- Cell current: 850A
	The traveled amount of Bi from electrolytic solution	7.20 t	Slime	0.17 t +	- Current density: 500 A/m^3
			Anode scrap	13.25 t +	- Cell voltage: 0.2V
			Lead sulfate	0.39 t	- Current efficiency: 93%
	Sulfuric acid (removing of lead)	0.12 t			- 25-day continuous run
	Other additives	+ α			- Total number of electrolytic cells: 16
	The circulating amount of electrolytic solution	720,000 L			- The grade of electrolytic bismuth: 99.9%
	(Other additives)				- Electric power consumption of electrolytic furnace: 100 kWh/t-electrolytic Bi
	Glue				
	Electric power	25 GJ	【CO_2emission】	0.9 t	
3. Secondary refining	Electrolytic bismuth	26.64 t	Refining bismuth	26.62 t	- The grade of refining bismuth: 99.99%
	Other additives	+ α	Dross	0.02 t +	
	(Other additives)				
	Sulfur powder				
	Caustic soda				
	Niter				
	Hydrofluosilic acid				
	Nitric acid				
	Ammonium carbonate				
	Heavy oil	(unknown)	【CO_2emission】	(unknown)	
Total	Sulfur powder	**0.85 t**			
	Caustic soda	**2.93 t**			
	Niter	**0.53 t**			
	Hydrofluosilic acid	**1.20 t**			
	Nitric acid	**0.69 t**			
	Ammonium carbonate	**0.45 t**			
	Electric power	**389GJ**			
	Fuel	(unknown)			
Grand total	【energy】	389GJ	【CO_2emission】	14.2 t	

Data source: produced by NIR using various data.

Data source: Shoichi Asahina, et al., “History of Bismuth Refining in Kunitomi Smelting Works (in Japanese),” J. Min. Metal. Inst. Jpn., 90, 1035 (1974-75) p.373-

(24) Uranium (U)

1) Overview of smelting

a. Smelting method

Uranium smelting can be roughly divided into crude smelting, in which yellow cake with a U_3O_8 quality of 70 - 80 % is produced, and fine smelting to get a higher quality for the atomic power industry. The crude smelting is usually the wet type one using acid or alkaline leaching. From the economical and operational viewpoints, a method with sulfuric acid is used generally.

Smelting method	Starting materials	Main producers Name of company (country)	Smelting method adopted in the present report
Wet method (Solvent extraction)	Pitchblende (UO_2), etc.	Companies in France, USA, and U.K.	×
PNC method (Wet method)	Uranium ore (UO_2)	Power Reactor and Nuclear Fuel Development Corporation (Japan), etc.	○ (For yellow cake smelting process or later process)

Source: The Japan Institute of Metals, “Shin-Kinzoku Koza (New Metal Lectures) - Smelting of Non-Ferrous Metals”

b. Status of domestic utilization

Main applications for final products
Atomic fuel
Glaze of ceramic wave

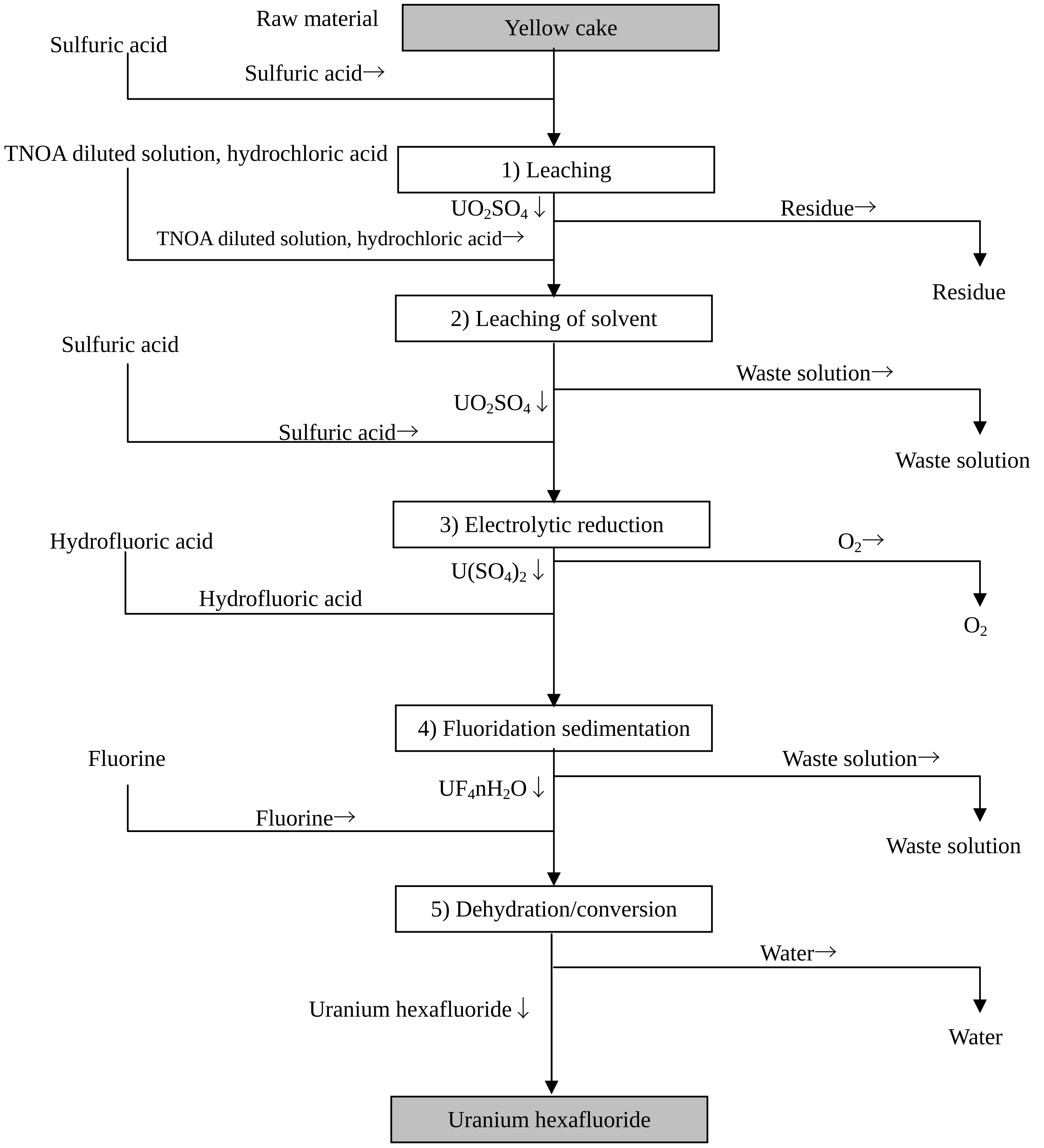
Data source: Rare Metal Dictionary, etc.

