

International **A**luminium **I**nstitute



The Aluminium Sector Greenhouse Gas Protocol

(Addendum to the WRI/WBCSD Greenhouse Gas Protocol)

Greenhouse Gas Emissions Monitoring and Reporting by the
Aluminium Industry

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The Aluminium Sector Addendum to the WBCSD/WRI Greenhouse Gas Protocol

Introduction

This document, the International Aluminium Institute (IAI) *Aluminium Sector Addendum to the WBCSD/WRI Greenhouse Gas Protocol*, maintains, as an underlying premise, that the international aluminium industry generally accepts and endorses *The Greenhouse Gas Protocol Corporate Accounting and Reporting Standard (revised edition)*ⁱ (GHG Protocol) developed by the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI). This *Addendum* has been developed by the IAI and endorsed by WRI/WBCSD to supplement the *GHG Protocol*, by providing additional interpretation, guidance and examples tailored to the international aluminium industry.

The *GHG Protocol* addresses the following GHG accounting and reporting topics:

1. GHG accounting and reporting principles;
2. Business goals and inventory design;
3. Setting organizational boundaries;
4. Setting operational boundaries;
5. Tracking emissions over time;
6. Identifying and calculating GHG emissions;
7. Managing inventory quality;
8. Accounting for GHG reductions;
9. Reporting GHG emissions
10. Verification of GHG emissions;
11. Setting GHG targets.

The goal of this *Addendum* is to provide specific guidance to the international aluminium industry and stakeholders on the following areas:

1. Emission sources;
2. Definitions;
3. Methodologies for measuring and calculating GHG emissions;
4. Inventory boundaries;
5. Best practices in GHG measurement and reporting.

It covers carbon dioxide and perfluorocarbon (PFC) emissions resulting from primary aluminium production and supporting processes. Emissions from the combustion of fossil fuels associated with the production of electricity, primary aluminium production, bauxite mining, bauxite ore refining, and aluminium production from recycled sources are covered in the WRI/WBCSD *Calculation Tool for Direct Emissions from Stationary Combustion, version 2.0.*ⁱⁱ

The intent of this guidance is to help achieve reliable, consistent and transparent calculation and reporting of GHGs throughout the aluminium sector. This will benefit internal and external stakeholders alike. The methodologies outlined herein constitute a standard for

the aluminium industry. When using this standard for reporting, any deviations should be clearly noted.

Specific examples of aluminium industry emissions calculations are provided to support clarity and consistency in the preparation and maintenance of GHG inventories and reports.

This document has been prepared with the support and approval of the IAI Board of Directors acting on behalf of its [Member Companies](#). A number of groups have been given the opportunity to comment and contribute to the enclosed document, including the WBCSD and WRI, which endorse this *Addendum*.

This *Addendum* will be updated by the IAI as necessary, to remain consistent with changes made to the *GHG Protocol* and with further developments within the industry, with an update on or before 2010.

Section 1 *GHG Accounting and Reporting Principles*

This Addendum accepts and endorses the view outlined in the *GHG Protocol*, that GHG accounting and reporting by the aluminium industry should be based on the principles of relevance, completeness, consistency, transparency and accuracy.

Section 2 *Business Goals and Inventory Design*

Improving understanding of individual companies' GHG emissions, by compiling a GHG inventory, makes good business sense. As articulated in the *GHG Protocol*, the five categories of business goals most frequently listed by companies as reasons for compiling a GHG inventory are:

1. GHG risk management and the identification of reduction opportunities;
2. Public reporting and participation in voluntary initiatives;
3. Participation in mandatory reporting programmes;
4. Participation in GHG markets;
5. Recognition for early voluntary action.

Section 3 *Setting Organizational Boundaries*

Consistent with the *GHG Protocol*, emissions information should be collected and reported in a transparent manner using either the control approach, the equity share approach, or both approaches in parallel. Equity share is defined as the percentage of ownership or economic interest in an operation. The equity approach increases the usability of GHG information for different users and aims, as far as possible, to mirror the approach adopted by financial accounting and reporting standards. The control approach provides a simple way to make sure that all emissions are accounted for and mirror the agreed management responsibility for operations. Under the control approach, a company accounts for 100 percent of the GHG emissions from operations over which it has control. It does not account for GHG emissions from operations in which it owns an interest but has no control. Control can be defined in either financial (the ability to direct the financial and operating policies of an operation with a view to gaining economic benefits from its activities) or operational (the full authority to introduce and implement operating policies at the operation) terms.

Companies involved in partially-owned facilities or joint operations may have agreements that specify how the ownership of emissions or the responsibility for managing emissions and associated risk is distributed between the parties. Where such agreements exist, companies may optionally provide a description of the agreements and include information on allocation of GHG related risks and obligations.

Section 4 *Setting Operational Boundaries*

The *GHG Protocol* introduces and explains the concept of “Scope”. Consistent with the *GHG Protocol*, this *Addendum* requires that aluminium companies account for and report Scope 1 and Scope 2 emissions. It should also be noted that it is optional for companies to account for and report Scope 3 emissions. Scope 1 2 and 3 emissions should all be kept separate during the accounting and reporting process.

Scope 1 emissions account for GHG emissions from sources that are owned or controlled by the reporting company. These are also known as direct emissions and include:

1. Emissions from fuel combustion for the production of electricity, heat or steam;
2. Emissions from physical or chemical processing;
3. Emissions from transportation of materials, products, waste, and employees in company owned/controlled transportation equipment;
4. Fugitive emissions (e.g. intentional or unintentional releases such as equipment leaks from joints and seals, mines, and electrical switchgear).

Examples of Scope 1 emissions sources for the aluminium sector include:

1. Fuel Combustion in Furnaces/Boilers
2. Coke Calcination;
3. Anode Production;
4. Anode Consumption;
5. PFC Emissions;
6. Lime Production.

Emissions attributable to the generation of electricity, heat or steam by the reporting company, but then exported/sold should be reported as Scope 1.

Scope 2 emissions account for GHG emissions from the consumption of imported/purchased electricity, heat, or steam. These are known as indirect emissions, because they are a consequence of the reporting company, but occur at sources owned or controlled by another company. Emissions attributable to imported/purchased electricity, heat, or steam that is resold to end-users should be reported as Scope 3 emissions. Emissions attributable to imported/purchased electricity, heat, or steam that is resold to intermediaries should be reported separately as supporting information. To increase data transparency, emissions data associated with Scope 1 activities should not be subtracted from or netted against emissions data from Scope 2 activities.

Scope 3 emissions account for all other indirect emissions. Companies may consider reporting emissions from Scope 3 activities that are important to their business and goals and for which they have reliable information.

Examples of Scope 3 emissions include:

1. Emissions from production of purchased materials;

2. Emissions from transportation in vehicles not owned or controlled by the reporting company;
3. Emissions from outsourced activities, contract manufacturing, and franchises;
4. Emissions from the use and end-of-life phases of products and services produced by the reporting company.

As an example of the Scope 3 emissions impact of substituting aluminium for higher density, traditional materials, calculations have shown that there is the potential to save over 20 kilograms of CO₂ equivalents per kilogram of additional aluminium products used in automotives, through enhanced vehicle fuel efficiency.ⁱⁱⁱ

Section 5 *Tracking Emissions Over Time*

This *Addendum* recommends setting a historic performance datum for comparison over time, based on 1990 as the base year, if verifiable emissions data is available to support such base year emissions. If verifiable emissions data is not available to support 1990 as the base year, then companies should establish the earliest verifiable emissions after 1990 to represent the base year.

The following situations, as stipulated in the *GHG Protocol*, shall trigger a recalculation of base year emissions.

1. Structural changes that have a significant impact on the company's base year emissions. A structural change involves the transfer of ownership or control of emissions-generating activities or operations from one company to another. While a single structural change might not have a significant impact on the base year emissions, the cumulative effect of a number of minor structural changes can result in a significant impact. Structural changes include:

- Mergers, acquisitions, and divestments;
- Outsourcing and insourcing of emitting activities;

2. Changes in calculation methodology or improvements in the accuracy of emission factors or activity data that result in a significant impact on the base year emissions data.

3. Discovery of significant errors, or a number of cumulative errors, that are collectively significant.

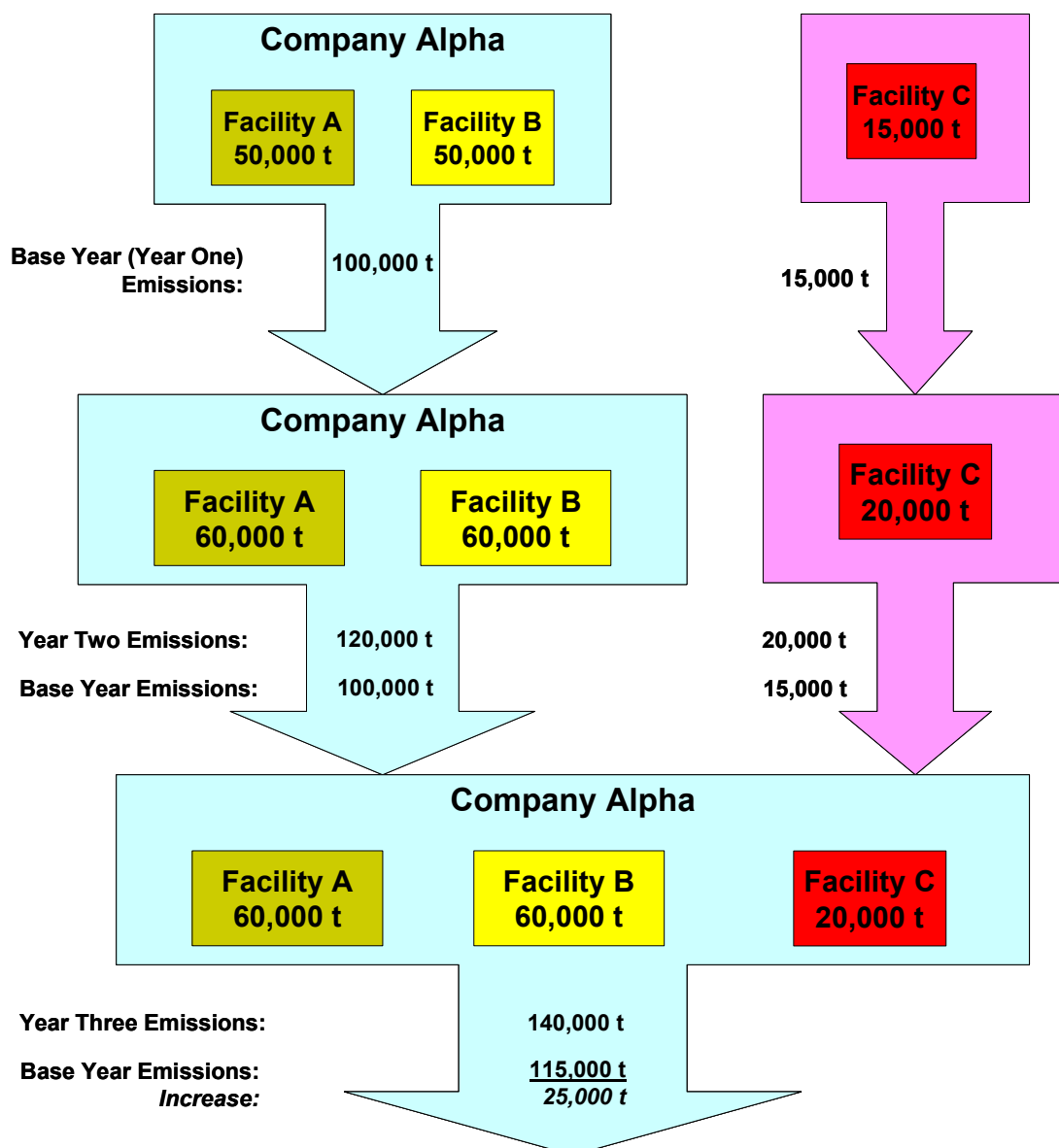
Base year emissions and any historic data are not recalculated for organic growth or decline. Organic growth/decline refers to increases or decreases in production output, changes in product mix, and closures and openings of operating units that are owned or controlled by the company.

The following are general examples. Specific situations may result in a different distribution of emissions.

Base year emissions adjustment for an acquisition

Aluminium Company Alpha consists of two business units (A and B). In its base year (year one), each business unit emits 50,000 tonnes CO₂ and the total emissions for the company are 100,000 tonnes CO₂. In year two, the company undergoes organic growth, leading to an increase in emissions to 60,000 tonnes CO₂ per business unit, (i.e. 120,000 tonnes CO₂ in total). The base year emissions are not adjusted in this case. In the beginning of year three, Alpha acquires a production facility C from another company. The annual emissions of facility C in year one were 15,000 tonnes CO₂, and 20,000 tonnes CO₂ in years two and three. The total emissions of company Alpha in year three, including facility C are therefore 140,000 tonnes CO₂ (i.e. 120,000 + 20,000). To maintain consistency over time, the company recalculates its base year emissions to take into account the acquisition of facility C. The base year emissions increase by 15,000 tonnes CO₂ – the quantity of emissions produced by facility C during Alpha’s base year. The adjusted base year emissions are 115,000 tonnes CO₂ (i.e. 100,000 + 15,000).

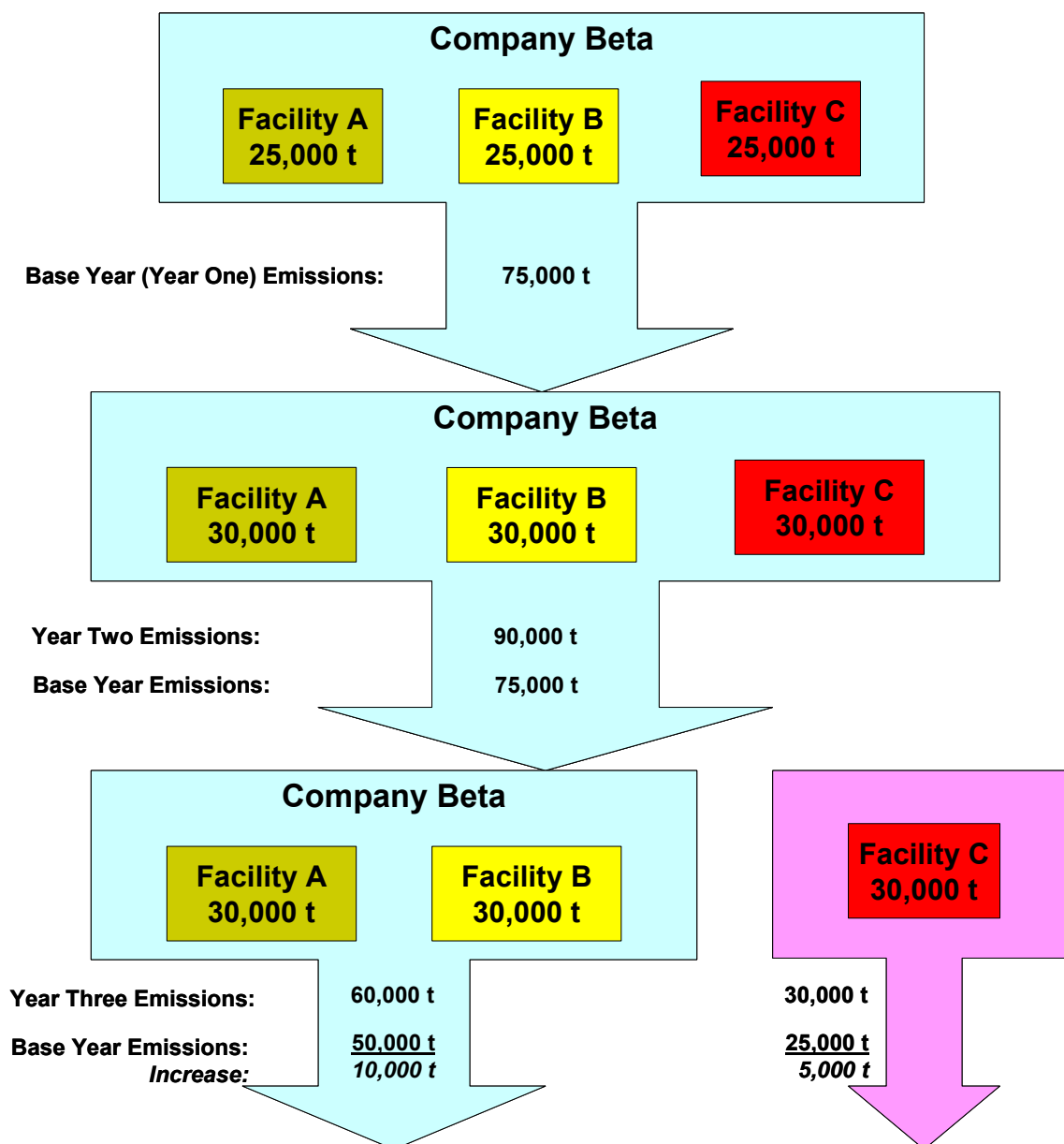
Figure 1 Base year emissions adjustment for an acquisition



Base year emissions adjustment for a divestment

Aluminium Company Beta consists of three business units (A, B and C). Each business unit emits 25,000 tonnes CO₂ and the total emissions for the company are 75,000 tonnes CO₂ in the base year (year one). In year two, the output of the company grows, leading to an increase in emissions to 30,000 tonnes CO₂ per business unit (i.e. 90,000 tonnes CO₂ in total). In year three, Beta divests business unit C, and its annual emissions are now 60,000 tonnes, representing an apparent reduction of 15,000 tonnes relative to the base year emissions. However, to maintain consistency over time, the company recalibrates its base year emissions to take into account the divestment of business unit C. 25,000 tonnes CO₂ – the quantity of emissions produced by the business unit C in the base year, lowers the base year emissions. The adjusted base year emissions are 50,000 tonnes CO₂ and the emissions of company Beta are seen to have risen by 10,000 tonnes CO₂ over the three years.

