International Aluminium Institute

LIFE CYCLE ASSESSMENT OF ALUMINIUM: INVENTORY DATA FOR THE WORLDWIDE PRIMARY ALUMINIUM INDUSTRY

MARCH 2003

CONTENTS

1. Introduction

The worldwide collection of aluminium data to be used in life cycle assessments was initiated by the IAI Board in 1998 with the following resolution:

“The Board of Directors of the International Aluminium Institute desires that the Institute develop as complete an understanding as possible of the positive contributions that the aluminium makes to the environmental and economic well-being of the world’s population; of any negative economic or environmental impacts that its production may cause; and of the balance between these positives and negatives during the entire “life cycle” of the material.”

A first IAI Report was prepared as “Aluminium Applications and Society. Life Cycle Inventory of the Worldwide Aluminium Industry with regard to Energy Consumption and Emissions of Greenhouse Gases. Paper 1 – Automotive” dated May 2000. This first report provided a complete understanding of the energy requirements and greenhouse gas emissions associated with the primary aluminium production.

The present Report has been prepared with the view of collecting all significant Life Cycle Inventory data for primary aluminium (i. e. raw materials and energy use, air and water emissions, solid waste generated), with worldwide coverage (except Russia and China). This report summarizes the cumulative inputs and outputs of environmental significance (air emissions, waste generation, resource consumption) associated with producing *primary aluminium ingot* from bauxite ore.

The Report does not include the inputs and outputs associated with the further processes related to the production of final products from ingots and the recycling of the end-of-life product to obtain recycled aluminium ingots. For these processes data sets on a regional basis, e.g. European data of the European Aluminium Association (EAA) are available.

When constructing a life cycle assessment related to aluminium, which includes aluminium production, fabrication, product usage, and product end-of-life issues, a methodology in accordance with internationally accepted practice (ISO 14040 series standards) should be used. A guidance document produced by the European Aluminium Association, “Key Features How to Treat Aluminium in LCA’s, with Special Regard to Recycling Issues” can be found at the end of this report in Appendix D. It especially deals with the case where recycled aluminium is used for aluminium products.

2. Purpose of this inventory and relation to life cycle assessment

2.1. Goal and Scope Definition

The intended purpose of this Inventory report is to accurately characterize resource consumption and significant environmental aspects associated with the worldwide production of primary aluminium. It reflects the fact that primary aluminium is a globally traded commodity.

The collected data will serve as a credible basis for subsequent life cycle assessments of aluminium products.

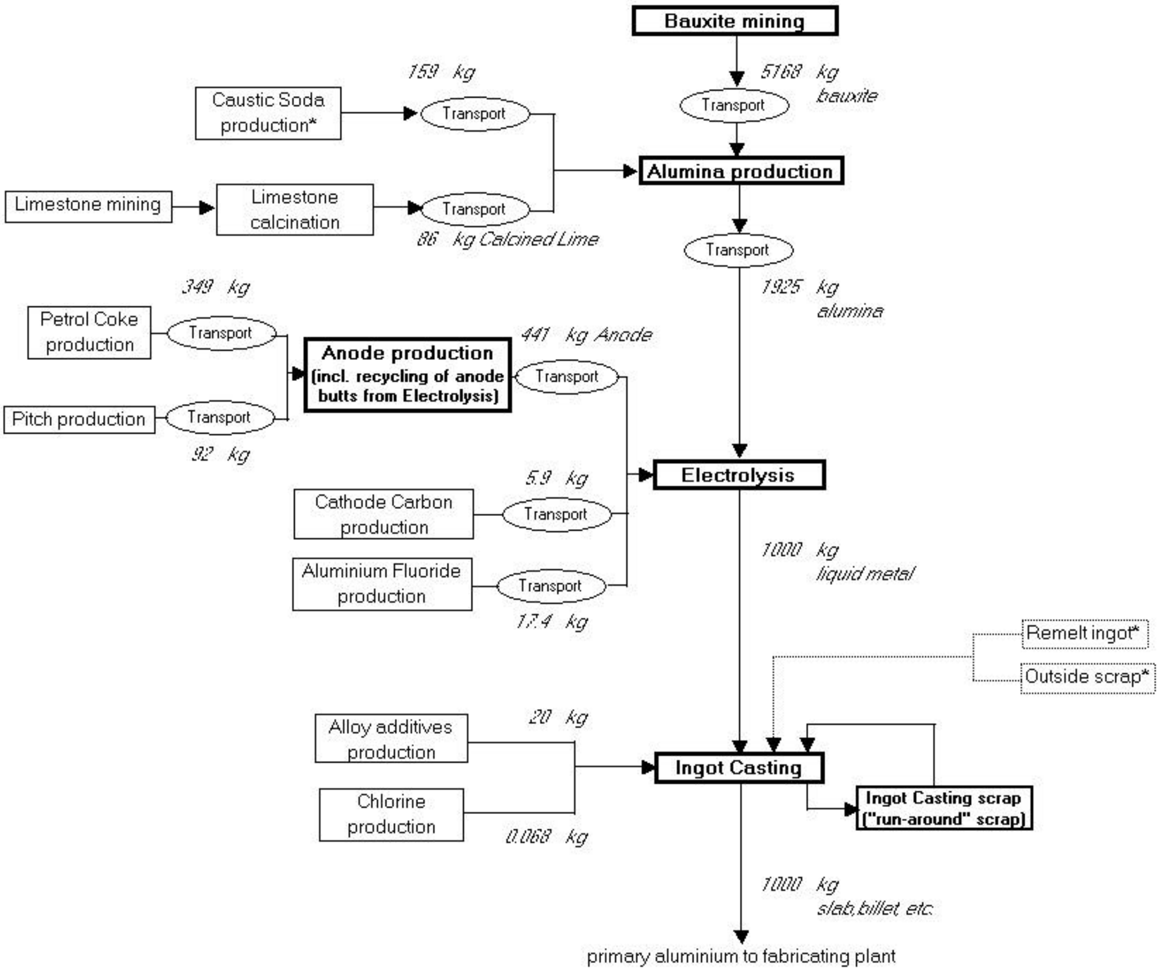
2.2. Process description and System Boundaries

The primary aluminium production covered by this study includes the following unit processes:

- bauxite mining;
- alumina production;
- anode production: production of pre-baked anodes, production of Söderberg paste;
- electrolysis;
- ingot casting.

Unit Process descriptions are reported in Appendix A1.

The interrelationships of these unit processes are shown on the diagram below (in block characters and boxes), which provides an overview of material flows in the primary aluminium production. A short summary of this production is as follows: aluminium is extracted from bauxite as aluminium oxide (alumina), this oxide is then broken down through an electrolysis process into oxygen, emitted as CO2 by reaction with a carbon anode, and aluminium as liquid metal; next aluminium is cast into an ingot, the usual form suitable for further fabrication of semi-finished aluminium products. The diagram also shows other unit material processes not documented in the present work.



* input from remelt or recycled aluminium ("cold metal") is excluded as not representative for primary aluminium (see para. 2.3 reference flow)

No specific additional unit processes, in particular about energy production, transport, petrol coke and pitch production, caustic soda production, etc. have been added to the process in order to avoid non-elementary flows. LCA Practitioners who will use the data of this report may include such additional unit processes from their own databases **(*)**.

However special care is needed to include the appropriate electricity supply process, according to the reference information collected by IAI about energy source use. The global breakdown by source of electricity used at primary aluminium smelters in the IAI Energy Survey for 2000, was as follows: Hydro 52.5%; Coal 31.6%; Oil 0.8%; Natural Gas 9.0%; and Nuclear 6.1%.

Data related to the transport of materials were not covered in this Report. Environmental aspects from transport can be illustrated with a case from the "Environmental Profile Report for the European Aluminium Industry (April 2000)", which yields the following air emission levels from transport in proportion of those generated from primary aluminium production: Particulates: 1.1%; HC: 29%; NO_x: 18.5%; SO_2: 6.7%.

2.3. Data collection

This document contains only as-collected data, eventually combined together into an Inventory table for the worldwide Primary Aluminium Industry presented in section 5. Selection of data for this Inventory was based on their environmental relevance, either specific for the primary aluminium production (printed in block in the table below) or as generally acknowledged environmental issues. The data selection was confirmed early 2001 with a special meeting of the IAI LCA/LCI Working Committee. These data are listed below, with explanatory notes reported in Appendix A1.

It should be noted that only direct energy consumption figures were documented for this Inventory and that CO2 emission data were not included. Comprehensive energy data and CO2 emission data, including those associated with the generation of electricity, the production of fuel (pre-combustion) and the combustion of fuel, were previously published in the IAI Report "Aluminium Applications and Society. Life Cycle Inventory of the Worldwide Aluminium Industry with regard to Energy Consumption and Emissions of Greenhouse Gases. Paper 1 – Automotive" dated May 2000. This May 2000 Report is available from the International Aluminium Institute or can be found on the IAI website at www.world-aluminium.org. A brief note about the May 2000 Report and a summary of the CO2 emission data contained in that Report are at Appendix C.

(*) Note: a caution issue lies with air emissions from fuel combustion, namely Particulates, SO2 and NOx emissions. Reporting from plants in the present report included these emissions, together with process emissions, for improved reliability (see discussion about data interpretation in section 5) in particular as regards the effect of the actual sulphur content of fuel oil used on SO2 emissions. Accordingly LCA Practitioners who would include their own data sets about emissions from fuel combustion are recommended to remove their data about Particulates, SO2 and NOx emissions, in order to avoid double counting (note: this applies only to fuel combustion and not to "pre-combustion" data sets).

Inputs	Unit	**Outputs**	Unit
Raw materials		**Air emissions**	
Bauxite	kg	**Fluoride Gaseous (as F)**	kg
Caustic Soda (for Alumina production)	kg	**Fluoride Particulate (as F)**	kg
Calcined Lime (for Alumina production)	kg	Particulates	kg
		NOx (as NO2)	kg
Petrol Coke (for Anode production)	kg	SO2	kg
Pitch (for Anode production)	kg	Total PAH	kg
		BaP (Benzo-a-Pyrene)	g
Aluminium Fluoride (for Electrolysis)	kg	**CF4**	kg
Cathode Carbon (for Electrolysis)	kg	**C2F6**	kg
		HCl (Hydrogen Chloride)	kg
Alloy additives (for Ingot Casting)	kg	Mercury	kg
Chlorine (for Ingot Casting)	kg	**Water emissions**	
Other raw material inputs			
Fresh Water	m3	Fresh Water	m3
Sea Water	m3	Sea Water	m3
Refractory materials	kg	**Fluoride (as F)**	kg
Steel (for anodes)	kg	Oil/Grease	kg
Steel (for cathodes)	kg	PAH (6 Borneff components)	g
		Suspended Solids	kg
Fuels and electricity		Mercury	kg
		By-products for external recycling	
Coal	kg	**Bauxite residue**	kg
Diesel Oil	kg	**Dross**	kg
Heavy Oil	kg	Filter dust	kg
Natural Gas	m3	Other By-products	kg
Electricity	kWh	Refractory material	kg
		Scrap sold	kg
		SPL carbon fuel/reuse	kg
		SPL refr.bricks-reuse	kg
		Steel	kg
		Solid waste	
		Bauxite residue (red mud)	kg
		Carbon waste	kg
		Dross - landfill	kg
		Filter dust - landfill	kg
		Other landfill wastes	kg
		Refractory waste - landfill	kg
		Scrubber sludges	kg
		SPL - landfill	kg
		Waste alumina	kg

2.4. Reference flow

For each unit process the reference flow is 1 metric tonne. For the whole primary aluminium process as shown above and consolidated below in section 5, the reference flow is 1 metric tonne primary aluminium output from ingot casting.

Remark: for the unit process Ingot Casting, the reference flow has been specified excluding the contribution of remelt or recycled aluminium, which was considered outside the scope of the present work.

Namely, the overall average from the Survey results for the process Ingot Casting yielded a higher weight output (1000 kg) than the corresponding electrolysis metal input (874 kg), due to a "cold metal" input contribution from remelt aluminium (133 kg remelt ingot) and recycled aluminium (101 kg outside scrap). Because the scope of this Inventory report is primary aluminium and not remelt or recycled aluminium, data for the unit process Ingot Casting were calculated excluding the contribution from "cold metal", i.e. all inputs and outputs from the Survey average were adjusted by a factor of 0.79 (input ratio (electrolysis metal+ alloy additives = 892 kg) / (total metal input = 1126 kg) – see table 4a).

According to the ISO standards on LCA, this can be described as a situation of joint process where a mass allocation approach is applied.

2.5. Time Period Coverage

For this study, responses from worldwide aluminium producers were requested for the calendar year 2000.

2.6. Technology Coverage

The Aluminium Electrolysis data supplied came from all existing major technology types. About 15% of the total capacity surveyed was from Söderberg facilities and the remaining 85% was produced in Prebake facilities. Alumina production data supplied came from facilities currently in operation.

3. Organisation of data collection

3.1 General organisation and timing

During spring 2000, the IAI Board approved to carry out the present Inventory of the worldwide Primary Aluminium Industry. The preparation of the corresponding Life Cycle Survey forms to be distributed as LCI questionnaires to individual primary aluminium companies started accordingly and was finalised early 2001 through the IAI LCA/LCI Working Committee.

The Life Cycle Survey forms were distributed to primary aluminium and alumina producing companies from May 2001, mostly through regional and country Aluminium Associations of Australia, Europe, Brazil, Canada, South Africa, Japan and the USA. Forms for companies operating in other regions and countries were distributed by the IAI Confidential Statistical Officer.

From mid-2001, the IAI LCA/LCI Working Committee set up a LCA data review Subcommittee to monitor the data collection and processing. This LCA data Subcommittee, chaired by John Pullen (Alcoa Australia), consisted of Ken Martchek (Alcoa), Kurt Buxmann (Alcan), Bernard de Gélas (EAA), working on the “de-identified” data (see below) with Reggie Gibson (IAI Confidential Statistical Officer). The Subcommittee worked through monthly telephone conferences and dedicated meetings held in conjunction with the regular IAI LCA/LCI Working Committee meetings.

Since the beginning the whole procedure of LCA data collection has been submitted to and discussed with the IAI LCA Advisory Panel, consisting of Konrad Saur (Five Winds), Bruce Vigon (Battelle), Ron Williams (General Motors).

3.2 Organisation of data collection

The Life Cycle Survey forms were the following:

- IAI LCS 001 – Primary Aluminium Smelting
- IAI LCS 002 – Alumina Production
- IAI LCS 003 – Ingot Casting

Attached to these was an “Explanatory Notes” form (IAI LCS 004) providing guidance for the Survey Respondents.

The Life Cycle Survey forms were designed in order to collect all required LCI data except those already collected through established yearly IAI Surveys, namely the IAI Energy Survey and the IAI PFC Survey. These are carried out using the corresponding survey forms:

- IAI Form ES 001 – Electrical Energy used in Primary Aluminium Smelting
- IAI Form ES 001A (smelters) and B (independent Anode Producers) – Anodes used in Primary Aluminium Smelting
- IAI Form ES 011 – Energy for the Production of Metallurgical Alumina
- IAI PFC Survey – Form PFC 001

The Life Cycle Survey forms have been distributed through the Regional Associations as mentioned above. Responses were collected (confidentially) through the same channel, then forwarded to the IAI Confidential Statistical Officer, who tabulated all data and “de-identified” them by removing names (leaving only Regional location) to preserve confidentiality in the use by the data Subcommittee. The Statistical Officer also calculated the normalised data values, i.e. values referred to the process unit production (for instance, kWh per metric tons of aluminium produced in electrolysis), as well as the corresponding standard deviation, for subsequent review by the Subcommittee experts. Last, once the apparent inconsistency issues had been sorted out (“outliers”, see below), he worked out the weighted mean values appearing in the final result tables.

