PFC Emissions Reductions: The Domestic and International Perspective

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Introduction

As the political and policy issues of climate change are being resolved, industry has an unprecedented opportunity to contribute to environmental protection and the needs of future generations by taking early action to reduce emission of greenhouse gases. Primary aluminum producers are already setting an example for other industries by taking steps to evaluate and reduce emissions of one of the most potent greenhouse gases: perfluorocarbons (PFCs). Primary aluminum production is the largest source of emissions of two PFCs, tetrafluoromethane (CF_4) and hexafluoroethane ($C2F_6$). Through a partnership between the U.S. Environmental Protection Agency (EPA) and the U.S. aluminum industry known as the Voluntary Aluminum Industrial Partnership (VAIP), twelve U.S. primary aluminum producers are reducing these emissions. PFCs contribute to the greenhouse effect by trapping heat in the atmosphere and are amongst the most persistent atmospheric pollutants known to man. The importance of PFCs in the atmosphere has become the focus of international attention as concern about greenhouse gas emissions increases. The Kyoto Protocol, negotiated in December 1997, established total greenhouse gas emissions reduction targets for developed countries, while allowing each country the flexibility to determine the most cost-effective policies for meeting its target. PFCs are one of six gases that the Protocol includes for potential emissions reductions.

Primary aluminum producers in most of the major aluminum producing countries have taken steps to reduce PFC emissions. However, ongoing efforts indicate further reductions can be expected. Systematic information sharing on emission reduction techniques, refining emission measurement methods, additional basic research on the generation of PFCs and triggers for anode effects will better enable the industry to achieve cost-effective, technically feasible emission reductions. Early action to reduce emissions has a double benefit for aluminum manufacturers. PFC emissions reductions improve production process efficiency and will enable the industry to stay ahead of policy decisions on climate change. This article outlines current U.S. and international activities by the industry to reduce emissions and opportunities for further action.

PFCs and Global Climate Change

CF_4 and C_2F_6 are formed as intermittent by-products during anode effects in the production of primary aluminum. In addition to generating PFCs, anode effects negatively impact aluminum current efficiency. These PFCs are greenhouse gases, characterized by strong infrared radiation absorption and relative inertness in the atmosphere. The "global warming potential" (GWP) of these compounds, a measure that considers expected atmospheric lifetime and infrared absorbing capacity, is high. One ton of CF_4 and C_2F_6 emissions is equivalent to approximately 6,500 and 9,200 tons respectively of carbon dioxide emissions when the warming effect is considered over a 100-year period. Estimated atmospheric lifetimes of CF_4 and C_2F_6 are on the order of 50,000 and 10,000 years respectively. Annual PFC emissions from U.S. aluminum smelting plants in 1996 were estimated by EPA to be the equivalent of about 11 million metric tons of carbon dioxide (CO_2).[1]

VAIP and PFC Emission Reductions

The U.S. government and the aluminum industry are interested in reducing PFC emissions. The government seeks to reduce emissions of greenhouse gases and increase awareness of successful domestic efforts to reduce those emissions. Industry is interested in reducing emissions because, in addition to protecting the environment, reducing PFC emissions can boost profits since anode effects negatively impact current efficiency and reduce productivity.

To reduce PFC emissions, the aluminum industry and EPA jointly developed the VAIP Program. The VAIP sets company-specific PFC emission reduction targets and includes periodic reporting of progress achieved toward those emissions reduction goals.[2,3,4,5] As of November 1998, 11 U.S. primary aluminum producers have joined the VAIP and set company-specific emission reduction targets jointly with EPA. As shown in Table I, the VAIP partner companies represent about 94% of U.S. production capacity. While each company's emissions reduction goal is tailored to site-specific conditions, the overall program goal is to reduce PFC emissions from VAIP partners by 45% from 1990 levels by the year 2000, assuming that production levels in 2000 will be similar to those in 1990. This is equivalent to reducing about 8 million metric tons of carbon dioxide emissions annually.

The primary approach for reducing PFC emissions from aluminum smelting in this time frame is to reduce the frequency and duration of anode effects to the extent that is technically and economically practical. Previous studies have established that PFCs are only emitted during the occurrence of anode effects.[7,8] In general, PFC emissions for a given level of aluminum production increase with increases in the frequency and/or duration of anode effects. The three main strategies for reducing anode effect frequency and duration and, hence, emissions are: training staff on methods and practices which minimize the frequency and duration of anode effects, upgrading alumina feed practices to point feed control systems and using improved computer controls to optimize cell performance. Brief summaries of partner activities under the VAIP are presented in Figure 1.