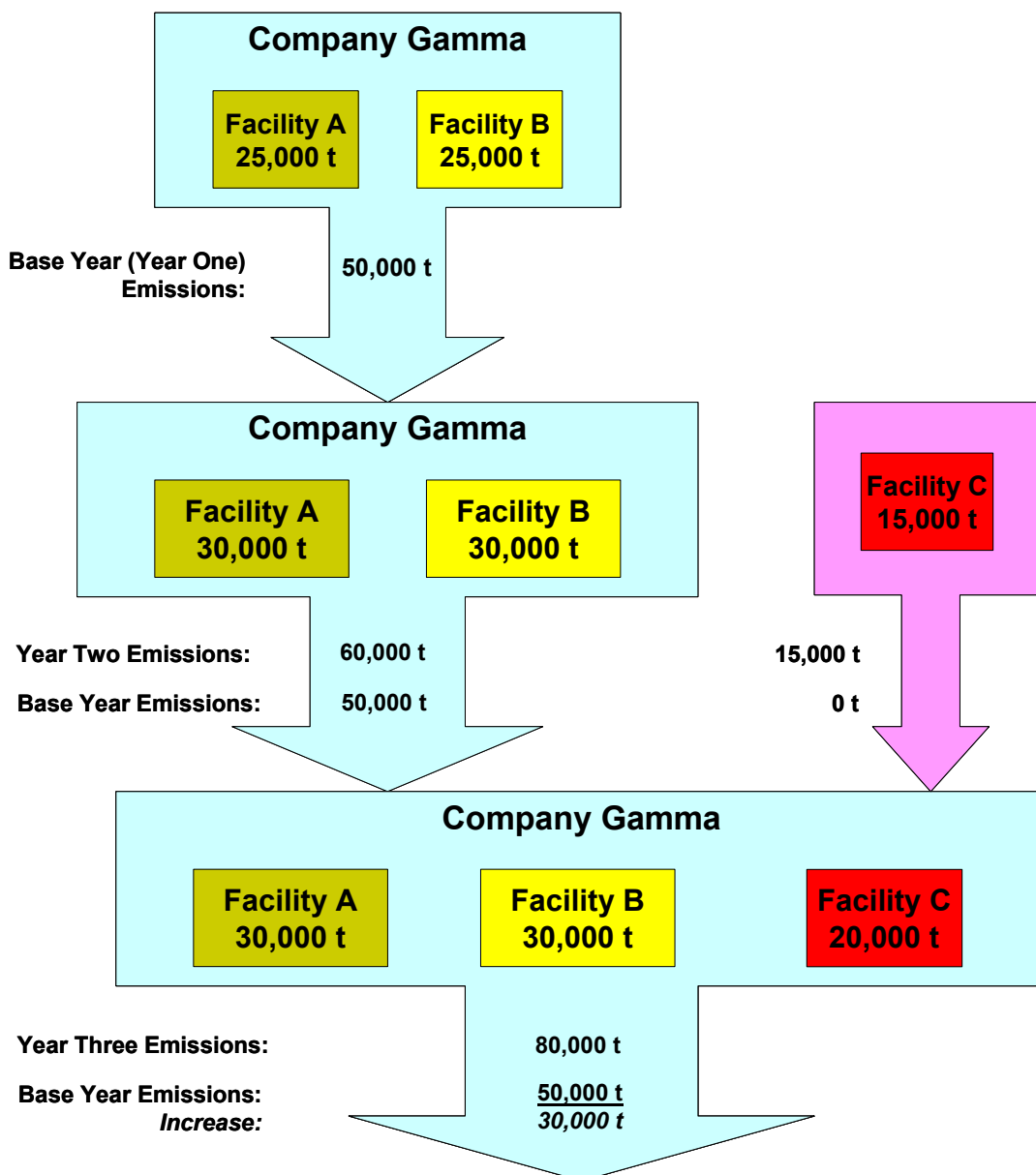
Figure 2 Base year emissions adjustment for a divestment



Acquisition of a facility that came into existence after the base year was set

Aluminium Company Gamma consists of two business units (A and B). In its base year (year one), each business unit emits 25,000 tonnes CO₂, and the total emissions for the company are 50,000 tonnes CO₂. In year two, the company undergoes organic growth, leading to an increase in emissions to 30,000 tonnes CO₂ per business unit (i.e. 60,000 tonnes CO₂ in total). The base year emissions are not adjusted in this case. In the beginning of year three, Gamma acquires a production facility C from another company. Facility C came into existence in year two, its emissions being 15,000 tonnes CO₂ in year two and 20,000 tonnes CO₂ in year three. The total emissions of company Gamma now include facility C and are therefore 50,000, 75,000, and 80,000 tonnes CO₂ in years one, two and three respectively. In this acquisition case, the base year emissions of company Gamma do not change because the acquired facility C did not exist in year one when the base year of Gamma was set. The base year emissions datum of Gamma therefore remains at 50,000 tonnes CO₂.

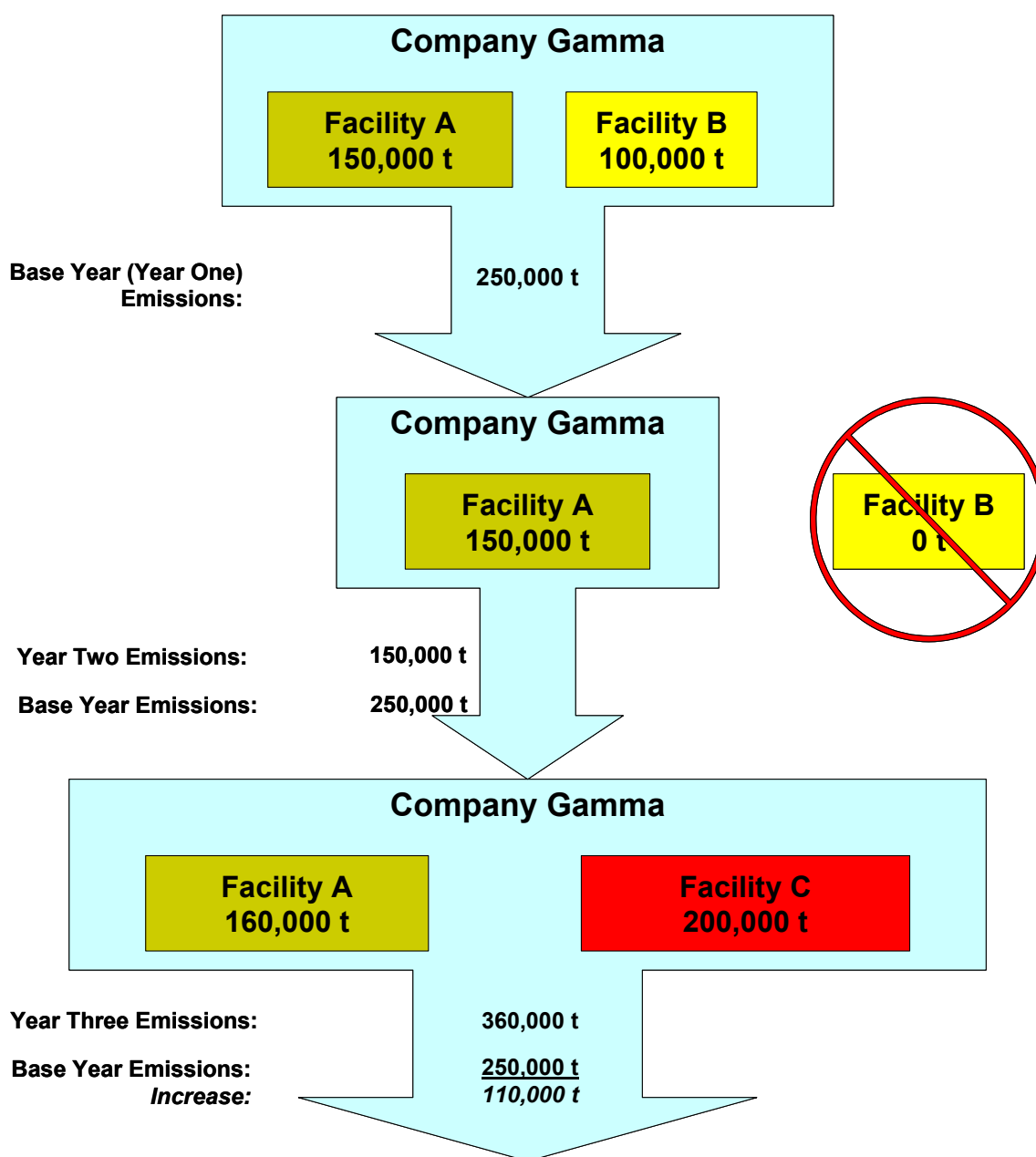
Figure 3 Acquisition of a facility that came into existence after the base year was set



Organic growth, plant closure and opening of a new plant

Aluminium Company Delta initially operates smelter A, which emits 150,000 tonnes of CO₂, and smelter B, which emits 100,000 tonnes of CO₂. Therefore, Delta's base year (year one) emissions are 250,000 tonnes of CO₂. In year two smelter B is closed. In year three, smelter A emissions increase to 160,000 tonnes of CO₂ due to organic growth, and a new smelter C is commissioned, which emits 200,000 tonnes of CO₂. The base year emissions (year one) of Aluminium Company Delta remain unchanged at 250,000 tonnes of CO₂ because the new plant C did not exist in year one when the base year was set and the emissions from smelter B remain in the baseline. Emissions from plant C are included in the inventory from year three. The total emissions of company Delta are 250,000, 150,000, and 360,000 tonnes CO₂ in years one, two, and three respectively.

Figure 4 Organic growth, plant closure and opening of a new plant



In summary, base year emissions shall be recalculated to reflect changes in the company that would otherwise compromise the consistency of the reported GHG emissions information.

Section 6 *Identifying and Calculating GHG Emissions*

This *Addendum* generally accepts and endorses the recommended practices in the *GHG Protocol* for identifying and calculating GHG emissions, which include the following steps:

1. Identify GHG emissions sources;
2. Select a GHG emissions calculation approach;
3. Collect activity data and choose emissions factors;
4. Apply calculation tools;
5. Roll-up GHG data to corporate level.

GHG emissions should be calculated using a bottom-up approach. This involves calculating emissions at the level of an individual source or facility and then rolling this up to the corporate level using either the equity or control approach.

[Appendix A](#) of this *Addendum* includes guidance and examples representing current best practices for calculating CO₂ and PFC emissions from various operations associated with primary aluminium production.

[Appendix B](#) contains a spreadsheet tool that can be used to assist in the calculation of these emissions.

Section 7 *Managing Inventory Quality*

Ensuring inventory quality by minimizing systemic and inherent uncertainty is important for maintaining accurate inventories and reports. The following steps should be included to improve inventory quality:

1. Adopt and apply GHG accounting and reporting principles;
2. Use a standardized system for calculation and internal reporting of GHGs across multiple business units/facilities;
3. Select an appropriate calculation methodology;
4. Set up a robust data collection system;
5. Establish appropriate information technology controls;
6. Undertake regular accuracy checks for technical errors;
7. Conduct periodic internal audits and technical reviews;
8. Ensure management review of the GHG information;
9. Organize regular training sessions for inventory development team members;
10. Perform uncertainty analysis;
11. Obtain independent external verification, where appropriate.

These methods are explained in detail in the *GHG Protocol*.

Section 8 Accounting for GHG Reductions

Reductions in corporate emissions are calculated by comparing changes in the company's actual emissions inventory over time relative to a base year. Focusing on overall corporate or organizational level emissions has the advantage of helping companies manage their aggregate GHG risks and opportunities more effectively. It also helps focus resources on activities that result in the most cost effective GHG reductions.

Consistent with the flowcharts in [Appendix A](#) regarding the choice of method, it is recommended to use facility specific process data where available. Reductions over time should be tracked, documented, and subsequently reported based on the data source that has the highest degree of accuracy (i.e. the lowest level of uncertainty). For instance, anode effect process measurement data is a preferred data source for tracking and subsequently verifying PFC emissions reductions. Section 2.1.2 of [Appendix B](#) highlights how to calculate PFC emissions from these process data.

Emissions from the use and end-of-life phases of products and services produced by the reporting company may be considered if they are important to the company's business and goals and for which they have reliable information. In such cases these emissions should be clearly documented as part of the accounting process¹ and reported as Scope 3 emissions. Scope 1 2 and 3 emissions should all be kept separate during the accounting and reporting process.

Section 9 Reporting GHG Emissions

Reported information should be relevant, complete, consistent, transparent and accurate. GHG reports should be based on the best data available at the time of publication. Any limitations should be fully documented and disclosed. Any discrepancies identified should be corrected and communicated in subsequent years.

The following should be considered as minimum content of a public GHG inventory:

1. A description of the reporting company and inventory boundary:
 - Outline of organizational boundaries chosen and the approach used;
 - Outline of the operational boundaries chosen and if Scope 3 emissions are included, a list specifying which types of activities are covered;
 - Reporting period covered.
2. Information on emissions:
 - Total Scope 1 and Scope 2 emissions;
 - Emissions data separate for each scope;

¹ Further information can be found in the IAI *Life Cycle Assessment of Aluminium: Inventory Data for the Worldwide Primary Aluminium Industry*, 2003: <http://www.world-aluminium.org/iai/publications/documents/lca.pdf>.

- Emissions data for all six GHGs separately in metric tonnes and tonnes CO₂ equivalent;
- Emissions data for direct CO₂ emissions from biologically sequestered carbon (e.g. CO₂ from burning biomass/biofuels), reported separately from the Scopes;
- Base year and emissions profile over time;
- Context of significant changes in emissions;
- Calculation methodologies used;
- Any specific exclusions of facilities or sources.

Additional optional information, which should be included if applicable, is also detailed in the *GHG Protocol*.

Section 10 *Verification of GHG Emissions*

Definition

The *GHG Protocol* indicates that verification is an objective assessment of the accuracy and completeness of reported GHG information and the conformity of this information to pre-established GHG accounting and reporting principles.