Data processing by the IAI Statistical Officer from the IAI Energy Survey and the IAI PFC Survey was basically the same. However no review of the results for inconsistency was needed, as the two Surveys are carried out on a regular annual basis. With the IAI Energy Survey, each individual answer is checked for consistency, in particular as regards anode data; inconsistency issues are sorted out by direct contact with the respondent prior to data processing.

As the Life Cycle Survey, the IAI Energy Survey and the IAI PFC Survey were carried out separately, they have not exactly the same survey response base. This is acknowledged in the inventory analysis tables in the following section 5, where results and survey base are differentiated between the Life Cycle Survey (normal characters) and the IAI Energy Survey or the IAI PFC Survey (italic letters).

4. Survey coverage and data quality

Survey coverage

Data for the Life Cycle Survey were obtained from:

- 82 world-wide aluminium electrolysis plants producing 14.7 million metric tons of primary aluminium, representing about 60% of world-wide aluminium smelting operations (base: primary aluminium from WBMS 24,464,400 t).
- 23 world-wide alumina facilities producing 30.8 million metric tons of alumina, representing about 59% of world-wide alumina operations (base: world alumina production 52,419,000 t, as 48,119,000 t from IAI plus 4,300,000 t estimated for China etc.).
- 72 world-wide aluminium cast houses producing 14.0 million metric tons of primary aluminium ingot, representing about 57% of world-wide aluminium ingot casting operations (total world aluminium production in the year 2000 from WBMS 32,623,800 t, of which 24,464,400 t primary aluminium taken as cast house production base, plus 8,159,400 t secondary aluminium not relevant here).

The survey response base was higher for the IAI Energy Survey and the IAI PFC Survey, which were carried out separately as mentioned above. Overall, primary aluminium energy returns represented about 69% of world primary aluminium production; alumina energy returns represented about 70% of world alumina production; and PFC returns represented about 66% of world primary aluminium production.

Data were collected along the following Unit Processes: Alumina Production, Anode Production (Prebake), Paste Production (Söderberg), Reduction (Electrolysis), Ingot Casting.

Geographic coverage

The data were reasonably evenly distributed on a worldwide basis, the non-availability of data from China and Russia being mainly responsible for the comparatively poor coverage of Asia and Europe. For example, the survey's coverage of electrolysis plants in terms of reported primary aluminium production as a percentage of total primary aluminium production was about 82% in Africa, 75% in North America, 58% in Latin America, 34% in Asia (data for China not available), 52% in Europe (data for Russia and other CIS countries not available) and 100% in Oceania.

Data consistency

Monitoring the data collection process, experts of the LCA data review Subcommittee noticed a significant scatter in individual data items. Beyond obviously unrealistic outliers, high- and low-value outlier responses appeared likely to influence wrongly the final weighted average values. The following procedure has been implemented to address the issue.

All individual answers beyond 2 standard deviations from the average value have been considered as outliers. Every individual outlier respondent has been queried accordingly (about 100, during January-March 2002), with a request to check the response item for correction or confirmation. On a deadline set at end-March, all outliers were adjusted according to answers received (typically half were confirmed and half were corrected). If no answer had been received to the outlier query (about 60 % of outliers), the individual outlier item has been removed from the Survey.

The effect of this correction from outliers can be assessed from the table reported in Appendix A3 showing the percent difference in Inventory results obtained by using the initial Survey results, i.e. reintroducing the outliers (individual answers beyond 2 standard deviations from the average value, identified in the initial Survey results and not commented on query). This effect was very variable according to the particular data however, corrections are in line with the likely reasons applicable for the particular outlier occurrence, as discussed in Appendix A3.

Data reporting

Data reporting for the present Inventory of the world-wide Primary Aluminium Industry has been organised with quantitative and qualitative Data Quality Indicators (DQI), calculated for each data item:

Quantitative Data Quality Indicators: Precision (weighted mean values), Standard Deviation, Minimum and Maximum, Completeness.

- Precision: all values presented in the text of this report represent production weighted mean values for worldwide aluminium processes.
- Completeness: for each data item, this quality indicator covers the possibility where not all

Survey respondents provided an answer. It is the ratio (number of responses for the data item) / (total number of responses to the Survey).

Data statistics assume a normal distribution of results. Examples of cumulative distribution graphs are reported in Appendix A4.

Qualitative Data Quality Indicators: DQI average and DQI range as representative indexes, calculated from the quality indicator provided by respondents for each individual answer among:

1 (measured), 2 (calculated) and 3 (estimated)

Note: for data collected from the IAI Energy Survey and the IAI PFC Survey, those qualitative indicators were not collected, due to the different Survey procedure. However the DQI level can be considered as 1, in view of the thorough experience from these Surveys.

Missing process data supplemented

During the course of the Survey, it was realised that the Life Cycle Survey forms distributed to companies had omitted two sets of process data needed for the Inventory, namely Bauxite Mining life cycle data and Ingot Casting energy consumption data. Missing data have been worked out from currently available information as described below.

Bauxite Mining data

	Selected	**2 Australian mines**		**9 mines (Aachen)**		**N.American LCI 1998**	
Inputs							
Diesel	**2 kg/t***	0.90	kg/t	0.67 – 1.8	kg/t	4.37	kg/t
Other oil	**-**	(1.16 kg/t medium fuel oil, 0.27 kg/t gasoline)>				1.43	kg/t
Electricity	**-**	0.002	kWh/t			0.4	kWh/t
Fresh water	**-**	0.031	m3/t				
Outputs							
Particulates	**2.35 kg/t***			0.002–0.005	kg/t	2.35	kg/t
Solid waste	**136 kg/t***					136	kg/t

*per t of bauxite output

Life cycle data thus selected were accepted as quite representative, from industry experts. Other inputs and output were not selected because they were scarcely documented and generally would have a minor likely contribution in the final Inventory calculation (other oil 3%, electricity 0,01%, fresh water 1%).

Ingot Casting energy data

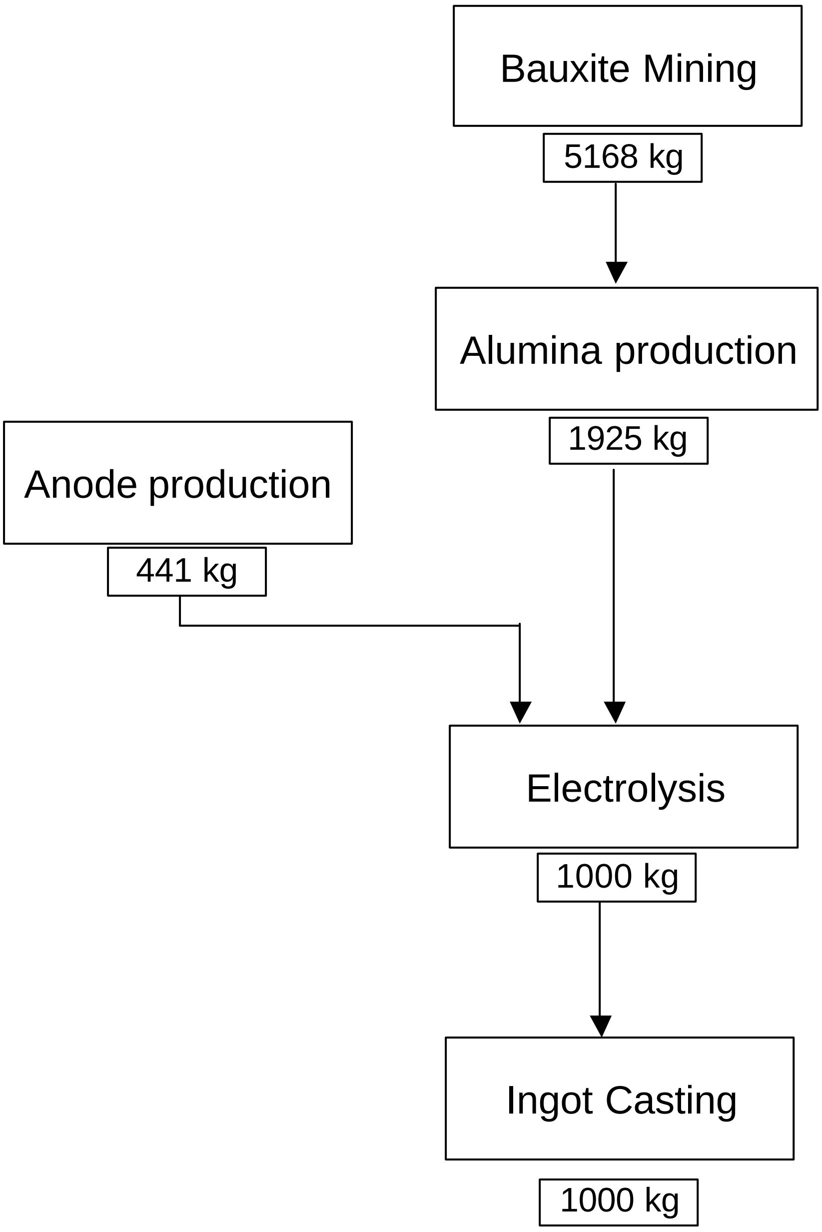
	Selected	EAA 1995		Alcoa US		2 Australian		North American LCI 1998	
		(25 cast houses, 3.3 Mio t, typical primary)		(K. Martchek)		(J.Pullen)			
Fuel oil	**10.0 kg/t***	10.9	kg/t	about 10	kg/t			17.4	kg/t
Diesel	**0.1 kg/t***	0.1	kg/t			0.9	l/t	<0.2	kg/t
Gas	**52 m3/t***	17.6	m3/t	52	m3/t	84	m3/t	52	m3/t
Electricity	**81 kWh/t***	16	kWh/t	111	kWh/t	81	kWh/t	211	kWh/t

*per t of cast metal output

Life cycle data thus selected are considered quite representative, from industry experts. Moreover these data have a relatively minor contribution in the Inventory calculation, which would make acceptable some uncertainty with their numerical values (fuel oil 4%, diesel 0.8%, gas 17%, electricity 0.5%).

5. Inventory for the worldwide Primary Aluminium Industry

The Inventory table for worldwide Primary Aluminium Industry reported below has been calculated from all results of inventory data (presented in Appendix). For this purpose the processes were combined together as shown in the following flow diagram.



Data interpretation items

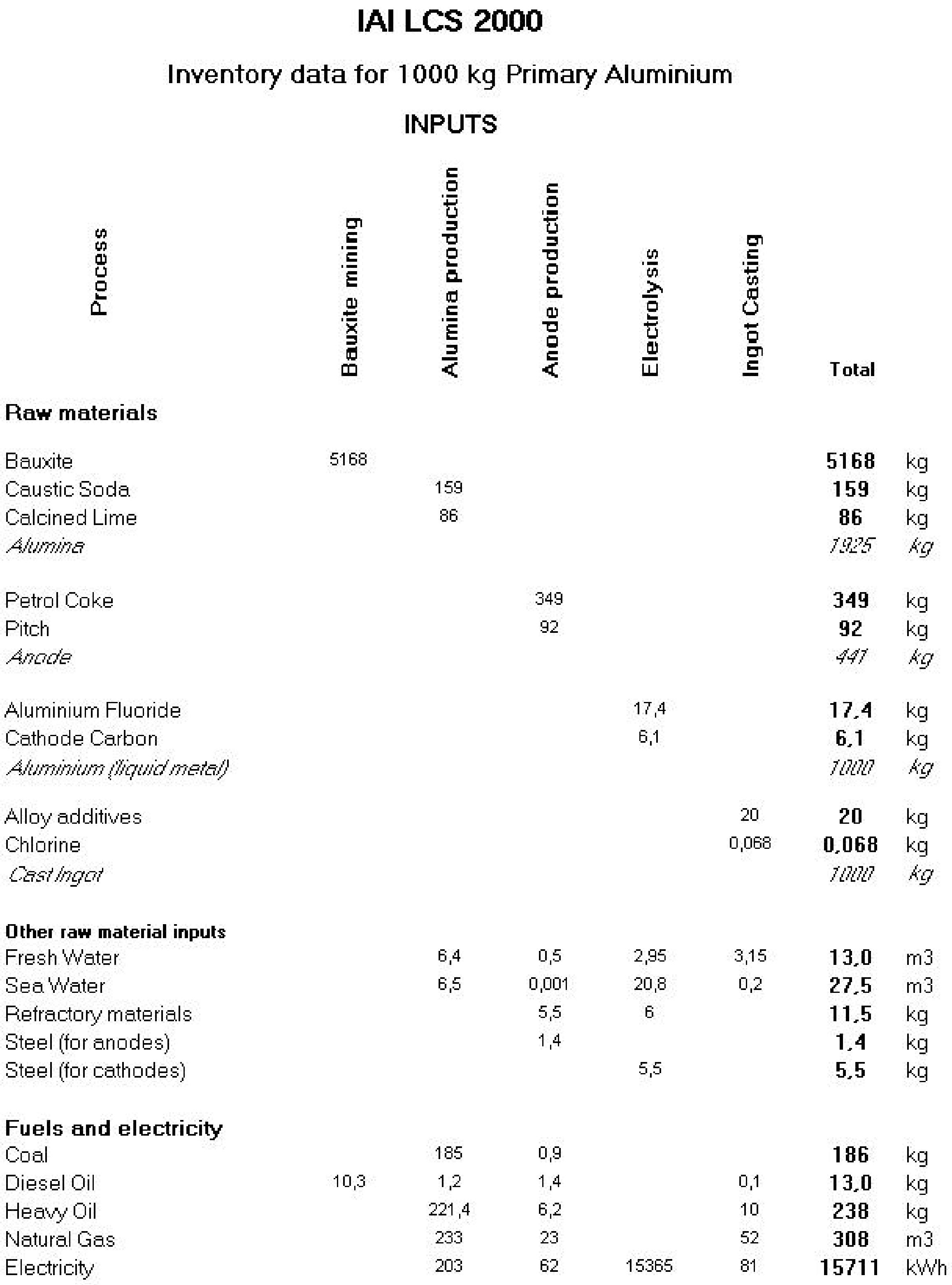
- Missing data for bauxite mining and ingot casting energy have been worked out as discussed at the end of section 4.

- Data are normally reported as production weighted mean values derived from the effective responses to the Survey, as mentioned under "organisation of data collection", section 3.2. In several situations mentioned below, however, this was leading to inconsistent results. Data reporting then took place as industry weighted use (reported as such in the tables in the Appendix), i.e. the ratio "total consumption or emission reported from the Survey (total of all responses) to total corresponding industry production":
  1) Petrol coke and pitch consumption for anodes (see table 3a), because weighted mean values from anode production tables are altered due to anode butt recycling.
  2) Fresh Water and Sea Water use (inputs and outputs), as here this correction avoided the apparent input-output imbalance visible when using weighted mean values.
  3) Fuel and electricity consumption for alumina and anode production, the rationale here being that the mix of fuel use is typically company-specific, i.e. using weighted mean values lead to overestimated results.

- Some air emission data from fuel combustion (an energy unit process not documented in the present work), namely Particulates, SO2 and NOx emissions, are included together with process emissions in the results reported from plants. This arises from the fact that the two emission types (from fuel combustion and from process) do occur together, however also corresponds to an improved reliability on actual emission levels from fuel combustion as compared to general fuel combustion emission data. In particular the actual sulphur content of fuel oil used, e.g. in alumina production, is thus most accurately accounted for in SO2 emissions.