Company	% of Total
Aluminum Company of America (Alcoa)*	34%
Alumax, Inc.*	14%
Reynolds Metals, Inc.	11%
Kaiser Aluminum & Chemical Co.	7%
Century Aluminum Co.	5%
Noranda, Inc.	5%
Southwire Co.	4%
Alcan Aluminum Corp.	4%
Columbia Falls Aluminum	4%
Goldendale Aluminum Co.	4%
Vanalco	3%
Northwest Aluminum	2%
Total	94%

* Alcoa purchased Alumax, Inc. in 1998.
Source: Aluminum Statistical Review for 1996.[6]
Total 1996 capacity = 4,201,000 tons
Totals may not sum due to independent rounding.

Table I. Summaries of VAIP partner activities.

The Alcan Ingot, Sebree Aluminum plant began to realize reductions of calculated PFC's in May 1998. These reductions were accomplished through the use of a computer-based "demand feed" system which optimizes the alumina feed rate into the aluminum reduction cells, thereby reducing "anode effects" and the resulting liberation of PFCs. Alcan-Sebree has spent $1.6 million to date installing the equipment. The reductions of calculated PFC emissions have been dramatic. Typical values prior to May 1998 were 0.30 to 0.40 kg CF_4 / MT Al, whereas the emissions since that date are calculated to be at 0.16 kg CF_4 / MT Al.

Alcoa has made excellent progress toward the year 2000 Voluntary Aluminum Industrial Partnership goal with a reduction in anode effects by almost 70% from the 1990 baseline. Currently Alcoa is pursuing both near term strategies and longer term, breakthrough strategies for making further decreases in emissions of polyfluorinated carbon compounds (PFCs). For the near term, continuing emphasis is being placed on reducing the frequency of occurrence of anode effects through increased attention to work practices and sharing of best practices across Alcoa's international primary aluminum operations. Looking toward the longer term, Alcoa is participating in a joint research program at MIT with U.S. EPA and other U.S. aluminum producers to better understand the fundamentals of PFC generation with an objective of reducing emissions when anode effects occur, or, eliminating anode effects altogether. Other research in a program with the U.S. Department of Energy is being conducted at the Alcoa Technical Center on new inert materials to replace the carbon anodes that produce the PFCs during anode effects.

Century Aluminum has made efforts to improve process control and reduce anode effect frequency through refined computer feed control and a better-educated workforce. Today's workforce is being armed with key information and accurate process control to quickly react to feed and operational issues. Enhanced stability and efficiency of its operation will result in improved cell-related emissions at Century Aluminum.

Columbia Falls Aluminum Company has installed a computerized anode effect suppression system to reduce PFC emissions. This system, which is activated at a preset voltage, significantly reduces anode effect duration. Columbia Falls is also investigating the optimum alumina feed rate to reduce anode effects. In addition to reducing PFC emissions, the company expects these activities to reduce emissions of other gases as well.

Goldendale Aluminum Company has taken several actions to reduce anode effect frequency during the past couple of years. An employee involvement team regularly meets to identify, develop, and implement anode effect, voltage, and energy reduction measures. The team developed a predictive anode effect suppression program using the cell line computer system. Testing has shown an anode effect decrease, and the program has been implemented plant-wide. Goldendale expects that reducing anode effects will also reduce energy consumption and lower cell line emissions.

Kaiser Aluminum is pursuing two main approaches for reducing PFC emissions: educating employees on both operating practices for reducing the frequency and duration of anode effects and on the environmental impacts of anode effects; and continuing to refine feed control strategies used by the computer system that manages cell operations. This combination of activities has proven effective for Kaiser and will produce benefits in addition to reducing PFC emissions. For example, the cost of the latest control strategy upgrade was offset significantly by the reduction in anode effect minutes per ton of aluminum produced.

Noranda Aluminum, Inc. has reduced PFC emissions by improving its computer control systems. For example, in 1983, Noranda adopted a new control system that significantly reduced anode effects on a potline that began operation in that year. As a result of upgrades and continual improvement in potline operations, Noranda has reduced anode effects by more than 70 percent since 1990. In addition to reducing PFC emissions, these upgrades have improved energy efficiencies and process stability.

Northwest Aluminum Company installed a computerized anode effect suppression system to reduce anode effect times. Northwest has also been investigating the optimum alumina feed rate to reduce anode effects. In addition to reducing PFC emissions, Northwest Aluminum expects these activities will reduce power consumption and other gas emissions.