ISO Standard 14,064 Part 3 defines verification as the “systematic, impartial and documented periodic review or determination by the verifier of the reported GHG emissions, removals, and emissions reductions.”^{iv}

Objectives

Before commissioning and planning an independent verification, a company should clearly define its goals and decide whether an external verification is appropriate. Reasons for undertaking an external verification include:

1. To add credibility to publicly reported information and reduction goals, and to enhance stakeholder trust in the reporting organization;
2. To increase management and board confidence in reported information;
3. To improve internal GHG accounting and reporting practices (data calculation, recording and internal reporting systems, application of GHG accounting principles, e.g. checks for completeness, consistency, accuracy), and to facilitate learning and knowledge transfer within the organization;
4. To meet or anticipate the requirements of future trading programmes;
5. To comply with voluntary or mandatory requirements.

Process

As stated in the *GHG Protocol*, many companies interested in improving their GHG inventories may subject their information to internal verification by personnel who are

independent of the GHG accounting and reporting process. Both internal and external verification should follow similar procedures and processes.

The *ISO 14,064 Part 3* illustrates the major process steps in conducting a verification including:

1. An agreement with the verifier on the verification objectives, scope, criteria, and level of assurance,
2. The development of an appropriate sampling plan and verification approach,
3. The assessment of GHG data and information controls,
4. An evaluation of the GHG information against pre-determined performance criteria or requirements, and
5. A written verification statement or conclusion.

Additional References

In 2003, the Aluminium Association of Canada developed for aluminium smelters a *GHG Auditing Manual*^v for verifying inventory values related to agreements with the province of Quebec.

Draft ISO 14,064 Part 3 also contains requirements for validation of project related GHG plans and reductions. Validation is the “systematic, impartial and documented process for the evaluation of a GHG project against pre-defined validation criteria”.

Section 11 Setting GHG Targets

There are two types of GHG reduction targets: absolute and intensity-based. Absolute targets are concrete reduction goals that do not take factors such as organizational growth into account (e.g. 10% reduction in GHG emissions below 2000 levels by 2010). Intensity objectives are usually expressed as a reduction in the ratio of GHG emissions relative to another business metric, such as tonne of product produced.

As part of its *Aluminium for Future Generations* sustainability initiative^{vi}, the International Aluminium Institute has developed a global voluntary intensity objective to reduce PFC emissions (per tonne of aluminium produced) from the aluminium industry as a whole by 80% between 1990 and 2010. As of 2004, the global industry has achieved a reduction of 74%. Check the [IAI website](#) for latest reduction figures.

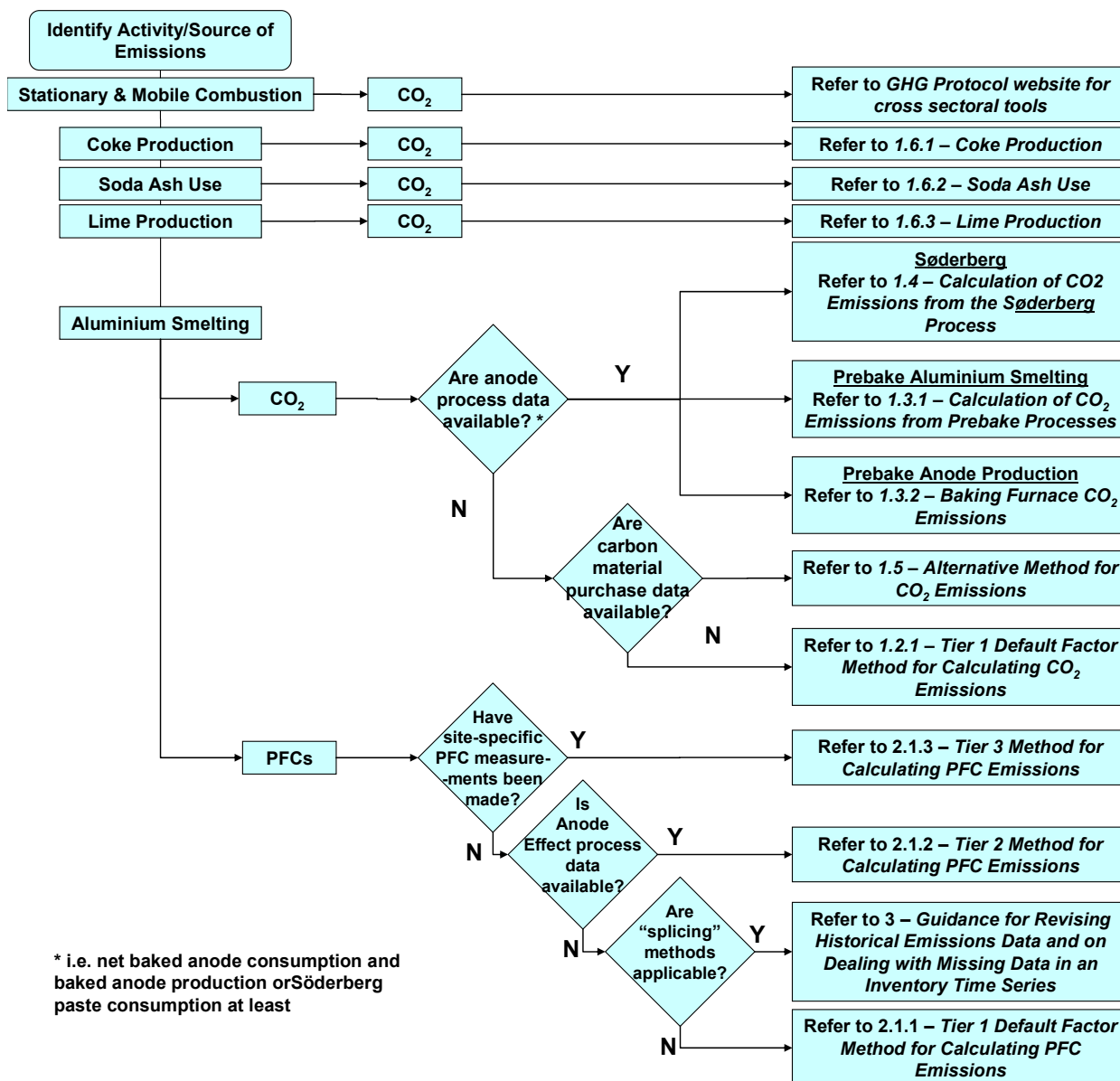
Some IAI member companies have established specific GHG reduction targets by entering formal voluntary agreements with government jurisdictions. The following are examples of voluntary agreements entered into by aluminium companies around the world:

Country Agreement	Period	Reduction type	GHGs	Objective
Australia Greenhouse Challenge Plus Programme – 2005 Facilitative Agreement replacing original Aluminium Industry Framework Agreement (and associated Alumina and Aluminium Supplementary Agreements).	Ongoing (since 1996)	Reporting absolute and intensity metrics	CO ₂ (direct and indirect) CF ₄ C ₂ F ₆	Seeking improvements in energy efficiency and process emissions
Bahrain	1995 – 2000			
Canada Framework Agreement on Voluntary Greenhouse Gas Reductions in Québec (2002)	1990 – 2007	Absolute	CO ₂ CF ₄ C ₂ F ₆	200kt reduction in CO ₂ eq emissions
France AERES voluntary commitment	1990 – 2007	Absolute	CO ₂ CF ₄ C ₂ F ₆	48% reduction in CO ₂ eq emissions
Germany	1990 – 2005	Absolute	CF ₄ C ₂ F ₆	50% reduction in PFC emissions
New Zealand Negotiated Greenhouse Agreement	1990 – 2000			
Norway Norwegian Aluminium Industry GHG Agreements (1997)	1990 – 2005	Intensity	CO ₂ CF ₄ C ₂ F ₆	55% reduction in CO ₂ eq emissions per tonne aluminium
United Kingdom	1990 – 2010	Absolute	CF ₄ C ₂ F ₆	89% reduction in PFC emissions
United States of America Voluntary Aluminum Industrial Partnership (1995)	1990 – 2000	Intensity	CF ₄ C ₂ F ₆	45% reduction in PFC emissions per tonne aluminium
	2000-2010		CO ₂ CF ₄ C ₂ F ₆	53% reduction in CO ₂ eq emissions per tonne aluminium

This *Addendum* supports the approach of setting specific objectives for reducing GHG emissions.

Appendix A Calculation Methods for Process Carbon Dioxide and Perfluorocarbon Emissions Resulting from Aluminium Reduction and Supporting Processes

Figure 5 Decision Tree for Process Carbon Dioxide and Perfluorocarbon Emissions from Primary Aluminium Production



1. Process Carbon Dioxide Emissions

The following recommendations are consistent with the basic three tier framework of the Intergovernmental Panel on Climate Change (IPCC) *Guidelines for National Greenhouse Gas Inventories*^{vii}. Process CO₂ emissions in state of the art aluminium smelters comprise around 90% of total direct CO₂ equivalent emissions, with the balance of emissions consisting of CO₂

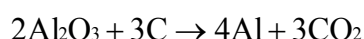
from fossil fuel combustion and PFC emissions. Guidance on CO₂ emissions from fuel combustion is not included in this document. Methodology for calculating CO₂ emissions from the combustion of fuel in anode baking furnaces is described elsewhere, while methodology for calculating process CO₂ emissions is given in Section 1.3.2.1 of this document.

1.1 Sources of Carbon Dioxide

1.1.1 Electrolysis

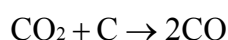
Most of the CO₂ emissions result from the electrolytic reaction of the carbon anode with alumina (following Reaction 1).

Reaction 1

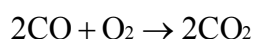


Carbon dioxide is also emitted during the electrolysis reaction as the carbon anode reacts with other sources of oxygen, primarily from the air. Carbon dioxide is also formed as a result of the Boudouard reaction where CO₂ reacts with the carbon anode forming carbon monoxide, which is then oxidized to form CO₂. Each unit of CO₂ participating in the Boudouard reaction (Reaction 2) produces two units of CO₂ after air oxidation (Reaction 3).

Reaction 2



Reaction 3



All carbon monoxide formed is assumed to be converted to CO₂. By industry convention no correction is made for the minute amount of carbon consumed as PFCs rather than CO₂ emissions. No CO₂ is produced from cathode consumption unless there is on-site incineration and no recommendation is included here for such operations.

1.1.2 Aluminium Smelting Supporting Processes

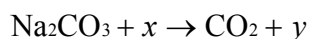
Another source of CO₂ emissions, specific to Prebake technologies, is the baking of green anodes, wherein CO₂ is emitted from the combustion of volatile components from the pitch binder and, for baking furnaces fired with carbon based fuels, from the combustion of the fuel source. Some of the packing coke used to cover the anodes is also oxidized, releasing CO₂ during anode baking.

A further source of CO₂ is coke calcination for the production of anodes. While many operating facilities purchase coke materials in a pre-calcined state, formulas for calculating

CO₂ from calcining are included here because some facilities operate their own calcining furnaces.

Another potential source of CO₂ is the use of soda ash (Na₂CO₃) when used in the flue gas scrubbing process (Reaction 4).

Reaction 4

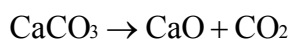


Where x and y are acidic flue gas components and the sodium salt reaction product of the acidic gas component, respectively.

1.1.3 Alumina Refining Supporting Processes

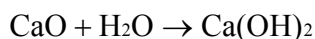
Carbon dioxide is not produced directly in the Bayer Process, the process through which alumina is refined from bauxite ore. Most of the emissions associated with alumina refining are from the combustion of fossil fuels, which are covered in the WRI/WBCSD *Calculation tools for GHG emissions from energy and electricity*. However, some CO₂ is released during the calcination of calcium carbonate (CaCO₃), an operation sometimes performed by alumina refineries for the production of quicklime (CaO) or slaked lime (Ca(OH)₂). The chemical reactions are described in Reaction 5, Reaction 6 and Reaction 7:

Reaction 5



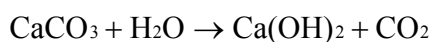
Potentially followed by hydrolysis as shown below.

Reaction 6



The overall combined reaction can be written as follows.

Reaction 7



1.2 Methods for Calculation of Process Carbon Dioxide Emissions

Guidance is given here on the calculation of direct CO₂ emissions from aluminium production in three tiers:

- Tier 1: Industry wide emission factors by process technology.
- Tier 2: Process specific equations with industry typical parameters.

- Tier 3: Process specific equations with site or company specific parameters.

Reference should be made to Figure 5 as an overall guide on how to proceed when calculating direct CO₂ emissions.

1.2.1 Tier 1 – Default Factor Method for Carbon Dioxide Emissions

The Tier 1 method should only be used for calculating CO₂ process emissions for periods when no specific process data is available other than reduction technology type and aluminium production levels. Default emission factors from Table 1 are multiplied by aluminium production levels to obtain total emissions of CO₂. Aluminium facilities typically record parameters enabling calculation of emissions in accordance with Tier 2 or Tier 3 methods.

Table 1 Tier 1 Technology Specific Emission Factors for Calculating Carbon Dioxide Emissions from Anode or Paste Consumption^{viii}

Technology	Emission Factor (tonnes CO ₂ per tonne aluminium)	Uncertainty (±%)
Prebake ²	1.6	10
Söderberg	1.7	10

1.2.2 Tier 2 – Method Using Process Specific Equations with Industry Typical Parameters for Carbon Dioxide Emissions

Tier 2 method for the calculation of total direct CO₂ emissions is based on the calculation of CO₂ emissions from each individual process step which are then summed to calculate total emissions. Equations in 1.3 describe the calculation of CO₂ for Prebake technologies, while 1.4 contains the equations for Söderberg technologies.

1.2.3 Tier 3 – Method Using Process Specific Equations with Facility Specific Parameters for Carbon Dioxide Emissions

The most accurate inventories of CO₂ are obtained by using site or company specific data in the equations for calculating emissions (Tier 3 method). This data might come from measurements made on site or from data from suppliers. The equations are identical to those used in the Tier 2 method described above. However, facility specific or company specific data, rather than industry typical data, are used. The equations for calculating CO₂ emissions from facility or company specific data are embedded in the Excel spreadsheet tools included in [Appendix B](#).

² The emission factor for Prebake cells includes CO₂ emissions from the combustion of pitch volatiles and packing coke from baking anodes.

1.3 Calculation of Carbon Dioxide Emissions from Prebake Processes

Carbon dioxide emissions resulting from CWPB and SWPB reduction technologies have as their sources electrolysis and anode baking.

1.3.1 Carbon Dioxide Emissions from Prebake Anode Consumption During Electrolysis

Equation 1 Calculation of Carbon Dioxide Emissions from Prebake Anode Consumption During Electrolysis

$$E_{CO_2} = \left[MP \times NAC \times \left(\frac{100 - S_a - Ash_a}{100} \right) \right] \times \frac{44}{12}$$

where:

E_{CO_2} = CO₂ emissions in tonnes per year

MP = Total metal production, tonnes aluminium per year

NAC = Net anode consumption, tonnes per tonne aluminium

S_a = Sulphur content in baked anodes, wt %

Ash_a = Ash content in baked anodes, wt %

44/12 = CO₂ Molecular Mass : Carbon Atomic Mass Ratio, dimensionless

Parameters used in Equation 1 are defined in Table 2 together with industry typical values for calculating CO₂ emissions from Prebake anode consumption during electrolysis.

Table 2 Data Sources and Uncertainties for Parameters Used in Tier 2 or 3 Method for Carbon Dioxide Emissions from Prebake Cells^{ix}

Parameter	Tier 2 Method		Tier 3 Method	
	Data Source	Data Uncertainty (± %)	Data Source	Data Uncertainty (± %)
MP: total metal production (tonnes aluminium per year)	Individual facility records	2	Individual facility records	2
NAC: net anode consumption (tonnes per tonne aluminium)	Individual facility records	5	Individual facility records	5
S_a: sulphur content in baked anodes (wt %)	Use industry typical value, 2	50	Individual facility records	10

Ash_a : ash content in baked anodes (wt %)	Use industry typical value, 0.4	85	Individual facility records	10
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1.3.2 Baking Furnace Carbon Dioxide Emissions

Baking furnace emissions result from three sources:

1. Combustion of the fuel for firing the furnace;
2. Combustion of volatile matter released during the baking operation;
3. Combustion of baking furnace packing material.