- Review of results could raise remarks for apparent inconsistency or weakness of evidence. Noted examples are the steel input-output imbalance (likely to be attributed to a used steel output from general maintenance work), the Ingot Casting mass balance (probably linked to the cold metal contribution) and a low response rate for dioxins emissions in Ingot Casting (commented below). These cases can probably be considered as relatively non-significant, given the overall purpose of the present Inventory. It is also clear that the present Survey produced the best currently available knowledge for the worldwide Primary Aluminium Industry.

- Results for dioxins emissions from Ingot Casting have not been included in the final inventory calculation, as they are related to aluminium scrap remelting, which is outside the scope of this report (see reference flow section 2.4). Chlorine present in aluminium scrap (from painting or coating residues) is the origin element for dioxin emissions during aluminium remelting and there is no chlorine is in primary aluminium. The relation with aluminium scrap remelting has been confirmed from the Survey results with higher dioxin emissions results reasonably correlated with higher scrap use, despite the limited number of answers received (6 over 72 cast houses) and a high scatter in values.

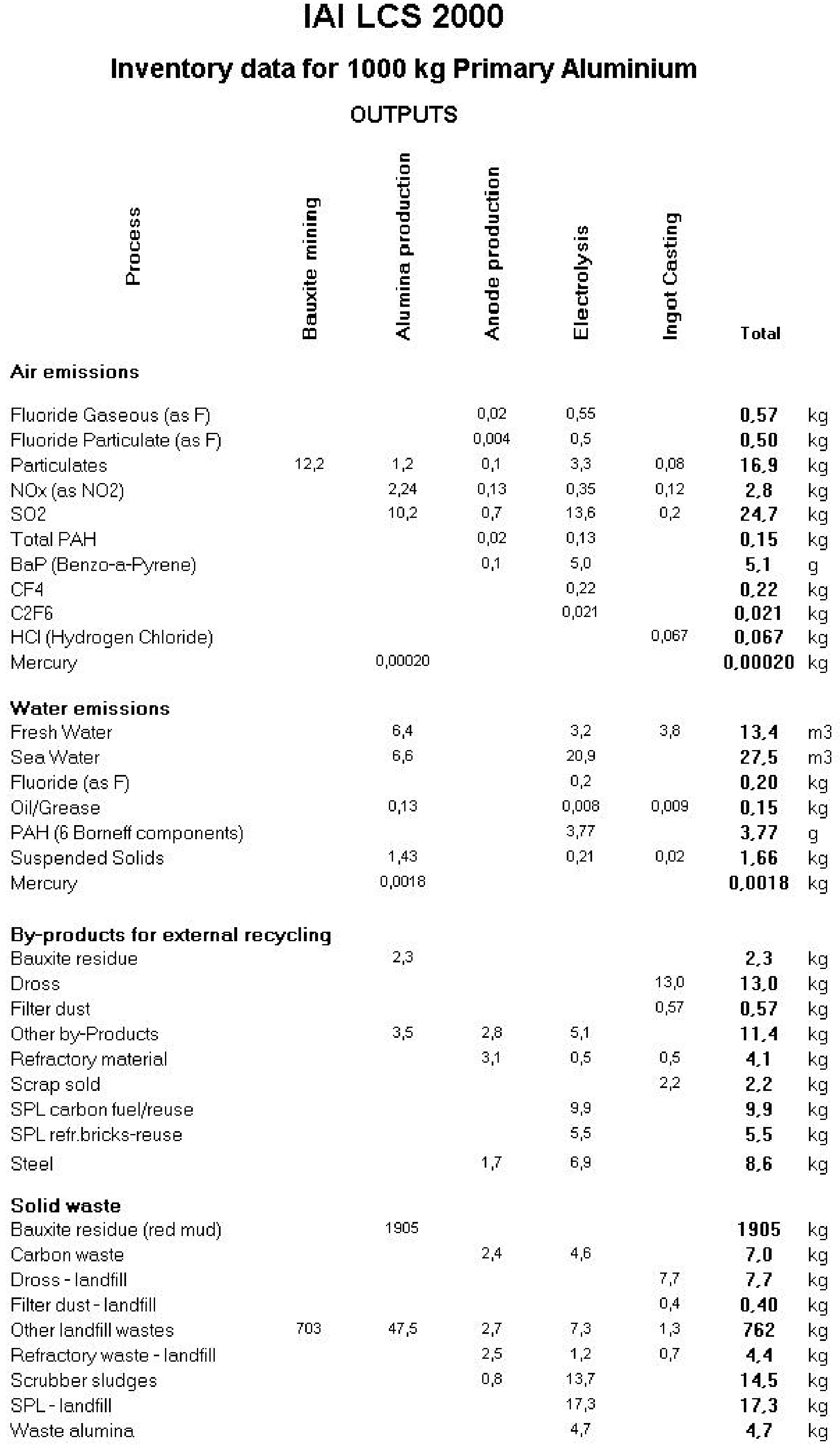


IAI LCS 2000

Inventory data for 1000 kg Primary Aluminium

INPUTS

Process	Bauxite mining	Alumina production	Anode production	Electrolysis	Ingot Casting	Total	
Raw materials							
Bauxite	5168					**5168**	kg
Caustic Soda		159				**159**	kg
Calcined Lime		86				**86**	kg
Alumina						*1925*	*kg*
Petrol Coke			349			**349**	kg
Pitch			92			**92**	kg
Anode						*441*	*kg*
Aluminium Fluoride				17,4		**17,4**	kg
Cathode Carbon				6,1		**6,1**	kg
Aluminium (liquid metal)						*1000*	*kg*
Alloy additives					20	**20**	kg
Chlorine					0,068	**0,068**	kg
Cast Ingot						*1000*	*kg*
Other raw material inputs							
Fresh Water		6,4	0,5	2,95	3,15	**13,0**	m3
Sea Water		6,5	0,001	20,8	0,2	**27,5**	m3
Refractory materials			5,5	6		**11,5**	kg
Steel (for anodes)			1,4			**1,4**	kg
Steel (for cathodes)				5,5		**5,5**	kg
Fuels and electricity							
Coal		185	0,9			**186**	kg
Diesel Oil	10,3	1,2	1,4		0,1	**13,0**	kg
Heavy Oil		221,4	6,2		10	**238**	kg
Natural Gas		233	23		52	**308**	m3
Electricity		203	62	15365	81	**15711**	kWh

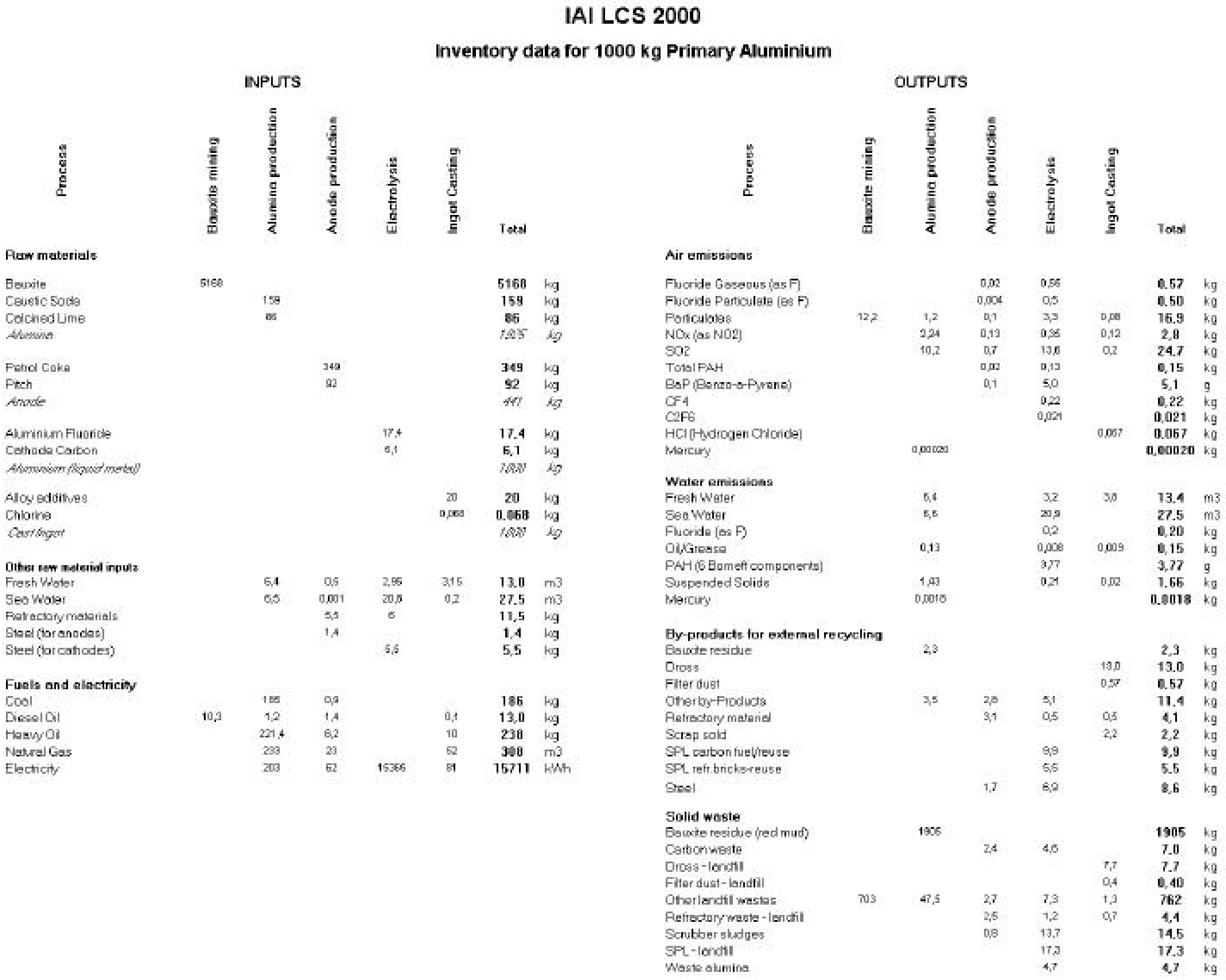


IAI LCS 2000

Inventory data for 1000 kg Primary Aluminium

OUTPUTS

Process	Bauxite mining	Alumina production	Anode production	Electrolysis	Ingot Casting	Total	
Air emissions							
Fluoride Gaseous (as F)			0,02	0,55		**0,57**	kg
Fluoride Particulate (as F)			0,004	0,5		**0,50**	kg
Particulates	12,2	1,2	0,1	3,3	0,08	**16,9**	kg
NOx (as NO2)		2,24	0,13	0,35	0,12	**2,8**	kg
SO2		10,2	0,7	13,6	0,2	**24,7**	kg
Total PAH			0,02	0,13		**0,15**	kg
BaP (Benzo-a-Pyrene)			0,1	5,0		**5,1**	g
CF4				0,22		**0,22**	kg
C2F6				0,021		**0,021**	kg
HCl (Hydrogen Chloride)					0,067	**0,067**	kg
Mercury		0,00020				**0,00020**	kg
Water emissions							
Fresh Water		6,4		3,2	3,8	**13,4**	m3
Sea Water		6,6		20,9		**27,5**	m3
Fluoride (as F)				0,2		**0,20**	kg
Oil/Grease		0,13		0,008	0,009	**0,15**	kg
PAH (6 Borneff components)				3,77		**3,77**	g
Suspended Solids		1,43		0,21	0,02	**1,66**	kg
Mercury		0,0018				**0,0018**	kg
By-products for external recycling							
Bauxite residue		2,3				**2,3**	kg
Dross					13,0	**13,0**	kg
Filter dust					0,57	**0,57**	kg
Other by-Products		3,5	2,8	5,1		**11,4**	kg
Refractory material			3,1	0,5	0,5	**4,1**	kg
Scrap sold					2,2	**2,2**	kg
SPL carbon fuel/reuse				9,9		**9,9**	kg
SPL refr.bricks-reuse				5,5		**5,5**	kg
Steel			1,7	6,9		**8,6**	kg
Solid waste							
Bauxite residue (red mud)		1905				**1905**	kg
Carbon waste			2,4	4,6		**7,0**	kg
Dross - landfill					7,7	**7,7**	kg
Filter dust - landfill					0,4	**0,40**	kg
Other landfill wastes	703	47,5	2,7	7,3	1,3	**762**	kg
Refractory waste - landfill			2,5	1,2	0,7	**4,4**	kg
Scrubber sludges			0,8	13,7		**14,5**	kg
SPL - landfill				17,3		**17,3**	kg
Waste alumina				4,7		**4,7**	kg



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Fresh Water		6,4	0,6	2,96	3,15	**13,0**	m3
Sea Water		6,5	0,001	20,8	0,2	**27,5**	m3
Refractory materials			5,5	6		**11,5**	kg
Steel (for anodes)			1,4			**1,4**	kg
Steel (for cathodes)				5,5		**5,5**	kg
Fuels and electricity							
Coal		185	0,9			**186**	kg
Diesel Oil	10,3	1,2	1,4		0,1	**13,0**	kg
Heavy Oil		221,4	6,2		10	**238**	kg
Natural Gas		233	23		52	**308**	m3
Electricity		203	62	15366	81	**15711**	kWh

OUTPUTS

Process	Bauxite mining	Alumina production	Anode production	Electrolysis	Ingot Casting	Total	
Air emissions							
Fluoride Gaseous (as F)			0,02	0,56		**0,57**	kg
Fluoride Particulate (as F)			0,004	0,5		**0,50**	kg
Particulates	12,2	1,2	0,1	3,3	0,08	**16,9**	kg
NOx (as NO2)		2,24	0,13	0,35	0,12	**2,8**	kg
SO2		10,2	0,7	13,6	0,2	**24,7**	kg
Total PAH			0,02	0,13		**0,15**	kg
BaP (Benzo-a-Pyrene)			0,1	5,0		**5,1**	g
CF4				0,22		**0,22**	kg
C2F6				0,021		**0,021**	kg
HCl (Hydrogen Chloride)					0,067	**0,067**	kg
Mercury		0,00020				**0,00020**	kg
Water emissions							
Fresh Water		6,4		3,2	3,8	**13,4**	m3
Sea Water		6,6		20,9		**27,5**	m3
Fluoride (as F)				0,2		**0,20**	kg
Oil/Grease		0,13		0,008	0,009	**0,15**	kg
PAH (6 Borneff components)				3,77		**3,77**	g
Suspended Solids		1,43		0,21	0,02	**1,66**	kg
Mercury		0,0018				**0,0018**	kg
By-products for external recycling							
Bauxite residue		2,3				**2,3**	kg
Dross					13,0	**13,0**	kg
Filter dust					0,57	**0,57**	kg
Other by-Products		3,5	2,8	5,1		**11,4**	kg
Refractory material			3,1	0,5	0,5	**4,1**	kg
Scrap sold					2,2	**2,2**	kg
SPL carbon fuel/reuse				9,9		**9,9**	kg
SPL refr.bricks-reuse				5,5		**5,5**	kg
Steel			1,7	6,9		**8,6**	kg
Solid waste							
Bauxite residue (red mud)		1905				**1905**	kg
Carbon waste			2,4	4,6		**7,0**	kg
Dross - landfill					7,7	**7,7**	kg
Filter dust - landfill					0,4	**0,40**	kg
Other landfill wastes	703	47,5	2,7	7,3	1,3	**762**	kg
Refractory waste - landfill			2,5	1,2	0,7	**4,4**	kg
Scrubber sludges			0,8	13,7		**14,5**	kg
SPL - landfill				17,3		**17,3**	kg
Waste alumina				4,7		**4,7**	kg

Appendix A1: Unit Process descriptions and explanatory notes about Inventory inputs and outputs

The different Inventory inputs and outputs are reported in block italic letters within the following Unit Process descriptions for aluminium production.