NSA - A Division of Southwire has continually improved computer control systems and control programs to minimize the frequency and duration of anode effects, and thereby reduce PFC emissions. In addition to reducing PFC emissions, these efforts improve cell efficiency and reduce energy consumption, thereby reducing all emissions associated with primary aluminum production.

Reynolds Metals Company's commitment to environmental responsibility has been a core value for the company since its founding in 1919. Today, social responsibility, which includes environmental performance, is one of Reynolds' six corporate values by which the company manages its worldwide businesses. Since 1970, the company has decreased anode effect events by 42 percent at its operating U.S. reduction plants. Reynolds is continuing its research on anode effects to achieve further improvement, and has also instituted the AWARE program, a company-wide employee involvement program to prevent pollution.

Vanalco, Inc. completed computerization of its potlines in the late 1980s and implemented anode effect suppression control. In 1995, upgraded computer hardware allowed more sophisticated control of anode effects. The focus of the effort has been to prevent pollution by installation and optimization of computer control systems which tightly regulate the amount of alumina in solution to avoid anode effects, promptly identify anode effects when they occur and correct them as soon as possible. Vanalco made a commitment under VAIP in 1995 to reduce PFC emissions by 60% from a 1990 baseline level by the year 2000 as measured by anode effect frequency. Vanalco's five potlines, which are the oldest operating potlines in the United States, had an average of 1.81 anode effects per pot day during the 1990 baseline year. The control system was implemented plant-wide six months ago. Since that time anode effect frequency has been reduced to 0.52 anode effects per pot day which constitutes a 71% reduction.

Figure 1. VAIP partners and portion of 1996 national production capacity.

U.S. PFC emissions from aluminum production are estimated to have declined from the equivalent of 18 million metric tons of CO_2 in 1990 to the equivalent of 10.6 million metric tons in 1996, a reduction of 41%.[1] This decline was both due to reductions in domestic aluminum production and actions taken by the VAIP partners to reduce the frequency and duration of anode effects (Table II). The average PFC emissions rate for VAIP partners is estimated to have declined from the equivalent of about 4.5 tons of CO_2 per metric ton of aluminum in 1990 to the equivalent of about 3 tons of CO_2 per metric ton of aluminum in 1996, a reduction of about 33%. The change in emission rates incorporates data on reductions in the frequency and duration of anode effects reported by the

VAIP partners. As of 1996, the VAIP had achieved over 70% of its emission reduction goal (assuming a 45% reduction target and that production levels in 2000 will be similar to those in 1990).

PFC emissions were estimated by multiplying annual aluminum production by a PFC emission rate that changes over time. U.S. industry-average emission rates presented in the Climate Change Action Plan (CCAP) Technical Supplement — 0.6 and 0.06 kg per metric ton of aluminum for CF_4 and C_2F_6 respectively — are assumed for all smelters for the base year 1990.[1] In subsequent years, PFC emission rates are assumed to decline over time as a result of VAIP progress. The rate of decline in the emission rate is equivalent to the rate of decline in the operating parameter targeted for reduction by each smelter (e.g., anode effect frequency or duration). To calculate VAIP reductions, estimated emissions were subtracted from "baseline" emissions, which are those anticipated in the absence of the VAIP program and assuming that the CCAP emissions rate remains constant over the period of analysis.

Improving the Understanding of PFC Emissions

A better understanding of the mechanism of PFC generation at the anode during aluminum smelting is essential for improving the accuracy of estimated emissions and identifying strategies to reduce emissions. VAIP has initiated two projects to improve the understanding of PFC emissions and key factors influencing their generation: (1) a PFC Emissions Measurement Program, and (2) bench-scale investigations of the processes that control PFC generation in the electrolytic cell at the Massachusetts Institute of Technology (MIT).

PFC Emissions Measurement Program: VAIP is sponsoring emission measurements at individual smelters to better understand PFC emissions and develop algorithms to relate emission rates to operating parameters and smelter characteristics. Data from these measurements will assist in identifying how operating parameters can be changed to reduce emissions and contribute to the empirical basis for tracking progress toward reducing emissions under VAIP. A first set of measurements has already been completed at seven partner smelters, and additional measurements at six partner smelters are underway.