1.3.2.1 Fuel for Bake Furnace Firing

Carbon dioxide emissions resulting from the fuel consumed during baking furnace firing can be calculated using the WRI/WBCSD *Calculation tools for GHG emissions from energy and electricity*.

1.3.2.2 Pitch Volatile Matter Oxidation from Pitch Volatiles Combustion

Equation 2 Calculation of Carbon Dioxide Emissions from Pitch Volatiles Combustion

$$E_{CO_2} = \left[GA - \left(\frac{H_w \times GA}{100} \right) - BA - WT \right] \times 44/12$$

where:

E_{CO_2} = CO₂ emissions in tonnes per year

GA = Weight of loaded green anodes = $\left(\frac{GAW}{BAW} \right) \times BA$

GAW = Green anode weight, tonnes

BAW = Baked anode weight, tonnes

BA = Baked anode production, tonnes baked anode per year

H_w = Hydrogen content in green anodes, wt %

WT = Waste tar collected, tonnes

44/12 = CO₂ Molecular Mass : Carbon Atomic Mass Ratio, dimensionless

Parameters included in Equation 2 are defined and industry typical values noted in Table 3.

Table 3 Data Sources for Parameters Used in Tier 2 or 3 Method for Carbon Dioxide Emissions from Bake Furnace Pitch Volatiles Combustion^{ix}

Parameter	Tier 2 method		Tier 3 Method	
	Data Source	Data uncertainty (±%)	Data Source	Data uncertainty (±%)
GAW: weight of green anodes (<i>tonnes</i>)	Individual facility records	2	Individual facility records	2
BAW: weight of baked anodes (<i>tonnes</i>)	Individual facility records	2	Individual facility records	2
H_w: hydrogen content in green anodes (<i>wt %</i>)	Use industry typical value, 0.5	50	Individual facility records	10
BA: baked anode production (<i>tonnes per year</i>)	Individual facility records	2	Individual facility records	2
WT: waste tar collected (<i>tonnes</i>) a) Riedhammer furnaces b) All other furnaces	Use industry typical value, a) 0.005 x GA b) Insignificant	50	Individual facility records	20

1.3.2.3 Baking Furnace Packing Material

Equation 3 Calculation of Carbon Dioxide Emissions from Packing Coke

$$E_{CO_2} = \left[PCC \times BA \times \left(\frac{100 - S_{pc} - Ash_{pc}}{100} \right) \right] \times \frac{44}{12}$$

where:

E_{CO_2} = CO₂ emissions in tonnes per year

PCC = Packing coke consumed, tonnes per tonne of baked anode

BA = Baked anode production, tonnes baked anode per year

S_{pc} = Sulphur content in packing coke, wt %

Ash_{pc} = Ash content in packing coke, wt %

44/12 = CO₂ Molecular Mass : Carbon Atomic Mass Ratio, dimensionless

Parameters included in Equation 3 are defined and industry typical values noted in Table 4.

Table 4 Data Sources for Parameters Used in Tier 2 or 3 Method for Carbon Dioxide Emissions from Oxidation of Bake Furnace Packing Material

Parameter	Tier 2 Method		Tier 3 Method	
	Data Source	Data Uncertainty (±%)	Data Source	Data Uncertainty (±%)
PCC: packing coke consumption (tonnes per tonne BA)	Use industry typical value, 0.015	25	Individual facility records	2
BA: Baked anode production (tonnes per year)	Individual facility records	2	Individual facility records	2
S_{pc}: Sulphur content in packing coke (wt %)	Use industry typical value, 2	50	Individual facility records	10
Ash_{pc}: Ash content in packing coke (wt %)	Use industry typical value, 2.5	95	Individual facility records	10

1.4 Calculation of Carbon Dioxide Emissions from the Söderberg Process

Equation 4 Calculation of Direct Carbon Dioxide Process Emissions for Söderberg Technologies³

$$E_{CO_2} = \left[(MP \times PC) - \left(CSM \times \frac{MP}{1000} \right) - \left[\left(\frac{BC}{100} \right) \times PC \times MP \times \left(\frac{S_p + Ash_p + H_p}{100} \right) \right] - \left[\left(\frac{100 - BC}{100} \right) \times PC \times MP \times \left(\frac{S_c + Ash_c}{100} \right) \right] - (MP \times CD) \right] \times \frac{44}{12}$$

where:

E_{CO_2} = CO₂ emissions in tonnes per year

MP = Total metal production, tonnes aluminium per year

PC = Paste consumption, tonnes per tonne aluminium

³ An acceptable alternative method is to use the parameter of 'pitch coking' in lieu of deducting measured or default values for S_p , H_p , Ash_p and CSM from Equation 4. The pitch coking value is a commonly determined parameter for many facilities with Söderberg cells.

International Aluminium Institute

CSM = Emissions of cyclohexane soluble matter, kg per tonne aluminium

BC = Typical binder content in paste, wt %

S_p = Sulphur content in pitch, wt %

Ash_p = Ash content in pitch, wt %

H_p = Hydrogen content in pitch, wt %

S_c = Sulphur content in calcined coke, wt %

Ash_c = Ash content in calcined coke, wt %

CD = Carbon in skimmed dust from Söderberg cells, tonnes carbon per tonne aluminium

$44/12$ = CO_2 Molecular Mass : Carbon Atomic Mass Ratio, dimensionless

Parameters used in Equation 4 are defined in Table 5 together with industry typical values for calculating CO_2 emissions for Söderberg technologies.

Table 5 Data Sources and Uncertainties for Parameters Used in Tier 2 or 3 Method for Carbon Dioxide Emissions from Söderberg Cells

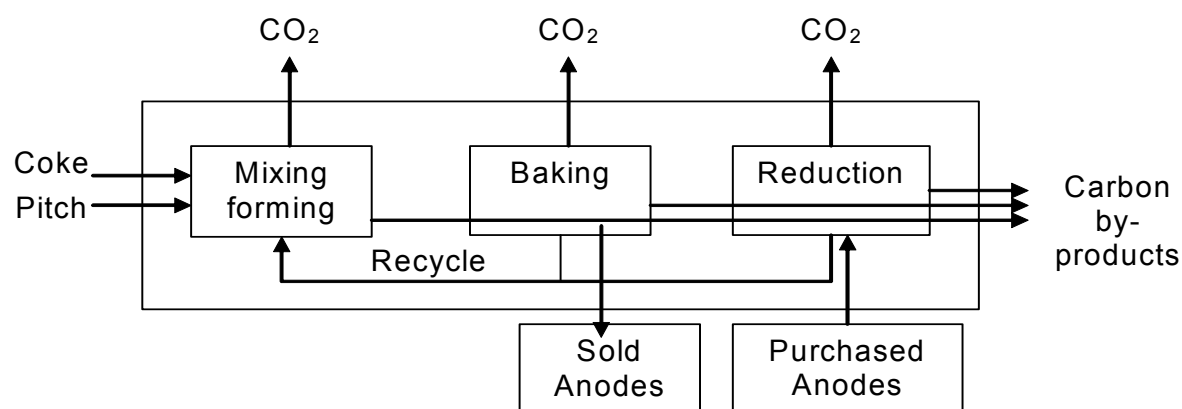
Parameter	Tier 2 Method		Tier 3 Method	
	Data Source	Data Uncertainty ($\pm\%$)	Data Source	Data Uncertainty ($\pm\%$)
MP: total aluminium production (<i>tonnes per year</i>)	Individual facility records	2	Individual facility records	2
PC: paste consumption (tonnes per tonne aluminium)	Individual facility records	2-5	Individual facility records	2-5
CSM: emissions of cyclohexane soluble matter (<i>kg per tonne aluminium</i>)	Use industry typical value, HSS – 4.0 VSS – 0.5	30	Individual facility records	15
BC: typical binder content in paste (<i>wt %</i>)	Use industry typical value, Dry Paste – 24 Wet Paste – 27	25	Individual facility records	5
S_p: sulphur content in pitch (<i>wt %</i>)	Use industry typical value,	20	Individual	10

	0.6		facility records	
Ash_p : ash content in pitch (wt %)	Use industry typical value, 0.2	20	Individual facility records	10
H_p : hydrogen content in pitch (wt %)	Use industry typical value, 3.3	50	Individual facility records	10
S_c : sulphur content in calcined coke (wt %)	Use industry typical value, 1.9	20	Individual facility records	10
Ash_c : ash content in calcined coke (wt %)	Use industry typical value, 0.2	50	Individual facility records	10
CD : carbon dust from anode (tonnes per tonne aluminium)	Use industry typical value, 0.01	99	Individual facility records	30

1.5 Alternative Method for Process Carbon Dioxide Inventory Based on Raw Materials Purchases

This alternative method for calculation of CO₂ emissions is applied to the aluminium production processes within the process boundaries shown in Figure 6. Carbon dioxide emissions are calculated from the carbon content of carbon-containing materials consumed for the period of the inventory.

Figure 6 Process Boundaries for Carbon Content of Consumed Materials Method for Calculation of Carbon Dioxide Emissions Inventory



Equation 5 is used to calculate total CO₂ emissions for the period considered. Inputs into the anode process system boundary are pitch, coke, purchased anodes and packing coke.

Fuel and electricity are not included. Outputs from the anode process system boundary are CO₂ resulting from mixing and forming, baking and the reduction of the anode in the cell. Carbon by-products including fines or sludge and sold anodes are also a system output. The sum of the carbon inputs from pitch, coke and packing coke can only leave the system boundary as CO₂ or as scrap carbon, fines and residues. The carbon mass balance will be maintained. It is assumed that all carbon except verifiable carbon output, is converted to CO₂ during the process. This assumes that any CO produced is further oxidized in the atmosphere to CO₂. Corrections are made for non-carbon constituents of pitch and coke including sulphur, ash and hydrogen that do not contribute to the greenhouse effect and are therefore not included in the calculation. Finally, fuels and electrical energy used in mixing, forming, baking, rodding and transporting anodes are not included in the anode calculation. Greenhouse gas emissions from these inputs are calculated and reported separately.

Equation 5 Calculation of Carbon Dioxide Emissions Based on Raw Materials Purchases

$$E_{CO_2} = \left[\left(\frac{TPC \times PC}{100} \right) + \left(\frac{Coke \times CC}{100} \right) + \left(\frac{TPCC \times PCC}{100} \right) - TWC + \left(\frac{PA \times PAC}{100} \right) - \left(\frac{SA \times SAC}{100} \right) \right] \times \frac{44}{12}$$

where:

E_{CO_2} = CO₂ emissions in tonnes per year

TPC = Total pitch consumed, tonnes pitch per year

PC = Carbon content of pitch, wt %

$Coke$ = Total coke consumed, tonnes coke per year

CC = Carbon content of coke, wt %

$TPCC$ = Total packing coke consumed, tonnes packing coke per year

PCC = Carbon content of packing coke, wt %

TWC = Total carbon by-products or waste, tonnes carbon per year

PA = Total mass of purchased anodes, tonnes purchased anodes per year

PAC = Carbon content of purchased anodes, wt %

SA = Total mass of sold anodes, tonnes sold anodes per year

SAC = Carbon content of sold anodes, wt %

44/12 = CO₂ Molecular Mass : Carbon Atomic Mass Ratio, dimensionless

1.6 Additional Sources of Process Carbon Dioxide

1.6.1 Coke Calcination

For those production facilities that have coke calcining operations Equation 6 is used to calculate CO₂ emissions from this source.

Equation 6 Carbon Dioxide Emissions from Coke Calcining

$$E_{CO_2} = \left[\left[\left[GC \times \left(\frac{100 - H_2O_{gc} - V_{gc} - S_{gc}}{100} \right) \right] - \left[(CC + UCC + DE) \times \left(\frac{100 - S_{cc}}{100} \right) \right] \right] \times \frac{44}{12} \right] + \left[GC \times 0.035 \times \left(\frac{44}{16} \right) \right]$$

where:

E_{CO_2} = CO₂ emissions in tonnes per year

GC = Green coke feed, tonnes green coke per year

H_2O_{gc} = Humidity in green coke, wt %

V_{gc} = Volatiles in green coke, wt %

S_{gc} = Sulphur content in green coke, wt %

CC = Calcinated coke produced, tonnes calcined coke per year

UCC = Under-calcinated coke collected, tonnes under-calcined coke per year

DE = Coke dust emissions, tonnes coke dust per year

S_{cc} = Sulphur content in calcinated coke, wt %

44/12 = CO₂ Molecular Mass : Carbon Atomic Mass Ratio, dimensionless

44/16 = CO₂ Molecular Mass : CH₄ Molecular Mass Ratio, dimensionless

Parameters included in Equation 6 are defined and industry typical values noted in Table 6.

Table 6 Data Sources for Parameters Used in Tier 2 or 3 Method for Carbon Dioxide Emissions from Calcining Operations

Parameter	Tier 2 Method Data Source	Tier 3 Method Data Source
GC: green coke feed (<i>tonnes per year</i>)	Individual facility records	Individual facility records
H₂O_{gc}: humidity in green coke (<i>wt %</i>)	Use industry typical value, 10	Individual facility records
V_{gc}: volatiles in green coke ⁴ (<i>wt %</i>)	Use industry typical value, 10	Individual facility records
S_{gc}: sulphur content in green coke (<i>wt %</i>)	Use industry typical value, 3	Individual facility records
CC: calcinated coke produced (<i>tonnes per year</i>)	Use industry typical value, 0.8 x GC	Individual facility records
UCC: under calcinated coke collected (<i>tonnes per year</i>)	Use industry typical value, 0	Individual facility records
DE: coke dust emissions (<i>tonnes per year</i>)	Use industry typical value, 0.075 x GC	Individual facility records
S_{cc}: sulphur content in calcinated coke (<i>wt %</i>)	Use industry typical value, 2.5	Individual facility records

Any fuel consumption for coke calcination is included in the overall plant fuel consumption and is thus excluded from the above calculation.

1.6.2 Soda Ash Use

Equation 7 should be used for calculation of CO₂ emissions from the use of soda ash, associated with aluminium production.

Equation 7 Carbon Dioxide Emissions from Soda Ash Use

$$E_{CO_2} = Q_{soda_ash} \times P_{soda_ash} \times 44/106$$

where:

⁴ Based on past research work, it is assumed that volatiles content in coke is about 3.2% CH₄, 0.3% tars and 7.1% H₂. The contribution of CH₄ and tars (3.5%) to CO₂ emissions is included in the equation. (Ref.: Jean Perron, *Modélisation mathématique d'un four de calcination du coke de pétrole* (mathematical model of a petroleum coke calcination furnace), doctorate thesis, Université de Montréal, École polytechnique, 1991.)

E_{CO_2} = CO₂ emissions in tonnes per year

Q_{soda_ash} = Quantity of soda ash (Na₂CO₃) consumed, tonnes soda ash per year

P_{soda_ash} = Purity of soda ash consumed, decimal fraction

44/106 = CO₂ Molecular Mass : Na₂CO₃ Molecular Mass Ratio, dimensionless

Parameters in Equation 7 are described in Table 7 along with industry typical values.

Table 7 Data Sources for Parameters Used in Tier 2 or 3 Method for Carbon Dioxide Emissions from Soda Ash used in Aluminium Production Processes

Parameter	Tier 2 Method Data Source	Tier 3 Method Data Source
Q_{soda_ash} : Quantity of soda ash (Na ₂ CO ₃) consumed (<i>tonnes per year</i>)	Individual facility records	Individual facility records
P_{soda_ash} : Purity of soda ash consumed (<i>decimal fraction</i>)	Use industry typical value, 0.95	Individual facility records

1.6.3 Lime Production

Equation 8 should be used for calculation of CO₂ emissions from the production of lime associated with aluminium production.