1. BAUXITE MINING

Inventory analysis unit process description: Bauxite Mining

This unit process begins with the removal of overburden from a bauxite rich mining site. Reusable topsoil is normally stored for later mine site restoration.

The operations associated with this unit process include:

- the extraction of bauxite rich minerals from the site;
- beneficiation activities such as washing, screening, or drying;
- treatment of mining site residues and waste; and
- site restoration activities such as grading, dressing and replanting.

The output of this unit process is the bauxite that is transported to an alumina refinery.

Bauxite mining activities mainly take place in tropical and subtropical areas of the earth. Most all bauxite is mined in an open pit mine. The known reserves of alumina containing ore will sustain the present rate of mining for 300 to 400 years.

Commercial bauxite can be separated into bauxite composed of mostly alumina trihydrates and those composed of alumina monohydrates. The trihydrate aluminas contain approximately 50% alumina by weight, while monohydrates are approximately 30%. Monohydrates are normally found close to the surface (e.g. Australia), while trihydrates tend to be at deeper levels (e.g. Brazil).

The only significant processing difference in bauxite mining is the need for beneficiation. Beneficiation occurs with ores from forested areas, while the grassland type typically does not require washing. The wastewater from washing is normally retained in a settling pond and recycled for continual reuse.

2. ALUMINA PRODUCTION

Inventory analysis unit process description: Alumina Production
This unit process begins with the unloading of process materials to their storage areas on site. The operations associated with this unit process include: • ***Bauxite*** grinding, digestion and processing of liquors; • alumina precipitation and calcination; • maintenance and repair of plant and equipment; and • treatment of process air, liquids and solids. The output of this unit process is smelter grade alumina transported to an Electrolysis plant (Primary Aluminium smelter).

In alumina production, also commonly named alumina refining, ***Bauxite*** is converted to aluminium oxide using the Bayer process, which uses ***Caustic Soda*** and ***Calcined Lime*** *(Limestone)* as input reactants. ***Bauxite*** is ground and blended into a liquor containing sodium carbonate and sodium hydroxide. The slurry is heated and pumped to digesters, which are heated pressure tanks. In digestion, iron and silicon impurities form insoluble oxides called ***Bauxite residue***. The ***Bauxite residue*** settles out and a rich concentration of sodium aluminate is filtered and seeded to form hydrate alumina crystals in precipitators. These crystals are then heated in a calcining process. The heat in the calciners drive off combined water, leaving alumina. ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) or ***Sea Water*** is used as cooling agent.

The major differences in processing are at the calcination stage. Two types of kilns are used: rotary and fluid bed. The fluid bed or stationary kiln is newer and significantly more energy efficient. Energy requirements (***Coal, Diesel Oil, Heavy Oil, Natural Gas, Electricity***) have almost been halved over the last 15 years with the introduction of higher pressure digesters and fluid flash calciners.

Air emissions mostly arise from the calcination stage *(**Particulates; NOx (as NO2), SO2,*** from fuel combustion*; **Mercury*** found in ***Bauxite*** ores*),* while Water emissions come from cooling use (***Fresh Water, Sea Water, Oil/Grease***) or are linked with the digestion stage *(**Suspended Solids, Mercury*** found in ***Bauxite*** ores*).*

Most of the ***Bauxite residue*** currently turns out as Solid waste, while a small but growing fraction is reused. ***Other*** by-products for external recycling are reaction chemicals. ***Other Landfill Wastes*** are typically inert components from ***Bauxite*** such as sand, or waste chemicals.

3. ANODE PRODUCTION

Inventory analysis unit process description: Anode Production

This unit process begins with the unloading of process materials to their storage areas on site.

The operations associated with this unit process include:

- recovery of spent anode materials;
- anode mix preparation, anode block or briquette forming and baking;
- rodding of baked anodes;
- maintenance and repair of plant and equipment; and
- treatment of process air, liquids and solids.

The output of this unit process is rodded anodes or briquettes transported to an Electrolysis plant (Primary Aluminium smelter).

There are two types of aluminium smelting technologies that are distinguished by the type of anode that is used in the reduction process: Söderberg and Prebake.

Söderberg design uses a single anode, which covers most of the top surface of a reduction cell (pot). Anode paste (briquettes) is fed to the top of the anode and as the anode is consumed in the process, the paste feeds downward by gravity. Heat from the pot bakes the paste into a monolithic mass before it gets to the electrolytic bath interface.

The Prebake design uses prefired blocks of solid carbon suspended from ***Steel*** axial busbars. The busbars both hold the anodes in place and carry the current for electrolysis.

The process for making the aggregate for briquettes or prebake blocks is identical. ***Petrol Coke*** is calcined, ground and blended with ***Pitch*** to form a paste that is subsequently formed into blocks or briquettes and allowed to cool. While the briquettes are sent direct to the pots for consumption, the blocks are then sent to a separate baking furnace.

Baking furnace technology has evolved from simple pits that discharged volatiles to atmosphere during the baking cycle to closed loop type designs that convert the caloric heat of the volatile into a process fuel that reduces energy consumption for the process. Baking furnace use ***Refractory materials*** for linings, ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) (or possibly ***Sea Water***) as cooling agent. Baking furnace account for most of energy consumption (***Coal, Diesel Oil, Heavy Oil, Natural Gas, Electricity***).

<u>Air emissions</u>**:** ***Fluoride Gaseous (as F), Fluoride Particulate (as F)*** arise from recovered spent anode materials (un-used anode ends - "anode butts") from Electrolysis (see below) recycled within Prebake Anode Production. ***Particulates, NOx (as NO2), SO2***, come typically from fuel combustion.

Total PAH, which includes ***BaP (Benzo-a-Pyrene)***, are air emissions generated from the basic Anode Production process. A common practice for their prevention and monitoring is water scrubbing, a process using ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) or ***Sea Water*** as input and resulting in corresponding ***Fresh Water*** or ***Sea Water*** discharges (the latter accounted for in the Inventory together with the Electrolysis water discharges from scrubbing – see below).

By-products for external recycling: this means recovery of used ***Steel*** from anode bars, or of used ***Refractory material*** from baking furnaces. Various ***Other*** by-products are also recovered, e.g. carbon recovered for re-use.

Solid waste not recycled (landfill): ***Waste Carbon or mix*** is a residue from anode production, ***Scrubber sludges*** arise from water scrubbing used for control of air emissions mentioned above, ***Refractory*** waste comes out from baking furnaces Other landfill wastes arise as various residues, e.g. carbon fines.

4. ELECTROLYSIS

Inventory analysis unit process description: Electrolysis
This unit process begins with the unloading of process materials to their storage areas on site. The operations associated with this unit process include: • recovery, preparation and handling of process materials; • manufacture of major process equipment (e.g. cathodes); • process control activities (metal, bath, heat); • maintenance and repair of plant and equipment; and • treatment of process air, liquids and solids. The output of this unit process is hot metal transported to an ingot casting facility.

The Electrolysis process is also commonly named Aluminium Smelting.

Molten aluminium is produced from alumina (aluminium oxide) by the Hall-Heroult electrolytic process that dissolves the alumina in a molten cryolite bath (re: ***Aluminium Fluoride*** input) and passes current through this solution, thereby decomposing the alumina into aluminium and oxygen. Aluminium is tapped out of the reduction cell (pot) at daily intervals and the oxygen combines with the carbon of the anode to form carbon dioxide.

The pot consists of a ***Steel (for cathodes)*** shell lined with ***Refractory materials*** insulation and with a hearth of carbon (***Cathode Carbon (for Electrolysis)***). This is known as the cathode. The cathode is filled with a cryolite bath and alumina and an anode is suspended in the bath to complete the circuit for the pot. Once started, a pot will run continuously for the life of the cathode, which may last for in excess of 10 years. At the end of its life each pot is completely refurbished. ***Steel*** from used ***cathodes*** is recovered for recycling. ***Refractory materials*** are either recycled as by-products or landfilled (***Refractory waste – landfill***). Spent pot linings (SPL), which include a carbon-based (***SPL carbon***) and a refractory-based part (***SPL refractory bricks***) are either recycled as by-products (***SPL carbon fuel/reuse, SPL refr.bricks-reuse***) or landfilled (***SPL – landfill***).

The current in a pot varies from 60,000 to over 300,000 amperes at a voltage drop of 4.2 to 5.0 volts. Pots produce about 16.2 plus/minus 0.6 pounds per day of aluminium for each kiloampere at an operating efficiency of 91% plus/minus 4%. ***Electricity*** consumption is the major energy aspect of Electrolysis.

Aluminium smelters typically use air pollution control system to reduce emissions. The primary system is typically a scrubber. Some plants use dry scrubbers with alumina as the absorbent that is subsequently fed to the pots and allows for the recovery of scrubbed materials. Other plants use wet scrubbers, which recirculate an alkaline solution to absorb emissions: the wet scrubbing process uses ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources) or ***Sea Water*** as input and result in corresponding ***Fresh Water*** or ***Sea Water*** discharges. Unlike dry scrubbers, wet scrubbers absorb carbon dioxide, nitrogen oxide and sulphur dioxide that are entrained in the waste water liquor (which is subsequently treated prior to final discharge). ***Scrubber sludges*** are landfilled.

Air emissions: specific aluminium Electrolysis process emissions are ***Fluoride Gaseous (as F), Fluoride Particulate (as F)***, which arise from the molten bath; ***Total PAH***, which includes ***BaP (Benzo-a-Pyrene)***, which arise from anode consumption; ***CF4*** and ***C2F6***, commonly reported as PFC, are gases generated with an uncontrolled anode overvoltage situation named “anode effect”. ***Particulates, NOx (as NO2), SO2***, come typically from fuel combustion.

Water emissions: ***Fluoride (as F)*** and ***PAH (6 Borneff components****: which are monitored because of their particular environmental effect****)*** arise from the same origin as their air emission equivalents above. ***Suspended Solids*** and ***Oil/Grease (***or ***total HC)*** are monitored in water discharges from wet scrubbing.

Solid waste: ***Other landfill wastes*** consist typically of about 60 % of "environmental abatement" waste (such as dry scrubber filter bags) and 40 % of "municipal" waste (source: North American Aluminum Association LCI report 1998).

5. INGOT CASTING

Inventory analysis unit process description: Ingot Casting
This unit process begins with the unloading of process materials to their storage areas on site. The operations associated with this unit process include: • pre-treatment of hot metal (cleaning and auxiliary heating); • recovery and handling of internal process scrap; • batching, metal treatment and casting operations; • homogenizing, sawing and packaging activities; • maintenance and repair of plant and equipment; and • treatment of process air, liquids and solids. The output of this unit process is packaged aluminium ingots or alloyed hot metal transported to an aluminium fabricating facility.

Molten metal syphoned from the pots (***Electrolysis metal***) is sent to a resident casting complex found in each smelter. In some cases, due to proximity, molten metal is transported directly to a shape casting foundry. ***Remelt ingot*** and ***Outside scrap*** may also be used as metal input. Molten metal is transferred to a holding furnace and the composition is adjusted to the specific alloy requested by a customer, by use of ***Alloy additives***. In some instances, depending on the application and on the bath composition in the pots, some initial hot metal treatment to remove impurities may be done.

When the alloying is complete, the melt is fluxed to remove impurities and reduce gas content. The fluxing consists of slowly bubbling a combination of nitrogen and ***chlorine*** or carbon monoxide, argon and chlorine through the metal (***Chlorine*** use result in ***HCl (Hydrogen Chloride)*** air emissions). Fluxing may also be accomplished with an inline degassing technology, which performs the some function in a specialized degassing unit.

Fluxing removes entrained gases and inorganic particulates by floatation to the metal surface. These impurities (typically called ***dross***) are skimmed off. The skimming process also takes some aluminium and as such drosses are normally further processed to recover the aluminium content and to make products used in the abrasives and insulation industries.

Depending on the application, metal is then processed through an inline filter to remove any oxides that may have formed. Metal is then cast into ingots in a variety of methods: open molds (typically for ***remelt ingot***), through direct chill molds for various fabrication shapes, electromagnetic molds for some sheet ingots, and through continuous casters for aluminium coils. ***Fresh Water*** (input taken conservatively whether the water used is from fresh, underground, mine waste water, etc. sources), seldom ***Sea Water***, is used for cooling (often with re-circulation through a cooling tower and water treatment plant) and is subsequently discharged, where ***Suspended Solids*** and ***Oil/Grease (***or ***total HC)*** are monitored.

Energy used for Ingot Casting is ***Electricity***, ***Natural Gas*** or ***Heavy Oil***. ***Diesel Oil*** is normally used for internal plant transport.

While recovery and handling of internal process scrap is usually included in the Ingot Casting operation as mentioned above, some prefer to sell it out (***Scrap sold*** as <u>By-product for external recycling</u>). ***Dross***, ***Filter dust*** from melting furnace air filtration and ***Refractory*** material from furnace internal linings are either recovered as <u>By-products for external recycling</u>, or landfilled (***Dross – landfill***, ***Filter dust – landfill***, ***Refractory waste – landfill***).

<u>Solid waste</u>: ***Other landfill wastes*** consist typically of about 80 % of "environmental abatement" waste (such as metal filter box and baghouse) and 20 % of "municipal" waste (source: North American Aluminum Association LCI report 1998).

Particulates, SO2, ***NOx (as NO2)*** <u>air emissions</u> are linked with fuel combustion.

Appendix A2: Overall mass balance in the aluminium production process

This section is to explain the main components of the mass distribution between 1000 kg aluminium output and other outputs from 5168 kg of bauxite input of the aluminium production process. This cannot be an exact calculation because reaction mechanisms are just outlined, due to uncertainty margins (inaccuracies) from the Survey results and also because the list of inputs and outputs is not complete due to data cut-off beyond the inputs and outputs selected for the inventory.

5168 kg of bauxite is the input for production of alumina (aluminium oxide). However there is always a significant water component in the bauxite, typically around 20 % (1034 kg). The non aluminium-containing part of the bauxite is disposed of as bauxite residue (red mud, 1905 kg). The mass balance out of the alumina production process would be around 2200 kg, after deduction of water component and bauxite residue.

Aluminium oxide (alumina) is converted in the electrolysis process (primary aluminium smelting) by the following reaction:

$$2\,Al_2O_3 + 3C = 4\,Al + 3CO_2$$

with a stoichiometric minimum requirement of 1890 kg Al_2O_3 for 1000 kg of primary aluminium.

The actual production process could be described as an alumina breakdown by electrolysis producing 1000 kg of aluminium and oxygen released on the carbon anode as CO_2 (where 441 kg coke and pitch input considered as carbon weight yield 1176 kg oxygen by difference with 1617 kg CO_2 corresponding output).

Appendix A3: Impact from outlier exclusion on the Inventory results

The table below shows the percent difference in Inventory results obtained by reintroducing the outliers (individual answers beyond 2 standard deviations from the average value, identified in the initial Survey results and not commented on query). Reasons for the occurrence of outliers range from reporting mistakes (e.g. one non-realistic low alumina consumption report, bringing in the same percent difference in all alumina production related data) to allocation issues between operations within plants (e.g. water input and output, steel input) and to measurement issues (e.g. Fluoride, PAH, Mercury air and water emissions, BaP air emissions, “other by-products” for external recycling), the latter being generally responsible for the largest differences.