In the first round of measurements, PFC emissions were measured from the exhaust ducts that remove gases from the cells as well as from the potroom roofs using a "time-integrated" sampling technique. Data on smelter operating parameters (anode effect frequency and duration) were collected simultaneously while measurements were underway. The data were then analyzed to identify whether the operating parameters could be used to predict PFC emissions. The measurements offered useful insights into PFC generation and emissions. The data showed a clear trend toward lower PFC emissions with reduced anode effect frequency and duration. Comparison of these results with other smelter measurements further supported the hypothesis that reducing anode effect frequency and duration reduces PFC emissions. However, there was considerable variability in emissions across smelters, which suggest that there may be other operational parameters or smelter characteristics that affect emission rates.[5]

While the "time-integrated" sampling technique was appropriate for estimating overall site emission rates, it did not provide emissions data for individual anode effects. To collect data on individual anode effects, "continuous real-time" measurements of PFC emissions and simultaneous operational data collection are proposed for the second round of measurements at six partner smelters in 1999. The second round of measurements also involves collecting data on the voltage profile of anode effects, which has shown correlation to emissions in both bench-scale studies at MIT (discussed below) and other measurements.[8,9]

Anode Effect Research at MIT: The VAIP Program, in conjunction with the Aluminum Association, is sponsoring anode effect research at MIT's Department of Materials Science and Engineering, under the direction of Professor Donald R. Sadoway. The purpose of this research is to understand the mechanism of PFC generation and determine the relationship between PFC emissions and process variables. This understanding should provide insights into which operational strategies would likely lead to further reductions in PFCs.

The first phase of this research, conducted from 1995 through 1997, involved constructing and testing a laboratory-scale electrolytic cell. Tests of the cell indicate that it mimics performance of a commercial cell in many respects, including current density, temperature, melt composition, anode composition and PFC production during anode effect. Results with the cell confirm that PFCs are generated only during anode effects. The measured ratios between CF_4 and C_2F_6 were within the range of those found in measurements at smelters.[8]

Electrolysis experiments were conducted to examine the impacts of the systematic variation of cell operating parameters on PFC emissions. The results indicate that the excess cell voltage attributed to anode effects, or anodic overvoltage, is the major factor influencing the intensity of PFC generation.[8] Efforts are currently ongoing to conduct experiments designed to provide an understanding of the underlying kinetics of an anode effect. Preliminary results indicate that PFC evolution occurs at cell potentials exceeding 6.0 V. Also, contrary to a recent study claiming that detection of certain fluorocarbon compounds (e.g., COF_2) may be used as a precursor to determine if a cell is about to go on anode effect, the experiments found no indication of such gases at the initial stages of an anode effect.[10]

International Efforts to Reduce PFC Emissions

PFCs are one of six gases that the Kyoto protocol specifically includes for potential emissions reductions—the others are carbon dioxide, methane, nitrous oxide, sulfur hexafluoride and hydrofluorocarbons. It is up to each country to decide what combination of emissions reductions, from the various gases, would be pursued to meet their emissions reduction goal. A country could meet its protocol obligations through a number of means, including domestic emissions reductions, domestic activities to

	1990	1991	1992	1993	1994	1995	1996
Primary Production ('000 m tons)	4,048	4,121	4,042	3,695	3,299	3,375	3,577
Emissions Rate (m tons CO_2/ ton Al)	4.5	4.2	3.7	3.5	3.2	2.9	2.9
Emissions (m tons CO_2)	18.0	17.3	15.0	13.0	10.4	9.9	10.6
VAIP Reductions (m tons CO_2)		1.1	3.0	3.5	4.3	5.2	5.3

The GWPs used for CF_4 and C_2F_6 are 6,500 and 9,200 respectively, over a 100-year period.[1]

Table II. Estimated PFC emissions and VAIP reductions: 1990 - 1996.

absorb carbon (e.g., planting trees) or international emissions trading. To understand the scope of international PFC reduction activities, VAIP completed a survey of the programs established by other countries to reduce PFC emissions from aluminum smelting.

Worldwide Aluminum Production and PFC Emissions: In 1996, 20.7 million tons of aluminum were produced worldwide in 44 countries. Production has been on the rise since 1990, largely due to increased production in developing countries. In 1996, however, the majority of aluminum was produced in industrialized countries and in those transitioning into market economies.[11]

Figure 2 shows aluminum production and the share of global production for the leading producer nations for 1996. The U.S. topped the list with 17% of the world total, followed by Russia with 14% and Canada with 11%.[11] Most major producer nations have programs to reduce PFC emissions from aluminum smelting (Figure 2). These countries accounted for 56% of total production in 1996. China and Russia are the two largest producers that do not have programs to reduce PFC emissions from aluminum smelting. These countries accounted for 23% of total production in 1996.