Equation 8 Carbon Dioxide Emissions from Lime Production

$$E_{CO_2} = (Q_l \times P_l \times 44/56) + (Q_s \times P_s \times 44/74)$$

where:

E_{CO_2} = CO₂ emissions in tonnes per year

Q_l = Quantity quick lime produced, tonnes quick lime per year

P_l = Purity of quick lime, decimal fraction

Q_s = Quantity of slaked lime produced, tonnes slaked lime per year

P_s = Purity slaked lime, decimal fraction

44/56 = CO₂ Molecular Mass : CaO Molecular Mass Ratio, dimensionless

44/74 = CO₂ Molecular Mass : Ca(OH)₂ Molecular Mass Ratio, dimensionless

Parameters in Equation 8 are described in Table 8 along with industry typical values.

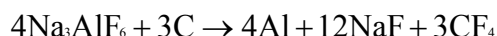
Table 8 Data Sources for Parameters Used in Tier 2 or 3 Method for Carbon Dioxide Emissions from Lime Production

Parameter	Tier 2 Method Data Source	Tier 3 Method Data Source
Q_i : Quantity quick lime produced (<i>tonnes per year</i>)	Individual facility records	Individual facility records
P_i : Purity of quick lime (<i>decimal fraction</i>)	Use industry typical value, 0.95	Individual facility records
Q_s : Quantity of slaked lime produced (<i>tonnes per year</i>)	Individual facility records	Individual facility records
P_s : Purity slaked lime (<i>decimal fraction</i>)	Use industry typical value, 0.95	Individual facility records

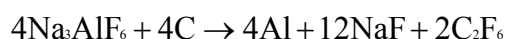
2 Calculating Perfluorocarbon Emissions

Two perfluorocarbon gases (PFCs), tetrafluoromethane (CF₄) and hexafluoroethane (C₂F₆), may be produced during primary aluminium production.

Reaction 8



Reaction 9



The following recommendations for calculating PFC emissions are consistent with the inventory guidance of the Intergovernmental Panel on Climate Change (IPCC).

2.1 Methods for Calculation of PFC Emissions

Three sequential steps described below lead to calculation of the carbon dioxide equivalent emissions represented by PFC emissions from primary aluminium production.

- Emissions of each of the two PFC gases are first calculated per tonne of primary aluminium produced.
- These emission rates per tonne of aluminium are multiplied by the total production of aluminium during the time period for which the inventory is being developed.
- The equivalent CO₂ emissions are calculated by multiplying the PFC emissions by appropriate Global Warming Potential (GWP) factors.

Three separate approaches are described below for calculating PFC emissions per tonne of aluminium with relative uncertainty varying from low to high. As shown in Figure 5 this *Addendum* strongly recommends the use of Tier 3 method where PFC emissions make up a significant share of a facility's GHG emissions.

2.1.1 Tier 1 Default Factor Method

It is expected that all primary aluminium production facilities operating today will collect and archive anode effect process data needed to calculate PFC emissions by one of the two methods above. However, in cases where only aluminium production data is available and anode effect data is not available, the default CF₄ and C₂F₆ emission factors in Table 9 should be used. Total PFC emissions and CO₂ equivalent emissions should be calculated as in the Tier 2 and Tier 3 methods using Equation 13, Equation 14 and Equation 15 from 2.2.2 and 2.2.3.

Table 9 Default Emission Factors and Uncertainty Ranges for the Calculation of PFC Emissions from Aluminium Production by Cell Technology Type

Technology	CF ₄		C ₂ F ₆	
	R _{CF₄} kg/tonne Al ^a	Uncertainty Range (%) ^b	R _{C₂F₆} kg/tonne Al ^c	Uncertainty Range (%) ^d
CWPB	0.4	-99/+380	0.04	-99/+380
SWPB	1.6	-40/+150	0.4	-40/+150
VSS	0.8	-70/+260	0.04	-70/+260
HSS	0.4	-80/+180	0.03	-80/+180

a. Default CF₄ values calculated from median anode effect performance from 1990 IAI survey data.
b. Uncertainty based on the range of calculated CF₄ specific emissions by technology from 1990 IAI anode effect survey data^x.
c. Default C₂F₆ values calculated from global average C₂F₆:CF₄ ratios by technology, multiplied by the default CF₄ emission factor.
d. Uncertainty range based on global average C₂F₆:CF₄ ratios by technology, multiplied by calculated minimum and maximum specific CF₄ emissions from 1990 IAI survey data.
NOTE: These default emission factors should only be used in the absence of Tier 2 or Tier 3 data.

2.1.2 Tier 2 Method for calculating PFC emissions

This method is based on calculations using site specific anode effect or overvoltage process data but industry average coefficients in place of coefficients calculated from site specific measurements of PFC gases. PFC emission rates and CO₂ equivalent emissions should be calculated as in the Tier 3 method using Equation 13 and Equation 14. The current recommended average slope and overvoltage coefficients are listed in Table 10.

Table 10 Technology Specific Slope and Overvoltage Coefficients for the Calculation of PFC Emissions per Tonne Aluminium from AE Process Data

Technology ^a	Slope Coefficient ^{b, c} [(kg PFC/t _{Al}) / (AE-Mins/cell-day)]		Overvoltage Coefficient ^{b, c, d, e} [(kg CF ₄ /t _{Al}) / (mV)]		Weight Fraction C ₂ F ₆ /CF ₄	
	S _{CF₄}	Uncertainty (±%)	OVC	Uncertainty (±%)	F _{C₂F₆/CF₄}	Uncertainty (±%)
CWPB	0.143	6	1.16	24	0.121	11
SWPB	0.272	15	3.65	43	0.252	23
VSS	0.092	17	NR	NR	0.053	15
HSS	0.099	44	NR	NR	0.085	48

a. Centre Worked Prebake (CWPB), Side Worked Prebake (SWPB), Vertical Stud Søderberg (VSS), Horizontal Stud Søderberg (HSS).
b. Source: Measurements reported to IAI, US EPA sponsored measurements and multiple site measurements.
c. Embedded in each Slope and Overvoltage coefficient is an assumed emissions collection efficiency as follows: CWPB 98%, SWPB 90%, VSS 85%, HSS 90%. These collection efficiencies have been assumed based on measured PFC collection fractions, measured fluoride collection efficiencies and expert opinion.
d. The noted coefficients reflect measurements made at some facilities recording positive overvoltage and

others recording algebraic overvoltage. No robust relationship has yet been established between positive and algebraic overvoltage. Positive overvoltage should provide a better correlation with PFC emissions than algebraic overvoltage.
 e. Overvoltage coefficients are not relevant (NR) to VSS and HSS technologies.

2.1.3 Tier 3 Method for calculating PFC emissions

This method is based on calculations using site specific anode effect process data, aluminium production data and coefficients based on direct local facility measurements of PFCs. The measurements on which the coefficients are based should be made according to the *PFC Measurement Protocol* describing good measurement practices.^{xi}

2.2 Calculation of PFC Emissions from Aluminium Reduction Processes

2.2.1 Step 1 – Calculate the emissions of each PFC gas per tonne of aluminium

PFC emissions per tonne aluminium are calculated by either the slope method or the overvoltage method depending on the type of anode effect process data recorded at the facility.

2.2.1.1 Calculation of Emission Rate of CF₄ and C₂F₆ per Tonne Aluminium using Anode Effect Minutes Per Cell Day (Slope Method)

Slope Coefficient: The slope coefficient is the kg of CF₄ per metric tonne of aluminium produced, divided by anode effect minutes per cell-day⁵. Since PFC emissions are measured per tonne of aluminium produced, the slope coefficient includes the effects of pot amperage and current efficiency, the two main factors determining the amount of aluminium produced in the pot.

Equation 9 and Equation 10 should be used when anode effect minutes per cell day is the anode effect process data correlated with emission rate. The equations should be applied for each operating potline in the facility to obtain the specific emissions per tonne aluminium produced for each potline.

Equation 9

$$R_{CF_4} = AEM \times S_{CF_4}$$

Equation 10

$$R_{C_2F_6} = R_{CF_4} \times F_{C_2F_6/CF_4}$$

where:

⁵ The term ‘cell-day’ refers to the number of cells operating multiplied by the number of days of operation.

R_{CF_4} = Emission rate for CF_4 , kg CF_4 per tonne aluminium

AEM = Anode effect minutes per cell day

S_{CF_4} = Slope coefficient for CF_4 , kg CF_4 per tonne aluminium per anode effect minute per cell day

$R_{C_2F_6}$ = Emission rate for C_2F_6 , kg C_2F_6 per tonne aluminium

$F_{C_2F_6/CF_4}$ = Weight fraction of C_2F_6/CF_4

2.2.1.2 Calculation of Emission Rate of CF_4 and C_2F_6 per Tonne Aluminium using Anode Effect Overvoltage (Overvoltage Method)

Overvoltage Coefficient: Some process control systems characterize anode effects by calculating an Anode Effect Overvoltage⁶ (AEO) statistic. AEO is defined as the extra cell voltage above the target operating voltage. This is calculated by summing the product of time and voltage above the target operating voltage and dividing this figure by the time over which data were collected.

Equation 11 and Equation 12 should be used when anode effect overvoltage is the process data correlated with the emission rate. As with the Slope Method noted above the equations should be applied for each individual potline operating at the facility.

Equation 11

$$R_{CF_4} = OVC \times (AEO/CE)$$

Equation 12

$$R_{C_2F_6} = R_{CF_4} \times F_{C_2F_6/CF_4}$$

where:

R_{CF_4} = Emission rate for CF_4 , kg CF_4 per tonne of aluminium

OVC = Overvoltage coefficient for CF_4 as calculated from facility specific measurements according to guidance in the *PFC Measurement Protocol*

AEO = Anode effect overvoltage, millivolts

⁶ Computer control systems report either 'positive' or 'algebraic' overvoltage depending on the version of software used. Use of the expression 'overvoltage' should not be confused with the classical electrochemical terminology, which usually means the extra voltage needed for an electrochemical reaction to occur.

CE = Current efficiency for aluminium production, %

$R_{C_2F_6}$ = Emission rate for C_2F_6 , kg C_2F_6 per tonne aluminium

$F_{C_2F_6/CF_4}$ = Weight fraction of C_2F_6/CF_4 , dimensionless

2.2.2 Step 2 – Calculate the total kilogram emissions of each PFC gas

Total PFC emissions should be calculated from Equation 13 and Equation 14. For each operating potline the emission rate (from Step 1) of each PFC gas per tonne of primary aluminium produced is multiplied by the tonnes of aluminium produced on that potline to calculate total PFC emissions for the line. Total PFC emissions are calculated by summing the emissions over all operating potlines at the facility⁷.

Equation 13

$$E_{CF_4} = R_{CF_4} \times MP$$

Equation 14

$$E_{C_2F_6} = R_{C_2F_6} \times MP$$

where:

E_{CF_4} = Emissions of tetrafluoromethane, kg CF_4 per year

$E_{C_2F_6}$ = Emissions of hexafluoroethane, kg C_2F_6 per year

R_{CF_4} and $R_{C_2F_6}$ = Emission rates of CF_4 and C_2F_6 , kg per tonne of aluminium produced

MP = Metal production, tonnes aluminium per year

2.2.3 Step 3 – Calculate the total tonnes of carbon dioxide emissions equivalent to the PFC emissions

The CO_2 equivalent emissions for PFC emissions are calculated by summing the product of each PFC emission and its respective Global Warming Potential (GWP). The GWP used for this calculation are those noted in the *IPCC Second Assessment Report*⁸.

⁷ If facility process statistics (anode effect minutes per pot day or anode effect overvoltage) are production weighted averages, the computations for each month or period can be performed at a facility versus potline level.

⁸ While the *IPCC Third Assessment Report* published newly revised global warming potential values for a number of gases including revisions for CF_4 and C_2F_6 , ***Kyoto Protocol Decision 2/CP.3, Methodological issues***

Equation 15

$$E_{CO_2\text{-eq}} = \frac{(6500 \times E_{CF_4}) + (9200 \times E_{C_2F_6})}{1000}$$

where:

$E_{CO_2\text{-eq}}$ = Carbon dioxide equivalent emissions in tonnes per year

E_{CF_4} = Emissions of tetrafluoromethane, kg CF_4 per year

$E_{C_2F_6}$ = Emissions of hexafluoroethane, kg C_2F_6 per year

related to the Kyoto Protocol, paragraph 3, reaffirms that global warming potentials used by Parties should be those provided by the IPCC in its *Second Assessment Report* ("1995 IPCC GWP values") based on the effects of the greenhouse gases over a 100-year time horizon, taking into account the inherent and complicated uncertainties involved in global warming potential estimates.

3 Guidance for Revising Historical Emissions Data and on Dealing with Missing Data in an Inventory Time Series

This section provides general guidance on the recalculation of historical emissions based on updated emission factors or revisions of a method⁹ and how to deal with developing a time series when some needed data is not available. It is desirable to maintain the same methodology throughout an inventory period in order to ensure that trends reflect changes in emissions and do not reflect changes in calculation method. The principles outlined in this section are generally more applicable to emissions of PFCs than to emissions of CO₂. Most facilities historically have measured and recorded anode or paste consumption. Where historic anode or paste consumption data is missing, CO₂ emissions can be estimated from aluminium production utilizing the Tier 1 method with only a slight reduction in accuracy. For PFC emissions it is recommended that facilities move from a lower tier methodology to a higher tier methodology, as soon as the data to support the higher tier methodology becomes available. In order to accurately assess emission trends it is important that the entire time series of emissions, both recent and historical data, reflect emission factors that incorporate the appropriate Tier 2 or Tier 3 PFC calculation coefficients when those values have been updated. Voluntary agreements or regulatory considerations should be based on the best available data and methods. Ideally, consistency in such methods should be maintained throughout the duration of the agreement or commitment period. However, certain regional or regulatory settings may dictate that adjustments to calculation methodology be made to meet specific needs.

This *Addendum* recognises that circumstances will require flexibility in applying these guidelines. In such situations it is recommended that facilities apply and document expert judgement when updating historical data.

To support verification activities and/or the potential for future recalculation companies should document and maintain detailed records of their:

1. aluminium production;
2. clearly defined anode effect process data (anode effect minutes per cell-day, anode effect frequency (AEF), anode effect duration (AED) or anode effect overvoltage (AEO));
3. current and historical PFC slope and/or overvoltage coefficients;
4. the method used to calculate PFC emissions including Tier and equations utilized;
5. details of any PFC emission measurements made at the facility¹⁰;
6. significant process changes¹¹;

⁹ IPCC Good Practices generally refers to methods consistent with Tiers. A change in a Tier would be a change in a method. Updates or revisions for the methodology within a Tier are referred to as “tuning” of the method.

¹⁰ Documentation guidelines are described in USEPA/IAI, “Protocol for Measurement of Tetrafluoromethane (CF₄) and Hexafluoroethane (C₂F₆) Emissions from Primary Aluminum Production,” May, 2003, or most recent revision.

¹¹ Significant process changes include a change in the ore feeding system (side feeding to point break) or the anode effect kill/termination strategy.

7. calculated PFC emissions.

Additional guidance on time series consistency is available from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

An updated version of this *Addendum* is scheduled for publication by IAI in 2010. Changes to the WRI/WBCSD Protocol or within the industry may precipitate an update to coefficients prior to this date. The [IAI website](#) should be consulted for recent updates.

3.1 Revisions Resulting from Change in Tier 1 Emission Factors

Tier 1 emission factors are calculated by applying Tier 2 slope or overvoltage coefficients to median anode effect performance, by technology, as reported in the 1990 IAI anode effect survey. Any revision in Tier 2 coefficients will therefore result in a revision of Tier 1 emission factors. When Tier 1 emission factors are revised, the historical inventory should be recalculated back to the baseline year using new emission factors.