Difference on the Inventory results from outlier reintroduction

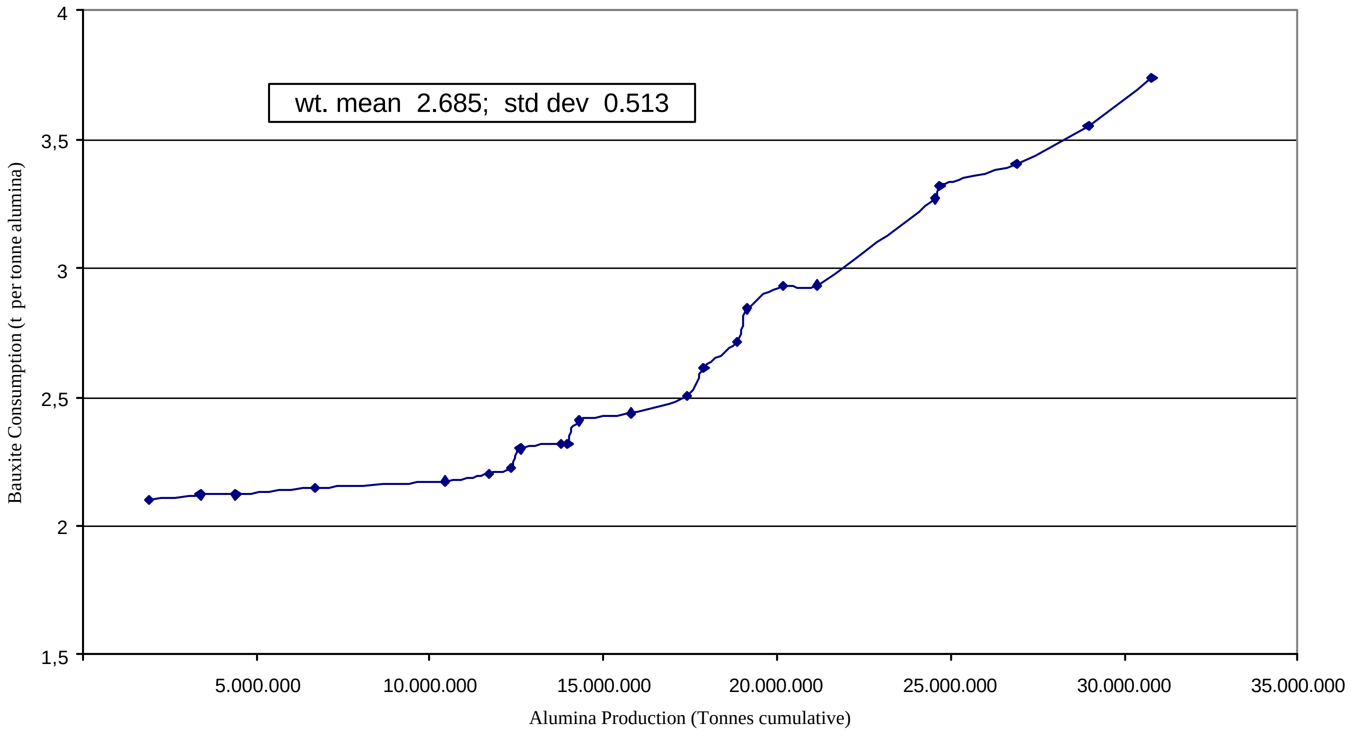
Inputs	Diff.%	Outputs	Diff.%
Raw materials		**Air emissions**	
Bauxite	-0,7%	Fluoride Gaseous (as F)	16%
Caustic Soda	-0,7%	Fluoride Particulate (as F)	17%
Calcined Lime	-0,7%	Particulates	20%
Alumina	*-0,7%*	NOx (as NO2)	14%
		SO2	2%
Petrol Coke (for Anode production)	0%	Total PAH	23%
Pitch (for production)	0%	BaP (Benzo-a-Pyrene)	6%
Anode	*0%*	CF4	0%
		C2F6	0%
Aluminium Fluoride	3%	HCl (Hydrogen Chloride)	8%
Cathode Carbon	6%	Mercury	139%
Aluminium (liquid metal)			
		Water emissions	
Alloy additives (for Ingot Casting)	0%		
Chlorine (for Ingot Casting)	6%	Fresh Water	28%
Cast ingot		Sea Water	-0,2%
		Fluoride (as F)	39%
Other raw material inputs		Oil/Grease	62%
		PAH (6 Borneff components)	102%
Fresh Water	46%	Suspended Solids	73%
Sea Water	-0,2%	Mercury	879%
Refractory materials	38%		
Steel (for anodes)	12%	**By-products for external recycling**	
Steel (for cathodes)	0,7%		
		Bauxite residue	-0,7%
Fuels and electricity		Dross	32%
		Filter dust	-2%
Coal	-0,7%	Other by-Products	123%
Diesel Oil	-0,06%	Refractory material	33%
Heavy Oil	-0,6%	Scrap sold	20%
Natural Gas	-0,5%	SPL carbon fuel/reuse	0%
Electricity	-0,01%	SPL refr.bricks-reuse	0%
		Steel	10%
		Solid waste	
		Bauxite residue (red mud)	7%
		Carbon waste	17%
		Dross - landfill	-2%

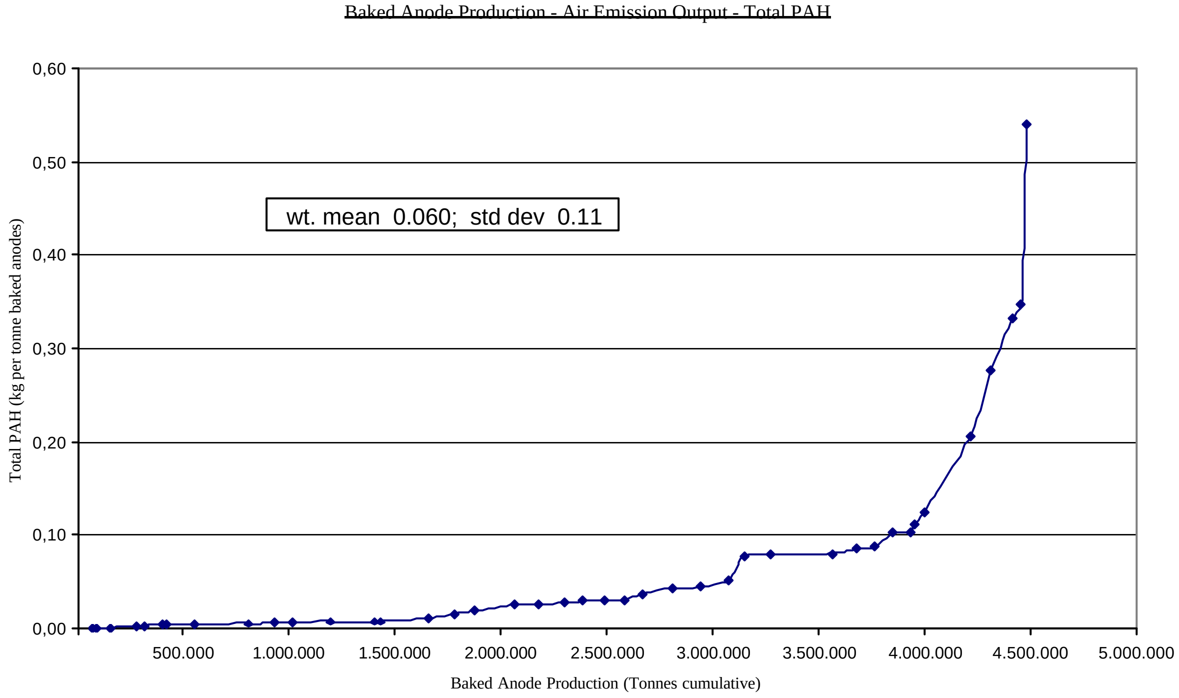
		Filter dust - landfill	7%
		Other landfill wastes	14%
		Refractory waste - landfill	26%
		Scrubber sludges	45%
		SPL - landfill	3%
		Waste alumina	53%

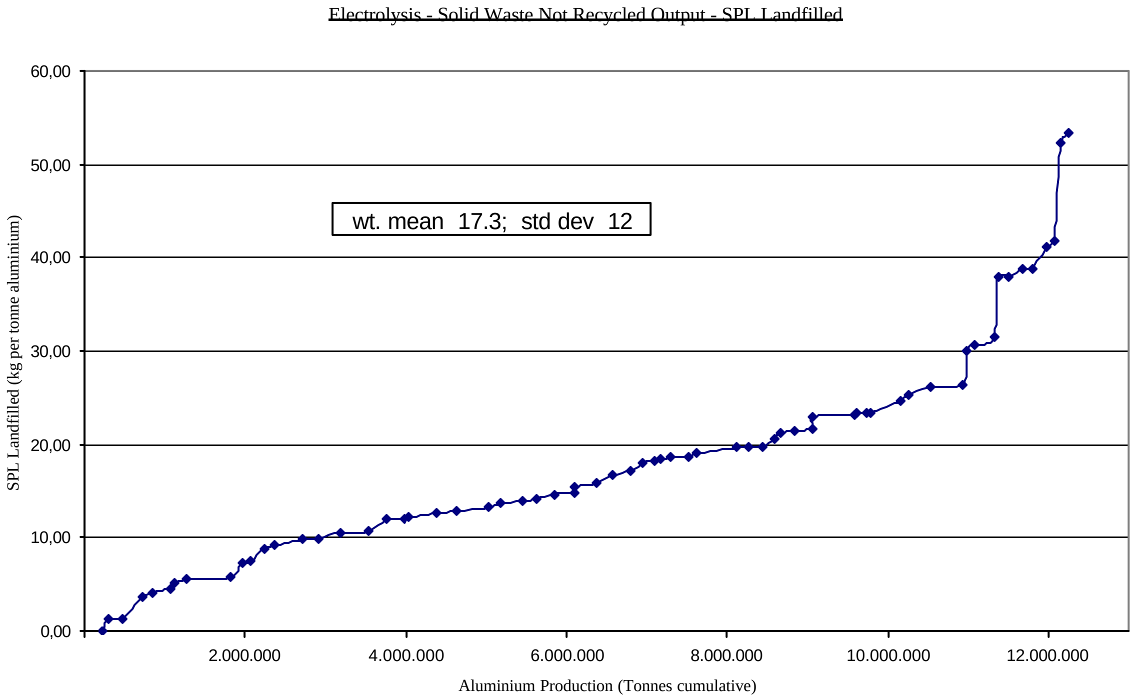
Appendix A4: Examples of cumulative distribution graphs

Data statistics assume a normal distribution of results. Examples of cumulative distribution graphs are reported below, in order to show typical actual data distribution:

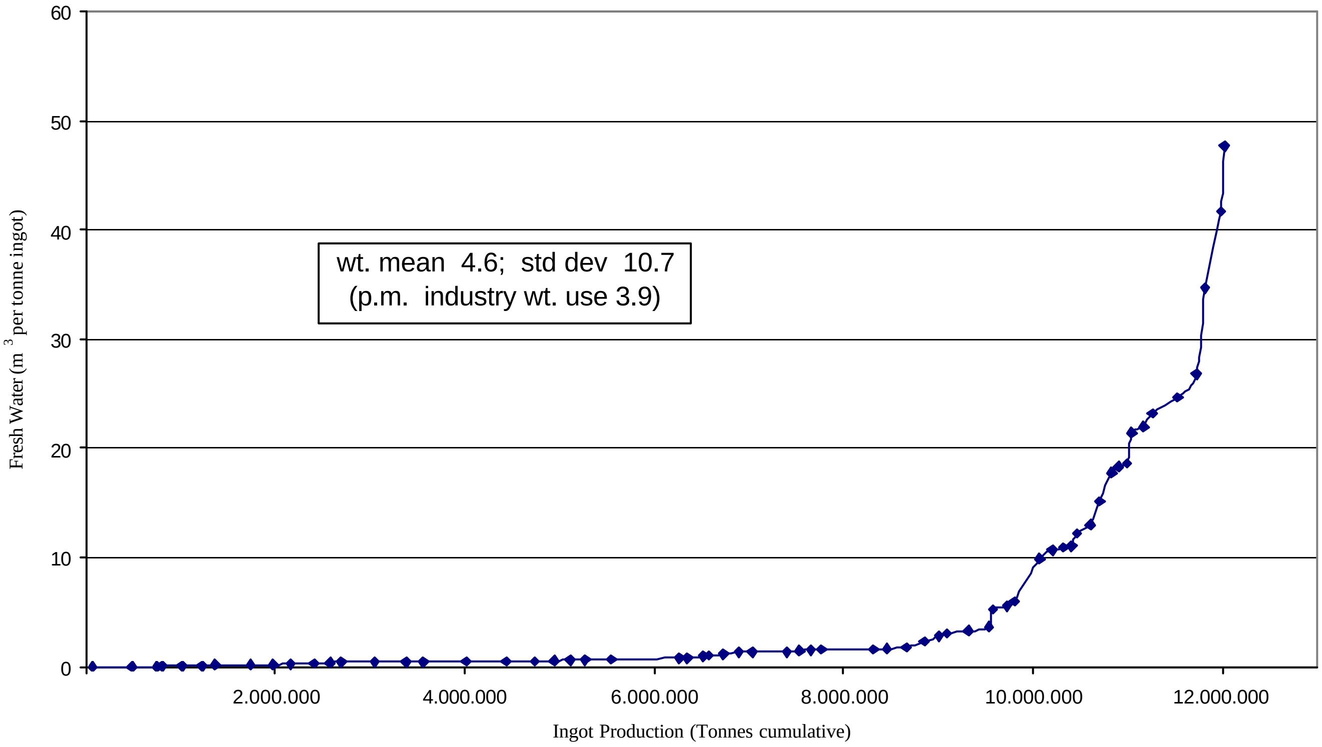
- Alumina production: Bauxite consumption (raw material input).
- Anode production: total PAH for Prebake anode production (air emission output).
- Electrolysis: SPL landfilled (solid waste not recycled output).
- Cast house: Fresh Water input.


Alumina Production - Raw Material Input - Bauxite Consumption


Baked Anode Production - Air Emission Output - Total PAH
wt. mean 0.060; std dev 0.11
Total PAH (kg per tonne baked anodes)
0,60
0,50
0,40
0,30
0,20
0,10
0,00
500.000
1.000.000
1.500.000
2.000.000
2.500.000
3.000.000
3.500.000
4.000.000
4.500.000
5.000.000
Baked Anode Production (Tonnes cumulative)


Electrolysis - Solid Waste Not Recycled Output - SPL Landfilled
wt. mean 17.3; std dev 12
SPL Landfilled (kg per tonne aluminium)
60,00
50,00
40,00
30,00
20,00
10,00
0,00
2.000.000
4.000.000
6.000.000
8.000.000
10.000.000
12.000.000
Aluminium Production (Tonnes cumulative)

Ingot Casting - Fresh Water Input



Appendix B: Results of the inventory analysis by process

Results from the IAI Aluminium Life Cycle Survey 2000 are presented along the following Unit Processes, which have been consolidated together in section 5 to form the Inventory for the worldwide Primary Aluminium:

- Alumina Production
- Anode Production (Prebake)
- Paste Production (Söderberg)
- Reduction (Electrolysis)
- Ingot Casting.