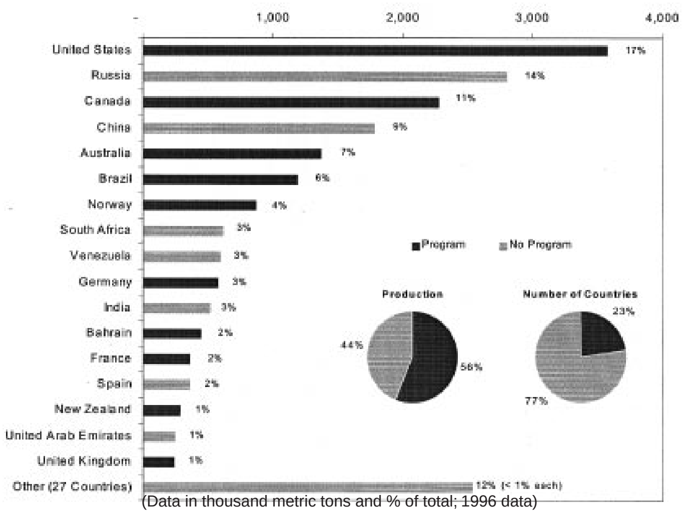

Figure 2. Countries with PFC reduction programs.

Global aluminum production is projected to increase from about 20 million metric tons in 1996 to about 30 million metric tons in 2020, a rate of increase of about 2% per year.[12] As a result of increased global aluminum production, PFC emissions will also likely increase, but at a slower rate than aluminum production. This is because emission factors are expected to decrease over time due to the industry/government emission reduction efforts in the major producer countries and the diffusion of modernized smelter technologies resulting from capital stock replacement.

International Reduction Efforts: International PFC reduction programs include voluntary programs between industry and government and regulatory programs mandated by government. Through voluntary programs, governments aim to provide incentives for producers to implement practices and technologies for reducing PFCs without mandating specific techniques. Typically, stakeholders set emission reduction targets, either company-specific or industry-wide. Once the targets are set, a process to monitor and track progress toward achieving these reductions is established. Methods include monitoring programs and periodic reporting by industry. The government is responsible for improving the diffusion of relevant science and technology research and practices. In addition, the government may highlight the accomplishments of the program and publicly recognize participating companies. Regulatory programs, on the other hand, may mandate best available technology or predefined performance standards that are economically feasible. Regulatory programs also generally require emission monitoring and reporting.

As of November 1998, ten countries have undertaken industry/government initiatives to reduce PFC emissions from aluminum smelting: Australia, Bahrain, Brazil, Canada, France, Germany, New Zealand, Norway, United Kingdom and the U.S. Eight countries have voluntary reduction programs, and two, New Zealand and the United Kingdom, have regulatory programs. Table III summarizes each country's program and the emission reduction activities undertaken at the smelter level.

The scope of emission reduction activities varies from country to country. In some countries, like the U.S., the programs are restricted to PFC emissions from aluminum smelting. Other countries, such as Australia and Canada, have included all greenhouse gases and cover the entire aluminum industry, including alumina refineries and semi-fabrication facilities. In these countries, the programs cover energy consumption related CO_2 emissions, as well as CO_2 and PFC emissions associated with the aluminum smelting process.

While the scope of the programs vary across countries in terms of the greenhouse gases covered and extent of aluminum industry involvement, the emission reduction activities undertaken at the company level are similar. The types of activities instituted at the company level to reduce PFC emissions from aluminum smelting can be divided into three categories: best management practices, technical initiatives and research initiatives.

• Best Management Practices: These activities are considered good operating practices and are instituted at some level in all smelters worldwide. Activities that comprise best management practices include: educating employees on practices that reduce the frequency and duration of anode effects; supplying employees the tools to monitor alumina concentrations; and holding regular employee involvement team meetings of help to identify, develop and implement anode effect, voltage, and energy reduction measures.

• Technical Initiatives: These initiatives involve the use of state-of-the-art technologies, which are best available technologies that have a proven track record in actual production environments. The state-of-the-art PFC emission reduction technologies that are being used in many countries include computerized anode effect suppression systems that reduce anode effect duration and point feed systems that control alumina feed.

• Research Initiatives: Many countries are engaged in research and development activities that will lead to the development of advanced technologies and practices that are expected to have a significant impact on PFC emissions in the next 10 to 20 years. A long-term industry initiative that is being pursued aggressively through government-industry research and development efforts in several countries is the development of the nonconsumable inert anode. These inert anodes do not utilize carbon, thereby eliminating the source of carbon for PFC and CO_2 generation during aluminum production. This technology also promises to reduce the energy required to produce a ton of aluminum significantly, thereby reducing energy related CO_2 emission as well.