3.2 Revisions Resulting from Changing from Tier 1 Method to Tier 2 Method

Anode effect process data is typically available at most facilities and enables the use of the Tier 2 method. This *Addendum* strongly discourages the use of the Tier 1 method unless no anode effect process data is available. When complete anode effect data is not available to support the Tier 2 method throughout all years of the inventory time series, the use of splicing¹² methods as described below are still preferable to the use of the Tier 1 method. Historical emissions should only be based on Tier 1 methodology if none of the following splicing methods is considered appropriate.

3.2.1 Surrogate Technique

Where historic data are incomplete for all needed process parameters, AEF data may well be available for the entire time series. In situations where AEF was recorded and AED or AEO was not recorded¹³, PFC emissions can be estimated based on trends in AEF¹⁴ with substantially better accuracy than using the Tier 1 method. Specifically, the PFC emission rate (kg CF₄/t Al) based on a Tier 2 or Tier 3 coefficient can be applied to previous years by the relationship in Equation 16.

¹² "Splicing" is terminology used in *IPCC Guidelines for National Greenhouse Gas Inventories* for filling in GHG inventory data for years in which some data may be missing or incomplete.

¹³ In such cases where AED was not recorded it is not likely that AED was being actively controlled.

¹⁴ The statistical correlation between anode effect minutes per cell day or overvoltage and PFC emissions per tonne aluminium is best; however, the correlation between average AEF alone is still good. Statistical analysis of 62 different measurements at aluminium smelters indicated a correlation coefficient of 78% between PFC emissions (kg CF₄ per tonne aluminium) and AEF. The correlation coefficient between emissions and AED alone was 3%, while the correlation coefficient between emissions and the cross product of AEF and AED was 97%.

Equation 16

$$R_{(period\ n-1)} = R_{(period\ n)} \times \frac{AEF_{(period\ n-1)}}{AEF_{(period\ n)}}$$

where:

$R_{(period\ n-1)}$ = Emission rate for CF₄ in kg CF₄ per tonne aluminium where full anode effect process data were not available

$R_{(period\ n)}$ = Emission rate for CF₄ in kg CF₄ per tonne aluminium where full anode effect process data were available

$AEF_{(period\ n-1)}$ = Anode effect frequency in production weighted average number of anode effects per cell day for period n-1

$AEF_{(period\ n)}$ = Anode effect frequency in production weighted average number of anode effects per cell day for period n

After estimating CF₄ emissions per tonne aluminium using the surrogate technique, C₂F₆ emissions per tonne aluminium are calculated by multiplying the Tier 2 or Tier 3 weight ratio of C₂F₆ to CF₄ as would be done with a complete anode effect process data set.

If only AEF data is available, the surrogate technique should be used rather than the Interpolation or extrapolation technique. This is consistent with guidance in Section 8 to use the best available data within a given period.

3.2.2 Interpolation Technique

Where AEO, AED or AEF data is available for some past years and not others, linear interpolation should be used to provide a continuous time series for the process statistics necessary for use of Tier 2 or Tier 3 methods. The accuracy of this splicing method depends in part on how the process activities that actually took place during the intervening years may have impacted AE performance.

3.2.3 Trend Extrapolation Technique

Where historical data for AEO, AED and AEF does not exist and in the absence of any activity directed at managing AEO, AED or AEF, it is suggested that the historical PFC emission rate per tonne of aluminium be extrapolated from emissions data for the first year in which the Tier 2 or Tier 3 method is used. In this case extrapolation for previous years would be based on the assumption that AEO or AEF and AED remained constant and emissions are extrapolated based on changes in production. This extrapolation should still result in a greater degree of accuracy than the use of the Tier 1 method.

3.2.4 Other Techniques for Recalculations

In some cases, it may be necessary to develop a customised approach to recalculate historic emissions, as not every situation can be envisaged. For example, the techniques above may not be valid when technical conditions are changing throughout the time series (e.g. due to specific actions being taken to reduce anode effects or due to the introduction of new technology such as point feeders). In this case, provided adequate supporting data is available, a customised approach using expert judgement may be possible. The need for and application of such an approach in lieu of one or more of those discussed above should be thoroughly documented.

3.3 Revisions Resulting from Change in Tier 2 Coefficients

If the Tier 2 slope or overvoltage coefficients are revised¹⁵ the revised Tier 2 coefficients should be used to recalculate emissions to the baseline year so that changes in reported emissions reflect actual anode effect performance and not changes in coefficients. However, as noted in the introduction to this section, provisions that neutralize the impact of a change in coefficients may be necessary to preserve the original intent of commitments or agreements established prior to the revision of Tier 2 coefficients. Expert opinion should be sought on any site specific circumstances which might be relevant.

3.4 Revisions Resulting from Changing from Tier 2 Method to Tier 3 Method

A change from using the Tier 2 to the Tier 3 method should present no significant problems for recalculations and time series consistency as long as no major change has been made in operating technology at the facility (see footnote 11). Both Tier 2 and Tier 3 use aluminium production (tonnes), anode effect minutes per cell-day (which is the product of AED and AEF) or AEO, as the key inputs to the emission calculation. When changing from Tier 2 to Tier 3 methodology, the new Tier 3 smelter specific coefficient should be applied retroactively to the original anode effect process data and aluminium production data as far back as possible unless circumstances such as significant process changes would make the Tier 3 coefficient less representative than a more general Tier 2 coefficient for a given period. The objective of applying the same coefficient retroactively is to have the emission inventory reflect actual emissions trends and not the change from Tier 2 to Tier 3 methods. As noted above, consistency should be maintained within reporting and commitment periods. Expert opinion should be sought for any site specific circumstances which might be relevant.

3.5 Revisions Resulting from a Change in Tier 3 Site Specific Coefficients

If newly calculated equation coefficients, based on subsequent facility PFC measurements, do not differ from the previously established coefficients beyond measurement error, which

¹⁵ Tier 2 slope and overvoltage coefficients are given in *IPCC Guidelines for National Greenhouse Gas Inventories*, which is subject to review every 5-10 years

is typically <20%, the previous coefficient should remain in use and no emission recalculation is needed for historical data.

If the newly calculated equation coefficients do differ from the previously established coefficients and no significant process change has occurred (see footnote 11) the historical data should be recalculated using the newly established and validated Tier 3 coefficient.

If the newly calculated equation coefficients are due to a significant process change, the new coefficients, based on the new measurement, should be applied beginning with the date of the process change. The old coefficient should be used for the time series prior to the process change. Guidelines on the repetition of PFC measurements are described in the reference in footnote 10.

As noted earlier, expert guidance may be useful for managing specific situations.

3.6 Changing from the Overvoltage Method to the Slope Method, or, from Slope Method to Overvoltage Method

Where a consistent relationship between the two calculations based on the slope method and the overvoltage method can be demonstrated through time, an overlap approach can be used to calculate a factor to convert overvoltage coefficients to slope coefficients, or slope coefficients to overvoltage coefficients. A time series should then be constructed by assuming that the same relationship existed in previous periods. In such cases, emissions for past years are proportionally adjusted based on the relationship observed during the period of overlap.

3.6.1 Change of Method When Using Tier 2 Calculations

The transition from Tier 2 overvoltage method to the Tier 2 slope method, or, vice versa, can be accomplished by using the alternative CF_4 coefficient, either slope or overvoltage, to calculate the emissions of CF_4 per tonne of aluminium. The ratio of the two CF_4 emission rates obtained by the two methods should be calculated for the periods for which both types of data are available.¹⁶ The ratio between the two rates should then be used to adjust historical CF_4 emission rates that were calculated from the alternative method. C_2F_6 emissions are calculated as normally by multiplying the adjusted CF_4 emissions in kg CF_4 per tonne aluminium by the technology specific weight ratio of C_2F_6 to CF_4 .

3.6.2 Change of Method When Using Tier 3 Calculations

It is only possible to change from the Tier 3 overvoltage method to the Tier 3 slope method if anode effect overvoltage and anode effect minutes per cell day (AEF * AED) were recorded during the PFC measurements and used to determine the applicable coefficients. The new coefficient is then used to recalculate historical emissions to the first year for which appropriate anode effect minutes per cell day or overvoltage data were available.

¹⁶ To reduce uncertainty in the calculated ratio it is strongly recommended that the overlap period be at least one year.

The overlap approach outlined in Section 3.6.1 can be used to reconstruct the time series using the new desired method for earlier time periods.

3.7 Changing from Use of Algebraic Overvoltage to Positive Overvoltage Process Data

Positive overvoltage data is preferred over algebraic overvoltage data to correlate with PFC emissions. However, positive AEO process data may not be available over the entire time series of the PFC inventory. In this case it is possible to establish an accurate correlation between positive and algebraic overvoltage. The correlation data should be documented and the correlation used to recalculate historical emissions using positive overvoltage.

Appendix B Excel Spreadsheet Tool and Guidance for Calculating Total Carbon Dioxide Equivalent Emissions from Primary Aluminium Production



AI GHG Tool Oct 2006

1 Overview

1.1 Purpose and domain of application

This guidance is written for plant managers and site responsible personnel to facilitate the regular calculation and reporting of their corporate greenhouse gas direct¹⁷ emissions resulting from the primary aluminium production process at their facility. Guidance on CO₂ emissions from fuel combustion (e.g. for electrical power production and for alumina production) is provided in the WRI/WBCSD *Calculation tools for GHG emissions from energy and electricity*. A step-by-step approach is used to cover every phase of the calculation process from data gathering to reporting. Alternative paths are presented here in some instances in the form of multiple spreadsheet tools for calculating equivalent emissions results for some steps in the overall primary aluminium production process. These multiple paths to the same end result are offered because of the diversity in requirements of different producers resulting from voluntary or national reporting requirements and because of different historical data collection practices.

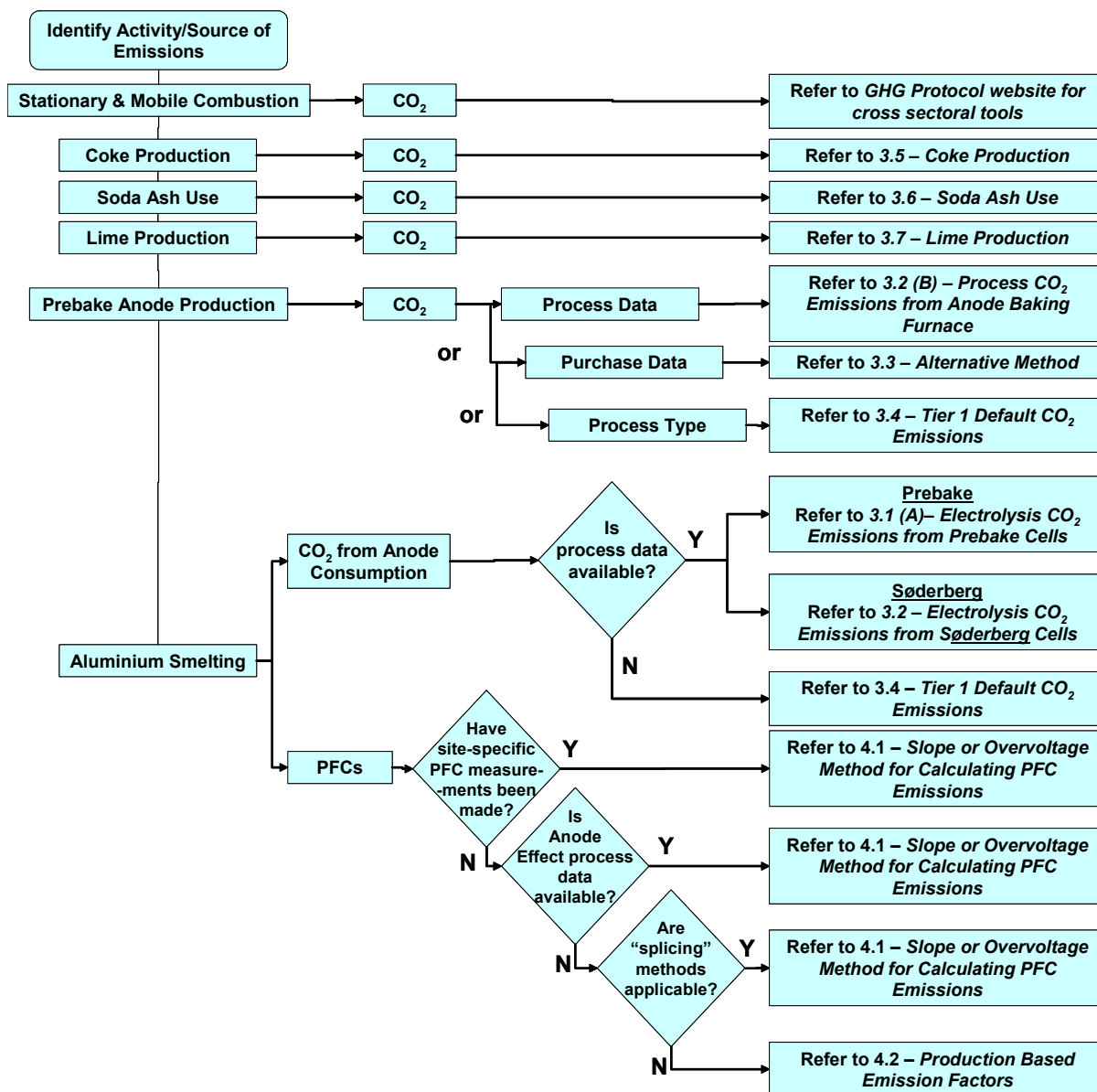
Figure 7 contains a flowchart to help guide the user in choosing which of the various spreadsheet tools available in the workbook to use in calculating emissions from primary aluminium production. Process boundaries should be carefully established according to the principles documented in the *GHG Protocol: A Corporate Accounting and Reporting Standard*.

The methodology proposed in this guideline is organised by type of greenhouse gas emissions. There are two main greenhouse gases produced during the production of aluminium (Al). Carbon dioxide (CO₂) is produced from the electrolytic reaction of carbon anodes with alumina. Two perfluorocarbons (PFCs), tetrafluoromethane (CF₄), and hexafluoroethane (C₂F₆) are also produced intermittently during brief process upset periods known as anode effects. SF₆ is not emitted during the electrolytic process and is only rarely

¹⁷ Direct emissions are those coming from sources that are owned or controlled by the reporting entity.

used in the aluminium manufacturing process, where small quantities are emitted when fluxing specialized high magnesium aluminium alloys¹⁸.

Figure 7 Calculation Tools for Evaluating Emissions from Primary Aluminium Production



1.2 Primary Aluminium Process Description

Primary aluminium is produced in two steps. Firstly, bauxite ore is ground, purified and calcined to produce alumina (also called aluminium oxide, Al₂O₃). Calculation of carbon dioxide emissions from this step is not covered in this document. The user can find the

¹⁸ A 2004 IAI survey found no evidence of SF₆ being emitted from primary aluminium smelting through the Hall-Heroult electrolytic production process.

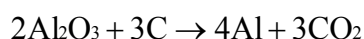
appropriate tools and guidance for calculation of CO₂ emissions from alumina production in the WRI/WBCSD *Calculation tools for GHG emissions from energy and electricity*.

Secondly, the alumina is electrolytically reduced to aluminium in large electrolytic cells (pots). These cells contain alumina dissolved in a molten cryolite bath (sodium aluminium fluoride). The electrolyte bath is contained in a carbon-lined steel shell, the lining of which acts as the cathode for the electrolytic reaction. The anode is carbon, which is partially submerged into the bath and is consumed in the reaction. Anodes may be either pre-baked in a separate process and attached to connecting rods for immersion in the bath (Prebake cells) or may be formed through self-baking from a paste of pitch and coke that is fed into the top of a steel casing above the cell (Søderberg design cells). The electrolysis of the aluminium oxide produces molten aluminium (Al) that deposits on the cathode, and carbon dioxide from oxidation of the carbon anode.