2) Integration status of data such as mass balance

Process	Used data		Untaken data
	Data obtained from literature, etc	Data assumed and estimated in this report.	
1. Leaching	【INPUT】 - Supplied amount of yellow cake: 50 t/day 【OUTPUT】 - U concentration in solution: 200 g/L	【INPUT】 - The supplied amount of sulfuric acid is estimated as the pure consumption excluding the circulating amount. - The energy consumption at the time of production of sulfuric acid is estimated. 【OUTPUT】 - The yield of U is assumed to be 90%. - The estimate of mass balance assumes that all main impurities (As, Ni, Fe, Al, and Nb) in yellow cake are removed. - The CO$_2$ emission at the time of production of sulfuric acid is estimated. 【Facility data】 - A stirrer (rated power 2.2 kW) and a filter press (rated power 0.4 kW) are assumed to run for 24 hours/day.	【INPUT】 - The grade of U in yellow cake - The supplied and circulating amounts of sulfuric acid 【OUTPUT】 - The amount of solution - The amount of residue and the grade of U. - The yield of U. 【Facility data】 - specifications for engine, processing power, etc. - Type and consumption of supplied energy. - Type and consumption of energy for heating leached liquid, etc.
2. Solvent extraction	【OUTPUT】 - Leaching rate of U: 86%	【INPUT】 - The supplied amount of hydrochloric acid is estimated as the pure consumption excluding the circulating amount. (The mass balance is estimated by referring to the data of copper wet smelting.) - The energy consumption at the time of production of hydrochloric acid is estimated. 【OUTPUT】 - Mass balance is estimated based on the reaction formula. - The CO$_2$ emission at the time of production of hydrochloric acid is estimated. 【Facility data】 - A stirrer (rated power 2.2 kW) is assumed to run for 24 hours/day.	【INPUT】 - The supplied and circulating amounts of dilute solution - The supplied and circulating amounts of hydrochloric acid 【OUTPUT】 - The amount of waste solution and the concentration of U - The extraction rate of U 【Facility data】 - specifications for engine, processing power, etc. - Type and consumption of supplied energy - Type and consumption of energy required for heating of leaching liquid
3. Electrolytic reduction	【Facility data】 - Electric power consumption per 1 kg of U: 1.5 kWh	【INPUT】 - The amount of hydrochloric acid is estimated as the pure consumption contributing to the reaction. - The energy consumption at the time of production of sulfuric acid is estimated. 【OUTPUT】 - The loss of U is assumed to be zero. - The CO$_2$ emission at the time of production of sulfuric acid is estimated.	【INPUT】 - Supplied amount of sulfuric acid, acid concentration, the circulating amount 【OUTPUT】 - The quantity and purity of U (SO4)2 - The yield of U. 【Facility data】 - specifications for engine, processing power, etc. - Type and consumption of supplied energy.
4. Fluorination sedimentation	【OUTPUT】 - Leaching rate of U: 98.5%	【OUTPUT】 - Mass balance is estimated based on the leaching rate of U.	【INPUT】 - The supplied amount of hydrofluoric acid 【OUTPUT】 - The amount of sedimentation and the grade of U. - The amount of waste solution and the concentration of U - The yield of U 【Facility data】 - specifications for engine, processing power, etc. - Type and consumption of supplied energy.
5. Dehydration/ conversion		【OUTPUT】 - Mass balance is estimated based on the reaction formula.	【INPUT】 - The supplied amount of fluorine 【OUTPUT】 - The amount of water removed 【Facility data】 - specifications for engine, processing power, etc. - Type and consumption of supplied energy