In countries whose programs include CO_2 and PFCs, CO_2 emission reductions have been achieved largely due to actions taken to improve the energy efficiency of the production process. The actions include developing more efficient baking furnaces, improvements in potline design that will reduce per unit electricity requirements and fuel

Country	Program Type	Program Description	Emission Reduction Activities
Australia	Voluntary	Aims to reduce PFCs from alumina refineries and aluminum smelters. From 1990–1997, PFC emissions decreased an estimated 73%.	• PFC reductions through employee training, improvements in the control of anode effects and refinement of automated control systems • Energy efficiency through modernization of pot line design and operation; improved management of compressed air; fuel switching etc.
Bahrain	Voluntary	Aims to reduce PFC and other GHG emissions from aluminum smelters. By 1998, PFC emissions were limited to 0.12 kg/metric ton of aluminum produced.	• Installation of automated control systems • Improved operator training for managing systems
Brazil	Voluntary	Targets PFC and CO_2 emissions from aluminum smelters. In 1996, average PFC emission factor dropped 31% from 1994 levels.	• Improved process control • Application of advanced computer control systems
Canada	Voluntary	Aims to improve energy efficiency and reduce PFC and CO_2 emissions from aluminum smelters. Program goals are reduce PFC emissions by 50% from 1990 levels by 2000 energy intensity by 0.3%/year until 2010.	• Use of computerized point-feeders • Use of automated control systems that reduce anode effect frequency and duration • Replacement of carbon cathode blocks by graphite blocks
France	Voluntary	Aims to reduce PFCs from aluminum smelters and CO_2 emissions from alumina refining, smelting, and recycling operations. The sole primary producer, Pechiney, has committed to reducing CO_2 and CF_4 by 34% from 1990 levels by 2000.	• PFC reductions through employee training, improvements in the control of anode effects and use and refinement of automated control systems • Energy efficiency through optimization of combustion equipment, fuel switching and cogeneration, improved fabrication processes etc.
Germany	Voluntary	Aims to reduce PFC emissions from smelters and other GHG emissions from the alumina refineries, smelters, and post-production processes. Goal is to reduce total PFCs by at least 50% from 1990 levels by 2005.	• Improved employee training on process management • Modernization of aluminum smelters using best available technology
New Zealand	Regulatory	Sole smelter is required to follow process and technology standards to reduce PFCs. From 1990-1995, PFC emissions from aluminum smelting decreased by 67%.	• Changes to control strategies to reduce the frequency and duration of anode effects and upgrades to reduction cell control systems • Efficiency improvements for fuel use
Norway	Voluntary	Aims to reduce CO_2-equivalent emissions from aluminum smelters. Goal is to reduce PFC emission rate by 50% from 1990 levels by 2000 and by 55% from 1990 levels by 2005.	• Installation of point-feed systems and improvements to existing point-feed systems • Refinement of process control systems and routines.
United Kingdom	Regulatory	Country has set technology standards to reduce PFC emissions from aluminum smelters. PFC emissions are expected to fall from 300 tons in 1990 to 30 tons in 2000.	• Training staff on practices to reduce anode effect frequency and duration • Installation of new computer controls of the primary pot lines.
United States	Voluntary	Aims to reduce annual PFC emissions from smelters by 30 to 60% by 2000 from 1990 levels. Program covers only PFCs from aluminum smelting.	• Training staff on practices to reduce anode effect frequency and duration • Upgrades to alumina feed practices to point feed systems • Improved computer controls to optimize cell performance

* In the Netherlands, Iceland, Spain and Sweden, internal discussions on programs to reduce PFC emissions have begun, but no agreements are in place as of November, 1998. The Netherlands does have a voluntary program on energy reduction in the aluminum industry.[13]

Table III. Summary of country programs.

switching.

Achievements and Challenges: The activities undertaken by companies have been successful in reducing PFC emissions. All countries have reported a decline in PFC emissions per ton of aluminum produced (i.e. the PFC emission factor). When evaluating the progress reported by different countries in reducing emissions, it should be recognized that emission estimation methods differ across countries, in addition to the technology mix of the smelters.

Some of the PFC estimation methods available to countries include the Faraday's Law Model, the Pechiney Over-Voltage Model, the Slope Model and Smelter Measurements.