Note: review of results displayed in the following tables should pay attention to data reporting either as production weighted mean values, which is the basic situation, or as industry weighted use, as discussed under “data interpretation items”, section 5. The applicable definitions are as follows:

- production weighted mean (“wt. mean"): total consumption or emission reported divided by total corresponding industry production of those plants which have reported data.
- industry weighted use (“industry wt. use”): total consumption or emission reported divided by total corresponding industry production.

Alumina production

Table 1

IAI LCS 2000: alumina

30-Aug-02

Life Cycle Survey **Total production: 30786116 t**
No. of refineries: 23
Est. survey coverage of total world production: **59%**

IAI Energy Survey ***Total production: 36911495 t***
No. of refineries: 31
Est. survey coverage of total world production: ***70%***

Inputs

Raw materials

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Bauxite		2685	513	kg/t	100	2102	3737	1,1	1-2
Caustic Soda		*82*	*30*	*kg/t*	*100*	*29*	*161*		
Calcined Lime		*45*	*44*	*kg/t*	*100*	*5*	*221*		
Fresh Water	3,3	3,5	4,4	m3/t	91	0,003	14	1,4	1-3
Sea Water	3,4	11,4	17	m3/t	22	1,2	42	1,2	1-2

Fuels and electricity

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Heavy Oil	*115*	*154*	*137*	*kg/t*	*81*	*0,5*	*437*		
Diesel oil	*0,6*	*1,7*	*2,4*	*kg/t*	*35*	*0,1*	*8*		
Gas	*121*	*222*	*118*	*m3/t*	*35*	*2*	*384*		
Coal	*96*	*374*	*266*	*kg/t*	*23*	*127*	*843*		
Electricity	*106*	*170*	*188*	*kWh/t*	*65*	*8*	*749*		

*per t alumina

Outputs

Product: **alumina** **1000** **kg**

Air emissions

	wt. mean	std deviation		response rate(%)	min	max	DQI avg	DQI range
Particulates	0,63	1,9	kg/t	91	0,12	7,2	1,6	1-3
SO2	5,3	8,9	kg/t	87	0,000003	24	1,6	1-2
NOx (as NO2)	1,17	0,68	kg/t	74	0,39	2,3	1,8	1-3
Mercury	0,10	0,06	g/t	26	0,004	0,16	2,1	1-3

Water emissions

	industry wt. use	wt. mean	std deviation		response rate(%)	min	max	DQI avg	DQI range
Fresh Water	3,3	3,7	7,7	m3/t	87	0,58	33	1,9	1-3
Sea Water	3,4	11,4	17	m3/t	22	1,2	42	1,3	1-2
Suspended Solids		0,74	1,1	kg/t	52	0,0002	3,7	1,6	1-3
Oil and Grease/Total HC		0,069	0,10	kg/t	48	0,000001	0,27	1,9	1-3
Mercury		0,00094	0,0035	g/t	30	0,00003	0,0095	1,9	1-3

By-Products (for external recycling)

Bauxite Residue	1,2	0,5	kg/t	13	0,33	1,3	1,5	1-3
Other	1,8	3,2	kg/t	43	0,07	10,6	1,8	1-3

Solid waste

	wt. mean	std deviation		response rate(%)	min	max	DQI avg	DQI range
Bauxite Residues (red mud)	990	407	kg/t	96	204	1916	1,7	1-3
Other Landfill Wastes	24,7	37	kg/t	87	0,18	161	1,9	1-3

*per t alumina

Anode production

Table 2a (P)

IAI LCS 2000: anode production (Prebake)

30-Aug-02

Inputs

Life Cycle Survey	**Total production (baked):**	**6443997**	**t**
	No. of anode plants:	54	
IAI Energy Survey	***Total production (baked):***	***6694481***	***t***
	No. of anode plants:	*56*	

Raw materials	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
petrol coke	***683***	***57***	*kg/t*	***100***	***599***	***888***		
pitch	***160***	***15***	*kg/t*	***100***	***135***	***200***		
total	*843*		*kg/t*					

**per t anode*

Note: recycled anode butts account for the raw material mass balance

Fuels and electricity

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Coal	***2,0***	***66***	***65***	*kg/t*	***4***	***4,1***	***96***		
Heavy oil	***17,0***	***75***	***32***	*kg/t*	***23***	***14***	***160***		
Diesel oil	***3,9***	***24***	***30***	*kg/t*	***13***	***0,02***	***72***		
Gas	***63***	***90***	***33***	*m3/t*	***70***	***13***	***217***		
Electricity	***158***	***185***	***96***	*kWh/t*	***86***	***0,19***	***450***		

**per t anode*

Other inputs

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
fresh water	**1,2**	**2,2**	**3,4**	m3/t	**56**	**0,004**	**12**	**1,8**	**1-3**
sea water	**0,0022**	**0,22**	NA	m3/t	**2**	**0,22**	**0,22**	**1**	**1**
refractory material		**12,5**	**18**	kg/t	**72**	**0,16**	**98**	**1,9**	**1-3**
steel		**3,1**	**3,0**	kg/t	**44**	**0,04**	**10**	**1,9**	**1-3**

*per t anode

Table 2a (S)

IAI LCS 2000: paste production (Söderberg)

30-Aug-02

Inputs

Life Cycle Survey	**Total production:**	**948457**	**t**
	No. of paste plants:	17	
IAI Energy Survey	***Total production:***	***1466841***	***t***
	No. of paste plants:	*27*	

Raw materials	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
petrol coke	***713***	***26***	*kg/t*	***100***	***669***	***760***		
pitch	***284***	***25***	*kg/t*	***100***	***240***	***331***		
total	*997*		*kg/t*					

**per t anode*

Fuels and electricity

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Coal	***2,6***	***65***	*NA*	*kg/t*	***4***	***65***	***65***		
Heavy oil	***0,40***	***6,4***	***83***	*kg/t*	***11***	***0,6***	***145***		
Diesel oil				*kg/t*					
Gas	***6,6***	***22***	***12***	*m3/t*	***19***	***5***	***37***		
Electricity	***65***	***106***	***69***	*kWh/t*	***63***	***33***	***264***		

**per t anode*

Other inputs

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
fresh water	**1,5**	**2,0**	**2,6**	m3/t	**53**	**0,0004**	**8,2**	**2,1**	**1-3**
sea water				m3/t					
refractory material				kg/t					

The following consolidated table (from tables 2a (P), (S) page 10) for anode production inputs is used for the final calculation (section 5) of the Inventory for the world-wide Primary Aluminium.

Table 2a

IAI LCS 2000: anode production (combined Prebake-Söderberg)

30-Aug-02

Inputs

Life Cycle Survey	**Total production:**	**7392454**	**t**
	No. of anode/paste plants:	71	
IAI Energy Survey	***Total production:***	***8161322***	***t***
	No. of anode/paste plants:	*83*	

Raw materials	**wt. mean**	unit*	**response rate(%)**
petrol coke	***689***	*kg/t*	**100**
pitch	***182***	*kg/t*	**100**
total	*871*	*kg/t*	

*per t anode

Note: recycled anode butts account for the raw material mass balance

Fuels and electricity

	industry wt. use	**wt. mean**	unit*	**response rate(%)**
Coal	***2,1***		*kg/t*	**4**
Heavy oil	***14,1***	***72***	*kg/t*	**19**
Diesel oil	***3,2***	***24***	*kg/t*	**8**
Gas	***53***	***85***	*m3/t*	**53**
Electricity	***141***	***175***	*kWh/t*	**78**

Other inputs

	industry wt. use	**wt. mean**	unit*	**response rate(%)**
fresh water	**1,2**	**2,2**	m3/t	**55**
sea water	**0,0019**	**0,22**	m3/t	**1**
refractory material		**12,5**	kg/t	**55**
steel		**3,1**	kg/t	

*per t anode

Table 2b (P)

IAI LCS 2000: anode production (Prebake)

30-Aug-02

Outputs

Life Cycle Survey **Total production (baked): 6443997 t**
No. of anode plants: 54

Product: **baked anodes** **1000** **kg**

By-products for external recycling

	average	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
refractory	6,9	6,2	kg/t	39	0,5	22,4	1,4	1-3
steel	3,9	2,4	kg/t	37	0,3	9,3	1,8	1-3
other	6,5	9,4	kg/t	31	0,0006	33,2	1,6	1-3

*per t anode

Solid waste not recycled	average	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
waste carbon or mix	6,0	4,9	kg/t	57	0,1	16,6	1,5	1-3
scrubber sludges	1,9	2,4	kg/t	15	0,04	6,5	1,4	1-3
refractory (excl.SPL)	5,7	9,5	kg/t	46	0,1	33,6	1,9	1-3
other landfilled waste	5,3	6,4	kg/t	43	0,4	23,5	1,6	1-3

*per t anode

Table 2b (S)

IAI LCS 2000: paste production (Söderberg)

30-Aug-02

Outputs

Life Cycle Survey **Total production: 948457 t**
No. of paste plants: 17

Product: **anode paste** **1000** **kg**

By-products for external recycling

	average	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
refractory			kg/t					
steel			kg/t					
other	0,63	NA	kg/t	6	0,63	0,63		

*per t anode

Solid waste not recycled	average	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
waste carbon or mix	0,11	0,01	kg/t	24	0,13	0,17	1,7	1-3
scrubber sludges			kg/t					
refractory (excl.SPL)			kg/t					
other landfilled waste	14,7	30	kg/t	18	0,4	53	1,7	1-3

*per t anode

The following consolidated table (from tables 2b (P), (S) page 12) for anode production outputs is used for the final calculation (section 5) of the Inventory for the world-wide Primary Aluminium.

Table 2b

IAI LCS 2000: anode production (combined Prebake-Söderberg)

30-Aug-02

Outputs

Life Cycle Survey

Total production:	**7392454**	**t**
No. of anode/paste plants:	71	

Product:	**anodes**	**1000**	**kg**

By-products for external recycling

	wt. mean	unit*	**response rate(%)**
refractory	**6,9**	kg/t	**30**
steel	**3,9**	kg/t	**28**
other	**6,4**	kg/t	**25**

*per t anode

Solid waste not recycled	**wt. mean**	unit*	**response rate(%)**
waste carbon or mix	**5,4**	kg/t	**49**
scrubber sludges	**1,9**	kg/t	**11**
refractory (excl.SPL)	**5,7**	kg/t	**35**
other landfilled waste	**6,2**	kg/t	**37**

*per t anode

The following table 2c (consolidated from tables 2c (P), (S) below) for anode production air emissions is used for the final calculation (section 5) of the Inventory for the world-wide Primary Aluminium.

Table 2c

IAI LCS 2000: anode production (combined Prebake-Söderberg)

30-Aug-02

Outputs **Air emissions**

Life Cycle Survey **Total production:** **7392454** **t**

No. of anode/paste plants: 17

Air emissions	**wt. mean**	unit*	**response rate(%)**
Particulates	**0,30**	kg/t	**85**
SO2	**1,7**	kg/t	**65**
NOx (as NO2)	**0,29**	kg/t	**59**
Particulate Fluoride (as F)	**0,010**	kg/t	**44**
Gaseous Fluoride (as F)	**0,046**	kg/t	**58**
Total PAH	**0,055**	kg/t	**70**
B(a)P	**0,24**	g/t	**51**
		*per t anode	

Table 2c (P)

IAI LCS 2000: anode production (Prebake)

30-Aug-02

Outputs **Air emissions**

Life Cycle Survey **Total production (baked):** **6443997** **t**

No. of anode plants: 54

Air emissions	**wt. mean**	**std deviation**	unit*	**response rate(%)**	**min**	**max**	**DQI avg**	**DQI range**
Particulates	**0,33**	**0,39**	kg/t	**89**	**0,02**	**1,8**	**1,4**	**1-3**
SO2	**1,8**	**1,6**	kg/t	**72**	**0,001**	**6,2**	**1,6**	**1-3**
NOx (as NO2)	**0,31**	**0,23**	kg/t	**69**	**0,02**	**1,3**	**1,7**	**1-3**
Particulate Fluoride (as F)	**0,010**	**0,02**	kg/t	**57**	**0,000002**	**0,06**	**1,4**	**1-3**
Gaseous Fluoride (as F)	**0,046**	**0,16**	kg/t	**76**	**0,00001**	**0,9**	**1,2**	**1-3**
Total PAH	**0,060**	**0,11**	kg/t	**76**	**0,00003**	**0,5**	**1,5**	**1-3**
B(a)P	**0,27**	**0,68**	g/t	**54**	**0,00003**	**3,4**	**1,7**	**1-3**
			*per t anode					

Table 2c (S)

IAI LCS 2000: paste production (Söderberg)

30-Aug-02

Outputs **Air emissions**

Life Cycle Survey **Total production:** **948457** **t**

No. of paste plants: 17

Air emissions	**wt. mean**	**std deviation**	unit*	**response rate(%)**	**min**	**max**	**DQI avg**	**DQI range**
Particulates	**0,11**	**0,20**	kg/t	**71**	**0,01**	**0,72**	**1,3**	**1-3**
SO2	**1,0**	**1,1**	kg/t	**41**	**0,002**	**2,57**	**1,6**	**1-2**
NOx (as NO2)	**0,11**	**0,09**	kg/t	**29**	**0,05**	**0,26**	**2,4**	**2-3**
Particulate Fluoride (as F)			kg/t					
Gaseous Fluoride (as F)			kg/t					
Total PAH	**0,0092**	**0,010**	kg/t	**53**	**0,001**	**0,03**	**1,1**	**1-2**
B(a)P	**0,079**	**0,084**	g/t	**41**	**0,0002**	**0,23**	**1,6**	**1-3**
			*per t anode					

Reduction (Electrolysis)

Table 3a

IAI LCS 2000: electrolysis

10-Dec-02

Inputs

Life Cycle Survey	**Total production:**	**14692748**	**t**	Est. survey coverage of total world production:	**60%**
	No. of smelters:	82			
	of which Söderberg:	**2001454**	**t**		
	No. of smelters:	29	(No. of PB smelters: 68)		
IAI Energy Survey	***Total production:***	***16822420***	***t***	*Est. survey coverage of total world production:*	***69%***
	No. of smelters:	*112*			

Raw materials

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
alumina (dry)		**1925**	**27**	kg/t	**96**	**1871**	**2033**	**1,3**	**1-3**
anode PB (net)		***426***	***25***	*kg/t*	***65***	***388***	***546***		
Söderberg paste		***510***	***32***	*kg/t*	***29***	***440***	***584***		
anodes (net)/Söd. paste	***441***			*kg/t*	***95***				
petrol coke	***349***			*kg/t*					
pitch	***92***			*kg/t*					

*per t aluminium (liquid metal)

Electricity consumption

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Electricity	***15365***	***1179***	*kWh/t*	***100***	***13405***	***19446***		

*per t aluminium (liquid metal)

Other inputs

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
fresh water	**2,9**	**3,9**	**7,8**	m3/t	**73**	**0,002**	**32**	**1,6**	**1-3**
sea water	**20,7**	**163**	**203**	m3/t	**16**	**0,5**	**594**	**1,3**	**1-3**
cathode carbon		**6,1**	**3,4**	kg/t	**93**	**1,1**	**16**	**1,6**	**1-3**
refractory material		**6,0**	**4,2**	kg/t	**88**	**0,2**	**18**	**1,8**	**1-3**
steel		**5,5**	**5,0**	kg/t	**85**	**0,1**	**35**	**1,8**	**1-3**
AlF3		**17,4**	**5,4**	kg/t	**94**	**6,9**	**32**	**1,1**	**1-2**

*per t aluminium (liquid metal)