Note: 【INPUT】: The amounts of materials, energy etc. supplied into processes concerned.
【OUTPUT】: The amounts of substances produced and emitted in the processes concerned.
【Facility data】: Data for equipment used in processes concerned.
The data indicated by 【INPUT】, 【OUTPUT】, and 【Facility data】 tend to have a major influence on the estimation of the environmental load such as the amount of energy consumption over the whole process because the amounts of supplied energy and CO$_2$ emission are large.

3) Flow diagram of processes and integration of mass balance data



Data source: Ippei Amamoto, Smelting and transversion of uranium in Ningyo-toge Factory, Sigen to Sozai, 109 (1993) No.12 1070-

Mass balance data

The amounts of material/energy are those per month.

	INPUT		OUTPUT		
Process	Supplied materials etc.	Supplied amounts	Product	Amounts of products	Remarks
1. Leaching	Yellow cake	**50.0 t-dry**	UO_2SO_4 solution	0.59 kL	- The yield of U is assume to be 90 %
	(including U)	(0.132 t)	(including U)	(0.12 t)	- All the main impurities (As, Ni, Fe, Al, Nb) contained in a yellow cake are assumed to be removed.
	Sulfuric acid	50.3 kL	(Others)	(19.8 t)	
		(92.6 t)	Residue	122.7 t	- A stirrer (rated power 2.2 kW) is assumed to run. - A filter press (rated power 0.4 kW) is assumed to run for 24 hours/day.
	Electric power	0.6 GJ	【CO_2emission】	0.06 t	- The environmental load for the production of sulfuric acid is considered.
	【Production of sulfuric acid)	0.5 GJ*	(including production of sulfuric acid)	(0.04 t*)	
2. Solvent leaching	UO_2SO_4 solution	0.6 kL	UO_2SO_4	0.16 t-dry	- Mass balance is estimated based on the reaction formula.
	(including U)	(0.12 t)	(including U)	(0.10 t)	
	(Other solutes)	(19.7 t)	Waste solution (at extracting)	(unknown)	- The leaching rate of U: 86%
	TNOA diluted solution	363.8 kL			- Hydrochloric acid is used for reverse extraction.
		(69.2 t)	Waste solution (at reverse extracting)	(unknown)	
	Hydrochloric acid	31.4 kL			- Additives are used for washing of organic solvents.
		(35.8 t)	(Residue in waste solution)	(19.6t)	
	Other additives	+ α			- A stirrer (rated power 2.2 kW) is assumed to run for 24 hours/day
	(Other additives)				- The environmental load for the production of hydrochloric acid is considered.
	Sulfuric acid				
					(The amount newly supplied, excluding the circulating amount, is calculated using the copper smelting data.)
	Electric powder	0.5 GJ	【CO_2emission】	0.18t	
	【Production of hydrochloric acid】	2.0 GJ	(including hydrochloric acid production)	(0.16t*)	
3. Electrolytic reduction	UO_2SO_4	0.16 t-dry	UO_2SO_4	0.2 t	- All U is assumed to be collected.
	(including U)	(0.10 t)	(including U)	(0.10 t)	- Only the amount of contributing to the reaction is considered for sulfuric acid.
	Sulfuric acid	0.04 t	O_2	0.01 t	- The environmental load for the production of hydrochloric acid is considered.
	Electric power	1.4 GJ	【CO_2emission】	0.06 t	
	【Production of sulfuric acid】	0.05 GJ*	(including sulfuric acid production)	(0.004 t)	
4. Fluorination sedimentation	$U(SO_4)_2$	0.18 t	UF_4nH_2O	0.14 t	- Leaching rate of U: 98.5%
	(including U)	(0.01 t)	(including U)	(0.10 t)	
	Hydrofluoric acid	**0.08 t-dry**	Waste solution	0.12 t-dry	
	Electric power	(unknown)	【CO_2emission】	(unknown)	
5. Dehydration/ conversion	UF_4nH_2O	0.14 t	Uranium hexafluoride	**0.15 t**	- Water is produced at the dehydration process.
	(including U)	(0.10 t)	(including U)	(0.01 t)	
	Fluorine	0.02 t	Water	0.01 kL	
				(0.01 t)	
	Electric power	(unknown)	【CO_2emission】	(unknown)	
Total	【Energy】	5.1 GJ	【CO_2emission】	0.3 t	
	(including raw material production)	(2.5 GJ)	(including production of raw material)	(0.2 t*)	

Data source: Data source: produced by NRI using various data.

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