•Faraday's Law Model: Proposed by Tabereaux,[7] this method assumes that the generation of CF_4 in electrolysis cell follows Faraday's Law. Faraday's Law states that the quantity of gas generated depends on the flow of electrical current in the cell. PFC emissions can be calculated using the following equation:

$$\text{kg } CF_4/\text{ton of aluminum} = 1.698 \times (p/CE) \times AEF \times AED$$

Where p is the average fraction of CF_4 in the cell gas during anode effects; CE is the current efficiency; AEF is the number of anode effects per cell day; and AED is the anode effect duration in minutes. Limiting the usefulness of this approach is uncertainty regarding how best to estimate p for various operating conditions and cell technologies.

• Pechiney Over-Voltage Model: This method uses the anode effect over-voltage as the relevant process parameter by integrating the fluctuation in voltage during an anode effect. The correlation formula was derived from numerous test measurements of PFC generation at different Aluminium Pechiney smelters.

$$\text{kg } CF_4/\text{ton of aluminum} = 1.9 \times AEO \;/\; \%\, CE$$

Where AEO is the anode effect over voltage in mV, CE is the current efficiency in percent.[9] One of the drawbacks of this method is that many smelter process systems do not have the capacity to collect the data required to compute the anode effect over voltage. These smelters, therefore, cannot use this model.

• Slope Model: This method proposes a linear relationship between anode effect minutes/cell-day and CF_4 emissions, expressed as:

$$\text{kg } CF_4/\text{ton of aluminum} = \text{slope} \times \text{AE minutes/cell-day}$$

Workers at Hydro Aluminium and Alcoa first expressed this relationship based on field measurements at their prebake facilities. Both companies independently arrived at a slope of 0.12.[14] The first round of VAIP sponsored measurements in the U.S. also indicate a slope of approximately 0.12 for prebake cells.[5]

• Smelter Measurements: The most accurate method is to measure PFC emission rates from smelters under normal operating conditions. Field measurements have been conducted in many countries, including Canada, Germany, Norway and the U.S. The main drawback is that field measurements are time consuming and expensive. Consequently, the data from these measurements are used to develop and validate models used to estimate emissions.

In addition to these methods, there are still others that are unique to certain countries. One such methodology is based on industry-average PFC emission factors, which is currently used by the VAIP and was described earlier (efforts are underway to enable the VAIP partnership to use the more site-specific smelter measurement approach in the future).

Table IV presents PFC emission factors, percent reduction in the PFC emissions factors and emission estimation methodologies reported by the individual countries. Using emission reductions reported by each country, PFC emissions rates were converted into a common unit, met-

Country	t CO_2-*e*/ t Aluminum[1]		Years	Reduction		Emission
	Start Year	End Year	Start-End	Overall %	% per year	Estimation Method[2]
Australia	3.9	0.9	'90-'97	78%	19%	Other[3]
Bahrain[2]	NA	1.1	1996	NA	NA	Pechiney Over-voltage Model
Brazil[2]	1.9	1.3	'94-'96	31%	17%	Faraday's Law Model
Canada	5.4	2.7	'90-'95	49%	13%	Smelter Measurements
France[2]	7.0	1.9	'90-'97	73%	17%	Pechiney Over-voltage Model
Germany[2]	3.3	2.5	'90-'96	23%	4%	Smelter Measurements
New Zealand	2.5	0.8	'90-'95	69%	21%	NA[4]
Norway	3.0	2.0	'90-'93	34%	13%	Smelter Measurements
United Kingdom	9.0	2.8	'90-'96	69%	18%	Other[5]
United States	4.5	3.0	'90-'96	33%	7%	Other[6]

1. The unit for the PFC emissions factor is tons of CO_2 equivalent per metric ton of aluminum. Both CF_4 and C_2F_6 are included. GWPs for CF_4 and C_2F_6 are 6,500 and 9,200 respectively. The emission factors reported are either (1) directly reported from the primary contact in each country, or (2) derived from data reported by the primary contact, the country's national communication submitted to the United Nations Framework Convention on Climate Change (FCCC), and production data provided in [11]. For more details on these numbers see the report "International Efforts to Reduce Pefluorocarbon (PFC) emissions from Aluminum Smelting" [13]
2. C_2F_6 emissions were not reported; for this analysis, it was assumed C_2F_6 emissions are 10% of CF_4 emissions.
3. Emission factor estimates are based on 1) a linear regression model of emissions in U.S. and Norway; 2) IPAI international survey; and 3) an estimating model developed for an Australian smelter.
4. Not available.
5. Specific method is unknown. Information gathered indicates that emission factors based on anode effect frequency and anode effect duration were developed for U.K. smelters.
6. Discussed earlier in the text.

Table IV. PFC emissions reductions.

ric ton of CO_2 equivalents per metric ton of aluminum produced.