1.3 Process Emissions

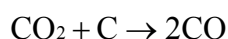
Most carbon dioxide is evolved from the reactions at the carbon anode, following Reaction 10.

Reaction 10

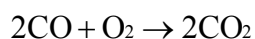


Some CO₂ is also formed as the anode reacts with air at elevated temperatures (following Reaction 11 and Reaction 12). This occurs during cell operation and, in the case of Prebaked electrodes, during anode production at the aluminium plant.

Reaction 11



Reaction 12

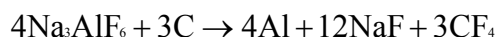


Additional CO₂ results from the oxidation of organic volatile materials during the baking of anodes for Prebake cells and cathode materials. The worksheet tool for calculation of CO₂ emissions from fuel combustion relating to the baking process is not provided in the Primary Aluminium Production Workbook; however the user is again referred to the WRI/WBCSD *Calculation tools for GHG emissions from energy and electricity*.

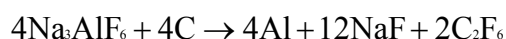
Some production facilities have integrated operations for using soda ash, calcining coke, and for the production of lime. Each of these processes produces CO₂.

PFCs are emitted intermittently during the electrolysis process during the time when electrolysis cells are on anode effect (following Reaction 13 and Reaction 14).

Reaction 13



Reaction 14



2 Choice of activity data and emission factors

This section identifies specific issues related to the choice of activity data (2.1) and emission factors (2.2) that are used in the emissions calculations. Because aluminium facilities typically track parameters enabling them to calculate emissions in accordance with Tier 2 or Tier 3 methods, as opposed to Tier 1, the factors involved in producing direct emissions of CO₂ from aluminium production do not vary greatly and errors involved in using Tier 1 methods should be less than ±6%.

2.1 Activity Data

Required data can be obtained from direct metering of aluminium production, facility process data records or from corresponding financial records.

2.2 Emission Factors and Slope/Overtoltage Coefficients

Table 11 shows the default CO₂ emission factors for Prebake and Søderberg cells.

Table 11 Tier 1 Technology Specific Emission Factors for Calculating Carbon Dioxide Emissions from Anode or Paste Consumption

Technology	Emission Factor (tonnes CO ₂ per tonne aluminium)	Uncertainty (±%)
Prebake ¹⁹	1.6	10
Søderberg	1.7	10

Table 12 shows the appropriate industry average emission factors for the calculation of PFCs emissions.

¹⁹ The emission factor for Prebake cells includes CO₂ emissions from the combustion of pitch volatiles and packing coke from baking anodes.

Table 12 Default Emission Factors and Uncertainty Ranges for the Calculation of PFC Emissions from Aluminium Production by Cell Technology Type

Technology	CF ₄		C ₂ F ₆	
	R _{CF₄} kg/tonne Al ^a	Uncertainty Range (%) ^b	R _{C₂F₆} kg/tonne Al ^c	Uncertainty Range (%) ^d
CWPB	0.4	-99/+380	0.04	-99/+380
SWPB	1.6	-40/+150	0.4	-40/+150
VSS	0.8	-70/+260	0.04	-70/+260
HSS	0.4	-80/+180	0.03	-80/+180

a. Default CF₄ values calculated from median anode effect performance from 1990 IAI survey data.
b. Uncertainty based on the range of calculated CF₄ specific emissions by technology from 1990 IAI anode effect survey data^{xii}.
c. Default C₂F₆ values calculated from global average C₂F₆:CF₄ ratios by technology, multiplied by the default CF₄ emission factor.
d. Uncertainty range based on global average C₂F₆:CF₄ ratios by technology, multiplied by calculated minimum and maximum specific CF₄ emissions from 1990 IAI survey data.
NOTE: These default emission factors should only be used in the absence of Tier 2 or Tier 3 data.

The slope and overvoltage methods for PFCs use industry average equation coefficients (Table 13). For more accurate inventories, direct PFC measurements are made at the specific facility to establish a smelter-specific relationship between operating parameters (i.e. frequency and duration of anode effects or Anode Effect Overvoltage).

Table 13 Technology Specific Slope and Overvoltage Coefficients for the Calculation of PFC Emissions per Tonne Aluminium from AE Process Data

Technology ^a	Slope Coefficient ^{b, c} [(kg PFC/t _{Al}) / (AE-Mins/cell-day)]		Overvoltage Coefficient ^{b, c, d, e} [(kg CF ₄ /t _{Al}) / (mV)]		Weight Fraction C ₂ F ₆ /CF ₄	
	S _{CF₄}	Uncertainty (±%)	OVC	Uncertainty (±%)	F _{C₂F₆/CF₄}	Uncertainty (±%)
CWPB	0.143	6	1.16	24	0.121	11
SWPB	0.272	15	3.65	43	0.252	23
VSS	0.092	17	NR	NR	0.053	15
HSS	0.099	44	NR	NR	0.085	48

a. Centre Worked Prebake (CWPB), Side Worked Prebake (SWPB), Vertical Stud Søderberg (VSS), Horizontal Stud Søderberg (HSS).
b. Source: Measurements reported to IAI, US EPA sponsored measurements and multiple site measurements.
c. Embedded in each Slope and Overvoltage coefficient is an assumed emissions collection efficiency as follows: CWPB 98%, SWPB 90%, VSS 85%, HSS 90%. These collection efficiencies have been assumed based on measured PFC collection fractions, measured fluoride collection efficiencies and expert opinion.
d. The noted coefficients reflect measurements made at some facilities recording positive overvoltage and others recording algebraic overvoltage. No robust relationship has yet been established between positive and algebraic overvoltage. Positive overvoltage should provide a better correlation with PFC emissions than algebraic overvoltage.

e. Overvoltage coefficients are not relevant (NR) to VSS and HSS technologies.

Where PFC emissions performance is such that no significant improvement can be expected in the overall facility GHG inventory using the Tier 3 rather than the Tier 2 method (where Tier 2 calculation indicates PFC emissions below 0.03 kg CF₄ per tonne of aluminium), facilities can elect to use either method.

2.3 Completeness of GHG Sources

The guidance provided here covers emissions and direct carbon dioxide and PFC emissions resulting from aluminium reduction and supporting processes. Emissions from the combustion of fossil fuels associated with the production of electricity, primary aluminium production downstream processes such as ingot casting or product fabrication, bauxite mining, bauxite ore refining, and aluminium production from recycled sources are covered in *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

3 Direct CO₂ Emissions from Reactions at the Carbon Anode

To calculate the CO₂ emissions evolved from aluminium production processes use **Worksheet 1** for Prebake cells.

For Söderberg cells use **Worksheet 2** if the quantity of carbon containing anode materials used is known (weight per reporting period or per unit of production in metric tons).

Worksheet 3 is applicable to either Prebake or Söderberg cells and provides an alternative way of calculating CO₂ emissions based on purchase records of carbon containing materials.

It is important to note that CO₂ emissions resulting from primary aluminium production originate directly from the electrolysis process described above, and also from the energy needed for the process, if this energy is produced from fossil-fuel combustion. If electrical energy is derived from fossil fuels, use the *WRI/WBCSD Calculation tools for GHG emissions from energy and electricity* to calculate indirect CO₂ emissions.

3.1 If the quantity of anode materials is known for Prebake cells

Calculation steps for Worksheet 1

Warning: The user should note that the lettering of columns as described here in the guidance and in the spreadsheet calculation tools correspond to the added labels and not to the inherent Excel column designations.

Part A –Electrolysis Carbon Dioxide Emissions from Prebake Cells

1. In **Column A** enter the amount of primary aluminium produced (in tonnes) during the reporting period. Enter data for each potline on a different line.
2. In **Column B** enter for each potline the net anode consumption per tonne of aluminium produced.
3. In **Column C** enter available data for non-carbon components of baked anodes. If no data is entered for sulphur and ash contents, industry typical values are used as defaults in the calculation.
4. In **Column D** the CO₂ emissions during the reporting period for each potline are auto calculated.
5. The total value for all potlines is auto calculated at the bottom of **Column D**.

Part B - Process Carbon Dioxide Emissions from Anode Baking Furnace

1. In **Column A** enter the average weight of green and baked anodes (in tonnes). The anode baking weightloss factor is autocalculated from these values.
2. In **Column B** enter the total weight of baked anodes produced (in tonnes) during the reporting period.
3. In **Column C** the weight of loaded green anodes (in tonnes) is autocalculated.
4. In **Column D** enter the average hydrogen content in green anodes (in weight percent). It can be calculated by multiplying hydrogen fraction in pitch by pitch fraction in green anode. If no data is entered for hydrogen content, an industry typical value is used as default in the calculation (0.5% of green anode weight).
5. In **Column E** enter the weight of waste tar collected from the furnace (in tonnes). If no data is available input the following values: *Riedhammer* furnace – 0.5% of green anode weight; all other furnaces – '0'.
6. In **Column F** enter available data for packing coke consumption per tonne of baked anode produced. If no data is entered, an industry typical value is used as a default in the calculation.
7. In **Columns G** enter available data for non-carbon components of packing coke. If no data is entered for sulphur and ash contents, industry typical values are used as defaults in the calculation.

8. In **Column H** the CO₂ emissions during the reporting period for each furnace are auto calculated.
9. The total carbon dioxide emissions for the baking periods for which data are entered are auto calculated at the bottom of **Column H**. Carbon dioxide emissions from the fuel consumed during baking are not counted here. Such emissions should be accounted for using tools in the WRI/WBCSD *Calculation tools for GHG emissions from energy and electricity*.

3.2 If the quantity of anode materials is known for Söderberg cells

Calculation steps for Worksheet 2

1. In **Column A** enter the type of Söderberg potline for which data is being entered, either Horizontal Stud Söderberg (HSS) or Vertical Stud Söderberg (VSS), using the drop-down box. Enter data for each Söderberg potline on a different line.
2. In **Column B** enter the amount of primary aluminium produced (in tonnes) during the reporting period corresponding to the technology type entered in **Column A**.
3. In **Column C** enter the weight of anode paste (in tonnes) used for each tonne of aluminium produced.
4. In **Column D** enter available data on weight of cyclohexane soluble matter emitted (in kg) per tonne of aluminium produced. If no data is entered, industry typical values are used as defaults in the calculation.
5. In **Column E** enter the average binder content in paste (as a weight percentage). If no data is available input the following values: Dry paste – ‘24’; Wet paste – ‘27’.
6. In **Columns F** and **G** enter composition data for pitch and coke used in anode formulation. If no data is entered in **Columns F** and **G**, industry typical values (VSS or HSS) are used for the calculation.
7. In **Column H** enter available data on weight of carbon dust emitted (in tonnes) per tonne of aluminium produced. If no data is entered, industry typical values are used as defaults in the calculation.
8. In **Column I** carbon dioxide emissions are auto calculated based on the data entered for each Söderberg potline.
9. The total value for all potlines is auto calculated at the bottom of **Column I**.

3.3 Alternative Method for CO₂ Emissions Based on Consumption of Carbon Containing Materials

Calculation steps for Worksheet 3

1. In **Columns A** through **F** enter the amount of carbon containing materials consumed (as tonnes) and the carbon content of the material consumed (as weight percent) for each reporting period. If no data is entered on carbon content in **Columns B, D** and **F**, industry typical values are used for the calculation.
2. In **Column G** enter the amount of carbon by-products or waste output for each reporting period. This entry reduces the amount of potential CO₂ emissions from materials consumed.
3. In **Columns H** through **K** enter the mass of anodes either purchased or sold (in tonnes) and the corresponding carbon content (as weight percent) to make appropriate adjustments for anode materials purchased and sold. If no data is entered on carbon content in **Columns I** and **K**, industry typical values are used for the calculation.
4. In **Column L** the amount of carbon dioxide emissions resulting from the consumed carbon containing materials is calculated for each reporting period.
5. The total value for all periods is auto calculated at the bottom of **Column L**.

3.4 Tier 1 Default CO₂ Emissions

If quantity of carbon containing material is not known use **Worksheet 4**, with emission factors for calculated from values presented in Table 11. It is good practice to use default emission factors only as a last resort, when only metal production statistics are available.

Calculation steps for Worksheet 4

1. In **Column A** enter the type of process potline (Prebake or Søderberg) for which data is being entered. Enter data for each potline on a different line.
2. In **Column B** enter the amount of aluminium produced (in tonnes) during the reporting period. Enter values for each process on a different line.
3. In **Column C2** the corresponding emission factor found in Table 11 is automatically entered upon entry of the type of process in **Column C**. Alternatively custom emission factors can be entered into **Column C1**.
4. In **Column D** the result of the multiplication of the weight of aluminium produced (**Column B**) by the emission factor (**Column C**) is auto calculated.

5. The total value for all periods is auto calculated at the bottom of **Column D**.

3.5 Coke Calcination CO₂ Emissions

For those facilities that operate coke calcination facilities Worksheet 5 should be used to calculate CO₂ emissions. The CO₂ emissions from the combustion of fuel associated with the calcination is not included here. Such emissions should be accounted for using tools in the *WRI/WBCSD Calculation tools for GHG emissions from energy and electricity*.

Calculation steps for Worksheet 5

1. In **Column A** enter the amount of green coke (in tonnes) calcined during each reporting period.
2. Enter non-carbon composition parameters for water, volatiles and sulphur contents (as weight percent) in **Columns B** for the green coke. If no data is entered in **Column B**, industry typical values are used for the calculation.
3. Enter in **Column C** the weight of calcined coke produced from the green coke in **Column A**.
4. Enter in **Columns D** through **F** parameters characterizing the calcined coke including sulphur content (as weight percent), undercalcined coke recovered and dust emissions from the calcining operation (in tonnes). If no data is entered in any of the **Columns D** through **F**, industry typical values are used for the calculation.
5. In **Column G** the CO₂ emissions are auto calculated from the entered data.
6. The sum of all the calculations for all the entered reporting periods is auto calculated and reported at the bottom of **Column G**.

3.6 Emission of CO₂ From Soda Ash used in Aluminium Production Processes

Calculation steps for Worksheet 6

1. In **Column A** enter the amount of soda ash consumed (in tonnes) during each reporting period.
2. Enter in **Column B** the purity of the soda ash consumed as a decimal fraction. If no data is entered, an industry typical value is used for the calculation.
3. In **Column C** the emissions of CO₂ are auto calculated from the data entered for each reporting period.

4. CO₂ emissions are auto totalled for all entries in **Column C**.

3.7 Lime Production CO₂ Emissions

Calculation steps for Worksheet 7

1. In **Column A** enter the amount of quick lime produced (in tonnes) during each reporting period.
2. In **Column B** enter the purity of the quick lime produced as a decimal fraction. If no data is entered, an industry typical value is used for the calculation.
3. In **Column C** enter the amount of slaked lime produced (in tonnes) during each reporting period.
4. In **Column D** enter the purity of the slaked lime produced as a decimal fraction. If no data is entered, an industry typical value is used for the calculation.
5. In **Column E** the emissions of CO₂ are auto calculated from the data entered for each reporting period.
6. CO₂ emissions are auto totalled for all entries in **Column E**.

4. Direct PFC Emissions from electrolysis reaction

Two PFCs, CF₄ and C₂F₆, are emitted from primary aluminium production. They are formed during brief upset conditions known as "Anode Effect" (AE), when alumina levels drop too low and the electrolytic bath itself undergoes electrolysis. This results in Reaction 13 and Reaction 14. PFC emissions increase with frequency, intensity and duration of AEs.

To calculate the PFCs emissions evolved from primary aluminium production process(es) two methods are proposed depending on the type of data available.

4.1 Slope or Overvoltage Method

For most primary aluminium facilities a slope factor calculated from the ratio of emissions in kg PFC per tonne aluminium to anode effect minutes per cell day is the appropriate factor to calculate PFC emissions. However, for point fed centre work Prebake or side work Prebake facilities using overvoltage control technology that record overvoltage, the overvoltage method should be used. The results of the most appropriate method should be used in **Worksheet 8**.