Table 3b

IAI LCS 2000: electrolysis

10-Dec-02

Outputs

Life Cycle Survey

Total production: 14692748 t
No. of smelters: 82
of which Söderberg: 2001454 t
No. of smelters: 29 (No. of PB smelters: 68)

Est. survey coverage of total world production:
60%

Product: **liquid aluminium** **1000** **kg**

Water Discharges

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
fresh water	3,1	4,7	8,0	m3/t	71	0,02	31,8	1,7	1-3
sea water	20,9	192	206	m3/t	15	0,1	594	1,4	1-3
suspended solids		0,21	0,56	kg/t	61	0,0002	2,7	1,4	1-3
oil & grease/total HC		0,0078	0,014	kg/t	41	0,00002	0,05	1,6	1-3
fluorides (as F)		0,20	0,7	kg/t	70	0,00001	3,9	1,4	1-3
PAH (6 Borneff components)		3,8	9,3	g/t	32	0,000002	32	1,5	1-3

*per t aluminium (liquid metal)

By-products for external recycling

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
SPL carbon	9,9	11	kg/t	35	0,25	41	1,2	1-3
SPL refractory	5,5	6,1	kg/t	26	0,60	19	1,2	1-3
refractory (other)	0,53	0,8	kg/t	12	0,11	2,6	1,3	1-3
steel	6,9	4,8	kg/t	74	0,13	20	1,6	1-3
other	5,1	7,7	kg/t	49	0,13	26	1,5	1-3

Solid waste not recycled

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
SPL	17,3	12	kg/t	79	0,09	53	1,4	1-3
waste alumina	4,7	7,3	kg/t	43	0,06	30	1,5	1-3
waste carbon or mix	4,6	5,4	kg/t	40	0,01	20	1,4	1-3
scrubber sludges	13,7	20	kg/t	16	0,04	50	1,3	1-3
refractory (excl.SPL)	1,2	1,6	kg/t	40	0,05	6	1,6	1-3
other landfilled waste	7,3	9,1	kg/t	71	0,06	33	1,6	1-3

*per t aluminium (liquid metal)

Table 3c

IAI LCS 2000: electrolysis

10-Dec-02

Outputs **Air emissions**

Life Cycle Survey **Total production: 14692748 t**
No. of smelters: 82
of which Söderberg: 2001454 t
No. of smelters: 29 (No. of PB smelters: 68)

Est. survey coverage of total world production: **60%**

IAI PFC Survey ***Total production: 16079065 t***
No. of smelters: 115

Est. survey coverage of total world production: ***66%***

Air emissions

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Particulates	**3,3**	**5,0**	kg/t	**89**	**0,04**	**26**	**1,3**	**1-3**
SO2	**13,4**	**6,6**	kg/t	**89**	**0,5**	**25**	**1,7**	**1-3**
NOx (as NO2)	**0,35**	**0,8**	kg/t	**52**	**0,000004**	**3,9**	**1,8**	**1-3**
Particulate Fluoride (as F)	**0,50**	**0,8**	kg/t	**88**	**0,005**	**3,7**	**1,3**	**1-3**
Gaseous Fluoride (as F)	**0,55**	**0,9**	kg/t	**91**	**0,02**	**4,7**	**1,2**	**1-3**
Total PAH	**0,13**	**0,4**	kg/t	**44**	**0,0001**	**1,3**	**1,8**	**1-3**
B(a)P	**5,0**	**16**	g/t	**35**	**0,0001**	**59,4**	**1,8**	**1-3**
CF4	***0,22***	***0,40***	*kg/t*	***100***	***0,007***	***1,8***		
C2F6	***0,021***	***0,040***	*kg/t*	***100***	***0,001***	***0,18***		

*per t aluminium

Ingot Casting.

Table 4a

IAI LCS 2000: ingot casting

30-Aug-02

Inputs

Life Cycle Survey **Total production: 14016405 t**
No. of cast houses: 72

Est. survey coverage of total world production: **57%**

Inputs

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Electrolysis metal		**874**	**165**	kg/t	**96**	**373**	**1229**	**1,03**	**1-2**
Remelt ingot		**133**	**101**	kg/t	**67**	**0,09**	**451**	**1,2**	**1-3**
Outside scrap		**101**	**107**	kg/t	**47**	**0,5**	**388**	**1,1**	**1-3**
Alloy additives		**18**	**14**	kg/t	**90**	**0,004**	**67**	**1,06**	**1-3**
total		**1126**		kg/t					
Fresh water	**3,9**	**4,6**	**10,7**	m3/t	**89**	**0,001**	**48**	**1,6**	**1-3**
Sea water	**0,23**	**10,5**	**12,7**	m3/t	**3**	**0,8**	**19**	**1,2**	**1-3**
Chlorine		**0,086**	**0,11**	kg/t	**61**	**0,001**	**0,42**	**1,3**	**1-3**

*per t aluminium

Note: metal input adjusted to exclude contribution from cold metal (see section 2.3 reference flow)

for 1000 kg ingot output

		adjusted to	unit*	
Electrolysis metal	**874**	**1000**	kg/t	share of ingot casting inputs and outputs
Alloy additives	**18**	**20**	kg/t	for primary aluminium Life Cycle calculation
total	**892**	**1020**	kg/t	**0,79** (=892/1126)

Table 4b

IAI LCS 2000: ingot casting

30-Aug-02

Outputs

Life Cycle Survey **Total production: 14016405 t**

No. of cast houses: 72

Est. survey coverage of total world production: **57%**

Product: **aluminium ingot** **1000** **kg**

Water Discharges

	industry wt. use	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Fresh water	4,8	7,6	13	m3/t	72	0,001	43	1,7	1-3
Suspended solids		0,027	0,047	kg/t	47	0,0002	0,20	1,8	1-3
Oil & grease/total HC		0,011	0,026	kg/t	46	0,0000004	0,10	1,9	1-3

*per t aluminium

By-products for external recycling

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Dross	16	7,4	kg/t	92	3,2	36	1,04	1-3
Filter dust	0,72	0,5	kg/t	10	0,2	1,4	1,2	1-3
Scrap sold	2,8	3,3	kg/t	29	0,08	10	1,1	1-3
Refractory	0,61	0,41	kg/t	11	0,014	1,2	1,4	1-3

Solid waste not recycled

	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Dross	9,7	10	kg/t	18	2,0	30	1,3	1-3
Filter dust	0,50	0,5	kg/t	22	0,001	1,6	1,6	1-3
Refractory	0,81	0,7	kg/t	49	0,04	4,3	1,7	1-3
Other landfilled waste	1,6	2	kg/t	49	0,01	7,8	1,7	1-3

*per t aluminium

Table 4c

IAI LCS 2000: ingot casting

30-Aug-02

Outputs Air emissions

Life Cycle Survey **Total production: 14016405 t**

No. of cast houses: 72

Est. survey coverage of total world production: **57%**

Air emissions	wt. mean	std deviation	unit*	response rate(%)	min	max	DQI avg	DQI range
Particulates	0,10	0,13	kg/t	71	0,001	0,53	1,5	1-3
SO2	0,29	0,89	kg/t	51	0,00005	3,2	1,9	1-3
NOx (as NO2)	0,16	0,14	kg/t	78	0,001	0,72	1,9	1-3
HCl	0,085	0,085	kg/t	39	0,0003	0,33	1,7	1-3
Dioxin/Furans	0,0061	0,014	mg/t	8	0,0000003	0,035	2,5	1-3

*per t aluminium

Appendix C: CO2 emission data

from the IAI Report "Aluminium Applications and Society. Life Cycle Inventory of the Worldwide Aluminium Industry with regard to Energy Consumption and Emissions of Greenhouse Gases. Paper 1 – Automotive" dated May 2000.

In light of the global attention to the climate change issue spurred by the International Kyoto Agreement, the IAI decided in 1998 to place a high priority on the development of comprehensive information related to energy consumption and greenhouse gas emissions related to aluminium. This decision resulted with the the IAI Report "Aluminium Applications and Society. Life Cycle Inventory of the Worldwide Aluminium Industry with regard to Energy Consumption and Emissions of Greenhouse Gases. Paper 1 – Automotive" dated May 2000.

Based on an expanded IAI energy survey (data for the year 1998), this Report provided a complete understanding of the energy requirements and greenhouse gas emissions associated with the primary aluminium production operations of alumina refining, anode production and aluminium smelting. Energy consumption and greenhouse gas emissions associated with upstream materials and energy supply, in particular electrical power generation, had been included consistent with the ISO 14040 and 14041 standards for Life Cycle Inventory.

The IAI May 2000 Report is available from the International Aluminium Institute or can be found on the IAI website at www.world-aluminium.org.

The table below quantifies average greenhouse gas emissions from each primary aluminium unit process included in this study.

GHG Emissions	**Bauxite**	**Refining**	**Anode**	**Smelting**	**Casting**
	kg of CO2 equivalents per 1000 kg of process output				
Process	0	0	388	1626	0
Electricity	0	58	63	5801	77
Fossil Fuel	16	789	135	133	155
Transport	32	61	8	4	136
Ancillary	0	84	255	0	0
PFC	0	0	0	2226	0
Total	48	991	849	9789	368

Appendix D: European Aluminium Association Guidance, “Key Features How to Treat Aluminium in LCA’s, with Special Regard to Recycling Issues”

Key features how to treat aluminium in LCAs, with special regard to recycling issues

Abstract

In the past, LCA studies varied to a high degree because of different methodological approaches, which caused market risks when different materials were compared by politicians or customers. Now, the standards of the ISO 14040 series have set common methodological rules, which should be applied to all LCA studies including those dealing with aluminium.

This paper illustrates the ISO rules and focuses on the major crucial aspects of aluminium in LCAs, e. g. energy aspects, the high recycling rates and the high value of recycled aluminium. The resulting statements should be considered when working out an LCA study dealing with aluminium products.

The recommended method how to treat recycling, the “substitution method” is explained and illustrated by examples. As all metals are characterised by their ability to maintain their inherent properties after recycling, contrary to wood, paper, concrete or plastics, this method can be applied for all metals including aluminium. In addition to this substitution method, the so-called “value-corrected substitution method” is also presented. This method tries to take into account the loss of substitution ability of the recycled material in special cases where the value of the material is not maintained by recycling.

A precedent version of this document has undergone peer reviews of different LCA experts (B. Weidema, R. Frischknecht, K. Saur, J. Gediga, E. Lindeijer). The version tries to reflect the comments of these experts, as far as possible.

1 Introduction

The aluminium industry applies LCA as a technique to identify significant environmental aspects of its products in order to improve the environmental performance of these products during their whole life cycle.

Customers of the aluminium industry, e. g. the automotive or the building industry, when designing their products, chose between different materials including aluminium. The degree of market penetration of aluminium for a given application depends on economic, environmental and social criteria. LCA studies help to position aluminium in the environmental discussion.

Politicians use LCA studies as a basis for environmentally motivated decisions or regulations. These decisions may affect the aluminium market significantly.

In the past, results of such studies varied to a high degree because of different methodological approaches. Now, the standards of the ISO 14040 series have set common methodological rules, which are recommended to be applied to all LCA studies including those dealing with aluminium. When it is claimed that the study has been performed according to ISO, the statements in ISO documents including the word “shall” must have been obeyed, and ISO statements including the word “should” can only be deviated from for well-argumented reasons.

The European Aluminium Association (EAA) has published LCA data for different aluminium products. The aluminium industry is actively promoting the careful use of this data based on state-of-the-art methods.

The following key features illustrate the ISO rules and their specific relevance to aluminium, e.g. energy aspects, the high recycling rates and the high value of aluminium after recycling. These statements should be considered by practitioners as guidance when working out an LCA study dealing with aluminium products.

More detailed guidance and scientific back-ground, particularly on recycling issues, is given by Werner (1)

2 General

Any LCA study, especially for comparative purposes, should be based on methodologies within the framework of the following International Standards:

- ISO 14040 Life cycle assessment - Principles and framework
- ISO 14041 Life cycle assessment - Goal and scope definition and inventory analysis
- ISO 14042 Life cycle assessment - Life cycle impact assessment
- ISO 14043 Life cycle assessment - Life cycle interpretation

In these standards, LCA is considered as a technique to assess the environmental aspects and potential impacts associated with a product or a service, on a life cycle basis

The LCA study includes four different phases:

- Goal and Scope Definition
- Life Cycle Inventory Analysis
- Life Cycle Impact Assessment
- Interpretation.

LCA deals with product systems which comprise the full life cycle of a product, including raw material acquisition, fabrication, transportation, use, recycling/disposal and the operations of energy supply, ancillary material supply and transports. Ideally, such a product system should only have input and output which are elementary flows, i. e. material or energy which is drawn from the environment or is discarded to the environment without subsequent human transformation.

In LCA studies where aluminium is compared to other materials, this comparison should be based on the same functional unit, e. g. 1 kg of aluminium in a car may in a specific case correspond to 1,8 kg of conventional steel, in order to fulfil the same function.

Quantitative aggregation over different impact categories, e. g. the calculation of a single score is not permitted by ISO 14042 for studies to be used for comparative assertions which are made available to the public, where the overall environmental superiority or equivalence of one product versus a competing product which performs the same function is claimed.

A thorough interpretation of the results of an LCA study is required. This may include the need of additional information about the data of this report, e. g. data quality or further information about the data, e. g. a temporal or spatial differentiation of the potential environmental impact.

3 Energy flows

Inventory data should not be added up if they represent different types of potential environmental impact. It is not appropriate to add up all emissions , e.g. on per kg basis, or all energy flows, in MJ. A "cumulative energy" which is understood as the sum of renewable (hydro) energy and non-renewable fossil energies has no ecological sense.

In the impact assessment phase, data representing elementary flows are aggregated to so-called "indicator results", if they belong to the same impact category, possibly after having been multiplied with a characterisation factor. The elementary flow data related to energy consumption can be determined as the mass or the energy content of the relevant energy resource.

Electricity supply data cannot be considered as elementary flow data, because electricity is not directly extracted from nature. The elementary flows of the relevant power plant, including extraction of fossil energy resources, have to be considered instead.

An example of an indicator result for the impact category "extraction of energy resources" is the low calorific value of the different fossil fuels extracted for the supply of a certain quantity of energy (see ISO/TR 14047). If e.g. 100 MJ of energy from natural gas are consumed in a plant, this may indicate an extraction of gas resources of 110 MJ, because 10 MJ may be used for the gas supply system or lost by leakage.

It is not appropriate to assign solar radiation or dam water, the elementary flow input of power plants based on renewable energy, to the impact category "extraction of energy resources". Renewable energy flows have a different associated type of impact (if considered) than fossil or nuclear energy flows. Generally, it is difficult to justify an impact category which comprises elementary flows both from renewable and non-renewable energy in accordance with the criteria as formulated in ISO 14042. On the other hand, other environmental impacts of power plants based on renewable energy, e. g. the land use of hydroelectric power plants have to be considered.

4 Recycling

4.1 General

For most aluminium products, aluminium is not completely consumed but rather used. Therefore, a life cycle of an aluminium product is not "cradle-to grave", but rather "cradle-to-cradle". This means that the life cycle of an aluminium product usually ends, when the recycled aluminium is rendered in a form usable for a new aluminium product e. g. as an ingot.

According to ISO 14041, allocation principles and procedures where input and output of specific processes have to be shared by more than one product system, also apply to recycling situations. In such cases the environmental burdens related to extraction and processing of raw materials and final disposal of products may have to be shared with subsequent product life cycles. This can also be addressed by using the substitution method (see section 4.2), based on parameters such as recycling rates and related metal yields. If a change in inherent properties is considered, the value of recycled material may play a role.