The number of estimation methods raises questions about accuracy and comparability. Each method has merits to recommend it, but none of them, with the possible exception of direct measurements, is free of methodological limitations that potentially affect its ability to accurately estimate PFC emissions. If applied to the same set of operating conditions, the various methods would quite likely predict different emissions levels. This complicates the picture that emerges when trying to compare and contrast emissions reductions across countries that use different methods, which might skew the results. No industry or government consensus on a PFC estimation method has yet emerged, but ongoing efforts promise to move us in that direction.

Research in the U.S. as well as other countries will continue to improve our understanding of the relationship between operating parameters and PFC emissions. The efforts of the International Primary Aluminium Institute (IPAI), especially with regard to the collection and analysis of anode effect data and PFC emissions, are further expanding this understanding.[14] Additionally, in coordination with the international community, the Intergovernmental Panel on Climate Change (IPCC) is currently working on refining the methods it recommends that countries use to inventory their greenhouse gas emissions, including PFCs.

Outlook for International PFC Reduction Efforts

There are readily available technologies and well-documented operational practices that will reduce PFC emissions from aluminum smelting. Many of the major producer countries are already taking advantage of these opportunities. Emission rates will continue to decline in these countries. Additional opportunity exists to make progress in other countries, including Russia and China, which are major producers.

Although most companies, countries and programs have generally been successful in their PFC emission reduction efforts, several challenges and uncertainties may hinder accelerated PFC reduction efforts worldwide. Some of these include:

- Making capital investments in new technologies, which may be difficult for some companies due to extremely high costs
- Understanding the mechanisms of PFCs generation during anode effects in order to identify and implement strategies to reduce emissions
- Quantifying emissions in order to verify emission reductions for international policy mechanisms

The first of these points, lack of access to capital, is especially a problem in developing countries and in those with economies in transition. The next two points are subjects of ongoing research worldwide, and are areas that could benefit significantly from international collaboration.

Conclusion

VAIP partners have been successful in reducing PFC emissions from aluminum smelters. They are well on their way to achieving the goal of reducing annual emissions of PFCs from aluminum smelters by 45% by the year 2000 from 1990 levels, assuming that production levels in 2000 will be similar to those in 1990. So far they have achieved over 70% of that goal. The initiatives under the VAIP are continuing to expand at both the national and international level.

In the U.S., two VAIP efforts are under way that have made significant progress in understanding PFC generation: 1) measurements at partner smelters and 2) bench-scale investigations into the PFC generation process at MIT. These activities have provided valuable insights into the operating parameters and smelter characteristics that may influence PFC emissions. Additional smelter measurements planned for 1999 will provide an expanded data set for validating and enhancing models for estimating PFC emissions. In addition, future bench-scale investigations will comprise experiments designed to provide a clearer understanding of PFC emissions and the mechanisms that generate them.

At the international level, VAIP has initiated a data collection effort on the programs established by other countries to reduce PFC emissions from aluminum smelting. Current data indicate that the aluminum industry has been responsive to government initiatives aimed at reducing PFC emissions from primary aluminum production. PFC emission reduction measures not only reduce PFC and other greenhouse gas emissions, but also improve process efficiency. As a result, both industry and government have an interest in implementing these measures. Technologies and practices for reducing PFC emissions from aluminum smelting are readily available, and many of the major producer countries are well underway to implementing these techniques. Additional opportunity exists to make progress in other countries, including Russia and China, which are major producers.

Primary aluminum producers are well positioned to meet the challenge of climate change. Current activities in the U.S. and across most of the major aluminum producing countries have been successful in reducing PFC emissions from aluminum smelters. Further action by all producers to minimize PFC emissions from the aluminum industry will give the public and government confidence that the aluminum industry is aggressively pursuing emissions reductions of greenhouse gases and minimizing the build up of long-lived atmospheric chemicals. Expanding cooperation through technical information sharing, partnerships with government and further investigations into the PFC generation process are expected to result in additional cost-effective emissions reductions that will benefit both the industry and the environment.

If you want more information about this paper, VAIP, or would like to receive a copy of EPA's upcoming report — International Efforts to Reduce Perfluorocarbon (PFC) Emissions from Aluminum Smelting (scheduled for April 1999) — please contact Dr. Dolin at (202) 564-9044 or dolin.eric@epa.gov.

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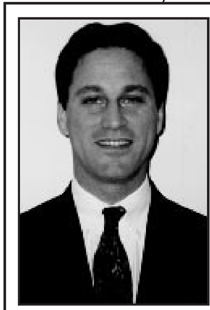

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