The most accurate calculations of PFC emissions are based on slope, overvoltage and proportion factors that are the result of making field measurements of emissions of CF_4 and C_2F_6 using good measurement practices to accurately establish the relationship between emissions and process data (See the USEPA/IAI *PFC Measurement Protocol* for information on conducting direct PFC measurements).

Calculation steps for Worksheet 8

Equation 1 – Anode Effect Minutes Per Cell Day (Slope Method)

1. In **Column A**, enter the type of cell from the drop down box and quantity of aluminium produced for the reporting period. Enter data from each potline on a different line.
2. In **Column B** enter the average anode effect minutes per cell day. To calculate average anode effect duration (**B2**) anode effect frequency values can also be entered into **B1**.
3. **Column C** contains the IPCC recommended Tier 2 slope factor for CF_4 . Replace this value with the facility specific Tier 3 slope factor if measurements have been made according to good practice guidance.
4. In **Column D** tetrafluoromethane (CF_4), emissions are auto calculated according to the slope method.
5. **Column E** contains the IPCC recommended Tier 2 weight fraction of C_2F_6 to CF_4 . Replace this value with the facility specific Tier 3 fraction if measurements have been made according to good practice guidance.
6. Emissions of hexafluoroethane, C_2F_6 , are auto calculated based on the weight fraction entry in **Column E** and CF_4 emissions calculated in **Column D**.
7. CF_4 emissions in **Column D** are multiplied by 6.5 and C_2F_6 emissions in **Column F** are multiplied by 9.2 to convert both to tonnes carbon dioxide equivalent emissions. The carbon dioxide equivalent emissions sum for both PFC compounds is automatically calculated in **Column G** for each type of reduction process.
8. The total carbon dioxide equivalent emissions are auto totalled at the bottom of **Column G**.

Equation 2 – Anode Effect Overvoltage (AEO) Method (Prebake potlines with Pechiney control system only)

1. In **Column A**, enter the type of cell from the drop down box and quantity of aluminium produced for the reporting period. Enter data from each potline on a different line.

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2. In **Column B** enter the average anode effect overvoltage (in mV per cell) and current efficiency for aluminium production (in %).
3. **Column C** contains the IPCC recommended Tier 2 overvoltage factor for CF₄. Replace this value with the facility overvoltage factor if measurements have been made according to good practice guidance.
4. In **Column D** tetrafluoromethane (CF₄), emissions are auto calculated according to the overvoltage method.
5. **Column E** contains the IPCC recommended Tier 2 weight fraction of C₂F₆ to CF₄. Replace this value with the facility specific fraction if measurements have been made according to good practice guidance.
6. Emissions of hexafluoroethane, C₂F₆, are auto calculated based on the weight fraction entry in **Column E** and CF₄ emissions calculated in **Column D**.
7. CF₄ emissions in **Column D** are multiplied by 6.5 and C₂F₆ emissions in **Column F** are multiplied by 9.2 to convert both to tonnes carbon dioxide equivalent emissions. The carbon dioxide equivalent emissions sum for both PFC compounds is automatically calculated in **Column G** for each type of reduction process.
8. The total carbon dioxide equivalent emissions are auto totalled at the bottom of **Column G**.

4.2 Production Based Emission Factors

If no data on anode effect minutes per cell day, or anode effect overvoltage are available, use **Worksheet 9**, with emission factors for CF₄ calculated from values presented in Table 12. It is good practice to use default emission factors only as a last resort, when only metal production statistics are available.

Calculation steps for Worksheet 9

1. In **Column A**, enter the type of cell from the drop down box and the amount of aluminium produced (in tonnes) during the reporting period. Enter values for each process on a different line.
2. In **Column B** the weight of CF₄ emitted is auto-calculated using the appropriate emission factor found in Table 12. Alternatively custom emission factors can be entered.
3. In **Column C** the weight of C₂F₆ emitted is auto-calculated using the appropriate emission factor found in Table 12. Alternatively custom emission factors can be entered.

4. CF₄ emissions in **Column B** are multiplied by 6.5 and C₂F₆ emissions in **Column C** are multiplied by 9.2 to convert both to tonnes carbon dioxide equivalent emissions. The carbon dioxide equivalent emissions sum for both PFC compounds is automatically calculated in **Column D** for each type of reduction process.
5. The total value for all periods is auto calculated at the bottom of **Column D**.

5 Total CO₂ Equivalent Emissions

Total CO₂ equivalent emissions from aluminium production for the entire facility can be calculated using **Worksheet 10**.

Calculation steps for Worksheet 10

1. The total CO₂ values from **Worksheet 1** through **9** are automatically entered in **Column A**.
2. Add all the values entered in **Column A**. This value is calculated automatically.

6 Quality control

To ensure the credibility of the inventory, rigorous QA/QC procedures should be followed to ensure the accuracy, transparency, and verifiability of the estimates. The following issues must be addressed:

1. Checks should ensure that the best and most accurate emission factors are being used. If custom emission factors are available, are there any significant differences with the corresponding default values?
2. What methodology was used to compute the company or plant specific emission factors?
3. Is it in line with IPCC guidelines?
4. Has the site documented the sources of its emissions factors?

7 Reporting and Documentation

The worksheets contained are not sufficient to provide fully transparent reporting. To improve transparency, *good practice* is to report emissions estimates for CF₄ and C₂F₆ separately on a mass basis, as well as in CO₂ equivalents. The GWPs used are consistent with the UNFCCC guidelines for compliance with Kyoto Protocol reduction targets, currently 6 500 for CF₄ and 9 200 for C₂F₆.

While the IPCC *Third Assessment Report*^{xiii} published newly revised global warming potential values for a number of gases including revisions for CF₄ and C₂F₆, **Kyoto Protocol Decision 2/CP.3, Methodological issues related to the Kyoto Protocol**, paragraph 3, reaffirms that

global warming potentials used by Parties should be those provided by the IPCC in its *Second Assessment Report*^{xiv} (“1995 IPCC GWP values”) based on the effects of the greenhouse gases over a 100-year time horizon, taking into account the inherent and complicated uncertainties involved in global warming potential estimates.

Appendix C Aluminium Industry Specific Definitions

Anode Effect

An 'anode effect' (AE) is a process upset condition of an aluminium electrolysis cell due to too little alumina dissolved in the electrolyte. The anode effect is accompanied by a release of CF_4 and C_2F_6 . Intervention is required to return the pot to a normal operating level, typically through the further addition and dissolution of alumina, and temporarily shorting between anodes and the metal pad to remove the gas film beneath the anodes.

The anode effect begins when the voltage rises rapidly and exceeds a threshold voltage (A), typically 6-10 volts.

The anode effect is considered to be terminated when the voltage falls below, and remains below a second voltage (B), typically 4.5-8 volts for a defined time (t), typically 15 minutes.

Anode Effect Minutes Per Cell Day

Anode effect minutes per cell day (24 hours) are the total minutes measured that the cell spends on anode effect, above the threshold voltage A.

Positive Anode Effect Overvoltage

During the anode effect, the AEO is calculated as the sum of the product of time and voltage above the threshold voltage B, divided by the time over which the data are collected (hour, shift, day, month etc.).

Algebraic Anode Effect Overvoltage

During the anode effect, the AEO is calculated as the sum of the product of time and voltage above and below the threshold voltage B, divided by the time over which the data are collected (hour, shift, day, month, etc.).

Non Steady State Emissions

The special condition of extended voltage operation during new cell start up is not counted as an anode effect, although the situation does result in a release of CF_4 and C_2F_6 .

Aluminium Smelting Technologies:

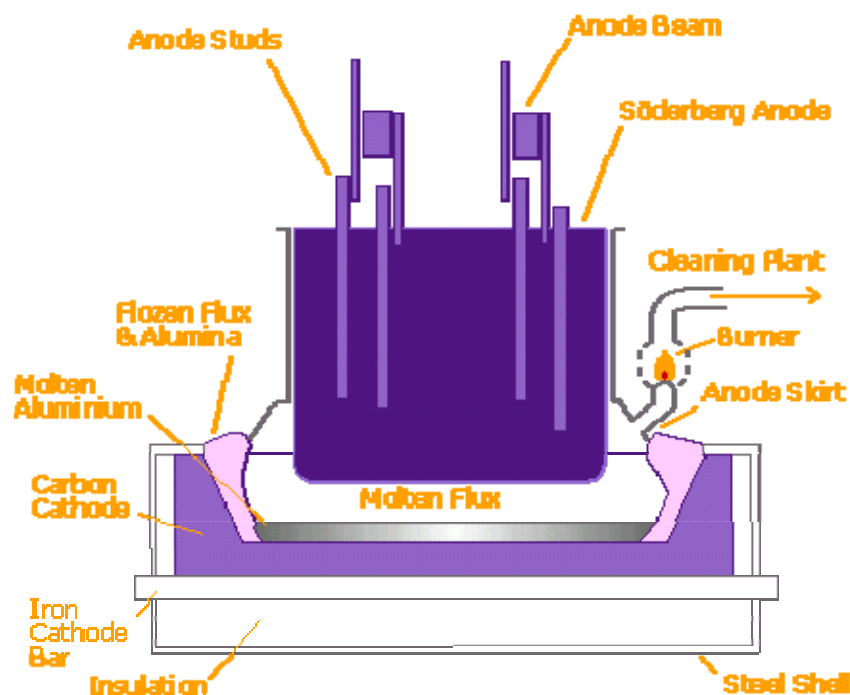
There are two main types of aluminium smelting technology - Søderberg and Pre-bake. The principal difference between the two is the type of [anode](#) used. Søderberg technologies use a continuous single anode. The anode is continuously formed by periodically adding a paste of coke and pitch to the top of the anode structure. The high temperature of the cell (pot)

bakes the paste into a solid anode. Prebake technologies use anodes made from a paste of coke and pitch, which are first pressed into rectangular “green” anodes and then pre-baked, or fired, in a special oven. The Prebake anodes are attached to “rods” and suspended in the cell. New anodes are exchanged for spent anodes - “anode butts”, which are recycled into new anodes.

Horizontal Stud Søderberg (HSS) Technology

The distinguishing feature of HSS technology is the placement of the electrical connections or studs, which are placed horizontally into the anode along its length on both sides of the cell. In general, the cells are hooded, with four moveable doors. Anode effect control ranges from manual to automated. Cell doors must be opened in order to feed alumina manually between the anode and the longitudinal side of the cell into the bath and manually terminate anode effects.

Vertical Stud Søderberg (VSS) Technology



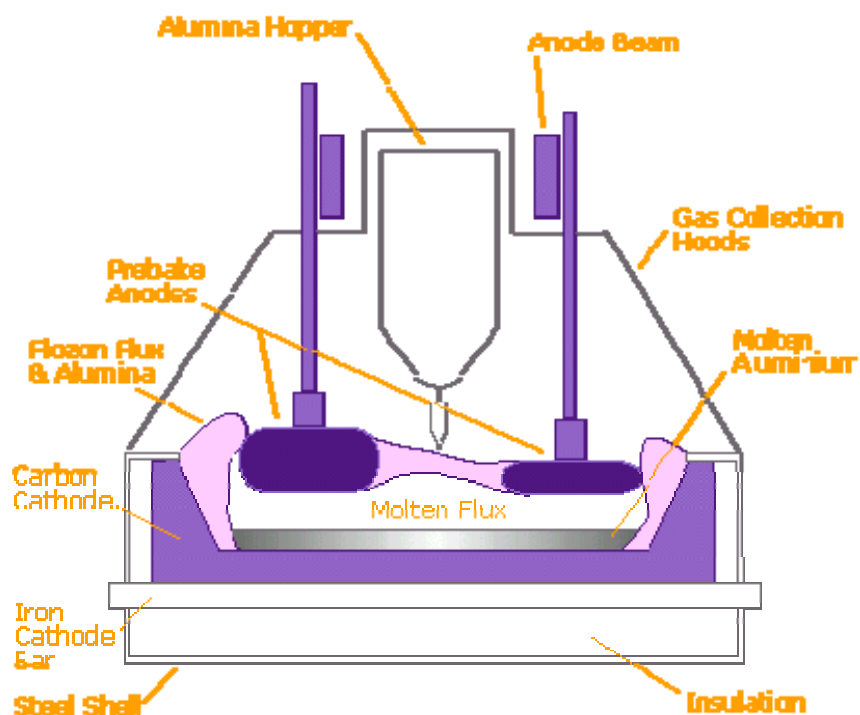
VSS technology studs are placed vertically into the top of the anode, as shown in the figure above. The exhaust gas from these cells is collected using a combination of a narrow “gas skirt” adjacent to the anode, and the frozen bath which forms the “hood” over the remainder of the electrolytic bath. Anode effect control ranges from manual to automated alumina feeding systems between the anode and the longitudinal side of the cell, as well as manual and automated anode effect termination.

Side Worked Prebake (SWPB) Technology

The distinguishing feature of SWPB technology is that alumina feeding and other cell activities are performed along the longitudinal sides of the cell. The cells are hooded in

general with a liftable panel on each side. Anode effect controls range from manual to automated alumina feed systems, in conjunction with automated anode movement capabilities. Cell panels must be opened in order to feed alumina manually into the bath.

Centre Worked Prebake (CWPB) Technology



The distinguishing feature of CWPB technology is that alumina feeding and all other cell activities are performed along the longitudinal centre line of the cell (see above). Cells are hooded with multiple small panels. Key features related to anode effects are an automated and individual alumina feeding system in conjunction with automated anode movement capabilities. Cell doors are not opened in order to feed alumina into the bath as all feeding is done through hoppers on the cells.

Appendix D References

- ⁱ WRI/WBCSD (2004), *The Greenhouse Gas Protocol – A Corporate Accounting and Reporting Standard (Revised Edition)*, World Resources Institute/World Business Council for Sustainable Development, Washington, DC: <http://www.ghgprotocol.org/DocRoot/7e9ttsv1gVKekh7BFhqo/ghg-protocol-revised.pdf>.
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- ⁱⁱⁱ IAI (2000) *Life Cycle Inventory Of The Worldwide Aluminium Industry, Paper 1 – Automotive*, International Aluminium Institute, London, UK: http://www.world-aluminium.org/iai/publications/documents/full_report.pdf
- ^{iv} ISO/FDIS 14064-3 (pending), *Greenhouse gases - Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions*: <http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=38700&scopelist=PROGRAMME>
- ^v Aluminium Association of Canada (2003) *Greenhouse Gas Audit Manual*, Aluminium Association of Canada, Montreal, Canada
- ^{vi} IAI (2004), *Aluminium for Future Generations Sustainability Update*: http://www.world-aluminium.org/iai/publications/documents/update_2004.pdf.
- ^{vii} IPCC (2006, pending), *IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 3, Section 4.3, CO₂ and PFC Emissions from Primary Aluminium Production, pp 4.25-4.38.
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- ^{ix} IAI Unpublished Data
- ^x IAI (2002), *Perfluorocarbon Emissions Reduction Programme 1990 - 2000*, International Aluminium Institute, London, UK: <http://www.world-aluminium.org/iai/publications/documents/pfc2000.pdf>
- ^{xi} USEPA/IAI (2002), *Protocol for Measurement of Tetrafluoromethane (CF₄) and Hexafluoroethane (C₂F₆) Emissions from Primary Aluminium Production*. U.S. EPA Climate Protection Partnerships Division, Washington, DC: http://www.world-aluminium.org/environment/climate/pfc_measurement.pdf.
- ^{xii} IAI (2002), *Perfluorocarbon Emissions Reduction Programme 1990 - 2000*, International Aluminium Institute, London, UK: <http://www.world-aluminium.org/iai/publications/documents/pfc2000.pdf>
- ^{xiii} IPCC (2001), *Third Assessment Report*, Geneva, Switzerland: <http://www.ipcc.ch/pub/reports.htm>
- ^{xiv} IPCC (1995), *Second Assessment Report*, Geneva, Switzerland: <http://www.ipcc.ch/pub/reports.htm>