4.2 System expansion and substitution

System expansion, an ISO 14041 recommended procedure, means expanding the system under study to include the end-of-life recycling, resulting in substitution of recycled aluminium to primary aluminium (see Annex B).

A closed-loop allocation procedure is not only applicable for really closed-loop product systems. It also applies to open-loop product systems e.g. when aluminium, after use, is recycled into a raw material which has the same inherent properties as primary aluminium. In this case, the system expansion and substitution method can be applied.

Unlike materials such as wood, paper, plastics or concrete, aluminium has the ability to readily maintain its inherent properties through recycling. The inherent properties of pure aluminium are not changed by remelting.

In the case of the open loop recycling approach, the substitution method can only be applied if the recycled raw material is similar enough to the primary raw material which it substitutes. In many instances however, there will be a difference between a recycled material and the primary material it may substitute. Strict interpretation of this rule hence limits the application of the substitution method only to special cases.

In practice, aluminium products follow generally an open-loop recycling scheme. Recycling operations which include collecting, sorting, remelting and refining produce recycled aluminium which fulfils the requirements for primary aluminium. Within these markets, recycled aluminium perfectly substitutes primary aluminium. As a result, in most cases, the substitution method is fully applicable to the LCA of aluminium products.

However, in some particular cases, the recycling operations can lead to a significant change of the inherent properties of the recycled material compared with primary aluminium, for example by the presence of metallic impurities which are entrapped during the remelting operation of poorly sorted or contaminated scrap. In this case an allocation procedure with a value-corrected approach is appropriate, as explained in section 4.3 and 4.4.

EXAMPLE 1:

100 kg of primary aluminium is required for a product system

80 kg of recycled aluminium ingots (with same inherent properties as primary aluminium) are obtained after recovery of the end-of life product and scrap remelting.

→ 20 kg of aluminium is lost, e. g. littered or land-filled.

→ 80 kg of recycled aluminium ingots substitute 80 kg of primary aluminium ingots.

The environmental burdens of the production of only the lost aluminium, i. e. 20 kg of primary metal, have to be charged to the product system under study, together with the burdens of the recovery operations.

The environmental burdens of the production of 80 kg of primary aluminium have to be charged to the next user(s) of the 80 kg of recycled aluminium

4.3 Value-corrected substitution

The so-called “value corrected substitution method” considers that the recycled metal is not able to fully substitute primary metal. This method assumes that the substitution ability is reflected by the ratio between the market prices of the recycled and primary material. As a result, if the price of the recycled material is 90% of the price of the primary material, 1 kg of recycled material will substitute only 900 g of primary material.

In the case of aluminium, this method assumes a proportion of the environmental loads caused by primary aluminium production and final disposal of aluminium and the value change of the recycled metal. This procedure is in line with ISO 14041, see Annex A. Nevertheless, based on the strategies as formulated in the goal and scope definition of the study, other methodologies such as how to treat open-loop recycling may be justified as alternatives. In this case, a comparison through a sensitivity analysis is required.

If aluminium is compared with other materials, then it must be clarified that the value-corrected substitution method can be applied to the other materials, as well.

EXAMPLE 2:

100 kg of primary aluminium is required for a product system.

80 kg of recycled aluminium ingots with 90 % of the value of primary aluminium result from recycling, including remelting.

→ 20 kg of aluminium is lost, e. g. littered or land-filled.

→ Additional loss by value correction: 10 % of 80 kg = 8 kg

→ Total value-corrected losses: 28 kg

→ After value correction, the recycled aluminium ingots (which have the value level of 72 kg of primary ingots) substitute 72 kg of primary aluminium ingots.

- **The environmental burdens of the production only of the lost aluminium, i. e. 28 kg of primary metal, have to be charged to the product system under study, together with the burdens of the recovery operations.**
- The environmental burdens of the production of 72 kg of primary aluminium have to be charged to the next user(s) of the 80 kg of recycled aluminium.

In many cases scrap from different products and different alloys is molten together in one furnace batch, and alloying elements may be added. If for example pure alloy scrap is molten together with AlMg3 (EN-AW-5754) scrap, then this melt may be cast to AlMg1,5 (EN-AW 5050) rolling ingots. In this case one could argue that the input material and the output material have different inherent properties. But, not considering the value of the alloying elements, it can be shown that the AlMg1,5 rolling ingots have the same market value as the unalloyed ingots and the AlMg3 ingot which were the origin of the scrap.

If the market value analysis shows that the market value of the aluminium ingots obtained from recycling of the end-of-life product is the same as the market value of primary aluminium, then a value correction is not necessary. In this case, the substitution can take place as in the case of identical inherent properties, effectively treating the product system as a closed loop one.

4.4 Recycled aluminium as input

IS0 14041 requires that allocation procedures have to be uniformly applied to similar inputs and outputs of the system under consideration. The rules on how to treat incoming recycled aluminium have to correspond with the methods for treating recycled metal which leaves the system.

a) Substitution method

If the substitution method is applied, there is no need to consider the incoming portion of recycled aluminium, since only the metal loss during the complete life-cycle of the product is considered.

This means that if 100 kg of aluminium ingots enter the system and 100 kg of recycled aluminium with the same inherent properties leave the system, then the environmental loads associated with the input metal and those associated with the output metal should be considered to be the same, even if the products from which the input metal is recycled are not known.

If for a product 100 kg of a secondary raw material, usually recycled from a mixture of production scrap and post-consumer scrap, with the same value of primary aluminium, is used and no recycling of this product happens, then the environmental loads of the production of 100 kg of primary aluminium have to be charged to the product.

EXAMPLE 3:

100 kg of aluminium is required for a product system. As an example, it may consist of 50 kg of primary aluminium and 50 kg of recycled aluminium with the same inherent properties as the primary aluminium.

80 kg of recycled aluminium ingots (with the same inherent properties as the primary aluminium) result from recycling, including remelting.

→ 20 kg of aluminium is lost, e. g. littered or land-filled.

- **The environmental burdens of the production only of the lost aluminium, i. e. 20 kg of primary metal, have to be charged to the product system under study, together with the burdens of the recovery operations. These environmental burdens are valid whatever the recycled content of the product system, as long as no value correction is necessary.**
- The environmental burdens of the production of 80 kg of primary aluminium have to be charged to the next user(s) of the 80 kg of recycled aluminium.

b) Value-corrected substitution method

However, if the value-corrected substitution method is applied for recycled metal at the output side, then value of the incoming recycled metal has to be considered, as well.

If for a product 100 kg of a secondary raw material, usually recycled from a mixture of production scrap and old scrap, with a value of 90 % of the value of primary aluminium, is used and no recycling of this product happens, then the environmental loads of the production of 90 kg of primary aluminium have to be charged to the product.

If end-of-life recycling can be considered, then a (possibly value-corrected) substitution can occur as described above. In this case, the mass of the lost aluminium on the value level of primary aluminium, i. e. the value-corrected mass of the input aluminium *minus* the value-corrected mass of the output aluminium has to be calculated and the environmental burdens of the production of this quantity of primary aluminium has to be charged to the product system under study (see EXAMPLE 4).

EXAMPLE 4:

100 kg of aluminium is required for a product system. It consists of 40 kg of primary aluminium and 60 kg of recycled aluminium ingots with 90 % of the value of primary

aluminium

80 kg of recycled aluminium ingots with 90 % of the value of primary aluminium result from recycling, including remelting. 20 kg of aluminium is lost, e. g. littered or land-filled.

The net aluminium loss, based on the value level of primary aluminium, is calculated as

- **value-corrected mass of input aluminium** *minus* **value-corrected mass of output aluminium,** both on the value level of primary aluminium**.**

Value-corrected mass of input aluminium: 40 kg + (60 kg x 0.9) = 94 kg aluminium ingots of the value level of primary ingots

Value-corrected mass of output aluminium: 80 kg x 0.9 = 72 kg aluminium ingots of the value level of primary ingots

et aluminium loss, based on the value level of primary aluminium, is 94 kg - 72 kg = 22 kg.

- **The environmental burdens of the production of the lost aluminium, i.e. 22 kg of primary metal, have to be charged to the product system under study, together with the burdens of the recovery operations.**
- The environmental loads of the production of 6 kg of primary aluminium had already been charged to the "producer" of the 60 kg of recycled aluminium

The environmental burdens of the production of 72 kg of primary aluminium have to be charged to the next user(s) of the 80 kg of recycled aluminium.

4.5 Long life-time products

The substitution method for recycling may apply for any life-time of a product, not only for aluminium cans but also for aluminium in buildings. Aluminium products often have extended life-times because of their high corrosion resistance, often further enhanced by specific measures of corrosion protection. Such products should not be mistreated in LCA studies by omitting recycling credits as described in section 4.2 above.

Any uncertainty about recycling rates and recycling techniques for long-life aluminium products is not sufficient to refuse recycling credits. It rather has to be dealt with by applying different recycling scenarios in the form of sensitivity analyses, which should include the state-of-the art recycling technique for the product under study.

Moreover, it may be necessary in the interpretation phase of comparative studies to consider the temporal aspects of the environmental impacts of the different materials, e. g. GHG emissions now compared with GHG emissions in 50 years.

4.6 The recycled material content approach

There have been cases of LCA studies in which the recycling of a product is disregarded and no recycling credits are given on the output side, even in the case of closed-loop recycling, i.e. when the recycled aluminium is used for the same product from which it has been recovered. Recycling credits are only given on the input side, if the aluminium product contains a certain amount of recycled aluminium (recycled material content approach).

There have also been cases of LCA studies in which a different form of recycled material content approach is applied. Here, recycling credits according to the substitution principle are given only in the case where the closed-loop recycling approach can be applied. In the case of open-loop recycling, no or only limited recycling credits are given. In addition, recycling credits are given on the input side, if the aluminium product contains a certain amount of recycled aluminium.

According to ISO 14041, allocation principles and procedures also apply to recycling situations. The recycled material content approach is not mentioned in this standard as a method to avoid allocation. This approach can only be used in specific cases where the omission of specific outputs of recycled material can be justified according to well-defined cut-off criteria, e. g. if recycled concrete is given free of charge for road construction.
The high value of aluminium recycled from end-of-life products can be demonstrated by the market price of recycled aluminium ingots which is identical or close to the price of primary aluminium.

In this context, methods such like the **recycled material content** approach which do not consider the end-of-life recycling or even the value or recycled material should be avoided. Ifunder certain conditions the recycled content method can be justified, the LCA study should at least include a sensitivity analysis with other methods that better address the end-of-life recycling of aluminium products.

EXAMPLE 5:

An LCA study of different window frame materials (aluminium, aluminium/wood, steel, copper, PVC) has been performed by K. Richter et al. (2) in 1996. The study used the recycled material content approach and was based on a window measuring 1650 x 1300 mm of two wings and a use time of 30 years. For the aluminium frame which had a mass of 40 kg, two different recycling scenarios were assumed,

a "realistic scenario" assuming a recycled aluminium content of 35 % (alternative 1)

a "future scenario" assuming a recycled aluminium content of 85 % (alternative 2).

The study did not show general disadvantages of the two aluminium alternatives compared to other window frame materials. Nevertheless, for green-house potential of alternative 1 was significantly higher (385 kg CO_2 equivalents); only alternative 2 showed results equivalent to the other materials (172 kg CO_2 equivalents).
From this study, the conclusion could be drawn that the aluminium industry should increase the recycled aluminium content e. g. by buying recycled aluminium on the market.

Nevertheless, as recycled aluminium is an expensive commodity available in a relatively constant quantity, any increase of the recycled aluminium content in a window frame would lead to a reduction of the recycled aluminium content in other products, which, accordingly, need more primary metal. Finally, new scrap and old scrap often have the same inherent properties and therefore are mixed together, which makes the determination of the recycled metal content impossible.

After the publication of the comparative window frame study, ISO 14041 was published. Therefore, an additional study on aluminium window frame was performed by K. Richter and F. Werner where the ISO rules were properly applied according to the guidance given in this paper (3).

As the recycling processes of window frames had been cut off in the first study, a main part of the second study was to identify the unit processes for the end-of-life recycling of window frames and to define the value of recycled aluminium when leaving the system boundaries. This work included the visit of different recycling plants and the acquisition of data of such locations.

The recycling studies showed that two different types of aluminium window frames existed, namely

- type 1 window frames containing components of zinc and brass or small steel parts which could not be separated from the aluminium fraction.
- type 2 window frames containing only aluminium, steel and plastic/rubber parts which can be easily separated by shredding, magnetic sorting and eddy-current sorting.

The green-house potential of these window frame has been calculated as

- 235 kg CO_2 equivalents for type 1 windows
- 179 kg CO_2 equivalents for type 2 windows

One recommendation of the new study was to apply design for recycling in a way that type 2 window frames should be built where aluminium can be easily separated from other materials and contamination of the metal with impurities can be avoided.

Literature:

(1) F. Werner: Treatment of aluminium recycling in LCA; development and evaluation of the value-corrected substitution procedure applied to window frames. Research & Work Report 115/47, Swiss Federal Laboratories for Materials Testing and Research (EMPA), Duebendorf (2002):

(2) K. Richter, T. Künninger and K. Brunner: Ökologische Bewertung von Fensterkonstruktionen, study, committed by SZFF (1996)

(3) F. Werner and K. Richter: Economic Allocation in LCA: A Case Study about Aluminium Window Frames, The International Journal of LCA, Vol. 5, 2 (2000), p. 79

Annex A. *Link between the value corrected substitution method and ISO 14041*

According to ISO 14041, allocation has to be considered when one or more unit processes are shared by different product systems including the product system under study. In this case it is required to identify these "multifunctional" processes and to select the appropriate allocation factors. The option to use economic parameters, e. g. market prices, for the calculation of allocation factors, is permitted by the standard, provided that

- no option to avoid allocation can be justified;
- no physical factor can be justified as allocation factor.

In the case of recycling, the ISO 14041 standard offers the option to share, between subsequent product systems, inputs and outputs only related to the processes of raw material acquisition and final disposal. This means that only specific unit processes within the product system are considered to be shared with other future product systems which can be unknown at the LCA study stage. This allocation principle avoids double counting of inputs and outputs and ensures that the product system is charged according to its actual material consumption.

Moreover, guidance is given in this standard to use economic value proportions (e. g. scrap value versus primary value). This option makes sense as long as reasonably free market prices of the primary and recycled material exist.

For aluminium recycling, the preconditions for this option are given. This means that the unit process of the production of aluminium ingots in a smelter and all unit processes upstream such as bauxite mining, alumina refining, anode production, energy supply and transports have to be considered as unit processes whose inputs and outputs are to be shared, by an adapted allocation procedure, between several product systems using consequently the recycled aluminium.

According to ISO 14041, the unit processes of waste disposal have to be considered for being shared with subsequent product systems, as well. This is relevant for those materials which are down-cycled to become a waste with significant environmental loads caused by final disposal. For aluminium, this is not relevant and can be neglected. The environmental loads of aluminium which is lost in a product system, e. g. during dross recycling or in a car shredder operation, are considered in any case.

Annex B. *System boundaries*

The system boundaries have to be defined in the goal and the scope definition phase of an LCA study. For the design for environment of aluminium products it is appropriate to define the system boundaries in a way that they include all processes which can be influenced by the design.

For aluminium products, material losses from recovery operations and metal yield by remelting depend on the form of the product, e. g. wall thickness and on the way how aluminium is joined with other materials which can be significantly influenced by the design.

This means that the end-of life recycling processes of the product under study should be included and the recycled aluminium should leave the system in the form of the recycled ingot.